TELESCOPE ARRAY: RECENT RESULTS, FUTURE PLANS

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4th Workshop on Air Shower Detection at High Altitude
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TA Experiment

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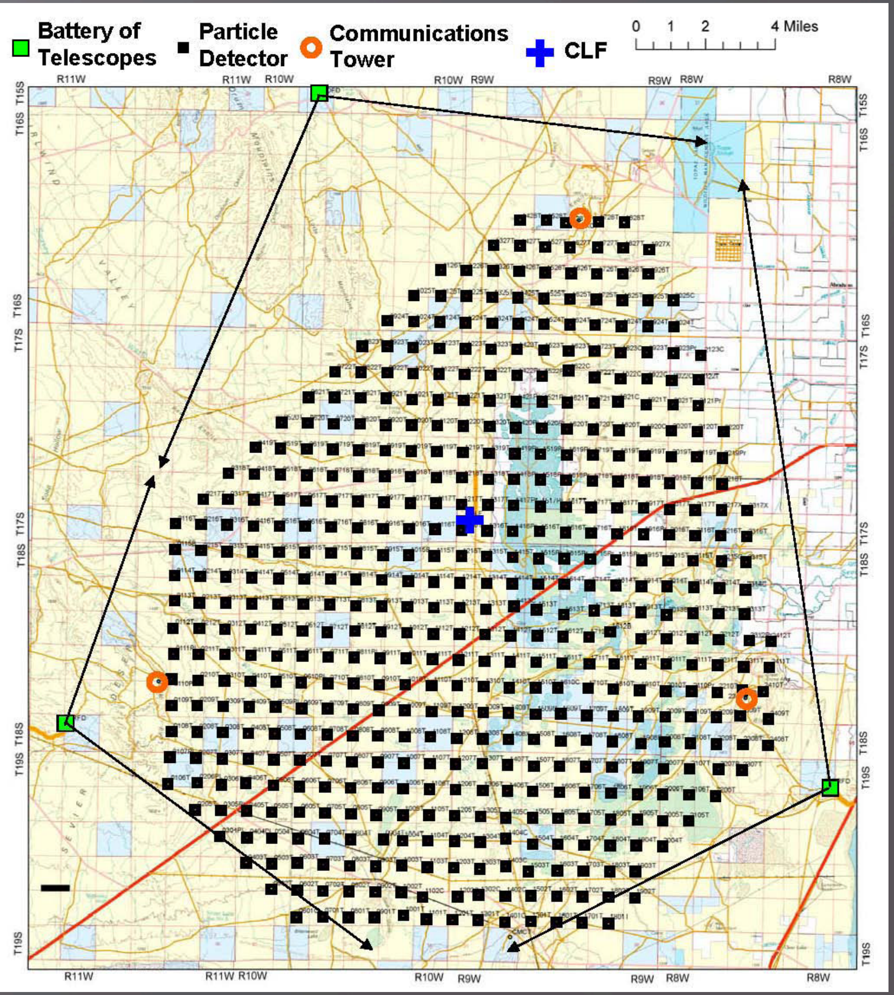
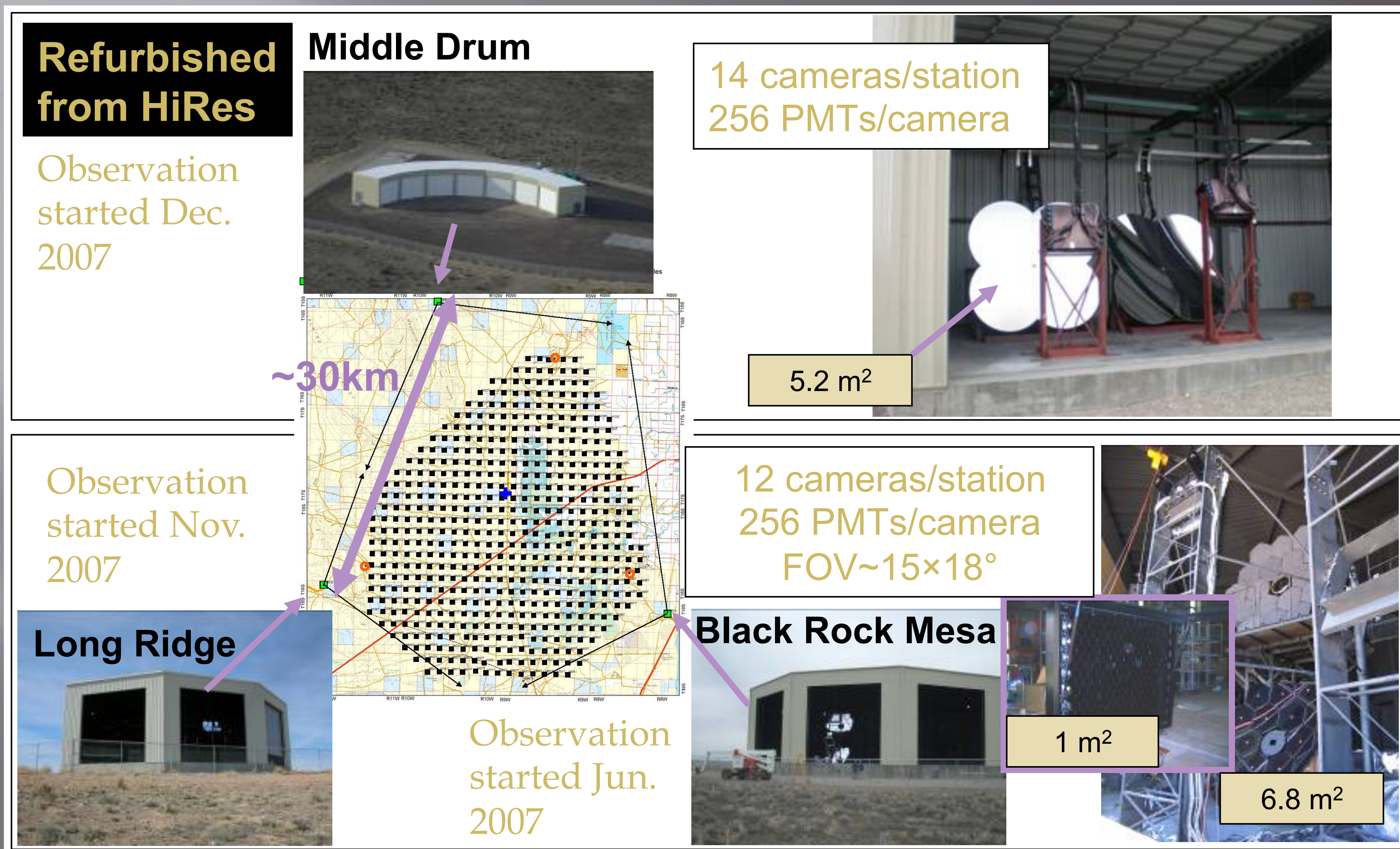
U.S., Japan, Korea, Russia, Belgium

TA Experiment

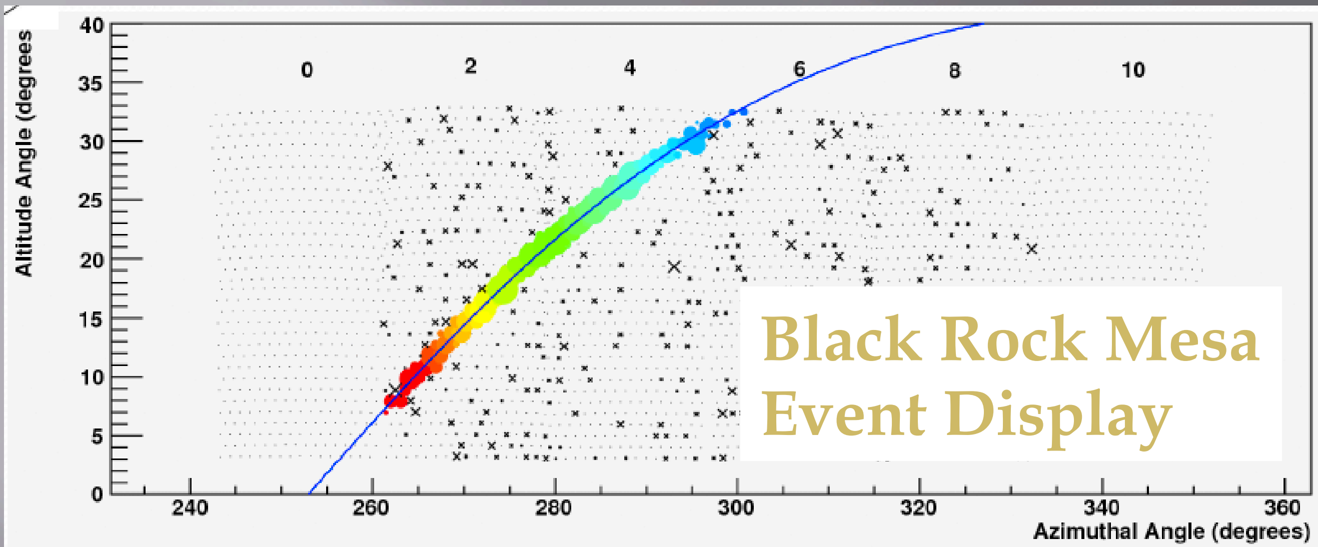
- TA is in Millard Co, Utah, 2 hours from SLC.
- SD: 507 scintillator counters, 1.2 km spacing, 3-m^2 active area, two layers.
- FD: 3 sites, each covers 120° azimuth, 3°–31° elevation
- Over 4.5 years of data have been collected.

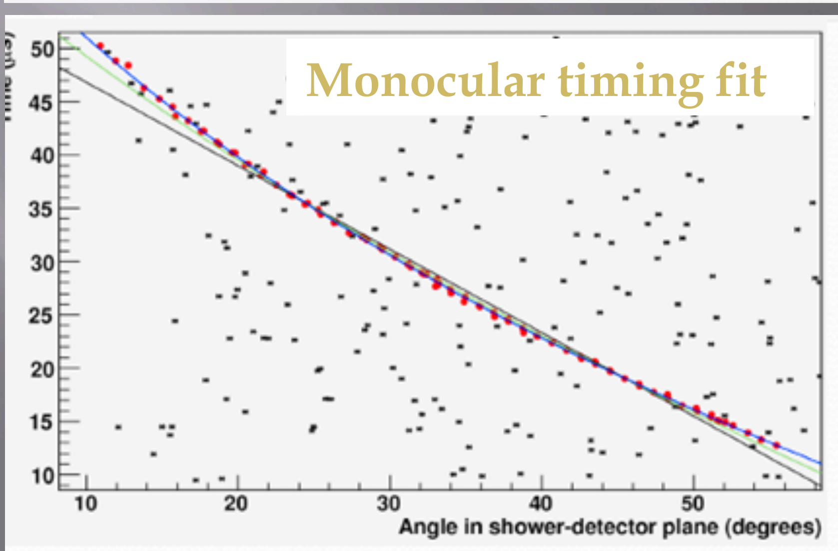


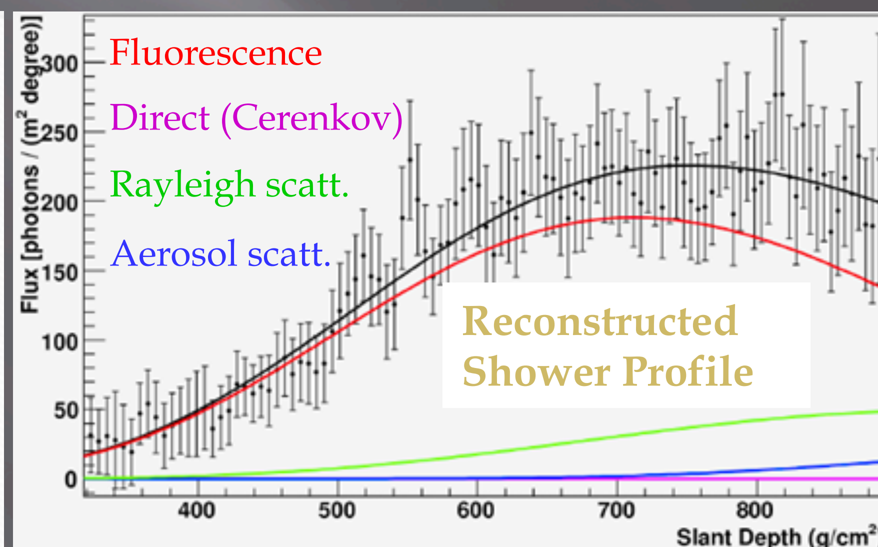
TA Fluorescence Detectors



Typical Fluorescence Event



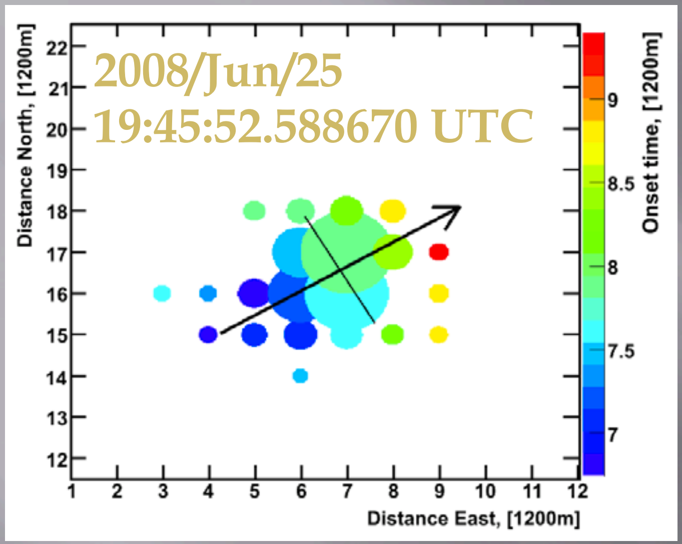


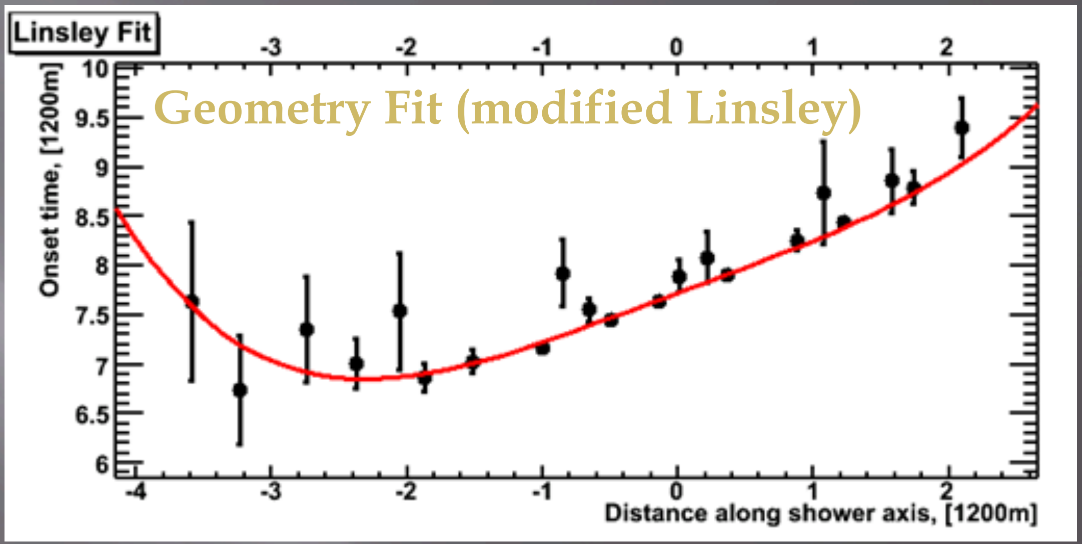


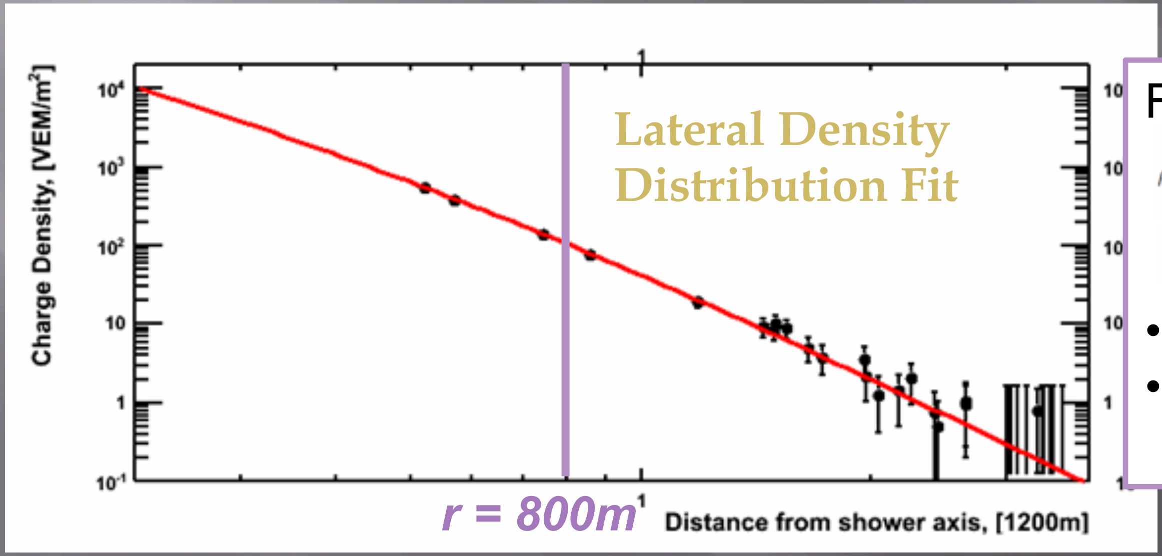
TA Surface Detector

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

Typical SD Event







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).

Stereo and Hybrid Observation

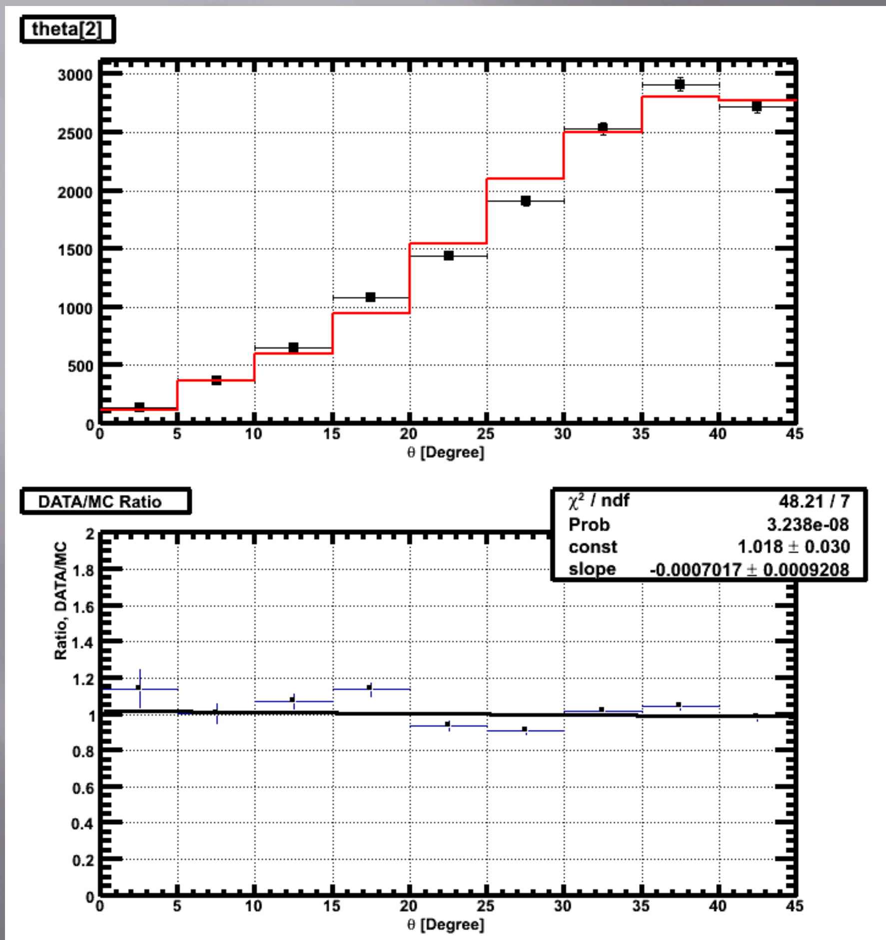
- Many events are seen by several detectors.
  - FD mono has ~5° angular resolution.
  - Add SD information (*hybrid* reconstruction) get ~0.5° resolution.
  - Stereo FD resolution ~0.5°
- Need stereo or hybrid for composition analysis.

- Independent SD and FD operation until 2010.
- Hybrid trigger is in operation now.

