PROCEEDINGS OF SCIENCE

Measurement of the fluctuations in the number of muons in inclined air showers with the Pierre Auger Observatory

PoS(ICRC2019)404

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We present the first measurement of the fluctuations in the number of muons in inclined air showers with energies above 4 EeV measured with the Pierre Auger Observatory. We find that the results agree well with simulations within the experimental uncertainties. In contrast, the measurement of the average number of muons has previously been found to deviate substantially from the predictions by high-energy hadronic interaction models. We analyse the implications of these findings for our understanding of hadronic interactions, especially to those at the highest energies.

36th International Cosmic Ray Conference — ICRC2019
24 July – 1 August, 2019
Madison, Wisconsin, USA

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1. Introduction

From early on, the study of cosmic rays has been dual in nature. We wonder about their origin in the cosmos, and whether they can teach us something about the extreme side of the universe. At the same time, we use their interactions in the atmosphere to study the microcosmos. Much of the early developments in particle physics was driven by cosmic-ray research [1]. While most of particle physics nowadays is done at accelerator facilities, the high-energy frontier is still held by ultrahigh-energy cosmic rays (UHECR), easily reaching center-of-mass energies ten times larger than CERN's Large Hadron Collider.

Not surprisingly, the observation of an excess in the number of muons, that was initially reported by the Pierre Auger Observatory [2, 3, 4], has raised secret hopes of another breakthrough in particle physics from cosmic rays. It certainly has stirred theorists imagination [5, 6, 7]. Other observables from ultrahigh-energy showers, like the average depth of shower maximum ($X_{\rm max}$) and its fluctuations [8, 9], or the muon production depth ($X^{\mu}_{\rm max}$) [10], limit the allowed range for explanations of the muon excess with new physics but do not definitely exclude it. This is the case because $X_{\rm max}$ and $X^{\mu}_{\rm max}$ mostly depend on the cross-section, i.e. the geometrical shape of hadrons, while the number of muons depends more strongly on particle production, which is more related to the deep, internal structure of hadrons [11, 12].

In these proceedings, we report the measurement of another observable of ultrahigh-energy air showers with the Pierre Auger Observatory which severely constrains the available phase space for exotic explanations of the muon excess: the shower-to-shower fluctuations in the number of muons.

2. Measurement of the shower-to-shower fluctuations

2.1 Reconstruction of the number of muons

The measurement of the fluctuations in the number of muons is based on the sample of inclined air showers detected at the Pierre Auger Observatory [13] between 01/01/2004 and 10/06/2019. Only air showers that were simultaneously detected with the surface detector array (SD) and at least one of the fluorescence detectors (FD), are used (hybrid detection).

The reconstruction of the number of muons relies on the fact that for inclined air showers, the electromagnetic cascade is mostly absorbed in the atmosphere so that signals at the ground are dominated by muons. By fitting the normalization factor of a reference model[1] for the muon density at the ground to the observed distribution of signals in the SD array, the number of muons can be extracted [14]. The reconstructed quantity R_μ, is the total number of muons at the ground relative to the average of the total number of muons in a shower with primary energy 10^{19} eV.

The reconstruction of the energy of the air showers is done by integrating the longitudinal shower profiles observed with the FD [15].

An event selection is applied to ensure a high quality of the reconstruction. For the FD, this means, for example, only events measured during good atmospheric conditions are selected. For the SD, only events with reconstructed energies above 4 EeV and zenith angles above 62° are

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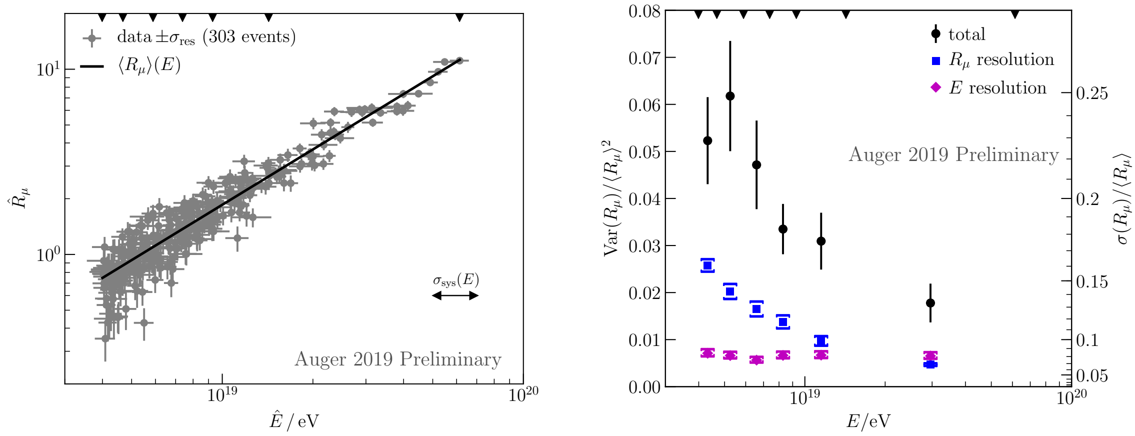

