p-air cross-section measurement at $10^{18.5}$ eV.

K. Belov[a] for the High Resolution Fly's Eye (HiRes) Collaboration.

[a]Department of Physics, University of Utah,
201 JFB 115 S 1400 E, Salt Lake City, Utah, 84112, USA

We present the first measurement of p-air inelastic cross-section at $10^{18.5}$ eV using the HiRes stereo fluorescence detector data. A new measurement technique employing de-convolution of the X_{max} distribution is proposed. Monte Carlo simulations with the CORSIKA air shower generator and QGSJet and SIBYLL2.1 interaction models are discussed.

1. Introduction.

The interaction cross-section is one of the fundamental properties of any elementary particle. For decades, only accelerator measurements of the particle cross-sections were available. Cross-section measurements at higher and higher energy become possible as more and more powerful accelerators are introduced. However, cosmic rays not only provide a constant flux of ultra high-energy particles, but also supply particles with energies inaccessible by modern accelerators already in service or planned.

Particle cross-section measurements using cosmic rays have their difficulties, however. The cosmic ray flux is very low at ultra-high energies, and there is no direct method to measure the particle cross-section using cosmic rays. These difficulties can be overcome by using cosmic ray detectors with large aperture and specially developed measurement techniques.

In this work, a novel de-convolution technique to measure the p-air inelastic cross-section using cosmic ray data is discussed in detail. This technique, applied to the data from HiRes stereo fluorescence cosmic ray detector allows us to measure this cross-section at $10^{18.5}$ eV for the first time.

2. Cross-section measurements using cosmic ray data.

The ultra-high energy cosmic ray flux intensity is very low and cosmic ray experiments use the earth's atmosphere as a giant calorimeter to increase the detector aperture. This makes a direct measurement of p-air inelastic cross-section impossible. A complex approach is required to measure particle cross-sections using cosmic ray data.

An extensive air shower starts when a high energy particle enters the earth's atmosphere and undergoes the first interaction with an air nucleus. A cascade of secondary particles (the air shower) grows in size until ionization losses start to exceed bremsstrahlung losses. The depth in the atmosphere where this happens is referred to as the depth of the shower maximum (X_{max}). From this point, the shower size starts to diminish until the primary particle energy is below the particle production threshold. Radio, Čerenkov and scintillation light are produced by the secondary particles of the extensive air shower making it possible to observe the shower from the earth. The HiRes detector uses the air fluorescence technique to observe the air showers and measure their parameters.

The point of first interaction (X_1) distribution can theoretically be employed for this measurement. It's exponential slope depends on the particle inelastic cross-section (see Fig. 1). Unfortunately, none of the existing cosmic ray experiments can detect the first interaction of the cosmic ray primary. The first cross-section measurement using cosmic ray data was done using an analysis of the form of the distribution of air shower maxima. It exploited the fact,
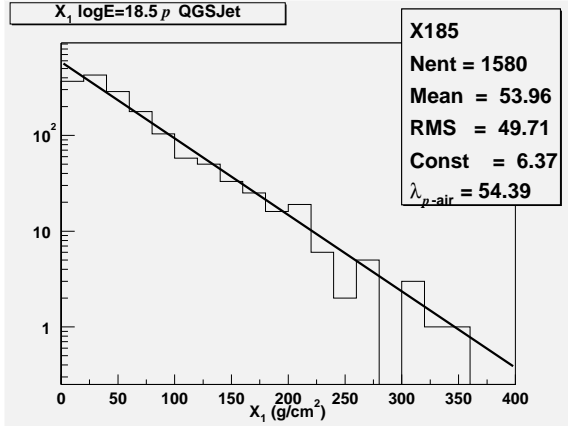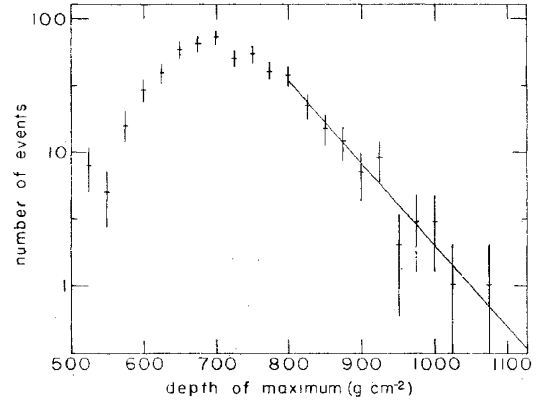
Figure 1. X_1 distribution.

