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Cosmic-ray air-shower simulations across the ankle: Combining mixed Galactic composition with new Physics above 50 TeV

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Cosmic rays (CRs) with energies below 10^{18} electron volts (eV) are believed to be atomic nuclei originating from within our Galaxy, while there is a transition to extragalactic cosmic rays occurring around 10^{18} eV. The characterization of this transition is important for understanding new physics phenomena proposed for Ultra-High Energy Cosmic Rays (UHECRs) with center-of-mass energies above 50 TeV. In this study, we conducted air-shower simulations using CORSIKA to investigate the energy range from just below the ankle (10^{17} eV) up to the highest energies (10^{20} eV), and compared our results with observations of the energy spectrum and composition obtained from the Auger experiment. To determine the flux and elemental ratios just below the ankle, we used data on the abundances and flux of low-energy cosmic ray components obtained from the KASCADE experiment. Due to confinement arguments, heavier nuclei exhibit greater bending in a given source and Galactic magnetic field, allowing them to reach higher energies for a given accelerator class. To account for this, we incorporated an exponential suppression term in the flux of heavier nuclei, which depends on their atomic number. Regarding extragalactic cosmic rays, we assumed a composition dominated by lighter elements; however, we also considered the presence of "new physics" effects at energies above 50 TeV, as discussed in our previous work *Romanopoulos, Pavlidou, and Tomaras (2022)*. Our analysis demonstrates that the observed penetration depth ($X_{\max}$) and its standard deviation ($\sigma_{X_{\max}}$) align well with our modeling of a Galactic CR composition below the ankle. Additionally, we found that the proposed new physics at a center-of-mass energy of 140 TeV requires a cross-section in the range of 752-836 mb and a multiplicity factor 1.7-3.6 times higher than predicted by the standard model.

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1. Introduction

Cosmic rays (CRs) represent an exceptional class of particles within the universe, exhibiting the highest recorded energies observed in nature. They occupy a prominent position among the realms where the established boundaries of physics and the prevailing Standard Model undergo rigorous testing. CRs manifest as highly energetic particles, capable of reaching astonishing energies up to approximately 5×10^{19} eV. This immense energy scale, equivalent to nearly 300 TeV in center-of-mass (CM) energy upon interacting with the Earth's atmosphere, surpasses the capabilities of the world's most powerful particle accelerator, the Large Hadron Collider (LHC) at CERN, by a factor of twenty. Consequently, the study of cosmic rays stands as an exceptional frontier for scientific exploration, offering a unique opportunity to probe the limits of known physics and challenge the theoretical framework of the Standard Model. Investigating CRs at these extreme energy levels holds the potential to uncover novel physical phenomena, expand our understanding of the fundamental laws that govern the universe, and propel the advancement of astroparticle physics into uncharted territories.

A significant area of inquiry in cosmic ray physics revolves around the yet-elusive composition of primary cosmic ray projectiles.

The flux of cosmic rays declines as a power law more steep than $E^{-2.5}$ At energies below 10^{15} electron volts (eV), the flux of cosmic rays is high enough that direct measurements with, e.g., balloons, is possible. This approach enables the characterization and differentiation of various cosmic ray particles, allowing strong constraints on their composition. In contrast, at energies around 10^{18} eV, fluxes of only one cosmic ray event per square kilometer per year render direct detection practically infeasible.

Instead, to investigate ultra-high-energy cosmic rays (UHECRs), vast ground-based detectors are used, encompassing thousands of square kilometers. Currently, two observatories actively engaged in UHECR research are the Auger observatory [2] in Argentina, covering an area of 3000 km^2, and the Telescope Array (TA) [3] located in Utah, USA, with a collecting area of 800 km^2. Determining the composition of cosmic rays in the ultra-high-energy regime from ground-based detectors involves measuring the penetration depth of the resulting air shower within the Earth's atmosphere and inferring the nature of the primary particle. However, this inference relies heavily on the underlying assumption that the extrapolations of the Standard Model of particle physics hold true even at these extraordinary energy levels. However, this assumption becomes increasingly uncertain with increasing energy.

