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Extension of the measurement of the proton-air cross section with the Pierre Auger Observatory

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With hybrid data of the Pierre Auger Observatory it is possible to measure the cross section of proton-air collisions at energies far beyond the reach of the LHC. Since the first measurement by the Pierre Auger Collaboration the event statistics has increased significantly. The proton-air cross section is now estimated in the two energy intervals in $\lg(E/\mathrm{eV})$ from 17.8 to 18 and from 18 to 18.5. These energies are chosen so that they maximise the available event statistics and at the same time lie in the region most compatible with a significant primary proton fraction. Of these data, only the 20% of most proton-like events are considered for the measurement. Furthermore, with a new generation of hadronic interaction models which have been tuned to LHC data, the model-dependent uncertainties of the measurement are re-visited.

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1. Introduction

The cross section of cosmic ray protons with air is derived from data collected with the Pierre Auger Observatory [1] at energies far beyond the reach of human-made particle accelerators. The evolution of the hadronic cross section with energy is a fundamental property of nature and can still not be calculated from first principles of the theory of quantum chromodynamics. The measurement of general particle-collision properties at ultra-high energies is a tool for the search of new physics.

In this paper the extension of the measurement of the proton-air cross section of the Pierre Auger Collaboration at 57 TeV [2] is presented. The technique has been kept identical. Significantly more data has become available and, due to improved external input, several sources of systematic uncertainty are re-visited. The 20% most deeply penetrating showers are used for the analysis in order to reduce the impact of primary cosmic ray nuclei heavier than protons. Since the measurement is sensitive only to the cross section of interactions that produce secondary particles, the quasi-elastic excitation of the target nuclei is not included in the measured cross section. The observable cross section is, thus, defined as $\sigma_{\rm prod} = \sigma_{\rm inel} - \sigma_{\rm q-el}$. Hybrid events are selected with a uniform acceptance over the full phase-space of the measurement.

The number of hybrid events available for the measurement has increased in total by a factor of about four. The range in primary energies is increased and the result is presented in the two regions $10^{17.8} - 10^{18}$ eV and $10^{18} - 10^{18.5}$ eV. The reason to chose this limited energy region is driven by the fact that in this interval the data of the Pierre Auger Observatory is compatible with a very high content of primary protons [3]. Besides the fact of more events and thus a smaller statistical uncertainty, also the systematic uncertainties are re-visited. Most importantly the impact of the first models tuned to LHC data (EPOS-LHC [4] and QGSJetII.4 [5]) on the analysis is demonstrated in respect to the same models before they were tuned to LHC data (EPOS-1.99 [6] and QGSJetII.3 [7]). The SIBYLL 2.1 [8] model is kept as a constant reference. A new release of SIBYLL, which will also be tuned with LHC data, will eventually complete this study and will be done as soon as the model becomes available for air shower simulations.

2. Experiment, data and simulations

The Pierre Auger Observatory currently has the largest aperture for the detection of ultra-high energy cosmic ray particles in the energy range from just above the second knee up to the highest accessible energies. The observatory is located near the town of Malargüe in Argentina and consists of two major components: Firstly, the surface detector, build by 1660 autonomous water-Cherenkov stations, is spread over a surface area of 3000 km^2 on a triangular grid with 1.5 km spacing. Secondly, five fluorescence telescope sites are overlooking the surface detector with a total of 27 Schmidt-optics telescopes. Light is focused by spherical mirrors of 12 m^2 area and 3.7 m radius on cameras build of 440 PMTs. The 24 telescopes with a field of view ranging from 1.5 to 30 degree in elevation are used for this analysis.

Hybrid data contains information from the fluorescence telescopes as well as from at least one surface detector station. This includes events below the trigger threshold of the surface detector by initiating the readout based on the trigger from the fluorescence telescopes. The reconstruction of hybrid events uses the timing from the surface detector to precisely determine the geometry of the shower. The light collected by the telescopes is corrected for all known effects to yield the energy deposit profile along the shower axis in the atmosphere [9]. The slant depth along the shower axis where the maximum energy deposit is observed, $X_{\max}$, is the main observable of this study.

