Results from the Telescope Array Experiment

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Outline

- Introduction
- TA Results:
  - Spectrum
  - Composition
  - Search for anisotropy
  - Search for photon, neutrino events
- TALE, Radar projects
- Conclusions

Cosmic Rays above 10^{18} eV are likely of Extragalactic Origin

- What are the sources?
  - **The biggest question.**
- Anisotropy.
  - Both galactic and extragalactic magnetic fields get in the way:
    - (1) the highest energy events are important;
    - (2) if the **composition** is heavy, sources are very hard to see.
- Spectrum.
  - There exists an absolute energy calibration: the GZK cutoff ➔ 5-6x10^{19} eV --- if protons. GZK develops in ~50 Mpc.
  - If heavy nuclei, spallation breaks them up above ~4x10^{19} eV, and distances < 50 Mpc. Spallation rate ~1 nucleon/Mpc.
- Composition. Protons, Fe, or what?
  - How does composition vary with energy?
  - **Disagreement among experiments.**

- **Everything talks to composition.**

Telescope Array Collaboration

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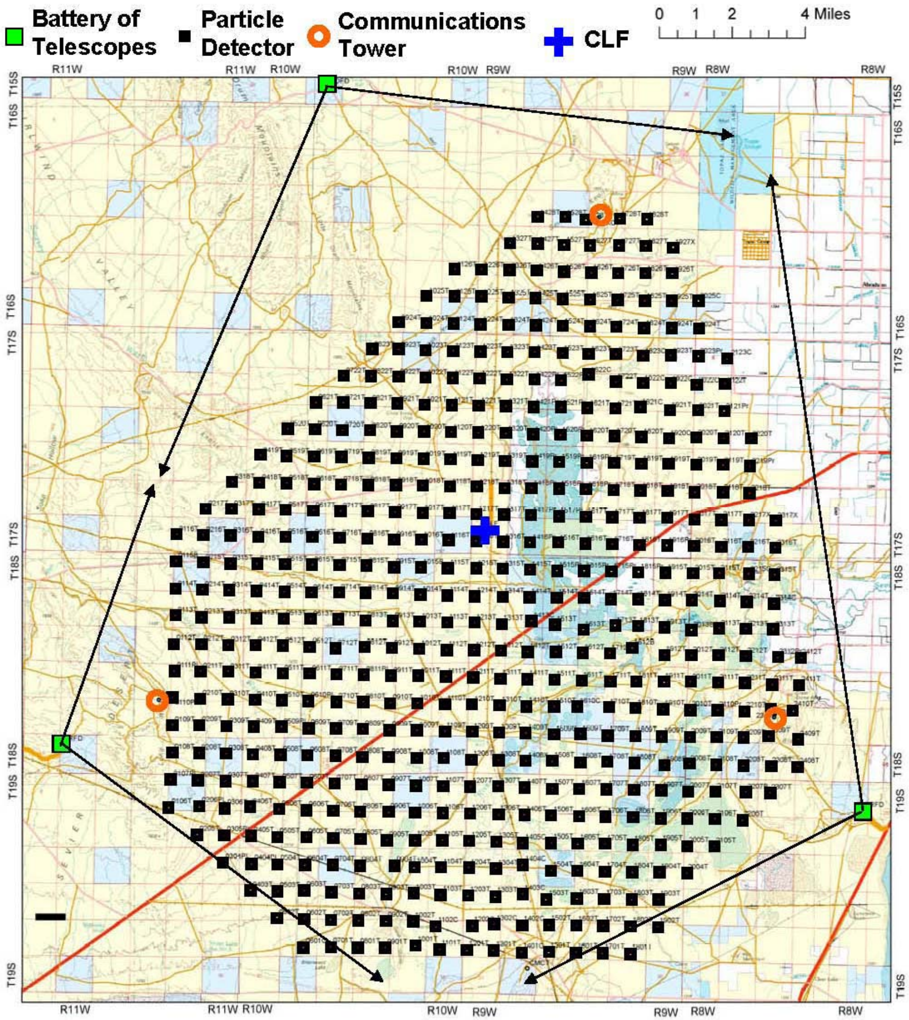
U.S., Japan, Korea, Russia, Belgium

TA is a Hybrid Experiment

- TA is in Millard Co., Utah, 2 hours drive from SLC.
- SD: 507 scintillation counters, 1.2 km spacing, scintillator area= 3 sq. m., two layers.
- FD: 3 sites, each covers 120° az., 3°-31° elev.
- ~4 years of data have been collected.

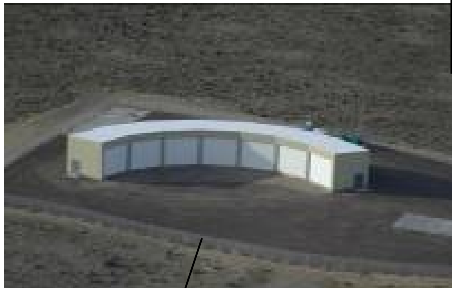


TA Fluorescence Detectors

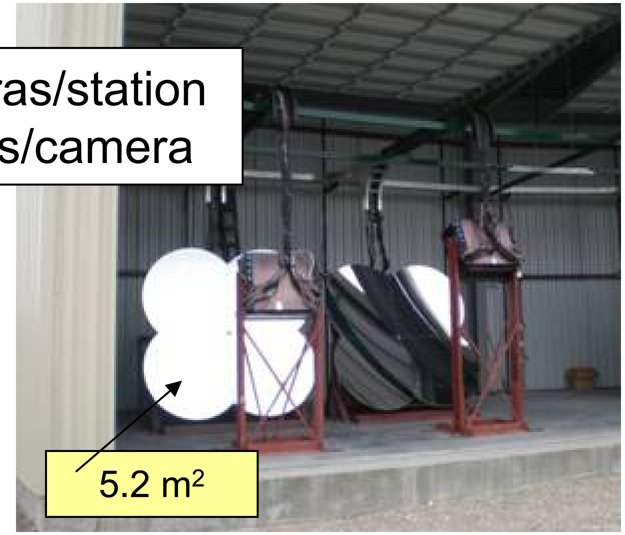
Refurbished from HiRes

Observation started Dec. 2007

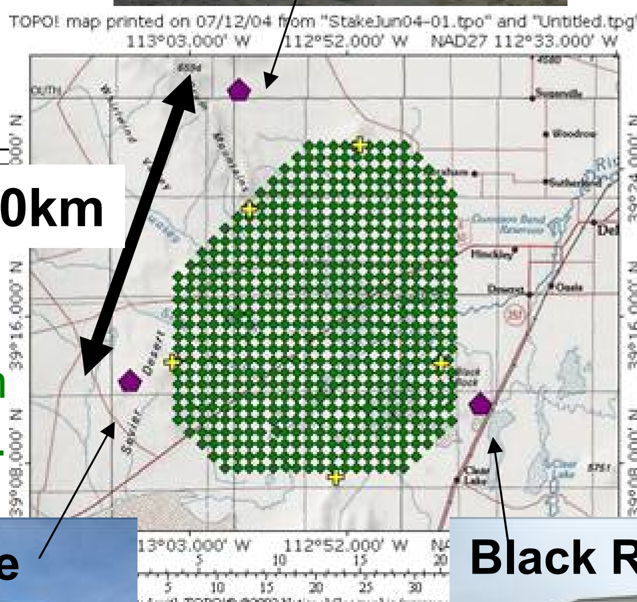
Middle Drum



14 cameras/station
256 PMTs/camera



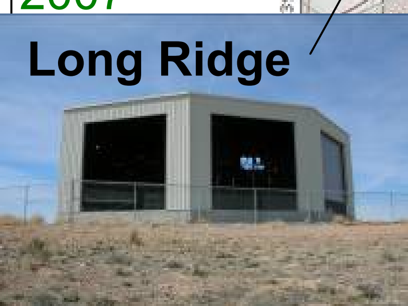
5.2 m²



~30km

Observation started Nov. 2007

Long Ridge



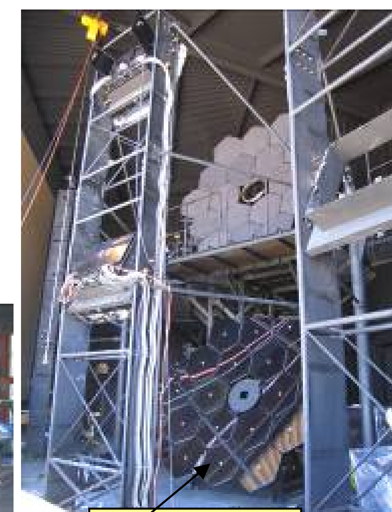
Black Rock Mesa

Observation started Jun. 2007

New FDs

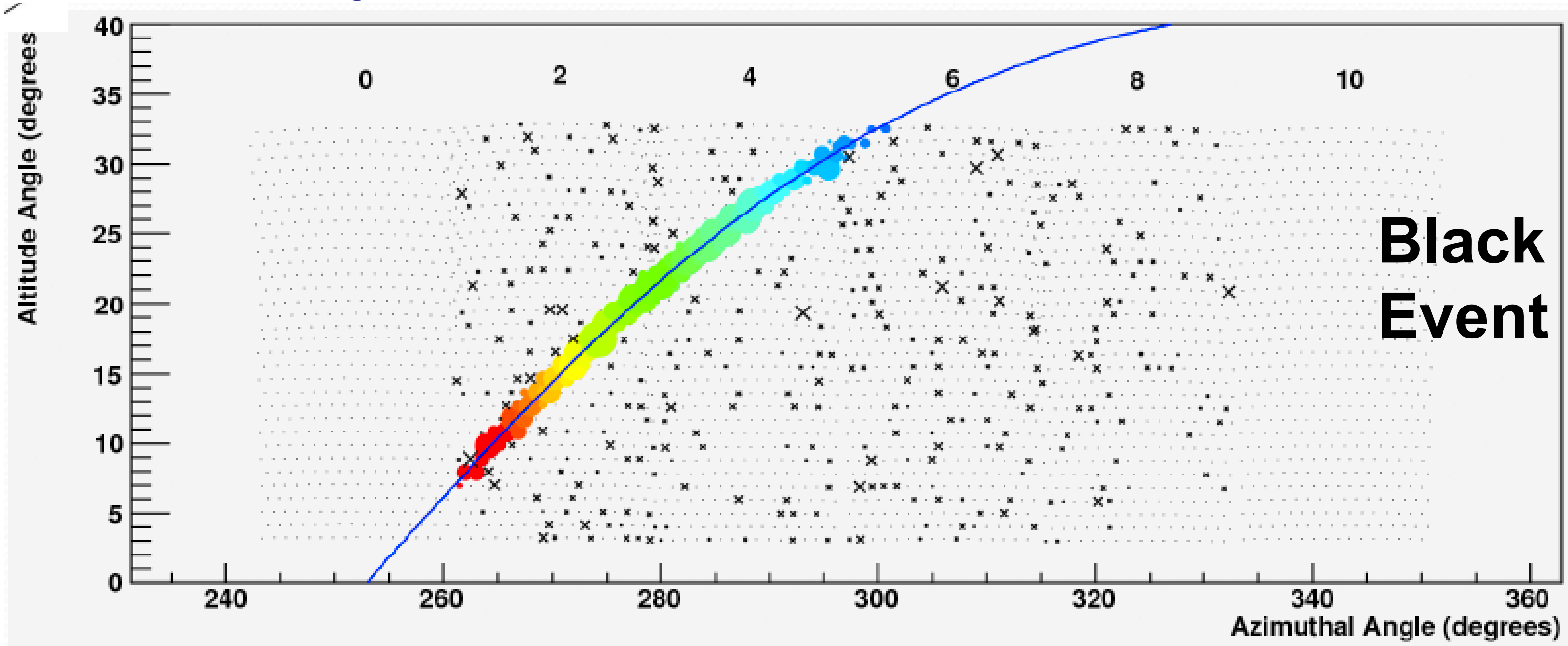
256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

~1 m²

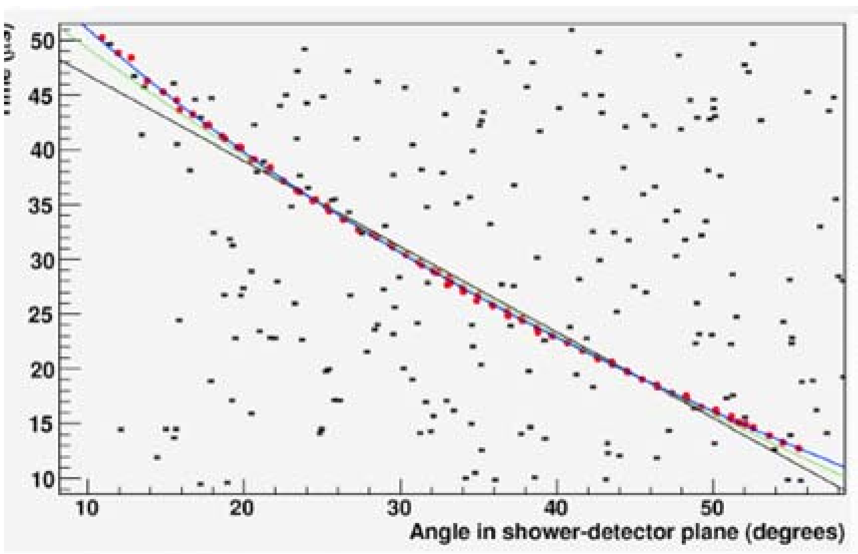


6.8 m²

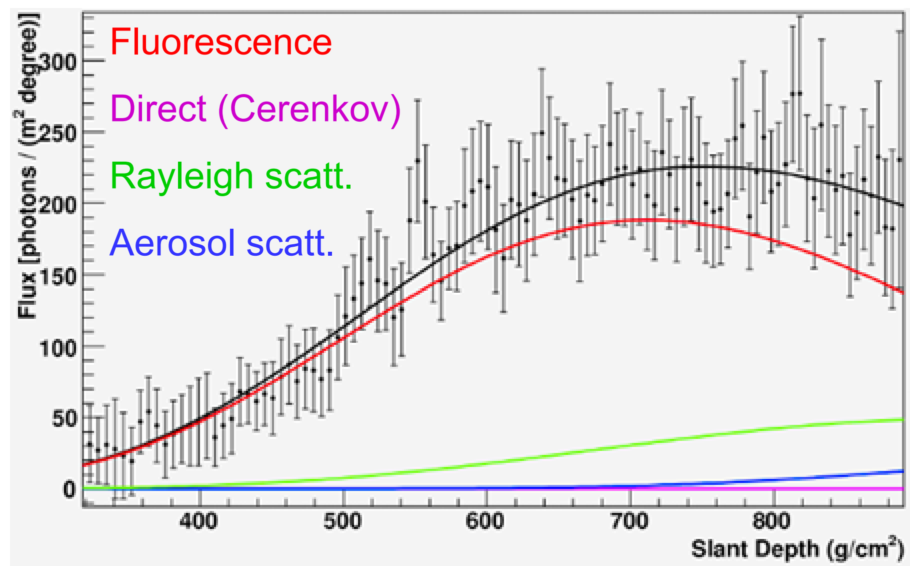
Typical Fluorescence Event



Black Rock Event Display



Monocular timing fit



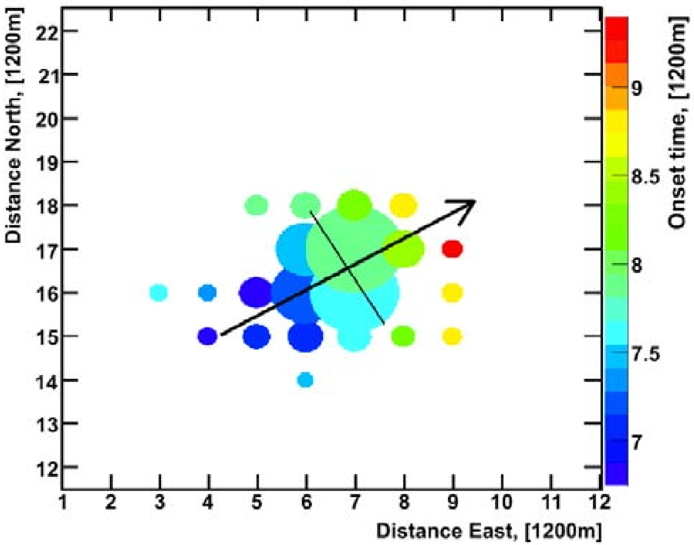
Reconstructed Shower Profile

TA Surface Detector

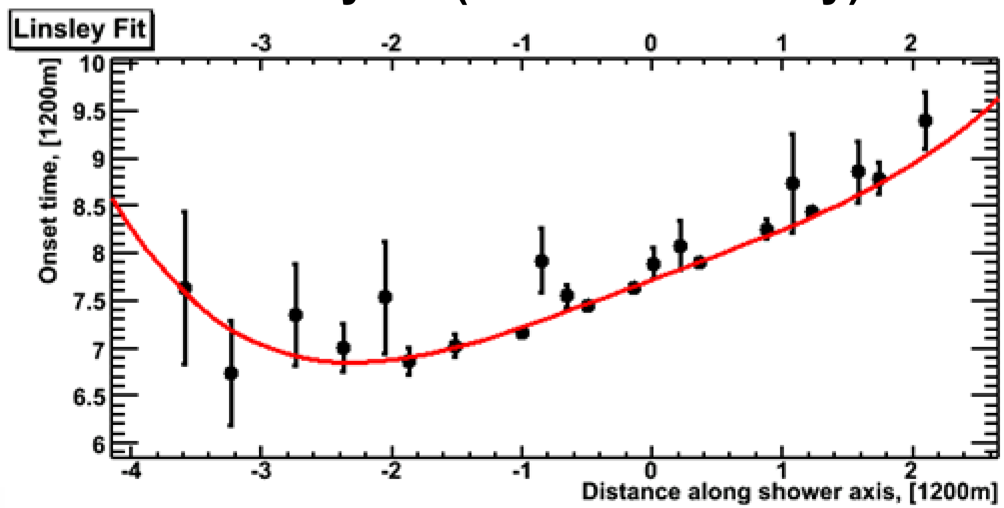
- Powered by solar cells; radio readout.
- Self-calibration using single muons.
- In operation since May, 2008.

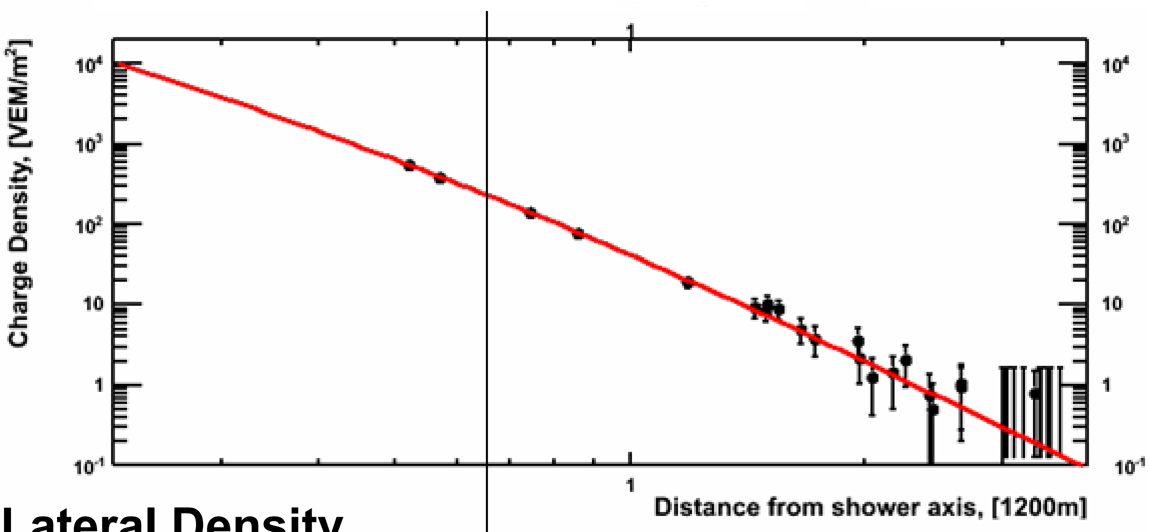
Typical surface detector event

2008/Jun/25 - 19:45:52.588670 UTC



Geometry Fit (modified Linsley)





Fit with AGASA LDF

$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2}\left(1+\frac{r}{R_M}\right)^{-(\eta-1.2)}\left\{1+\left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)(\sec\theta - 1)$$

- S(800): Primary Energy
- Zenith attenuation by MC (not by CIC).

