Particle physics @ $\sqrt{s_{pp}} > 50$ TeV with the Pierre Auger Observatory

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The Pierre Auger Observatory in Argentina provides the largest data sample of the cosmic ray events with energy above $10^{18}$ eV. These high energy events can be used to test our understanding of the hadronic interactions at energies beyond the reach of colliders and to probe the basic properties of these interactions such as the inelastic cross-section of proton-air collisions. The combination of an array of surface detectors and the fluorescence telescopes of the Pierre Auger Observatory reduces significantly the dependency of the shower energy estimation on MC simulations. Despite that, the interpretation of mass sensitive quantities such as the shower maximum in terms of chemical composition of cosmic rays still depends on the hadronic interaction models. This contribution describes the main results of the observatory concerning the chemical composition of the cosmic rays and focuses on the problem of muon deficit in hadronic interaction models and on the estimation of proton-air cross-section from air-shower data.

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1 Introduction

The Pierre Auger Observatory is situated in the Argentinian province Mendoza, close to the city of Malargüe. It consists of a $3000 \text{ km}^2$ surface detector array and a set of $24(+3)$ fluorescence telescopes. The surface detector stations are water Cherenkov tanks each equipped with 3 photomultipliers measuring light induced by electromagnetic particles and muons. Six fluorescence telescopes occupy one fluorescence detector building. In total four of these buildings are located on the array border on small hills and thus overlook the interior of the array measuring the longitudinal profile of electromagnetic shower [1]. Already in the year 2008 the Observatory was fully completed with successful operation of all four fluorescence detector buildings and by fulfilling the original aim of 1600 deployed and working surface detector stations. During the next years several observatory enhancements were built such as 3 High Elevation Atmospheric Telescopes (HEAT) and AMIGA Infill both used to to lower the energy threshold below $10^{18}$ eV.

The Pierre Auger Collaboration reports many results in the field of ultra-high energy cosmic rays (UHECR). The energy spectrum with the observation of the rapid flux suppression above $5 \times 10^{19}$ eV [2], various studies of expected anisotropy of ultra-high energy events (eg. [3]) or the estimates of the upper limits on the cosmic-ray photon and the diffuse neutrino fluxes.
are among the most important scientific outcomes of this project. In this contribution we rather focus on the results that are related to particle physics. Namely, we concentrate on the estimation of the proton-air cross-section, the connection between the analysis of chemical composition of cosmic rays (CR) and the hadronic interaction models. We focus also on the muon deficit in current hadronic interaction models.

2 Proton-air cross-section

The number of particles in an Extensive Air Shower (EAS) as a function of the atmospheric slant depth (the amount of atmosphere traversed from its upper edge in g/cm$^2$) is called the shower longitudinal profile. Most of the EAS energy is released via the electromagnetic subshower. Therefore, as in the electromagnetic calorimeter the shower size increases until the average energy of the $e^{\pm}$ in the EAS is about the critical energy. The slant depth at which the longitudinal profile of a shower reaches its maximum is denoted as $X_{\text{max}}$ and it is one of the primary observables measured by the fluorescence detector. Measurements of $X_{\text{max}}$ can be used both to get insight into the composition of primary cosmic ray particles (showers induced by light particles penetrate deeper in the atmosphere than the showers originating from heavier nuclei) and also to measure the proton-air cross-section.

The differences in $X_{\text{max}}$ between showers of the same primary energy and same primary particle type are due to fluctuations in hadronic interactions. For purely proton primaries, the $X_{\text{max}}$ distribution is a convolution of the fluctuations in the shower development from the point of the first interaction to the shower maximum (dependent on the hadronic interactions) and the exponential distribution of the depth of the first interaction. For this reason the fitted slope $\Lambda_f$ of the tail of the $X_{\text{max}}$ distribution is (inversely) proportional to the inelastic cross-section of proton-air (see Fig. 1 - left).

The data were selected in the energy range $10^{18} - 10^{18.5}$ eV where the proton component is expected to dominate CR chemical composition. To avoid biases in the measured $X_{\text{max}}$ distribution fiducial volume cuts based on the shower geometry were applied. The largest source of systematic uncertainties is the lack of knowledge of the helium component. Uncertainties due to model assumptions were also addressed. For details see [6]. The value $\sigma_{\text{inel}}^{p\rightarrow\text{air}} = 505 \pm 22(\text{stat})^{+28}_{-36}(\text{syst})$ mb of inelastic proton-air cross-section was finally obtained at laboratory energy $E_{\text{lab}} = 10^{18.2\pm0.005(\text{stat})}$ eV and compared to results of previous CR experiments (Fig. 1 - right).

Using the Glauber model (with intermediate inelastic states included) the proton-air cross-section can be converted to proton-proton inelastic cross-section ($\sigma_{\text{pp}}^{\text{inel}}$) at $\sqrt{s}_{\text{pp}} = 57 \pm 0.3(\text{stat}) \pm 3(\text{syst})$ TeV. The conversion is illustrated in Fig. 2 (left) in the $\sigma_{\text{pp}}^{\text{inel}}, B_{el}$ plane where $B_{el}$ is the elastic slope. The obtained value of $\sigma_{\text{pp}}^{\text{inel}}$ is compared to results of LHC experiments and model predictions in Fig. 2 (right).

