Composition and cross-section measurements with the HiRes .

Konstantin Belov

High Resolution Fly's Eye (HiRes) Collaboration

C2CR, Praha 2005.

- ***Columbia University***
- ***University of Adelaide***
- ***University of New Mexico***
- ***Rutgers University***
- ***University of Montana***
- ***Los Alamos National Laboratory***
- ***University of Tokyo***

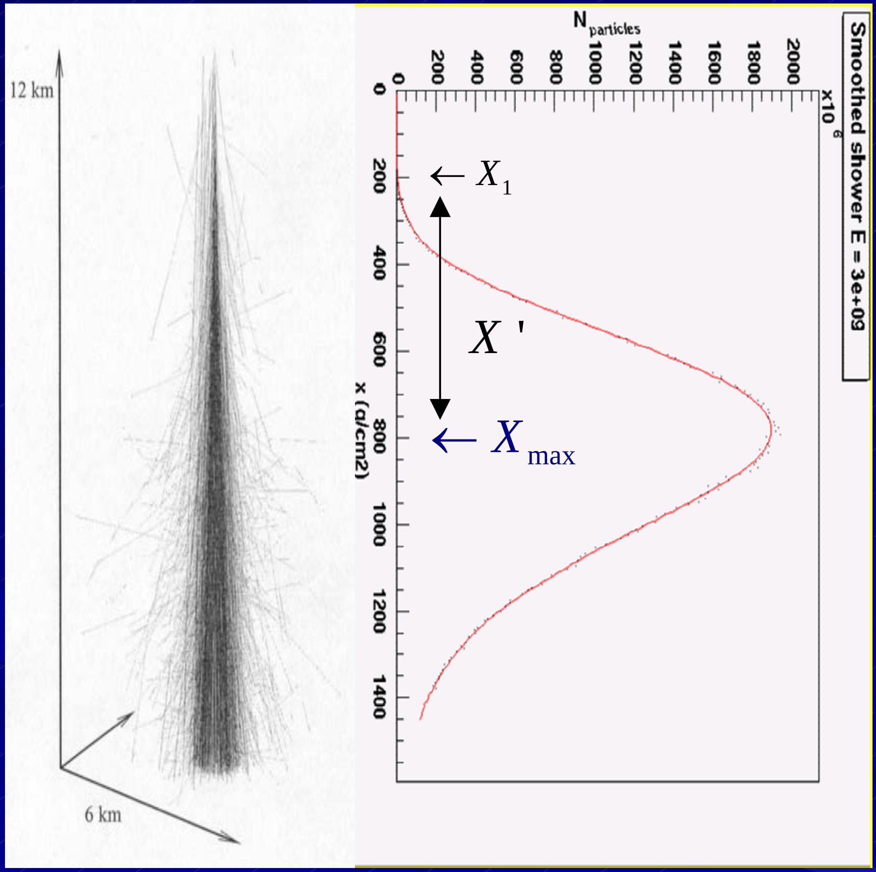
THE UNIVERSITY OF UTAH

Motivation

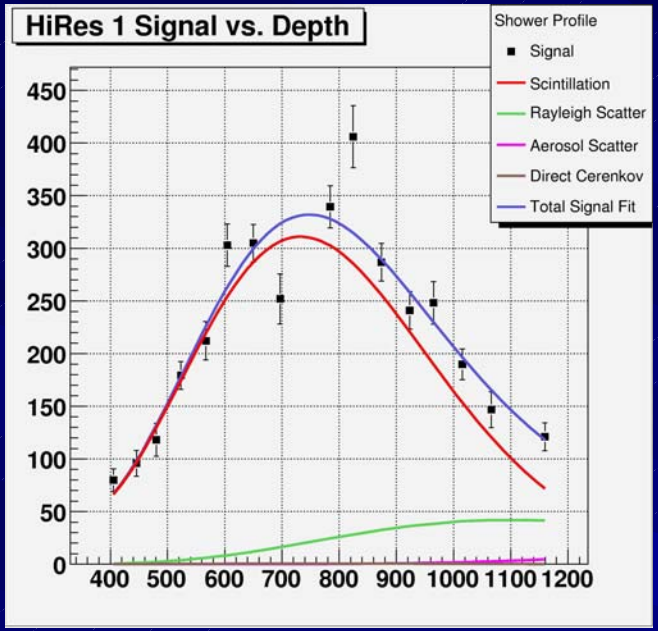
- Learn basic information about cosmic rays;
- In HiRes energy range ($10^{17.2}$-10^{20} eV) expect to see a transition between galactic and extragalactic sources:
  - Expect highest energy galactic cosmic rays to be heavy nuclei (iron);
  - Expect extragalactic cosmic rays to be light (protons)
- Fluorescence experiments observe X_{max} directly:
  - $\langle X_{max} \rangle$ for proton > $\langle X_{max} \rangle$ for iron;
  - Can see the difference directly.
- Cosmic ray physics.
  - Proton-air inelastic cross-section significantly influences the development of cosmic ray showers.
- High energy physics.
  - Proton-air inelastic cross-section can be used to determine p-p total cross-section energy dependence.
  - Is the Froissart bound saturated?
- Strong model dependence of the previous cosmic ray measurements.

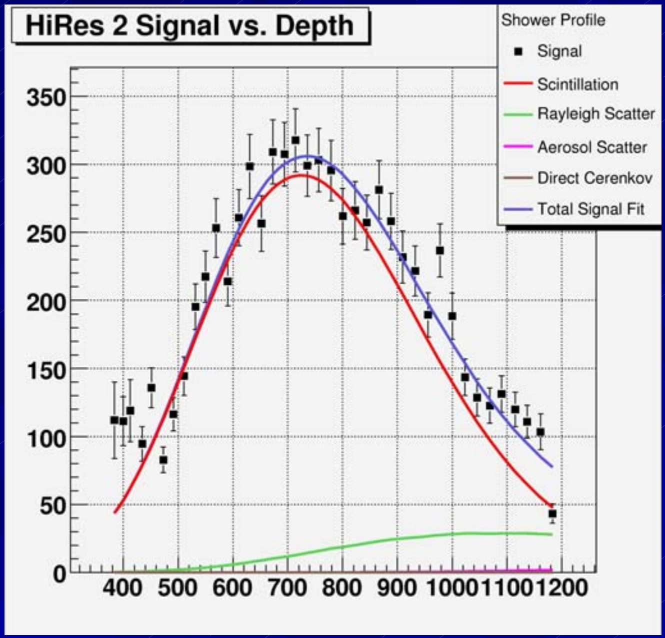
Air shower profile.

- X_{max} (g/cm^2)– slant depth of the shower where ionization losses start to exceed bremsstrahlung;
- X_{max} fluctuates event by event, but $<X_{max}>$ is a stable function of energy;
- $<X_{max}>$ different for light and heavy component;
- RMS of the X_{max} distribution is different for different primary.
- X_1 – depth of the first interaction.
- $X' = X_{max} - X_1$.



Measured shower profile.





Measured shower parameters.

Event by event:

- X_{max} in g/cm^2;
- Total energy of the primary particle:
- Arrival direction

Statistically:

- *p*-air inelastic cross-section;
- Mass composition.

Atmosphere

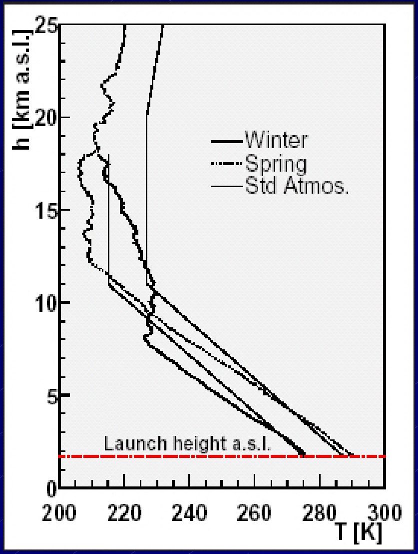
- Composition and cross-section measurements rely on knowledge of out calorimeter – the earth atmosphere;
- Choosing a correct atmospheric model will reduce the experiment's systematic errors;
- Atmospheric fluctuations will contribute to the statistical error.

HiRes Atmospheric model

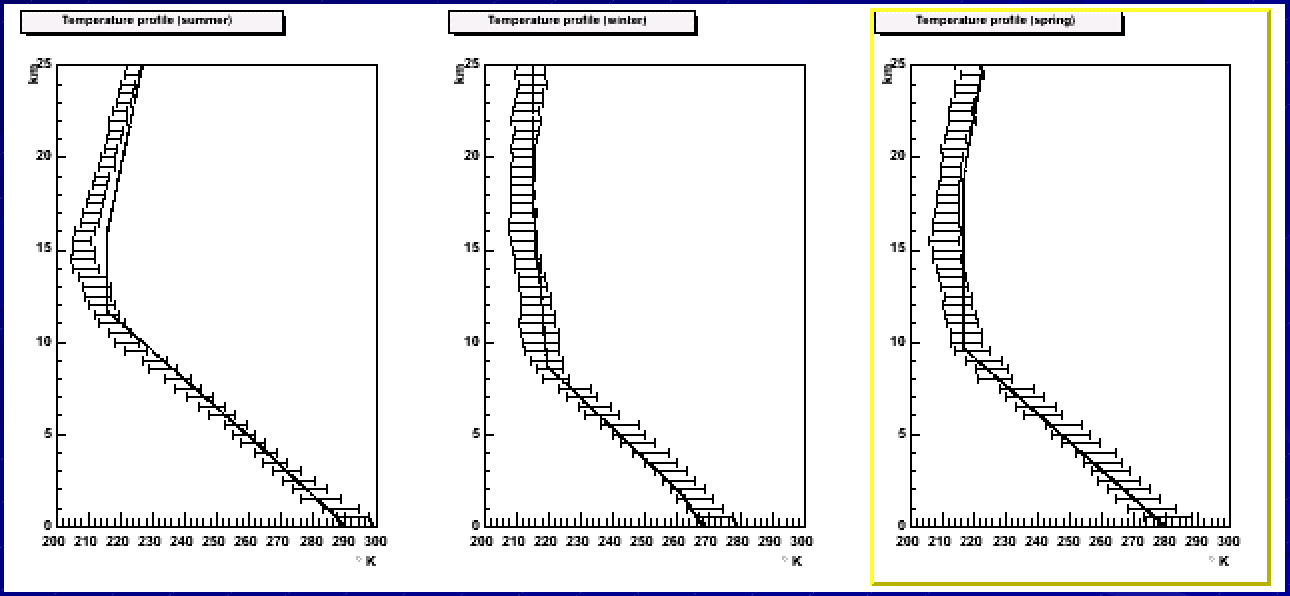
- 1976 US Standard Atmosphere
- 3 seasonal profiles: winter, summer, spring/fall
- For reconstruction the model is picked according to the season.
- Dec, Jan, Feb – winter
- June, July, Aug – summer
- All other months – spring/fall.

