HiRes Results

The Final Word (almost)

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HiRes Collaboration

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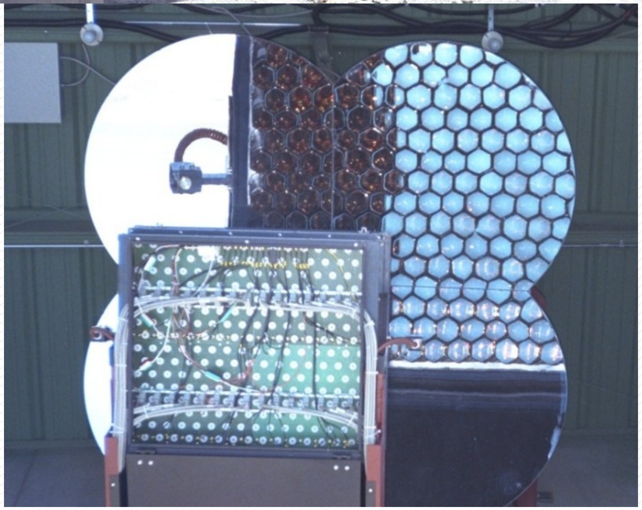
The HiRes Experiment

The HiRes Experiment

- HiRes was a stereo fluorescence detector, operated from 1997-2006 on Dugway Proving Grounds in Utah
- Observe the air-showers created by CR's by collecting fluorescence light

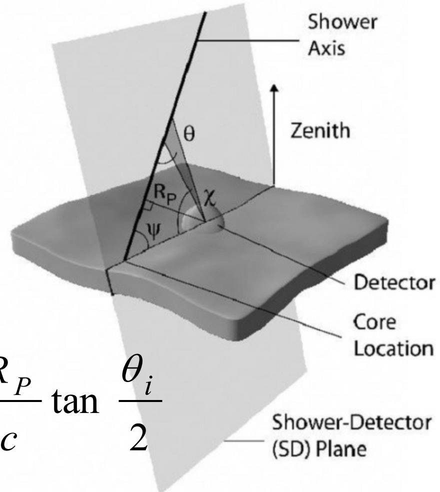
The HiRes Experiment

- Light collected by 5 m^2 mirrors onto an array of 256 (16×16) of PMT's
- Each PMT sees 1° cone
- Each PMT records time and amount of light seen

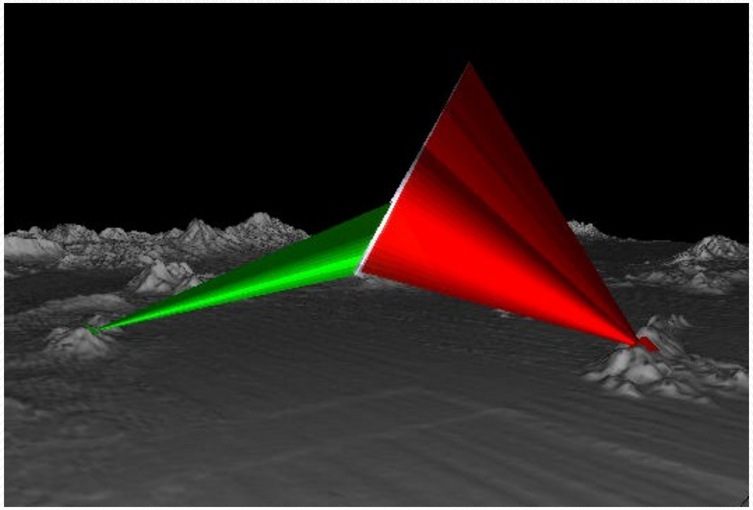


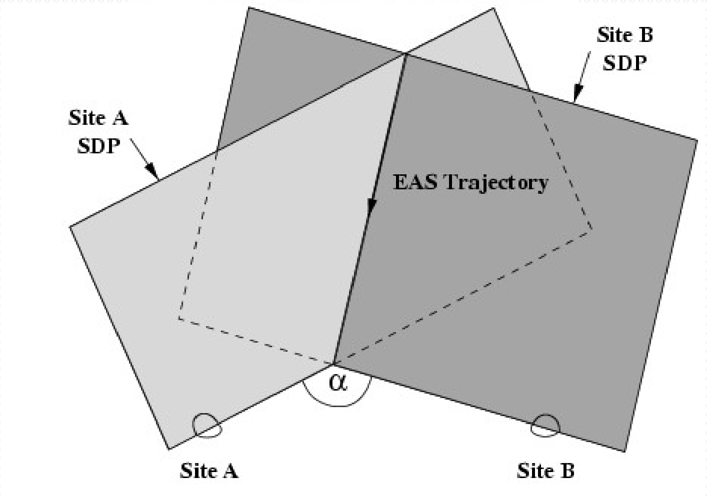
Event Reconstruction

- Two methods
  - Monocular using timing
  - Stereo using the intersecting shower-detector planes



$$t_i = t_0 + \frac{R_P}{c} \tan \frac{\theta_i}{2}$$



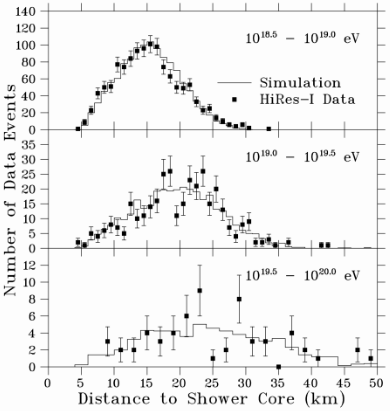


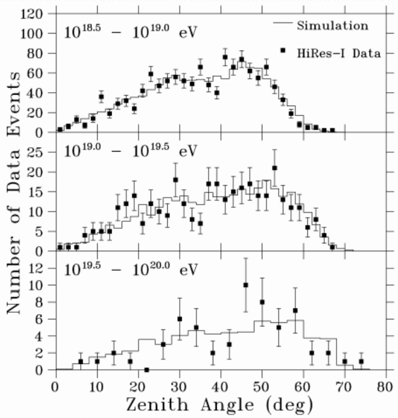
Analysis Paradigm

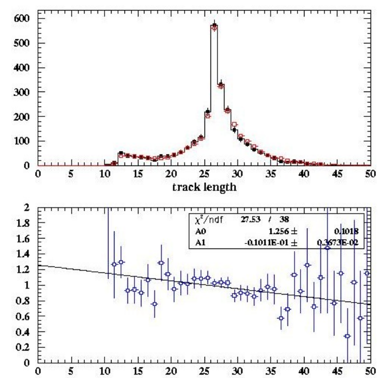
- For spectrum and composition analyses, thorough understanding of the detector is essential
  - Must understand the unavoidable biases the detector and the trigger impose on the collected data
  - Understanding the detector means simulating it, and sampling the parameter space in the same way as in nature, in other words use a Monte Carlo simulation
- How to know the simulation is good enough?
  - It must produce distributions indistinguishable from the actual data: Data/MC comparisons

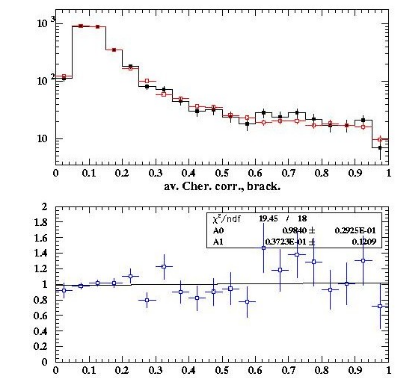
Data/MC Comparisons

- Inputs to MC: FE Stereo spectrum, HiRes/MIA & HiRes composition, library of CORSIKA produced showers, actual run-time parameters



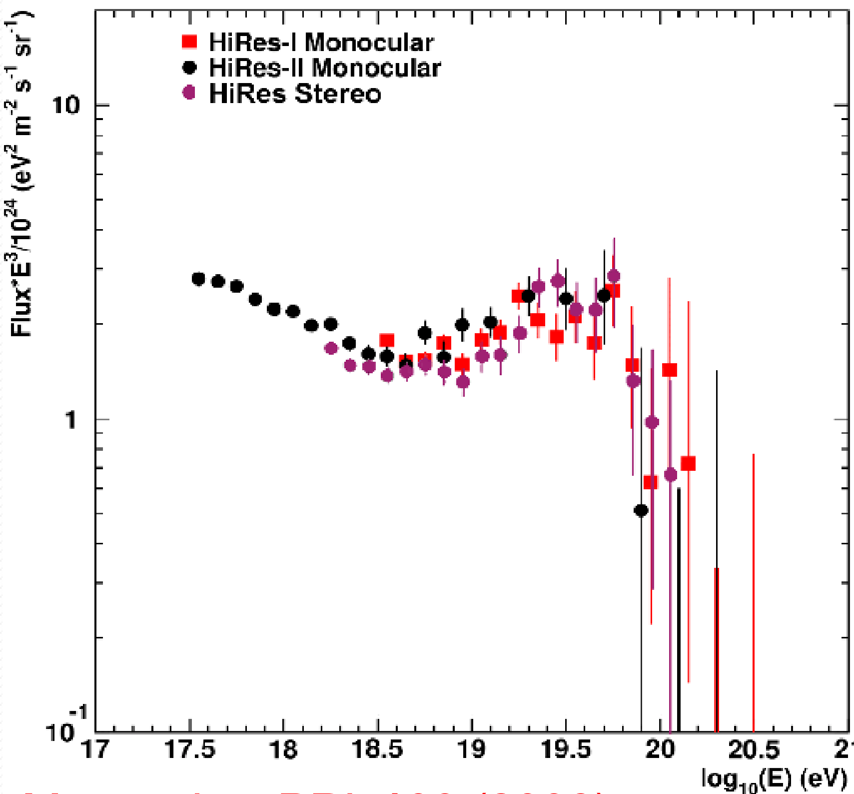






- Result: **excellent agreement, accurate aperture!**

HiRes Energy Spectra



Monocular: *PRL* **100** (2008)

Stereo: *Astropart. Phys.* **32** (2010)

Physics Today, May 2007

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-km² 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.

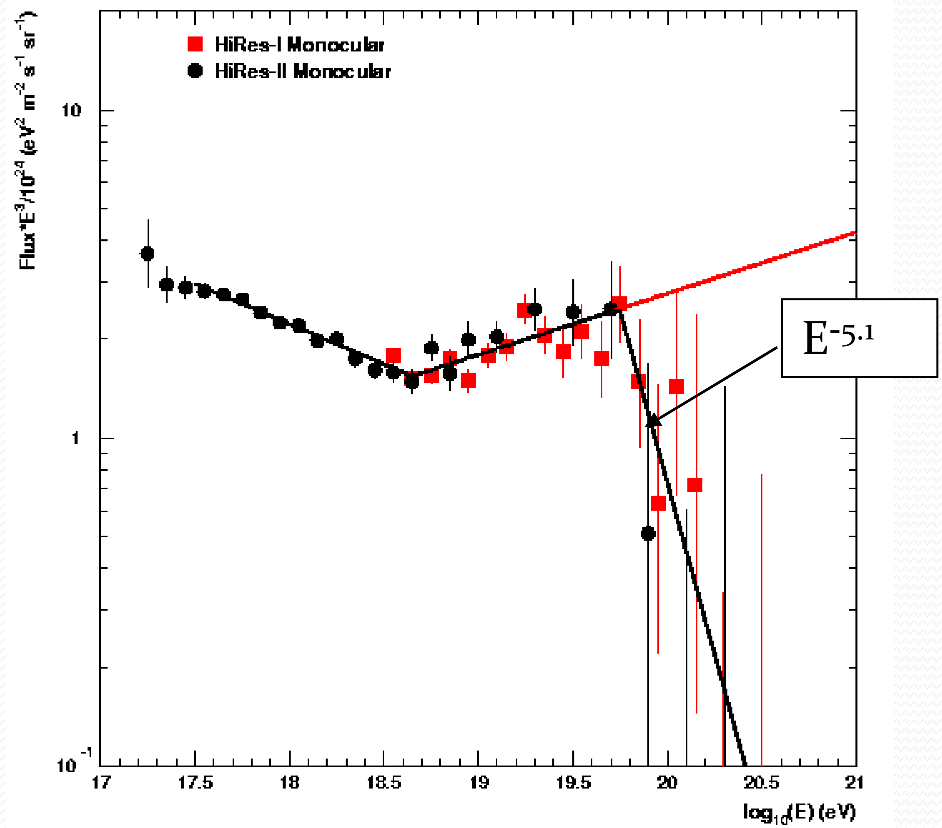
After forty years

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-m² 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.

