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Testing models of new physics with UHE air shower observations

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Abstract: Several air shower observatories have established that the number of muons produced in UHE air showers is significantly larger than that predicted by models. We argue that the only solution to this muon deficit, compatible with the observed X_{max} distributions, is to reduce the transfer of energy from the hadronic shower into the EM shower, by reducing the production or decay of π^0s. We present four different models of new physics, each with a theoretical rationale, which can accomplish this. One has a pure proton composition and three have mixed composition. Two entail new particle physics and suppress π^0 production or decay above LHC energies. The other two are less radical but nonetheless require significant modifications to existing hadron production models – in one the changes are only above LHC energies and in the other the changes extend to much lower energies. We show that the models have distinctively different predictions for the *correlation* between the number of muons at ground and X_{max} in hybrid events, so that with future hybrid data it should be possible to discriminate between models of new physics and disentangle the particle physics from composition.

Keywords: muon deficit, hadronic interactions, composition, models

1 Introduction

Measurements of the density of muons at ground in ultra-high energy (UHE) air-showers performed by hybrid observatories, first at CASA-MIA [1] and more recently at the Pierre Auger Observatory [2, 3, 4, 5], have revealed that there is a significant deficit of muons in Monte Carlo (MC) simulations of air showers. The number of muons in the data is greater than that predicted using even iron initiated air-showers. Explaining this is made more challenging by the measurements of the distribution of the depth of shower maximum, X_{max}. Measurements performed at Telescope Array and the Pierre Auger Observatory both show that, depending on the hadronic model used to interpret the X_{max} data, the mean mass at 10 EeV is light to intermediate [6, 7, 8, 9].

In the present study, we investigate potential resolutions to this discrepancy. We begin by exploring how generic properties of hadronic interactions are constrained by independent measurements of the density of muons at 1000 m from the shower core, N_μ, and X_{max}. We then present four schematic models of hadronic interactions which represent different methods to simultaneously fit measurements of both the mean X_{max} and N_μ. Each model can be tuned to reproduce the observed X_{max} distribution and mean N_μ. Fortunately, air shower observatories can differentiate the four models by studying the correlation between the X_{max} and the N_μ of hybrid air showers. Measurements of this nature should be feasible at both the Pierre Auger Observatory and Telescope Array, especially with upgrades to the muon sensitivity.

2 Constraints on Hadronic Interactions

N_μ and X_{max} are sensitive to several properties of hadronic interactions. Some properties, such as the primary cosmic ray mass composition and multiplicity of secondary particles, impact both these observables, while other properties impact only one or the other. By studying how MC predictions for N_μ and X_{max} behave under modifications to various hadronic interaction properties, we identify potential modifications which could resolve the muon deficit.

Table 1: A summary of the dependence of N_μ and X_{max} as various properties of the hadronic interactions are increased, with all others held fixed.

Property Increased	Change in N_μ	Change in X_{max}
Cross-section	–	Decreased
Elasticity	–	Increased
Multiplicity	Increased	Decreased
Primary Mass	Increased	Decreased
π^0 Eng. Frac.	Decreased	–

The mean N_μ is primarily sensitive to the multiplicity, the π^0 energy fraction (the fraction of incident energy carried by π^0s in hadronic interactions), and the primary mass. The mean X_{max} is primarily sensitive to the cross-section, elasticity, multiplicity, and primary mass. This dependence appears in the hadronic extension of the Heitler model [10], and has been studied quantitatively [11, 12]. Table 1 summarizes the qualitative impact that changing each property has on N_μ and X_{max}.

To explore how changes in these properties affect the mean N_μ and X_{max}, we modify the secondary particles of the hadronic interaction model in the MC simulations. Modifications are made in a similar manner to that in [11]. The simulations are performed using the SENECA [13] air shower simulation with EPOS 1.99 [14] as the underlying hadronic event generator (HEG), although any other HEG could be used as the starting point. The primary energy in all simulations in this paper is 10^{19} eV. The modifications discussed in this section are performed at energies above 10^{17} eV, and become stronger with increasing energy.

