Particle and nuclear physics instrumentation and its broad connections

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Particle and Nuclear Physics Instrumentation and Its Broad Connections

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Subatomic physics shares with other basic sciences the need to innovate, invent, and develop tools, techniques, and technologies to carry out its mission to explore the nature of matter, energy, space, and time. In some cases, entire detectors or technologies developed specifically for particle physics research have been adopted by other fields of research or in commercial applications. In most cases, however, the development of new devices and technologies by particle physics for its own research has added value to other fields of research or to applications beneficial to society by integrating them in the existing technologies. Thus, detector research and development has not only advanced the current state of technology for particle physics, but has often advanced research in other fields of science and has underpinned progress in numerous applications in medicine and national security. At the same time particle physics has profited immensely from developments in industry and applied them to great benefit for the use of particle physics detectors. This symbiotic relationship has seen strong mutual benefits with sometimes unexpected far reach.

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I. INTRODUCTION

The mission of particle physics is to study the fundamental constituents of matter and energy and the interactions between them and to explore the basic nature of space and time (CERN Council, 2006; US Department of Energy, 2015). The primary methods which have been used to carry out these studies have been a) detecting elementary particles present in naturally occurring cosmic radiation, particles emitted from decays of unstable nuclei, or particles emitted from nuclear reactors and measuring their properties, b) searching for new elementary particles as well as detecting and studying the number, kinematics, and properties of particles emerging from collisions between accelerator generated colliding particle beams or emerging from accelerator generated particle beams incident on a stationary target at increasingly higher beam energies, c) performing non-accelerator based experiments to study the properties of space itself or to search for new elementary particles, and d) performing non-accelerator experiments to detect and measure the properties of particles at ultra-high energies, well beyond those which can ever be reached by accelerators.

The nature of experiments in nuclear and particle physics has required the development of a variety of specialized instrumentation to deal with very large arrays of detectors sensitive to very small signals within large backgrounds. This has lead to the need to select the processes of interest at unprecedently high data rates in extreme radiation environments and to deal with uniquely large globally distributed data volumes. Exponentially growing levels of computational power are required to analyse experimental data, perform theoretical calculations and carry out simulations. Currently, the fidelity and precision of simulations of particle accelerators, detectors, and the evolution of the universe are determined by the state-of-the-art in computing and communication technologies. The instrumentation developed in particle physics often uses state-of-the art technology developed in fields such as computer science, condensed matter physics, materials science and integrated circuits. In particle physics these technologies are applied in non-commercial and often extreme contexts. In this paper we attempt to outline the connections between instrumentation development in nuclear and particle physics and trace their applications to other fields, as well as the use and adaptation of the rich palette of technologies that are continuously being developed in modern society (Allport *et al.*, 2009; Charpak, 2004). Within the physics community a subset of scientists make substantial contributions to the development of particle detector technologies. Many of these scientists come from the particle physics community but substantial contributions are also made by nuclear physicists and physicists from other sub-disciplines. In subsequent sections we will use the term "particle physics" to represent both particle physics and nuclear physics and "particle physicist" to represent the entire community of scientists developing particle detector technologies.

Progress in detector technology has been responsible for many of the major advances in particle physics research. Much of our current understanding of ordinary matter in the universe, such as the discovery of quarks, the nature of the neutrino, the imbalance between matter and antimatter and the forces that govern their interactions, could not have been accomplished without the increasingly sophisticated detectors, which have been developed and used in particle physics experiments in the past several decades. Today the mission of particle physics is carried out by using a spectrum of detectors and detection techniques in widely varying experimental environments.

DeBroglie's formula $\lambda = h/p$, where h is Plank's constant and λ is the wavelength of a particle with momentum p, shows that in order to confine a particle into a smaller volume by reducing its wavelength, the particle's momentum and, correspondingly, its kinetic energy must be increased. Smaller and smaller wavelengths and thus higher and higher particle energies are needed to probe deeper into matter. Furthermore, because of the equivalence of mass and energy through the equation $E = mc^2$, the search for new, high-mass particles has required the use of high energy accelerators. High energy particle accelerators have become a trademark of particle physics. Combined with sophisticated detector systems they are used to create new forms of matter often detected through the study of their decay products or inferred from the overall event topology. Large numbers of particle interaction products are measured at high rates generating the high statistics needed to study the detailed properties of these particle interactions as well as providing a sufficiently large sample size to search for rare events. These detector systems for accelerator experiments must operate reliably at very high rates over long periods of time, frequently in high radiation environments. They also require intelligent triggering and data acquisition systems capable of handling enormous data volumes and separating low-rate signals from very large backgrounds and rapidly storing the data produced.

Determining the physical properties of the reaction products emerging from these high energy interactions, either in collider or fixed target mode, requires very large, high-resolution detector systems. These very large, and very expensive, systems are virtually unique to particle physics research. As the need for larger, higher resolution, and faster detector systems has grown, they must be designed and developed by particle physics researchers, because they typically have no immediate commercial value and are customized to high energy particle physics research. Experimental particle physicists have long been forced to develop new technologies and refine existing technologies to meet the technological requirements of new experiments and to keep the costs manageable.

Particle physics is not only carried out using particle accelerators. Studies of ultra-high energy cosmic rays use detectors embedded in Antarctic ice, in large bodies of water, or use extensive arrays of land based detectors distributed over large areas. Experiments using nuclear reactors with nearby arrays of neutrino detectors are being carried out to study the properties of neutrinos.

Ultra-sensitive, radio-pure detectors are used to search for rare radioactive decays to study the properties of neutrinos, and to search for interactions between ordinary matter and dark matter, which is inferred to exist because of observed anomalies in the gravitational behavior of astronomical matter. Cryogenic detectors with ultra-high energy resolution are being used to study the cosmic microwave background to elucidate properties of the early universe. Similarly, large focal planes mounted on telescopes in the northern and southern hemisphere are used to study dark energy believed to be responsible for the accelerating expansion of the universe.

Many of the technologies developed and technological refinements carried out by particle physicists have proven useful to other fields of scientific research. Conversely, nuclear physics has made contributions that were highly beneficial to the whole scientific community. And sometimes particle and nuclear physics have shared in the development and refinement of detector technologies and occasionally detectors developed primarily for a particular specialized research area have become broadly useful in several others. For example, the construction of ultra-pure detector systems for dark matter or rare decay searches exploits many technologies and techniques developed and refined initially by nuclear physicists, while the Time Projection Chamber (TPC), which was initially developed by high-energy particle physicists, is now widely used in nuclear physics research.

Particle physics techniques and technologies have also been used in astrophysics, basic energy sciences, biology, and archeology. In addition there are many examples of the value of these technologies in medical and national security applications. In some cases, entire detector systems or technologies developed in particle physics have become generally useful. One classic example is the development of the World Wide Web, an information system of interlinked hypertext documents accessed via the internet which is credited to Tim Berners-Lee, then a scientist at CERN trying to solve the problem of making information quickly available to collaborators widely dispersed over the world. In many cases, however, existing detectors used in fields outside of particle physics have benefited by adopting wholly or in part technologies developed or refined in particle physics to improve detector capabilities, to reduce cost, or both. Technologies developed and/or refined by particle physicists have been particularly beneficial in fields where the scale of experiments or the need for large detectors has increased.

In this article we explore the relationship between science and society and the experimental tools, technologies and techniques developed specifically for particle physics research[1]. At the outset it must be emphasized that almost all particle physics detector systems and subsystems have in the past and continue to rely heavily on the available technology which has been developed over many years by all the sciences and industry. For example, some detectors widely used in particle physics such as the photomultiplier tube, whose invention is generally credited to industry (although there is some dispute about this (Lubsandorzhiev, 2006)) was originally adopted and then optimized and refined for a variety of particle physics applications. Today, there is still a close relationship between industry which develops photomultiplier tubes and the particle physics community which uses them for a variety of research applications. In other areas of detector development, such as the development of specialized and radiation hard electronics, fiber optic readout systems, and large-scale and distributed computing, particle physicists have built on an existing knowledge and technology base to develop new and specialized applications.

When existing technologies are not sufficient or too expensive, however, particle physicists have been forced to use fundamental physical principles to invent and exploit novel new devices, some of which have ultimately proved useful to other areas of science. The Time Projection Chamber (TPC) was invented as an electronic tracking detector to mitigate some of the drawbacks of multi-wire proportional chambers. The TPC, widely used in particle and nuclear physics, is currently being considered for security applications as a neutron detector (Heffner, 2009; Orwig, 2012).

Although particle physicists have played a major role in particle accelerator development and particle accelerators are now widely used in many scientific, medical, industrial, and national security applications, the majority of applications specifically associated with accelerator development are outside the scope of this article[2]. Also, although the technical and analytical skills of particle physicists has proving useful in many other fields such as high tech industry, information technology, medical instrumentation, electronics, communications, biophysics, and finance, this topic is also generally beyond the scope of this article. Here we concentrate on the technologies associated with particle detectors and their applications in other scientific work, in the medical community, in industry, and for national security.

The structure of this paper is as follows. In the first part of Section II we describe a variety of detectors and techniques particle physicists use to accomplish their mission. This provides the framework for the second part of Section II, which identifies areas of possible applications to other fields. Based on this list, Section III identifies many representative examples of applications of the technologies and expertise developed, extended, or refined by particle physicists to other sciences and areas which are beneficial to society as a whole. In Section IV we discuss the connection between developments in particle physics and industry. Section V describes opportu-

[1] We are not restricting applications to be only those involving *high* energy particles - as long as elementary particles are used in the application a broad range of particle energies are included. Thus, some applications blur the distinction between particle and nuclear physics

[2] Exceptions are when accelerators or reactors are used to activate materials which are then analyzed by the radiation they emit after activation.

nities where particle physics can exploit new technological developments in other areas of science and industry, and where, conversely, technologies developed by particle physicists are likely to find use outside of the field of particle physics. A final summary and concluding remarks are given in Section VI. A glossary which defines a number of words and abbreviations used in this article follows section VI.

II. PARTICLE PHYSICS DETECTOR TECHNOLOGIES AND TECHNIQUES

A. An Overview of Particle Physics Detectors

The experimental study of particle physics has, historically, relied on using detectors to measure the properties of particles from a variety of sources: occurring naturally in the building blocks of matter (electrons, protons, and neutrons), decays of radioactive nuclei (alpha particles, positrons, neutrinos and anti-neutrinos, and gamma rays), cosmic rays (muons, pions), and particles emerging from the interaction of a beam of accelerated particles with target nuclei in fixed target experiments or from interactions of two beams of accelerated particles in collider experiments.

Characterizing objects, which cannot be directly observed, by subjecting them to incident projectile particles and studying the distribution of the particles that emerge has been a powerful and useful technique for many years[3]. X-rays have long been used to shadow dense objects embedded in less dense materials. The idea of using particles to non-destructively study objects has also been exploited by archaeologists, geologists, chemists, material scientists, and the military and security communities. Biologists and the medical community have made use of them to study living things. Although the interest of particle physicists is to understand the characteristics of the particles and their interactions themselves, the tools and technologies involved in performing a detailed study of the collision between two particles over a broad range of energies by detecting and measuring the particles emerging from the collision are fundamentally the same as using particles to study larger objects. This is one of the reasons particle physics detector technologies have been useful to other fields. To carry out experiments particle physicists have developed a variety of detectors which are sensitive to single elementary particles. In general these detectors fall into one or several of the following categories:

1. Detectors for measuring the power of incident radiation. Ultra low energy phonons and photons can be detected using superconducting detectors such as transition edge sensors which typically make a transition from superconducting to normal when they absorb the energy of the photon or phonon. Arrays of these detectors are capable of ultra-high energy resolution, but they must be maintained at cryogenic temperatures.

2. Detectors for visible light photons. Photons can be detected by using the photoelectric effect to knock electrons off materials with low electron affinities or by using semiconductor detectors with band gap energies smaller than the incident photon energies. Photo-electrons are typically accelerated by an electric field and impinge on materials which produce secondary electrons to produce a large enough signal charge to be detected. Charged carriers produced in semiconductors typically need to be amplified electronically to obtain a detectable signal.

3. Detectors for X-rays or γ-rays. X-rays or γ-rays can be detected using the photoelectric effect, Compton scattering, or electron-positron pair production in semiconductors or absorbing materials where the electron can either be accelerated to generate secondary electrons or to generate visible light. Superconducting transition edge sensors can also be used to measure X-rays and gamma rays with very high energy resolution.

4. Detectors for charged particles. Charged particles can be detected by using their ionization in materials to generate scintillation light or ionization electrons, which can then be accelerated to generate secondary electrons. Suitable materials for detecting charged particles include noble gases in a liquid, gas, or solid phase, which can generate scintillation light or ionization electrons; other gases that generate ionization electrons, which can be accelerated to produce secondary or avalanche electrons in the gas; plastics or crystals, which generate scintillation light; and semiconductors, which detect ionization. Charged particles can also be detected in supersaturated liquids where their ionization forms nucleation sites for bubble formation and in emulsions where the ionization causes chemical changes, which can be detected.

5. Neutral particles other than photons. These can be detected by their interactions with matter in which charged particles and photons are produced and detected.

[3] This technique was used by Rutherford to discover the nucleus.

1. Photodetectors

The photomultiplier tube, whose invention is widely attributed to the Radio Corporation of America (RCA) in the 1930's, has been the workhorse of visible light detectors (RCA, 1940). A visible light photon incident on a photocathode, which is typically a bi-alkaline material with low electron affinity, produces an electron by the photoelectric effect. This electron is accelerated by an electric field in the tube toward a first dynode coated with a material which emits secondary electrons when an energetic incident electron hits it. These secondary electrons are then accelerated by the tube's electric field to a second dynode producing more secondary electrons. A typical tube will have 8-12 dynodes and the number of electrons leaving the last dynode is typically 10^6 or more. These electrons are then incident on the tube anode to generate a measurable signal.

In order to provide position resolution of the incident photon, photomultipliers have been manufactured with segmented anodes or with the dynodes replaced by capillary arrays of secondary emitting pores called microchannel plates (Morrow, 1988). Hybrid photodetectors use a photocathode and a shaped electric field to focus photoelectrons onto a high gain electron avalanche semiconductor detector.

Modern detectors for detecting visible light (and, near infrared) photons include semiconductor detectors in which free charge in the body of the detector is removed by applying a bias voltage (depleted region). A photon, which interacts in the body of the semiconductor via the photoelectric effect, generates an electron which accelerates in the bias field generating secondary electrons which produce an electronic signal in the detector (Renker, 2006). Silicon photomultipliers have been developed which use an array of avalanche photodiodes on a silicon substrate to generate signals from incident photons (Buzhan, 2003). Another semiconductor device which has been used extensively both for scientific and commercial applications is the charged coupled device (CCD).

Photodetectors sensitive to visible light have typically been used to measure X-rays or γ-rays by using a crystal converter in which the photons interact in a crystal producing electrons, which create scintillation light. A variety of crystals, each having different conversion properties and light generation characteristics, have been used. Electrically biased large volume semiconductor detectors are also widely used to detect X-rays and γ-rays.

Superconducting transition edge sensors act as bolometers and can be tuned to detect photons, which range in energy from very low energy (millimeter wavelength) to X-rays and γ-rays. These devices are biased very close to their superconducting transition temperature so the energy of the absorbed photon causes a detectable change in current flowing through the device. Because the superconducting transition temperature is so sharp, the energy resolution of these devices is superior to other photon detectors. Photons with energies greater than 10 MeV usually deposit their energies in matter by creating positron-electron pairs so detection methods for similar energy electrons can be used to detect these high energy photons.

2. Charged Particle Tracking Detectors

There are a variety of devices which have been designed to detect individual charged particles. In the early days of particle physics a volume containing a photographic emulsion, or a super-saturated vapor (cloud chamber) or liquid (bubble chamber) was used. The ionization trail in the grains of a silver halide emulsion produces a track, which can be detected when the emulsion is developed. Ionization in a saturated vapor or liquid creates a trail of bubbles, which nucleate on the charged particle's ionization trail and which can be photographed. Different types of particles have different rates of ionization, so the concentration of grain track density in the emulsion and bubble track density in saturated vapor or liquid detectors provides information about the type of particle. When these devices are inserted in a magnetic field the sign of the particle's charge and its momentum can be determined from the curvature of the track.

A commonly used detector is a gas-filled cylindrical tube with a central wire. When a charged particle traverses the tube, it ionizes the gas and, with the central wire maintained at high positive voltage with respect to the outer surface of the cylinder, electrons are accelerated toward the wire. If the voltage is high enough, the electrons cause avalanche breakdown in the vicinity of the wire and generate a relatively large signal on the wire. At lower voltages, the electrons produce a smaller signal, proportional to the amount of charge produced by ionization in the tube, which needs to be amplified to be detected.

The invention of the multi-wire proportional chamber (MWPC), combined with the then newly available modern electronics, was a breakthrough for particle physics and moved the field into the electronic era (Charpak, 1969). An MWPC has a plane of anode wires positioned between two cathode planes. Each anode wire acts as an individual proportional counter. Spatial resolution is determined by the anode wire spacing. Simultaneous readout from anode and cathode electrodes is possible. The next step in the evolution of charged particle detectors was the development of the drift chamber. In a drift chamber the drift time of ionization electrons in a gas is measured to calculate the spatial position of an ionizing particle. The construction of a conventional drift chamber is similar to an MWPC, but the cathode planes have distributed potentials to form a constant electric field strength. Electron clouds of the primary electrons drift with constant velocity to the anode. Near the thin anode wire there is gas multiplication and the signal detected. Multiple layers of anode-cathode planes allow for full track reconstruction in three dimensions.

Another powerful charged particle tracking detector is the time projection chamber (TPC) (Nygren and Marx, 1978). A TPC consists of a gas-filled detection volume, commonly a cylindrical chamber. Along its length, the chamber is divided into halves by means of a central high-voltage electrode disc, which establishes an electric field between the center and the end plates. Furthermore, a magnetic field is often applied along the length of the cylinder, parallel to the electric field, in order to minimize the diffusion of the electrons coming from the ionization of the gas. On passing through the detector gas, a particle will produce primary ionization along its track, which will drift in the electric field to a position-sensitive electron collection system at the ends of the cylinder. The collection system most often consist of MWPCs, gas electron multiplier (GEM) chambers or micromesh foils. The coordinate along the cylinder axis is determined by measuring the drift time from the ionization event to the MWPC at the end. Through a clever arrangement of the charge collection system, the three dimensional position of each ionization cluster is measured.

Particle physics has been able to take advantage of the transformational developments in the semi-conductor industry by applying their techniques to the design and production of silicon-based tracking detectors (Hartmann, 2009; Moser, 2009). Two types of detectors are now a cornerstone of all collider experiments: silicon strip and silicon pixel detectors. In these detectors a junction is formed near the surface of a lightly doped substrate, which is fully depleted by applying a reverse bias voltage. The passage of a charged particle creates electron-hole pairs and, depending on the exact configuration, the electrons or holes are collected by a charge-sensitive amplifier. In silicon strip detectors the charge is collected over a typical length of about 10 cm and read out at one end. The strip width can be as small as 25 μm and this high resolution is often used to measure the curvature of a track to measure the particle's momentum. Charge sharing between neighboring strips can be used to further improve on the position resolution. In pixel detectors, the whole sensor area is subdivided in readout regions that can be as small as 20 μm $\times$ 20 μm. An integrated circuit is bonded directly on top of the sensor to provide the readout of each individual pixel. Multiple layers of silicon sensors enable a precise reconstruction of the point of creation of the particles.

3. Čerenkov Detectors

When a charged particle traverses a transparent medium at a speed which exceeds the speed of light in the medium the Čerenkov photons produced have a directionality given by the formula $\cos\theta = \frac{1}{\beta n}$ where θ is the angle between the direction of the emitted photon and the direction of travel of the particle, n is the index of refraction of the medium, and $\beta \equiv v/c$ where v is the particle's speed and c is the speed of light in vacuum. If a charged particle's momentum can be determined, for example by measuring its curvature in a known magnetic field, and its speed is known, its rest mass and energy can be deduced. Thus the angle between a particle's motion and the Čerenkov radiation it emits can be used for particle identification. There are a variety of detectors which use Čerenkov radiation to identify the type of particle. One of these, the "Detection of Internally Reflected Čerenkov light", or DIRC, uses internal reflection of light in long quartz bars to determine the type of particle. Knowing the point of incidence of the particle, as determined from the tracking detector, and the time of propagation of the light in the bar, as measured by the photodetector, the Čerenkov angle of the radiation emerging from the charged particle traversing the bar can be determined and hence the type of particle.

A particle's speed can also be determined by its time of flight between two points a known distance apart if the time of flight can be determined with sufficient precision. These time-of-flight detectors typically require large area sensors at either end of a sufficiently long baseline which have a time-resolution of order tens of picoseconds to measure with sufficient precision the velocities of particles of interest.

Another type of radiation, called transition radiation occurs, when a charged particle traverses the boundary between two different materials. The relationship between the intensity of the radiation and the energy of the particle makes this radiation useful in some high-energy physics detectors to determine the mass of traversing particles with known energy.