The dataset used for the measurement comprises events collected from Dec 2004 to Dec 2012. Simulations of air showers are performed with the CONEX simulation program [10]. In these simulations the initial part of the air shower cascade is simulated in full 3D Monte Carlo mode, and as soon as secondary particle energies drop below $0.001E_0$, where E_0 is the primary cosmic ray energy, the simulation is completed with cascade equations. Hadronic interactions can be simulated with different event generators. For this purpose EPOS-LHC and QGSJetII.4, which both have been tuned to LHC data up to $\sqrt{s} = 8\,\text{TeV}$, as well as SIBYLL 2.1, which has not yet been tuned to LHC data, are used. The impact of the extrapolation of the description of hadronic interactions in air showers on the analysis is estimated based on these different models, and ad-hoc modifications of them. Each model comprises a set of different but self-consistent phenomenological and theoretical assumptions to describe hadronic interactions. EPOS is build from a parton-based Gribov-Regge theory with energy-conservation considered during the multiple-pomeron exchange. Many features of hadronic interactions like diffraction and remnant fragmentation are added in a phenomenological approach. QGSJetII is driven by the theory of multi-Pomeron amplitues calculated to all orders. This yields a theoretically clean description of diffraction up to high masses. SIBYLL is a minijet model combined with a Glauber calculation, where diffraction is added in phenomenological way. It is a big advantage to use a set of models which are internally so different in nature. It allows us to derive an estimate of the systematic uncertainties related to details of the description of hadronic interactions on the proton-air cross section measurement.

The limited acceptance caused by the field-of-view of the telescope detectors as well as by the absorption of light in the atmosphere is taken into account as described in Ref. [11]. In this way a measurement of the complete $X_{\max}$-distribution is obtained free of acceptance effects. This is achieved by accepting showers only when the range in slant depth along the shower axis, where the shower can be detected with an expected $X_{\max}$-resolution of better than $40\,\text{g/cm}^2$, does fully comprise the $X_{\max}$-interval required for the measurement. Furthermore, the resolution of the detector is taken into account by folding the Monte Carlo simulations with the parameterisation given in Ref. [11].

3. Analysis strategy and event selection

The analysis consists of two subsequent parts. The first step is the dedicated measurement of the observable Λ_η, which is a measure of the attenuation length of air showers in the atmosphere. The advantage of this well defined and dedicated measurement of Λ_η is that this observable can be eventually used also in a different context, and it can be re-evaluated at any later time with new air shower simulation models. The second analysis part is related to the conversion of Λ_η into the proton-air cross section $\sigma_{\text{p}-\text{air}}$. This depends on the simulation of air showers and hadronic interactions therein.

The total number of high-quality hybrid events in the data sample used for the measurement is 39360. Event quality cuts are applied as described in Ref. [11]. The depth of the maximum

Table 1: Measurement of Λ_η and $\sigma_{\mathrm{p-air}}$ in the two energy regions. Statistical uncertainties are quoted in the same line, while systematic uncertainties are listed explicitly.

