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Thermalization at the femtoscale seen in high-energy Pb+Pb collisions

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A collision between two atomic nuclei accelerated at a speed close to that of light creates a dense system of quarks and gluons. Interactions among them are so strong that they behave collectively like a droplet of fluid of ten-femtometer size, which expands into the vacuum and eventually fragments into thousands of particles. We report a new manifestation of thermalization in recent data from the Large Hadron Collider. Our analysis is based on results from the ATLAS Collaboration, which has measured the variance of the momentum per particle across Pb+Pb collision events with the same particle multiplicity. This variance decreases steeply over a narrow multiplicity range corresponding to central collisions. We provide a simple explanation of this newly-observed phenomenon: For a given multiplicity, the momentum per particle increases with increasing impact parameter. Since a larger impact parameter goes along with a smaller collision volume, this in turn implies that the momentum per particle increases as a function of density, which is a generic consequence of thermalization. Our analysis provides the first direct evidence of this phenomenon at the femtoscale.

Nucleus-nucleus collisions carried out at particle colliders display phenomena of macroscopic nature, which are unique in the realm of high-energy physics [1, 2]. These emergent phenomena occur due to a large number of created particles and to the nature of the strong interaction. A head-on collision between two ^{208}Pb nuclei at the Large Hadron Collider (LHC), at 5.02 TeV per nucleon pair (the current energy for ion beams), produces some 35000 hadrons [3], a fraction of which are seen in detectors. The emission of hadrons is the final outcome of a number of successive stages [1], one of which is the production of a state of matter called the quark-gluon plasma. In this phase, quarks and gluons, which are the elementary components of hadrons, are liberated [4]. They carry color charges, unlike hadrons which are colorless. Interactions induced by these charges are so strong that they behave collectively like a fluid [5].

Transient formation of a fluid in nucleus-nucleus collisions has been inferred from the observation that particles move collectively into preferred directions, suggesting that their motion is driven by pressure gradients inherent in a fluid. Most notably, one observes an elliptic deformation of the azimuthal distribution of outgoing particles [6, 7], which originates from the almond shape of the overlap area between the colliding nuclei (Fig. 1). These observations are reproduced by calculations using relativistic hydrodynamics to model the expansion of the fluid [8], which has become the standard description of nucleus-nucleus collisions.

Here, we report independent confirmation of the formation of a fluid, which does not involve the directions of outgoing particles, but solely their momenta. The ATLAS Collaboration at the LHC detects charged particles in an inner detector which covers roughly the angular range $10° < \theta < 170°$ (where θ is the angle between the collision axis and the direction of the particle) and measures their transverse momenta $p_t \equiv p \sin\theta$. The analysis includes all charged particles detected in the interval $0.5 < p_t < 5$ GeV/c. The observables of interest are, for every collision, the multiplicity of charged particles seen in the inner detector, denoted by N_{ch}, and the transverse momentum per charged particle, $(\sum p_t)/N_{ch}$, denoted by $[p_t]$. N_{ch} is used to estimate the centrality [11–14], since a more central collision, with a smaller impact parameter, produces on average more particles.

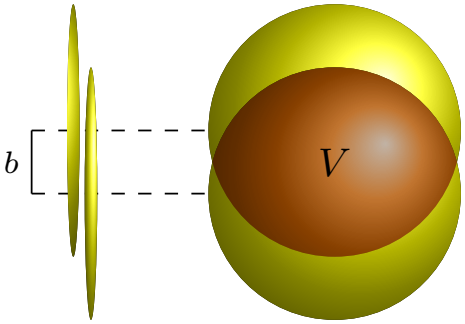


FIG. 1. Schematic representation of a collision between two identical spherical nuclei at impact parameter b. Left: Incoming nuclei just before the collision, flattened by the relativistic Lorentz contraction in the direction of motion. Right: View from the collision axis. Strongly-interacting matter is created in the region where the nuclei overlap, which is indicated in darker color, and V is the collision volume. Generally, smaller b is associated with larger V.

