Snowmass2021 - Letter of Interest

Studies of the Muon Excess in Cosmic Ray Air Showers

Thematic Areas:

■ (CF7) Cosmic Probes of Fundamental Physics
■ (EF6) QCD and Strong Interactions: Hadronic Structure and Forward QCD
■ (EF7) QCD and Strong interactions: Heavy Ions
■ (AF4) Multi-TeV Colliders

Contact Information: Dennis Soldin[1,2] (soldin@udel.edu)
[1] Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
[2] Working Group on Hadronic Interactions and Shower Physics (WHISP) of the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array Collaborations

Authors: D. Soldin, H. P. Dembinski, L. Cazon, T. Pierog, R. Adhikari, M. Albrow, L. A. Anchordoqui, J. C. Arteaga-Velázquez, P. Assis, X. Bai, J. J. Beatty, J. Bellido, D. Berge, A. G. Bogdanov, K. S. Caballero-Mora, J. M. Carceller, A. Castellina, A. Chiavassa, A. Coleman, R. Conceição, D. d'Enterria, P. Denton, C. Doglioni, J.C. D'Olivo, M. A. DuVernois, R. Engel, G. R. Farrar, A. Fedynitch, J. L. Feng, T. K. Gaisser, F. Gesualdi, C. Grupen, F. Halzen, A. Haungs, F. Kling, R. P. Kokoulin, J.-P. Lansberg, P. Lipari, J. Manshanden, J. Matthews, G. Medina-Tanco, M.S. Muzio, D. Nitz, A. A. Petrukhin, M. Pimenta, M. Plum, A. Porcelli, M. Reininghaus, F. Riehn, M. Roth, T. Sako, F. Sanchez, B. Sathyaprakash, D. Seckel, T. Stanev, S. Tilav, K. Tollefson, R. M. Ulrich, M. Unger, D. Veberic, J. Vicha, L. R. Wiencke, I. I. Yashin, B. Wundheiler, E. A. Zadeba, A. Zepeda, Y. Zhezher

Abstract: Observations of cosmic rays with PeV energies and higher rely on indirect measurements of extensive air showers (EAS) in the Earth's atmosphere. The inference of the properties of the initial cosmic ray requires precise physical models of the air shower. Evidence for an excess of GeV muons in EAS with respect to model predictions has been reported by many experiments over the last 20 years. This excess was recently confirmed in a meta analysis of measurements from eight air shower experiments, for all currently available hadronic interaction models. This letter of interest focuses on the current status of muon measurements from observations of EAS over four orders of magnitude in cosmic ray energy and their discrepancies with respect to predictions from recent hadronic interaction models. We will address the main challenges in the description of muon production in EAS and identify measurements that are required to improve current model predictions. We will further discuss ongoing studies and future perspectives for muon measurements, and emphasize the importance of synergies between air shower observations and dedicated collider measurements of nucleus-nucleus interactions in the forward region in order to understand the origin of the muon excess in EAS.

Introduction

Cosmic rays have been measured in the Earth's atmosphere with energies exceeding 10^{20} eV, but their sources remain unclear, their acceleration mechanisms and mass composition are uncertain, and several features observed in the energy spectrum are not well understood[1]. Large ground-based experiments are used to observe high energy cosmic rays indirectly through extensive air showers (EAS) that they generate in the atmosphere. The inference of cosmic ray properties requires a precise physical model of the air shower, but key properties of the EAS development are driven by forward hadron production in soft and semihard hadron-ion collisions, which cannot be computed *ab initio*, and their modeling is subject to large theoretical uncertainties. In fact, none of the current hadronic interaction models tuned to available collider data is able to correctly describe muon production in EAS[2;3], a problem commonly referred to as the *muon puzzle* in air shower physics[4].