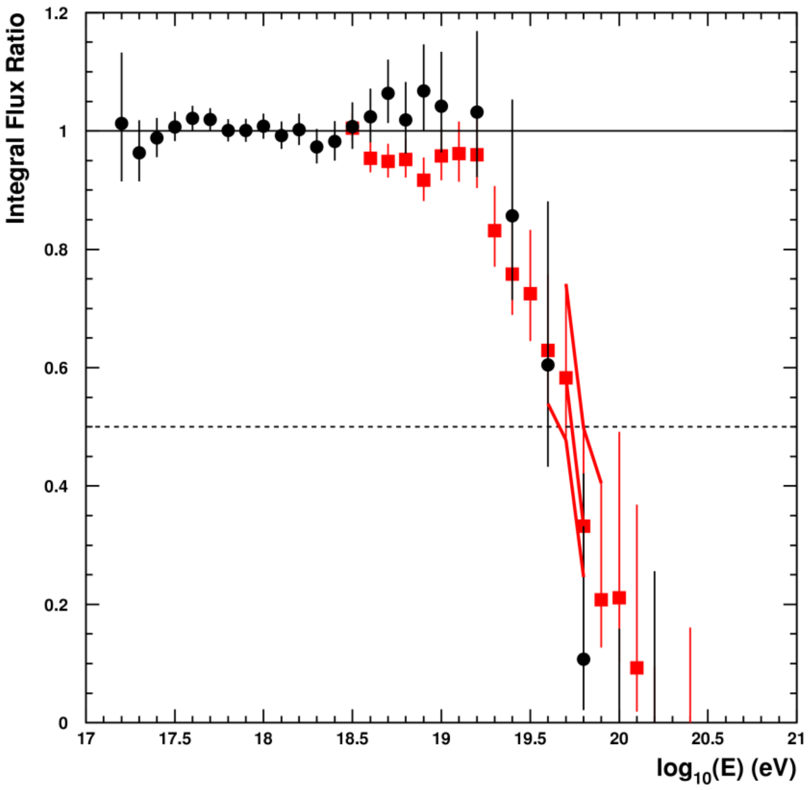
5-σ Obersvation of the GZK Break

- Broken Power Law Fits
  - Two BP with extension to test hypothesis that a break is present.
    - Expect 43 events
    - Observe 13 events
    - Poisson probability: P(13;43) = 7×10^{-8}, **5.3σ**
  - **The break is statistically significant.**
  - Break is at $(5.6 \pm 0.5) \times 10^{19}$ eV;
  - GZK expected between 5 and 6×10^{19} eV.
  - **The break is the true GZK cutoff.**



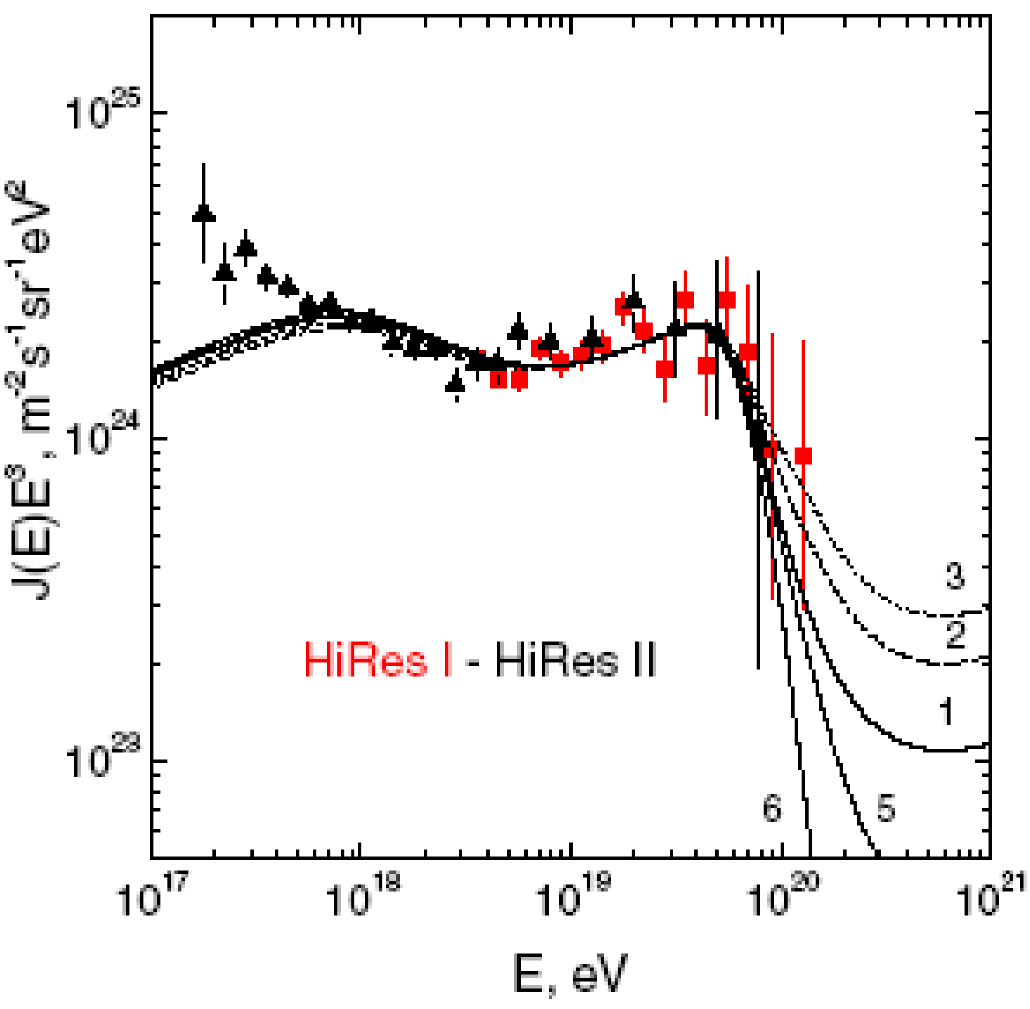
Berezinsky's $E_{½}$ Method as Test

- $E_{½}$ is the energy where the integral spectrum falls below the power-law extension by a factor of 2.
- Berezinsky *et al.*: $\log_{10}E_{½} = 19.72$, for a wide range of spectral slopes.
- Use 2 Break Point Fit with Extension for the comparison.
- $\log_{10}E_{½} = 19.73 \pm 0.07$
- **Passes the test.**



Local Density of Sources

- Theoretical predictions for spectrum shape agree with HiRes measurements.
- Compare HiRes spectrum slope above the GZK energy to Berezinsky *et al.* predictions:
  - Line 1: constant density.
  - Line 5: no sources within 10 Mpc.
  - Line 2: double density within 30 Mpc.



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  - Line 1: constant density.
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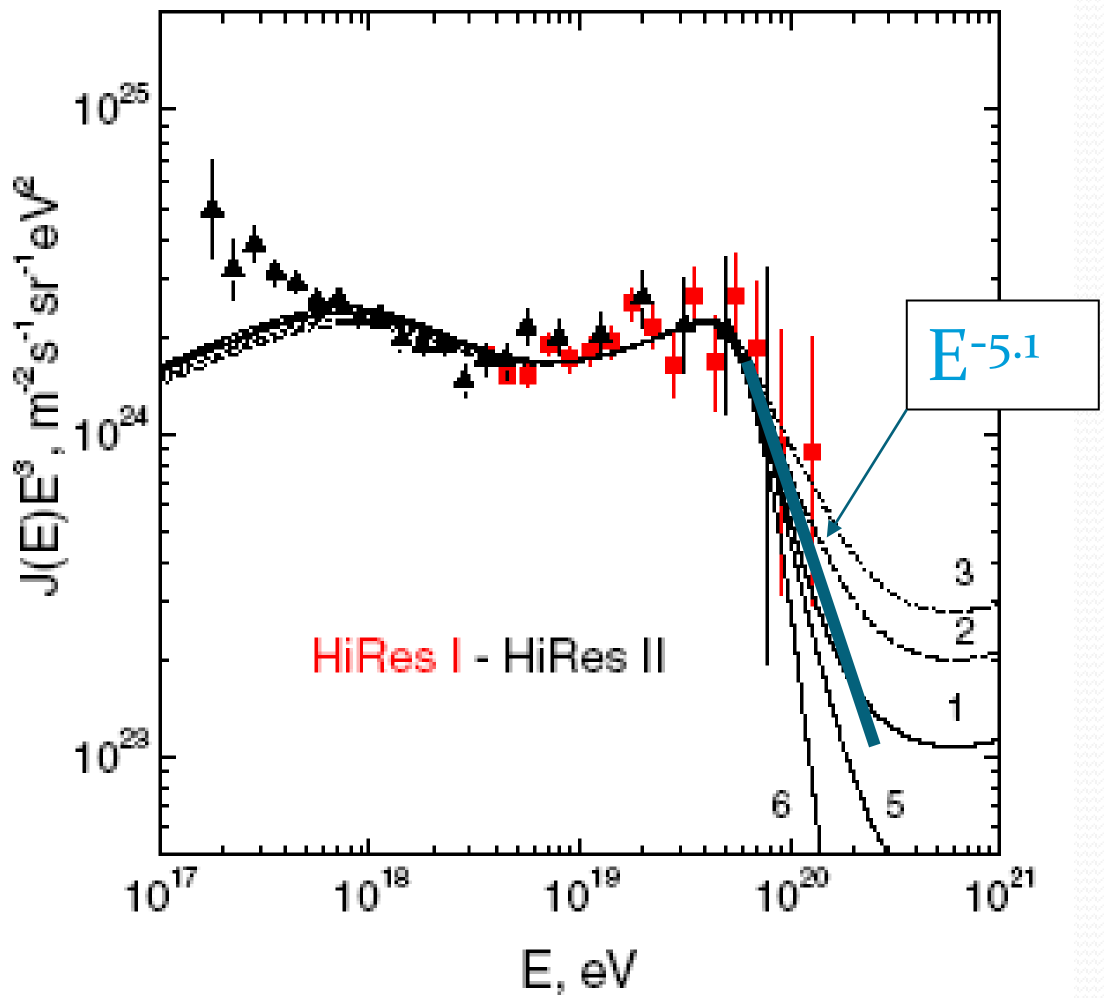
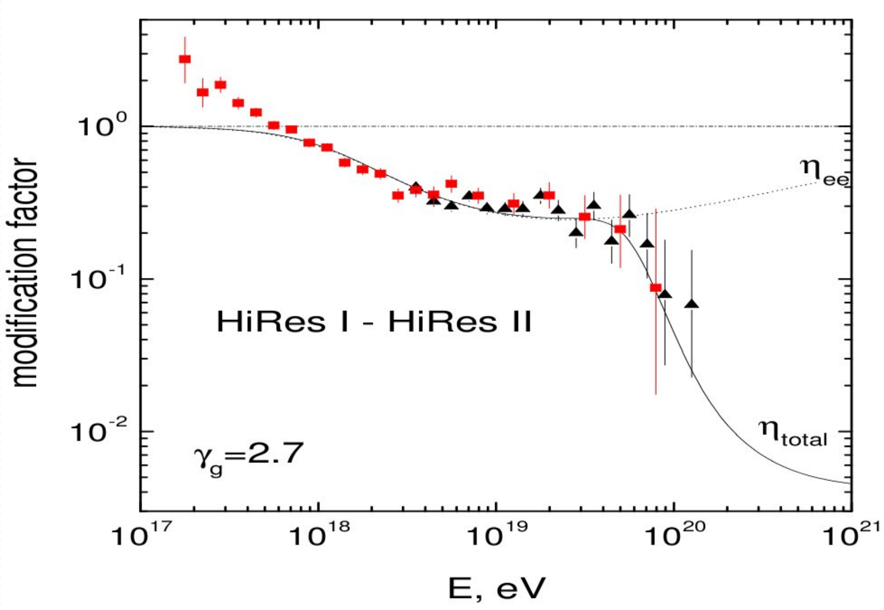
  - Line 2: double density within 30 Mpc.
  - HiRes: $E^{-5.1}$ fall-off.
- More work is needed to make a better comparison, but…

Constant density of sources is favored.

