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Probing hadronic interactions using the latest data measured by the Pierre Auger Observatory

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The Pierre Auger Observatory is the world's largest ultra-high energy cosmic ray observatory. Its hybrid detection technique combines the observation of the longitudinal development of extensive air showers and the lateral distribution of particles arriving at the ground. In this contribution, a review of the latest results on hadronic interactions using measurements from the Pierre Auger Observatory is given. In particular, we report on the self-consistency tests of the post-LHC models using measurements of the depth of the shower maximum and the main features of the muon component at the ground. The tensions between the model predictions and the data, considering different shower observables, are reviewed.

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1. Introduction

In high-energy physics, the hadronic interactions and the decay of the produced secondary particles were studied mainly in fixed-target experiments. To reach higher energies in the interactions, modern experiments are designed to study particle production with colliding beams. The Large Hadron Collider (LHC) was the first accelerator that allowed to study energies above the knee in the cosmic ray spectrum. Nevertheless, the most powerful accelerator reaches only to energy of 10^{17} eV ($\sqrt{s} \sim 13$ TeV in the center of mass frame). Therefore, the Ultra High Energy Cosmic Rays (UHECRs), characterized by the highest energies ($\sim 10^{20}$ eV corresponding to an equivalent center of mass energies of the interaction with air nuclei $\sqrt{s} \sim 430$ TeV for protons), give the unique chance to investigate hadronic interactions at energies well beyond those achievable with human-made accelerators through the measurement and the interpretation of the primary induced air showers.

The Pierre Auger Observatory [1], located on a vast plain in Argentina, in the Province of Mendoza, at 1440 m above sea level, is the largest observatory ever built to detect Extensive Air Showers (EAS) resulted from a high-energy cosmic ray interacting with an air molecule in the upper atmosphere. The observatory combines a Surface Detector (SD) consisting of 1600 water-Cherenkov detectors, arranged on an isometric triangular grid with 1500 m spacing, covers an area of 3000 km^2 and a Fluorescence Detector (FD), comprising 27 telescopes distributed on four sites. The array measures with high-statistics the secondary particles at the ground level. The primary energy and the shower geometry are retrieved from the signal and time information of the triggered stations. The FD observes the longitudinal development of the EAS through the florescence light emitted by the de-excitation of the nitrogen molecules. The measurements of the calorimetric energy and of the atmospheric depth at which the shower reaches the maximum number of particles, X_{max}, are provided by the FD. The properties of the air showers are, in this way, measured to determine the energy and arrival direction of each cosmic ray and to provide a statistical determination of the distribution of primary masses.

The measurements are compared with the simulated observables using the current high-energy hadronic interaction models. These models used to simulate EAS are based on the extrapolation of physical quantities towards cosmic ray energies and also phase-space regions inaccessible in human-made detectors. Currently, the available high-energy interaction models are not able to describe all observables of air showers consistently. In this sense, searches for inconsistencies and analysis of the relationship between some observables and the physical parameters are needed to improve the models. In this review, a selection of studies performed to investigate the agreements and the tensions between measured observables and the model predictions through both self-consistency tests and direct approaches are described. The hadronic interaction models considered are EPOS-LHC [2], Sibyll2.3 [3], Sibyll2.3c [4], Sibyll2.3d[5] and QGSJetII-04 [6].

2. Depth of the shower development

In this section, selected analysis concerning the depth of shower maximum, X_{max} are presented. First, the study performed to investigate the consistency between measured depth of the shower maximum and its value obtained from simulations done using different high-energy interaction

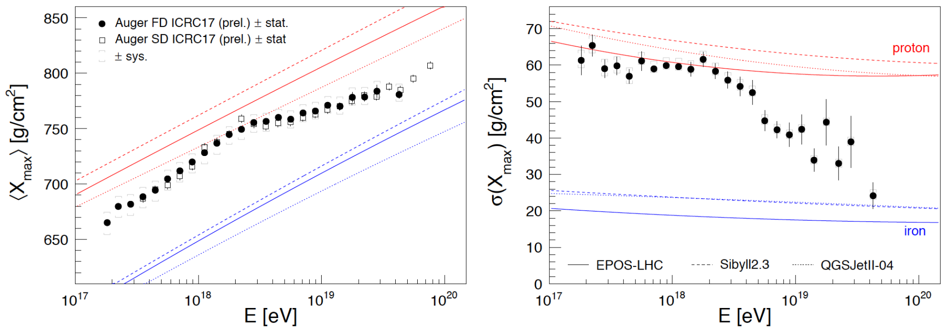

Figure 1: The mean (left) and the standard deviation (right) of the X_{max} distributions measured by Auger, as a function of energy compared to air shower simulations for proton and iron primaries. Figures from [7].

