The Composition of the Highest Energy Cosmic Rays

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The High-Resolution Fly's Eye (HiRes) Collaboration

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The High-Resolution Fly's Eye (HiRes)

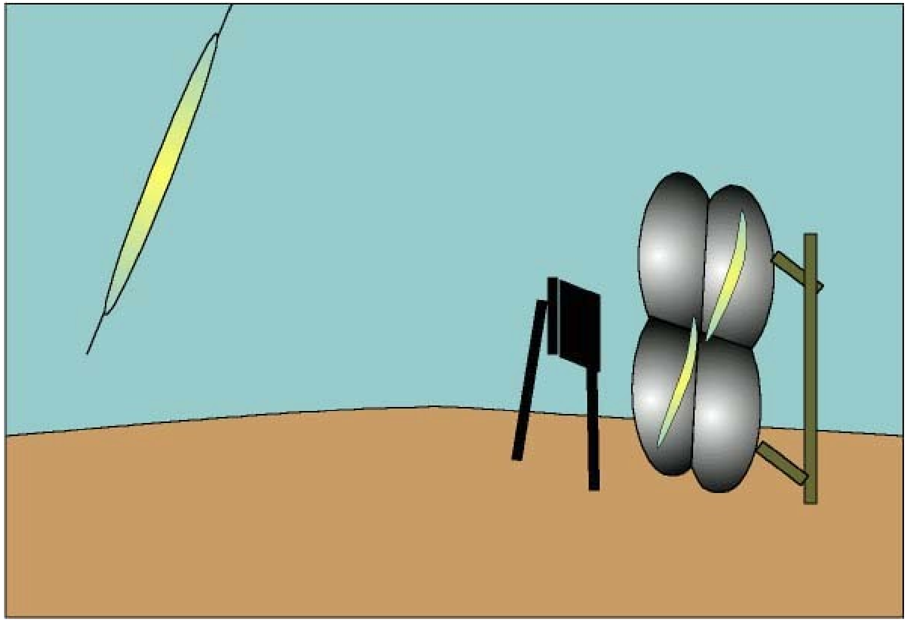
Two HiRes Detectors

HiRes-I:

- 21 mirrors, 1 ring, 3º < elev < 17º
- Readout pulse height and time

HiRes-II:

- 12.6 km SW of HiRes-I
- 42 mirrors, 2 rings, 3º < elev < 31º
- Electronics stores pulse shape vs time w/ 100 ns sampling

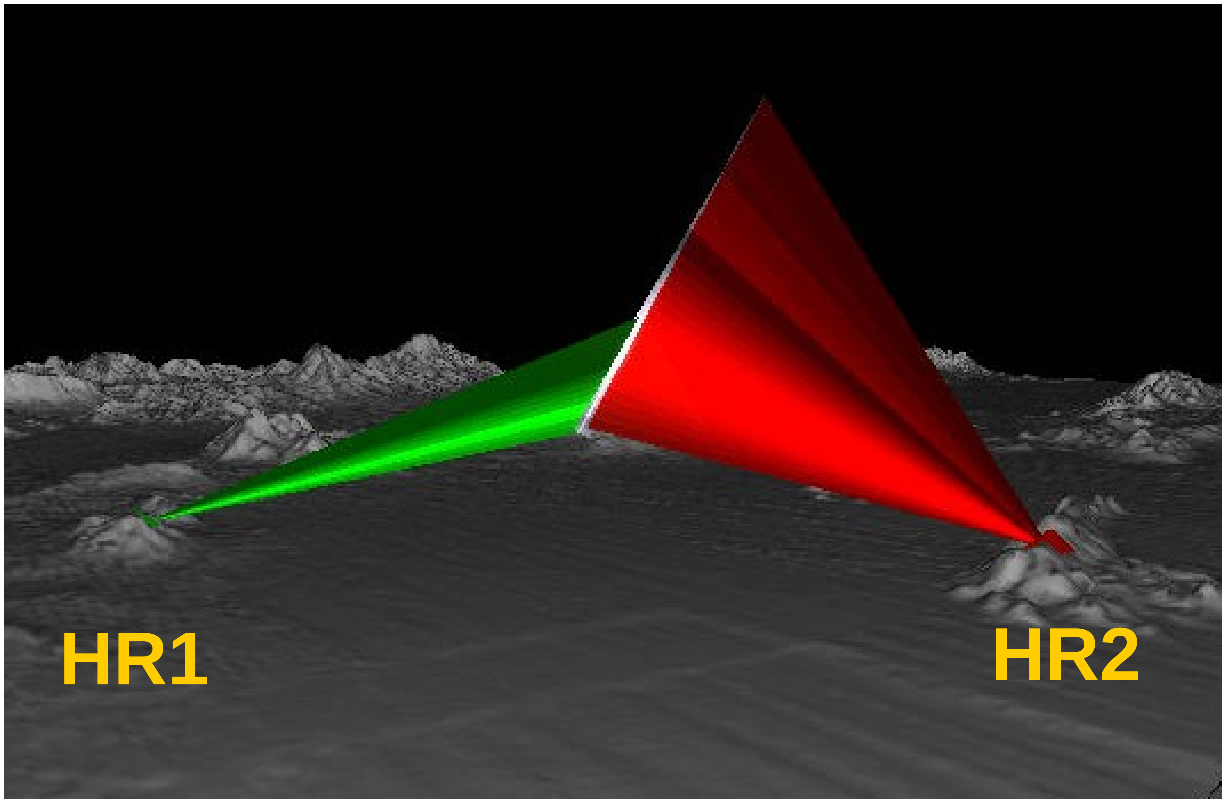


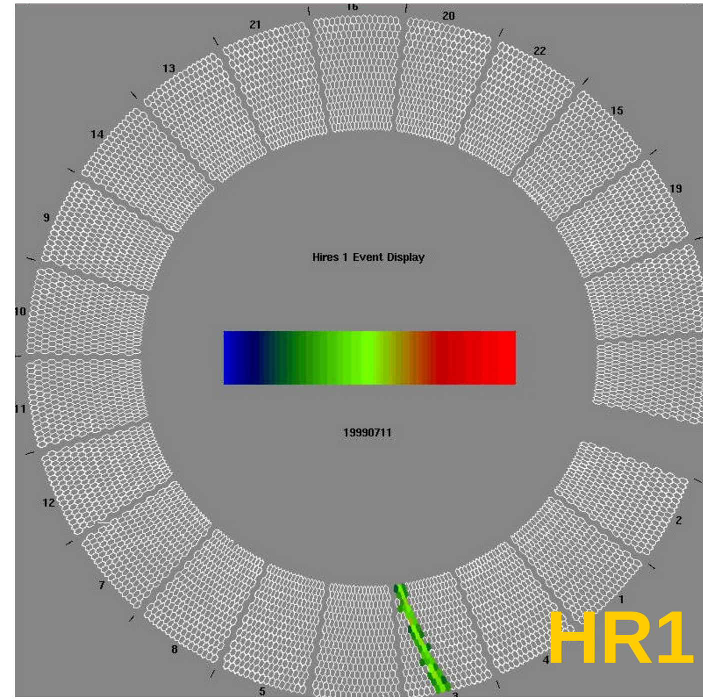
Observe nitrogen fluorescence from airshowers

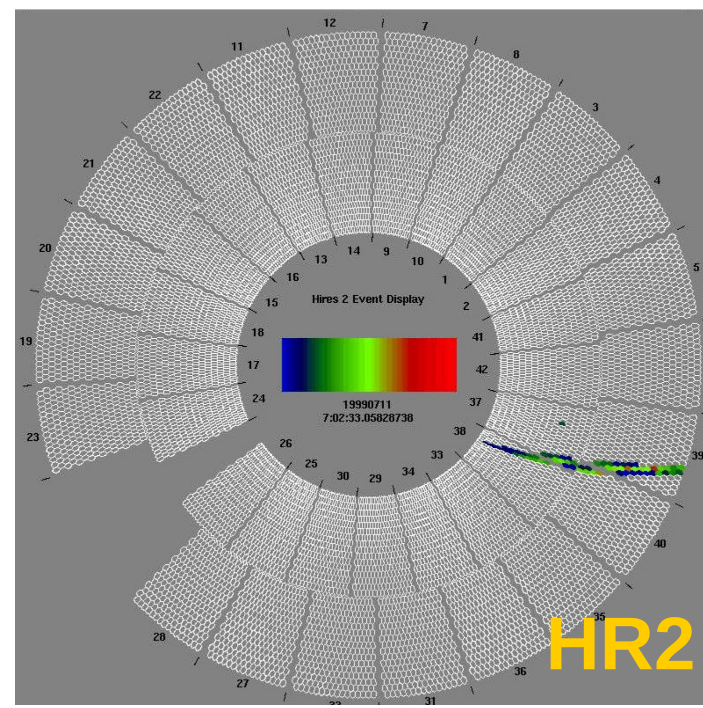
Mirrors and Phototubes

- 4.2 m^2 spherical mirror
- 16 x 16 array of phototubes, .96 degree pixels.

Event Reconstruction: Geometry

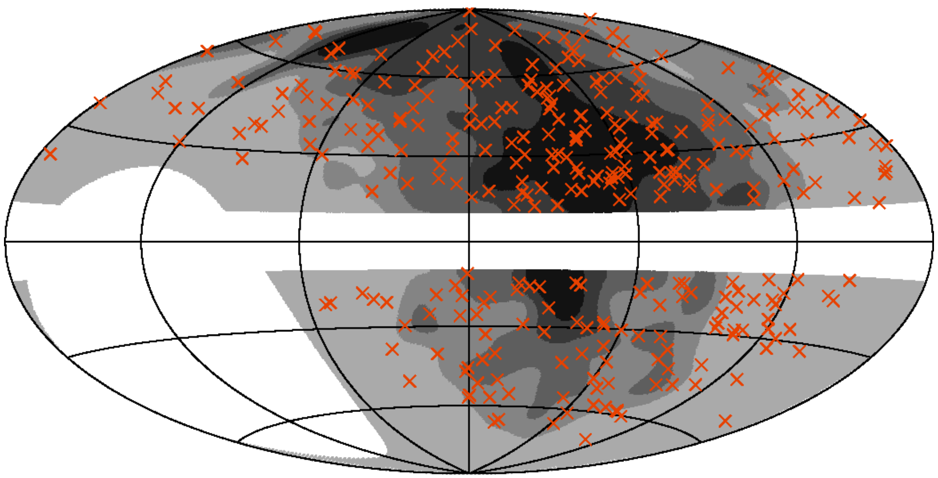




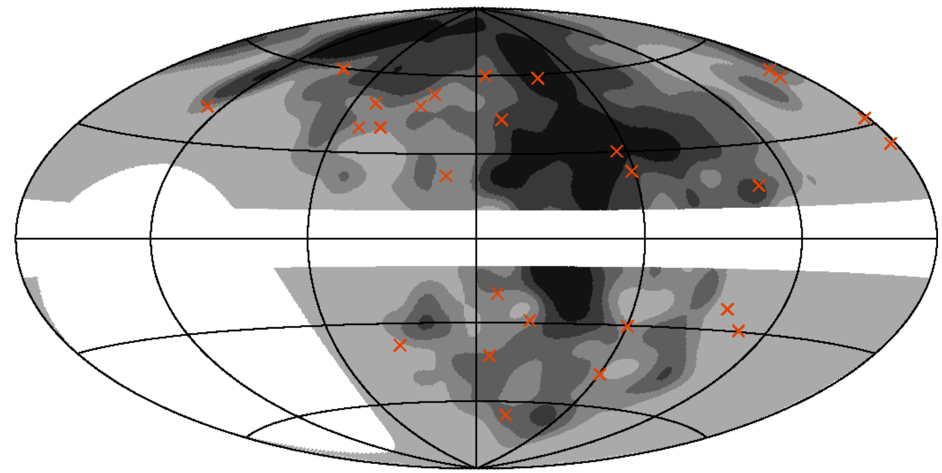


Obtain pointing directions for anisotropy searches...

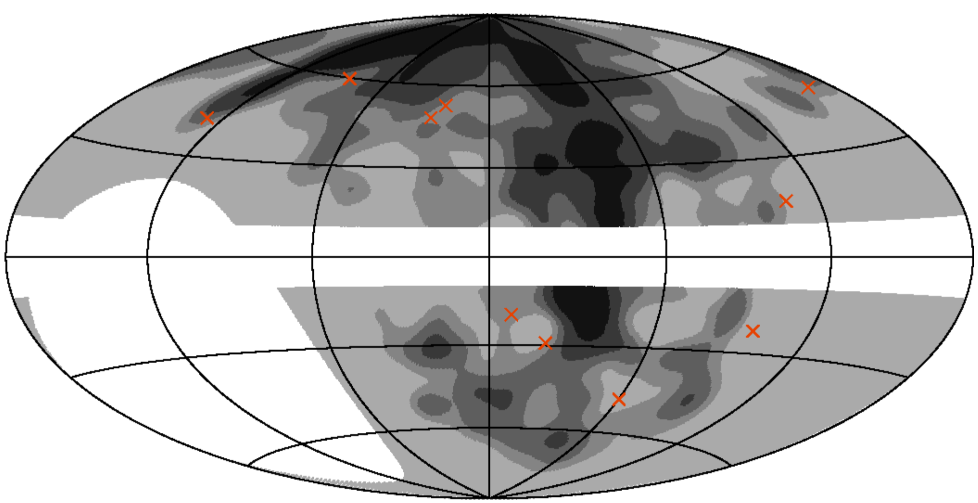
Search for Correlation with Large-Scale Structure



10 EeV



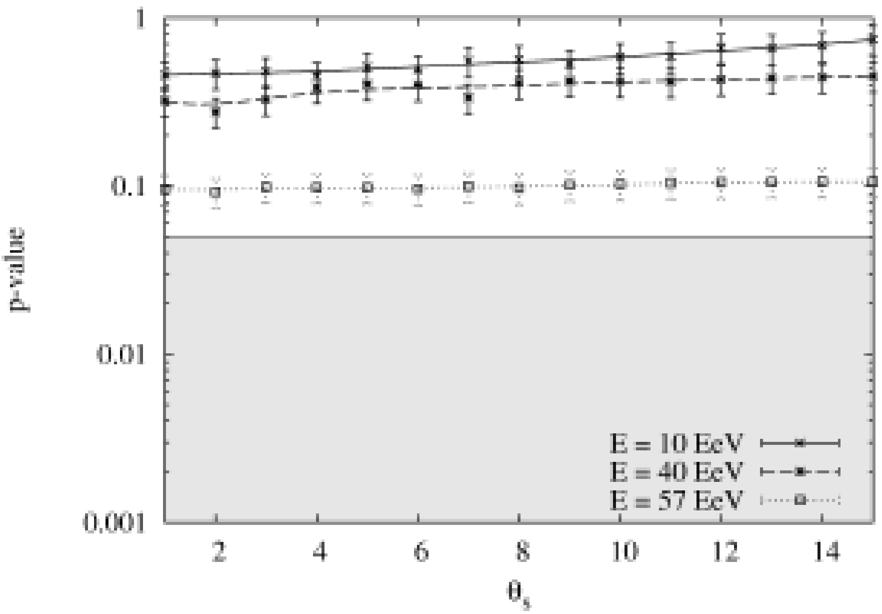
40 EeV

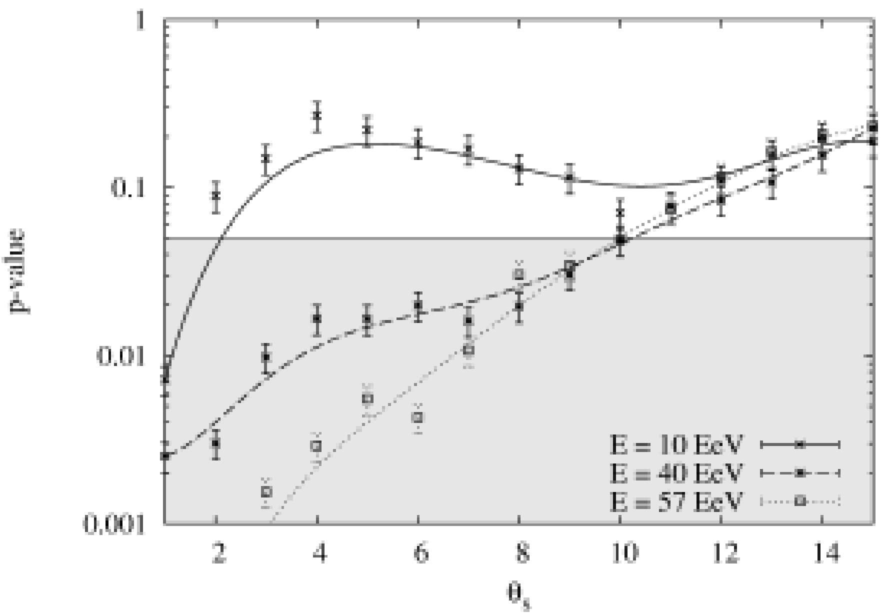


57 EeV

- Model HiRes sky based on 2 μm all sky survey (Huchra et al.)
- Allow smearing to simulate magnetic field effects
- Perform KS test under LSS-tracer, isotropic models...