Temperature Profile

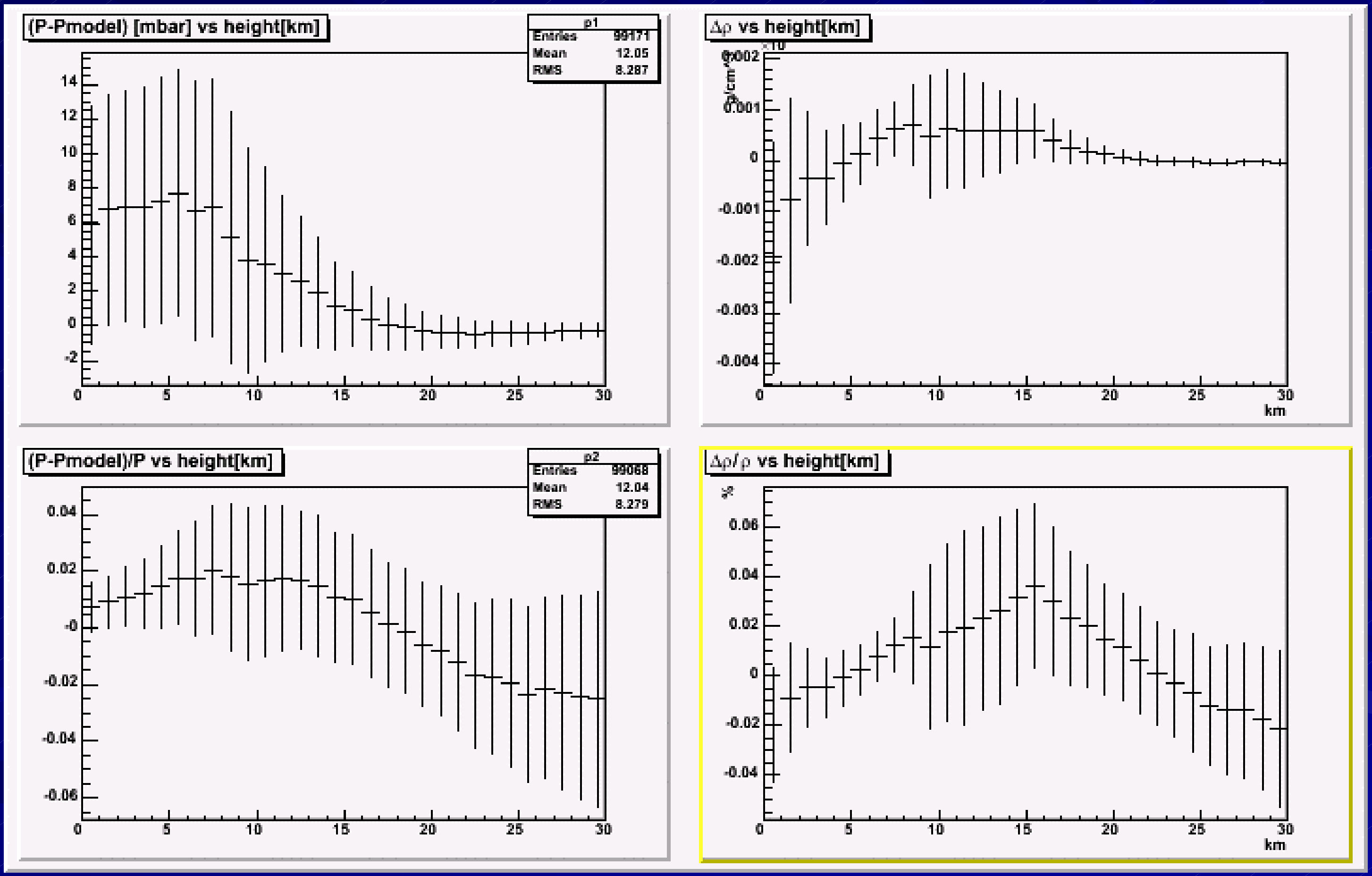
Auger



Hires

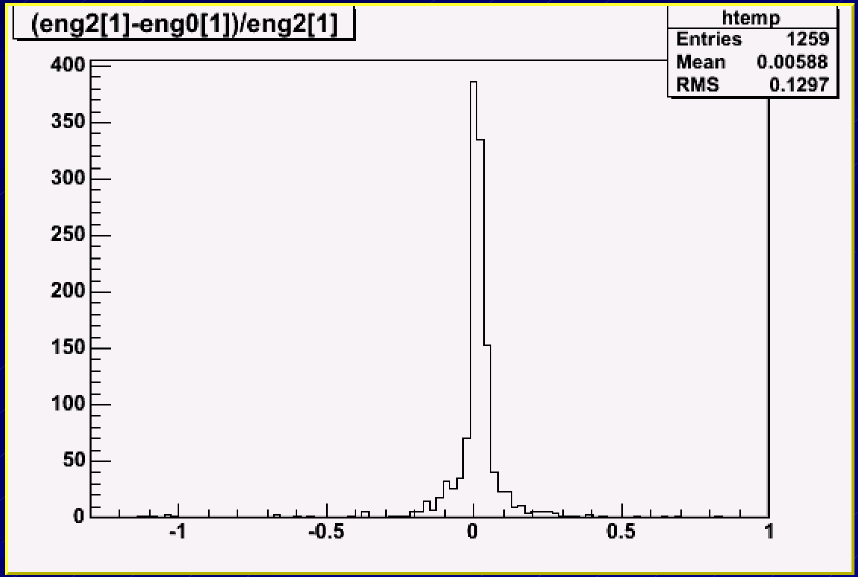


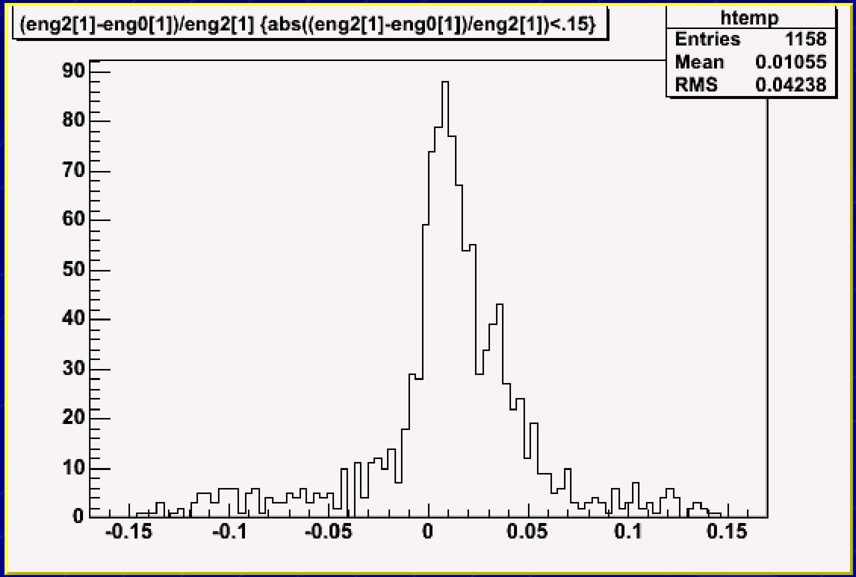
Radiosonde Data vs HiRes Model



Energy correction

Each event reconstructed With radiosonde data and Compared with reconstruction Using HiRes model.

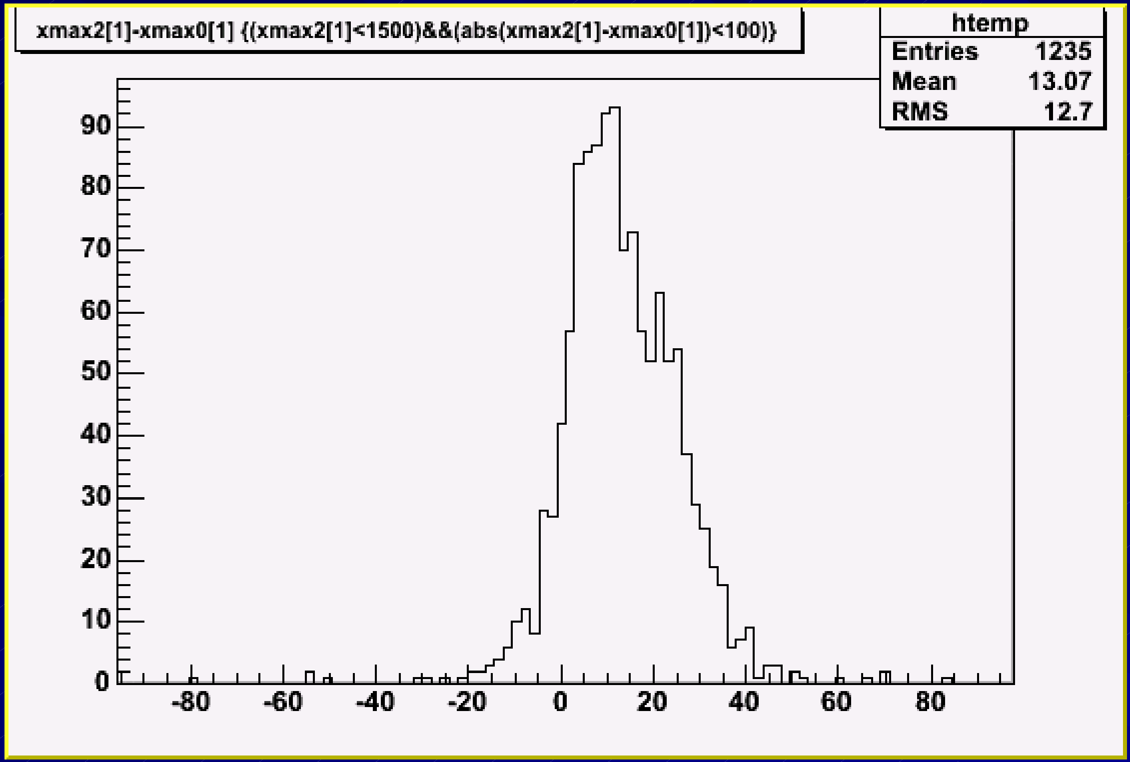




Eng2 – radiosonde
Eng0 – Standard HiRes model

Tails cut.

