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Testing the OPERA Superluminal Neutrino Anomaly at the LHC

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Abstract

The OPERA collaboration has reported the observation of superluminal muon neutrinos, whose speed v_ν exceeds that of light c, with $(v_\nu - c)/c \simeq 2.5 \times 10^{-5}$. In a recent work, Cohen and Glashow (CG) have refuted this claim by noting that such neutrinos will lose energy, by pair-emission of particles, at unacceptable rates. Following the CG arguments, we point out that pair-emissions consistent with the OPERA anomaly can lead to detectable signals for neutrinos originating from decays of highly boosted top quarks at the LHC, allowing an independent test of the superluminal neutrino hypothesis.

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The OPERA collaboration [1] has recently reported that the muon neutrinos from the CERN CNGS beam travel the approximately 730 km distance to Gran Sasso Laboratory at a speed v_ν that exceeds the speed of light c, with $(v_\nu - c)/c = [2.48 \pm 0.28\,(\text{stat.}) \pm 0.30\,(\text{sys.})] \times 10^{-5}$. This result, if confirmed, would be one of the most significant discoveries of recent times and would have important implications for fundamental physics. However, many observational considerations point to severe tensions between the OPERA result and well-established phenomena regarding neutrinos, such as flavor oscillations and the Supernova (SN) 1987a explosion [2, 3], among others [4]. It is thus important to subject this "anomaly" to as many tests as possible.

Cohen and Glashow [5] have very recently made the important observation that if a neutrino can travel faster than light several processes that are kinematically forbidden, within the current Lorentz invariant framework, would become allowed. In particular, Ref. [5] showed that bremsstrahlung processes in which superluminal neutrinos emit particles in vacuo and lose energy would lead to a severe depletion of the beam above about 12.5 GeV at Gran Sasso, in stark conflict with the reported OPERA data [1]. Assuming a flavor independent neutrino velocity v_ν, with negligible energy dependence, the leading process relevant for the analysis in Ref. [5] was $\nu_\mu \to \nu_\mu \, e^+ e^-$, mediated by a Z vector boson [6].

Inspired by the Cohen-Glashow (CG) analysis, we propose that the above vacuum bremsstrahlung processes could also lead to detectable signals at the LHC, assuming that the energy independence of v_ν will persist up to energies of order 100 GeV. This is a mild assumption, given that the OPERA results show no significant energy dependence up to about 50 GeV[1]. Our main observation is that decays of boosted top quarks at the LHC will contain neutrinos with energy $E_\nu \gtrsim 100$ GeV and such neutrinos would undergo CG vacuum bremsstrahlung processes, leading to the appearance of (multiple) charged lepton pairs or jets, with significantly displaced vertices, along the neutrino path.

Although our proposal is based on the mechanism considered in Ref. [5], the physical parameters characterizing the LHC experiments can in principle yield independent and complementary tests of the OPERA anomaly. Obviously, the LHC would directly probe the vacuum bremsstrahlung hypothesis, by searching for the emitted particles. In addition,

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[1] In fact, consistency with the SN 1897a data requires that v_ν steeply increase with energy, above ~ 10 MeV. However, we will assume that v_ν has reached its asymptotic value near the GeV-scale and will not increase further.

given the high energy and the short travel distance (limited to the size of the detector) of the neutrinos, possible oscillation effects, say into sterile states with negligible coupling to the Z boson, that could affect the efficiency of particle emission will not apply to our discussion. While we do not assert that such a possibility is phenomenologically compelling, it serves as an example of how LHC searches could be valuable as independent tests of Lorentz invariance in the neutrino sector and, by extension, the OPERA results. We will next discuss the quantitative aspects of our proposal.

