Measurement of the Energy Spectrum by the Telescope Array Surface Detector

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Telescope Array Collaboration

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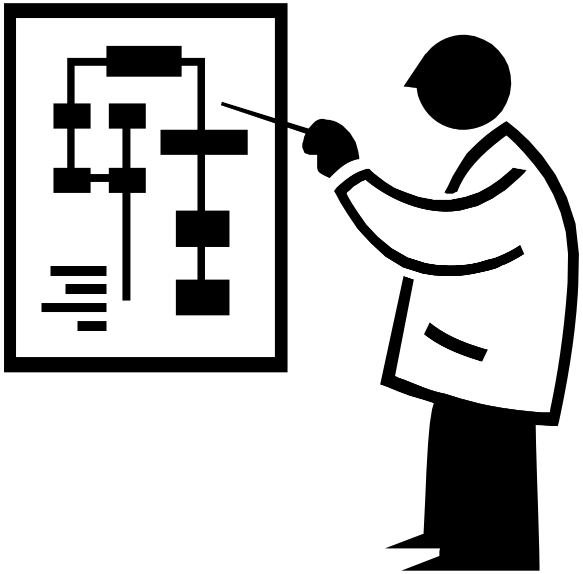
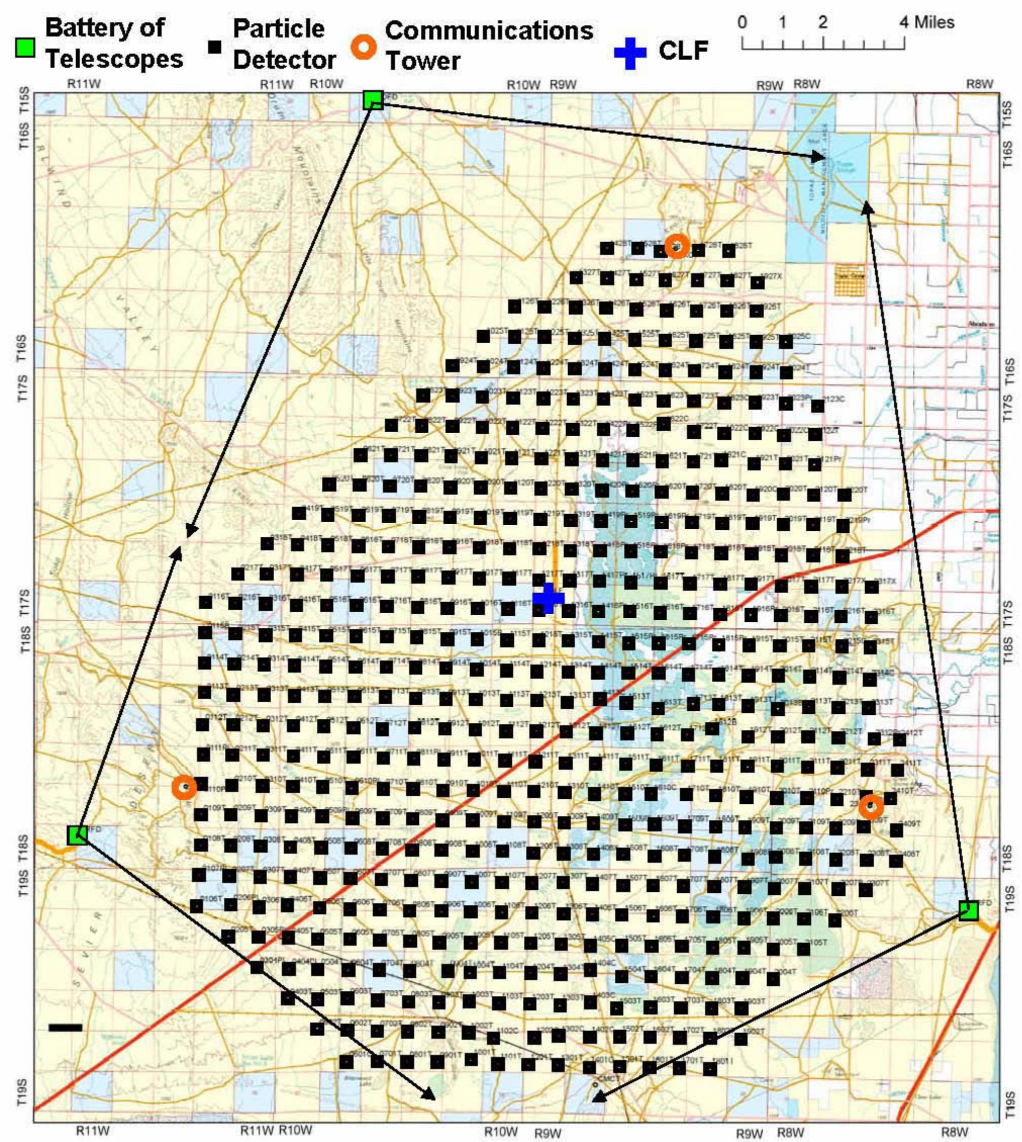
Outline