Figure 1: Left: Correlation between the reconstructed energy and the reconstructed number of muons in inclined air showers. The black line is the resulting evolution of the average number of muons after the unfolding procedure. Measured quantities are marked with a hat. Right: Raw variance of the number of muons (black) and the contributions from the detector (blue) and energy resolution (purple). The axis on the right shows the value of the standard deviation. The energy ranges for which the fluctuations are evaluated are marked by the black triangles at the top of the figure.

accepted to ensure a triggering probability of 100% and to avoid contamination of the signals at the ground by the electromagnetic component respectively. For each event, a minimum of four detector stations with signal in the SD was required to ensure high-quality reconstruction of R_μ. The selection criteria are described in detail in the previous publication [2]. The initial sample contains 52587 hybrid air showers, and after the selection without applying the energy threshold, 860 remain. There are 303 events above 4 EeV.

2.2 Intrinsic fluctuations

The relative shower-to-shower fluctuations in the number of muons $\sigma(R_\mu)/\langle R_\mu\rangle$ (intrinsic fluctuations) are extracted from the data, by fitting a statistical model to the measured pairs of energy $\hat{E}$ and number of muons $\hat{R}_\mu$. Measured quantities are marked with a hat to distinguish them from true quantities that contain only intrinsic fluctuations.

The model is based on the assumptions that: FD & SD measurements have fluctuations that follow Gaussian distributions, with widths given by the detector resolutions $\sigma_{\rm res}(\hat{E})$ and $\sigma_{\rm res}(\hat{R}_\mu)$; intrinsic fluctuations follow a Gaussian distribution; the average number of muons as a function of the primary energy is given by a power-law $\langle R_\mu\rangle(E) = a\,(E/(10^{19}\,{\rm eV}))^b$. The model is fitted by maximizing the log-likelihood

$$\ln\mathscr{L}(a,b,s) = \sum_i \ln\left[\sum_k C_k \exp\left(-\frac{1}{2}\frac{(\hat{E}_i-\hat{E}_k)^2}{\hat{\sigma}^2_{\hat{E},k}}\right)\exp\left(-\frac{1}{2}\frac{(\hat{R}_{\mu,i}-\langle R_\mu\rangle(\hat{E}_k))^2}{\hat{\sigma}^2_{\hat{R}_\mu,k}+(s(\hat{E}_k)\cdot\langle R_\mu\rangle(\hat{E}_k))^2}\right)\right], \tag{2.1}$$

where the outer sum over the index i, the usual sum over the log-likelihoods of events, includes only events above the energy threshold of 4 EeV. The inner sum over the index k includes all events, also below the threshold, to account for migration effects which, given the steeply falling spectrum