For collisions with the same N_{ch}, $[p_t]$ fluctuates from event to event. After subtracting trivial statistical fluctuations, the remaining dynamical fluctuations [15] are very small, below 1% in central Pb+Pb collisions at the

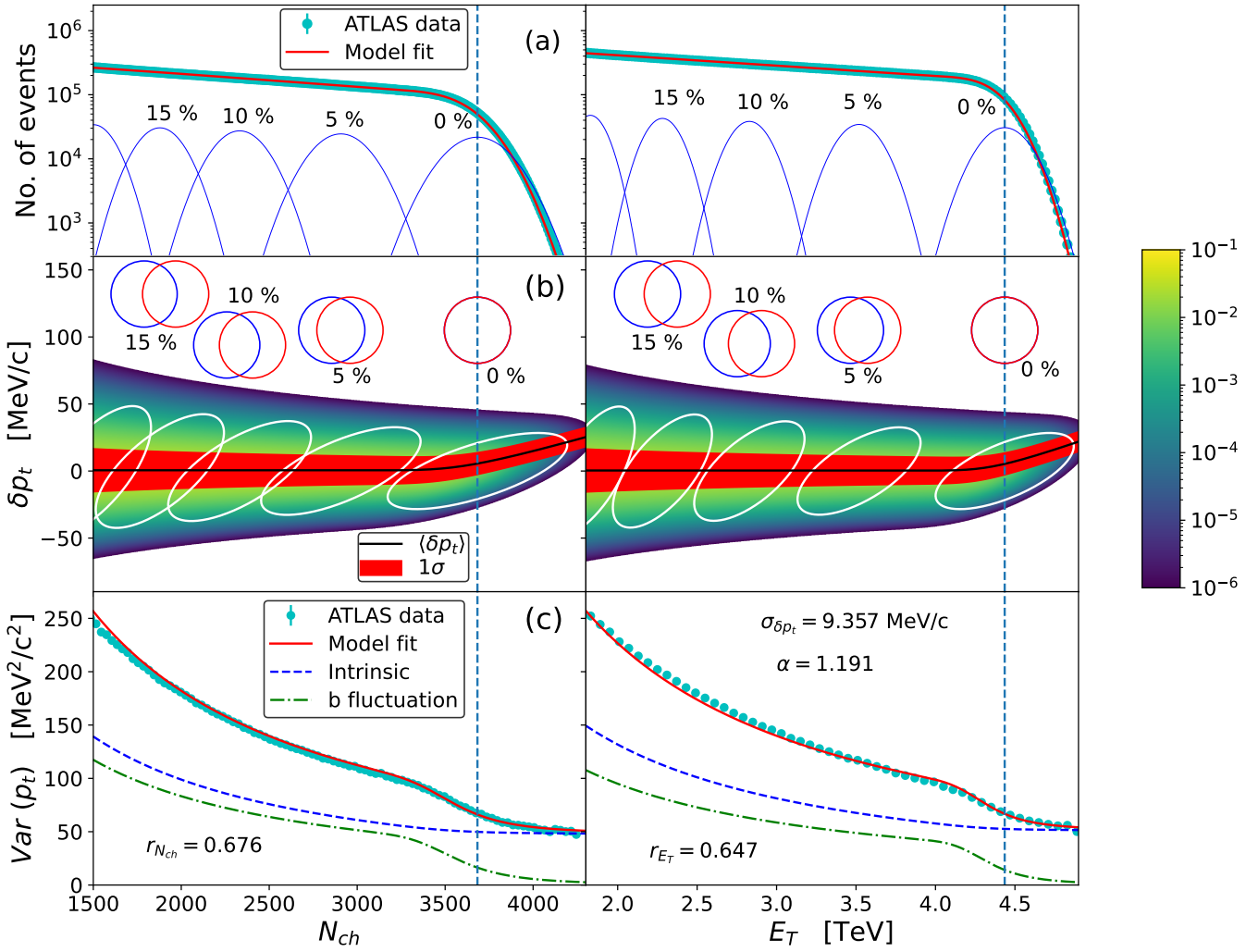


FIG. 2. (a) Histogram of the number of charged particles N_{ch} (left), measured in the inner detector of ATLAS, and of transverse energy E_T (right), measured in the forward and backward calorimeters. Solid lines are fits using superpositions of Gaussians. Contributions of collisions at fixed impact parameter b corresponding to centrality fractions 0, 5%, 10%, 15% are shown as thin blue lines ([9] Sec. I). The vertical dashed line corresponds to the knee, defined as the average value of N_{ch} or E_T for $b = 0$ collisions. (b) Joint distribution of the transverse momentum per particle $[p_t]$ and N_{ch} (or E_T) from our model. Rather than $[p_t]$, we plot the deviation $\delta p_t \equiv [p_t] - \overline{p_{t0}}$, where $\overline{p_{t0}}$ is the average value of p_t at fixed impact parameter, which is assumed to be constant. White curves are 99% confidence ellipses at fixed b. A schematic representation of the two colliding nuclei for these values of b is also shown ([9], Sec. I). The black line is the mean value of δp_t, and the red band is the 1-σ band. (c) Variance of the transverse momentum per particle $[p_t]$ as a function of the centrality estimator. The red solid line is the square of the half-width of the red band in panel (b). Symbols are ATLAS data [10]. We also display separately the two contributions to the variance, Eq. (1), in our model calculation, whose sum is the full line.

LHC [16]. These small dynamical fluctuations are the focus of our study. The left panel of Fig. 2 (c) displays their variance as a function of N_{ch} [10]. The striking phenomenon is a steep decrease, by a factor ~ 2, over a narrow interval of N_{ch} around 3700. This behavior is not reproduced by models of the collision in which the Pb+Pb collision is treated as a superposition of independent nucleon-nucleon collisions, such as the HIJING model [17, 18], where the decrease of the variance is proportional to $1/N_{ch}$ [16, 19] for all N_{ch}.

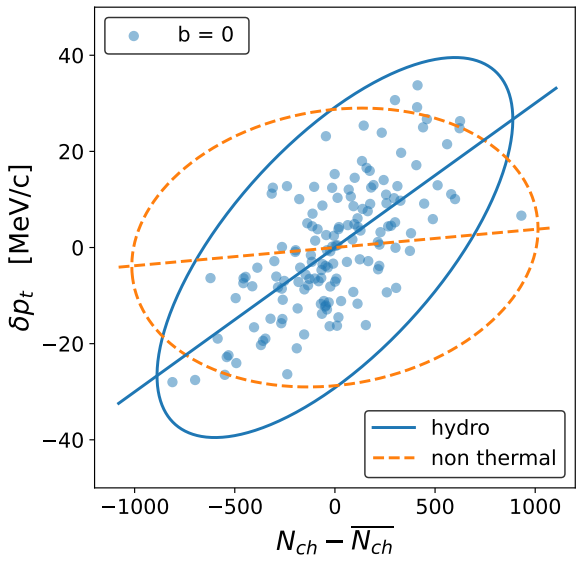


