Measurement of UHECR Composition by HiRes

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UHECR2010

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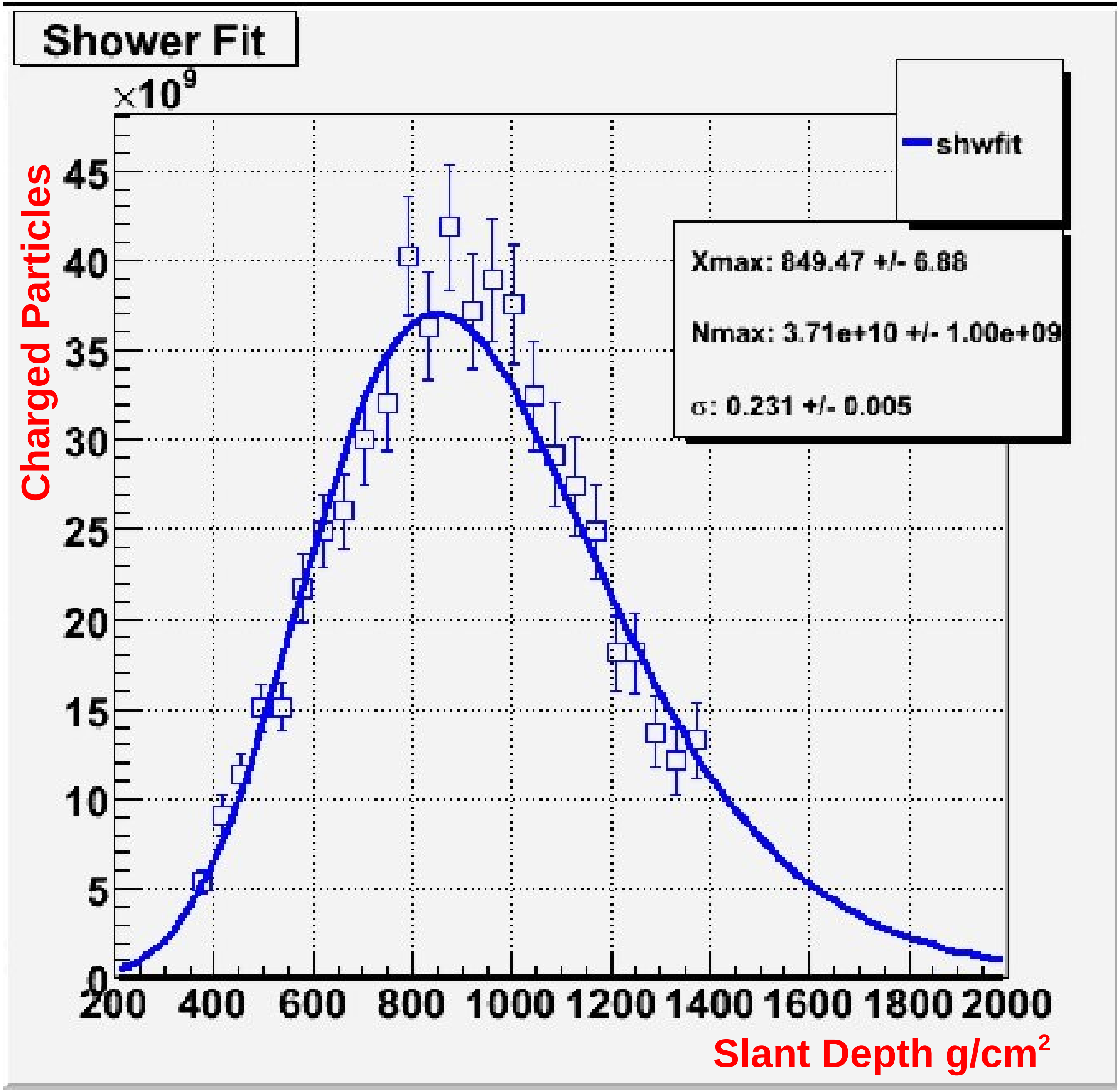
Event Reconstruction: The "Shower Profile"



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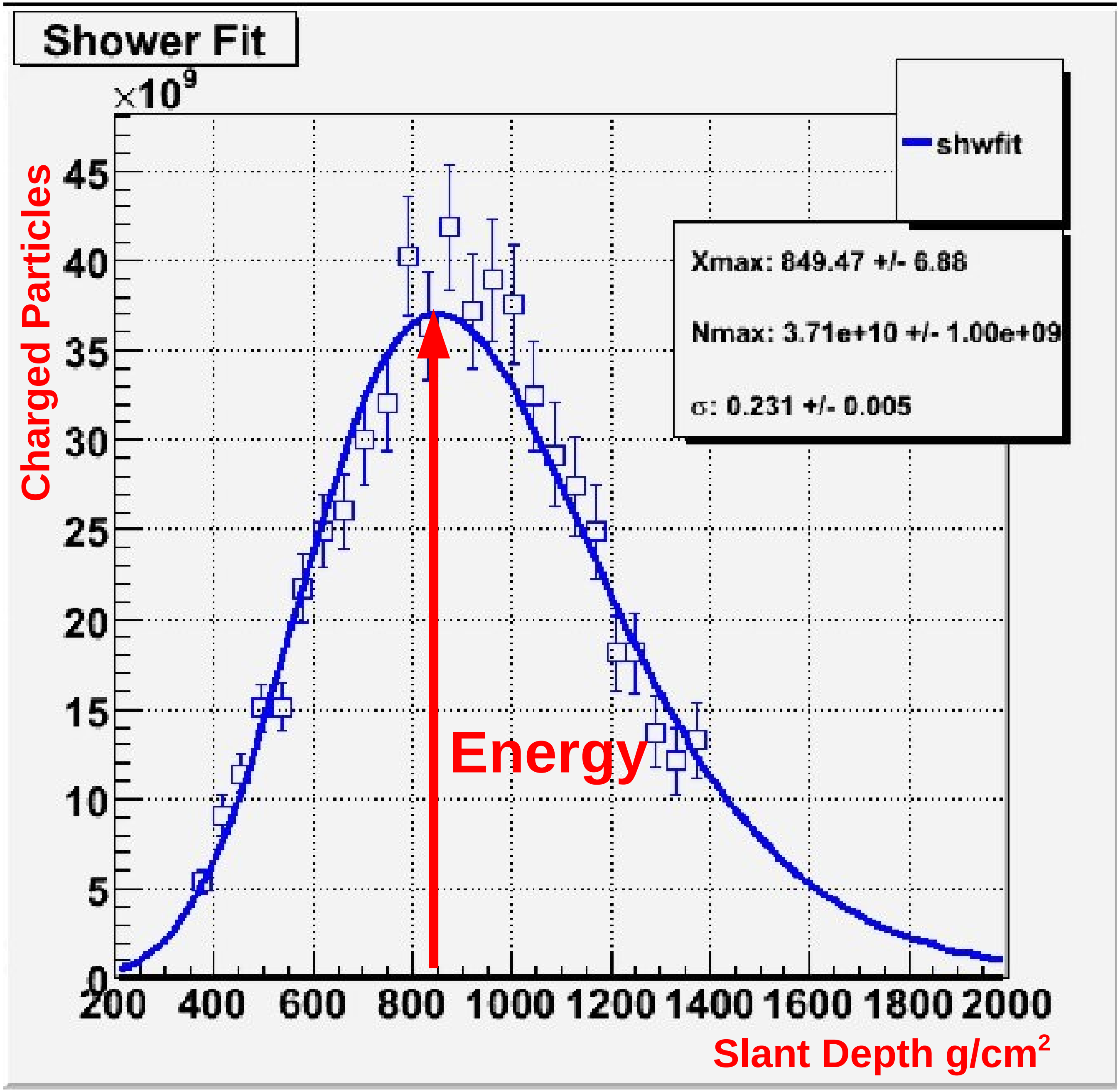

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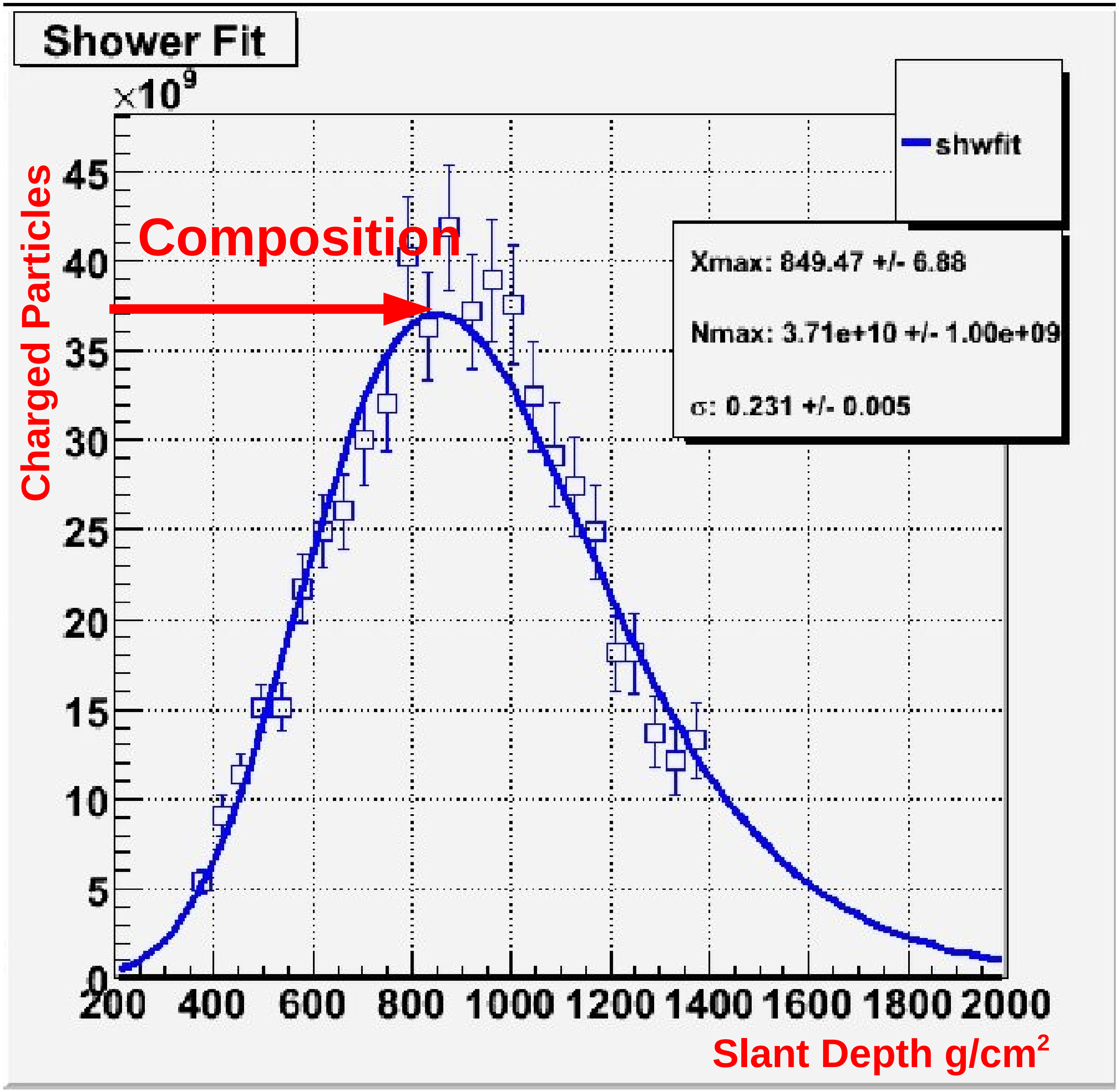

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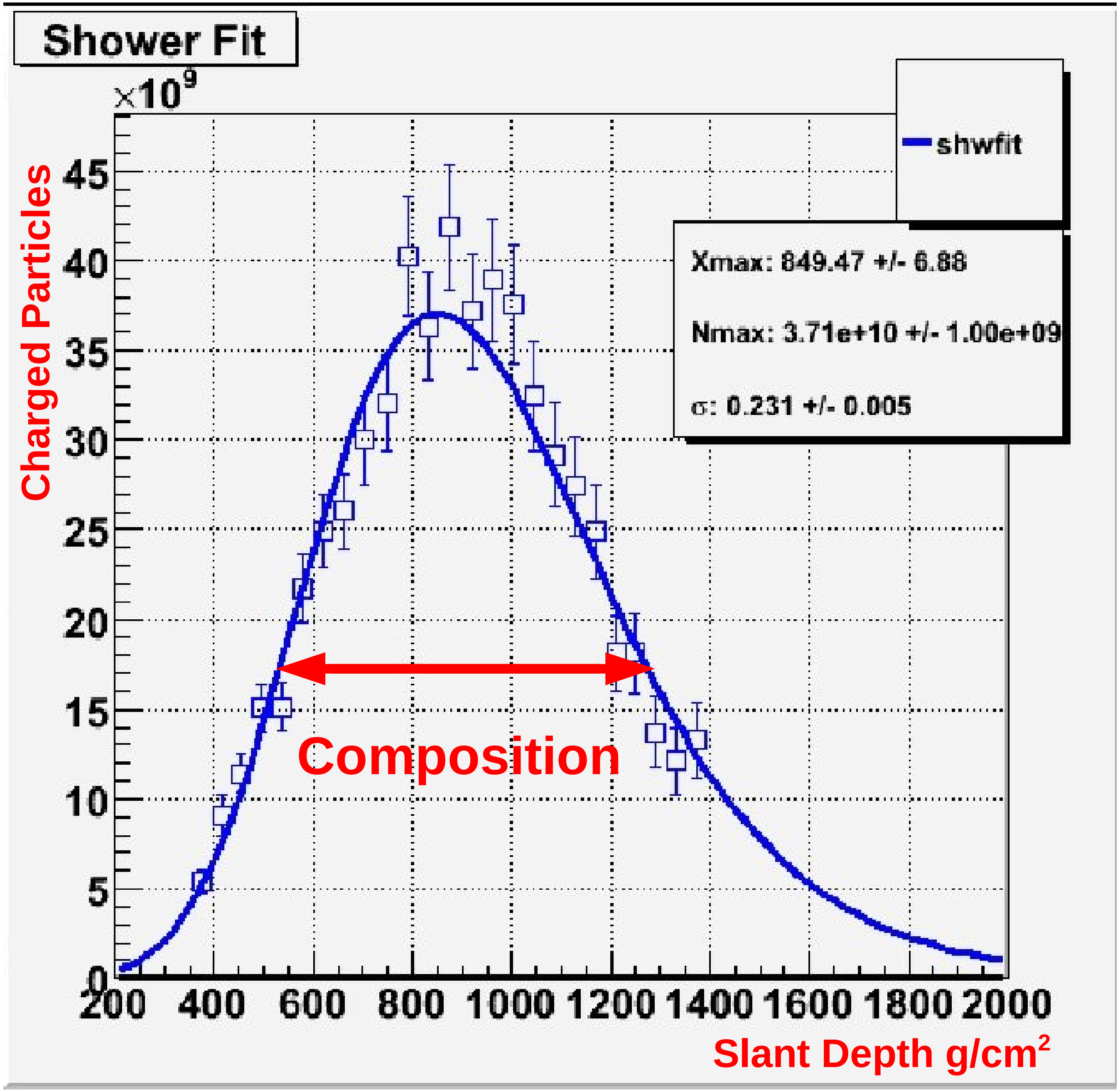
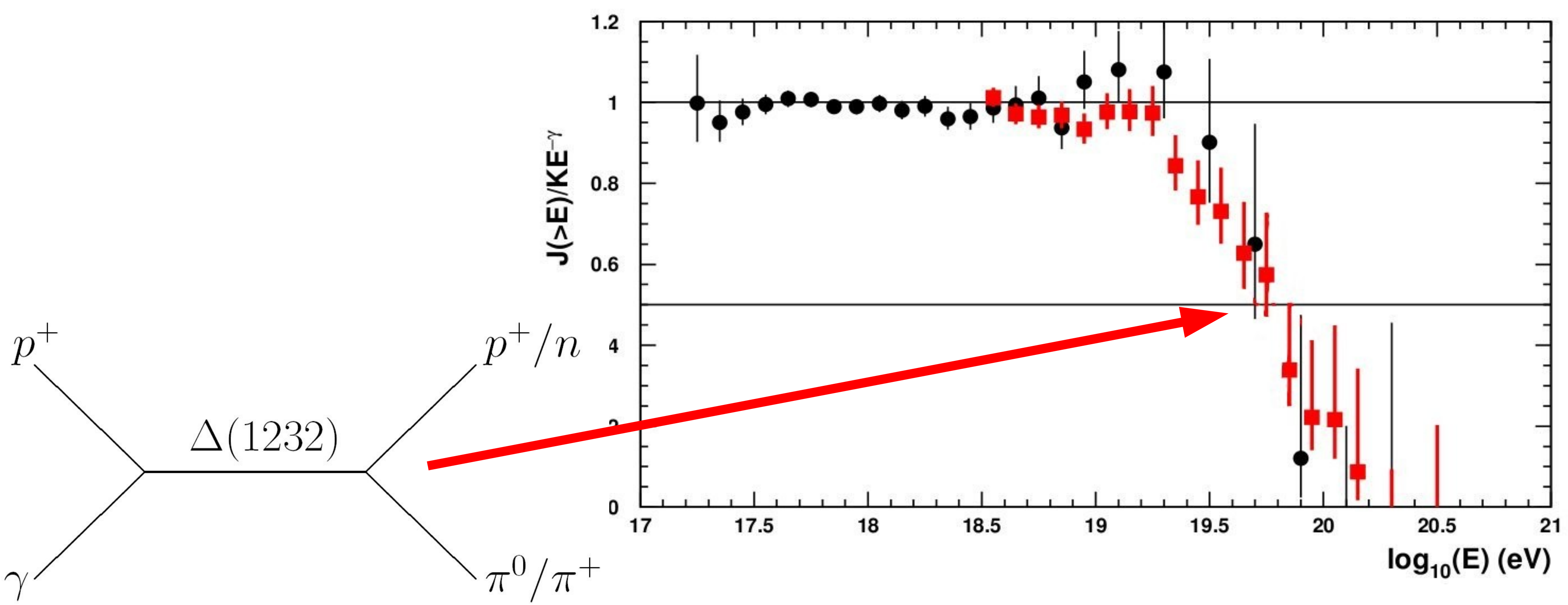


Spectrum: Implications for Composition

- CMBR: Two signatures in spectrum
  - Photoproduction of pions (“GZK Cutoff”)
  - Pair production “dip” at lower energy
- Three *model independent* clues to composition
  - Energy of cutoff
  - Shape of spectrum close to cutoff
  - Shape of pair production “dip”

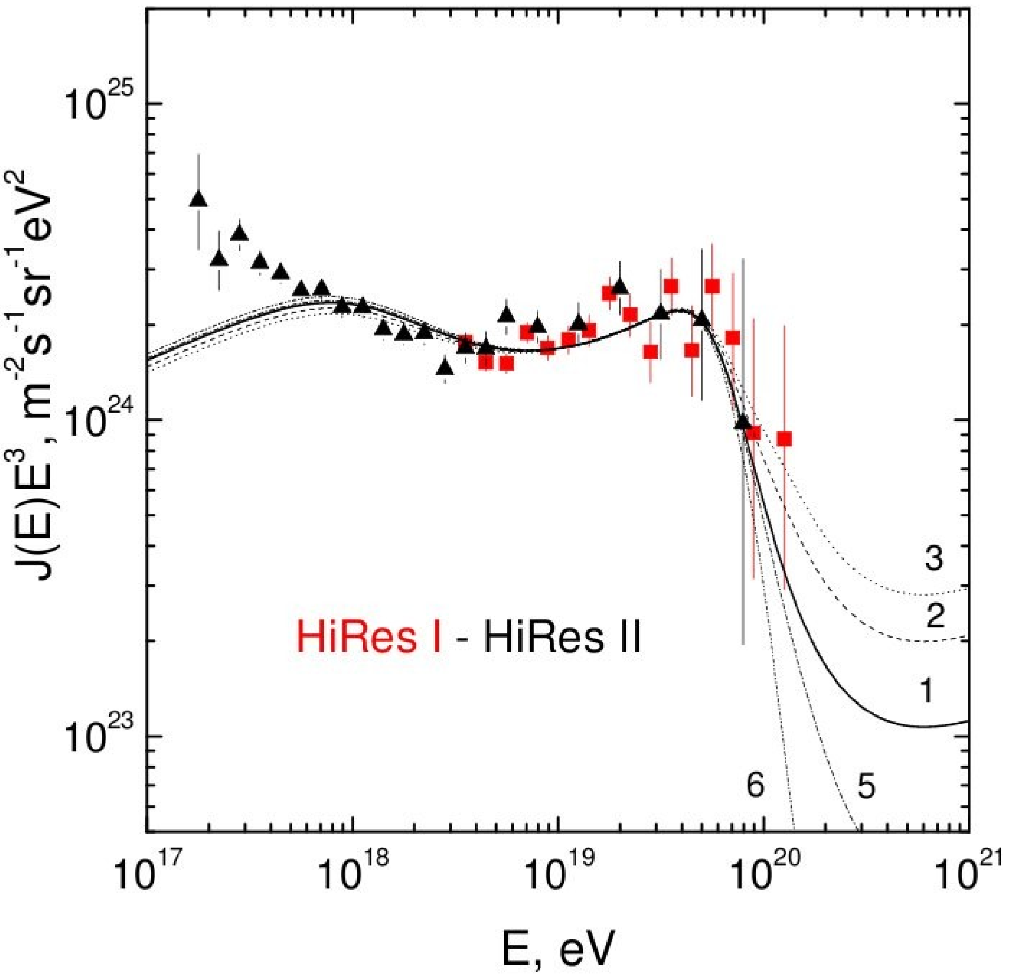
Energy of Cutoff

- Characterized by $E_{1/2}$; energy at which integral spectrum drops to ½ of power law extrapolation.
- Berezinsky et al, PRD **74** (2006): log(E) = 19.72
- HiRes: log(E) = 19.73 ± 0.07