4. Neutral Particle Detectors

Neutral particle detectors typically require the neutral particle to interact with an atomic nucleus. For neutral particles other than photons, its presence is inferred from the absence of a track before the interaction and the subsequent emergence of charged particles from the interaction point. In general, the identification of neutral particles is complicated and requires information about the entire interaction or chain of interaction products after a primary interaction. Neutral particles can also be identified from their charged decay products if they decay within a tracking volume and the charged decay particles can be reconstructed and identified. Neutral particle energies are measured in calorimeters, discussed in the next section.

5. Calorimeters

Particle energies are typically determined by stopping charged particles in so-called calorimeters. Many types of calorimeters are in use. A very common type of calorimeter is a sampling calorimeter which has alternating layers of a passive absorber and an active medium. The range of absorber materials is wide and includes among others iron, copper, uranium or tungsten; the choice of active media is even larger, ranging from noble liquids, to scintillator to various gas mixtures (Fabjan and Gianotti, 2003a). Another type of calorimeter is a homogenous calorimeter where there are no passive elements. These calorimeters typically consist of crystal detectors used for the measurement of the energy of electrons and photons.

The choice of which calorimeter technology to use depends on many conditions, but often a dominant requirement is the resolution with which the energy is measured. Typically the relative energy resolution of calorimeters ($\sigma(E)/E$) is parameterized as the quadrature sum of a stochastic, constant and noise term. The stochastic term is a constant divided by the square root of the incident particle's energy. Because the energy of the particle is "sampled" the accuracy depends on the statistical fluctuations in the number of secondary particles generated, which is roughly proportional to the particle's incident energy. The so-called constant term in the energy resolution is a constant independent of energy. This term has its origin in instrumental effects that cause variations of the calorimeter response with the particle impact point on the detector giving rise to response non-uniformities. The noise term is parameterized by a third constant divided by the incident's particle energy and is often due to readout electronics contributions. These three terms are added in quadrature. A detailed discussion of the performance characteristics of electromagnetic and hadron calorimeters can be found in the article "Calorimetry for Particle Physics" (Fabjan and Gianotti, 2003b).

Often, electromagnetic calorimeters are homogeneous, typically consisting of an array of crystals or a volume of a noble liquid, which convert electrons and photons into a shower of electron-positron pairs that cause the crystal to scintillate with an amount of light proportional to the total energy given up by the incident particle. Since this type of calorimeter is homogenous it is not sensitive to sampling fluctuations and often has superior energy resolution. A variety of crystals have been used depending on the wavelength and amount of scintillation light produced, and the speed with which the signal is produced and extinguished, and of course cost. Electromagnetic sampling calorimeters typically consist of alternating layers of absorber, such as iron, lead, uranium or tungsten, and an active material such as plastic, liquid scintillator, a noble liquid, silicon-based sensors or gas detectors. The active medium detects the charged particles in the showers produced in the absorber. These calorimeters are typically cheaper but do not have the energy resolution of the homogeneous calorimeters since not all the energy is deposited in the active material. Fluctuations in the electron shower development is the primary determinant of energy resolution in crystal calorimeters, while fluctuations in sampling statistics gives an additional contribution to the energy resolution in sampling calorimeters.

Hadron calorimeters are nearly always sampling calorimeters, which measure showers produced by hadrons or mesons via the strong force. The absorber material is typically iron, copper, lead, tungsten or uranium while the active sampling elements consist of scintillator, liquid argon or xenon, multi-wire proportional chambers or cylindrical wire detectors or resistive plate chambers which give position information as well as the ability to detect simultaneous hits from multiple particles. These calorimeters must be large and deep enough to absorb the full energy of the incident particles. The large area multilayer sampling elements must be relatively inexpensive to keep the overall cost of the calorimeter affordable.

6. Detector Systems

Large particle physics experiments typically require detectors made up of various subsystems. In a typical accelerator-based detector there is a cylindrically shaped inner, high-resolution, radiation-hard charged particle tracking detector, called a vertex detector, which can handle high interaction rates and which is designed to detect particles with short lifetimes. Outside the vertex detector there is typically a much larger cylindrically shaped tracking detector, which tracks charged particles for accurate momentum and charge determination. Time-of-flight or Čerenkov detectors sometimes complement the tracking chambers. This array of detectors is followed by electromagnetic calorimeters and hadron calorimeters for detecting and measuring the energy of electrons and gamma rays and showers produced by hadrons or mesons via the strong force.

All these detectors with the exception of the calorimeters which can be inside or outside can be enclosed in a normal or superconducting magnet with a field strength of several Tesla. This enables the measurement of the charge and momentum of charged particles emerging from the interaction point and separates particles of different momenta in hadronic showers providing a means to associate tracks with energy deposits in the calorimeter. Outside the magnet there are typically additional charged particle detectors to detect particles, which have a low probability of interacting with the material before and inside the magnet. Since these detectors are located at the outer edges of the detector, they tend to cover very large areas. Because of their size, these detectors must be relatively inexpensive to fabricate per unit area. They can consist of any of the charged particle detector technologies described above but often employ gas-based detection techniques.

To ensure that almost all the particles emerging from the interaction point are detected, there are typically endcap detectors which close off both ends of the cylindrical detector with a similar configuration of detectors.

7. Analog and Digital Electronics

Particle detectors often need to cope with small signals of just a few thousand electrons in the presence of potential noise sources (Radeka, 1988). Added to this are requirements for high speed, large channel count, and complex digital readout and data transmission systems. To overcome the small signal size, detectors often have an intrinsic gain, such as in Geiger or proportional counters, or in avalanche diodes. However, ionization detectors without intrinsic gain, such as liquid argon and silicon diodes, are often a good choice because of other characteristics. Their performance is often very stable and not susceptible to external parameters such as temperature. They often show very good linearity, low electronics noise and can be fast. The particle physics community has pioneered the development and signal processing of such systems, which includes the detailed development of an understanding of signal development and noise sources as well as how to simultaneously optimize integrated circuit design, power dissipation, and radiation hardness.

The design and operation of complex analog and digital systems, often with many millions of channels, requires a unique knowledge and experience base. Issues of cabling, cooling, grounding, shielding, separation of digital and analog signals, power provision and regulation are crucial to the success of such large systems. A particular important aspect of the electronics operating in a colliding beam environment is that it has to withstand large doses of radiation. The field of particle physics has pioneered the design of radiation-hard custom electronics, in particular the design of application specific integration circuits (ASICs). Many ASICs have been designed that provide signal amplification, shaping, sparsification and often first level event topology identification at the earliest stages of signal processing (Haller, 2013).

8. Trigger and DAQ Systems

Events which contain interesting physics may occur only once in 10^9 interactions in a collider experiment or even less frequently. Rare decay branching ratios may need to be explored at the 10^{-12} level. Recording all events without a filter which selects the most promising interactions would quickly overwhelm even the most powerful data acquisition system. In particle physics this filter is called "the trigger" and many experiments typically deploy sophisticated multi-level triggering systems. Such a system might employ at a first stage a Level 1 trigger that examines the topology of an event in individual subdetectors using custom designed hardware. A second level trigger might employ a mix of hardware and software. The highest trigger level is typically a farm of conventional processors which allow the execution of sophisticated algorithms. Level 1 triggers make extensive use of ASICs and custom hardware which buffers event information for microseconds while the Level 1 decision is made. Higher level systems make extensive use of FPGA systems and farms of processors to provide more sophisticated analysis.

Modern trigger systems must combine high rates of data from multiple sources, route the information to the appropriate processors, analyze the information, and either reject the event data or pass the information along to a higher level. This data flow is a challenge for even the most modern optical data transmission systems and routing systems. Modern tracking detectors used in accelerator experiments with tens of millions of readout channels, for example, are capable of detecting and recording the position of particle hits in them every 25 ns. Some experiments use advanced telecommunications architecture crates (ATCA) with full mesh backplanes to implement routing of information to arrays of FPGAs and custom integrated circuits (Liu, 2014). The experiments at the Large Hadron Collider (LHC), for example, will need to be able to process about 50 Tb/s of raw data and reduce it to an output stream of about 2 Gb/s for offline data analysis in their upgraded configurations. Since the highest number of particles per cm^2, the particle flux, is near the beamline and decreases with distance away from the beamline, the further the detectors are from the interaction point, the less stringent the requirements on data rate, though the capability to trigger still has to exceed many hundreds of kHz for even the outermost detectors.

9. Computing

Particle physicists realized early on that with the advent of the LHC and the resulting huge datasets and tremendous simulation requirements, a new paradigm for computing models needed to be developed (Berman *et al.*, 2003). The new computing model needed to provide rapid access to exabyte data stores; secure, efficient and well-managed access to worldwide computing resources; the ability to track state and usage patterns and to match resources to demands. To enable physicists

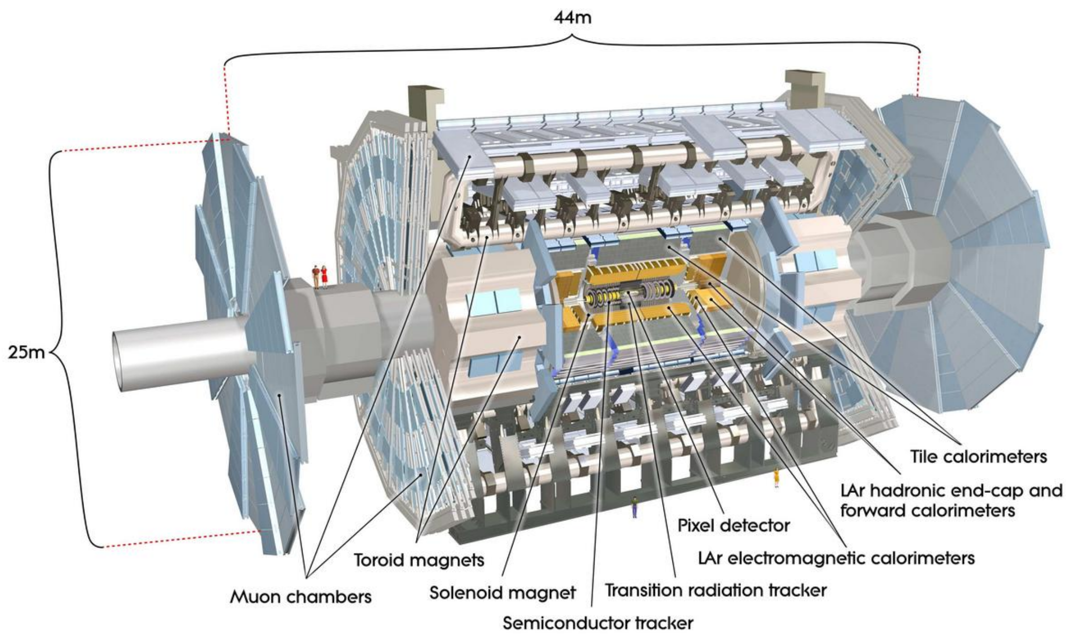

FIG. 1 A representative example of a collider detector: the ATLAS detector at the CERN Large Hadron Collider. The detector is built in concentric layers surrounding the interaction point. See text for more details (Figure courtesy of CERN).

in all world regions to collaborate, high-speed intercontinental networks needed to be built to support the above. In 1998 the Models Of Networked Analysis at Regional Centers (MONARC) for LHC Experiments project was launched to develop computing models that would provide viable solutions to meet the simulation, reconstruction, analysis, data storage and access needs for the LHC experiments, involving many hundreds of physicists at institutions around the world (MONARC, 2016). These models encompassed a complex set of wide-area, regional and local-area networks and a heterogeneous set of compute and data-servers to meet the demands for remote data and compute resources. A key conclusion of the MONARC simulation studies was that a tiered system with a regional central hierarchy of networked centers was the most appropriate solution for the LHC experiments.

Other studies took place at around the same time. The Globally Interconnected Object Databases (GIOD) project (Bunn *et al.*, 2000), a joint effort between Caltech and CERN, funded by the Hewlett-Packard Corporation, investigated the use of distributed object databases and mass storage systems for LHC data. The ALDAP project for "Accessing Large Data archives in Astronomy and Particle Physics", funded by the NSF, investigated data organization and architecture issues for particle physics and astronomy.

A plethora of grid projects then emerged whose target was "big science" and particle physics was in the vanguard of these efforts, a fact that can be attributed to its standing as a highly data intensive and highly collaborative discipline. The development of data grids build on the solid foundations put in place by these earlier projects, and the pioneering work of running experiments. Four projects in particular should be mentioned. The Particle Physics Data Grid (PPDG) focused on the development and application of Data Grid concepts to the needs of a number of U.S.-based high energy and nuclear physics experiments. The Grid Physics Network (GriPhyN) project was a collaboration of computer scientists and physicists from the two multi-purpose LHC experiments, ATLAS and CMS, and LIGO and the Sloan Digital Sky Survey (SDDS) (GriPhyN, 2002). Its focus was the creation of "Petascale Virtual Data Grids" (PVDG) through the development of tools that would support the automatic generation and management of derived, or "virtual" data for leading experiments in high-energy physics, gravitational wave searches and astronomy. GriPhyN led to the creation of the International Virtual Data Grid Laboratory (iVDGL), which targeted the creation of the computing infrastructure. The project deployed a grid laboratory with international partners in all major regions of the world linked by high-speed networks comprising heterogeneous computing and storage resources. The Data Trans-Atlantic Grid (DataTAG) project created a large-scale intercontinental Grid testbed with a focus on advanced networking issues and interoperability between intercontinental Grid domains (DataTAG, 2003). This project was carried out concurrent with the European Data Grid (EDG) project, aimed at developing an operational Data Grid infrastructure supporting high-energy physics, bioinformatics, and earth satellite sensing (EUDataGrid, 2004).

Through the adoption of grids by major HEP experiments spanning several world regions and the dependence of particle physics on high performance networks, the development of reliable wide-area networking became mission-critical. The development of the U.S. LHCNet was launched to meet the needs of the LHC experiments by providing a high performance network aiming at 99.95+% service availability through the use of multiple links across the Atlantic and across the U.S. (U.S. LHCNet, 2013). The network was developed in cooperation with the U.S. Department of Energy (DOE) Energy Science Network (ESnet) (ESNet, 1980) and configured to support the tiered computing model for the LHC experiments that emerged from the MONARC studies. It provided dedicated, high-bandwidth connectivity between CERN and the two highest tier U.S. sites, Fermilab and Brookhaven National Laboratory. The network also shared support in connecting the U.S. and Europe to many universities and laboratories, the lower tiers, where researchers can analyze the LHC data. The U.S. LHCNet provided robust fallback in case of link failure, and automatic re-direction of network traffic using redundant network equipment at each of the US LHCNet points of presence. An integrated software package, MONitoring Agents using a Large Integrated Services Architecture (MonALISA) was developed to analyze and process the network information in a distributed way, to provide optimization decisions in large scale distributed applications (MonALISA, 2005).

The development of the U.S. LHCNet took place in collaboration with Level 3 Communications, a leading international provider of fiber-based communications services, and Internet2, a U.S. advanced networking consortium led by the research and education community (Internet2, 1996). The mission of Internet2 is to bring together the U.S. research and academic community with technology leaders from industry, government and the international community to undertake collaborative efforts that have a fundamental impact on the development of the network infrastructure. The success of the U.S. LHCNet is a nice testament to the successful partnership between the Department of Energy, academia, industry and its international partners.

All these efforts, driven without exception by the needs of scientific experiments with particle physics at the forefront of the developments, have led to the creation of the LHC Computing Grid (LCG), which later morphed into the World-wide LHC Computing Grid for the LHC experiments (Bird, 2011). It is a global computing infrastructure whose mission is to provide computing resources to store, distribute and analyse the data generated by the Large Hadron Collider (LHC), making the data equally available to all partners, regardless of their physical location. The WLCG is the world's largest computing grid. It is supported by many associated national and international grids across the world, such as the European Grid Initiative and the US-based Open Science Grid (OSG) (Grid, 2013), as well as many other regional grids. These grids facilitate access to distributed high throughput computing. The resources accessible through the OSG are contributed by the community, such as the Energy Sciences Network (ESnet), that serves United States Department of Energy (DOE) scientists and their collaborators worldwide.

The study of the bandwidth and networking needs of the next generation particle physics experiments through detailed simulations and the subsequent development of the grid and network infrastructure in collaboration with international partners from academia, government and industry, was remarkably prescient of the particle physics community. The exponential growth in network use that particle physics has experienced over the last 15 to 20 years is expected to continue over the next decade and will surely lead to further rapid advances in scale of network bandwidth requirements for science and the community as a whole.

In many of today's particle physics experiments, a single event with a certain signature does not constitute a discovery. The data is subjected to rigorous statistical analyses determining the probability that other processes could mimic the same signal. Very sophisticated simulation programs have been developed to simulate the detectors and the interactions of particles with these detectors. The Geometry and Tracking (GEANT) Monte Carlo program is one such tool that has been developed by the community over many years (Agostinelli and collaborators, 2003). It can simulate complicated geometries and model particle behavior in many different materials, which comprise modern detector systems. GEANT has found wide application beyond particle physics and is described in greater detail in section III.R.

10. Non-Accelerator Experiments

There are many non-accelerator based detectors. All dark matter experimental searches require ultra-low backgrounds in order to identify extremely rare events from potential backgrounds. These experiments need to develop capabilities for screening materials for very low levels of radioactivity, and the sensors they use have severe constraints on acceptable levels of radioactivity. They also need to be located in environments which have very low natural background radiation and which are shielded from cosmic rays.

Ultra high energy cosmic ray experiments and large telescope arrays which study Čerenkov radiation produced in the atmosphere have the requirement that different parts of the detector arrays which are physically separated from each other by considerable distances need to communicate with each other with very high timing precision. Balloon-borne experiments and experiments which are deployed in spacecraft must be designed for very high reliability and with the ability to communicate to analysis centers on earth.

Cosmic microwave background experiments need very sensitive detectors to measure very small variations in the cosmic microwave background. These typically use arrays of transition edge sensors where novel readout schemes are being developed.

B. The Potential Value of Particle Physics Research to Applications Outside of Particle Physics

Particle physicists have developed the instruments to carry out their experiments, by using existing technologies and further developing them or, if the technologies did not exist, develop new technologies to achieve their goals. In parallel with this effort, a number of applications for the use of elementary particles and their detection techniques have arisen in other fields of science, medicine, some areas of national defense and in society at large. In what follows areas within particle physics detector technology expertise, which have the potential to make useful contributions to applications outside particle physics research are suggested. Representative specific cases in which this potential has been wholly or partially realized are given in Section III.

1. Applications Involving Cosmic Rays

Cosmic rays provide a natural source of penetrating radiation which in some cases can be used like X-rays for tomography to study large, otherwise inaccessible structures. Variations in cosmic ray intensities can also be studied to see if they correlate with other natural phenomena.

2. Applications Involving (Anti-)Neutrino Detection

Particle physics detectors can be used to detect neutrinos or anti-neutrinos from natural or man-made sources over energies ranging from MeV to PeV. Incident neutrino directional information provides additional information.

3. Applications Which Require Precise Time Coordination of Devices Separated by Large Distances

The ability to precisely correlate signals or measurements at widely separated distances has the potential to be scientifically and commercially useful.

4. Applications Which Use Elementary Particles to Carry Out Non-Destructive Measurements on Materials or Living Things

There is a long history of using X-rays to make non-destructive measurements on materials and living things. Particle physics detector technology has the potential to improve some X-ray detectors and to provide detectors for other elementary particles, which are in some cases better suited to non-destructive measurements than X-rays.

5. Applications Which Use Elementary Particles to Make Changes in Materials or in Living Things

In some cases, elementary particles can be used to make desirable changes to the structure of materials. Particle physics generally provides the basis for these applications.

6. Applications Which Require Detecting Very Low Levels of Visible Light

Low levels of visible light, down to single photons, can be produced when individual charged particles traverse a scintillating medium or when imaging in low ambient light levels is desirable.

7. Applications Which Require Measuring the Energy of Microwave Photons or Gamma Rays with High Precision

In many potential applications, the measurement of photon energy gives information about the mechanism and materials producing the photons. Determination of the directionality of the incident photons and time-of-flight provides information that can add significant benefits in some applications.

8. Applications Which Require the Detection of Neutrons Over a Range of Energies

Neutrons are a source of information about the existence of certain materials and their radioactivity.

9. Applications Which Use Particle Physics Detectors to Detect, Track and Record the Position of Charged Particles with High Precision

It is usually easier to detect and measure the directionality of charged particles than neutral particles. Charged particle tomography has the potential to provide precise information about the objects being studied. The prompt nature and angular dependence on particle velocity of Čerenkov radiation can be exploited in some applications.

10. Applications Which Require the Detection of Charged or Neutral Particle Hits with Precise Time Information or Which Require the Measurement of Charged or Neutral Particle Energies

The precise time of a charged or neutral particle hit in one or more detectors, measured at the level of picoseconds, has the capability to provide information about the source of the incident particles, which makes imaging possible. Determination of charged and neutral particle energy can provide additional information about the source of the incident particles.

