Proton-Air Cross Section and Composition of Ultra High Energy Cosmic Rays Observed by Telescope Array

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Ultra high energy cosmic rays (UHECRs) provide a natural source of particles accelerated to energies beyond those that can be attained in the laboratory. UHECRs have been observed with energies exceeding 10^{20} eV, which is equivalent to 433 TeV in the center-of-momentum frame. Using this natural source of particles physicists can extend the measurement of the pp cross section an order of magnitude above what is achievable in the lab, possibly identifying hints of new physics. The proton-air cross section and other properties of UHECR QCD physics are also important in their own right to the study of the sources and composition of UHECRs, but hadronic modelling at these energies is still reliant upon phenomenological and the theoretical extrapolations based upon terrestrial accelerator data. UHECR data can be used to improve these extrapolations of the proton-air cross section, but large uncertainties remain for other hadronic model parameters. We present the most recent measurement of the inelastic proton-air cross section at $\sqrt{s} = 95$ TeV measured by Telescope Array using high quality X_{max} data collected in hybrid observing mode. This measurement is also used to infer the total proton-proton cross section.

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1 Introduction

The total pp cross section has been measured up to $\sqrt{s} = 8$ TeV by ATLAS [1] and TOTEM [8]. Nature provides us with cosmic accelerators that inject particles with laboratory energies up to $\gtrsim 10^{20}$ eV, equivalent to $\sqrt{s} \gtrsim 430$ TeV. Using data from large cosmic ray experiments with exposures large enough to collect sufficient statistics, we can measure σ_{pp}^{tot} for energies beyond what terrestrial accelerators can provide. The two largest cosmic ray experiments currently operating have made such measurements. The Pierre Auger Observatory has measured $\sigma_{p-\text{air}}^{\text{inel}}$ from which σ_{pp}^{tot} can also be calculated and finds $\sigma_{pp}^{\text{tot}} = 133 \pm 13(\text{stat})_{-20}^{+17}(\text{sys}) \pm 16(\text{Glauber})$ mb at $\sqrt{s} = 57$ TeV [4]. Telescope Array has measured $\sigma_{p-\text{air}}^{\text{inel}}$ and σ_{pp}^{tot} at $\sqrt{s} = 95$ TeV. This paper will describe the method of measuring pp cross section using cosmic rays, the relation to air shower maximum size, and the results of Telescope Arrays most recent measurements of $\sigma_{p-\text{air}}^{\text{inel}}$ and σ_{pp}^{tot}. Understanding proton cross section is also important for understanding the composition, and ultimately, the source of ultra high energy cosmic rays (UHECRs). This is because $\sigma_{p-\text{air}}^{\text{inel}}$ and the depth of UHECR induced air shower maximum are related. At low energies where the properties of $\sigma_{p-\text{air}}^{\text{inel}}$ are constrained by accelerator measurements, hadronic models used for UHECR simulations are tuned using this information. The UHECR spectrum extends several orders of magnitude beyond the highest energy attained by Earth bound accelerators, so properties such as cross section, multiplicity, and elasticity must be extrapolated over a large energy range. Studying the energy dependence of these properties is important in constraining these models at large energies, and reducing systematic uncertainties in UHECR composition measurements.