Figure 2. Fly's Eye X_{max} distribution [1].

that the point of first interaction distribution should influence the distribution of air shower maxima (X_{max}). Indeed, the X_1 distribution should "propagate" into the X_{max} distribution and influence it's exponential tail. The exponential slope of the X_{max} distribution Λ can be related to the slope of the X_1 distribution λ_{p-air} through a coefficient k:

$$\Lambda = k\lambda_{p-air}, \tag{1}$$

where k is obtained by Monte Carlo simulations. Unlike the X_1 distribution, the X_{max} distribution can be measured by cosmic ray experiments either directly, in case of an air fluorescence experiment, or indirectly, in case of a ground array experiment. In that case, an additional step is required to recalculate the charged particle ground density profile into X_{max} for each air shower in order to obtain the X_{max} distribution.

The first cross-section measurement using the X_{max} distribution was done in 1984 by the Fly's Eye group using the air fluorescence technique [1], (see Fig. 2) followed by the Akeno ground array result in 1993 [2] at lower energies. Figure 3 illustrates the current status of the p-air inelastic cross-section measurements and theoretical predictions by the few interaction models widely used for the Monte Carlo simulations. It

is clearly seen that experimental values and theoretical predictions agree on the rising trend, but the predicted values are quite different from the measured ones. Part of the problem is in the measurement technique used. Indeed, the coefficient k depends on the interaction model used for the air shower simulations. Recent re-scaling of the Fly's Eye and Akeno measurements done by Block [3] using the most recent interaction models places the experimental data into a better agreement with the theoretical predictions. It also demonstrates the strong dependence of these measurements on the chosen interaction model.

3. The HiRes detector.

The HiRes stereo fluorescence detector is located at Dugway Proving Ground about 120 miles west from Salt Lake City, Utah. It consist of two detector stations HiRes1 and HiRes2 separated by 12.6 km. The HiRes1 detector consist of 20 spherical mirrors 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 field of view of the PMT is about $1°$. The detector mirrors are arranged in one ring providing a detector field of view approximately $3° - 17°$ in elevation and $280°$ in azimuth. The
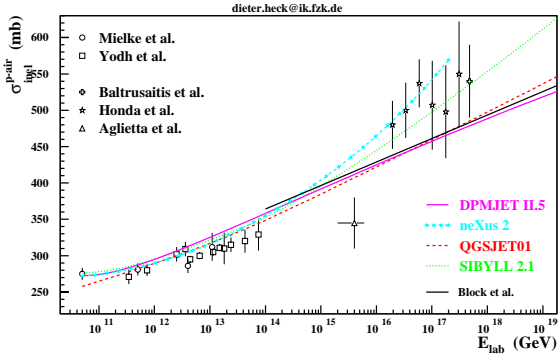
Figure 3. Cross-section measurements and theoretical predictions.

HiRes1 UV cameras utilize sample and hold type of electronics.

The HiRes2 detector has 42 mirrors identical to the HiRes1, but arranged in two rings. This gives the HiRes2 detector a wider field of view: approximately $3° − 31°$ in elevation and about $300°$ in azimuth. The HiRes2 detector uses flash analog-digital converter electronics, allowing for better timing measurement. A detailed description of the HiRes stereo detector can be found in [4].

Both detectors can operate independently or as a stereo pair. In the latter case, the air shower geometry reconstruction is greatly improved leading to better shower profile measurements and subsequently to higher X_{max} and energy resolution.