X_{max} correction



Each event reconstructed
With radiosonde data and
Compared with reconstruction
Using HiRes model.

Xmax2 – radiosonde
Xmax0 – HiRes model

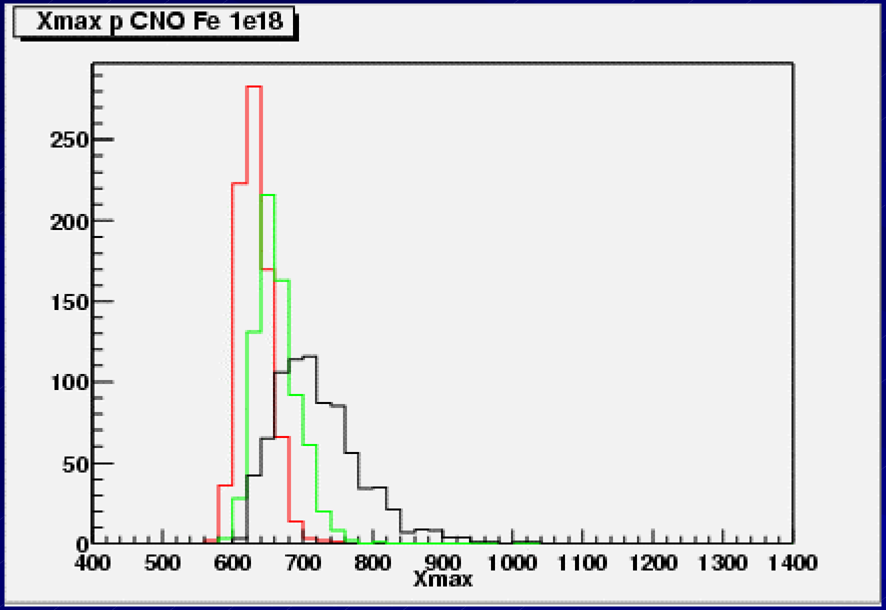
HiRes underestimates Xmax
By 13 g/cm2.

Effect on the elongation rate ~ 0.6 g/cm^2

Molecular atmosphere. Conclusions…

- HiRes molecular atmosphere is very stable;
- HiRes atmospheric model uncertainty leads to ~ 10-13 g/cm^2 energy-independent underestimation of $<X_{max}>$.

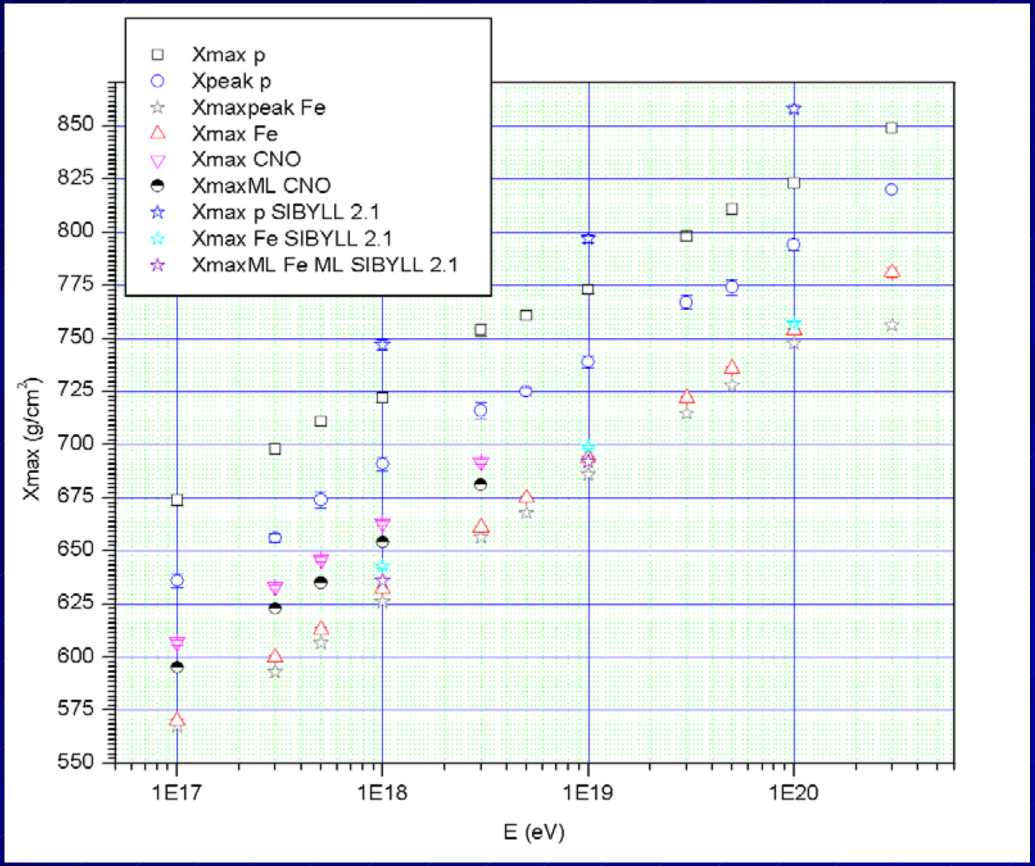
X_{max} distribution for p, CNO, Fe



QGSJet

- Heavier primaries develop earlier in the atmosphere.
- RMS of the X_{max} distribution is different.

Elongation rate p, CNO, Fe



$<X_{max}>$ can give us a clue about CR composition, but is very much model dependant.

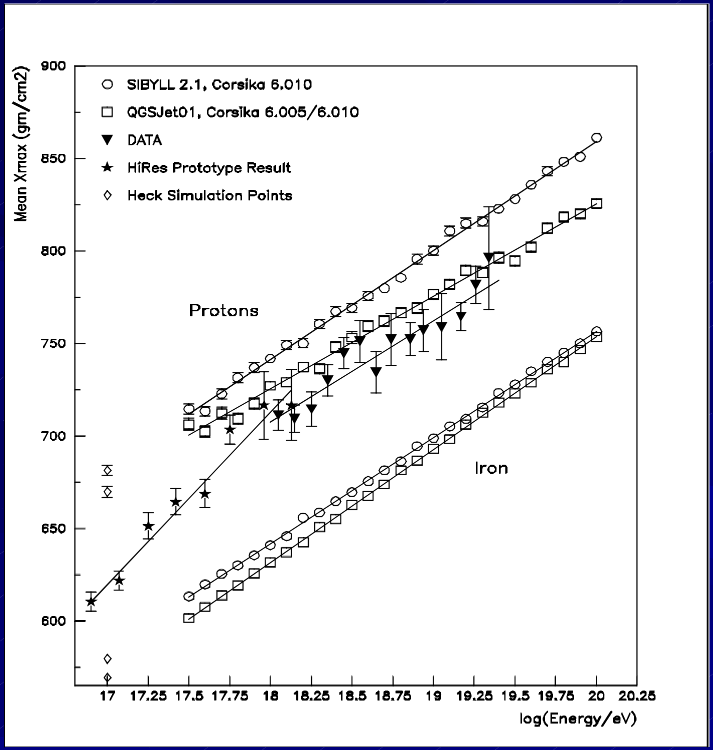
Fly's Eye detector.

- Two fluorescence detectors were positioned 3.5 km apart;
- The effective energy range extended from 10^{17} eV to 3×10^{19} eV;
- 5×5 degree pixel size;
- Geometry of the event was determined by the intersection of the two event-detector planes;
- Elevation angle range from 0 to 90 degrees;
- FE II had only partial azimuth coverage

HiRes prototype/MIA

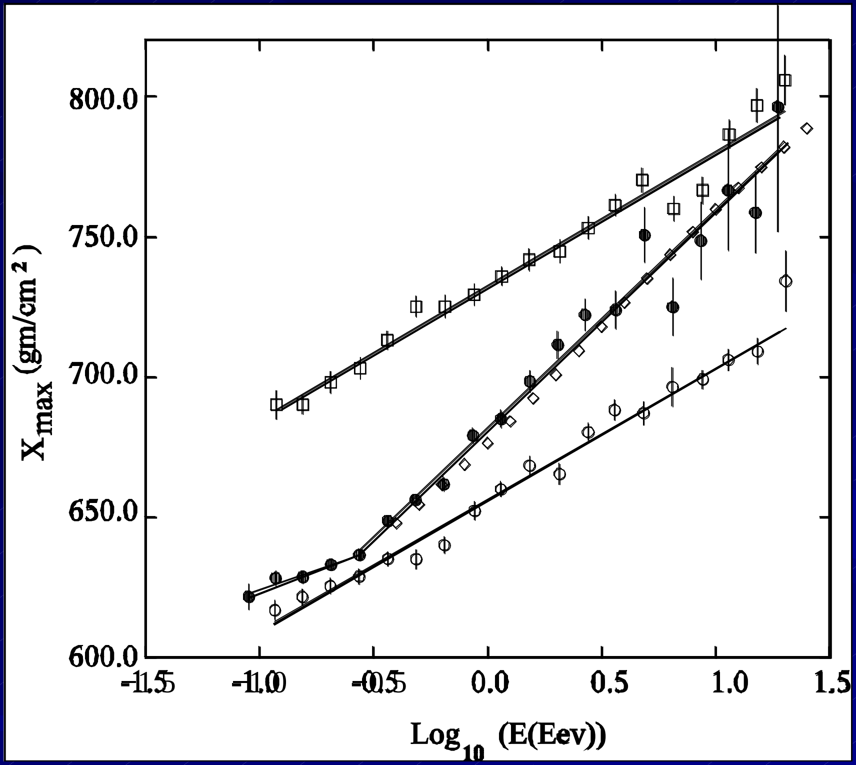
- Hybrid fluorescence - muon array detector;
- Fourteen mirror prototype of the current HiRes detector had a 1×1 degree pixel size;
- Was located 3.5 km from the center of the MIA muon array;
- The muon array sampled a part of muon lateral distribution. 3 km effective area;
- Energy range from 5×10^{16} eV to just above 10^{18} eV;
- Event geometry was determined by using the HiRes event-detector plane and timing from both detectors.