11. Applications Which Require the Design and Fabrication of Customized Electronics

Progress in electronics has been one of the primary drivers of technological innovation in almost all areas of modern society. Electronics which has been custom designed for research in particle physics can become useful for applications in other fields.

12. Applications Which Require Affordable Large Area or Large Volume Charged or Neutral Particle Detectors

Increased sensitivity to small or shielded sources of charged or neutral particles typically involves large area or large volume particle detectors. Individual detectors in particle physics often cover areas of many square meters or volumes of many cubic meters. Making these detectors efficient and affordable has considerable potential value.

13. Applications Which Require Radiation Hard Charged Particle Detectors

Particle physics detectors at colliders need to be able to withstand radiation doses sometimes exceeding levels of 10^{16} 1 MeV n_{eq}/cm^2. Detectors which need to detect signals in high radiation backgrounds can potentially be useful in a variety of scientific, industrial, or security environments.

14. Applications Which Require Very High Speed Readout of Particle Interactions in Detectors

Frequently, data of interest occurs at a much lower rate than uninteresting background but cannot be extracted from backgrounds in real time. The ability to record particle interactions in detectors at very high rates, for example up to 40 MHz at the LHC, makes it possible to extract small signals from large backgrounds. This is valuable in many applications.

15. Applications Which Require Distributed Monitoring, Documentation, and Control over Large-Scale Systems

Large systems with hundreds of millions of individual detectors and controls generally require sophisticated monitoring and control capabilities, and general purpose tools can be valuable to many different types of systems.

16. Applications Which Require Access to Sophisticated Computing Software

Distributed access to powerful computing resources and storage of data sets exceeding many petabytes, or analysis software combined with detailed simulations of detector or device design and standardized software analysis packages can be useful for many different fields.

17. Applications Which Require Ultra-Low Radioactivity Materials or Which Exploit the Measurement of Low Radiation Levels

The ability to detect and potentially remove low levels of radioactivity from materials can be important in applications involving the measurement of radioactivity or when radioactivity causes physical damage or when it creates undesirable backgrounds. Low background detectors are also useful to detect and measure small numbers of specific nuclei in materials which have been radioactively activated.

18. Applications Which Require Extensive Project Management During Construction and Operation

The study of the management and successes (and also failures) of large particle physics projects over the past several decades, launched by hundreds of research institutions in tens of countries spread across the globe with many different funding agencies involved, can provide useful information on the management of future large-scale projects.

19. Applications Which Make Use of Particle Physics Laboratories or the Infrastructure Available at Particle Physics Laboratories

Particle physics research often requires developing laboratories in remote locations, such as the Atacama desert in Chile or the South Pole. These locations have the potential to be useful to other fields. In addition there are facilities and capabilities at particle physics laboratories, which may be useful to other fields.

20. Applications Which Use Data About Particle Properties from Particle Physics Measurements or Calculations

Large databases of elementary particle properties have been constructed over many decades of particle physics research. The use of this information underlies many applications of elementary particles which are useful to society.

III. SPECIFIC APPLICATIONS OF PARTICLE PHYSICS DETECTOR TECHNOLOGY AND TECHNIQUES TO OTHER FIELDS

In the previous section, we identified a non-exhaustive list of possible applications of technology outside particle physics for which a connection to particle physics detector technology and/or expertise could prove useful. In this section we describe a variety of specific applications, ranging from the very speculative to those which have had great impact on other areas of science, technology, and society as a whole. A number of these applications, described in a recent article by Demarteau and Yurkewicz (Demarteau and Yurkewicz, 2014), are distributed throughout this section. This section is meant to give a broad and representative rather than exhaustive description of specific applications.

A. Cosmic Rays

1. Tomography Applications

One of the more well-known examples of the application of particle physics techniques to a field outside of physics is an experiment that particle physicist Luis Alvarez from Lawrence Berkeley Laboratory and collaborators carried out to measure the distribution of cosmic ray muons incident on two 1.8 m^2 horizontal wire spark chambers with digital readout located in a chamber of the second pyramid of Giza in Egypt (Alvarez *et al.*, 1970). Scintillation counters above and below the wire spark chambers triggered the application of voltage to the chambers when a charged particle was detected in each chamber over a small time interval. The goal of the experiment was to detect hidden chambers in the pyramid by analyzing the detected distribution of muons and comparing it to the expected distribution of muons if there were no hidden chambers. After the analysis was completed and all the necessary corrections were applied to the data, the conclusion was that no hidden chambers with volumes similar to the known chambers in other pyramids exist within the volume of the second pyramid of Giza contained in angles within 45 degrees of the vertical above the wire chambers.

The use of cosmic ray muons and charged particle detectors to "X-ray" large structures has now become a standard technique called muon tomography (Presente *et al.*, 2009). Geologists use muon tomography to study the inner structure of volcanoes. Resistive plate chambers are being used as the detectors in the TOmography with atmospheric MUons of VOLcanoes (TOMUVOL) experiment (Portal *et al.*, 2013). Another project to perform volcano radiography, the MU-RAY project (Marteau *et al.*, 2012) uses a detector based on plastic scintillator bars with wavelength-shifting fibers. The scintillation signals are detected with silicon photomultipliers and are read out with an ASIC developed for calorimetry for the International Linear collider.

Scientists at Los Alamos National Laboratory have invented a more sensitive technique, which studies the scattering of muons using two muon trackers to measure the incoming and outgoing tracks of individual muons where the region of interest is contained within the acceptance of the tracker pair. This technique is proposed to scan trailers and shipping containers for special nuclear materials since the high atomic number of nuclear materials causes more muon scattering than materials with lower atomic number. A recently proposed application of muon scattering tomography using gas filled ionization drift tubes is to study the damage of the reactor cores in the Japanese Fukushima Daiichi nuclear reactor (Miyadera, 2012). A group at NSTech and Fermilab is studying the feasibility of expanding this technique by using silicon strip detectors as a replacement for drift tubes (Green, 2016). Silicon strips provide a more compact, robust and precise option to reconstruct objects by measuring the multiple scattering of through-going cosmic rays.

2. Cosmic Ray Correlation Applications

Cosmic rays are also being used to study global weather patterns and weather evolution (Dayananda, 2013). This study searches for correlations between cosmic ray fluxes and natural phenomena using detailed measurements of cosmic radiation using a liquid scintillator detector to study global weather phenomena. GEANT4 is being used to carry out numerical simulations of the cosmic muon and neutron flux variations at the surface of the earth with varying air densities in the troposphere and stratosphere.

3. Other Cosmic Ray Applications

Cosmic rays are a concern in commercial aviation. Studies have been carried out to determine the health risks of airline crews to cosmic ray exposures at typical flight altitudes (Bagshaw, 2014). EPCARD, one of the computer packages developed on behalf of the European commission used in these studies is based on the FLUKA transport code, which was developed to carry out detailed simulations for particle physics detectors. The sun's and earth's magnetic field and the earth's atmosphere are modeled and dose rates are determined as function of altitude, geomagnetic latitude and solar cycle. Radiation doses can be measured during flight and the location of dosimeters has been guided by detailed simulation studies and the interaction of the cosmic rays with the construction materials of the aircraft. During a long-haul flight the typical exposure rate is 4-5 μSv/h.

B. Neutrino and Anti-Neutrino Applications

1. National Security Applications

Although neutrinos have extremely small interaction probabilities with materials, they are beginning to find useful applications in several areas. An indication of how extensive these applications have become can be found in the talks at the 10$^{\text{th}}$ Applied Anti-Neutrino Workshop[4]. Watchman, a non-nuclear proliferation application, is the deployment of large water Čerenkov detectors doped with Gadolinium to detect anti-neutrino elastic scattering, which provides directional information. The ultimate goal of this project is to find hidden reactors at distances up to 1000 km (Bernstein, 2014).

Another potential anti-neutrino application involves monitoring heavy water reactors, such as the Iranian reactor at Arak, the IR-40, as a non-proliferation measure if an anti-neutrino detector can be developed with a sufficiently low background on the surface of the earth (Christensen *et al.*, 2014). By measuring the anti-neutrino flux over a period of several months, along with detailed nuclear reactor burning calculations, it can be verified that all of the reported reactor fuel products are being used in the reactor, both during operation and during shutdowns.

2. Geophysical Applications

Geophysicists are interested in measuring the neutrino flux from the earth to better understand the thermal processes within the earth. Presently, the rates of cooling and the primordial heat loss are poorly constrained due to the uncertainty of radiogenic heating, the heat arising from the decay of radioactive nuclei. Geochemistry strongly suggests that geo-neutrinos originate only from uranium, thorium, and potassium in the earth's mantle and crust. Better understanding and thus greater exposure to geo-neutrinos would improve the accuracy of the radiogenic heating estimate by constraining the thermal evolution (Dye, 2014). Some useful geo-neutrino information has already been obtained from the Kamland (Araki *et al.*, 2005) and Borexino (Agostini *et al.*, 2015) experiments. The Hawaiian Anti-Neutrino Observatory (Hanohano) is a proposed experiment to build a liquid scintillator detector, similar to Kamland, with an overall exposure of 10 kiloton-years located 4 kilometers deep in the ocean in the vicinity of the Big Island of Hawaii (Maricic and the Hanohano collaboration, 2011).

Sometimes particle physics experiments produce results which are of interest to other fields. The deployment of photodetectors at a depth of 2500 meters to detect neutrinos established a connection between particle physics and glaciology. This is discussed in Section V.B.

3. Communications Applications

Because of the extreme difficulty in interfering with neutrino propagation, beams of neutrinos have been pro-

[4] http://aap2014.in2p3.fr/ Accessed: 2015-6-8

posed as a vehicle for communication in environments where electromagnetic waves are damped and do not penetrate easily. Some potential applications include point-to-point global communication, communication with submarines, and secure communications. But because of their weak interaction with matter, very intense neutrino beams and very massive detectors would be required to realize this type of communication using today's technology. However, a communication proof-of-principle has been established at Fermilab using the NuMI beamline and the MINERνA detector (Stancil *et al.*, 2012).

If detectors with sufficiently high energy sensitivity and low backgrounds can be developed, coherent neutrino nuclear scattering may be detectable for low energy neutrinos[5]. There are a number of groups who are attempting to measure coherent neutrino nuclear scattering using a variety of detectors, which have been optimized to reduce noise. The cross section for coherent neutrino scattering off heavy nuclei, which is approximately given by the formula $\sigma \approx 0.4 \times 10^{-44}\mathrm{cm}^2\,\mathrm{A}^2\,\mathrm{E}_\nu(\mathrm{MeV})^2$, increases with the square of the atomic mass A. This has the potential for reducing the size of low energy neutrino detectors for future neutrino applications.

C. Precise Time Coordination of Detectors Distributed over Large Areas

White Rabbit is a project being developed by particle physics laboratories and academic research labs in collaboration with industry with the aim of creating a distributed timing and data network in which a large number of nodes are synchronized with an accuracy better than 1 nanosecond relative to a master timing station (Jansweijer *et al.*, 2013). The advantages of being able to precisely time synchronize over the internet has immediate applications to particle physics experiments which extend over large areas, but this ability is also of interest to the astronomy community that is interested in precise timing of astronomical events, gravitational wave experiments, and any other scientific experiments using detectors distributed over large distances.

D. The Use of Particles in Non-Destructive Analysis of Materials

1. Security Applications

The use of particles to carry out non-destructive analysis of materials is a well known technique applied in several fields. Non-destructive analysis has become a key technique in the fight against terrorism, especially in the transportation sector (Viesti *et al.*, 2008). At present luggage and container inspections are based on gamma or X-ray scanners that produce high resolution images. In addition, photon inspections provide material recognition when the traditional transmission measurements at fixed energy are complemented with special technologies such as "dual energy radiography", "backscatter imaging", or "computed tomography" (Vogel and Haller, 2007). The material recognition is based on atomic number Z dependence of the relevant photon absorption coefficients.

In cases when photon irradiation is incapable of providing sufficiently detailed inspection information, the use of neutrons as probing radiation has often been proposed. Sophisticated techniques have been developed to enhance material recognition, especially for low-atomic-number materials in an effort to optimize the detection of explosives and drugs in customs operations. Examples of such developments are the "combined fast-neutron and gamma-radiography" and the "fast neutron resonance radiography" or by detection of neutron-induced gamma rays. In the latter case, gamma rays are utilized to characterize carbon, oxygen and nitrogen nuclei, which are the major components of explosives or narcotics. Discrimination between threat materials and common goods is generally obtained by measuring relevant elemental ratios such as C/O and C/N. Some systems, based on the neutron-in/gamma-out technique are already operational or commercially available. However, because the gamma-ray production cross-sections are of the order of a few hundred millibarns, such systems require a rather long interrogation time (5-10 minutes) and are therefore adequate only to detect threat materials of the order of several kilograms. On the other hand fast neutron total cross sections are typically of order a few barns and therefore transmission measurements, exploiting all possible neutron interactions are more appealing. A device based on this technique has been designed and is now in operation at Brisbane airport in Australia. Limitations of this technique are mainly due to its application to rather large aircraft containers in which averaging over all materials crossed by the radiation represents a severe smearing of the information. Moreover, there is no specific signature delivered that identifies the presence of C, N, and O nuclei in the material directly.

The EURopean Illicit TRAfficking Countermeasures Kit (EURITRACK) inspection system uses 14 MeV neutrons produced by the T(D,n)α reaction to detect explosives in cargo containers (Carasco *et al.*, 2007). Fast-neutron-induced reactions inside the container produce gamma rays which are detected in coincidence with the associated alpha particle. The definition of the neutron path and the time-of- flight measurement allow for the determination of the location of the source of the gamma rays inside the container, while the chemical composi-

[5] Very small energies must be detected since nuclear recoil energies are given by the formula $E_{\mathrm{recoil}} \leq 716\,\mathrm{eV}\,\frac{E_\nu^2(\mathrm{MeV})}{\mathrm{A}}$, where A is the atomic mass of the scattering nucleus.

tion of the target material is correlated with the energy spectrum of the coincident gamma rays.

In order to improve material recognition, identifying single elements in the sample, proposals have been made to measure neutron transmission at different neutron energies corresponding to the resonance region in the total cross-section for a number of key light elements. This is currently an active area of research and development.

2. Commercial Applications

Another example of the use of particles in non-destructive testing is the use of neutron imaging for the study of honeycomb structures in aircraft (Hungler *et al.*, 2009). Many of the flight control surfaces on modern aircraft are constructed of composite honeycomb panels. This manufacturing technique is ideal for aerospace applications due to the high strength to weight ratio it provides. However, one of the pitfalls of this type of composite is that it is susceptible to water ingress. Water infiltrates the components and causes adhesive bond degradation which compromises the structural integrity of the component. In response, the Canadian Air Force conducted a study into the various non-destructive testing techniques available to identify water ingress in honeycomb composites. This study concluded that neutron imaging was the most sensitive technique available for the identification of water.

Neutrons have also been used to quantify water penetration into concrete through cracks (Kanematsu *et al.*, 2009). The behavior of moisture in concrete, which affects every stage of concrete from fresh to deteriorating, is one of the phenomena most difficult to detect in situ. Moisture behavior in concrete is commonly detected by resistance humidity sensors made of ceramic, polymer, or other materials that are sensitive to moisture content. However, these methods always adversely affect the concrete or cement matrix, because the sensors have a limited size and this size restrains the system. Neutron radiography allows engineers to quantify the evaporable water behavior in cementitious materials with high resolution.

3. Scientific Applications

Museums in South Africa have used neutron tomography to investigate archaeological artifacts (de Beer *et al.*, 2009), in particular ironstone slabs found in a late Earlier Stone Age context at Wonderwerk Cave, Northern Cape Province, South Africa. These slabs have markings on the surface that might be anthropogenic, and thus signicant to understanding the emergence of human symbolic behavior. While X-rays fail to penetrate the samples, neutrons can easily reveal, in a non-invasive manner, the content and structure. The South African Neutron Radiography (SANRAD) facility, located at the SAFARI-1 nuclear research reactor near Pretoria, South Africa, was utilized in a tomography mode during the investigation. For the 3D tomographical reconstruction of the sample, 375 projections were collected while the sample was rotated around a defined axis through a 360^o rotation interval. The results show that the technique is able to reconstruct structural features very well and in particular highly absorbing zones and the presence of defects in the bulk.

Neutron radiography has also been used to study and understand the effects of liquid water in an operating fuel cell. Neutron radiography, coupled with locally resolved current and ohmic resistance measurements, gives insight into water management and fuel cell performance under a variety of conditions. The effects of varying the inlet humidification level and the current density of the 50 cm^2 cell are studied by simultaneously monitoring electrochemical performance with a 10×10 matrix of current sensors, and liquid water volumes are measured using the National Institute of Standards and Technology (NIST) neutron imaging facility (Gagliardo *et al.*, 2009).

Another example of neutron radiography is the non-destructive testing to detect alien materials in a turbine blade that are otherwise undetectable. The detection of 0.2 mm diameter shot balls in gas-cooled turbine blades is possible with thermal neutron radiography with a 5 minute exposure time (Sim *et al.*, 2009).

4. Remote Imaging of Radiation

A Compton camera that utilizes segmented silicon and CdTe detectors has been developed that combines strip detector technology from particle physics with radiation sensors from nuclear physics. The original application was for the ASTRO-H satellite mission. The technology has now been re-purposed as a remote radiation sensing system capable of both imaging the location of radioactive regions and identifying the radioisotope species. This technology has been used to map part of the Fukushima Daiichi nuclear power plant site and has resulted in a commercial "Radiation Visualization Camera", the ASTROCAM-7000HS (Takeda *et al.*, 2012).

5. Neutron Activation

Neutron activation analysis consists of detecting nuclei of interest in materials by activating them with neutrons and then using γ-spectroscopy to identify the characteristic gamma ray energies and intensities of the activated nuclei. There are a variety of examples of the use of neutron activation analysis to understand the composition of materials. In one example, aerosol samples were collected in the Azores to track long-range transport of contaminate nuclei in air masses from surrounding continents over the North Atlantic Ocean from Africa, Europe, and North-Central America from July 2001 to April 2004. Samples were assessed through neutron activation analysis and lanthanoids and actinides were detected, providing information about the migration of aerosols (Freitas and Pacheco, 2010).

Neutron activation is also used to non-destructively detect art forgeries (Wiescher, 2014). An entire painting is irradiated with a homogeneous neutron flux (typically outside a reactor) followed by a raster activation detection process using X-ray and γ-ray detectors. The chemical elements manganese, copper, sodium, arsenic, phosphorus, mercury, and cobalt, are associated with pigments most frequently used by seventeenth-century Dutch and Flemish painters. Activating these isotopes and detecting their characteristic signature allows identification of the paint pigments used. Paintings whose pigments do not have these characteristic elements in the correct amounts could be identified as forgeries.

Other examples of the use of neutron activation analysis include characterizing suspended sediments from the Piracicaba River Basin (Franca *et al.*, 2010a) and its use in determining chemical elements in bird feathers in Brazil (Franca *et al.*, 2010b).

The National Institute of Standards and Technology (NIST) has developed a $\gamma\gamma$ coincidence spectrometer for neutron-activation analysis (Tomlin *et al.*, 2008). It consists of two high-purity germanium γ-ray detectors and an all-digital data acquisition system for the purpose of exploring nuclear activation analysis and its value in characterizing reference materials. In principle $\gamma\gamma$ coincidence counting can achieve a higher degree of discrimination than non-coincidence ("singles") spectroscopy since it applies a more stringent definition of what constitutes a valid event, namely the observation of two decay-correlated γ-rays within a specific time window. This provides for much more efficient rejection of uncorrelated "background" events.

6. Proton Activation

Although neutrons are most often used for non-destructive analysis, protons are sometimes used as well. When a proton beam interacts with the material of a sample, it can liberate atomic electrons from the inner shells. As other electrons fill the vacancies, they emit electromagnetic radiation, which provides information about the shell structure of the atoms. PIXE is a technique that determines the elemental composition of a sample by detecting the characteristic electromagnetic radiation emitted after proton irradiation (Collon and Wiescher, 2012).

There are several advantage of using proton irradiation over other forms of irradiation such as X-ray or γ-radiation. Since protons have an energy-dependent penetration depth in materials, varying the proton beam energy varies the depth sample activation making depth profiling possible. Microscopic analysis can be carried out using thin beams. PIXE also has good signal-to-noise making it possible to observe trace elements in a sample.

7. Use of Particles to Carry Out Non-Destructive In Vivo Measurements

For many years X-rays have been the primary elementary particles to carry out non-destructive measurements in vivo. The contributions of particle physics to X-ray measurements have been primarily in developing and characterizing the instruments for X-ray detection used in many X-ray medical imaging applications.

There are a variety of modern X-ray detectors, which are similar to those being used in modern particle physics detectors. These include photon counting X-ray detectors and chemical vapor deposition diamond detectors (Galbiati *et al.*, 2009; Spahn, 2013). Although these technologies were not invented by particle physicists, modern particle physics experiments at the Large Hadron Collider are driving new developments in these technologies and providing a stringent environment in which to test them.