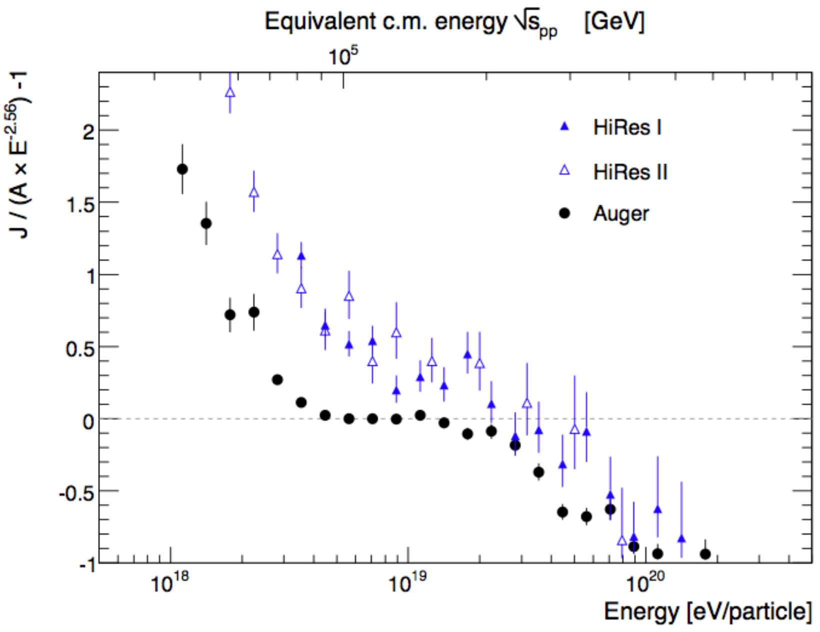


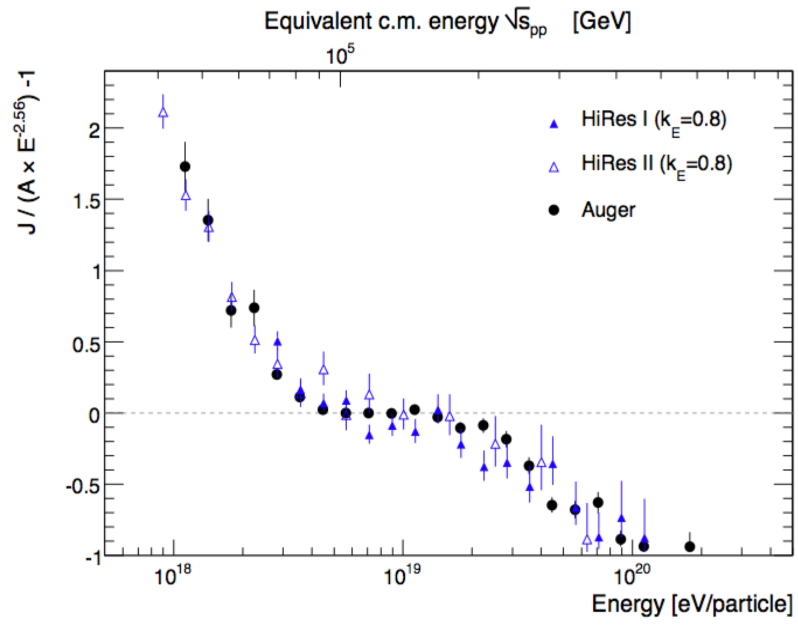
Pair Production “Dip”

- Another indication of CMBR interactions:
  - Photon pair production
  - Lower threshold than pion production
- The dip and its shape essentially model independent, provided primaries are protons
  - Aloisio *et al*, *Astropart. Phys.* **27** (2007).
- Consistent with “ankle” feature observed by HiRes (and also AGASA, Yakutsk, PAO…)



Spectrum Comparison with Auger





Auger confirms all the spectral features of HiRes spectrum

Summary, Spectrum Analysis

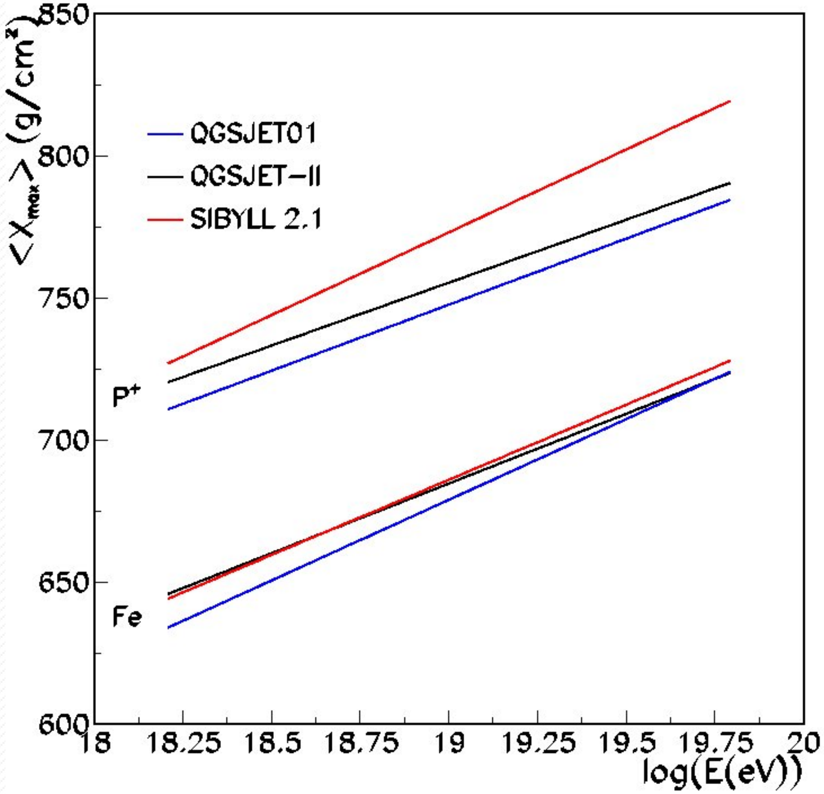
- The GZK Cutoff is present, first observed by HiRes
- Spectrum details consistent with and indicative of a primarily protonic composition
  - The energy of the GZK cutoff is as expected for *protons*.
    - Highest energy extragalactic cosmic rays travel > 50 Mpc.
    - The fall-off above the cutoff is evidence for a constant density of sources. CR's travel a long distance. Spallation breaks up all nuclei at high energies: proton flux results.
  - The ankle has been observed by HiRes, at $10^{18.65}$ eV. The spectral index changes from -3.2 to -2.8
    - Shape and energy of the ankle are consistent with electron pair production in collisions between extragalactic protons and photons of the CMBR.

Direct Composition Measurements

- Several ways to measure composition using the longitudinal shower profile
  - Mean X_{max}
    - Mean itself is very model dependant
    - The rate of change with energy (elongation rate) is less
  - Width of X_{max} distribution
    - Model independent but easily biased ("fat tail")
  - Individual shower widths

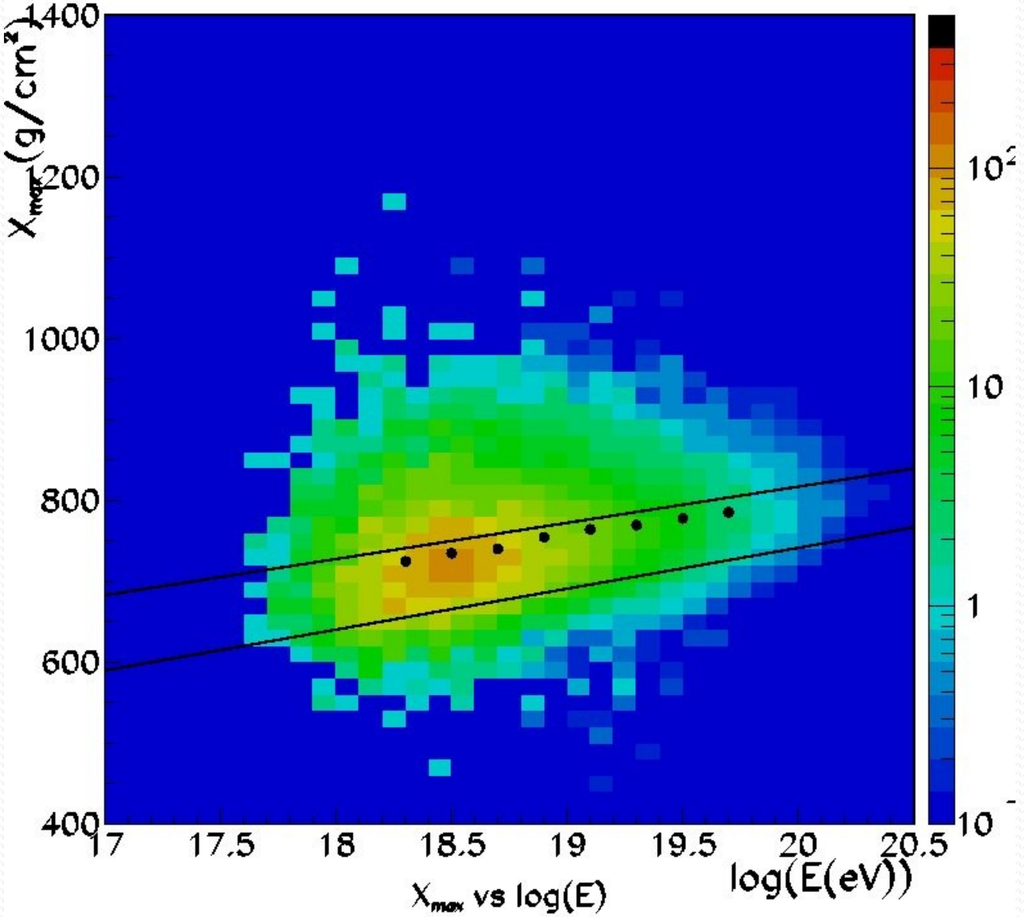
Mean X_{max} Measurement

- 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



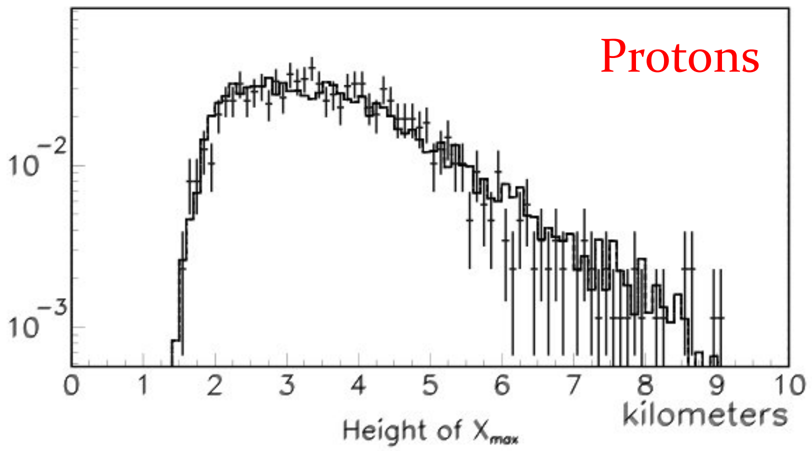
Simulation for QGSJet-II protons

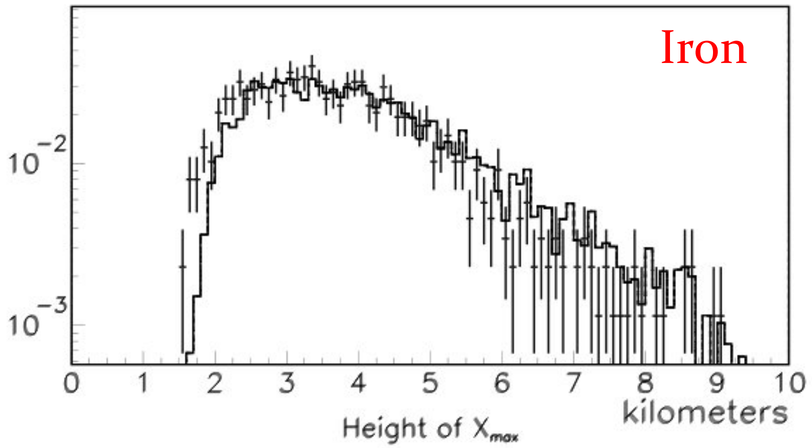
- Lines are mean X_{max} for protons & iron from CORSIKA before detector simulation
- Black dots are the mean X_{max} for the same simulation after detector effects
  - The full distribution is shown as a color map
  - Note the bias



Does the simulation work?