4. De-convolution measurement technique.

The cross-section measurement technique briefly described in 2 has some major deficiencies. As was emphasized before, the measured cross-section values strongly depend on the interaction model used for the Monte Carlo simulation.

In addition, only the deeper portion of the X_{max} distribution tail is used to obtain Λ. This is done to increase the method's sensitivity and to reduce the influence of heavier nuclei. Heavier

primaries tend to develop air showers earlier in the atmosphere. This allows us to reduce their influence in the p-air cross-section measurements by focusing on the deeper portion of the X_{max} distribution. A drawback, however, is the dependence on the chosen X_{max} cutoff point.

A measurement technique which helps to overcome these difficulties is proposed in [5]. It exploits the fact, that the X_{max} distribution is a convolution of two distribution. The first one is the above mentioned X_1 distribution, (see Figure 1). The second distribution in the convolution is due to the air shower fluctuations in the atmosphere. This is a distribution of the value $X' = X_{max} − X_1$. Neither X_1 nor X' can be measured in the experiment. The X' distribution however can be obtained from Monte Carlo simulations. An example of such a simulated distribution is shown in Figure 4. Knowing this,
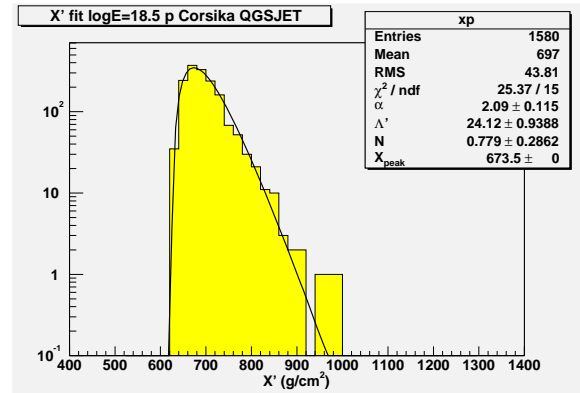

Figure 4. X' distribution.

the X_1 distribution can be de-convoluted from the X_{max} distribution to obtain the p-air inelastic cross-section. The advantages of such an approach include a direct fitting of the X_{max} distribution with a single fitting parameter λ_{p-air}, greater result stability due to usage of a bigger portion of the X_{max} distribution and much less sensitivity to the interaction model used. Indeed,

air shower fluctuations in the atmosphere occur at much lower energy than the energy of the first interaction of the primary particle. The discrepancy between the interaction models diminishes as the energy of the interaction goes down, and becomes negligible at accelerator energies. Thus, the measurement technique dependence on the interaction model is greatly suppressed. The normalized difference between the MC generator input interaction length and the one obtained by the X_{max} distribution de-convolution is shown in Figure 5. The results of the QGSJet and
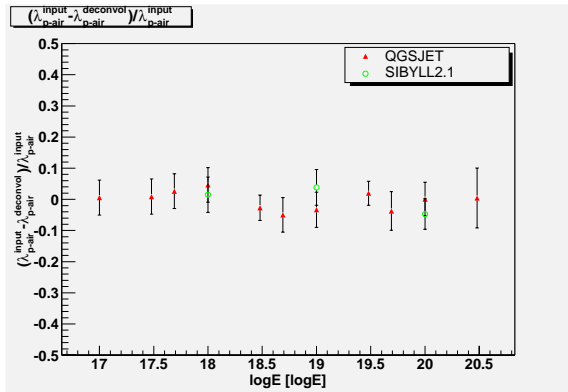
Figure 5. Measurement technique resolution for different models and energies.

SIBYLL2.1 interaction models are shown. Figure 5 illustrates the good agreement between the input cross-section and the "de-convoluted" one. It also shows no dependence on the interaction model.