Remarkably, observations from the Auger observatory [4] suggest that cosmic rays at the highest energies predominantly consist of nitrogen nuclei, an astrophysically puzzling outcome that raises intriguing questions about the mechanisms responsible for generating and accelerating such a significant population of nitrogen particles to these extraordinary energy levels.

As cosmic rays are charged, they are deflected along their trajectories by the magnetic field pervading the Galaxy. Analysis of arrival direction measurements from both the Auger and TA observatories reveals a striking observation: CRs display a uniform distribution across the celestial sphere up to energies of $10^{18.3}$ eV [5, 6]. However, at energies higher than $10^{18.3}$ eV, a dipole anisotropy becomes detectable, strongly hinting towards an extragalactic origin of these cosmic rays, as the hotspot of the dipole distribution is located away from the Galactic center. The presence

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of a discernible hotspot in the northern sky is also associated with the generation of these ultra-high-energy cosmic rays (UHECRs) suggests the existence of extragalactic sources. While the precise information regarding the initial sources may be blurred, it is not entirely erased, offering valuable insights into the nature and origins of these exceptional cosmic phenomena.

The extragalactic origin of UHECRs would naively imply that they are predominantly composed of either protons or iron nuclei. This conclusion arises from the fact that every other element would photodisintegrate along the vast distances of the intragalactic medium.

In our previous publication [1], we explored a scenario where extragalactic cosmic rays were assumed to consist exclusively of protons. The transition to lower-than-expected-for-protons penetration depths was attributed to some novel physics phenomenon at center-of-mass (CoM) energies of 50 TeV. This hypothetical phenomenon was postulated to alter the cross-section of the initial collision and the multiplicity of the products, imparting a "heavy" appearance to the cosmic rays. Although this assumption successfully reconciled discrepancies between simulations and observations for the highest-energy cosmic rays, some residual disagreements persisted at lower energies within the region predominantly populated by Galactic cosmic rays. These disagreements stem from our oversimplified assumption for the Galactic component of cosmic rays, which we limited to only helium.

Motivated by these discrepancies, the present study aims to expand upon our earlier investigations by adopting a more realistic composition for Galactic cosmic rays. Recognizing the diverse nature of particles comprising Galactic cosmic rays, we endeavor to incorporate a comprehensive understanding of their composition and properties into our analysis. By considering a broader range of constituents, we anticipate a refined and nuanced examination of the observed data, with a particular focus on the energy regime primarily influenced by Galactic cosmic rays. Through this approach, we aim to illuminate further the fundamental mechanisms governing the origin, propagation, and interactions of cosmic rays within our galaxy.

2. Cosmic Ray flux and low energy abundances

At lower energies, Galactic cosmic rays (CRs) play a dominant role. Their flux follows a power law, which can be attributed to Fermi acceleration of the primaries. However, there exists a maximum energy that CRs can attain for Galactic sources. This limitation arises from the gyroradius of the particles for any given source class, which is directly proportional to the charge of the CR particles. Consequently, we assume that each CR flux experiences an exponential suppression as a function of energy, reflecting the influence of this

We gather data on the fluxes of various components of the primary cosmic radiation, specifically focusing on the energy range below 10^6 GeV. In this energy range, we assume that the exponential suppression has not yet come into effect. We use data from multiple experiments [8] and fit a power law function $F_{c,\gamma}(E) = c \cdot E^{-\gamma}$ to each element, where c and γ are the parameters of the fits. The resulting fit parameters are presented in Table (1). The flux has dimensions $(m^2\, sr\, s\, GeV)^{-1}$.

We incorporate the exponential suppression into the flux of each cosmic ray element, resulting in the expression:

$$F(E) = F_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(\frac{E}{ZE_G}\right), \tag{1}$$

Element	log(**c**)	γ
H	3.9115	2.6622
He	2.6560	2.6019
C	1.1097	2.5923
O	1.1695	2.6227
Ne	0.2023	2.5456
Mg	0.6019	2.7174
Si	0.5679	2.7204
S	−0.2548	2.6377
Ar	−0.9879	2.4625
Ca	−0.5036	2.6507
Fe	0.2349	2.5896

Table 1: Parameters of power-law fits.

where E_G represents the cutoff energy for protons and Z the charge of the CR.