2 Experimental Method and Results

Telescope Array (TA) is a large cosmic ray observatory employing 507 scintillator surface detectors (SD) covering 700 km^2 and three fluorescence detector (FD) stations overlooking the SD array. There are a total of 48 FD telescopes that record the passage of UHECR induced air showers as they pass through the atmosphere. This analysis utilizes air shower data collected in hybrid mode, in which events that simultaneously trigger both SDs and FDs are used to make precise measurements of air shower maximum depth, also called X_{max} measured in units of g/cm^2. A description of the TA experiment and its equipment can be found in [5, 6, 14, 15]. The hybrid data set used for this analysis contains 439 events from five years of hybrid data recorded by the Middle Drum FD station collected between May 2008 and May 2013 [3]. The range of (laboratory frame) energies accepted for this analysis is $10^{18.3}$ to $10^{19.3}$ eV. Figure 1 shows the $\langle X_{\text{max}} \rangle$ as a function of energy measured by this analysis, as well as predictions of $\langle X_{\text{max}} \rangle$ expected for pure proton, nitrogen, and iron compositions.
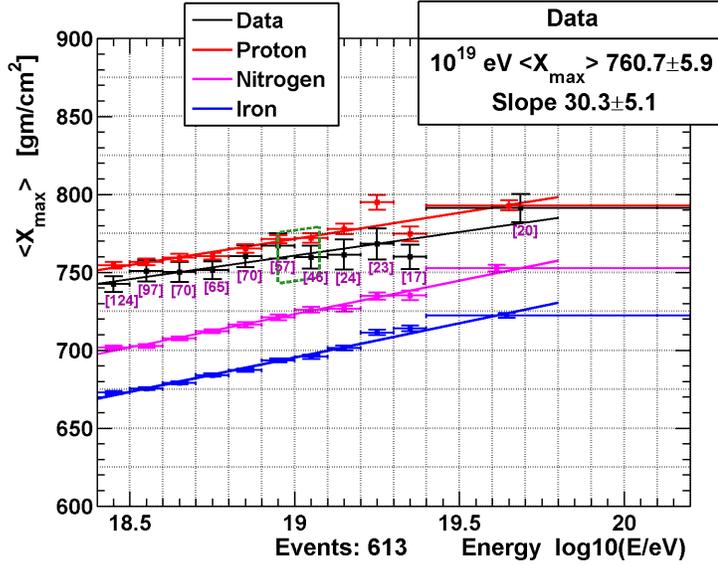
Figure 1: $\langle X_{\mathrm{max}} \rangle$ versus energy for five years of Telescope Array hybrid data observed using the Middle Drum fluorescence detector station. The data is compared to QGSJet II-03 protons, nitrogen, and iron pure chemical compositions. The data used for TA's $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ and $\sigma^{\mathrm{tot}}_{pp}$ measurements uses a subset of this data.

The hadronic model used for the simulations is QGSJet II-03.

Hybrid reconstruction of UHECR induced air showers uses the simultaneous measurement of geometry from the SD array, which accurately measures the location of the shower core on the Earth's surface, and the FDs, which measure the shower detector plane and shower track vector in the atmosphere. Observation by these two independent apparatuses provides excellent geometrical resolution, which in turn provides good resolution in determining air shower X_{max}. The X_{max} resolution for this analysis was ~ 23 g/cm^2.

Telescope Array measures $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ using the *K-factor method*. This method relates the attenuation length of protons in air to the exponential tail of the distribution of X_{max} observed from many showers. Due to fluctuations in the first interaction of an UHECR proton and an air molecule, the X_{max} distribution of protons exhibits a long tail at deep X_{max}. This tail is fit to the functional form $\exp(-X_{\mathrm{max}}/\Lambda_{\mathrm{m}})$, where Λ_{m} is the attenuation length. Figure 2 shows the X_{max} distribution of the data and the fit to the tail found using this method.

Λ_{m} is related to $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ by the relationship $\Lambda_{\mathrm{m}} = K\lambda_{p-\mathrm{air}} = K \cdot (14.45 m_p / \sigma^{\mathrm{inel}}_{p-\mathrm{air}})$. K is dependent upon the hadronic model chosen to simulate UHECR air showers. To determine the value of K used for this analysis, simulated data sets of UHECR air showers reconstructed by TA were used. Four hadronic models were used to