Lateral Density Distribution Fit

r = 800m

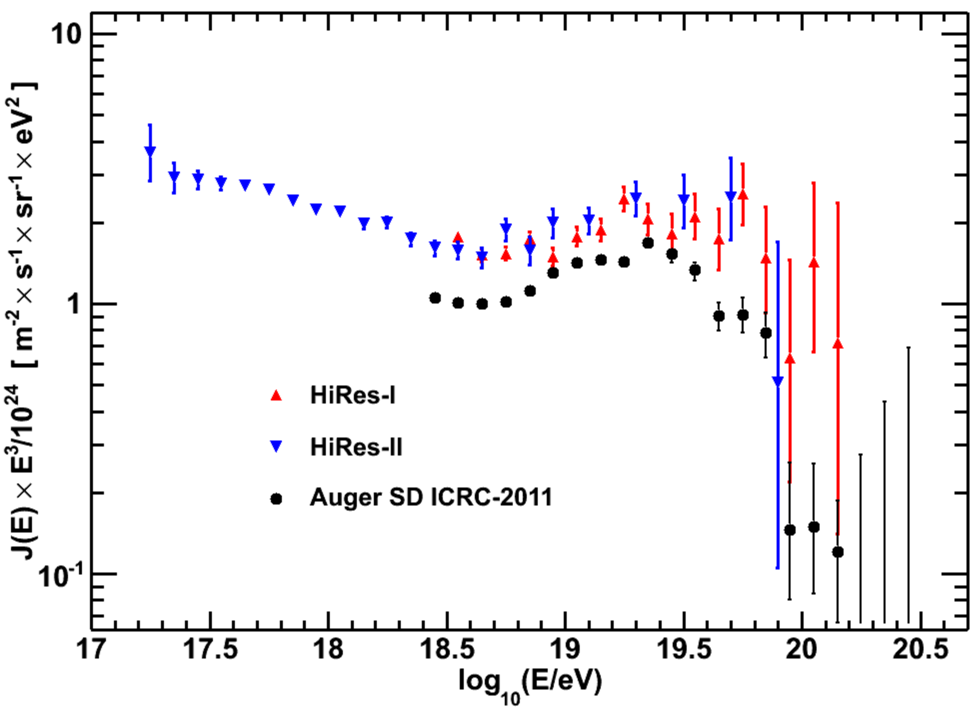
Stereo and Hybrid Observation

- Many events are seen by several detectors.
  - FD mono has ~5° angular resolution.
  - Add SD information (hybrid reconstruction) ➔ ~0.5° resolution.
  - Stereo FD resolution ~0.5°
- Need stereo or hybrid for composition analysis.

- Independent operation until 2010.
- Hybrid trigger is in operation.

Cosmic Ray Spectrum

- Status: the GZK cutoff was first observed by HiRes; Auger sees it also.
- The ankle shows up clearly in both spectra.



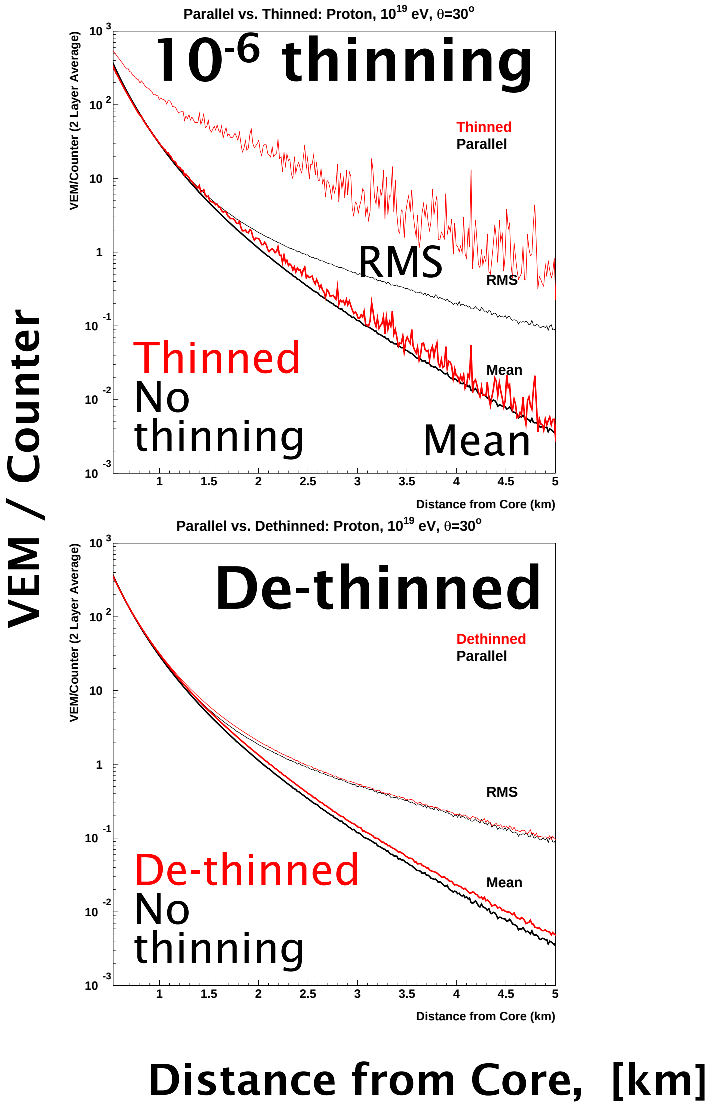
TA Spectrum (Measured by the Surface Detector)

- 3 years of data, 10997 events.
- We use a new analysis method.
  - Must cut out SD events with bad resolution. ➔ Must calculate aperture by Monte Carlo technique.
  - This is an important part of UHECR technique, and must be done accurately.
  - We use HEP methods for this purpose.

SD Monte Carlo

- Simulate the data exactly as it exists.
  - Start with previously measured spectrum and composition.
  - **Use Corsika/QGSJet events (solve "thinning" problem).**
  - Throw with isotropic distribution.
  - Simulate trigger, front-end electronics, DAQ.
- Write out the MC events in same format as data.
- Analyze the MC with the same programs used for data.
- Test with data/MC comparison plots.

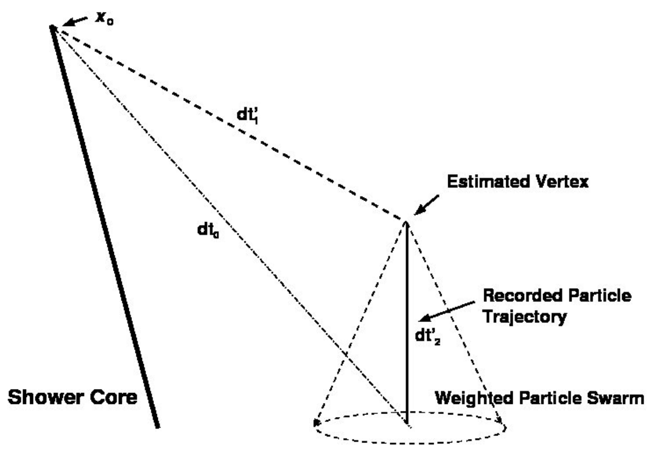
How to Use Corsika Events

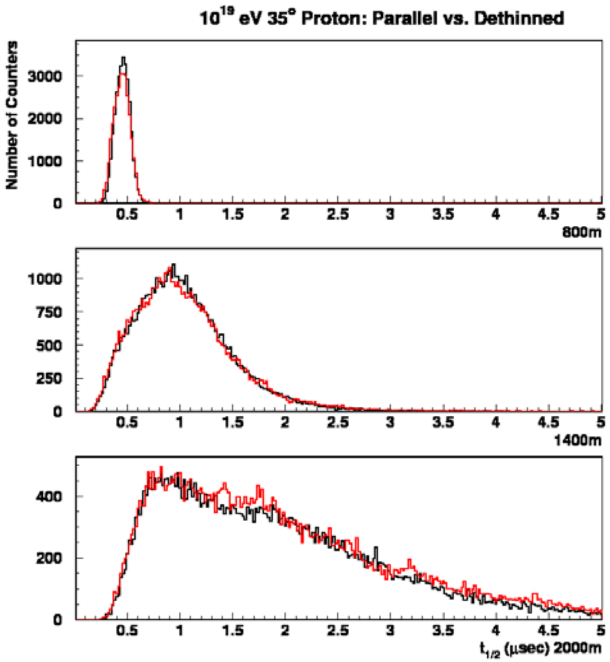


- Use 10^{-6} – thinned CORSIKA QGSJET-II proton showers that are de-thinned in order to restore information in the tail of the shower.
- De-thinning procedure is validated by comparing results with un-thinned CORSIKA showers, obtained by running CORSIKA in parallel
- We fully simulate the SD response, including actual FADC traces

Dethinning Technique

- Change each Corsika "output particle" of weight *w* to *w* particles; distribute in space and time.
- Time distribution agrees with unthinned Corsika showers.

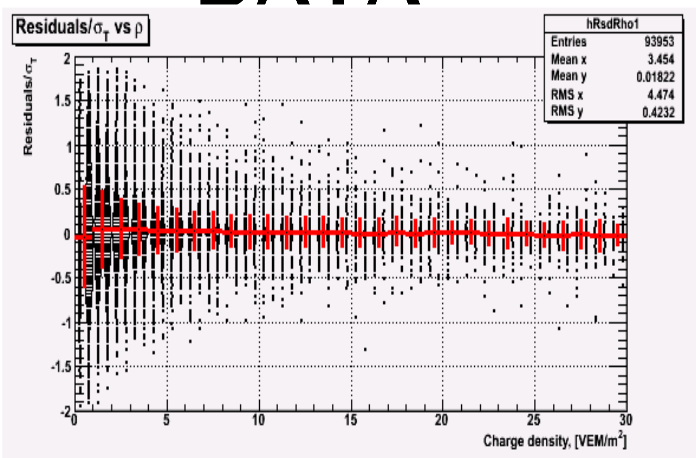




Fitting results

Time fit residual over sigma

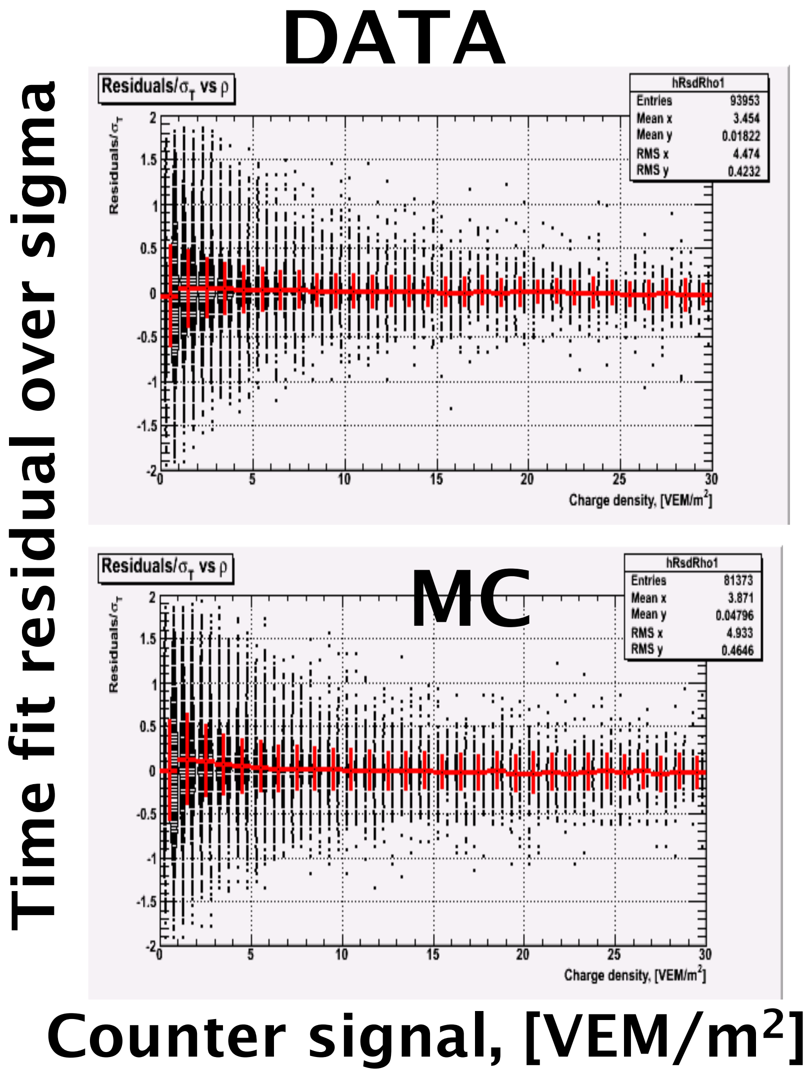
DATA



Counter signal, [VEM/m^2]

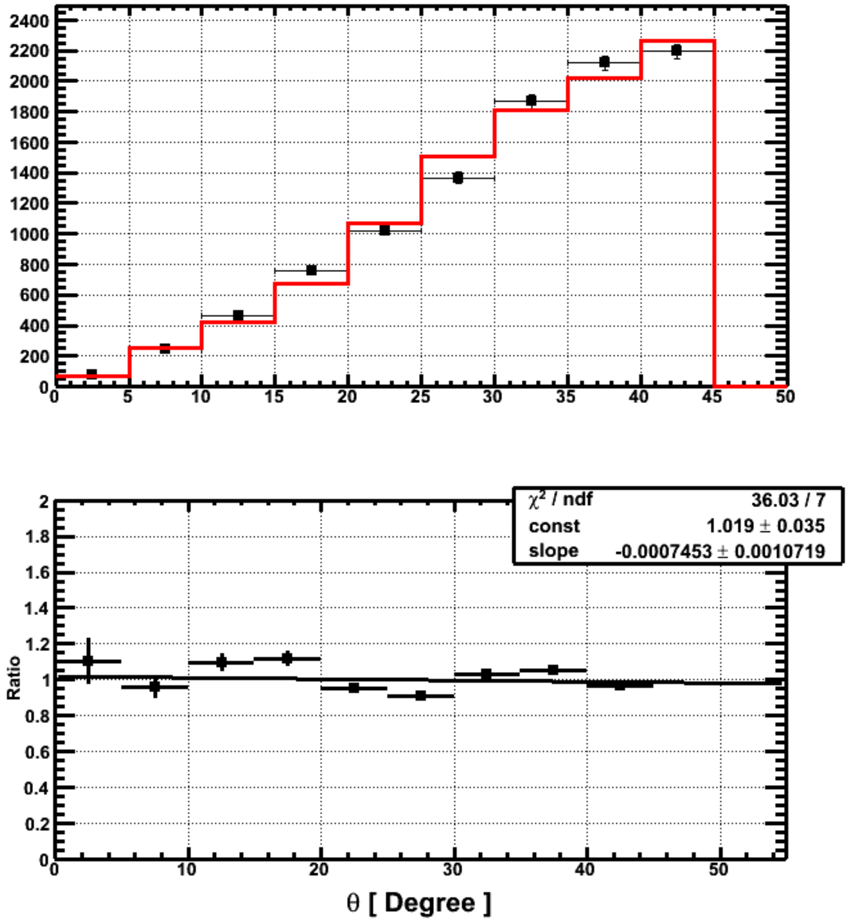
- **Fitting procedures are derived solely from the data**

Fitting results

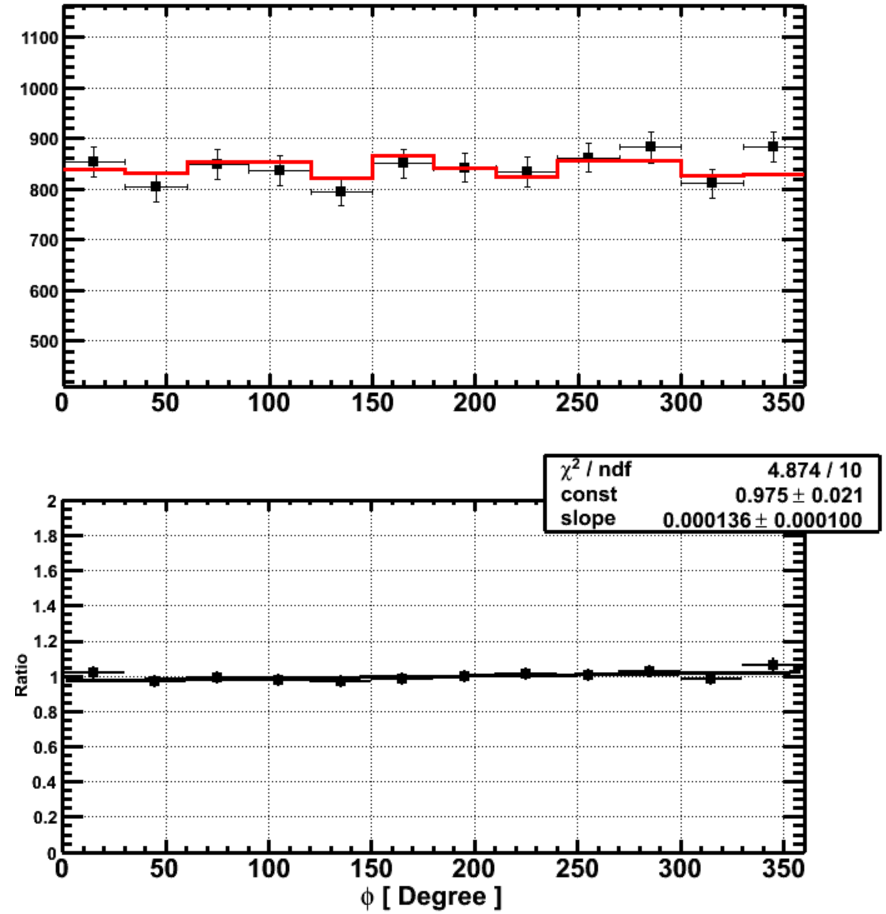


- Fitting procedures are derived solely from the data
- Same analysis is applied to MC
- Fit results are compared between data and MC
- MC fits the same way as the data.
- Consistency for both time fits and LDF fits.
- Corsika/QGSJet-II and data have same lateral distributions!