5. Detector Monte Carlo.

The de-convolution technique described in the previous section is robust in obtaining the p-air inelastic cross-section from the X_{max} distribution of extensive air showers. The previous discussion however does not take into account the HiRes detector itself. The HiRes detector has finite reso-

lution and electronic noise. The data is also subject to the night sky noise and and artificial light sources, imperfect reconstruction and other biases. A detector Monte Carlo (detector MC) is a program, which simulates the HiRes detector response to a simulated atmospheric air shower. It takes into account all the factors mentioned above. As an input, it takes a random air shower from a large shower library simulated using the CORSIKA generator. The output of the detector MC is similar to one produced by a real cosmic ray event. This output is run through a standard HiRes reconstruction routines and later through a set of quality cuts. In the case of the cross-section study, the quality cuts are designed to maximally preserve the shape of the X_{max} distribution. A delicate balance must be achieved between removing poorly reconstructed events and introducing minimal or no bias into the X_{max} reconstruction. Besides serving as another test of the measurement technique and as a development tool for the quality cuts, the detector MC allows us to study the HiRes detector resolution function.

To achieve all these goals, sets of about 12000 MC simulated air showers have been created with a E^{-3} spectrum using the detector MC. These sets are run through the HiRes standard reconstruction routines and through a set of quality cuts. The reconstructed X_{max} distribution is shown in Figure 6. The cross-section value obtained by de-convolution of this distribution is within 1σ of the input into the MC generator. The good agreements confirms that the proposed measurement technique is very robust.

Figure 7 shows the X_{max} resolution function. The achieved X_{max} resolution is $21g/cm^2$. The resolution function is symmetrical with no tails and only $2g/cm^2$ systematic shift. This resolution function was calculated assuming a clear atmosphere and average atmospheric parameters. [7] shows that the average parameters of the Dugway atmosphere are very well known and the fluctuations from the average atmosphere will result in an X_{max} uncertainty much smaller than the detector intrinsic resolution.

The energy resolution for the MC data set is shown in Figure 8. It should be noted, that 12%
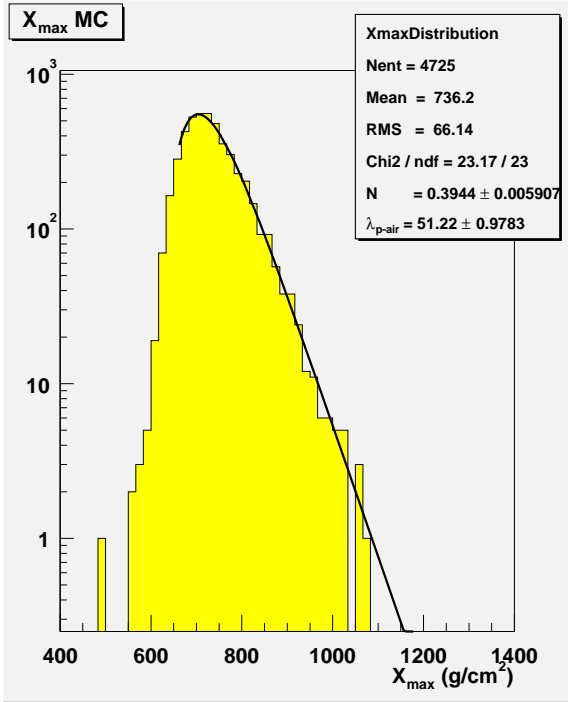
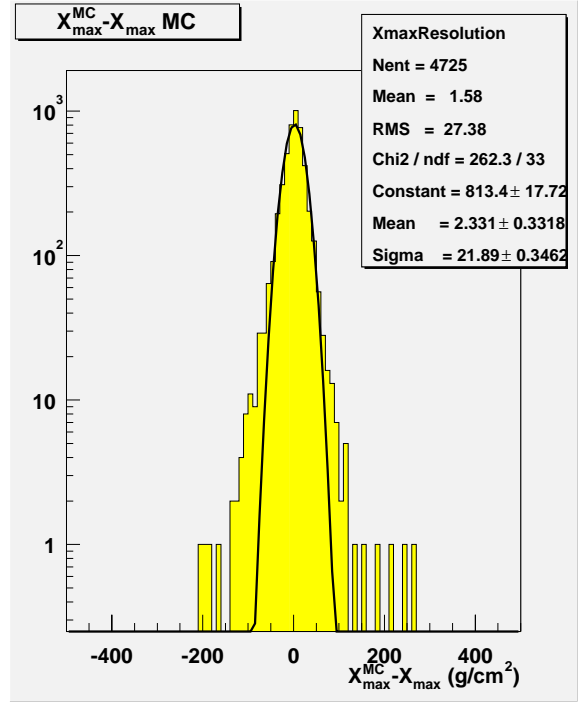Figure 6. X_{max} distribution. Detector MC.