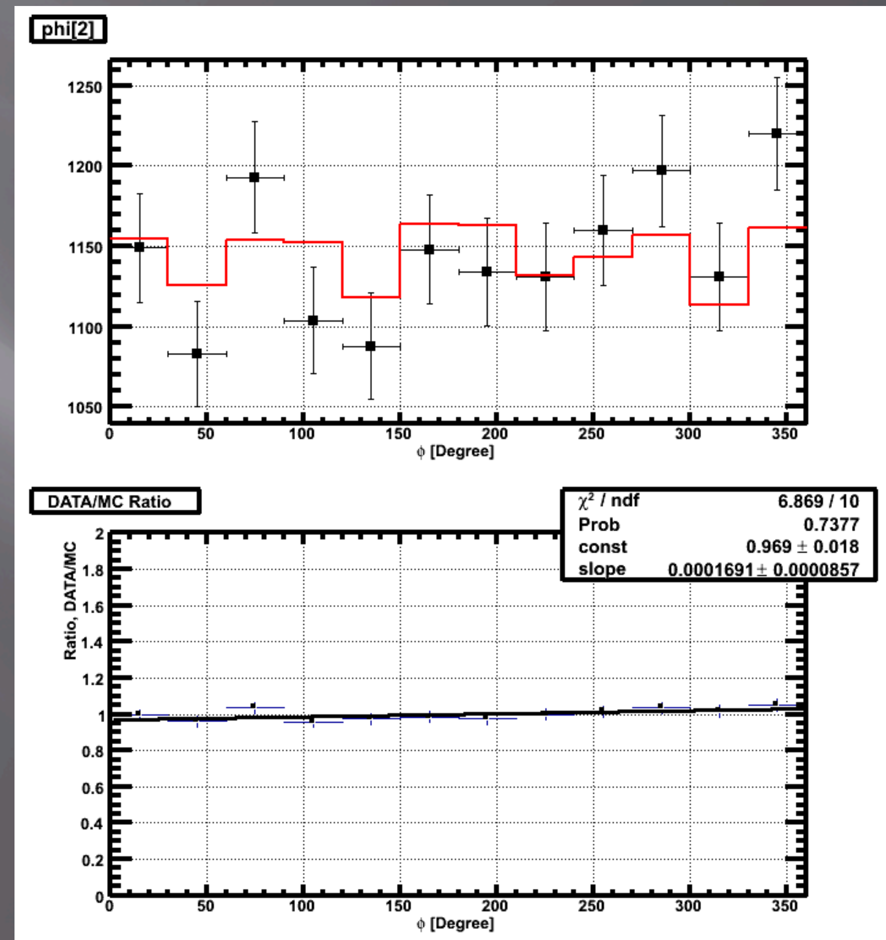
SD Spectrum

- 4 years of data
- 11909 events
- New analysis method
  - Constant-intensity-cut and geometric aperture no longer sufficient
  - Can extend measurement below the energy plateau
  - Use HEP methods of Data/MC comparisons in calculating acceptance (aperture)
- Aperture calculation
  - Generate using measured spectrum and composition
  - Treat simulated data *exactly* the same as real data: same format, same analysis chain, same cuts
- Verify aperture calculation via Data/MC comparisons

Data/MC Comparisons

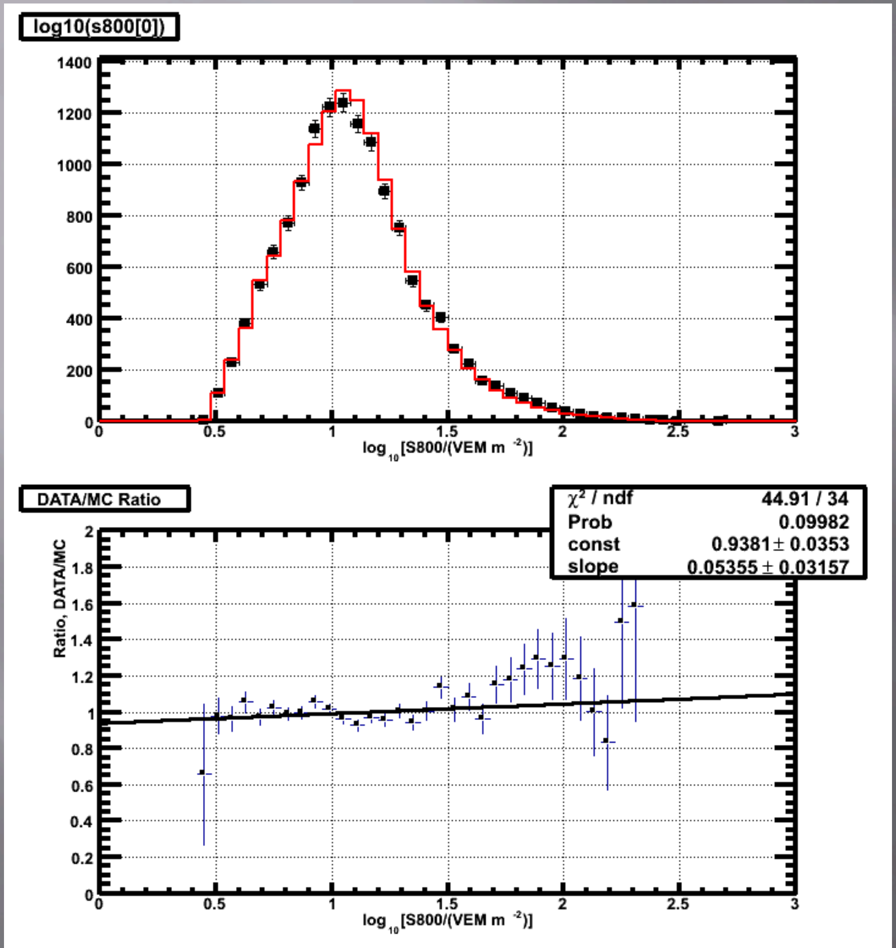


Zenith angle

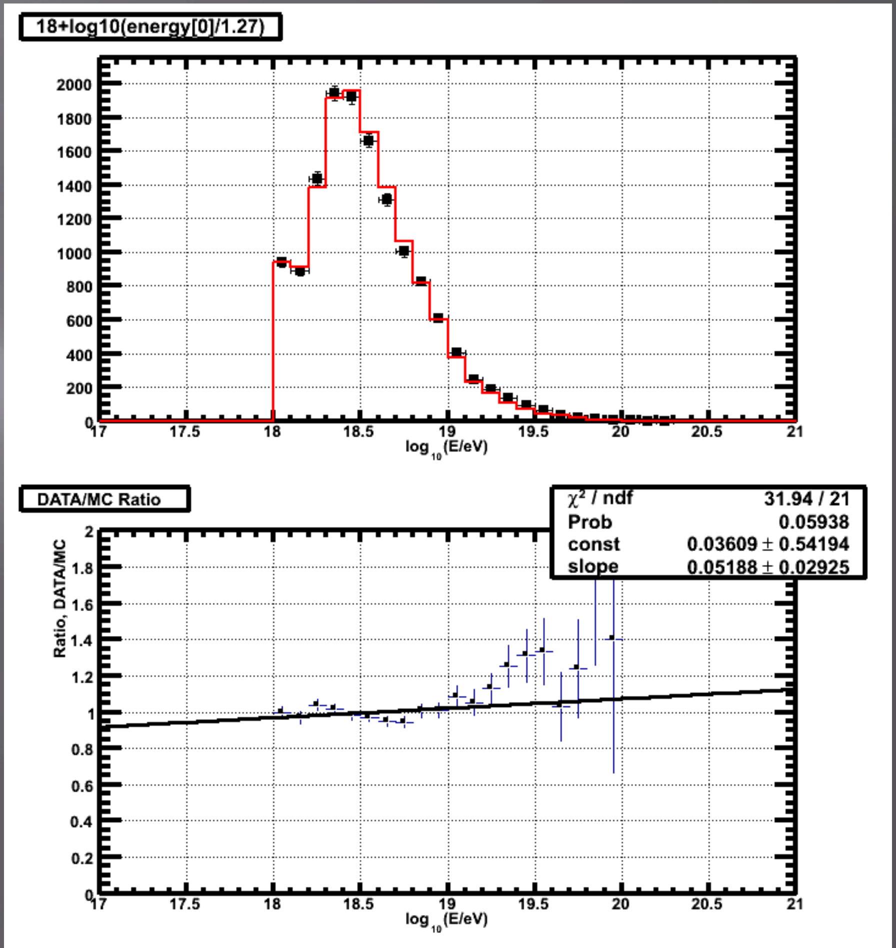


Azimuth angle

Data/MC Comparisons



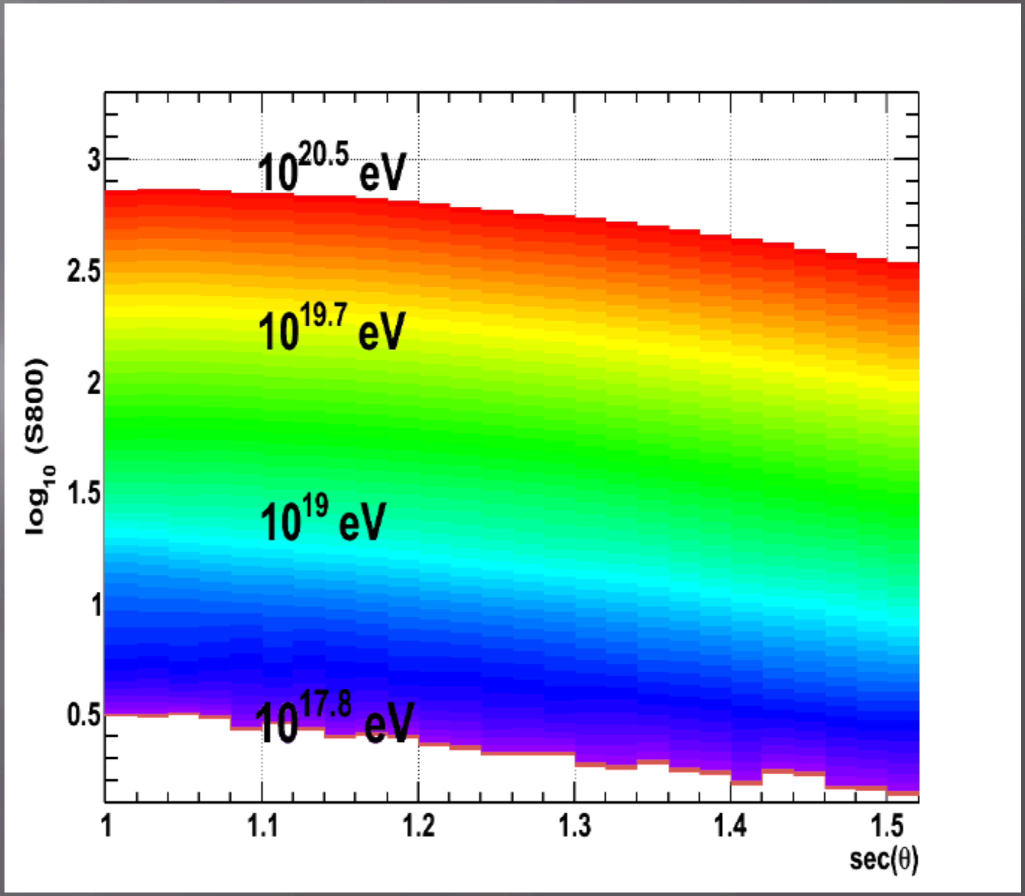
S_{800}



Energy

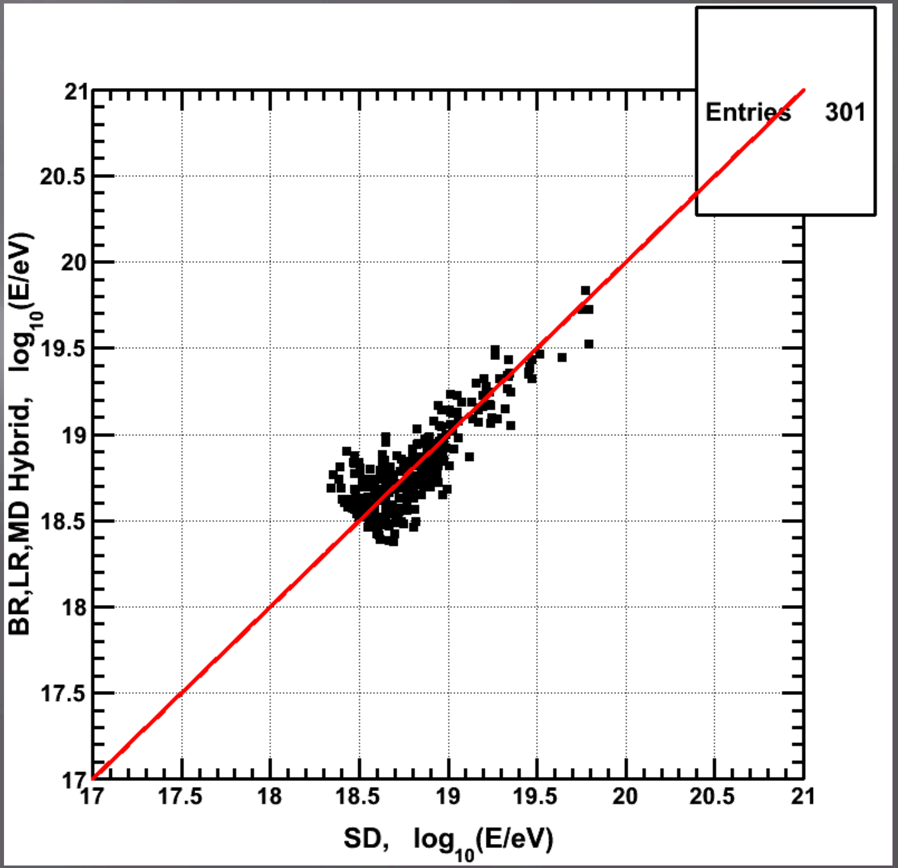
First Energy Estimate

- For each energy find make $\log_{10}$S800-vs-secθ curve from MC
- Estimation energy by looking up, interpolating between $\log_{10}$S800-vs-secθ curves

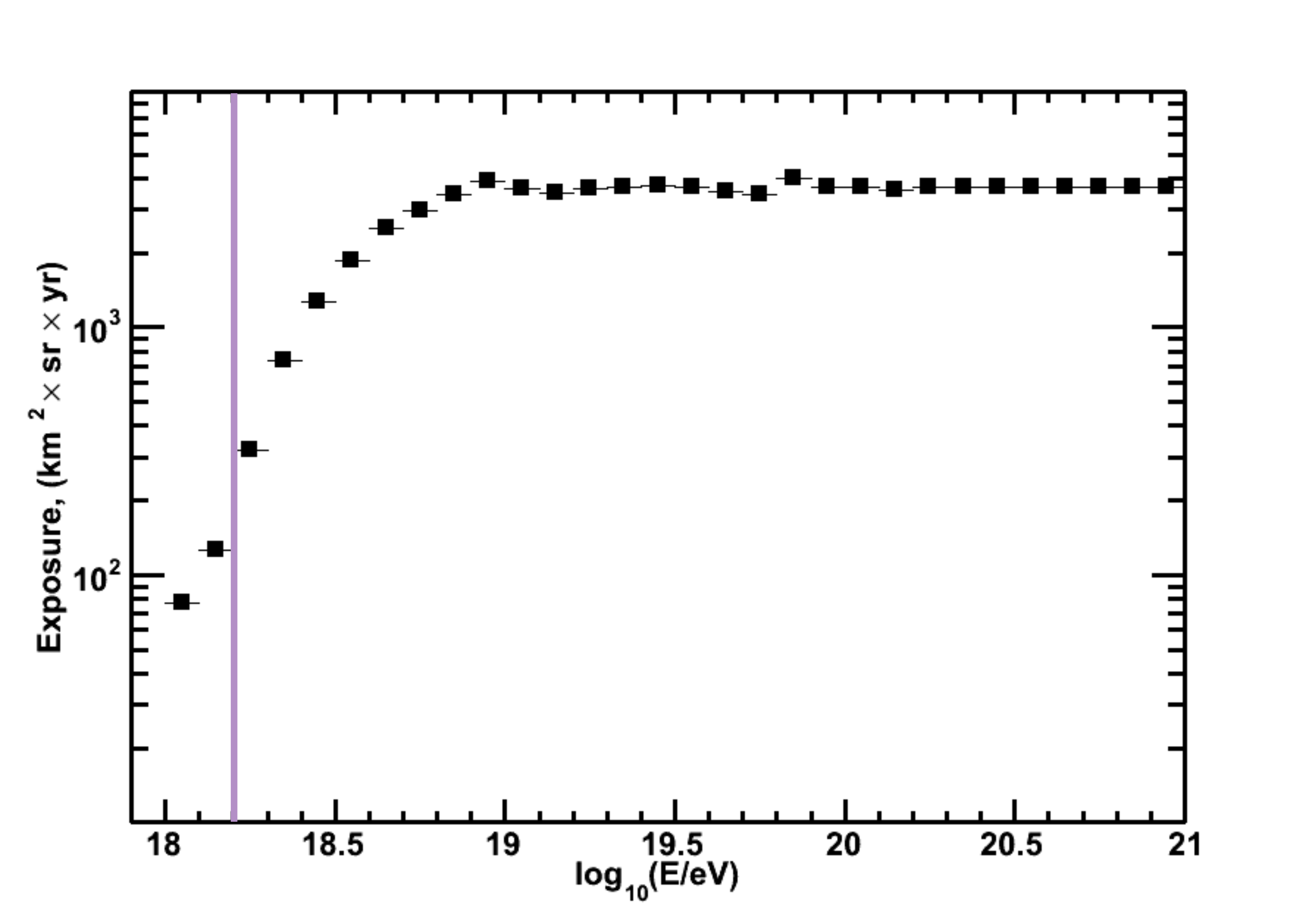


Energy Scale

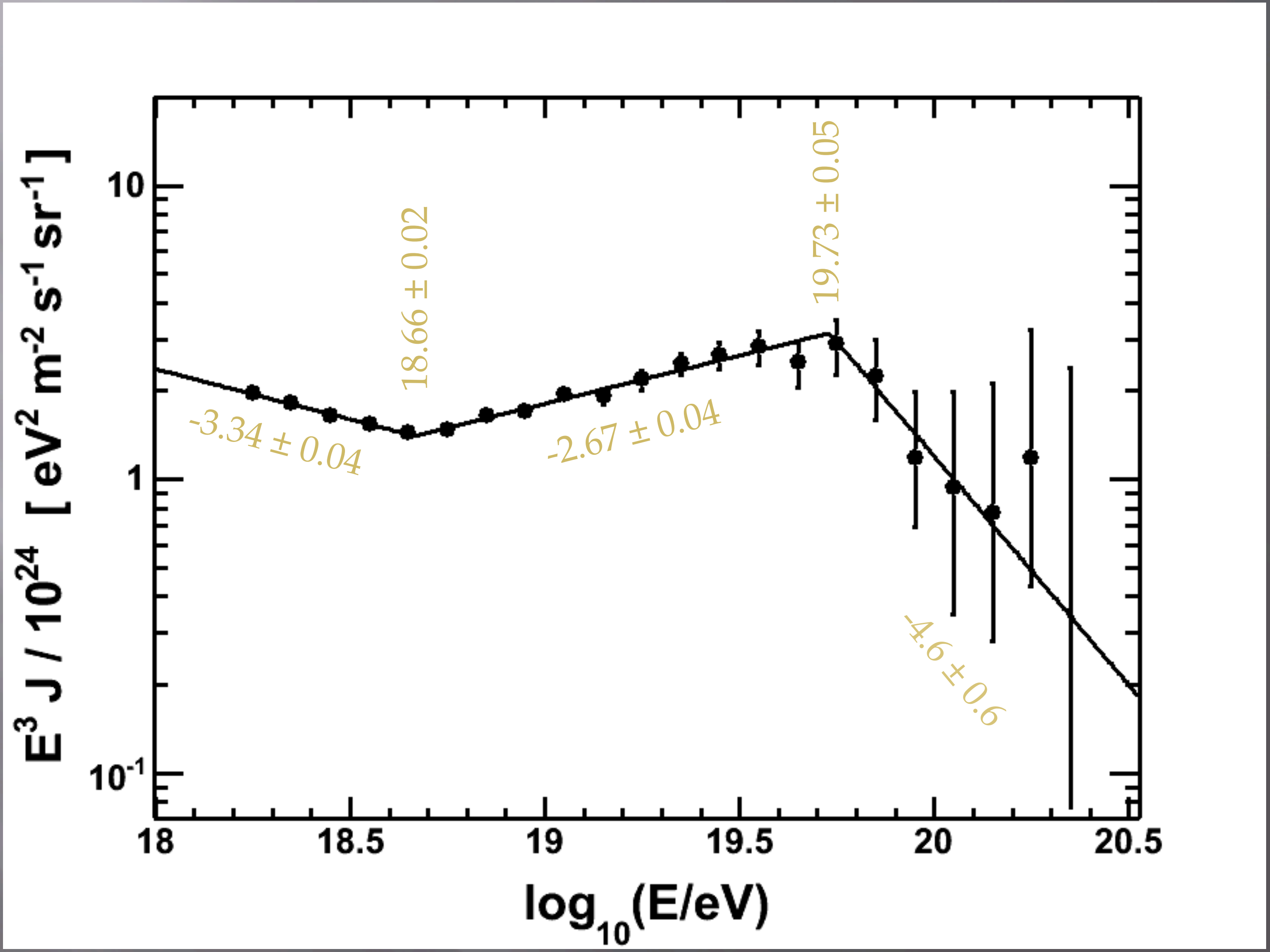
- SD and FD energy estimations disagree
- FD estimate possesses less model-dependence
- Set SD energy scale to FD energy scale using well-reconstructed events from all 3 FD detectors
- **27% renormalization.**
- 21% systematic uncertainty in FD energy scale