Data/MC Comparisons

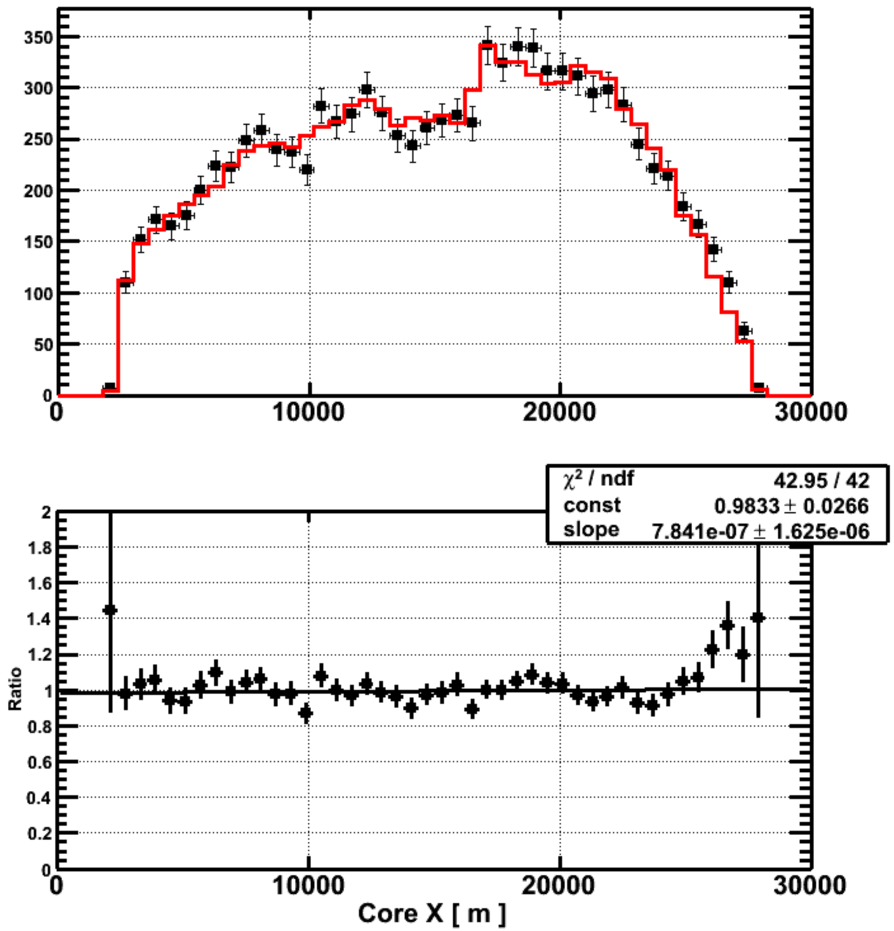


Zenith angle

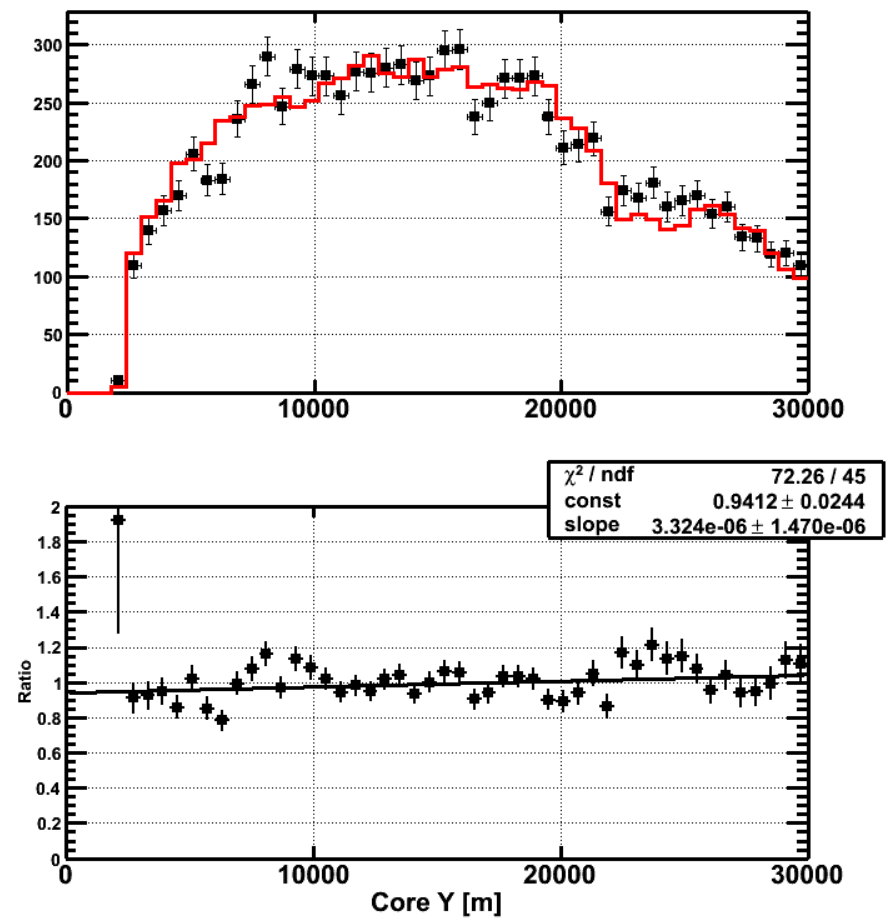


Azimuth angle

Data/MC Comparisons

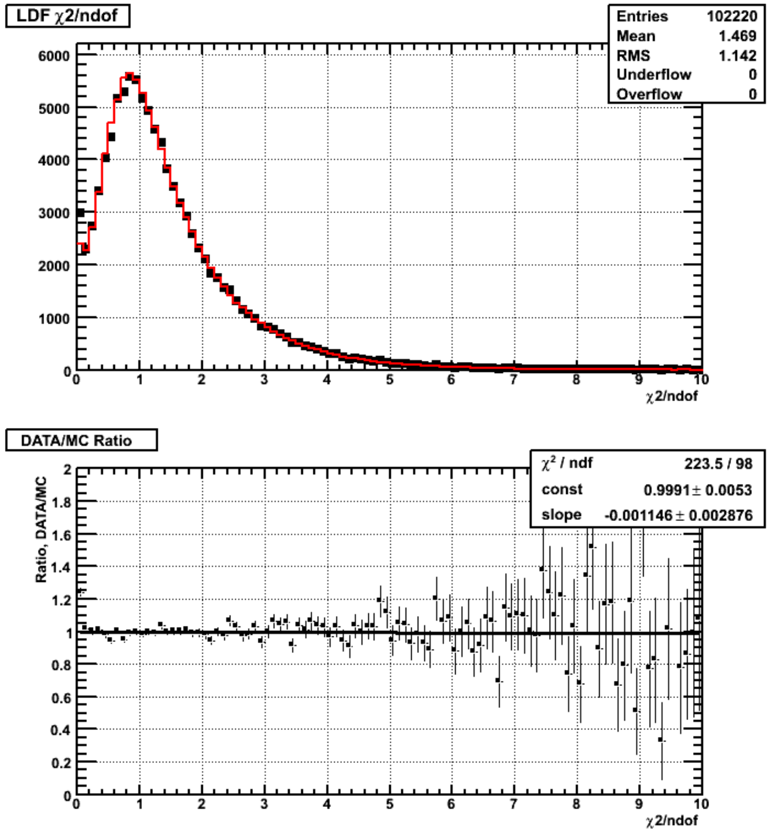


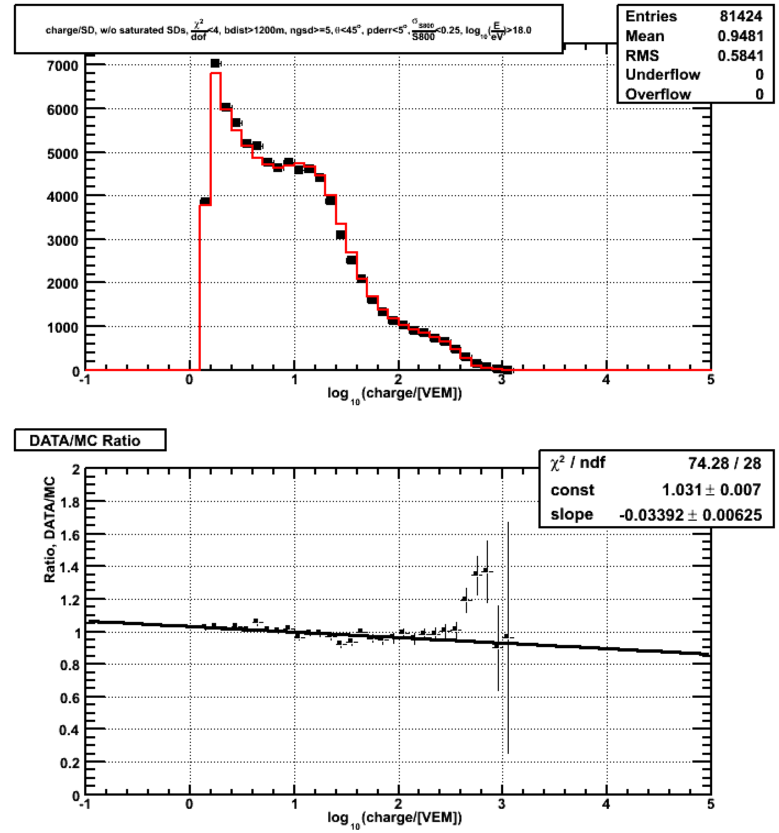
Core Position (E-W)



Core Position (N-S)

Data/MC Comparisons

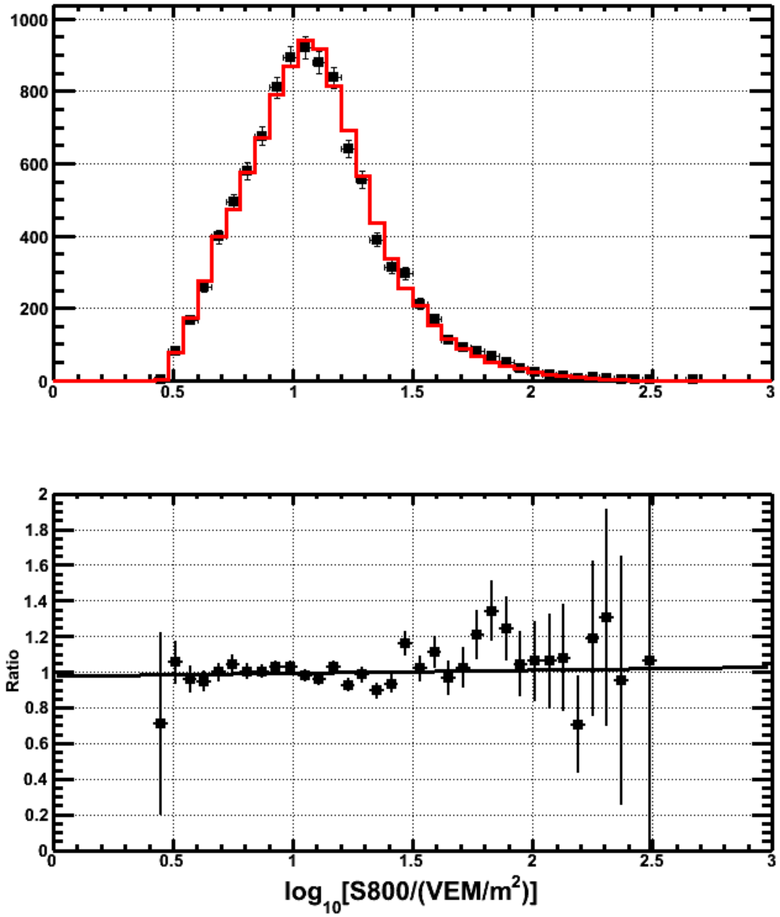




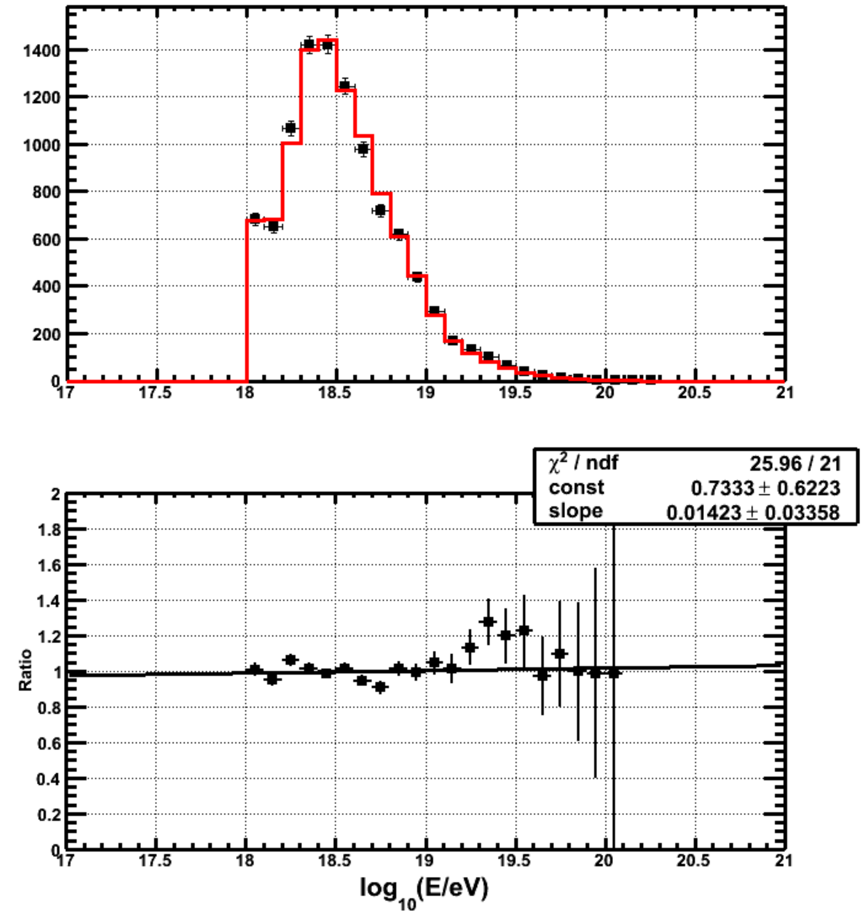
LDF χ^2/dof

Counter pulse height

Data/MC Comparisons

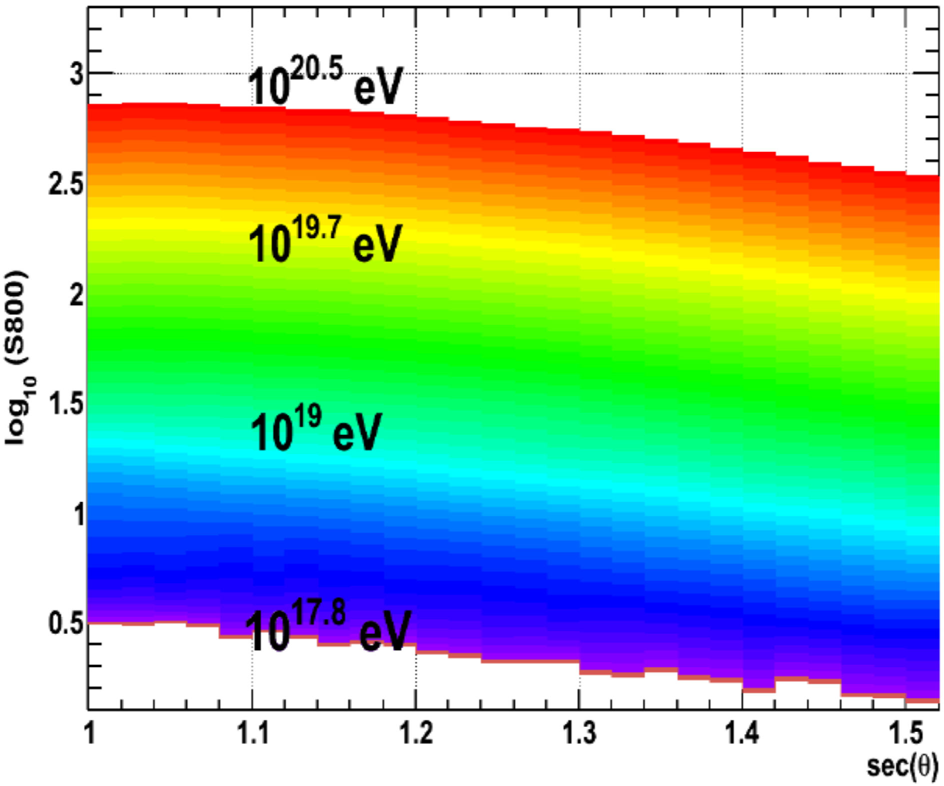


S_{800}



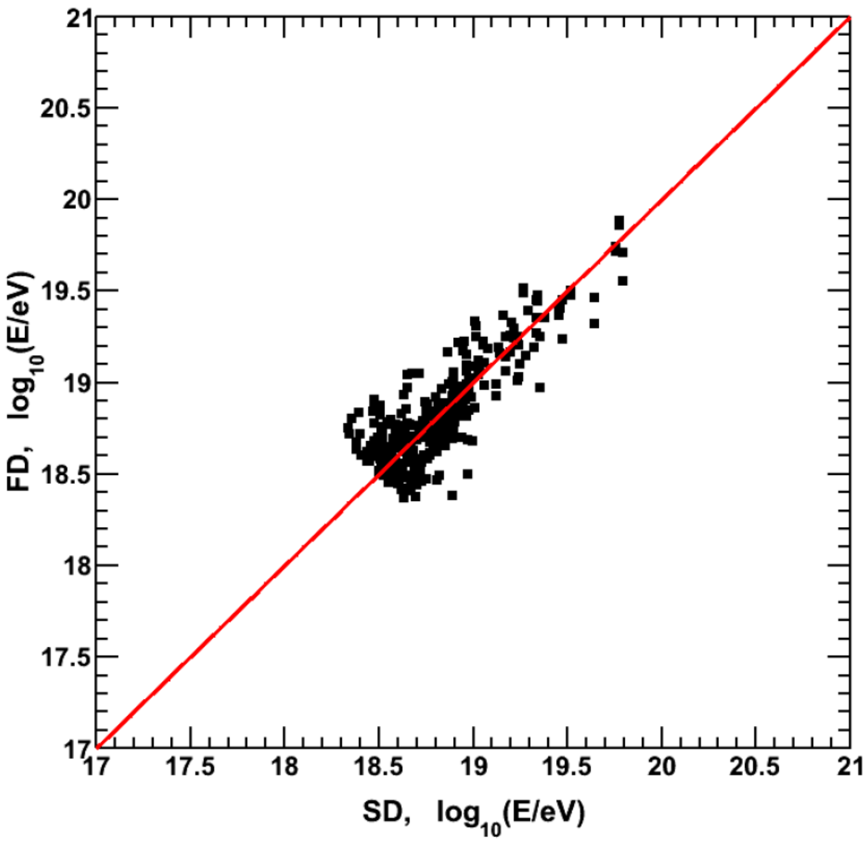
Energy

First Estimate of Energy



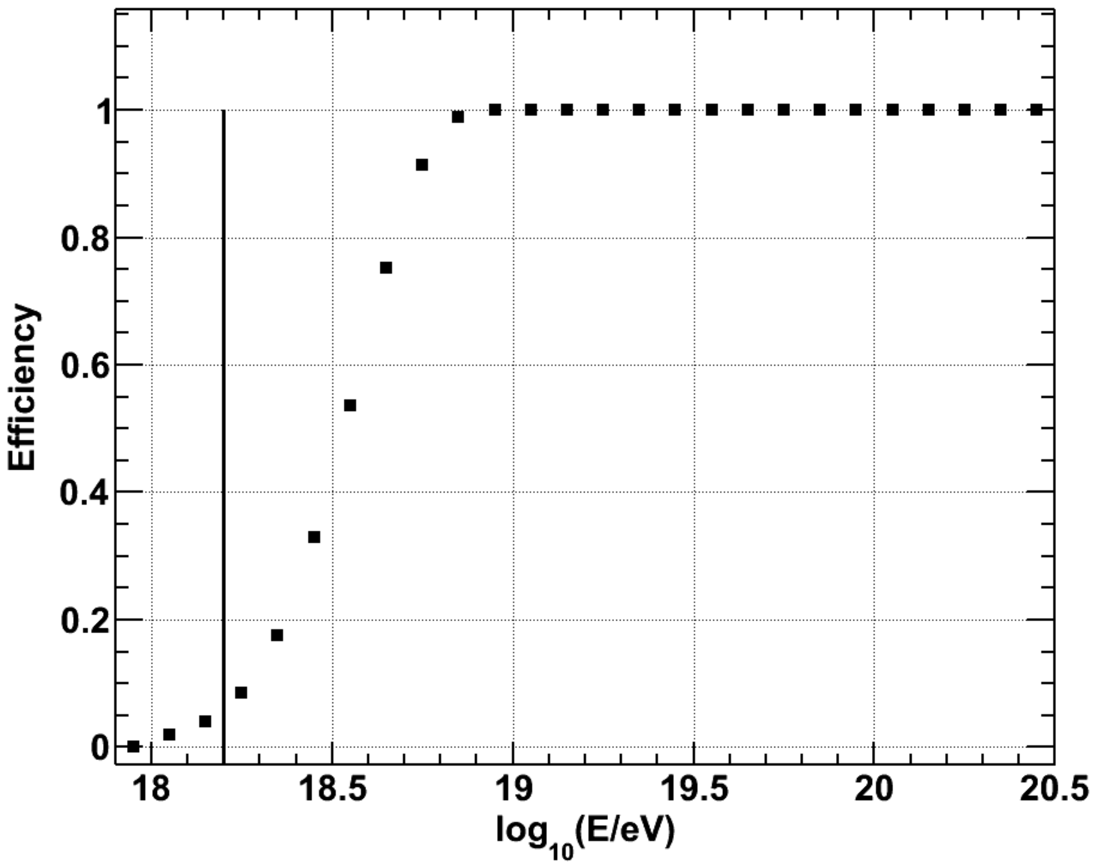
- Energy table is constructed from the MC
- First estimation of the event energy is done by interpolating between S800 vs sec(θ) lines