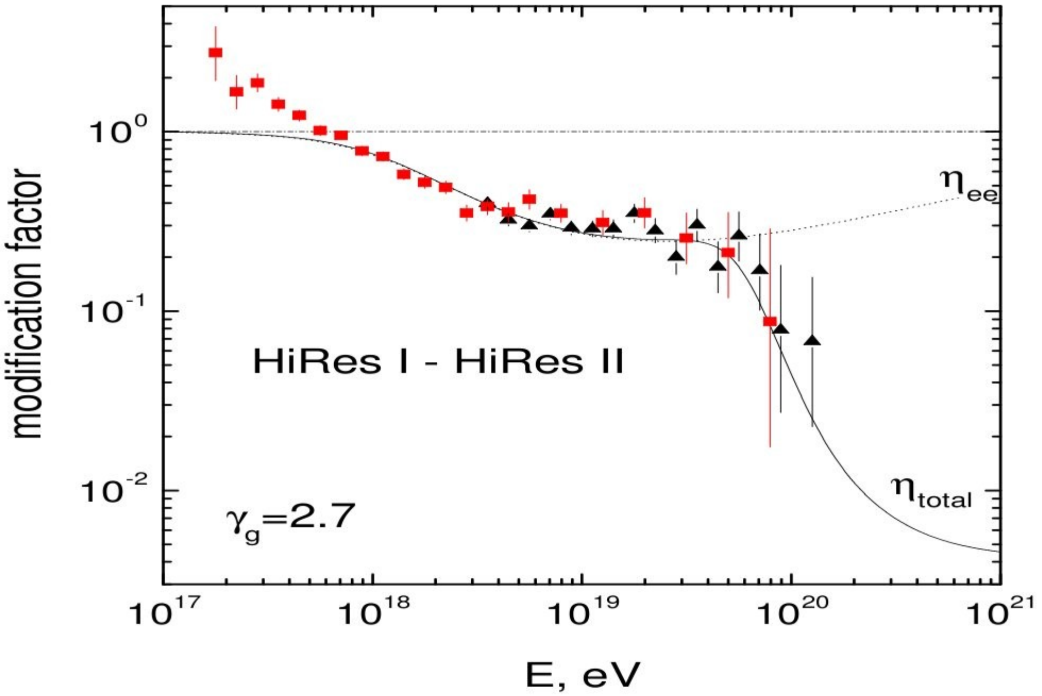
Shape of Spectrum above Cutoff

- Generally, depends on source density and energy cutoff.
- *Model independent* near cutoff
- Consistent with HiRes observations, although statistics low.



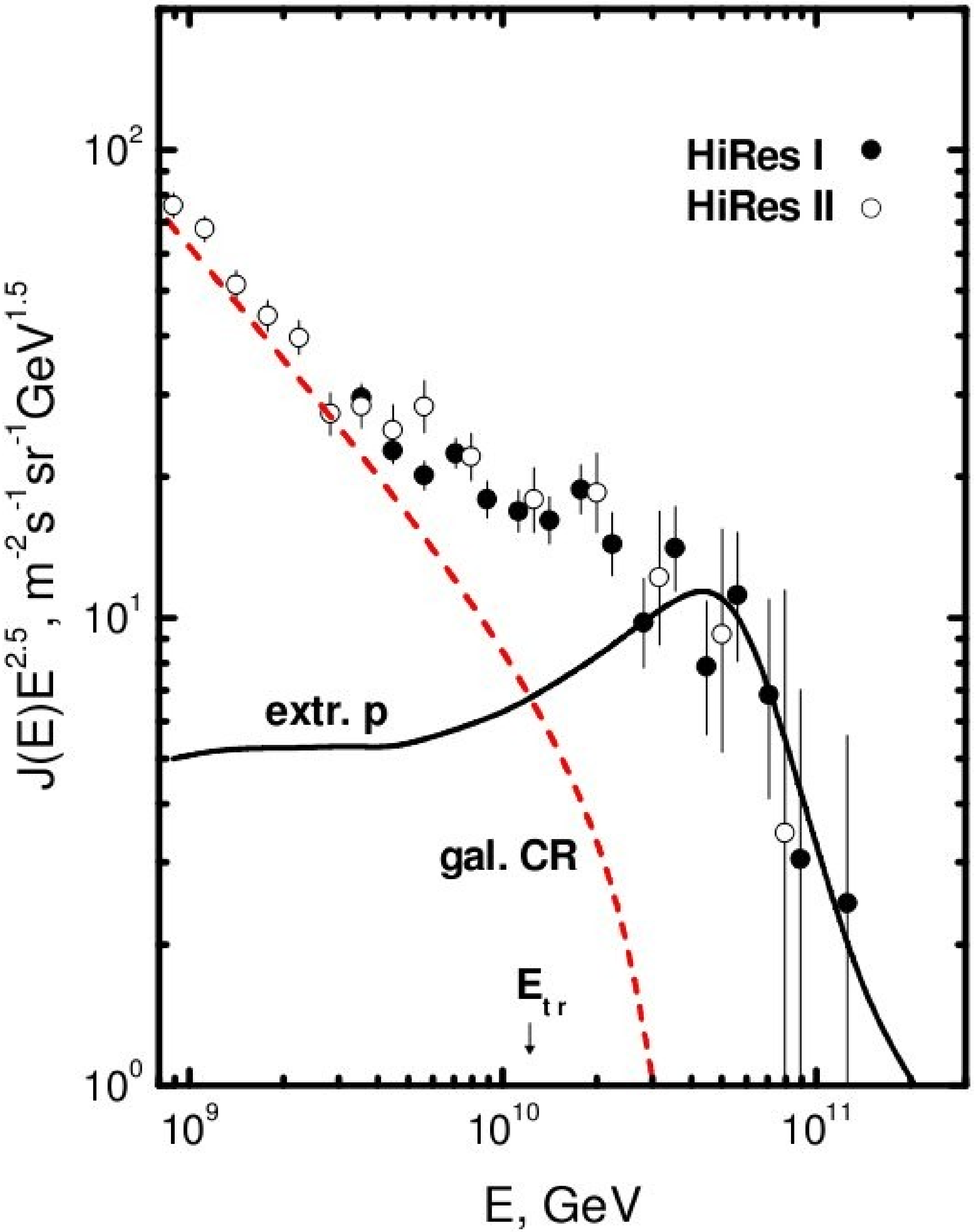
Pair Production "Dip"

- 2^{nd} indication of CMBR interactions: Photons pair produce in presence of high-energy nucleon
- Presence, shape essentially *model independent,* provided primaries are protonic. Aloisio et al *Astropart. Phys.* **27** (2007).
- Consistent with "ankle" feature observed by HiRes (also AGASA, Yakutsk, PAO...)



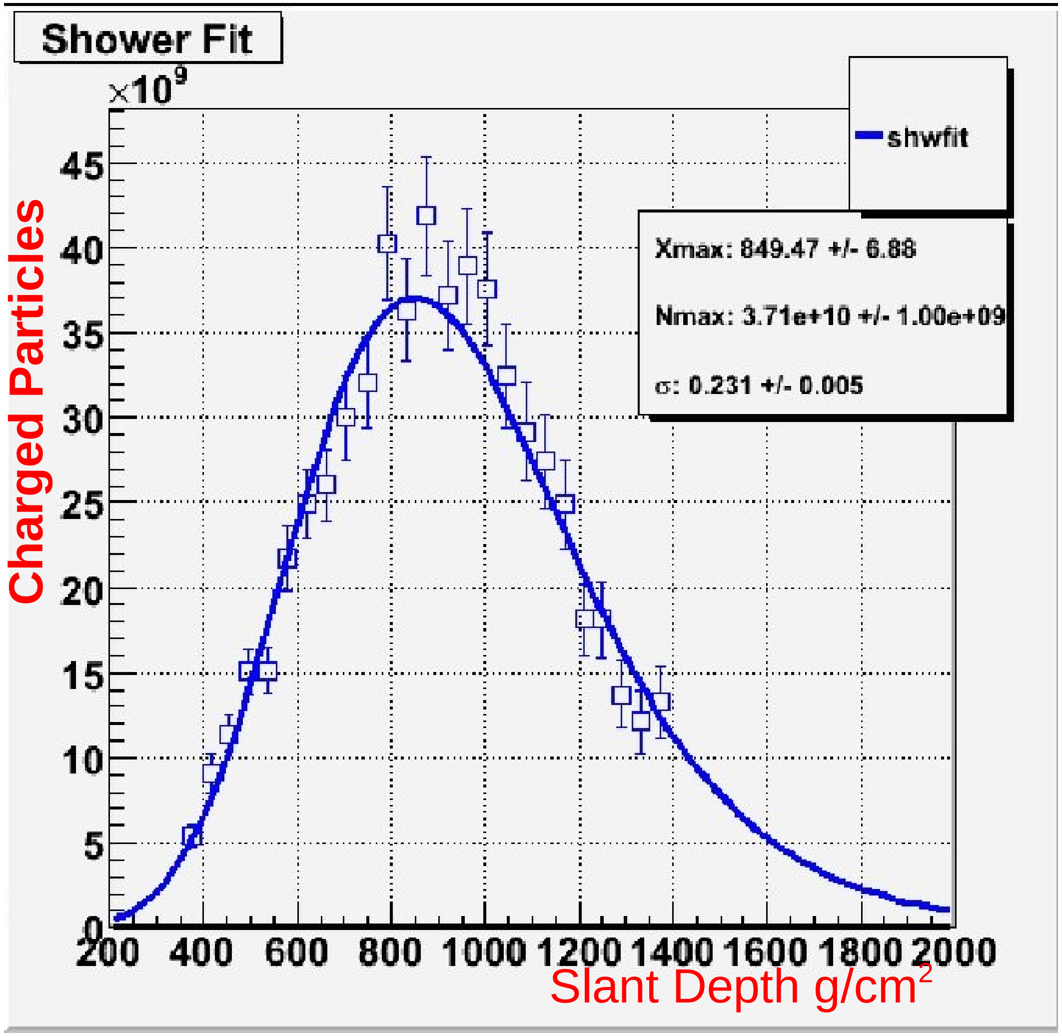
Alternatives

- Ankle is galactic-to-extragalactic transition, e.g. Hillas, *Nucl. Phys. Proc. Supp.* **136** (2004).
- Should be accompanied by heavy (galactic) to light (extragalactic) composition change.
- Decisive role for composition studies!



Composition Studies via Depth of Airshower Maximum X_{max}

X_{max} and Composition



Average Position of Shower Maximum:

$$<X_{max}>= \lambda_r \left(\ln \frac{E}{E_c} - \ln A \right) + C$$

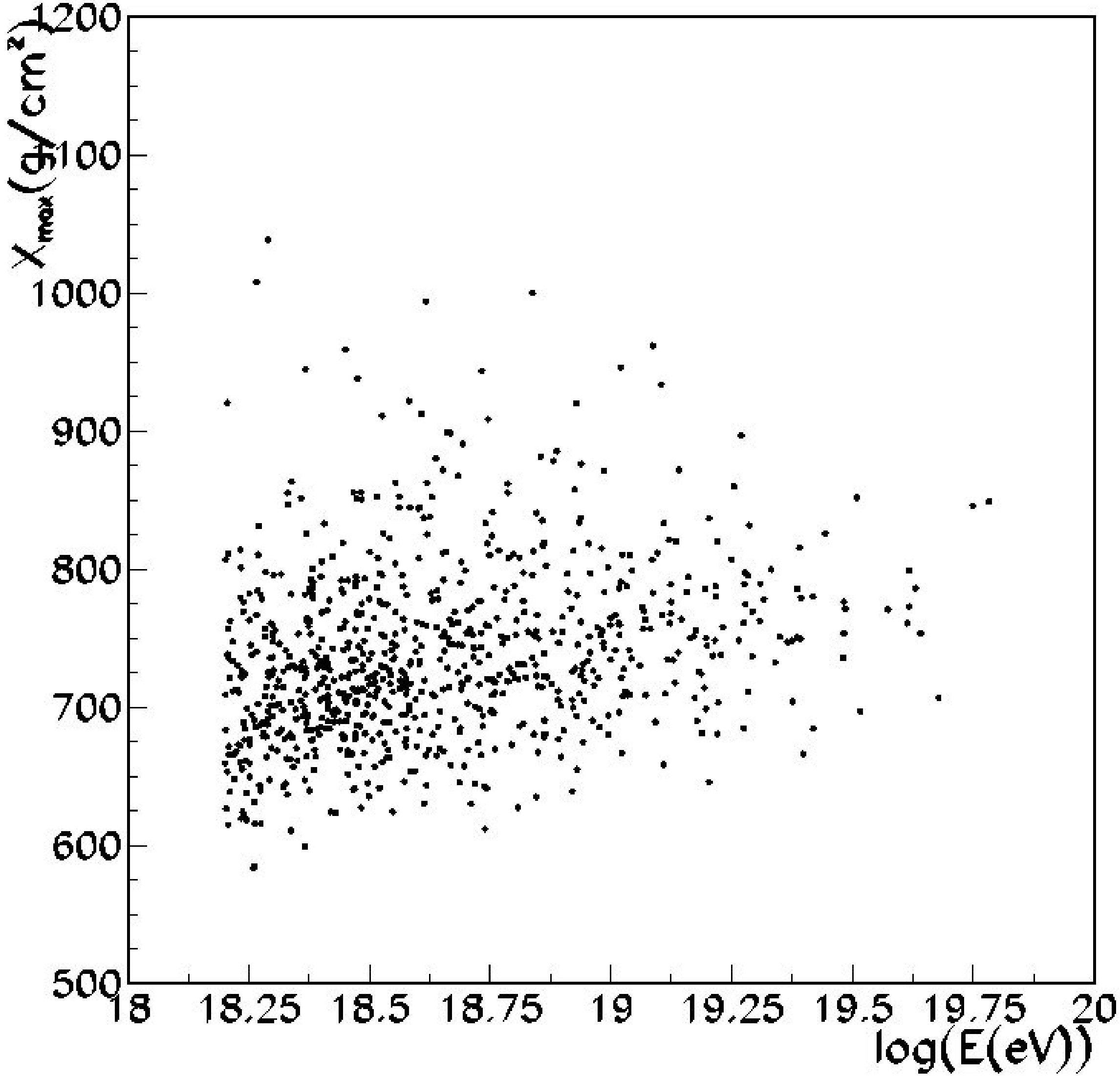
Evolution with Energy:

$$\Lambda_A = \frac{d <X_{max}>}{d \log E} \approx \lambda_r \left(2.3 - \frac{d \ln A}{d \log E} \right)$$

Width of X_{max} Distribution (Superposition):

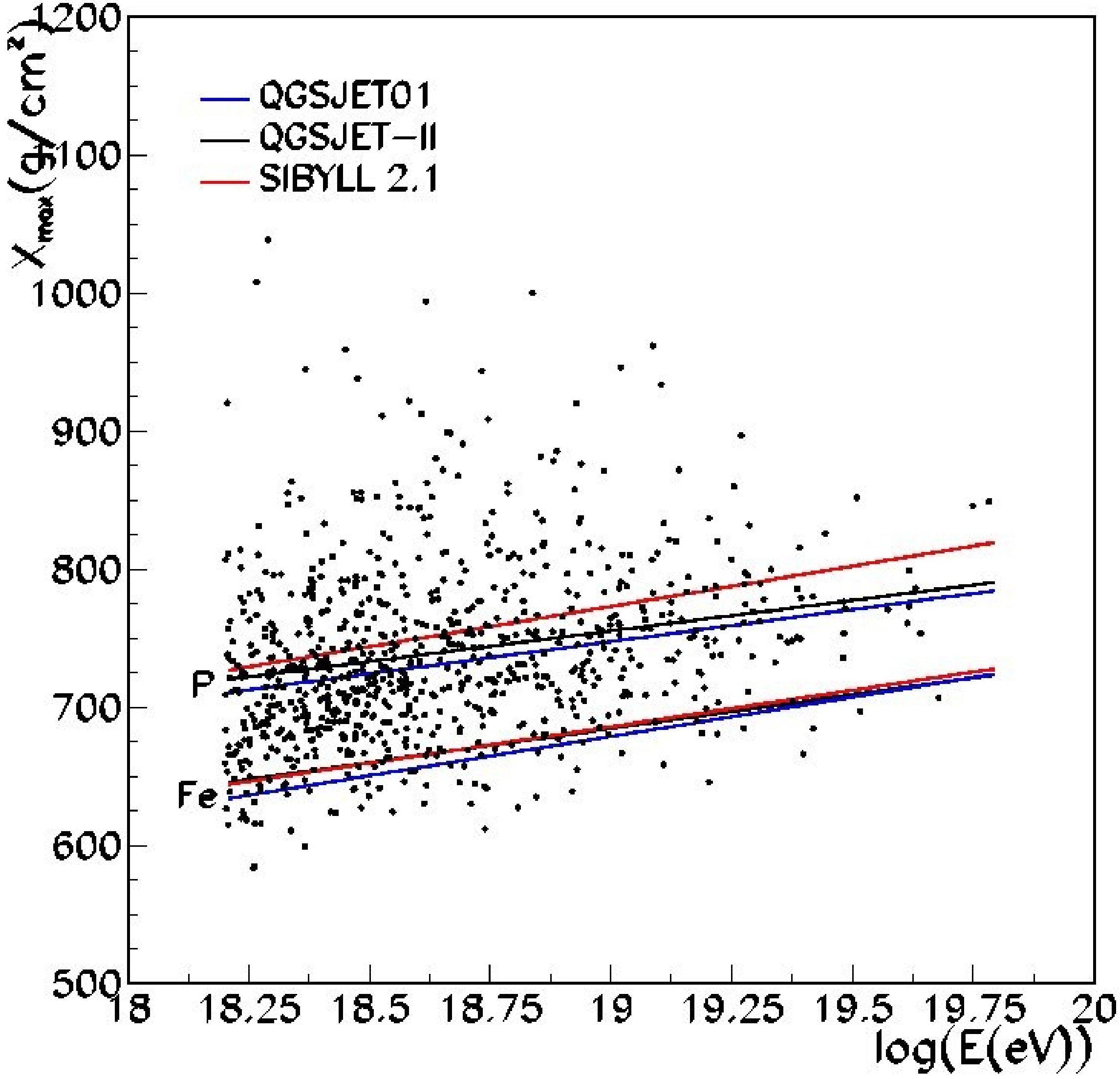
$$\sigma_x(A) \sim \frac{\sigma_x(P^+)}{\sqrt{A}}$$

X_{max} versus log(E)



