

# Measuring the Inelastic and Total Cross-Sections for $p$ -Air and $p$ - $p$ Collisions at $s^{1/2} \sim 44$ TeV Using HiRes Stereo Data

Tyler Poniatowski  
Indiana University, Bloomington, IN

## Abstract

We make a measurement of  $p$ -Air and  $p$ - $p$  cross-sections using MC data to provide necessary parameters and then applying parameters to real HiRes data. Findings are given in context of results from previous research and our values are found to be consistent with both theory and previous measurements. Includes a brief introduction to astro-particle physics and the HiRes project.

# 1 Introduction

Cosmic rays (subatomic particles of solar, galactic, and extra-galactic origin, found often at energies of up to  $10^{20}$  eV) are one of the great enigmas in modern particle physics. For many years, these particles were the only way to study subatomic matter due to their extremely high energies. An incident cosmic-ray particle in our atmosphere will interact strongly and produce an Extensive Air Shower (EAS).

At  $10^{19}$  eV, an EAS will contain on the order of  $10^{10}$  charged particles and will cover a ground-level area of 10-20 km<sup>2</sup>. The shower caused by the primary cosmic ray will produce said charged particles, which can be detected by ground-type arrays (such as AGASA), but it will also produce detectable quantities of forward Cerenkov radiation and UV fluorescent photons of isotropic emission (see Fig. 1). This luminescence is caused by the excitation of Nitrogen in the atmosphere, which creates photons.

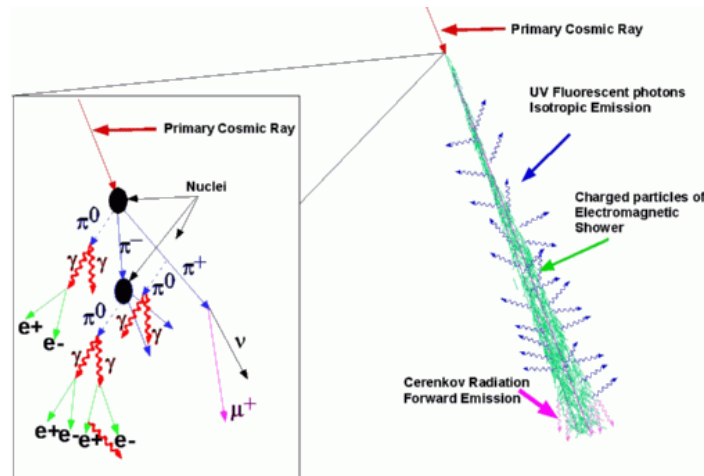


Fig. 1

There are four main quantities that cosmic ray researchers are interested in measuring: energy, arrival direction, composition and development, and CR cross-sections. Cosmic ray physicists are interested in the elements of clustering/isotropism of the incident CR and of the element of magnetic path distortion, both of which could help in determining the source of the highest energy cosmic rays, one of the great mysteries in modern physics.

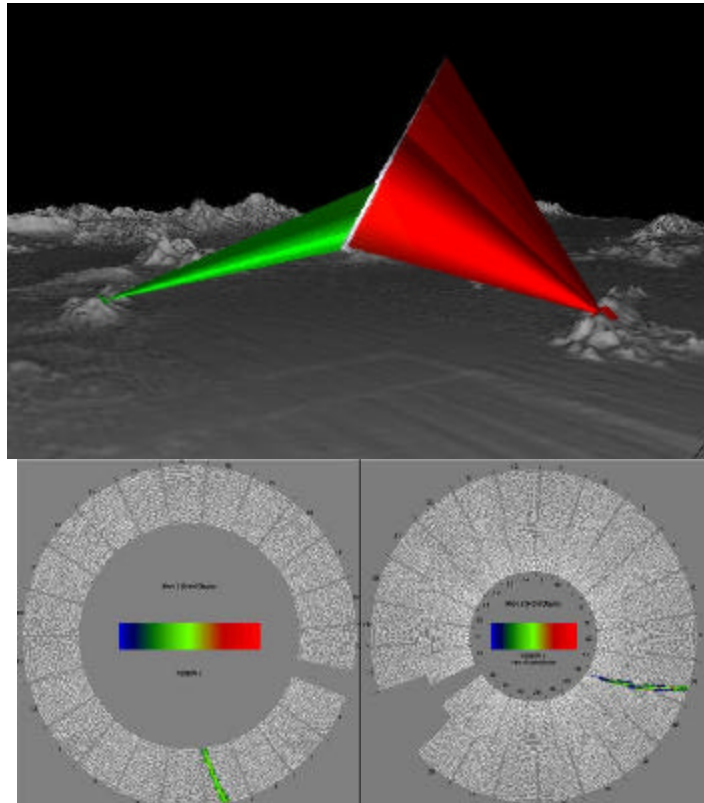
In terms of measuring the composition and development of CR and the following EAS events, it is an ideal situation when the full development of EAS can be directly observed in the atmosphere and the height of the shower maximum can be measured directly, and not found as the result of a backward extrapolation. This is possible by imaging the isotropic air fluorescence caused by these events, which is what the HiRes project, along with its predecessor Fly's Eye, has been able to do.