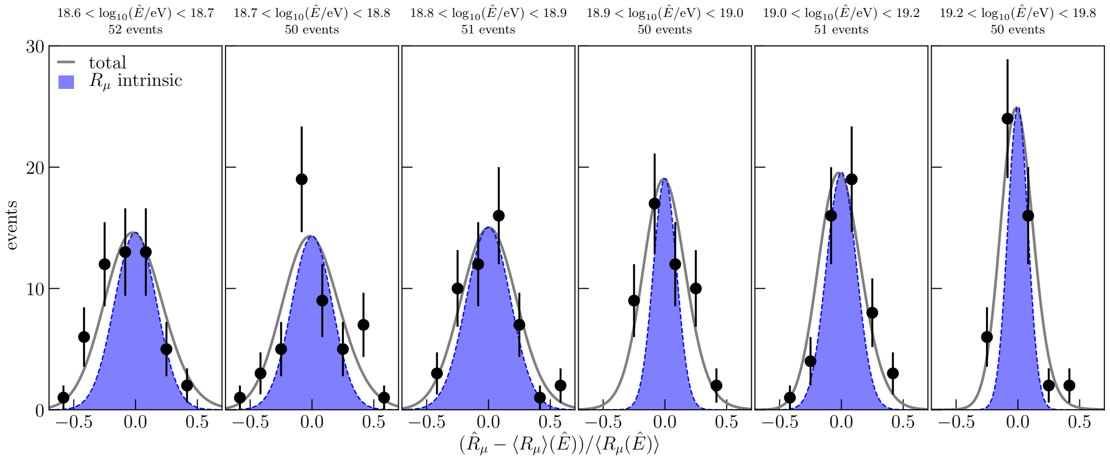

Figure 2: Distribution of the relative number of muons in six bins of energy from $10^{18.6}$ eV to $10^{19.8}$ eV. The model for the full distribution is shown in gray, the inferred intrinsic distribution of the number of muons is shown by the filled-in curve.

of CRs, can be sizable [16]. The factor C_k contains the normalization factors from the double Gaussian. The relative intrinsic fluctuations at energy $\hat{E}_K$ are written as $s(\hat{E}_k) \equiv \sigma(\hat{E}_k)/\langle R_\mu \rangle(\hat{E}_k)$.

The detector resolutions enter Eq. (2.1) through the variances $\hat{\sigma}^2_{\hat{E},k}$ and $\hat{\sigma}^2_{\hat{R}_\mu,k}$, which are the uncertainties in the individual measurements. We have tested the assumption that on average the $\hat{\sigma}^2_k$ describe the detector resolution with simulations and data.

To obtain the energy dependence of the fluctuations we split $s(\hat{E}_k)$ in Eq. (2.1) into six independent parameters for the different energy bins (see markers at the top of Figs. 1). Within one bin the fluctuations are constant. The bins are chosen such that the number of events in each is similar.

The distribution of events above the threshold that enter the fit is shown in Fig. 1 (left).

In the right panel of Fig. 1, the raw variance in the data and the average contributions from the SD and FD resolutions are shown for illustration. In Fig. 2, the distribution of the relative number of muons $(\hat{R}_\mu - \langle R_\mu \rangle)/\langle R_\mu \rangle$ in the six energy bins is shown together with the best-fit model of Eq. (2.1) as well as the corresponding intrinsic distributions. For the current number of events, the assumption of Gaussian distributions for the detector and intrinsic fluctuations seems to hold.

2.3 Systematic uncertainties & corrections

The intrinsic fluctuations extracted in the unfolding will only represent the true intrinsic fluctuations if all other sources of fluctuations have been correctly accounted for. Since the detector fluctuations are sizable (see Fig. 1 right), we first check whether the distribution of the detector resolutions is estimated correctly.

The Pierre Auger Observatory is equipped with four FD stations which overlook a common area covered by the SD array. By using events which are simultaneously observed by telescopes in two FD stations, we get two estimates for the energy and the resolution. On average, these should be the same. We find that a small correction of -1% for the energy resolution is necessary.

For the SD resolution, we find two corrections are necessary. One is found by using simulations where one can reconstruct the same shower multiple times, leaving only fluctuations due to

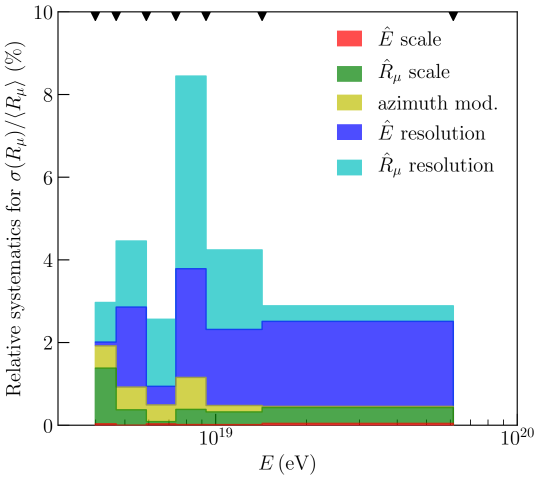

Figure 3: Stacked histogram of the contributions to the systematic uncertainty in the standard deviation. The dominant contributions are from the uncertainties in the SD and FD resolutions.

the detection process and the reconstruction. Comparing the variance in the reconstructed muon scale in this sample with the expectation, i.e. the detector resolution $\sigma_{\text{res}}(\hat{R}_\mu)^2$, we find a correction of $+1\%$ is necessary. While many sources of detector fluctuations can be included in the simulation, a difference to real data remains. To estimate that remaining difference, we calculate and compare the jackknife variance [17] for both data and simulations. We find that in this case, a correction of -1% to the estimated resolution is necessary. In combination these corrections almost entirely cancel each other.