For the multiplicity modification, non-leading secondary particles are split into multiple particles, conserv-

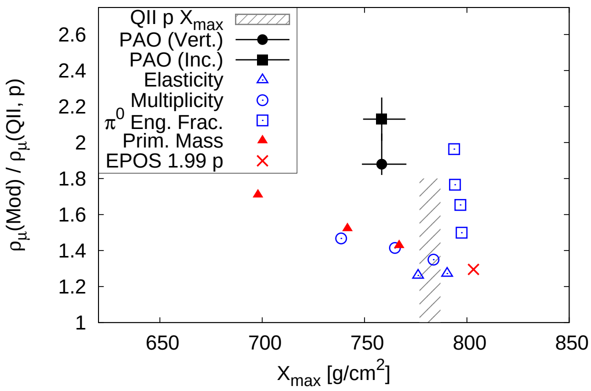

Figure 1: The mean X_{max} and density of muons at 1000 m, relative to that predicted by QGSJET-II-03 for proton showers, as a function of modifications to hadronic interactions. The behavior qualitatively follows that described in Table 1. The magnitude of the modifications are described in the text. The primary masses shown are helium, carbon, and iron. The data for the Pierre Auger Observatory point is from [6] for the mean X_{max} at 10^{19} eV and [2, 3] for the mean muon density at 10^{19} eV. The gray box shows the mean X_{max} for QGSJET-II-03 using proton showers, which is compatible with HIRES data [9].

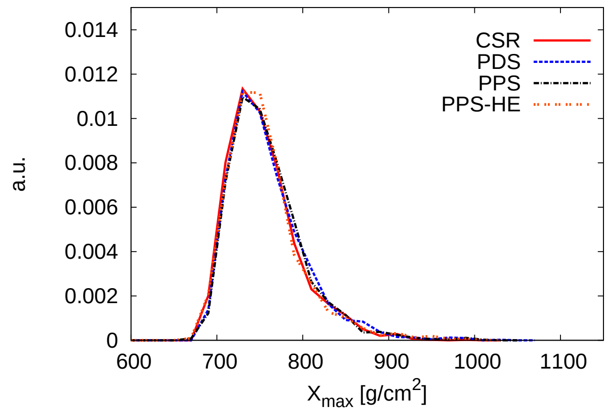

Figure 2: The distribution of X_{max} for the four models described in the text.

ing energy, with the probability of splitting being a tunable parameter which we vary in Fig. 1 to produce a 100% to 700% increase. For the elasticity modification, interactions which have an elasticity above a threshold have a chance of being re-simulated with a probability that is a tunable parameter, which we vary to reduce the number of elastic events by 50% to 80%. Finally, for the π^0 energy fraction modification, forward pions are converted into baryons, and all pions are converted into kaons with a common probability as a tunable parameter which we vary from 8% to 60%.

Fig. 1 shows how the mean X_{max} and N_μ change under the above modifications. As expected, increasing the multiplicity or primary mass decreases the X_{max} and increases N_μ. However, due to the measured X_{max}, these mechanisms cannot solve the muon deficit. X_{max} becomes too shallow before N_μ is sufficiently increased.

These studies of basic modifications to the hadronic event generators demonstrate that the π^0 energy fraction is the hadronic interaction property of most interest. It is the only modification which can increase the mean N_μ without encountering any restrictions from the X_{max} observations. Primary mass and multiplicity can play at most a partial role in the resolution of the deficit.