Next, we use data from the Auger experiment to obtain the total cosmic ray flux in the energy range between 10^{17} up to 10^{20} GeV. Using the previously derived fits for the Galactic cosmic ray fluxes, we extrapolate the fluxes of Galactic cosmic rays at these higher energies. Since the Galactic component is expected to dominate at around 10^{17} GeV, we determine that E_G should be approximately $10^{9.75}$ GeV. By subtracting the Galactic component from the total flux, we can isolate the flux of the extragalactic cosmic ray component. The resulting flux ratios for each component are plotted in Figure (1).

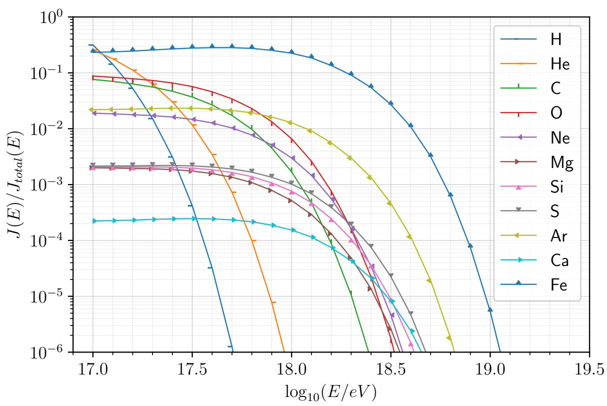


Figure 1: Extrapolated fluxes of Galactic cosmic-ray components relative to the total Galactic flux.

2.1 Formulas for $\langle X_{max} \rangle$, $Var(X_{max})$

In order to draw conclusions for the nature of primary CR particles scientists measure the penetration depth X_{max} of the air shower in the atmosphere, which is a column density.

We consider a mixture of Galactic and extragalactic cosmic rays (CR), where the extragalactic component is treated as a single entity, while the Galactic component is divided into its constituent elements. The probability density function of $X_{\max}$ can then be expressed as:

$$p(X_{\max}) = \sum_i f_i p^i_{\rm G}(X_{\max}) + (1-f)p_{\rm EG}(X_{\max}) \quad (2)$$

Here, $f(E)$ represents the fraction of Galactic CR relative to the total CR and is further analyzed into f_i, which corresponds to each element in the Galactic CR. It should be noted that f is given by $\sum_i f_i$.

Based on this, we can calculate the average shower maximum as:

$$\langle X_{\max}\rangle = \sum_i f_i \langle X^i_{\max}\rangle_{\rm G} + (1-f)\langle X_{\max}\rangle_{\rm EG} \quad (3)$$

Additionally, the variance of $X_{\max}$ is given by:

$$\begin{aligned}\mathrm{Var}(X_{\max}) = &\sum_i f_i \mathrm{Var}(X^i_{\rm max,G}) + (1-f)\mathrm{Var}(X_{\rm max,EG}) + f(1-f)\langle X_{\max}\rangle^2_{\rm EG} + \sum_i f_i \langle X^i_{\max}\rangle^2_{\rm G} \\ &- \left(\sum_i f_i \langle X^i_{\max}\rangle_{\rm G}\right)^2 - 2(1-f)\langle X_{\max}\rangle_{\rm EG} \sum_i f_i \langle X^i_{\max}\rangle_{\rm G} \end{aligned} \quad (4)$$

where the subscripts G and EG represent the Galactic and the extragalactic component, respectively.

In the context of the extragalactic component of X_{max}, we adopt a methodology akin to our prior research outlined in reference [1]. This approach serves to emulate novel physical phenomena that may manifest at energies beyond 50 TeV in the center-of-mass frame. Our strategy involves the incorporation of a parameter denoted as δ, which imparts modifications to the cross-section of the initial interaction of protons with the Earth's atmosphere.

