



Estimate of the proton-air cross-section with the Pierre Auger Observatory

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Abstract: Using the tail of the distribution of the depth of shower maxima observed with the Pierre Auger Observatory, we derive an estimate of the proton-air cross-section for particle production at center-of-mass energies of 57 TeV. Air showers observed with the fluorescence detector and at least one station of the surface detector array are analysed in the energy range from 10^{18} to $10^{18.5}$ eV. Systematic uncertainties in the cross-section estimate arising from the limited knowledge of the primary mass composition, the need to use shower simulations and the selection of showers are studied in detail.

Keywords: Proton-air, Cross-section, Pierre Auger Observatory

1 Introduction

One of the biggest challenges towards a better understanding of the nature of ultra-high energy cosmic rays is to improve the modeling of hadronic interaction in air showers. Currently, none of the models is able to consistently describe cosmic ray data, which most importantly prevents a precise determination of the primary cosmic ray mass composition.

Studies to exploit the sensitivity of cosmic ray data to the characteristics of hadronic interactions at energies beyond state-of-the-art accelerator technology began over 50 years ago. While first measurements were based on the direct observation of cosmic ray particles [1], the rapidly shifting focus towards higher energies required the use of extensive air shower observations [2,3]. The property of interactions most directly linked to the development of extensive air showers is the cross-section for the production of hadronic particles (e.g. [4,5]).

We present the first analysis of the proton-air cross-section based on hybrid data from the Pierre Auger Observatory. For this purpose we analyse the shape of the distribution of the largest values of the depth of shower maxima, X_{\max} , the position at which air showers deposit the maximum energy per unit of mass of atmosphere traversed. This *tail* of the X_{\max} -distribution is very sensitive to the proton-air cross-section, a technique first exploited in the pioneering work of Fly's Eye [3]. To obtain accurate measurements of X_{\max} , the timing data from the fluorescence telescopes is combined with that from the surface detector array for a precise reconstruction of the geometry of events.

An over-riding concern of the analysis has been the assignment of realistic systematic uncertainties to the result. We recognise and identify the unknown mass composition of cosmic rays as *the* major source of systematic uncertainty for the proton-air cross-section analysis and we evaluate its impact on the final result. The analysis is optimised to minimise the impact of contamination by the presence of particles other than protons in the primary beam.

2 Analysis approach

The method used to estimate the proton-air cross-section is the comparison of an appropriate air shower observable with Monte Carlo predictions. A disagreement between data and predictions is then attributed to a modified value of the proton-air cross-section. The present analysis is a two-step process.

Firstly, we measure an air shower observable with high sensitivity to the cross-section. Secondly, we convert this measurement into an estimate of the proton-air cross-section for particle production, σ_{p-air} , in the energy interval 10^{18} to $10^{18.5}$ eV. The selection of this energy range has the following advantages and features:

Statistics: A large number of events are recorded.

Composition: The shape of the X_{\max} -distribution is compatible with there being a substantial fraction of protons in the cosmic ray beam. The situation is less clear at higher energies.

Energy: The average center-of-mass energy for a cosmic ray proton interacting with a nucleon in the atmosphere

is 57 TeV, significantly above what will be reached at the LHC.

As the primary observable we define Λ_f via the exponential shape $dN/dX_{\max} \propto \exp(-X_{\max}/\Lambda_f)$ of the X_{\max} -distribution of the fraction f of the most deeply penetrating air showers. Considering only these events enhances the contribution of protons in the sample as the average depth at which showers maximise is higher in the atmosphere for non-proton primaries.

The choice of the fraction f is a crucial part of the definition of the observable Λ_f . While a small value of f will enhance the proton fraction, since protons penetrate most deeply of all primary nuclei, it also reduces the number of events for the analysis. By varying f we investigate how much the bias due to non-proton induced showers can be reduced without statistical uncertainties being dominant. Following these studies we have chosen $f = 20\%$ so that for helium-fractions up to 15% biases induced by helium are kept below the level of the statistical resolution. At the same time this choice suppresses elements heavier than helium very efficiently.