SD Exposure

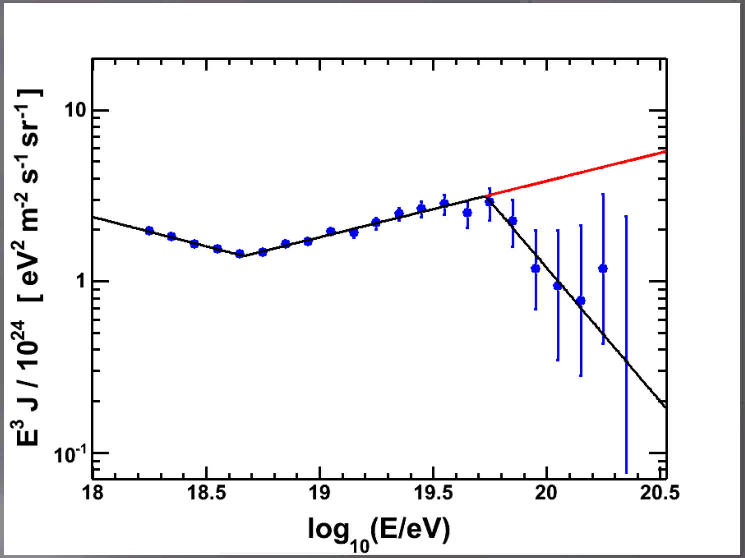


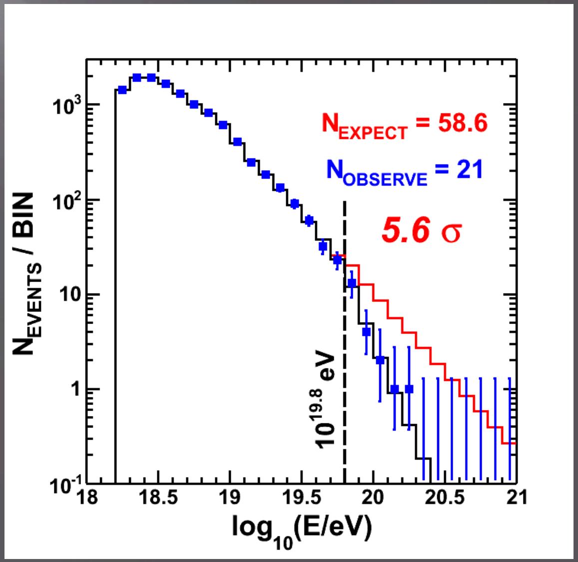
SD Spectrum with Broken PL Fit



GZK Significance

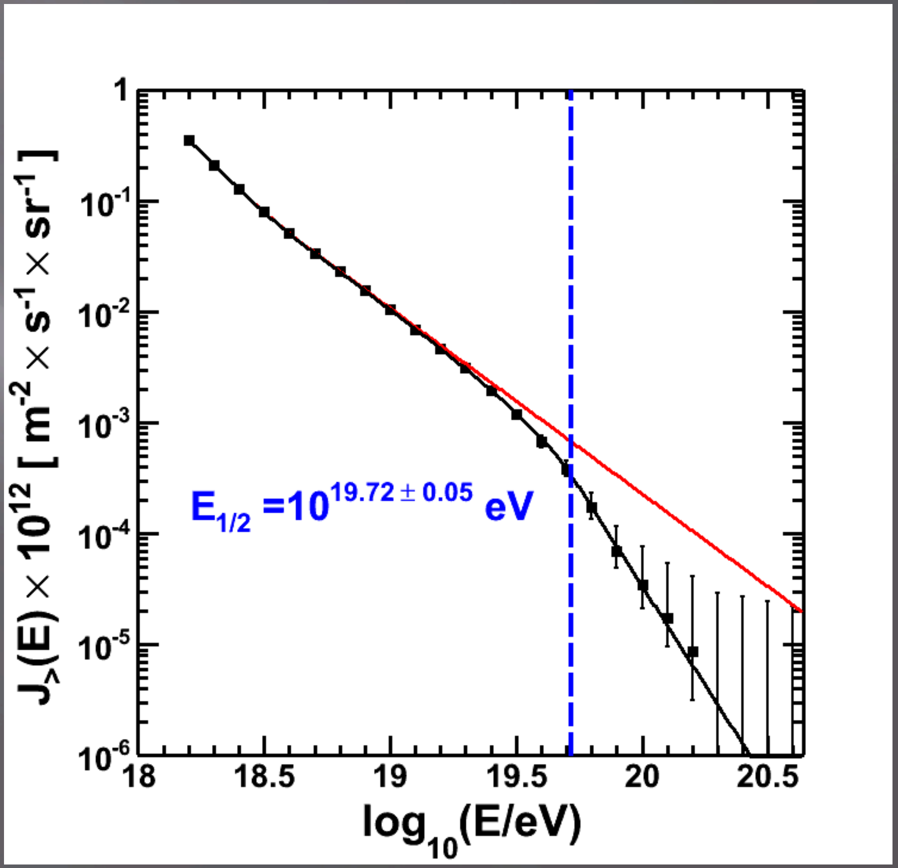
- What's the statistical significance of the HE break (GZK cut-off)?
- Calculate the number expected with no break and compare to the number seen
- Expect 58.6, observe 21, 5.6 σ



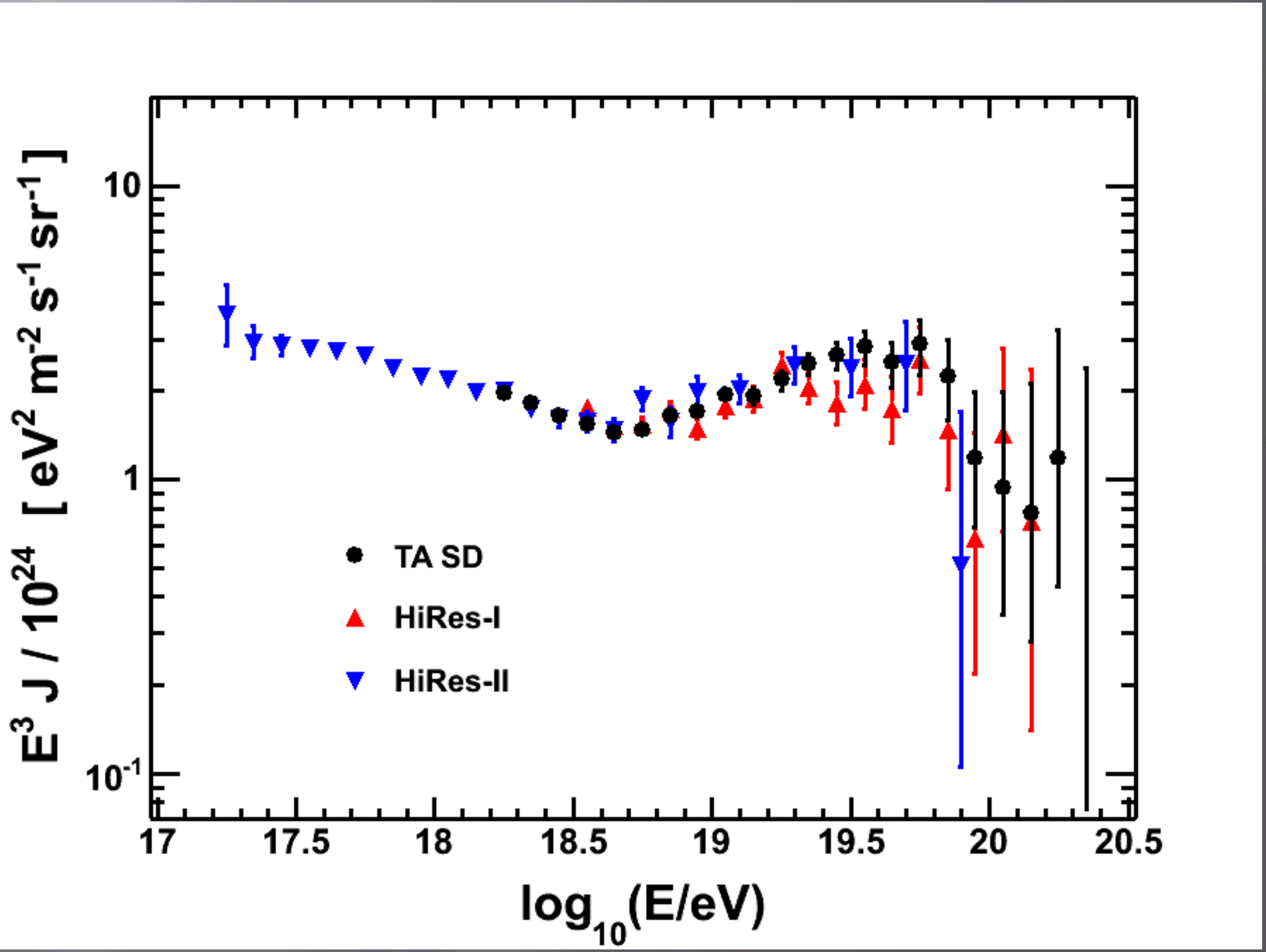


Integral Flux: $E_{½}$ Measurement

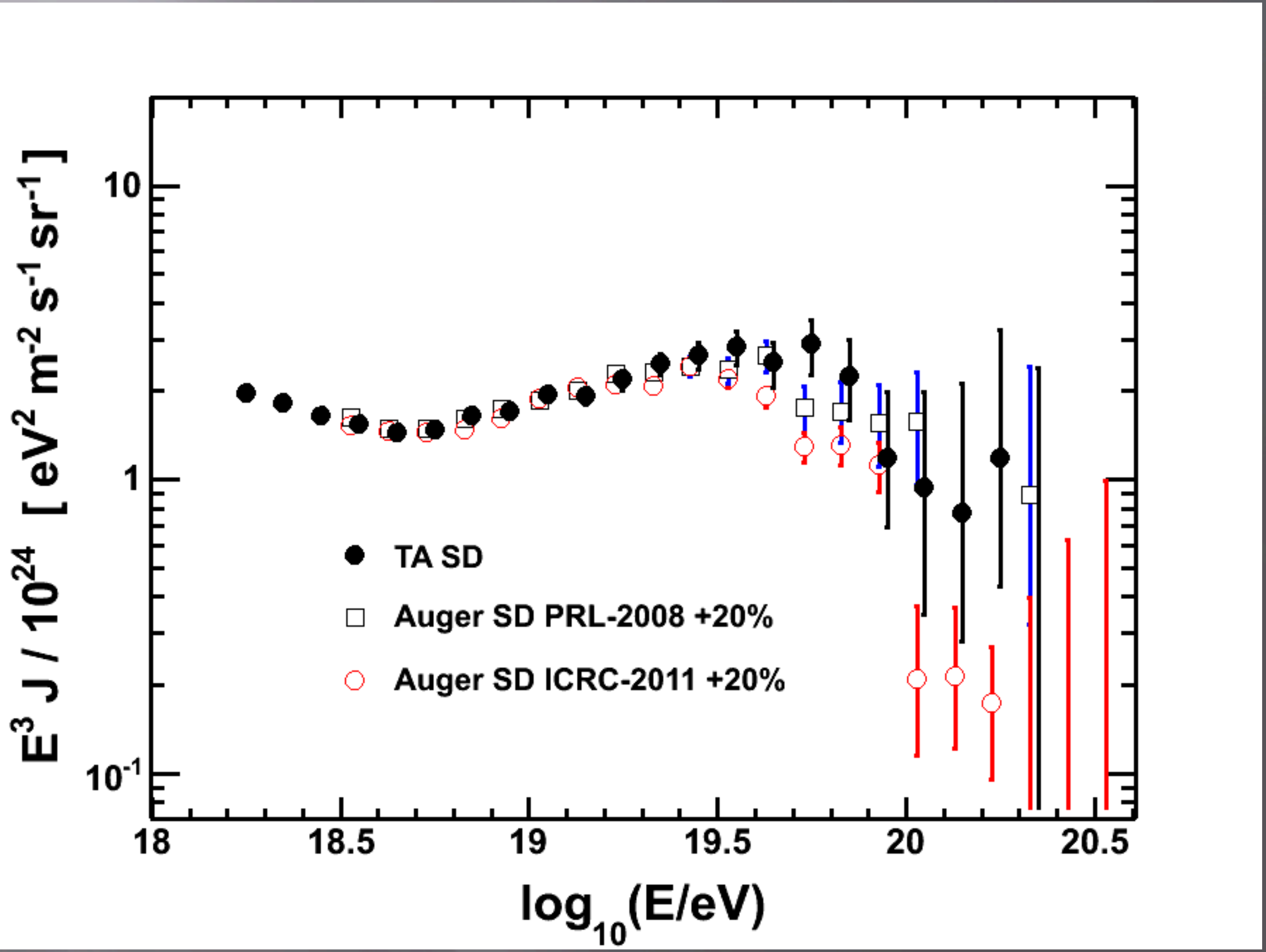
- Can also ask where is the flux down by half from what it would have been without the GZK.
- Have to compare the *integral* fluxes
- Our measurement compares well with Berezinsky's prediction from protons



Comparison: TA-SD with HiRes



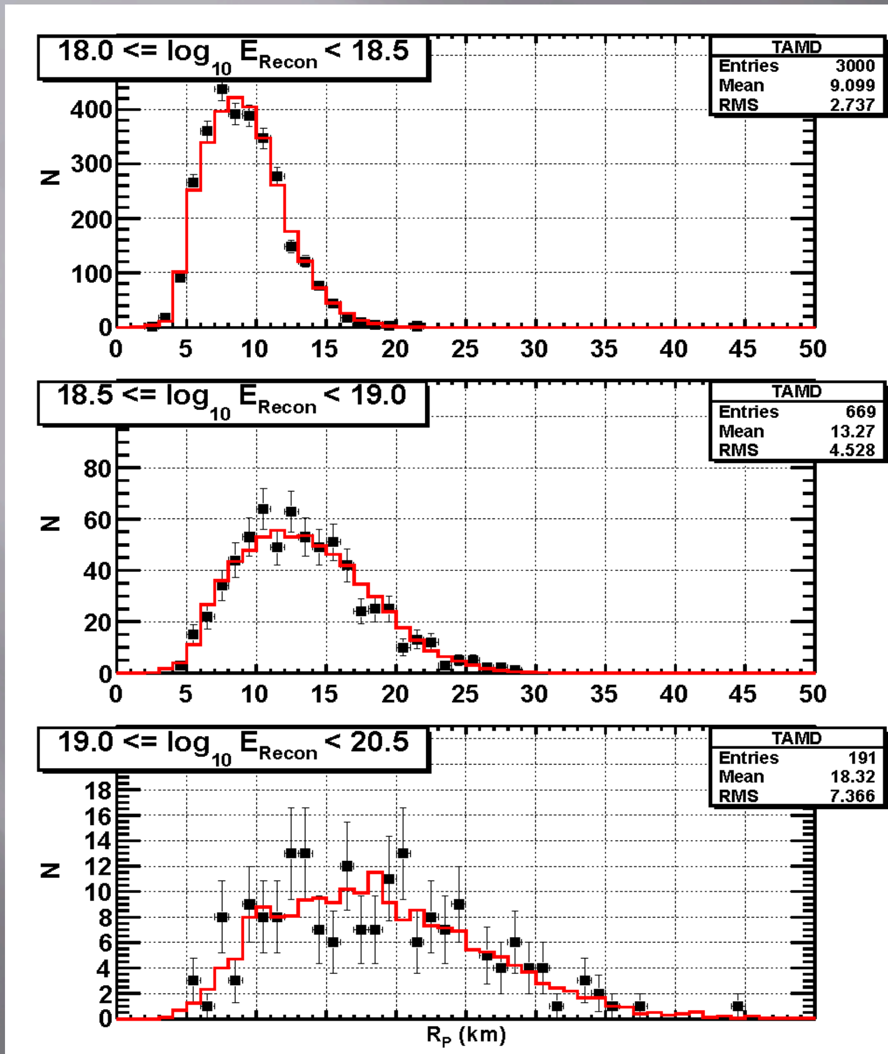
Comparison: TA-SD with Auger



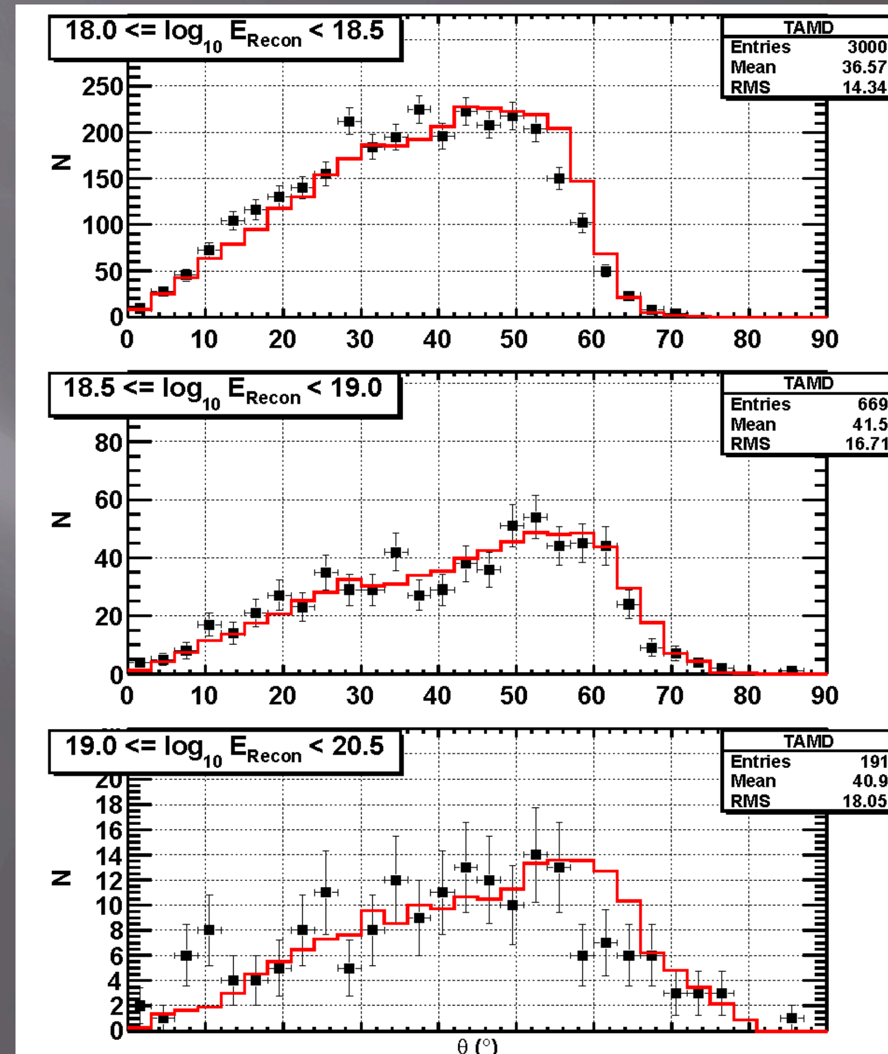
Middle Drum Mono Spectrum

- All FD spectrum measurements (monocular, stereo, hybrid) depend on a changing aperture. The aperture grows with energy.
- This changing aperture *must* be calculated by MC simulation.
- Again we rely on full analysis of simulated data in the same format as actual data, and comparisons of distributions between data and MC, to verify this calculation.