Energy Scale

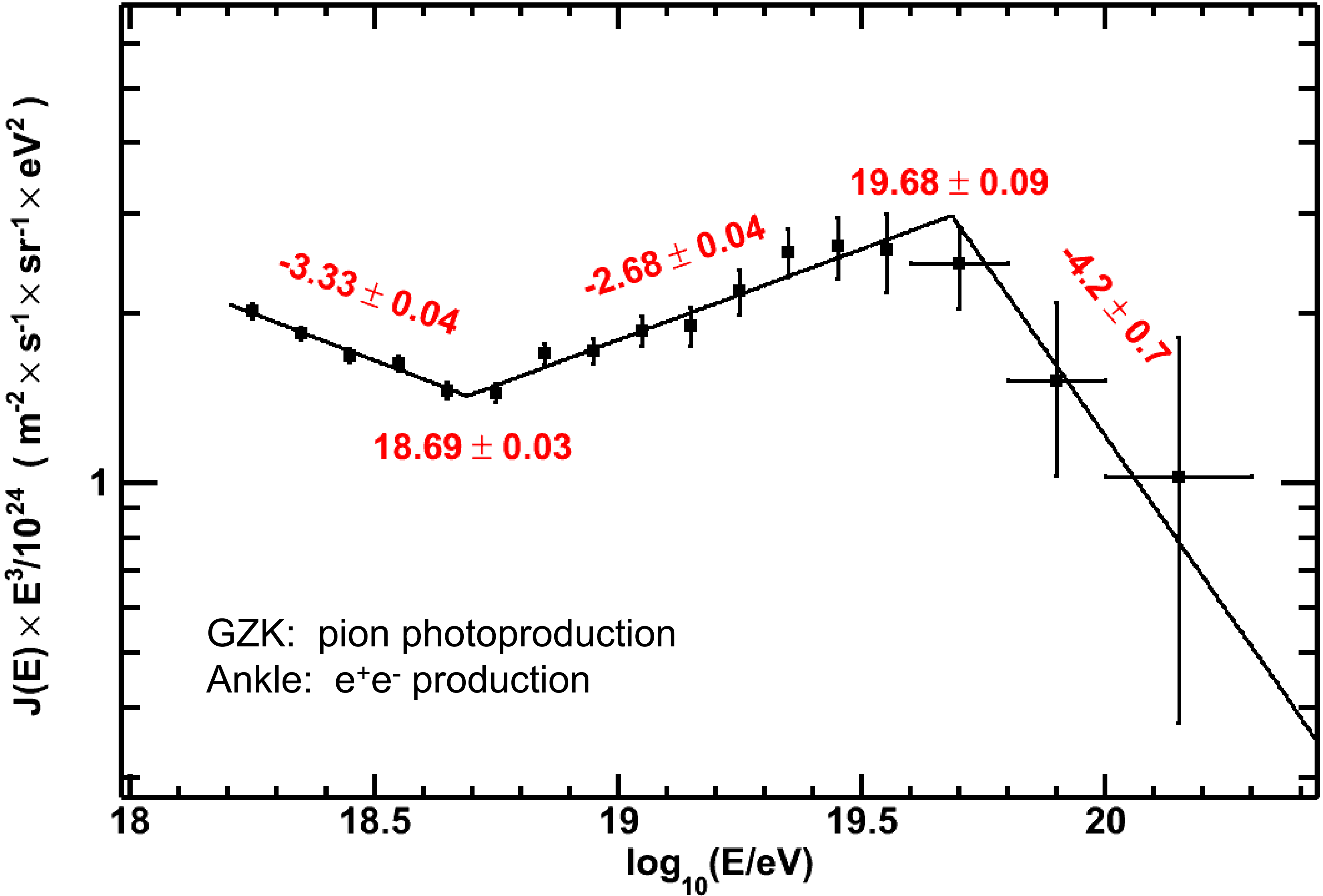


- SD and FD energy estimations disagree
- FD estimate possesses less model-dependence
- Set SD energy scale to FD energy scale using well-reconstructed events from all 3 FD detectors
- **27% renormalization.**

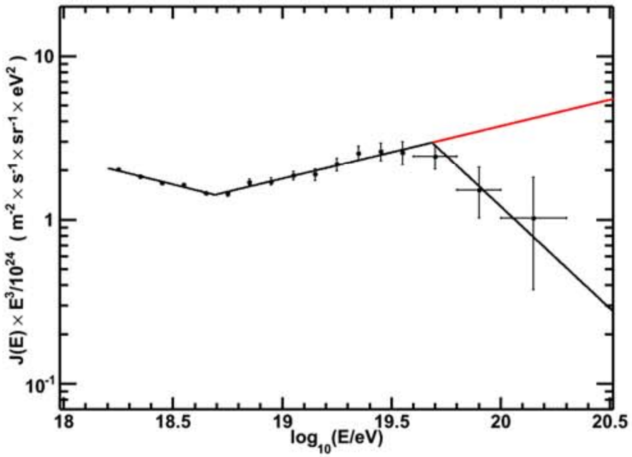
Acceptance

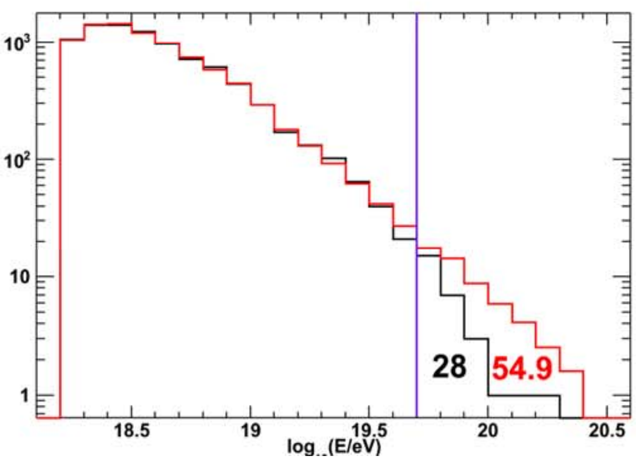


SD Energy Spectrum: Broken Power Law Fit



SD Energy Spectrum: GZK Feature



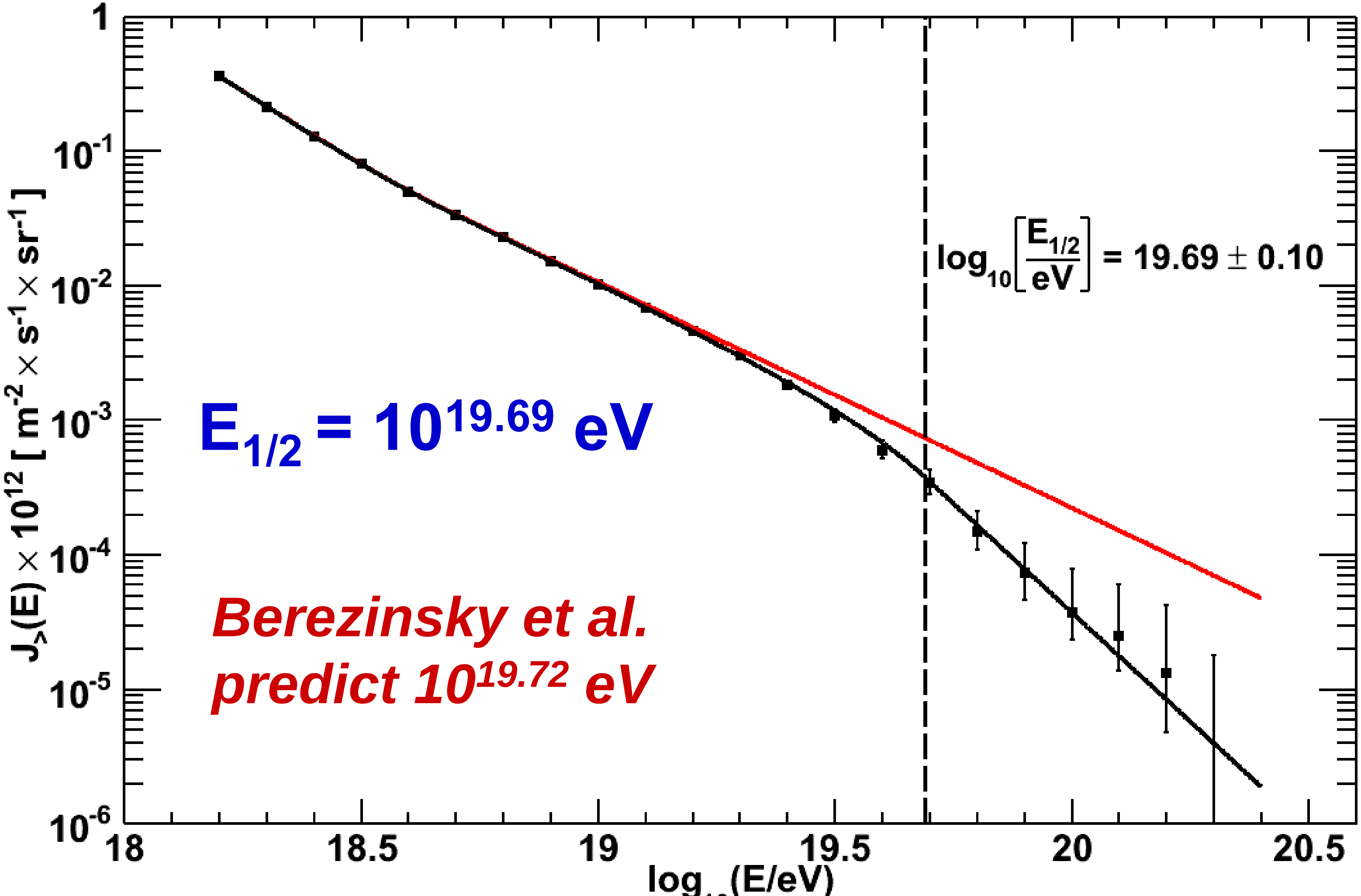


- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TA SD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}E$ bins after $10^{19.7}$eV bin:
  - $N_{EXPECT} = 54.9$
  - $N_{OBSERVE} = 28$

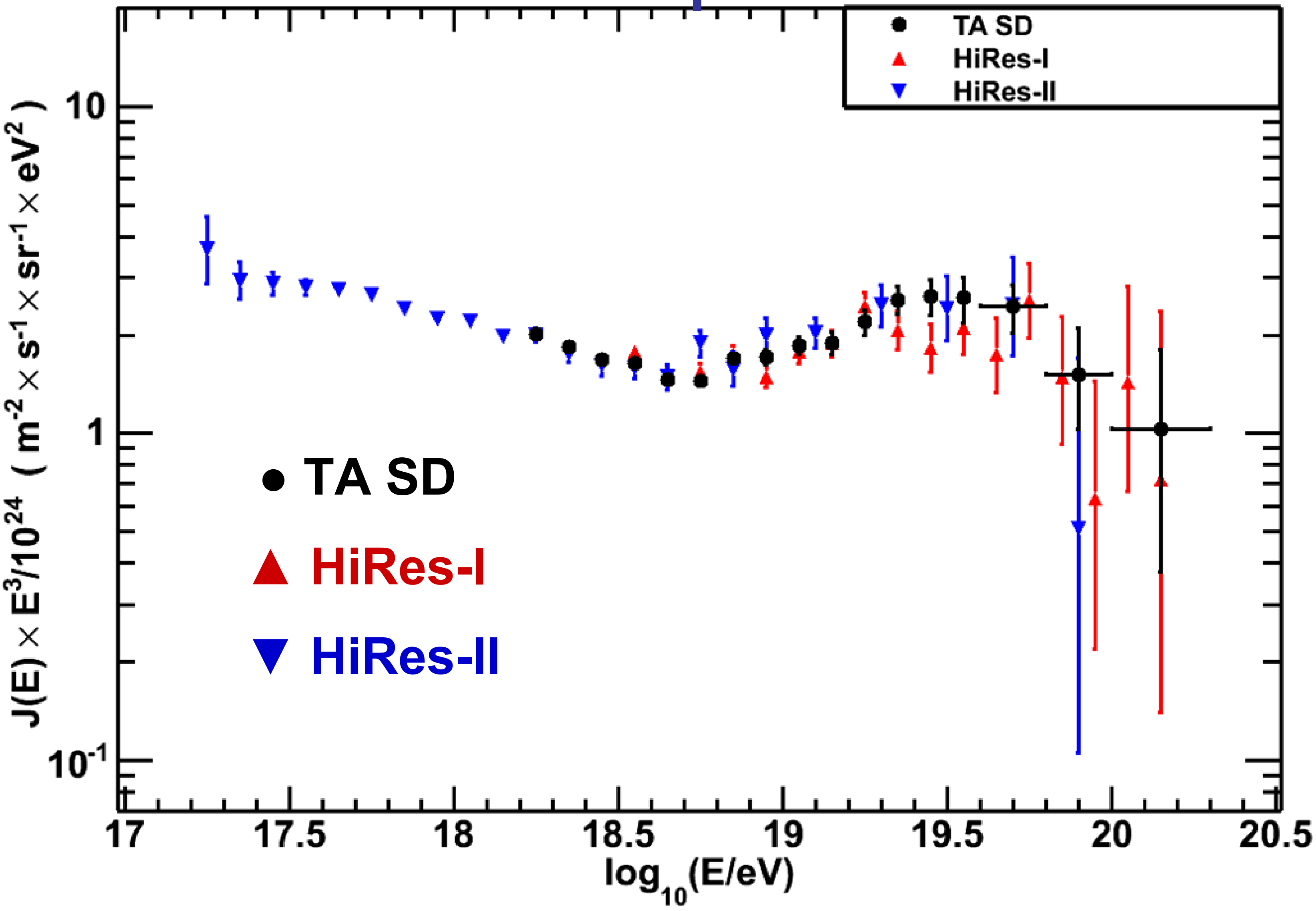
$$\mathrm{PROB} = \sum_{i=0}^{28} \mathrm{Poisson}(\mu = 54.9; i) = 4.75 \times 10^{-5}$$

(3.9σ)

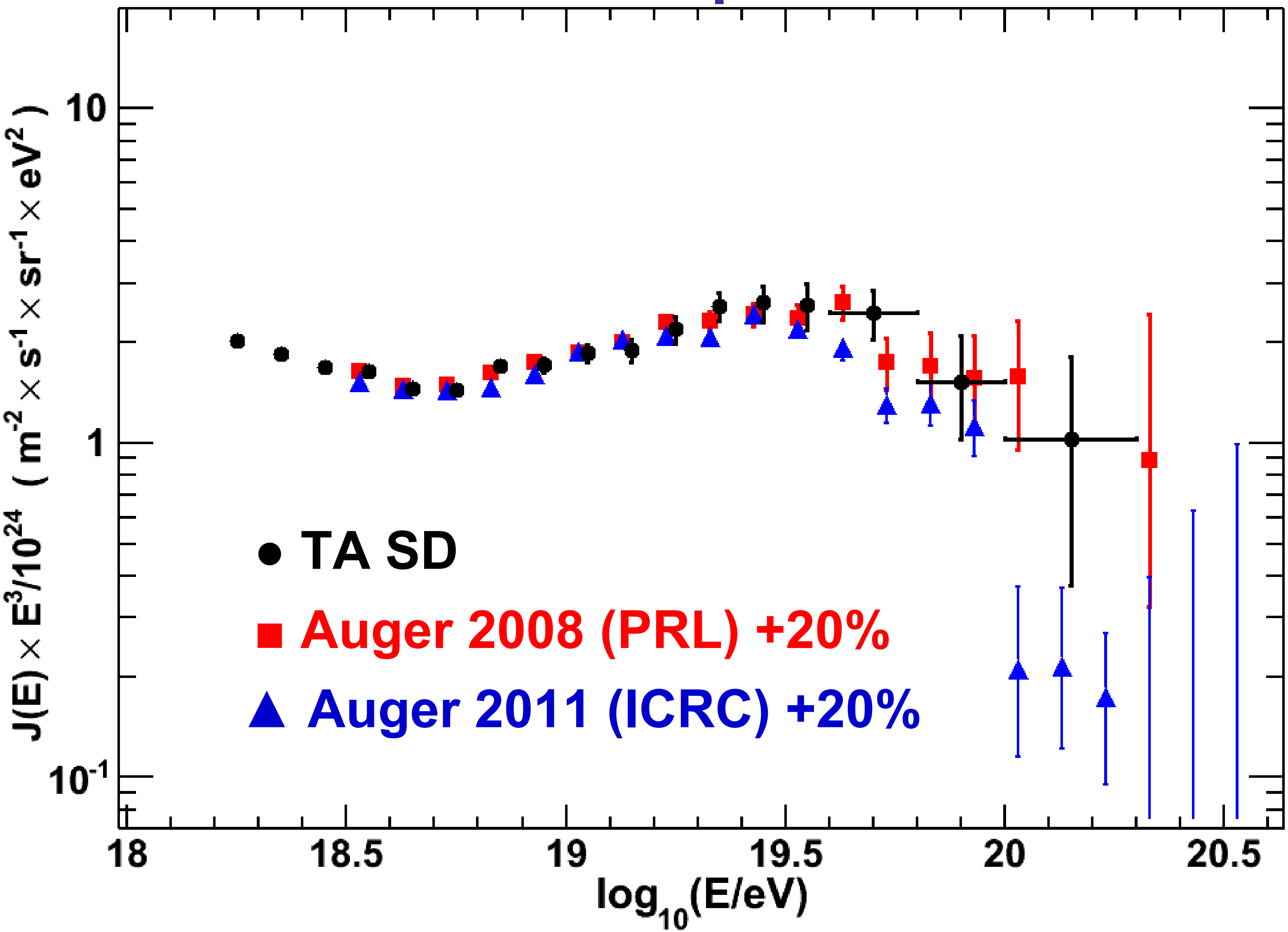
SD Energy Spectrum: Integral Flux $E_{1/2}$ Measurement



SD Energy Spectrum: Comparison



SD Energy Spectrum: Comparison



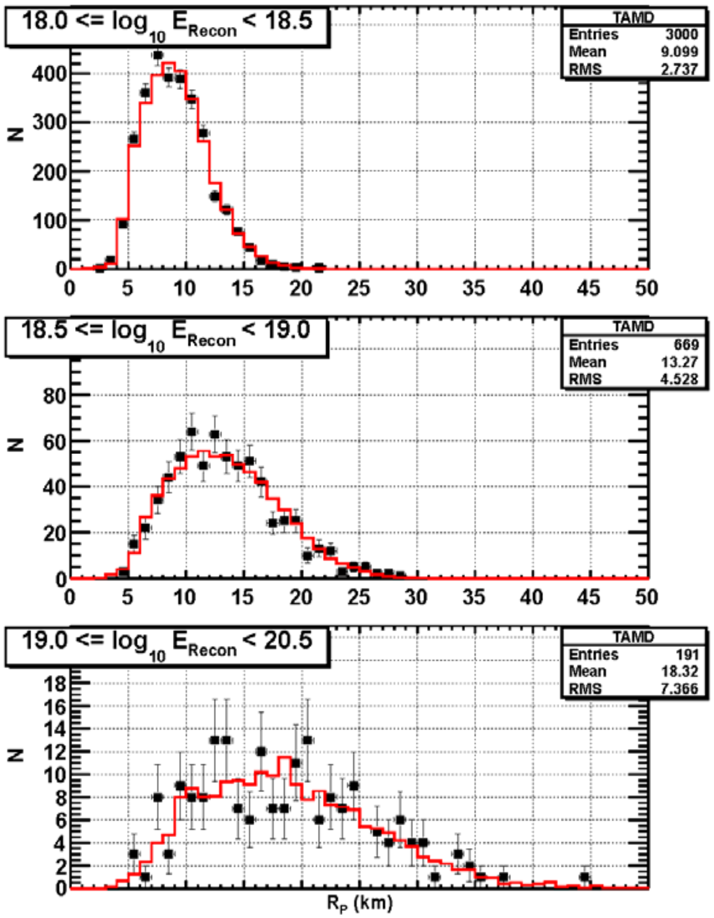
Fluorescence Detector (FD) Monocular Spectrum