3 Description of New Models

We have developed four schematic models which rely primarily upon modifying the fraction of energy which is transfered to decaying π^0s in order to fit both the mean N_μ and X_{max} observed at the Auger Observatory. The models are implemented by modifying the secondary particles of EPOS 1.99. The energies of the initial interactions of an ultra-high energy air-shower are well above those achieved at accelerators. The center of mass energy of a 10 EeV proton incident upon a nucleon in the atmosphere is 137 TeV, and many secondary interactions are above the energy of the LHC. This justifies taking considerable freedom in exploring potential, new physics scenarios. We investigate new physics scenarios to uncover signatures of new physics and to explore a broad range of mechanisms which have the potential to solve the muon deficit.

3.1 Chiral Symmetry Restoration

In the Chiral Symmetry Restoration (CSR) model [15], we imagine that at the energy densities achieved in the hadronic interactions in UHE air showers chiral symmetry is restored, and the production of pions becomes greatly suppressed. In the CSR model, the primary cosmic rays are protons in order to achieve the highest energy density. The energy density of an interaction is determined by the impact parameter. We use the elasticity of the interaction as a tracer of the impact parameter; when the elasticity of the interaction is below a certain threshold, the interaction enters the CSR phase.

More modifications are necessary to realize an acceptable pure-proton scenario than simply a reduction of the production of pions; the average X_{max} predicted by EPOS using proton primaries is deeper than observations by both the Auger Observatory and Telescope Array. In the CSR phase, the multiplicity is increased and elasticity decreased. The cross section is rapidly increased at high energies to reduce the *RMS* of the predicted X_{max} distribution. The tunable parameters of the CSR model include the strength of the pion production suppression, the elasticity threshold for entering the CSR phase, the elasticity of CSR interactions, and the increase in the proton-Air cross-section. Through suitable adjustment of the energy dependence of the parameters, an acceptable mean X_{max} and $RMS(X_{max})$ can be found for all energies. The CSR model thus provides an example of a proton-only model which can fit many air shower observables [15].

3.2 Pion decay suppression

Pion decays in air shower MCs are treated as if they take place in a vacuum. However, in the rest frame of high energy pions, the atmosphere is in fact a very dense medium. We postulate that pion decay could be suppressed through interactions with the dense air medium [16]. In the pion decay suppression (PDS) model, pion decay is suppressed at high energies. The impact this has on air shower development is similar in effect to simply decreasing pion production; since the π^0s do not decay, they do not feed the

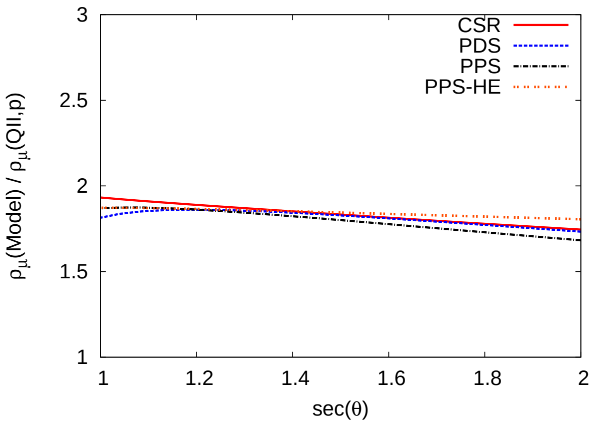

Figure 3: The density of muons at 1000 m, relative to QGSJET-II-03 proton showers, as a function of zenith angle for the four models described in the text.

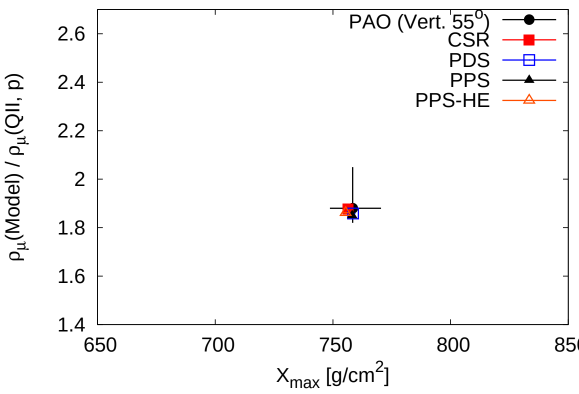

Figure 4: The average X_{max} and density of muons at 1000 m relative to QGSJET-II-03 proton showers in the four models compared to Auger Observatory measurements. The Auger Observatory data is the same as that in Fig. 1.

electromagnetic shower. There is only one tunable parameter of the model, which is the energy above which pion decay is suppressed for a reference air density. The primary mass composition is assumed to be mixed in order to provide freedom in the mean X_{max}.