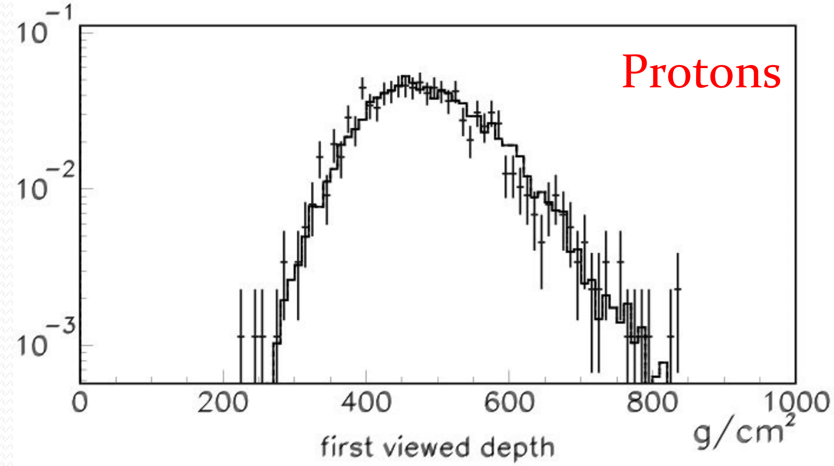
- Yes, with protons
  - Height of max

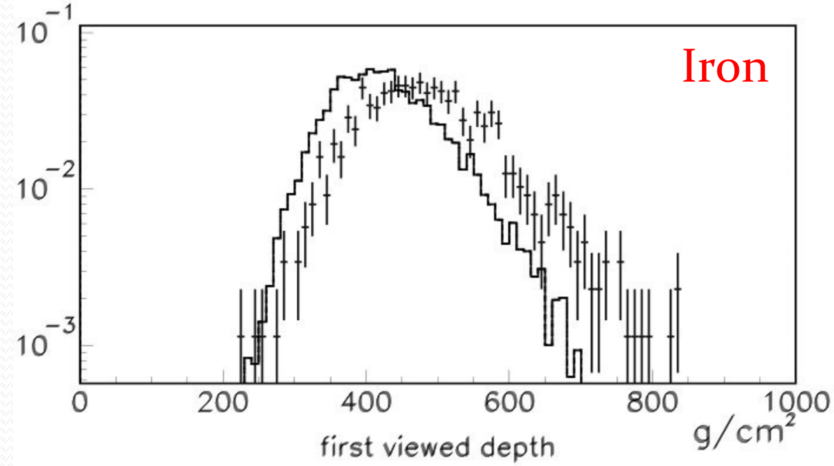




Does the simulation work?

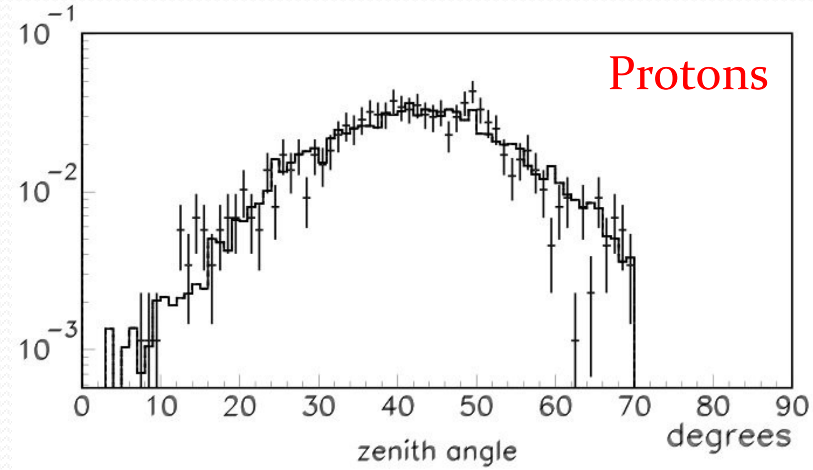
- Yes, with protons
  - Height of max
  - First view depth

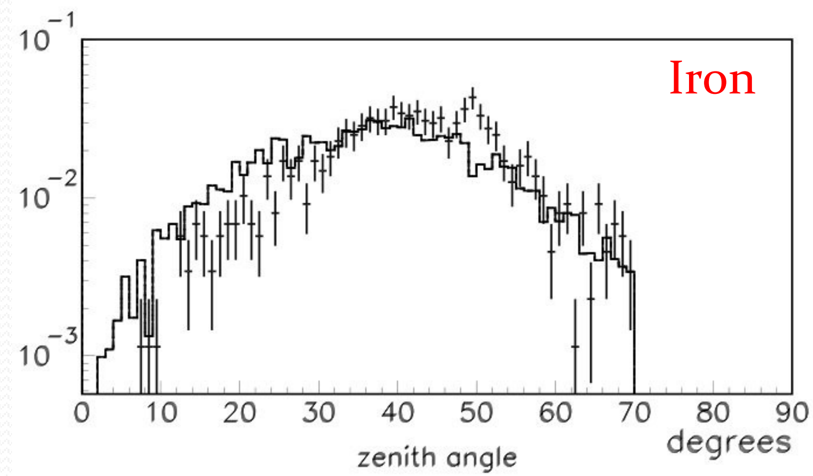




Does the simulation work?

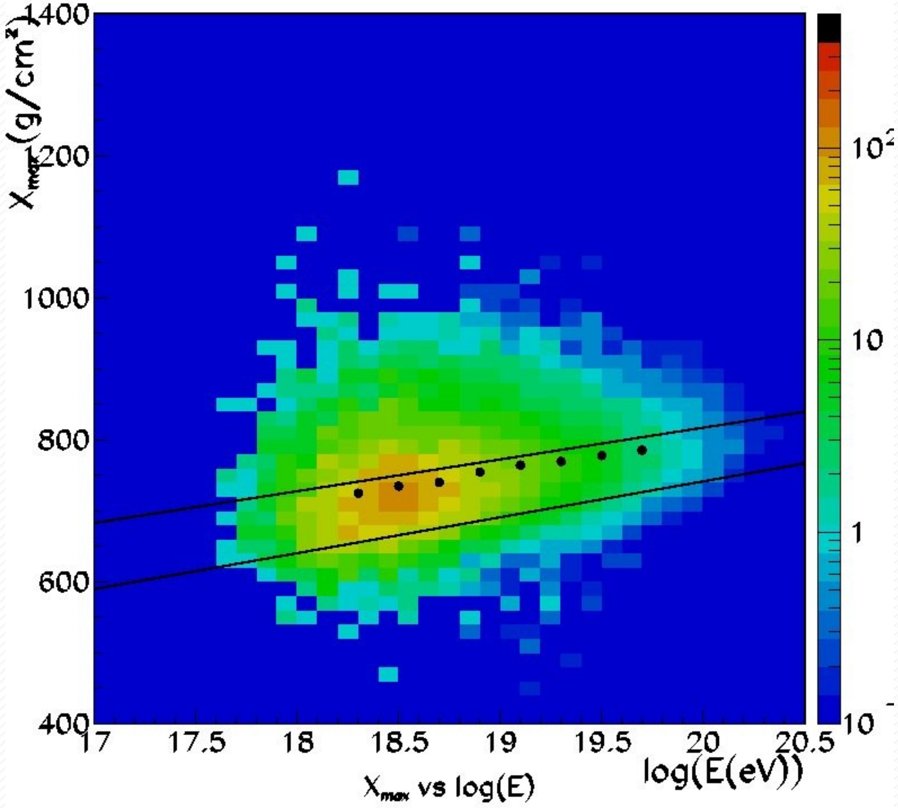
- Yes, with protons
  - Height of max
  - First view depth
  - Zenith angle



