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Core-corona hadronization model and muon puzzle in extensive air showers

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The discrepancy between models and measurements concerning the muon content of air showers produced by ultra-high energy cosmic rays, the so-called muon puzzle, remains unsolved. String fragmentation models currently used in hadronic interactions fail to reproduce the observations, while recent measurements at the LHC hint towards the existence of production mechanisms, such as collective statistical hadronization, which lead to an increase in the muon production in hadronic interactions. The core-corona model of heavy ions combines both production mechanisms, i.e. the large-density region of interaction (core) hadronizes statistically, while the low-density region (corona) hadronizes through string fragmentation. In this contribution, we present an implementation of the core-corona model in the CONEX simulation framework for air showers. We demonstrate a significant impact of the core effect, as observed at the LHC, on the muon content in air showers generated by ultra-high energy cosmic rays.

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1. Introduction

Several riddles remain unsolved in the fields of high and ultra-high energy cosmic rays. For energies above 10^{15} eV, cosmic rays are detected indirectly by means of the secondary particles produced when they interact with nuclei in the Earth's atmosphere, a phenomenon denominated *extensive air shower* (EAS). In a subsequent chain of interactions, mostly neutral and charged pions are created. The neutral pions decay almost immediately to photons that feed the electromagnetic (EM) component (photons, electrons, and positrons) by successive pair creation and Bremsstrahlung processes. Consequently, the number of EM particles increases as the shower advances in the atmosphere until individual energies are low and particles start being absorbed in the atmosphere. As a consequence, EASs exhibit a depth of maximum development X_{max}. On the other hand, the low energy charged pions typically decay to muons that reach the ground almost unaltered and form the muonic component.

One of the biggest puzzles in air shower physics nowadays is the discrepancy between the muon density measured with surface arrays and the one predicted by hadronic interaction models. Following Refs. [1, 2], this so-called *muon puzzle* seems to be present in a broad energy range, from about 10^{16} eV up to 10^{20} eV, at experiments measuring showers under different geometries, atmospheric conditions and using different techniques. This discrepancy ultimately leads to uncertainties in the estimation of primary cosmic ray features, such as mass and energy, which challenge the understanding of the astrophysical scenarios in which cosmic rays are produced and accelerated. In this contribution, the implementation of the core-corona model of heavy ions in the air shower simulation framework CONEX is presented (published in [3]). Simulations performed with this modification can render a muon content consistent with the measured number of muons but only in extreme scenarios.

2. The core-corona model

The muon deficit in air shower simulations described in Sec. 1 is closely related to how the fraction of energy carried by EM particles in hadron collisions $R = E_{\mathrm{em}}/E_{\mathrm{had}}$ is modeled in hadronic interaction generators. Here, E_{had} refers to the energy carried by hadronically interacting particles. Since muons mostly stem from charged pion decays, the R parameter has a direct impact on muon production. On the other hand, neutral pions are the main particle group that diverges energy to the EM component. As a consequence, the pion production ratio $\pi^0/\pi^{\pm}$ dominates the value of R. Different hadronic interaction simulations rely on different hadronization mechanisms to describe the product particles of an interaction and thus each gives a different R value.

Currently, hadronic interaction models used to simulate air showers mostly implement the string fragmentation model for hadronization processes. Electron-positron and low-energy proton-proton collisions are known to be successfully described by this model. However, in heavy ion collisions, where energy densities are larger, a fluid-like behavior with statistical hadronization is expected. Here, the production of heavy particles is favored, reducing the fraction of π^0 compared to other types of particles, and hence also the R value.

These so-called *collective effects* were observed in heavy ion collisions (*large* systems) at RHIC [4–7] and in proton-proton collisions (*small* systems) at the LHC [8] (see Ref. [9] for a

