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New physics Air-Shower simulations for UHECR above 50 TeV

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The average shower depth $\langle X_{\max} \rangle$ of Ultra-high Energy Cosmic Rays is observed to flatten with energy at the highest energies. The standard interpretation of these data is that the composition is getting heavier; an alternative interpretation is the existence of new effects in proton interactions above ∼ 50 TeV center-of-mass energy. We have used CORSIKA to study, through air-shower simulations, observational signatures of a possible increase in cross-section and multiplicity in collisions exceeding this threshold. We have simulated hadronic collisions for primaries with energies in the range $10^8 - 10^{11}$ GeV. We have used two different high energy models for the simulations, QGSJETII-04 and EPOS LHC, with Fluka for low energy interactions on both. A smooth transition from Galactic to extragalactic cosmic rays was implemented, by fitting a Galactic component with an exponential suppression at $\sim 10^9$ GeV. The remaining flux in Auger data was interpreted as extragalactic protons. Above 10^9 GeV, the proton-air cross-section and the multiplicity of secondary particles were altered, so as to bring the simulated $\langle X_{\max} \rangle$ in agreement with Auger data. The parameter space of the viable cross-section and multiplicity in the scenario where the composition of Auger cosmic rays at the highest energies remains unchanged and light, places constraints on the phenomenology of any new physics affecting the interactions for high energy protons that may be probed by $\sqrt{s} > 50$ TeV collisions. We found out that if new physics indeed sets in, the cross-section of proton-Air interactions has to be ∼ 800-900 mb at 140 TeV center-of-mass energy, accompanied with an increase of the number of secondary particles by a factor between 2-3.

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1. Introduction

Cosmic Rays (CR) are the most energetic particles in the universe. Over 100 years have passed since they were first discovered by [1], yet still their composition, origin and acceleration mechanism are subjects of debate. Cosmic Rays with energies above 10^9 GeV are called Ultra High Energy Cosmic Rays (UHECR) and they can reach energies up to $5 \cdot 10^{10}$ GeV. As these UHECR collide with Earth's atmosphere, the CM energy reaches $\sqrt{s} \simeq 300$ TeV. For reference LHC can reach energies of $\sqrt{s} = 14$ TeV with future plans of $\sqrt{s} = 100$ TeV in the next 20 years [2].

Cosmic rays are rare events and we do not have knowledge over their position in the sky a priori. Around 10^6 GeV we observe 1 CR per m^2 per year. In the regime of UHECR there is 1 per km^2 per year dropping down few per km^2 per century above 10^{10} GeV. Above this energy UHECR interact with photons of the Cosmic Microwave Background (CMB) radiation, producing pions and lose its energy. This process makes them extremely rare and sets an upper energy limit called the GZK cutoff, predicted independently by [3] and [4].

In recent years Telescope Array (TA) project in the northern hemisphere and Auger Collaboration in the southern hemisphere, with huge observing areas (762 km^2 and 3000 km^2 respectively) made it possible to study UHECR systematically by observing Extensive Air Showers (EAS) cosmic rays produce after interacting with the atmosphere. It was reported by both TA [5] and Auger [6] that cosmic rays have a dipole anisotropy at energies above 10^9 GeV that is not correlated with the Galactic plane, indicating that they are of extra-galactic origin.

Recent studies have shown that Galactic magnetic field is approximately an order of magnitude stronger than previously thought [7] in a small region near the reported hotspot from TA [8]. If indeed the average Galactic magnetic field is proven to be just a few times stronger than the existing models, combined with the dipole anisotropy at high energies, we can conclude that UHECR are light nuclei. Heavy nuclei are strongly deflected by Galactic magnetic fields and their arrival directions would spread over all the sky, eliminating all traces of anisotropy. The assumption of light composition though does not agree with EAS simulations. In fact above $10^{9.3}$ GeV simulations and observations do not agree by any type of model extrapolation [9]. If the SM holds up to the highest energies, these models suggest that there is a transition into heavier nuclei at high energies, like Nitrogen. This assumption contradicts the need for a light composition to maintain anisotropy with strong Galactic magnetic fields.

A possible alternative scenario is that above a threshold energy E_{th}, proton-Air interactions change due to new physics setting in, as previously discussed, e.g., by [10].

Our main goal in this paper is to study the parameter space of cross section and multiplicity for proton-Air interactions in order for simulations to agree with observational data. After the first interaction, we will simulate the further development of EAS with CORIKA[1] [11] using two models for high energies, EPOS LHC [12] and QGSJETII-04 [13] and FLUKA[2] [14] for low energy interactions. Our results will impose constrains on the possible alternative models for proton interaction.