- Surface detector configuration
- Simulation program
  - Dethinning
  - Spectral event set generation
- Event reconstruction
  - Lateral distribution function
  - Data/Simulation comparisons
- Energy spectrum estimation



Telescope Array
Surface Detector Configuration



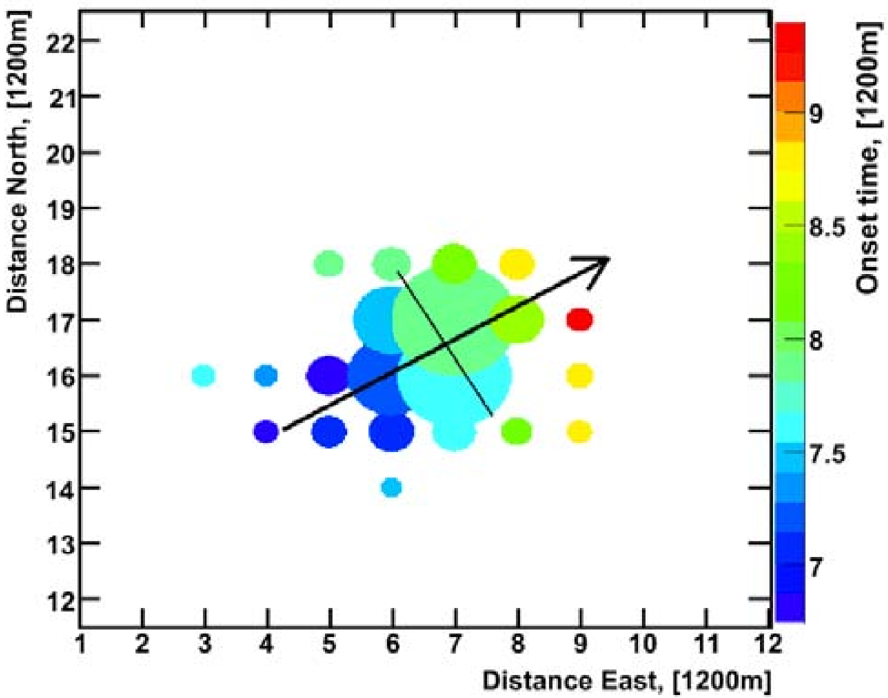
- Located 200 km SW of Salt Lake City
- 507 surface units on 1.2 km rectangular grid
- Total area: 680 km^2
- SD augmented by 3 air fluorescence stations
- SD commissioned in May 2008

SD Configuration: Surface Detector Unit

- 3 m^2 bi-layer scintillator
- 2 channel 50 MHz ADC readout
- Self-calibrating (via atmospheric $\mu^+\mu^-$)
- Solar power
- Radio Communications
- Most units require servicing less than once per year

SD Configuration: Surface Array Triggering

- Level 0: ~0.3μ equivalent (740 Hz)
  - Readout 2.5 μsec waveform to counter buffer
- Level 1: 3μ equivalent (30 Hz)
  - Readout L1 trigger time to central DAQ
- Level 2: 3 adjacent counters with L1 trigger within 8 μsec (5 mHz)
  - Readout to central DAQ all L0 trigger waveforms within ±32 μsec of L2 trigger