As pointed out in Ref. [5], the threshold for emission of a pair of particles $\bar{\psi}\psi$, is $E_0 = 2m_\psi/\sqrt{v_\nu^2 - v_\psi^2}$, where m_ψ is the mass of ψ and v_ψ is its maximum speed in vacuo; as in the CG framework, we assume conservation of energy and momentum [7]. For economy of assumptions, we take $v_\psi = c$; we set $c = 1$, henceforth. Using the CG notation, we define $\delta \equiv v_\nu^2 - 1$, and hence $E_0 = 2m_\psi/\sqrt{\delta}$. We will set $\delta = 5.0 \times 10^{-5}$ hereafter. For the emission of e^+e^-, one then gets for the threshold energy $E_0(e) \simeq 145$ MeV. Neglecting the mass of the electron, *i.e.*, far above the energy threshold, the rate for emitting e^+e^- from a neutrino of energy E_ν was estimated in Ref. [5] by

$$\Gamma = k' \frac{G_F^2}{192\pi^3} E_\nu^5 \delta^3 \,, \tag{1}$$

where $k' = 1/14$ and G_F is the Fermi constant, assuming negligible vector coupling, c_V^e, for the electron to the Z boson.

From the above Eq. (1), we see that requiring the neutrino to have a "decay" length of ~ 1 m, so that the e^+e^- pair emission could typically occur within an LHC detector, yields $E_\nu \sim 300$ GeV. This suggests that a neutrino coming from the decay of a parent particle with ~ 1 TeV of energy would typically have one pair emission before leaving the detector volume. Such a pair emission will lead to an energy loss of about $\sim 0.8E_\nu$ [5], dramatically decreasing the expected missing energy signal associated with a neutrino final state. However, note that in such a case both the e^+ and e^- would each carry more than ~ 100 GeV of energy making them easily visible in an LHC detector. We also note that for $E_\nu \sim 100 - 300$ GeV, as required here, other emission channels, in particular into $\mu^+\mu^-$, $\bar{u}\,u$, and $\bar{d}\,d$ (*i.e.* jets) and possibly heavier quark pairs are also open. A simple generalization of Eq. (1), to include these additional channels, then yields (once their associated thresholds are passed)

$$\Gamma = k' \frac{G_F^2}{192\pi^3} E_\nu^5 \delta^3 \sum_f N_c(f)({c_V^f}^2 + {c_A^f}^2) PS_f \,, \tag{2}$$

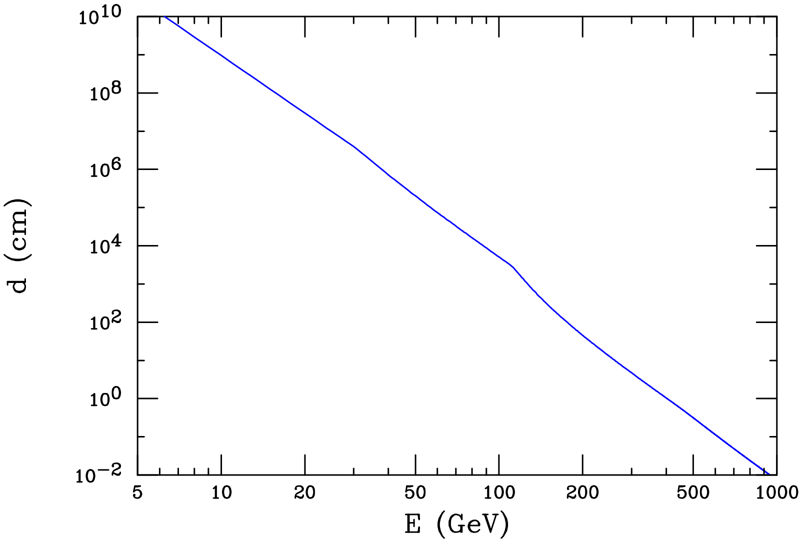

FIG. 1: Neutrino "decay" length, d, in units of centimeters as a function of neutrino energy in GeV.