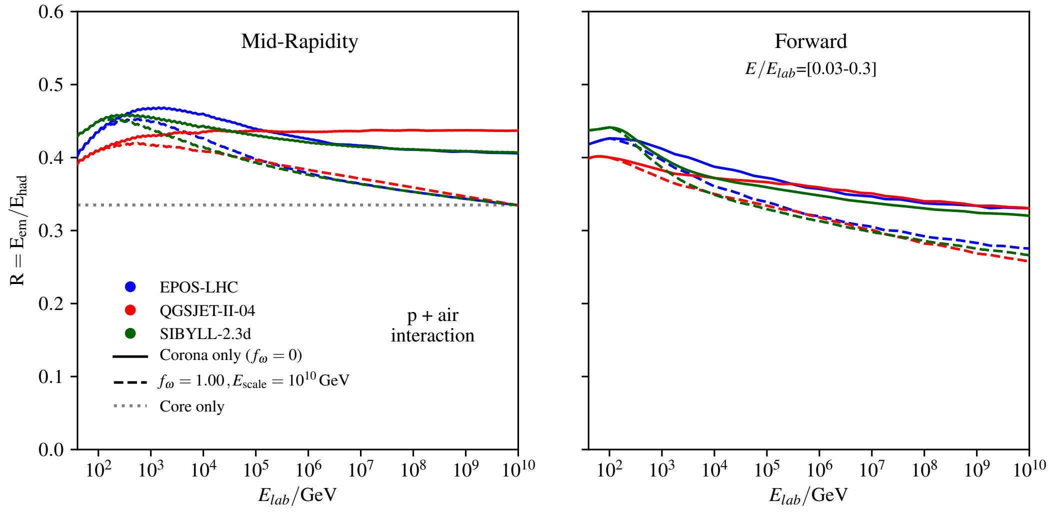

Figure 1: R value as a function of the projectile energy E_{lab} at mid-rapidity (left) and in the forward region $0.03 \leq x_{\text{lab}} \leq 0.3$ (right), where x_{lab} is the energy fraction in the laboratory system. The default models are shown in solid lines and the modified ones with $f_\omega = 1.00$ and $E_{\text{scale}} = 10^{10}$ GeV are shown with dashed lines. R reaches the value given by the statistical model at the maximum energy (see Sect. 3).

detailed review). In large systems, the formation of a quark-gluon-plasma (QGP), which follows the laws of hydrodynamics and eventually decays statistically, is commonly assumed as a phase of parton matter where confinement is no longer required [10–12]. In small systems on the other hand, first works indicate that the energy densities in central collisions may be large enough to create a QGP, as well [13–15]. Nonetheless, other recent theories, such as microscopic effects in string fragmentation [16] or QCD interference [17], have shown that collective effects can be reached through alternative mechanisms.

A change in R for hadronic interactions in small systems could potentially solve the muon deficit in air shower simulations. However, the R value is constrained by collider data, and each theoretical framework results implicitly in a specific R value, which may even change with energy, as shown with full lines in Fig. 1. The phase space is also relevant because, for large longitudinal momentum (forward direction), the baryon number conservation from the projectile implies a lower value of R.

The value of R could be the result of a combination of phenomena. The core-corona model is an approach of this kind [18, 19]. Here, the more dense region of an interaction behaves as a QGP and decays according to statistical hadronization (core), whereas low-density regions produce particles via string fragmentation (corona). An illustration of this model is shown in Fig. 2 (left) for a high-energy collision.

3. Core-corona implementation in the CONEX framework

Monte Carlo (MC) simulation is the most common method used to describe an air shower's development in detail. However, full MC simulations of ultra-high energy air showers require very large computing times. A different approach is to perform explicit MC treatment of high-energy particles in combination with a numerical description of the ensemble of low-energy particles [21].