FIG. 3. Simulations of Pb+Pb collisions at 5.02 TeV and $b = 0$. The first set of simulations, shown as solid lines and symbols, consists of 150 collisions modeled using relativistic hydrodynamics [20]. The second set, shown as dashed lines, consists of 1.4×10^6 collisions simulated with HIJING [18], in which there is no thermalization mechanism. The figure represents the distribution of the charged particle multiplicity N_{ch} and the transverse momentum per particle $[p_t]$, where N_{ch} is calculated using the same acceptance cuts on θ and p_t as in the ATLAS analysis. We plot, rather than N_{ch} and $[p_t]$ themselves, the differences $N_{ch} - \overline{N_{ch}}$ and $\delta p_t \equiv [p_t] - \overline{p_t}$, where $\overline{N_{ch}} = 6662$ and $\overline{p_t} = 1074$ MeV/c are the values averaged over collisions. The straight lines indicate the average value $\overline{\delta p_t}(N_{ch}, b = 0)$, and the ellipses are 99% confidence ellipses (as in Fig. 2 (b)). Both are evaluated by assuming that the distribution is Gaussian (see [9], Sec. III). Note that the fluctuations contain a contribution from statistical Poisson fluctuations in the HIJING model, which is a particle-based description, not in hydrodynamics, which is a continuous description ([9] Sec. II).

We will argue that the impact parameter, b, plays a crucial role in this phenomenon. The relation between N_{ch} and b is not one-to-one, and $[p_t]$ depends on both quantities. In order to illustrate this dependence, we simulate 150 collisions at $b = 0$ using relativistic viscous hydrodynamics, and evaluate N_{ch} and $[p_t]$ for every collision. Figure 3 displays their distribution. The first observation is that they span a finite range. Fluctuations around the mean extend up to $\sim 14\%$ for N_{ch}, and to $\sim 3\%$ for $[p_t]$. They originate from quantum fluctuations at different levels: In the positions of nucleons at the time of impact [21], in the partonic content of the nucleons [22], and in the process of particle production.[1] Modern hydrodynamic simulations take these fluctuations into account [25] by implementing a different initial density profile (the initial condition of hydrodynamic equations) in every collision. The second observation in Fig. 3 is that there is a positive correlation between $[p_t]$ and N_{ch} in hydrodynamics.

