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Proton-air Inelastic Cross-Section Measurement at Ultra-High Energies by HiRes

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Abstract: We present a proton-air inelastic cross-section measurement using the cosmic-ray data collected by the High Resolution Fly's Eye fluorescence cosmic ray detector from December 1999 to November 2005. We used a deconvolution technique to obtain the cross-section directly from the X_{max} distribution. A possible influence on this measurement by strong interaction models is discussed. Potential systematic errors from He and gamma ray fluxes are taken into account.

Introduction

Cosmic rays provide an opportunity to measure a particle cross-section at energies greatly exceeding those achievable by the Large Hadronic Collider, LHC, the newest and most powerful man made particle accelerator. Such a measurement can lead to discovery of a new physics or, on the opposite, confirm the current theoretical predictions. It can also help to bound the lower energy accelerator data extrapolation and obtain a prediction for the *pp* total cross-section value to be measured by the LHC.

Cosmic Ray flux at ultra-high energies is very weak. A direct measurement is not possible and a special observation technique is needed to collect meaningful statistics for the measurement. The High Resolution Fly's Eye fluorescence detector is using the fluorescence technique to observe extensive air showers caused by the ultra-high energy cosmic particles. These air showers emit fluorescence light in UV. The fluorescence light is emitted uniformly and can be observed from the ground by a special telescope. The observed amount of light is proportional to the number of charged particles in the electro-magnetic cascade. Thus, it is possible to measure the air shower profile - the number of charged particles as a function of the slant depth in the atmosphere. The shower reaches it's maximum size when ionization losses start to exceed bremsstrahlung. The slant depth where this happens is usually denoted as an X_{max}. The X_{max} distribution for many cosmic ray events can be used to measure the p-air inelastic cross-section.

The cross-section measurement using the X_{max} distribution requires a special technique. We used a deconvolution technique briefly described in section 3.

The HiRes Detector

The High Resolution Stereo Fluorescence detector observes the UV fluorescent light emitted by the secondary particles of the extensive air shower. It consists of two detector stations the HiRes1 and the HiRes2 separated by 12.6 km. The HiRes1 station is assembled from 20 telescopes and the HiRes2 is assembled from 42 telescopes. Each telescope consist of a spherical mirror with the effective area about 3.8 m^2. A UV sensitive camera is placed in the focal plane of the mirror. The camera is assembled from 256 photo-multipliers with 1° field of view. Telescopes are arranged to provide almost 360° azimuthal field of view. The HiRes1 detector covers the field of view from 3° to 17° in elevation and 322° in azimuth. The HiRes2 station covers the field of view from 3° to 31° in elevation and 336° in azimuth. The Hires1 detector has sample and hold electronics while the HiRes2 has flash ADC electronics. A more detailed description of the HiRes stereo detector can be found in literature [1].

The HiRes stereo fluorescence detector operated from December 1999 to April 2006.

Measurement Technique

Although the usage of the exponential tail of the X_{max} distribution to obtain the *p*-air inelastic cross-section from the cosmic ray data was proposed earlier, we used a technique first proposed in [2] that has significant advantages. This so called "deconvolution" technique considers the X_{max} distribution as a convolution of two other distributions, the distribution of the first interaction depth, X_1, and the distribution of the depth of the parameter $X' = X_{max} - X'$. The mean of the first distribution is the interaction length, λ_{p-air}, which is inversely proportional to the inelastic cross-section, σ_{inel}^{p-air}. Because the first interaction is not visible by the detector, it is not possible to measure the interaction length directly. The X' distribution is due to the air shower statistical fluctuations in the atmosphere. The interactions responsible for this distribution occur at much lower energies than the energy of the first interaction. While not necessarily agreeing at highest energies, the theoretical models agree very well in describing the lower energy interactions because of the existence of the accelerator data at lower energies to tune the models. Thus, it is safe to use the theoretical models to study the X' distribution using Monte Carlo simulations. The X' distribution can be approximated by a power-exponent function:

$$P(X') = [\frac{X' - X_{peak} + \alpha\Lambda'}{e}]^{\alpha} e^{-\frac{X' - X_{peak}}{\Lambda'}} \quad (1)$$

where X_{peak}, α and Λ' are three parameters obtained as a function of energy from Monte Carlo simulations. Figure 1 illustrates the approximation of the X' distribution of the MC simulated air showers. Such an approximation is done at many energy bins to find the energy dependence of the three parameters mentioned above. This makes $P(X')$ a known function of energy.

