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New physics Air-Shower simulations for UHECR above 50 TeV

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Introduction

Two of the biggest mysteries in Cosmic Ray (CR) physics are their origin and their composition. Cosmic rays as charged particles deflect from Galactic magnetic field. It was reported both by Auger Collaboration [1] and Telescope Array [2] that above 10^9 GeV there is an anisotropy in the distribution of cosmic rays that do not correlate with the galactic plane. This indicates that Ultra High Energy Cosmic Rays (UHECR) are of extra-galactic origin.

Recent studies [3] have shown that the strength of the Galactic magnetic field in a small region near a reported hotspot [4] is an order of magnitude larger than previously thought. If indeed the galactic magnetic field is in the range of tens of μG this lead us to conclude that UHECR are light nuclei - otherwise, all anisotropy would have been wiped out.

Observational data, such as the shower maximum, shows that there is a transition in the composition of cosmic rays into heavier elements like Nitrogen. Furthermore, data from muons reaching the ground favour even heavier nuclei.

This interpretation originates from extrapolated models in energy regions where the Standard Model has not been tested yet. Thus we are not actually sure how proton interactions behave at the highest energies.

An alternative solution to the composition problem is the existance of new physics above a threshold energy as suggested, e.g., by [5].

Cosmic Ray Flux

We assume a mixture of galactic and extragalactic CR with the fraction of galactic CR over the total being $f(E)$. The probability density function of $X_{\max}$ will be

$$p(X_{\max}) = f\, p_G(X_{\max}) + (1-f)p_{EG}(X_{\max}) \tag{1}$$

For Galactic cosmic rays, we fit a power law flux at low energies and an exponential suppression at around 10^9 GeV. This is due to the maximum energy cosmic rays can reach in Galactic sources. The residual flux from observational data is characterized as extragalactic cosmic ray flux (see Figure 1). For simplicity we assume that galactic CR are Carbon nuclei. Extragalactic CR are assumed in this work to be protons. Deviations in Xmax from the predictions for protons are assume to be entirely due to new physics.

Mathematical Formulation

The shower maximum consist of two parts

$$X_{\max} = X_{\text{int}} + X_{\text{long}} \tag{2}$$

The first one

$$X_{\text{int}} = \frac{\bar{m}_{\text{Air}}}{\sigma_{\text{p-Air}}} \tag{3}$$

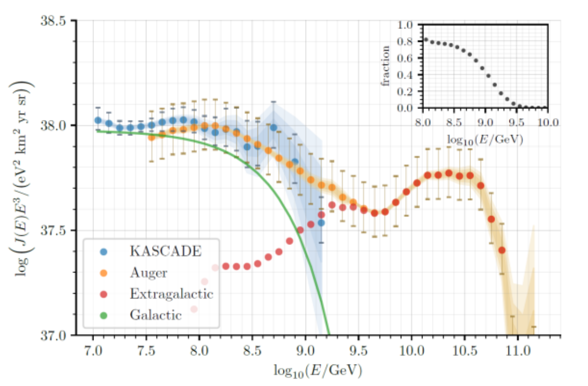

Figure 1: Cosmic Ray flux data from KASCADE (blue) and Auger Collaboration (orange). Flux of Galactic CR is described by a power law plus an exponential cutoff at $10^{8.9}$ GeV (green). The residual from the observed data is interpreted as extra-galactic CR (red) and the fraction of Galactic to the total CR can be seen in the upper right subplot

depends only on the first interacion of the cosmic ray with the atmosphere that has an average mass $\bar{m}_{\text{Air}}$. High energy models report a cross section of the form

$$\sigma^{\text{new}}_{\text{p-Air}} = \sigma_0 + \beta(1+\delta)\log\varepsilon \tag{4}$$

where ε is the energy of the CR over a threshold energy $\varepsilon = E/E_{\text{th}}$.

The second part has to be infered from the longitudilal development of the air shower and has a logarithmic behaviour

$$X_{\text{long}} = X_0 + \beta \log \frac{\varepsilon}{n(\varepsilon)} \tag{5}$$

The constants $\sigma_0, \alpha, X_0, \beta$ depend on the model used in the air shower. A new parameter δ is introduced to emulate new physics. Changing the behaviour of the cross-section above a threshold energy will also alter the production of secondary particles. For $\delta = 0$ we get the usual Standard Model predictions. The function $n(\varepsilon)$ is the multiplicity of the secondary particles and $n(1) = 1$. Forcing this new shower maximum to be equal to the observational data, above a threshold energy from Auger, we get how the multiplicity has to changed as a function of energy and the new parameter δ.

Corsika Simulations

We used CORSIKA to perform air shower simulations for QGSJETII-04 for high energy and Fluka for low energy interactions. We used protons with energy in the range $10^8 - 10^{11}$ GeV with step of $10^{0.1}$ GeV. At each energy bin we perform 1000 EAS simulations to obtain the Standard Model predictions.