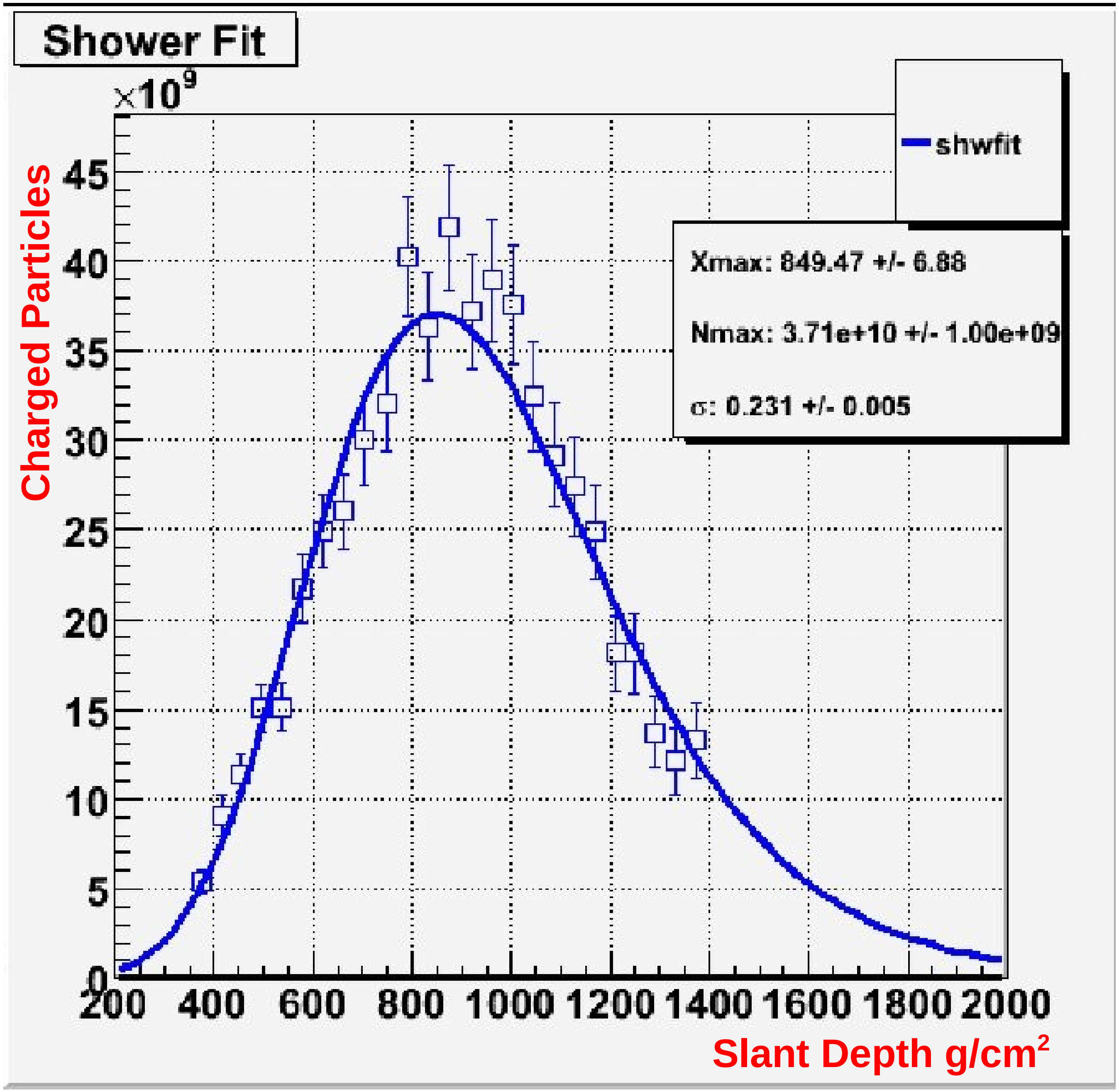
LSS Correlation: Results



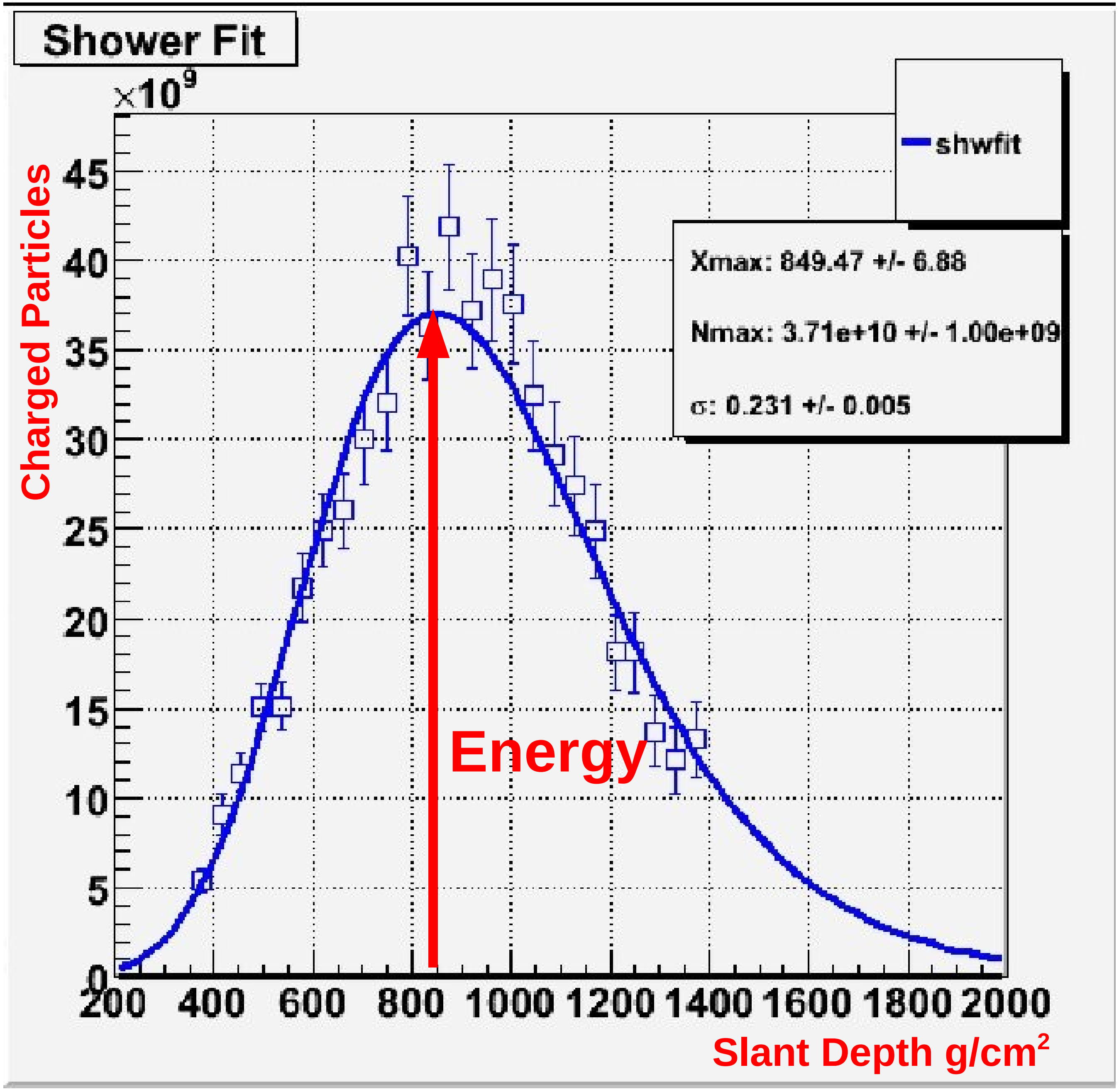


- For isotropic model, get good agreement.
- **For local LSS model get poor agreement.**
- Exclude correlation at 95% c.l. for $\theta_s < 10°$, $E \geq 40$ EeV
- P. Tinkakov, this conference
- R. Abbasi *et al.*, *Ap.J. Lett.* **713** (2010)

Next step: The "Shower Profile"



The “Shower Profile”



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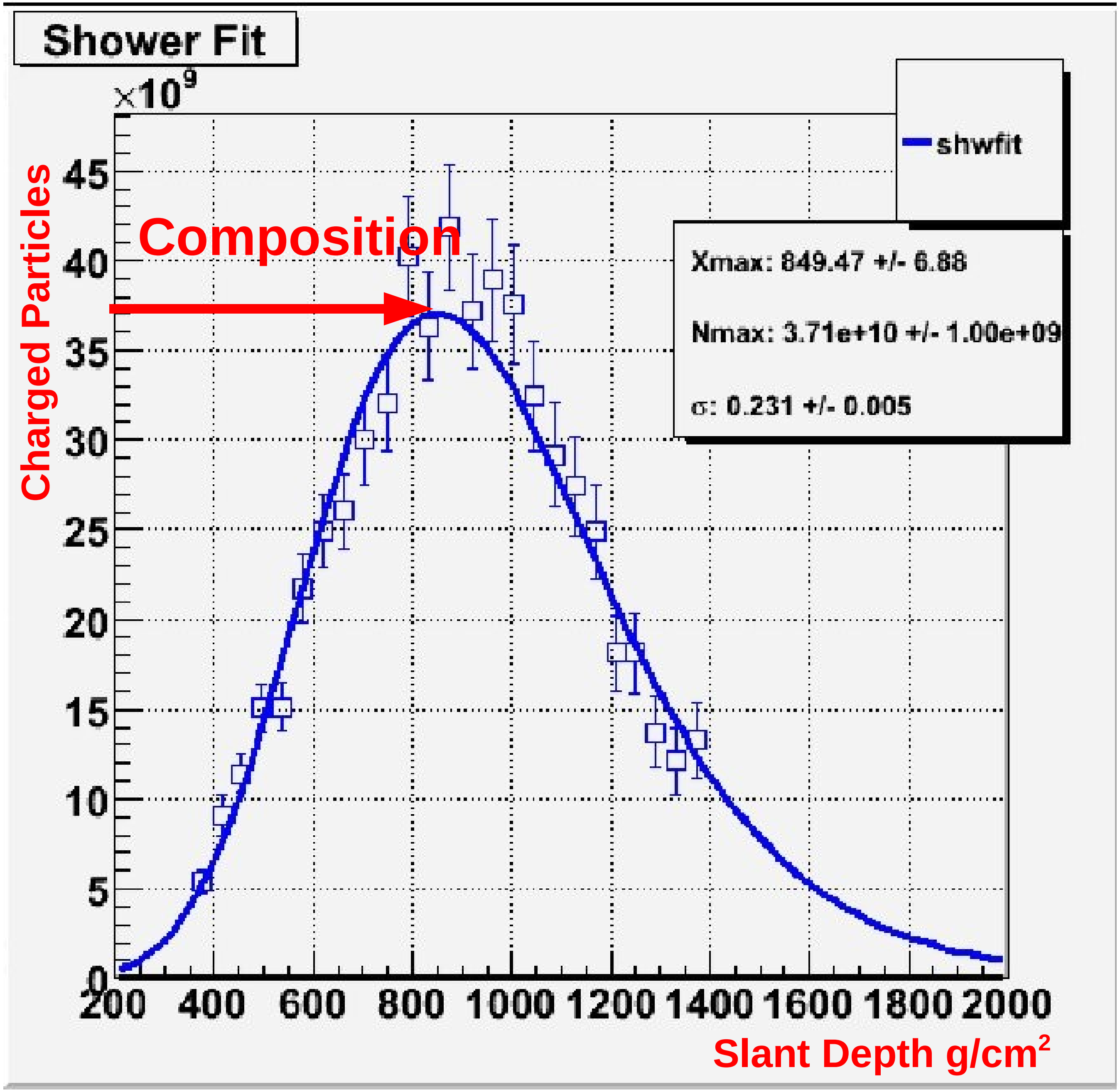

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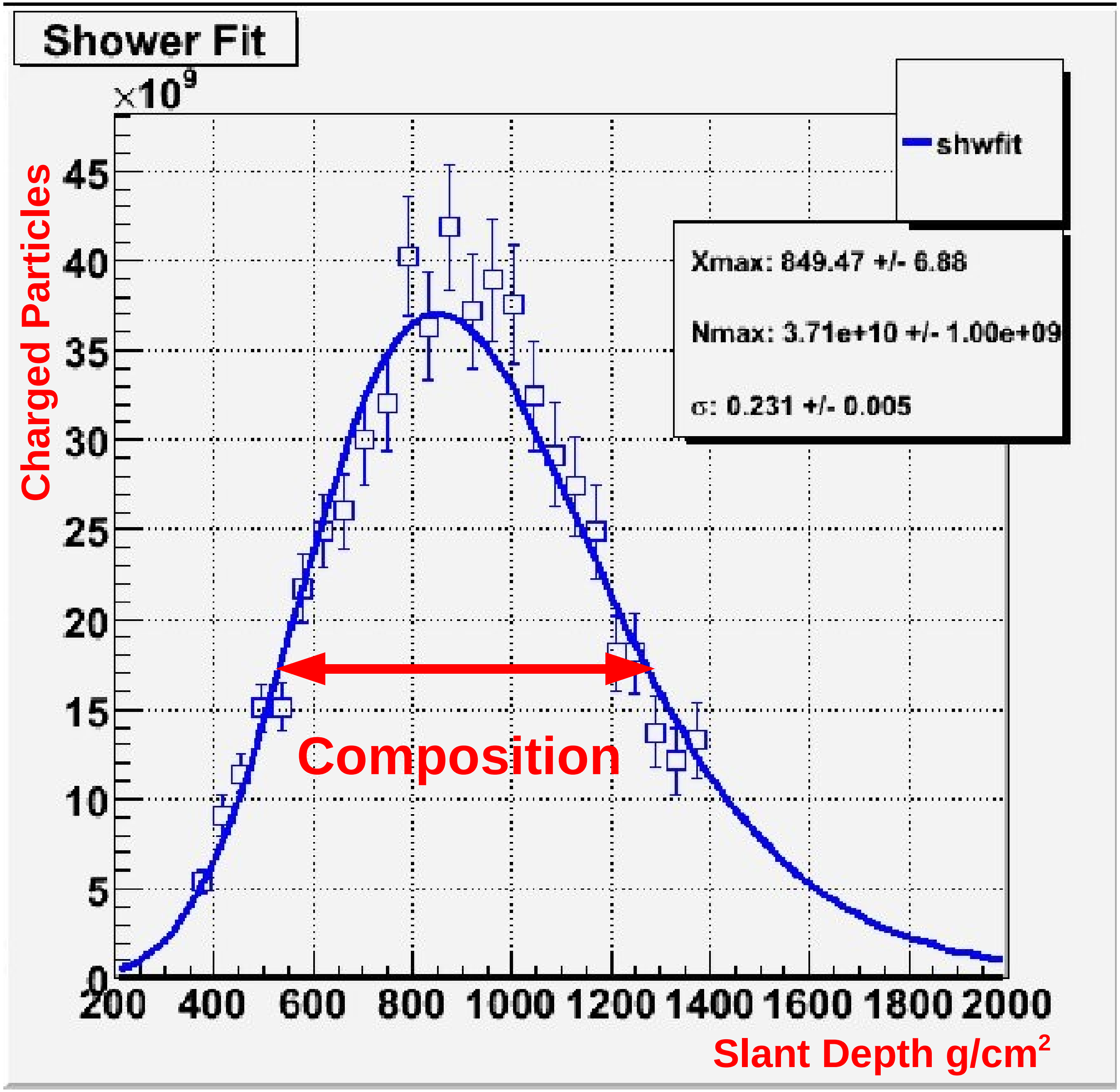
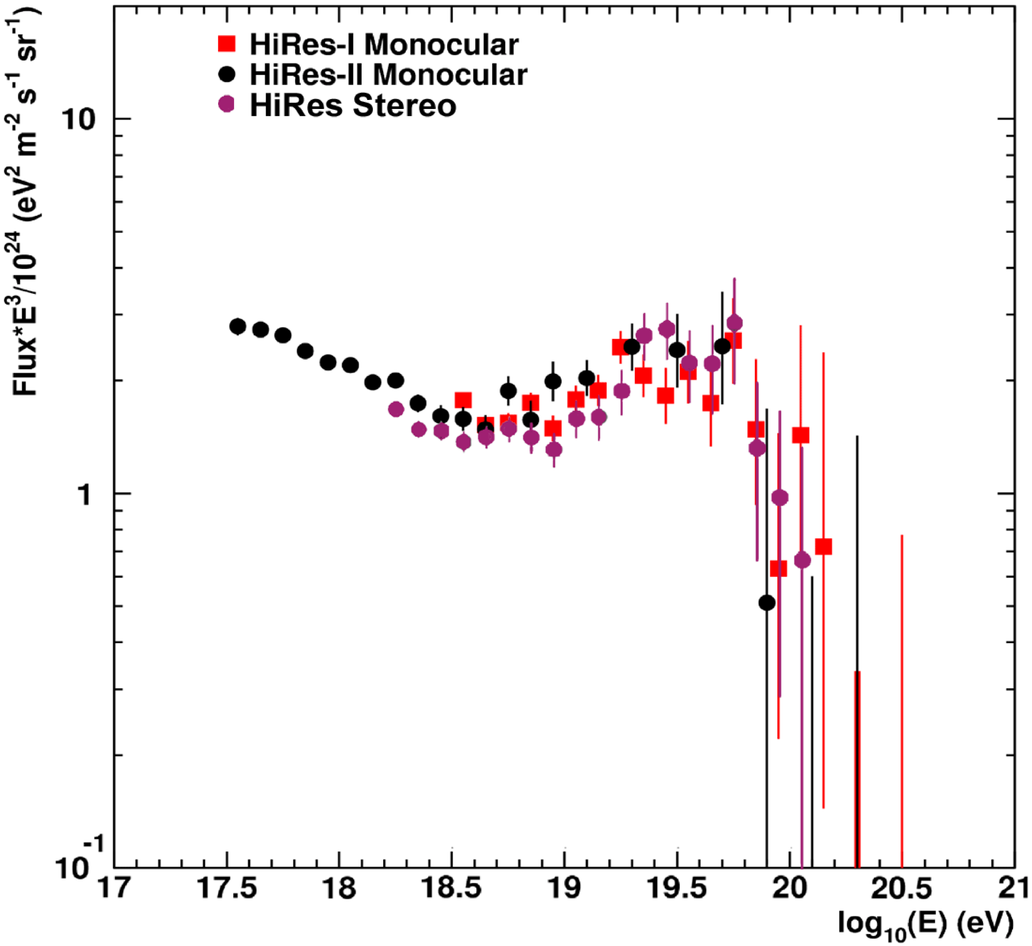


HiRes Energy Spectra



search & discovery

Fluorescence telescopes observe the predicted ultrahigh-energy cutoff of the cosmic-ray spectrum

When a cosmic-ray proton has as much kinetic energy as a well-hit tennis ball, it can create pions and thus lose energy in intergalactic space simply by plowing through the cosmic microwave background.

The flux of ultrahigh-energy cosmic rays is very small, and it falls steeply with increasing energy. From 10^{12} to 10^{19} eV, the flux falls roughly like E^{-3}, where E is the energy of the primary cosmic-ray particle hitting the top of the atmosphere. If the cosmic-ray spectrum continued indefinitely with an E^{-3} falloff, one would see only a few dozen cosmic rays per square kilometer *per century* with energies above 10^{19} eV. That's why observers studying ultrahigh-energy cosmic rays want detection facilities with effective areas of thousands of square kilometers (see the article by Thomas O'Halloran, Pierre Sokolsky, and Shigeru Yoshida in PHYSICS TODAY, January 1998, page 31).

By 10^{19} eV, the cosmic-ray flux is dominated by protons of extragalactic origin. In 1966, not long after the discovery of the cosmic microwave background, Kenneth Greisen at Cornell University pointed out that the CMB should impose a rather abrupt cutoff on the cosmic-ray energy spectrum at about 6×10^{19} eV, even if protons emerge with much higher energies from distant extragalactic sources. Greisen argued that the center-of-mass collision energy of a 6×10^{19}-eV proton hitting a millielectron-volt CMB photon would be just enough to excite the proton to its first excited state—the Δ(1232 MeV) resonance discovered by Enrico Fermi in 1952.

The excited state decays immediately to a nucleon and a pion. So 6×10^{19} eV is, in effect, the threshold energy for pion production by high-energy protons plowing through the ubiquitous CMB. A cosmic-ray proton starting out at higher energy would keep losing energy to pion production until, after 150 million light-years at most, it falls below Greisen's threshold. A source of sufficiently energetic cosmic rays closer to us than that would be exempted from the cutoff. But within our neighborhood, thus delimited, there are few obvious active galactic nuclei of the kind that might be capable of producing 10^{20}-eV protons.

Because much the same argument was made at about the same time by Georgii Zatsepin and Vadim Kuzmin in Moscow, the predicted sharp flux downturn at 6×10^{19} eV is called the GZK cutoff. Observers have now been looking for it for 40 years. Its absence would suggest that there are covert sources of protons above the GZK energy within our neighborhood. The protons might, for example, be local decay products of as-yet unknown exotic particle species that can travel far through the CMB without losing energy. In 2003, the Akeno Giant Air Shower Array (AGASA) collaboration reported that its 100-km^2 ground array in Japan had found 11 events above 10^{20} eV and no evidence of a GZK cutoff in 10 years of exposure.[1] That negative finding provoked much theoretical speculation as to how nonstandard particle physics or astrophysics might trump the predicted cutoff.

After forty years

Now, at long last, the High Resolution Fly's Eye (HiRes) collaboration writes that "forty years after its initial prediction, the HiRes experiment has observed the GZK cutoff."[2] The HiRes facility is a pair of atmospheric-fluorescence telescopes (HiRes-1 and HiRes-2) on hilltops 12 miles apart at the US Air Force's Dugway Proving Ground in Utah. It was built under the leadership of Sokolsky and his University of Utah colleague Eugene Loh. Except for a seven-month hiatus when civilians were barred from the proving ground after the 11 September 2001 attacks, HiRes has been recording showers generated by cosmic-ray primaries with energies above 10^{17} eV since 1997.

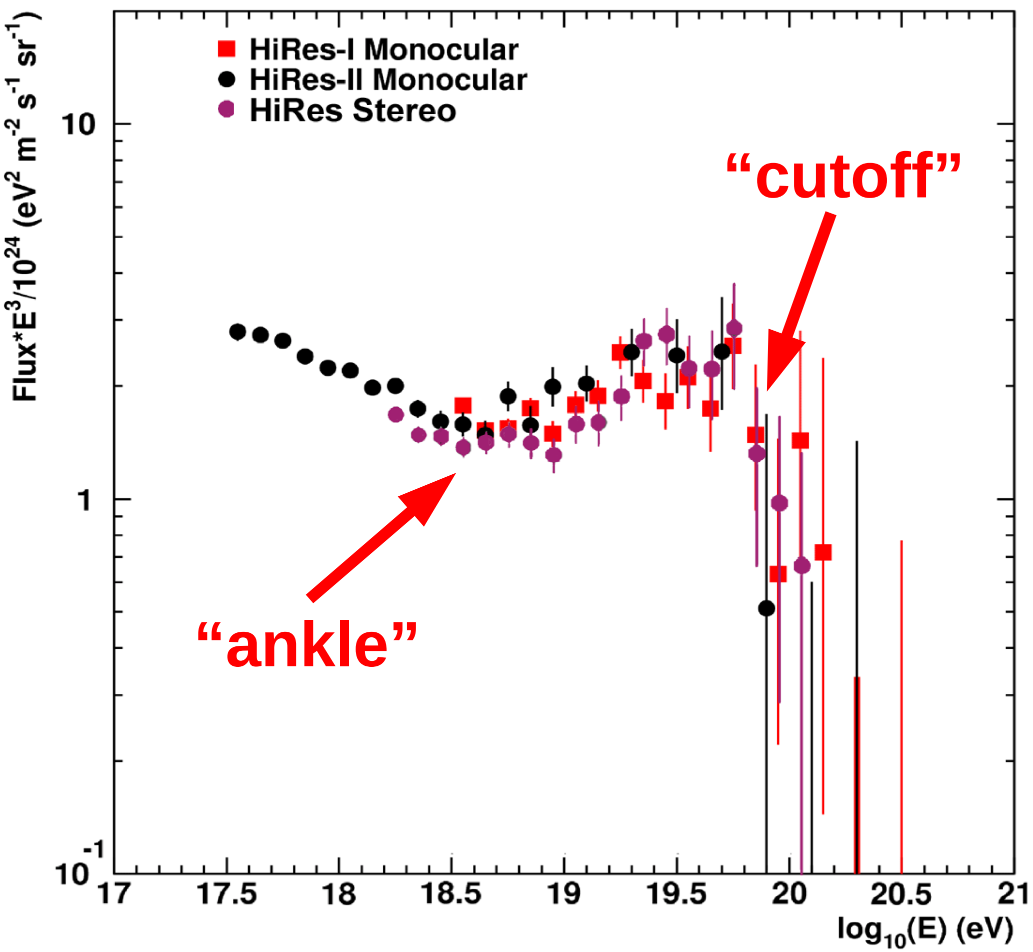
Figure 1. Two mirror modules of the HiRes-2 fluorescence telescope in Utah's high desert. HiRes-2 has 42 such 4-m^2 mirrors, each focusing a different patch of sky onto its own imaging array of 256 fast photomultiplier tubes (seen here from behind) sensitive to UV fluorescence from nitrogen excited in the air showers generated by ultrahigh-energy cosmic rays. HiRes-2 and its nearby smaller companion HiRes-1 record such showers propagating across the sky, making it possible to estimate the energy of the initiating cosmic-ray particle.