models is shown. Afterwards, a direct approach to retrieve the cross section of proton-air interactions from the X_{max} distributions is described.

2.1 Self-consistency tests of the hadronic interaction models through the X_{max} distributions

The mass composition of the UHECRs can be estimated from the distributions of the depth of the shower maximum. In particular, air showers induced by light cosmic rays develop deeper in atmosphere than those generated by a heavier primary. Moreover, heavy nuclei are expected to produce shower-shower fluctuations smaller than protons. In Fig. 1, the latest FD measurements [7] of the two first moments of the X_{max} distribution as a function of the energy are shown. Moreover, the simulated mean and standard deviation of the distributions for protons (red curve) and iron (blue curve) induced air showers using three different hadronic interaction models are shown. It can be noticed that the models reproduce well the measured X_{max} and, independently of the hadronic interaction models, it is found that below the ankle the spread of the masses in the primary cosmic rays is larger than for higher energies. As shown in Fig. 1, these results are also supported by the SD observables sensitive to the mass composition. In this case the information about the mass composition is retrieved from the time structure of the signals recorded by the water-Cherenkov detectors (see [8] for the details). Nevertheless, a certain tension can be observed for QGSJetII-04 by comparing the energy evolution of the mean and the standard deviation of X_{max}. At $10^{18.2}$ eV a pure proton flux can be observed from the mean of the X_{max} with respect to a mixture of lighter primaries shown in the standard deviation in that energy bin.

2.2 Proton-air cross section (direct approach)

The proton-air cross section for particle production at the center of mass energy per nucleon of 57 eV has been derived from the distribution of the depth of the shower maxima [9]. X_{max} is strongly correlated with the first interaction depth, X_0. The distribution of X_0, for a fixed energy, is given by the cross section of proton-air interactions at that energy. To determine the measurement of the proton-air cross section a specific parameter, strictly related to the cross section, of the X_{max} distribution has been considered. This parameter, called Λ_η (where η denotes the fraction of the most deeply penetrating air showers), described the exponential shape of the tail of the X_{max} distribution, $\mathrm{d}N/\mathrm{d}X_{\mathrm{max}} \propto \exp(-X_{\mathrm{max}})/\Lambda_\eta$. The observable Λ_η for energy of $10^{18.24}$ eV was

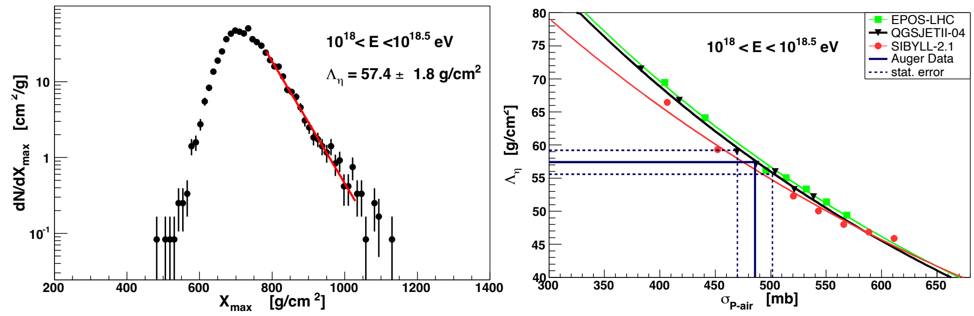

Figure 2: $X_{\max}$ distribution in the considered energy value as measured at the Pierre Auger Observatory. The red line corresponds to the unbinned log-likelihood fit performed to obtain the parameter Λ_η, which describes the tail of the distribution. (left) Conversion function between Λ_η and the proton-air cross section for the same energy interval and for different high-energy hadronic interaction models (right). Figures from [9, 10].