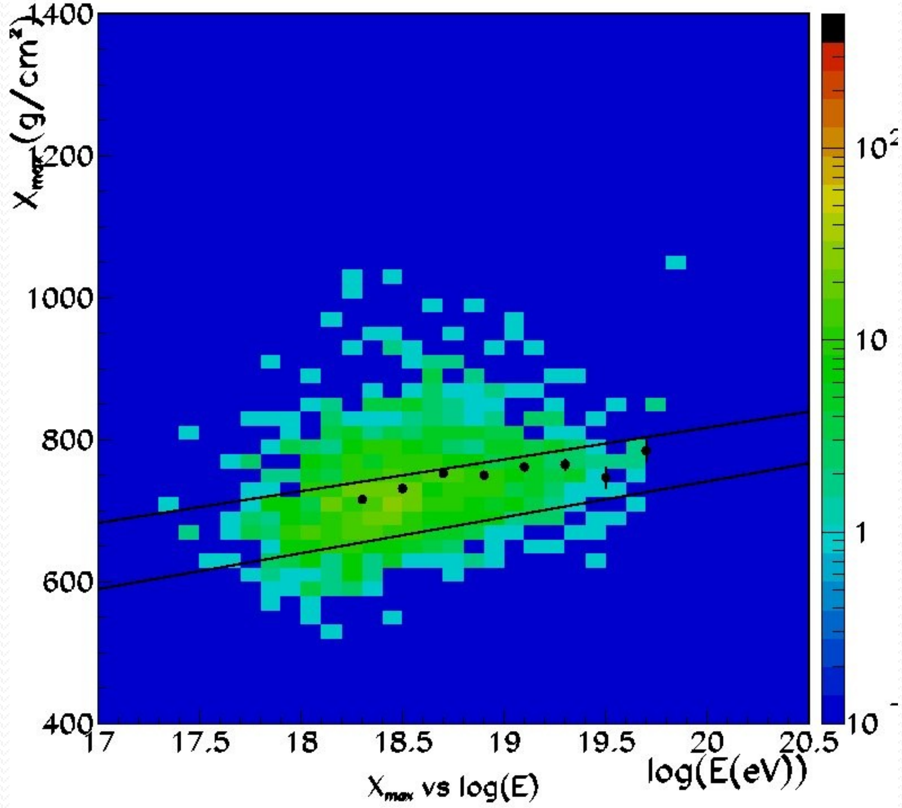


Mean X_{max} Measurement

QGSJet-II Protons

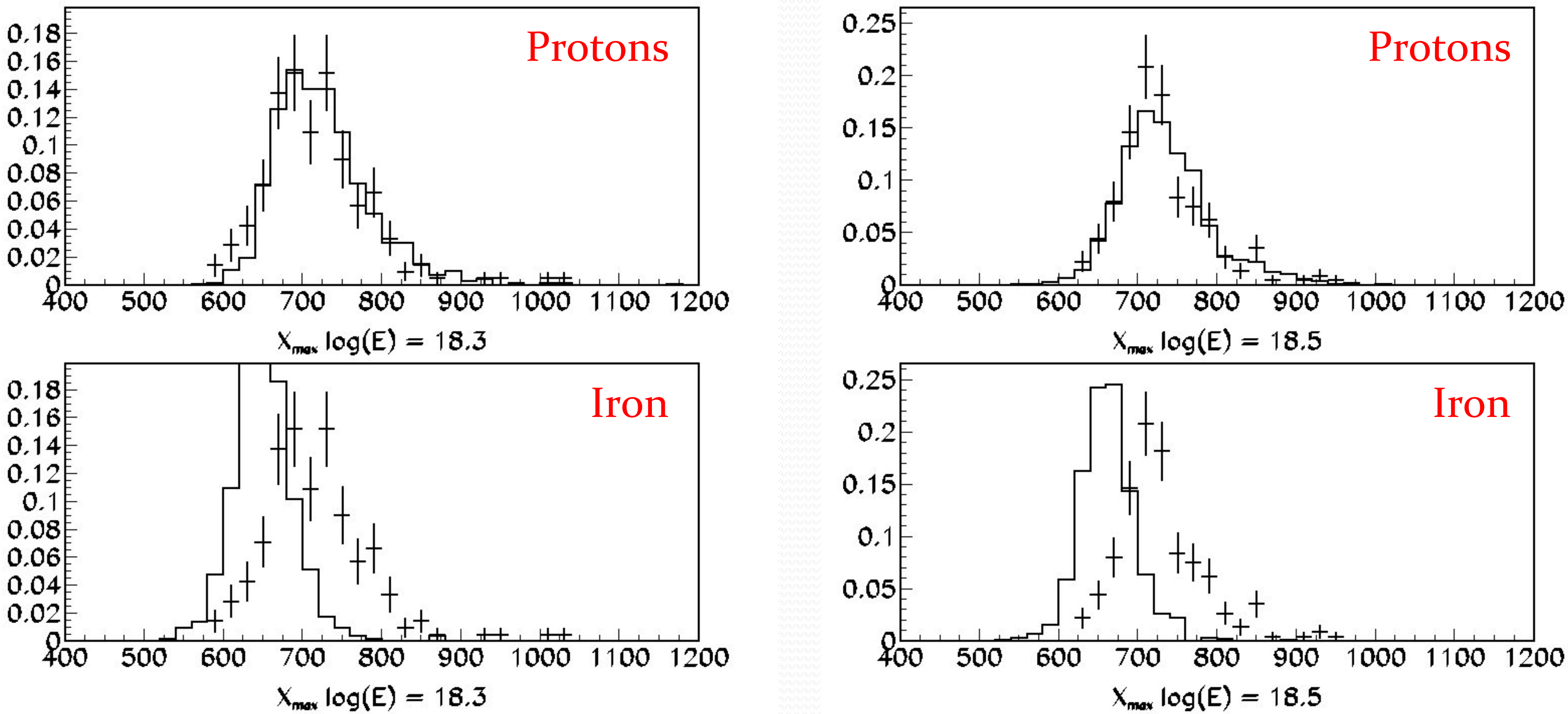


HiRes Stereo Data



Mean X_{max} Measurement, Bin-by-bin

Histogram: QGSJet-II
Points: HiRes Stereo Data



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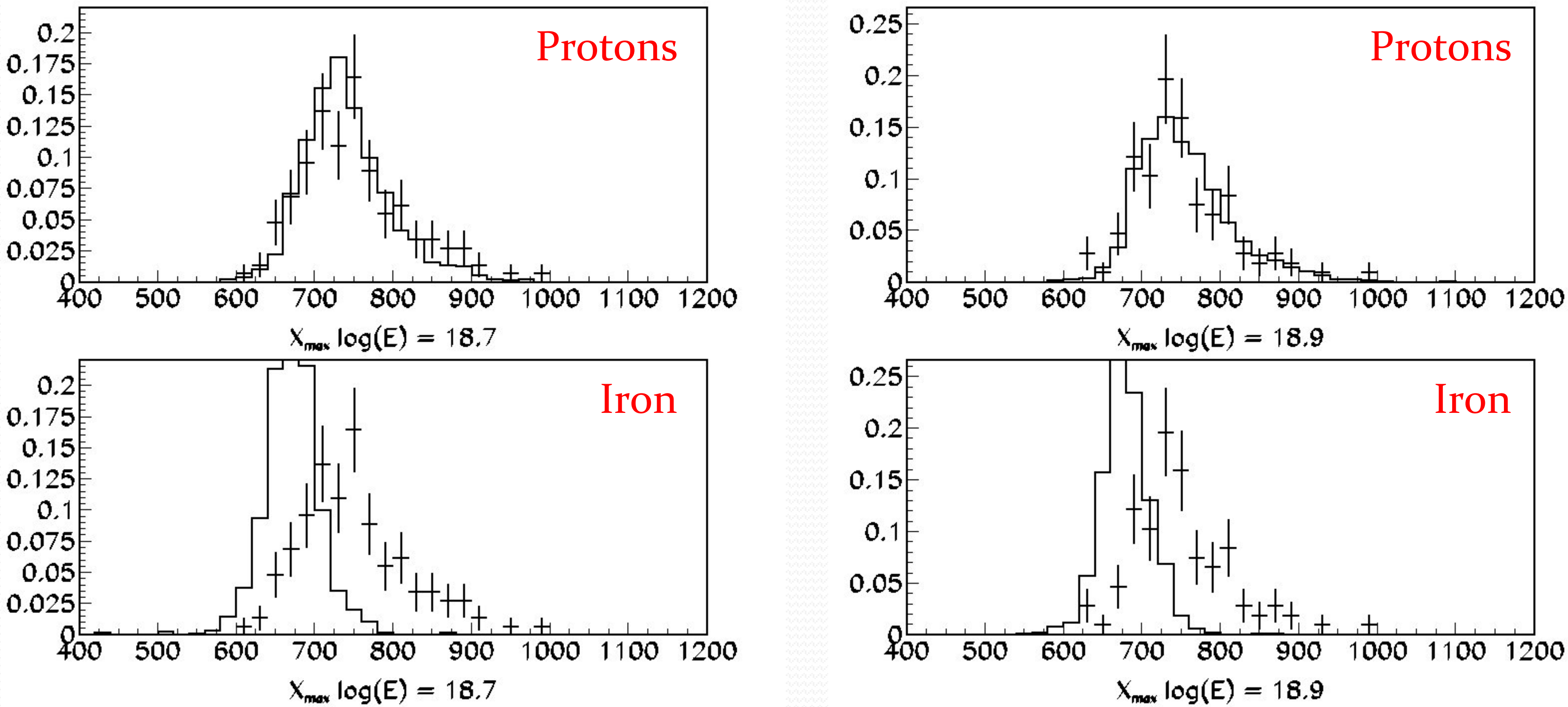

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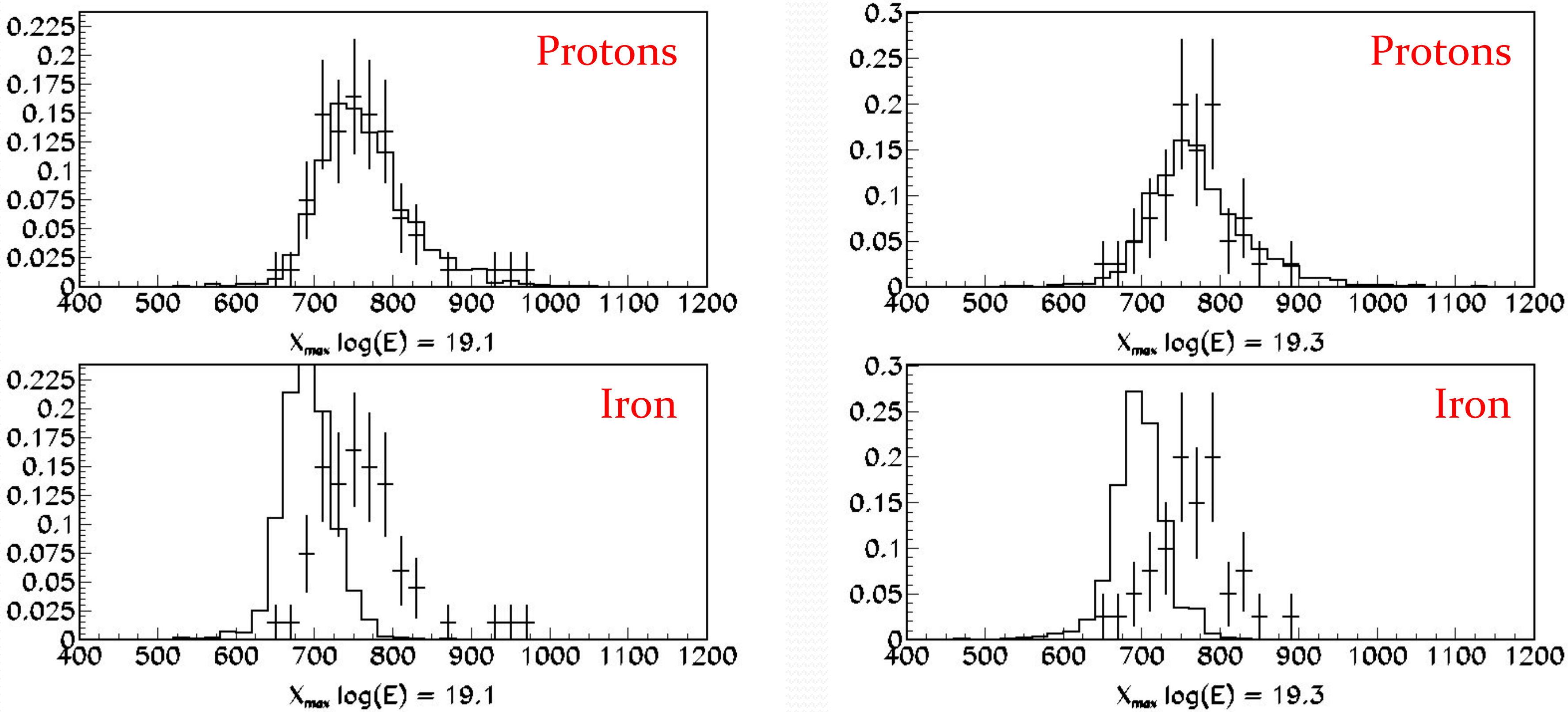