Figure 7. X_{max} resolution function.

energy resolution is specific for the selected quality cuts which are tuned to preserve the X_{max} distribution shape and might potentially introduce some bias into the energy spectrum.

6. Composition influence.

The cosmic ray mass composition can greatly influence the cross-section measurements. For the purpose of the p-air inelastic cross-section study, non-proton primaries can be separated into two groups: heavier nuclei and gamma rays. The air showers caused by the heavier nuclei develop earlier in the atmosphere as it is illustrated in Figure 9. The X_{max} distributions for 20% of Fe and 20% of CNO are shown on the same scale as 100% proton. A recent study [6] indicates that there are no more than 20% of heavier nuclei in the cosmic ray flux at 10^{18} eV and above. If that is the case,

the heavy nuclei influence can be greatly reduced by using only the deeper part of the X_{max} distribution. An $X_{max} > 740 g/cm^2$ is then a safe cut.

If a significant gamma ray flux exists at these energies, it will introduce a systematic error into the p-air inelastic cross-section measurements. In order to estimate the possible systematic error, sets of proton induced air showers are simulated with an E^{-3} spectrum and different levels of gamma ray "contamination", as described in the previous section. Each data set is reconstructed and it's X_{max} distribution is de-convoluted in order to obtain a p-air cross-section value. Figure 10 shows the predicted cross-section value as a function of the gamma ray "contamination" of the data set. The upper and lower curve indicate the statistical uncertainty. These curves provide a gamma ray induced systematic error envelope
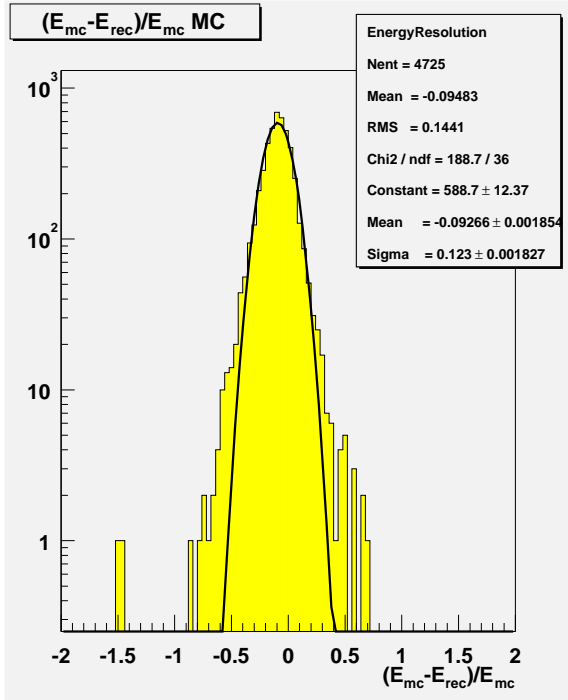
Figure 8. Energy resolution function.