3. CORSIKA Simulations

In our EAS simulations, we aim to assess the combined effect of our previous implementation of new physics above 50 TeV and the improved representation of Galactic cosmic ray (CR) components. Our goal is to achieve more coherent results that align with observations from the Auger experiment. Additionally, we seek to determine the optimal phenomenological parametrization, specifically the cross section and multiplicity, which are quantified by δ and $n(\varepsilon)$ in our model. These parameters characterize any new proton-air interaction that would be necessary for the EAS simulations to reproduce the observed data in Auger, while assuming that the composition of primary particles remains light up to the highest energies. By investigating these aspects, we aim to refine our understanding of the underlying physics and improve the agreement between simulations and experimental observations.

In our study, we conducted extensive simulations of extensive air showers (EAS) using the CORSIKA software. The EAS simulations were initiated by primary particles consisting of various elements, including H, He, C, O, Ne, Mg, Si, S, Ar, Ca, and Fe. The primary particle energies spanned the range of 10^{17} to 10^{20} eV, with a logarithmic energy step size of 0.1. For each energy bin, we performed a total of 1000 EAS simulations.

In our simulations, we considered two scenarios for the treatment of the first collision in the EAS development. For the Galactic component and for proton primaries with energies below the threshold value of 10^{18} eV, we used the standard model (SM) extrapolations to simulate the EAS. However, for proton primaries with energies exceeding 10^{18} eV and for the extragalactic component, we implemented new physics based on our phenomenological model [1].

4. Results

We conducted EAS simulations using CORSIKA with various values of δ (0, 2.9, 3.5, 4, 6, 8, 10). Our results for the average shower maximum, $\langle X_{max} \rangle$, perfectly agree with Auger simulations, indicating that our more realistic Galactic approximation resolves the discrepancy observed at low energies in the variance of $\langle X_{max} \rangle$.

To assess the agreement between the new-physics $\sigma_{\langle X_{max} \rangle}$ and Auger data, we calculated the reduced χ^2 statistic. Figs. 2 illustrates the variation of reduced χ^2 with δ for our EAS simulations. We fitted parabolic curves (dashed lines) to our data points to determine the δ values corresponding to the minimum χ^2. For EPOS-LHC, the minimum χ^2 is 6.0 at $\delta = 3.0$, while for QGSJETII-04, the minimum χ^2 is 7.4 at $\delta = 7.9$. EPOS-LHC demonstrates better overall performance. At the minimum χ^2, the cross section at an energy of 10^{19} eV increases to 727 mb (833 mb) for EPOS-LHC (QGSJETII-04). Additionally, the multiplicity increases by a factor of 3.6 (1.7) at the same energy.

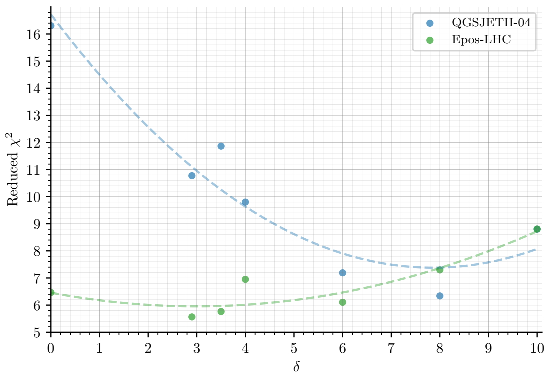
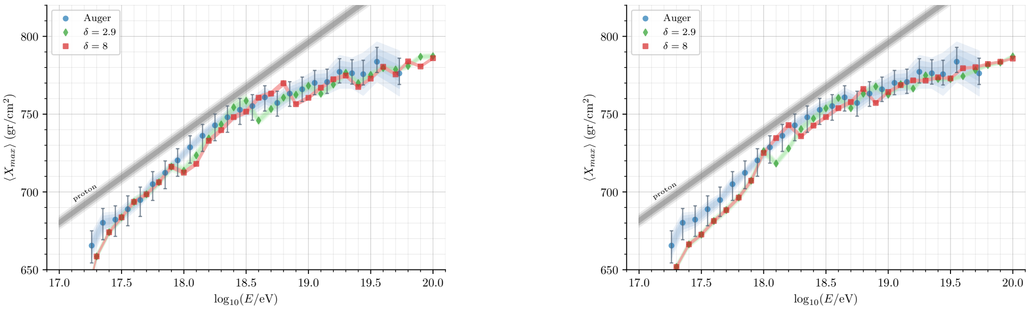