measured from the $X_{\max}$ distribution observed at the Pierre Auger observatory shown in Fig. 2 (left side) with the unbinned log-likelihood fit. To enhance the proton fraction in the considered data set, the $X_{\max}$-distribution includes a fraction $\eta = 0.2$ of the most deeply penetrating air shower. To convert the measured Λ_η and determine the proton-air cross section, the use of air shower simulation is required, which introduces some dependence on model assumptions. In particular, the effect of changing cross section empirically has been explored by multiplying all hadronic cross sections by an energy dependent factor that is unity below 10^{15} eV where the simulation models agree with the LHC data. For each interaction model the factor value is obtained in order to reproduce the measured value Λ_η. The resulting conversion functions for the different hadronic interaction models are shown in Fig. 2 (right side). The cross section obtained by projecting the measurement from Auger is $505 \pm 22(\text{stat})^{+28}_{-36}(\text{syst})$ mb.

3. Muon content distribution measured at ground

The number of muons is sensitive to hadronic interaction and also to the nature of the primary cosmic ray because the higher the mass of the primary cosmic ray, the more muons are produced. The number of muons, N_μ measured at ground is obtained by considering only inclined showers (exceeding 62°). For these showers, the electromagnetic component is mainly absorbed during the passage in the atmosphere, and the particles measured at the ground are dominated by the muon component. In Fig. 3, the average number of muons (left) and its relative fluctuation (right) as a function of energy are shown [11]. In particular, R_μ is the integrated number of muons at the ground divided by a reference value given by the average number of muons produced by proton initiated air-showers with energies of 10^{19} eV. The measurements are compared to simulations with proton (red curve) and iron (blue curve) primaries. It is clear that the average number of muons is not reproduced by simulations. For any hadronic interaction model the measured number of muons exceeds all the simulated predictions. This is the so-called muon deficit problem. On the other hand, the measurement of the relative fluctuations, that depend mainly to the first interaction, falls within the range that is expected from current high-energy hadronic interaction models. This agreement between models and data for the fluctuations combined with the deficit in the predicted number of muons, suggests that the origin of the models muon deficit consisting on a small

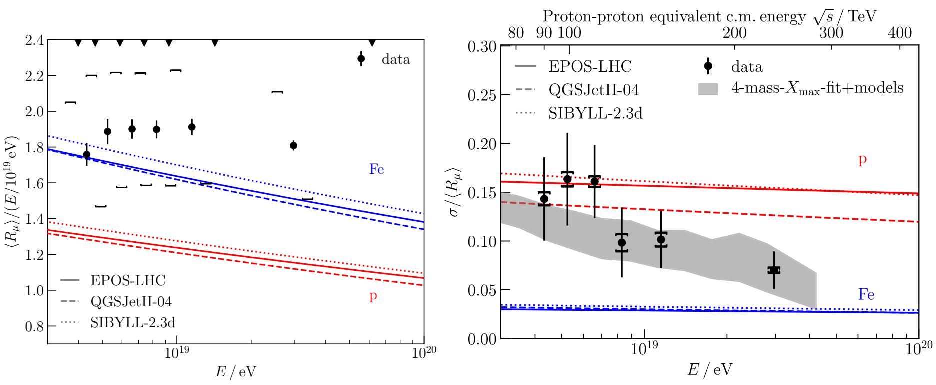

Figure 3: Energy evolution of the average number of muons (left) and its relative fluctuation (right) measured at the Pierre Auger Observatory for inclined showers. The results are compared to proton (red curve) and iron (blue curve) shower simulations. Figures from [11].