3.3 Pion production suppression

The popular HEGs, such as QGSJET-II [17], SIBYLL [18], and EPOS, predict a wide range of π^0 energy fractions. For example, QGSJET-II-03 predicts that 25% of all the energy in secondary particles are carried by π^0s and ηs, while for EPOS 1.99 and SIBYLL 2.1 this is closer to 20%. This difference in the models persists at all energies. It is thus possible that the fraction of energy carried by pions in hadronic interactions may be less than any of the models currently predict.

We consider two variants of a pion production suppression model: i) (PPS) at all energies, pions in the forward direction, chosen to be above a pseudorapidity of 5 at LHC energy, are converted to baryons, and all pions, regardless of pseudorapidity, are converted to kaons, with a shared probability that is a tunable parameter, and ii) (PPS-HE) the same modification is made but only for interactions with incident energy above 10^{17} eV. The high-energy variant is introduced to explore the impact of performing the pion production suppression in different energy regimes of shower development and would be similar to modifications to the string percolation probabilities [19], or if heavy flavor production is enhanced in kinematic regimes where quark masses may be insignificant. As in the pion decay suppression model, the primary mass composition is assumed to be mixed.

3.4 Comparison between models and data

Figs. 2-4 show that each of these models can be tuned through their various parameters to fit both the X_{max} data and the density of muons at 1000 m. The mean N_μ constrains primarily the strength of the pion production/decay suppression in the models. The mean X_{max} constrains the mass composition in the PDS, PPS, and PPS-HE models and the cross section and elasticity in the CSR model. A comparison of the X_{max} distributions is shown in Fig. 2, and a comparison of the muon density at 1000 m as a function of zenith angle is shown in Fig. 3. There is sufficient freedom in the models to tune them to produce nearly identical predictions for X_{max} and N_μ.

4 The N_μ - X_{max} Plane

As demonstrated in Sec. 3, we can construct models which fit the muon ground density and X_{max} data using various deviations from standard HEGs. Fortunately, the four models can be discriminated by observing correlations between the depth of shower maximum and the number of muons at ground for an ensemble of showers.

To discriminate between the models, the distribution of showers in the N_μ-X_{max} plane must be observed. Any observable which is related to the total number of muons in the showers is suitable, but we continue to use the density of muons at 1000 m. The correlation of N_μ and X_{max} is primarily sensitive to two basic properties of hadronic interactions: the mass composition, and the energy threshold for the suppression of pion decay and production.

The number of muons produced in air showers is determined, in part, by the number of generations between the energy at which pion production begins and the energy at which pions decay. In the current HEGs, iron and other heavy primaries have fewer generations and thus produce more muons, since, in each generation, energy is lost to the electromagnetic sub shower [20, 10]. This causes a large negative correlation between N_μ and X_{max} when the composition is mixed, and a slight correlation in the case of a proton-only composition [21]. However, when pion production is suppressed above an energy threshold, then both proton and iron will have the same number of generations between the energy of pion production and decay, and thus produce a similar number of muons. This causes the strength of the correlation to decrease as the degree of the pion production/decay suppression is increased.