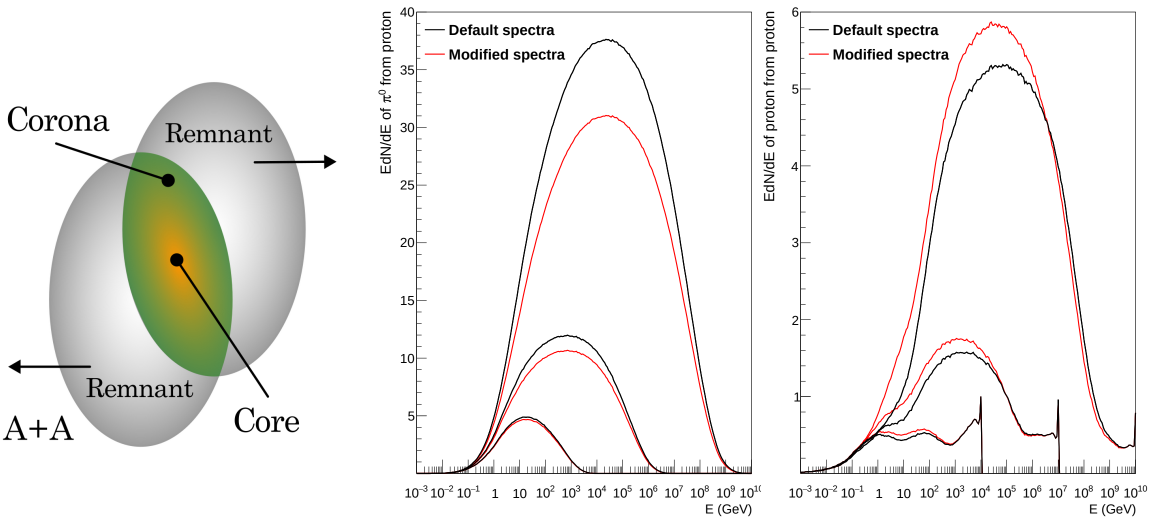

Figure 2: Left: A schematic representation of high energy collisions, where a volume of high temperature and high energy density is generated (core). Figure taken from [20]. Center and right: Default and modified energy spectra of secondary neutral pions (center) and protons (right) for 10^4, 10^7 and 10^{10} GeV proton-projectile energies, using QGSJETII.04. The diffractive peaks are not altered by the implementation of the core-corona model.

The air shower simulation framework CONEX implements this hybrid approach and gives accurate results for average shower parameters as well as their fluctuations [22]. The MC treatment of particles with energies above a predefined threshold is carried out in the standard way, similar to the procedure followed in the most widely used CORSIKA framework [23]. The numerical description of lower energy sub-cascades is based on the solution of cascade equations (CEs). This approach for air shower simulations is, because of its short computing times, ideal to study the impact of modifications of hadronic properties on the final showers.

CONEX implements the latest updated high-energy hadronic interaction models in the MC simulations: EPOS LHC, QGSJETII.04, and SIBYLL 2.3d. For the numerical analysis, these same models are used to pre-calculate the energy spectra of secondary particles. This means that for each hadronic interaction model, CONEX provides a spectrum for each projectile particle type, for each projectile energy, and for each secondary particle type. Here, the *projectile particles* are those particles whose interactions and propagation are followed by the framework and *secondary particles* are those produced in these interactions.

These energy spectra are used in the resolution of the CEs in CONEX and thus characterize how particle interactions are modeled. Consequently, any modification in these energy spectra has an impact on the air shower simulation. This makes it possible to implement the core-corona approach by means of appropriate changes in the secondary particle spectra. More specifically, in this work, secondary particle ratios are modified [18]. Since the core-corona model affects only the central region of the interaction, the remnant hadronization is not affected by it. The most prominent contribution of the remnant occurs when the secondary particle is the same as the projectile particle and if the energy loss is very small, which translates in a *diffractive peak* at the maximum energy (see Fig. 2, right). This particle is called the *leading particle*. Ultimately, this means that any

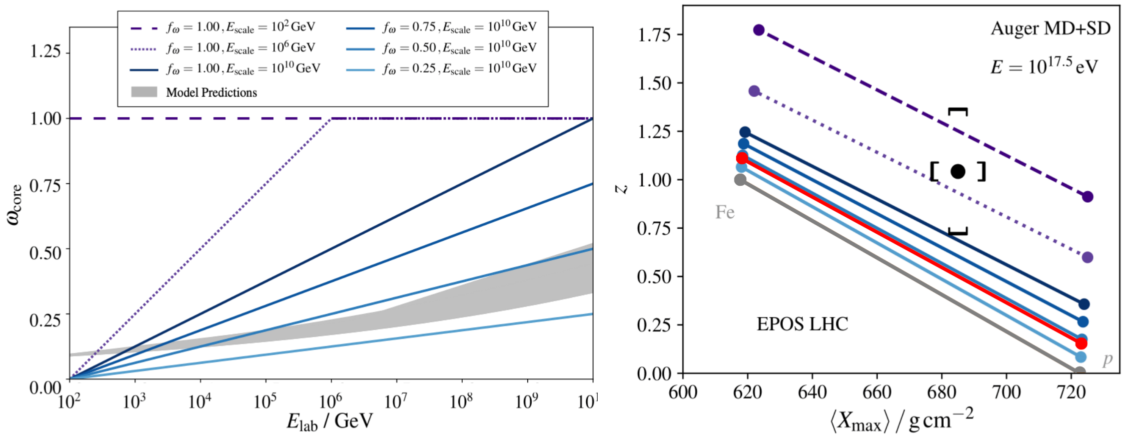

Figure 3: Left: Energy evolution of the weight ω_{core} (used in Eq. 1) for the core-corona mixing scenarios considered in this work. The shaded area corresponds to predictions on particle densities of the EPOS3 model. Right: Comparison of the effect of the different core-corona scenarios on the air shower observables $\langle X_{max} \rangle$ and z for simulations of proton primaries of $10^{17.5}$ eV using QGSJetII.04, together with the result from the Pierre Auger Collaboration [24]. The default model in gray corresponds to corona-only simulations, while the red line represents a realistic mixing scenario. In both figures, the solid lines represent changes in the factor f_ω from equation (2), while the dashed lines indicate the effect of changing the reference energy scale E_{scale}.

modification on the spectra should not affect the diffractive peak.