MD Mono Data/MC

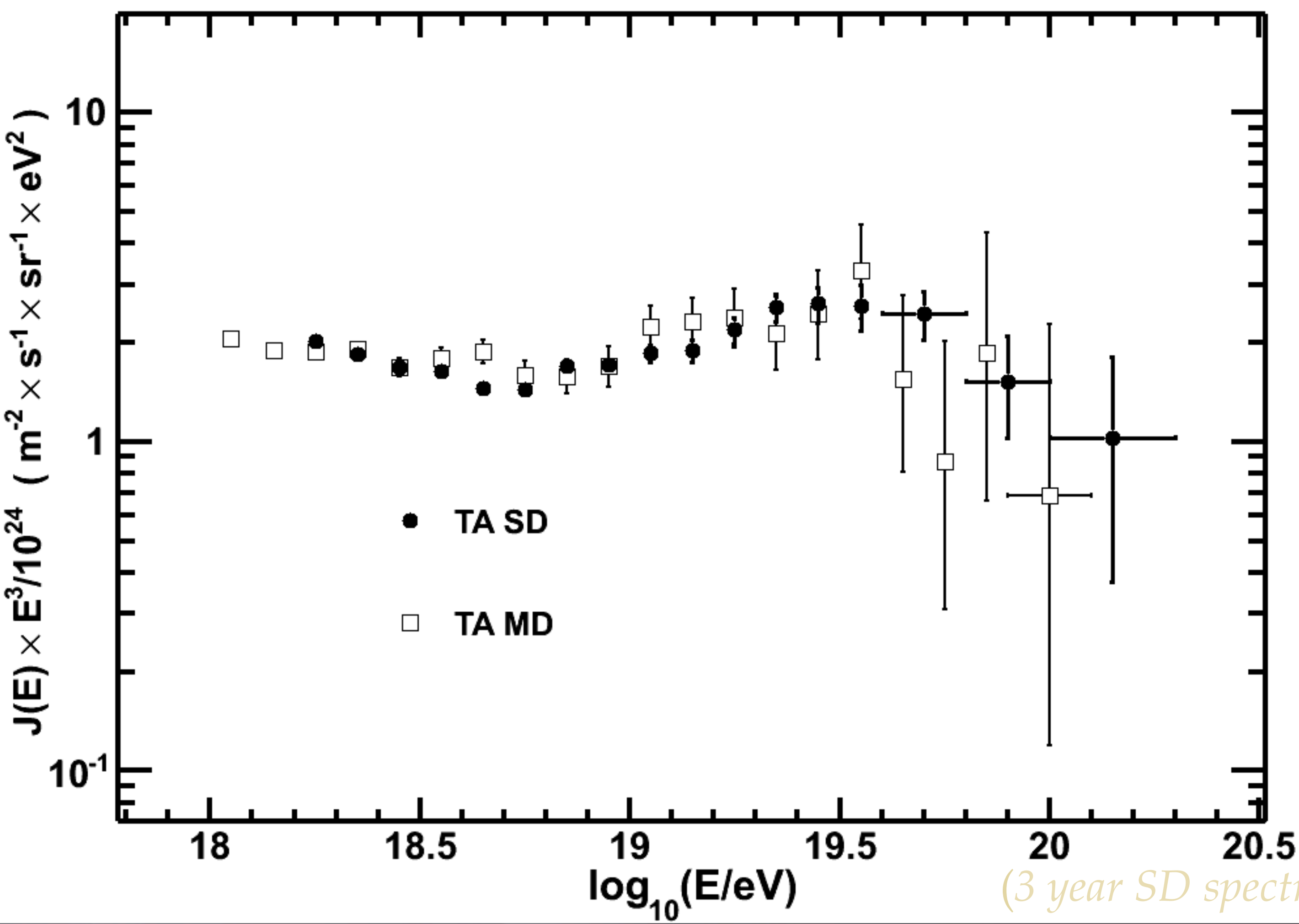


R_p



Zenith angle

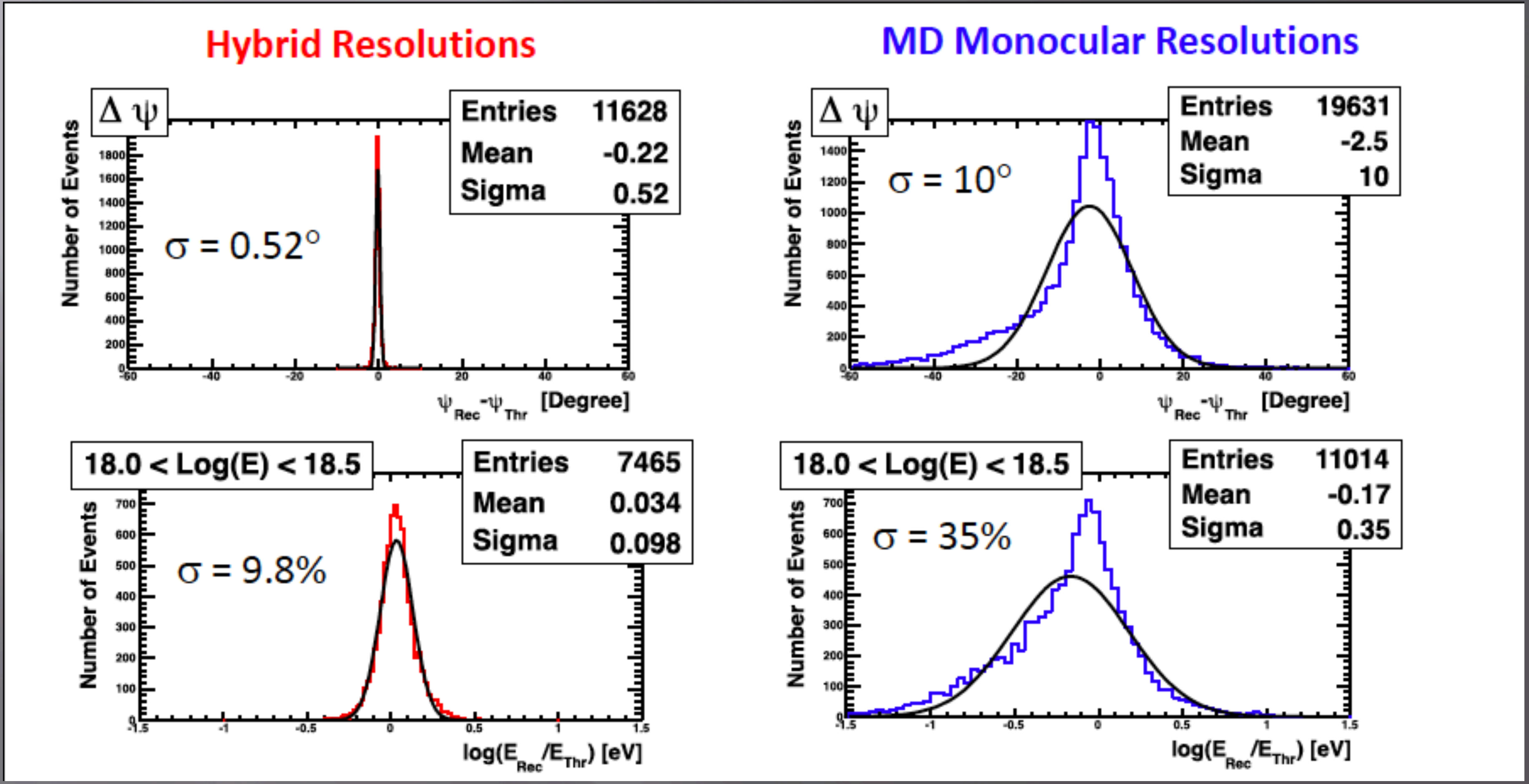
SD & FD Comparisons



(3 year SD spectrum)

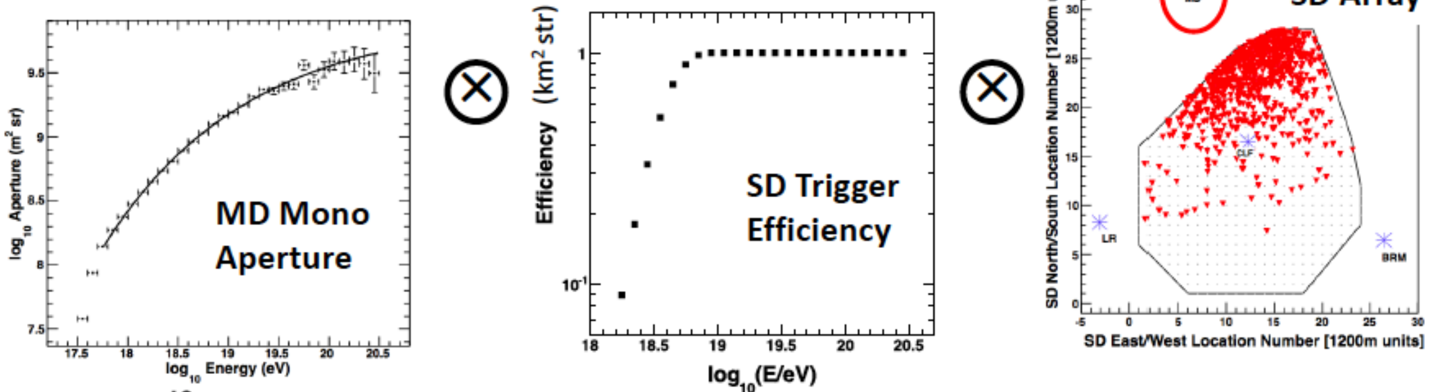
MD-SD Hybrid Spectrum

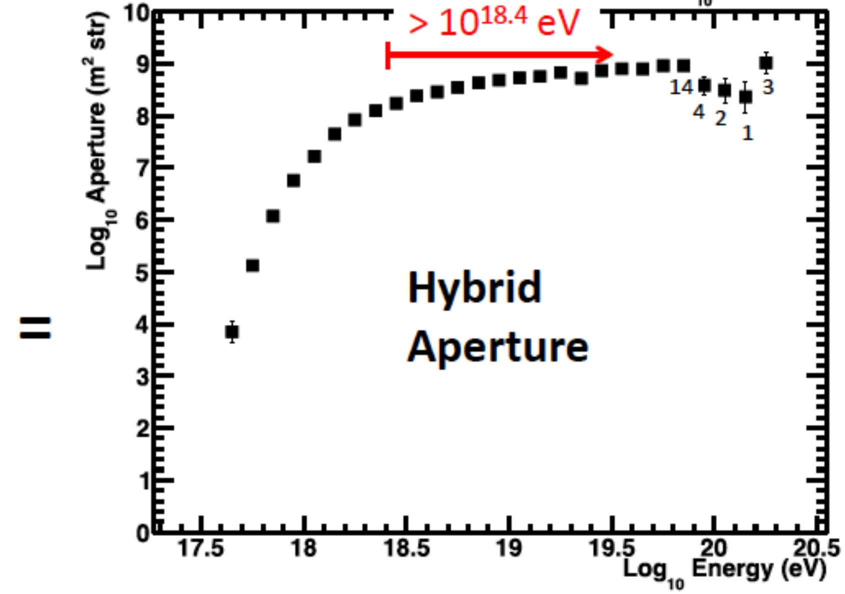
- Hybrid: fewer events, much better resolution



MD-SD Hybrid Spectrum

Aperture Calculation





- Generate Energy Spectrum in region where aperture flattens out ($E > 10^{18.4}$)

$$J(E) = \frac{N(E)}{A\Omega(E) \times \Delta t \times \Delta E}$$

$$A\Omega = A_0\Omega_0 \frac{N_{Accepted}}{N_{Generated}}$$

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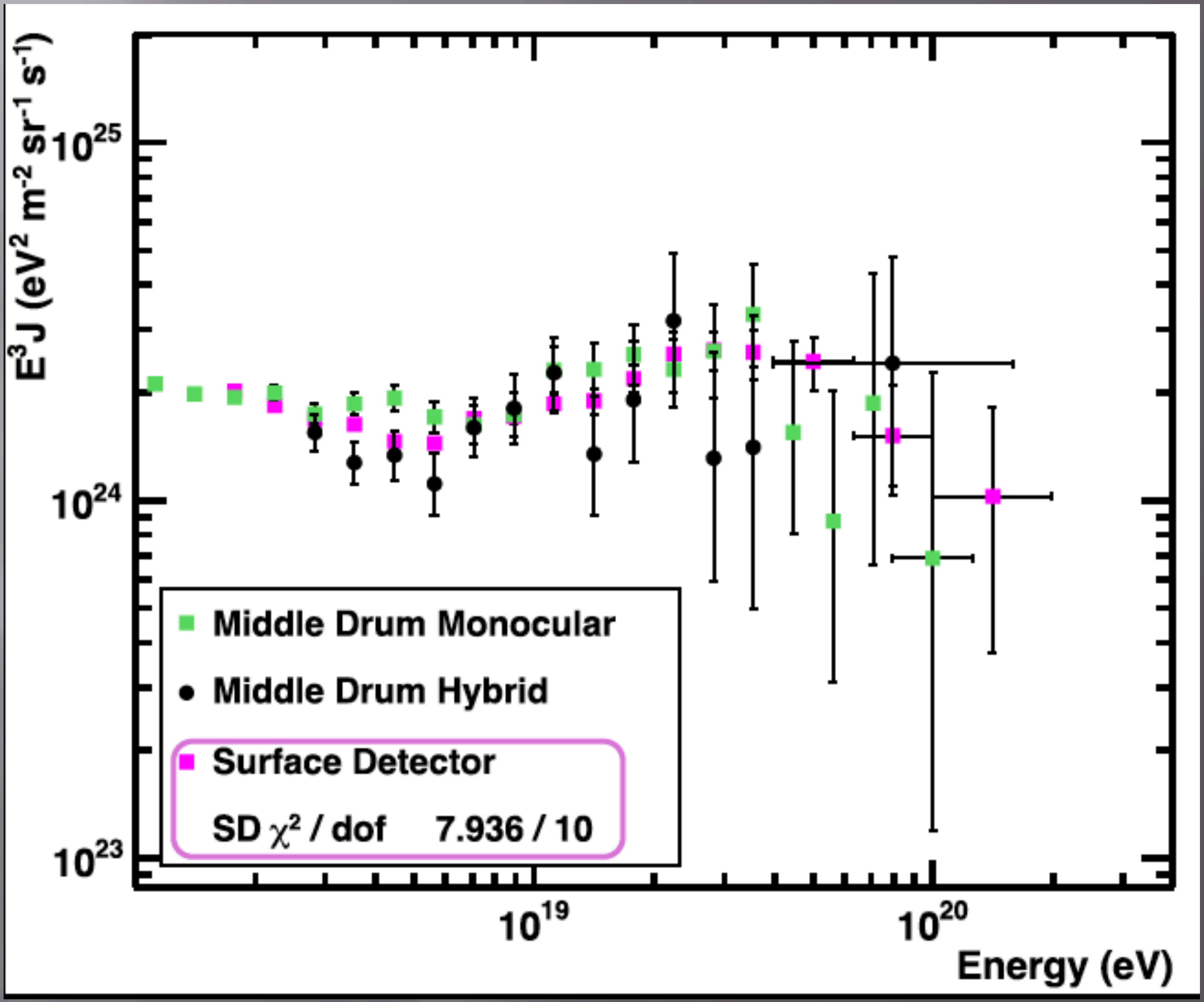
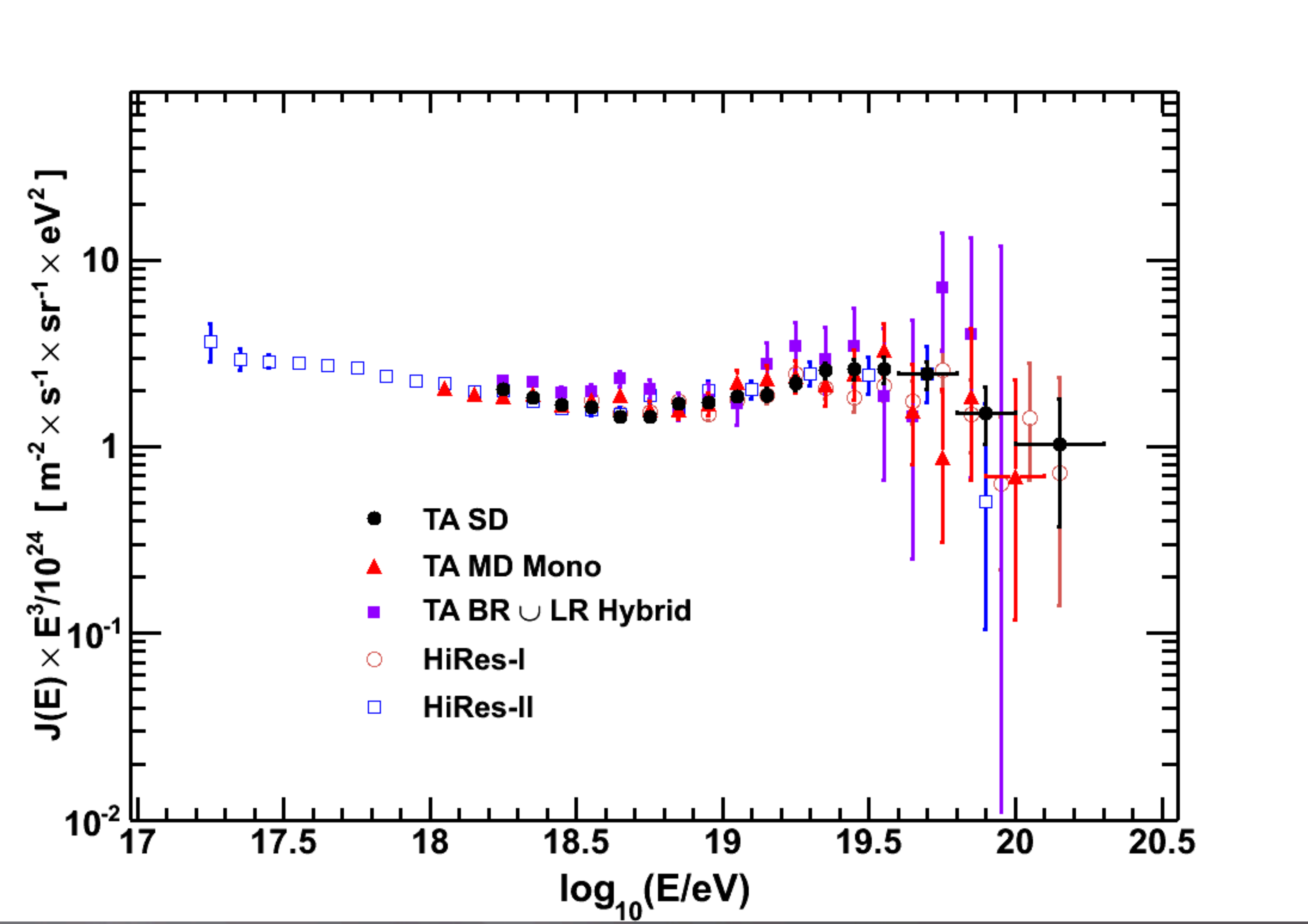
SD, MD Mono, MD Hybrid



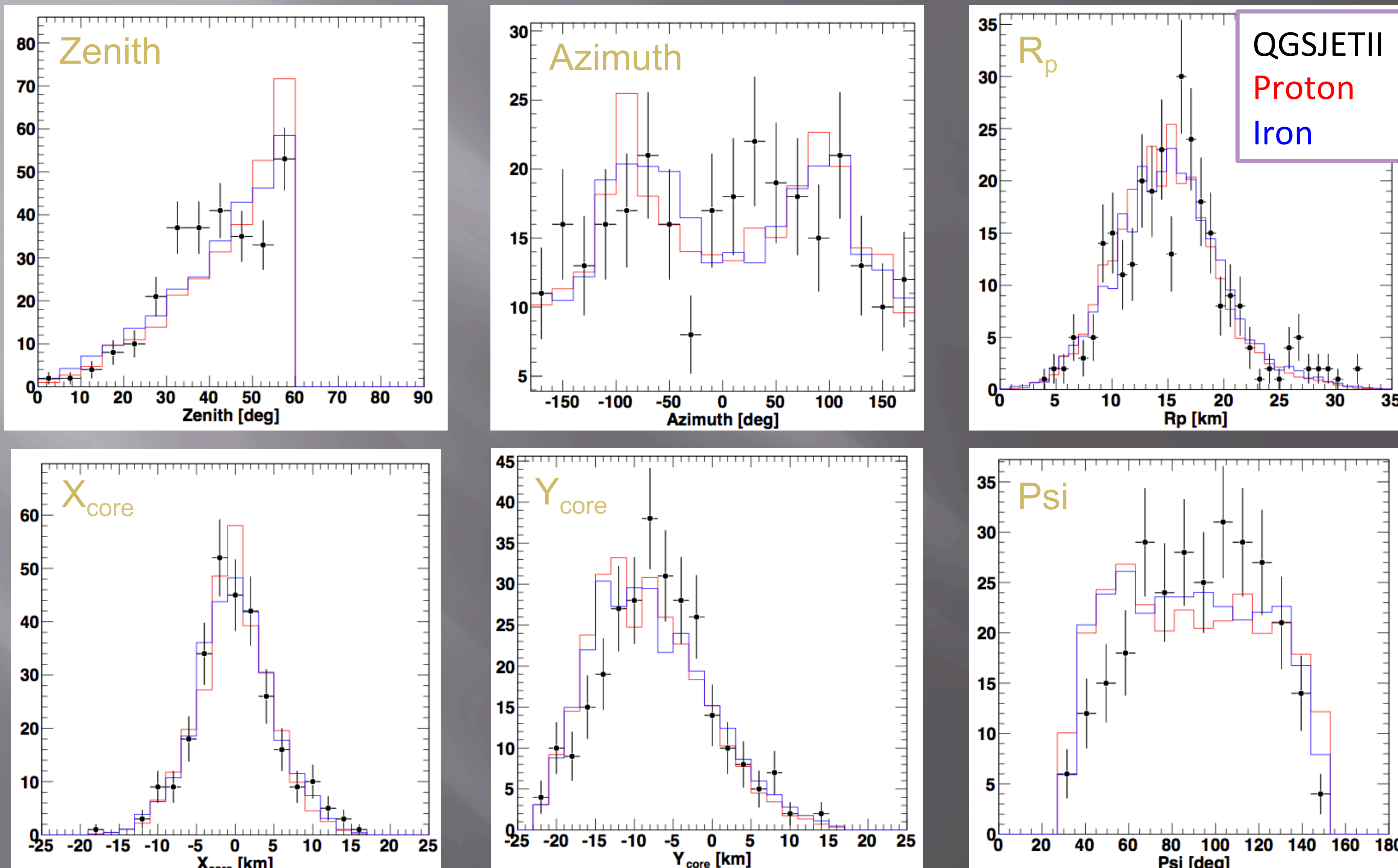
SD, Mono, Hybrid, HiRes



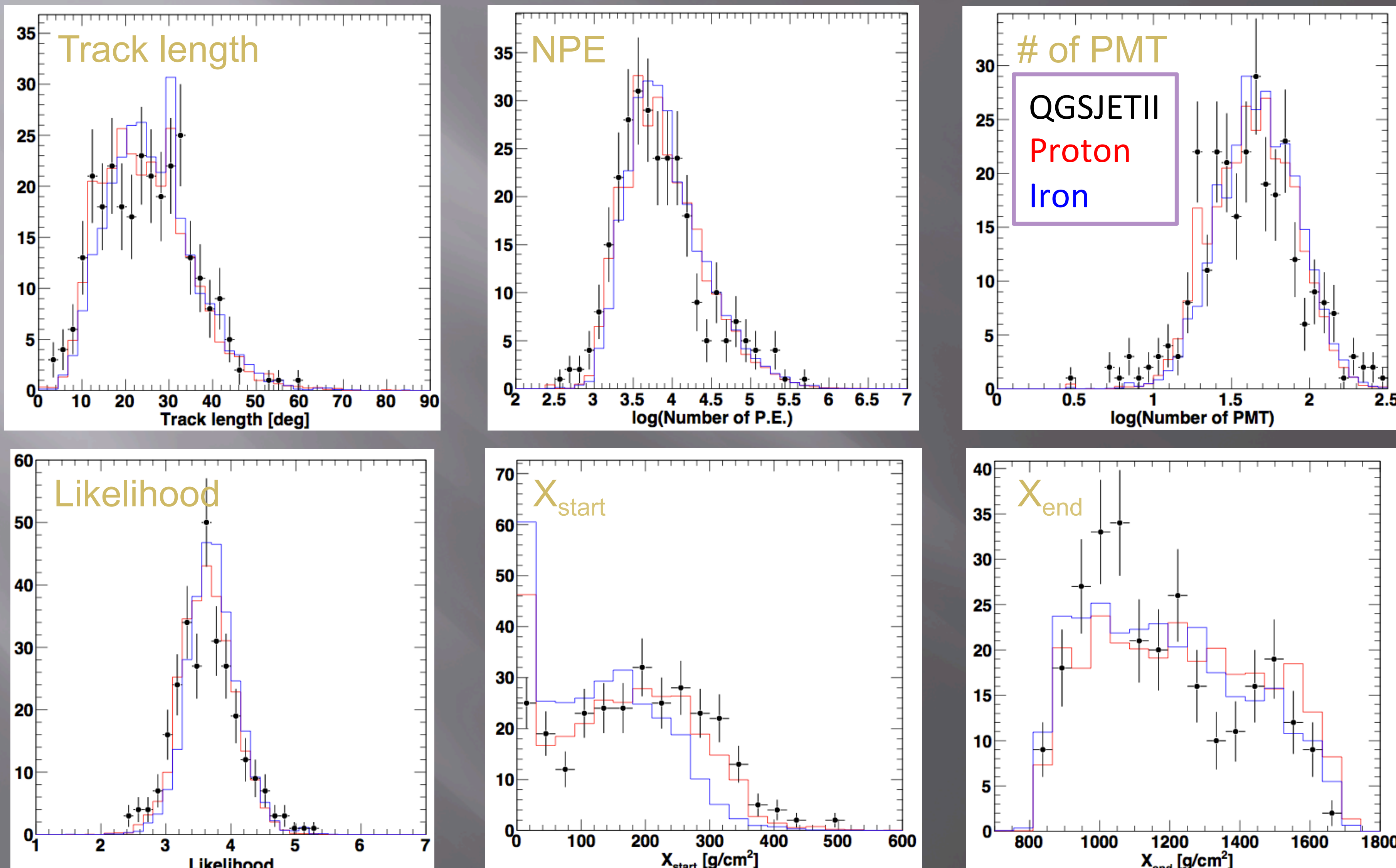
Stereo FD Composition

- Measure X_{max} for Black Rock Mesa/Long Ridge FD stereo events
- Create simulated MC event set
- As always, apply exactly the same procedures in simulated data as with the actual data