The HiRes detector array is made up of two detector sites separated by 13km and located on Dugway Proving Ground in Utah. Each of the sites utilize large

spherical mirrors (3 meters in diameter) to collect the luminescence given off by the Nitrogen interactions in an EAS and focus that light onto fast cameras composed of photo-multiplier tubes (PMTs).



The first HiRes site in operation (HiRes1) is located to the northeast of center and is composed of 21 mirrors enclosed by weatherproof sheds. It covers a  $3\text{-}16^\circ$  slice of the sky over the full azimuthal range. HiRes2 is the most recently constructed site and has to be run locally by colleagues in Utah. It has twice as many mirrors as HiRes1 (42) and covers a  $3\text{-}30^\circ$  slice over the full azimuthal range. The obvious benefit to having two sites covering a large amount of the same sky is that events seen in both detectors can be reconstructed in stereo (see Fig. 2). HiRes has an observable energy range starting around  $10^{18}\text{eV}$  and covers the atmosphere about  $3000\text{ km}^2$  of ground area. As a result of this extensive sky coverage, HiRes is able to see around 300 events above  $10^{19}\text{eV}$  every year.

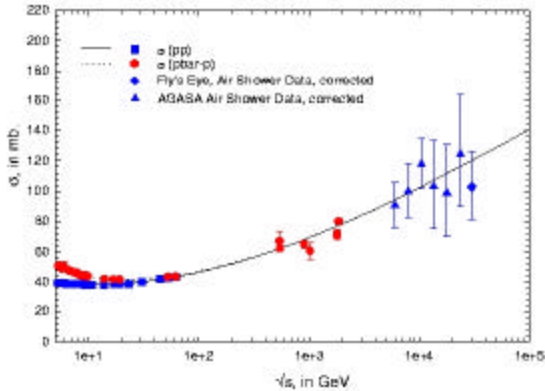


**Fig. 2**

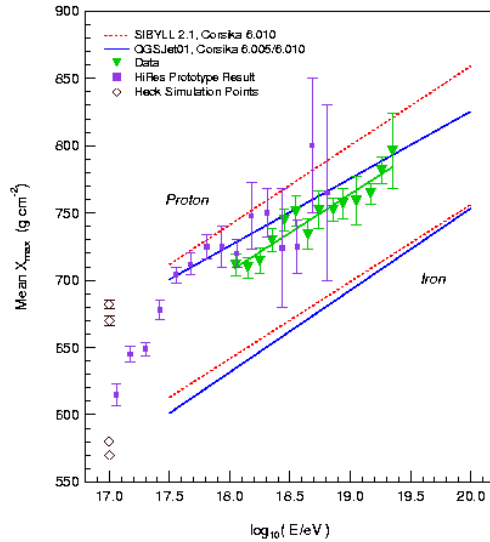
## 2 Analysis

Measurements of the cross-section have been conducted around this energy range before, but there is simply not enough data yet to feel comfortable with a definition of how the cross-section behaves at energies above 3GeV or so. We set out to find the cross-section in an energy range ( $s^{1/2} \sim 44\text{TeV}$ ) where very few measurements have been made to date (see Fig. 3).