Monocular: *PRL* **100** (2008)
Stereo: *Astropart. Phys.* **32** (2010)

May 2007 *Physics Today*

(ankle, cutoff confirmed by Auger observatory, *PRL* **101** (2008))

HiRes Energy Spectra



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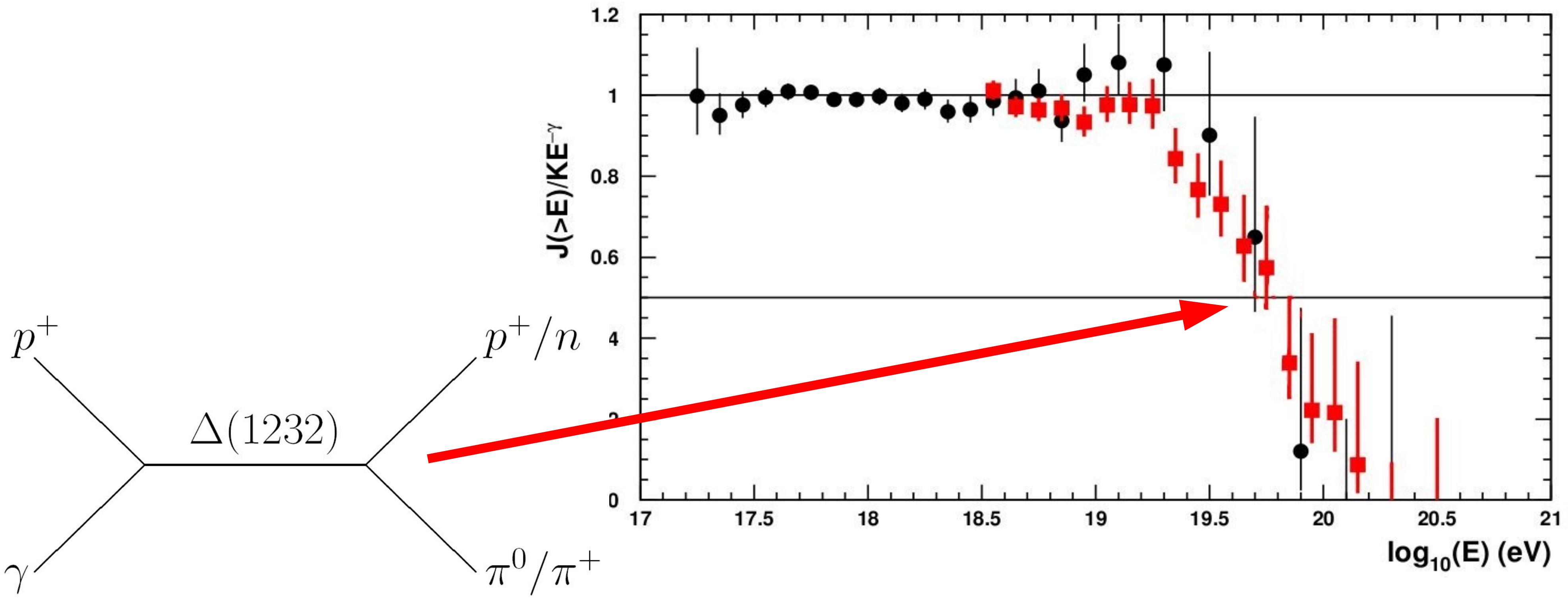
Spectrum: Implications for Composition

- 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”

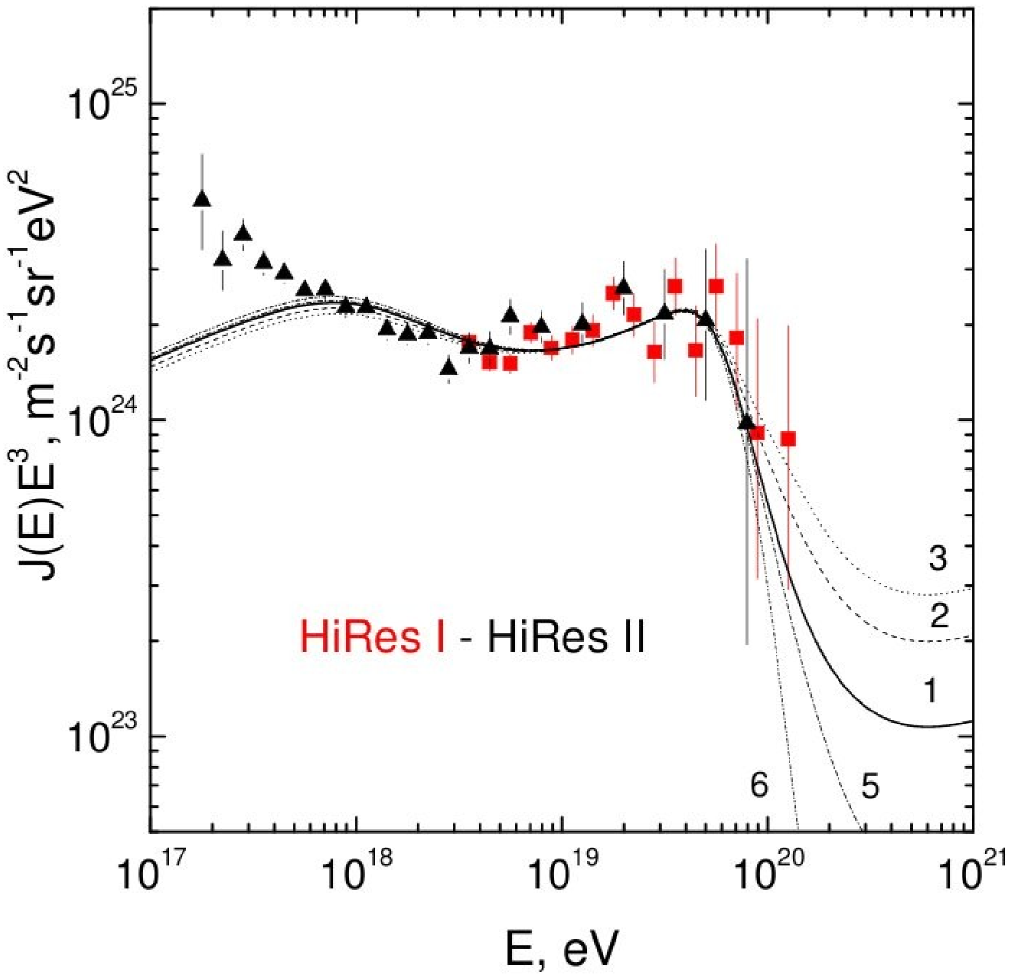
Energy of Cutoff

- 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



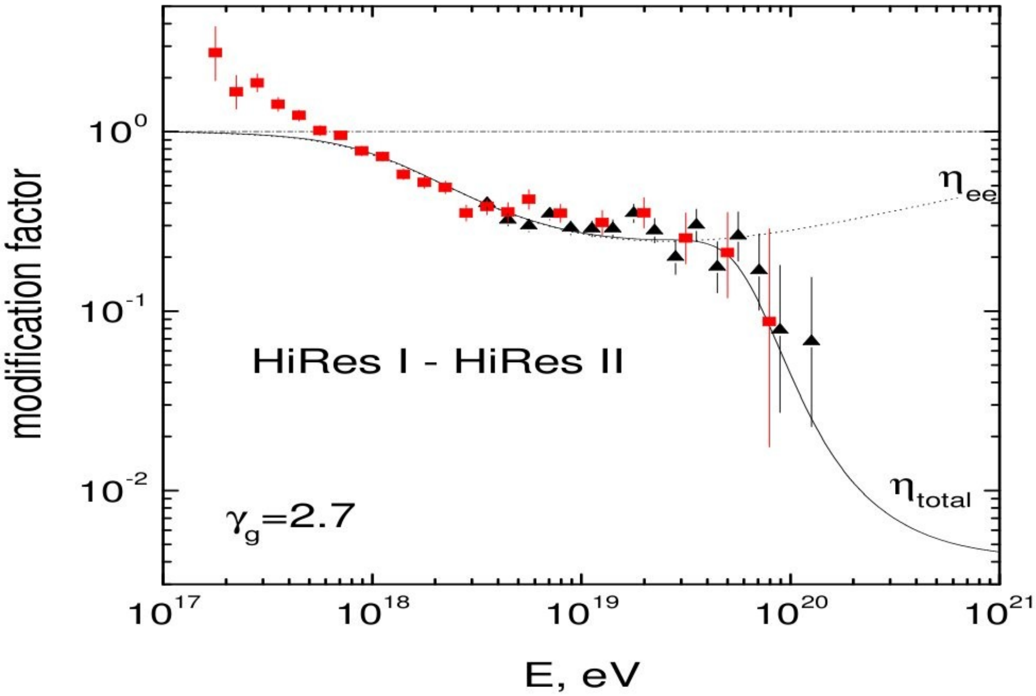
Shape of Spectrum above Cutoff

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



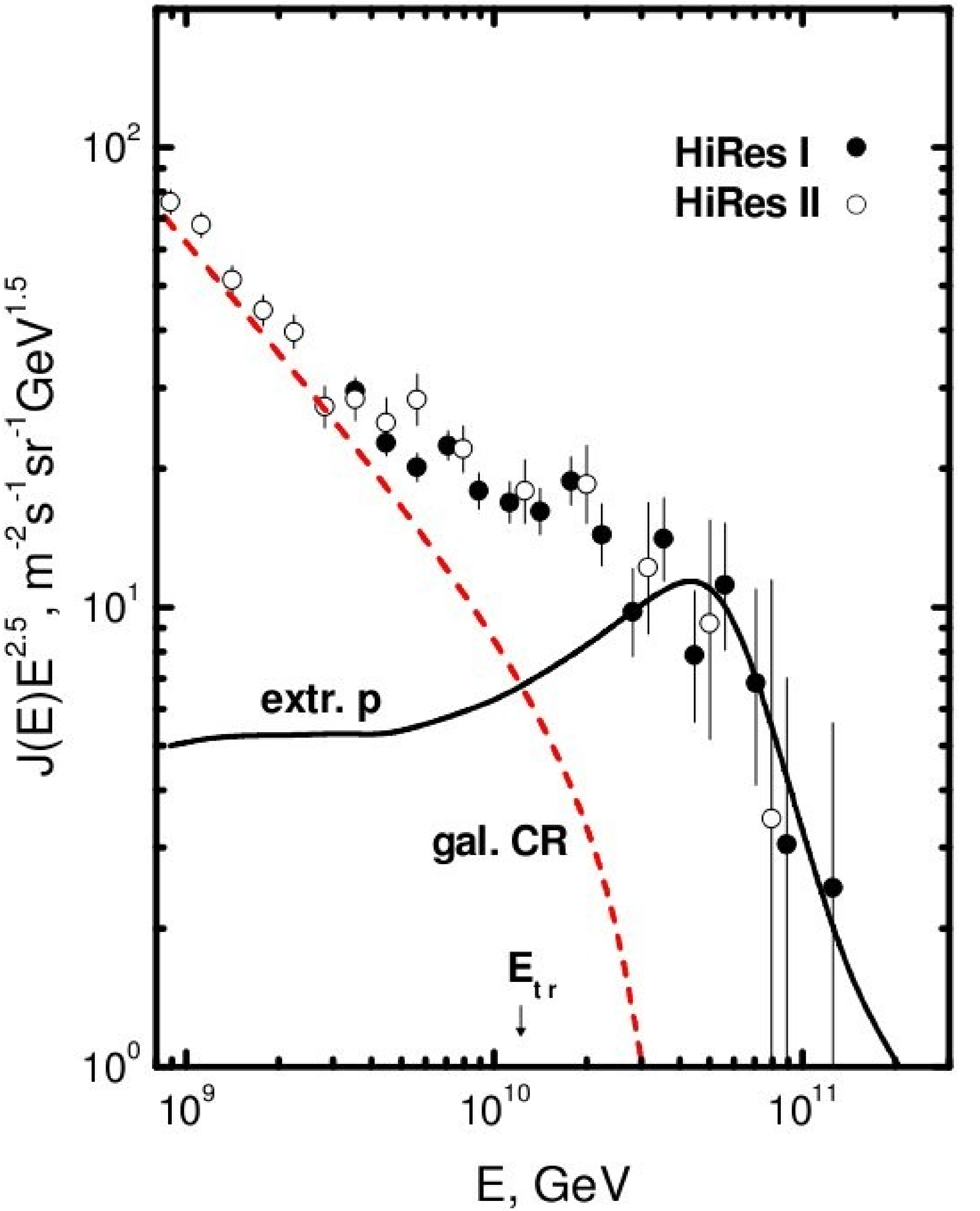
Pair Production "Dip"

- 2nd 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...)



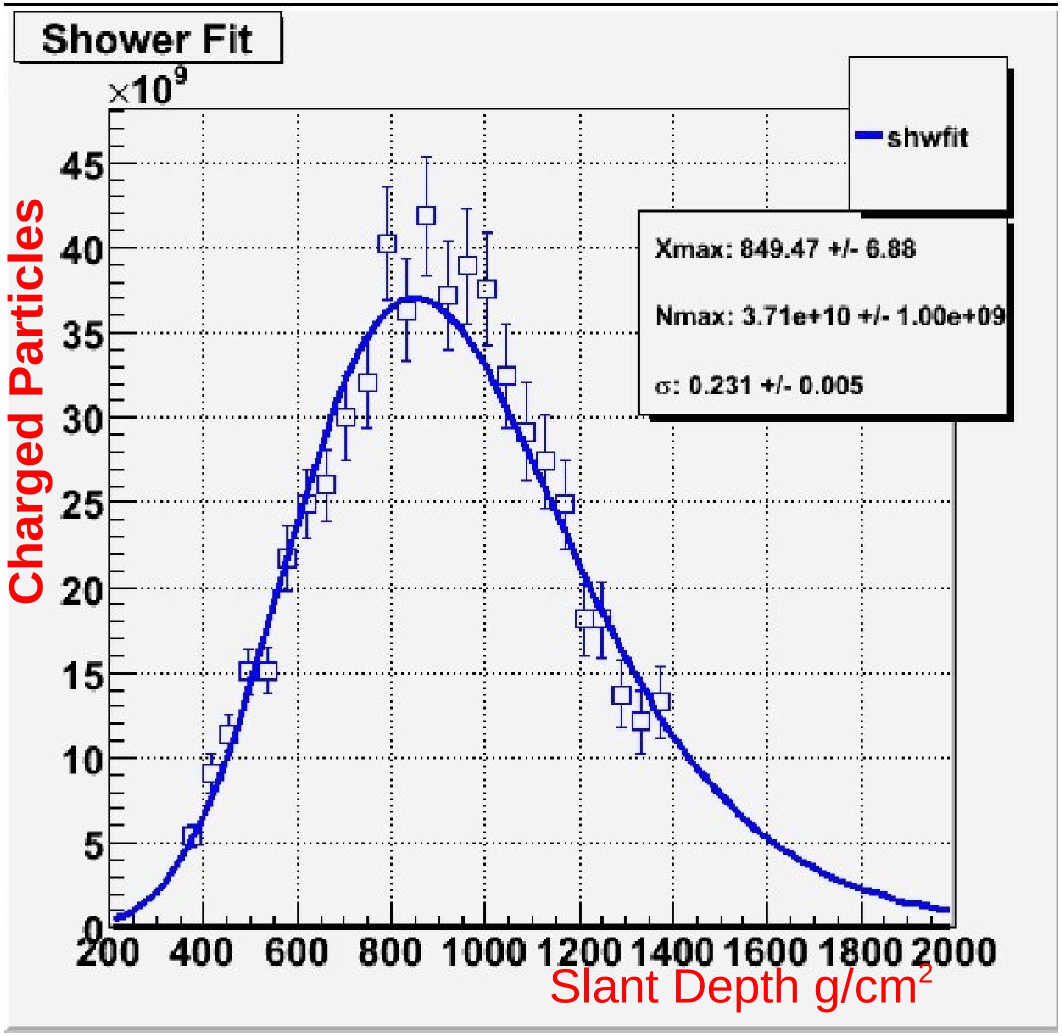
Alternatives

- 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:

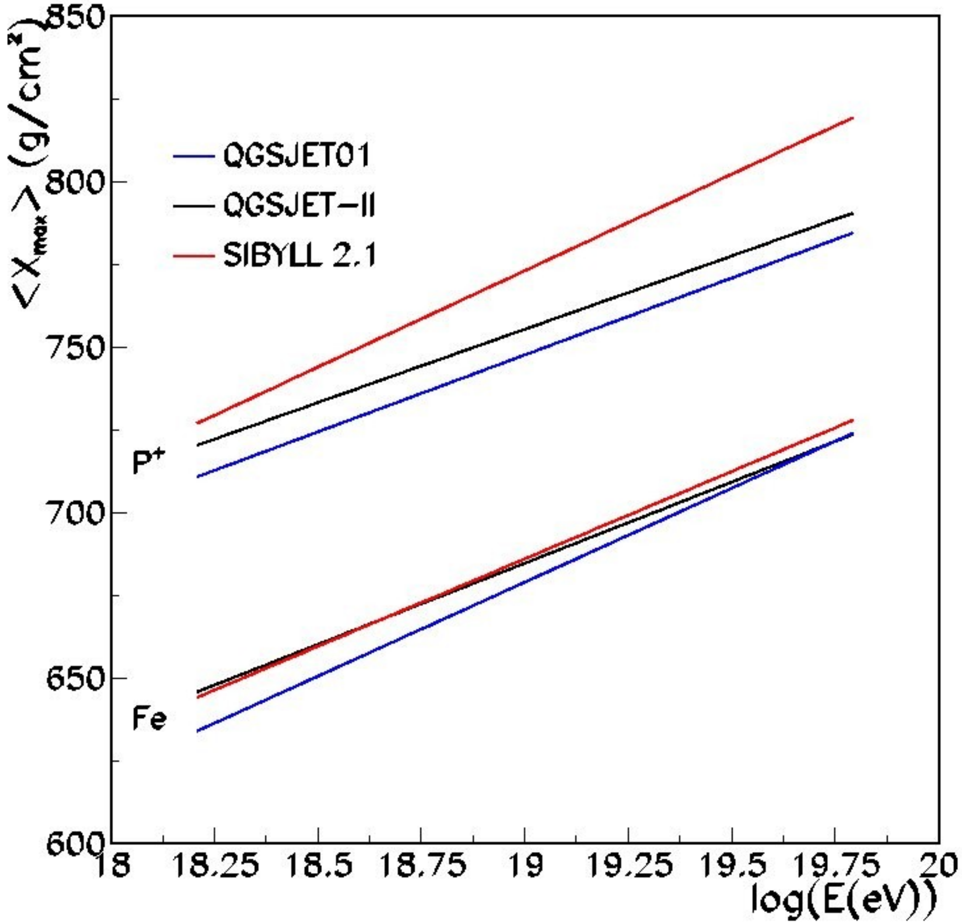
$$\Lambda_A = \frac{d <X_{max}>}{d \log E} \approx \lambda_r \left(2.3 - \frac{d \ln A}{d \log E}\right)$$

Width of X_{max} Distribution (Superposition):

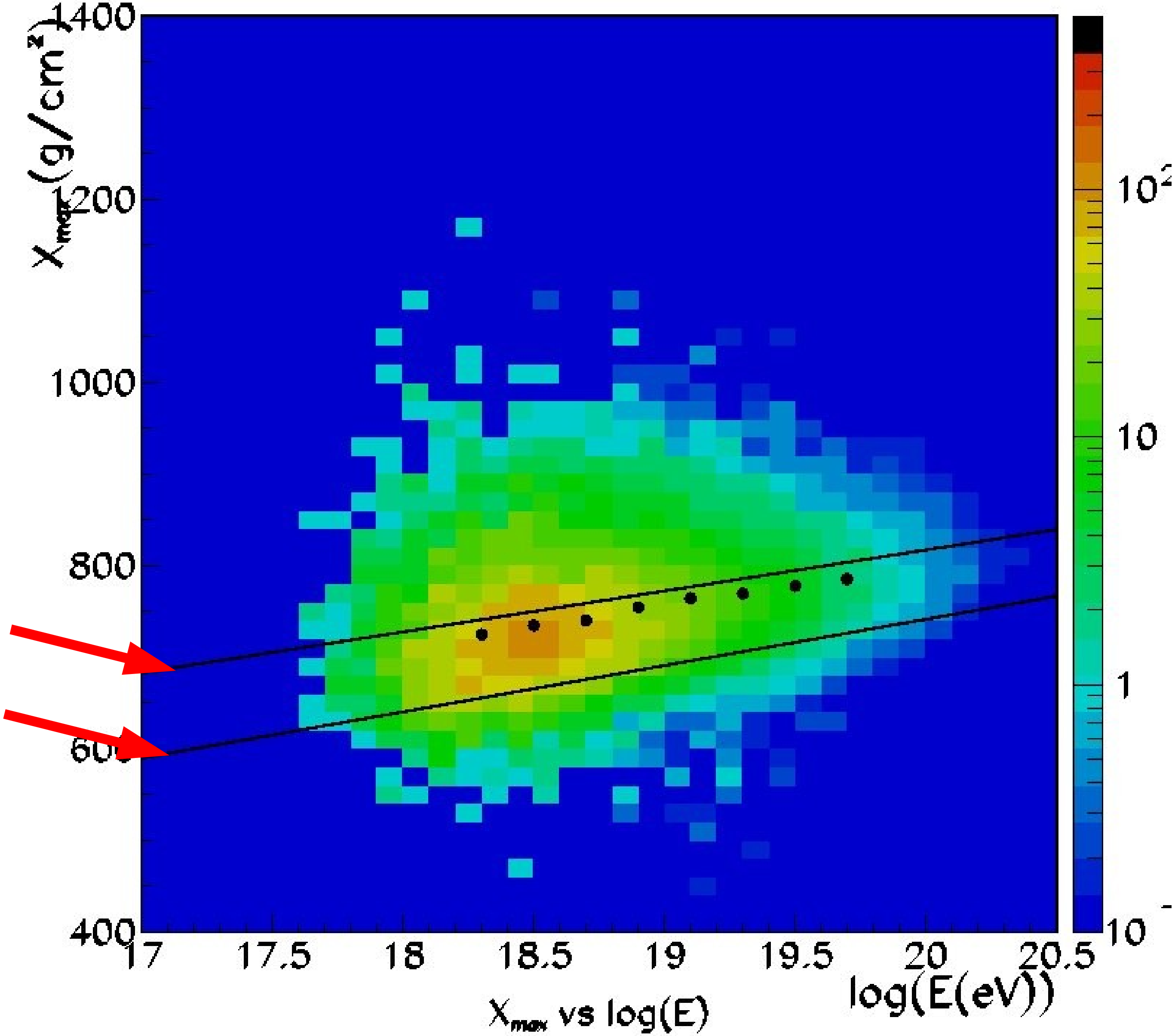
$$\sigma_x(A) \sim \frac{\sigma_x(P^+)}{\sqrt{A}}$$