The Muon Excess in Extensive Air Showers

An excess of muons with respect to simulated air showers was first experimentally observed in the year 2000[5]. Subsequently, the excess was qualitatively confirmed by several experiments[6–9], while other experiments reported no excess[10–13]. The most unambiguous experimental evidence of the excess was revealed in the analysis of Auger data[14;15]. As hadronic interaction models were further developed and tuned to more data, in particular from LHC and SPS, their predictions for air showers improved but discrepancies in predicted muon production remained. Recently, a global picture of the energy dependence and high statistical significance of the muon excess was found using measurements of GeV muons from eight air shower experiments[8–16], ranging over more than four orders of magnitude in shower energy, by a multi-collaborative *Working Group on Hadronic Interactions and Shower Physics* (WHISP)[2;3]. Key aspects of this analysis are a cross-calibration of the energy scales of the different experiments and the definition of the z-value, an abstract measure of the muon content which is comparable between experiments and different analyses. The value $\Delta z = z - z_{\text{mass}}$, where z_{mass} is the number of muons predicted by a hadronic model assuming a mass composition of the primaries based on experimental parameterizations[17], measures the difference between the experimental data and the inferred number of muons for a given hadronic interaction model. A positive value indicates an excess of muons in data with respect to simulations and 0 indicates a perfect match. The resulting distribution of Δz is shown in Fig. 1 for two hadronic models, EPOS-LHC[18] and QGSJet-II-04[19]. The experimental measurements are consistent within uncertainties with predictions up to energies of approximately 100 PeV, corresponding to proton-air collisions at nucleon-nucleon center-of-mass energies of $\sqrt{s_{NN}} \lesssim 14\,\text{TeV}$. However, above 100 PeV a muon excess is observed that systematically increases with the shower energy. The slope of a linear fit to this excess is found to be non-zero at $\sim 8\sigma$ for all hadronic interaction models considered.

Discrepancies in measurements of the attenuation length of GeV muons[12] suggest a problem in the description of the energy spectra of muons at production[20–22]. Preliminary studies also indicate differences in

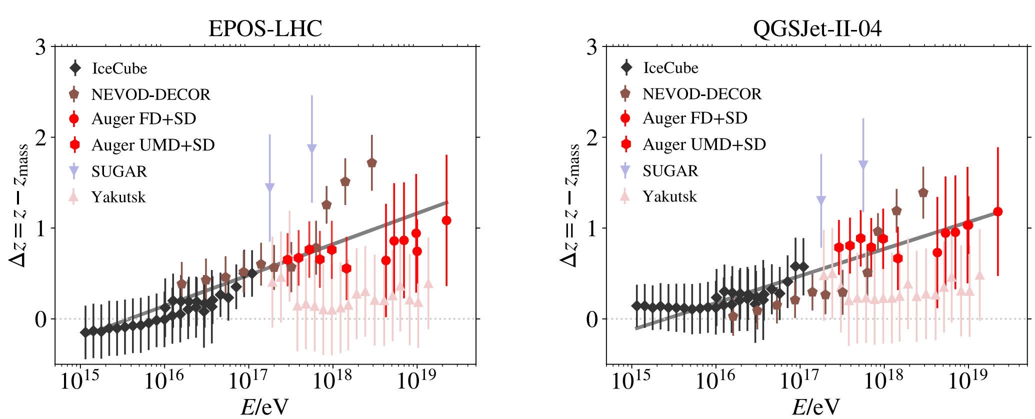

Figure 1: Distribution of $\Delta z = z - z_{\text{mass}}$ from various experiments and corresponding linear fit for two hadronic interaction models, EPOS-LHC and QGSJet-II-04 (see WHISP report[2] for details).

the discrepancies of GeV and TeV muons[23] and inconsistencies in the zenith angle distributions of simulated TeV muons have been reported[24–26] which are not yet understood. The muon production depth in the atmosphere[27;28] has also been shown to have strong discrepancies with respect to models, which has been linked to a poor description of pion-air interactions in EAS.