In addition to the accuracy of the resolution, we investigate for a possible presence of drifts or modulations in the data, as these would also increase fluctuations. We do this by splitting the data in percentiles along a specific variable and compare. We find no significant trends, except for a modulation of the average number of muons with azimuth angle. This modulation is most probably related to the approximations going into the modeling of the muon densities at the ground [14]. For the average number of muons the modulation averages out. For the fluctuations, we calculate the contribution from the modulation to be $\sigma_\phi/\langle R_\mu\rangle = (-0.04\pm0.02)/\sqrt{2}$ and correct the final result accordingly.

For all corrections, we apply half of their value directly and report the second half as a systematic uncertainty. In case of the SD resolution, this means even though the two corrections that are discussed above, cancel each other, there is still a contribution to the systematic uncertainty. The effects of the energy scale uncertainty (14%) and the systematic uncertainty in the number of muons R_μ (11%) are small. Largest contributions are from the uncertainties in the resolutions. The impact of the systematic uncertainties on the relative fluctuations is shown in Fig. 3. Overall systematic effects on the fluctuations are below the level of 8%.

3. Results & discussion

The final result for the relative fluctuations is shown in Fig. 4 on the left. We find that the observed fluctuations fall in the range of the predictions from air shower simulations with current

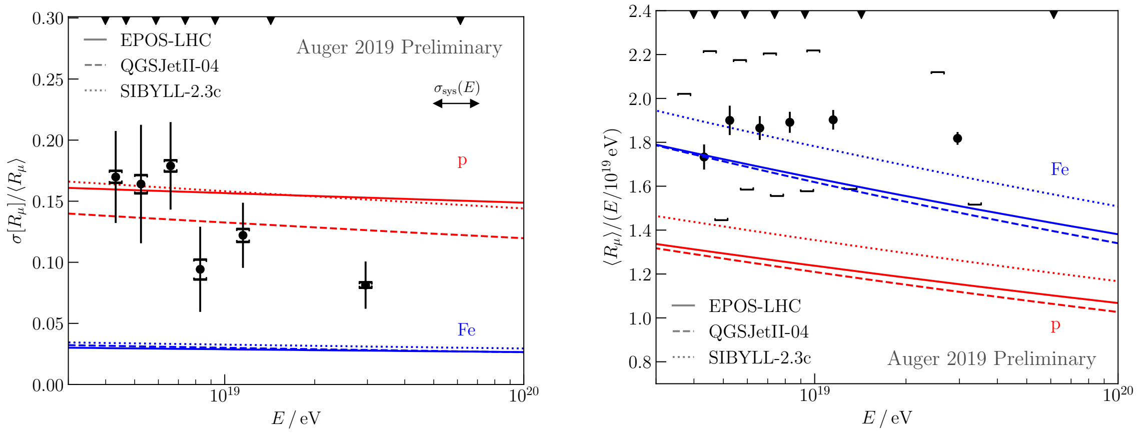

Figure 4: Shower-to-shower fluctuations (left) and the average number of muons (right) in inclined air showers as a function of the primary energy. For the fluctuations, the statistical uncertainty (error bars) is dominant, while for $\langle R_\mu \rangle$ the systematic uncertainty (square brackets) is dominant. The shift in the markers for the systematic uncertainty in the average number of muons represents the uncertainty in the energy scale.