This correlation is a consequence of local thermalization, which is an underlying assumption of the hydrodynamic description. Larger N_{ch} implies a larger density N_{ch}/V, as the volume V (Fig. 1) is essentially defined by the impact parameter, which is fixed. In hydrodynamics, one assumes that the system is locally thermalized, and larger density corresponds to higher initial temperature. Note that relativity plays an essential role in this correspondence. In non-relativistic thermodynamics, density and temperature are independent variables. Heating a system at constant volume does not change its density, because the number of particles is conserved. In a relativistic system, on the other hand, particles can be created by converting kinetic energy into mass, and a higher temperature implies a higher density. It also implies a higher energy per particle, which eventually results in a larger momentum per particle $[p_t]$ [4].

In order to illustrate that the positive correlation between $[p_t]$ and N_{ch} is not trivial, Fig. 3 also displays results of simulations using the HIJING model [18], in which particles do not interact after they are produced. The correlation is smaller by a factor ~ 10. Note, however, that while thermalization always implies a positive correlation, the converse statement does not hold. In the color-glass condensate picture of high-energy collisions, such a correlation is already present at the level of particle production, since both the momentum per particle and the particle density increase with the saturation scale [22].

We now discuss the implications of thermalization on the observed $[p_t]$ fluctuations. First, note that the experimental analysis is done at fixed N_{ch}, while our hydrodynamic simulation is done at fixed b. Both choices are dictated by practical reasons. Experimentally, b is not measured. In the simulation, on the other hand, one must define b before starting the simulation, while N_{ch} is only evaluated at the end.

In order to understand experimental results, we must reason at fixed N_{ch}, where b varies. Larger b implies smaller collision volume V and larger density N_{ch}/V, hence larger $[p_t]$ on average. We denote by $\overline{p_t}(N_{ch}, b)$

[1] We only consider spherical nuclei. For deformed nuclei, one must also consider fluctuations in their orientations, which affect both the multiplicity [23] and the momentum per particle [24].

the expectation value of $[p_t]$ at fixed N_{ch} and b. It increases with N_{ch} at fixed b, and with b at fixed N_{ch}. In addition, there are fluctuations of $[p_t]$ even if both N_{ch} and b are fixed, as illustrated by the simulation in Fig. 3. We denote by $\mathrm{Var}(p_t|N_{ch},b)$ their variance. We then average over b at fixed N_{ch}. The average value of $[p_t]$ is $\langle\overline{p_t}(N_{ch},b)\rangle_b$, where $\langle\cdots\rangle_b$ denotes an average over b. The average value of $[p_t]^2$ is $\left\langle\overline{p_t}(N_{ch},b)^2+\mathrm{Var}(p_t|N_{ch},b)\right\rangle_b$. Therefore, the variance of $[p_t]$ is the sum of two positive terms:

$$\begin{aligned}\mathrm{Var}(p_t|N_{ch}) &= \left(\left\langle\overline{p_t}(N_{ch},b)^2\right\rangle_b-\left\langle\overline{p_t}(N_{ch},b)\right\rangle_b^2\right)\\ &\quad+\left\langle\mathrm{Var}(p_t|N_{ch},b)\right\rangle_b,\end{aligned}\tag{1}$$

The first term stems from the variation of $\overline{p_t}(N_{ch},b)$ with b. We refer to the second term as the intrinsic variance, in the sense that it is not a by-product of b fluctuations. As we shall see, both terms are of comparable magnitudes, and the first term explains the peculiar pattern observed for large N_{ch}.