3 The Measurement of Λ_f

We use events collected between December 2004 and September 2010. The atmospheric and event-quality cuts applied are identical to those used for the analysis of $\langle X_{\max} \rangle$ and $\text{RMS}(X_{\max})$ [6, 8]. This results in 11 628 high quality events between 10^{18} and $10^{18.5}$ eV.

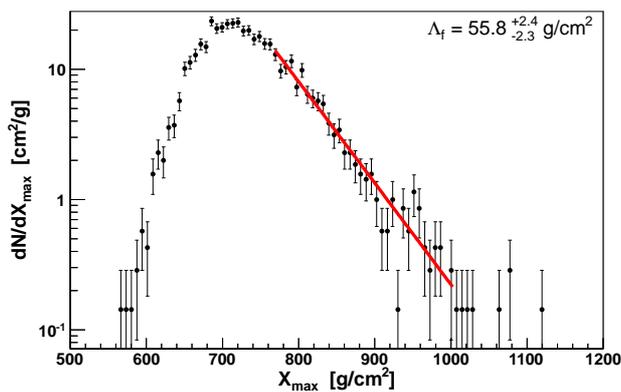


Figure 1: Unbinned likelihood fit of Λ_f to the tail of the X_{\max} distribution.

The X_{\max} distribution of the data is affected by the known geometrical acceptance of the fluorescence telescopes as well as by detection limitations related to atmospheric light transmission. The impact of the telescope acceptance on the X_{\max} distribution is well understood and can be studied by using data (see [8]) and with detailed Monte Carlo simulations of the shower detection process. In the following we use the strategy developed for the measurement of

the $\langle X_{\max} \rangle$ and $\text{RMS}(X_{\max})$ [6, 8] to extract a data sample that has an unbiased X_{\max} distribution.

In the first step we derive the range of values of X_{\max} that corresponds to the deepest $f = 20\%$ of the measured showers. We select only event geometries that allow, for each shower, the complete observation of the slant depth range from 550 to 1004 g/cm^2 , which corresponds to 99.8% of the observed X_{\max} -distribution. These fiducial volume cuts reduce the data sample to 1635 events, providing a good estimate of the unbiased X_{\max} -distribution. This distribution is then used to find the range of values of X_{\max} that contains the 20% deepest showers, which is identified to extend from 768 to 1004 g/cm^2 . Due to the limited statistics involved in this range estimation, there is a $\pm 1.5 \text{ g}/\text{cm}^2$ uncertainty on the definition of the range of the tail, which will be included in the estimation of the systematic uncertainties.

In the second step we select those events from the original data sample of 11 628 high quality events that allow the complete observation of values of X_{\max} from 768 to 1004 g/cm^2 , corresponding to the 20%-tail of the unbiased distribution. This is a more relaxed fiducial volume cut since we are not requiring that a shower track can be observed at depths higher in the atmosphere than 768 g/cm^2 , which maximises the event statistics and still guarantees an unbiased X_{\max} distribution in the range of interest. In total there are 3082 showers passing the fiducial volume cuts, of which 783 events have their X_{\max} in the selected range and thus directly contribute to the measurement of Λ_f . The average energy of these events is $10^{18.24}$ eV, corresponding to a center-of-mass energy of $\sqrt{s} = 57$ TeV in proton-proton collisions.

In Fig. 1 we show the data and the result of an unbinned maximum likelihood fit of an exponential function over the range 768 to 1004 g/cm^2 . This yields

$$\Lambda_f = (55.8 \pm 2.3_{\text{stat}} \pm 0.6_{\text{syst}}) \text{ g}/\text{cm}^2. \quad (1)$$

The systematic uncertainty arises from the precision with which the range of depths that are used can be defined.

Values of Λ_f have been calculated for modified event selections and for different ranges of atmospheric depths. It is found that the changes in Λ_f lie within the statistical uncertainties. The re-analysis of sub-samples selected according to zenith-angle, shower-telescope distance and energy produces variations of the value of Λ_f consistent with statistical fluctuations. We conclude that the systematic uncertainties related to the measurement are below 5%.

4 Determination of the cross-section

We must resort to Monte Carlo simulations to derive an estimate of the proton-air cross-section from the measurement of Λ_f . These have been made using the same energy distribution as in the data, and the events from the simulations have been analysed with the identical procedures used for the data.