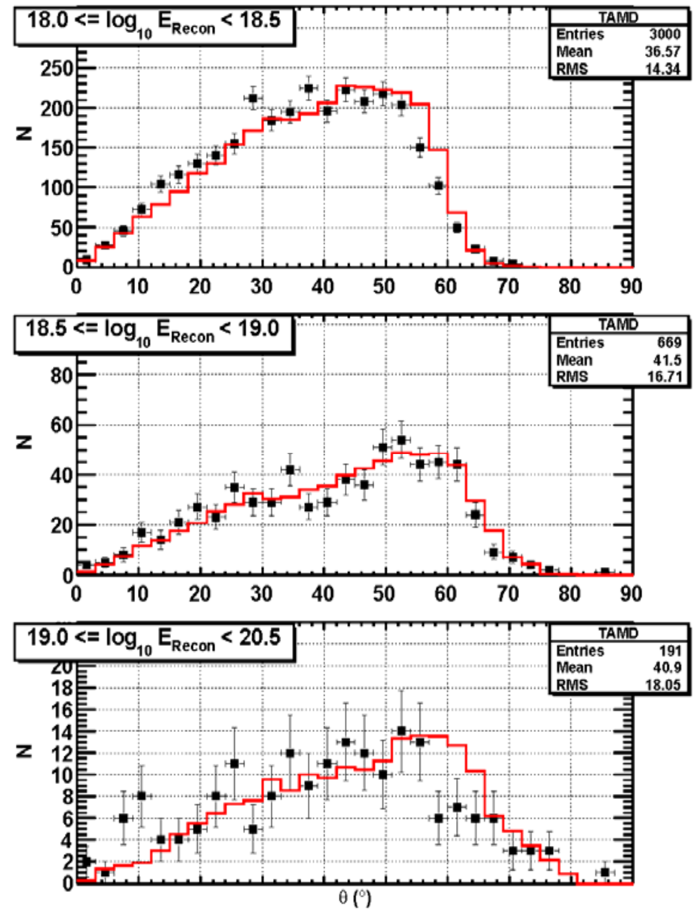
- For FD (mono, hybrid, stereo) measurements, the aperture depends significantly on energy. ➔ Must calculate it by Monte Carlo technique.
- This is an important part of UHECR technique, and must be done accurately.
- We use HEP methods for this purpose.

MC Method

- Simulate the data exactly as it exists.
  - Start with previously measured spectrum and composition.
  - Use Corsika/QGSJet events.
  - Throw with isotropic distribution.
  - Include atmospheric scattering.
  - Simulate trigger, front-end electronics, DAQ.
- Write out the MC events in same format as data.
- Analyze the MC with the same programs used for data.
- Test with data/MC comparison plots.
- This method works.

DATA/MC Comparisons

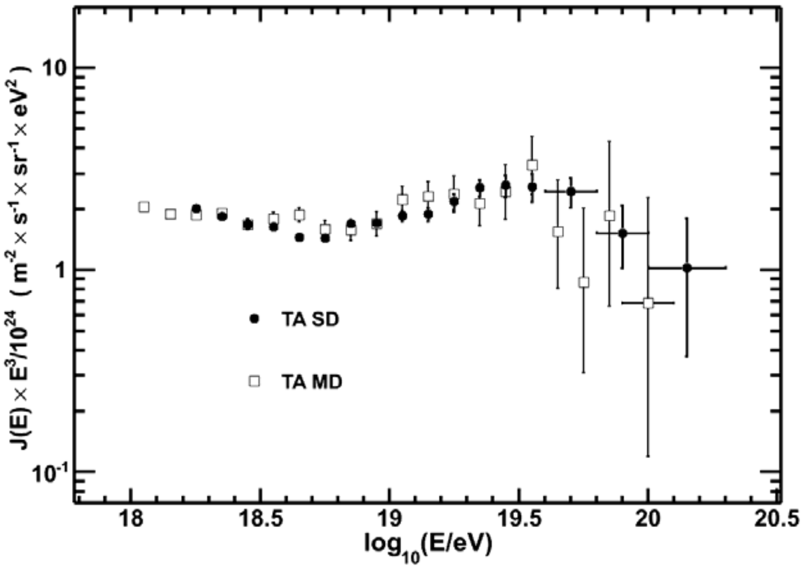


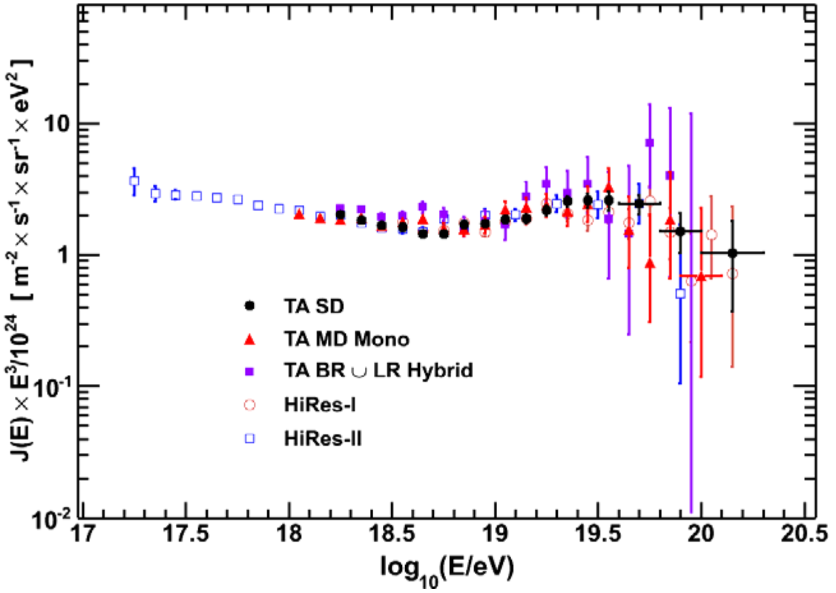


R_p

Zenith angle

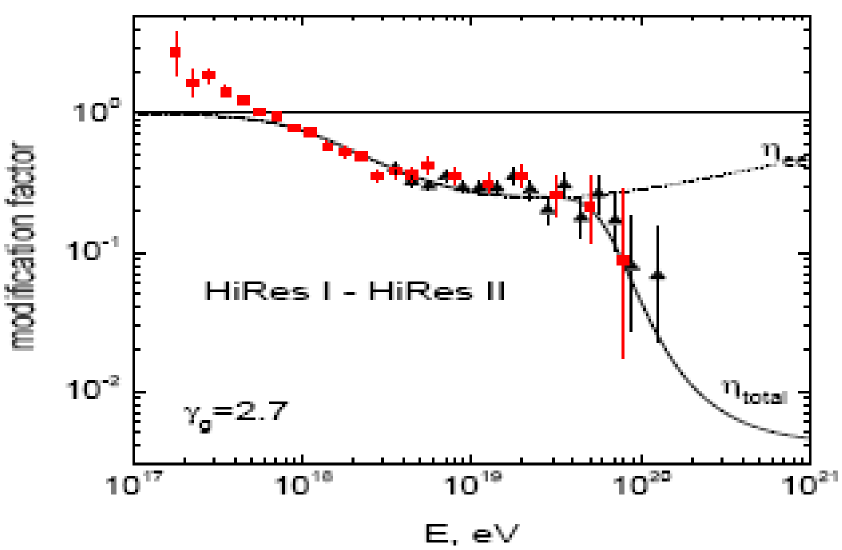
FD and SD Energy Spectra:

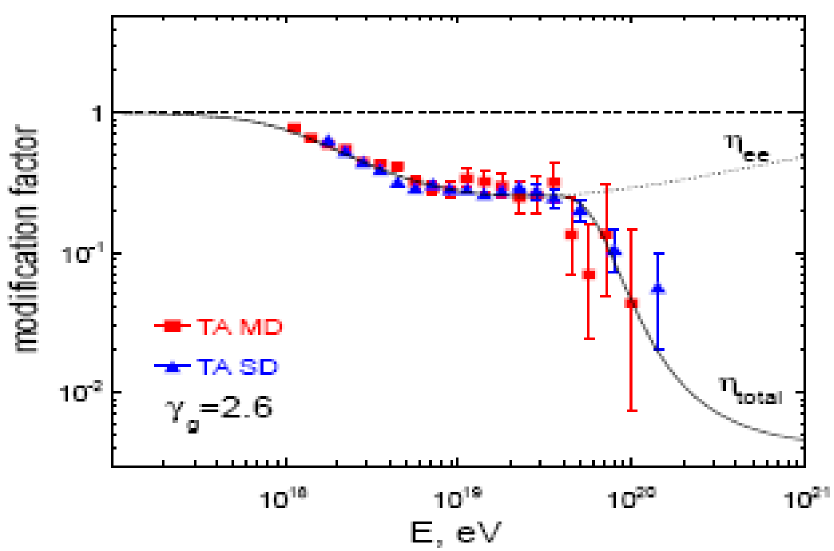




Comparison with Theoretical Model (Berezinsky et al., 2012)

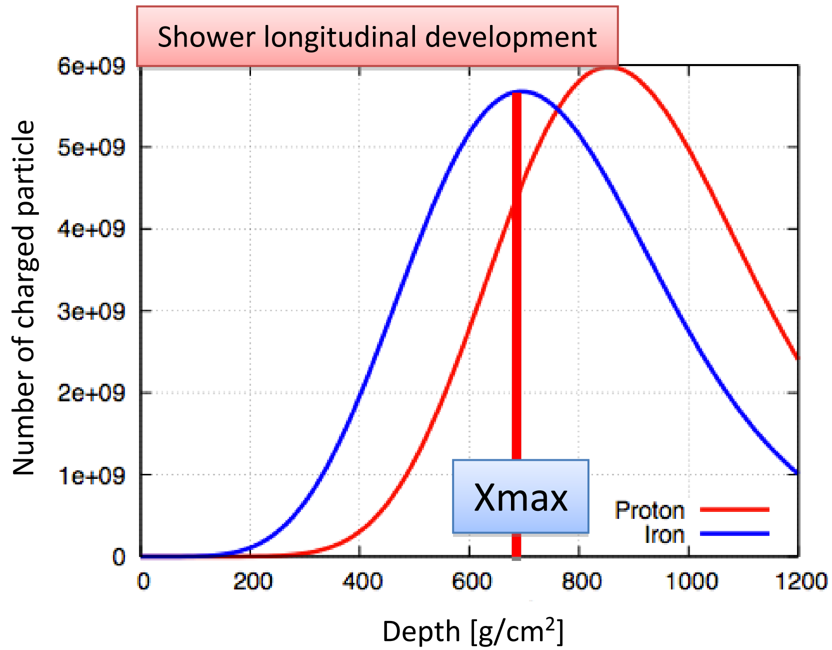
- Assume constant density of sources, calculate the "modification factor" due to propagation; compare with HiRes and TA data.

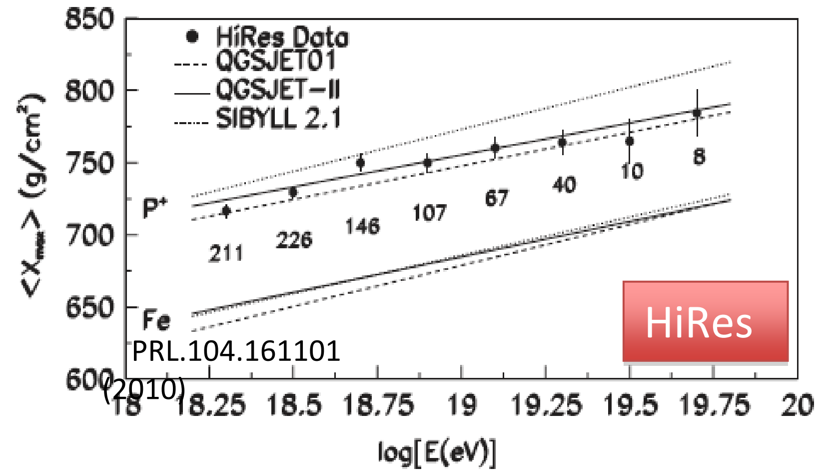


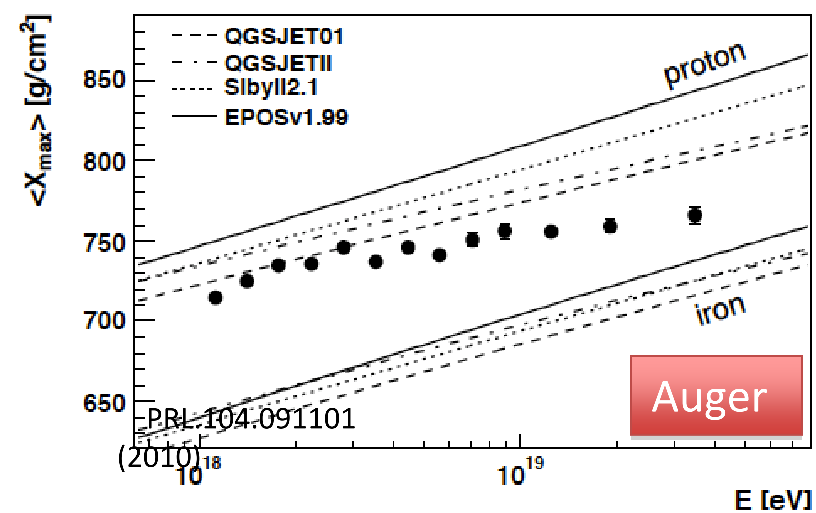


Composition from Xmax

- Shower longitudinal development depends on primary particle type.
- FD observes shower development directly.
- Xmax is the most efficient parameter for determining primary particle type.







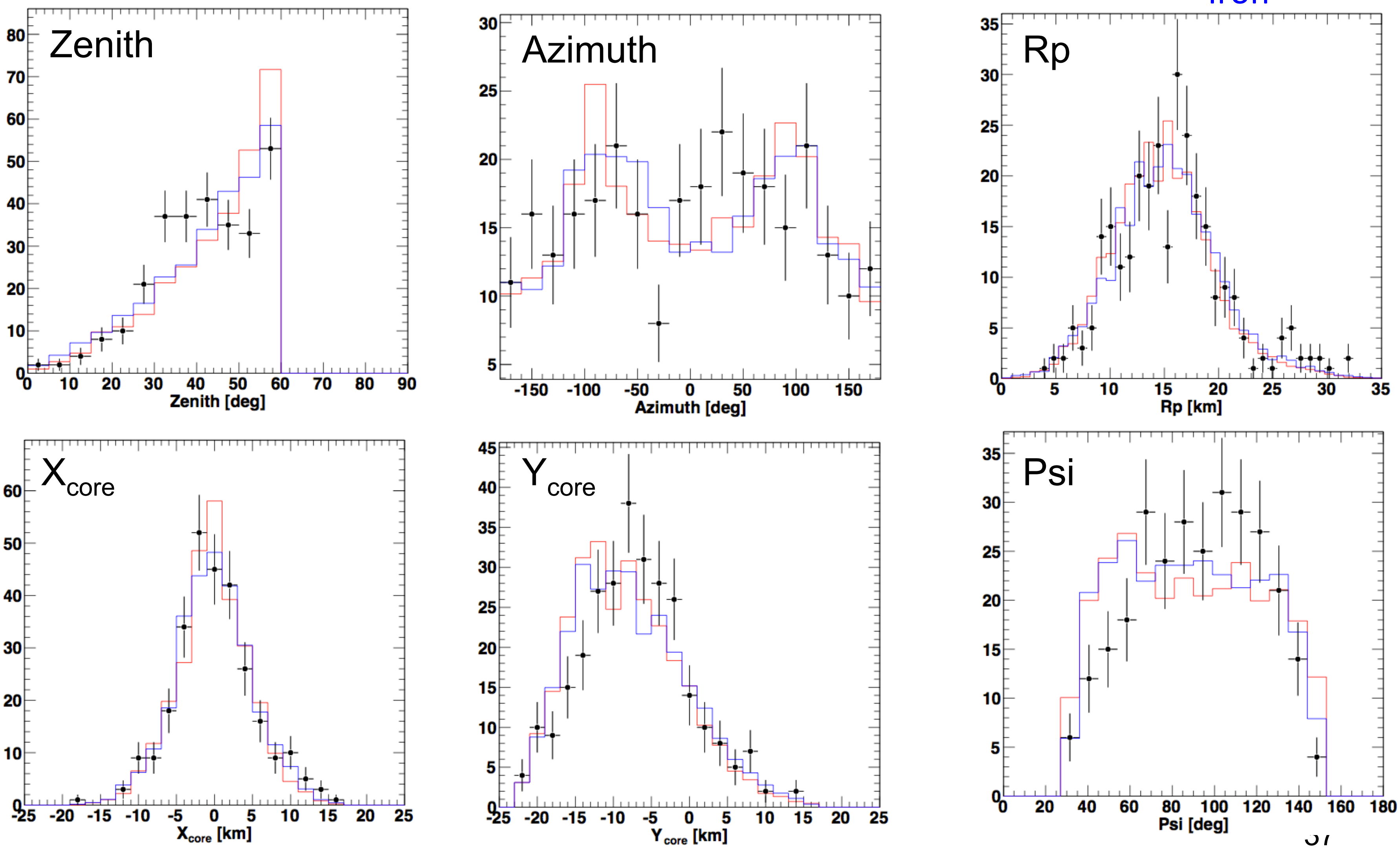
TA FD Stereo Composition

- Measure x_{max} for Black Rock/Long Ridge FD stereo events
- Create simulated event set
- Apply exactly the same procedure as with the data