We now carry out a quantitative calculation, which can be compared with data. First, precise information can be obtained, without any microscopic modeling, about the probability distribution of b at fixed N_{ch}, $P(b|N_{ch})$ [26]. This is achieved by solving first the inverse problem, namely, finding the probability distribution of N_{ch} for fixed b, $P(N_{ch}|b)$, and then applying Bayes' theorem $P(b|N_{ch})P(N_{ch}) = P(N_{ch}|b)P(b)$. As explained above, collisions at the same b differ by quantum fluctuations, which result in fluctuations of N_{ch}. In nucleus-nucleus collisions, these fluctuations are Gaussian to a good approximation. They are characterized by the mean, $\overline{N_{ch}}(b)$, and the variance, $\mathrm{Var}(N_{ch}|b)$.

What one measures is the distribution $P(N_{ch})$, obtained after integrating over all values of b, shown in Fig. 2 (a), left. We only display values of N_{ch} larger than some threshold such that only 20% of the events are included, corresponding to fairly central collisions on which our analysis focuses. $P(N_{ch})$ varies mildly up to $N_{ch}\sim 3500$, then decreases steeply. By fitting it as a superposition of Gaussians, one can precisely reconstruct $\overline{N_{ch}}(b)$ and $\mathrm{Var}(N_{ch}|b=0)$ [27] ([9], Sec. I). This fit is shown in Fig. 2 (a). The "knee" of the distribution, defined as the mean value of N_{ch} for collisions at $b=0$, is reconstructed precisely, and indicated as a vertical line. The steep fall of $P(N_{ch})$ above the knee gives direct access to $\mathrm{Var}(N_{ch}|b=0)$. [Note that the variance is only reconstructed at $b=0$, and one must resort to assumptions as to its dependence on b. We have checked that our results are robust with respect to these assumptions, see [9], Secs. I and IV.] We refer to events above the knee as ultracentral collisions [28, 29]. They are a small fraction of the total number of events, 0.35%, but ATLAS has recorded enough collisions that a few events are seen with values of N_{ch} larger than the knee by 20%, corresponding to 4 standard deviations. Note that Poisson fluctuations contribute only by 15% to the variance [27], so that the fluctuations of N_{ch} are mostly dynamical.

We then model the fluctuations of $[p_t]$. In the same way as we have assumed that the probability of N_{ch} at fixed b is Gaussian, we assume that the joint probability of N_{ch} and $[p_t]$, such as displayed in Fig. 3, is a two-dimensional Gaussian ([9], Sec. III). It is characterized by five quantities: The mean and variance of $[p_t]$ and N_{ch}, which we denote by $\overline{p_t}(b)$, $\overline{N_{ch}}(b)$, $\mathrm{Var}(p_t|b)$, $\mathrm{Var}(N_{ch}|b)$, and the covariance or, equivalently, the Pearson correlation coefficient $r_{N_{ch}}(b)$ between $[p_t]$ and N_{ch}, which we expect to be positive as illustrated in Fig. 3. $\overline{N_{ch}}(b)$ and $\mathrm{Var}(N_{ch}|b)$ are obtained from the fit to $P(N_{ch})$, as explained above. The mean transverse momentum is essentially independent of centrality for the 30% most central collisions [30], therefore, we assume that $\overline{p_t}(b)$ is independent of b, and we denote its value by $\overline{p_{t0}}$. Since we only evaluate the fluctuations around $\overline{p_{t0}}$, results are independent of its value. The variance $\mathrm{Var}(p_t|b)$ may have a non-trivial dependence on the impact parameter, but a smooth one. For statistical fluctuations, it is proportional to $1/N_{ch}$. We allow for a more general power-law dependence $\mathrm{Var}(p_t|b)=\sigma^2_{\delta p_t}(\overline{N_{ch}}(0)/\overline{N_{ch}}(b))^\alpha$, where $\sigma_{\delta p_t}$ and α are constants. Finally, we ignore the impact parameter dependence of the correlation coefficient $r_{N_{ch}}$ for simplicity.

With this Gaussian ansatz, one can evaluate analytically the quantities entering the right-hand side of Eq. (1) as a function of the parameters of the Gaussian ([9], Sec. III), and the averages over b are evaluated using the probability distribution $P(b|N_{ch})$ obtained using the Bayesian method outlined above ([9], Sec. I). The remaining three parameters ($\sigma_{\delta p_t}$, α and $r_{N_{ch}}$) are fitted to ATLAS data.