We started by compiling Monte Carlo (MC) simulations for the shower max ( $x_{\text{max}}$ ) distribution and the initial interaction length ( $x_0$ ). Two assumptions were initially made when approaching this project. One was that there is some correlation between the falling exponential that describes initial interaction length of an incident proton and the falling exponential that describes the curve of the shower max distribution. The second assumption made was that at energies of  $10^{18}\text{eV}$  and above, the CR composition was light (i.e. protons). This assumption was based on previous experimental evidence from HiRes and other groups that have measured the composition at 1 EeV (see Fig. 4). After producing the MC sets, we split the  $x_{\text{max}}$  set randomly into two equal sets half the original size. These two sets will hereafter be referred to as MC1 and MC2 (but keep in mind there is yet another MC, the one containing the initial interaction length ( $x_0$ ) data). The  $x_{\text{max}}$  MC was split because it needed to perform two functions: MC1 would be used to determine a value for the coefficient  $k$  (discussed later) and MC2 would be used as a test of the  $k$  value, which was necessary were we to be confident with our result once we applied our method to real data.



**Fig. 3**



**Fig. 4**

To understand the nature of the  $k$  parameter, it is perhaps easiest to look at it as follows: if the incident proton were to dissipate all of its energy instantaneously, the shower maximum would always be at the primary interaction point and we could measure the initial interaction length ( $\lambda_0$ ) by fitting  $x_{\text{max}}$  to:

$$P(x_{\max}) \sim e^{-x_{\max}/I_0}$$

The proton, however, dissipates its energy at some rate, so the falling exponential is distorted, and this distortion is quantified by the inelasticity parameter  $k$  with:

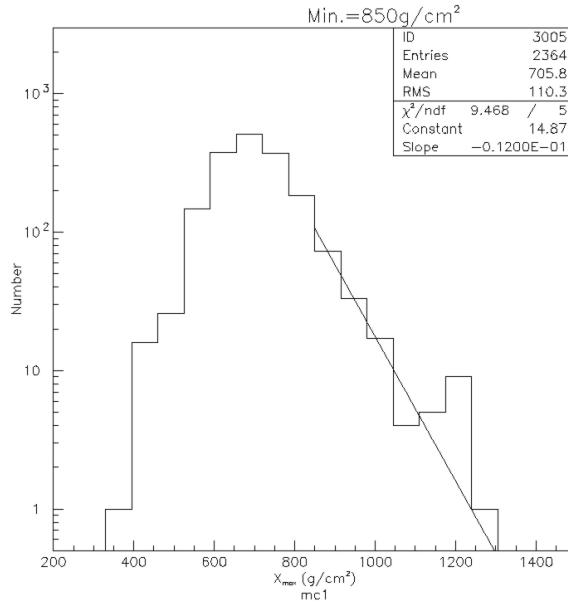
$$P(x_{\max}) \sim e^{-kx_{\max}/I_0}$$

Therefore:

$$\Lambda_M = kI_0 = k \frac{14.5m_p}{S_{p-Air}^{inel.}}$$

where  $m_p$  is the proton mass and  $\sigma$  is the inelastic  $p$ -Air cross-section.

The value of  $k$  was found by designing a fitting function the MC1 data set that incrementally increased the lower limit of the fit to the logarithmic plot of  $x_{\max}$  until a preferable probability was attained ( $>850\text{g/cm}^2$  on our data set)(see Fig. 5). Once this fit was determined, the slope was measured and taken as the negative inverse of  $\Lambda_M$ . The two plots of  $x_0$  (one at  $1 \times 10^{18.0}\text{eV}$  and one at  $1 \times 10^{18.1}\text{eV}$ ) were then fit, on a logarithmic scale, and the slope of those fits were taken as values of  $\lambda_0$ . Since  $\Lambda_M$  is equivalent to  $\lambda_0$  multiplied by the elongation factor  $k$ , a simple ratio of  $\Lambda_M/\lambda_0$  yielded a value (rather two values which were later resolved to one) for  $k$ .