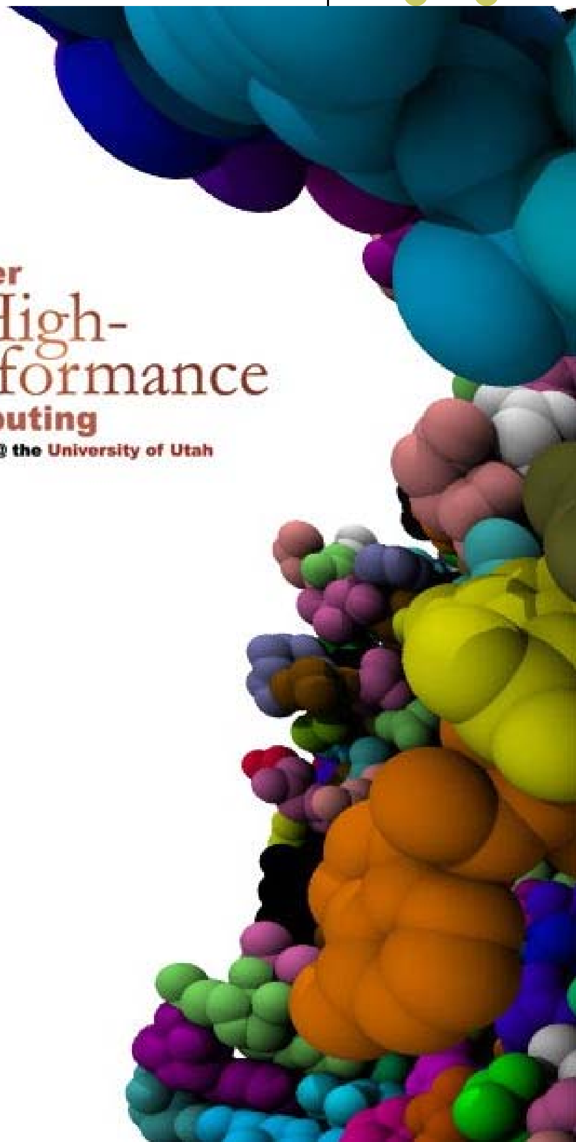


SD Configuration: Surface Detector Milestones

- 485 counters deployed: Mar 2007
- Test with 3 small arrays: Jun 2007
- Observations with 507 counters divided into 3 sub-arrays: Mar 2008
- Thresholds stabilized: May 2008
- Observations with full array trigger: Nov 2008

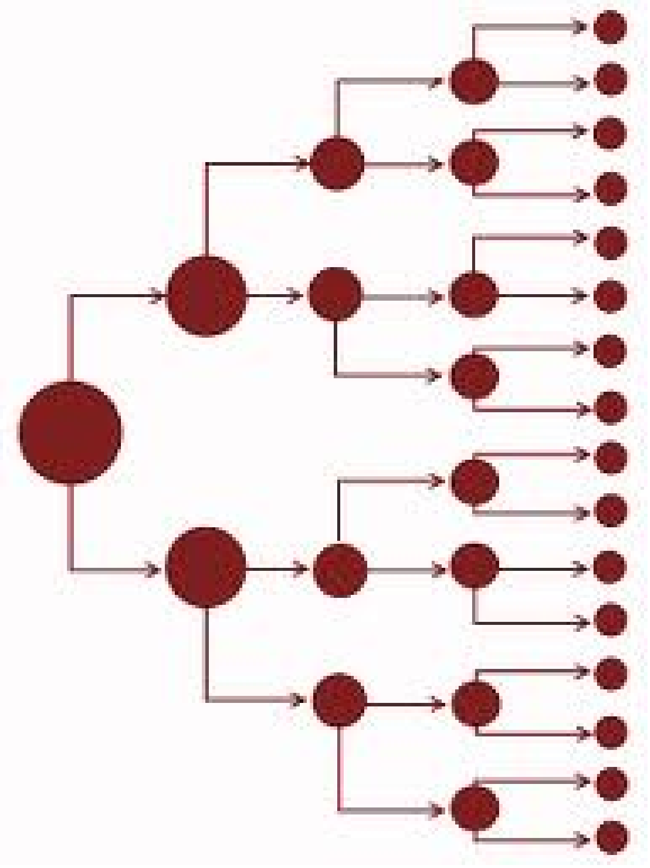
Simulation Program

- CORSIKA 6.960 QGSJET-II/FLUKA
  - Parallelization
  - Dethinning
- GEANT4
- Superb detail
- Very computationally intensive