Points available at: www.cosmic-ray.org/journals/prl.html

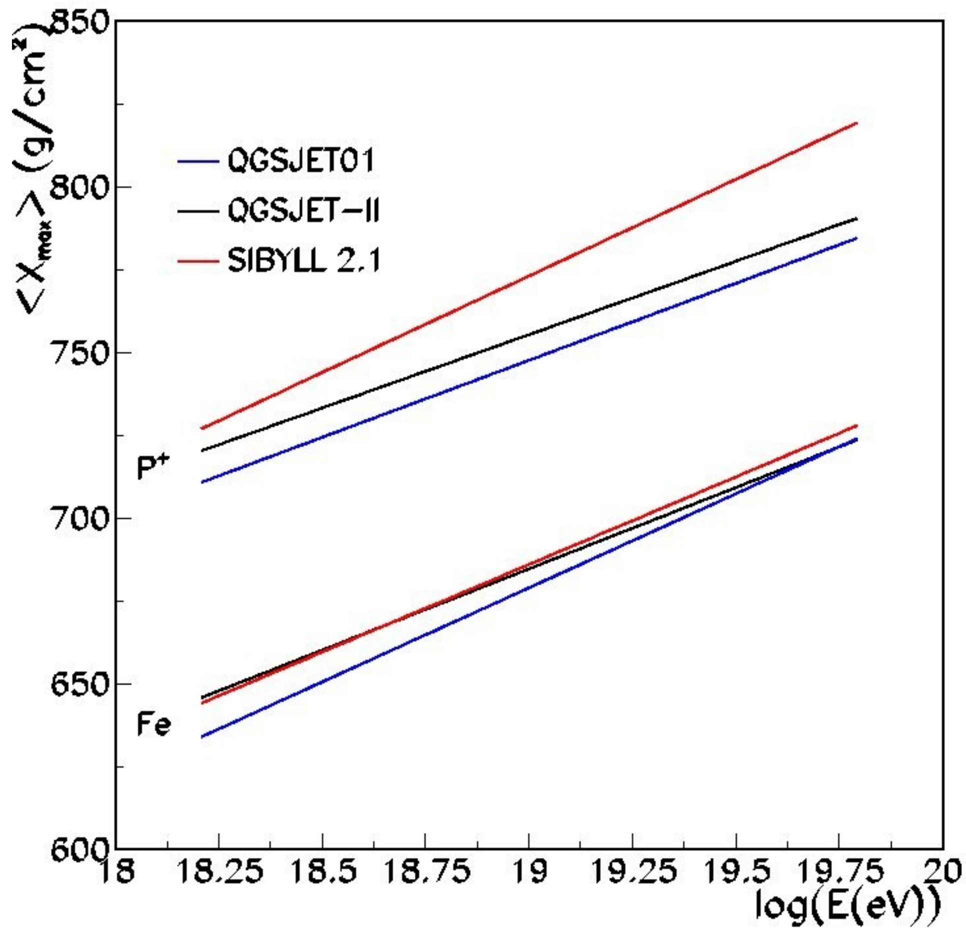
X_{max} versus log(E)



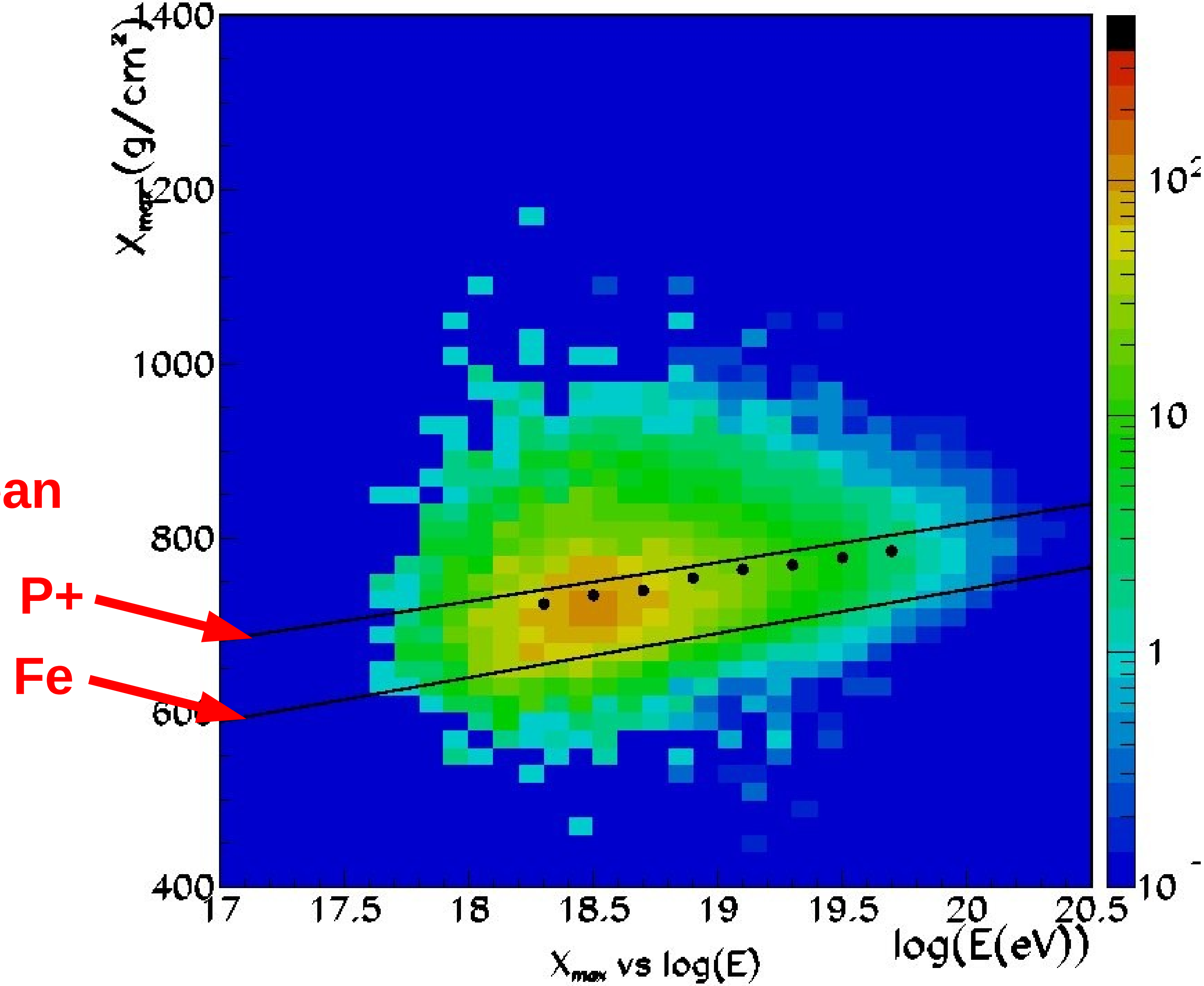
Points available at: www.cosmic-ray.org/journals/prl.html

Comparing Mean X_{max} to Expectation

- No model-independent way to determine composition via X_{max}.
- Simulated airshowers are mandatory, as is understanding detector response to these airshowers.
- Use full detector simulation to model the response to simulated airshowers:
  - Atmosphere (hourly)
  - Ray tracing fluorescence light to mirrors and camera
  - Simulated PMT response
  - Simulated trigger
  - Full analysis chain



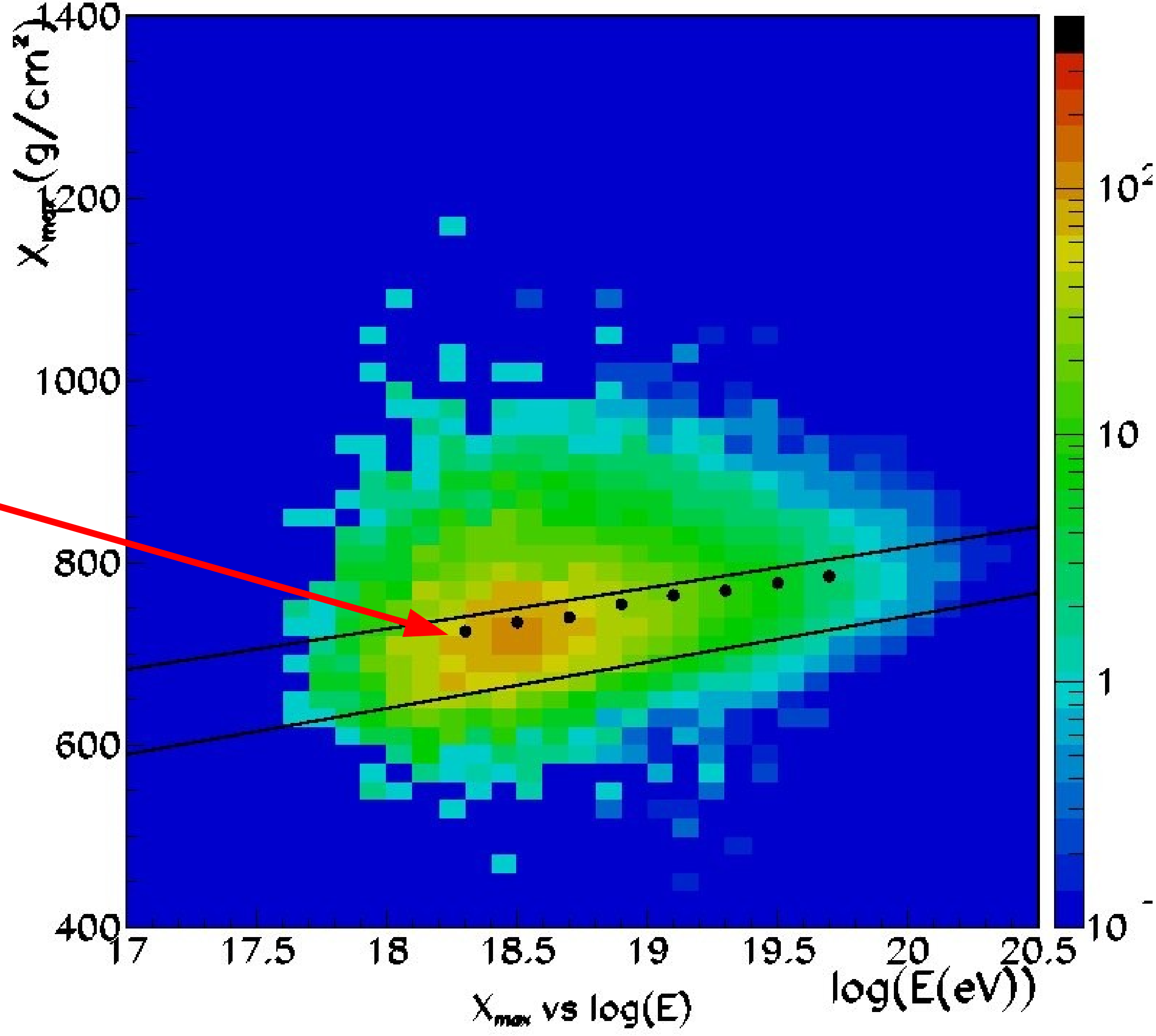
X_{max} vs Energy, QGSJET-II Protons



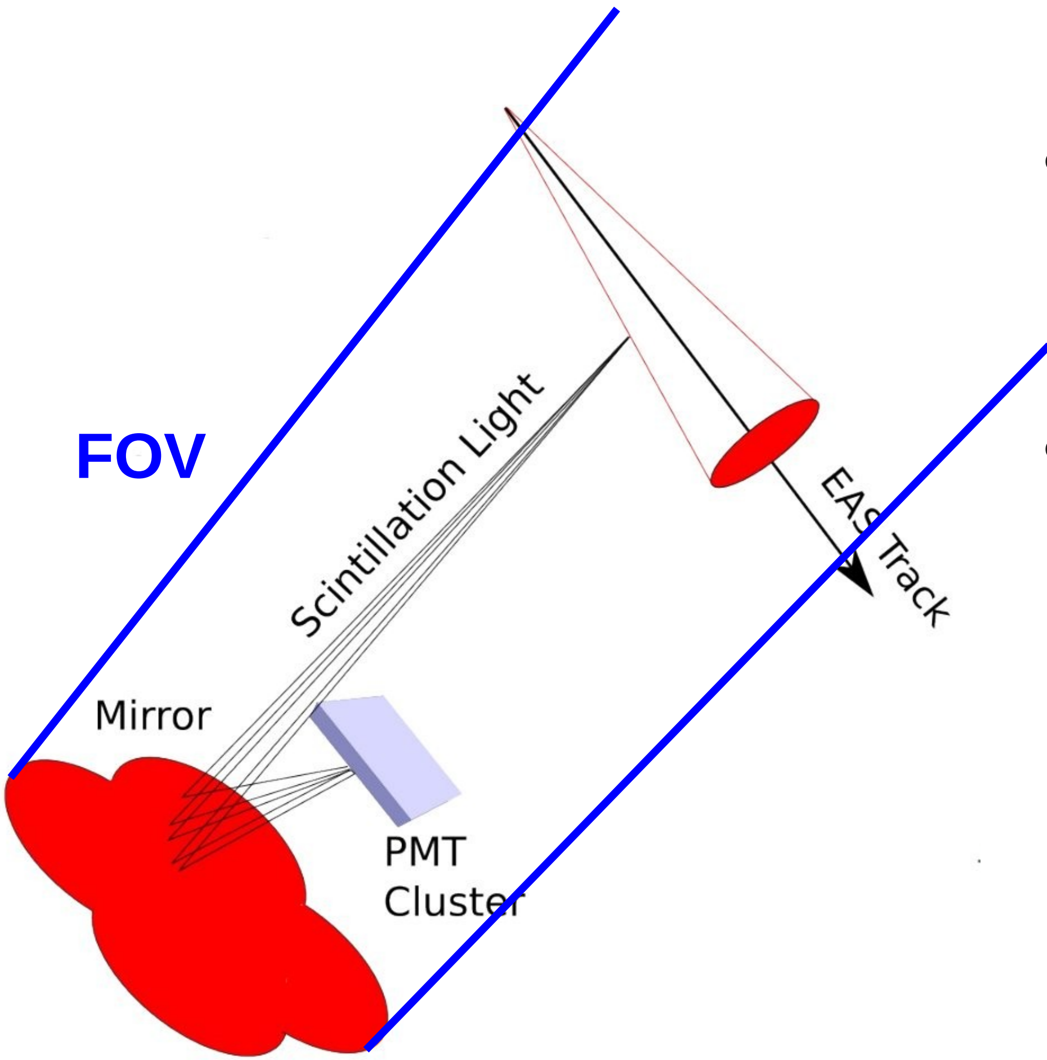
Predictions for mean X_{max}, before detector effects.

X_{max} vs Energy, QGSJET-II Protons

Proton mean Xmax after detector effects (Note acceptance bias)



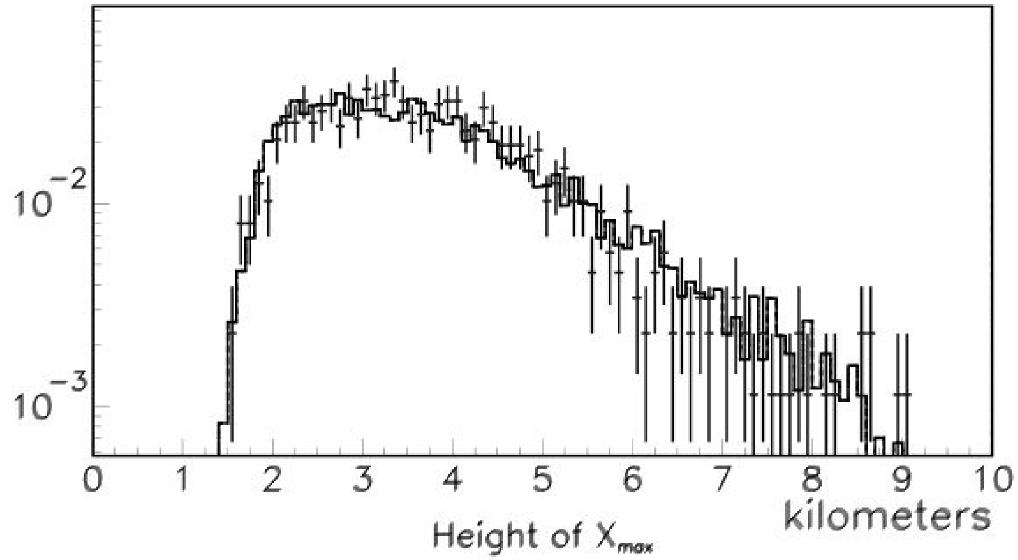
Biasing Effect: Optical Aperture



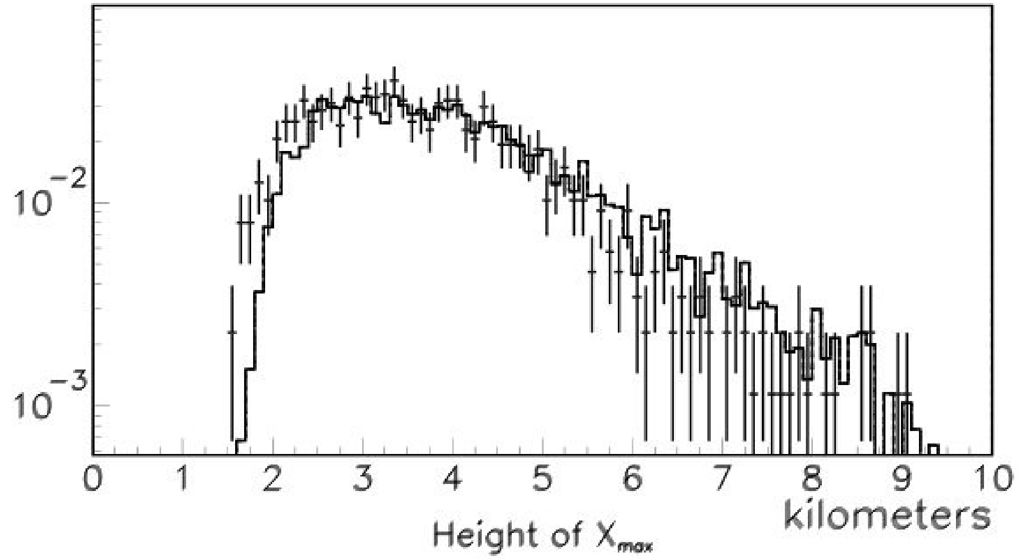
- Are upper and lower limitations on field of view (FOV) well understood?
- If not, relative to MC
  - Can shift mean X_{max} by cutting low or high tails
  - Can make X_{max} distribution appear artificially narrow or wide

Data (points) versus QGSJET-II Monte Carlo (histogram)

Protons



Iron



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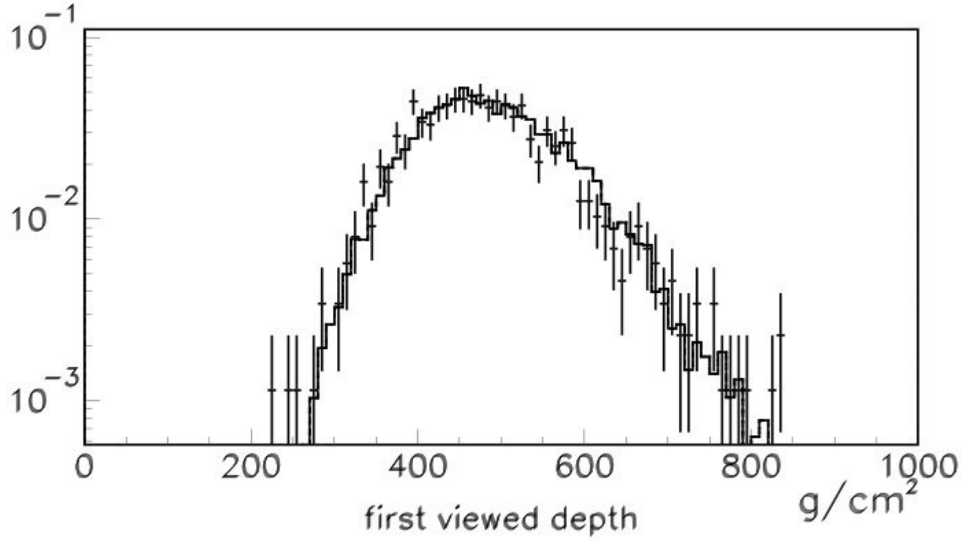

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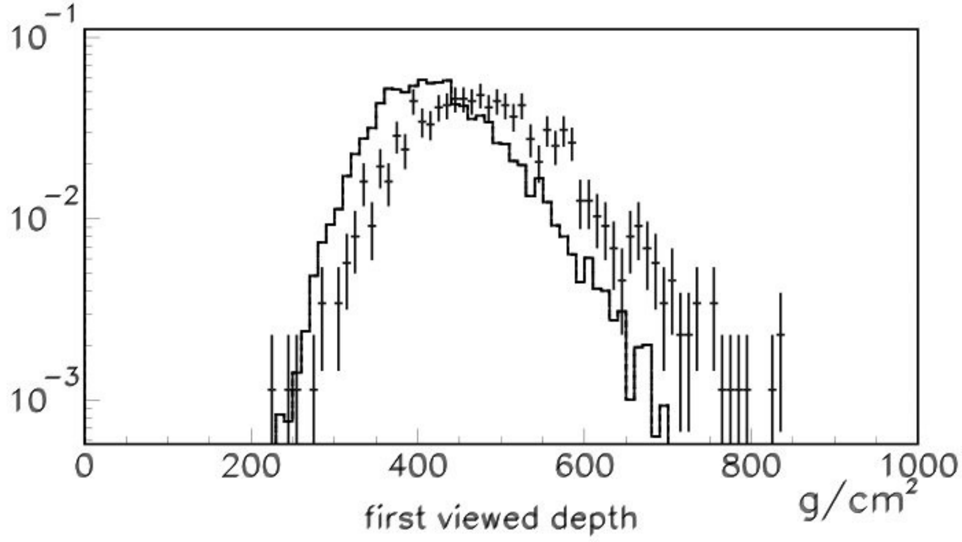