**Fig. 5**

Cuts on the  $x_0$  and  $x_{\max}$  files were made (mostly) in accordance with those of a previous HiRes study conducted by Konstantin Belov. Energy was limited to be below  $10^{22}\text{eV}$ ,  $x_{\max}$  had to be seen in at least one detector, and a good Gaisser-Hillas fit to the track was required. No angular cuts were used and  $x_{\max}$  was only required to be greater than or equal to zero (the initial interaction had to occur in the atmosphere).

We selected our energy bins ( $10^{18.0}$  and  $10^{18.1}$  eV) because we wanted to be able to compare our results with previous measurements. It was understood that if our data was found to be in some degree of accordance with prior data, we would continue to higher energies such as  $10^{19.0-19.1}$  eV and  $10^{20.0-20.1}$  eV. However, to make sure that the MC1 set was in agreement between the  $10^{18.0}$  and  $10^{18.1}$  energy bands, a Kolmogorov test was run and it returned a value of 11.26% (good agreement). Based on the result, it was felt a justified energy range had been selected.

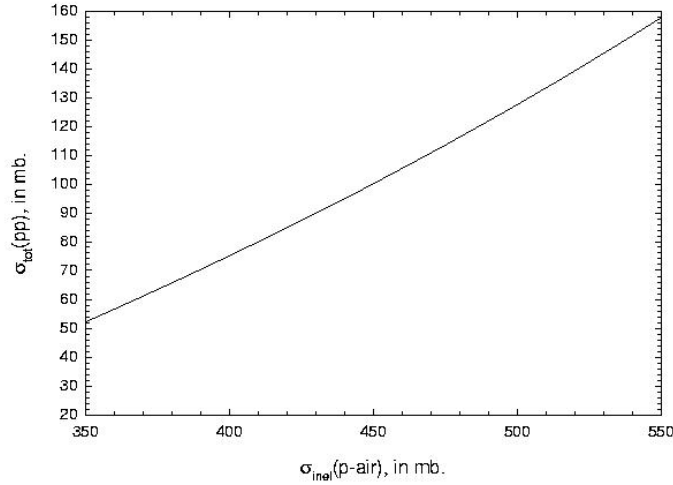
The next step was to find a value of the inelastic  $p$ -Air cross-section from  $x_0$  according to:  $\mathbf{s}_{p-Air}^{inel.} = 14.5 \frac{m_p}{\mathbf{I}_0}$ , where 14.5 was used as the average atomic mass.

This value was to be taken as the 'right' value for the cross-section. This value could be compared to the value obtained from MC2 (the 'test' sample) following the relation:  $\mathbf{s}_{p-Air}^{inel.} = 14.5k \frac{m_p}{\Lambda_M}$ .

The final step of the analysis using MC data was to determine the  $p$ - $p$  cross-section from the  $p$ -Air values. This was done in two ways, one resulting in an inelastic  $p$ - $p$  value and the other resulting in a total (elastic plus inelastic)  $p$ - $p$  value. To arrive at the inelastic value, a simple permutation of Glauber theory predicts:

$$\mathbf{s}_{p-p}^{inel.} = A^{\frac{-2}{3}} \mathbf{s}_{p-Air}^{inel.}$$

To arrive at the total cross-section, a plot produced by M. M. Block can be used (see Fig. 6).



**Fig. 6**

### 3 Results and Conclusions

By running the full analysis with MC data, values were obtained that established what should be expected once real data was applied. Using the value of the