The four models span a wide range of primary compositions and mechanisms for suppressing pion production or decay and, thus, have different correlation strengths between N_μ and X_{max}. The average N_μ as a function of X_{max}, at a fixed shower zenith angle of 38°, is shown in Fig. 5 for each of the four schematic models. The negative correlation between N_μ and X_{max} is strongest when the modification is made at all energies, and weaker when the modification is applied only at high energy. The PPS and PPS-HE

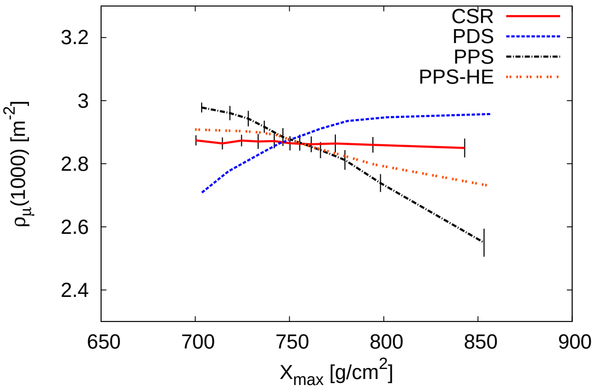

Figure 5: The density of muons at 1000 m as a function of X_{max} for the four template models. The black error bars represent the expected variance when the relation is measured for 800 hybrid events, which is a number achievable at the Pierre Auger Observatory and Telescope Array.

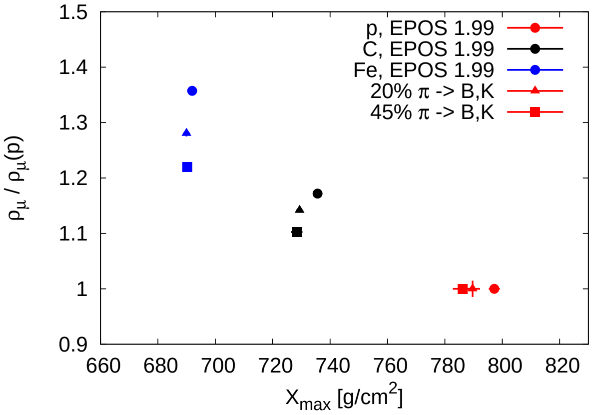

Figure 6: The dependence of the density of muons at 1000 m, relative to protons, on pion production at high energy.

models show a negative correlation while the CSR model shows almost no correlation. Finally, the PDS model actually shows a positive correlation: showers with a shallow X_{max} produce fewer muons than showers with a deep X_{max}.

The behavior of the PDS and PPS models demonstrates that the correlation is sensitive to the energy threshold of the pion modifications. This is made explicit in Fig. 6, which compares the average N_μ and X_{max} of iron, carbon, and proton initiated showers, for different degrees of pion production suppression at high energy. As pion production suppression is increased, the relative difference between the mean N_μ in iron and proton showers decreases.

Fig. 5 shows the expected variance in the N_μ-X_{max} correlation in a sample of 800 hybrid events, which should be achievable at both the Auger Observatory and Telescope Array. Although the simulations in Fig. 5 are simulated at a fixed zenith angle and energy, the same effect could be achieved by normalizing showers to a fiducial energy and angle. The models can be discriminated at high significance.

5 Conclusion

We argue that the muon deficit in simulations of air showers indicates that the hadronic models are incorrectly predicting the fraction of energy which is transfered to the electromagnetic sub shower. Changing the π^0 energy fraction or suppressing pion decay are the only modifications which can be used to increase the number of muons at ground without coming into conflict with the X_{max} observations.

We have developed four schematic models of hadronic interactions, all of which are capable of correctly describing the X_{max} distributions and number of muons at ground. They utilize both pure proton and mixed primary compositions, which demonstrates the need for models to correctly describe all air shower observables before they are used to interpret the primary mass composition.

The four models can be distinguished by observations of the correlation of the number of muons and X_{max} for an ensemble of hybrid events. This correlation provides a crucial new observable for determining the nature of UHE air showers, and can be observed in hybrid events at the Pierre Auger Observatory and possibly Telescope Array.

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