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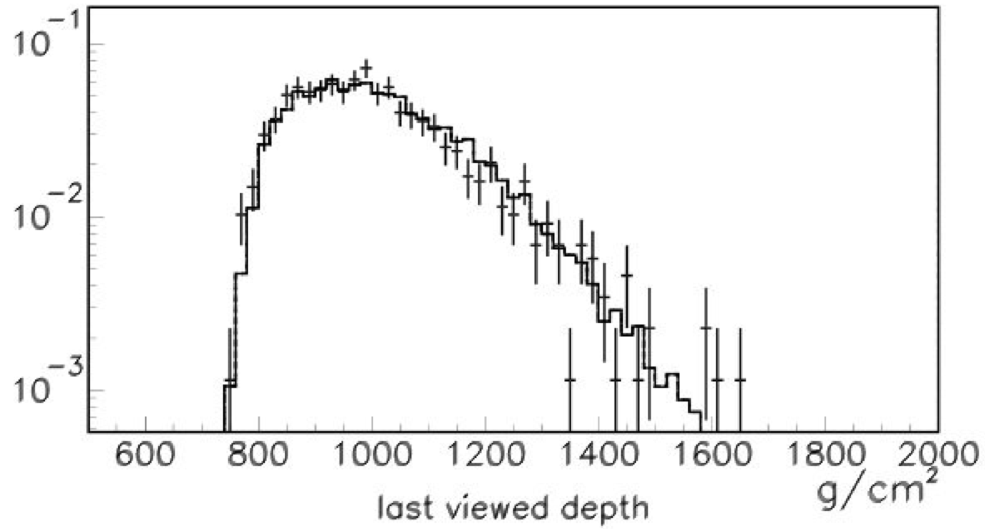

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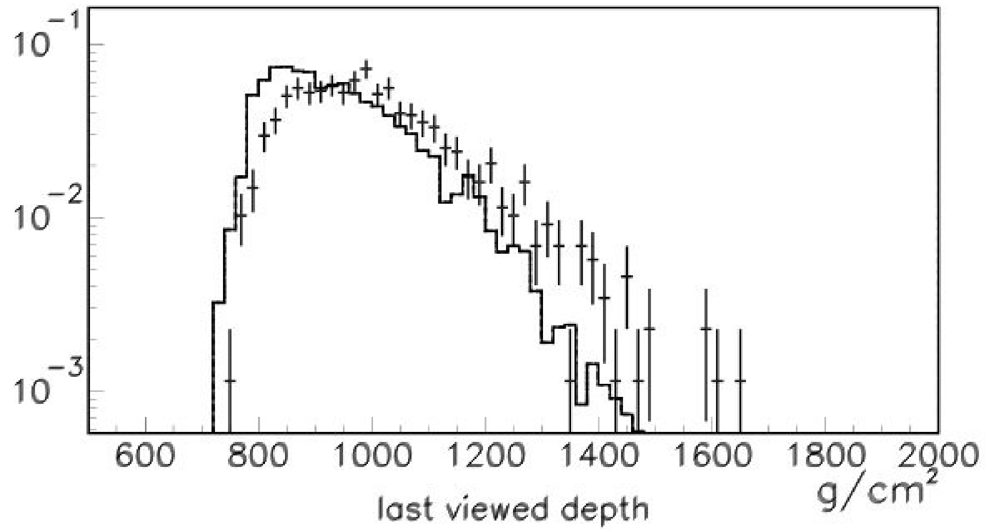

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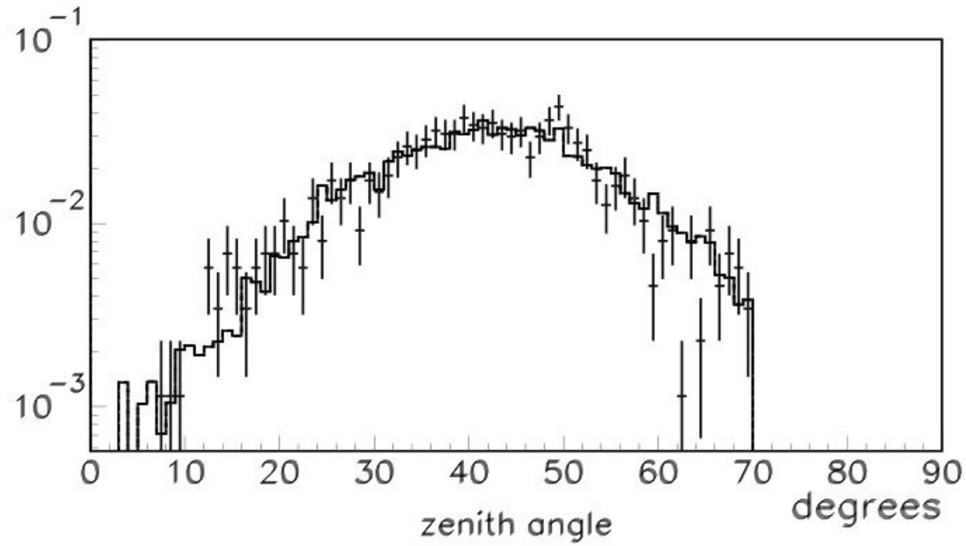

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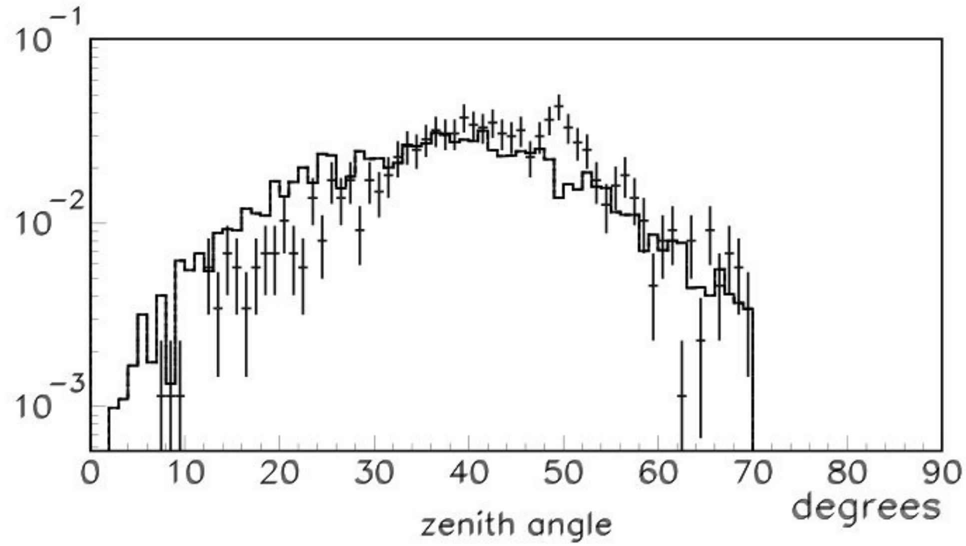
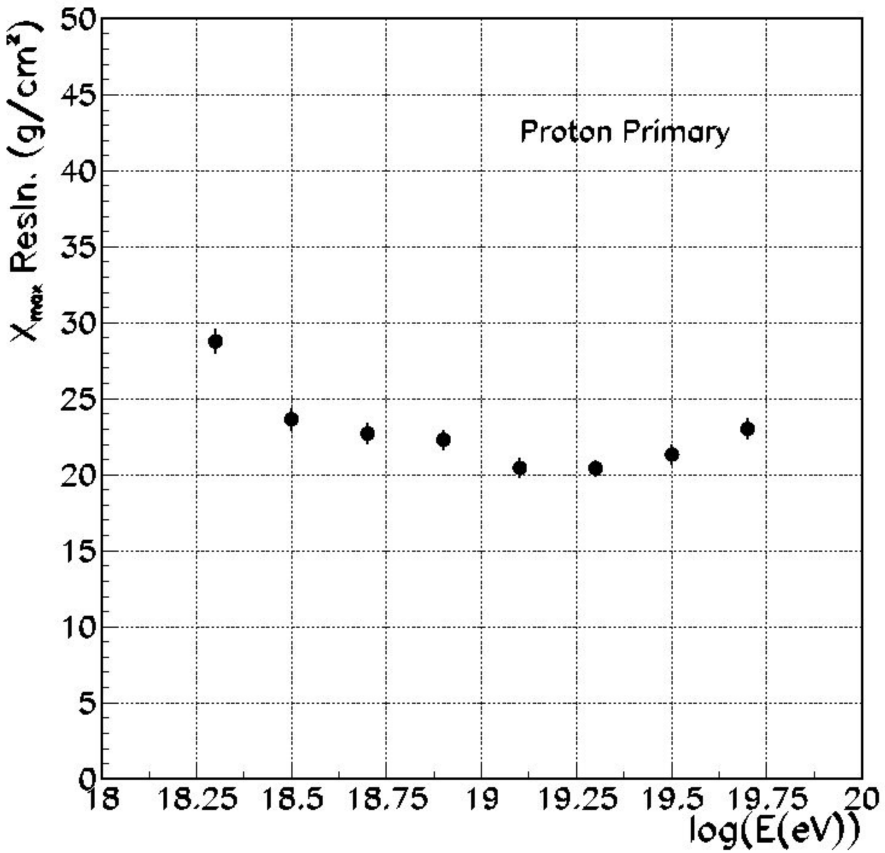
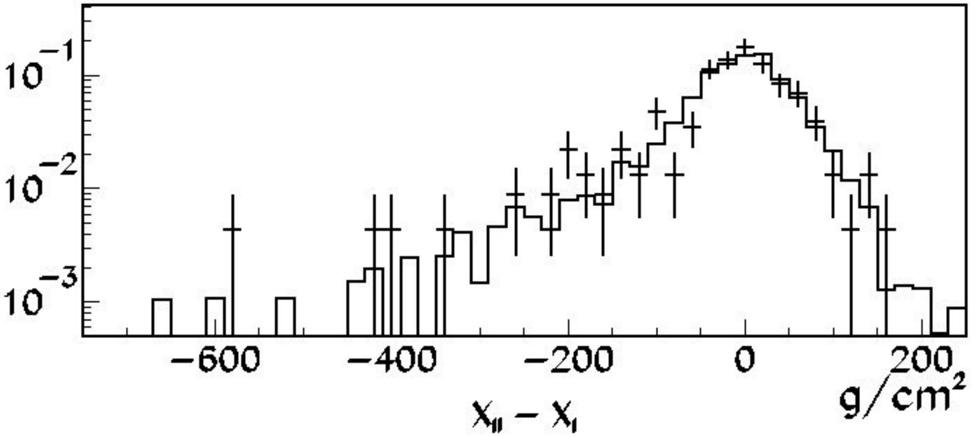


Check of X_{max} Resolution



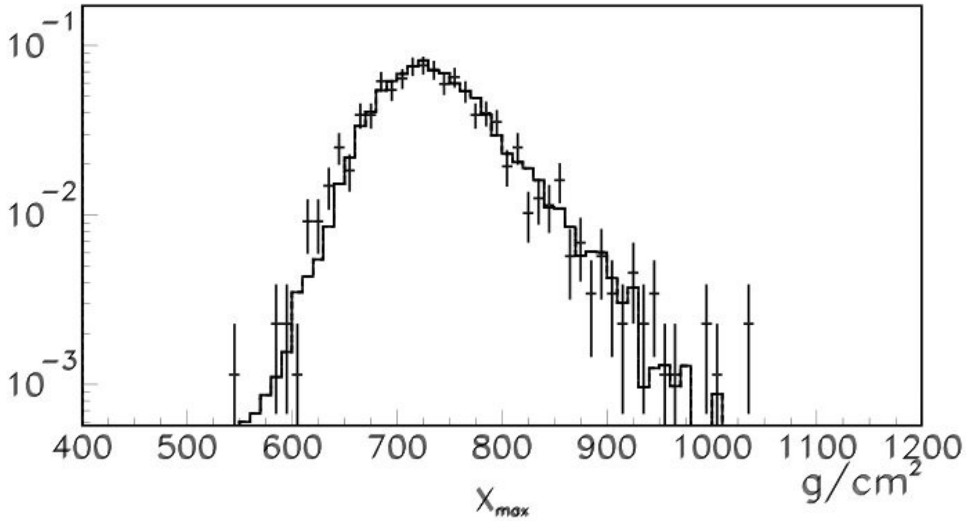
Compare X_{max} as measured by HiRes-I and HiRes-II



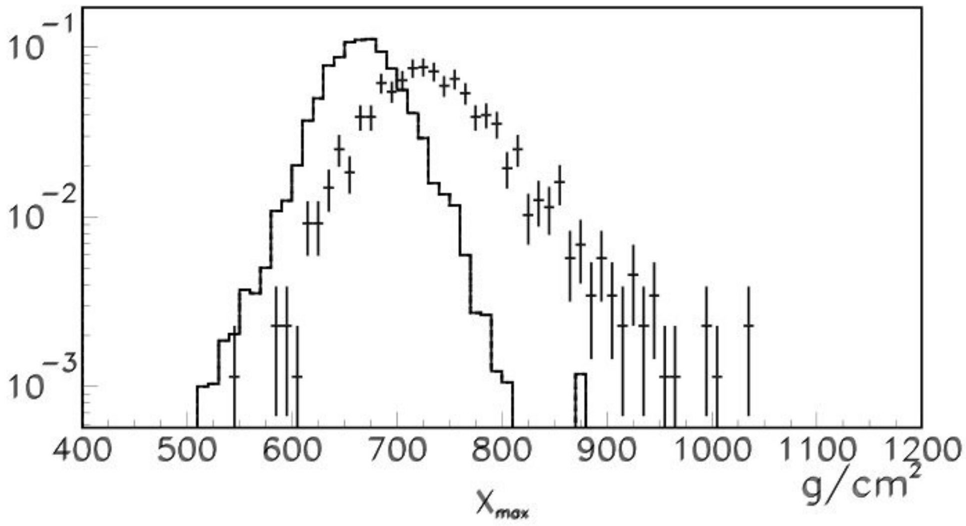
HiRes stereo data (points) vs QGSJET-II protons (histogram).

Data (points) versus QGSJET-II Monte Carlo (histogram)