In Section 2 we will discuss the main observed quantities that are essential in cosmic ray physics and how these quantities depend on the cross-section and multiplicity. In Section 3 we

[1]CORSIKA version 7.7402
[2]FLUKA version 2020.0.3

will analyze our approach to Air-Shower simulations with new physics and discussing our results in Section 4. Finally in Section 5 we have our conclusions.

2. Mathematical Formulation

One of the most important quantities in CR physics is the slant depth of the shower

$$X = \int_{\infty}^{x} \rho(l)\, dl \tag{1}$$

where ρ is the density of the atmosphere and l is the path of the cosmic ray in it. This quantity does not depend on the inclination of the incoming CR, but rather on the total path traversed in the atmosphere.

In the course of air shower development, charged particles are created via bremsstrahlung or pair production. This process continues until the energy of the shower's particles drops below a threshold and after that fewer and fewer charged particles are fed into the shower. The generated charged particles ionize the atmosphere and as atoms recombine they emit a characteristic fluorescent light. With this light we can observe the development of the air shower and measure how much energy the shower loses as it penetrates deeper into the atmosphere. The height at which the air shower's energy loss is maximum corresponds to a special slant depth called X_{max}. Fluctuations of X_{max} are mainly due to fluctuations in the location of the first interaction of the primary with the atmosphere and the randomness in the development of the shower. For that reason the distribution of X_{max} provides information about the interactions of elementary particles.

The maximum of each shower consists of two components

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

where X_{int} is the depth of the first interaction and X_{long} is the depth of the longitudinal development of the air shower until it reaches its maximum.

The probability that a CR has not interacted with the atmosphere in the vicinity of height x is $\exp(-x\, n\sigma_{\text{p-Air}})$ where n is the particle density of the atmosphere and $\sigma_{\text{p-Air}}$ the cross section of the projectile with it. If the medium is not uniform the probability is

$$\exp\left(-\frac{\sigma_{\text{p-Air}}}{m} \int_{\infty}^{x} \rho(l)\, dl \right) \tag{3}$$

The atmosphere consists mainly by nitrogen, so $m = 13.04$ GeV. The inverse of the constants in front of the integral is the average value of the depth of first interaction

$$\langle X_{\text{int}} \rangle = \frac{m}{\sigma_{\text{p-Air}}} \tag{4}$$

The cross-section has a logarithmic behavior at high energies. For that reason we parametrize the cross section as

$$\sigma_{\text{p-Air}} = \sigma_0 + \beta \log \varepsilon \tag{5}$$

where σ_0 and β are constants and $\varepsilon = E/E_{\text{th}}$. The previous process indicates that X_{int} follows Poisson statistics and thus its variance will be

$$\text{Var}(X_{int}) = \langle X_{int} \rangle^2 \tag{6}$$

The dependence of X_{long} with energy can easily be calculated from the simple Heitler model [15]. In reality X_{long} is more complicated because more phenomena take place than summarized here. The final behavior though is the same as Heitler's toy model

$$\langle X_{\text{long}} \rangle = X_0 + \alpha \ \log \varepsilon \tag{7}$$

where X_0 and α are constants. The four parameters σ_0, β, X_0 and α depend slightly on the model used to perform air shower simulations. Nevertheless all models reproduce similar results.

If new phenomena take place at energies above some energy threshold E_{th}, this means that the cross section of the first interaction will change

$$\sigma_{\text{p-Air,new}} = \sigma_0 + \beta' \ \log \varepsilon = \sigma_{\text{p-Air}} + (1 + \delta)\, \beta \ \log \varepsilon \tag{8}$$

where $\delta = \beta'/\beta - 1$. The production of secondary particles will also change, creating more particles. The initial energy is now distributed among more particles and the longitudinal depth will reach its maximum in higher altitude leading to

$$\langle X_{\text{long}} \rangle = X_0 + \alpha \ \log \varepsilon / n(\varepsilon) \tag{9}$$

where $n = N/N_{\text{SM}}$ is multiplicity increment of the secondary particles N compared to the SM predictions N_{SM}.

