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# $p$–air inelastic cross–section at ultra–high energies

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Cosmic Rays present an opportunity to measure the proton cross–section at the energies unaccessible by modern accelerators. We use the High Resolution Fly's Eye stereo fluorescence detector data and a novel deconvolution technique to find the $p$–air inelastic cross–section to be $456 \pm 17(stat) + 39(sys) - 11(sys)$ mb at $10^{18.5}$ eV. The result links ultra–high energy cosmic ray measurements with lower energy accelerator data for the first time. It also favors the Froissart bound saturation at ultra–high energies.

## 1. Introduction

The energy of cosmic rays can exceed the capability of modern accelerators by orders of magnitude extending above $10^{20}$ eV [2, 3]. However, the cosmic ray flux is very weak at these energies, rendering direct measurements implausible. Extensive air showers generated by the ultra–high energy cosmic particles present an opportunity for indirect measurements. The Fly's Eye air fluorescence experiment [1] has successfully measured the $p$–air inelastic cross–section at $10^{17.6}$ eV using a distribution of the air shower maxima. The procedure is as follows. The amount of UV scintillation light coming from a segment of the air shower is proportional to the number of charged particles. This allows us to measure the air shower profile, which is the number of charged particles as a function of the slant depth in the atmosphere. The peak of the shower profile is defined as $X_{max}$ and is measured in $g/cm^2$. An $X_{max}$ distribution is then found for many showers within a given energy range. In the Fly's Eye measurement, the exponential slope of the $X_{max}$ distribution is related to the $p$–air interaction length using a proportionality coefficient $k$ found from Monte Carlo simulations. We use the $X_{max}$ distribution for our measurement as well, but employ a novel deconvolution technique, described in greater details in [4]. This deconvolution technique allows us to greatly reduce the interaction model dependence and increase the stability of the $X_{max}$ distribution fit, leading to a more reliable result.

## 2. Detector

The High Resolution Fly's Eye stereo fluorescence detector (HiRes) is located in the western Utah desert about 120 miles west of Salt Lake City, USA. It consists of two detector stations separated by 12.6 km. One station, HiRes–1, has 20 mirrors and covers a field of view (FOV) of about 280° in azimuth and from 3° to 17° in elevation. The other detector station, HiRes–2, has 42 mirrors with about 300° azimuthal and 3°–31° elevational FOV coverage. All mirrors are spherical with 3.84 $m^2$ effective area. A UV sensitive camera with 256 photo-multiplier tubes (PMT) is installed in the focal plane of each mirror. The FOV of each PMT is about 1°. HiRes–1 uses sample and hold electronics while HiRes–2 uses more modern flash digital to analog converter electronics for better time resolution. Stereo observations are possible when both detector stations are observing the night sly simultaneously. Stereo observations greatly improve the $X_{max}$ resolution contributing to the smaller error bars. A detailed description of the Hires detector can be found in [5].

## 3. Measurement Technique

We used a novel deconvolution measurement technique described in details in [4]. The $X_{max}$ distribution is approximated by a convolution function:

$$f(x_m) = N \int_0^{x_m - x_{peak} + \alpha \Lambda'_m} e^{-\frac{x_1}{\lambda_{p-air}}} [\frac{x_m - x_1 - x_{peak} + \alpha \Lambda'_m}{e}]^{\alpha} e^{-\frac{x_m - x_1 - x_{peak}}{\Lambda'_m}} dx_1 \qquad (1)$$

where $N$ is a normalization factor, $x_m$ is the depth of the shower maximum, $x_1$ is the depth of the first interaction and $\lambda_{p-air}$ is the *p*–air interaction length. The parameters of this fit: $x_{peak}$, $\Lambda'_m$ and $\alpha$ are known from Monte Carlo simulations. The function $f(x_m)$ convolutes two distributions: the distribution of the depth of the first interaction approximated by the first exponential term in Eq. 1 and the distribution of the depth $x_m - x_1$, approximated by the second power-exponential term. The first distribution is statistical and it's mean value is the *p*–air interaction length. The second distribution is due to shower fluctuations in the air.

This approximation allows us to fit directly for the $\lambda_{p-air}$, thus, "deconvoluting" it from the $X_{max}$ distribution. The deconvolution technique is more stable than a previously used method [1]. Most importantly, this method significantly reduces the result dependence on the interaction model. The lower energy part of the air shower, the air shower development in the atmosphere, is separated from the highest energy part of the shower, the first interaction. The former is studied with Monte Carlo simulations. Most modern interactions models are in good agreement with each other and with the experimental data at lower energies and lead to nearly identical values of $x_{peak}$, $\Lambda'_m$ and $\alpha$.