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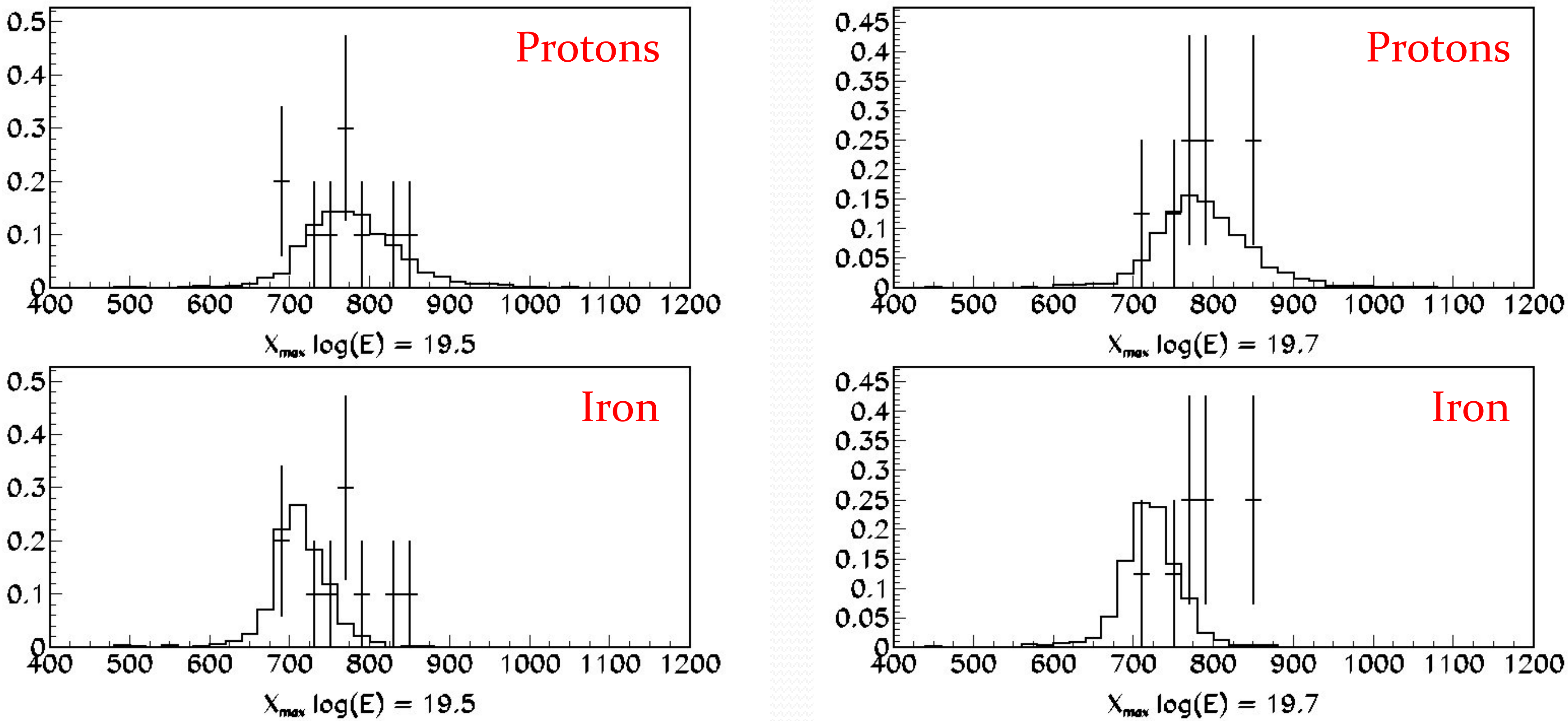
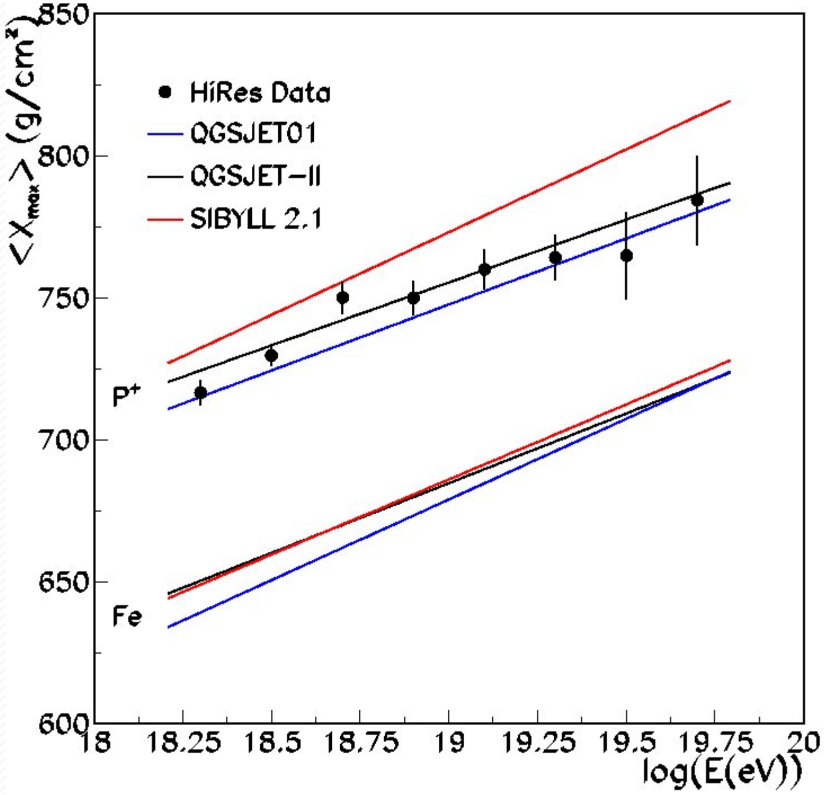


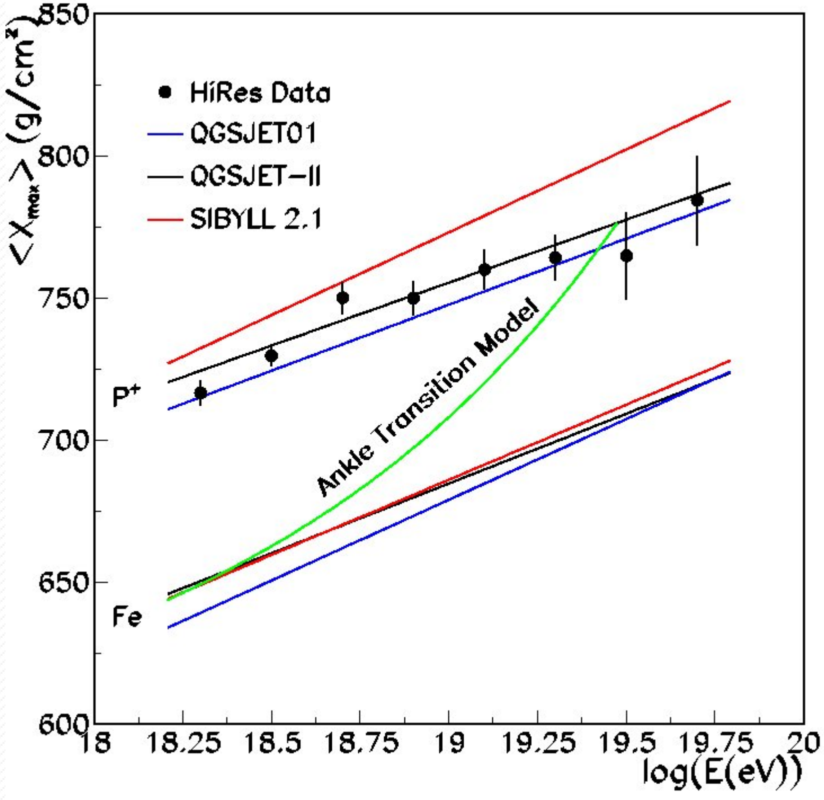
Mean X_{max} Measurement

- Each data distribution replaced by *one* number, the mean
- Comparison with 3 high-energy hadronic interaction models.
  - Expectation *after* detector effects is shown



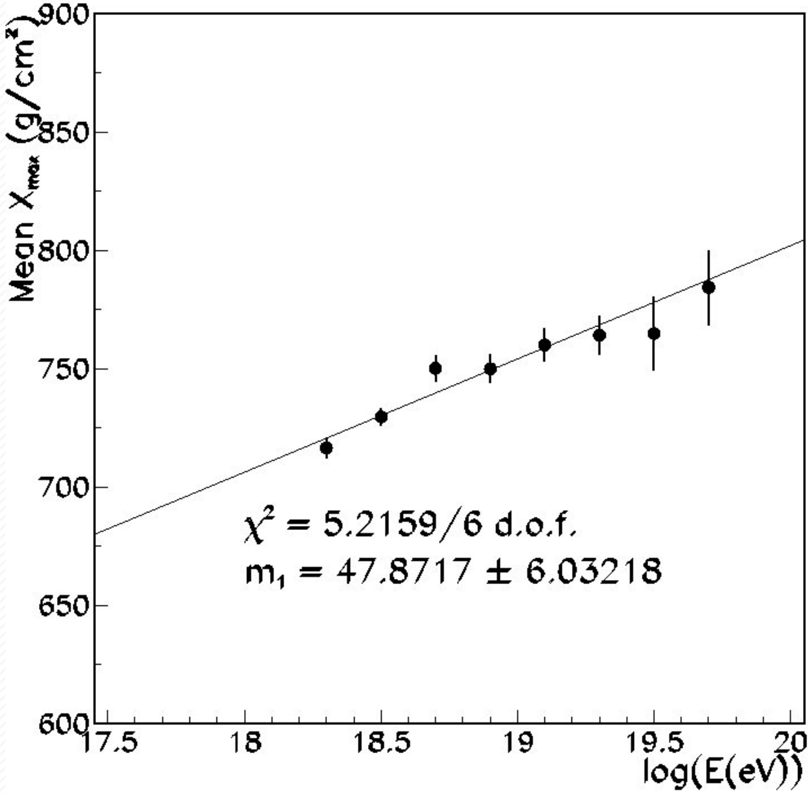
Mean X_{max} Measurement

- Each data distribution replaced by *one* number, the mean
- Comparison with 3 high-energy hadronic interaction models.
  - Expectation *after* detector effects is shown
- HiRes rules out models in which “ankle” is location of galactic-to-extragalactic transition. (Berezinsky, 2007 ICRC)