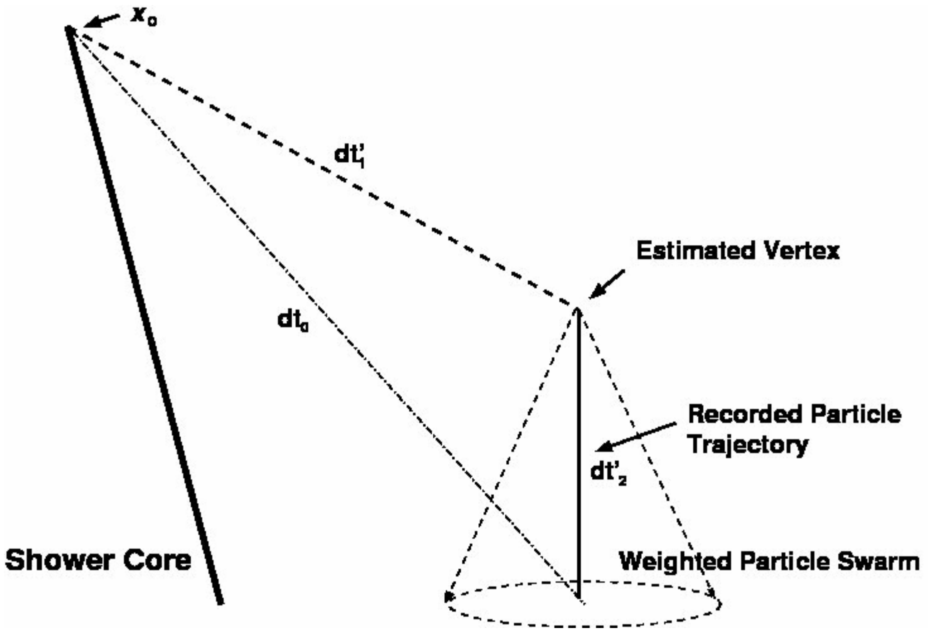
Simulation Program: Augmentations to CORSIKA

- Parallelization
  - Wrapper scripts and binaries
  - CORSIKA itself left untouched
  - 100+ showers
    - $10^{18.5}$ to $10^{19.5}$ eV
    - 0^o to 60^o zenith
    - *p*, Fe



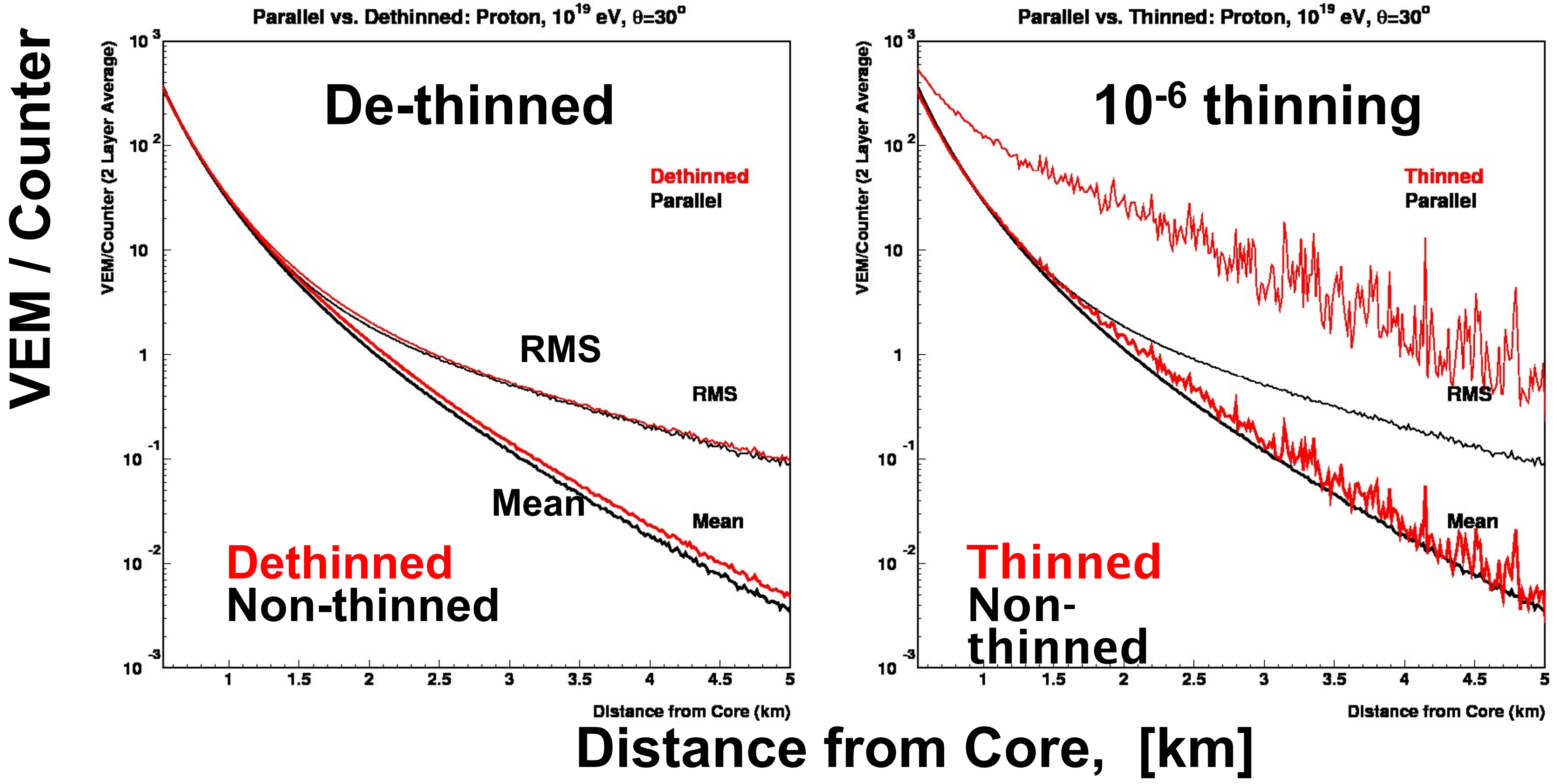
Simulation Program: Augmentations to CORSIKA