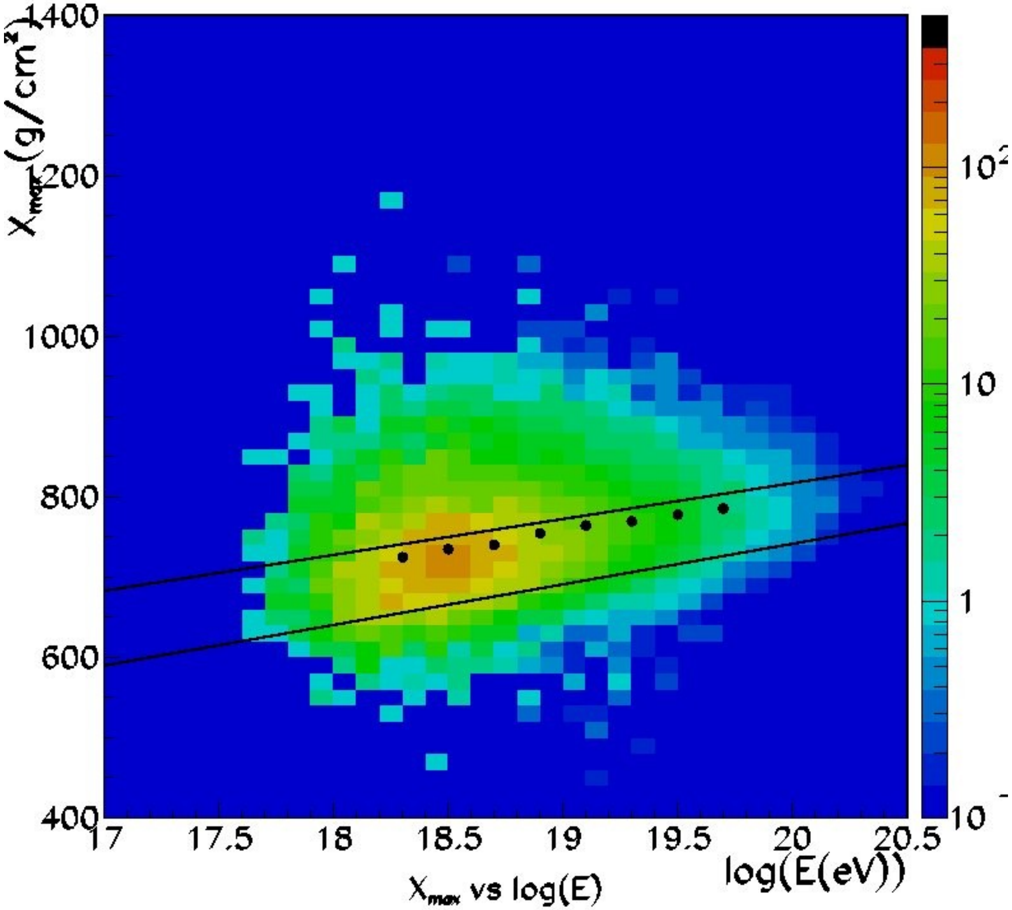
Protons



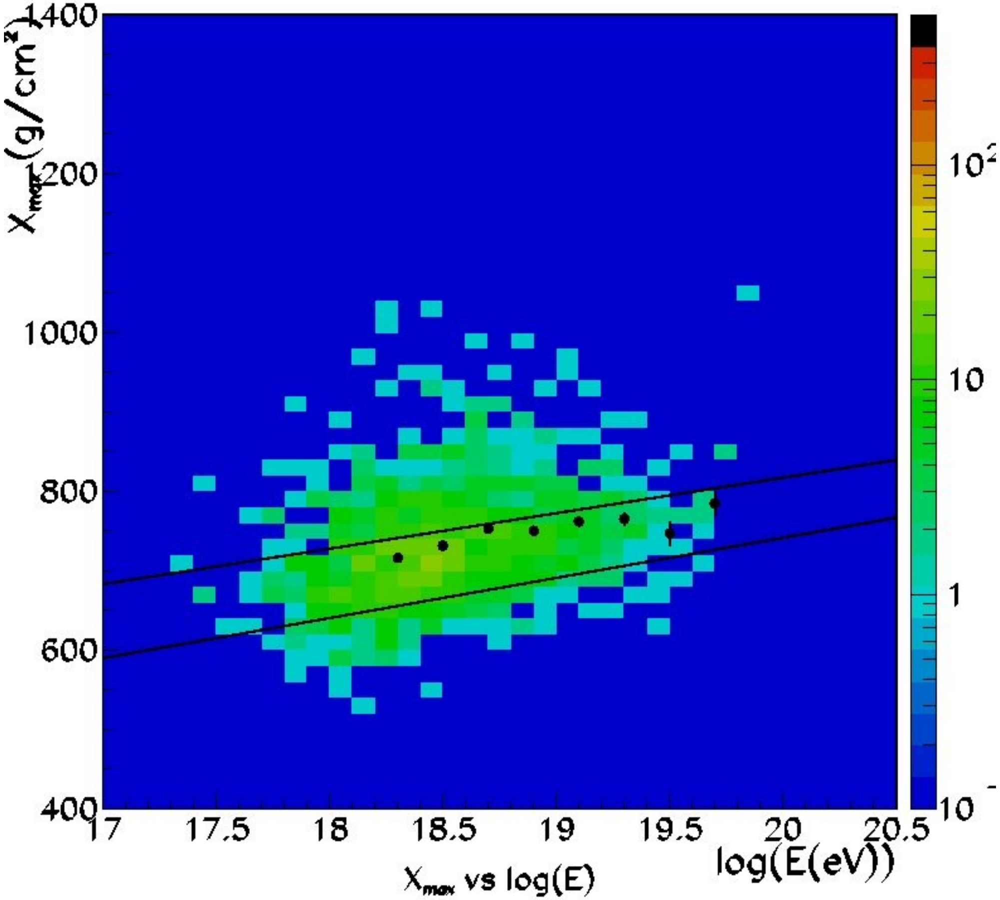
Iron



X_{max} vs Energy, HiRes Stereo Data



QGSJET-II Protons

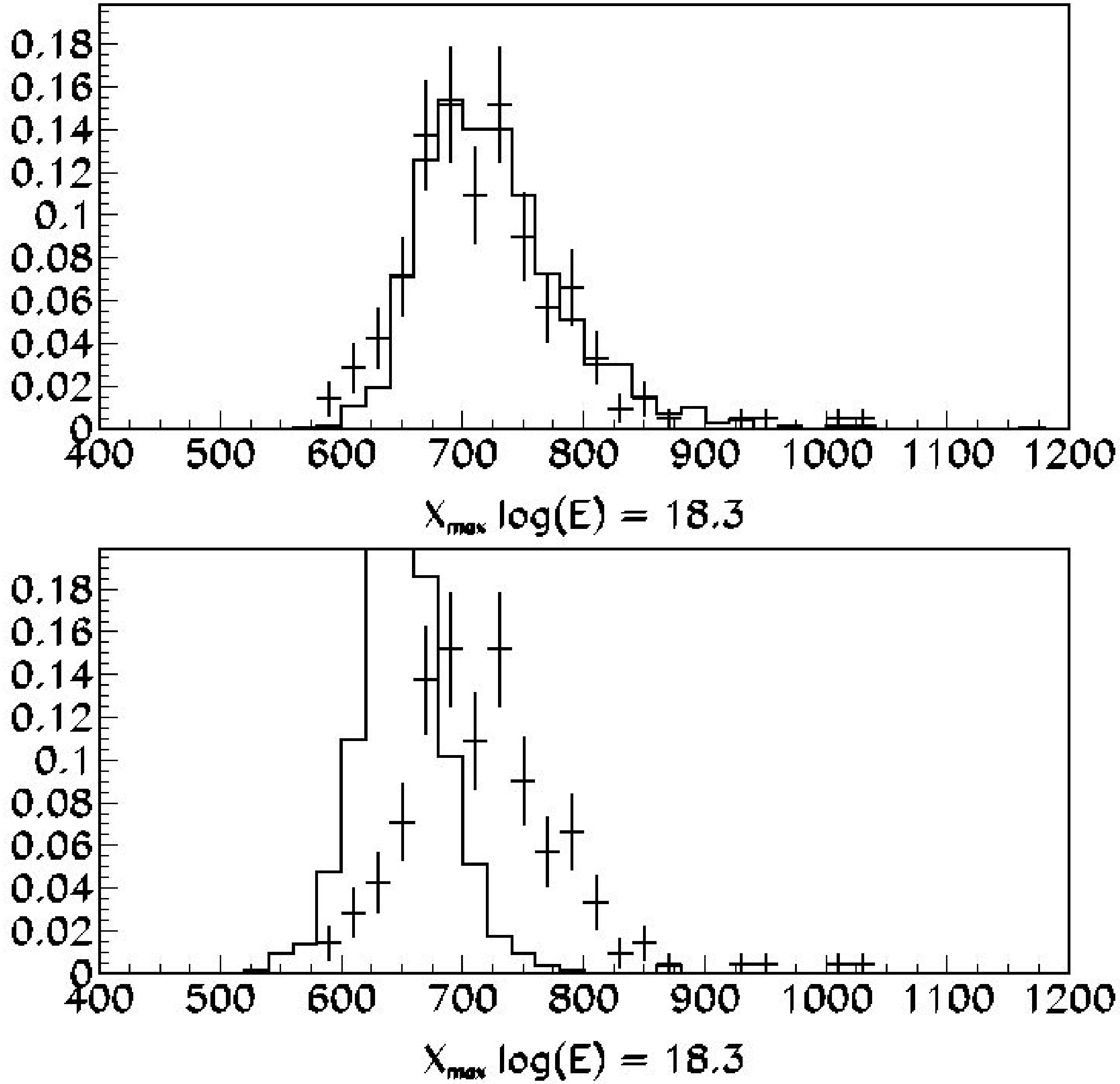


HiRes Stereo Data

Data (points) versus QGSJET-II MC, in Energy Bins

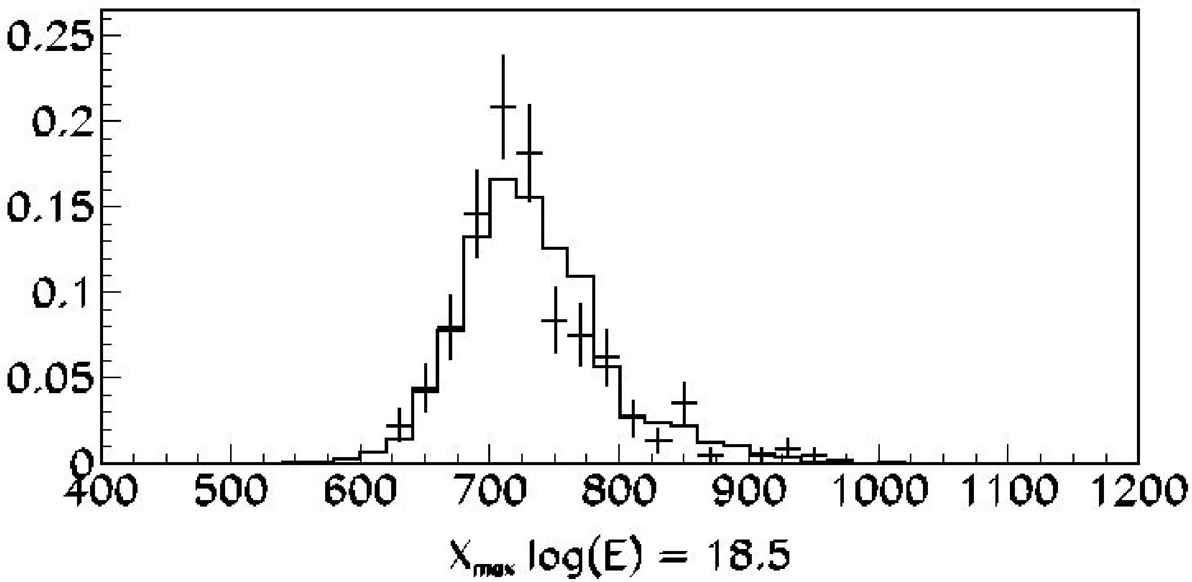
Protons

Iron



Data (points) versus QGSJET-II MC, in Energy Bins

Protons



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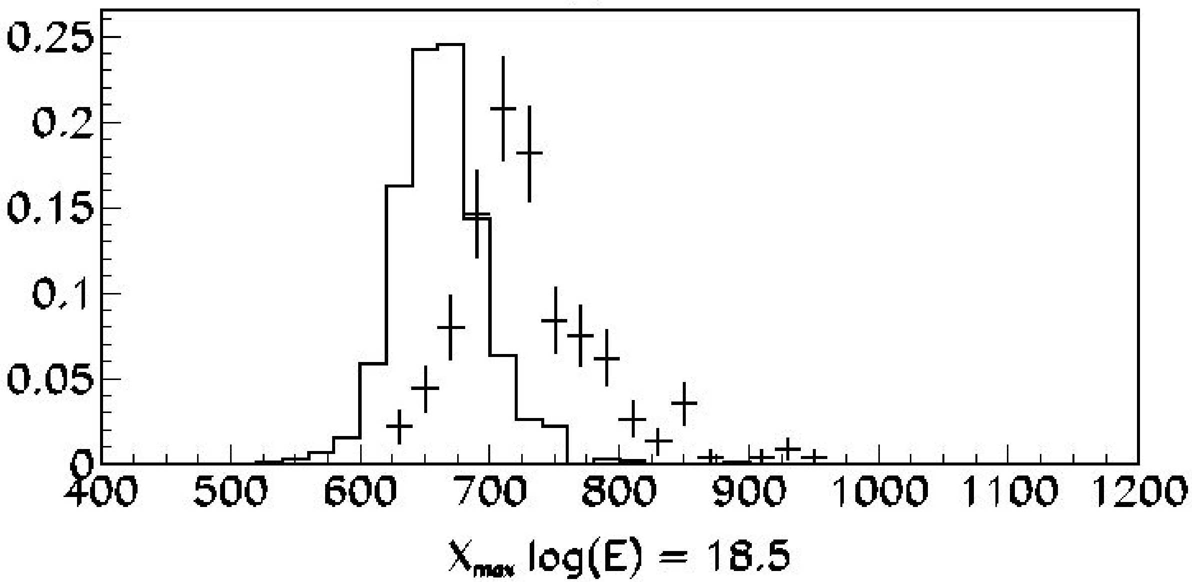
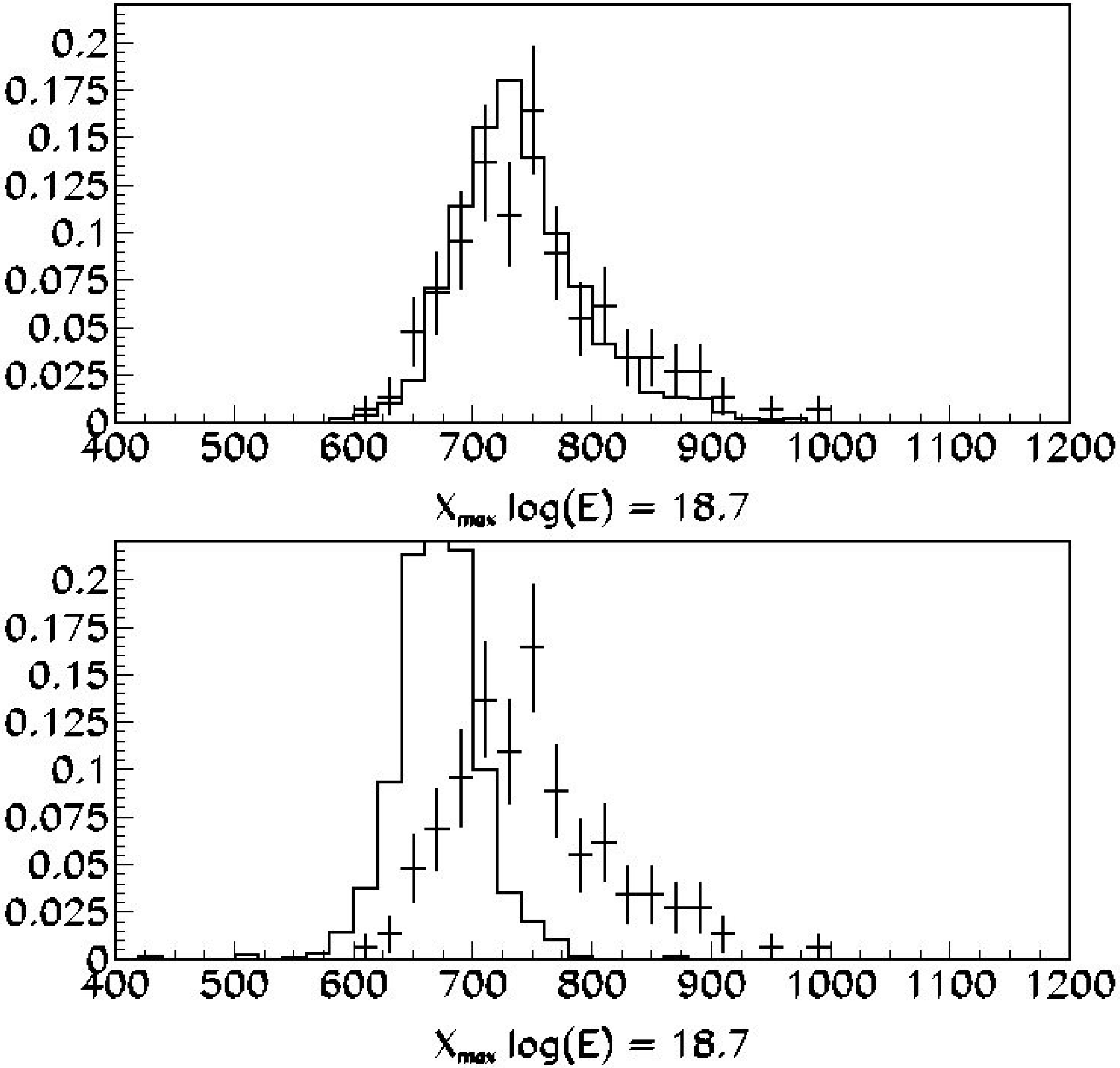


Data (points) versus QGSJET-II MC, in Energy Bins

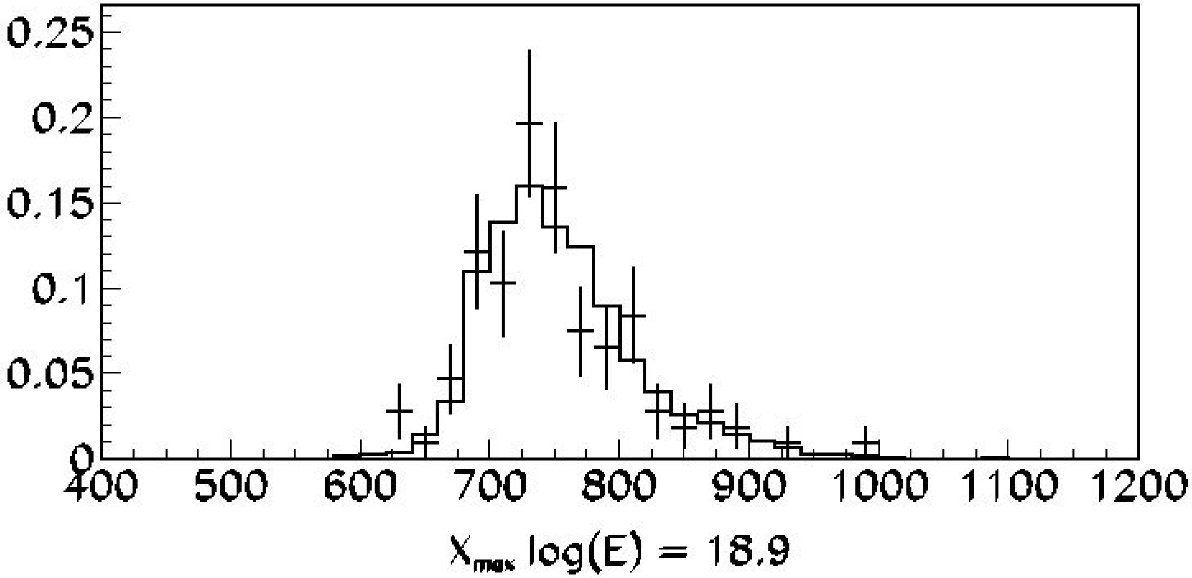
Protons

Iron



Data (points) versus QGSJET-II MC, in Energy Bins

Protons



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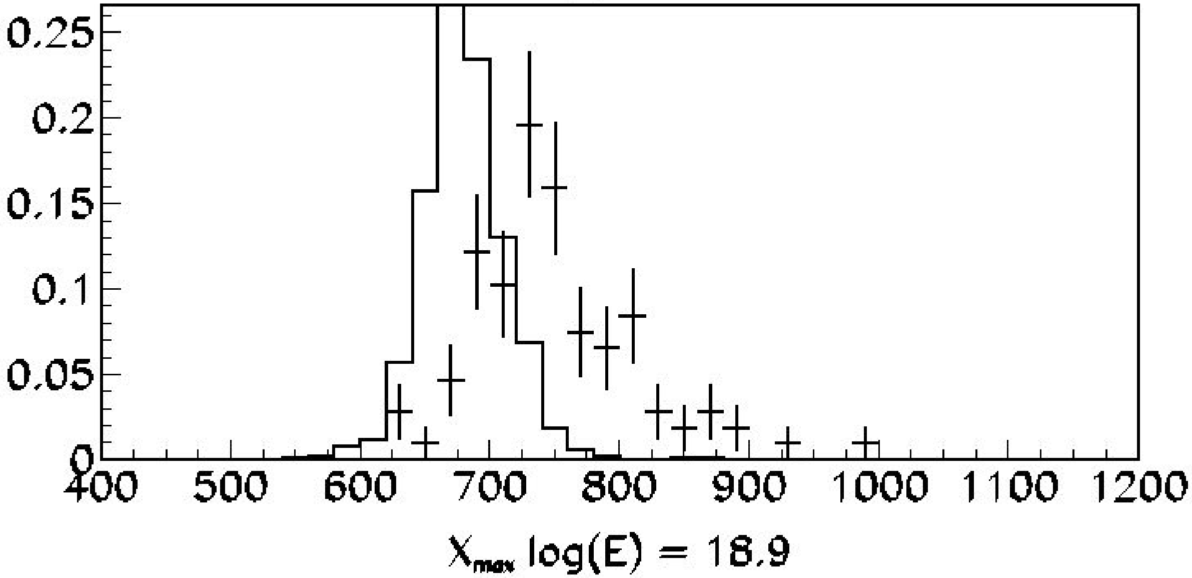
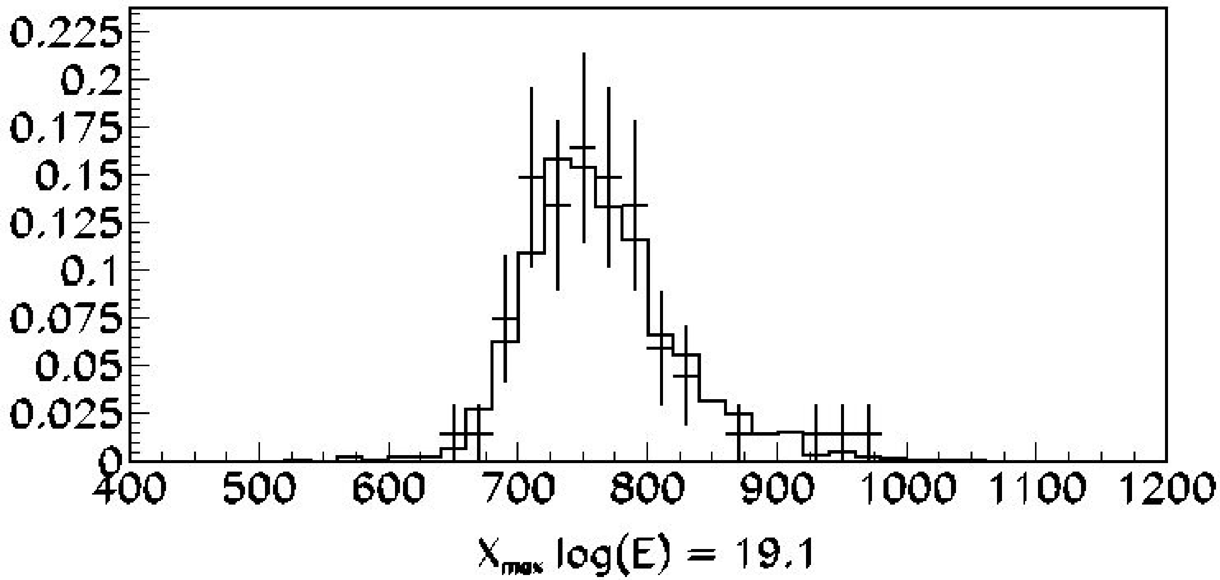
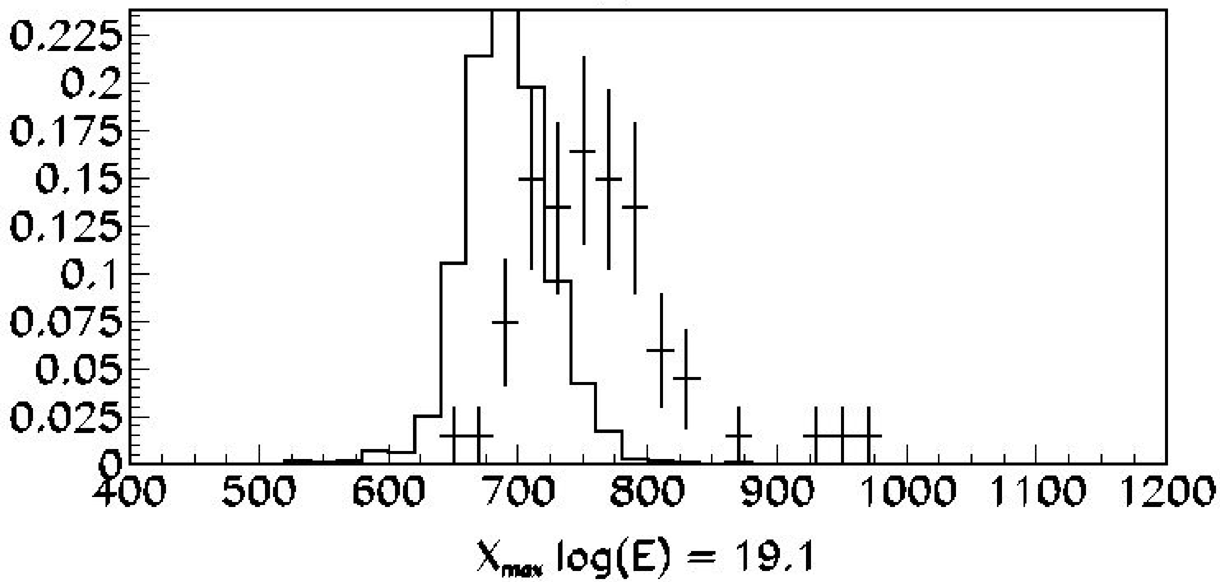