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



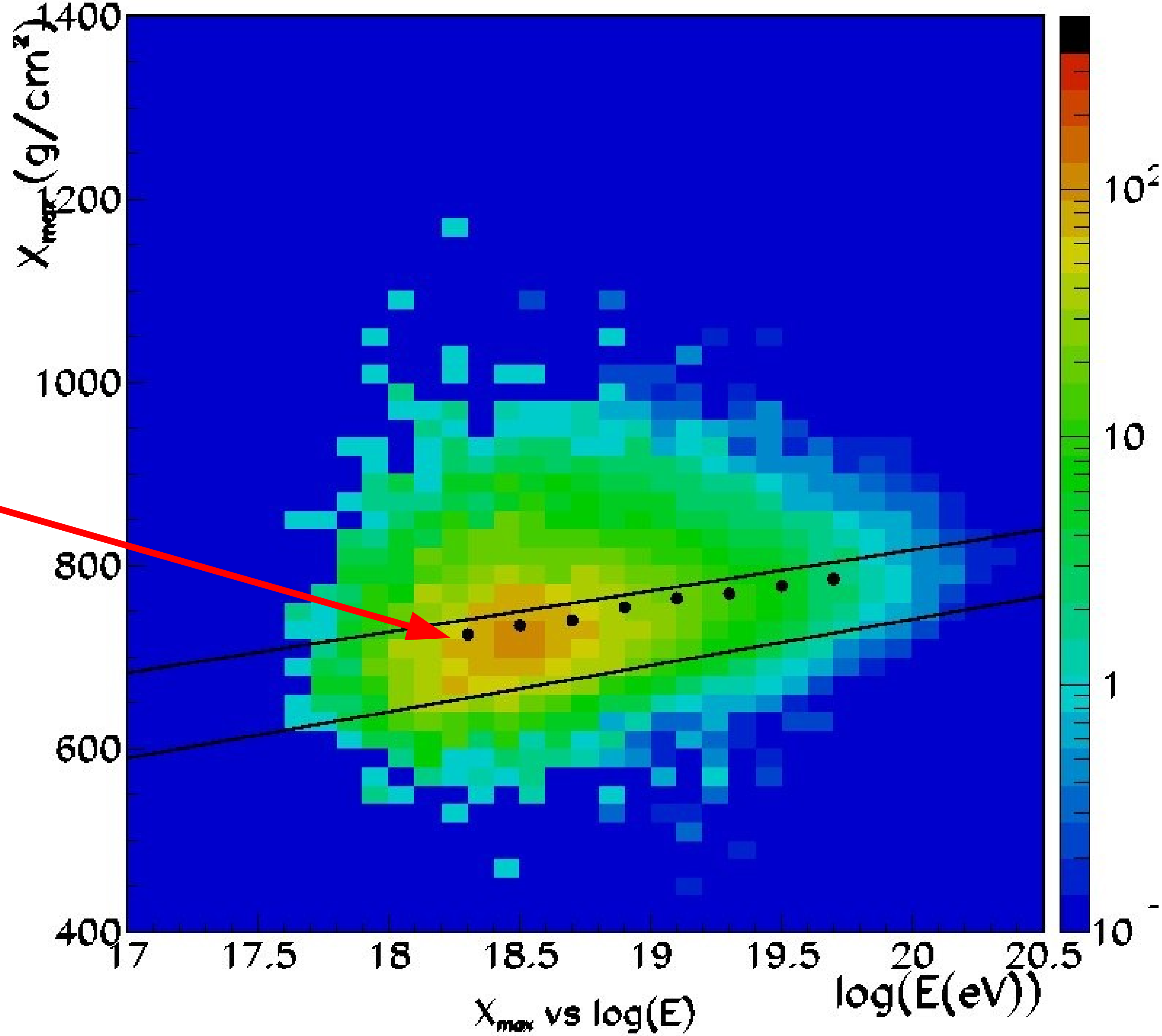
Predictions for mean *X_{max}*, before detector effects.

P+

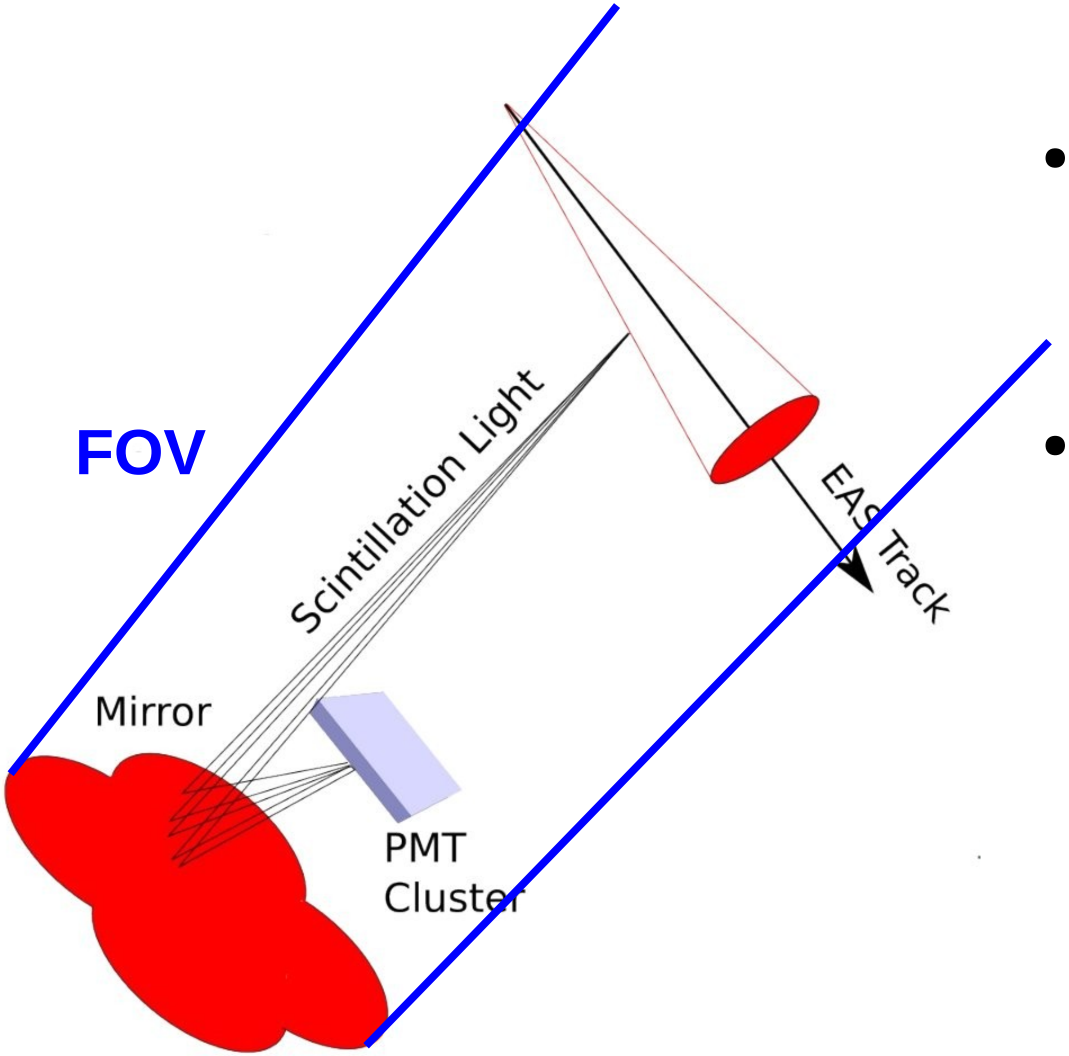
Fe

X_{max} vs Energy, QGSJET-II Protons

Proton mean Xmax after detector effects (Note acceptance bias)



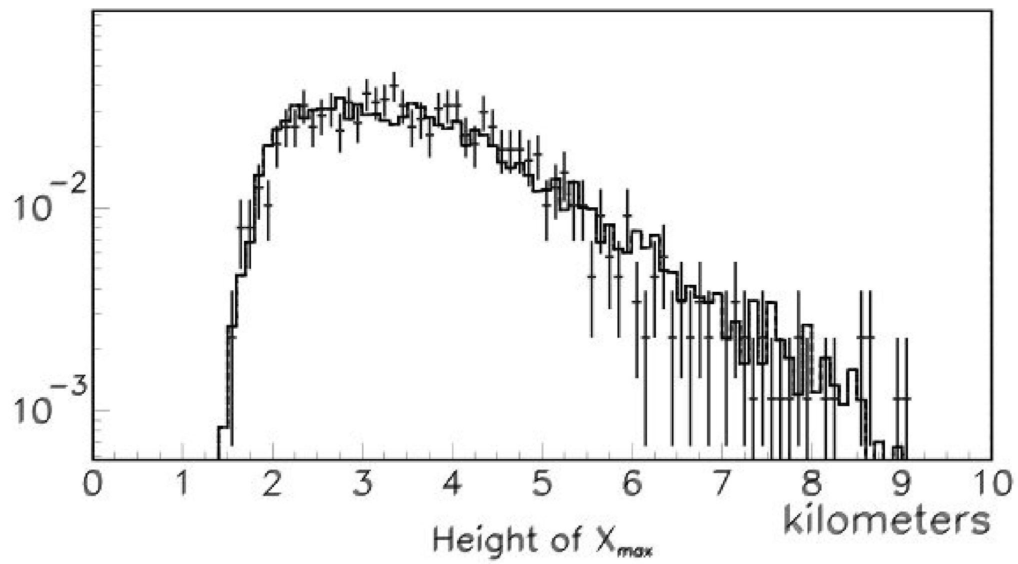
Biasing Effect: Optical Aperture



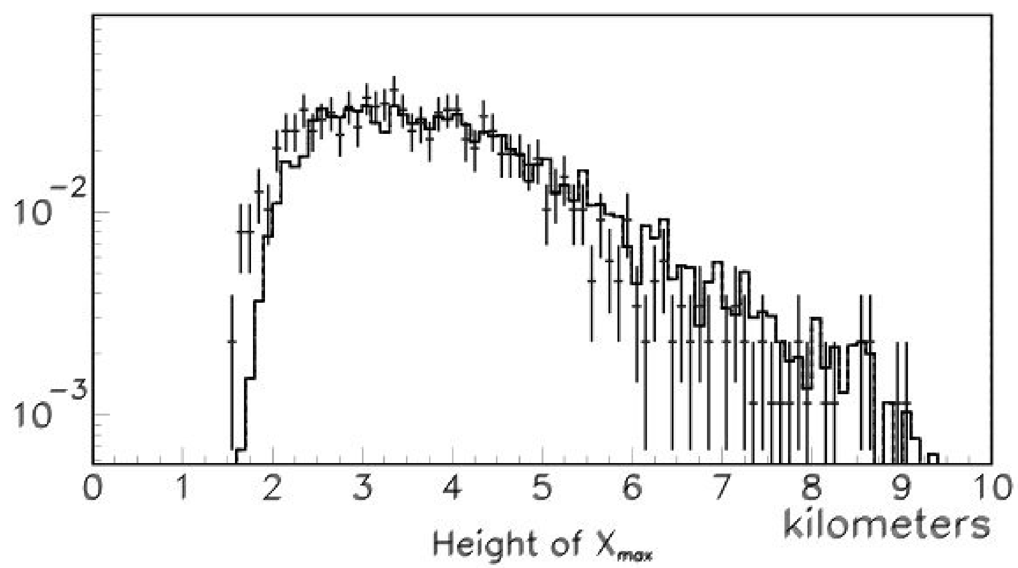
- Are upper and lower limitations on field of view (FOV) well understood?
- If not, relative to MC
  - Can shift mean X_{max} by cutting low or high tails
  - Can make X_{max} distribution appear artificially narrow or wide

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

Protons



Iron



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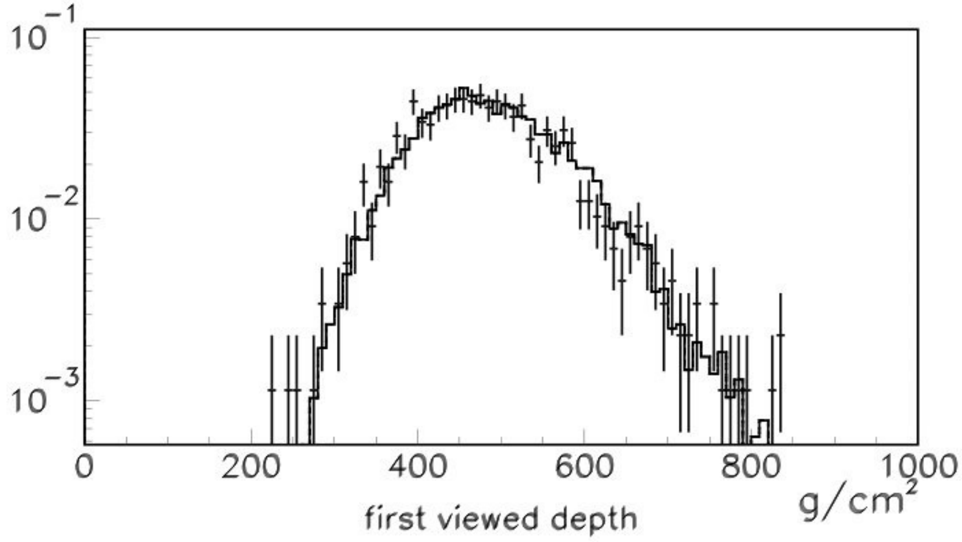
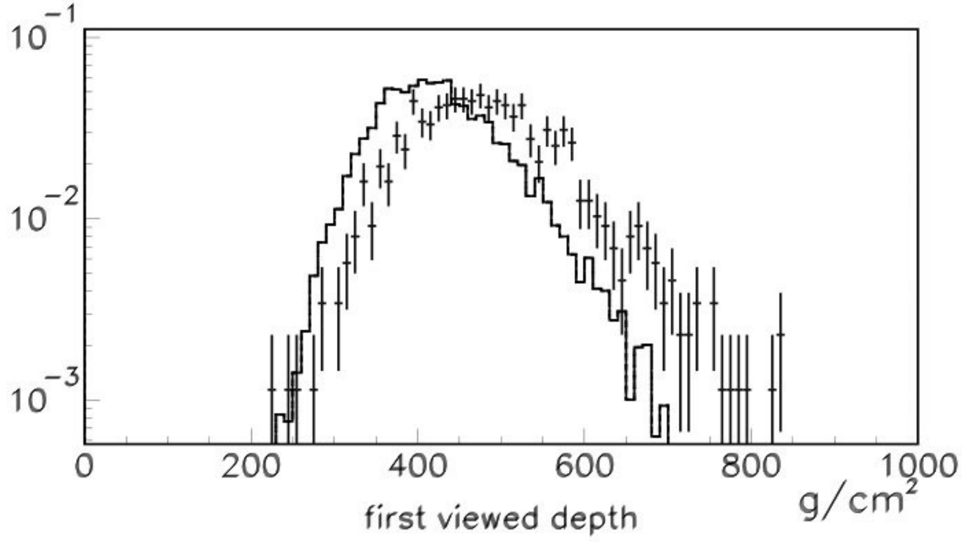


Iron



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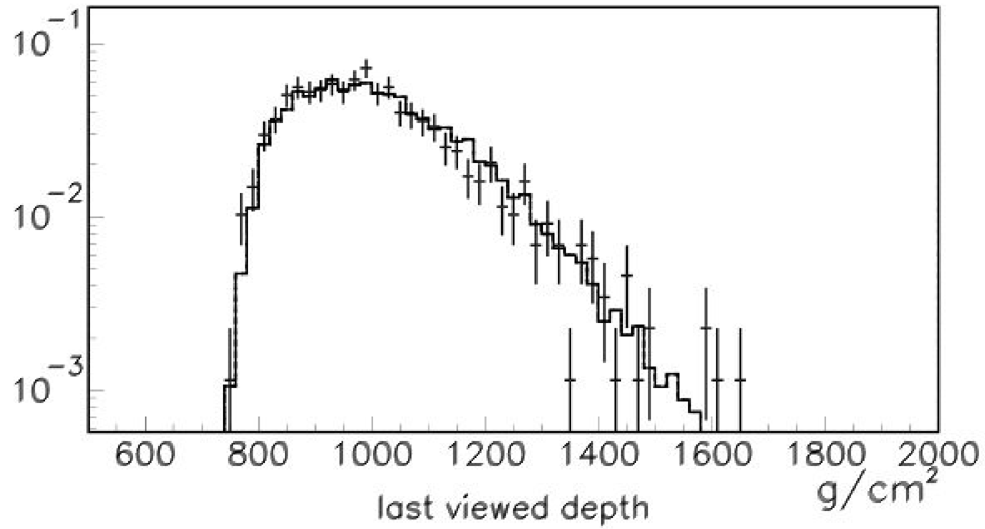

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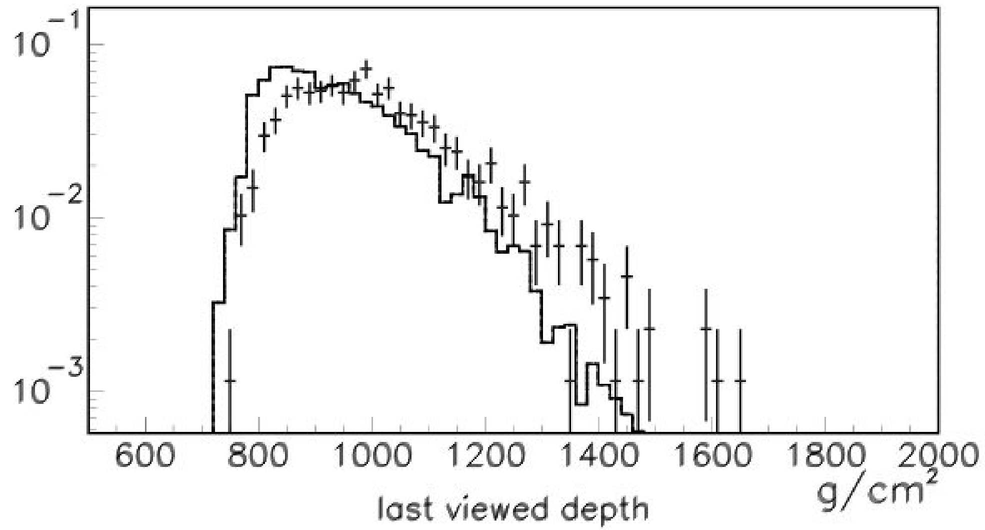