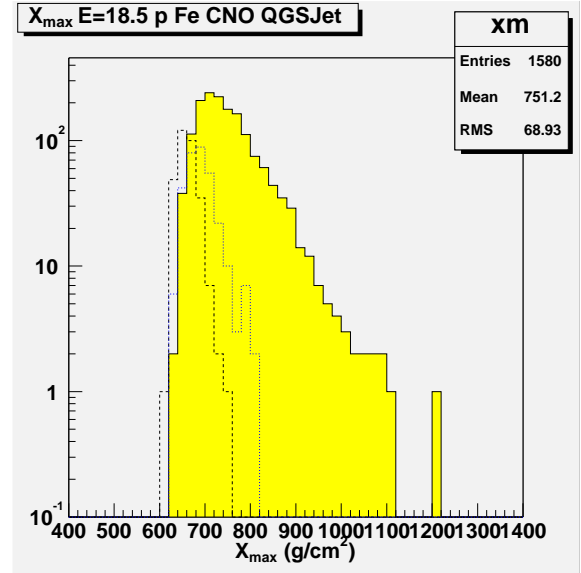Figure 9. p, CNO and Fe X_{max} distribution.

for the p-air cross-section measurement.

A different analysis (in preparation) shows that the HiRes cosmic ray data is inconsistent with a gamma ray flux exceeding 5%. A systematic error was estimated taking such an upper limit into consideration.

7. The HiRes measurement.

HiRes data from December 1999 till March 2003 is used for this cross-section measurement. The whole data set consists of 3346 reconstructed stereo events. 1348 events passed the quality cuts. The energy distribution for those 1348 cosmic ray events is shown in Figure 11. The mean energy for the data set is $10^{18.52}$ eV. This is considered to be the energy of our cross-section measurement.

The X_{max} distribution for the data set is shown in Figure 12. The interaction length obtained

by de-convolution of the X_{max} distribution is $\lambda_{p-air} = 52.88 \pm 1.98$ g/cm^2 which corresponds to the p-air inelastic cross-section $\sigma_{in}^{p-air} = 456 \pm 17(stat)$ mb.

8. Systematic error and bias check.

To estimate the total systematic error and to check for potential bias sources the following have been checked. We summarize the results:

- the model dependence is negligible at energies that produce the air shower fluctuation;

- 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 estimated 5% gamma ray contamination introduces a systematic error of less than 4 g/cm^2;

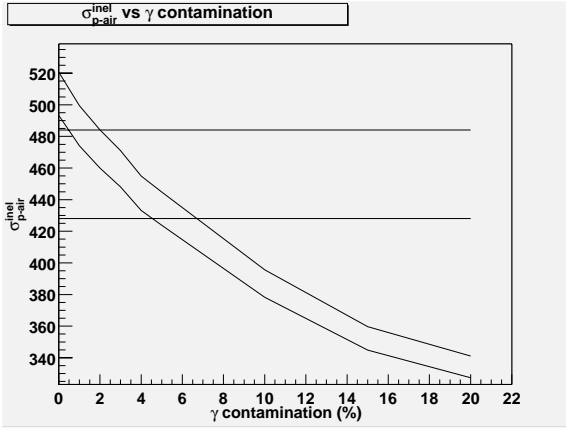- the reconstruction and quality cuts bias does not exceed 1.5 g/cm^2;

Figure 10. Cross-section prediction as a function of gamma contamination.

- the fitting biases are less than 1 g/cm^2;

- the atmospheric influence is less than the detector intrinsic resolution and is minimized by selecting only clear nights.

Taking into account all systematic uncertainties, the measured value of the p-air inelastic cross-section at $10^{18.5}$ eV is:

$$\sigma_{in}^{p-air} = 456 \pm 17(stat) + 39(sys) - 11(sys) \quad (2)$$

. The asymmetric systematic error is due to the potential gamma ray flux influence. A better knowledge of the gamma ray flux should improve the systematic uncertainty on the cross-section measurement.