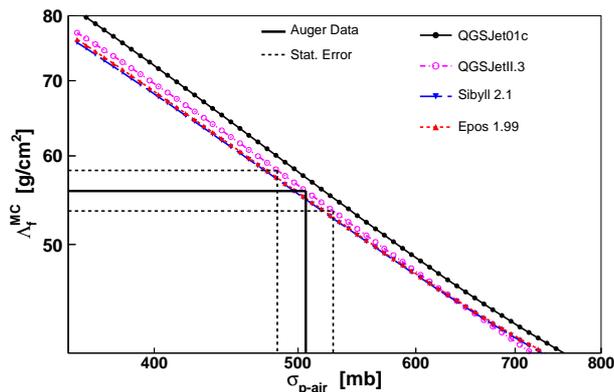


Figure 2: Relation between Λ_f^{MC} and σ_{p-air} . As example we show the conversion of the measurement $\Lambda_f^{MC} = \Lambda_f$ with the QGSJetII model.

Table 1: Cross-sections derived from the measured Λ_f using different interaction models. The given uncertainties are statistical only. The rescaling factor, $m(E, f_{19})$, is a measure of how much the original cross-section of the model have to be changed.

Model	Rescaling factor at $10^{18.24}$ eV	σ_{p-air}/mb
QGSJet01	1.04 ± 0.04	524 ± 23
QGSJetII.3	0.95 ± 0.04	503 ± 22
SIBYLL 2.1	0.88 ± 0.04	497 ± 23
EPOS 1.99	0.96 ± 0.04	498 ± 22

In general, the Monte Carlo values of Λ_f^{MC} do not agree with the measurement. It is known from previous work that the values of Λ_f^{MC} derived from simulations are directly linked to the hadronic cross-sections used in the simulations. Accordingly we can explore the effect of changing cross-sections in an empirical manner by multiplying the cross-sections that are input to the simulations by an energy-dependent factor [7]

$$m(E, f_{19}) = 1 + (f_{19} - 1) \frac{\lg(E/10^{15} \text{ eV})}{\lg(10^{19} \text{ eV}/10^{15} \text{ eV})}, \quad (2)$$

where E denotes the shower energy and f_{19} is the factor by which the cross-section is rescaled at 10^{19} eV. The rescaling factor is unity below 10^{15} eV reflecting the fact that measurements of the cross-section at the Tevatron were used for tuning the interaction models. This technique of modifying the original cross-sections predictions during the Monte Carlo simulation process assures a smooth transition from accelerator data up to the energies of our analysis. For each hadronic interaction model, the value of f_{19} is obtained that reproduces the measured value of Λ_f . The cross-section is then deduced by multiplying the factor Eq. (2) to the original model cross-section.

In Fig. 2 we show the conversion curves for simulations based on the four most commonly used high-energy hadronic interaction models for air shower simu-

lations (Sibyll2.1 [9], QGSJet01 [10], QGSJetII.3 [11] and EPOS1.99 [12]).

The need to use Monte Carlo calculations introduces model-dependence to this section of the analysis. It is known that other features of hadronic interactions, such as the multiplicity and elasticity, have an impact on air shower development [4, 5]. We use the very different multiparticle production characteristics of the four models to sample the systematic effect induced by these features.

The proton-air cross-sections for particle production derived are given in Table 1. Only SIBYLL needs to be modified with a rescaling factor significantly different from unity to describe the tail of the measured X_{max} distribution. The systematic uncertainty of 22% [13] in the absolute value of the energy scale leads to systematic uncertainties of 7 mb in the cross-section and 6 TeV in the center-of-mass energy.

Furthermore, the simulations needed to obtain σ_{p-air} from the measured Λ_f as shown in Fig. 2 depend on additional parameters. By varying for example the energy distribution, energy and X_{max} resolution of the simulated events, we find that related systematic effects are below 7 mb.

The average depth of X_{max} of showers produced by photons in the primary beam at the energies of interest lies about 50 g/cm^2 deeper in the atmosphere than for protons. The presence of photons would bias the measurement. However, observational limits on the fraction of photons are $< 0.5\%$ [14, 15] and the corresponding underestimation of the cross-section is less than 10 mb.