	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
Number of high-quality hybrid events	18090	21270
Determination of the 20% tail range		
Range of 99.8% central X_{max}-values (g/cm^2)	$556.6 - 1009.7$	$573.3 - 1030.1$
Fiducial selection of 99.8% central range, events	1818	2807
Start of 20% tail range, $X_{\eta,\mathrm{start}}$ (g/cm^2)	762.2	782.4
Fiducial selection of 20% tail range, number of events	4847	6906
Λ_η determination		
Number of events in tail range	1196	1384
Power-law slope of energy distribution	-0.65 ± 0.31	1.85 ± 0.28
Average energy (eV)	$10^{17.90}$	$10^{18.22}$
Corresponding $\sqrt{s_{\mathrm{pp}}}$ (TeV)	38.7	55.5
Energy scale uncertainty on $\sqrt{s_{\mathrm{pp}}}$ (TeV)	2.5	3.6
Λ_η (g/cm^2)	60.7±2.1	57.4±1.8
Λ_η, systematic uncertainties (g/cm^2)	1.6	1.6
$\sigma_{\mathrm{p-air}}$ determination		
EPOS-LHC (mb)	466.1	494.1
QGSJetII.04 (mb)	458.7	487.9
SIBYLL 2.1 (mb)	447.8	475.3
Central value, all models (mb)	457.5±17.8	485.8±15.8
$\sigma_{\mathrm{p-air}}$ uncertainties		
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\mathrm{p-air}}$ (mb)	7	7
Photons (mb)	4.7	4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\mathrm{p-air}}$ (mb)	+19/-25	+19/-25

energy deposit, X_{max}, can be reconstructed with a resolution of 25.0 ± 1.1 g/cm^2 at $10^{17.8}$ eV and 18.6 ± 1.1 g/cm^2 at $10^{18.5}$ eV. This includes uncertainties e.g. from the atmospheric density profile.

The available data sample is divided into two energy intervals, one ranging from $10^{17.8}$ to 10^{18} eV and the other from 10^{18} to $10^{18.5}$ eV with 18090 and 21270 events, respectively. All steps and results of the analysis are summarized in Tab. 1.

4. Measurement of Λ_η

In both energy ranges selected for the measurement the X_{max}-range is determined independently in a two step procedure. First, the X_{max}-interval containing the 99.8% most central events

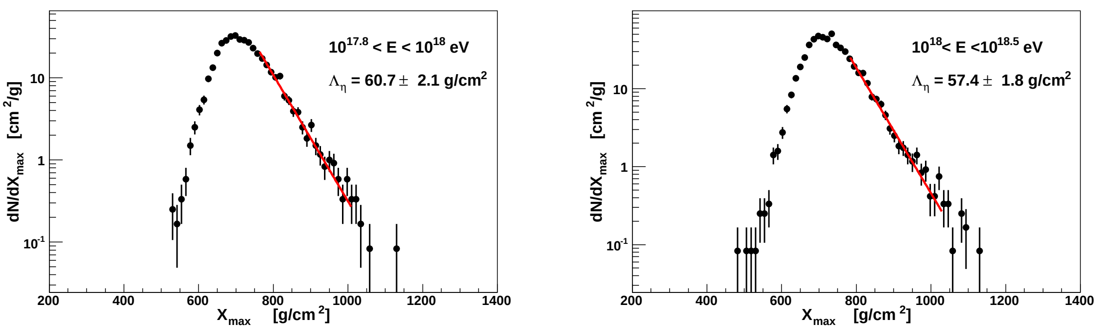

Figure 1: The X_{max}-distributions in the two energy intervals. The result of the unbinned log-likelihood fit to derive Λ_η is shown in the range of the tail fit.

is identified, and only showers with an unbiased X_{max} measurement within this range are considered. This provides the best possible estimate of the shape of the whole X_{max}-distribution, but with a significant cost in terms of available event statistics. This distribution is used to determine the X_{max}-intervals containing the 20% most deeply penetrating showers.

Given this X_{max}-interval, the event selection is updated by only requiring an unbiased X_{max}-measurement in the tail region of the distribution. This step increases the available statistics for the measurement of Λ_η by a factor of about three. At this stage the X_{max}-distributions exist containing the unbiased tail from $X_{\eta,\mathrm{start}} = 762.2\,\mathrm{g/cm^2}$ to $X_{\eta,\mathrm{end}} = 1009.7\,\mathrm{g/cm^2}$ for the $10^{17.8} - 10^{18}$ eV range and $X_{\eta,\mathrm{start}} = 782.4\,\mathrm{g/cm^2}$ to $X_{\eta,\mathrm{end}} = 1030.1\,\mathrm{g/cm^2}$ for the $10^{18} - 10^{18.5}$ eV range. The upper end of the fit-range, chosen to exclude 0.1% of all available showers, also reduces the sensitivity to any possible primary photon contribution.