HiRes stereo and HiRes prorotype data.



- HiRes/MIA - hybrid experiment. Resolution function estimated from simulations ~ 45 gm/cm^2
- HiRes stereo - X_{max} resolution measured, 30 gm/cm^2

Fly’s Eye stereo data.



- Fly’s Eye Stereo - X_{max} resolution ~45 gm/cm^2 measured resolution function

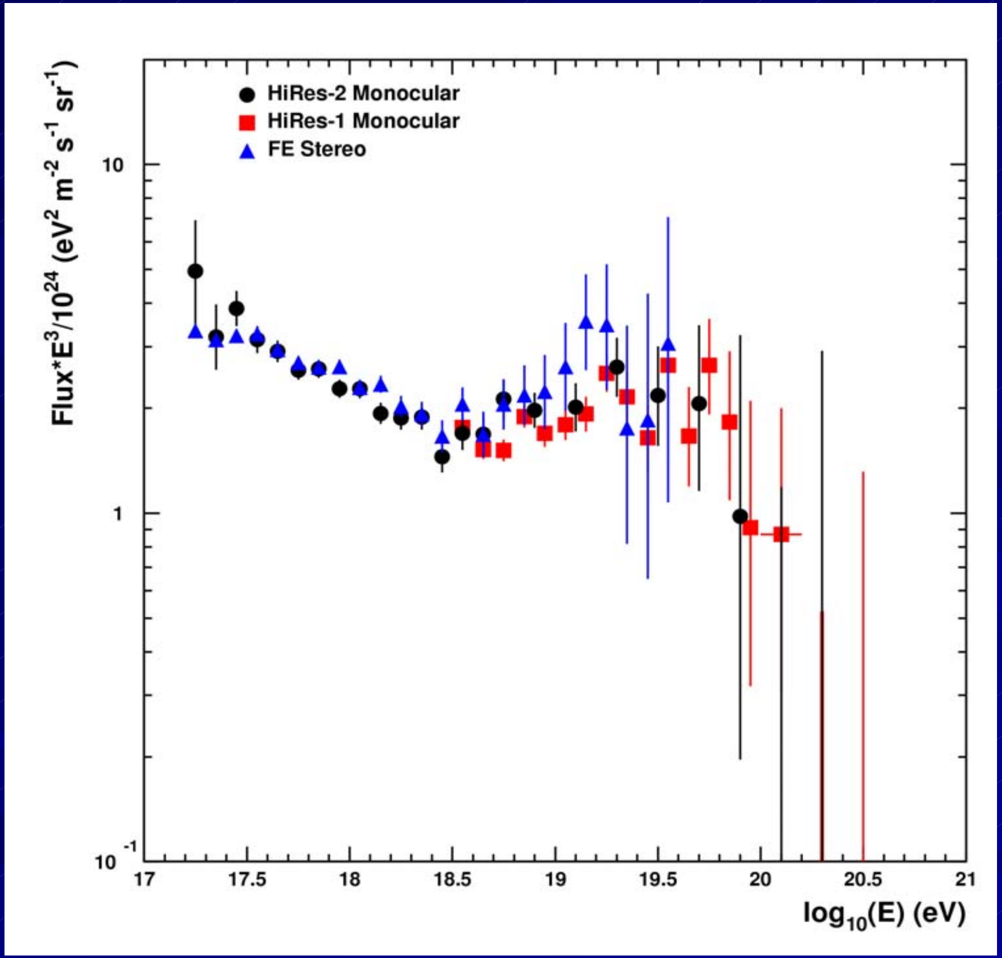
Systematic errors

- All three experiments quote systematic errors ~ 25 gm/cm^2.
- Dominant contributions
  - Mirror survey
  - Cherenkov subtraction
  - Atmospheric profile
  - Aerosol corrections
- Highest energy data is best measurements

  - most complete profile

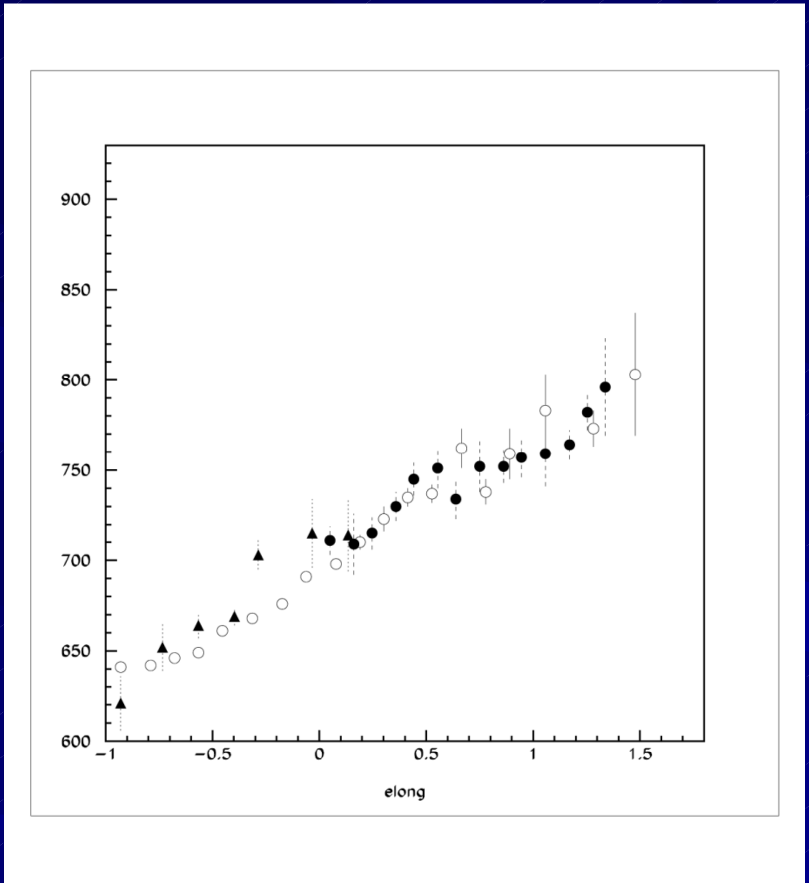
  - minimum Cherenkov subtraction

Comparison of Fly's Eye Stereo and HiRes energy scales



Energy scale for all three experiments is consistent (location of ankle and second knee).

Elongation rate



Filled circles, HiRes; Triangles, HiRes/MIA, Open circles, Fly's Eye (shifted).

- Use HiRes stereo average X_{max} and Fly's Eye stereo average Xmax above 10^{18} eV.
- Require a 13 gm/cm^2 upward shift for Fly's Eye to bring means into agreement
- Shift all Fly's eye X_{max} data points by the same amount.

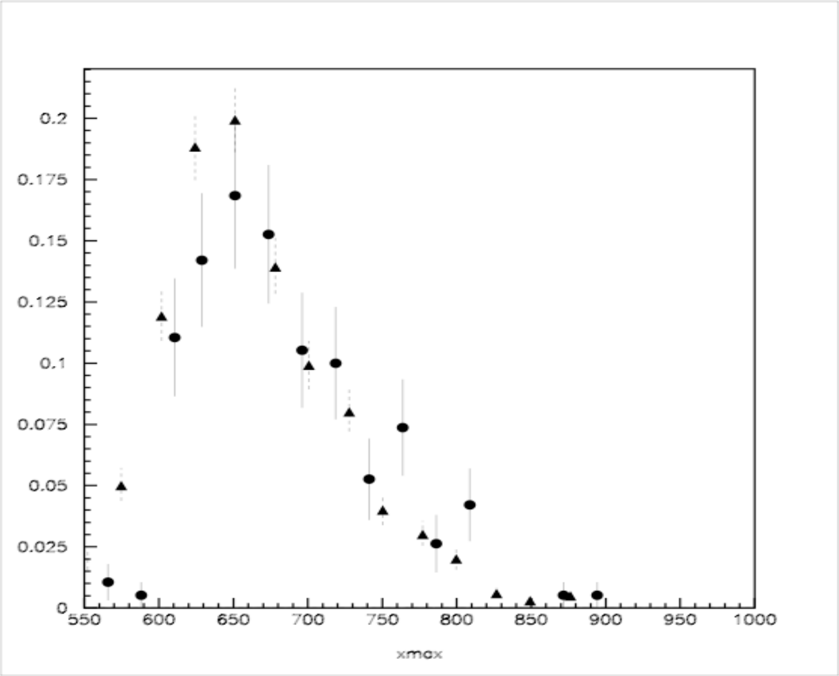
Elongation Rate

- Simple shift of Fly’s Eye data brings all data into reasonable agreement.
- Fly’s Eye and HiRes data are in excellent agreement above 10^{18} eV.
- HiRes/MIA shows earlier transition to “protons”, but point by point discrepancy is small.
- HiRes/MIA systematics are better understood, however.

X_{max} distributions consistent?