Upgrades to EAS Detectors and Synergies with Accelerator Measurements

The main challenge in the description of muon production in the atmosphere is the treatment of hadron-ion interactions in the forward region over many orders of magnitude in energy[22;29]. Conventional options to improve the description of muon production in hadronic models are the enhancement of the production of baryon-pairs, neutral rho mesons[30], or heavy quarks[31], as well as possibly missing physics in the soft-QCD regime of hadron-ion collisions[31–34], or other new phenomena[35–37].

Various analyses of atmospheric muons in the GeV range are in preparation[38–41], using improved analysis methods and the most recent hadronic models. Analyses based on global fits of different shower observables have been developed which will provide reduced uncertainties[42–45] and machine learning techniques will further enhance the capabilities of existing detectors[46;47]. Ongoing detector upgrades of existing facilities, such as AugerPrime[48–50] and IceCube-Gen2[51–55], will enhance the precision of air shower measurements and reduce uncertainties in the interpretation of muon data which arise from energy scale or mass composition uncertainties. Upgrades of the NEVOD-DECOR experiment[56;57] will improve the measurement of the energy deposition of muons which will also help to test and constrain hadronic model predictions. It has also been shown that the shower-to-shower fluctuations of the number of muons are strongly dominated by the first interaction of the EAS[58;59]. Thus, they are a direct probe of the hadron production spectra and provide a test of multiparticle production in hadron-ion interactions at center-of-mass energies above those reachable at the LHC. IceCube offers the unique opportunity to measure the EAS muon content simultaneously at two vastly different energy scales, in the deep ice detector (TeV muons), as well as with IceTop[23;60] and new detectors[52;53] at the surface (GeV muons), which will test and strongly constrain muon enhancement models[30].

Ongoing studies on the muon discrepancy at the LHC include detailed measurements of prompt hadron production cross-sections in the forward region in proton-proton and proton-lead collisions and measurements of the ratio of electromagnetic and hadronic energy flows, to which the production of GeV muons is particularly sensitive[34;61–63]. Similar studies at central rapidities improved the hadronic models with the first LHC data[64]. Running the LHC with oxygen beams is planned for 2023[62], which was largely motivated by the muon excess and the need to study the nuclear modification of hadron production in the first collisions in EAS. The LHCb SMOG-2 upgrade[65] will extend the unique capability of LHCb to perform LHC fixed target experiments to study late interactions in EAS, and ALICE will extend LHC fixed-target measurements to a wider rapidity range[66]. Data from the FASER[67] and FASERν[68;69] experiments, measuring forward muon and neutrino fluxes at the LHC, as well as from AFTER@LHC[70] and LHCf[71], will also provide useful information. Further details of the synergy between air shower and collider physics are discussed in a separate letter of interest[72] for Snowmass2021.

Conclusions

A meta analysis of muon data from multiple experiments recently confirmed an excess of atmospheric muons in EAS. Some observations also suggest a problem in the modeling of muon production spectra but a possible connection to the physics of the excess remains unknown. Updates of analyses from existing and new air shower facilities, which include measurements of the muon production depth, the muon energy deposit, and measurements of muons at multiple energies, as well as shower-to-shower fluctuations, will provide crucial information on hadron-ion interactions beyond the phase space of existing colliders in order to constrain muon production models. Dedicated collider measurements will provide complementary information of prompt hadron production in the forward region. This synergy between air shower and collider experiments will be a crucial step towards an understanding of the origin of the muon discrepancies in EAS.

References:

[1] K.-H. Kampert and M. Unger. Measurements of the cosmic ray composition with air shower experiments. *Astropart. Phys.*, 35(10):660 – 678, 2012.

[2] H. P. Dembinski et al. Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers. *EPJ Web Conf.*, 210:02004, 2019.

[3] L. Cazon et al. Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments. *PoS*, ICRC2019:214, 2019.

[4] A. A. Petrukhin. Muon puzzle in cosmic ray experiments and its possible solution. *Nucl. Instrum. Meth. A*, 742:228–231, 2014.