To estimate the variance of X_{long} we take the $X_{long} = \frac{1}{n} \sum_i X_{long,i}$ to be a reasonable estimation of X_{long}. Then X_{long} is the sample mean of n draws from the underlying distribution of $X_{long,i}$ and the distribution of these sample means has a variance that is given by the error in the mean formula,

$$\text{Var}(X_{long,new}) = \frac{\text{Var}(X_{long,i})}{n(\varepsilon)} \tag{10}$$

Here $\text{Var}(X_{long,i})$ is the variance of $X_{long,i}$, and it can be assumed to follow the SM predictions, since the individual energies of the decay products initiating the CS are below E_{th}. Furthermore $\text{Var}(X_{long,i})$ is relatively constant and for that reason all the underlying showers will have the same value, $\text{Var}(X_{long})$.

The variance of X_{max} will be

$$\text{Var}(X_{max,new}) = \text{Var}(X_{int}) \left(\frac{\sigma_{\text{p-Air}}}{\sigma_{\text{p-Air,new}}} \right)^2 + \frac{\text{Var}(X_{long})}{n(\varepsilon)} \tag{11}$$

The Auger Collaboration reports, for energies $E \geq 10^{9.3}$ GeV

$$X_{\text{max, Auger}} = X_{0,\text{ Auger}} + \alpha_{\text{Auger}} \ \log \varepsilon \tag{12}$$

with $X_{0,\text{Auger}} = 749.74$ gr/cm^2 and $\alpha_{\text{Auger}} = 23.98$ gr/cm^2. Simulated data of pure protons air showers indicate a difference from Auger observations above this energy.

	σ_0 (mb)	β (mb)	X_0 (gr/cm^2)	α (gr/cm^2)
EPOS LHC	527.75	49.05	707.60	62.64
QGSJETII-04	499.59	35.91	692.07	60.23

Table 1: Model dependent parameters

By equating the behavior of Auger data to the results of the "new physics" above E_{th} we have

$$X_{\text{max,Auger}} = \frac{m}{\sigma_{\text{p-Air}} + (1+\delta)\,\beta\,\log\varepsilon} + X_0 + \alpha\,\log\varepsilon/n(\varepsilon) \tag{13}$$

and solving for the multiplicity we end up with

$$\log n = \frac{X_0 - X_{0,\text{Auger}}}{\alpha} + \frac{\alpha - \alpha_{\text{Auger}}}{\alpha}\log\varepsilon + \frac{1}{\alpha}\frac{m}{\sigma_{\text{p-Air}} + (1+\delta)\,\beta\,\log\varepsilon} \tag{14}$$

and the cross section will be given by Eq.(8). Both cross section and multiplicity depend only on the energy and this new free parameter δ.

At energies around 10^8 GeV, X_{max} is dominated by Galactic CR. We simulate the Galactic component as Carbon for simplicity as previously discussed by [10].

3. CORSIKA simulations

We used CORSIKA to perform EAS simulations with EPOS LHC and QGSJETII-04 for high energy combined with FLUKA for low energy interaction. We also used CONEX which perform Monte Carlo Simulations decreasing the simulation time dramatically.

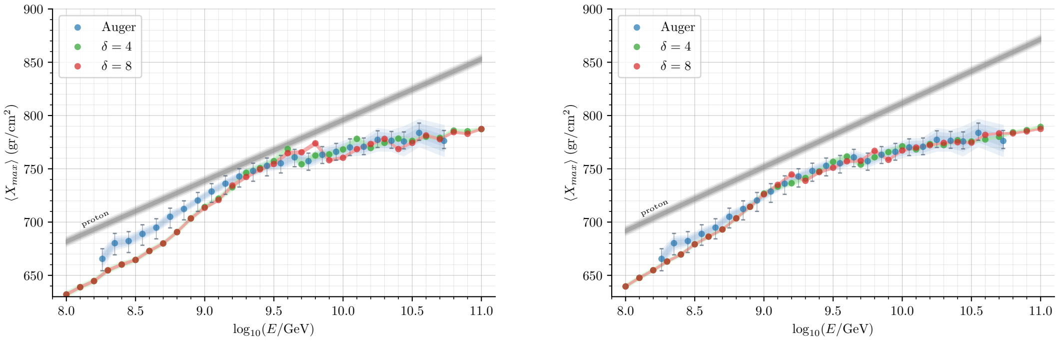
We used protons with energy in the range $10^8 - 10^{11}$ GeV with step of $10^{0.1}$ GeV. At each energy bin we perform 1000 EAS simulations.

After that we increase the multiplicity according to Eq.(14) for each Stack file by combining Stack files in the same energy bin taking into account energy and momentum conservation. We perform simulations for $\delta = 4$ and 8.