Due to the nature of the analysis, where the exponential tail of a distribution is measured, it is crucial to consider the Poissonian fluctuations of the data. This is achieved by numerically optimizing the following unbinned log-likelihood function for the Λ_η parameter

$$\log L = \sum_{i=1}^{N_{\mathrm{evts}}} \log p(X_{\mathrm{max},i};\Lambda_\eta) \qquad \text{with} \tag{4.1}$$

$$p(X_{\mathrm{max}};\Lambda_\eta) = \left[\Lambda_\eta \left(\mathrm{e}^{-X_{\eta,\mathrm{start}}/\Lambda_\eta} - \mathrm{e}^{-X_{\eta,\mathrm{end}}/\Lambda_\eta}\right)\right]^{-1} \mathrm{e}^{-X_{\mathrm{max}}/\Lambda_\eta}\ . \tag{4.2}$$

The statistical uncertainty of the result is determined using the values of Λ_η where the likelihood exceeds $\log L_{\mathrm{min}}$+0.5. For simulated showers the default choice of $X_{\eta,\mathrm{end}} = \infty$ is used, which analytically yields the optimal result $\Lambda_\eta^{\mathrm{opt,MC}} = \sum_{i=0}^{N_{\mathrm{evts}}} (X_{\mathrm{max},i} - X_{\eta,\mathrm{start}})/N_{\mathrm{evts}}$, and the uncertainty can be derived from error propagation. The fit-range as well as the result is shown in Fig. 1.

The stability of the measurement of Λ_η from data is tested by subdividing the data sample according to the zenith angle and to the distance of showers. The event selection cuts are changed within their experimental uncertainties. The observed variation of Λ_η are consistent with statistical fluctuations. The standard deviation of these various observed deviations is considered as a systematic uncertainty for the measurement of Λ_η.

5. Determination of $\sigma_{\mathrm{p-air}}$

The value of $\sigma_{\mathrm{p-air}}$ is derived from the comparison of $\Lambda_\eta^{\mathrm{MC}}$, as calculated from full Monte

Carlo simulations of air showers, with the measured value of Λ_η. Air showers are generated with the same energy distribution as found in data as well as smeared with the X_{max} and energy resolution of the Pierre Auger Observatory. By default, none of the hadronic interaction models used for the air shower simulations is able to reproduce the measurement. For the purpose of the proton-air cross section measurement we exploit the fact that only the extrapolation of $\sigma_{\text{p-air}}$ can significantly affect Λ_η^{MC}. It is an important feature of this analysis that a change of $\sigma_{\text{p-air}}$ is not just considered for the first interaction of the cosmic ray primary particle in the atmosphere, but also for all subsequent hadronic interactions at lower energies in a self-consistent way. For this purpose the energy-dependent scaling factor [12]

$$F(E,\, f_{19}) = 1 + (f_{19} - 1)\, \frac{\log(E/E_{\text{thr}})}{\log(10^{19}\,\text{eV}/E_{\text{thr}})} \tag{5.1}$$