- **This measurement is independent of HiRes and Auger.**

Data/MC Comparison

QGSJETII
Proton
Iron



Data/MC Comparison

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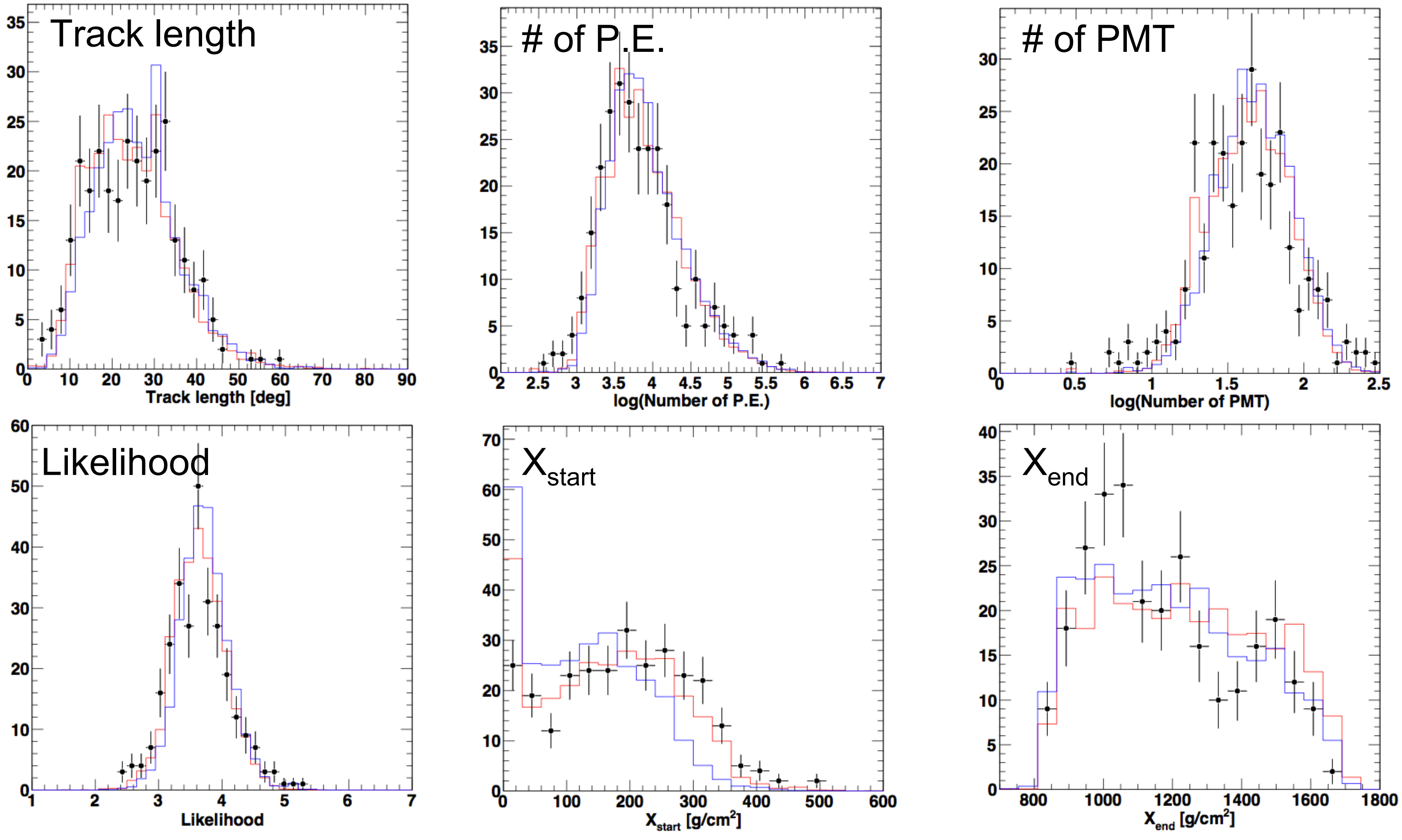
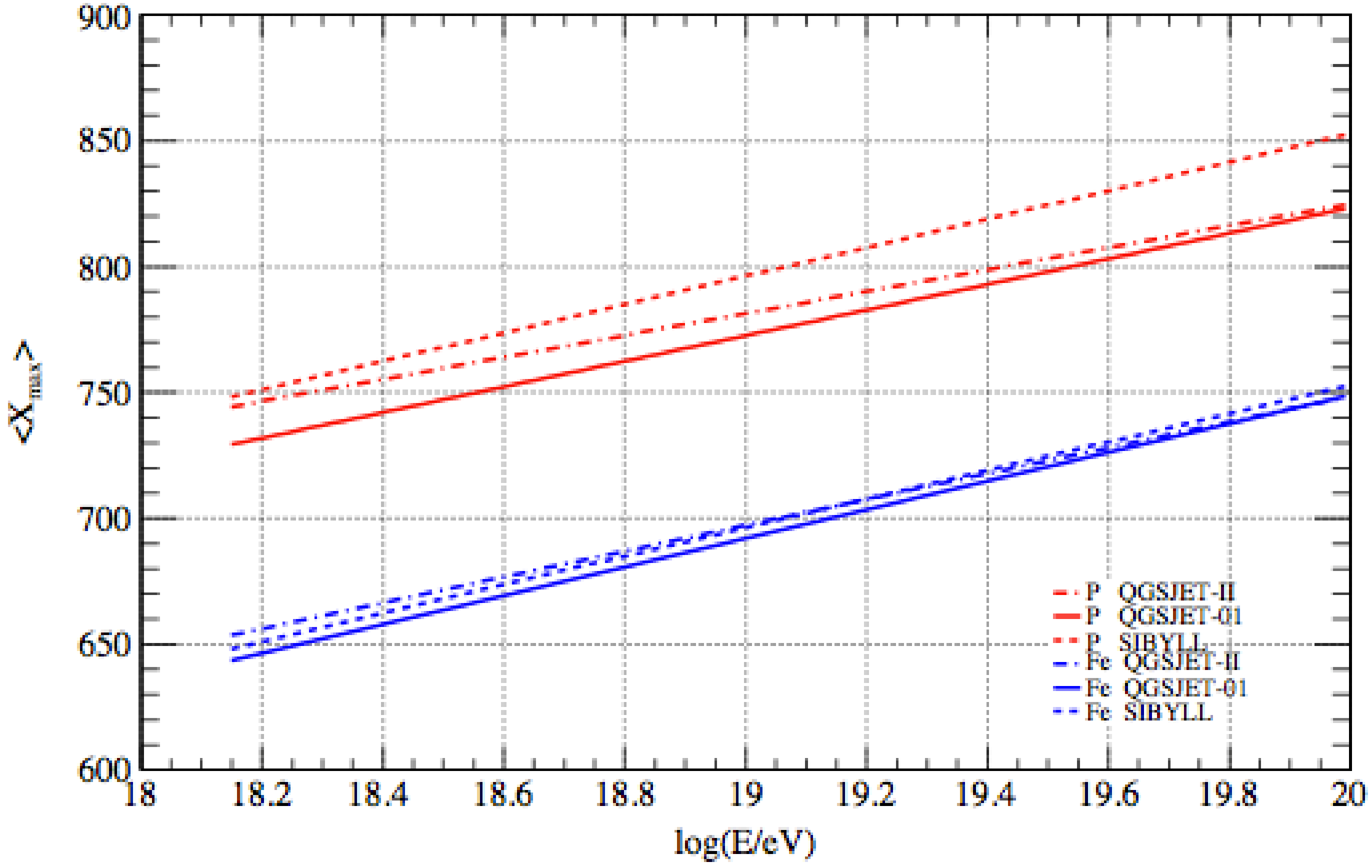
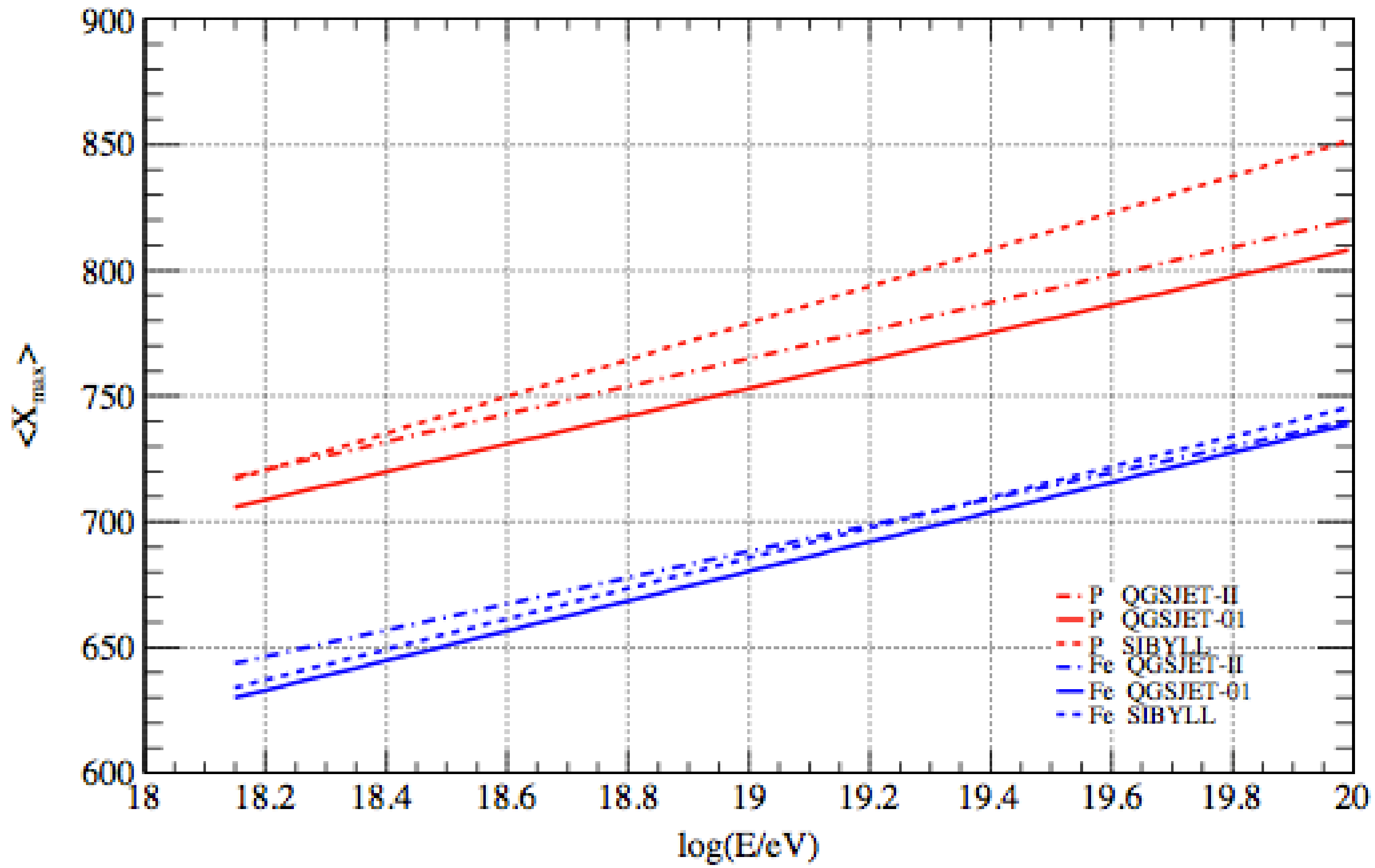


Prediction of <Xmax>, directly from CORSIKA

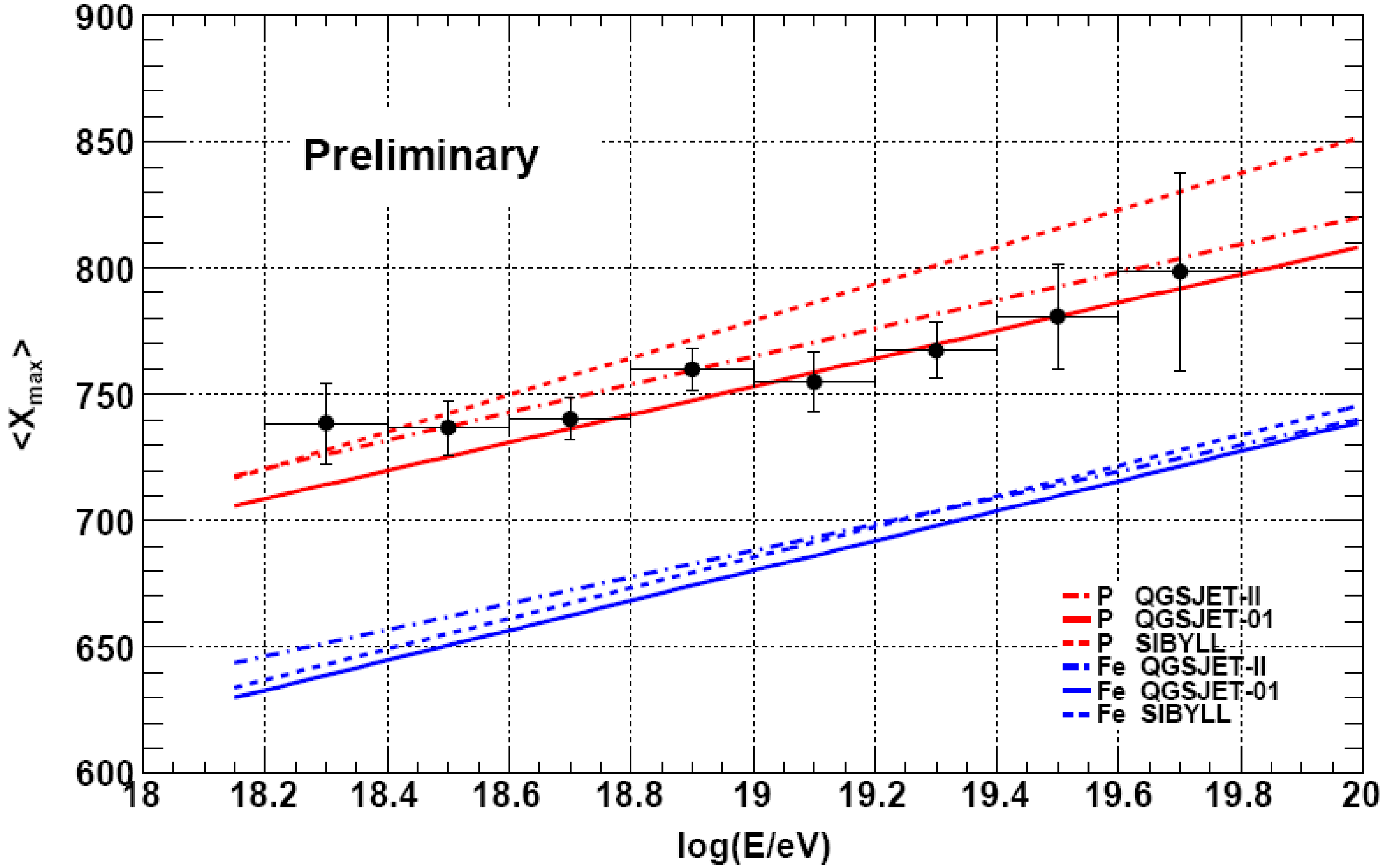


Prediction of <Xmax>, Reconstructed



These rails which include acceptance and reconstruction bias can be compared with data

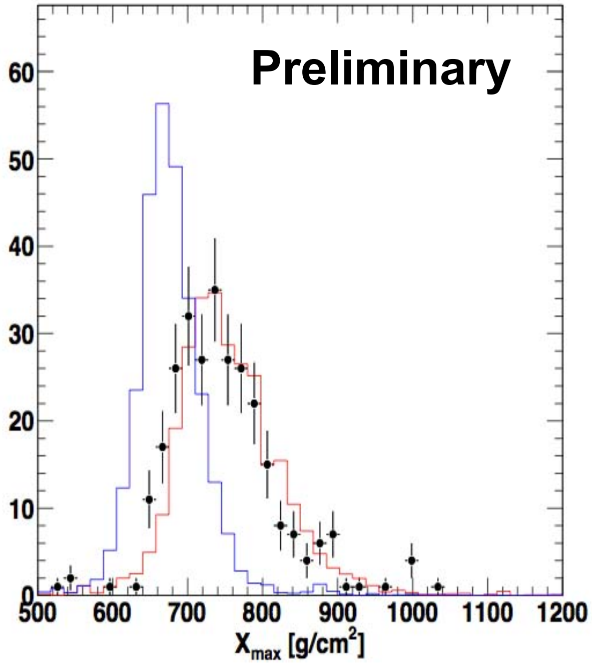
Energy vs <Xmax>



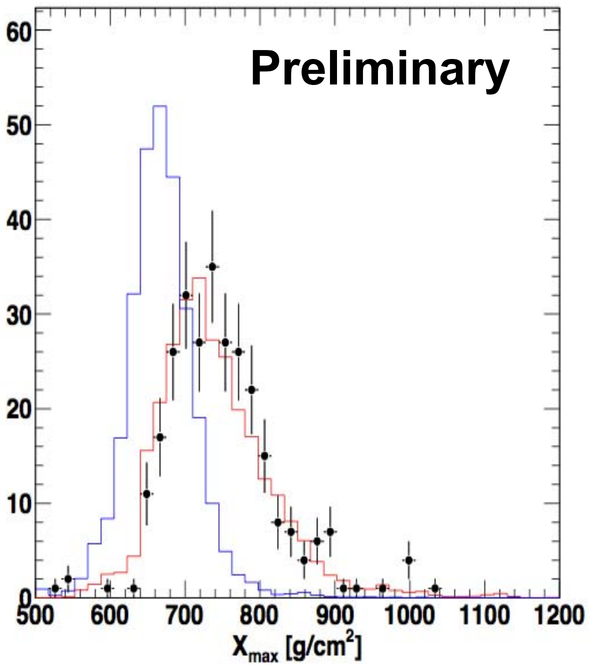
Xmax distribution ($10^{18\text{-}20}$eV)