[5] T. Abu-Zayyad et al. Evidence for Changing of Cosmic Ray Composition between $10^{17}\,\mathrm{eV}$ and $10^{18}\,\mathrm{eV}$ from Multicomponent Measurements. *Phys. Rev. Lett.*, 84:4276–4279, 2000.

[6] A. G. Bogdanov et al. Investigation of the properties of the flux and interaction of ultrahigh-energy cosmic rays by the method of local-muon-density spectra. *Phys. Atom. Nucl.*, 73:1852–1869, 2010.

[7] R. Engel. Test of hadronic interaction models with data from the Pierre Auger Observatory. In *30th International Cosmic Ray Conference*, volume 4, pages 385–388, 6 2007.

[8] R. U. Abbasi et al. Study of muons from ultrahigh energy cosmic ray air showers measured with the Telescope Array experiment. *Phys. Rev. D*, 98(2):022002, 2018.

[9] A. G. Bogdanov et al. Investigation of very high energy cosmic rays by means of inclined muon bundles. *Astropart. Phys.*, 98:13–20, 2018.

[10] Yu. A. Fomin et al. No muon excess in extensive air showers at 100–500 PeV primary energy: EAS–MSU results. *Astropart. Phys.*, 92:1–6, 2017.

[11] J. G. Gonzalez et al. Measuring the Muon Content of Air Showers with IceTop. *EPJ Web Conf.*, 99:06002, 2015.

[12] W. D. Apel et al. Probing the evolution of the EAS muon content in the atmosphere with KASCADE-Grande. *Astropart. Phys.*, 95:25–43, 2017.

[13] A. V. Glushkov, M. I. Pravdin, and A. Sabourov. for the Yakutsk collaboration, private comm. 2018.

[14] A. Aab et al. Muons in Air Showers at the Pierre Auger Observatory: Mean Number in Highly Inclined Events. *Phys. Rev. D*, 91(3):032003, 2015. [Erratum: Phys.Rev.D 91, 059901 (2015)].

[15] A. Aab et al. Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory. *Phys. Rev. Lett.*, 117(19):192001, 2016.

[16] J. A. Bellido et al. Muon content of extensive air showers: comparison of the energy spectra obtained by the Sydney University Giant Air-shower Recorder and by the Pierre Auger Observatory. *Phys. Rev. D*, 98(2):023014, 2018.

[17] H. P Dembinski et al. Data-driven model of the cosmic-ray flux and mass composition from 10 GeV to 10^{11} GeV. *PoS*, ICRC2017:533, 2018.

[18] T. Pierog et al. EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider. *Phys. Rev. C*, 92(3):034906, 2015.

[19] S. Ostapchenko. QGSJET-II: physics, recent improvements, and results for air showers. *EPJ Web Conf.*, 52:02001, 2013.

[20] J. Espadanal, L. Cazon, and R. Conceição. Sensitivity of EAS measurements to the energy spectrum of muons. *Astropart. Phys.*, 86:32–40, 2017.

[21] L. Cazon. Probing High-Energy Hadronic Interactions with Extensive Air Showers. *PoS*, ICRC2019:005, 2019.

[22] S. Ostapchenko. High energy cosmic ray interactions and UHECR composition problem. *EPJ Web Conf.*, 210:02001, 2019.

[23] S. De Ridder, E. Dvorak, T. K. Gaisser, et al. Sensitivity of IceCube Cosmic-Ray measurements to the hadronic interaction models. *PoS*, ICRC2017:319, 2017.

[24] M. G. Aartsen et al. Characterization of the Atmospheric Muon Flux in IceCube. *Astropart. Phys.*, 78:1–27, 2016.

[25] R. U. Abbasi et al. Lateral Distribution of Muons in IceCube Cosmic Ray Events. *Phys. Rev. D*, 87(1):012005, 2013.