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

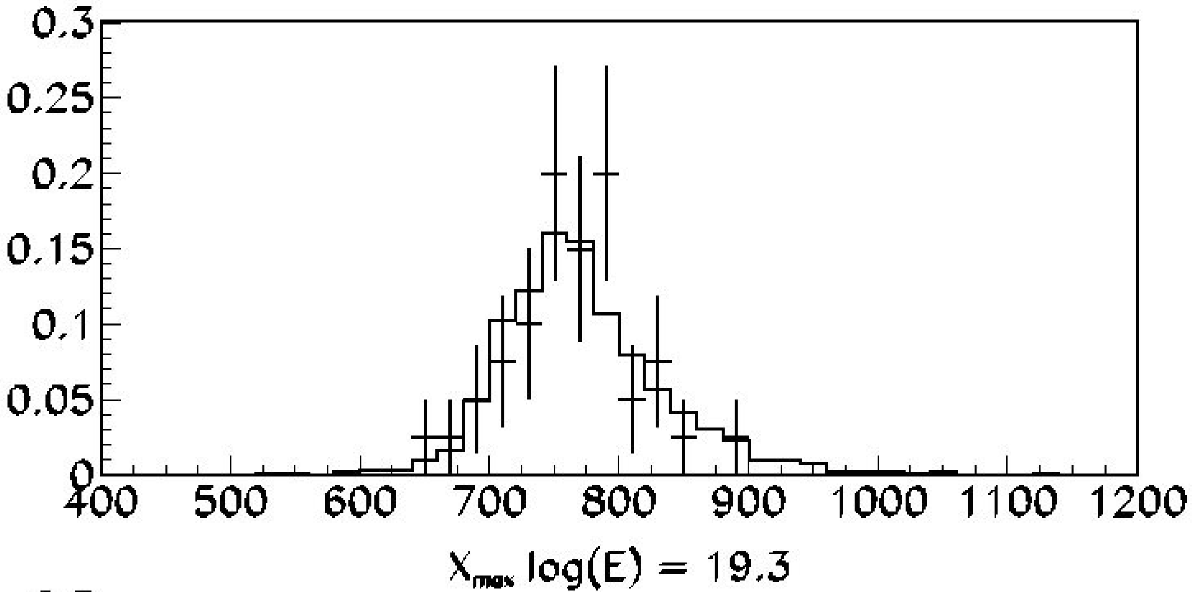


Iron

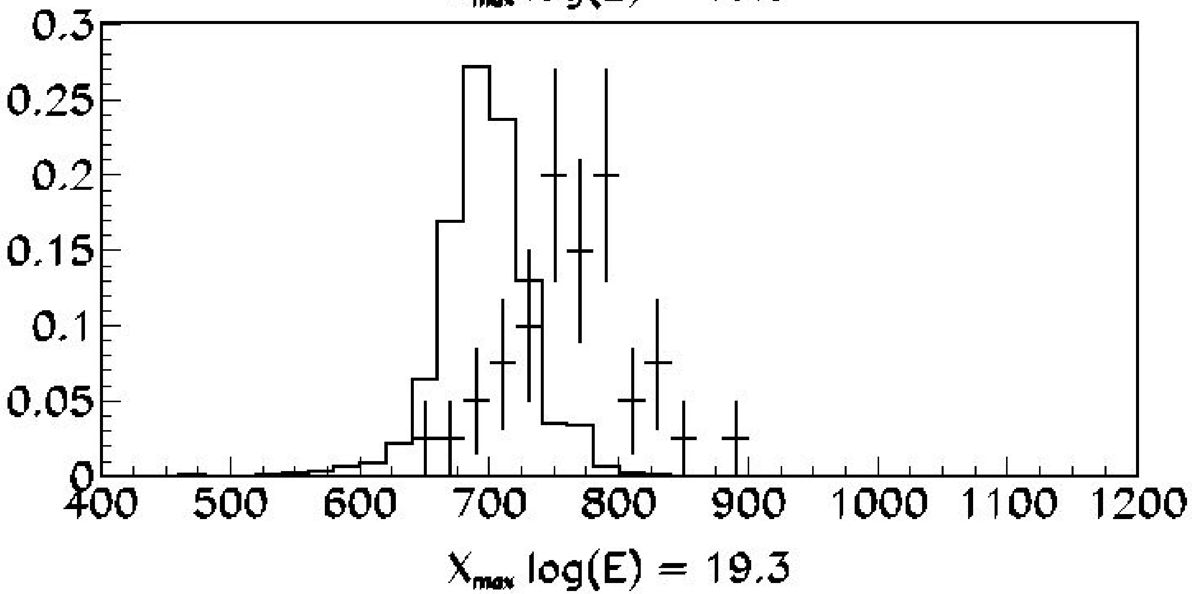


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

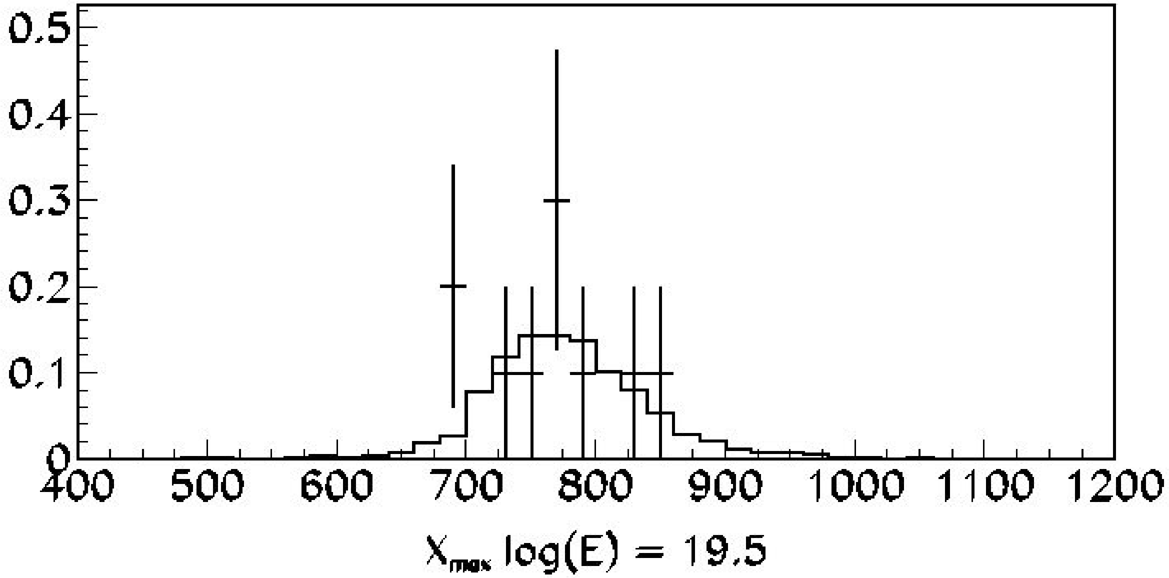


Iron

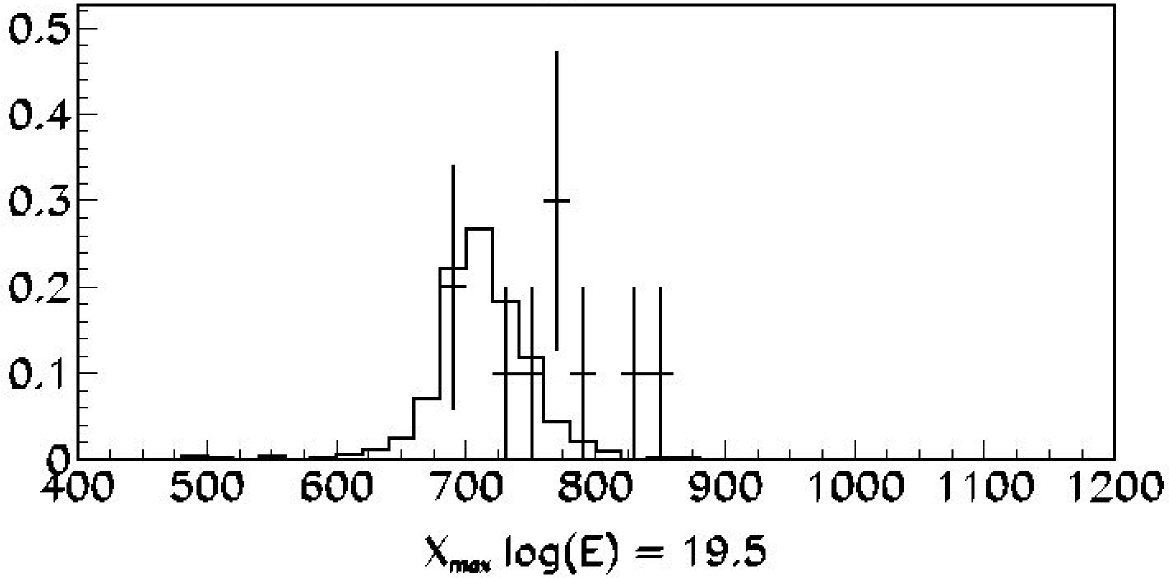


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

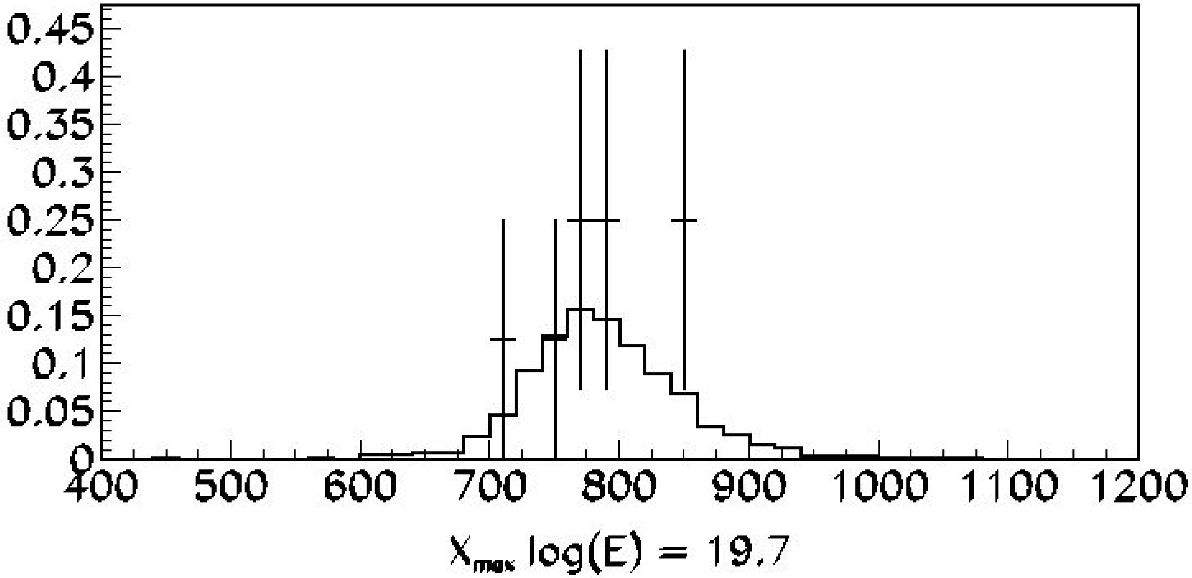


Iron



Data (points) versus QGSJET-II MC, in Energy Bins

Protons



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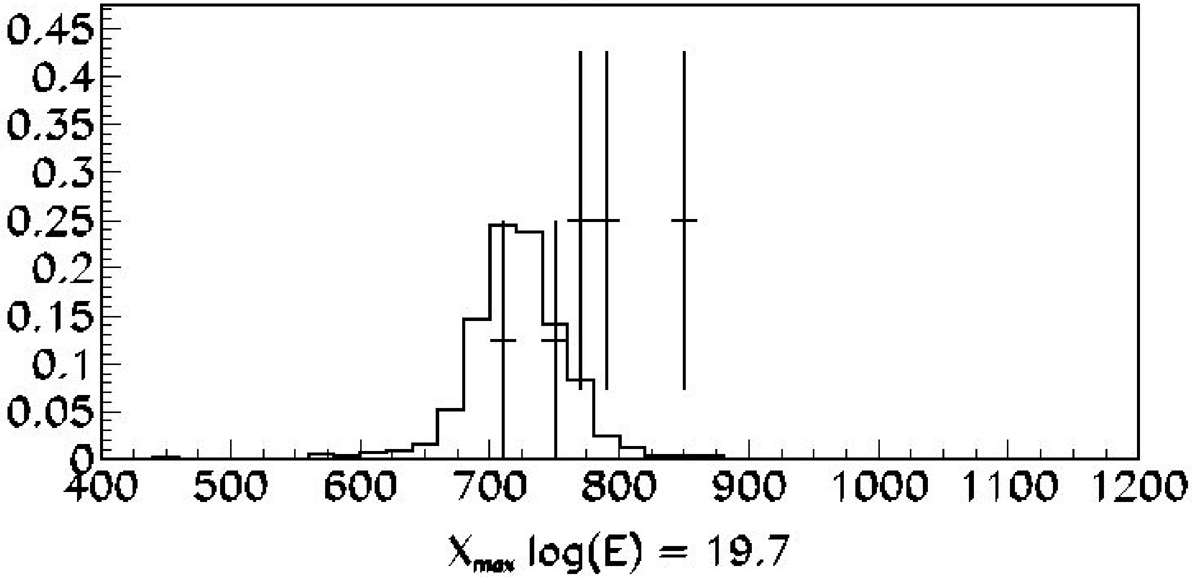
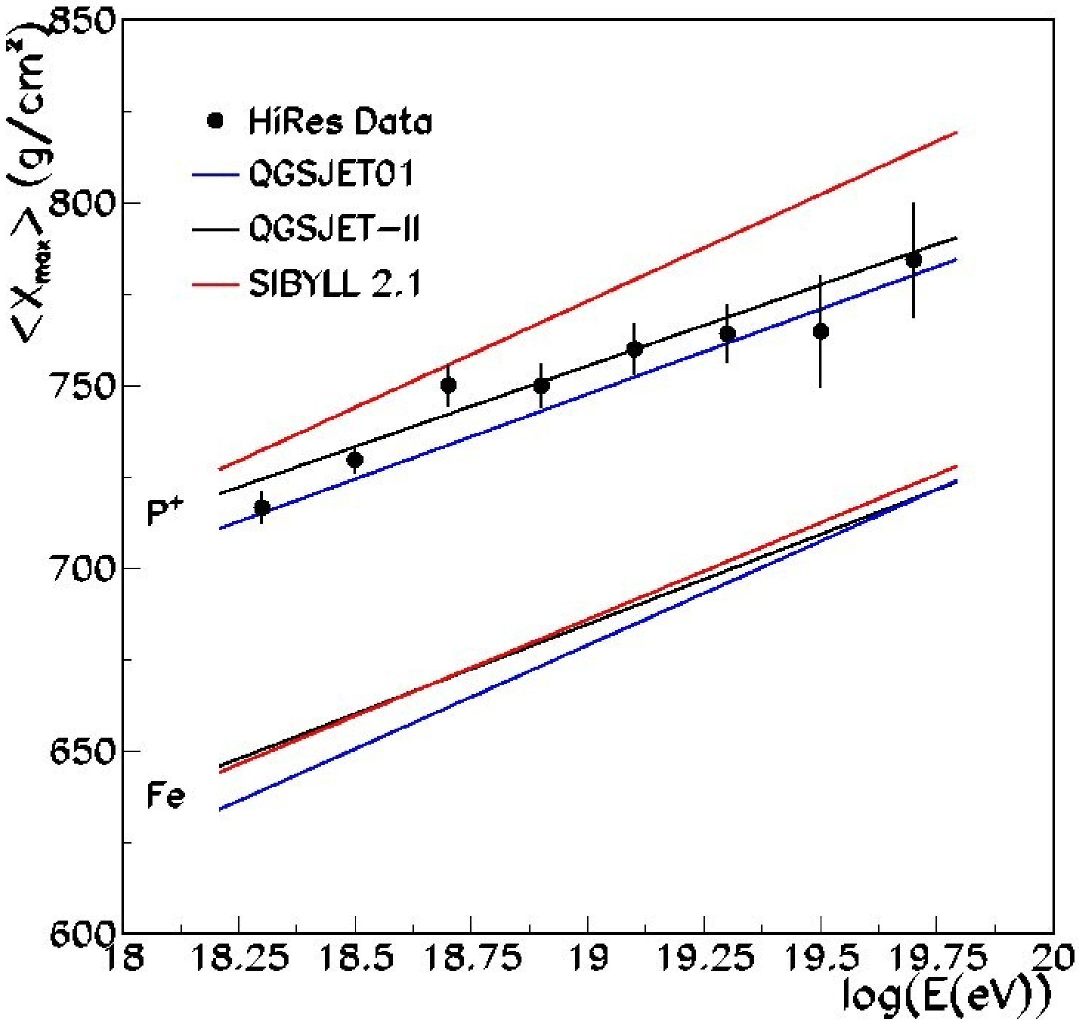


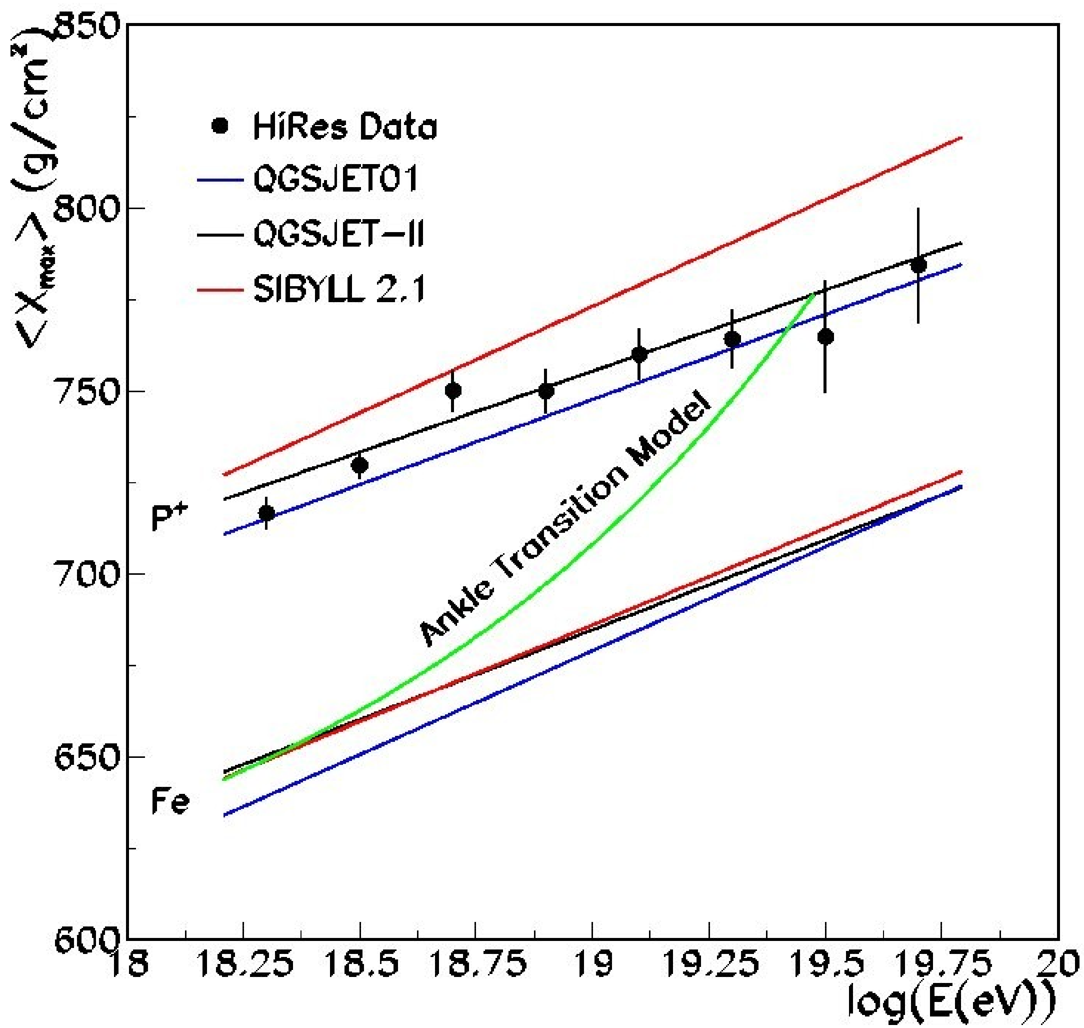
Elongation rate: Evolution of Mean X_{max} with Energy

- Each distribution replaced with a single number representing the mean airshower maximum.
- Comparison with 3 high-energy hadronic interaction models. For each, expectation *after* detector effects is shown.