Let us first examine the distribution of $[p_t]$ and N_{ch} returned by our fit, which is represented in the left panel of Fig. 2 (b). The white curves represent 99% confidence ellipses at fixed impact parameter [27]. One sees that they are tilted with respect to the horizontal axis, as in the hydrodynamic calculation of Fig. 3. This tilt reflects the positive correlation between $[p_t]$ and N_{ch}, parameterized by $r_{N_{ch}}$. As explained above, this correlation is a natural consequence of thermalization. The width of the $[p_t]$ distribution for fixed N_{ch} is due in part to the fact that several ellipses contribute for a given N_{ch} (first term in Eq. (1)), and in part to the vertical width of a single ellipse (second term in Eq. (1)).

The left panel of Fig. 2 (c) displays the data and the model fit, as well as the two terms of Eq. (1). The model explains precisely the observed decrease of the variance around the knee. It comes from the first term, namely, from impact parameter fluctuations at fixed N_{ch}, whose effect becomes negligible in ultracentral collisions. The magnitude of this term is essentially determined by the correlation coefficient $r_{N_{ch}}$, which is thus constrained by data.

As a corollary, we predict a small increase in the average transverse momentum, represented as a black line in Fig. 2 (b), in ultracentral collisions. This effect, which had been predicted a while ago [31, 32], has recently been

observed by CMS collaboration [33]. Note that the increase is quantitatively predicted by our model calculation.

A specificity of the ATLAS analysis is that it uses, in addition to N_{ch}, an alternative centrality estimator, which is the transverse energy E_T (defined as energy multiplied by $\sin\theta$) deposited in two calorimeters located symmetrically on both sides of the collision point, which cover roughly the ranges $1^\circ < \theta < 5^\circ$ and $175^\circ < \theta < 179^\circ$. The analysis of the variance is repeated by sorting events according to E_T, rather than N_{ch}, and shown in the right panel of Fig. 2. In the same way, our model calculation can be repeated, replacing N_{ch} with E_T everywhere. This is a useful and non-trivial check of the validity of our approach. Even though the distributions of N_{ch} and E_T look similar in shape (Fig. 2 (a)), the fall above the knee is steeper for E_T than for N_{ch}, and there are only 0.26% of events above the knee for E_T, as opposed to 0.35% for N_{ch}. It is interesting to notice that despite this significant difference, the decrease of the variance observed by ATLAS (Fig. 2 (c)) still occurs around the knee. The parameters $\sigma_{\delta p_t}$ and α, which determine the dependence of the variance of $[p_t]$ on impact parameter, should not depend on whether one classifies events according to N_{ch} or E_T. We determine the values that give the best simultaneous agreement with N_{ch} and E_T-based data ([9] Sec. IV). The Pearson correlation coefficient r_{E_T} between $[p_t]$ and E_T need not coincide with $r_{N_{ch}}$ and is fitted independently. Note that $r_{N_{ch}}$ corresponds to the correlation between $[p_t]$ and N_{ch} for the *same* particles, while r_{E_T} represents the correlation between $[p_t]$ and the E_T measured in different angular windows. One therefore expects $r_{E_T} < r_{N_{ch}}$, which is confirmed by our fit. Values, however, are very similar, which shows that particle depositions in different θ windows are very strongly correlated.

We have revealed a new effect of thermalization which involves the momenta of particles, rather than their direction. It is spectacular because of its unique centrality dependence (as opposed to the presence of excess photons, also interpreted as resulting from thermal production [47, 48]). Our study thus highlights the importance of impact parameter, which defines the geometry and is an essential ingredient of the hydrodynamic description: The momentum per particle depends on its magnitude, much in the same way as elliptic flow is driven by its orientation. It is interesting to note that the impact parameter is a classical quantity, in the sense that its quantum uncertainty is negligible: Heisenberg's principle gives $\delta b \equiv \hbar/P \sim 4 \times 10^{-7}$ fm for a Pb+Pb collision at the LHC, negligible compared to the range spanned by b, of order 15 fm.[2] It is actually the *only* classical quantity characterizing a collision, and collisions with the same impact parameter differ only by quantum fluctuations. Due to the high energy of the collision, however, a single quantum fluctuation can produce a large number of particles, which promotes it to the status of a classical fluctuation. (Elliptic flow in central collisions [34] and triangular flow [35] are driven by a similar mechanism.) The effect studied in this paper involves a subtle interplay between classical fluctuations of impact parameter, and quantum fluctuations of the collision multiplicity.

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