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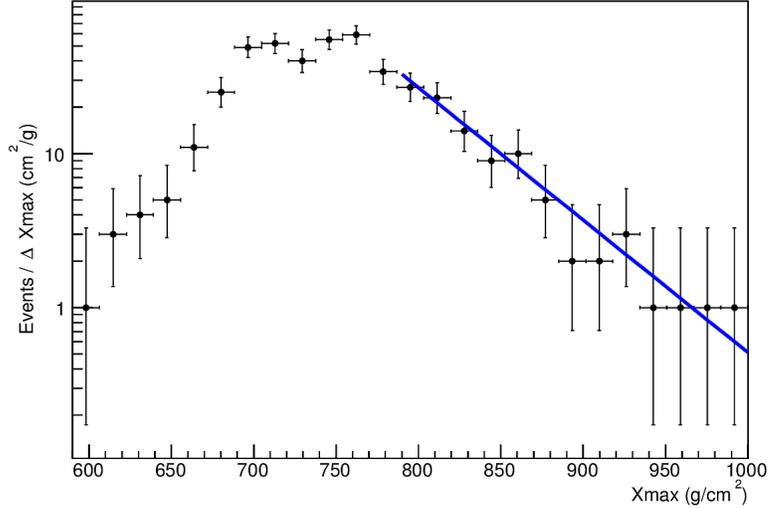
Figure 2: Number of data events per X_{max} bin used to measured $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$. The fit in the tail determines the slope which is related to the attenuation length of protons in air for $10^{18.3} < E < 10^{19.3}$ eV.

generate the air showers: QGSJet01 [11], QGSJet II-04 [12], SIBYLL 2.1 [7], and EPOS LHC [13]. The values of K and the $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ determined from the data are

Model	K	$\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ (mb)
QGSJet01	1.22 ± 0.01	583.7 ± 72.6
QGSJet II-04	1.15 ± 0.01	550.3 ± 68.5
SIBYLL 2.1	1.18 ± 0.01	564.6 ± 70.2
EPOS LHC	1.19 ± 0.01	569.4 ± 70.8

Several sources of systematic uncertainty are measured. Model dependence measured from the differences in $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ among the four models used to determine K and the proton-air inelastic cross section contributes ± 17 mb. The tail of the X_{max} distribution is used to determine K under the assumption that nearly all of those events are initiated by a proton UHECR primary. The systematic effect of contamination from several elements is examined with helium producing the largest shift in $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$. Varying amounts of helium contamination are examined as well as possible gamma ray contamination. The systematic uncertainties studied and their values are found to be
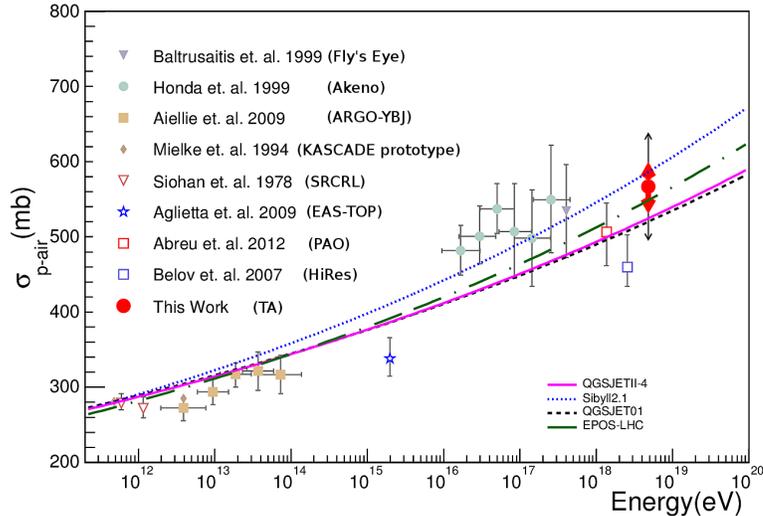
Figure 3: Telescope Array's measurement of p-air inelastic cross section. Statistical errors are indicated by the thin black lines around the data point, and systematic errors are indicated by the thick red lines. Other experimental results are shown, as well as predictions based on different hadronic models.