where the sum extends over kinematically accessible fermions, PS_f represents the appropriate phase space suppression factor and $N_c(f) = 1(3)$ is a color factor for the fermion f. Here, c_V^f and c_A^f are the corresponding, appropriately normalized, vector and axial vector couplings of f to the Z, respectively; *e.g.*, $c_V^u = 1-8x/3$, with $x = \sin^2\theta_W \simeq 0.23$. Note that fully including electron, muon and $u\bar{u}$ and $d\bar{d}$, *etc* final states can increase the value of Γ by more than an order of magnitude leading to a corresponding shortening of the decay length $d = \Gamma^{-1}$. In the calculations presented here we will assume that $PS_f \simeq (1 - E_\nu^2/E_0^2(f))^{3/2}$, where $E_0(f)$ is the threshold energy for opening up "decays" into $\bar{f}f$. Other choices for PS_f make very little difference in our numerical results except very close to thresholds. The result of this calculation over a wide range of neutrino energies is displayed in Fig.1, where we have included all of the additional decay channels that open up when the various energy thresholds, $E_0(f)$, are crossed. For concreteness we have assumed that the relevant hadronic mass scales are those of ρ, ϕ, J/ψ, and Υ, corresponding to the emission of u/d, s, c, and b quark pairs, respectively. Thus, for example, "decays" to $\bar{s}s$ ($\bar{c}c$) have a neutrino threshold energy $E_0(f)$ of $m_{\phi\,(J/\psi)}/\sqrt{\delta} \simeq 144$ (438) GeV.

Now let us address whether such a signal can be detected, in practice, at the LHC. Since the decay length for the neutrinos scales as $\sim 1/E^5$ and we are looking for a somewhat unusual process, it is advantageous to search for a copious production mechanism that leads to neutrinos of significantly high energy. One such likely possibility is $t\bar{t}$ production at large

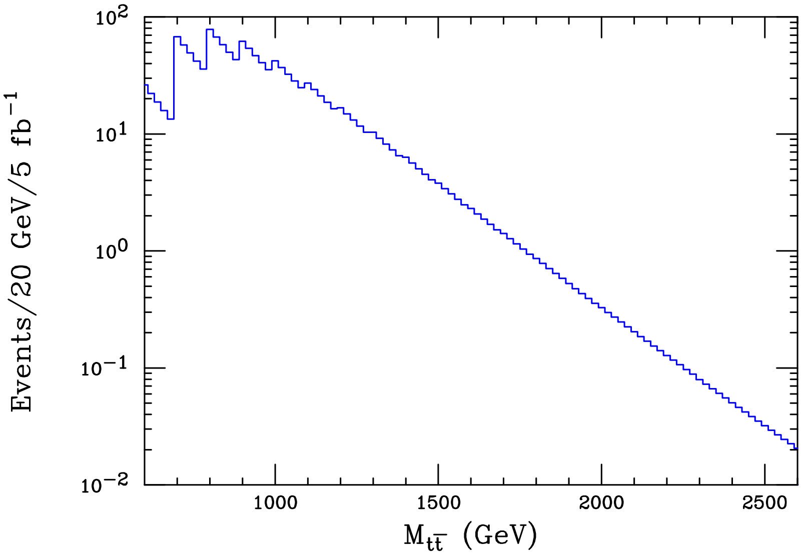

FIG. 2: $M_{t\bar{t}}$ distribution at the 7 TeV LHC for $\bar{t}t$ events, where one top decays leptonically, using the results of Ref. [8].

invariant masses, $M_{t\bar{t}}$, where one of the tops decays leptonically ($i.e.$, $t \to b\,W \to b\,\ell\,\nu_\ell$; $\ell = e, \mu$) and the resulting neutrino carries away $\sim 1/3$ of the parent t (or $\bar{t}$) energy. In such a case, neutrino energies in the interesting $\sim 100 - 300$ GeV energy range can easily result for $M_{t\bar{t}} \gtrsim 0.6 - 2$ TeV. We have plotted the $M_{t\bar{t}}$ distribution for these semileptonic top decay events per 5 fb^{-1} in Fig.2, using the numerical results obtained from Ref. [8], that account for effects of top tagging efficiencies, leading to the modulated behavior for invariant masses below ~ 1000 GeV. In this figure, the next-to-leading order K-factors are included and a sum over both e and μ final states has been performed. At the 7 TeV LHC with an integrated luminosity of ~ 5 fb^{-1} this would typically yield a sample of ~ 1400 events with $M_{t\bar{t}} > 600$ GeV. Assuming an approximate equipartition of energy (which is verified by explicit calculations), so that $\langle E_\nu \rangle \sim M_{t\bar{t}}/6$, the results shown in Fig.2 can be used to estimate the corresponding distribution as a function of E_ν. Here we assume that both ν_e and ν_μ are superluminal with equal speeds, as suggested by astrophysical and neutrino oscillation considerations [2, 3, 5].