CORSIKA provides files with data for the secondary particles after the first interaction. At each energy we randomly combine files to create new ones taking into account energy and momentum conservation. The number of combined files is equal to the factor by which the multiplicity is assumed to increase.

We also asume that after the first interaction, the secondary particles have energies below the threshold of the new physics thus we can do Air-Shower simulations for the secondary particles using these models.

Results

With new cross-section and multiplicity, simulations are in excelent agreement with the observational data for $\delta = 8$. For this value the cross-section at an energy of 10^{10} GeV rises to 800 mb. Furthermore at the same energy the multiplicity is about twice as Standar Model indicates. In Figure 2 and 3 we also see that our simulations do not agree with observations at low energies. This is due to the assumption of the galactic component consisting exclusively of Carbon. A more reasonable assumption is a mixture of Helium, Oxygen and Carbon with ratios that depend on the energy.

For lower values than $\delta = 4$, standard deviation will increase, approaching the SM predictions for $\delta = 0$.

On the other hand, further increment of δ beyond 8 will not bring any more significant changes on standard deviation for energies around 10^{11} GeV. A second problem that arises with larger δ values is that cross-section increases fast reaching values larger than 1000 mb at 140 TeV center-of-mass energy. While we attribute $\delta > 0$ to new physics, it should be noted that all values of δ we have presented here are within errors of Standard Model cross-section extrapolations to higher energies. This means that no dramatic increase in cross-section is necessary in any new-physics scenario to match the $\sigma_{X_{\max}}$ data of Auger.

References

[1] A. Aab et al. [Pierre Auger], Astrophys. J. **868**, no.1, 4 (2018) doi:10.3847/1538-4357/aae689, arXiv:1808.03579.

[2] R. U. Abbasi et al. [Telescope Array], Astrophys. J. Lett. **898**, no.2, L28 (2020) doi:10.3847/2041-8213/aba0bc, arXiv:2007.00023

[3] A. Tritsis, C. Federrath and V. Pavlidou, Astrophys. J. **873**, no.1, 38 (2019) doi:10.3847/1538- 4357/ab037d, arXiv:1810.00231

[4] R. U. Abbasi et al. [Telescope Array], Astrophys. J. Lett. **790**, L21 (2014) doi:10.1088/2041- 8205/790/2/L21 [arXiv:1404.5890 [astro-ph.HE]]

[5] V. Pavlidou and T. Tomaras, Phys. Rev. D **99**, no.12, 123016 (2019), doi:10.1103/PhysRevD.99.123016, arXiv:1802.04806

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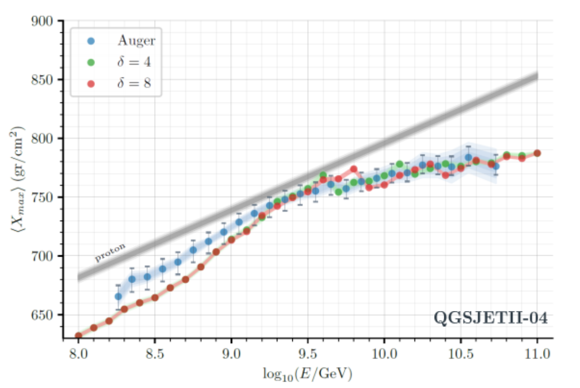

Figure 2: Shower maximum as a function of energy. It is evident that the standard model predictions (gray) do not agree with the observations from Auger Observatory (blue) above $E_{\text{th}} = 10^9$ GeV. Changing the multiplicity behaviour with energy of protons in the first interaction, air shower simulations with proton as a primary particle (green and red) will reproduce the observed data at the highest energies. The choice of a single-component galactic CR flux is the reason for the discrepancy between simulations and data at low energies.

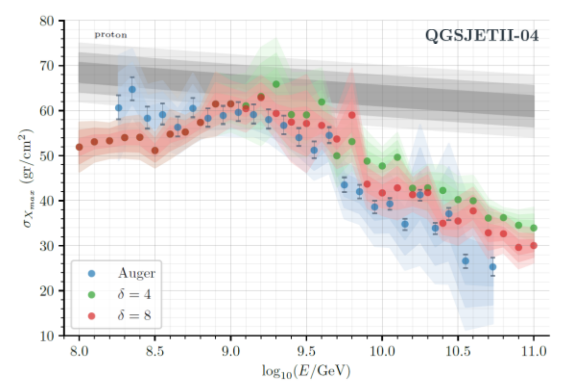

Figure 3: Standard deviation of $X_{\max}$ as a function of energy. Although the shower maximum does not depend on the parameter δ, here we see that the standard deviation from simulations agrees with observations for a value $\delta = 8$. Further increment of the δ parameter will not bring significant change at large energies, as the standard deviation will reach a limiting behaviour.