Proton
Iron

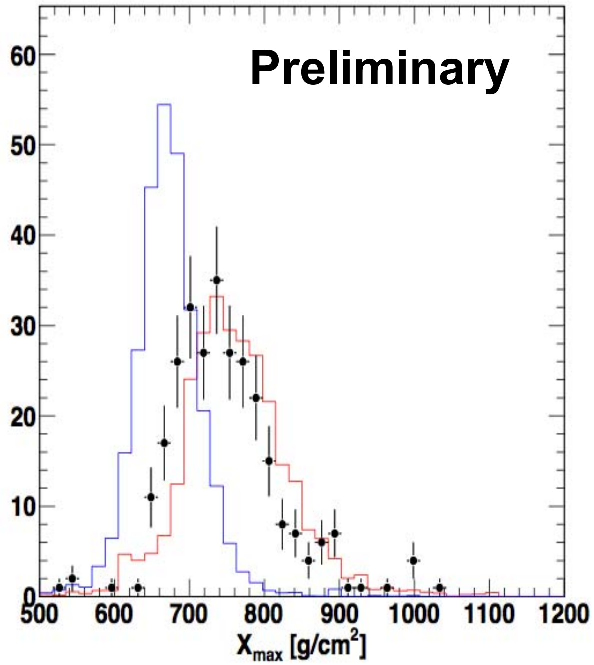
QGSJET-II



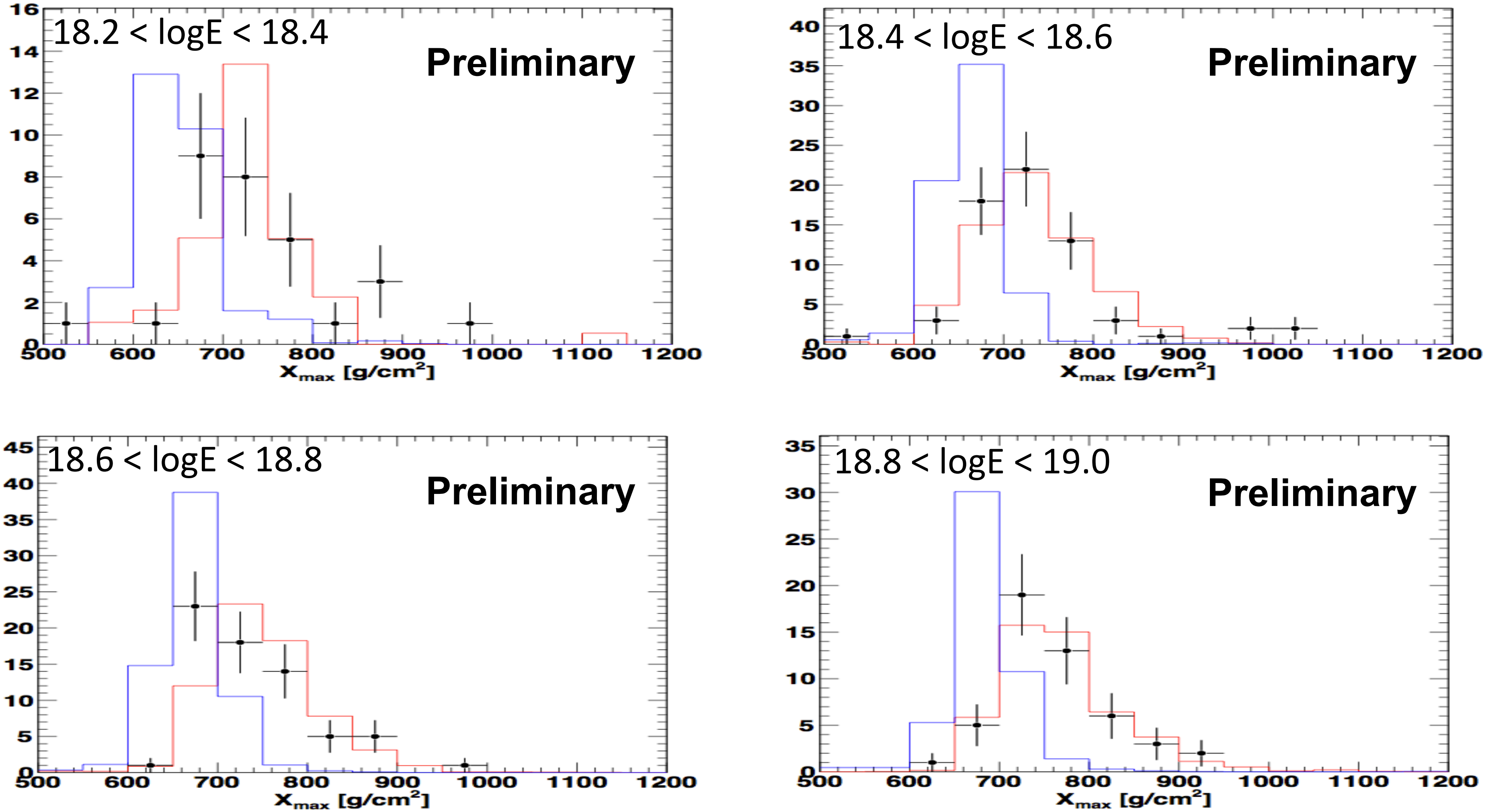
QGSJET01



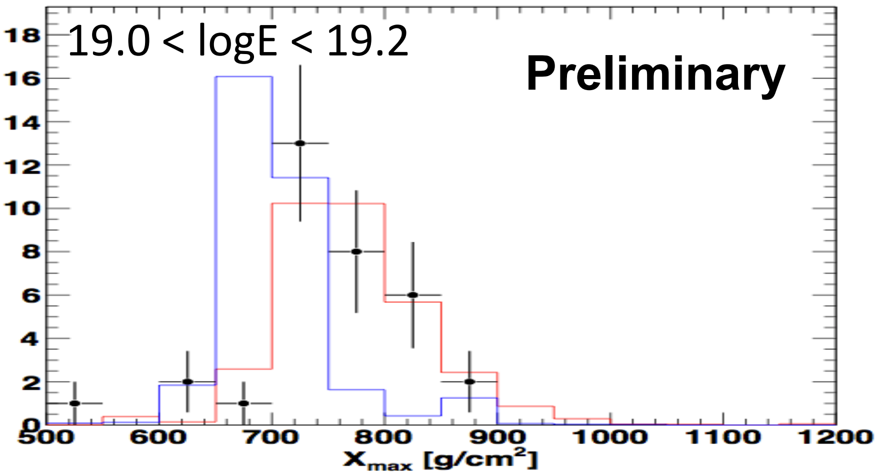
SIBYLL

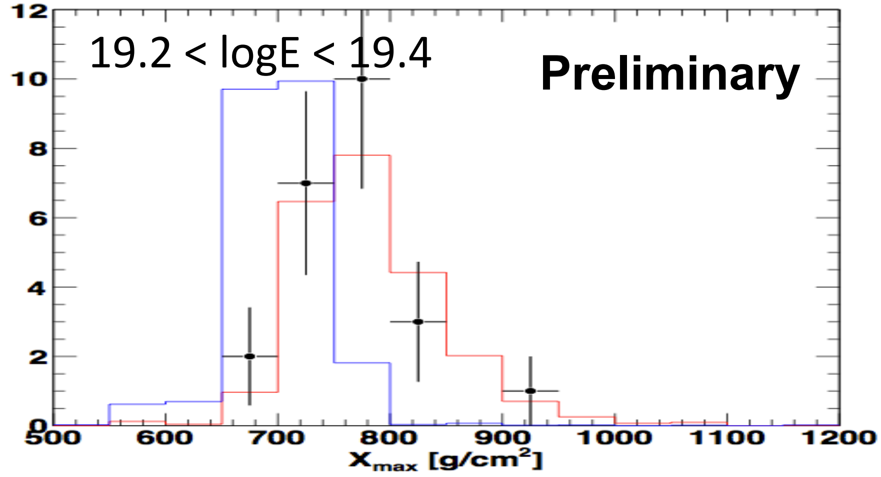


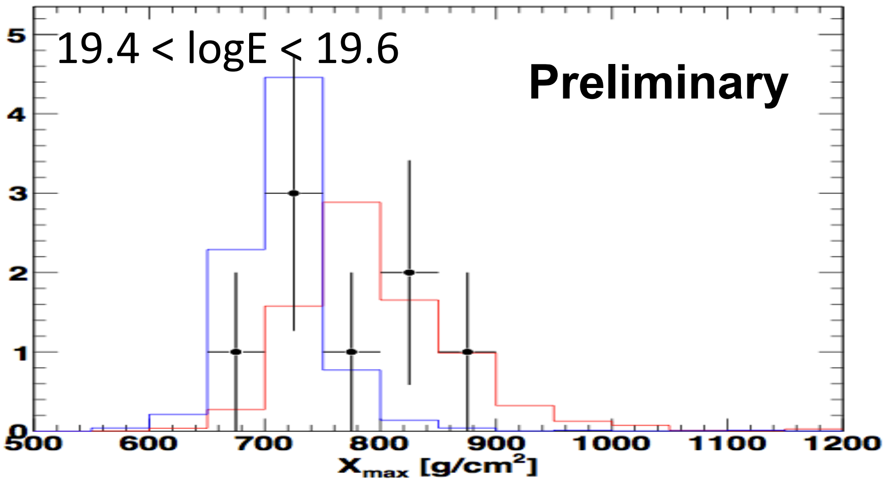
Xmax dist. QGSJET-II

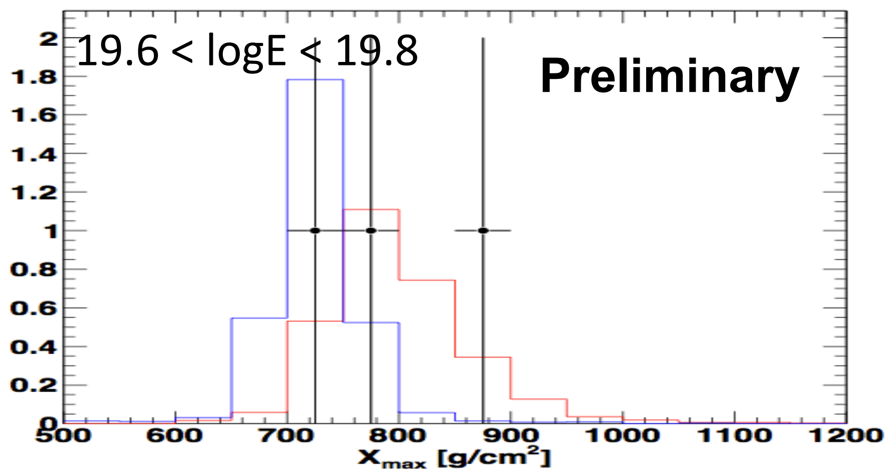


Xmax dist. QGSJET-II

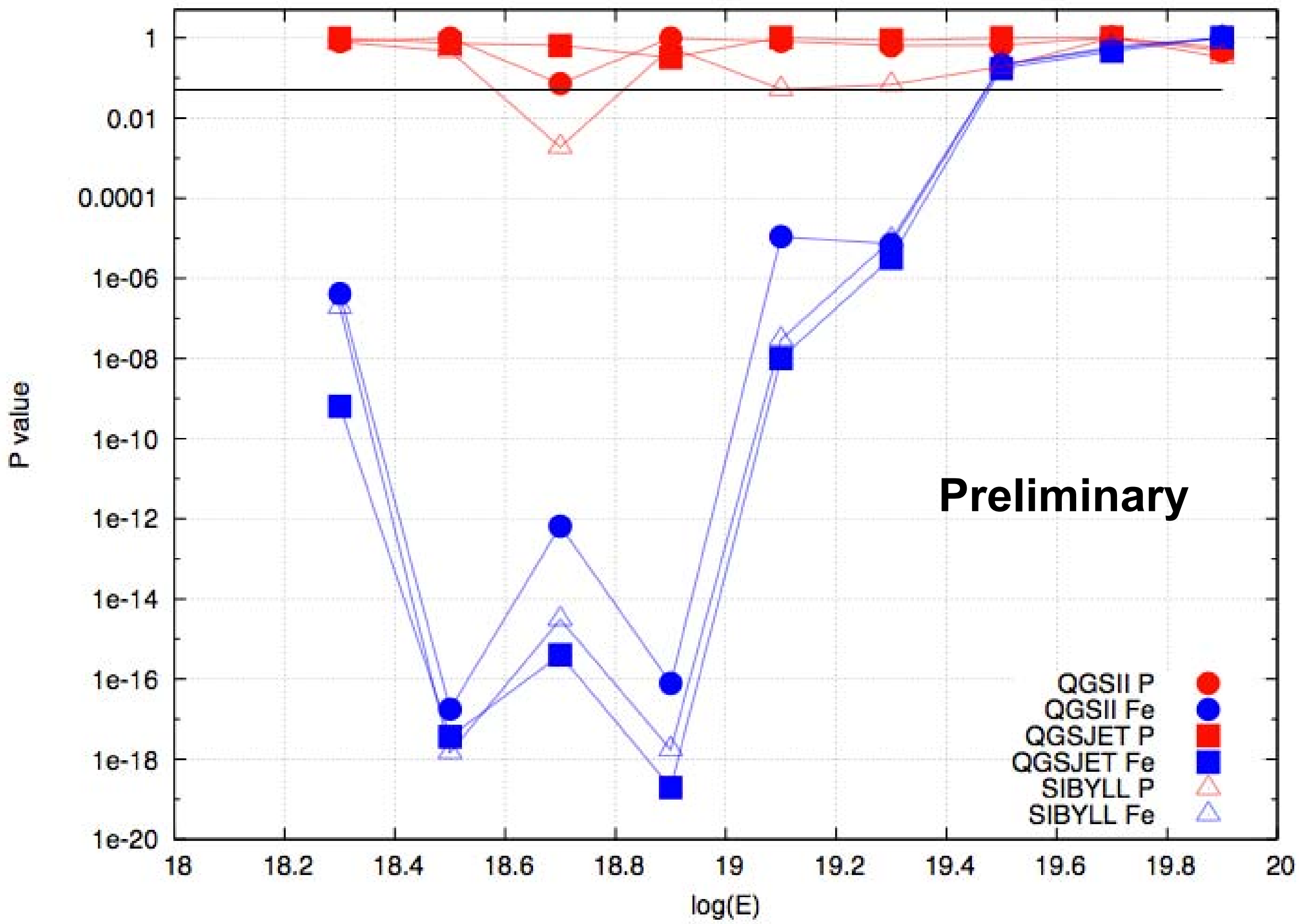








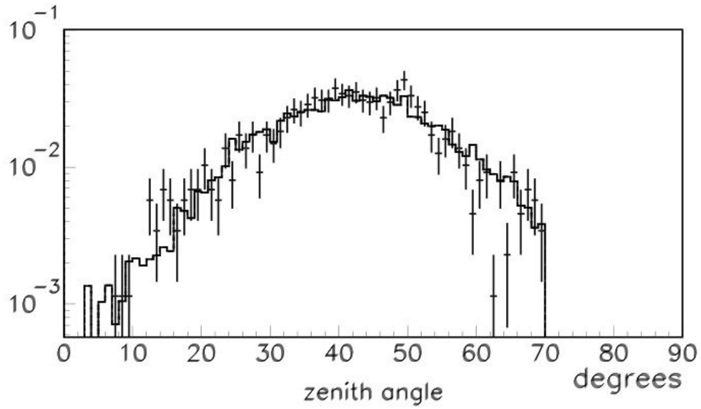
Xmax dist. : KS Test



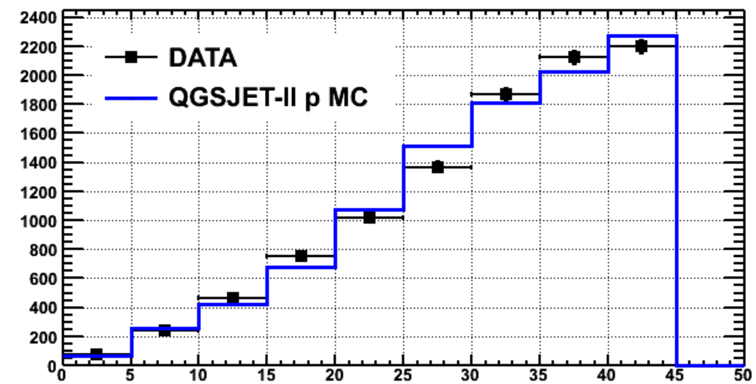
95% C.L.

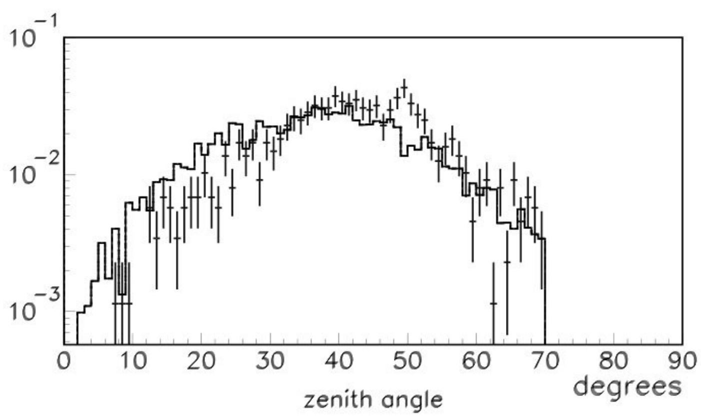
Simple Tests

There exist simple tests (not dominated by systematics) to check composition results; e.g., zenith angle comparison plots.

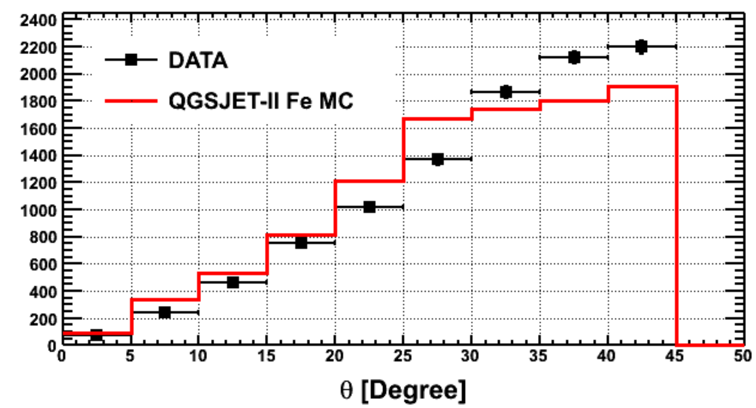


protons





iron



HiRes fluorescence detector

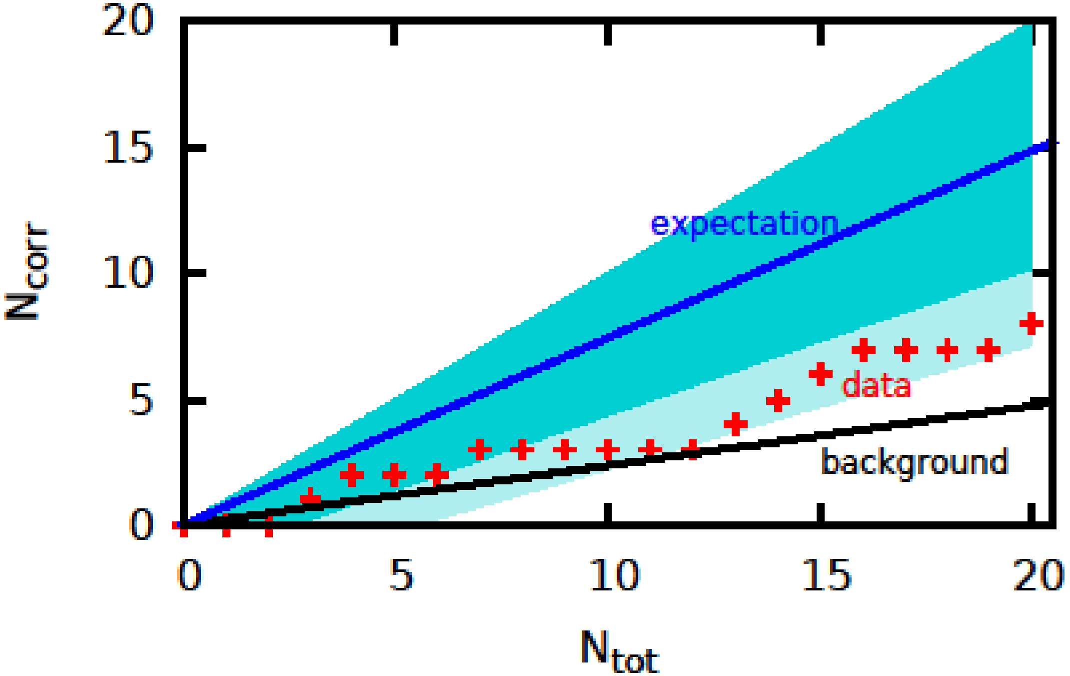
TA surface detector

Search for AGN Correlations

- Auger found correlations with AGN's with (57 EeV, 3.1°,0.018). 14 events scanned + 13 event test sample appeared in Science article; 2.9σ chance probability.

- Later Auger data (71, 19, 16) show no significant correlations.
- HiRes data (13, 2, 3) show no significant correlations.
- TA data (20, 8, 5) show no significant correlations.