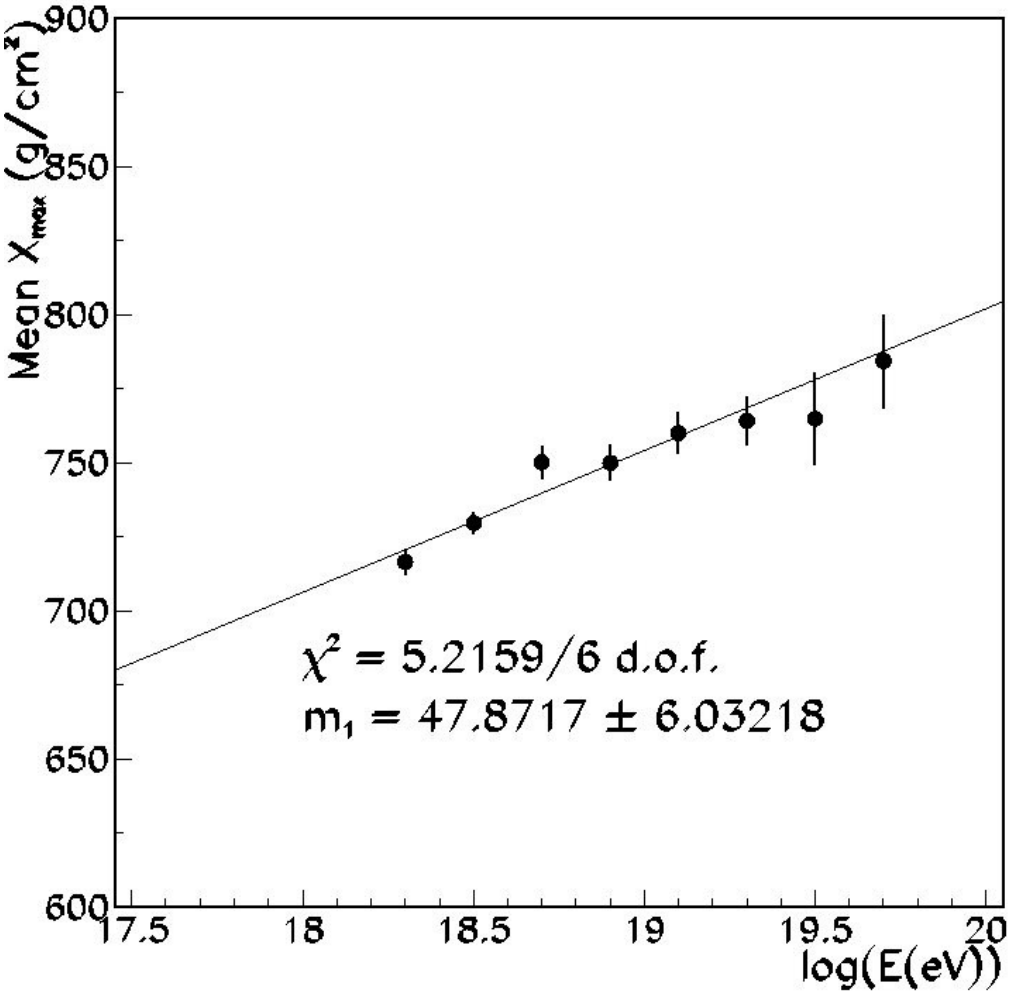
Elongation rate: Evolution of Mean X_{max} with Energy

- Each distribution replaced with a single number representing the mean airshower maximum.
- Comparison with 3 high-energy hadronic interaction models. For each, expectation *after* detector effects is shown.
- HiRes rules out models in which "ankle" is location of galactic-to-extragalactic transition. (Berezinsky, 2007 ICRC)



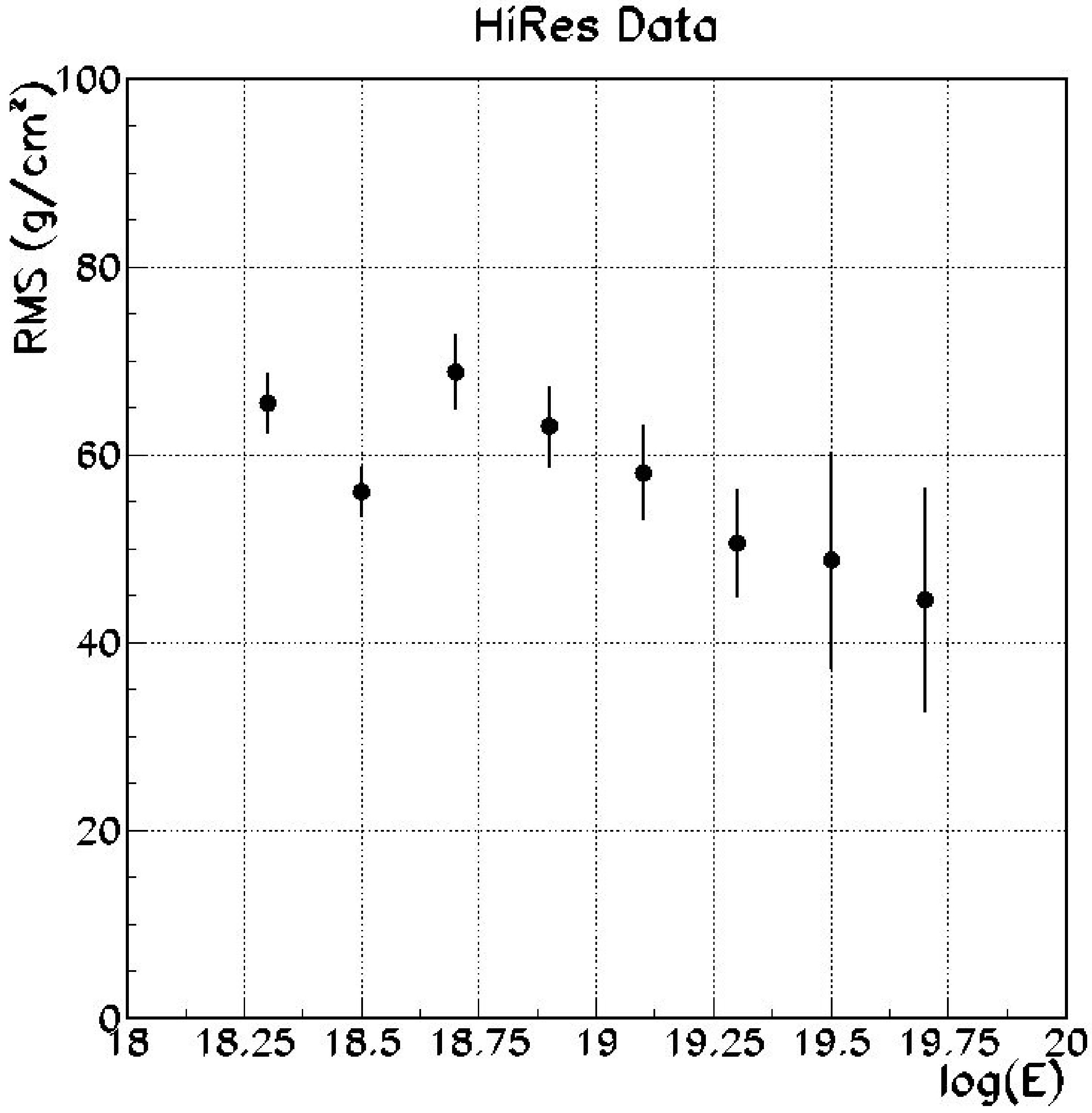
Elongation Rate

- Acceptance bias is *energy independent*. Allows linear fit to determine E.R.
- Linear fit consistent with constant elongation rate, i.e. *constant composition*.