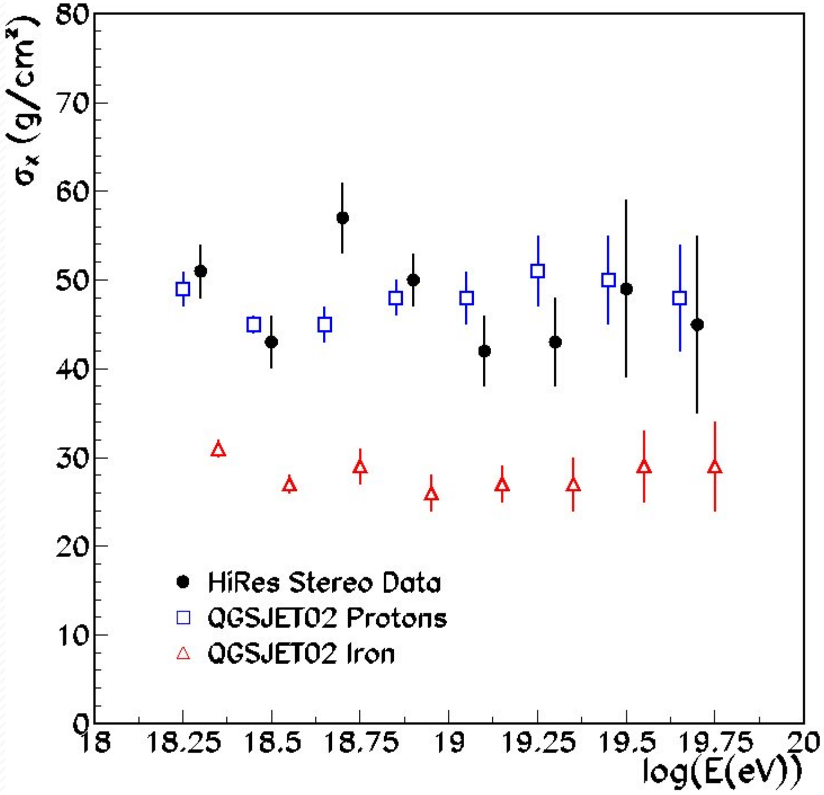
Elongation Rate

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



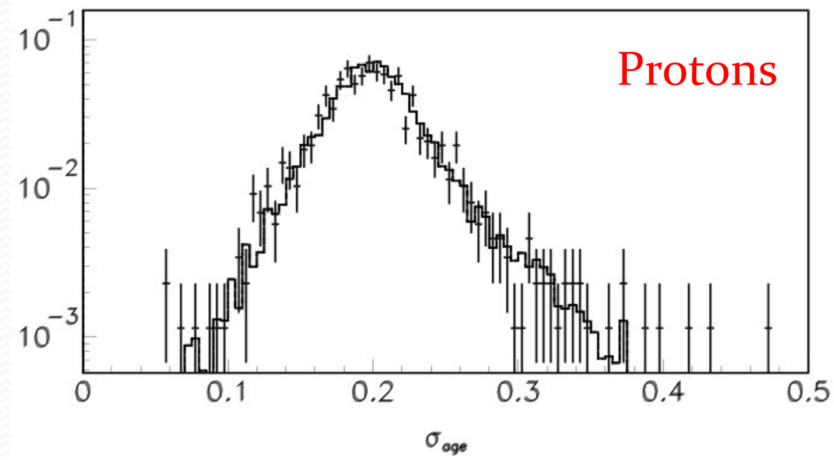
Width of X_{max} Distribution

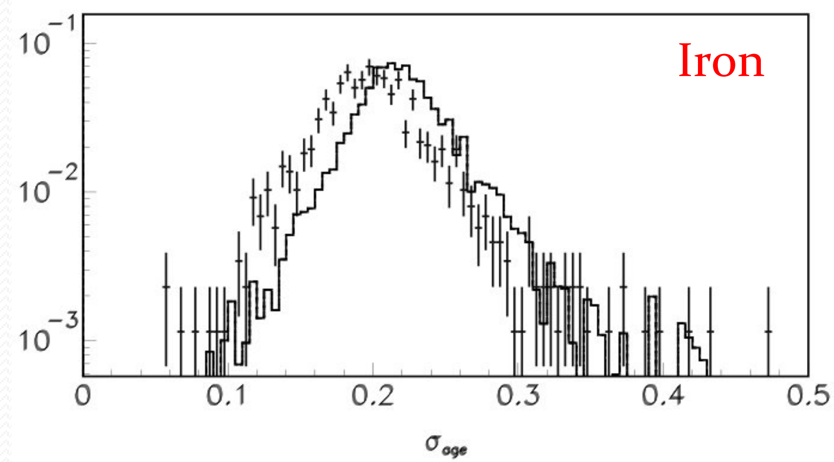
- Tails of X_{max} Distribution may not be Gaussian (especially for protons)
  - Need to treat width carefully
- Define width as σ of a fit Gaussian, where the fit is truncated at 2×RMS
  - Focus attention on core of distribution
  - Avoid RMS undersampling bias
- Data consistent with QGSJET-II protons
- R. Abbasi *et al., Phys. Rev. Lett.* **104** (2010).



Width of Individual Showers

- Each shower has a width
  - Shower well modelled by Gaussians in *age*
  - Distribution of widths also favors protons (QGSJet-II)





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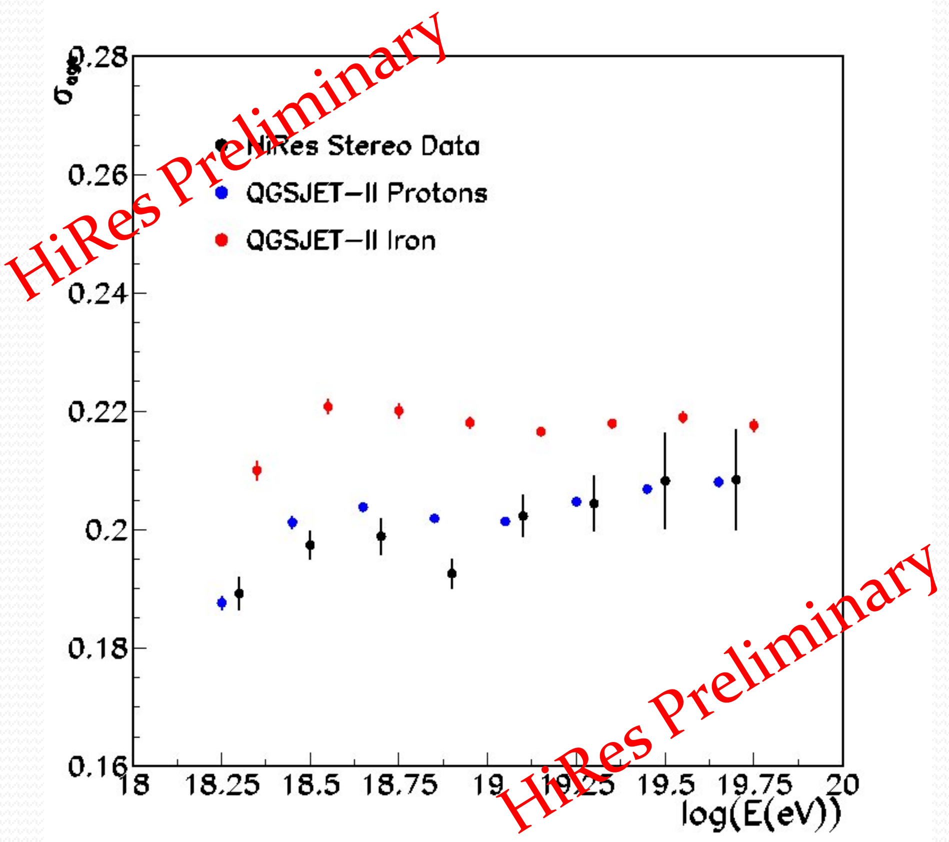
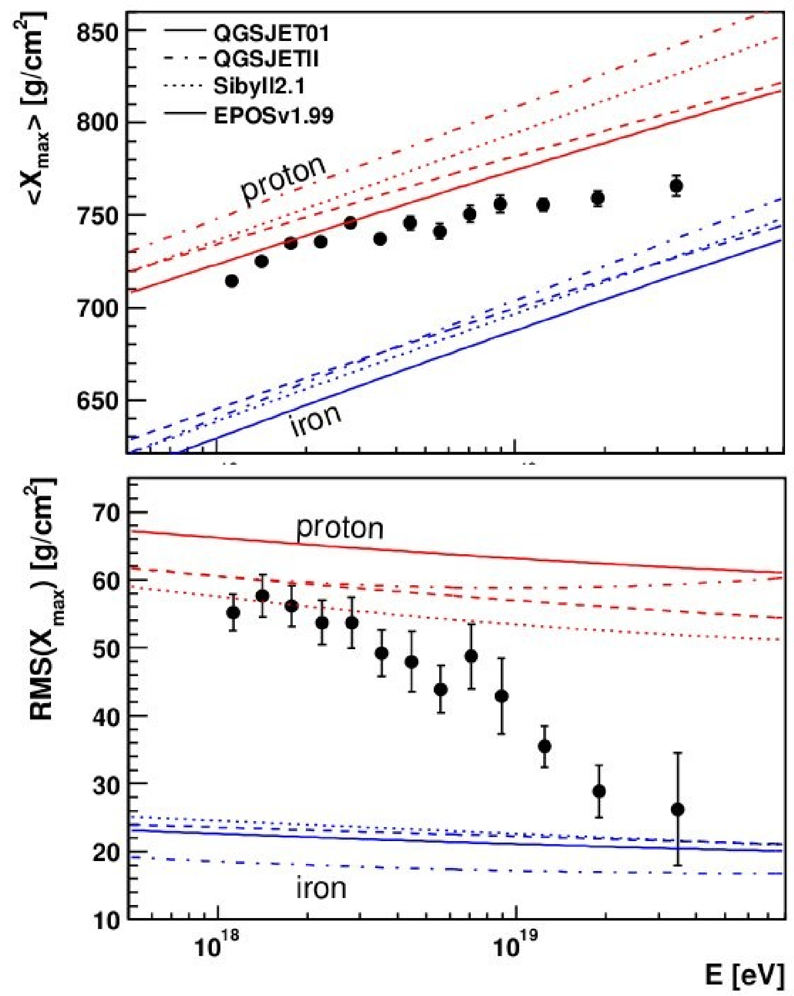


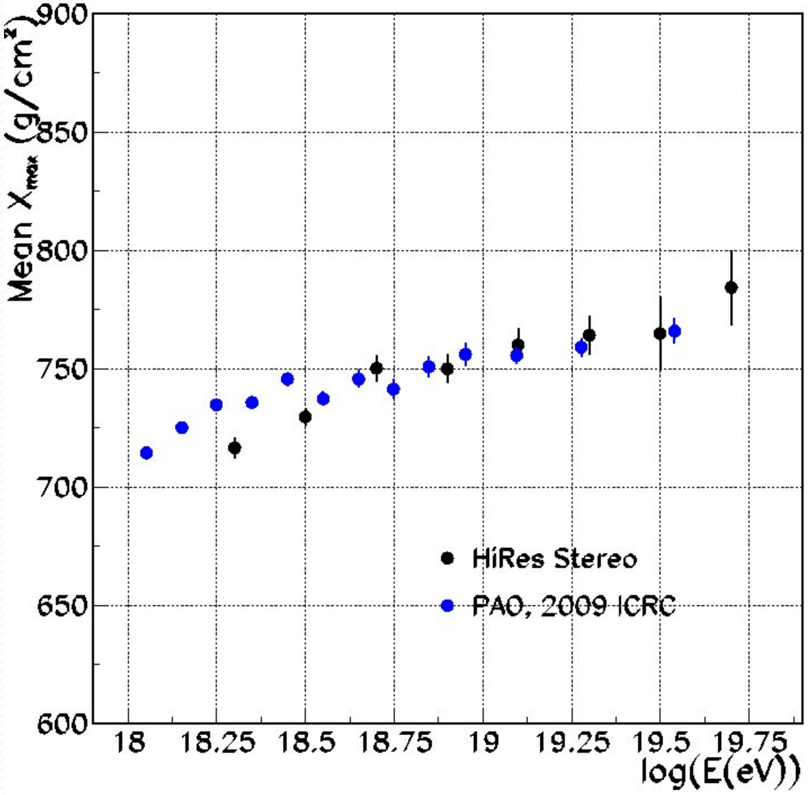
Composition Comparison with Auger

- Southern Hemisphere observatory reaches startlingly different conclusions
- Mean X_{max} indicates composition getting heavy.
- Width indicates all iron by 3×10^{19}!



Composition Comparison with Auger

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



Spectrum & 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 > 1.6 EeV
  - 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.
- HiRes spectral and composition results can be explained with a simple model:

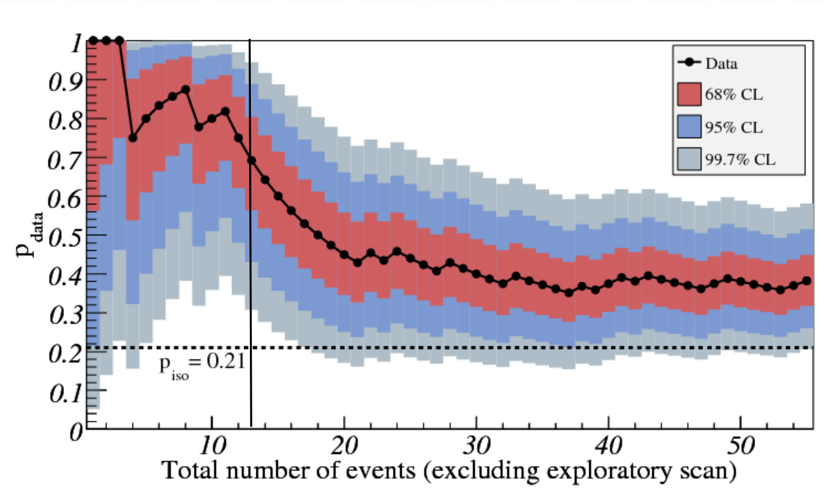
  Cosmic rays above 1 EeV are protons of extragalactic origin. The high-energy spectrum is shaped by interactions of these protons with the CMBR.