- Dethinning
  - Change each CORSIKA output particle of weight *w* to *w* particles with similar characteristics to the original particle
  - Adjust dethinning parameters to agree with full CORSIKA generated via parallelization

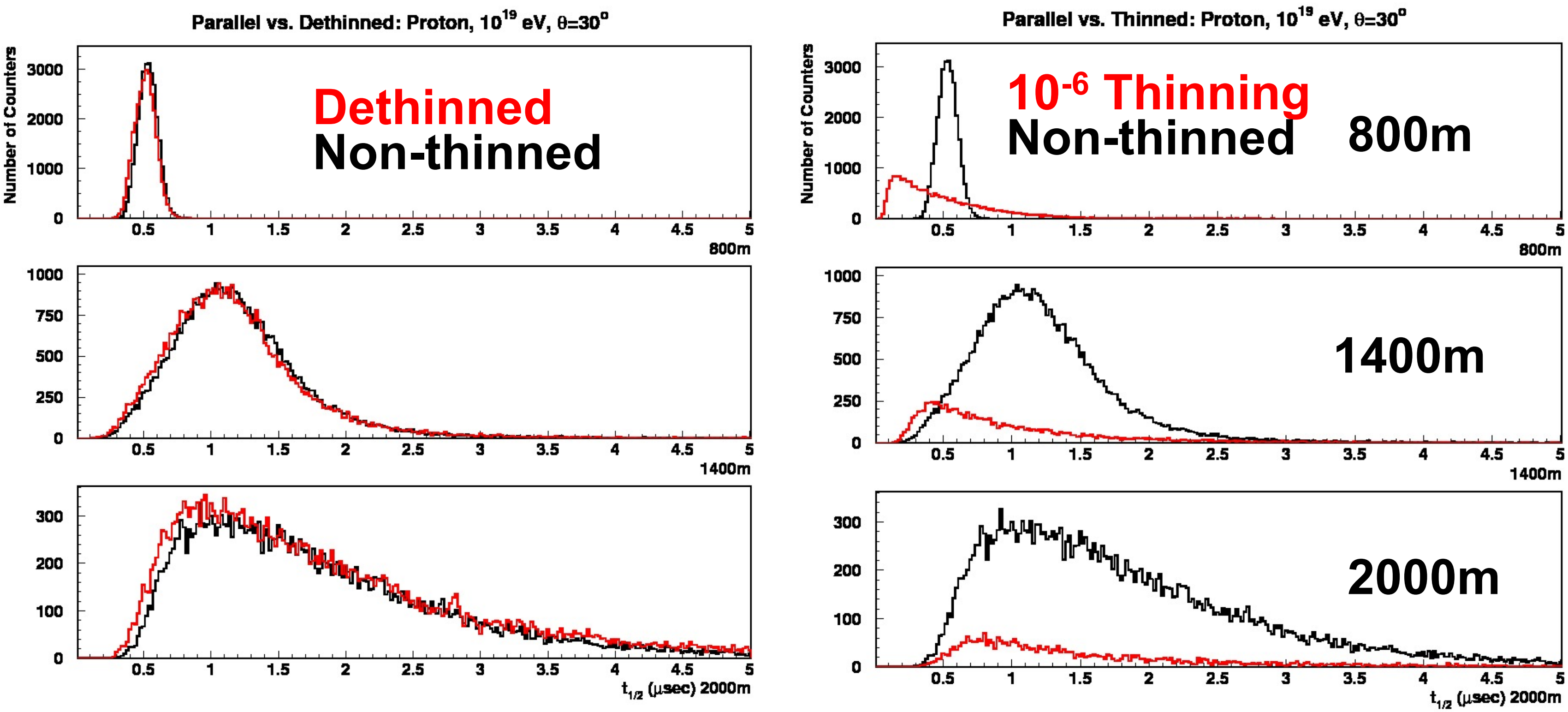


Verifying Dethinning: Lateral Profile

Proton, 10^{19} eV, 30^o zenith angle



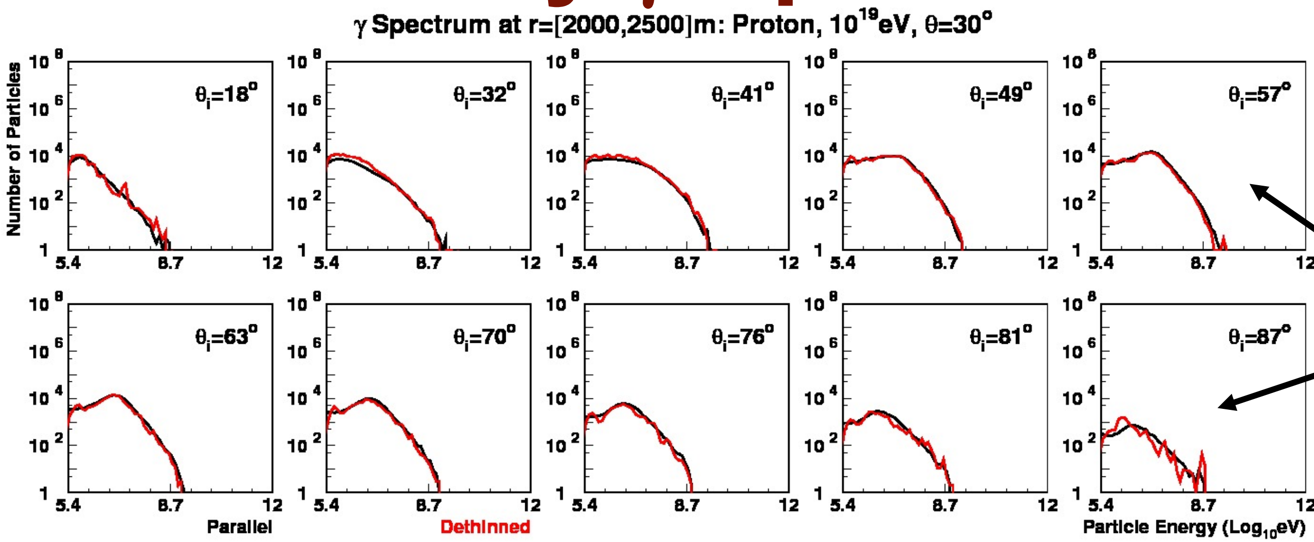
Verifying Dethinning: Temporal Distribution