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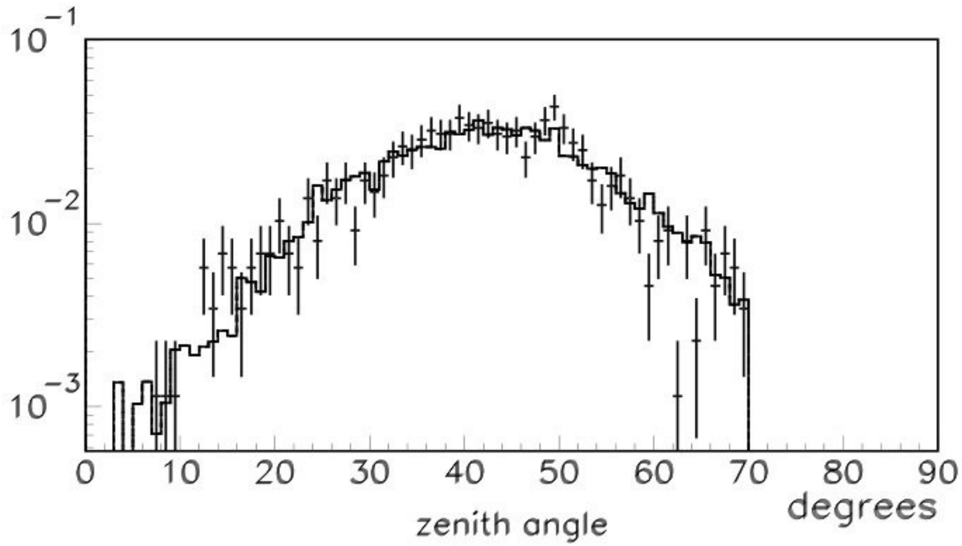
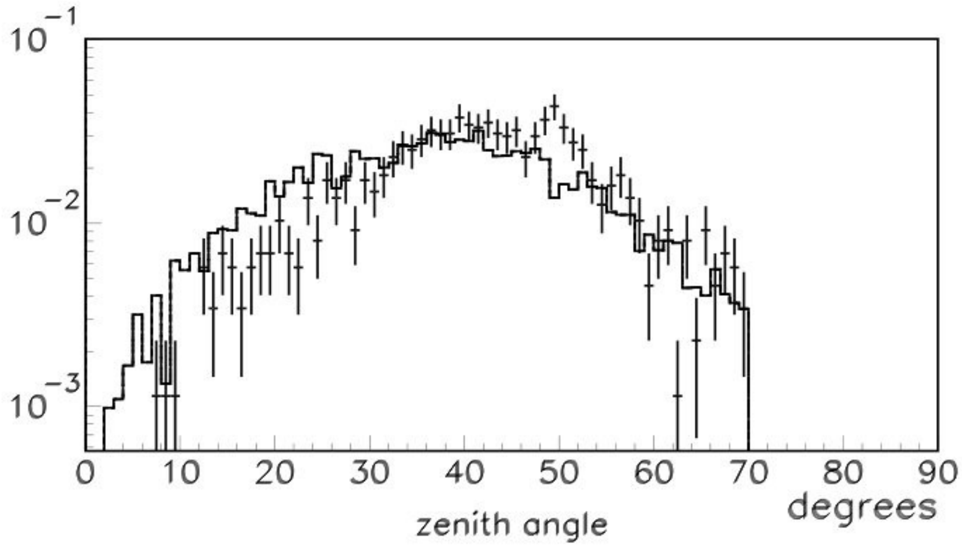
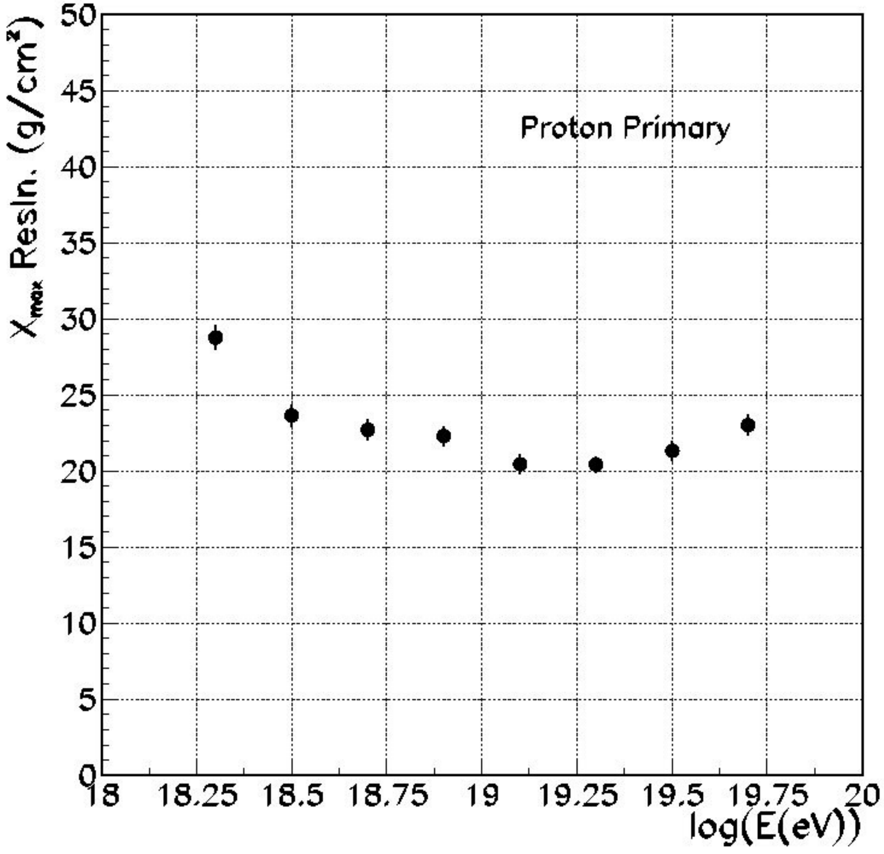


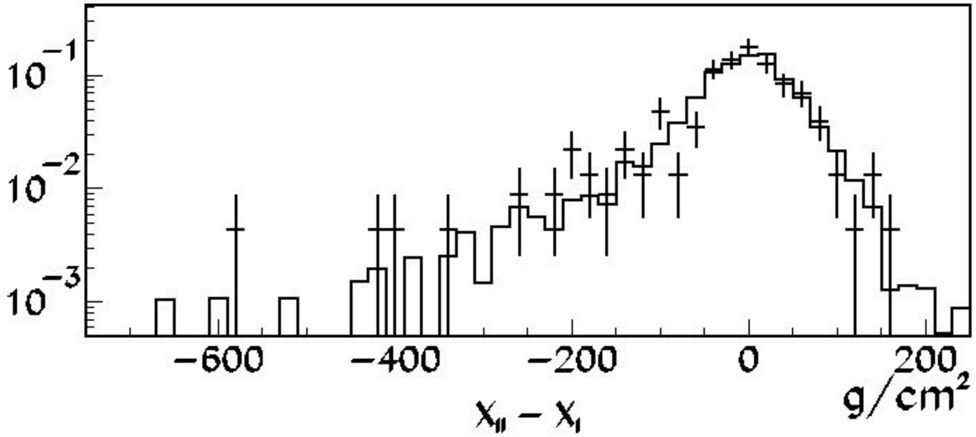
Iron



Check of X_{max} Resolution



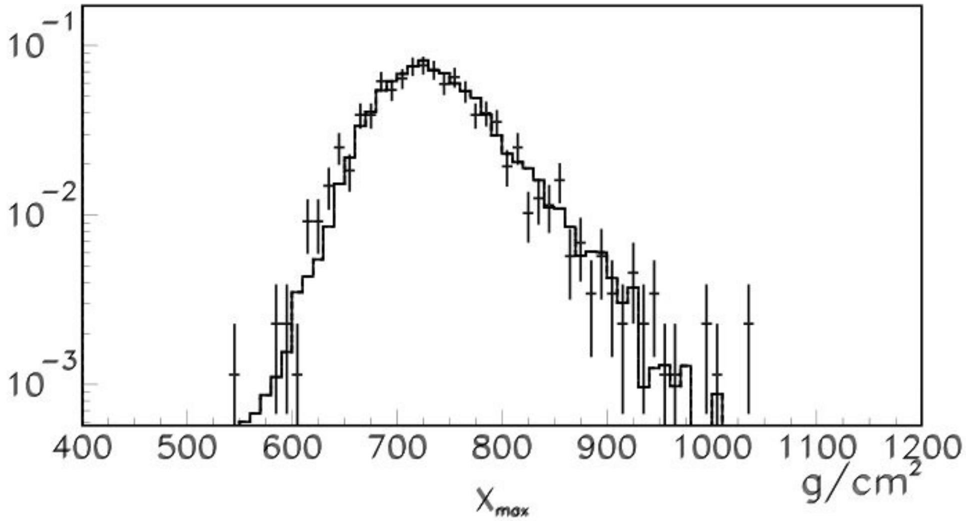
Compare X_{max} as measured by HiRes-I and HiRes-II



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

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

Protons



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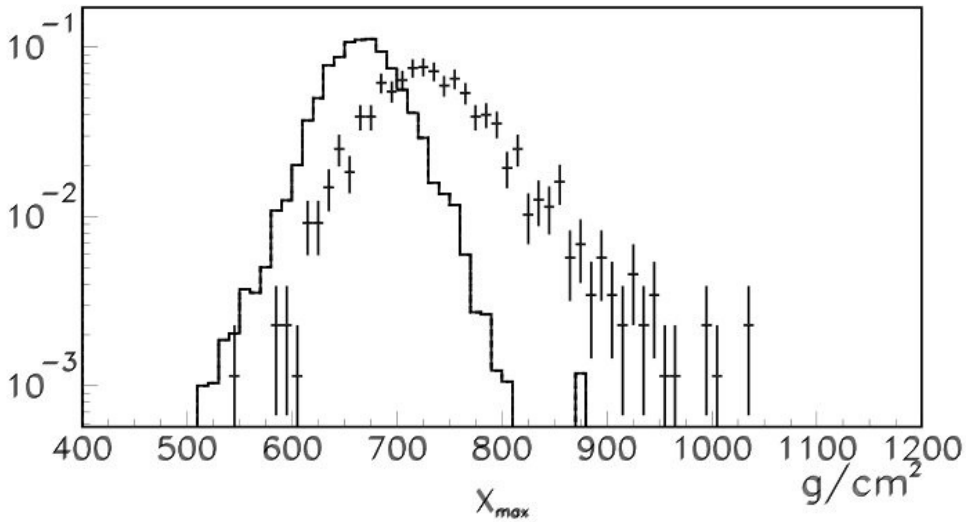
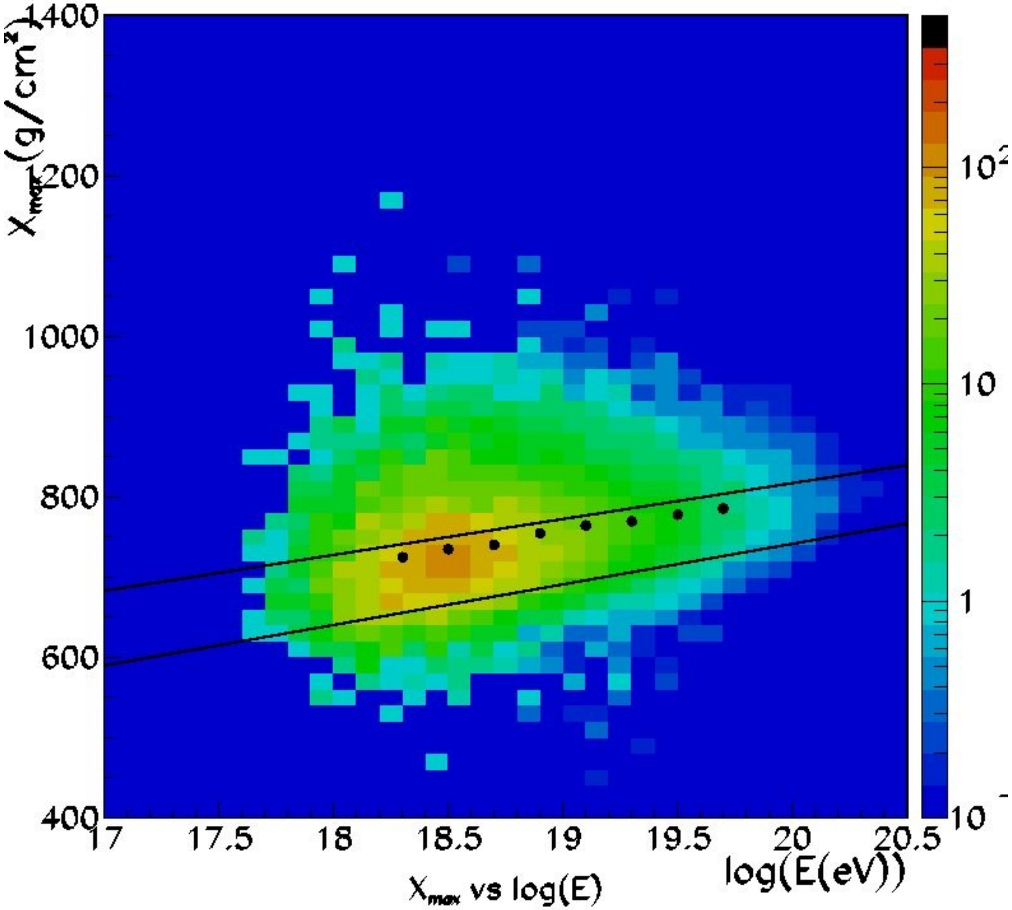
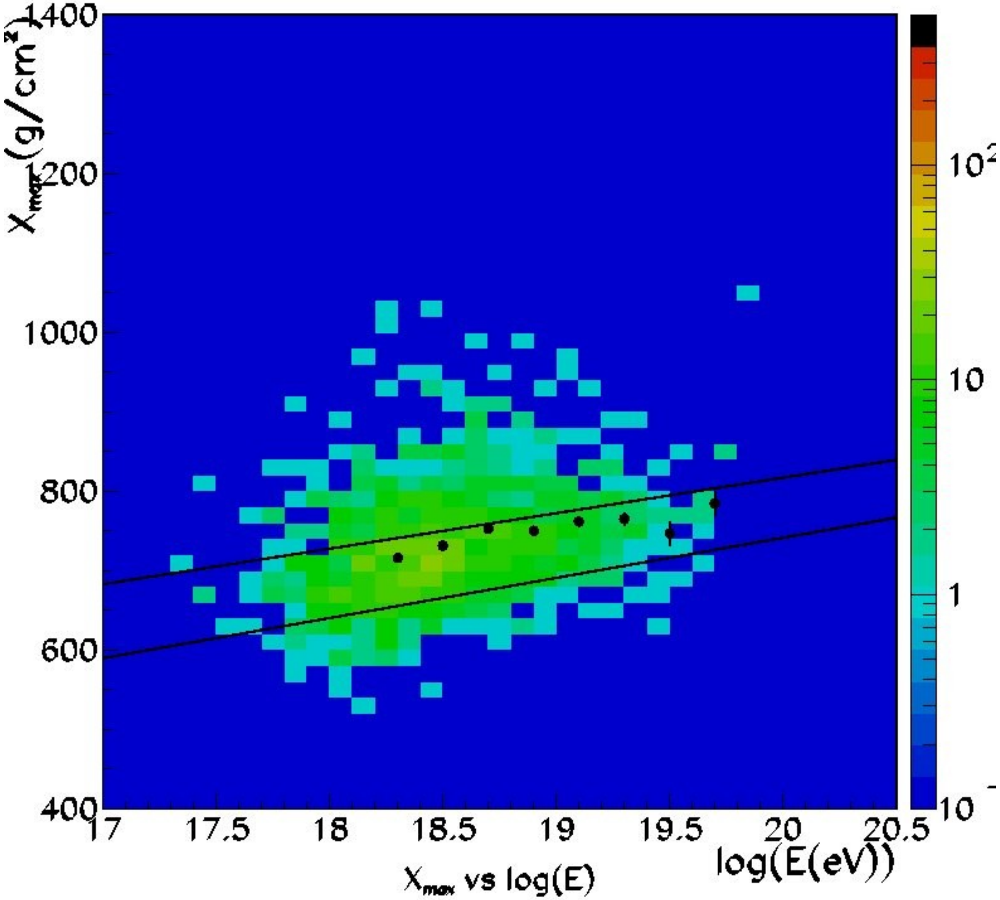


X_{max} vs Energy, HiRes Stereo Data



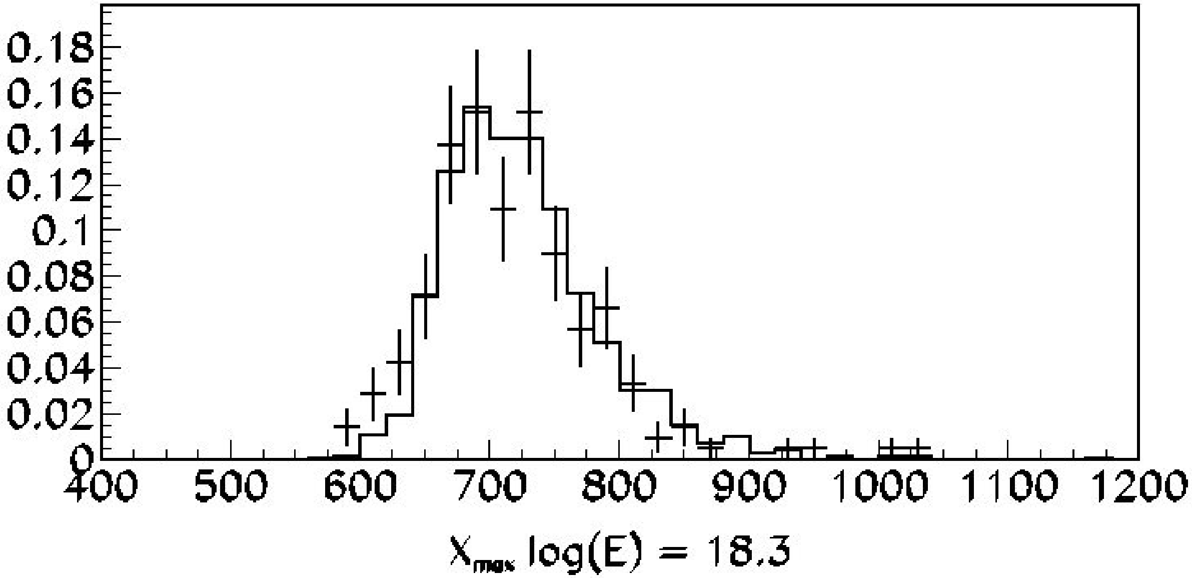
QGSJET-II Protons



HiRes Stereo Data

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

Protons



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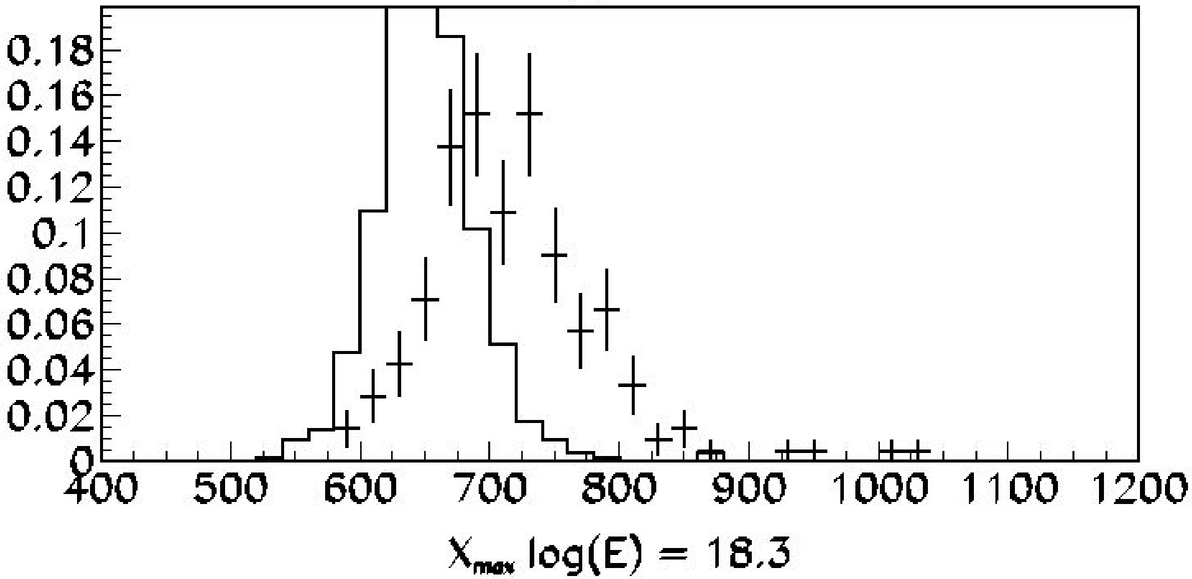
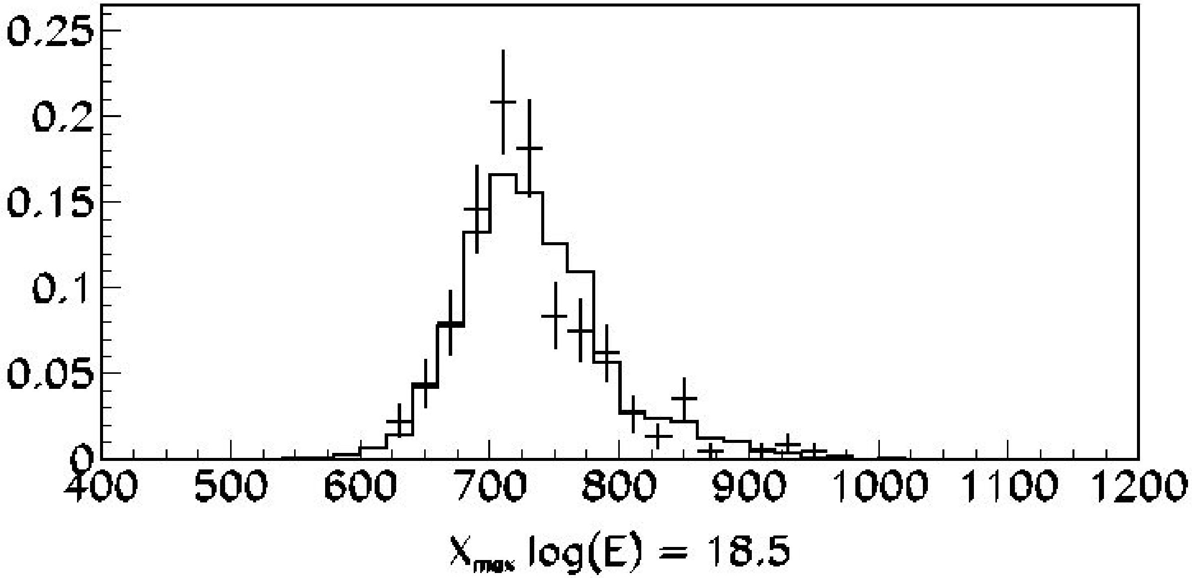
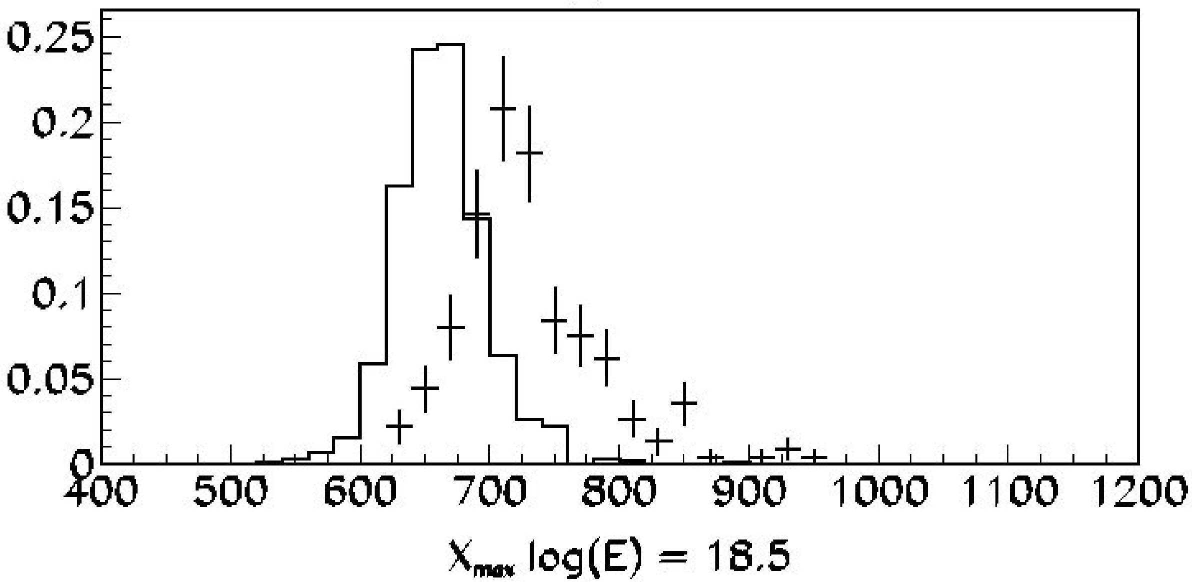