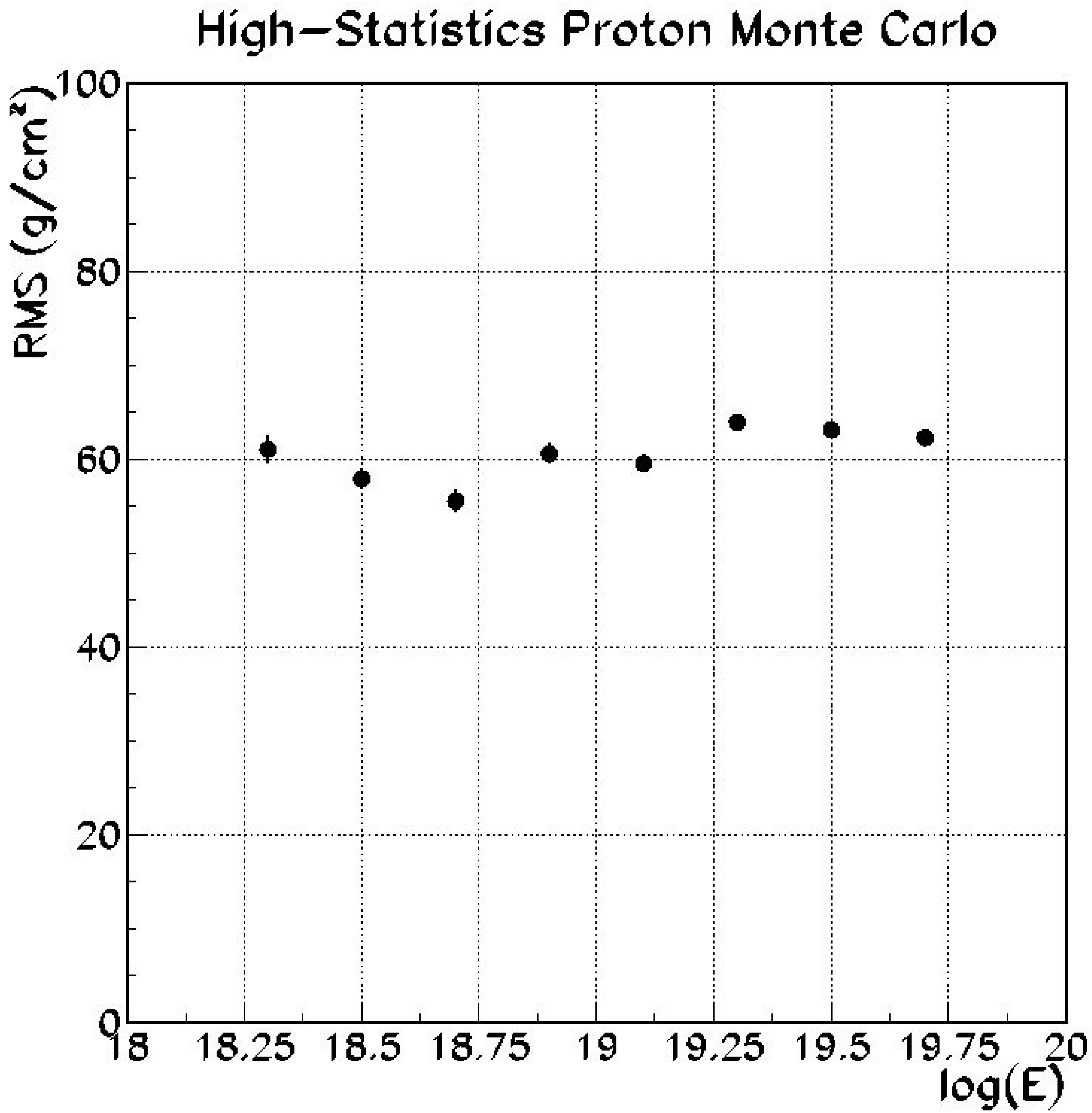


Other Clues to Composition: Shape of X_{max} Distribution

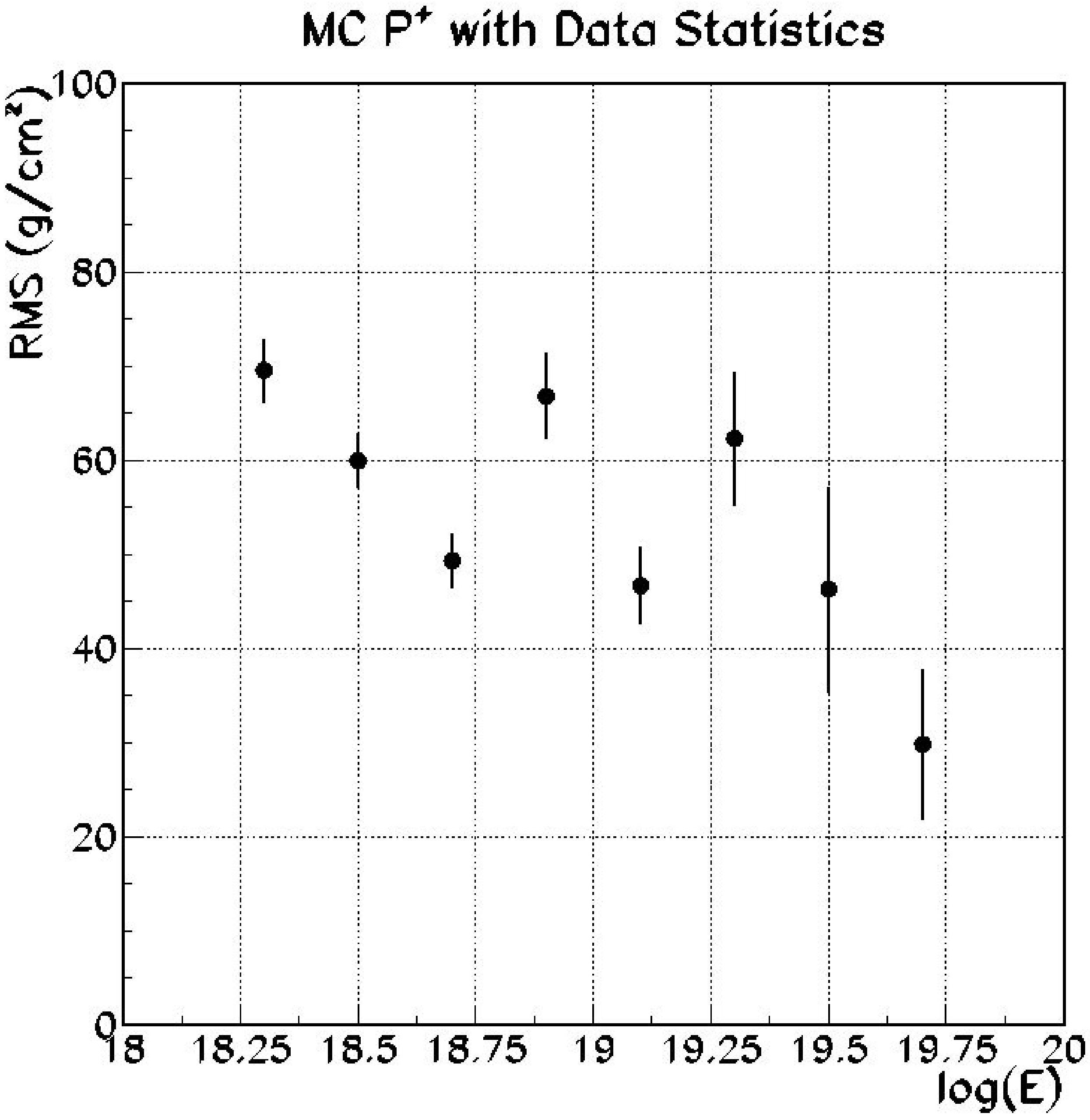
Issues with RMS



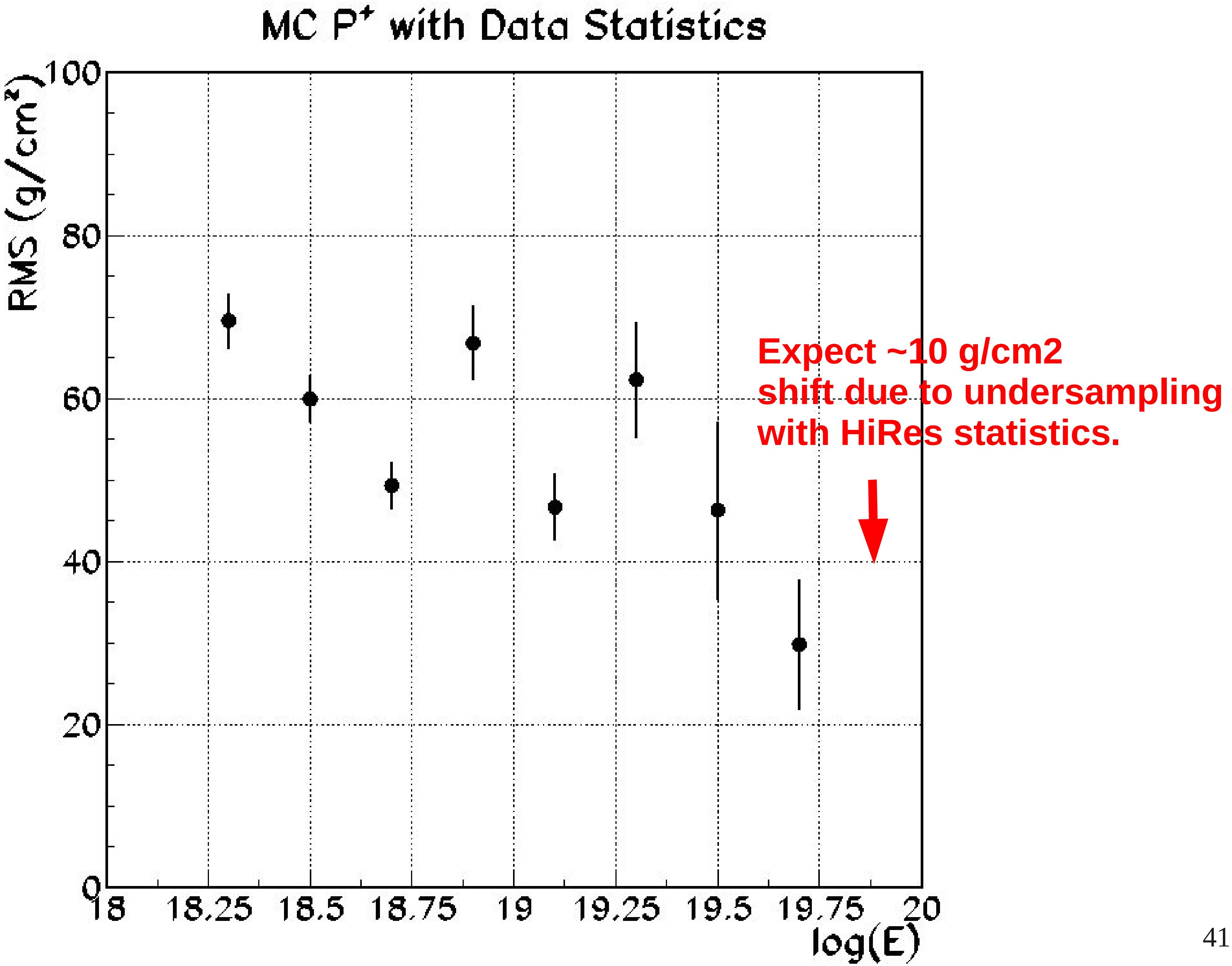
Issues with RMS



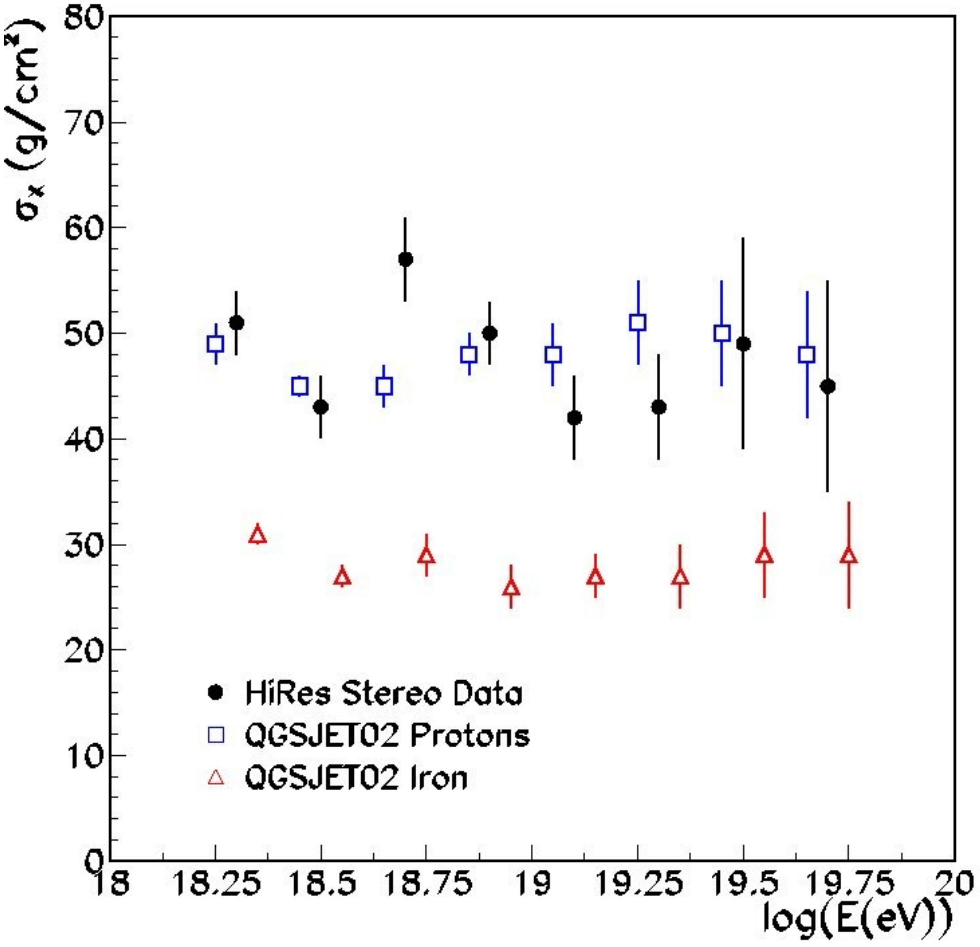
Issues with RMS



Issues with RMS



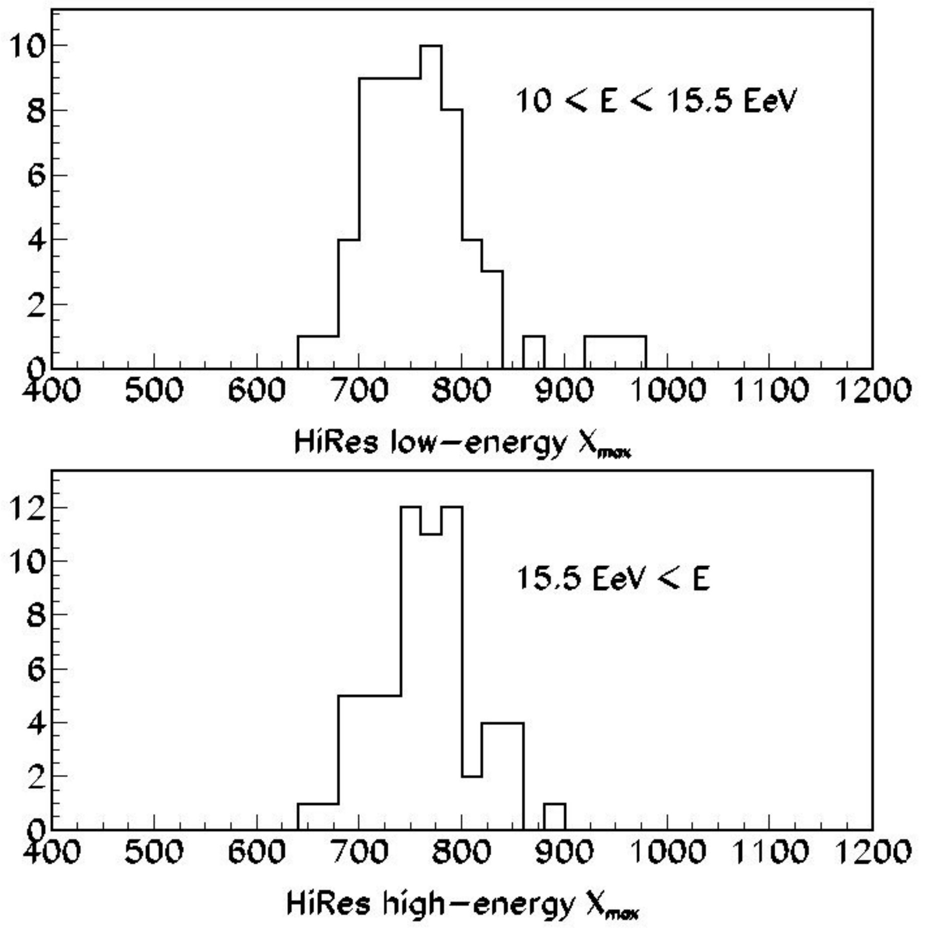
Width of X_{max} Distribution vs Energy



- Define width as σ of Gaussian, truncated at 2xRMS
  - Focus attention on core of distribution
  - Avoid RMS undersampling bias
- Data consistent with QGSJET-II protons

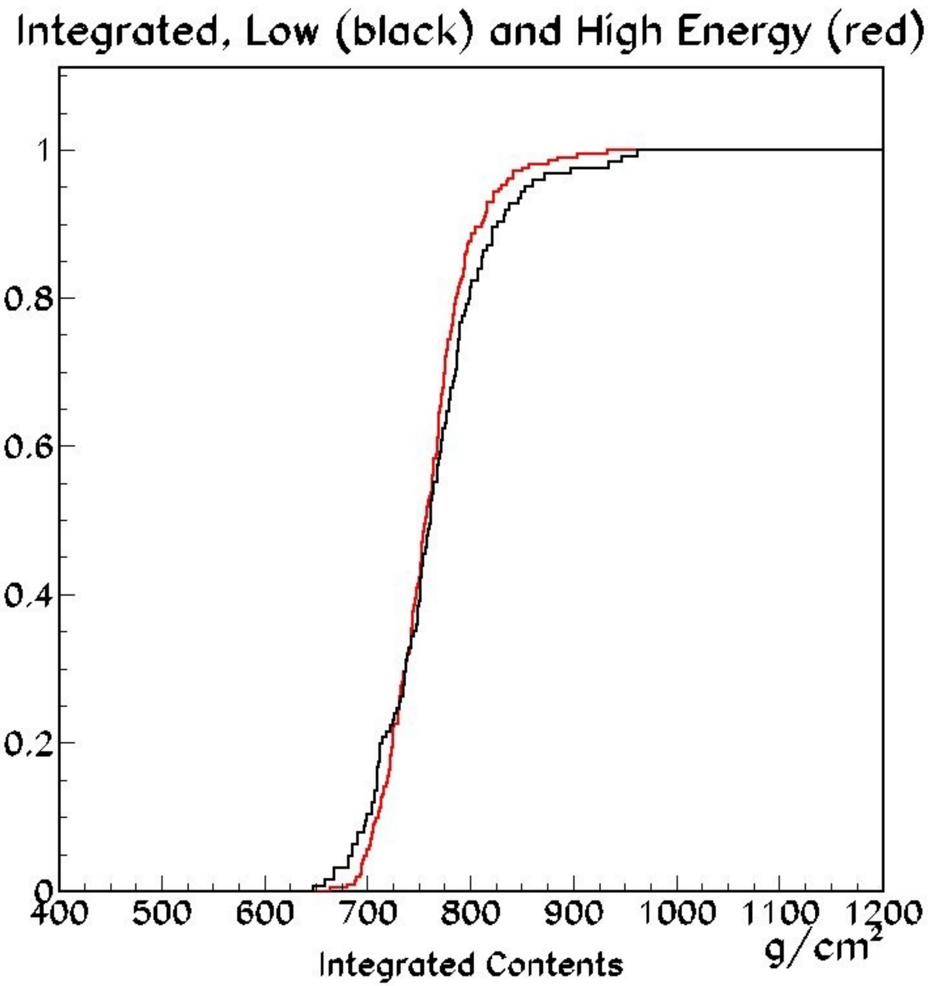
Study Distributions via KS-Tests

- KS p-value handles statistical limitations fairly.
- First question: Do high- and low-energy halves of HiRes data above 10 EeV exhibit narrowing?
- Shift distributions to account for elongation rate...



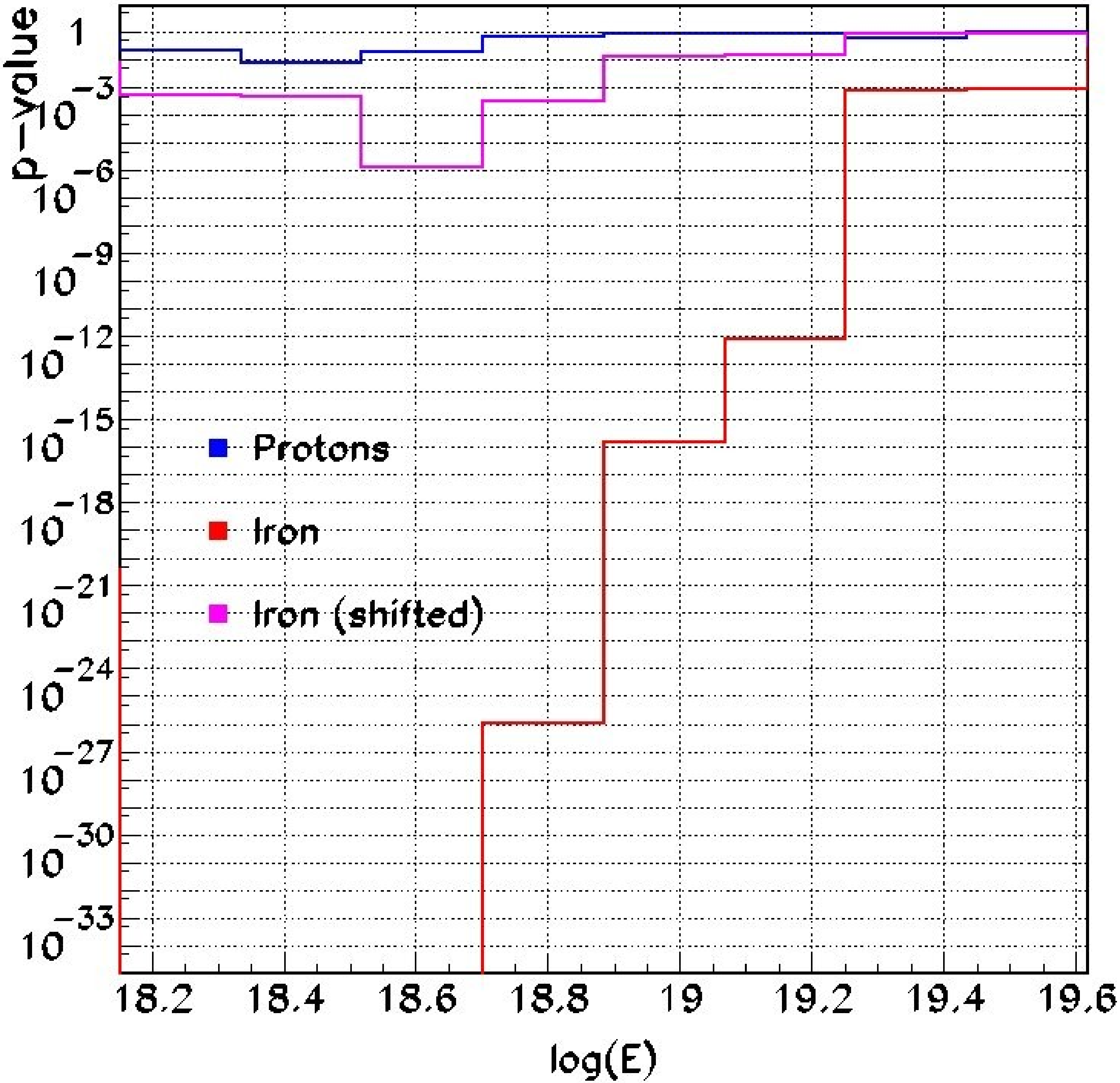
Study Distributions via KS-Tests

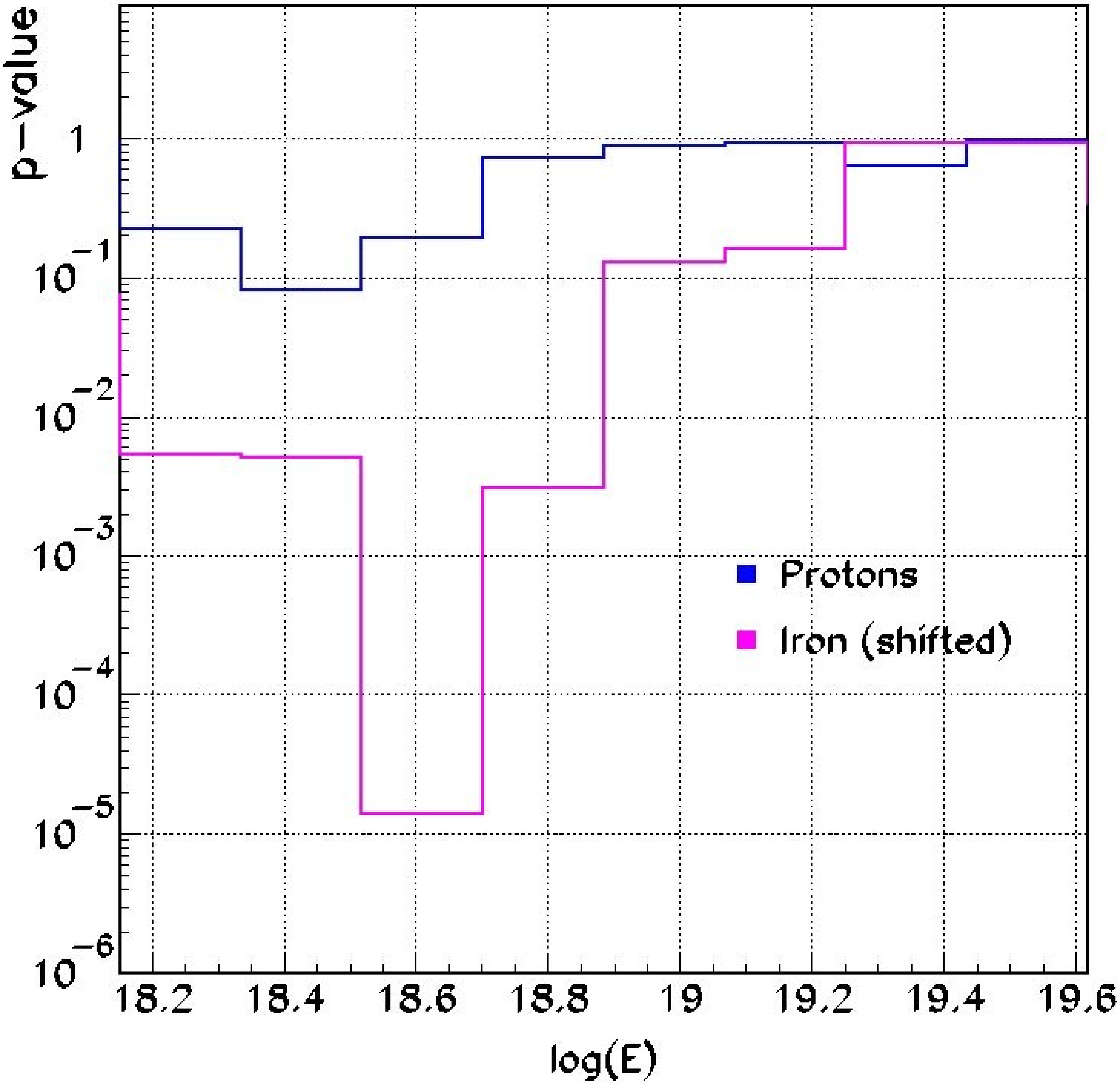
- ...perform KS test to compare shapes.
  - D = 0.13364
  - P = 63%
- No evidence distribution is narrowing.



Study Distributions via KS-Tests

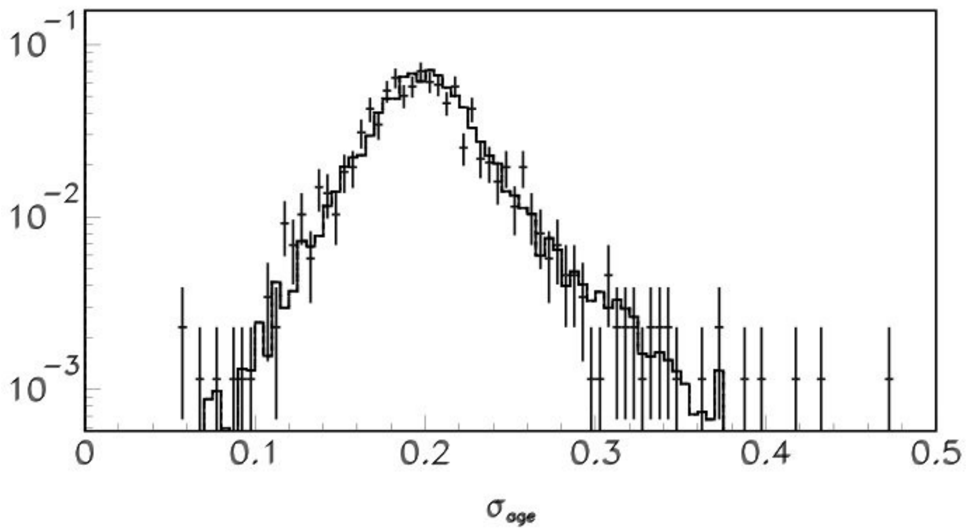
- Bin-by-bin evaluation of the shape of X_{max} distributions
- Protons: Perform direct KS tests between data and QGSJET-II proton distributions, in energy bins.
- Iron:
  - Perform direct KS tests, in energy bins
  - Shift iron mean X_{max} to agree with data. Perform KS test to compare *shape* of distributions.


p-value
1
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
10^{-30}
10^{-33}
Protons
Iron
Iron (shifted)
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
log(E)

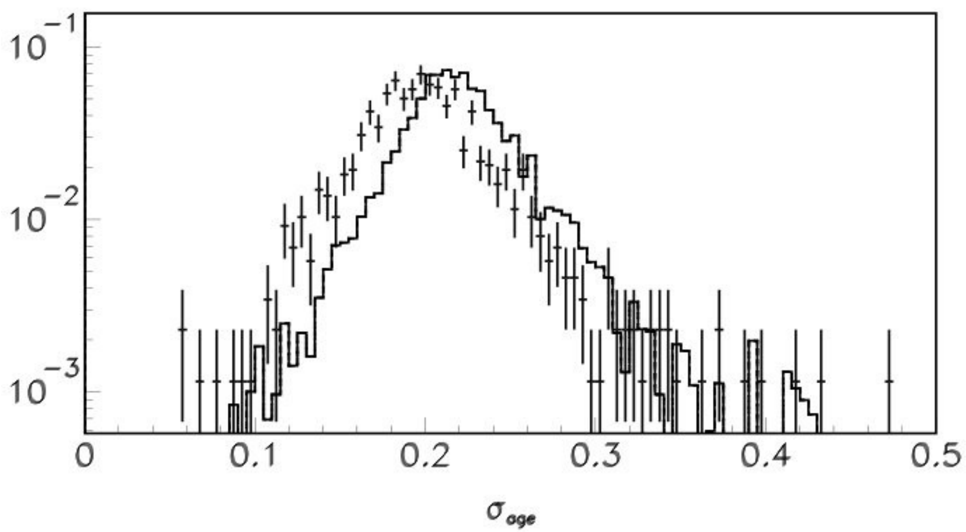

p−value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
log(E)
Protons
Iron (shifted)

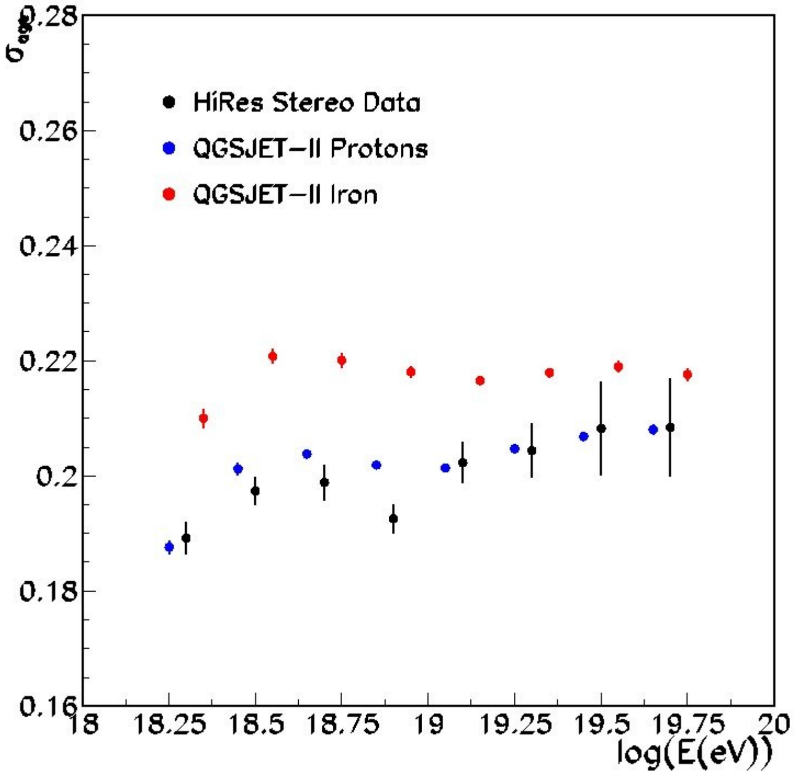
Data (points) versus QGSJET-II Monte Carlo (histogram)

Protons



Iron





σ_{age} is dimensionless measure of shower width, anticorrelated with X_{max}

HiRes Spectrum and Composition: Synthesis

- HiRes data explained in all particulars by QGSJET01 & II proton Monte Carlo
  - Does QGSJET describe real protons at these energies?
  - Mixed models (e.g. Sibyll) require unchanging elongation over two orders of magnitude!
- Proton composition consistent with spectral observations.
  - Location and shape of cutoff
  - Shape of ankle .
- *Synthesis - HiRes spectral and composition results can be explained with a simple model: Cosmic rays above 1 EeV are protons of extragalactic origin. The high-energy spectrum is shaped by interactions of these protons with the CMBR.*
- ***R. Abbasi et al., Phys. Rev. Lett. 104 (2010).***
- ***Points available at: www.cosmic-ray.org/journals/prl.html***