The new particle yield N_i for the particle species i is assumed to have a production contribution N_i^{core} from statistical hadronization and a contribution N_i^{corona} from string fragmentation hadronization:

$$N_i = \omega_{core}\, N_i^{core} + (1 - \omega_{core})\, N_i^{corona}. \tag{1}$$

This approach encloses the following assumptions. First, only the change of hadronization is taken into account, neglecting particle correlations in the core and the nuclear effect of the projectile particle. In addition, the core-corona effect is applied equally at all pseudorapidities (except for the leading particle). Core hadronization has been established experimentally at mid-rapidity mainly, but it is not excluded at large rapidities. Then, the implementation of the core-corona effect is performed on all the types of hadronic projectiles. Finally, the core weight ω_{core} effectively increases logarithmically with energy, since the average multiplicity does so, as well:

$$\omega_{core}(E_{lab}; E_{th}, E_{scale}, f_\omega) = f_\omega \frac{\ln(E_{lab}/E_{th})}{\ln(E_{scale}/E_{th})} \Theta(E_{lab} - E_{th}). \tag{2}$$

Here, the Heaviside step function Θ ensures no core at energies below E_{th} and it is assumed that models are well constraint by accelerator data. The conservative value of $E_{th} = 100$ GeV is used. Different energy dependencies are explored by changing the reference energy scale E_{scale} and the factor f_ω (see Fig. 3). In addition, the shaded area corresponds to predictions on particle densities of the EPOS3 model. (see [3] for details).

The new particle yields are computed using equation 1, excluding those corresponding to the respective projectile type (in order not to alter the diffractive peak). The yield of the projectile-type particles is then determined resorting to energy conservation. In Fig. 2, an example is shown where the spectra of the π^0 (center) and the protons (right) coming from a proton-air interaction are modified for three different projectile energies. Each choice of $\omega_{\rm core}(E_{\rm lab})$ gives a different value of $R = R(E_{\rm lab})$. In Fig. 1, the default values of R are compared to the case where $f_\omega = 1$, at mid-rapidity and in the forward region. For each hadronic interaction model considered, R decreases when considering the core-corona model at all energies.

4. Impact on the muon number

The core-corona scenarios considered in Fig. 3 (left) have been used to simulate full air showers with CONEX, using cascade equations from the first interaction to the ground, for proton and iron primary particles from $E_0 = 10^{16}$ eV up to $E_0 = 10^{19}$ eV. In order to study the effect of the core-corona model on the muon production as a function of energy in relation to results of experiments performed under very different conditions, the z-scale is introduced in [2]:

$$z = \frac{\ln N_\mu - \ln N_\mu^{\rm p}}{\ln N_\mu^{\rm Fe} - \ln N_\mu^{\rm p}}. \tag{3}$$

Here, N_μ is an observable related to the expected muon content at a given experiment. $N_\mu^{\rm p}$ and $N_\mu^{\rm Fe}$ are the same observables for simulated proton and iron showers, respectively. For the latter, corresponding detector effects are taken into account. Each hadronic interaction model gives a different value of z. Fig. 3 (right) shows the Auger datum at $10^{17.5}$ eV [24] and the core-corona mixing scenarios in the $\langle X_{\rm max}\rangle$-$z$ plane. Lines in this figure represent all possible resulting mean values of $X_{\rm max}$ and z for any mass composition of cosmic rays between pure proton (bottom right end of lines) and pure iron (top left end of lines). The resulting values of $\langle X_{\rm max}\rangle$ and z are located on a straight line because the mean values of both are linear functions of the mean-logarithmic mass of cosmic rays, given a fixed air shower energy [25, 26]. Current hadronic interaction models predict lines that are too low compared to experimental data from air shower measurements, as indicated by the vertical gap between the data point and the model line. This discrepancy reflects the muon problem outlined in Section 1. The core-corona examples illustrate that with modified hadronization in air showers it is well possible to describe the air shower observations.