## 4. Data

The Hires stereo data set used for this study consists of 3346 reconstructed stereo events collected between December 1999 and March 2003. Quality cuts were applied to these events, insuring that only cosmic ray showers for which $X_{max}$ can be determined precisely are used for the analysis. A detailed Monte Carlo study shows that the achieved $X_{max}$ resolution is about 21 $g/cm^2$ and energy resolution is about 15%. The $X_{max}$ resolution function is shown in Figure 1 and the energy resolution function is shown in Figure 2.

The quality cuts are designed to introduce no $X_{max}$ bias in the final data set. A detailed description of the quality cuts and the resolution function study can be found in [5].

1348 cosmic ray events passed the quality cuts forming is our final data set. The energy distribution for the final data set is shown on Figure 3. The mean energy is $10^{18.52}$ eV. The $X_{max}$ distribution for the selected events is shown on Figure 4. The $\lambda_{p-air}$ deconvoluted from the $X_{max}$ distribution is $\sim 52.5 \pm 2.0$ $g/cm^2$ which corresponds to the *p*–air inelastic cross–section of $456 \pm 17(stat)$ mb.

## 5. Systematic Errors

As indicated above, the model dependence, as estimated by using different models, is negligible due to the technique used. The detector trigger bias and heavy nuclei contamination is avoided by using the 700 $g/cm^2$ or deeper portion of the $X_{max}$ distribution. The atmospheric aerosol influence is less than the detector intrinsic resolution and is minimized by selecting data only from clear nights. Uncertainty in the molecular atmosphere introduces an elongation rate bias of less than 1 $g/cm^2$, see [6], and can be safely ignored. The reconstruction and quality cuts bias does not exceed 1.5 $g/cm^2$, the fitting uncertainty is less than 1 $g/cm^2$. For this study, we assumed that the gamma ray flux at these energies is undetectable, with an upper limit of 5%. Using Monte