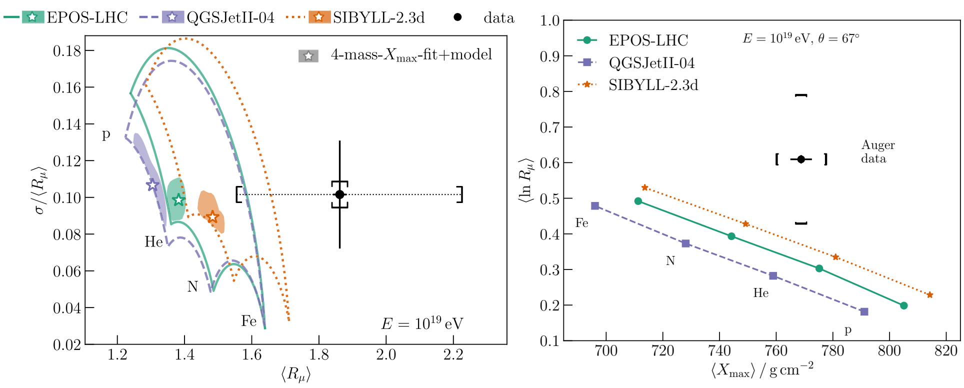

Figure 4: Data (black dot with error bars) compared to models for the fluctuations and the average number of muons. The simulated expected values are obtained for any mixture of four different primaries and are represented by the colored contours. The star symbols are obtained using the mass composition mixture derived from $X_{\max}$ measurements (left). Average logarithmic muon content as a function of the average shower depth (right). Figures from [11].

deficit at every stage of the shower that accumulates along the shower development, rather than a discrepancy in the first interaction. Adjustments to models to address the current muon deficit must therefore not alter the predicted relative fluctuations. Although increasingly disfavoured, if the deficit could be originating from the highest energy interactions, a possible interpretation could be found considering exotic phenomena. To compare directly the measured and simulated results for the average number of muons and its relative fluctuation, a certain energy value has to be taken into account. The result obtained for a primary energy of 10^{19} eV is shown in Fig. 4 (left side). Moreover, in Fig. 4, the effects of different composition scenario considering four different primaries (colored contours) on both the fluctuations and the average number of muon are shown. None of the predictions given by the hadronic interaction models and by the mass composition retrieved from $X_{\max}$ measurements (star markers), is consistent with the measurement (black dot) within the uncertainty. The increases in the average number of muons, necessary to reconcile the simulated values with the measurement, correspond to 26% for Sibyll2.3d, 35% for EPOS-LHC and to 43% for QGSJetII-04. From the comparison of the simulated and measured values of the mean

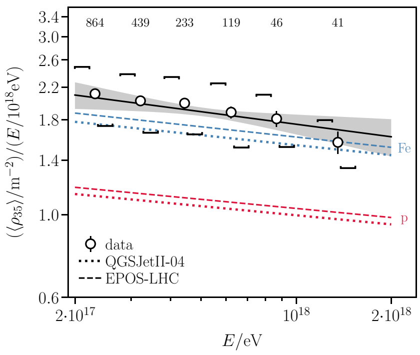

Figure 5: Energy-normalized densities as a function of E compared to the expectations for protons induced air showers (red curve) and iron induced air showers (blue curve). Figure from [15].

logarithmic muon content and the average maximum shower depth, shown in Fig. 4 (right side), it is worth noting that even though the simulated mean X_{max} is consistent with data, the muon content is not well reproduced. Therefore, the correction needed in the high-energy hadronic interaction models to reproduce the average number of muons would lead to a change in the X_{max} value and in the interpretation of the mass composition. In this regard, multivariate comparison between simulations and measurements, involving simultaneously the X_{max} values and the muon content, could reveal inconsistencies not clear from one dimensional analysis [12]. Furthermore, an upgrade of the observatory, AugerPrime, is currently being deployed [13]. Its main goal is the improvement of the measurement of the composition-sensitive observables allowing to disentangle the number of muon [14]. A deficit in the number of muons predicted by hadronic interaction models is also observed from the direct measurement of the muon density with buried muon counters [15]. The results are based on 1 year of calibrated data collected by the engineering array of the Auger Muons and Infill for Ground Array (AMIGA) Detector for showers above $10^{17.5}$ eV and zenith angle between 0° and 45°. In Fig. 5, it can be noticed that the observations suggest that the current hadronic interaction models fail to reproduce the measured number of muons. In particular, the simulations between $10^{17.5}$ eV and $10^{18.0}$ eV show that for EPOS-LHC an increase 38% is required at both the energies, while for QGSJetII-04 an increase of 50% and 53% is needed at each energy respectively.

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