Since the X_{max} distribution is the convolution of the X_1 distribution and the X' distribution, and the former one can be approximated by an exponent with the exponential index λ_{p-air} , the X_{max}

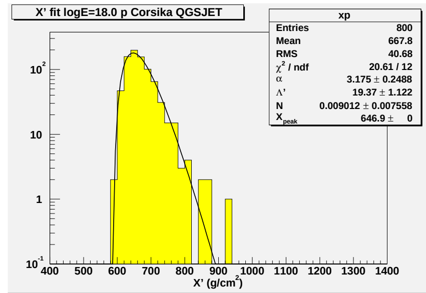

Figure 1: x'_m distribution. Proton QGSJET $E = 10^{18}$ eV.

distribution can be approximated by a convolution function:

$$f(X_{max}) = \int \frac{N}{\lambda_{p-air}} e^{-\frac{X_1}{\lambda_{p-air}}} P(X') dX_1 \quad (2)$$

where the integration goes from 0 to $X_{max} - X_{peak} + \alpha\Lambda'$. The only fitting parameter of this function besides the normalization is λ_{p-air}. Thus, it becomes possible to obtain the p-air inelastic cross-section from the X_{max} distribution directly.

Experimental Data

The experimental data collected by the HiRes stereo detector from December 1999 till November 2005 is used. Only the events with so called "global fit" were used for this study. Those are the events for which the profiles measured independently by the HiRes1 and the HiRes2 detectors can be combined, and the resultant profile is fit to obtain the final air shower profile. The energy of the primary particle as well as the X_{max} of the air shower is then determined.

3346 stereo events survive all the data quality cuts. The final X_{max} distribution of the real cosmic ray data is shown on Figure 2.

The deconvolution of this distribution yields $\lambda_{p-air} = 52.44 g/cm^2$ which corresponds to the $\sigma_{inel}^{p-air} = 460$ mb. A statistical error on this measurement is 14 mb.

Many potential sources of the systematic error were analyzed. These sources include: the detector resolution, data reconstruction bias, atmo-

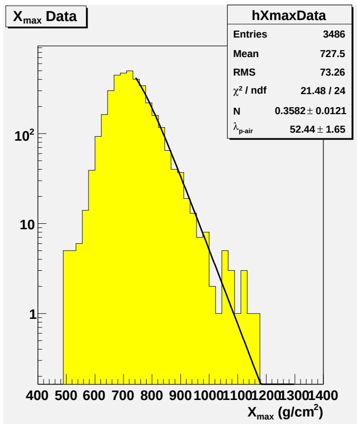

Figure 2: X_{max} distribution for the cosmic ray events.

spheric profile uncertainty, the measurement technique bias and others. The final systematic uncertainty on this measurement is estimated to be 11 mb.

Heavier and lighter components of the cosmic ray flux can introduce an additional systematic error. This is discussed in the section below.

Systematic Error due to Heavier and Lighter components

Heavier components of the cosmic ray flux, for example Fe, CNO, He, should develop earlier in the atmosphere. We only use a part of the X_{max} distribution deeper than 740 g/cm^2 to eliminate the influence of Fe and heavy elements. The mean X_{max} for He is closest to the proton one. To estimate a possible influence on the cross-section measurement from He we generated Monte Carlo data sets containing pure proton, 95% proton plus 5% He and 90% proton plus 10% He. We used Corsika package with QGSJET interaction model to generate the libraries of simulated air showers. Each data set consists of not less than 10000 events. These events are then run throughout a set of subroutines which simulate the detector response. This set of subroutines is call the Detector Monte Carlo. It simulates the finite resolution of the HiRes detector, sky noise, photomultiplier imperfections, dead zones between the photocathodes and so on. Next we attempt to reconstruct each event using the same programs that are used for the real data. Our final result is the X_{max} distribution for each data set. We deconvolute each distribution to obtain a prediction for the cross-section. The cross-section as a function of the He contamination is shown on Figure 3.