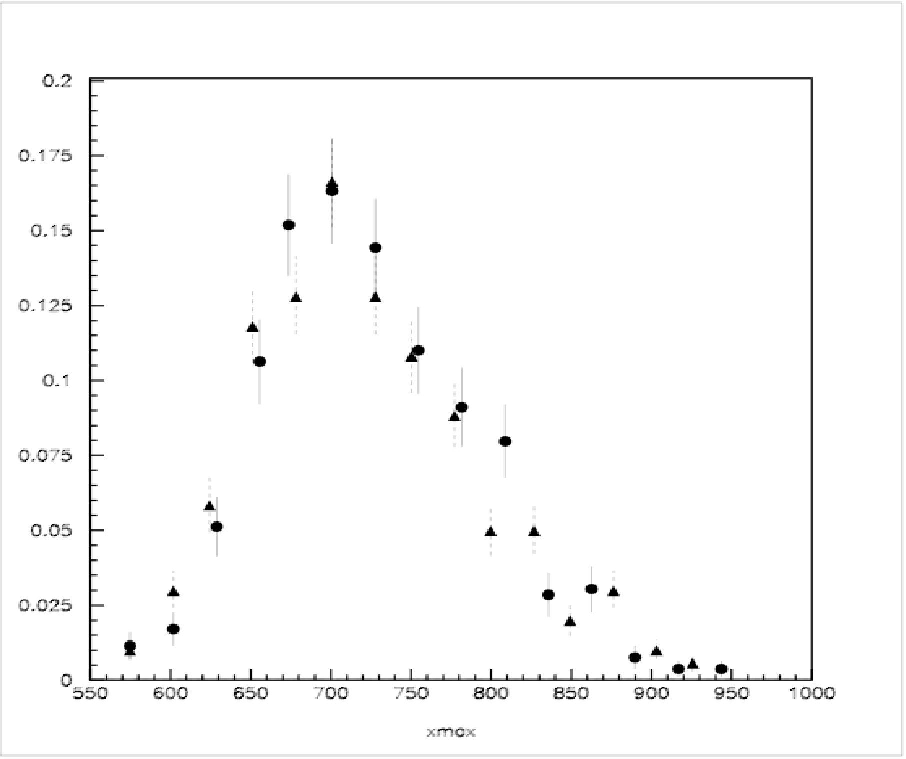
- Are Xmax distribution widths consistent?
- Two overlap regions
  - Fly's Eye and Hires/MIA in $3x10^{17}$ to 5×10^{17} eV bin.
  - Fly's Eye and HiRes stereo in > 10^{18} eV bin.
- No evidence of discrepancy in distribution widths.

Fly's Eye vs HiRes/MIA X_{max} at 3-5 x 10^{17} eV



Triangles: Fly's Eye Stereo;
Circles: HiRes/MIA.

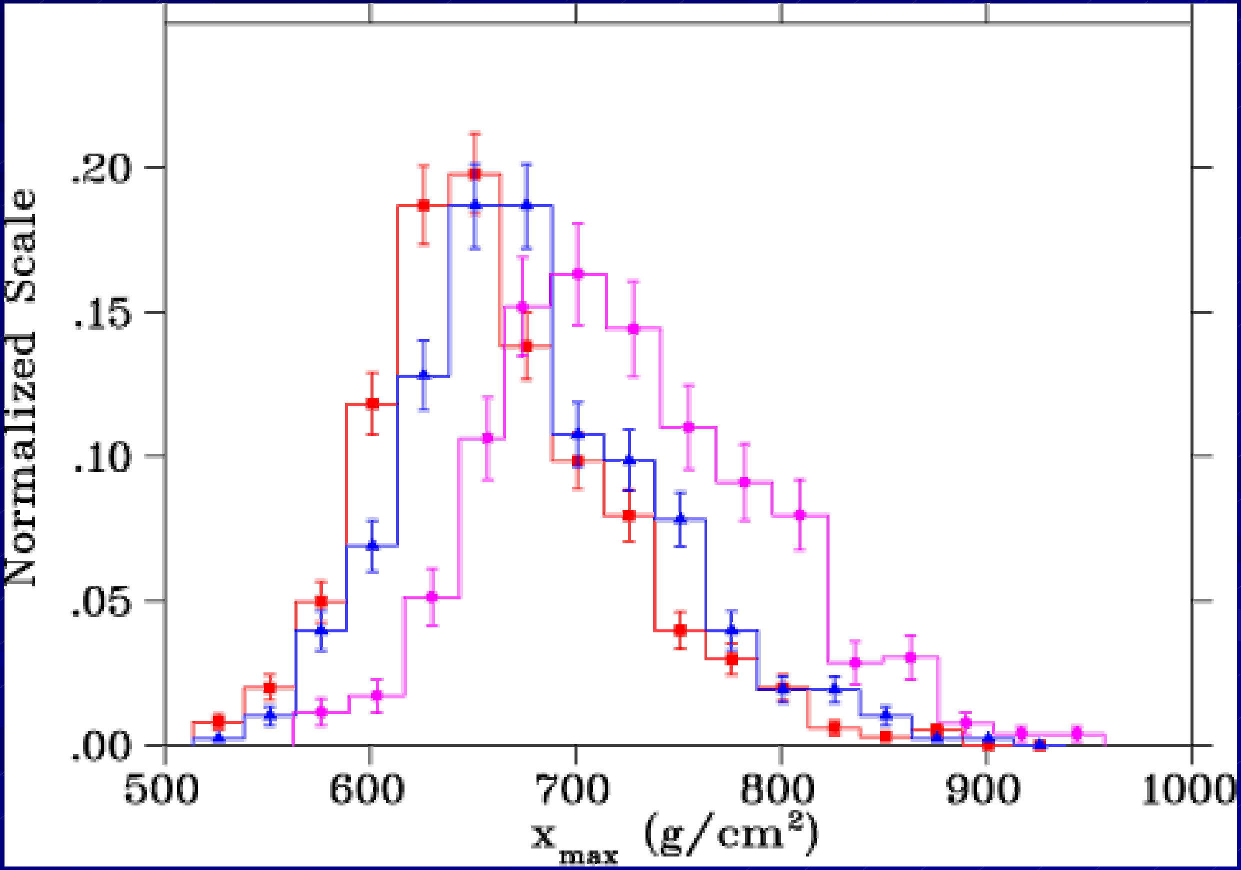
Fly's Eye vs HiRes X_{max} > 10^{18} eV



Triangles: Stereo Fly's Eye;

Circles: HiRes.

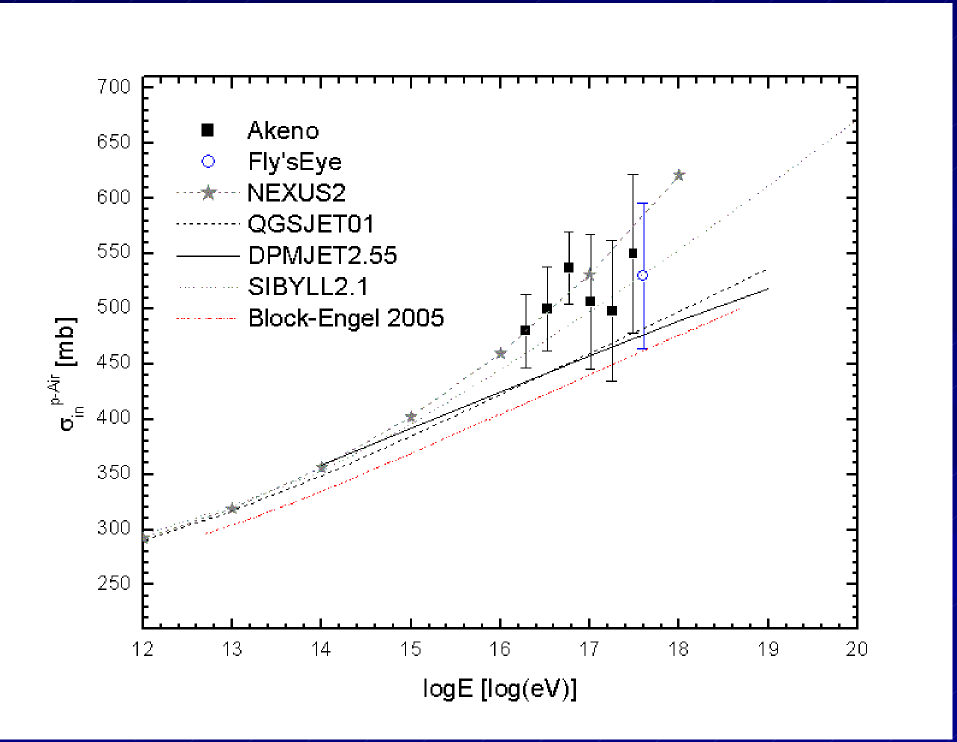
Sequence of X_{max} distributions in three increasing energy bins 3-5×10^{17}, 5-10×10^{17} and > 10^{18}eV.



Mass composition. Conclusions…

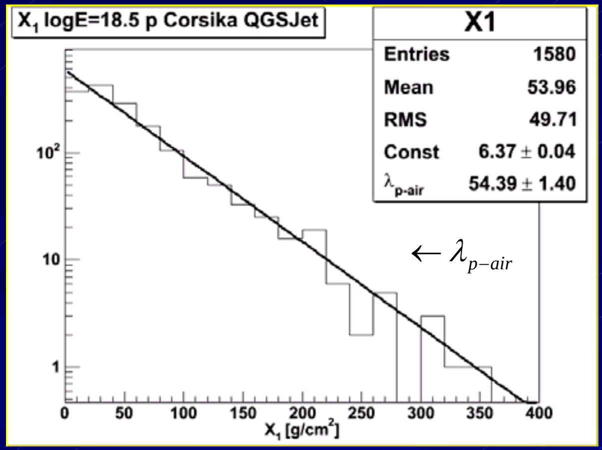
- A simple X_{max} shift brings all three experiments into reasonable agreement.
- Widths of X_{max} distributions are in agreement.
- Normalized X_{max} distribution show jump to wider distribution above 10^{18}, consistent with change to protons.
- Interpretation of elongation rate over limited energy range is problematic - Need large dynamic range in a single experiment!

