Snowmass2021 - Letter of Interest

Synergy of astro-particle physics and collider physics

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) EF06, EF07, NF05, NF06,AF4

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Abstract:

Seeking the fundamental nature of matter and associated mysteries bridges the energy, neutrino, and cosmic frontiers, thus connecting astro-particle physics and accelerator-based particle physics. Ergo, the study of astro-particle physics can have significant implications in the search for physics beyond the Standard Model at the LHC and future colliders. Correspondingly, LHC experiments provide the laboratory for measurements relevant to understand the subtleties of astro-particle physics. This Letter of Interest for SNOWMASS21 highlights some of the synergistic links between astro-particle physics and collider physics, focusing on cosmic rays and neutrinos. Related discussions by the European Community can be found in the European Particle Physics Strategy (EPPS)[1] and the Astroparticle Physics European Consortium (APPEC) roadmap.[*]

[*] https://europeanstrategyupdate.web.cern.ch/; https://www.appec.org/roadmap

The history of cosmic-ray/neutrino studies has witnessed many discoveries central to the progress of high-energy physics, from the watershed identification of new elementary particles in the early days, to the confirmation of long-suspected neutrino oscillations, to measuring cross-sections and accessing particle interactions far above accelerator energies. Two major recent achievements in this direction are: *(i)* the measurement of the proton-proton cross section at center-of-mass energy $\sqrt{s} \sim 75$ TeV[2–4], which provides evidence that the proton behaves as a black disk at asymptotically high energies[5;6]; *(ii)* the measurements of both the charged current neutrino-nucleon cross section[7;8] and the neutral to charged current cross section ratio[9] at $\sqrt{s} \sim 1$ TeV, which provide restrictive constraints on fundamental physics at sub-fermi distances.

The Pierre Auger Observatory has also demonstrated that it is possible to test particle physics models at $\sqrt{s} \gtrsim 100$ TeV using hybrid measurements of extensive air showers, even with a mixed primary composition[10;11]. A significant discrepancy in the shower muon content is found ($> 2\sigma$, statistical and systematic errors combined in quadrature) between predictions of LHC-tuned hadronic event generators[12] and observations. This discrepancy has been confirmed by the Telescope Array[13]. Moreover, thorough studies by the *Working Group on Hadronic Interactions and Shower Physics* (WHISP) show that while air shower measurements are consistent within their uncertainties with predictions up to cosmic ray energies $E \sim 10^8$ GeV, at higher energies a muon excess is observed that systematically increases with rising shower energy[14;15]. The slope of a fit to this excess is found to be significant at about 8σ when considering the hadronic event generators EPOS-LHC[16] and QGSJet-II.04[17]. The onset of the discrepancy corresponds to a center-of-mass energy per nucleon $\sqrt{s_{NN}} \lesssim 14$ TeV that has been in principle probed by LHC experiments. It is thereby challenging to imagine beyond the Standard Model (SM) physics being the main reason for this discrepancy. Recent Auger measurements on muon fluctuations in air showers initiated by ultrahigh-energy cosmic rays (UHECRs) have further increased the challenge[18]. Analytical and numerical studies indicate that the energy evolution of the muon number and its fluctuations are directly related to the ratio of the energy deposited in neutral pions to that of other hadrons: E_{π^0}/E_h[19–22]. This ratio is mostly driven by the hadronization process. At present, all hadronic interaction models used in UHECR physics are based on the same string-like (Lund model) hadronization[23]. Tests using Sibyll2.3c and EPOS-QGP[24] show that the discrepancy in the number of muons can be reduced by decreasing E_{π^0}/E_h. A separate Letter of Interest (LoI) discusses in detail the cosmic ray data[25].

The ALICE Collaboration has reported an enhancement of the yield ratio of strange and multi-strange hadrons to charged pions as a function of multiplicity at mid-rapidity in pp, pPb, PbPb, and XeXe scattering[26;27]. This observation provides evidence that a quark-gluon plasma (QGP) could be partly formed in high multiplicity events of both small and large colliding systems. The almost equal column-energy density in UHECR-air collisions and PbPb collisions at the LHC[28] allows for a direct test of next-generation QGP event generators: LHC PbPb scattering at $\sqrt{s_{NN}} = 5.02$ TeV and UHECR N-air collisions at $\sqrt{s_{NN}} \simeq 12$ TeV (corresponding to $E \simeq 10^9$ GeV) should produce the same hadron-to-pion yield ratios as a function of the charged multiplicity[29]. The formation of QGP blobs could play a significant role in the development of extensive showers. In particular, the enhanced production of multi-strange hadrons in high-multiplicity small and large colliding systems would suppress the ratio E_{π^0}/E_h[30–34]. ALICE data also indicate a smooth transition from a string-like hadronization to a QGP-like statistical hadronization as a function of central multiplicity. This transition could address the muon puzzle but with the strong assumptions that the transition should start already at relatively low energy and should be effective at large Feynman x_F[35]. From the theoretical perspective, this provides a new pathway connecting LHC soft hadronic physics with extensive air showers to be fully explored in the next decade.