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

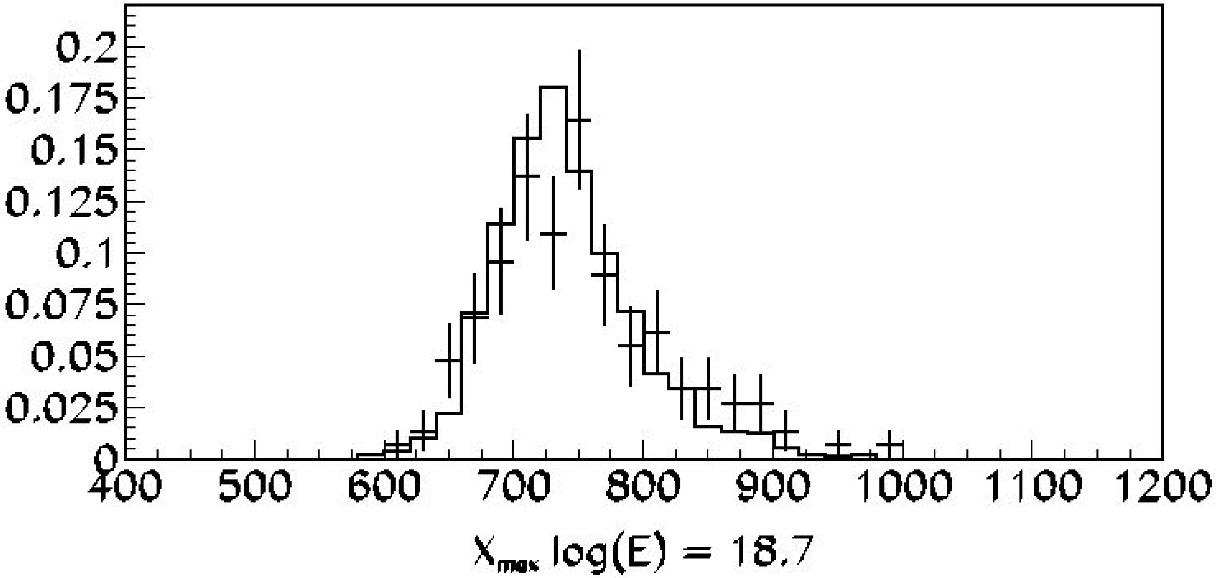


Iron

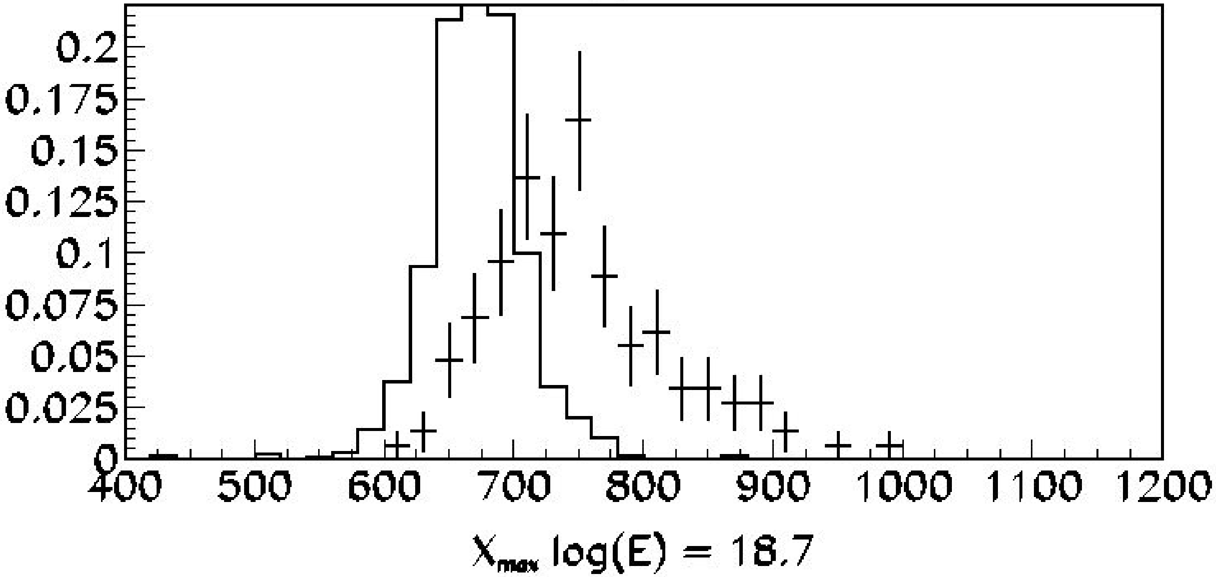


Data (points) versus QGSJET-II MC, in Energy Bins

Protons



Iron



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

Protons

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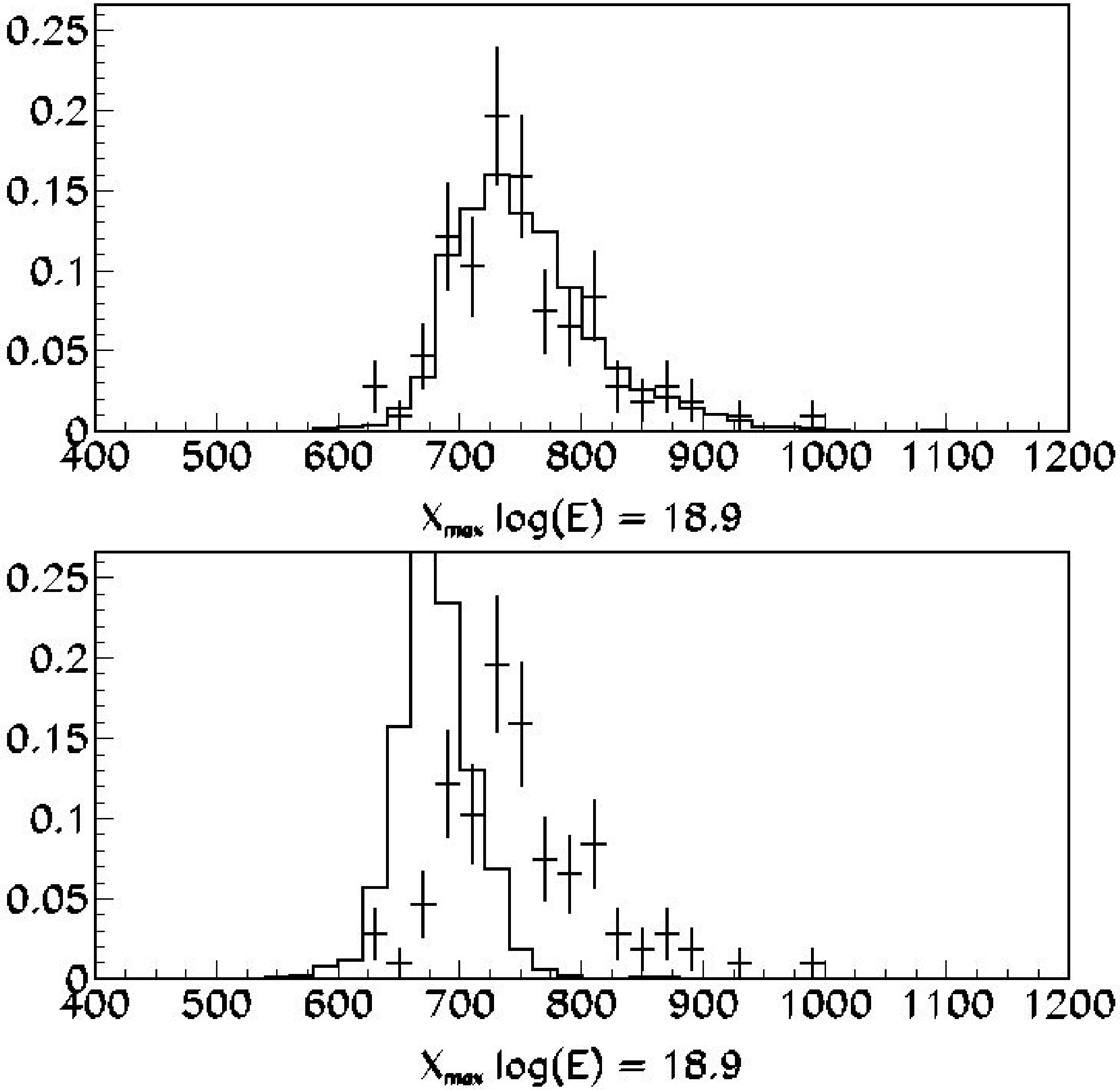
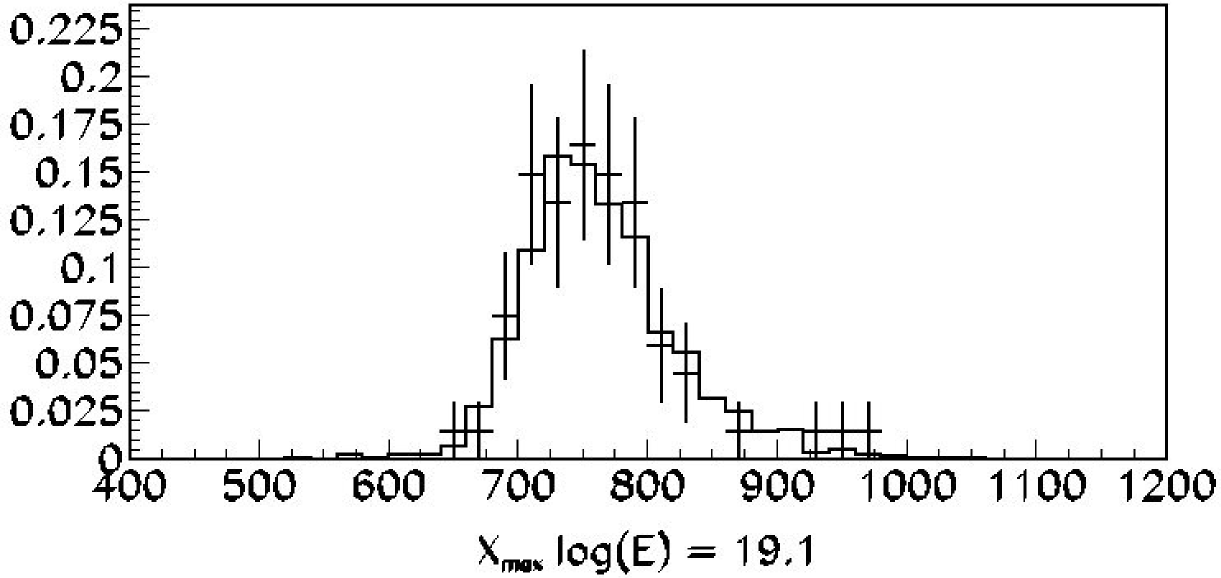


Data (points) versus QGSJET-II MC, in Energy Bins

Protons



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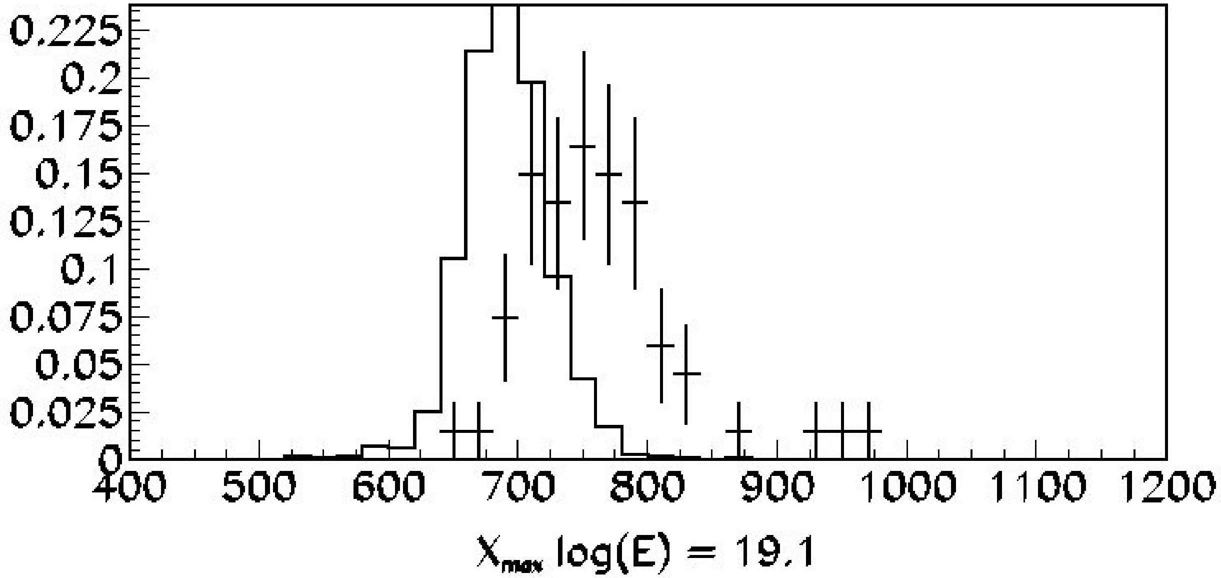
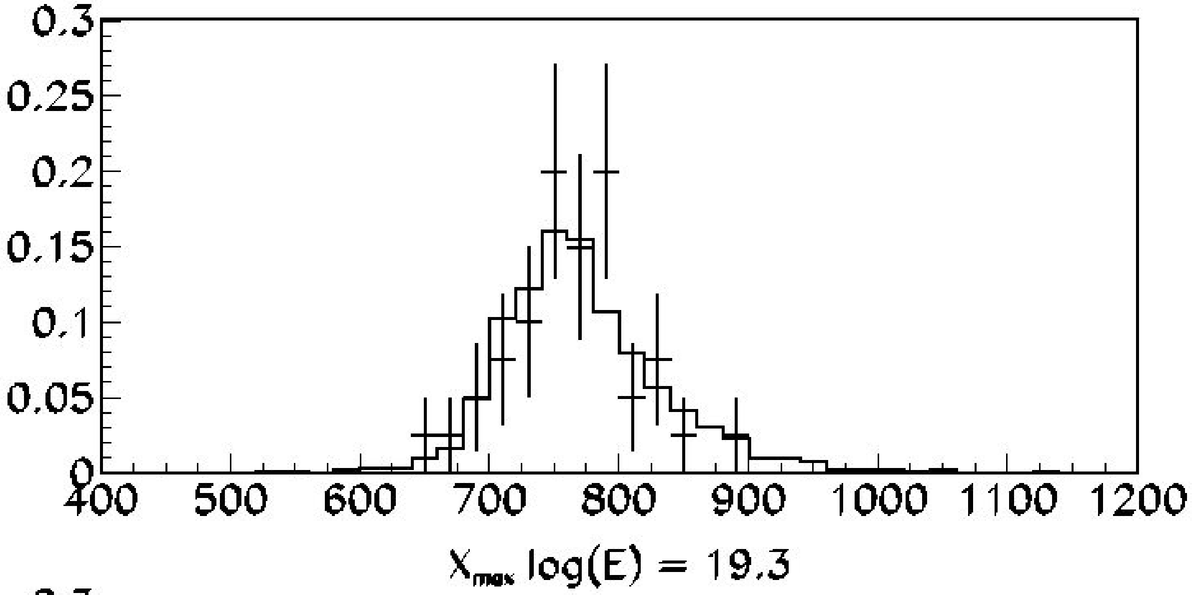


Data (points) versus QGSJET-II MC, in Energy Bins

Protons



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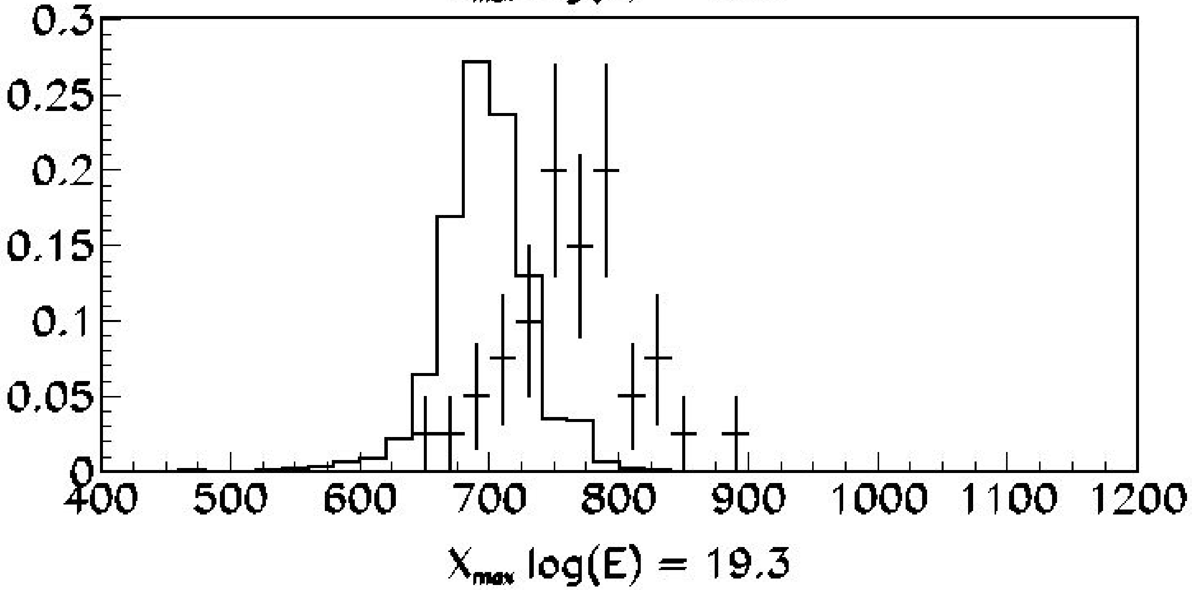
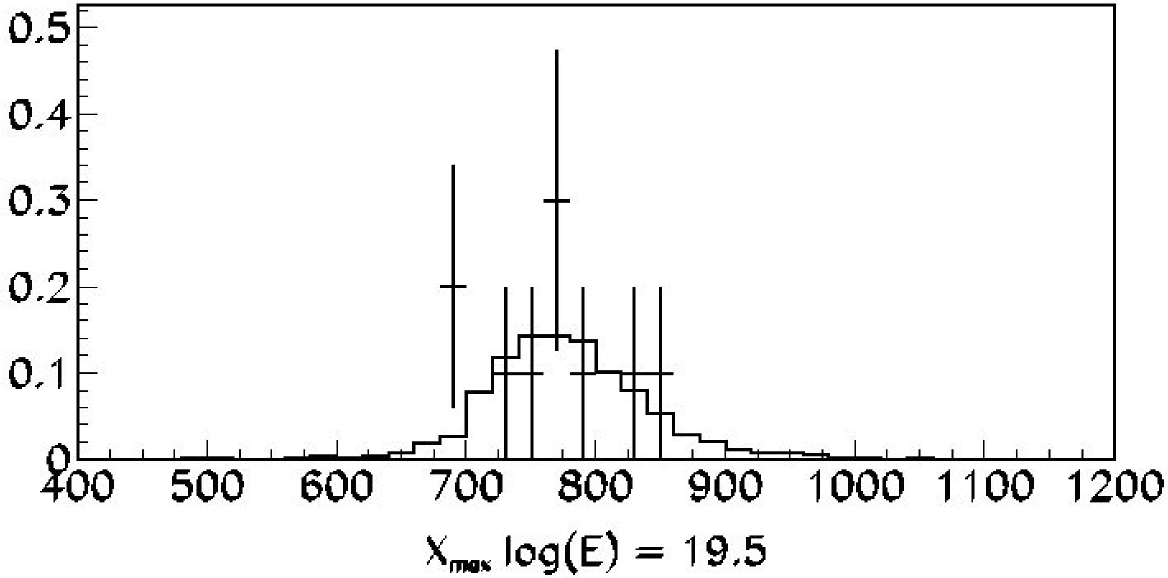
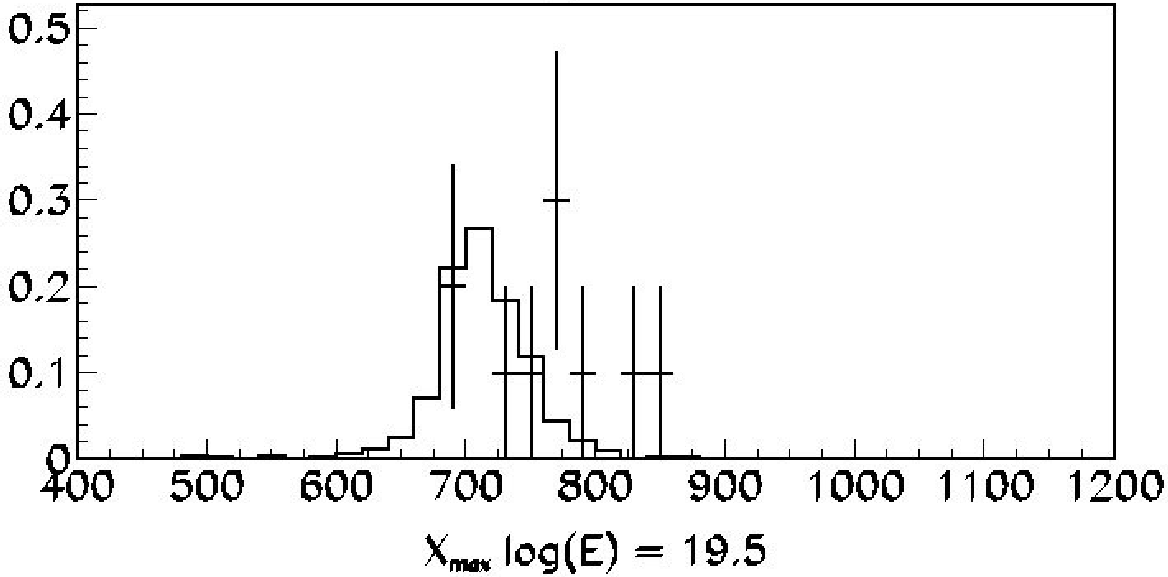