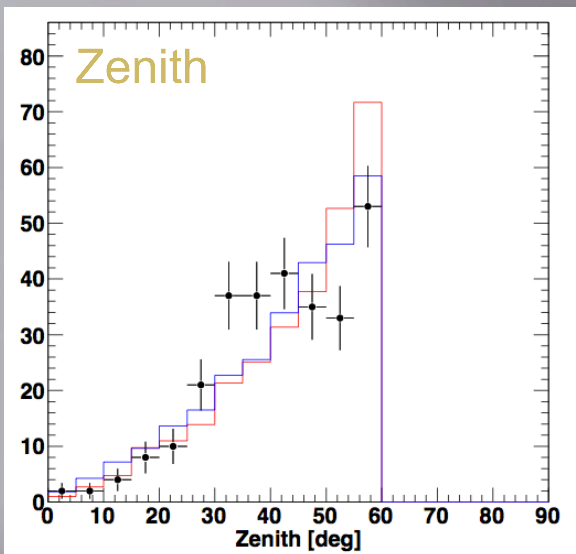
Stereo Data/MC Comparisons

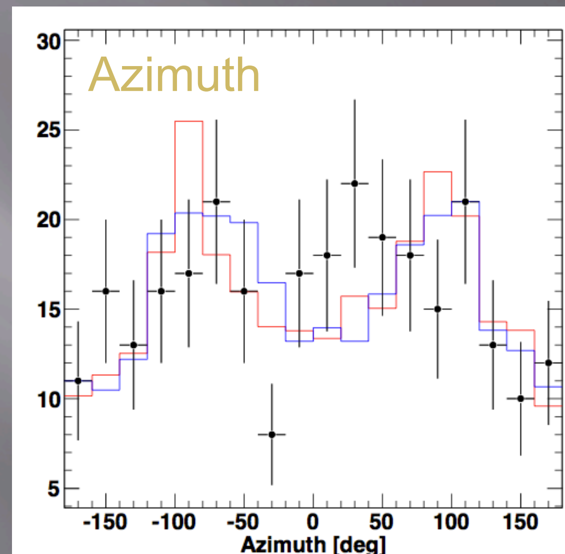


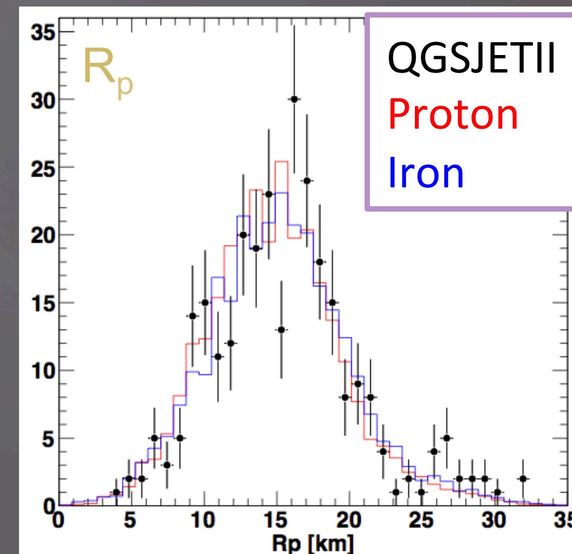
Stereo Data/MC Comparisons

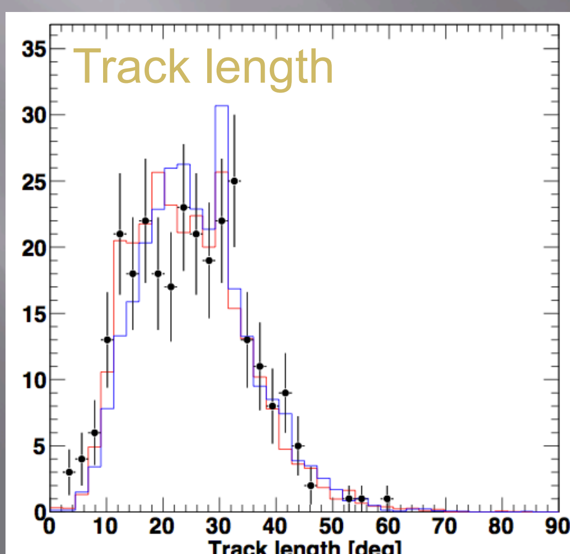


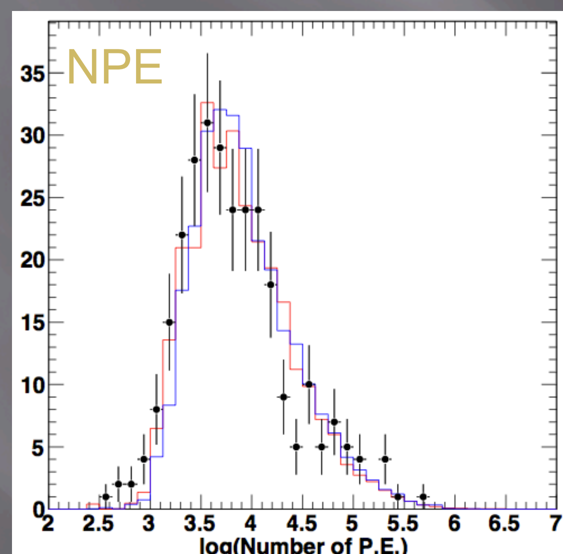
Stereo Data/MC Comparisons

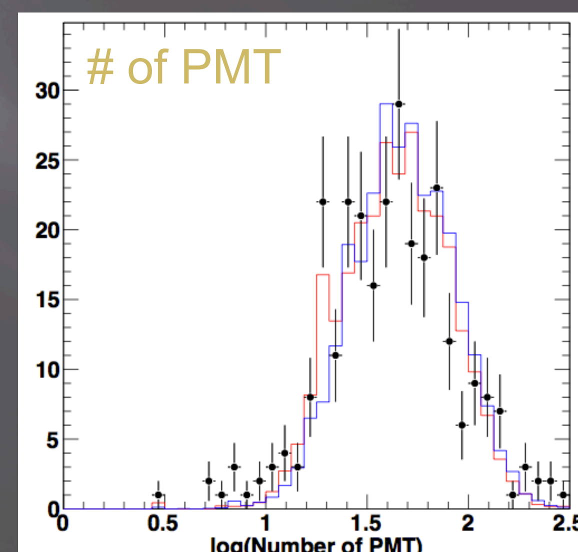




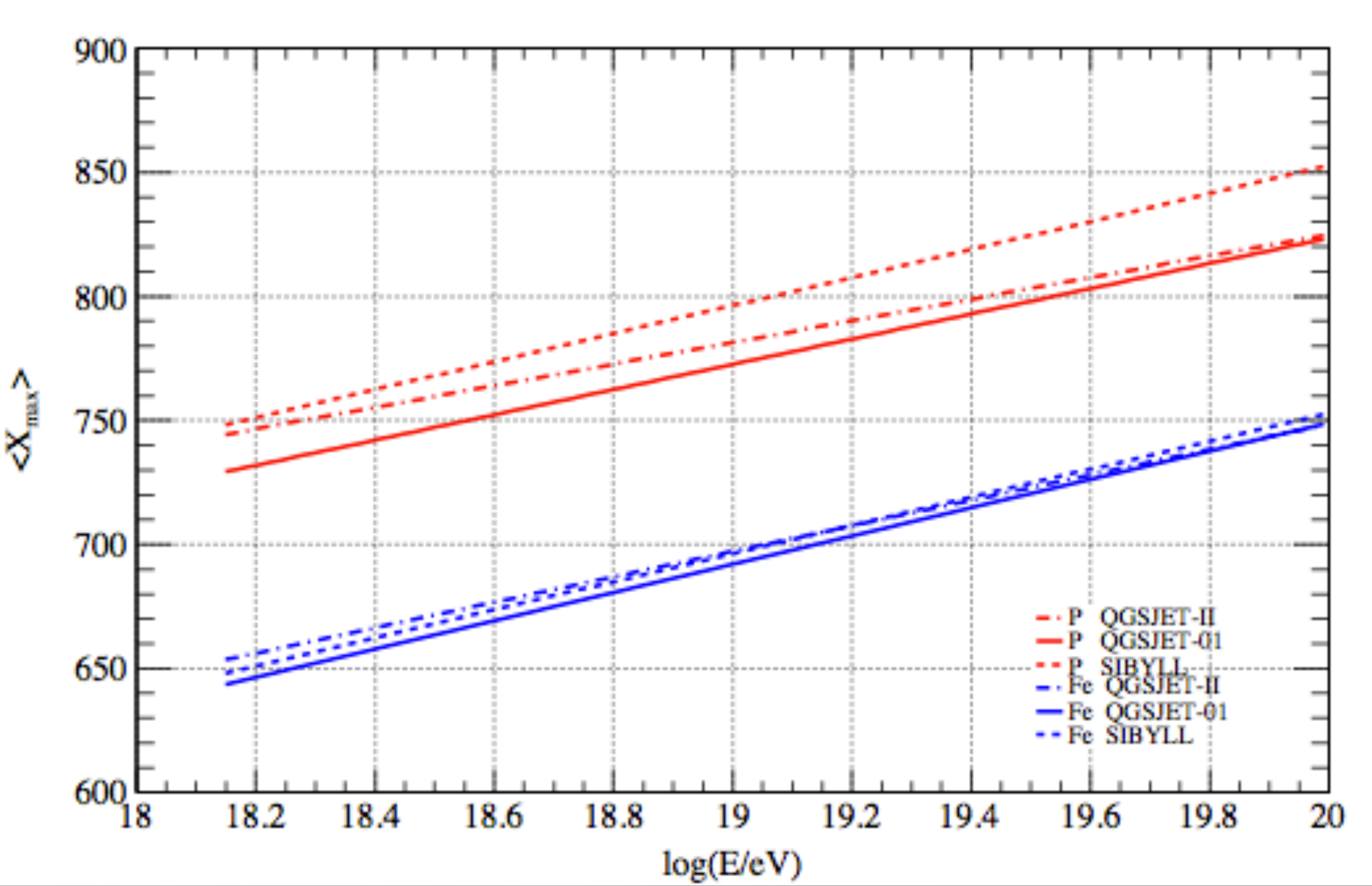




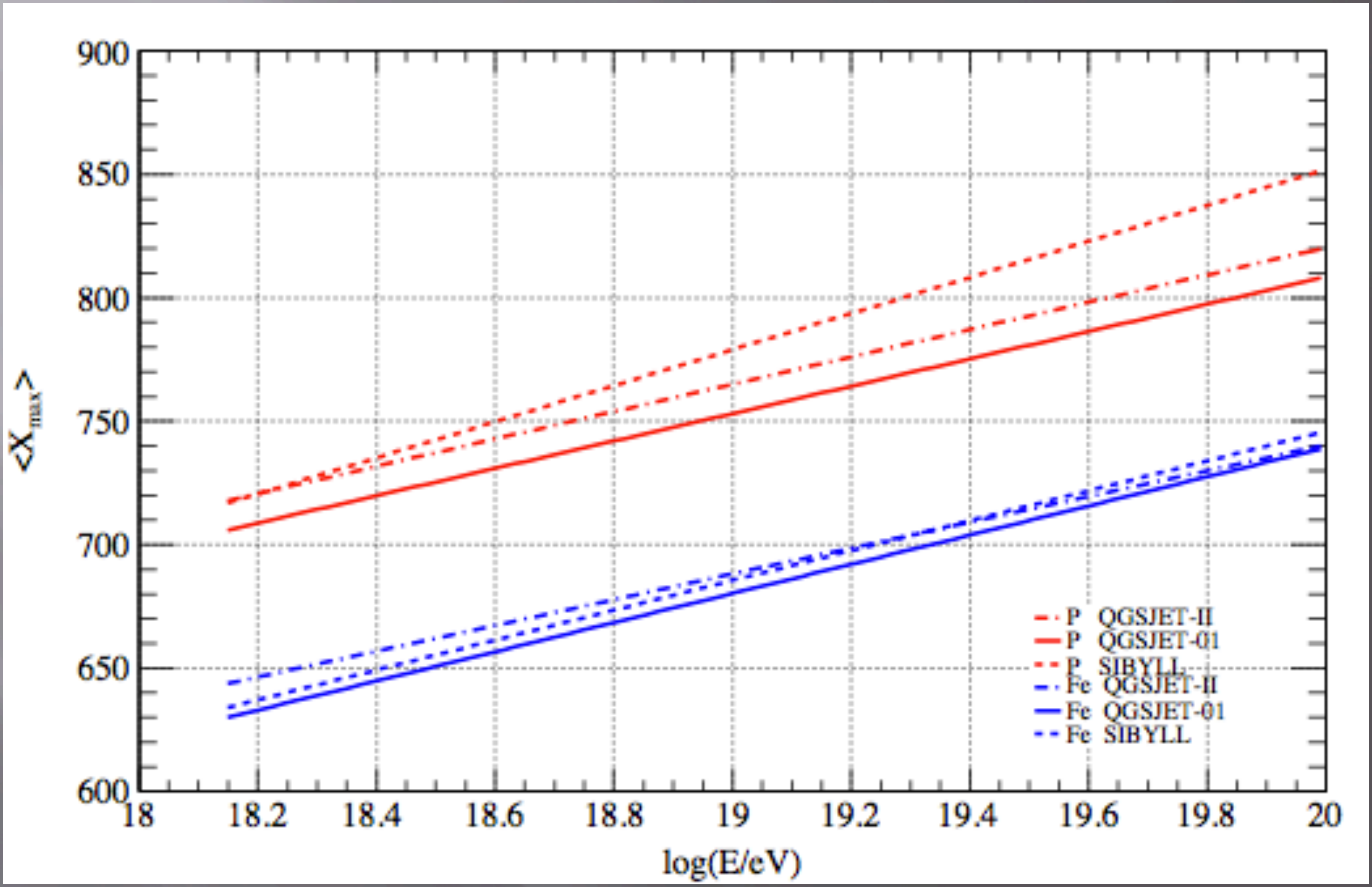




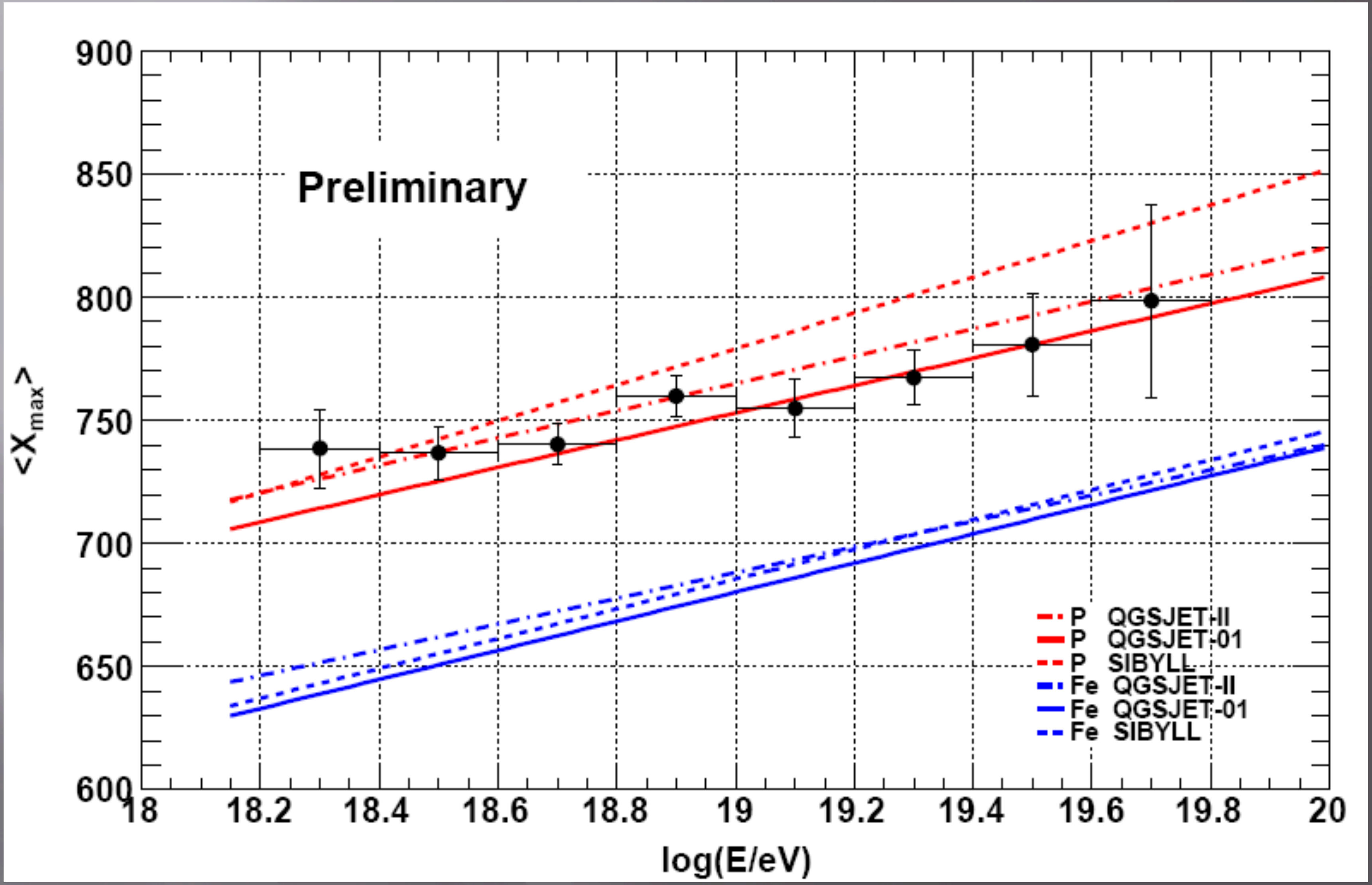
$<X_{max}>$ from Corsika



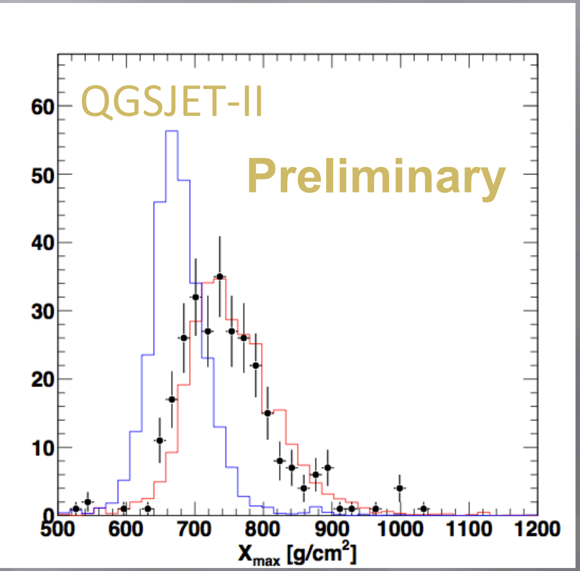
<X_{max}> after reconstruction

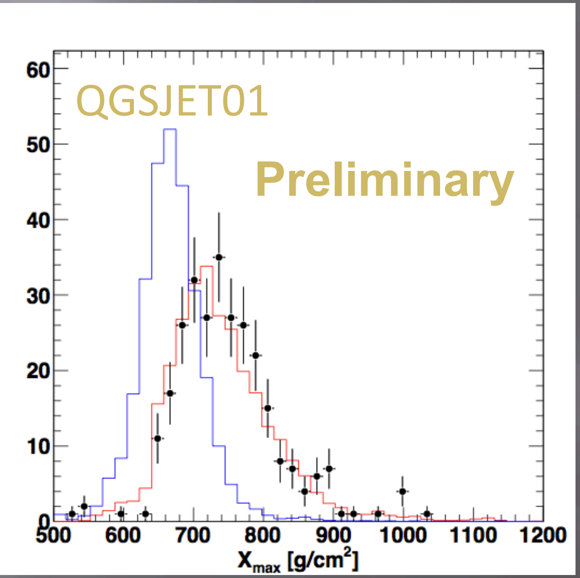


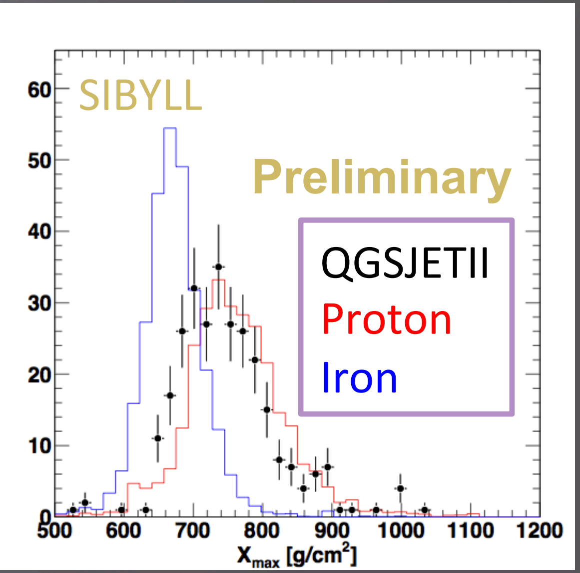
Measured <X_{max}> vs $\log_{10}E$



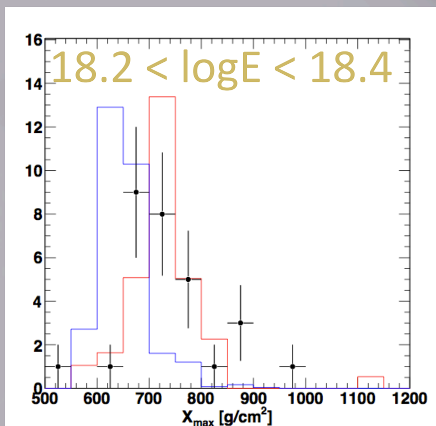