3 UHECR composition and hadronic interactions

Quantitative estimates of the mass composition of cosmic rays deduced from measured mass sensitive observables can be obtained only when distributions of these quantities are compared to predictions of hadronic interaction models for different primary particle types. Hadronic interaction models, when used to describe UHECR showers, naturally rely on uncertain extrap-
lations to an order of magnitude larger centre-of-mass energies than are the energies currently achievable at accelerators. Even now when hadronic interaction models are extensively tested and tuned at the LHC it is not obvious at which point the models reliability would be such that they can be universally used to unambiguously interpret UHECR shower data in terms of CR composition. For this reason the statements concerning the mass composition of cosmic rays have large uncertainties. The behavior of the $X_{\text{max}}$ distributions (e.g. their main characteristics $<X_{\text{max}}>$ and $\sigma(X_{\text{max}})$) strongly suggests that at energy $\sim 10^{18.4}$ eV the mean mass of CR components starts to increase [7, 8] (see Fig. 3). This conclusion is valid whatever model of hadronic interactions is compared to data of the Pierre Auger Observatory. In other words the only alternative explanation other than a sudden change of chemical composition deduced from the behavior of $X_{\text{max}}$ is that the hadronic interactions change at that energy and that the important parameters inside the hadronic interaction models (such as the cross-section) must behave very differently than expected. The problems of the measurement of UHECR chemical composition and studies of hadronic interaction models are thus coupled subjects which shall be addressed at the same time. The cross-study of both problems using the first two moments of the $X_{\text{max}}$ distribution ($<X_{\text{max}}>$ and $\sigma(X_{\text{max}})$) is presented in [9].

The situation gets even more complicated when other observables related to chemical composition are included. Namely, it was shown [10, 11, 12] that current models of hadronic interactions predict fewer muons at ground than what is actually observed at the Pierre Auger Observatory. Figure 4 shows an estimation of the relative number of muons in data normalized to predictions of QGSJETII-03 (Fig. 4 left) and QGSJETII-04 (Fig. 4 right) for proton primary particles at $10^{19}$ eV. The data are compared to predictions of two post-LHC interaction models QGSJETII-04 and EPOS-LHC for proton and iron nuclei as primary particles. The figures summarize the results of independent studies, one done for inclined showers, with zenith angles larger than 62° [10], and another for showers with zenith smaller than 60° [11] and using two different methods based on the time-structure of the surface detector signals to estimate the muon content of the shower. The mentioned independent methods together with the analysis of hybrid events [12] consistently indicate that the hadronic interaction models predict smaller size of the muon component than what is observed in the data unless pure iron composition is assumed. Such a heavy composition would be in contradiction with the $X_{\text{max}}$ data when interpreted using the same models. This leads to the conclusion that shower models do not correctly describe the muonic ground signal.

4 Conclusions

The data from extensive air shower measurements can be used to address problems of hadronic interactions at energies far from the reach of current accelerators. Namely the inelastic proton-air cross-section at $E_{\text{lab}}=10^{18.24}$ eV was estimated and converted to inelastic p-p cross-section at $\sqrt{s_{\text{pp}}}=57$ TeV. The estimation of the chemical composition of cosmic rays and the behavior of the hadronic interactions at ultra-high energies are coupled problems. However, using any current model of hadronic interactions to interpret the evolution of the measured $X_{\text{max}}$ distributions with energy, an increase of the mean mass of CR species is needed above $\sim 10^{18.4}$ eV. A muon deficit in the predictions based on current hadronic interaction models is observed when compared to the data of the Pierre Auger Observatory.
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Figure 1: Left: Dependency between the fitted slope ($\Lambda_{f}^{MC}$) of the $X_{\text{max}}$ distribution tail and the inelastic cross-section for several hadronic interaction models. The estimated slope is obtained by fitting the tail of the $X_{\text{max}}$ distributions by $dN/dX_{\text{max}} \sim \exp(-X_{\text{max}}/\Lambda_{f})$. Right: Resulting inelastic proton-air cross-section compared to other measurements and several hadronic interaction models.

Figure 2: Left: Correlation of elastic slope parameter, $B_{el}$, and the inelastic proton-proton cross section in the Glauber model. The solid line shows combinations of the parameters that yield the observed proton-air production cross section, and the dotted lines are the statistical uncertainties. The hatched area corresponds to the predictions by SIBYLL, QGSJET, QGSJETII, and EPOS. Right: Derived $\sigma_{pp}^{inel}$ together with model predictions and accelerator data.
Figure 3: Evolution of $X_{\text{max}}$ (left) and $\sigma(X_{\text{max}})$ (right) as a function of energy [8]. Measurements are from the hybrid data set. Data (points) are shown with the predictions for protons and iron nuclei as primary particles for several hadronic interaction models.

Figure 4: Left: Average value of muon number (scaled to $E = 10^{19}$ eV) $R_{\mu}/(E_{FD}/10^{19}$ eV) relative to prediction of QGSJETII-03 (protons) as a function of shower energy. Theoretical curves for proton and iron showers simulated with QGSJetIII-04 and EPOS-LHC are shown for comparison. Open circles indicate the result if the FD energy scale is varied by its systematic uncertainty. The gray thick error bars indicate the systematic uncertainty of $R_{\mu}$. Right: The measured muon signal rescaling at $E = 10^{19}$ eV and at 1000 m from the shower axis vs. zenith angle, with respect to QGSJETII.04 proton as baseline. The rectangles represent the systematic uncertainties, and the error bars represent the statistical uncertainties added to the systematic uncertainties. The points for Auger data are artificially shifted by $\pm 0.5$ for visibility.