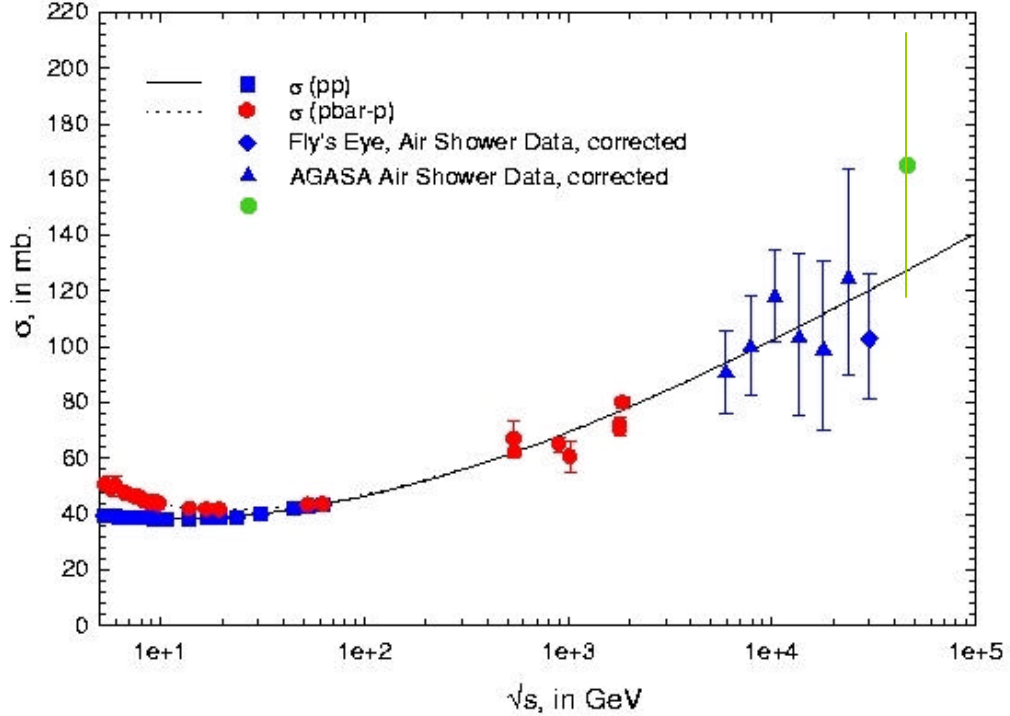
shower attenuation length ( $\Lambda_M = 96.49 \pm 9 \text{g/cm}^2$ ) a value of  $1.86 \pm 0.33$  was attained for  $k$ .

Once  $k$  had been established, it was possible to arrive find the estimated inelastic  $p$ -Air cross-section and the total  $p$ - $p$  cross-section using Block's method.  $S_{p\text{-Air}}^{inel.}$  was found to be  $468.46 \pm 82 \text{mb}$  and the corresponding  $S_{p-p}^{tot.}$  was  $112 \pm 19 \text{mb}$ .

Upon application of real HiRes stereo data, and using the  $k$  value from MC data the value of  $S_{p\text{-Air}}^{inel.}$  found equal to  $558 \pm 85 \text{mb}$  and the corresponding  $S_{p-p}^{tot.}$  was  $167 \pm 40 \text{mb}$ . For comparison, previous measurements of the total proton-proton cross-section around the  $\sqrt{s} = 40 \text{TeV}$  energy range were  $133 \pm 10 \text{mb}$  (AGASA) and  $175 \pm 40 \pm 27 \text{mb}$  (Fly's Eye).

Uncertainties were evaluated for the error in  $k$  arising from statistical uncertainties in the Monte Carlo data were evaluated, as was the statistical error in the fit to  $x_{\text{max}}$  in the real data. The small (.08%) uncertainty in Block's relational plot of  $p$ -Air to  $p$ - $p$  was also included. Uncertainties in energy scale and composition were not considered.

The cross-sectional values for proton-air and proton-proton interactions determined using our method are found to be consistent with both theory and previous measurements. This method is a good, albeit primitive, method for use in determining the cross-section and it can easily be applied to higher energies ( $s^{1/2} > 100 \text{TeV}$ ) in future studies.



(Our  $p$ - $p$  value is added as the green dot)

## 4 Acknowledgements

The entire staff of both Nevis Laboratories, and the staff at the Nevis Annex in Pupin on Columbia campus for all of the help. Dr. John Parsons and Stefan Westerhoff for all the work they put into organizing the REU program at Columbia. Again Stefan for all the help in putting together a workable presentation and giving me guidance throughout the summer. Brian Connolly for being an incredibly brilliant mentor, teacher and friend. All of HiRes (esp. Andy and Segev) for their support and help. The National Science Foundation for the funding of the REU program which made this possible.

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