4. Results

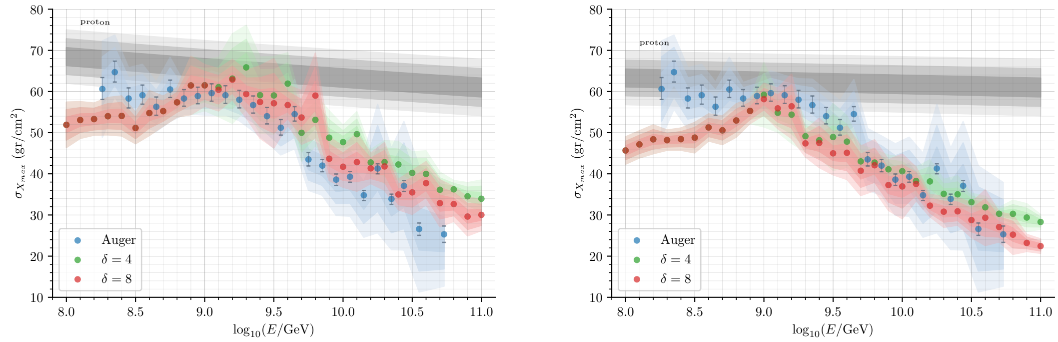
With new cross section $\sigma_{\text{p-Air,new}} = \sigma_{\text{p-Air}} + \delta\,\beta\,\log\varepsilon$ and new multiplicity in the first interaction, the simulation data are in excelent agreement with the observational data for $\delta = 8$ (see Fig.(1) and Fig.(2)). For this value the cross section at an energy of 10^{10} GeV rises to 800 mb for QGSJETII-04 and to 900 mb for EPOS LHC. At the same energy the multiplicity is 2 and 3 respectively. In Fig.(1) and Fig.(2) we also see that our simulations do not agree with observations at low energies. This is due to the assumption of a Galactic component consisting purely of Carbon. A more realistic assumption would have been a mixture of Helium, Oxygen, Carbon and Iron with ratios that depend on the energy. Such a scenario however would add significant complexity without changing the results at the highest energies, which is the regime of interest here.

For $\delta = 4$ the standard deviation of X_{max} gives marginally larger values than what is observed. Although for EPOS LHC $\delta = 4$ is an acceptable value, we observe that overall for both models the



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

Figure 1: Shower maximum as a function of energy. It is evident that the standard model extrapolation through the models QGSJETII-04 and EPOS LHC (gray) do not agree with the observations from Auger Observatory (blue) above $E_{\mathrm{th}} = 10^9$ GeV. Changing the cross section and the multiplicity behavior with energy of protons in the first interaction as indicate Eq.8 and Eq.14, air shower simulations with proton as a primary particle (green and red) will produce the observed data at the highest energies. The choice of a single component galactic CR is the reason our simulation results deviate from observational data. A multi component Galactic CR spectrum with Helium, Oxygen, Carbon and Iron would have been a more realistic scenario.



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

Figure 2: Standard deviation of shower maximum as a function of energy. Although the shower maximum does not depend on the parameter δ, here we see that its 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 behavior

value $\delta = 8$ has better results. For lower values, the standard deviation of the shower depth will have larger values approaching the SM predictions for $\delta = 0$ (note however that the change in multiplicity alone will produce a better agreement with the observations than the pure SM prediction).

On the other hand, further increment of the δ parameter above 8 will not bring any more significant changes on the Var($X_{\text{max,new}}$) at energies around 10^{11} GeV. This is because Var($X_{\text{int,new}}$) goes to zero very fast as the new cross section increases dramatically. This will also make the Var($X_{\text{max,new}}$) to deviate significantly from the observed data around $10^{9.5}$ GeV regime. A second problem that arises with higher δ values is that cross-section increases fast reaching values larger than 1000 mb at 140 TeV center-of-mass energy. It should be noted that although we have considered the increase in the cross section to be a result of new physics, the preferred cross-section value that we find is within uncertainties of the extrapolations of standard-model calculations to higher energies. This implies that the changes required to the Standard Model will result to only minor changes in cross section.

5. Conclusions

If new physics sets in at energies above $10^{9.0}$ GeV, proton interactions will change, leading to revised values for the cross section and for the multiplicity of the secondary particles. Our hypothesis of new cross section and multiplicity describe remarkably well the observational data of slant depth and its standard deviation for $\delta = 8$. These parameters (cross section, multiplicity) set constraints on the possible new proton-air interactions at high energies. These results are part of ongoing work, and future upgrades will include the treatment of a more realistic Galactic component with a mixture of heavy nuclei, and a detailed scan of the acceptable δ parameter space.

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