Cross-section: models and accelerator data extrapolation

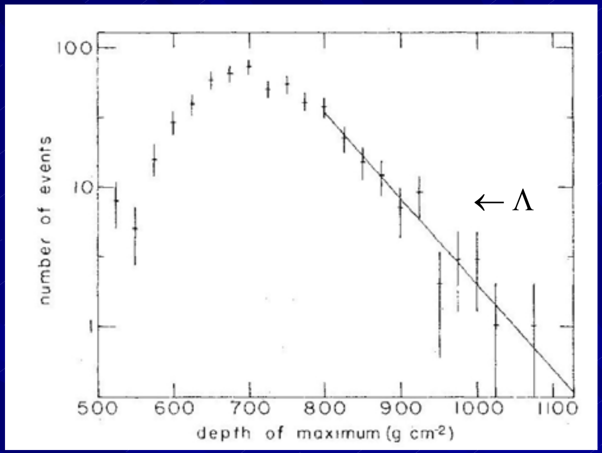


- Model uncertainties are large;
- Extrapolation goes orders of magnitude;
- AGASA and Fly's Eye measurements are model dependant.

CS measured by Fly's Eye and AGASA



$$k\lambda_{p-air} = \Lambda$$



Baltrusaitis *at.al.* 1984.

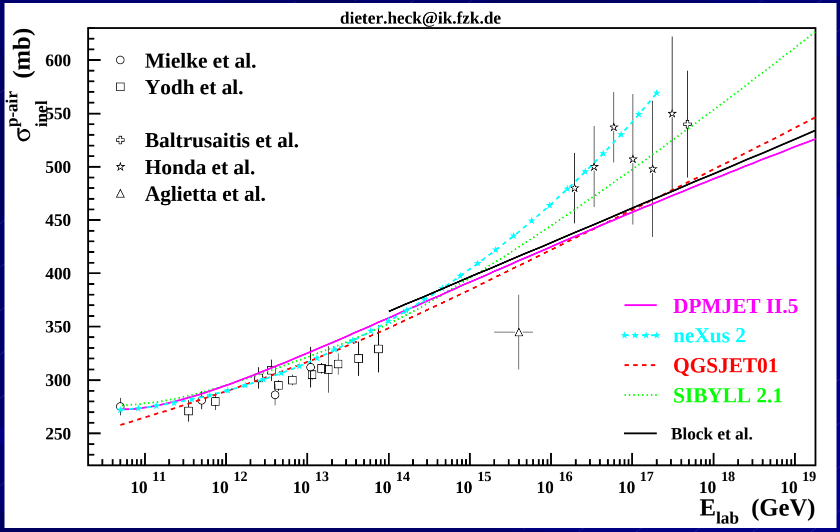
k – is obtained from MC study.

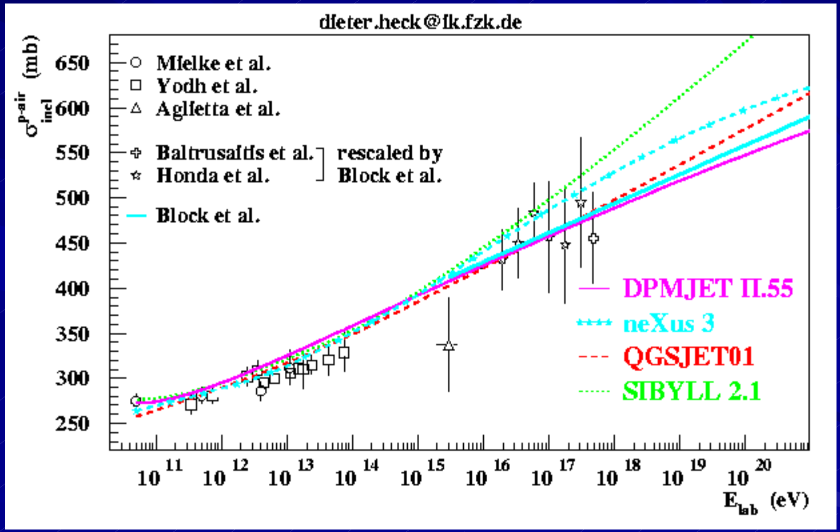
- An indirect measurement technique proposed for Fly's Eye and Akeno.
- The distribution of the point of first interaction (X1 distribution) propagates into the Xmax distribution and manifests itself in it's exponential tail.

k-factor limitations.

– k is dependent on the interaction model;

– Λ measurement depends on the X_{max} exp. slope cutoff point.



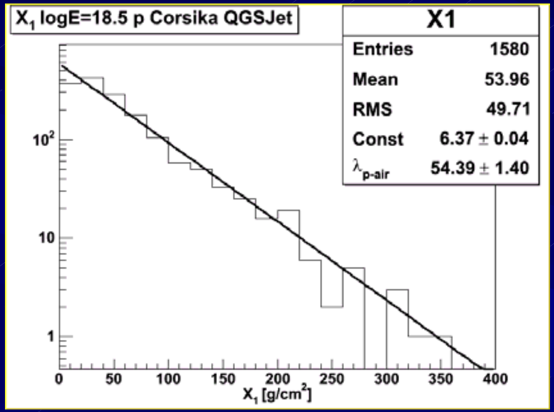


HiRes stereo observables.

- Being an air fluorescence experiment HiRes stereo observes X_{max} directly;
- Calorimetric measurements of the primary particle energy;
- Can still use X_{max} distribution to measure the p-air inelastic cross-section, but a new technique is needed to reduce the interaction model dependence.

Deconvolution technique.
MC simulations.

Point of first interaction distribution. Exponential index reflects inelastic Cross-section

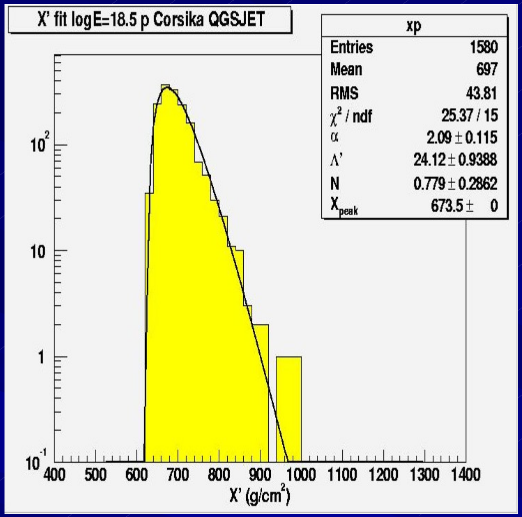


$$f_{\mathrm{int}} = e^{-\frac{x_1}{\lambda_{p-Air}}};$$

$$\lambda_{p-Air} = \frac{1}{\tilde{n}\,\sigma^{inel}_{p-air}};$$

$\otimes$

Atmospheric part of air shower fluctuations



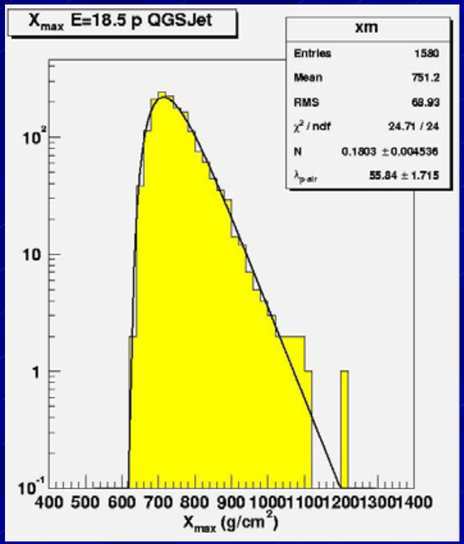
$$X' = X_{\max} - X_1$$

$$f_{fluct} = \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max} - x_1 - x_{peak}}{\Lambda'}}$$