[26] D. Soldin et al. Atmospheric Muons Measured with IceCube. *EPJ Web Conf.*, 208:08007, 2019.

[27] W. D. Apel et al. Muon production height studies with the air shower experiment KASCADE-Grande. *Astropart. Phys.*, 34:476–485, 2011.

[28] A. Aab et al. Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth. *Phys. Rev. D*, 90:012012, Jul 2014.

[29] R. Engel, D. Heck, and T. Pierog. Extensive Air Showers and Hadronic Interactions at High Energy. *Annual Review of Nuclear and Particle Science*, 61(1):467–489, 2011.

[30] F. Riehn et al. The hadronic interaction model sibyll 2.3c and extensive air showers. *Preprint: arXiv:1912.03300*, Dec 2019.

[31] D. d'Enterria, T. Pierog, and G. Sun. Impact of QCD jets and heavy-quark production in cosmic-ray proton atmospheric showers up to 10^{20} eV. *Astrophys. J.*, 874:152, 2019.

[32] L. A. Anchordoqui, H. Goldberg, and T. J. Weiler. Strange fireball as an explanation of the muon excess in Auger data. *Phys. Rev. D*, 95(6):063005, 2017.

[33] L. A. Anchordoqui et al. Through the Looking-Glass with ALICE into the Quark-Gluon Plasma: A New Test for Hadronic Interaction Models Used in Air Shower Simulations. *Preprint: arXiv:1907.09816*, Jul 2019.

[34] S. Baur et al. Core-corona effect in hadron collisions and muon production in air showers. *Preprint: arXiv:1902.09265*, Feb 2019.

[35] J. Alvarez-Muniz et al. Muon production and string percolation effects in cosmic rays at the highest energies. *Preprint: arXiv:1209.6474*, Sep 2012.

[36] G. R. Farrar and J. D. Allen. A new physical phenomenon in ultra-high energy collisions. *EPJ Web Conf.*, 53:07007, 2013.

[37] G. Brooijmans, P. Schichtel, and M. Spannowsky. Cosmic ray air showers from sphalerons. *Phys. Lett. B*, 761:213–218, 2016.

[38] A. M. Botti et al. The AMIGA underground muon detector of the Pierre Auger Observatory - performance and event reconstruction. *PoS*, ICRC2019:202, 2019.

[39] J. C. Arteaga-Velázquez, D. Rivera Rangel, et al. Muon content in air showers between 10 PeV and 1 EeV determined from measurements with KASCADE-Grande. *PoS*, ICRC2019:177, 2019.

[40] J. G. Gonzalez et al. Muon Measurements with IceTop. *EPJ Web Conf.*, 208:03003, 2019.

[41] J. Bellido et al. Self-consistent approach for measuring the energy spectra and composition of cosmic rays and determining the properties of hadronic interactions at high energy. *Letter of Interest for Snowmass2021*, Aug 2020.

[42] J. Vicha et al. Testing Hadronic Interactions Using Hadronic Observables. *PoS*, ICRC2019:452, 2019.

[43] F. Schmidt et al. A Model-Independent Method of Determining Energy Scale and Muon Number in Cosmic Ray Surface Detectors. *Astropart. Phys.*, 29:355–365, 2008.

[44] M. Ave, M. Roth, and A. Schulz. A generalized description of the time dependent signals in extensive air shower detectors and its applications. *Astropart. Phys.*, 88:46–59, 2017.

[45] M. Ave, R. Engel, M. Roth, and A. Schulz. A generalized description of the signal size in extensive air shower detectors and its applications. *Astropart. Phys.*, 87:23–39, 2017.

[46] M. Erdmann, J. Glombitza, and D. Walz. A Deep Learning-based Reconstruction of Cosmic Ray-induced Air Showers. *Astropart. Phys.*, 97:46–53, 2018.

[47] A. Guillen et al. Deep learning techniques applied to the physics of extensive air showers. *Astropart. Phys.*, 111:12–22, 2019.