Considering the energy dependence of z, there is an implicit dependence on the cosmic-ray mass A given by $z_{\rm mass} = \frac{\langle \ln A\rangle}{\ln 56}$. Hence, $\Delta z = z - z_{\rm mass}$ is zero in the case of full consistency between all the experimental observables and the simulations, based on a valid reference model. This means that, when plotting Δz for experimental data, $\Delta z = 0$ implies the reference model is perfect, whereas $\Delta z > 0$ implies a muon deficit in the simulations.

The impact of the different energy evolutions of $\omega_{\rm core}$ for EPOS LHC and QGSJetII.04 on Δz is shown in Fig. 4, where data from several experiments are also presented [27]. Here, the new simulations are treated like data and the z-scale is calculated using the original (quoted) models as a reference, so that the new Δz can be compared to the data points directly. The values of Δz indicate a larger muon production when $\omega_{\rm core}$ increases and the positive slopes mean that the slope of the muon production as a function of the primary energy is larger when $\omega_{\rm core}$ increases. By including a consistent core-like hadronization, it is possible to reproduce the energy evolution observed in data. This is even possible for values of $\omega_{\rm core} < 1$.

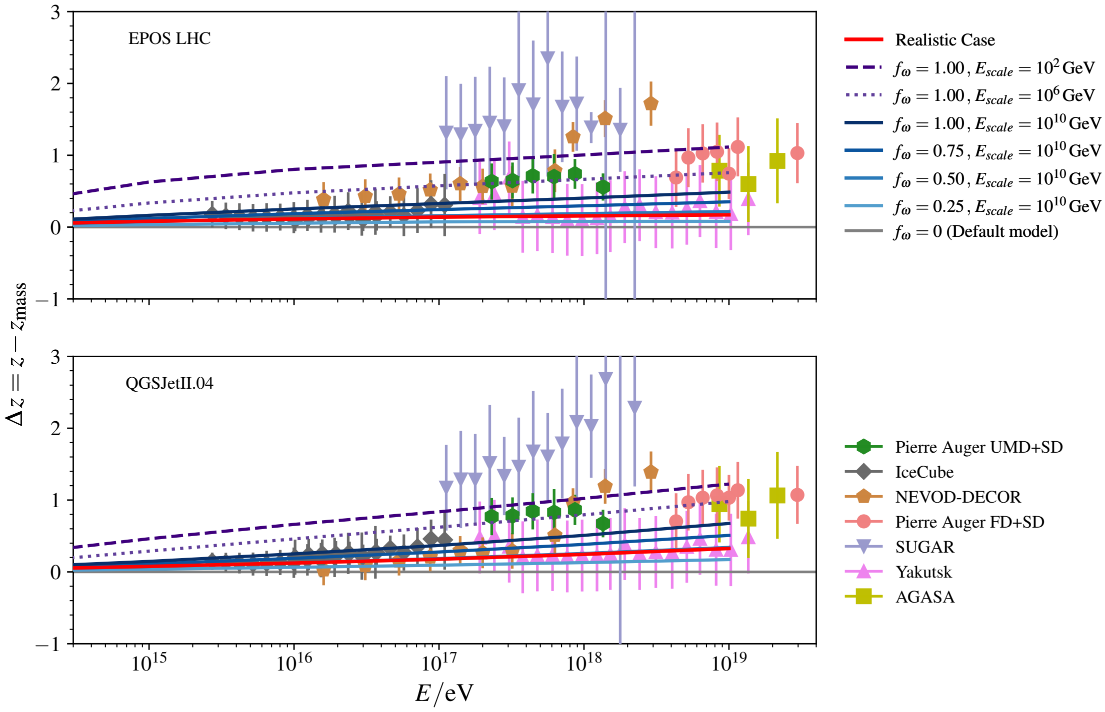

Figure 4: Evolution of the mass corrected z-scale $\Delta z = z - z_{\rm mass}$, as a function of the primary energy. Experimental z values are taken from [27] and the updated Auger data from [24]. Overlayed are predictions obtained from changing the scales f_ω (solid lines) and $E_{\rm scale}$ (dashed and dotted lines) and using EPOS LHC (top) and QGSJetII.04 (bottom) in air shower simulations.