Measured X_{max} Distributions

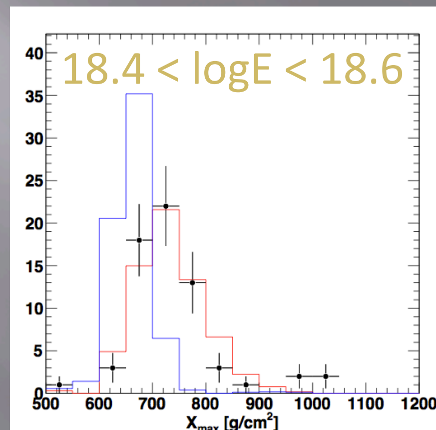


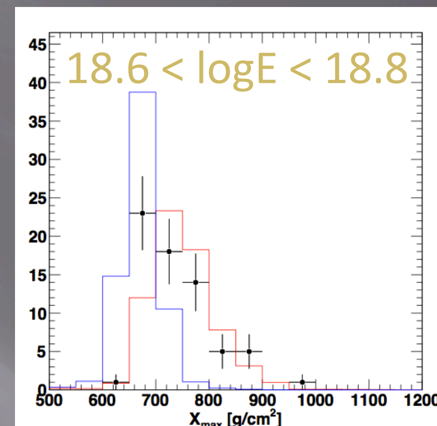


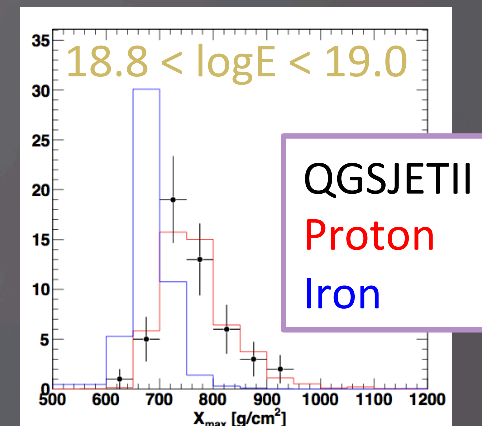


X_{max} Distributions, QGSJetII

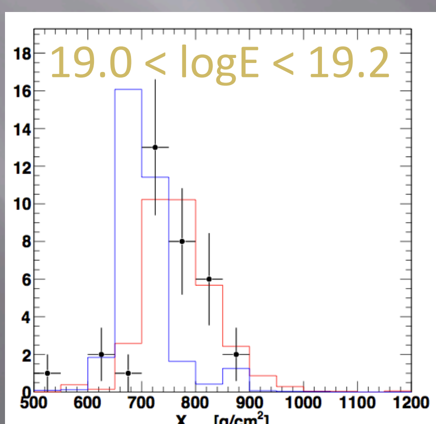


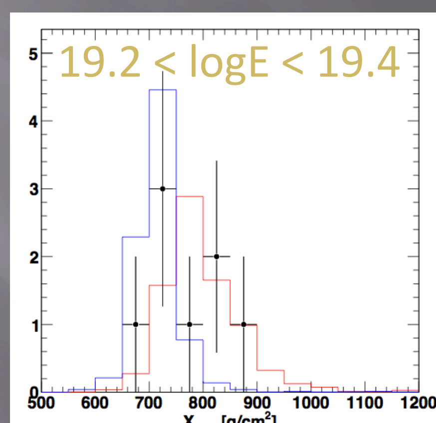


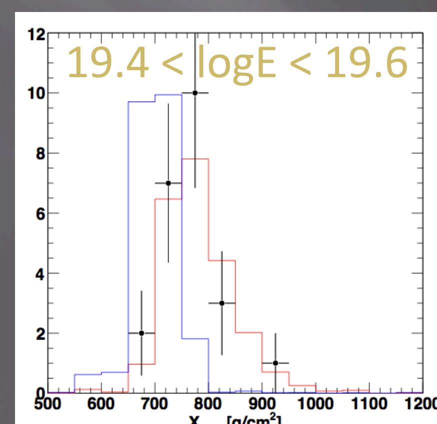


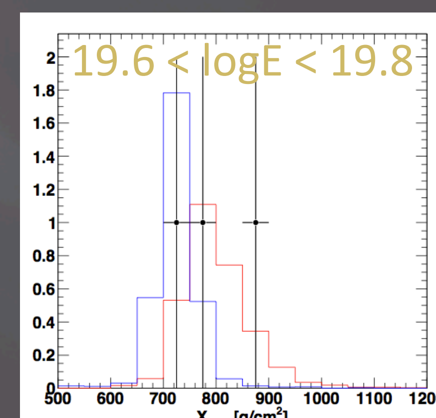


Preliminary

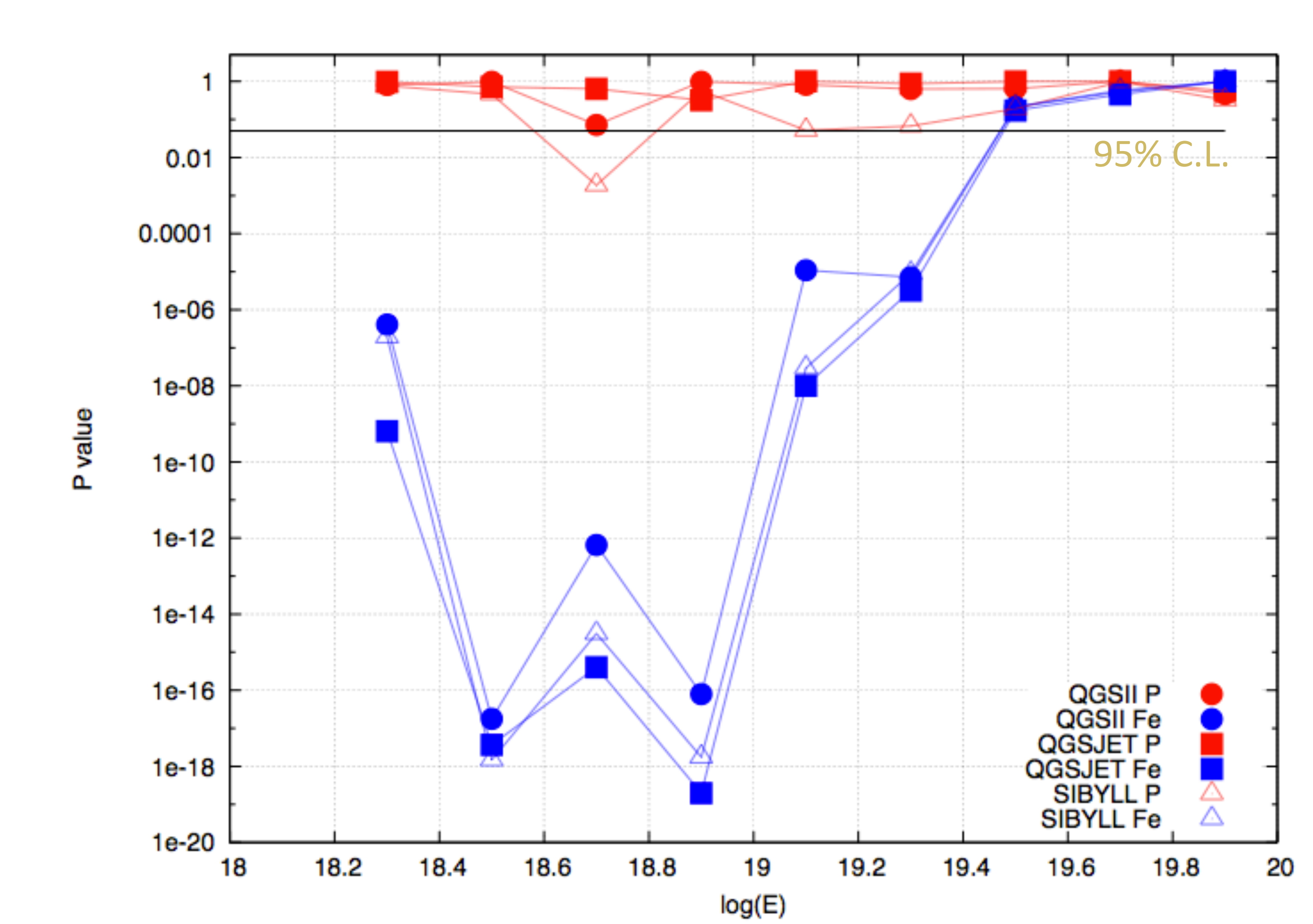








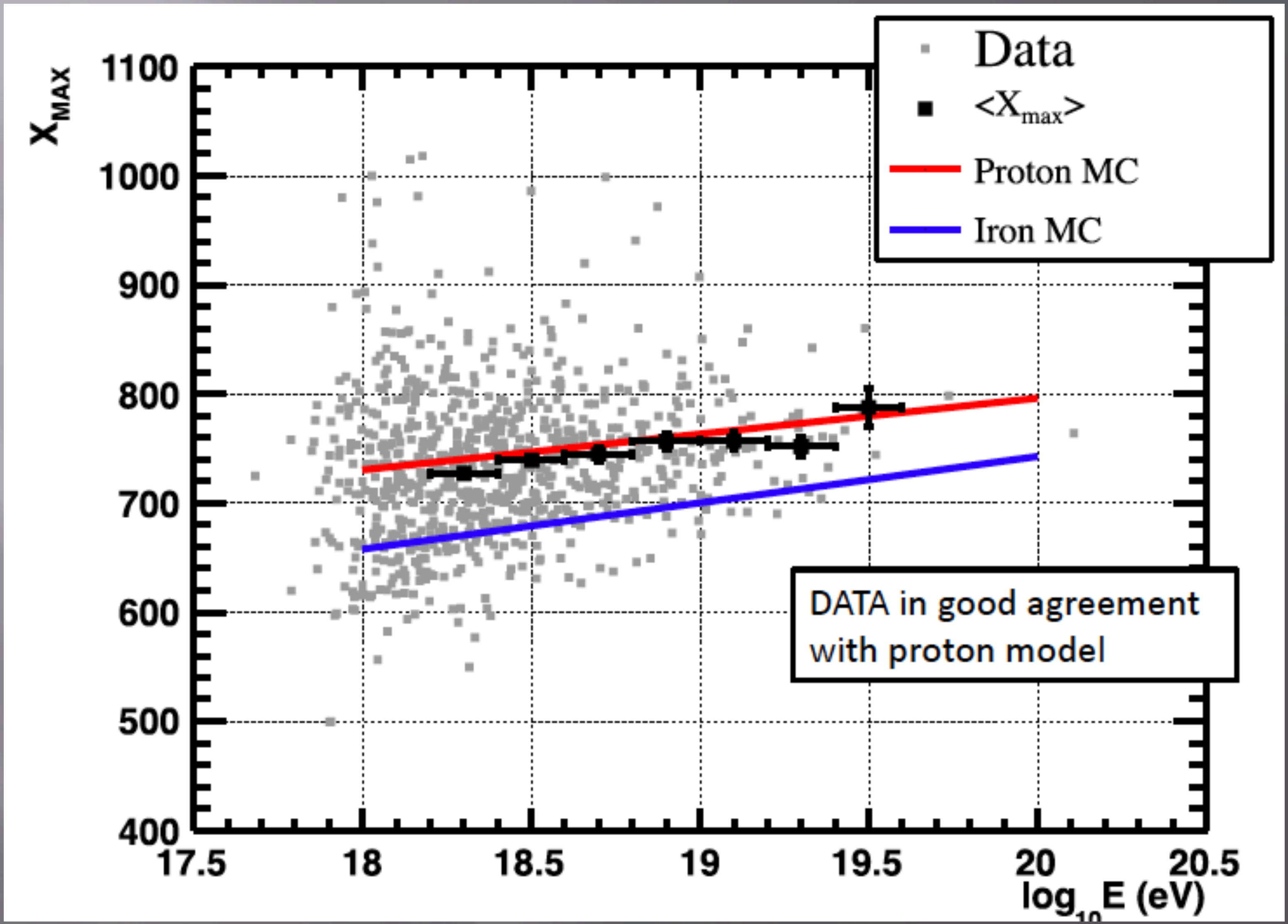
X_{max} Distributions: K-S Tests



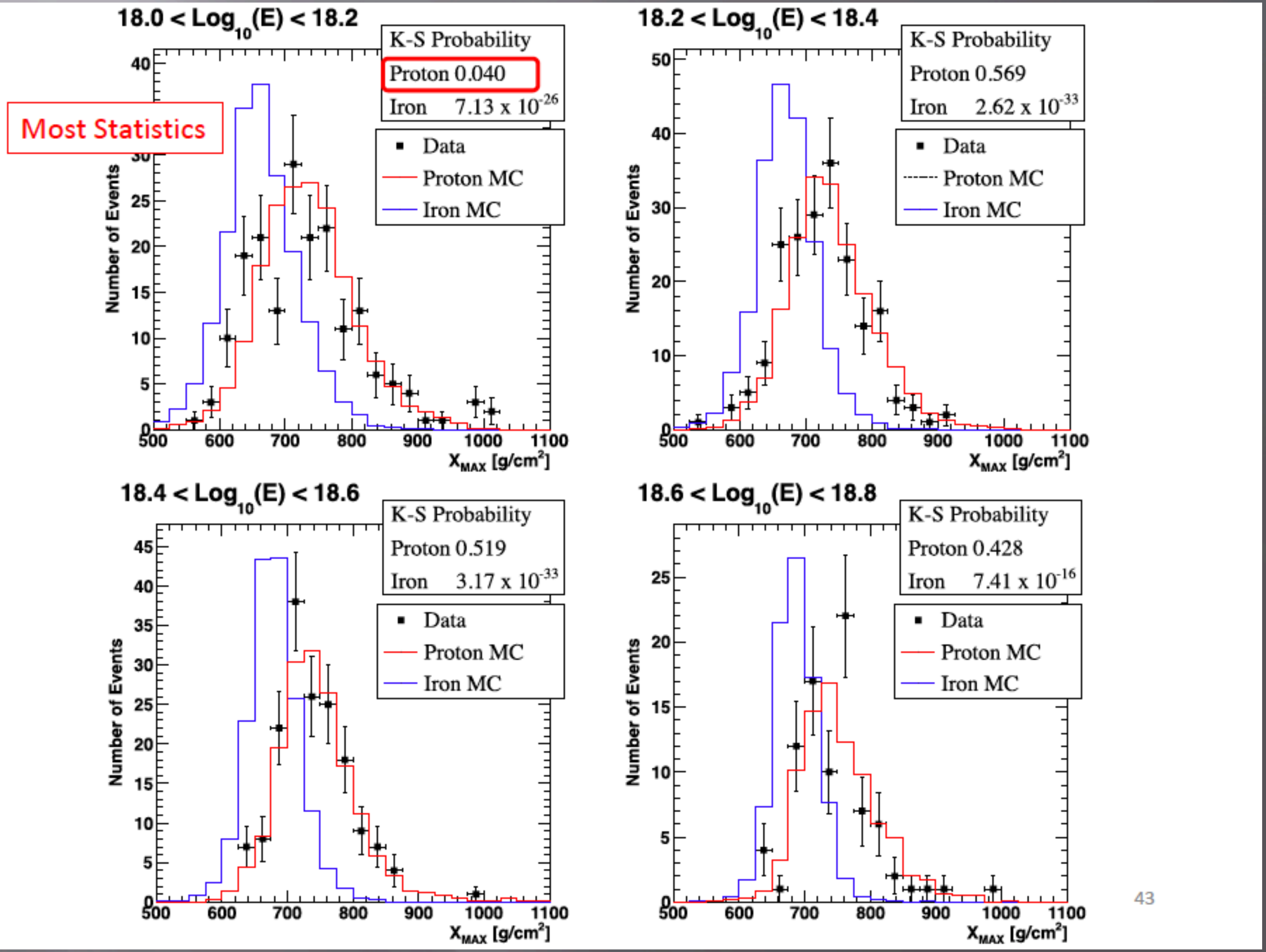
MD Hybrid Composition

- X_{max} comes from MD FD detector
- SD just aids geometrical resolution
- Will again compare measured $\langle X_{max} \rangle$ to full-detector-simulated model results