[48] A. Aab et al. The Pierre Auger Observatory Upgrade - Preliminary Design Report. *Preprint: arXiv:1604.03637*, Apr 2016.

[49] A. Aab et al. Muon counting using silicon photomultipliers in the AMIGA detector of the Pierre Auger observatory. *JINST*, 12(03):P03002, 2017.

[50] A. Aab et al. Direct measurement of the muonic content of extensive air showers between 2E17 eV and 2E18 eV at the Pierre Auger Observatory. *Eur. Phys. J. C*, 80:751, 2020.

[51] A. Ishihara et al. The IceCube Upgrade – Design and Science Goals. *PoS*, ICRC2019:1031, 2020.

[52] A. Haungs et al. A Scintillator and Radio Enhancement of the IceCube Surface Detector Array. *EPJ Web Conf.*, 210:06009, 2019.

[53] F. Schroeder et al. Science Case of a Scintillator and Radio Surface Array at IceCube. *PoS*, ICRC2019:418, 2019.

[54] A. Haungs et al. Highest Energy Galactic Cosmic Rays. *Letter of Interest for Snowmass2021*, Aug 2020.

[55] F. Schröder et al. Radio Detection of Cosmic Rays. *Letter of Interest for Snowmass2021*, Aug 2020.

[56] R. P. Kokoulin et al. Measuring the Cherenkov light yield from cosmic ray muon bundles in the water detector. *Nuclear Instruments and Methods in Physics Research A*, 952:161586, February 2020.

[57] E. A. Zadeba et al. The coordinate-tracking detector based on the drift chambers for ultrahigh-energy cosmic ray investigations. *Journal of Instrumentation*, 9(08):C08018–C08018, 2014.

[58] L. Cazon, R. Conceição, and F. Riehn. Probing the energy spectrum of hadrons in proton air interactions at ultrahigh energies through the fluctuations of the muon content of extensive air showers. *Physics Letters B*, 784:68 – 76, 2018.

[59] F. Riehn et al. Measurement of the fluctuations in the number of muons in inclined air showers with the Pierre Auger Observatory. *PoS*, ICRC2019:404, 2019.

[60] R. U. Abbasi et al. IceTop: The surface component of IceCube. *Nucl. Instr. and Meth.*, A700:188 – 220, 2013.

[61] R. Ulrich, R. Engel, and M. Unger. Hadronic Multiparticle Production at Ultra-High Energies and Extensive Air Showers. *Phys. Rev. D*, 83:054026, 2011.

[62] Z. Citron et al. *Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, volume 7, pages 1159–1410. 2019.

[63] R. Gauld et al. Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy. *JHEP*, 11:009, 2015.

[64] D. d'Enterria et al. Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics. *Astropart. Phys.*, 35:98–113, 2011.

[65] CERN (Meyrin) LHCb Collaboration. LHCb SMOG Upgrade. Technical Report CERN-LHCC-2019-005. LHCB-TDR-020, CERN, Geneva, May 2019.

[66] F. Galluccio et al. Physics opportunities for a fixed-target programme in the ALICE experiment. *CERN Report: https://cds.cern.ch/record/2671944*, Apr 2019.

[67] A. Ariga et al. Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC. *Preprint: arXiv:1812.09139*, Dec 2018.

[68] H. Abreu et al. Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC. *Eur. Phys. J. C*, 80(1):61, 2020.

[69] H. Abreu et al. Technical Proposal: FASERnu. *Preprint: arXiv:2001.03073*, Jan 2020.

[70] C. Hadjidakis et al. A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies. *Preprint: arXiv:1807.00603*, Nov 2018.

[71] O. Adriani et al. The LHCf detector at the CERN large hadron collider. *Journal of Instrumentation*, 3(08):S08006–S08006, 2008.

[72] L. A. Anchordoqui et al. Synergy of astro-particle physics and collider physics. *Letter of Interest for Snowmass2021*, Aug 2020.