In addition to the hadronic decay of the t (or $\bar{t}$), the other side of the event would consist of the conventional b-jet plus a high-p_T electron or muon. However, instead of the usual large $\sim 100 - 300$ GeV missing transverse energy $\not{E}_T$ signal from the neutrino something different happens. After traveling ~ 1 m from the interaction point (IP) (the exact value depending on the neutrino energy as shown in Fig.1), the neutrino "decays" into a pair of leptons or into a hadronic jet plus a secondary neutrino, losing on average $\sim 80\%$ of its energy in the process [5]. Since the initial neutrino is so highly boosted these decay products (which now also include the reduced $\not{E}_T$ carried by the secondary neutrino) will approximately follow the original parent neutrino direction and leave tracks which point back to the IP but begin $\sim$ 1m away at a displaced vertex [9]. Furthermore, if the parent neutrino energy is sufficiently high, there is a small chance that this process may be observed *twice* in the detector when the secondary neutrino again "decays", producing an extraordinary signature. However, this signature is most likely not relevant for the early run at the 7 TeV LHC, as we will discuss below.

Taking $d \simeq 10$ m as the maximum allowed decay length by typical dimensions of an LHC detector, Fig.1 suggests that the secondary neutrino, after the first emission depletes the initial energy by about 80% [5], should have $E_\nu \gtrsim 100$ GeV. This would require an initial neutrino energy larger than about 500 GeV. Under the assumption of energy equipartition for typical top decays, we then would require $M_{\bar{t}t} \gtrsim 3000$ GeV. Hence, as indicated by the distribution in Fig. 2, the 7 TeV run of the LHC would require a data sample much larger than $\mathcal{O}(10)$ fb^{-1} in order to search for the double-emission signal. Seeing this effect would likely require the 14 TeV LHC at full design luminosity.

Finally, we would like to add that when both the t and $\bar{t}$ decay leptonically, the neutrino decay processes will typically take place on both sides of the $t\bar{t}$ event. However, in this case, due to the smaller branching fraction the statistics will be reduced by a factor of about 6.

In conclusion, if the OPERA anomaly [1] is due to superluminal neutrinos, the results of Ref. [5] imply that distinct signals should appear in the decays of highly boosted top quarks (unless the superluminal behavior becomes less prominent above the OPERA beam energies; this would seemingly require such behavior to be only limited to neutrino energies of roughly 1-100 GeV). Our estimates suggest that the currently available center of mass energy (7 TeV) and integrated luminosity (~ 5 fb^{-1}) should be sufficient to test the OPERA anomaly at the LHC.

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[4] See for example, A. Drago, I. Masina, G. Pagliara, R. Tripiccione, [arXiv:1109.5917 [hep-ph]]; R. Cowsik, S. Nussinov, U. Sarkar, [arXiv:1110.0241 [hep-ph]]; B. Altschul, [arXiv:1110.2123 [hep-ph]].

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[6] Similar processes were also considered for astrophysical neutrinos by X. -J. Bi, P. -F. Yin, Z. -H. Yu, Q. Yuan, [arXiv:1109.6667 [hep-ph]].

[7] The assumed violation of Lorentz invariance in our work, as in Ref. [5], leaves energy-momentum conservation intact. For other possibilities that may evade vacuum bremsstrahlung constraints see G. Amelino-Camelia, L. Freidel, J. Kowalski-Glikman, L. Smolin, [arXiv:1110.0521 [hep-ph]].

[8] See, for example, J. L. Hewett, J. Shelton, M. Spannowsky, T. M. P. Tait, M. Takeuchi, [arXiv:1103.4618 [hep-ph]].

[9] Searches for highly displaced vertices have now begun at the LHC. See, *e.g.*, G. Aad *et al.* [ATLAS Collaboration], [arXiv:1109.2242 [hep-ex]] and S. Chatrchyan *et al.*[CMS Collaboration], PAS EXO-11.004.