E. Use of Particles to Make Changes In Vivo in Materials

Elementary particles and ions are widely used in making modifications to materials and for treating abnormalities in vivo. These include polymer modification by electron beams, ion implantation in semiconductors, glasses, metals, and ceramics and radioisotope production for medical applications. A very significant use of particle accelerators and its physics is in radiation therapy. In proton therapy a beam of protons is accelerated and aimed at a tumor that is often deeply buried inside the human body and not operable. It is a prime example of the exploitation of elementary particle physics for medical purposes (Misaelides, 2013). As early as 1904, William Bragg published curves for the ionization of air by alpha particles emitted by radium and demonstrated that the ionization density increased sharply near the end of the range. Subsequent measurements and calculations carried out by particle physicists show that the interaction cross section of a charged particle moving through matter increases as the particle's energy decreases causing a peak in energy deposition near the end of the particle's range, called the Bragg peak. By carefully adjusting the proton energy, the energy deposition can be tuned and aimed at the exact location of the malignant tumor.

Particle physicists have developed the tools and technologies to accurately predict and measure the range of a charged particle in a variety of materials as a function of its energy. Robert Wilson, the first director of Fermilab, was one of the first people to point out how this information could be used for medical purposes (Wilson, 1946) and was a pioneer in proton cancer therapy. There are currently a handful of proton therapy facilities operating in the US. The energy deposition is even more localized for elements heavier than a proton, such as carbon and as such damage less healthy tissue than protons. The Helmholtz Center for Heavy Ion Research is one facility which uses carbon ions for cancer research. However few heavy ion therapy facilities are currently under construction. The applications of particle accelerators in society has been extensively reported on in the report "Accelerators for America's Future" (W. Henning, 2010) and, although very much within the bounds of particle physics research and development, is left outside the scope of this article.

F. Ultra-Low Light Level Applications

For years, particle physicists have used very sensitive photon detectors to detect the frequently very low light levels associated with Čerenkov and scintillation light generated by charged particles passing through, or created in, transparent materials in large detectors. Photomultipliers, image intensifiers, and photosensitive detectors with external amplifiers have all been used over the years to detect visible light produced by the motion of charged particles.

Low-light detectors and multi-detector imagers enable a wide range of applications, including cell imaging, biodiagnostic instrumentation, semiconductor wafer inspection, particle counting, nuclear medicine, radiation detection and quantum cryptography. These applications rely on the ability of the sensor to detect light levels that range from a single photon to millions of photons per second incident on the detector surface (Jackson, 2007).

One area where very low light level detection is important is in nighttime military operations. In night vision devices an objective lens focuses the available light onto the photocathode of an image intensifier. This causes electrons to be released from the cathode, which are accelerated by an electric field and enter holes in a microchannel plate where they cause secondary emission from the pores of the plate. The final cloud of electrons representing an intensified version of the original object hits a phosphor screen whose green glow generates a visual intensified image of the original object.

Low-level light detectors are essential to detect Čerenkov radiation in large volume water Čerenkov detectors, which are used to detect neutrinos and antineutrinos. A current area of research is the development of large-area, fast, photodetectors. These have the potential to detect Čerenkov and scintillation light in large detectors and, using fast timing, to do track reconstruction of the charged particle emitting the light. Photodetectors which have very fast timing and good spatial resolution also have the potential to exploit photon correlations in partially coherent thermal light sources to do "ghost imaging", that is, to obtain an optical image from the reflected light which is not affected by variable refractive-index gradients in the optical path because these affect photons traversing both paths in the same way and cancel out (Adams, 2015). This would open the possibility to "see through fog", for example.

G. Precise Measurement of Photon Energies

The technology for measuring the energy of γrays, X-rays, and visible light photons has improved dramatically over many years. Sodium iodide crystals coupled to photomultiplier tubes have been used to measure the energy of γ-rays from typical radioactive materials such as ^{60}Co to 7% full width half maximum (FWHM) but sodium iodide has largely been replaced in high energy physics applications by cesium iodide or more exotic crystals which are discussed in a following section on crystals[6]. Semiconductor detectors such as high purity germanium cooled to liquid nitrogen temperature are able to make the same measurements with a precision of less than 1% FWHM. These detectors have been used in a variety of particle physics experiments, most recently in the search for neutrinoless double-beta decay and dark matter. High purity germanium detectors are now widely used to identify natural or induced radioactivity in materials in applications ranging from characterization of materials to nuclear nonproliferation (Knoll, 2000).

Transition edge sensors were developed by the particle physics community to search for dark matter. The development of these detectors has provided an order of magnitude improvement in energy resolution of photons with energies ranging from 10^{-3} eV (microwave) up to 10^5 eV (γ-rays). Transition edge X-ray detectors can provide $\sim$50 times better energy resolution than silicon detectors, and a scanning electron microscope mounted transition edge sensor spectrometer is now a commercial product for STAR Cryoelectronics (Irwin, 2012). These detectors can resolve γ-peaks in nuclear spectra, which can help identify the presence of nuclear materials such as plutonium, and can also resolve X-ray chemical shifts to detect trace amounts of explosives. The infrastructure needed to deploy cryogenic detectors currently lim-

[6] Lanthanum halide ($LaBr_3$:Ce) scintillators offer better than 3% energy resolution at 662 keV but internal radioactivity reduces resolution below that of sodium iodide below 100 keV.

its their range of applications, but, as cryogenic technology becomes cheaper and more readily available commercially, the number of applications which benefit from high resolution photon measurements is bound to increase.

H. Charged Particle and Charged Particle Tracking Applications

Charged particle tracking detectors have a long history in particle physics. Over the years tracking detectors have consisted of nuclear emulsions, arrays of optical spark chambers, wire spark chambers, wire proportional counters, various types of gas detectors such as streamer chambers, arrays of scintillating plastic with photomultiplier or photodiode readout, time projection chambers, and silicon strip and pixel detectors.

1. The Nuclear Emulsion

The nuclear emulsion, one of the earliest particle detectors used in particle physics, is rarely used today in its research because read-out and data recovery speed is extremely slow compared to conventional systems based on electronic readout. An exception is the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) experiment which uses them to detect the τ-neutrino appearance in a pure μ-neutrino beam (Adam *et al.*, 2007). However, for use in geological research, where remote locations with no electrical power makes it difficult or impossible to use electronic detector systems and where charged particle counting rates from cosmic rays are small, nuclear emulsions have several advantages. These include high resolution, zero electric power consumption, robustness and portability, and low cost. Furthermore, the development of automated scanning systems have made the use of nuclear emulsions more attractive. It has been proposed to carry out muon tomography of ice filled cleft systems in steep bedrock permafrost using nuclear emulsions (Ihl, 2010). Nuclear emulsions are also used in autoradiography in biology and medicine to locate radioactive labels in samples of cells and tissues. They are also commonly used in proton radiography.

2. Silicon Detectors

The exploitation of silicon detectors, with their spatial resolution in the 5-10 μm range, to track charged particles started in the early 1980s when experimental physicists began to look for detectors to measure short-lived particles. The introduction of planar technology provided an additional boost to the industrial production and use of silicon strip detectors. The development of dedicated very large-scale integrated readout, which allowed for integration of detectors and electronics, further enabled this technology.

There were also attempts to develop two-dimensional detectors. CCD devices were the subject of one early approach[7] (Strauss, 1994). A second approach involved pixel devices bump bonded to silicon sensors; they began to be successfully implemented in experiments towards the end of the 1990s. Radiation effects in detectors and electronics quickly became apparent, but after many years of study, the physics of radiation damage in detectors and their associated electronics is being understood (Baselga Bacardit, 2015). Currently, detectors and electronics exist which are capable of surviving doses of 10 Megarad and fluxes of 10^{15} neutrons/cm^2, or higher. The application of silicon tracking detectors has expanded to nuclear physics, solid-state physics, astrophysics, biology, and medicine (Turala, 2005).

There are a number of specific applications of silicon tracking detectors. The Silicon strip technology developed by particle physicists is being explored for medical imaging, notably in proton-computed tomography (pCT) (Sadrozinski, 2013; Schulte *et al.*, 2004). Active pixel sensors, developed for LHC detectors, are candidates for retinal implants which have the potential to restore partial sight to the blind (Woodcraft, 2009).

In the early 2000s researchers at the University of Bonn slightly modified the ATLAS pixel sensor to create the The Multi Picture Element Counter (MPEC). The MPEC and the follow-up CiX chips created clearer, cleaner X-ray images than conventional technology, while eliminating over- or under-exposure (Yuhas, 2010).

3. Time Projection Chamber

The Time Projection Chamber (TPC), invented by David Nygren at the Lawrence Berkeley Laboratory in the late 1970s (Nygren and Marx, 1978), was originally designed to permit full reconstruction of events with up to 20 charged particles at an electron-positron collider. It was intended to provide 3D information for tracking and momentum measurement together with particle identification by multiple ionization sampling in a compact detector. This powerful combination soon found applications in other fields. At one extreme, TPCs are being used for studies of rare events of simple structure; at the other, they are used for heavy ion collisions, handling ever higher particle densities, up to many thousands of tracks in a single event, still providing information on a track-by-track basis. The largest TPC currently in operation is the central detector of the ALICE experiment at CERN, which studies the creation of the quark-gluon

[7] The SLAC Linear Detector (SLD) at the SLAC linear collider (SLC) used CCDs in their vertex detector.

plasma (Hilke, 2010). The TPC technology is now also being used with liquid argon as the active medium for the study of neutrino interactions.

There have also been several TPC-based projects at Lawrence Livermore National Laboratory, two of which involve applications outside of particle physics research. One of these involves the use of a TPC to measure neutron induced fission cross sections with reduced systematic error to improve simulations of engineering choices for advanced fission reactors. The second involves building a hydrogen filled TPC to identify neutrons and measure their direction for homeland security purposes (Heffner, 2009).

In addition, there is a nuclear medical imaging project using $\beta^+ - \gamma$ coincidences from ^{44}Sc radionuclides with liquid xenon (LXe) as the detection medium. This imaging technique is capable of locating a $\beta^+ - \gamma$ emitter in three dimensions with a spatial resolution of a few mm. The LXe detector prototype is based on the time projection chamber (TPC). The scintillation signal ($\sim$15000 UV photons/MeV) is prompt and is detected by a photomultiplier tube. It gives the start time for the drift time measurement along the z-axis. The 12 cm depth of LXe was chosen to efficiently detect the 1.157 MeV γ-ray. The ionization signal ($\sim$60000 e^-/MeV) is collected by a segmented anode of 3 $\times$ 3 cm^2 in the xy plane after crossing a micromesh "Frisch-Grid". This micromesh is a copper grid of 3 μm thickness and 50 μm pitch placed 50 μm above the anode. The localization of the individual photoelectric and Compton interactions in the liquid volume is then provided by the TPC readout principle: the conversion depth is determined by the electron drift time while the two other coordinates and the energy are provided by the anode signal sampling (Grignon *et al.*, 2007).

I. Čerenkov Radiation Applications

Muon tomography, which is increasingly being used by geophysicists to study large structures, can be improved by using Čerenkov radiation to measure the velocity of the muons and reject low velocity muons with low energies whose scattering reduces the image resolution. The Maya Muon Group at the University of Texas, Austin, proposes using a Čerenkov detector in conjunction with plastic scintillation detectors with wavelength shifting fibers to track muons and reject those with low energy when reductions in the size, cost, and weight make such a detector feasible at remote locations (Ihl, 2010).

There is also a recent medical application called Čerenkov Luminescence Imaging (CLI) for the *in vivo* imaging of small animals such as mice. CLI is based on the detection of Čerenkov radiation by beta particles (both electrons and positrons) as they travel into the animal tissues with a sufficient velocity to emit Čerenkov radiation. The basic idea is to use a beta emitter which preferentially accumulates in malignant tissues relative to normal tissues. Commercially available imagers using CCD cameras in bioluminescence mode can be employed to detect the Čerenkov radiation photons using wide and narrow band filters (Spinelli *et al.*, 2011).

Čerenkov radiation is also being proposed to improve the measurements of the arrival time difference of the two 511 keV photons arising from annihilation of a positron in positron emission tomography (PET). The use of PbF_2 crystals with microchannel plate-based photodetectors with excellent timing resolution has been proposed to detect the Čerenkov radiation (Korpar *et al.*, 2011).

J. Pattern Recognition Applications

Pattern recognition plays an important role in particle physics in the identification of particle tracks and the identification of the particles themselves. Sophisticated algorithms have been developed to identify electrons and photons and distinguish them from π^0s, for example. Many are based on elaborate statistical techniques, verified by detailed Monte Carlo simulations and benchmarked using real data. With the current trend in particle physics detectors to go to ever larger channel counts, these techniques are becoming more and more refined. Coarse grained calorimeters are trending towards imaging calorimeters and the additional information is being used to identify, based on the pattern of hits, the identify of the particle creating those hits.

The problem of extracting and identifying exotic particles in high-energy physics experiments has led to the use of deep learning - *e.g.* neural networks with multiple hidden layers - as an attractive possibility for improving the classification power extracted from experimental data. A recent study has shown that the current analysis techniques used in high-energy physics fail to capture all the available information, even when boosted by manually constructed physics-inspired features (Baldi *et al.*, 2014). The study asserts that the novel environment of high-energy physics, with high volumes of relatively low-dimensional data containing raw signals hiding under enormous backgrounds, can inspire new developments in machine learning tools. Aside from the feedback to the developers, success in using these more powerful algorithms should eventually find application in a broad range of areas, be it scientific or commercial.

K. Particle Energy Applications - Crystals

Scintillating crystals have been used to measure the energy of electrons and photons in particle physics experiments for many years. Bismuth Germanium Oxide (BGO) scintillating crystals were discovered in the 1970s;

they have very good performance characteristics for the detection of electromagnetic showers. In the late 1980s, the L3 experiment at the electron-positron collider, LEP, at CERN decided to build the first BGO crystal calorimeter, consisting of 11,400 BGO crystals with a total volume of 1.5 m^3. The Shanghai Institute of Ceramics (SIC) was selected to be the supplier of the crystals. At the time of the order, the growth of BGO crystals was a one-shot market for SIC. The large production volume required by the experiment, however, led to the development of the multi-crucible growth technology that allowed the growth of up to 36 crystal ingots per oven. This breakthrough opened up the BGO medical market. GE Healthcare has since built more than 1,500 PET scanners with SIC BGO crystals.

In a very similar vein, particle physics has led directly to the development of Lutetium Yttrium Orthosilicate (LYSO) scintillating crystals in 2005. Lutetium Orthosilicate (LSO) was invented in the 1990s at Schlumberger, but was not very radiation tolerant. Radiation damage studies of scintillating crystals for the LHC experiments showed that thermal annealing of the crystals in an oxygen atmosphere and yttrium doping were quite effective for improving crystal radiation hardness. These LHC radiation-hardness studies led directly to the development of the LYSO crystals. With brighter and faster scintillation light than BGO, LYSO now dominates the market for PET scanners, with thousands of LYSO-based PET scanners marketed to date by GE and Phillips.

One use of the LYSO crystals is in the COMPET project, a high resolution and high sensitivity PET scanner with a novel readout concept. This device uses a four block detector geometry with each block consisting of five layers of 80 mm long LYSO crystals lying in the trans-axial plane. The incident γ-rays transfer their energy in subsequent processes to scintillation light. Some fraction of this light leaves the crystals and enters wave length shifting fibers (WLS), which are arranged perpendicularly to the LYSO crystals in the axial direction. Since the WLS do not touch the crystals, only a small fraction of the scintillation light will enter the fibers. Within the WLS, the scintillation light has a certain probability to be absorbed and re-emitted, which allows for the determination of the point of interaction along the length of the LYSO crystal. The energy deposition and the point of interaction in all three dimensions can thus be reconstructed. Due to the fine pixelisation of the detector, the parallax error is small and uniform across the whole field of view yielding a uniform point source distribution, which allows the detector to be placed close to the imaged object. Furthermore, not only photoelectric events, but also Compton scattered γ-rays within the detector material can be reconstructed (Bolle *et al.*, 2011).

L. Custom Electronics Applications

During the construction of prototype pixel detectors for the LHC experiments, radioactive sources were used to test the system integrity. These test quickly showed that pictures were being taken of the sources themselves. This led to the development of devices for X-ray detection reminiscent of a camera. With the help of enlightened management, an informal collaboration was formed to produce the Medipix1 chip in 1997. The chip was used extensively to test Gallium-Arsenide sensors, a material that is particularly well suited to the detection of X-ray photons in the low-energy part of the diagnostic spectrum, a region used in mammography. The readout chip was also combined with silicon as a sensor, and these devices were used in applications ranging from soft X-ray imaging to β-ray imaging, and even as a detector in an electron microscope (Demarteau and Yurkewicz, 2014).

The success of the first Medipix chip stimulated a growing interest in the approach, and the team designed a new version that built on their experience developing pixel readout architectures for the nuclear physics experiment ALICE at CERN. The new circuit had two thresholds per pixel, which made the chip sensitive to deposited charges between an upper and lower threshold, the idea being to move towards spectroscopic or "color" X-ray imaging. The Medipix2 chip was produced in 2005 after a four-year development cycle. This chip was then followed by the Timepix chip which is also sensitive to particle arrival time (Liopart *et al.*, 2008, 2002).

These two chips have generated over 150 refereed scientific papers and were important components of a large number of PhD theses. The devices are used in a wide range of applications, only some of which were foreseen, including electron microscopy, neutron imaging, nuclear power plant decommissioning, adaptive optics, dosimetry in space, readout of gas detectors with time resolution, and beam collimation studies for the upgrade of the CERN large hadron collider.

The Medipix2 chip has been coated with neutron converter materials for neutron imaging applications. Thermal or slow neutrons are converted in the coating which can consist of ^{6}Li, ^{10}B, ^{113}Cd, ^{155}Gd or ^{157}Gd. Measurements were carried out using neutron beams at the Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague (NPI) and at the NEUTRA facility at the Paul Scherrer Institute (PSI) at Villigen in Switzerland. The best spatial resolution was achieved with a ^{10}B converter with a detection efficiency of 1.5 %. Better detection efficiency of 3 % was achieved with a ^{6}LiF converter achieving a spatial resolution of about 100 μm. Because of the superiority of the Medipix-2 detector in terms of spatial resolution, linearity, and dynamic range compared with other neutron imaging systems the system appears to be very promising in applications for neutron microtomography (Jakubek *et al.*, 2006).

FIG. 2 A commercial Positron Emission Tomography (PET) scanner. Much of the technology underlying this scanner and recent improvements come from particle physics (Figure courtesy of GE Health Care).

A third generation chip, the Medipix3 has been developed for use with a segmented semiconductor sensor. Like its predecessor, Medipix2, it acts as a camera taking images based on the number of particles which hit the pixels when the electronic shutter is open. However, each Medipix3 pixel has 2 thresholds and two counters. This makes it possible to select a pixel energy range (color) for color imaging and a deadtime free operation by reading one counter while writing the other. It is also possible to bond only 1 pixel in 4 to get 4 separate thresholds in deadtime free mode, or 8 thresholds in sequential read/write mode[8].

An important partner for the Medipix2 and Timepix collaborations has been the X-ray materials analysis industry[9]. This segment of industry utilizes highly scientific X-ray analysis technology in their commercial products that provides researchers (in industrial as well as in scientific laboratories) the tools to study materials. The early commitment to the Medipix2 chip provided the collaboration with the motivation (and the much-needed money) to take the chip beyond the prototype stage to an industry-standard level. This "diversion" into imaging has not only proven to be beneficial for the non-particle physics community, but also for the field itself. The latest version of the Timepix chip meets nearly all the specifications for the upgraded vertex pixel detector for the LHCb experiment at the LHC, saving significantly on development time.

[8] medipix.web.cern.ch/medipix/ Accessed: 2015-5-27
[9] PANalytical http://www.panalytical.com/ Accessed: 2015-5-27

1. Pixel Applications

Pixel detectors developed for Particle Physics are now extensively used for X-ray imaging and spectroscopy at synchrotron light sources. These integrated circuits require radiation hardness similar to that required for particle physics experiments and benefit from the extensive development and testing of radiation hard circuit design techniques. The complex pixel design, often including timing, pulse height, and photon counting, direct related to pixel detector systems developed for collider experiments. A prime example is the PILATUS multi-megapixel focal planes developed at the Paul Scherrer InstituteI and commercialized by Dectris (Hulsen-Bollier, 2005).

Three dimensional (3DIC) integrated circuit technologies that were developed for particle physics are also being applied to large area focal planes. The VIPIC system contains two layers of 0.13 micron circuitry directly bonded to a sensor wafer (Deptuch *et al.*, 2016). The two layers of readout are 34 microns thick and all connections are made through the top of the chip. The VIPIC is designed for for X-ray time correlated spectroscopy at light sources and was part of a developmental 3DIC run for particle physics. The 3DIC technology enables large arrays with no area lost to readout chip or sensor edges and a density of electronics not attainable in two dimensional designs.