$$f_{fluct}(x_{peak}(E), \Lambda'(E), \alpha(E)) \Rightarrow f_{fluct}(E)$$

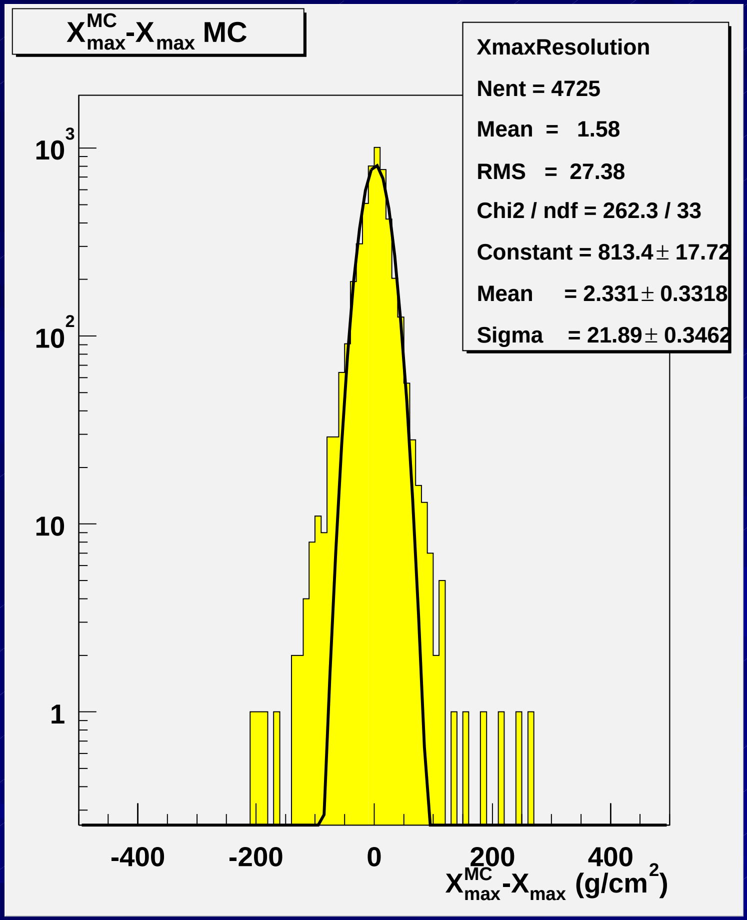
$=$

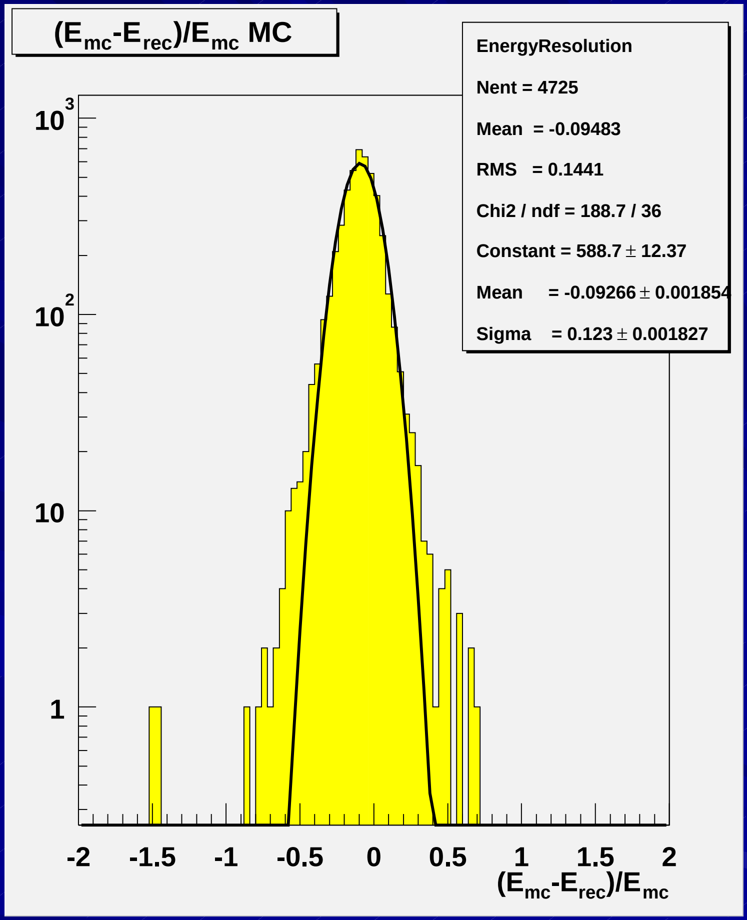
X_{max} distribution



$$P_m(x_m) = N \int_0^{x_m - x_{peak} + \Lambda'\alpha} e^{\frac{-x_1}{\lambda_{p-Air}}} \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max} - x_1 - x_{peak}}{\Lambda'}} dx_1;$$

X_{max} and Energy Resolution– detector MC.



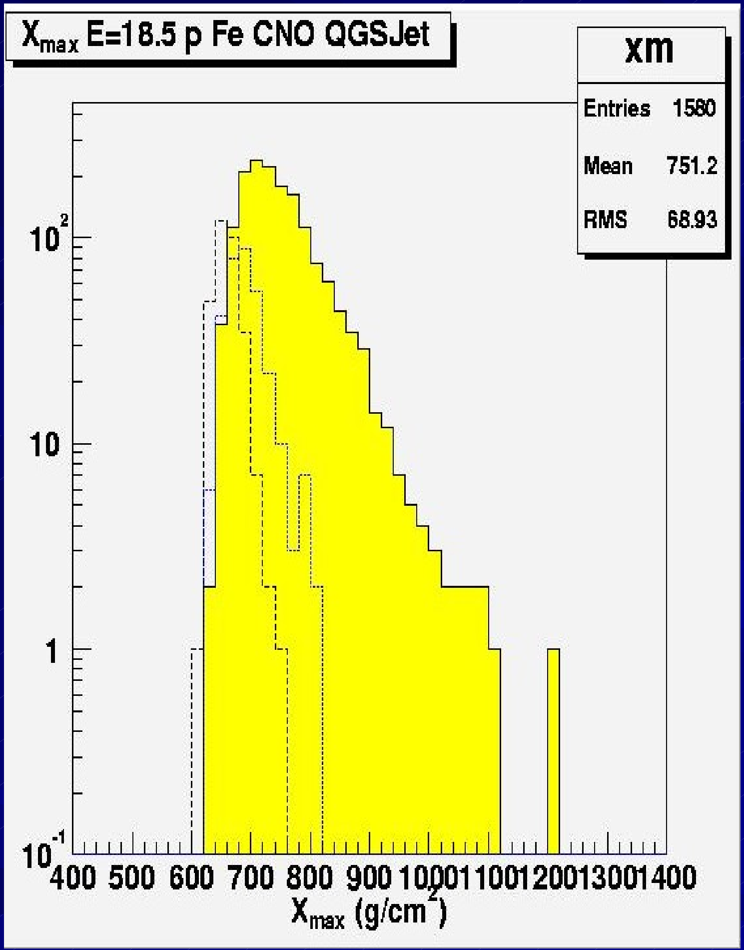


$$\Delta X_{\max} \approx 22\, g / cm^2$$

$$\text{shift of } < X_{\max} > \approx 2\, g / cm^2$$

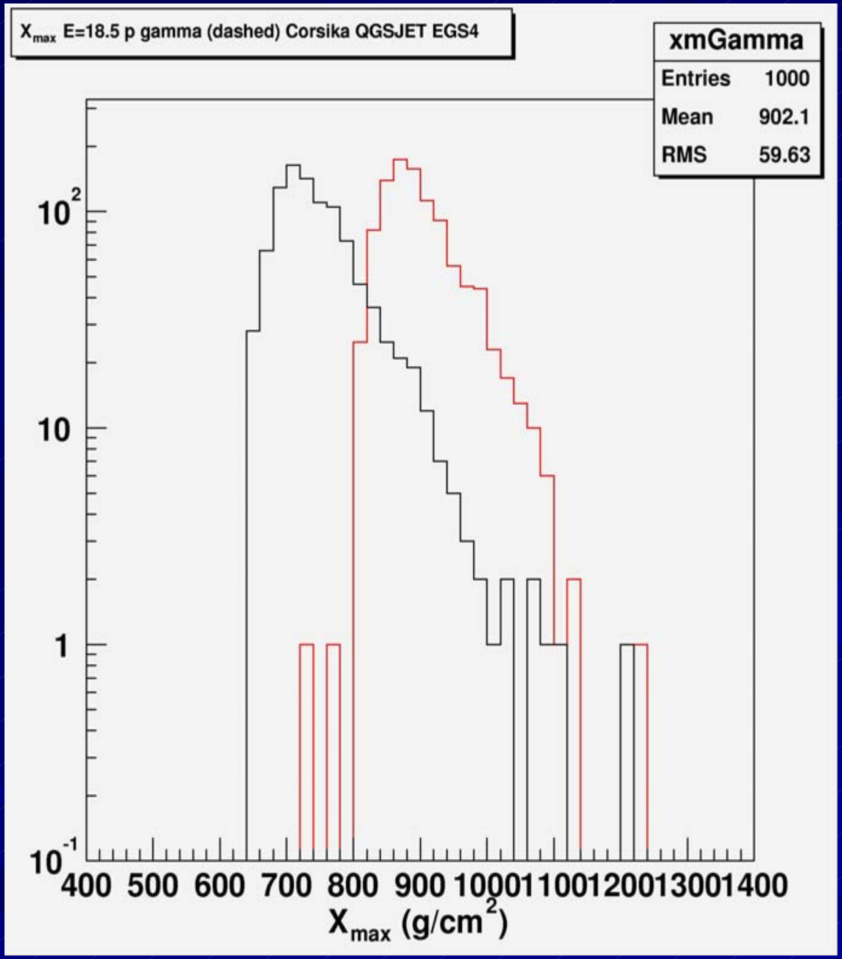
$$\Delta E = 12\%$$

Composition influence – Fe & CNO.



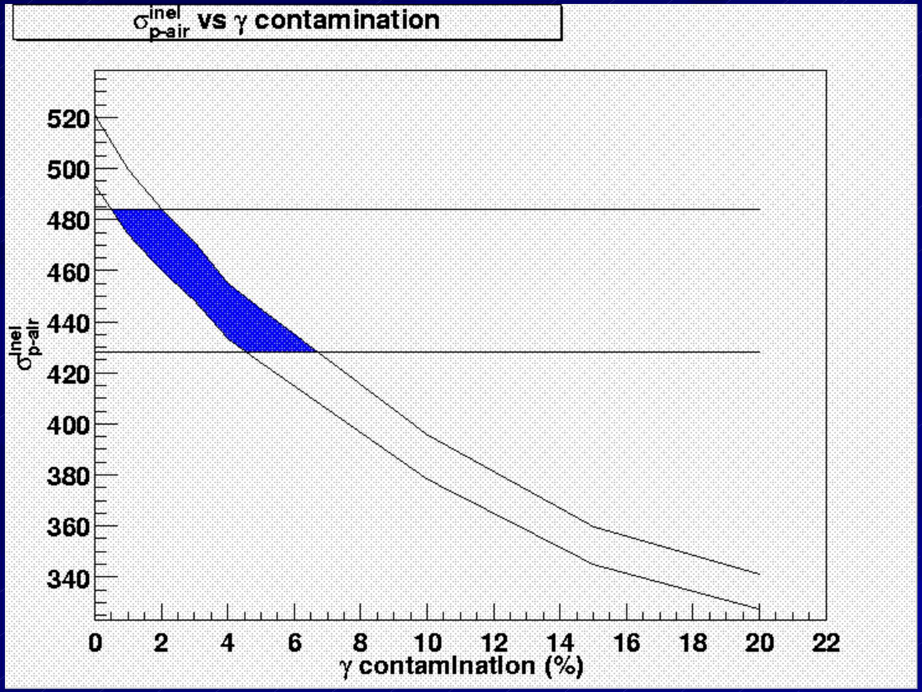
- 20% Fe is shown as dotted line.
- Heavier nuclei influence can be reduced by only using a part of the distribution deeper than 700 g/cm^2.