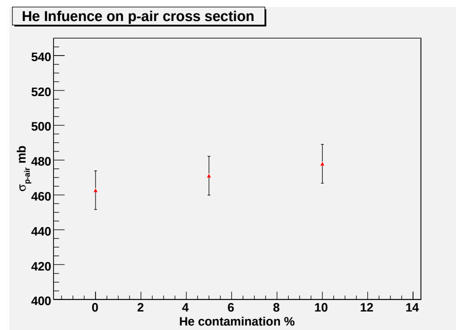

Figure 3: Cross-section value as a function of He contamination. MC simulation.

It is reasonable to assume that the HiRes detector trigger efficiency and our reconstruction efficiency are similar for proton and He. The plot on the Figure 3 illustrates that influence of 10% of He is well within the statistical errors of the X_{max} distribution approximation. Nevertheless, we take this influence as an additional -15 mb of the systematic error.

We apply a similar approach to estimate the influence from gamma ray flux. The air showers initiated by the gamma ray primaries should develop deeper in the atmosphere that the proton initiated ones. We assume zero gamma ray flux at this energy, but put a 5% upper limit on it taking into account possible precision of such a measurement. This will add +28 mb to the total systematic error.

Discussion

The p-air inelastic cross-section at $10^{18.5}$ eV measured by the HiRes is:

$$\sigma_{inel}^{p-air} = 460 \pm 14(stat) + 39(sys) - 26(sys) \quad (3)$$

It is shown on the Figure 4 with previous cosmic ray measurements and extrapolation of some theoretical models. While the measured value is in very

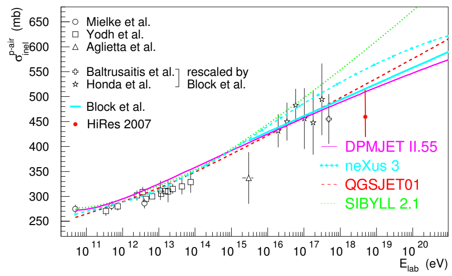

Figure 4: HiRes cross-section measurement.

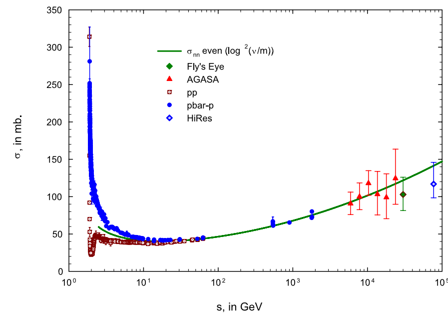

Figure 5: Accelerator data extrapolation for pp total cross-section and rescaled cosmic ray measurements [6].

good agreement with predictions by some theoretical models, it also disagrees with the others. Since model dependence of this measurement is negligible, it can serve as a point to reconsider some theoretical models. It should be noted, that because previous cosmic ray measurements done by the Fly's Eye and Akeno experiments depend significantly on the interaction model chosen for the Monte Carlo simulations, these measurements are rescaled to take into account the theoretical model developments, the accelerator data extrapolation [3] and an independent experimental measurement of the scaling coefficient [4]. These measurements are shown on the same plot.

It is extremely valuable to compare this measurement with the accelerator data. However, there is no accelerator measurement at this energy. One has to rely on the extrapolation of the lower energy data. Such an extrapolation poses a challenge because it goes several orders of magnitude. The accelerator data also contains many points that lie far away from any proposed extrapolation model. A recent work [3] offers a reliable extrapolation of the accelerator data. The proposed extrapolation model, $ln^2(s)$, is anchored at low energy points. A sophisticated sifting algorithm [5] eliminates bad data points using objective criteria. The resultant extrapolation is shown on Figure 5.

The cosmic ray measurements are also shown on the same plot rescaled from *p*-air inelastic to pp total cross-section. The HiRes measurement confirms the validity of the accelerator data extrapolation, and, in turn, a prediction for the pp total cross-section of 107.3 ± 1.2 mb [7] to be measured by the LHC. The HiRes measurement does not contradict an assumption [7] about the Froissart bound saturation. It should be noted that the diffractive part of the total cross-section is model dependent. This introduces an uncertainty in the pp total cross-section recalculated from the p-air inelastic cross-section.

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