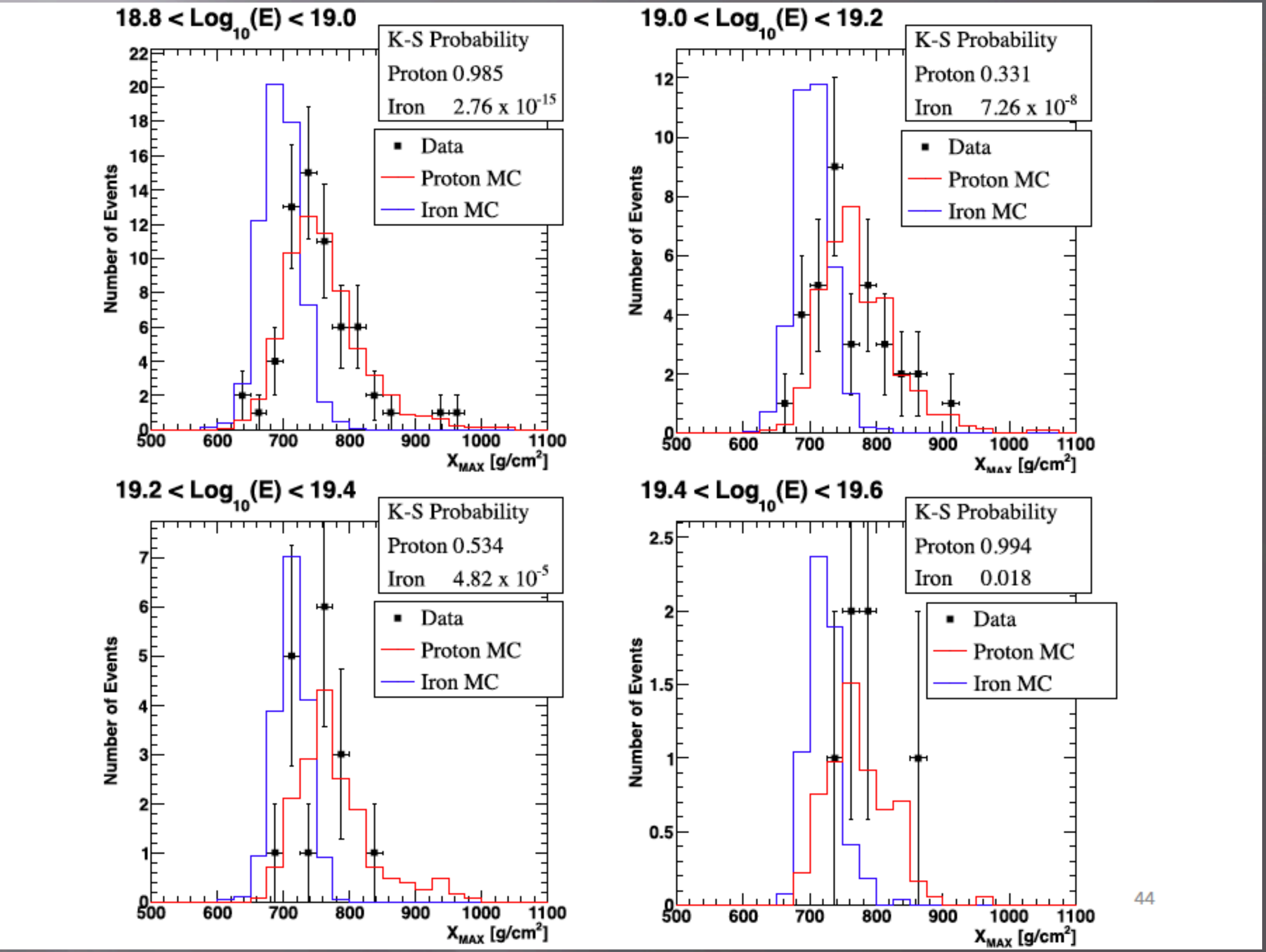
MD Hybrid: X_{max}



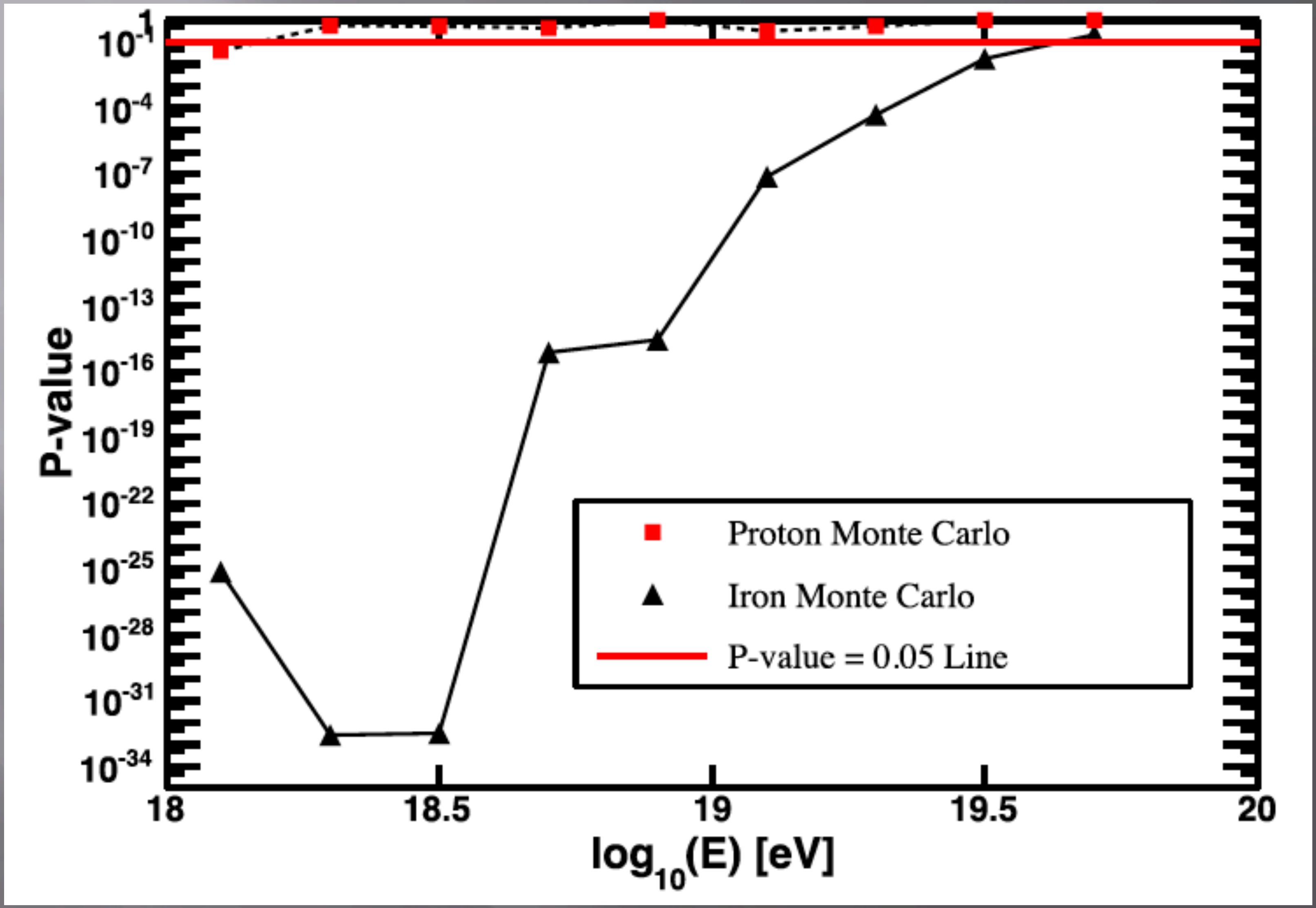
MD Hybrid: X_{max} Distributions



MD Hybrid: X_{max} Distributions



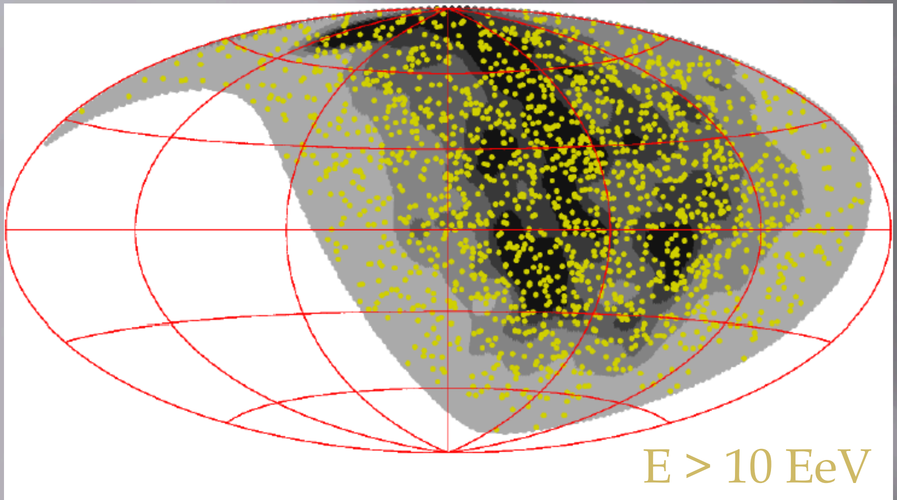
MD Hybrid: K-S Tests

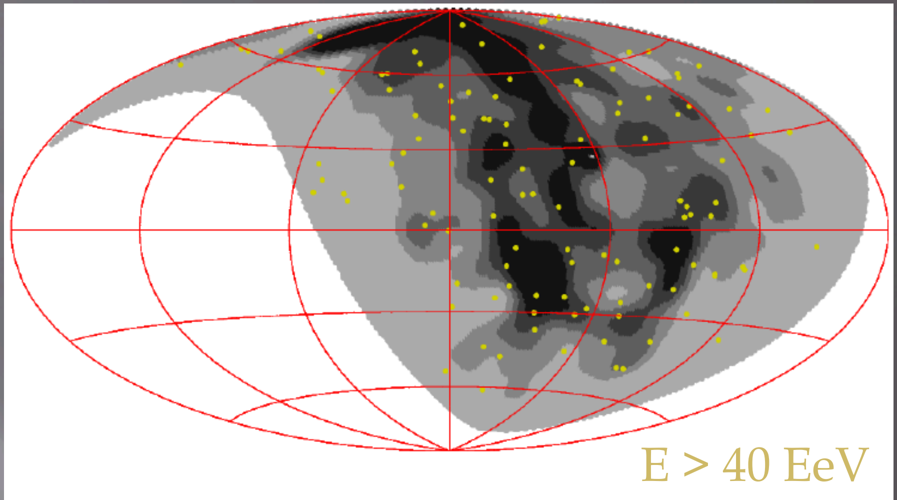


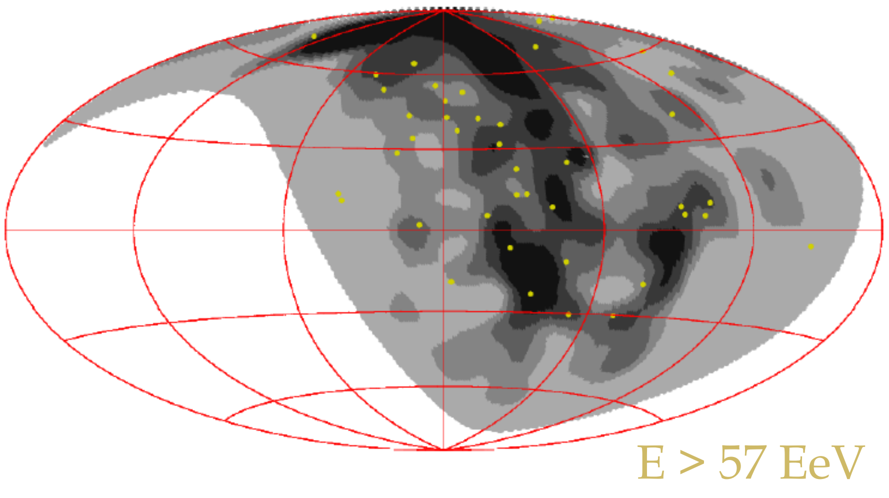
Large Scale Structure

- The only real *a priori* expectation for anisotropy is that it should be associated with the matter distribution in the Universe
- Method
  - Calculate a flux from the actual distribution of galaxies (2MASS XSCz): 110 000 galaxies from 5 Mpc to 250 Mpc
  - Take flux from beyond 250 Mpc as uniform
  - Assume proton primaries
  - Account for all interactions and redshift losses
  - Apply Gaussian smearing in arrival direction, with the angular size treated as a free parameter. This mimics magnetic field deflections and angular resolution.
  - Compare prediction to data by the flux sampling test

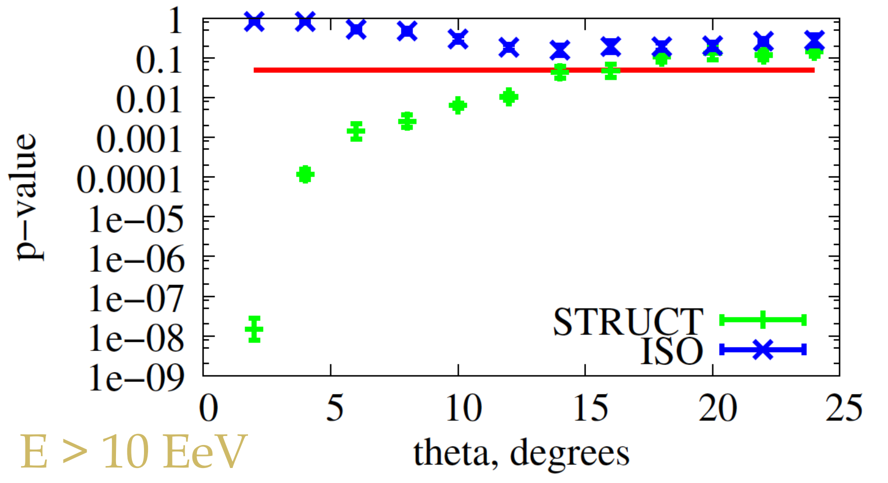
LSS: Data & Models (at 6°)

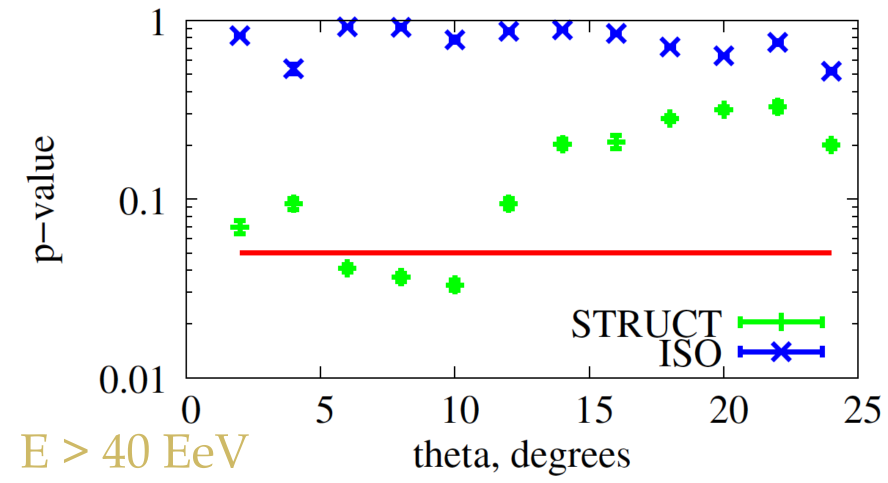


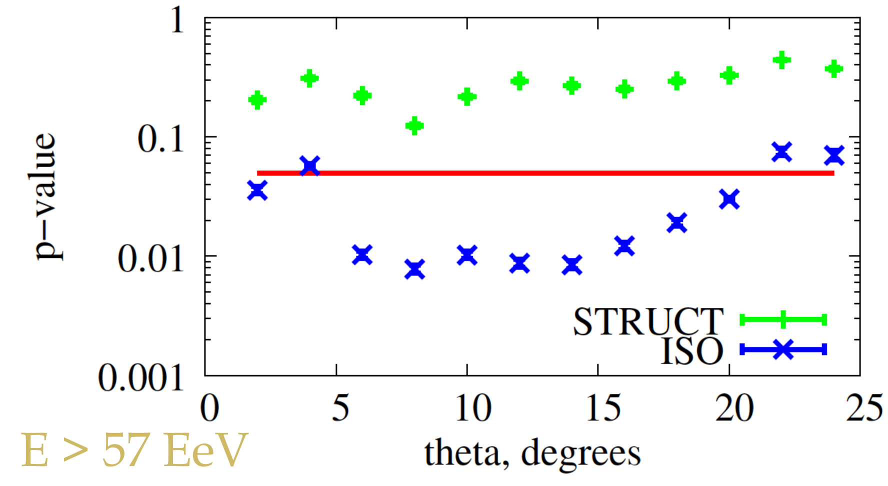




LSS: Result of K-S Test

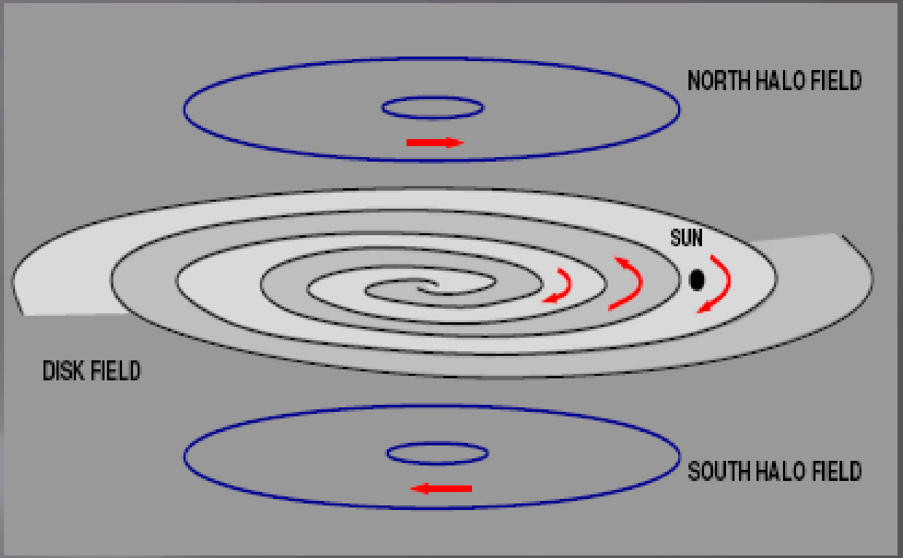


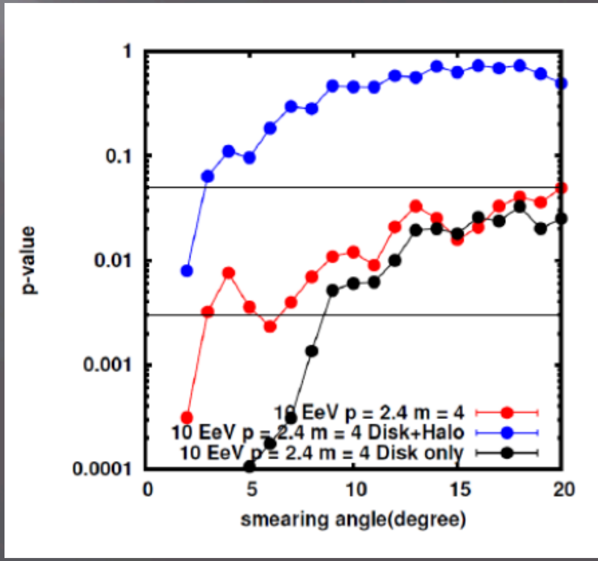




LSS: Add Galactic Field

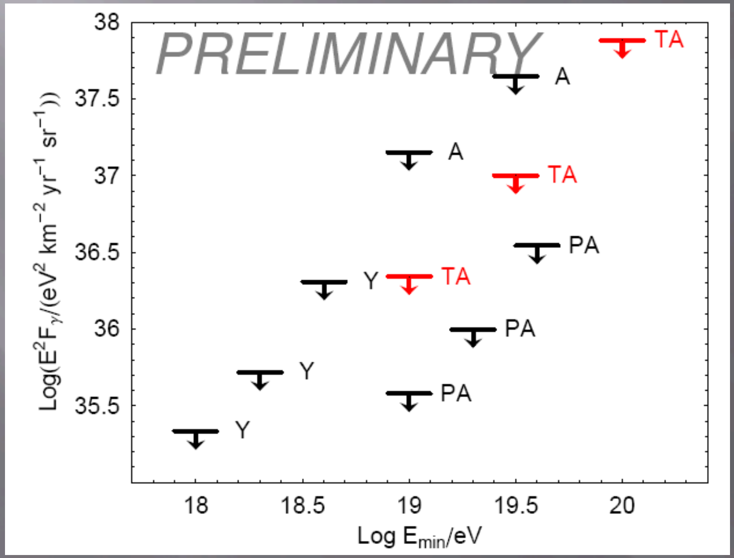
- Can improve compatibility with structure by including deflections in the Galactic field
- Use field model consistent with Faraday rotation measurements
- Need both disk and halo components

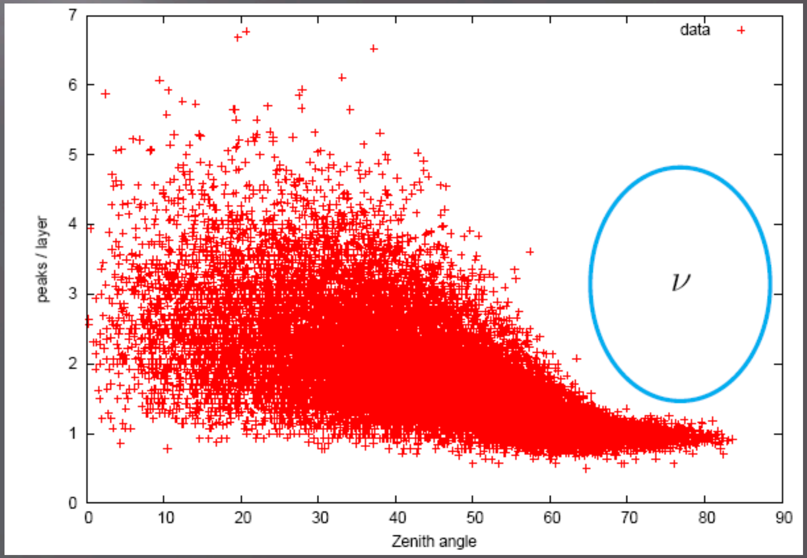




Exotic Searches

- Photons
  - Use shower front curvature
- Neutrinos
  - Use old/new shower discriminant: number of muon peaks in FADC trace.





Conclusions on Current Results

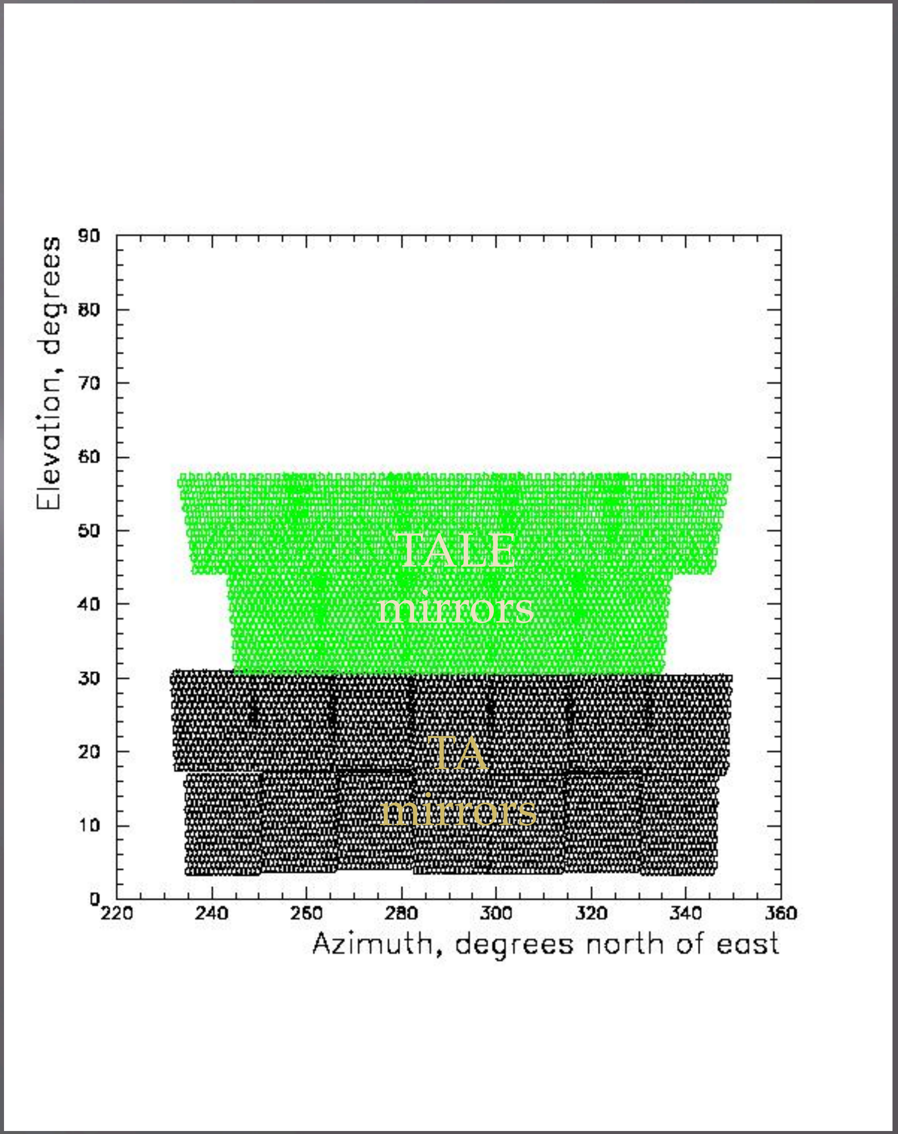
- SD spectrum observes the GZK Cutoff with 5.6 σ signfificance
- All the TA spectra agree well and agree with HiRes, consistent with proton origin of GZK Cutoff.
- Two independent measurements of composition both show proton-dominated or light composition
- Arrival directions better compatible with large-scale structure than isotropy at the highest energies.
- Galactic field is important at lower energies.