is used, where f_{19} is the value of the scaling at 10^{19} eV and E_{thr} is the threshold above which $F(E,\, f_{19}) \neq 1$. EPOS-LHC and QGSJetII.04 are both tuned up to cross sections measured by the TOTEM experiment at $\sqrt{s} = 8$ TeV [13], while SIBYLL 2.1 is tuned to Tevatron at $\sqrt{s} = 1.96$ TeV. The latter corresponds to primary cosmic ray protons of $E_{\text{cr}} \approx 10^{16.5}$ eV and the former to $E_{\text{cr}} \approx 10^{15}$ eV. Thus, for EPOS-LHC and QGSJetII.04 $E_{\text{thr}} = 10^{16.5}$ eV and for SIBYLL 2.1 $E_{\text{thr}} = 10^{15}$ eV is used. The results obtained with these simulations are shown in Fig. 2 and are used to convert the measured Λ_η into values of $\sigma_{\text{p-air}}$. The results for EPOS-LHC, QGSJetII.04 and SIBYLL 2.1 are summarized in Tab. 1. The central value for all three models is 457.5 mb at $10^{17.9}$ eV and 485.8 mb at $10^{18.2}$ eV. The model uncertainty is estimated to be 10 mb for both energies. As long as the LHC-tuned SIBYLL model is not available, SIBYLL 2.1 is used as the third model in order to estimate the model dependence of the analysis approach. The modelling of interactions in air shower cascades is still a process with significant inherent uncertainties. Many phenomenological assumptions and parameters are part of any interaction model. The physics of diffraction, fragmentation, inelastic intermediate states, nuclear effects, QCD saturation, etc. are all described at different levels using different, but self-consistent, approaches in these models. It is not known whether by using these three different interaction models the true range of uncertainties of the modelling of hadronic interactions in air showers is covered. Thus, additional studies are done to investigate this. Characteristic features of hadronic interactions that are known to be particularly important for the air shower development have been studied independently. The secondary multiplicity, the inelasticity, the pion charge-ratio, as well as a separate scaling of the $\sigma_{\pi\text{-air}}$ have been modified inside the models to determine the impact on Λ_η^{MC}. Of those parameters, only the elasticity is found to have a potential relevance. The current level of systematic uncertainties of $\sigma_{\text{p-air}}^{\text{prod}}$ of 10 mb corresponds to altering the elasticity by about 10 %. Furthermore, the extreme assumption that the cross section of pions with air is modified in a different way as for protons with air by a factor two, is also checked. The effect on $\sigma_{\text{p-air}}^{\text{prod}}$ analysis is < 1% and is, thus, negligible.

For the conversion of Λ_η to $\sigma_{\text{p-air}}$ also other parameters are important. Scaling the simulated showers by the energy scale uncertainty of the Pierre Auger Observatory of 14% leads to a different conversion as well as changing the X_{max}- and energy-resolution. Varying these within their precision yields an overal effect on $\sigma_{\text{p-air}}^{\text{prod}}$ of less than 7 mb for both energy regions.

While the composition of primary cosmic rays in the energy range under investigation is compatible with being dominated by protons, a contamination with Helium cannot be excluded. In

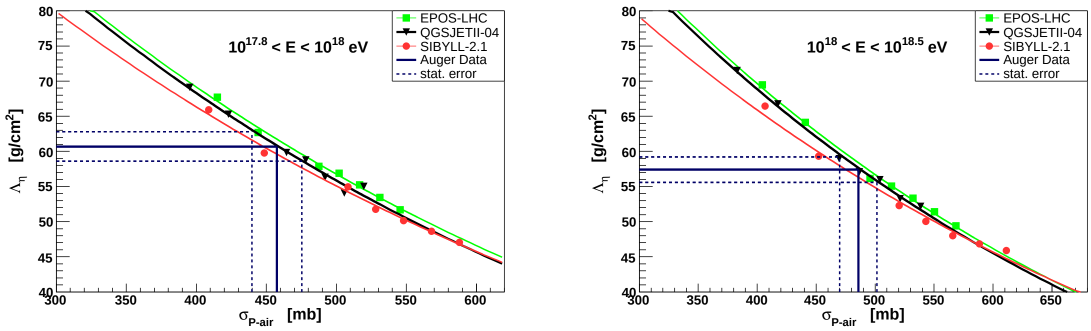

Figure 2: Conversion of Λ_η to $\sigma_{\text{p-air}}$. The simulations includes all detector resolution effects, while the data is corrected for acceptance effects. The solid and dashed lines show the Λ_η measurement and its projection to $\sigma_{\text{p-air}}$ as derived using the average of all models.