While the ALICE data suggest a rather universal picture of particle production at mid-rapidity, data from LHCb show significant nuclear modification of production cross sections of forward produced charmed mesons[36;37] which break universality. The LHCf experiment[38] finds even stronger nuclear modification for π^0 production in the extreme forward region[39]. LHCb is ideally suited to study the transition between universal and non-universal hadron production in pp and pPb collisions and to precisely measure spectra of π's, K's, and p's with LHCb's unique particle identification capabilities in the forward region, with the goal to reduce the current model spread five-fold. The LHCf experiment is made of two double arm high precision calorimeters placed on both side of ATLAS interaction point[40] and covers the very forward region with precision measurements of neutral particles. These measurements[41;42] are of utmost importance for the calibration of hadronic interaction models used in the Monte Carlo codes developed for UHECR physics. A proposal to accelerate oxygen beams in LHC was strongly supported by LHCb and LHCf to study the nuclear modification in the pO system[43], which directly mimics UHECR-air collisions. A week of LHC running with oxygen beams is planned for 2023. Solving the muon discrepancy also comes with LHC fixed-target (FT) data. Let us cite the LHCb SMOG-2 upgrade[44], extending the[45] unique capability of LHCb to run in the FT mode with H and O targets. ALICE could also take LHC FT data in a wider rapidity range[45]. These mimic the last stages of air shower development, where measuring the transverse momentum distribution is very important for the shape of the lateral muon density profile. In addition, charged hadron spectra in the very forward region at the LHC could be measured with a forward multiparticle spectrometer (FMS) described in a separate LoI[46]. This would require an enlarged beam pipe between the superconducting dipole D1 and the TAXN absorber in Run 4 and beyond. The spectra of $\pi^{\pm}, K^{\pm}, p$ and $\bar{p}$ and light antinuclei with $x_F = 0.1 - 0.3$ as well as charmed hadrons $(D^0, \bar{D}^0, \Lambda_c^+)$ at higher x_F in low pile-up pp, pO, and OO collisions would greatly improve our understanding of very high energy cosmic ray showers[47].

Complementary information to address the muon puzzle will come from novel gamma-ray, neutrino and UHECR experiments such as LHAASO-KM2A[48], SWGO[49] (TeV), IceCube/IceTop[50], Tibet AS-gamma[51], ALPACA[52] (PeV), AMIGA/MARTA[53;54] (0.1EeV), and AugerPrime[55] which will measure the muon distributions of air showers in a broad range of energy overlapping with collider data. This new arsenal of data will provide a profitable arena for testing next-generation models of high-energy hadronic collisions.

A key player for establishing the connection between cosmic messengers and collider physics is the ForwArd Search ExpeRiment (FASER), which is located in the very forward direction at the LHC[56]. FASER will measure forward going muons which can be proxies of forward-produced pions, providing complementary information to address the muon puzzle. FASER has also a dedicated neutrino detector FASERν[57;58] for measuring forward neutrinos that could give critical information on perturbative charm[59] and associated charm production (the charm analogue to $K + \Lambda$ for strangeness) at Feynman x_F close to 1. These processes almost certainly yield the dominant atmospheric background for IceCube cosmic neutrinos above 100 TeV[60–62], and at the moment we have no data and we have no theory for the process. A separate LoI discusses in detail the potential of FASERν[63]. The Search for Hidden Particles (SHiP) could provide similar information on the charm contribution to atmospheric neutrinos[64]. Finally, FASER will search for light and weakly interacting particles that could mimic neutrino interactions in cosmic-ray/neutrino facilities[65].

Neutrinos are veracious astronomical messengers as they propagate without interactions between source and Earth, providing compelling probes of fundamental physics[66–69]. The neutrino's direction and energy (modulo the usual red-shifting due to expansion of the universe) are preserved, and the neutrino's flavor is altered in a calculable way. IceCube-Gen2 measurements[70] will complement collider data in the search for physics beyond the SM. For example, IceCube-Gen2 observations will allow for searches sensitive to putative supersymmetry production, reaching mass scales far beyond those probed at colliders[71;72]. Measurements of the cosmic neutrino flux[73–75] are consistent with an s-channel enhancement of neutrino-quark scattering by a leptoquark that couples to the τ-flavor and light quarks[76]. With the large statistics sample to be collected by IceCube-Gen2, we will be able to study the inelasticity distribution of events that provides a unique method for SM background rejection, allowing powerful discrimination of resonant processes[77;78]. The importance of cosmic neutrinos to probe fundamental physics is discussed in a separate LoI[79].

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