With the present limitations of air shower observations, it is impossible to distinguish showers that are produced by helium nuclei from those created by protons. Accordingly, lack of knowledge of the helium fraction leads to a significant systematic uncertainty. From simulations we find that σ_{p-air} is overestimated by 10, 20, 30, 40 and 50 mb for percentages of helium of 7.5, 20, 25, 32.5 and 35% respectively. We find that CNO-group nuclei introduce no bias for fractions up to $\sim 50\%$, thus we assign no systematics on the cross-section for it.

In Table 2, where the systematic uncertainties are summarised, we quote results for 10, 25 and 50% of helium.

Table 2: Summary of the systematic uncertainties.

Description	Impact on σ_{p-air}
Λ_r systematics	± 6 mb
Hadronic interaction models	$^{+16}_{-9}$ mb
Energy scale	± 7 mb
Simulations and parameterisations	± 7 mb
Photons, $< 0.5\%$	$< +10$ mb
Helium, 10%	-12 mb
Helium, 25%	-30 mb
Helium, 50%	-80 mb
Total (w/o composition)	-15 mb, +20 mb

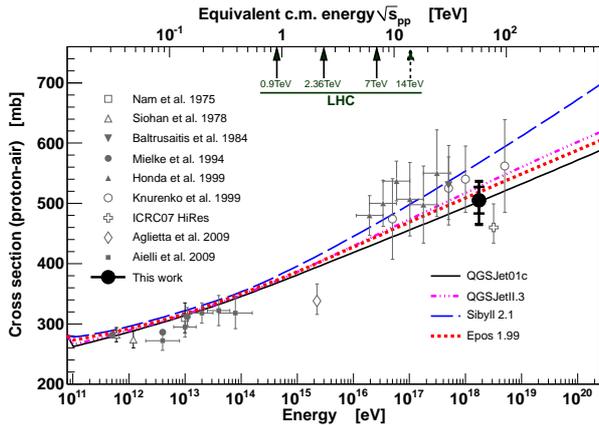


Figure 3: Resulting $\sigma_{p\text{-air}}$ compared to other measurements [1–3] and model predictions. The inner error bars are statistical only, while the outer include all systematic uncertainties for a helium fraction of 25 % and 10 mb photon systematics.

It is interesting to note that the model-dependence is moderate and does not dominate the measurement.

We summarise our results by averaging the four values of the cross-section (Table 1) to give

$$\sigma_{p\text{-air}} = (505 \pm 22_{\text{stat}} \left({}^{+20}_{-15} \right)_{\text{syst}}) \text{ mb}$$

at a center-of-mass energy of 57 ± 6 TeV. The helium-induced systematics is -12, -30 and -80 mb for 10, 25 and 50 % of helium, respectively and the photon-induced bias $< +10$ mb. In Fig. 3 we compare this result with model predictions and other measurements derived from cosmic ray data.

5 Discussion

We have developed a method to determine the cross-section for the production of particles in proton-air collisions from data of the Pierre Auger Observatory. We have studied in detail the effect of the primary cosmic ray mass composition, hadronic interaction models, simulation settings and telescope fiducial volume limits on the final result. The fundamental assumption for the analysis is that the light cosmic ray mass component in the selected data set is dominated by proton primaries. The systematic uncertainties arising from the lack of knowledge of the helium and photon components are potentially the largest source of systematic uncertainty. However, for helium fractions up to 25 % the induced bias remains small. One could also argue that only a specific amount of helium is allowed in the data since otherwise the hadronic cross-sections at ultra-high energies would become very small and at some point inconsistent with the extrapolation of accelerator data to $\sqrt{s} = 57$ TeV.

Our result favours a moderately slow rise of the cross-section towards higher energies. This has implications for

expectations at the LHC. First analyses at the LHC also indicate slightly smaller hadronic cross-sections than expected within many models [16].

We plan to convert the derived $\sigma_{p\text{-air}}$ measurement into the more fundamental cross-section of proton-proton collisions using the Glauber framework [17]. Thus, a direct comparison to accelerator measurements will be possible.

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