Another cross-disciplinary application is the Retinal Readout project. This project combines particle physics expertise in ASIC design and multi-channel small signal data acquisition with neurobiology and nanofabrication. Retinal tissue is placed in a chamber on top of an array of microscopic electrodes interfaced to an ASIC similar to the circuits used for silicon detectors in particle physics. These signals are processed and recorded with the goal of understanding the correlations of the pulse trains generated by the neurons. The studies have discovered a new functional type of primate retinal output (ganglion) cell that may be involved in motion perception. It has also led to the creation of a functional connectivity map of the primate retina at the resolution of individual cones and individual retinal output cells (Litke *et al.*, 2004).

Gamma imaging is another technique of great interest in several fields such as homeland security or decommissioning of nuclear facilities in order to localize hot spots of radioactivity (Gmar *et al.*, 2011). A γ-camera to address this issue called GAMPIX has been developed by CEA LIST in France[10] based on the Medipix2 chip hybridized to a 1 mm thick CdTe substrate. This compact device which weights less than 1 kg without any shielding is easy to handle and use.

2. The Touchscreen

The touchscreen, which is now ubiquitous in electronic devices, was demonstrated by Frank Beck and Bent Stump, engineers from CERN in the early 1970s. This capacitive touchscreen was manufactured by CERN and put to use in 1973 in the control room of CERN's SPS accelerator. Although touchscreen technology has evolved substantially since the 1970's, the CERN control room was one of the earliest applications of this technology.

3. Timing Applications

When timing information of individual particle hits is available, there are a number of data processing advantages which can be realized. In 3D Time-of-Flight (TOF) positron emission tomography (PET), for example, where the data is a set of coincidences within a coincidence window, a precision measurement of the time difference between photon arrivals makes it possible to estimate the location of the position along the line where the electron-positron annihilation took place and improve the signal-to-noise ratio of reconstructed images. Although TOF PET systems were developed in the 1980s, the scintillation medium, primarily BaF_2 had low stopping power and low light yield and therefore these systems could not compete with non-TOF based systems using BGO crystals. Fast scintillators with high stopping power like LSO and $LaBr_3$ have generated a renewed interest in TOF PET (Vanderberghe and Karp, 2006).

As stated above, the Medipix2 ASIC is a 256×256 pixel readout matrix developed at CERN where each pixel has an amplifier, discriminator, and counter. It was initially designed to have a semiconductor diode array bump bonded to its input pads to become sensitive to x- and γ-rays as well as higher energy particles to make it particularly appropriate for medical applications. Its sensitive spectral range was extended to the ultraviolet and optical bands by using microchannel plates to convert and amplify photoelectrons into charge clouds ($\sim 10^4 e^-$) that are above the minimum threshold of the Medipix2 amplifiers and discriminators ($\sim 1000\, e^-$). In this case a bare Medipix2 is used without its semiconductor diode array. The advantage of such an optical and UV detector is its extremely fast readout ($>$ 1 kHz frame rate) with zero readout noise, though the small number of pixels (65,536) and larger pixel size (55×55 μm^2) limit its use to certain niche applications, e. g. adaptive optics. The Timepix has also been used to measure the spatial distribution of charge coming from a microchannel plate (MCP) event. The centroid of this charge can be determined very accurately to a fraction of a pixel, allowing the location of the incoming radiation on the front surface of the top MCP (Vallerga *et al.*, 2008).

Since the structure of an object can be imaged by measurement of the energy loss of individual particles from a beam of mono-energetic heavy charged particles (protons, alphas, etc.), the Timepix ASIC coupled with a pixelated silicon sensor can be used as a suitable position and energy-sensitive detector. Studies have been carried out using alpha particles and a Timepix based detector. The spatial resolution in the detector plane depends on

[10] www-list.cea.fr/index.php/en/ Accessed: 2015-6-9

the particle energy and can reach submicron levels. The specimen thickness can be determined with a precision up to 320 nm for organic materials if the energy loss of individual alpha particles is measured (Jakubek *et al.*, 2008). The Timepix has also been applied to a variety of time-resolved mass spectroscopy applications, including pixel imaging mass spectroscopy and bio-molecular ion spectroscopy (Jungmann *et al.*, 2011).

The Timepix ASIC coupled with a pixelated silicon sensor has also been used to detect photoelectrons of energies between 6 and 20 keV in a device being developed for astroparticle physics experiments (Anton *et al.*, 2009). When the pixelated silicon sensor is coated with a thin layer of ^{6}Li or ^{10}B, the detector can be used to detect ultra-cold neutrons with micron spatial resolution (Jakubek *et al.*, 2009).

M. Large Area Applications

To make the very large detectors for accelerator based particle physics experiments affordable, there is an increasing need for cheaper technologies for large area particle detectors[11]. Over the years, large-area charged particle detectors have consisted of sheets of plastic scintillator or arrays of cells of liquid scintillator with photodetector readouts, or gas filled detectors with wire or pad readout. Recent years have seen a resurgence of gas-based detectors to cover large areas due to improved manufacturing techniques and their cost effectiveness. Resistive plate chambers have been developed which consist of parallel plates made out of a phenolic resin (bakelite) or glass coated with a conductive graphite paint to form high voltage and ground electrodes. A gas between the plates ionizes when a charged particle passes through it and the device is read out using metal strips separated from the graphite coating by an insulating plastic film. Large GEM foils can now be produced both at CERN and commercially in any required form factor and due to their radiation hardness and cost-effectiveness are often the technology of choice for tracking detectors. MicroMegas detectors are equally popular.

Recently a water-based liquid scintillator has been developed as an alternative to the widely used oil-based liquid scintillator. This water-based scintillator is several times cheaper than oil-based scintillator and is being considered for initial adoption in several particle physics experiments. If successful, it could provide the basis for less expensive detectors for future geological or security (anti)neutrino detectors.

[11] In this context, large area means detectors with surface areas ranging from tens to several hundreds of square meters.

N. Applications for Radiation Hard Detectors

Silicon has been the material of choice for tracking detectors for particle physics for many years. Segmented detectors, processed using microelectronic planar technology, have been used successfully to precisely image the tracks of charged particles in many experiments. The operation of such devices, however, is compromised when they are irradiated with high fluences (above 5×10^{14} particles/cm^2) of neutrons or high-energy hadrons. Defects are introduced into the crystal lattice transforming its electrical properties. One solution to this problem is the 3D silicon sensor in which the positive and negative charge collection surfaces are columns in the detector volume perpendicular to the surfaces rather than on the detector surfaces. This makes the charge collection distance several times shorter, the collection time faster, and the voltage needed to extend the electric field throughout the volume between electrodes (full depletion) an order of magnitude smaller for 300 μm thick silicon (DaVia *et al.*, 2005). Because of its radiation hardness, 3D silicon detectors can be used in applications requiring imaging of charged particles and X-rays. Applications include medical beam luminosity monitoring, and X-ray mammography and structural biology proton folding studies (DaVia, 2003).

Radiation hard detectors are also useful for measuring radiation doses in hospitals and in other locations where there are health risks from radiation. Sensitive dosimeters developed using LHC ATLAS sensor technology address this need[12].

Diamond detectors have been used for many years in applications in which its physical properties, which include a large bandgap (5.45 eV), high thermal conductivity, high electrical resistance, high melting point, and high index of refraction (n = 2.419 at λ = 589.3 nm) make it particularly suitable. In medical X-ray dosimetry, diamond detectors are preferred because its atomic number 6 closely matches the effective atomic number of human tissue which is usually given as 7.5. Since many of the processes involved in the interaction of X-rays with matter show strong dependence on atomic number as well as X-ray energy, the use of detectors with substantially different atomic number is problematic.

In recent years, particle physics experiments have needed to develop increasingly radiation hard sensors to handle the increase in radiation associated with higher accelerator luminosities. The close collaboration between particle physicists and the manufacturers of artificial diamonds has enabled a long and difficult process of improvements in the properties of these materials, and there are now prospects of having diamond detectors play an

[12] https://www.iop.org/publications/iop/2009/file_38212.pdf

increasingly important role in future particle physics experiments.

In order to make the use of diamonds feasible for future particle physics detectors, it is necessary to obtain, at reasonable cost, thin sheets of diamond at centimeter dimensions. This is now possible as a result of the process known as chemical vapor deposition (CVD), which, although discovered in the 1950s has only now become widely practiced and understood. Using this method, it is possible to make diamond wafers resembling silicon wafers which can be polished, laser cut to shape, coated and treated in other ways to yield the blanks from which detectors can be made by depositing electrodes on the surface.

The cost of the development of the CVD for diamond manufacture has been driven by the requirements, not of particle physics with its relatively small market, but by other applications which exploit the remarkable properties of diamonds in other ways. These applications include the use of diamond as a "heat-sink" material in electronics, and the manufacture of infra-red-transparent diamond windows for defense applications. However, there is a large potential market for electronic devices such as diodes and transistors using diamond as the active medium and the requirements for these devices have much in common with the requirements for diamond detectors (Tapper, 2000).

Diamond detectors are now being used for X-ray synchrotron radiation monitoring, ultraviolet radiation monitoring and are being considered for thermal and fast neutrons detectors (Galbiati, 2009).

O. High Speed Readout Applications

High energy collider detectors process data approaching 50 Tb/s. The high-speed data communication components, operating in a high radiation environment, must perform with high reliability. This extreme communication environment of these experiments provides a stringent test of high speed communication system components.

Many recent data acquisition systems use high speed optical fibers driven by modulated lasers such as Vertical-Cavity-Surface-Emitting Lasers (VCSELs) operating at gigahertz frequencies. However, VCSELs have proven to be somewhat unreliable in these particle physics applications (Weidberg, 2012). One possible solution to the VCSEL reliability problem is to use optical modulators with a continuous wave laser instead of modulated lasers (Underwood *et al.*, 2010). This allows the use of continuous wave lasers outside the tracking volume and very low power modulators (50 μW at 1 GHz, scaling with frequency) versus 16 mW for approximately 300 μW of light from a VCSEL and 45 mW for a 10 GHz driver. There are no known failure mechanisms for these modulators and the bit error rate is $\sim 10^{-18}$ versus a typical error rate of 10^{-12} for a VCSEL-based system (Underwood *et al.*, 2012).

Because modulators can be integrated into CMOS, there is commercial interest in this integration for fast communication between chips with no copper. Several organizations and companies, including IBM and Intel, are developing devices for beams between chips using this technology[13].

P. Applications for Distributed Monitoring, Documentation, and Control Of Large-scale Systems

The very large size and complexity of systems of multiple components for particle physics accelerator experiments has necessitated developing software tools to control and monitor the performance of these detectors. Typical distributed control systems comprise tens or even hundreds of computers, networked to allow communication between them and to provide control and feedback of the various parts of the device from a central control room or even remotely over the internet. For some detector systems control software has been developed specifically for each detector system, but for others, general purpose control software toolkits, which have been extensively used and debugged, have been used. One such set of control software tools is the Experimental Physics and Industrial Control System (EPICS), a set of Open Source software tools, libraries and applications developed collaboratively and used worldwide to create the software infrastructure for distributed real-time control systems for scientific instruments such as particle accelerators, telescopes, and other large scientific experiments[14].

EPICS originally evolved from the control system developed for the linear, proton, Ground Test Accelerator (GTA) at Los Alamos National Laboratory (LANL) in 1988 and 1989. In April of 1989, a control group at Argonne National Laboratory (ANL) decided to adopt the GTA control system for use in the Advanced Photon Source (APS), a synchrotron radiation facility whose accelerator and storage ring handled positrons, and formed a collaboration with the GTA group. From the beginning the two groups sought to maximize the system's utility, convenience, and cross-platform transparency by having both teams carefully examine and approve each proposed system modification and this led to a new version, EPICS, which could be successfully implemented on both projects. Subsequently control groups from other

[13] Light for Communication between Computer Chips http://www.epanorama.net/newepa/2010/03/29 Accessed: 2015-6-10

[14] www.aps.anl.gov/epics/index.php Accessed: 2015-5-27

national laboratories joined the EPICS collaboration[15].

EPICS is or has been used on a variety of particle physics, nuclear physics experiments including the BaBar detector at SLAC, the CDF and Dzero detectors at Fermilab, the STAR and PHENIX detectors at Brookhaven, the BELLE detector at KEK, Halls A, B, and C slow controls at Jefferson Lab, the Advanced Light Source Beamlines at Argonne, and the High Acceptance Di-Electron Spectrometer at GSI in Darmstadt. It is used on a number of telescopes including the Keck-II Telescope (CARA), the Kitt Peak Observatory (NOAO), and the Sloan Digital Sky Survey/Telescope Performance Monitor (SDSS) and for the gravitational wave detector LIGO. It is also widely used for accelerator control.

Although the high-energy physics detector community did not develop the original EPICS software, it has provided considerable added value by 1) providing a laboratory to extensively test existing software, 2) contributing new software extensions, and 3) providing documentation and expertise for new users (Savage, 2006). The EPICS software is being used in a wide variety of commercial applications (EPICS, 2016).

Q. Applications Involving the Handling and Analysis of Very Large Data Sets and Computing

The role of particle physics in the creation of the World-Wide-Web is well known and has been highlighted in a report from the President's Council of Advisors on Science and Technology (PCAST) (Holdren *et al.*, 2012) and on the web[16]. In 1989, Tim Berners-Lee, a software engineer at CERN, submitted a proposal to his management which specified a set of technologies that would make the internet truly accessible and useful to people. By October of 1990 he had specified three fundamental technologies that remain the foundation of today's Web:

1. HTML: HyperText Markup Language. The publishing format for the Web, including the ability to format documents and link to other documents and resources.
2. URI: Uniform Resource Identifier. A kind of "address" that is unique to each resource on the Web.
3. HTTP: HyperText Transfer Protocol. Allows for the retrieval of linked resources from across the Web.

He also wrote the first web page editor and browser and the first web server. By 1991, people outside CERN joined the new web community. In April 1993, CERN announced that the World-Wide-Web technology would be available to anyone to use on a royalty-free basis.

Today the World-Wide-Web has pervaded every corner and every aspect of society and social interaction. It is probably the technology that originated in particle physics, which has had the greatest impact on modern life. As early as 2003, Network Physics in Mountain View California launched a network management application that relied on high-energy physics experiments to help companies better manage large corporate networks (Hamblen, 2003).

More recently particle physicists have helped develop distributed "grid" computing technology to increase data analysis power by accessing remote computer installations in widely dispersed institutions. This was motivated primarily by the need for experiments at the CERN large hadron collider to substantially increase their data analysis and simulation capabilities. By launching grid computing in Europe and the United States, particle physicists demonstrated the capability to unite and operate globally distributed computing resources into a coordinated computing service. The European and U.S. grids are now used by a wide spectrum of sciences including archeology, astronomy, computational chemistry and materials science.

The computational and data challenges of "big science" projects such as the large hadron collider experiments are not limited to the unprecedented size of the "big data" generated. The highly distributed locations of researchers who need to access and analyze the data require sophisticated workload and distributed data management systems. One of these, developed in the U.S. and used primarily by the ATLAS experiment at the LHC, is PanDA, the Production and Distributed Analysis System (Maeno, 2008). This system supports data-intensive science by delivering transparency of data and processing in a distributed and heterogeneous computing environment. Communities outside particle physics have recognized this, and PanDA is becoming a broader enabling technology fostered by partnerships with computing and software companies.

One of the first non-particle physics applications of the LHC computing grid was a molecular modelling program, WISDOM, used to develop new drugs to treat malaria. More than 46 million molecular structures were computer examined to find candidates with potential bioactivity. Grid based technology is now also being applied to manage databases of cancer patients which will help in assessing their treatment (Kasam *et al.*, 2009).

There are many fields benefiting from grid applications. In astronomy, the Low Frequency Array for radio astronomy (LOFAR), which makes observations at radiofrequencies below 250 MHz, has transferred observation to the Grid to reduce pressure on the 500 terabyte central storage capacity which was becoming a bottleneck

[15] http://csg.lbl.gov/EPICS/ (Option: Epics at LBL) Accessed: 2015-5-27

[16] http://webfoundation.org/about/vision/history-of-the-web/ Accessed: 2015-5-27

for continued observations. In the natural sciences grid computing is being used to correlate data from millions of calculations to unveil the rock structure of an oil field under the North Sea and to trace tapeworms infecting Northern African fish back to Europe. In medicine the grid is being used to design better antibiotics, to hunt for viruses, and for tracking a biomarker for Alzheimer's disease.

Grid computing is used in a variety of business applications. In France, the OpenPlast project was a French R&D program from 2003-2006 to develop and deploy a grid platform for the plastic industry for small and medium-sized enterprises (SME). The company NICE, based in Italy, delivers comprehensive grid and cloud solutions for companies and institutions, and GridWisetech in Poland provides database services and data analytics services to corporations and public institutions. CGGVeritas in France manages in-house informational technology infrastructures and sells services to the petrochemical industry. DataMat in Italy provides grid services to the automotive industry (Jones, 2014).

At present grid computing is supported by several organizations. The European Grid Infrastructure (EGI) is a federation of over 350 resource centers and coordinated by EGI.eu, a not-for-profit foundation created to manage the infrastructure on behalf of its participants: National Grid Initiatives (NGIs) and European Intergovernmental Research Organizations (EIROs). Its mission is to connect researchers from all disciplines with the reliable and innovative information and communications technology services they need for their collaborative research. In the United States, the Open Science Grid (OSG), which is jointly funded by the Department of Energy and the National Science Foundation, provides a common service and support for resource providers and scientific institutions using a distributed fabric of high throughput computational services. Aside from high-energy physics, OSG supports structural biology (SBGrid) and multiple other sciences through OSGConnect. Similar organizations are also available in Asia.

In the area of networking, for more than a decade large-scale particle physics data flows have been the primary driver for the evolution of the architecture and implementation of the Energy Sciences Network (ESnet). ESnet is a high-bandwidth network that connects and enables the research of scientists at national laboratories and universities across the U.S. Spurred by the needs of particle physics, ESnet developed the virtual circuit service called OSCARS, the On-demand Secure Circuits and Reservation System. This software service creates dedicated bandwidth channels for scientists who need to move massive, time-critical data sets around the world. OSCARS received a 2013 R&D 100 award[17] and is now used by other data-intensive science communities (Kramer, 2014). In addition, major international network traffic exchange locations associated with DOE Office of Science programs are also driven by the requirements of particle physics.

Data management tools developed in particle physics experiments have been used successfully in condensed matter experiments at DOE light sources (G. Roberts, 2013). This has initiated discussions to establish multidisciplinary partnerships between condensed matter scientists, particle physicists, and computer scientists to address the challenges of big data via collaborations that may produce better tools and avoid duplication.

Particle physics research, in collaboration with the astronomy and astrophysics communities, has innovated special data systems to deal with "big data" as part of its quest to probe the universe via the Cosmic Frontier. The community's expertise in building very complex facilities and processing very large data sets was used very successfully in the Sloan Digital Sky Survey (SDSS) (York *et al.*, 2000a), whose science goals served both the particle physics and astronomy communities.

The Scientific Linux operating system developed at Fermilab and CERN and based on the Red Hat Enterprise Linux operating system is an example of a no-cost, value-added technology customized to support particle physics research, which now powers other sciences. Scientific Linux runs on the International Space Station as well as the majority of the campus grid at, for example, the University of Wisconsin-Madison where it is used for research from economics to engineering.

Scientific computing has become a cornerstone of modern science and has arguably reached the same level of importance as theory and experiments, facilitating scientific breakthroughs impossible to achieve without it. Scientific computing enables discovery science and predictions of new phenomena, complex modeling of accelerators, detectors, or telescopes that guide the design and understanding of new instruments, the analysis of complex data both in real time and in post-processing, the controlled investigation of systematic errors in the experiment or data, and also the extraction of fundamental parameters and results from the data by comparing it to detailed predictions from simulations.

Particle physics has played a unique role in this development and is expected to continue to play a central role in the development of the next generation of software-defined networks and the architecture of future high performance computers. The field provides some of the most

[17] R&D Magazine, "Allowing Research Anywhere: 2013 R&D 100 Winner," 29 August 2013 http://www.rdmag.com/award-winners/2013/08/allowing-research-anywhere Accessed: 2015-5-27

data intensive and compute intensive problems. With the upcoming upgrades of the LHC experiments and new cosmological surveys, multi-petabyte workflows will have to be managed by networks with a high degree of built-in intelligence Cosmological simulations that evolve the universe from its early beginnings to the present time put strong demands high performance computing. New application areas that take advantage of HPC systems are also proliferating; these include detector modeling, event generators, perturbative QCD, and observational data pipelines.

Particle physics, in cooperation with the major Research and Education (R&E) networks and industry, has played a central role in the emergence of the next generation of software-defined networks and the emergence of high performance computing. Particularly in the field of networks capable of coherently distributing and helping to manage multi-petabyte workflows the contributions have been significant. It is fully expected that the field will continue to play a crucial role in the development of networks with a high degree of built-in intelligence and the emerging generation of Exascale supercomputing systems for data and compute intensive applications.