Figure 2: Agreement between new-physics EAS simulations and Auger data for $\sigma_{X_{\mathrm{max}}}$ quantified through the reduced χ^2 statistic, as a function of the value of the δ parameter. Overall, EPOS-LHC simulations produce results more consistent with observational data. To find the position of the minimum χ^2, we perform a parabolic fit to the datapoints. The locations of the minima are at $\delta = 3.0$ for EPOS-LHC and at $\delta = 7.9$ for QGSJETII-04.

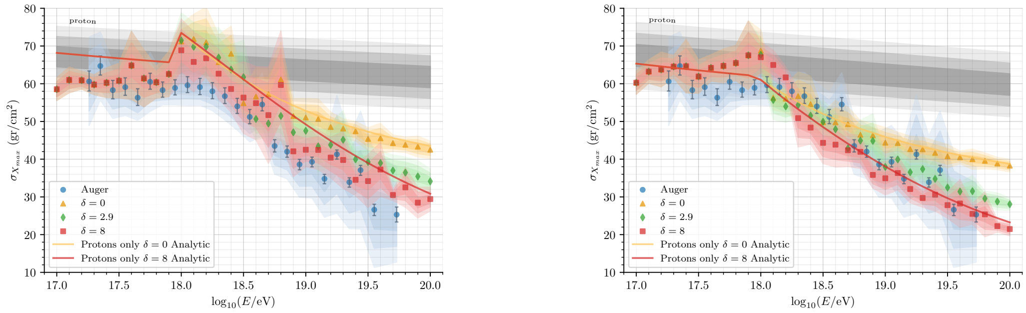
5. Summary and conclusion

We conducted extensive EAS simulations using CORSIKA for UHECR, considering protons as the extragalactic cosmic ray component and a more realistic mixture of chemical elements for the Galactic cosmic ray component. We also introduced a new physics scenario that comes into effect at a center-of-mass energy of 50 TeV, modifying the cross section and multiplicity of the first interaction.



(a) QGSJET-04 **(b)** EPOS-LHC

Figure 3: Average shower maximum as a function of energy. The more realistic representation of Galactic CR fixes the inconsistencies we observed in our previous work for the QGSJET-04 model. In the plots, there are some sudden jump features. These are caused due to the rounding of the multiplicity number in the creation of the secondary files



(a) QGSJET-04 **(b)** EPOS-LHC

Figure 4: The standard deviation of shower maxima, $\sigma_{X_{\max}}$, exhibits a dependence on the parameter δ, unlike the mean value of $X_{\max}$ which remains unaffected by δ (see Figure 3). We find that the simulated $\sigma_{X_{\max}}$ aligns best with Auger observations when δ is approximately 8 for QGSJETII-04 (upper plot) and around 2.9 for EPOS-LHC (lower plot). Further increasing the δ parameter does not lead to significant changes at high energies, as $\sigma_{X_{\max}}$ reaches an asymptotic behavior. Additionally, we observe a perfect agreement at low energies between our simulated results and Auger observations. This improved agreement can be attributed to our more realistic assumption for the Galactic component in the simulations.

Our simulations demonstrate that the penetration depth and its variance can be made to agree well with the observational data from Auger for specific values of the parameter δ. For the EPOS-LHC model, the optimal value of δ is found to be 3.0, while for the QGSJET model, it is 7.9. Should therefore new physics set in above CM energies of $\sim 50TeV$ and be solely responsible for the break in the elongation rate observed at the highest energies, then the cross section at a center-of-mass energy of 140 TeV should be around 800 mb, accompanied by an increase of $2-3$ times in the number of secondary particles produced after the first collision.

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