earlier studies it was shown that primary particles heavier than Helium have only negligible impact on the analysis. The consequence of helium on the result is studied with simulations by producing samples of mixed proton-helium composition and testing the response of the analysis. There are indications that the helium content in the used data is not larger than on the order of 25% [3], which is also the number used in the past for this purpose. The impact of 25% helium on the cross section result is thus considered as systematic uncertainty towards smaller values of $\sigma_{\text{p-air}}$. The contamination with primary photons is excluded to be larger than 0.5% in the energy range under investigation [14] and the impact on the cross section is added as systematic uncertainty towards larger values of $\sigma_{\text{p-air}}$.

6. Results and summary

An updated measurement of the proton-air cross section with hybrid data of the Pierre Auger Observatory is presented. The result is shown in Fig. 3 and compared to previous measurements and model predictions. With respect to the previous measurement, the number of events is increased by about a factor of four. The measured value of $\Lambda_\eta = 57.4 \pm 1.8\,\text{g/cm}^2$ in the energy range $10^{18} - 10^{18.5}$ eV is within 0.5 standard-deviations from the previous measurement. The statistical uncertainty of the measurement is consistent with a scaling by $1/\sqrt{N}$.

New hadronic interaction models, EPOS-LHC and QGSJetII.04, which are tuned to LHC data, are used for the conversion of Λ_η to $\sigma^{\text{prod}}_{\text{p-air}}$. It is interesting to note, that the difference between these two models has changed by almost a factor of two with respect to the models prior to tuning to LHC data (EPOS-1.99 and QGSJetII.03). However, currently we keep also the SIBYLL 2.1 model as part of the analysis in order to get a more diverse estimation of the underlying modeling uncertainties. Since SIBYLL has not changed with respect to the previous analysis and both EPOS-LHC as well as QGSJetII.04 consitently predict larger values of $\sigma_{\text{p-air}}$, the use of SIBYLL 2.1 leads to a slightly smaller central value of the final measurement and, even more relevant, a larger model-dependence. This will be revisited as soon as the next version of SIBYLL, also tuned to the LHC data, will be released for air shower simulations. It is a very interesting question, whether the trend observed with EPOS and QGSJetII continues and the overal model-dependence is further reduced.

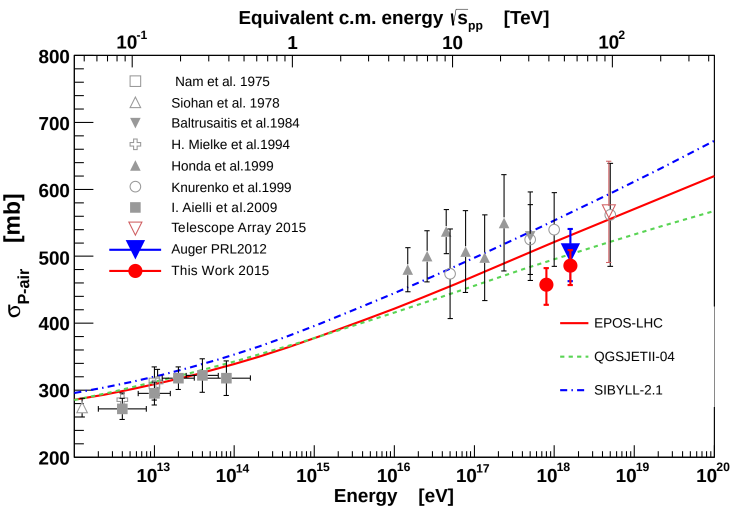

Figure 3: The σ_{p-air}-measurement compared to previous data and model predictions. For references see [2] and [15].

For the present measurement the data is split in two energy intervals. The data is consistent with a rising cross section with energy, however, the statistical precision is not yet sufficient to make a statement on the functional form.

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