R. Applications Involving Detailed Simulations of Complicated Systems or Complex Calculations

1. Simulations - GEANT4

Another example of the interplay between the particle physics community and the broader community is the sophisticated GEANT4 (GEometry ANd Tracking software) toolkit which provides simulation and tracking of particle interactions in complex detectors and devices using Monte Carlo methods. The GEANT4 toolkit supports all particles and complex geometries. It can handle motion in magnetic and electric fields (including time varying fields), it uses a modern programming language (C^{++}), and, very important to its success outside particle physics, is open source and free to use. GEANT's ability to describe intricate geometries, define the unique material properties of every element a particle encounters on its path and track the passage of particles through matter keeping track of their primary and secondary interactions has made it a vital tool, not only for particle physics simulations but also for advances in medicine, aerospace, nuclear physics, accelerator modeling, nanoscale science, geophysics, and industry. In some cases, new specialized Monte Carlo packages have been developed based on the GEANT4 toolkit.

The medical community has found GEANT4 so useful as a simulation tool, they have developed their own custom simulation toolkit based on GEANT4. The GEANT4 Application for Tomographic Emission or GATE encapsulates the GEANT4 libraries to achieve a modular, versatile, scripted simulation toolkit adapted to the field of nuclear medicine (Jan *et al.*, 2004). The GATE simulation program is supported by the OpenGATE collaboration and has its own homepage (www.opengatecollaboration.org) where program downloads, documentation, training materials, and training sessions can be obtained. In 2009, the OpenGate collaboration was awarded the Physics in Medicine and Biology (PMB) Citations Prize for its research paper "GATE: a simulation toolkit for PET and SPECT", which is awarded annually to the authors of the PMB research paper that received the most citations in the preceding five years.

Emission tomography has become increasingly important in modern medicine for both diagnostic and treatment monitoring, with a demand for higher imaging quality, accuracy, and speed. The availability of powerful computing capability has made Monte Carlo simulations an essential tool for current and future emission tomography development. Research areas benefiting from these developments in simulation are the design of new medical imaging devices, the optimization of acquisition protocols and the development and assessment of image reconstruction algorithms and correction techniques. Unlike other available Monte Carlo packages which are difficult to tailor to PET and SPECT, the GATE Monte Carlo toolkit is capable of accommodating complex scanner geometry and imaging configurations in a user-friendly way while retaining the comprehensive physics and modelling abilities of the general purpose C^{++} code. In addition, it provides a platform that can model decay kinematics, dead-time, and movement. The OpenGATE collaboration was formed to foster long-term support and maintenance by sharing code development among many research groups.

A specific application of a GATE based Monte-Carlo simulation study is for a detector array design for dedicated breast metabolic imaging systems (Raylman *et al.*, 2005). The goal of this investigation was to utilize Monte-Carlo simulations to determine the effect of detector element dimensions on breast lesion detectability.

Another application transpired in proton therapy where pencil-like beams are obtained through collimation. The protons hitting the collimator will occasionally produce a neutron which could pose a significant hazard to the patient. GEANT4 has been used to determine the dose a patient receives from these undesirable, but unavoidable, background neutrons.

In space science, GEANT4 is at the core of tools used by Boeing and Lockheed Martin to evaluate the radiation effects and protection of shielding and single-event effects of semiconductor devices in space environments. Boeing, which also uses GEANT4 to estimate the radiation dose of flight crews, hosted the 7$^{\text{th}}$ GEANT4 Space Users workshop in 2010.

2. Massively Parallel Computing - Lattice Gauge Calculations

Lattice Quantum Chromodynamics (LQCD) uses advanced computing techniques to solve the non-perturbative regime of QCD on a space-time lattice. Quarks and gluons that make up many of the observed particles of matter, called "hadrons", are held together and interact via QCD, historically called "strong interactions." LQCD relies on high-performance computing (HPC) and advanced software to provide precision computational results and predictions for explaining experiments and exploring new physics. The LQCD community is comprised of particle physicists and nuclear physicists studying different aspects of strong interactions of particles and nuclei. LQCD tools and techniques are developed collaboratively by the two disciplines, eliminating duplicative effort.

The LQCD community has been an avid user of advanced computing platforms and one of the major drivers and contributors to early developments in the supercomputing industry. Interactions between LQCD and computer designers go back as far as 1982 at the founding of the Thinking Machine Corporation. At the time, physicist Richard Feynman and his son Carl were working on the network of the Connection Machine and optimizing LQCD algorithms. This was followed by the development of "QCD on a chip," or QCDOC computers, by a group from Columbia University (Boyle *et al.*, 2005). A collaborator from the Columbia group went on to join IBM and designed the closely related commercial project, the IBM BlueGene/L computer (Chromodynamics, 2015).

The connections between lattice QCD and advanced computing continue today with collaborations of both particle and nuclear physics researchers with the computing science community and IBM, NVIDIA, and Intel Corporation. Such partnerships between the scientific, computing, and software communities and industry allow this area of particle physics access to cutting-edge computing technology, avoid duplication of effort and continue to drive advanced computing platforms.

LQCD techniques are also applied to condensed mater physics. Such systems intrinsically involve physical lattices, rather than space-time constructs like those used in lattice gauge theories. They exhibit a rich variety of non-perturbative phenomena, and their properties are often controlled by gauge symmetries. Systems of interest in both fields are frequently studied with Monte Carlo methods, and in both cases fermionic degrees of freedom make these studies challenging. Algorithms and calculational methods developed in each of these fields have been transferred to the other. For example, hybrid Monte Carlo algorithms invented in lattice gauge theory have been used to study models of high-temperature superconductivity. Continued interaction between the two communities is likely to yield further fertile ground for cross-seeding of methods.

Modeling and simulation of cosmological probes, of interest to particle physics, has an intimate connection with astronomy and astrophysics, particularly the clustering and physical properties of galaxies, galaxy groups, and clusters. Large-scale cosmological simulations studying different aspects of the "dark universe," dominated by the mysterious duo of dark energy and dark matter, make significant use of leading-edge supercomputing architectures and are one of the important drivers of hardware and software co-design for future exa-scale systems.

S. Applications Involving Standardized Analysis of Data

For many years CERN has provided a standard software analysis toolbox to the high-energy physics community for data analysis. Initially, this software was written in FORTRAN and the analysis package was called HBOOK, which evolved into PAW, the Physics Analysis Workstation. More recently, these tools have been rewritten in C^{++} and the analysis package is now called ROOT with an extension for data fitting called RooFit[18] [19].

Aside from a large number of high-energy physics, nuclear physics, and astrophysics experiments which use these analysis tools[20], there are a number of other applications which are using software based on ROOT[21].

One application is a computational neuroscience project MIIND (de Kamps *et al.*, 2008), which provides a simulation framework for neural simulations. It focuses on population level descriptions of neural dynamics which does not provide a simulator for individual neurons but models population activity directly.

Another application is the VEGA (Visual Environment for Gravitational waves data Analysis), which is designed to be a framework in which one can analyze data in the frame format coming from the interferometric gravitational wave detectors VIRGO and LIGO, but which is now also used by other such experiments.

The Forex Automation project, which is also based on ROOT software, is a public information service providing financial markets forecasts based on proprietary forecasting tools. It is also used to discover, quantify, and monitor the existence of sustainable opportunities for profit-making via systematic trading.

DAQ is a ROOT based Data AcQuisition platform for debugging embedded devices. It is supported by Erika

[18] https://root.cern.ch/drupal/ Accessed: 2016-1-27
[19] https://root.cern.ch/roofit/ Accessed: 2016-3-27
[20] According to Wikipedia, there are at least 21 running and 5 planned future particle physics experiments and at least 17 astrophysics (X-ray and γ-ray astronomy, and astroparticle physics) projects using software based on ROOT
[21] https://root.cern.ch/drupal/content/example-applications Accessed: 2015-5-27

Enterprise which provides support for software used by more than 20 universities and various companies in the automotive market.

The HRS Computing project supports ROOT based software, which simulates Hyper Rayleigh Scattering, a non-linear optics phenomenon. It is available in six languages and supports 3D visualization. ROOT software also underlies the application called Fracion, which stores interesting fractal information contained in a 2D scanned binary image (black/white) data in a ROOT file for later analysis. Build-in algorithms can be used to determine the fractal dimension or lacunarity.

In addition, there are a variety of software packages based on ROOT, which are designed to support various scientific, X-ray, medical, and security programs. The GSI Analysis System GO4 (GSI Object Oriented Online Off-line system) is an object-oriented system based on ROOT with extensions to meet the specific requirements of the low and medium energy nuclear and atomic physics experiments. It runs on a variety of Linux and Unix operating systems. The ROOT based Offline and Online Analysis framework ROAn provides an analysis framework for X-ray detector data (Thomas Lauf, 2014). MathROOT is a tool that allows access to ROOT data stores from within Mathematica. The MEGAlib (Medium-Energy Gamma-ray Astronomy library) is a set of software tools which are designed to simulate and analyze data of gamma-ray detectors, with a specialization in Compton telescopes. While MEGAlib was originally developed for astrophysics, it has been expanded and used for ground-based applications such as medical imaging and homeland security. The library comprises all necessary data analysis steps from simulation to measurements via event reconstruction to image reconstruction and is written in C^{++} and utilizes ROOT and GEANT4.

T. Applications Involving Ultra-Low Background Materials

Dark matter searches and neutrinoless double-beta decay experiments are two types of particle physics experiments, which require materials containing ultra-low amounts of radioactivity. Two techniques which have been used to screen detector materials for these experiments are low-level gamma counting with large, high-purity germanium detectors in shielded, underground facilities, and neutron activation studies of materials. Whenever possible, materials which are intrinsically pure such as single crystal silicon, petroleum based products in which any contaminating radioactive materials have decayed away, or noble gases with no radioactive isotopes, are used in these detectors. The requirements of these experiments has pushed the detection of very small amounts of radioactivity in materials to their limits, but the technologies employed to do this are also useful for screening materials for other applications. Ultimately, the dark matter or double-beta detectors themselves become the most sensitive detectors for ultra-low levels of radiation and can be used as a screen for materials for the next generation of the experiment.

Low background materials are also needed in the construction of commercial radiation detectors such as Geiger counters and ultra-low background high-purity germanium detectors for medical applications involving whole body scanning and lung counters. Ultra-low background detectors are used in a variety of scientific applications such as neutron activation analyses, radiochemistry, waste assay, natural and artificial samples analysis, food and life activity product analysis and for environmental counting.

Radioactivity is also a problem in the semiconductor industry. As the dimensions and operating voltages of semiconductor devices are reduced to satisfy the ever-increasing demand for higher density and lower power, their sensitivity to radiation increases significantly. Radiation can induce localized ionization events capable of upsetting internal data states. While the upset causes a data error, the circuit itself is undamaged and this type of event is called a “soft” error. The rate at which these events occur is called the soft error rate (SER) (Baumann and Smith, 2001). Three types of radiation cause SER: alpha particle emission from thorium and uranium impurities (and their daughter products) in the device fabrication materials; cosmic rays creating energetic neutrons and protons; and thermal neutrons. Of these, reducing the thorium and uranium impurities in the semiconductor fabrication materials is the only control device makers have. To enable acceptable SER performance, the semiconductor fabrication materials must be extremely pure to ensure that the emission of alpha particles from the thorium and uranium (and daughters) is minimized.

U. Large Project Management Applications

Today, most of the particle physics experiments are very large, international collaborations involving huge, expensive, custom designed detectors with complicated system engineering that span many technical frontiers. Since it is impossible for single institutions to provide all the necessary resources on their own, cooperation among many different institutions, countries, and funding agencies is required (Zhu and Qian, 2012). Given that the research relies heavily on very large scale international cooperation, the study of the management of both the successful and unsuccessful projects is a valuable resource for managing large projects in other fields.

Very large scientific projects in the United States probably had their origin at the Lawrence Berkeley Laboratory after the second world war, where Ernest Lawrence campaigned extensively for government sponsorship of large scientific programs and was a forceful advocate of

"Big Science" with its requirements for big machines and big money. He backed Edward Teller's campaign for a second nuclear weapons laboratory, which Lawrence located in Livermore, California (Herken, 2002).

R.R. Wilson, Fermilab's founding director from 1967-78 received his formal undergraduate and graduate education at Berkeley where he received his doctorate under the supervision of Ernest Lawrence for his work on the development of the cyclotron. Wilson's management capabilities, very much adopted from Lawrence at Berkeley, enabled him to complete construction of Fermilab on time and under the $250 million budget, while making it aesthetically pleasing, a rarity for very large government projects, and thereby providing a model for how to accomplish this feat.

Following this success, several new particle physics facilities were proposed and funded. The Superconducting Super Collider (SSC) project, was to leapfrog all existing accelerators and was approved by President Reagan in 1984. However, between 1988 when the design was completed and the site was determined and 1992 the projected cost of the SSC rose from about $4.0 billion dollars to $8.3 billion dollars with little reason to believe that the number would not rise higher. The project was perceived to lack coherent project management and effective cost control. The accelerator was initially conceived as a national project and failed to attract international funding and participation needed to justify the increased cost (Neal *et al.*, 2008; Riordan *et al.*, 2016). In 1993 Congress voted to kill the SSC.

The success of Fermilab, the failure of the SSC, and the successes and failures of other very large high-energy physics facilities throughout the world, and particularly the success of CERN, provide case study information for other scientific or commercial programs involved with or moving toward very large scale, expensive, international projects. One example is the 2003 book "Large-Scale Biomedical Science: Exploring Strategies for Future Research" (Nass and Stillman, 2003) where the Appendix of the book is titled "A History of Government Funding of Basic Science Research and the Development of Big-Science Projects in the Context of High-Energy Particle Physics", and Part II of the Appendix is titled "Issues in Conducting Large Scale Collaborations in High-Energy Particle Physics". These issues include funding, organization, management, staffing and training, and intellectual property. One observation that the authors make in this book is that "The success of big-science projects in fields such as high-energy physics has been attributed in part to the fact that the products of the research have no commercial value, and thus the scientists involved in a project are quite willing to share results and information."

Another example involves the Large Hadron Collider (LHC) along with the two major multi-purpose particle physics detectors ATLAS and CMS, which are the largest scientific experiments ever built. A May 20, 2009 article in Bloomberg Business by Krisztina Holly Has identified several factors which contribute to the success of this very large project (Holly, 2009):

1. The Power of Collective Ownership. There are no directors, no CEO's or presidents. LHC leaders create the framework for people to share and contribute. Everyone feels ownership and commitment.

2. Building a Sense of Trust. The CERN community operates with a sense of trust that comes from a mutual code of ethics where everyone is expected to work hard and share.

3. Failed Experiments equal Learning Opportunity. People don't fail, experiments do, so failure is a valuable learning opportunity. Risk taking is accomplished by a natural process of experimentation and peer review.

4. Shared Vision. The CERN scientists are dedicated to a singular goal - what is the best choice for the physics of interest? Leaders don't waste time and energy trying to control everything. Instead they focus on nurturing the right environment for innovation.

One of the more intriguing impactful aspects of the relationship between particle physics, industry, society and funding agencies has been the creation of new "global system concepts". The World Wide Web was the first example, and was followed by an ongoing vision of a global, coherent, autonomous system of networks, computing and storage system interacting with its "actors", which is increasingly important given the exponential growth in scale and the complexity of operations spanning global distances. The level of data intensiveness and truly global extent required by particle physics was unique among the sciences.

The Organization for Economic Co-Operation and Development (OECD) is a unique forum with 34 member countries where governments work together to address the economic, social, and environmental challenges of globalization. In 2014 it published a report titled "The Impacts of Large Research Infrastructures on Economic Innovation and on Society: Case Studies at CERN" (OECD, 2014). This report identified six impact categories: 1) Purely scientific results, intended to advance fundamental knowledge; 2) Direct impact of spending for construction and operation of the laboratory; 3) Training of scientists, engineers, administrators, and other professionals; 4) Achieving national, regional and global goals, strengthening international scientific co-operation; 5) Developing and diffusing technological innovations while pursuing the scientific mission, which is broken down into three subcatagories: a) Innovations needed for major component development and procurement with both HEP and non-HEP impacts; b) Non-HEP Innovations that can become external impacts with only minor modifications; and c) Non-HEP Innovations that can become external impacts with major additional efforts; and 6) Education (of teachers and/or students), and various forms of public outreach. Various case studies in category 5 include a discussion of procurement, manufacturing and testing in an international, inter-governmental organization, and risk management and governance.

The "big science" research facilities that particle physics has constructed and operates have been a role model for other organizations to follow. In these large-scale international collaborations multiple partners have their own program management methods and practices. Furthermore, because the goal is basic fundamental research which often pushes the boundaries of existing technology, fast track and overlapping phases of R&D with engineering design and construction are needed in parallel to the overall construction of the experiments. It is a tribute to the particle physics community that key project management methodologies of the HEP community are being adopted by many other organizations.

V. Particle Physics Laboratory Infrastructure

Some of the scientific demands on particle physics experiments require unique laboratory capabilities, which can be useful to other scientific and commercial disciplines. Underground laboratories, in particular, are essential to reduce cosmic ray backgrounds in ultra-low level counting experiments such as searches for neutrinoless double-beta decay and direct detection experiments for dark matter. Until recently, many of the deep underground laboratories were located in Europe, Japan, and Canada, but private donors, the state of South Dakota, and U.S. federal support primarily from the Department of Energy have created an underground facility, the Sanford Underground Research Facility (SURF), at the site of what was originally the Homestake gold mine in South Dakota.

Aside from particle physics experiments to search for dark matter and neutrinoless double-beta decay and a planned site for the detector for a long-baseline neutrino oscillation experiment, the Sanford Laboratory hosts biological and geological research experiments. Biological research includes studies of the deep terrestrial subsurface environment to better understand the Earth's primordial microbial ecosystems and possibly lead to discoveries such as novel metabolic products with potential use in industrial, pharmaceutical, or environmental applications. The goal of the geological research experiment GEOX^{TM} is to create the world's largest, deepest network of underground fiber-optic strain and temperature sensors and tiltmeters to measure the movement of rock systems in the underground laboratory (Heise, 2015).

In addition to specific research projects in scientific fields outside particle physics, underground laboratories enable ultra-low level counting to quantitatively measure radioactive elements in materials. Combined with increasingly sensitive detectors, in many cases using materials and technologies from ultra-low level physics detectors, these underground counting facilities are the world's most sensitive. Although widely used to measure radioactive contaminants in materials used in ultra-low background scientific experiments, they are useful for applications described in the previous section on applications involving ultra-low background materials. The use of particle physics accelerator laboratories also has potential value to other fields. Some examples are given in Section V.B.

W. Particle Data from Particle Physics Measurements and Calculations

The study of particle physics has been enabled by the iterative process consisting of the development of detectors followed by the use of these detectors to determine the properties of elementary particles or to discover new particles followed by the development of new detectors using the insights gained from the use of earlier detectors. Measurements are then used to check or refine theories which can then also be used in the development of new detectors. Very large databases of information about the properties of elementary particles and their interactions with matter are now available, and they can be widely used for any application involving interactions or detection of elementary particles. Much of this information is available in files which are used by GEANT4 and is freely available.

Proton therapy for cancer treatment is an example of the exploitation of elementary particle data in a medical application. As early as 1904, William Bragg published curves for the ionization of air by alpha particles emitted by radium and demonstrated that the ionization density increased sharply near the end of the range. Subsequent measurements and calculations carried out by particle physicists show that the interaction cross section of a charged particle moving through matter increases as the particle's energy decreases causing a peak (called the Bragg peak) in energy deposition near the end of the particle's range. Particle physicists have also developed the tools and technologies to accurately predict and measure the range of a charged particle in a variety of materials as a function of its energy. Today the medical community has exploited this information by developing proton accelerators which accelerate protons over a range of energies which allows them to range out in the body of cancer patients at the depth of the tumor. This produces minimal damage to healthy tissue on the path to the tumor and maximal damage to the tumor itself.

The information obtained by particle physicists about the properties of elementary particles over many years is widely exploited by much of the scientific community in detector design. Large scale nuclear physics experiments and many astrophysical and basic energy science experiments benefit from access to this information, either directly or by the use of programs such as GEANT4, and in many cases contribute new information to these databases.

X. Particle Data Group

Each year the Particle Data Group publishes a Review of Particle Physics and extracts a summary booklet as a service to the scientific community (Olive *et al.*, 2014a,b). While the majority of information in these publications is useful primarily to particle physicists, many elements of the review, such as the description of the passage of particles through matter, radioactivity and radiation protection, commonly used radioactive sources, and atomic and nuclear properties of many materials, are a useful resource for anyone working with detectors and elementary particles.

IV. RELATIONSHIPS BETWEEN PARTICLE PHYSICS DETECTOR RESEARCH AND DEVELOPMENT AND INDUSTRY

The science that drives particle physics requires detectors with properties that are often not available as commercial products. Engagement with industry is necessary to develop and produce specialized devices such as fast scintillators, high resolution, large-area photodetectors, and segmented semiconductor radiation detectors. These devices are often extensions of existing technologies with specific characteristics or in unusual volumes or areas. Many detector systems need to be produced on an industrial scale for specific experiments whose needs are unique and/or episodic. If they exist, applications of the relevant technologies beyond particle physics can provide both lower cost and improved availability and quality.