5. Summary

The understanding of the muon puzzle is one of the most challenging present problems in high-energy physics. The muon content obtained in simulations is significantly lower than the one measured in most air showers experiments for the current mass composition based on $X_{\rm max}$ measurements. This fact implies that the hadronic component of EASs has to retain in some way more energy than in current hadronic interaction models. Recent measurements at the LHC show collective behavior even in small systems. This behaviour can be described by the core-corona model, where the particles in large-density regions behave as a QGP and decay according to statistical hadronization (core), whereas those in low-density regions produce particles via string fragmentation (corona). Both mechanisms produce different particle ratios, and in particular, the number of produced muons is larger in the core because the ratio of the electromagnetic to the hadronic energy density R is lower in core hadronization.

In order to implement the core-corona model, a novel approach was developed to modify the hadronization mechanism used by the hadronic interactions models. This is achieved by modifying the part where air showers are described numerically by CEs in the CONEX event generator. This is done by means of changes in the effective energy spectra of secondary particles of hadron interactions. These changes, in turn, modify particle ratios of particles produced at mid-rapidity, while the leading particle effect in the forward region is not altered. These changes increase logarithmically with the interaction energy and a transition from full corona to full core is analyzed. The comparison of several cosmic-ray based experiments by means of the z-scale is presented, which allows a direct comparison between different muon observables. This shows that more core-like contributions are needed compared with what is currently provided by the models. With some core-corona scenarios, it seems to be possible to reproduce the data using a modification of the full phase space of the secondary particles. This means that QGP-like effects also in light colliding systems may play a decisive role in muon production, but more data are needed to constrain the approach.

References

[1] J. Albrecht et al., *Astrophysics and Space Science* **367** (2022) 27.
[2] L. Cazon, *arXiv preprint arXiv:2001.07508* (2020) .
[3] S. Baur et al., *Phys. Rev. D* **107** (2023) 094031.
[4] STAR collaboration, *Nucl. Phys. A* **757** (2005) 102 [nucl-ex/0501009].
[5] PHENIX collaboration, *Nucl. Phys. A* **757** (2005) 184 [nucl-ex/0410003].
[6] BRAHMS collaboration, *Nucl. Phys. A* **757** (2005) 1 [nucl-ex/0410020].
[7] B. B. Back *et al.*, *Nucl. Phys. A* **757** (2005) 28 [nucl-ex/0410022].
[8] CMS collaboration, *JHEP* **09** (2010) 091 [1009.4122].
[9] K. Dusling, W. Li and B. Schenke, *Int. J. Mod. Phys. E* **25** (2016) 1630002 [1509.07939].
[10] E.V. Shuryak, *Phys. Rept.* **61** (1980) 71.
[11] H. Stöcker and W. Greiner, *Phys. Rept.* **137** (1986) 277.
[12] P.F. Kolb and U.W. Heinz, in *Quark Gluon Plasma 3*, pp. 634–714, 2003 [nucl-th/0305084].
[13] K. Werner, I. Karpenko and T. Pierog, *Phys. Rev. Lett.* **106** (2011) 122004 [1011.0375].
[14] P.M. Chesler, *Phys. Rev. Lett.* **115** (2015) 241602 [1506.02209].
[15] P.M. Chesler, *JHEP* **03** (2016) 146 [1601.01583].
[16] C. Bierlich, G. Gustafson and L. Lönnblad, *Phys. Lett. B* **779** (2018) 58 [1710.09725].
[17] B. Blok, C.D. Jäkel, M. Strikman and U.A. Wiedemann, *jhep* **2017** (2017) 074 [1708.08241].
[18] K. Werner et al., *EPJ Web Conf.* **17** (2018) 10900 [1812.06330].
[19] A.G. Knospe et al., *Phys. Rev. C* **104** (2021) 054907 [2102.06797].
[20] A. Ayala et al., *Phys. Lett. B* **810** (2020) 135818 [2003.13757].
[21] G. Bossard et al., *Physical Review D* **63** (2001) 054030.
[22] T. Bergmann et al., *Astroparticle Physics* **26** (2007) 420.
[23] D. Heck et al., *Report fzka* **6019** (1998) .
[24] Pierre Auger collaboration, *Eur. Phys. J. C* **80** (2020) 751.
[25] Pierre Auger collaboration, *JCAP* **02** (2013) 026 [1301.6637].
[26] H.P. Dembinski, *Astropart. Phys.* **102** (2018) 89 [1711.05737].
[27] EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array collaboration, 2019 [1902.08124].