Composition influence – gamma.



- <X_{max}> is ~ 130 g/cm^2 deeper for gamma showers;
- Can not be simply cut off.

Composition influence – gamma.



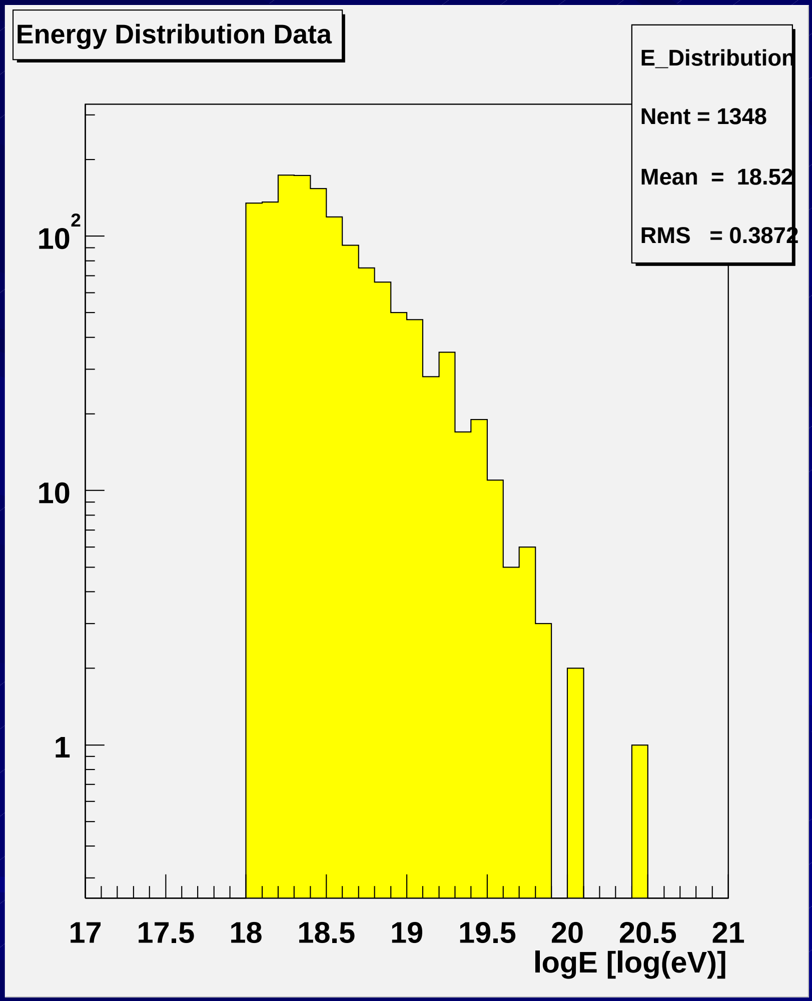
- For this cross-section study – a systematic error estimation due to gamma ray flux.

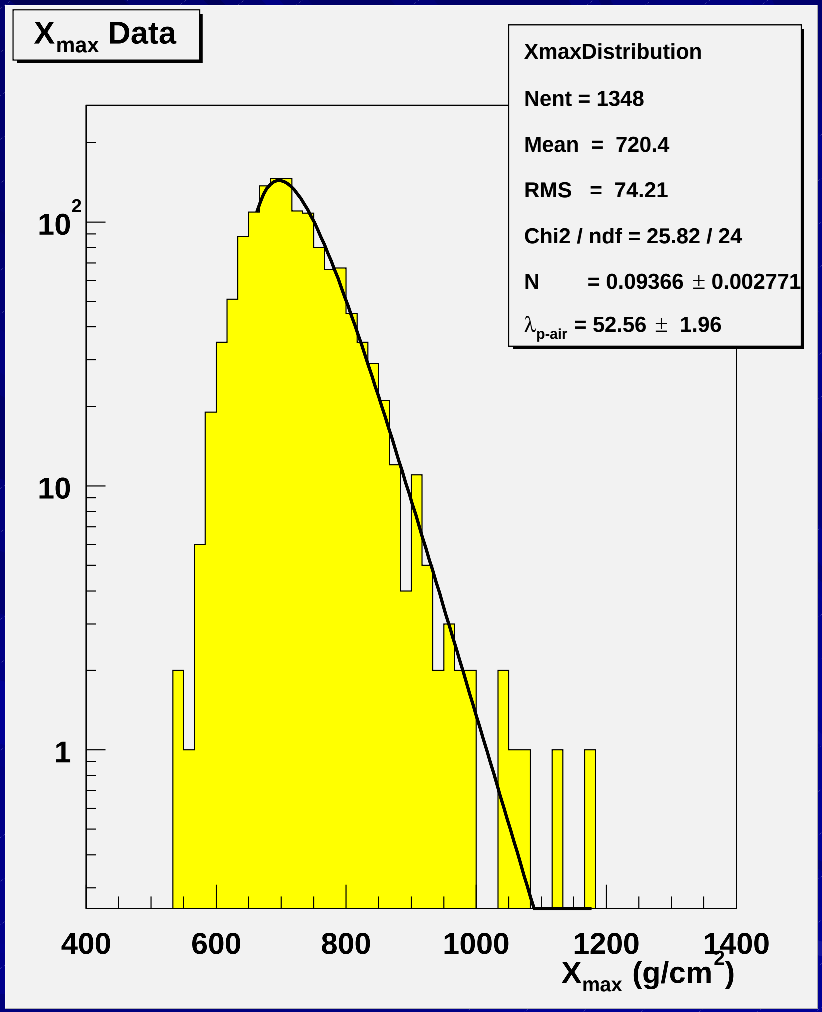
MC predicted p-air cross-section vs gamma flux.

Possible λ_{p-air} bias and systematic errors summary

- Model dependence – negligible at shower development in the air energies.
- Detector trigger bias and Fe contamination – avoided by using 700 g/cm^2 or deeper portion of Xmax distribution.
- gamma contamination (assuming ~5% gamma flux) < 4 g/cm^2.
- Reconstruction and quality cuts bias < 1.5 g/cm^2
- Fitting bias < 1 g/cm^2
- Atmosphere influence minimized by selecting only clear nights.

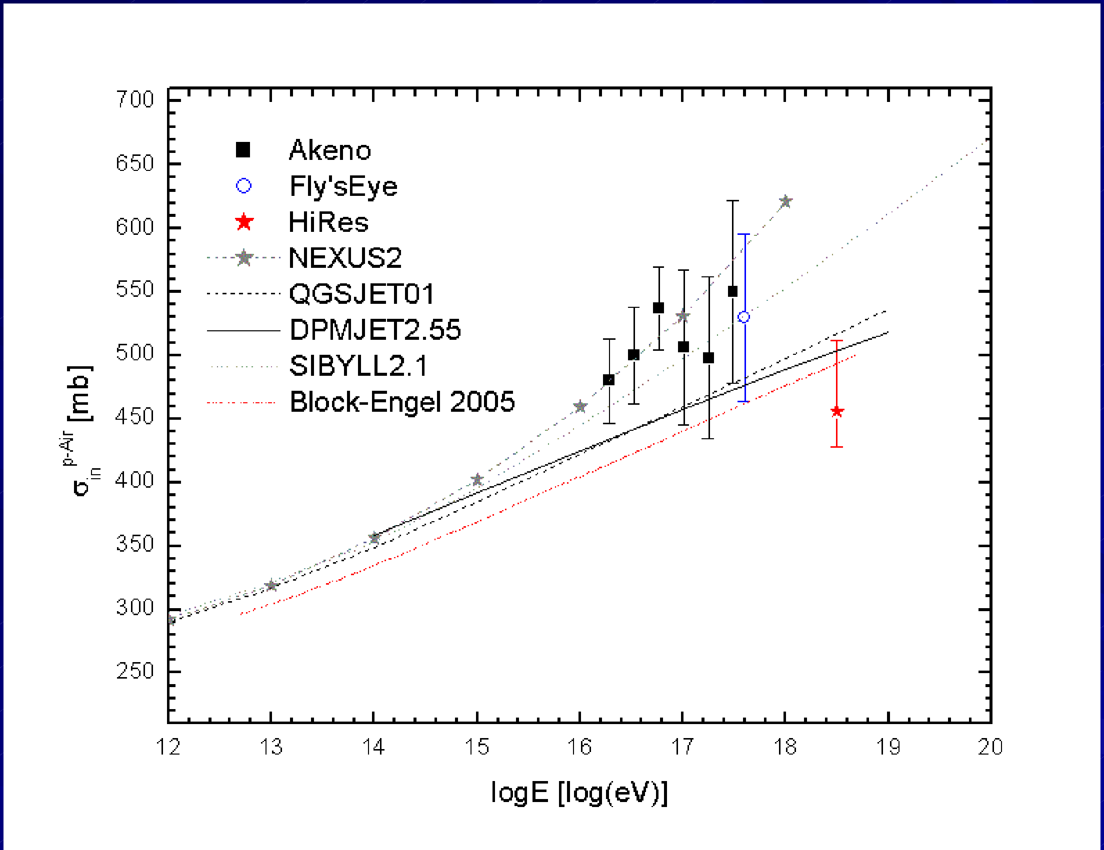
Data





- 1348 out of 3346 (thru March 2003) stereo events pass the quality cuts

HiRes measurement.



$$\text{HiRes}: \quad \sigma_{in}^{p-Air} = 456 \pm 17\,(stat) + 39(sys) - 11(sys)\ mb$$

Conclusions

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

$$\sigma_{in}^{p-Air} = 456 \pm 17\,(stat) + 39(sys) - 11(sys)\ mb$$

- Accelerator data extrapolation strongly favor the Froissart bound saturation! HiRes data is consistent with it.
- "A solid link between cosmic ray and accelerator measurements is established for the first time!" – M.Block.
- Gamma ray flux upper limit will improve systematic errors.
- CS energy trend – need more statistics to have some leverage.