Engagement with industry works best if detectors required by particle physics have commercial application. Synergistic applications in, for example, medical imaging and homeland security, help drive engagement with industry and can provide the infrastructure for robust technological development spanning different fields. Medical imaging often utilizes detectors and techniques inherited from particle physics. The close relation is demonstrated by the IEEE Nuclear Science Symposium and Medical Imaging Conference that are always held jointly. Particle physicists and engineers typically develop detector systems rather than isolated detector technologies. This means that the field has the ability to deliver not only particular sensors, but the mechanical supports, powering, cooling, data acquisition, and full simulation required to fabricate and operate a fully integrated detector system. Particle physics also develops the tools to utilize new detector systems, such as Monte Carlo simulations and fast data acquisition systems. These tools themselves are valuable to industry, as is the expertise that is developed in establishing and exploiting the technology.

A few companies, such as CAEN and, in the past, LeCroy Research Systems, focus primarily on the nuclear and particle physics research market. CAEN designs, produces and supplies electronics instrumentation for international particle physics research, Canberra Industries manufactures semiconductor detector systems, which are used to measure the levels of radioactive materials used in ultra low-level counting experiments such as dark matter or double-beta decay searches. Hamamatsu designs, produces and supplies a variety of sensors used to detect visible light. These companies frequently collaborate with researchers from academic institutions or research laboratories to develop new products.

In addition to developing new technologies, particle physics can act as “first adopters” to explore and develop promising new technologies. Resources and technical support can be dedicated to new technologies, which are promising for detectors but are not yet ready for full commercialization. An example is three dimensional electronics, which is a focus of the electronics industry, but struggles with the economics of a large, highly integrated, supply chain. Technologies to manufacture 3D circuits are available, but are economically viable in limited markets, such as image sensors and high end FPGAs. Particle physics has worked with industry to identify, explore and demonstrate the capabilities of some of these new technologies.

A. Extensions of Conventional Technologies

Many particle detectors apply existing technologies and capabilities in new and different contexts and scales. Often desired technologies are only available in small areas or as prototypes and must be produced on a much larger scale with improved tolerances for particle physics experiments.

As examples of scale, the CMS experiment required 75,848 high quality lead tungstate crystals. Each crystal was 230 mm long with a tapered shape that varied with position and had to meet strict mechanical and optical tolerances (Bloch, 2010). The crystals were grown with conventional crystal growth techniques, but the process nonetheless required a 4 year R&D period during which the radiation hardness was improved and the growth process industrialized. The production of the crystals took 10 years, with 55% of the crystals grown in the final 3 years.

The NOvA neutrino experiment required 15,000 tons of PVC panels constituting the world's largest PVC structure[22]. Ferrmilab and Argonne worked with Extrutech Plastics for 2 years in process and quality control development and three years of construction. Extrutech produced 22,000 panels, each about 15.6 meters long, 6.35 cm thick by 65 cm wide for assembly at the NOvA site in Minnesota.

Another extension of conventional technology to large area and high tolerance has been in the development of large area GEM foils. These are copper clad polyimide foils with arrays of holes designed to provide a high enough local field for gas multiplication of ionization caused by impinging charged and neutral particles. The original foils were fabricated at the CERN shop and have application in medical imaging, material analysis, and other areas (Surrow *et al.*, 2007). CERN now grants royalty-free licenses for research and development use of GEM foils. Several companies are independently developing the capability to produce foils with the necessary small vias and tight tolerances in large areas.

B. Collaborative R&D

Particle physics is largely a national government-funded enterprise. Although the goal of particle physics is basic science, an important feature of the work is the application of innovative ideas, processes, and technologies developed in particle physics to national economies (Block and Keller, 2011; Mazzucato, 2013). Funding agencies and governments understand this and try in a variety of ways to support application of basic science R&D to industry. This is often not straightforward, with issues of intellectual property ownership, funding sources, and government bureaucracy to navigate. Governments engaged in particle physics research have addressed collaborative R&D by setting up a variety of programs aimed at fostering collaboration with and technology transfer to industry.

Direct collaboration with industry is an effective and often necessary route to development of detector technology. Mechanisms for collaboration vary with region and country. CERN maintains a Technology Transfer office with opportunities for collaborative R&D, as well as direct access to intellectual property (IP) and open licensing agreements[23]. CERN also provides mechanisms for development of spin-off companies as well as business incubation centers across Europe. In the U.S., laboratories collaborate with industry utilizing Cooperative Research And Development Agreements (CRADA), which define collaboration responsibilities and associated intellectual property.

The European Union has funded a series of EU-wide R&D programs under the Framework 7 and Horizon 2020 programs. These multi-faceted, Europe-wide initiatives have funded programs such as AIDA[24] and INFIERI[25], that focus on research infrastructure and detector development. These programs are centrally managed and include multiple work packages aimed at technology development, infrastructure, training as well as outreach. These programs also have strong industrial partnerships.

The high-energy physics technology-transfer network, HEPTech, is another technology transfer program which is designed to bring together leading European high-energy physics research institutions so as to provide academics and industry with a single point of access to the skills, capabilities, and technologies and R&D opportunities of the high-energy physics community in a highly collaborative open-science environment[26]. As a source of technology excellence and innovation, the network bridges the gap between researchers and industry, and accelerates the industrial process for the benefit of the global economy and wider society.

The United States maintains a government-wide Small Business Innovative Research (SBIR) program, which sets aside a fraction of government research budgets for R&D that both supports the government programs and have commercial potential. The SBIR program is funded through a "tax" on federal program R&D budgets. It is administered in two government funded phases. Phase I, the feasibility study part of the program, consists of an award of typically $150,000 and is carried out over a six to nine month period. If Phase I is successful, Phase II, the project development to prototype phase, consists of an award of up to $1,000,000 and is carried out over a 24 month period. In the final commercialization phase of the project, Phase III, small businesses are expected to get private funding or government funding outside the SBIR program[27]. Other countries support similar programs.

Another class of collaborating institutions are private/government laboratories that specialize in cutting-edge R&D. These laboratories typically are more receptive to the unusual requests coming from the particle physics community. Examples include LETI in France[28],

[22] http://www.epiplastics.com/novapanel.html Accessed: 2015-8-23
[23] http://knowledgetransfer.web.cern.ch/technology-transfer Accessed: 2015-6-23
[24] http://www.aida-project.eu/ Accessed: 2016-1-24
[25] http://infieri-network.eu/ Accessed: 2016-1-24
[26] http://www.heptech.org/ Accessed: 2015-6-23
[27] http://www.sbir.gov/about/about-sbir#sbir-three-phase-program Accessed: 2015-5-27
[28] http://www-leti.cea.fr/en/Discover-Leti/About-us Accessed: 2015-6-23

CNM in Spain[29], FBK in Italy[30], VTT in Norway[31], and university nanotechnology centers in the U.S. Many of these institutions encourage the formation of spin-off companies to commercialize research. Some particle physics-related spin-off companies include Alibava detector readout from CNM[32] , AVACAM sensor development from VTT[33], Advansid silicon photomultipliers from FBK[34], and PNSensors[35], a CCD, DEPFET and silicon drift sensor spin-off from the Max Planck Institute in Munich.

In addition to these specialized structures for technology development and transfer, experiments and projects can directly fund industry to develop or implement technologies for HEP. Development of radiation hard sensors for the LHC involved submissions to a mix of private and government supported companies including Hamamatsu[36], ST Microelectronics[37], VTT, FBK, CNM, Micron Semiconductor[38], Infineon, Tezzaron/Novati[39], and CIS[40]. The goals of this research program include exploring thinned sensors, epitaxial layers, sensor oxygenation, active edge and 3D sensors, and various base materials. Similarly the fine pitch interconnects needed for the LHC pixel detectors have been extensively explored with IZM[41], LETI, Tezzaron[42], Paul Scherrer Institute, Ziptronix[43], RTI[44] and others. The Large Area Photodetector Project (LAPPD) project required large arrays of inexpensive glass capillary planes which could be used to produce microchannel plates based on atomic layer deposition. INCOM Inc., which specializes in fiber optic faceplates, eventually became a research and commercialization partner and received commercialization funding through the SBIR program[45].

[29] http://www-imb-cnm.csic.es/ Accessed: 2015-6-23
[30] https://srs.fbk.eu/ Accessed: 2015-6-23
[31] http://www.vttresearch.com/ Accessed: 2015-6-23
[32] http://www.alibavasystems.com/ Accessed: 2015-6-23
[33] http://www.advacam.com/en/ Accessed 2016-1-23
[34] http://advansid.com/home Accessed:2016-1-23
[35] http://www.pnsensor.de/Welcome/Company/ Accessed:2016-1-23
[36] http;//www.hamamatsu.com/us/en/index.html Accessed: 2016-1-20
[37] http://www.st.com/us/home.html Accessed: 2016-1-20
[38] http://www.micronsemiconductor.co.uk/ Accessed: 2016-1-20
[39] http://www.novati-tech.com/ Accessed: 2016-1-20
[40] http://www.cismst.org/en/loesungen/strahlungsdetektor/ Accessed 2016-1-20
[41] http://www.izm.fraunhofer.de/en/institute.html Accessed: 2016-1-23
[42] http://www.tezzaron.com/ Accessed: 2015-6-23
[43] http://www.ziptronix.com/ Accessed: 2015-6-23
[44] http://www.rti/org/page.cfm/Wafer-Level_Microsystem_Integration Accessed: 2015-6-23
[45] http://www.incomusa.com/ Accessed: 2016-2-11

C. Technology Transfer

Technologies developed by universities and laboratories engaged in particle physics research are often appropriate for commercial application. This is especially true in the medical imaging field, with its emphasis on radiation-based imaging technologies. Particle physics has particular expertise in areas such as fast timing detectors for triggering and particle identification, intelligent, finely segmented pixel detectors, fast scintillators, optical to electrical conversion and simulation of radiation interaction with matter. Such fast electronics and detectors are crucial for providing three dimensional resolution in Positron Emission Tomography (PET) scanners.

The exploitation of bismuth germanium oxide (BGO) scintillating crystals, which were discovered in the 1970s is an example of a technology, which was brought to scale by particle physicists and which now has a significant medical market. In the late 1980s the L3 experiment at the electron-positron collider (LEP) at CERN built the first BGO crystal calorimeter consisting of 11,400 BGO crystals. The size of the order led to the development of multi-crucible growth technology that allowed the growth of up to 36 crystal ingots per oven. This manufacturing breakthrough opened up the BGO medical market and GE Healthcare has built more than 1,500 PET scanners with SIC BGO crystals.

The Medipix chip grew out of developments at CERN and has been followed by designs which improve resolution (Medipix 2), add timing information (Timepix) and add energy information (Medipix 3) (Plackett *et al.*, 2010). Medipix is now used by seven start-up companies in Europe as well as a large number of research institutes. Similar expertise in pixelated detectors at PSI led directly to the formation of Dectris[46], which supplies X-ray imaging detectors to light sources around the world.

This work extends to software as well, with the best-known example being the HTML/World Wide Web protocol developed at CERN. There are many other software developments applicable to industry, GEANT software is an extensive suite of Monte Carlo simulation tools aimed at the simulation of radiation propagation through matter. In addition to particle physics, GEANT is now extensively utilized for space science and medicine. Other widely used software tools include ROOT, a powerful and flexible data analysis suite; Scientific Linux, a Linux variant optimized for physics analysis; and the development of large-scale worldwide computing grids for LHC experiments.

[46] https://www.dectris.com/ Accessed: 2016-1-15

D. First Adopters

New ideas in the commercial world are often constrained by needs for short-term profits. By identifying and exploring promising new technologies, particle physics can utilize its expertise to help develop these ideas to the stage that they can be more fully commercialized. One example is the Silicon Photomultiplier (SiPM) (Laurenti *et al.*, 2008). The SiPM is an array of Geiger-mode avalanche photodiodes, with passive quenching based on polysilicon resistors. This device, which can replace the photomultiplier tube, provides optical to electrical conversion with higher quantum efficiency, a smaller package, and lower cost than the conventional phototube. The concept originated in a physics laboratory and has been pursued both within and beyond the particle physics community. Particle physics was involved with the development of the concept, testing of radiation resistance, measuring noise, and testing time and energy resolution of various devices, and utilizing large numbers of SiPMs for proposed ILC experiments and for the LHC experiments. There are projects to exploit the properties of Geiger-mode semiconductor detectors by examining alternate materials such as GaAs, as well as efforts to build digital versions of the SiPM utilizing three dimensional integrated circuit technology. All of these require the collaboration of industry with the specialized resources to fabricate the devices.

Another example is three dimensional electronics. 3DIC is a set of technologies developed by the electronics industry to stack integrated circuits vertically, interconnecting layers of circuitry with through-silicon-vias. This promise of high density fine pitch interconnect with close packing of electronics is of substantial interest to particle physics. The technology promises fine pitch pixelated devices with very high density electronic instrumentation at a reasonable cost. However industry development has been hampered by the need to develop a full supply chain for commercial exploitation. Particle physicists collaborated with industry to explore the relevant concepts, develop designs, solve numerous technical issues, and provide feedback to industry. As a result the 3DIC collaboration demonstrated the first three-tier three-dimensional stack of two layers of integrated circuits and one layer of silicon sensors (Lipton, 2015). There is now both a better understanding of the promise and constraints of 3D circuits and a base of expertise for further development both in industry and in the laboratories.

V. PROSPECTS

The quest of particle physics to understand nature at its most fundamental level will require the continued development of new detector technologies. This R&D will take place at different levels. At the lowest level, research will be carried out to address known technological problems and shortcomings with existing experiments. This R&D is likely to be incremental in nature. At a higher level there is the need to make improvements in current and planned experiments. This more generic R&D is aimed not only at addressing technological barriers but also to reduce the cost of the very large scale particle physics detectors required to continue to carry out future experiments at the frontiers of the field. At the highest level is the R&D that has added value to the field as a whole with the potential to be truly transformative.

R&D has traditionally been carried out by particle physicists building on existing technologies, when they exist, or developing the technologies and then enhancing them to address the science goals of the experiments. This old paradigm for detector development may fall short in the future in meeting the needs of the community. Paradigm altering advances are happening in other branches of science, which hold the potential to lead to transformational new technologies for the field of particle physics. Particle physics needs to benefit from increased collaboration with other scientific fields to take advantage of advances in chemistry, materials science and surface physics, electronics and electrical engineering, basic energy sciences, and computing. This new approach, however, will also bring new challenges, which will be elaborated on in Section V.C.

A. Directed R&D

Directed R&D that takes place within the field of particle physics is typically carried out with various time horizons. Based on current experiments and upgrade needs, known issues are tackled to yield results on a relatively short time scale. For the Phase-II upgrades of the LHC experiments, for example, a number of areas are targeted for improvements in existing technologies. Some of these areas are radiation hard vertex and tracking detectors, including the development of 3D silicon, pixel detectors, diamond detectors and radiation hard calorimeters. With the large number of interactions per crossing anticipated at high luminosities, significant challenges are imposed on fast track finding. Better hit resolution is required to disentangle the many different interaction vertices per bunch crossing, which in turn demands smaller pixel size of the sensors in the vertex detector. To be able to implement the required front-end logic in a much smaller area, the ASIC development is forced to go to smaller feature size, with the 65 nm being the current baseline technology. The certification of the radiation hardness of this technology is progressing. At the same time this new generation of ASIC has to be able to handle data rates up to 4 Gb/s per ASIC. Focused efforts are under way to meet these stringent technical requirements. Although this R&D is very targeted towards the upgrades of the

LHC experiments, it is highly likely that this development will benefit future space missions and experiments at the next generation light sources, to name a few.

The very high data volume these experiments have to handle poses new demands on the trigger and data acquisition systems. Intelligent data reduction algorithms are required to whittle down the data to manageable size, while at the same time improving the overall trigger performance. Active R&D is being carried out in developing new trigger primitives and new trigger algorithms. This often involves significant enhancements of existing technologies. For the trackers for the upgraded LHC experiments, triggers based on stubs, rather than the traditional hit-based triggers, are being developed. Another approach employs very fast (1 ns) pattern recognition using vast arrays of associated memories that store billions of hit patterns. High luminosity particle physics accelerator experiments are pushing and will continue to push the limits on data selection, data acquisition, data storage, and data processing. Progress in detector development and data acquisition, storage, and processing will be immediately applicable to many other scientific fields, the medical community, security applications and industry.

Modern particle physics detectors are characterized by their enormous size and the cost of the detectors is becoming more and more of an acute problem going forward. One of the fundamental goals of a balanced R&D program is to fund high risk – high reward R&D which, if successful, would lead to the development of novel, lower-cost technologies to replace existing technologies, preferably with better performance. The development of GEM and MicroMegas foils is one such an example that is being successfully used in the LHC experiments. Detectors covering many square meters are now commonplace, cost effective and have superior performance over existing technologies.

The development of water-based liquid scintillator as a replacement for oil-based liquid scintillator is another example of a successful outcome of this type of R&D, since the water based liquid scintillator can be considerably cheaper than mineral oil based liquid scintillator whose cost fluctuates with the price of crude oil. In addition, water-based scintillator is biodegradable substantially reducing the cost of decommissioning large liquid scintillator experiments. Water-based liquid scintillator also has potential applications in medium and large neutrino and anti-neutrino detectors, which have geological and security applications.

Extremely-low-background detectors have the possibility of detecting coherent elastic neutrino scattering on nuclei. The cross section for coherent elastic neutrino scattering is roughly proportional to the square of the number of nucleons in the nucleus making it between 100 and 1000 times larger on nuclei of interest compared to neutrino scattering on elementary particles. However, the recoil energy of coherent neutrino scattering on nuclei is so small, typically a few tens of eV, that the signal is buried in the noise in current detectors. Even though there is no controversy in the Standard Model prediction for coherent neutrino scattering, the technological challenges in detecting it unambiguously make it an active area of research (Brice *et al.*, 2013; Collar, 2008). Detectors capable of detecting coherent elastic neutrino scattering on nuclei could have a major impact on applications involving neutrino and anti-neutrino detection in the future, particularly on reducing the size and potentially the cost of future neutrino detectors.

B. Interdisciplinary Collaborations

In general, the tools, techniques, and technologies developed in a single scientific discipline typically cross the boundaries of many disciplines. The technologies which have enabled advances in particle physics are often embraced and developed by other fields and, conversely, commercial technologies or technologies developed in other scientific fields are embraced and developed by particle physicists. Enabling and encouraging multidisciplinary developments would almost always stimulate and accelerate technological innovation in science, applied science, and industry in the United States and throughout the world.

Particle physics has often pushed the boundaries of what was technically feasible and has repeatedly been at the cutting edge of technology. Currently, paradigm shifting advances are being made in other scientific disciplines, which could significantly benefit the particle physics community. The field of opto-electronics and wireless communication is developing at break-neck pace and to date none of these newer developments are finding their way into the R&D being carried out for particle detectors. Lasers are being integrated in ASICs, which could markedly simplify data transmission; nanoparticles are being used to design scintillation characteristics; two-dimensional materials, such as graphene and trans-metal dichalcogenides, are being studied for low-power applications and the list goes on.

Particle and nuclear physics in recent years have been slow to adopt breakthrough developments in other fields of science. This is particularly evident in the recent proposals for new detectors and upgrades of experiments. In the next decade many if not all of these new technologies will be widely available, and could be highly advantageous in terms of cost versus performance, especially if high-energy physics undertakes to develop a selected set of these, and deploy them on a large scale. The field has to start taking advantage of these developments. Furthermore, as already mentioned in the previous section, stronger ties with industry are crucial. Many developments are driven by industry, and the pull of a large market, could result in highly cost-effective detectors.

There is a nascent effort, originating at multi-disciplinary laboratories, of interdisciplinary detector development. A recent development, which could substantially reduce the cost and enhance the performance of existing detectors, is the application of Atomic Layer Deposition (ALD) to different substrates. For example, superconducting accelerating cavities can be made out of pure solid niobium, a very expensive material but atomic layer deposition is now being used to deposit engineered thin films of niobium on different, i.e. cheaper, substrates to produce cavities that are as performant as pure niobium-based cavities. This represents a huge cost saving. Another example is the use of the ALD process for the development of microchannel plate (MCP) based photodetectors. The MCP in conventional MCP-based photodetectors is lead glass, where the properties of the lead glass provide for the secondary electron emission. The lead glass presents two significant limitations. The secondary electron emission yield is an intrinsic property of the material with little to no room for improvement. Secondly, lead glass MCPs cannot be produced in large areas. Very large (20 cm $\times$ 20 cm) borosilicate-based microchannel plates have been fabricated in industry at a cost which is one to two orders of magnitude less than conventional lead glass microchannel plates. Using the ALD process, these plates have been developed as the gain stage of a large area photomultiplier. With the proper chemistry, the secondary electron emission can be engineered and currently a secondary electron yield a factor 3-4 higher than lead glass has been obtained. These inexpensive, ALD functionalized microchannel plates could have a substantial impact on low light or large-area applications.