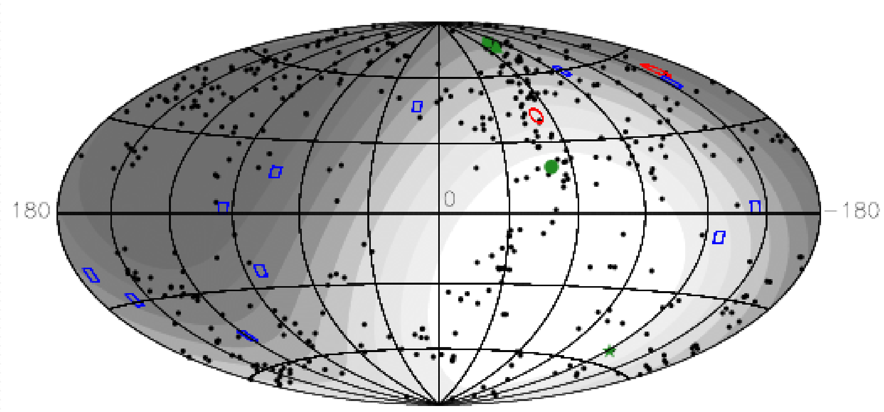
Searches for Anisotropies

- HiRes data indicates:
  - UHECR's are protons
  - Many come from far away
    - Otherwise no GZK
    - Beyond 50 Mpc
- Trajectories rigid enough to point back to origin
  - Look for correlations with various objects (say AGN as Auger has done)
  - Or look for correlation with mass structure out to 250 Mpc using flux limited samples (2MASS)

AGN Correlations

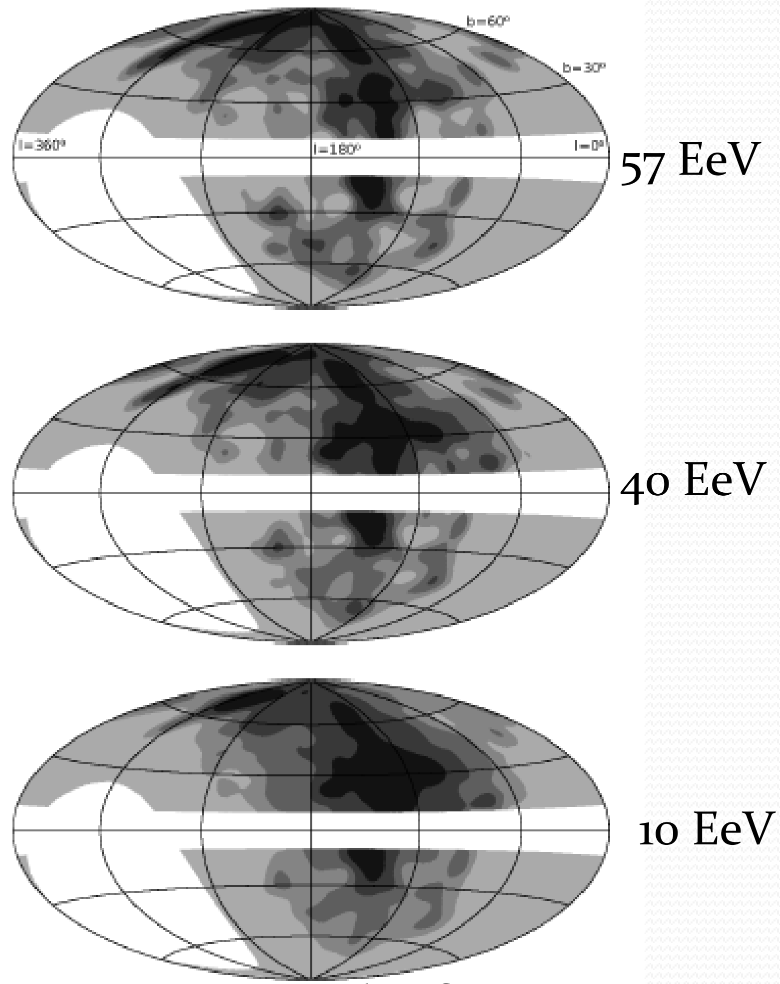
- Auger had found evidence of correlations with AGN
  - Best at (57 EeV, 3.1°, .018)
  - Tested with later data: 8/13, 0.002 (2.9σ)
  - With more data: 12/42, 8.8 e3xpected (only 1σ)
- HiRes tested
  - Using Auger point: 2/12, P = 0.23
  - Best point in HiRes data:
    - (15.8 EeV, 2.5°, 0.016), 46/198 P = 0.29





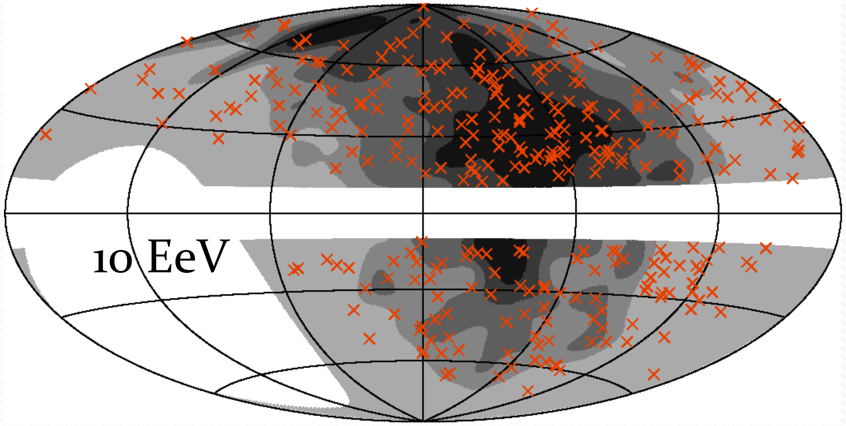
UHECR Correlation with LSS

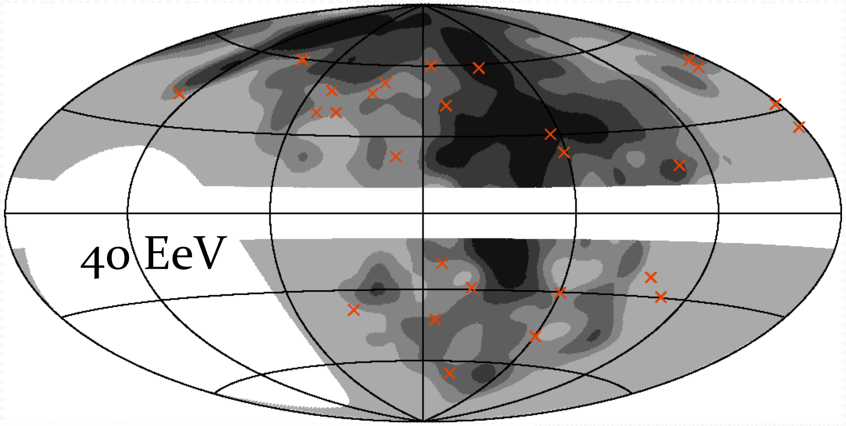
- Start with 2MASS to create LSS model
  - Smear by variable angle
  - Limit distance by energy
- Convolve with HiRes exposure
- Perform K-S test based on density of LSS model

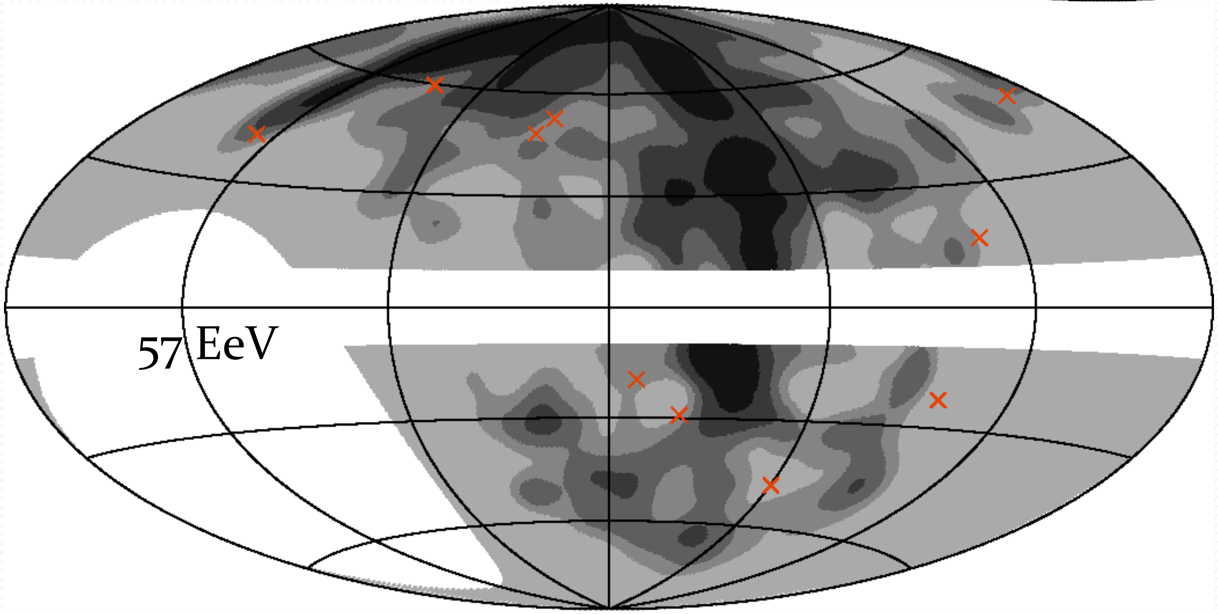


Smearing angle of 6°

UHECR Correlation with LSS

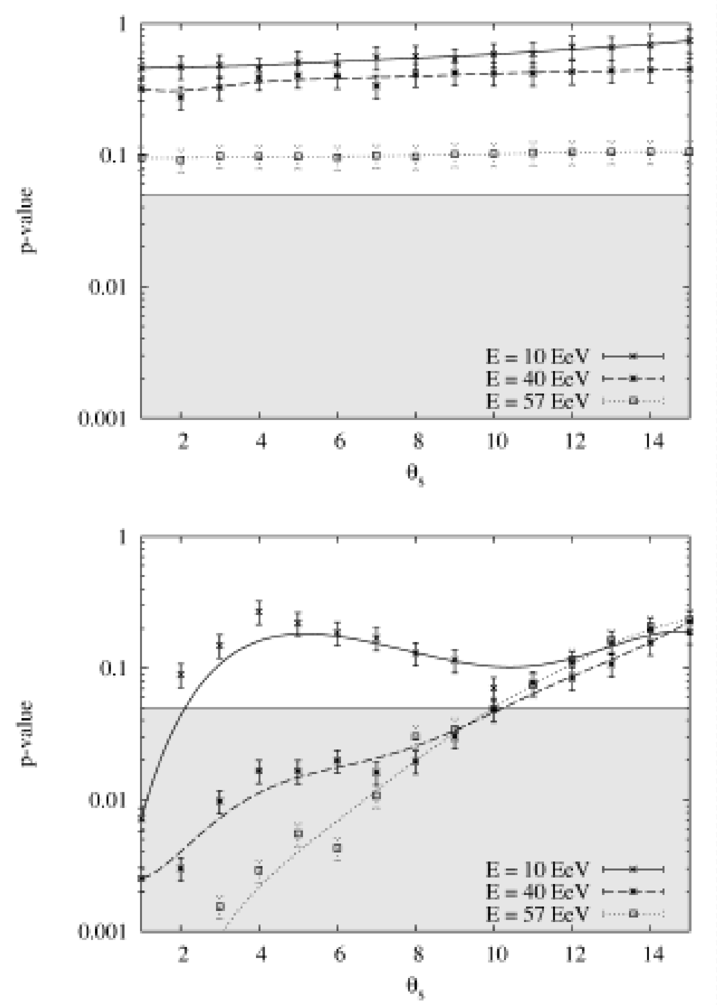






UHECR Correlation with LSS

- Plot K-S probability for both isotropic and LSS models
- Choose 95% CL *a priori*
- Good agreement with isotropy
- Poor agreement at small scattering angles for LSS
- No correlation at 95% CL for E > 40 EeV and $\theta_s < 10°$



Conclusions

- HiRes has observed the GZK cutoff in both monocular and stereo modes
- HiRes finds the composition of UHECR's above 1 EeV to be predominantly light, as one might expect from the presence of the GZK cutoff
- HiRes observes no correlation with the local, large-scale structure of the universe
  - The lack of correlations is surprising since magnetic field smearings are only expected to be at the 5° level
  - The Telescope Array is currently operating in the North, and will provide much more anisotropy data