Systematic source	Systematic Uncertainty (mb)
Model dependence	± 17
10% helium	-9
20% helium	-18
50% helium	-42
Gamma rays	$+23$
Total (20% helium)	$(+29, -25)$

A conservative estimate of up to 20% helium contamination is used to measure the total systematic uncertainty to be $(+29, -25)$ mb. The final value of $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ is measured to be $567.0 \pm 70.5[\mathrm{stat}]^{+29}_{-25}[\mathrm{sys}]$ mb for $E = 10^{18.68}$, which is the mean energy of the data X_{max} distribution. This corresponds to $\sqrt{s} = 95$ TeV. Figure 3 shows TA's result in comparison to model predictions and other experimental measurements.

The total pp cross section can be calculated using $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ and Glauber formalism [10]. The relationship between $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ and $\sigma^{\mathrm{tot}}_{pp}$ is highly dependent on the forward elastic scattering slope. We use the model developed by Block, Halzen, and Stanev [9] which successfully describes Tevatron data and is consistent with unitarity to calculate $\sigma^{\mathrm{tot}}_{pp}$ from our data. Propagating statistical and systematic errors from the calculation of $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}$ we find $\sigma^{\mathrm{tot}}_{pp} = 170^{+48}_{-44}[\mathrm{stat}]^{+19}_{-17}[\mathrm{sys}]$ mb at $\sqrt{s} = 95$ TeV. The placement of this result compared to other measurements is shown in figure 4. Further details about this measurement are in [2].

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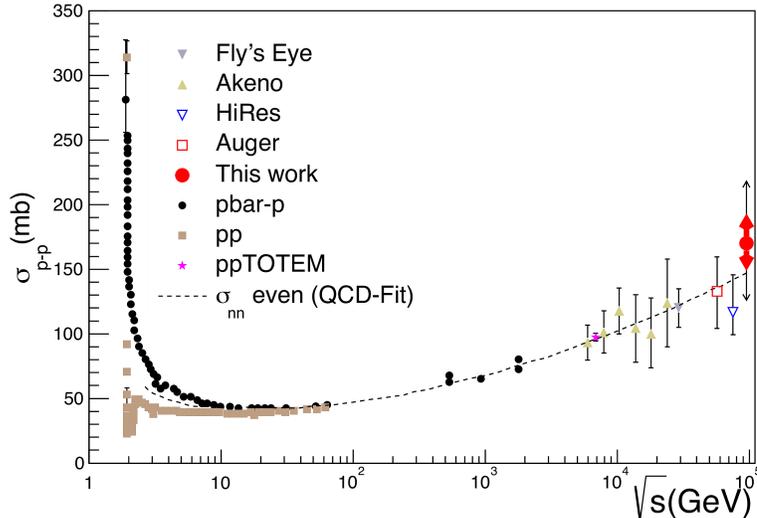
Figure 4: The total *pp* cross section measured by Telescope Array at $\sqrt{s} = 95$ TeV. Statistical errors are indicated by the thin black lines around the data point, and systematic errors are indicated by the thick red lines. The dashed line shows the prediction of the QCD inspired fit by Block, Halzen, and Stanev.

3   Conclusions

Telescope Array has used five years of high quality $X_{\max}$ data to measure the proton-air inelastic cross section and proton-proton total cross section. Utilizing the distribution of $X_{\max}$ for events with energies $10^{18.3} < E < 10^{19.3}$ eV and the K-factor method, $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ is found to be $567.0 \pm 70.5[\mathrm{stat}]_{-25}^{+29}[\mathrm{sys}]$ mb at a mean lab energy of $E = 10^{18.68}$ eV or $\sqrt{s} = 95$ TeV. This measurement can be used to calculate the *pp* total cross section using Glauber formalism and the QCD inspired fit to Tevatron data. Using this method we measure $\sigma_{pp}^{\mathrm{tot}} = 170_{-44}^{+48}[\mathrm{stat}]_{-17}^{+19}[\mathrm{sys}]$ mb at $\sqrt{s} = 95$ TeV. Both results are consistent with model predictions and other high energy measurements from other experiments. Telescope array continues to collect $X_{\max}$ data and by using other, larger hybrid data sets this result can be updated to higher precision in the near future.

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