Future Plans: Low Energy

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

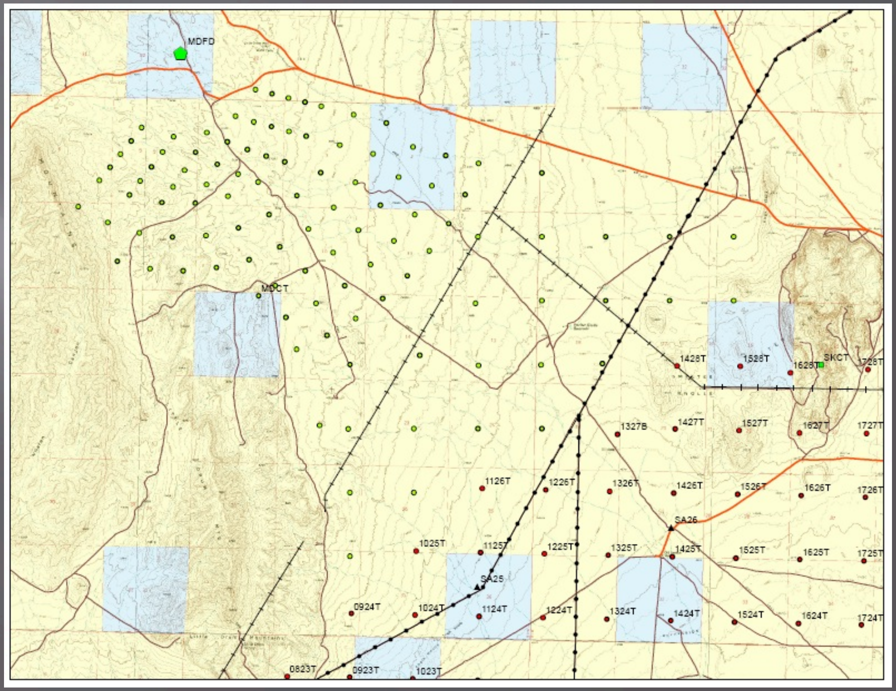
TALE

- Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.
  - Operate in conjunction with the TA Middle Drum FD.
- High elevation allows measurement of close-by showers



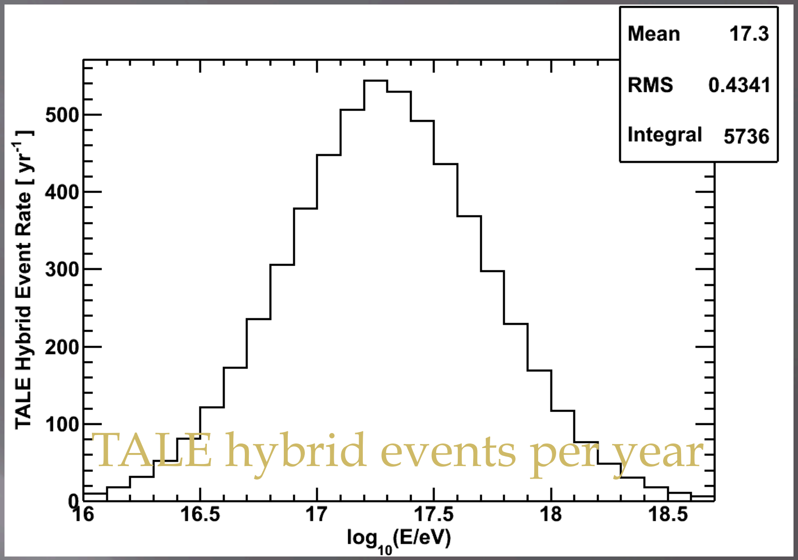
TALE

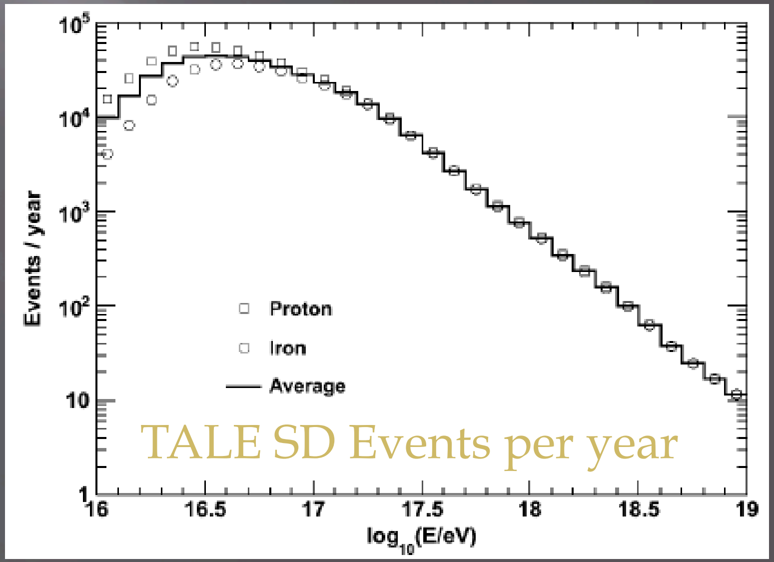
- Add infill array (400m and 600m spacing) for hybrid observation.
- Hybrid provides accurate geometric reconstruction for composition measurements



TALE

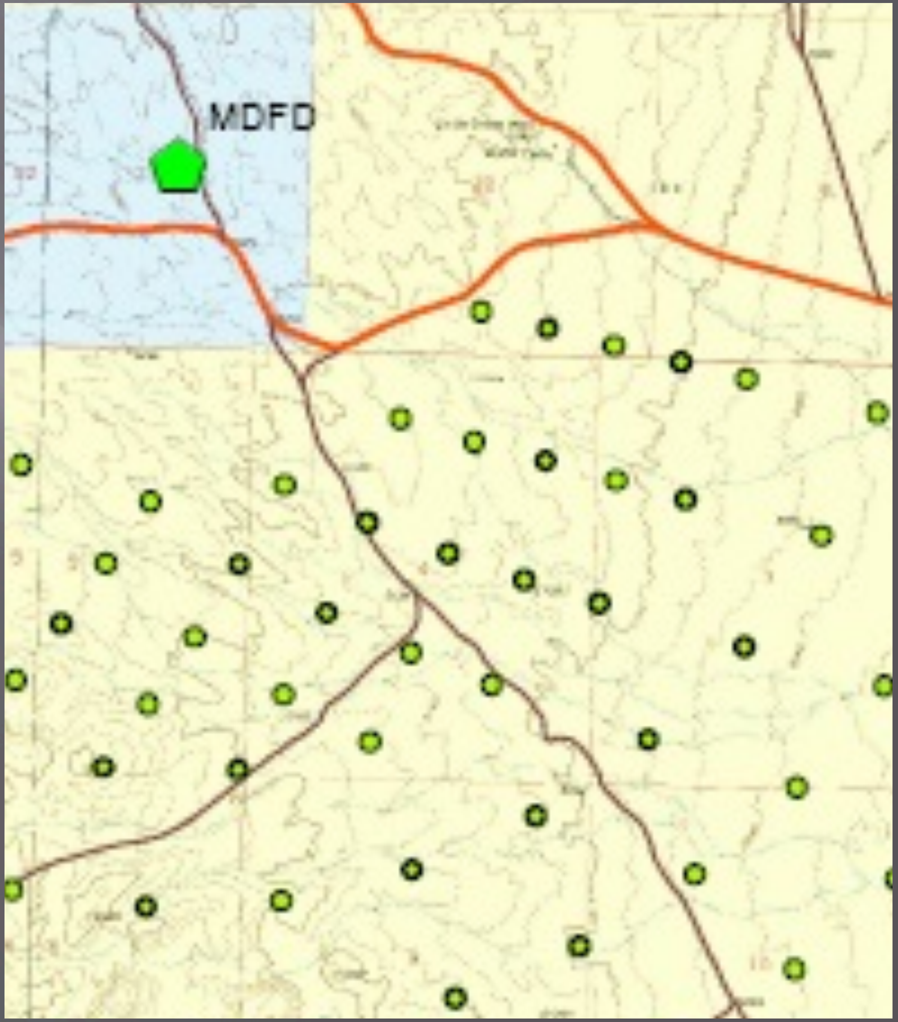
- TALE hybrid will cover energies down to $10^{16.5}$ eV
- TALE will be able to confirm the observation of the Iron knee seen by Kascade-GRANDE and measure the heavy-to-light composition change expected in the 10^{17} eV decade.





NICHE

- To go lower in energy than TALE, need to use Cherenkov light
- Aim to build a Non-Imaging CHErenkov array (NICHE) within the field-of-view of the TALE FD.



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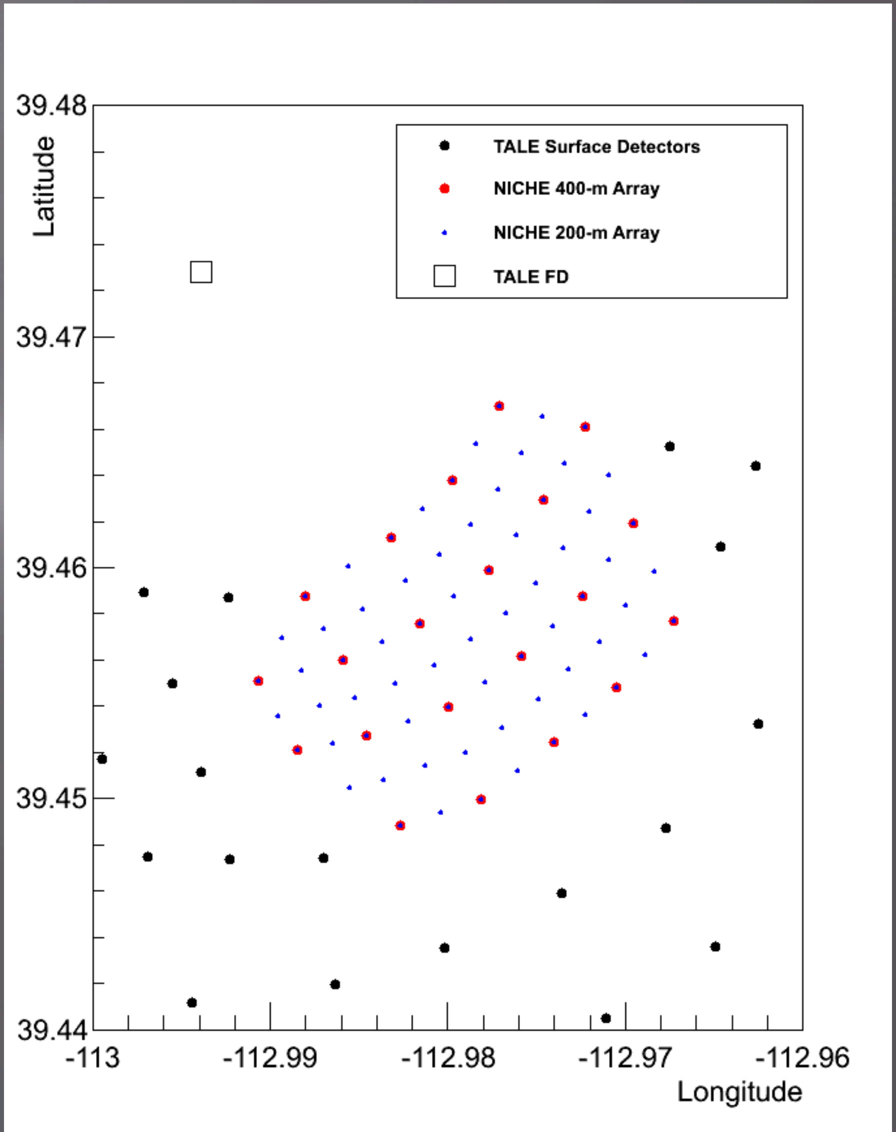
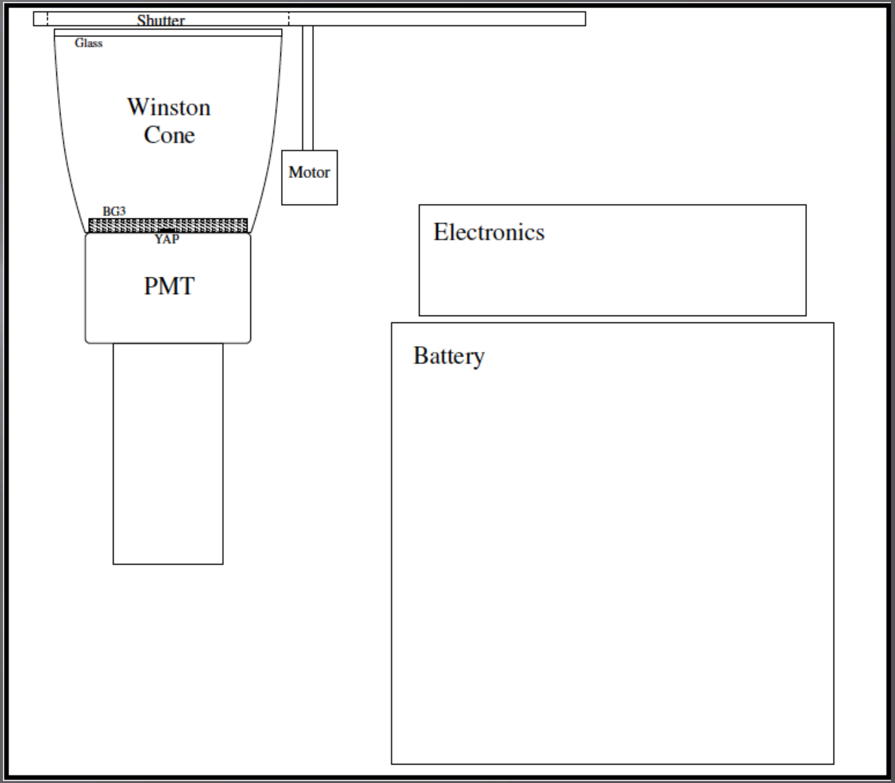


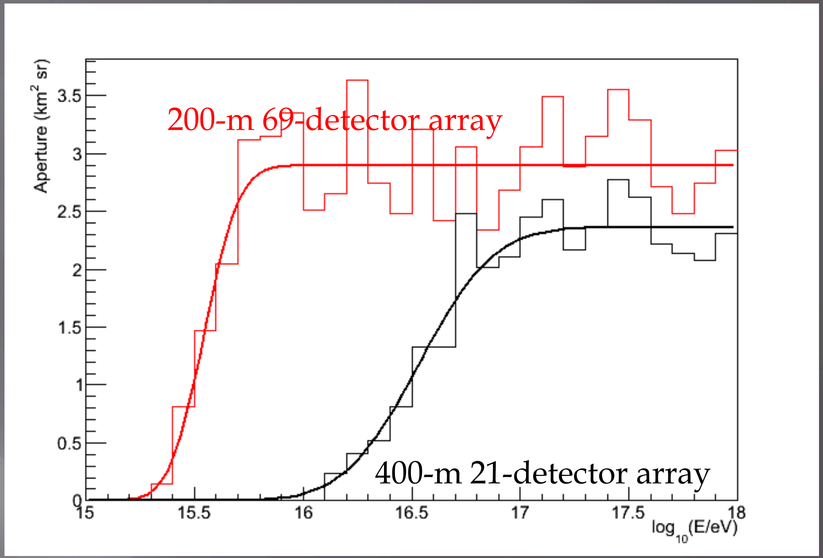
NICHE

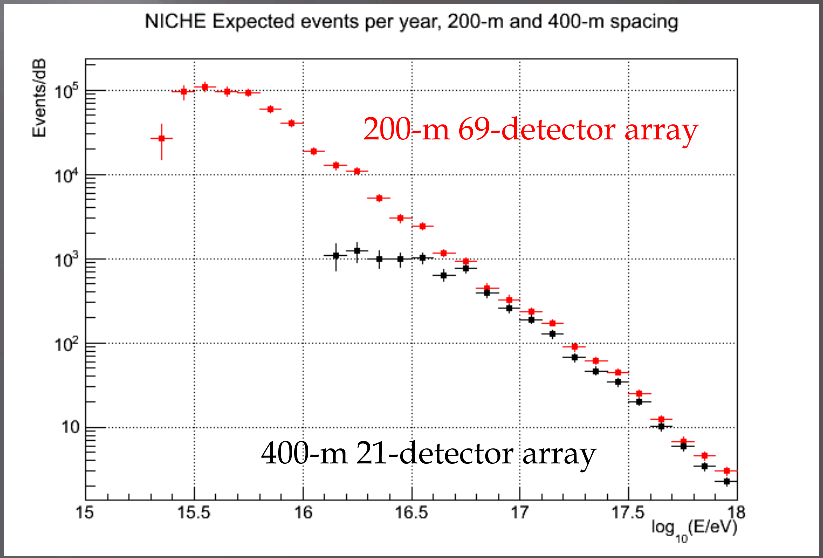
- To go lower in energy than TALE, need to use Cherenkov light
- Aim to build a Non-Imaging CHErenkov array (NICHE) within the field-of-view of the TALE FD.
- Use light, easy-to-deploy counters
- Rely on timing width for composition



NICHE

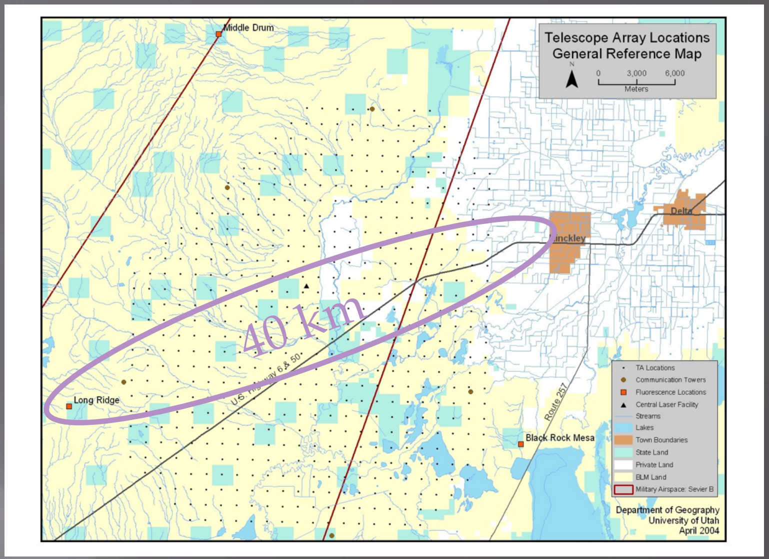
- Can easily measure below 10^{16} eV with fairly wide spacing
  - Can go below Knee with smaller spacing
- Expect overlap of at least a decade in energy with TALE
  - Cross calibration of energy and X_{max} measurements

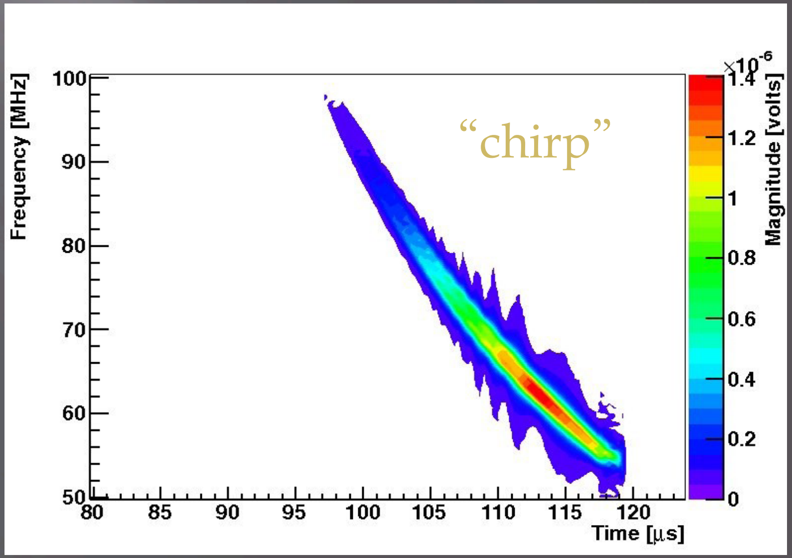




TARA

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





Conclusion

- TA has spectrum and composition measurements consistent with protonic extragalactic cosmic rays
- There are plans to extend the low energy down to the Knee to be able to measure the composition and spectrum of UHECRs over 5 orders-of-magnitude in energy
- We are also working on new techniques to extend the available aperture to measure reasonable fluxes at even higher energies