TA AGN Correlations



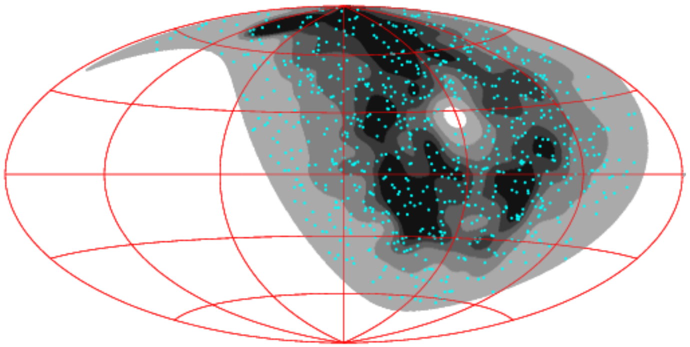
Search for Correlations with Local Large Scale Structure

METHOD

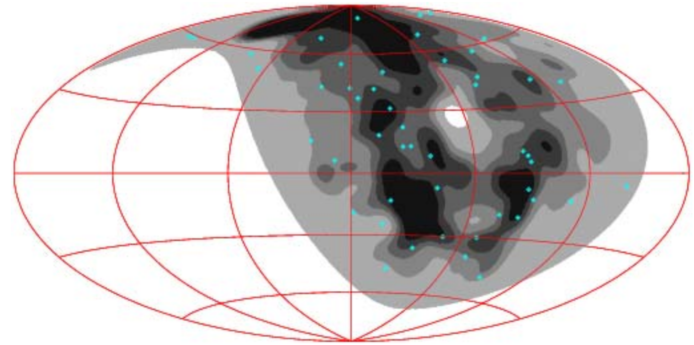
- The flux distribution over the sky is calculated from the actual distribution of galaxies (2MASS XSCz catalog, T. Jarrett, private communication)
- 110 000 galaxies at distances from 5 Mpc to 250 Mpc are included
- The flux from beyond 250 Mpc is taken uniform
- Proton primaries are assumed
- All interaction and redshift losses are accounted for
- Gaussian smearing is applied with the angular size treated as a free parameter. At small angles, this mimics the deflections in magnetic field and finite angular resolution.
- The predicted flux is compared to the data by the flux sampling test

Data, and Models

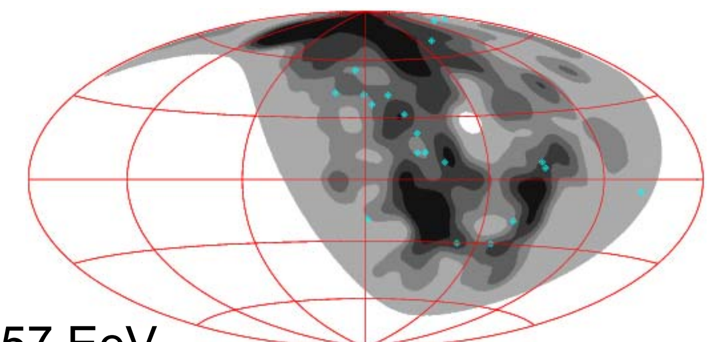
E > 10 EeV



E > 40 EeV

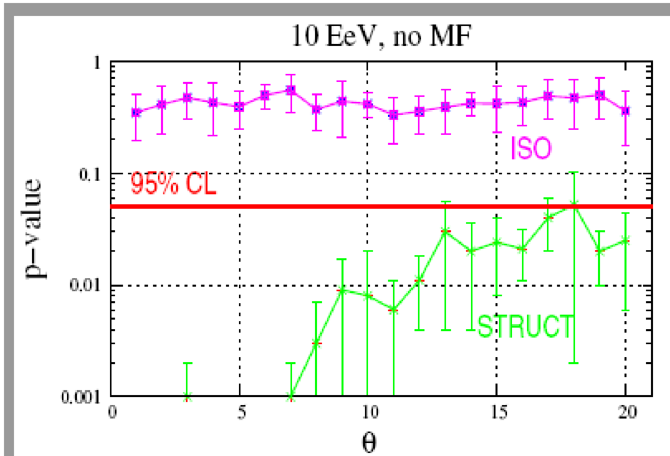


(smearing angle = 6°)

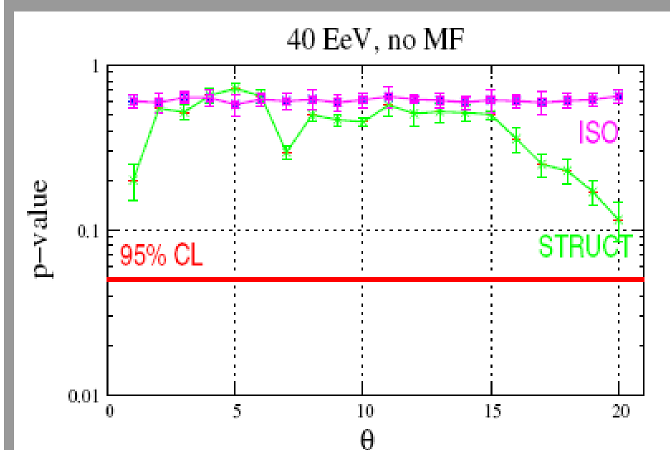


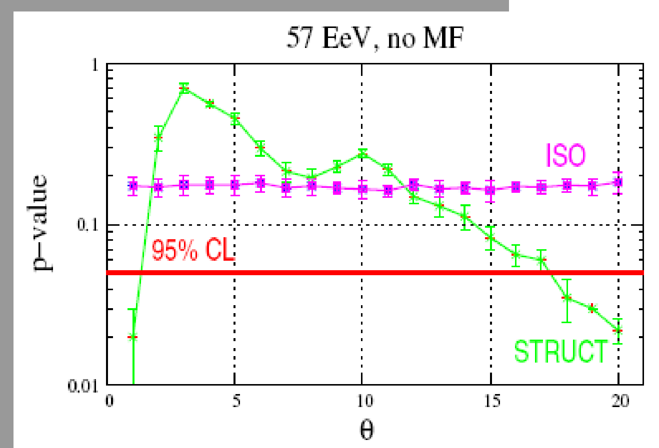
E > 57 EeV

Results of K-S Test

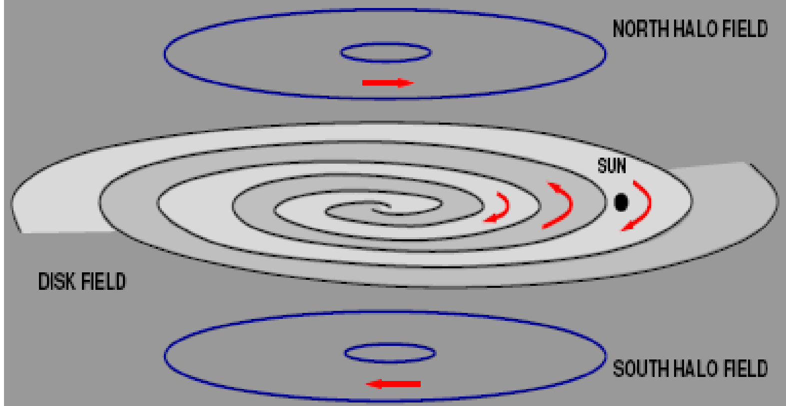


- Without correction for GMF, compatibility with both structure and isotropy, except at $E > 10$ EeV where data are not compatible with structure





Add Galactic Magnetic Field

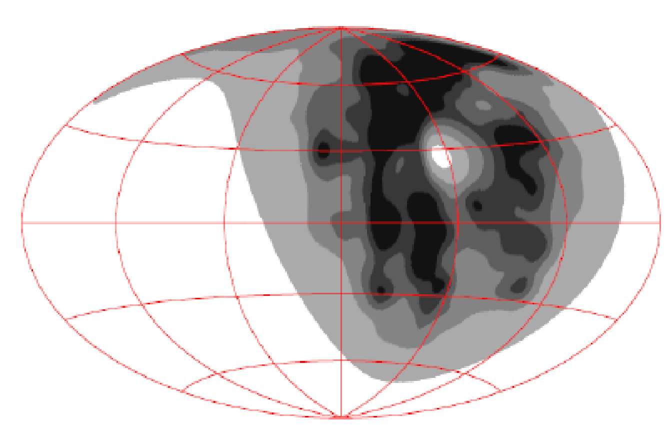


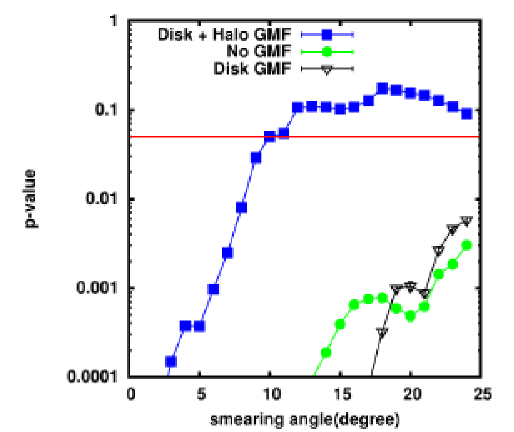
- Two-component model: antisymmetric halo + symmetric disk field
- Fits NVSS RM data [Pshirkov et al, ICRC-2011, talk 163 (to appear in ApJ)]

Strategy:

- Calculate the expected flux map including deflections in GMF
- Compare to the observed distribution
- Check if the parameters of GMF can be chosen so as to make CR data compatible with the structure model

Flux Map and K-S Plot



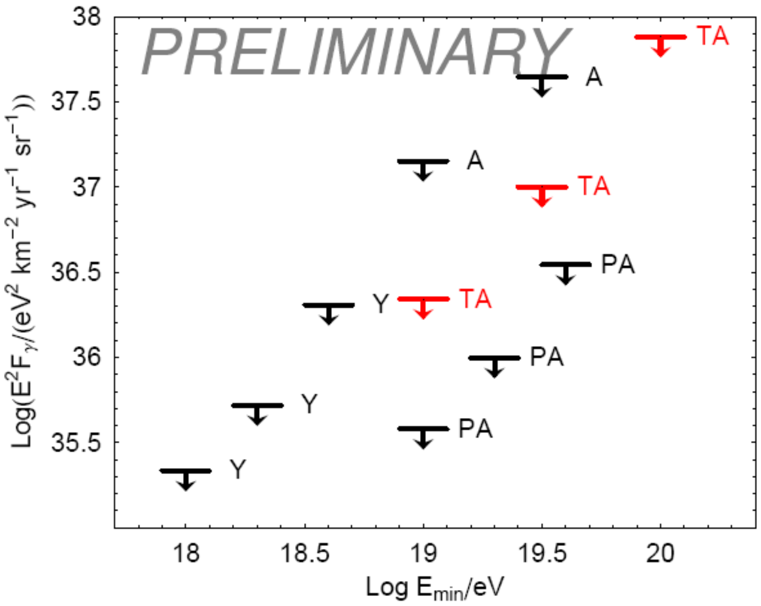


- Compatibility with structure cannot be improved by the disk component only $\Longrightarrow$ halo component is required
- Rather strong or extended halo field is needed for noticeable improvement of correlation
- The required extended halo does is compatible with the RM measurements if the standard electron density distribution is assumed

Search for Photons and Neutrinos

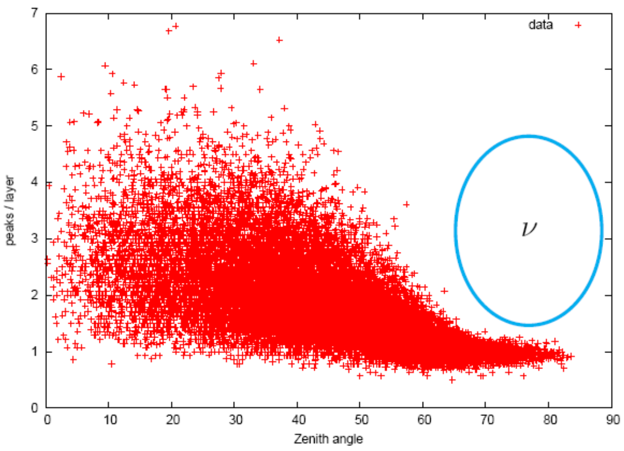
Photons:

Use curvature of shower front.



Neutrinos:

Use old/new shower discriminant: number of muon peaks in FADC trace.

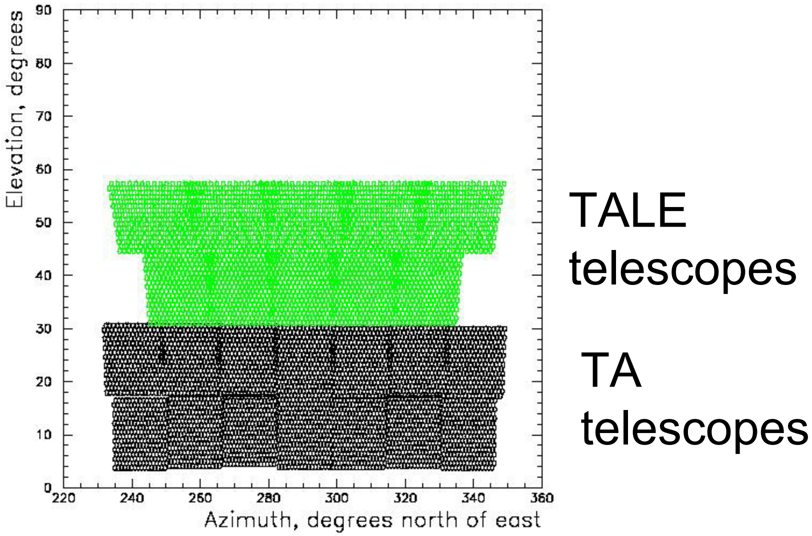


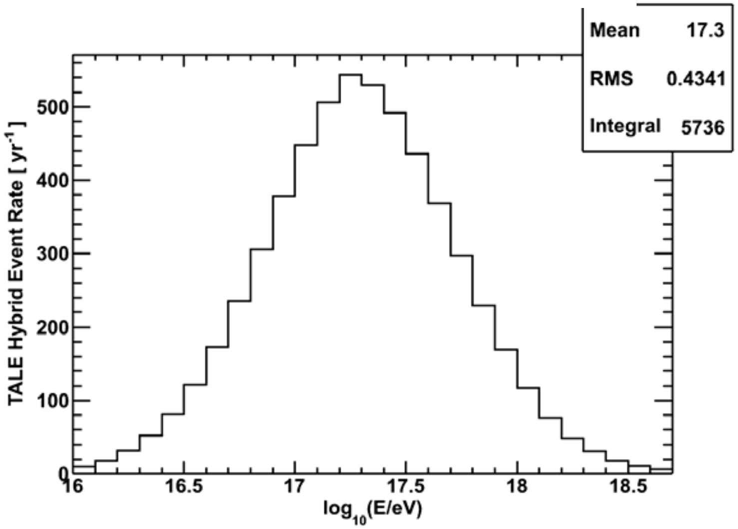
TA Low Energy Extension (TALE)

- A lot of physics was skipped in the push to observe the GZK cutoff. ➔ Study the 10^{16} and 10^{17} eV decades with a hybrid detector.
  - End of the rigidity-dependent cutoff that starts with the knee (at 3×10^{15} eV).
  - The second knee
  - The galactic-extragalactic transition
- Need to observe from 3×10^{16} eV to 3×10^{20} eV all in one experiment. That is TA and TALE.

TALE FD

- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
- Operate in conjunction with the TA Middle Drum FD.
- Together cover $10^{16.5} < E < 10^{20.5}$ eV

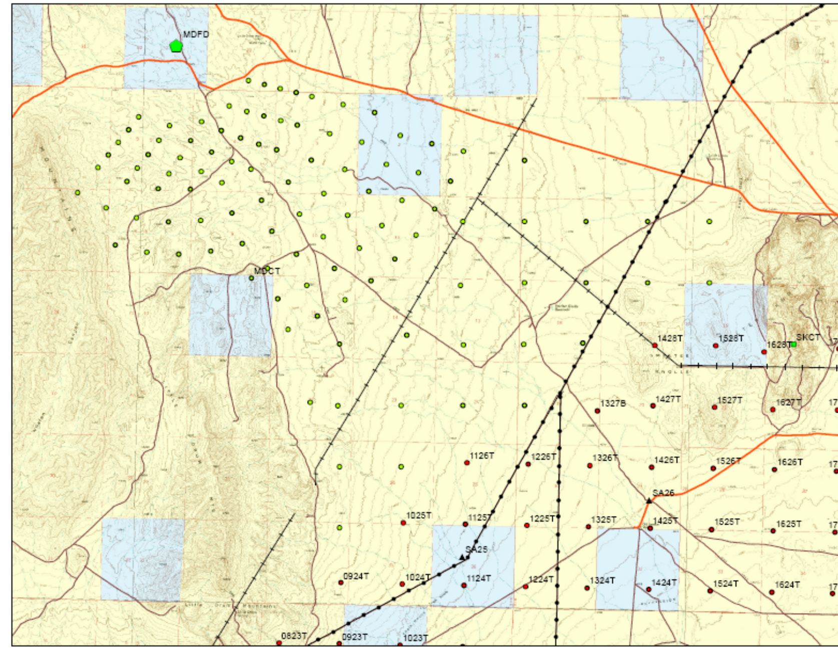


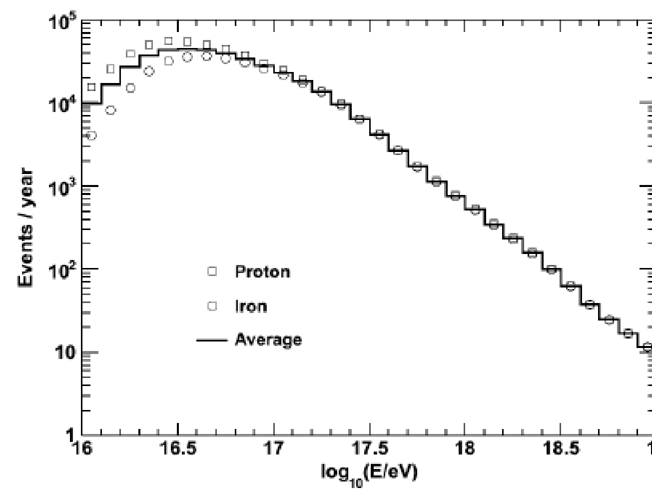


TALE hybrid events per year

TALE Infill Array

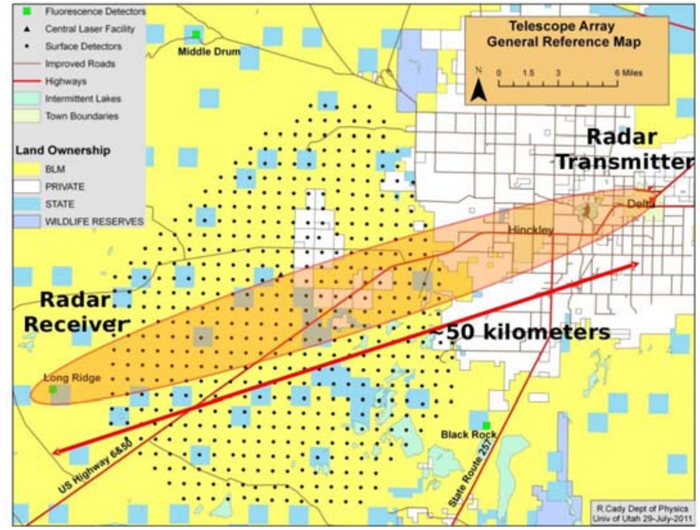
- Add infill array (400m and 600m spacings) for hybrid and stand-alone observation.
- Also add counters to build out main TA SD array (1200m separation).
- 105 counters in all.



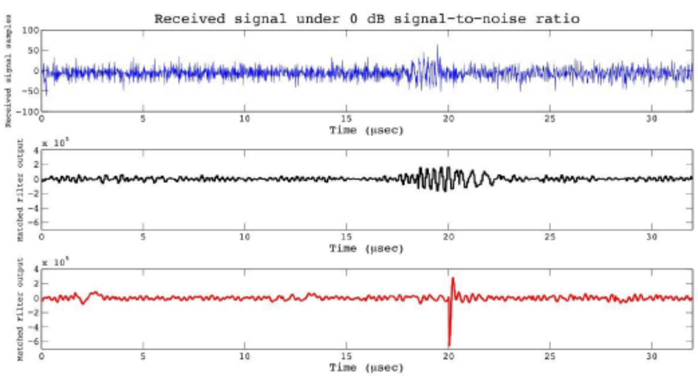


Events per year

Radar Detection of Cosmic Ray Showers



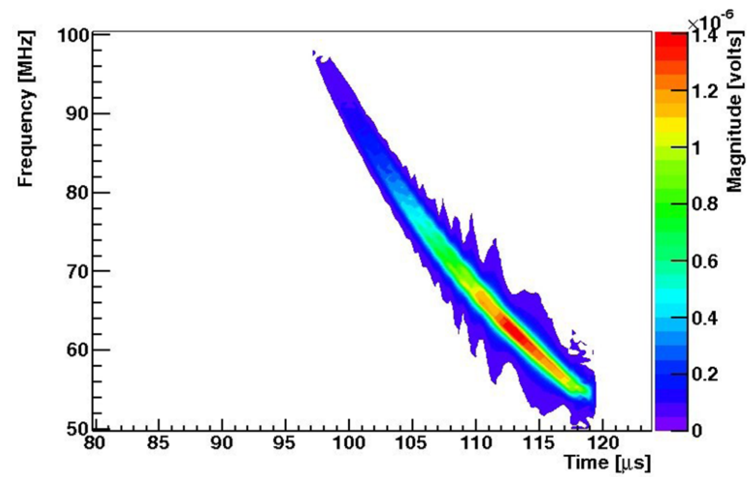
- Rates at the highest energies are too low ➔ need bigger experiments.
- Bistatic radar detection:
  - Remote sensing
  - Inexpensive
  - 100% duty cycle



Input 3.5 MHz/microsec "chirp"

1 MHz/microsec filter output

3.5 MHz/microsec filter output



"chirp"

Chirp detection by matched filters (0db above noise)

Conclusions

- The Telescope Array (TA) Experiment is collecting data in the northern hemisphere.
- TA is a LARGE experiment which has excellent control of systematic uncertainties.
- SD mono, FD mono, stereo, hybrid, hybrid-stereo analyses are all ongoing.
- Important TA spectrum, composition, and anisotropy results are being presented. With more to come.
- TA is a discovery experiment.