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

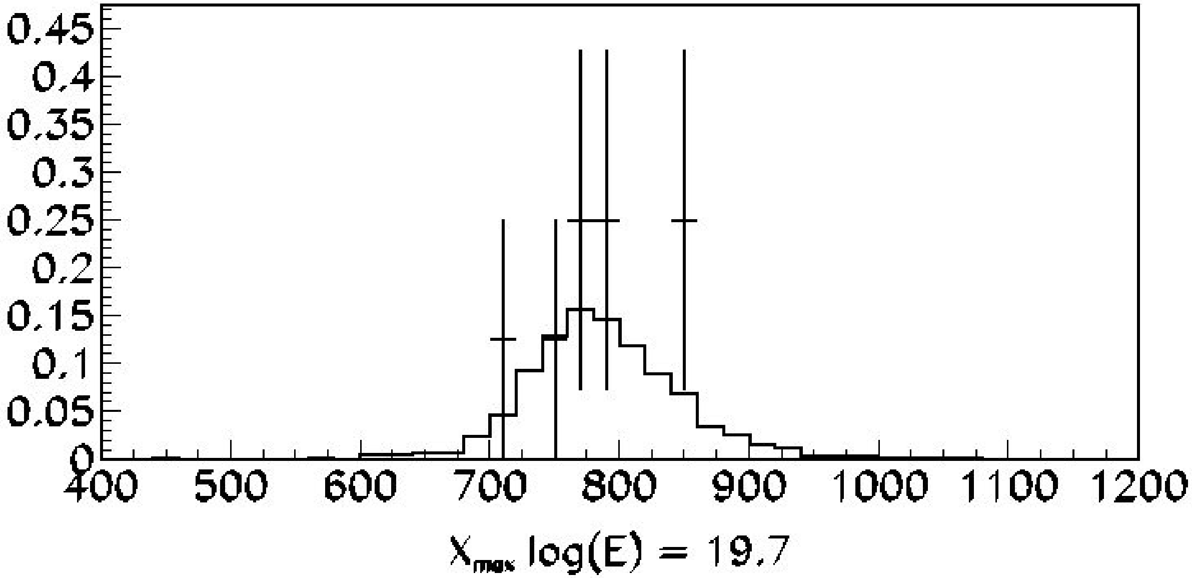


Iron

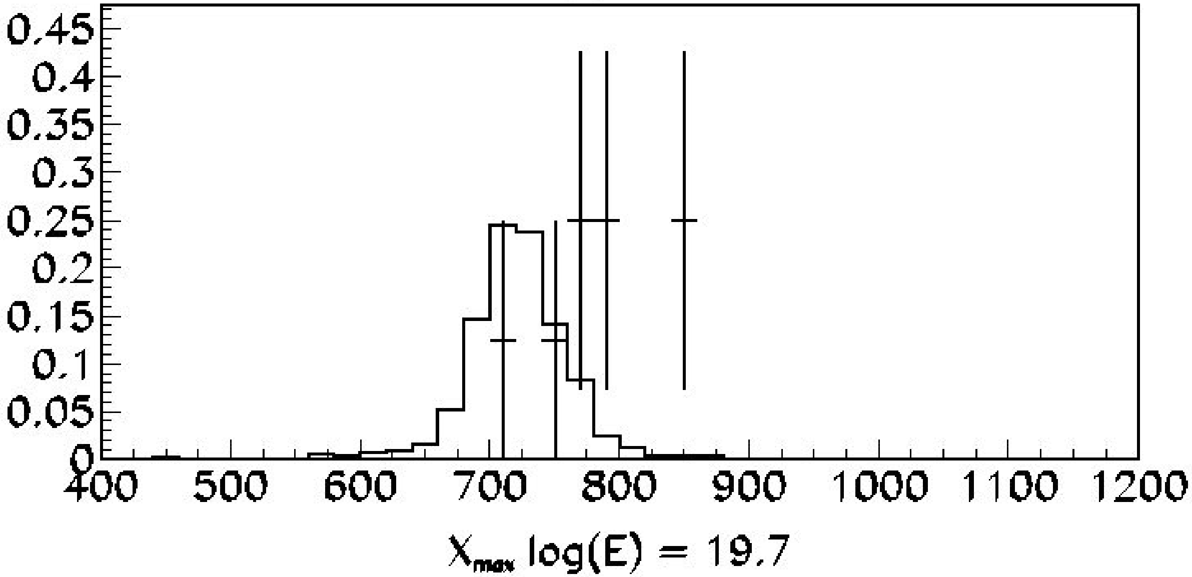


Data (points) versus QGSJET-II MC, in Energy Bins

Protons

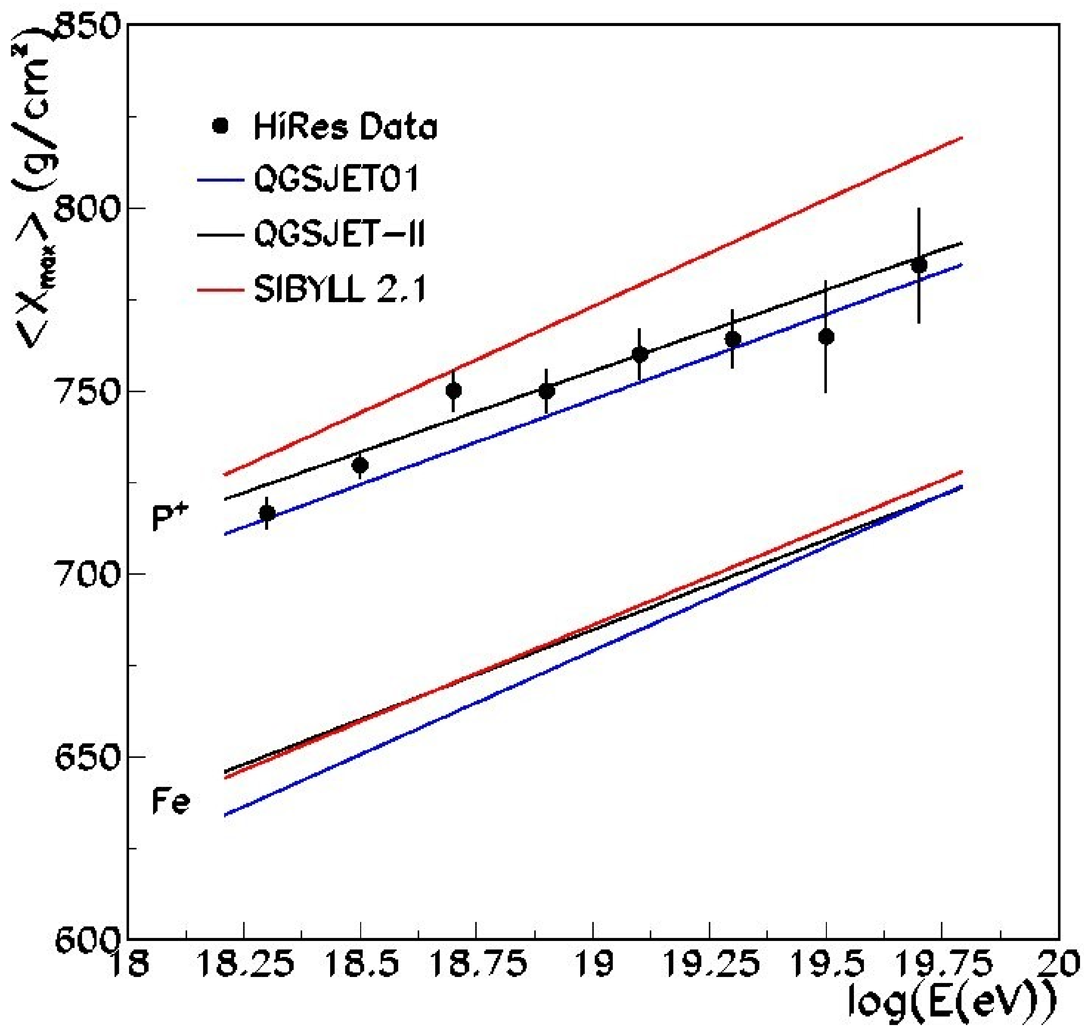


Iron



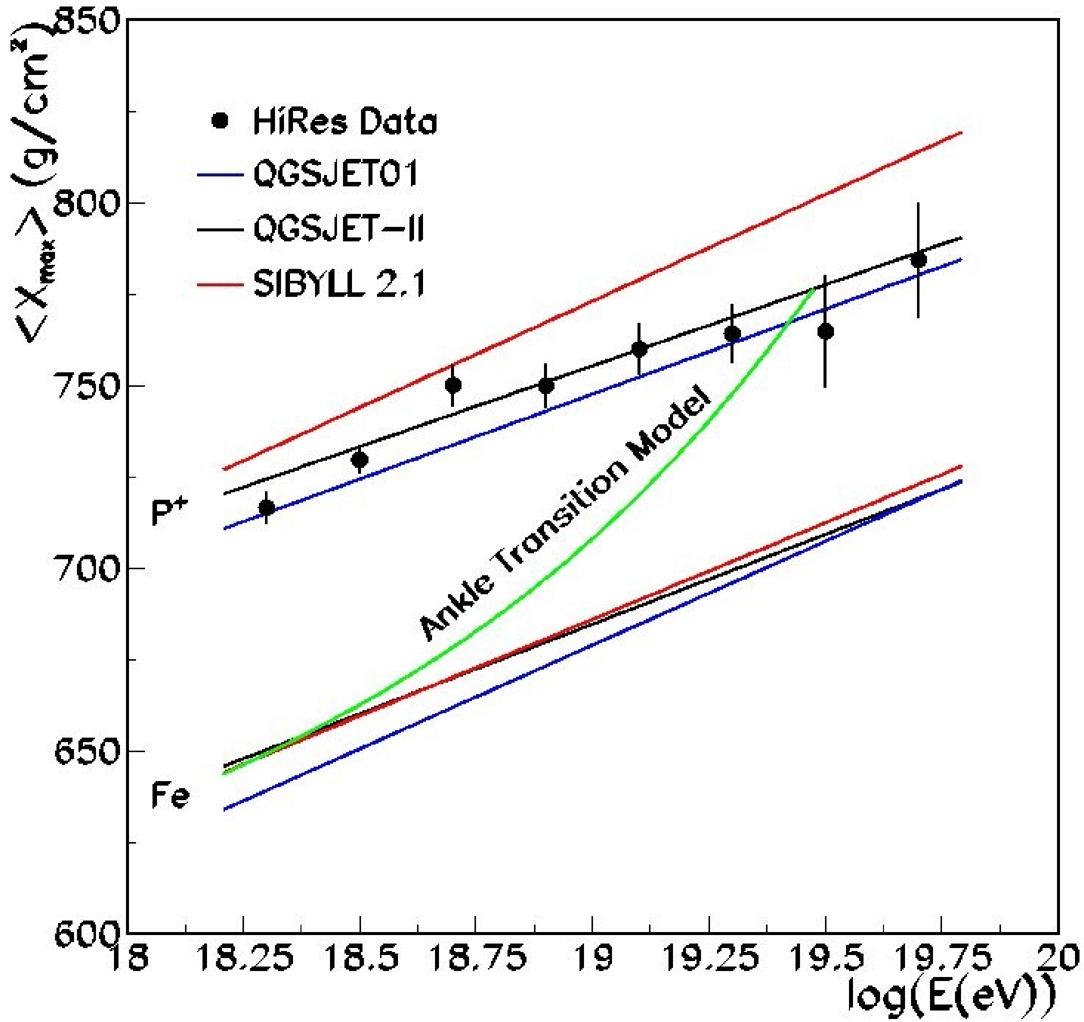
Elongation rate: Evolution of Mean X_{max} with Energy

- 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.



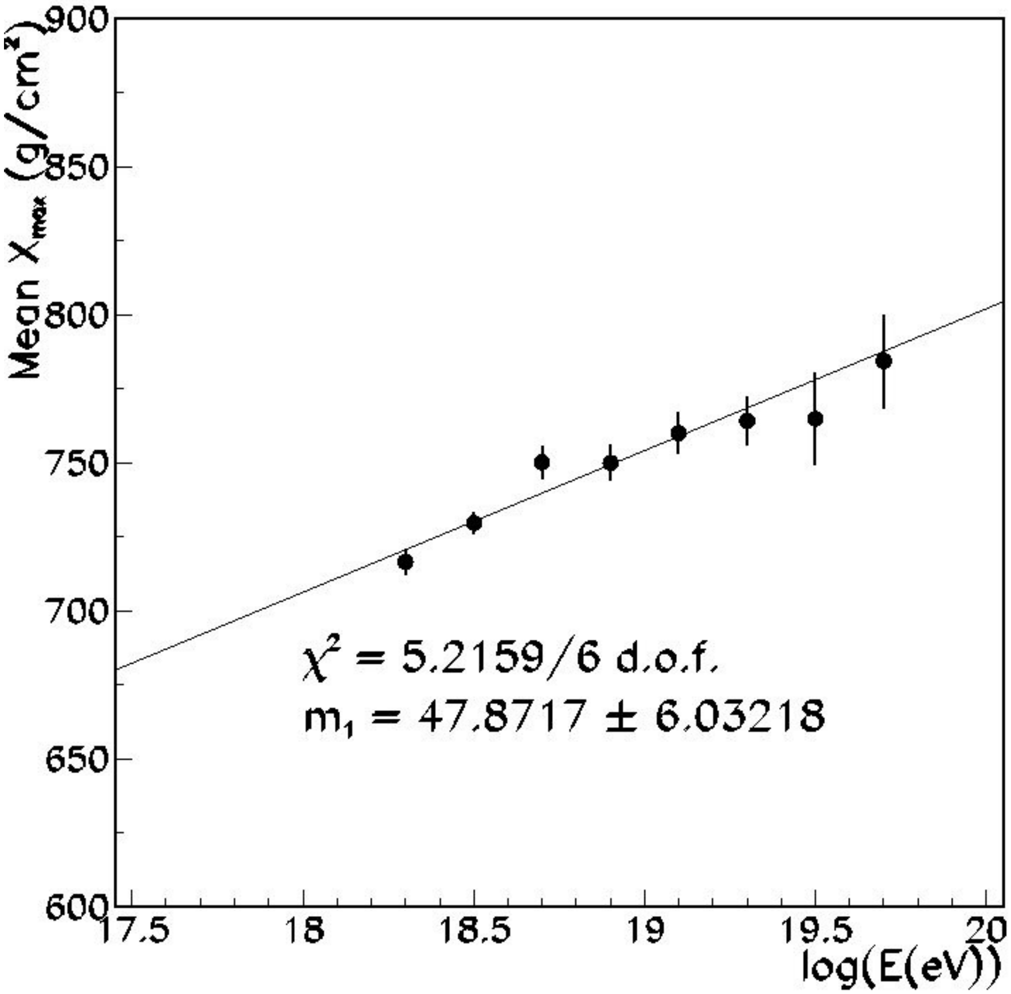
Elongation rate: Evolution of Mean X_{max} with Energy

- 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)

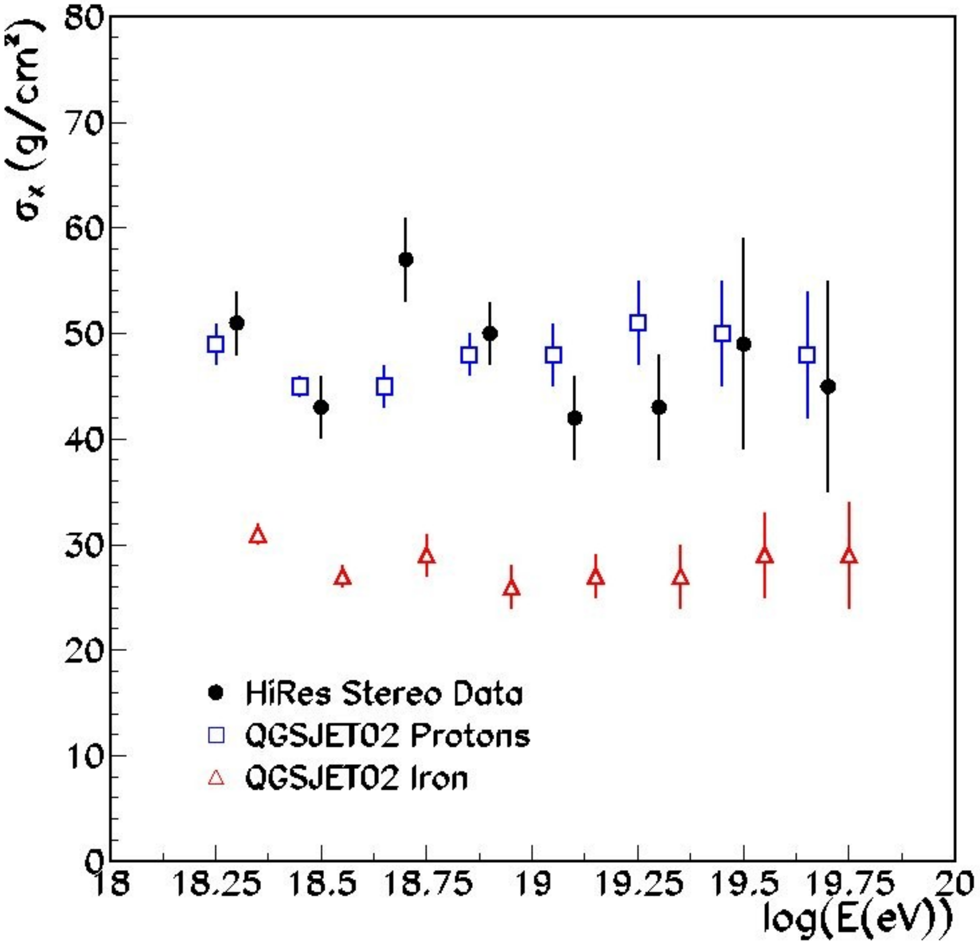


Elongation Rate

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



Width of X_{max} Distribution vs Energy



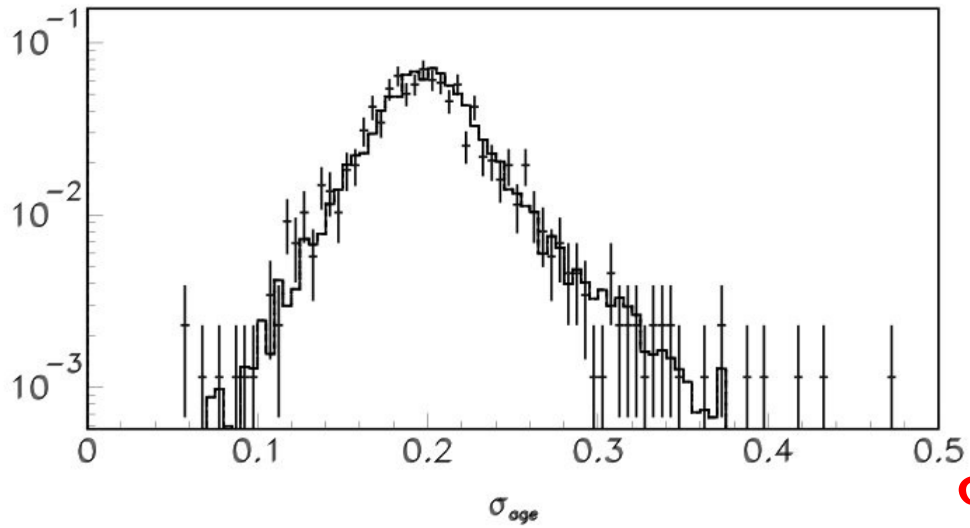
- Define width as σ of Gaussian, truncated at 2xRMS
  - Focus attention on core of distribution
  - Avoid RMS undersampling bias
- Data consistent with QGSJET-II protons

X_{max}: Comments

- Data best modeled by QGSJET-II protons
- Absolute value of mean $\langle X_{max} \rangle$ bracketed by QGSJET01 and QGSJET-II protons. Elongation rate consistent with either.
- Data falls between SIBYLL protons and helium
  - Suggests a mixed composition
  - Constant elongation rate suggests this mixture is unchanging over two orders of magnitude. Unlikely!
  - Mix inconsistent with shape of ankle (pair production). Or, galactic-to-extragalactic transition occurring with constant composition. Unlikely!
- Width of X_{max} distributions also consistent with protons.
- R. Abbasi *et al.*, *Phys. Rev. Lett.* **104** (2010).