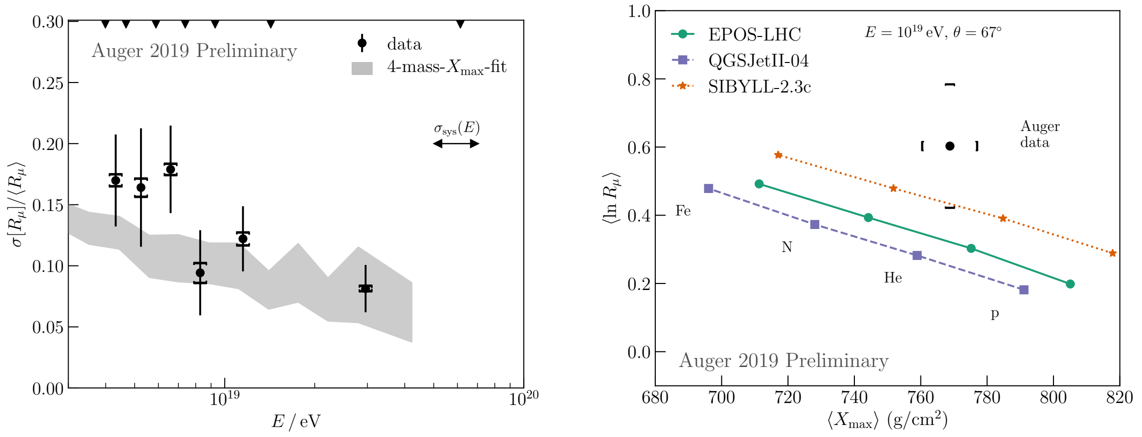

Figure 5: Left: Comparison of the measured fluctuations of the number of muons as a function of the primary energy with the expectation derived from hadronic models and the CR composition from the fit of four primary mass components to the measured $X_{\rm max}$-distributions [21, 22]. Right: Average number of muons as a function of the average depth of shower maximum at 10^{19} eV.

hadronic interaction models [18, 19, 20]. The measured fluctuations seem to slightly decrease with the primary energy. Fitting $p_0 + p_1 \log_{10}(E/\mathrm{eV})$ to the fluctuations, we find a significant non-zero value for the slope with $p_1 = -0.11 \pm 0.04$.

In addition to the fluctuations, we also obtain new results for the measurement of the average number of muons. The results are shown on the right in Fig. 4. Note that in the figure, $\langle R_\mu \rangle$ is divided by the factor $(E/10^{19}\,\mathrm{eV})$. In contrast to the fluctuations, the measurement here falls outside the range of the predictions from simulations (see also the discussion in [4]).

For the parameters of the energy evolution of the number of muons, $\langle R_\mu \rangle = a\,(E/(10^{19}\,\mathrm{eV}))^b$, we find:

$$\begin{aligned} a &= 1.85 \pm 0.02(\text{stat.})\ ^{+0.36}_{-0.31}(\text{syst.}) \\ b &= 0.99 \pm 0.02(\text{stat.})\ ^{+0.03}_{-0.03}(\text{syst.})\ , \end{aligned}$$

which is compatible with our previous results [2].

A comparison between the measured fluctuations in the number of muons and the predictions from interaction models given the measured CR composition is shown in Fig. 5 left. The composition that is used here is inferred from the measured distributions of X_{max} by assuming proton, helium, nitrogen and iron as primary components and fitting the fractions to the overall distributions [21, 22]. Although there are some differences in the estimated composition for the different interaction models, and the predictions for the relative fluctuations for protons also differ between models, the results for the fluctuations in the number of muons are very similar. In the figure, the phase space covered by interaction models with the statistical and systematic uncertainties from the composition fit added in quadrature is shown by the gray band. The measured fluctuations in the number of muons (black points) are compatible with the expectation from composition and interaction models. Fitting a linear evolution in energy to the central value of the model band and comparing with the data, we get a p-value of 34%.

In Fig. 5 right, the average logarithm of the number of muons is shown as a function of the average X_{max} for a primary energy of 10^{19} eV. Since both $\langle \ln R_\mu \rangle$ and $\langle X_{\text{max}} \rangle$ depend linearly on $\ln A$, the model predictions for an arbitrary composition between proton and iron reduce to the lines shown in the figure. Also here the results are consistent with the previous publication. A notable difference is the new prediction from SIBYLL 2.3c, which is just compatible with the data.

The fluctuations and the average of the number of muons depend on different stages in the development of air showers. While the average number of muons is influenced by the entire chain of interactions [11, 12, 23], the fluctuations are dominated by the first interaction, in particular by the partition of energy in the hadronic and the electromagnetic cascade [24, 25]. The good agreement between measurement and predictions for the relative fluctuations in the number of muons indicates that the first, high energy interaction is reasonably well described by hadronic interaction models. Given the good agreement for the fluctuations, the likely explanation for the disagreement in the average is that a small discrepancy in the particle production exists at all energies, which then is accumulated as the showers develop to create the deficit in the number of muons finally observed at the ground. This mechanism is also used to enhance the number of muons in SIBYLL 2.3c [26]. Explanations invoking modifications in the first interaction that change the intrinsic fluctuations are disfavored.