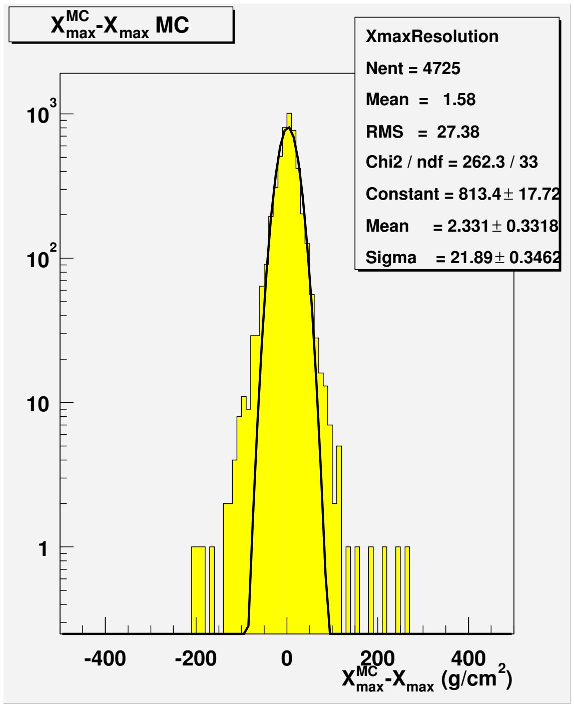

**Figure 1.** $X_{max}$ resolution function.

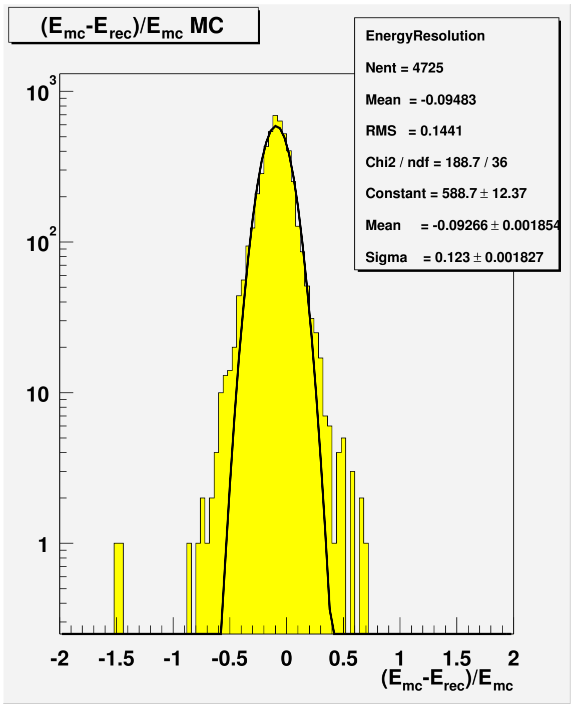

**Figure 2.** Energy resolution function.

Carlo simulations and assuming a 5% gamma ray flux, we estimated the systematic shift in our cross–section measurement does not exceed $4\ g/cm^2$. The total systematic error for Hires measurement of the $p$–air inelastic cross–section is estimated to be $-11 + 39\ g/cm^2$. An asymmetric systematic error is due to the potential gamma ray flux. Details about systematic errors and the gamma ray study can be found in [5].

## 6. Discussion

The $p$–air inelastic cross–section value measured by the HiRes is $456 \pm 17(stat) + 39(sys) - 11(sys)$ mb. It is in a good agreement with the cross–section values measured by Akeno [7] and Fly's Eye [1] at lower energies rescaled by M. Block [8] using newer interaction models. The HiRes value is also in a good agreement with the interaction model predictions and the accelerator data extrapolation [9].

## 7. Conclusions

The Hires stereo fluorescent detector provides us with the highest quality cosmic ray data. The ability to see the greater part of the air shower shower profile in stereo greatly improves the $X_{max}$ resolution. The deconvolution technique removes the interaction model dependence and increases the accuracy and stability of the cross–section measurement.

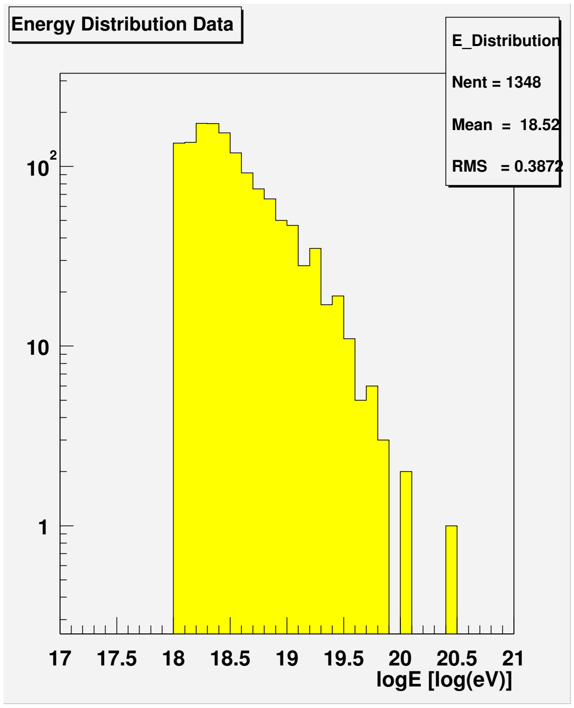

**Figure 3.** Energy distribution. Cosmic ray data.

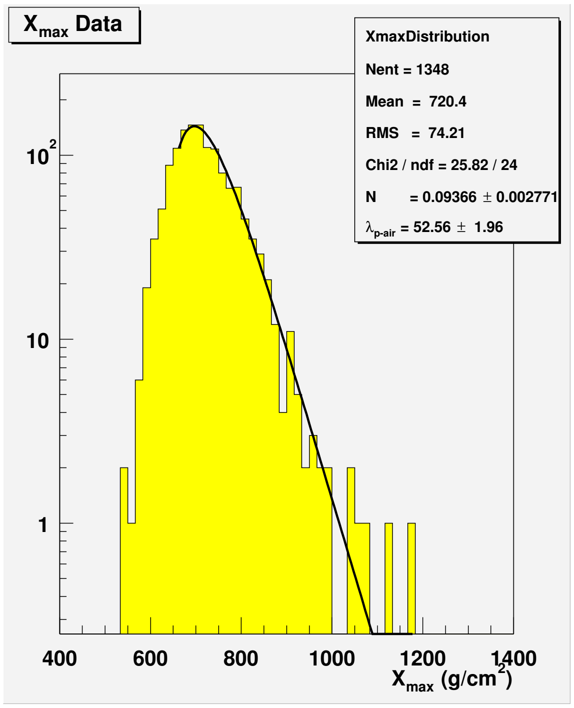

**Figure 4.** $X_{max}$ distribution. Cosmic ray data.

## 8. Acknowledgements

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