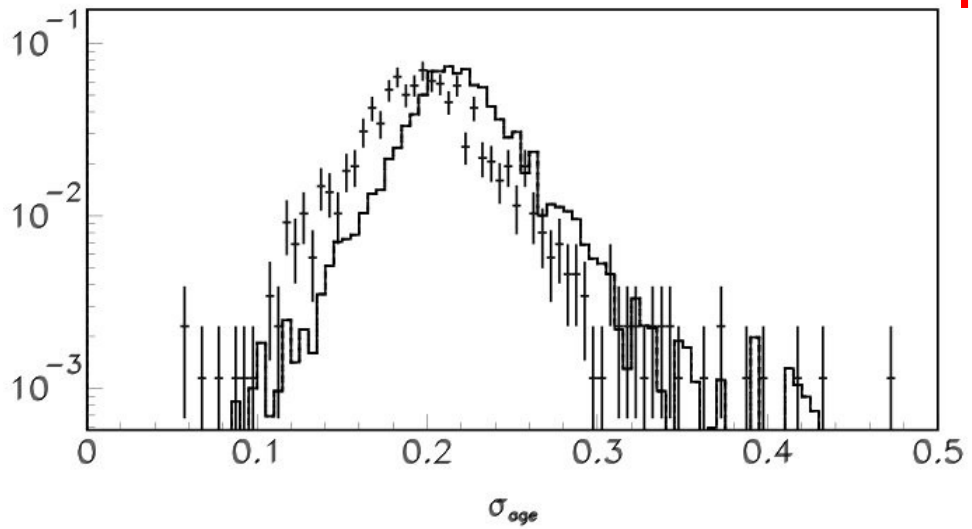
Data (points) versus QGSJET-II Monte Carlo (histogram)

Protons

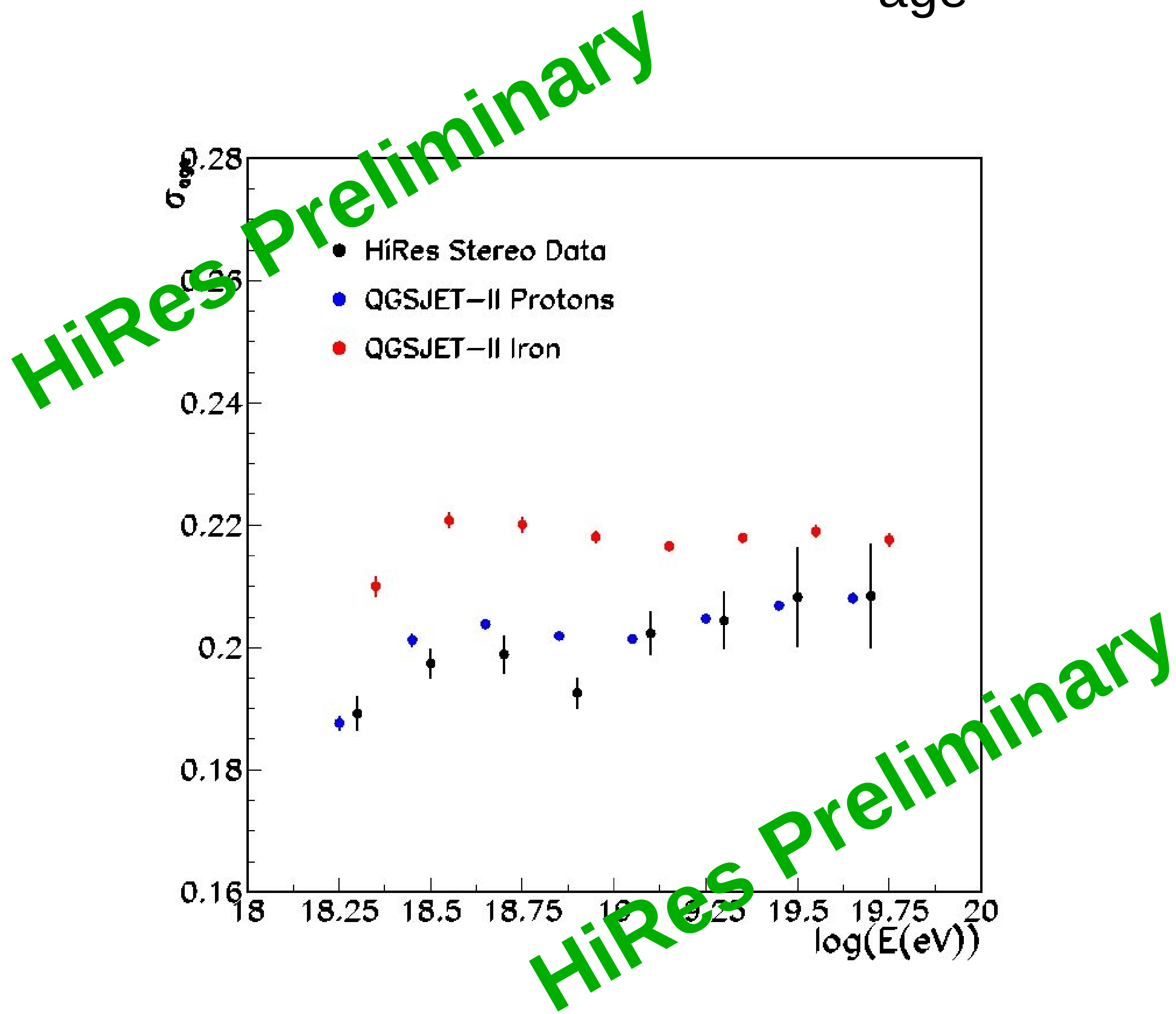


σ_{age} is dimensionless measure of width of individual airshowers.

Iron

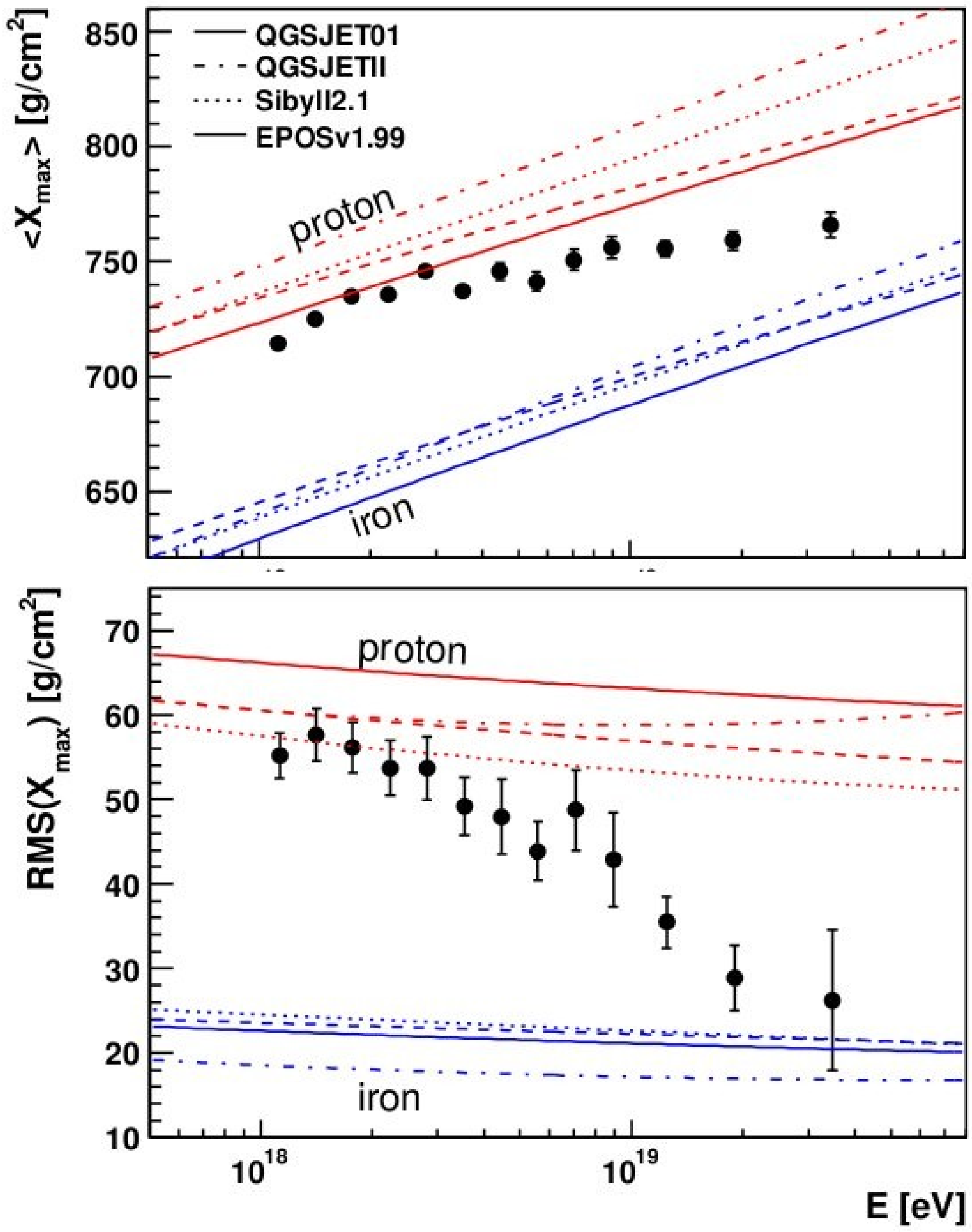


Mean Shower Width σ_{age} *vs* log(E)

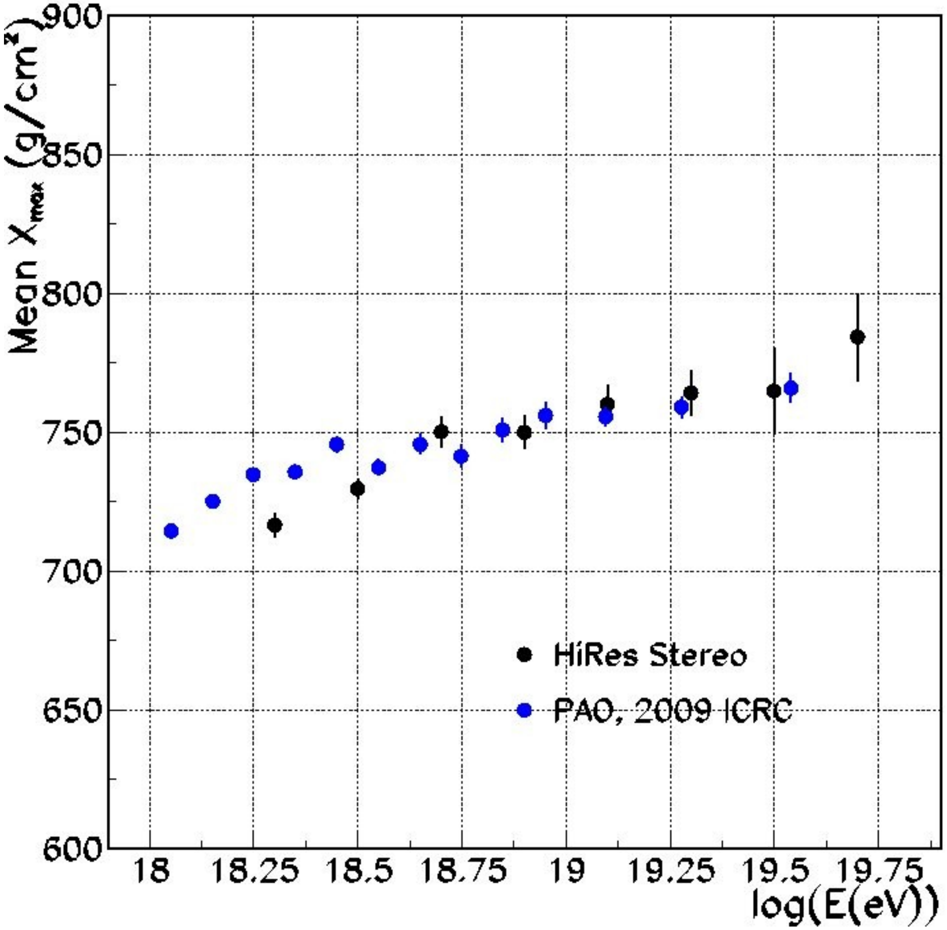


Contrast PAO Results

- Southern Hemisphere observatory reaches startlingly different conclusions
  - $<X_{max}>$ indicates composition getting heavy.
  - Width indicates all iron by $3x10^{19}$!

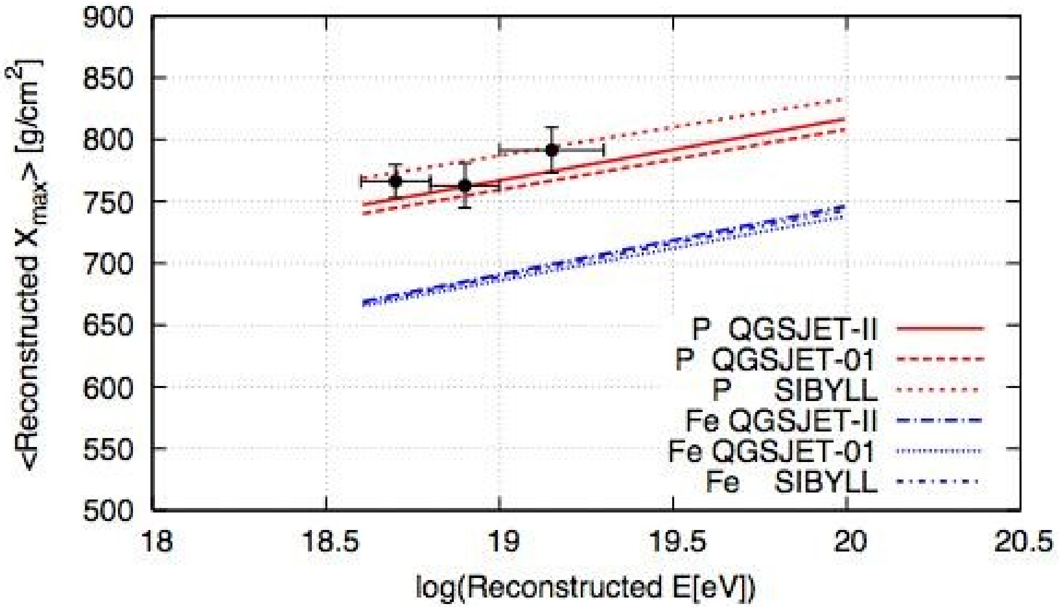


Compare PAO, HiRes < X_{max} >



- Mean X_{max} as observed by HiRes, PAO essentially identical
- Difference a matter of interpretation:
  - HiRes: When acceptance taken into account, this is what protons look like.
  - PAO: Composition is getting heavy.

Telescope Array is Online!



- *cf.* J. Matthews, this conference
- Low statistics first results suggest light primaries at 10 EeV
- Stay tuned...

HiRes Spectrum and Composition: Synthesis

- Spectrum consistent with protonic composition
  - Cutoff location, slope consistent with GZK cutoff (protons & CMBR)
  - “Ankle” has correct shape for CMBR e^+e^- production
- Elongation rate suggests constant light composition above 1.6 EeV
  - SIBYLL mixed composition model unlikely
  - Ankle ruled out as site of galactic-to-extragalactic transition
- Data well modeled by pure protons within QGSJET01, QGSJET-II high-energy hadronic interaction models.
- *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.*

Extras

Compare PAO, HiRes <X_{max}>

- Problem: Different X_{max} definitions
  - PAO: Gaisser-Hillas fit
  - HiRes: Gaussian-in-Age s fit

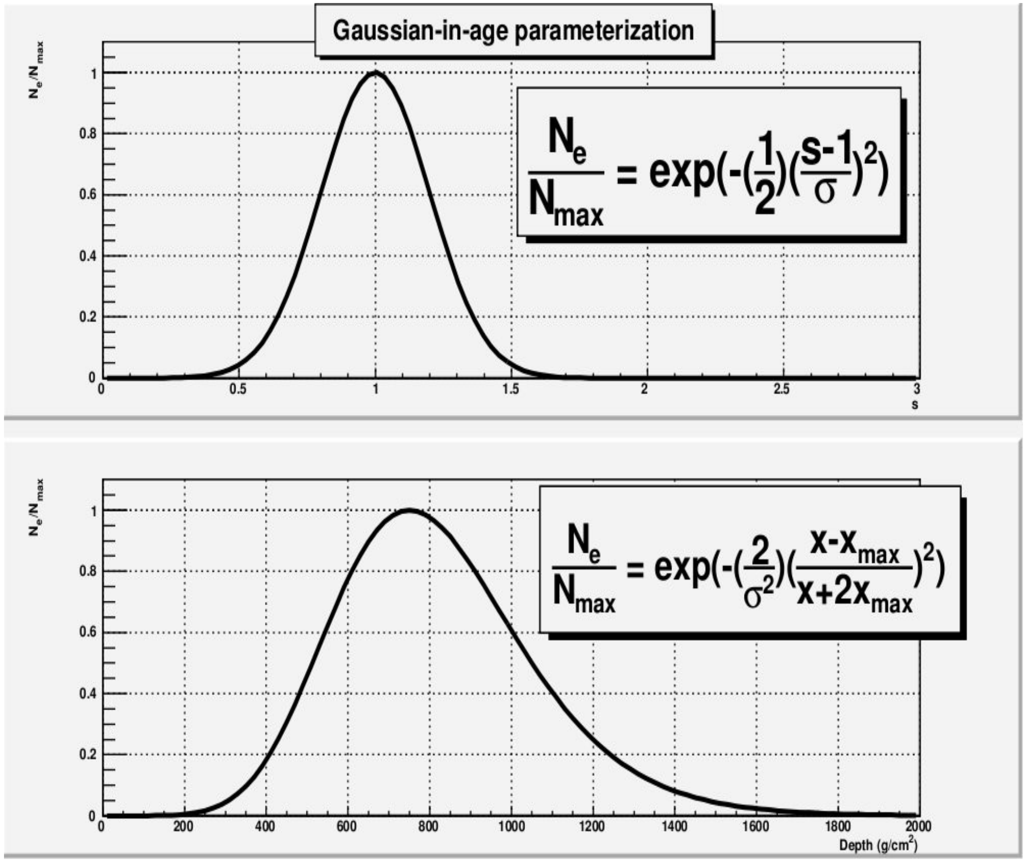
$$N(X) = N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max} - X_0}{\lambda}} \exp \left[\frac{X_{max} - X}{\lambda} \right]$$

$$s = \frac{3X}{X + 2X_{max}}$$

$$N(X) = N_{max} \exp \left[-\frac{2}{\sigma^2} \left(\frac{X - X_{max}}{X + 2X_{max}} \right)^2 \right]$$

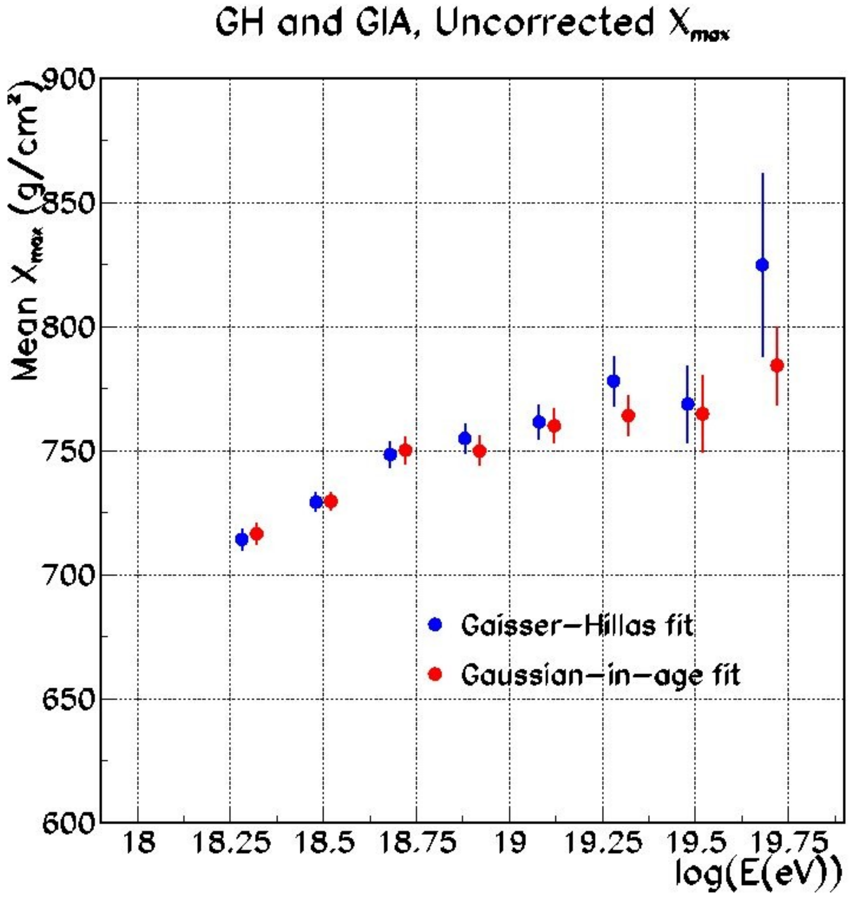
Compare PAO, HiRes $<X_{max}>$

- Problem: Different X_{max} definitions
  - PAO: Gaisser-Hillas fit
  - HiRes: Gaussian-in-Age *s* fit



Compare PAO, HiRes <X_{max}>

- Problem: Different X_{max} definitions
  - PAO: Gaisser-Hillas fit
  - HiRes: Gaussian-in-Age *s* fit
- Plot at right: HiRes <X_{max}> calculated both ways: Little difference!



Classifying Biases in <X_{max}>

- Reconstruction Bias; Due to events which are *successfully reconstructed and pass cuts* which have the wrong X_{max}.
- Acceptance Bias; Due to events which *fail reconstruction* altogether. May include
  - Detector triggering effects
  - Events failing reconstruction
  - Quality cuts, including those designed to minimize *reconstruction biases*.

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  - Events failing reconstruction
  - Quality cuts, including those designed to minimize *reconstruction biases*.

Must check understanding of biasing effects with detailed detector simulation