4. Summary

We report the first measurement of the fluctuations in the number of muons in extensive air showers above an energy of 4 EeV and an update to our previous measurement of the average number of muons. We find that the fluctuations are compatible with the predictions from air shower simulations with current hadronic interaction models and the measured composition of cosmic rays. We confirm our previous measurement of the average number of muons and note that SIBYLL 2.3c now gives a consistent interpretation when combining $\langle R_\mu \rangle$ and $\langle X_{\max} \rangle$ measurements. The agreement between measured fluctuations and predictions by standard hadronic interaction models means the models give a sufficiently good description of particle production in the first interaction between $10^{18.6}$ eV and $10^{19.8}$ eV.

References

[1] C. D. Anderson and S. H. Neddermeyer *Phys. Rev.* **50** (1936) 263–271.

[2] A. Aab [Pierre Auger Collaboration], *Phys. Rev. D* **91** (2015), no. 3 032003, [`1408.1421`]. [Erratum: Phys. Rev.D91,no.5,059901(2015)].

[3] A. Aab [Pierre Auger Collaboration], *Phys. Rev. Lett.* **117** (2016), no. 19 192001, [`1610.08509`].

[4] L. Cazon, Working group on hadronic interactions and shower physics `PoS(ICRC2019)214`.

[5] G. R. Farrar [`1902.11271`].

[6] G. R. Farrar and J. D. Allen *EPJ Web Conf.* **53** (2013) 07007, [`1307.2322`].

[7] L. A. Anchordoqui, H. Goldberg, and T. J. Weiler *Phys. Rev. D* **95** (2017), no. 6 063005, [`1612.07328`].

[8] A. Aab [Pierre Auger Collaboration], *Phys. Rev. D* **90** (2014), no. 12 122005, [`1409.4809`].

[9] P. Abreu [Pierre Auger Collaboration], *Phys. Rev. Lett.* **109** (2012) 062002, [`1208.1520`].

[10] A. Aab [Pierre Auger Collaboration], *Phys. Rev. D* **90** (2014), no. 1 012012, [`1407.5919`]. [Erratum: Phys. Rev.D92,no.1,019903(2015)].

[11] R. Ulrich, R. Engel, and M. Unger *Phys. Rev. D* **83** (2011) 054026.

[12] R. Engel, D. Heck, and T. Pierog *Ann. Rev. Nucl. Part. Sci.* **61** (2011) 467–489.

[13] A. Aab [Pierre Auger Collaboration], *Nucl. Instrum. Meth. A* **798** (2015) 172–213, [`1502.01323`].

[14] A. Aab [Pierre Auger Collaboration], *JCAP* **1408** (2014), no. 08 019, [`1407.3214`].

[15] J. Abraham [Pierre Auger Collaboration], *Nucl. Instrum. Meth. A* **620** (2010) 227–251, [`0907.4282`].

[16] H. P. Dembinski, B. Kégl, I. C. Mariş, M. Roth, and D. Veberič *Astropart. Phys.* **73** (2016) 44–51, [`1503.09027`].

[17] B. Efron and C. Stein *Ann. Statist.* **9** (05, 1981) 586–596.

[18] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner *Phys. Rev. C* **92** (2015), no. 3 034906, [`1306.0121`].

[19] S. Ostapchenko *Phys. Rev. D* **83** (2011) 014018, [`1010.1869`].

[20] F. Riehn, H. P. Dembinski, R. Engel, A. Fedynitch, T. K. Gaisser, and T. Stanev `PoS(ICRC2017)301` [`1709.07227`].

[21] A. Aab [Pierre Auger Collaboration], *Phys. Rev. D* **90** (2014), no. 12 122006, [`1409.5083`].

[22] J. Bellido [Pierre Auger Collaboration], `PoS(ICRC2017)506`.

[23] J. Matthews *Astropart. Phys.* **22** (2005) 387–397.

[24] L. Cazon, R. Conceição, and F. Riehn *Phys. Lett. B* **784** (2018) 68–76, [`1803.05699`].

[25] R. Conceição et al. `PoS(ICRC2019)226`.

[26] F. Riehn, R. Engel, A. Fedynitch T.K. Gaisser and T. Stanev *EPJ Web Conf.* **208** (2019) 11002.