9. Discussion.

The measured value of the p-air inelastic cross-section at $10^{18.5}$ eV is in the good agreement with previous measurements and theoretical predictions. The rising trend of the cross-section continues to these high energies. A rescaling of the previous measurements using modern interaction models [3] puts the previous measurements in event better agreement with the HiRes measurement and with theoretical predictions, (see Figure
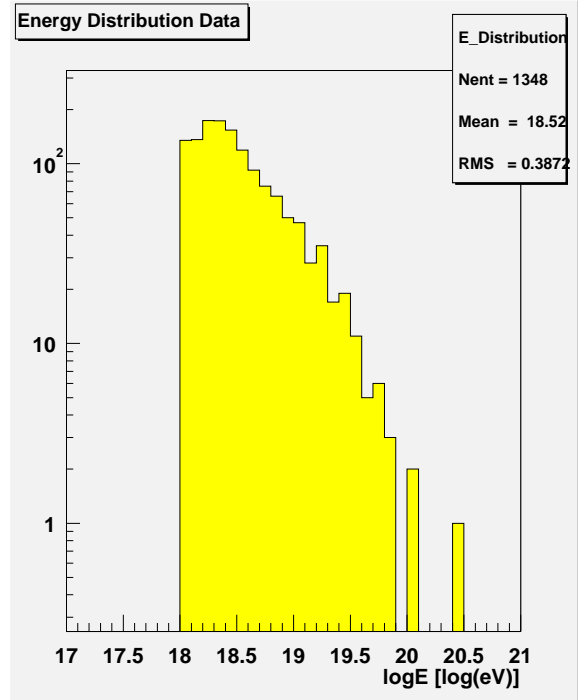

Figure 11. Energy distribution. Cosmic ray data.

13). Recent adjustments to theoretical models [8] based on new accelerator data at lower energies agree very well with the HiRes measurement.
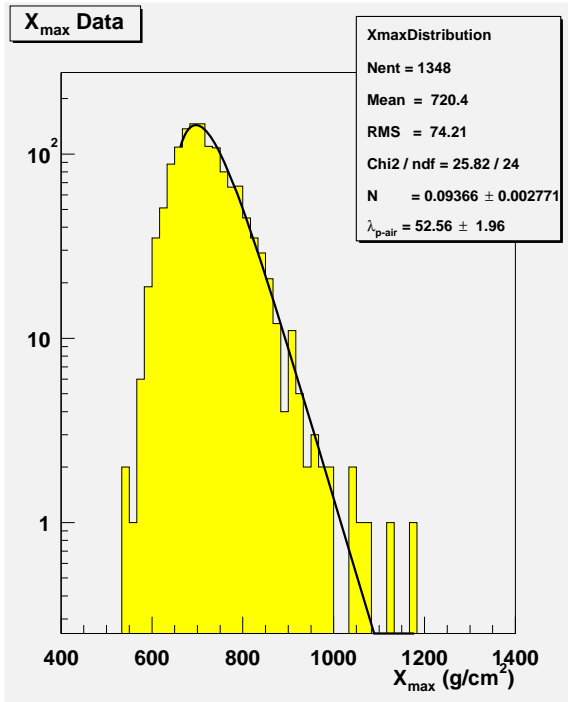
Figure 12. X_{max} distribution. Cosmic ray data.

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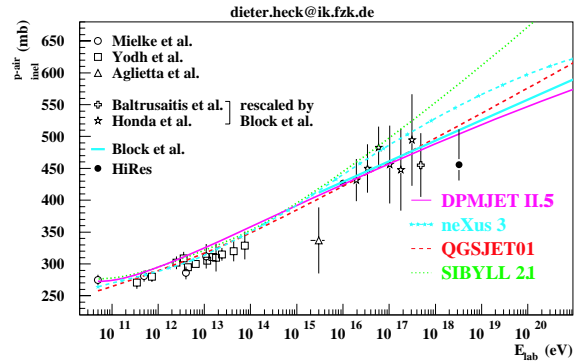1. R. M. Baltrusaitis et al., Phys. Rev. Lett., 52(1380), 1984.

Figure 13. HiRes, Fly's Eye and Akeno measurements and model predictions.

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