In the area of cosmology, the detection of cosmic microwave background (CMB) radiation has had for many years already a fruitful collaboration between different science disciplines. One method to detect CMB radiation is with transition edge sensors (TES). These are superconducting, voltage biased detectors where incident photons effect a transition from superconducting to normal conducting and the change in magnetic flux caused by the change in current is readout with a SQUID. The superconducting properties of these TES are engineered in collaboration with materials scientists.

New developments, improvements, and refinements in additive manufacturing or 3D printing also has the potential for making an enormous impact on the future detector development in particle physics and other sciences. Particle physicists are just now beginning to explore the capabilities of this technology for detector fabrication and to develop the expertise necessary to extend its capabilities. As printing resolution improves and the range of materials which can be used in fabrication increases, the range of scientific detectors which can be constructed using this technology increases dramatically. Additive manufacturing is particularly advantageous where relatively small numbers of complicated, sophisticated devices need to be constructed, and it provides a fertile ground for cross-disciplinary collaborations.

There is tremendous opportunity to engage in interdisciplinary research, which could enable rapid technological advancements to the benefit of the broader scientific community. In some areas, collaborative work is already underway. In others, previous projects have demonstrated the potential for future synergies.

1. Detector materials in partnership with materials science, including designer materials for radiation detection. With the materials genome project now underway, bringing together the fundamental materials science with the required technical challenges could prove extremely fruitful.

2. Instrumentation and data tools for the next generation of light sources and particle physics experiments, in partnership with both user communities. The science potential of next-generation light sources can best be exploited with state-of-the-art instrumentation. The particle physics experience in collaborative development of highly complex systems with large data volumes could be explored for adoption for use at light sources.

3. Detector technology advancement jointly between high energy and nuclear physics. Both communities are embarking on the development of closely related new detector technologies. The added value of stronger collaborative efforts could prove beneficial to both disciplines.

4. Advanced computing including simulation, data management tools, data analysis techniques, and advanced computing architectures in partnership with the computer science community. Rapidly evolving computer architectures as well as the exponentially increasing data volumes require effective, cross-disciplinary approaches. Improvements would benefit the particle physics mission as well as many other scientific fields that increasingly rely on similar computing tools, techniques, and architectures.

5. Lattice algorithm and computational techniques in partnership with condensed matter physics. Algorithmic development for high-performance computers aimed at solving complex multi-body problems could provide pathways for solutions in particle physics, condensed matter, and related science areas.

Another opportunity for collaborative interdisciplinary research is through the use of particle physics constructed and operated facilities. Existing facilities can advance the goals of other fields. For example, particle physicists use high-energy muon beams to explore "deep inelastic scattering," and low-energy muon beams to study fundamental symmetries. Low-energy and stopped positive muon beams are also of great significance to researchers in condensed matter and various technology areas due to the power of muon spin resonance (μSR). Because of maximal parity violation in weak decays, stopped muons are nearly 100% spin-polarized, which makes this technique significantly more powerful than other magnetic resonance probes such as nuclear magnetic resonance (NMR) or electron spin resonance (ESR). Because the muon spin and charge are exquisitely sensitive magnetic and electronic quantum probes of matter, they provide a unique time window for studying dynamic processes. Negative muon beams have been used for research on muon catalyzed fusion and muonic atom states (Breunlich *et al.*, 1989; Pohl *et al.*, 2005).

The Cosmics Leaving Outdoor Droplets (CLOUD) experiment is the first use of a particle physics accelerator to study atmospheric and climate science. Using beams from CERN's Proton Synchrotron, a cloud chamber is used to investigate the possible link between galactic cosmic rays and cloud formation, contributing to the fundamental understanding of aerosols and clouds and their effect on climate. The Proton Synchrotron provides an artificial source of "cosmic rays" that simulates natural conditions between ground level and the stratosphere. The ultra-vacuum technologies used by particle physicists are of interest to the atmospheric science community for their power in hosting "clean environments" for controlled experiments. Atmospheric science experiments of this kind are possible at any particle physics facility that has particle beams and vacuum technology infrastructure.

Particle physics researchers also partner with other fields to build facilities that advance multiple disciplines right from the start. This approach has enjoyed great success in the quest to understand the phenomenon of dark energy. Particle physics expertise in detector construction has coupled with the expertise of the astronomy and astrophysics communities in building advanced telescopes to advance the scientific goals of all three fields. A rapid increase in efforts to understand dark energy followed the 1998 discovery that this universe is expanding. With no identifiable candidate for the dark energy thought to cause this expansion, the particle physics community worked closely with the astronomy community to build and operate facilities for analyzing data from large sky surveys. These data are used by particle physicists to quantify the effects of dark energy, and by many members of the astronomy community to advance a large variety of astronomical research areas.

The first such sky survey built in partnership between particle physics and astronomy was the Sloan Digital Sky Survey (SDSS) (York *et al.*, 2000b). The Dark Energy Survey (DES)[47] further advanced the partnership between particle physics and astronomy with the construction of the 570-megapixel camera known as DECam, which forms the heart of the survey. As with the SDSS, DES data will advance the understanding of dark energy and power discoveries in many other areas of astronomical interest. This tradition of partnership between particle physics and astronomy continues with the Large Synoptic Survey Telescope (LSST), which will place a 3200-megapixel camera on a new telescope in Chile (Ivezic *et al.*, 2011).

An unlikely connection was established between particle physics and glaciology through the construction of a neutrino detector facility. The deployment of photodetectors at a depth of 2500m in the ice of the Antarctic for the study of neutrinos has provided the most clearly resolved measurements of Antarctic dust strata during the last glacial period and can be used to reconstruct paleo-climate records in exceptional detail (Aartsen *et al.*, 2013). As stated earlier, neutrino detectors are also being investigated as part of a comprehensive nonproliferation program, monitoring nuclear reactor activity and the assessment of the isotopic composition of reactor fuels (Bowden *et al.*, 2009).

Particle physics may also have the opportunity to assist other fields surmount challenges in the construction, operation, and management of large, complex multi-institutional and multi-national projects, due to its decades-long history of developing the methodology to bring such projects to successful completion. Fields which are moving into large, collaborative, possible international projects can study the reasons for the successes and failures in large particle physics projects to optimize their own chances for success. Conversely, collaboration with other fields may bring new techniques to particle physics that could improve the planning, construction, and operation and management of future projects.

C. Challenges and Opportunities

Modern day society looks very different from society a mere twenty years ago. New technologies are being developed and brought to market with breathtaking speed. As modern materials science and photonics move forward, the use of new materials, detection methods, electronics, communications, computing and production techniques, such as additive manufacturing, will all have a sweeping impact. Particle physics will need to adopt these new developments. Unfortunately, our field is currently not much engaged. The challenge of the accelerating pace of development in other fields of science and the difficulty

[47] http://www.darkenergysurvey.org/ Accessed: 2015-6-25

in keeping informed about the successes elsewhere that could have important benefits to particle physics needs to be addressed. Joint workshops, multidisciplinary training opportunities, and expanded opportunities for interaction between particle physicists and other scientists are a possible venue for the field to become more engaged and possibly start taking an innovative lead in certain area of development.

This multi-disciplinary approach to detector development with mutual benefit brings, however, new challenges. Across all fields of science and all types of scientific facilities there are still many obstacles to initiating, and identifying resources to support, and carry out multi-disciplinary research. Sufficient mechanisms do not currently exist to enable particle physicists to work collaboratively with other fields on projects of common benefit. The lack of multi-disciplinary training opportunities is another obstacle to fostering connections between fields in the areas of tools and technologies. Similarly, a lack of career paths for personnel skilled in, and dedicated to, the development of detectors and scientific computing techniques is often a major obstacle to continuing development of these tools. It is these areas that will define not only the future of particle physics but, increasingly, the future of other connected fields and segments of industry.

It is noted that the Community Research and Development Information Service (CORDIS) of the European Union has established framework programmes for research and technological development within countries of the European Union complementing the national research programmes (CORDIS, 2016). These research programs are carried out by consortia, which include participants from different European (and other) countries and fosters collaboration between industry, academia and various science disciplines. The latest incarnation of this program, Horizon 2020, aims at coupling research and innovation to ensure delivery of world-class science, while in the process removing barriers to innovation and making it easier for the public and private sectors to work together in delivering innovation (Horizon 2020, 2016). These framework programmes provide a bridge to overcome some of the challenges particle physics faces. There are tremendous opportunities for particle physics, and the fundamental sciences in general, to embark on a new paradigm for detector development with mutual benefits to all disciplines involved. Although we cannot predict the future, it is clear that it will bring transformative tools, technologies, and techniques, and greater connections between the particle physics field. It is up to us to seize this opportunity to realize these leaps forward in advanced technology which will benefit the entire fabric of science.

VI. SUMMARY AND CONCLUSIONS

Particle physics research involves the study of elementary particles and nuclei, the forces that mediate their interactions, and the fundamental properties of space and time. This research has consisted of the study of naturally occurring elementary particles and nuclei and controlled experiments using accelerators. The distinction between particle physics and nuclear physics is not always crisp. The parts of nuclear physics research that deal with heavy ions and *ep* scattering and studies in the nature of the neutrino, for example, are really pretty much indistinguishable from particle physics in their techniques. Although the recent discovery of dark matter and dark energy and insight into the history of the universe has historically used instrumentation, which is not part of typical instrumentation used in particle physics, these areas of research are now becoming part of a broadened research particle physics research program. The tools of particle physics and the development of new systems of highly sensitive detectors are essential and increasingly being used to carry out detailed large-scale astronomical observations and the study of the cosmic microwave background. In this article the term particle physics has been used to represent both particle physics and nuclear physics and the entire community of scientists developing particle detector technologies.

Interest in searching for new, high-mass particles has required the use of higher energy accelerators[48] and square kilometer arrays of detectors for ultra-high energy cosmic rays. Advances in technology are almost always required to keep detector costs manageable and to extract small signals in very large backgrounds.

Just as some of the technologies developed for the space program eventually became an important part of the commercial technology which benefits society today[49] some of the technologies developed, extended, or refined for particle physics research are now benefiting society in a variety of ways. In this article we have attempted to identify some aspects of particle physics technology, which could potentially be useful to other sectors of society and have provided specific examples of where this potential has been realized.

The World Wide Web is probably the best known example of a profound impact technology developed by particle physicists has made on society, but there are other important examples. The development and improvement of PET scanners used in medicine have relied heavily on particle physics detector technology. Particle physics

[48] Einstein's famous equation $E = mc^2$ shows the equivalence of mass and energy.

[49] See for example https://spinoff.nasa.gov/Spinoff2008/tech_benefits.html Accessed 2015-6-20

technology has played an important role in the development of gamma ray and neutron security screeners for baggage and cargo. Standardized simulation software packages such as GEANT4, and grid distributed computing are making significant contributions to the scientific, medical, and industrial communities. Neutrino and anti-neutrino detectors are beginning to have an impact in studies of the earth and monitoring nuclear reactors. Custom electronics such as the Medipix and Timepix chips are finding a variety of scientific and commercial applications. The development of relatively inexpensive, large-area detectors, such as resistive plate chambers with surface areas of many square meters, has made cosmic ray tomography a useful technique for studying large, inaccessible objects.

Today's large particle physics detectors are typically built, operated, and managed by large international collaborations. As such they are laboratories for testing not only new technologies but also for large-scale, international project management which is studied to determine what characteristics make these collaborations successful. In addition, since large-scale particle physics projects are typically funded by government agencies, the technologies developed by them and implemented by industry ultimately become part of the industrial knowledge base and available for future applications outside particle physics. Budgetary pressures to keep large-scale particle detector costs manageable should also ultimately benefit any applications based on these technologies.

It may ultimately turn out that the main practical value particle physics research provides to society comes from the solutions particle physicists develop to meet the technical demands of their research. Particle physics detectors are almost always unique and at the forefront of existing technology. To successfully conduct experimental frontier research, particle physicists have to solve a myriad of problems which arise, and many of the new, frequently innovative technological solutions they develop will almost certainly become beneficial to other areas of society in the future.

A. GLOSSARY

1 MeV n_{eq}/cm^2: A radiation unit corresponding to the radiation damage done by 1 MeV neutron equivalent fluence.

ALDAP: The **A**ccessing **L**arge **D**ata archives in **A**stronomy and **P**article Physics project.

Alpha Particle: A helium nucleus consisting of two protons and two neutrons with two units of positive charge. (1 unit of charge is the magnitude of electric charge on a proton or electron.)

Anode: A positively charged electrode.

Antiparticle: An elementary particle having the same mass as a given particle but opposite electric charge, magnetic properties and quantum numbers.

ASIC: An **A**pplication **S**pecific **I**ntegrated **C**ircuit.

ATCA: **A**dvanced **T**elecommunications **C**omputing **A**rchitecture is a specification standard for electronic hardware, which enables high speed data communication between modules and crates.

ATLAS: **A T**oroidal **L**HC **A**pparatu**s**, one of two very large detectors operating at the CERN Large Hadron Collider used for fundamental research in high-energy elementary particle physics.

Branching Ratio: The branching ratio (or branching fraction) for a decay is the fraction of particles or nuclei, which decay in a particular decay mode divided by the total number of particles or nuclei which decay.

Cathode: An negatively charged electrode.

CCD: **C**harge **C**oupled **D**evice, an electronic circuit consisting of an array of chained charge storage units with readout units at the ends of the chains. In the device, charge can be transferred from one storage unit to another and read out at the end of the chain.

Čerenkov Radiation: Electromagnetic radiation which is produced when a charged particle travels faster than the local speed of light in a dielectric medium. The radiation is produced at an angle which depends on the particle's speed.

CERN: The European Organization for Nuclear Research. The name is derived from the acronym for the French "Conseil Européen pour la Recherche Nucléaire", a provisional body founded in 1952 with a mandate to establish a world-class fundamental physics research organization in Europe.

CMS: **C**ompact **M**uon **S**olenoid, one of two very large detectors operating at the CERN LHC used for fundamental research in high-energy elementary particle physics.

Cross Section: The interaction area associated with the probability that two particles will collide and react in a particular way.

Cryogenic Device: A device which operates at very cold temperatures, typically at temperatures below the 4 Kelvin boiling point of liquid helium.

DAQ System: **D**ata **Acq**uisition System.

DIRC: **D**etection of **I**nternally **R**eflected **Č**erenkov light.

EDG: **E**uropean **D**ata **G**rid.

Elementary Particle: Any of various fundamental subatomic particles, including those that are the smallest and most basic constituents of matter (leptons and quarks) or are combinations of these (hadrons, which consist of quarks), and those that transmit one of the four fundamental interactions in nature (gravitational, electromagnetic, strong, and weak). In this article, we will typically not be concerned with quarks since they do not exist in isolation. Photons, electrons, protons, neutrons, muons, pions, neutrinos and their antiparticles are examples of elementary particles which occur naturally in cosmic rays and radioactive decays

ESnet: Energy Sciences high-speed computer network serving United States Department of Energy (DOE) scientists and their collaborators worldwide. All DOE Office of Science labs are directly connected to this network, which also serves over 100 other research and education networks.

eV, keV, MeV, GeV, TeV: eV is a unit of energy called an electron volt. It is the energy a particle with a charge equal to the charge on one electron increases when it moves through a field produced by a 1 volt potential difference. keV, MeV, GeV, and TeV are units of 1 thousand, 1 million, 1 billion, and 1 trillion electron volts respectively. In units where the speed of light equals 1, energy and mass have the same numerical value because of Einstein's equation $E = mc^2$.

Event: The pattern of detector hits occurring in a very short time span just after a fundamental interaction took place between elementary particles in a localized region of space.

FLUKA: **FLU**ktuierende **KA**skade: a fully integrated particle physics Monte Carlo simulation software package, available from CERN and INFN, the Italian National Institute for Nuclear Physics.

FPGA: **F**ield **P**rogrammable **G**ate **A**rray. An integrated circuit which can be custom programed by the user after manufacture.

FWHM: **F**ull **W**idth at **H**alf **M**aximum, a quantity which characterizes the width of an electronic pulse.

Gamma ray: A photon with an energy above 100 keV.

GEANT: A **GE**ometry **AN**d **T**racking software toolkit for the simulation of the passage of particles through matter. Its areas of application include high-energy, nuclear and accelerator physics, as well as studies in medical and space science.

GIOD: The **G**lobally **I**nterconnected **O**bject **D**atabases project.

Grid: The collection of computer resources from multiple locations to reach a common goal. The GRID can be thought of as a distributed system with non-interactive workloads that involve a large number of files.

GriPhyN: The **Gri**d **Phy**sics **N**etwork project.

Hit: The interaction between an elementary particle and a detector.

LCG: The **L**HC **C**omputing **G**rid.

LHC: The **L**arge **H**adron **C**ollider at CERN.

LIGO: **L**aser **I**interferometer **G**ravitational-wave **O**bservatory, an experiment with kilometer sized interferometer arms designed to detect gravitational waves.

Luminosity: The ratio of the number of events detected (N) in a certain time interval (t) to the interaction cross-section (σ). It has the dimensions of events per time per area.

Medipix1 - Medipix3: A set of custom integrated circuits with pixel arrays designed to make position sensitive measurements of X-rays, electrons, and neutrons.

MONARC: **M**odels **O**f **N**etworked **A**nalysis at **R**egional **C**enters

Monte Carlo: A broad class of computational algorithms that rely on repeated random sampling to obtain numerical results.

MWPC: **M**ulti**W**ire **P**roportional **C**hamber, a detector which has a plane of anode wires positioned between two cathode planes. Each anode wire collects the ionization charge produced when a charge particle traverses the chamber and gives a signal which is proportional to the amount of charge collected.

(Anti-)Neutrino: A neutral elementary particle with a mass close to zero which rarely interacts with matter.

NMR: **N**uclear **M**agnetic **R**esonance

Nuclear emulsion: A photographic plate with a thick emulsion layer and very uniform grain size. It records the tracks of charged particles passing through it, but it must be developed to make the tracks visible.

OSG: **O**pen **S**cience **G**rid

PAW: **P**hysics **A**nalysis **W**orkstation software available from CERN. PAW has been replaced by the software package ROOT.

pCT: **p**roton **C**omputed **T**omography.

PET: **P**ositron **E**mission **T**omography. A tracer compound which emits positrons is inserted in the body by injection, swallowing, or inhaling depending on which organ or tissue is being studied, and the scanner detects emissions from this tracer.

Photon: A quantum of electromagnetic radiation. Photons are characterized by their energy from very low energy microwave photons up to very energetic gamma ray photons.

PPDG: **P**article **P**hysics **D**ata **G**rid, which focused on the development and application of Data Grid concepts to the needs of a number of U.S.-based high energy and nuclear physics experiments.

QCD: **Q**uantum **C**hromo**D**ynamics, the current theory of strongly interacting particles.

Root: An object oriented framework for large scale data analysis based on the C++ programming language.

Scintillation Detector: A detector consisting of material which creates visible (scintillation) light when a charged particle passes through it.

Silicon Drift Detector: Radiation detectors used in X-ray spectrometry, electron microscopy and charged particle tracking. They are capable of high count rates and have comparatively high energy resolution (140 eV for the manganese Kα line at 5.887 keV).

SiPM: Silicon photomultiplier consisting of an array of avalanche photodiodes on a common silicon substrate operating at voltages between 20 and 100 volts.

SPECT: **S**ingle **P**hoton **E**mission **C**omputer **T**omography. An injected radioactive substance and a special camera is used to create 3D pictures of emitted gamma rays which can show how body organs work.

SSDS: **S**loan **D**igital **S**ky **S**urvey.

Timepix: A custom integrated circuit based on medipix integrated circuits which records the timing of pixel hits.

TPC: **T**ime **P**rojection **C**hamber. A TPC consists of a gas or liquid enclosed in a volume with a strong electric field in one coordinate direction. When a charged particle traverses the gas or liquid, it creates a track of ionized gas particles, which drift at a characteristic drift speed in the electric field toward an array of readout electrodes. These electrodes record both the pattern of hits in the transverse direction and the arrival time of the ions which provides enough information to reconstruct the charged particle track in three dimensions.

TES: **T**ransition **E**dge **S**ensors, a cryogenic particle detector, which uses the temperature increase from energy deposited by a passing elementary particle to make a superconducting phase transition. The resistance increase in this transition is large enough to be detected.

Trigger: A predefined pattern of detector hits or responses whose occurrence causes all detector information within a certain short time window be recorded for analysis.

WLCG: The Worldwide LHC Computing Grid (WLCG) is a global computing infrastructure whose mission is to provide computing resources to store, distribute and analyse the data generated by the Large Hadron Collider (LHC), making the data equally available to all partners, regardless of their physical location. It is supported by many associated national and international grids across the world, such as the European Grid Initiative (Europe-based) and Open Science Grid (US-based).

X-ray: A photon with an energy greater than the energy of a photon of ultraviolet light but less than the energy of a gamma ray, an energy between 100 eV and 100 keV.

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