Lateral Distance

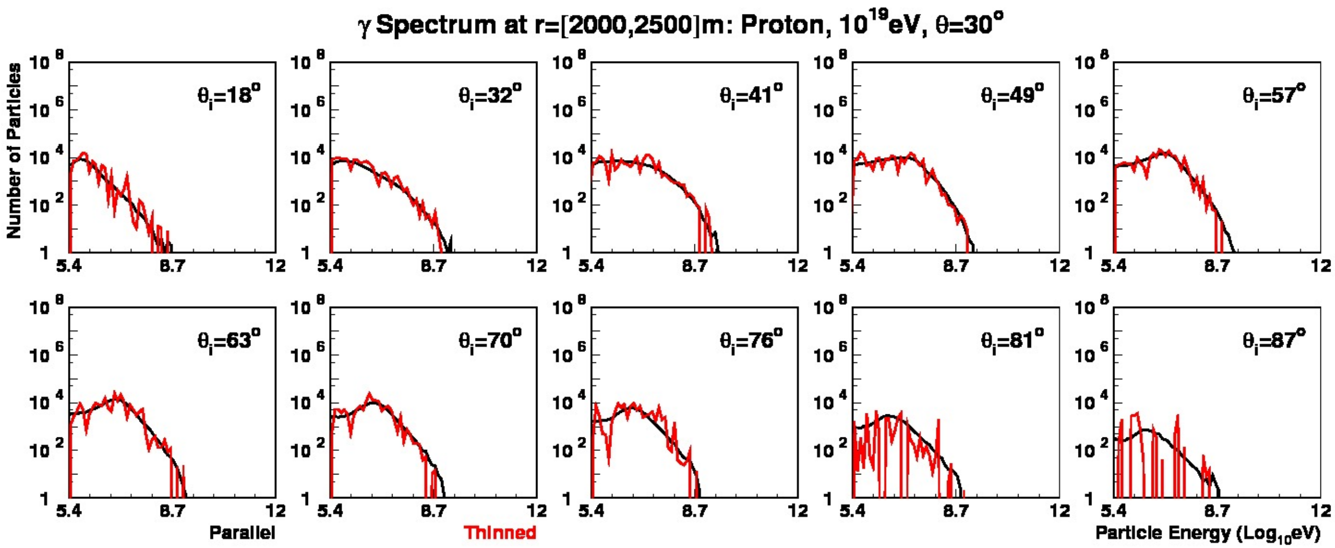
t_{50} (μsec normal to shower front)

Verifying Dethinning: Secondary γ Spectra



Dethinned
Non-thinned

Different
Incident
Angles

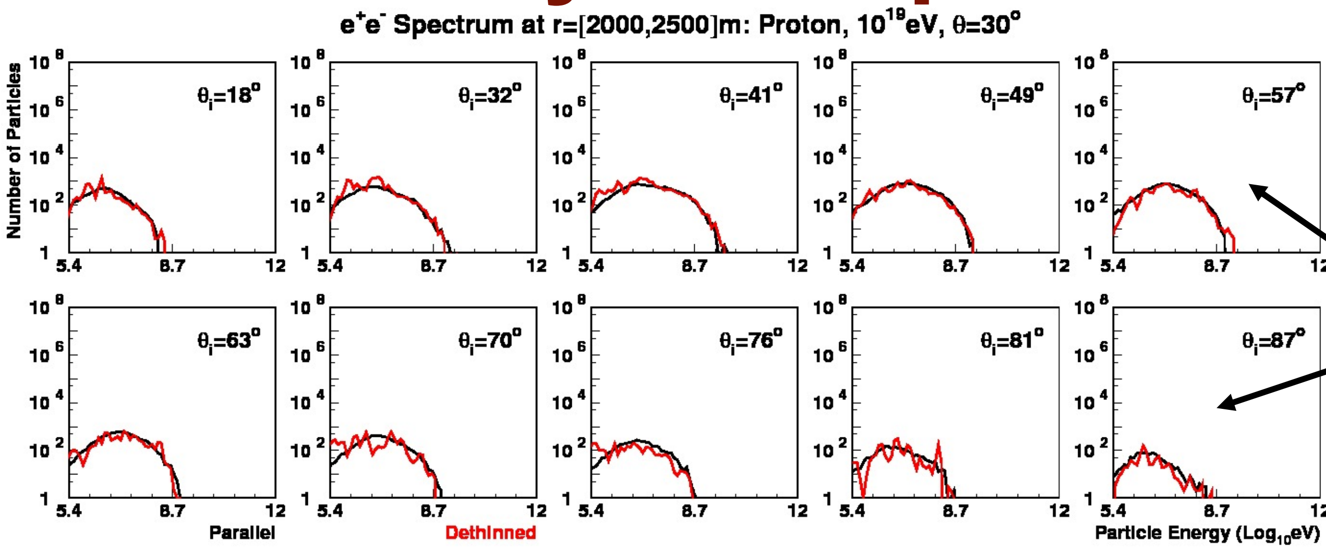


10^{-6} Thinning
Non-thinned

2-2.5km lateral distance *downstream* from shower core

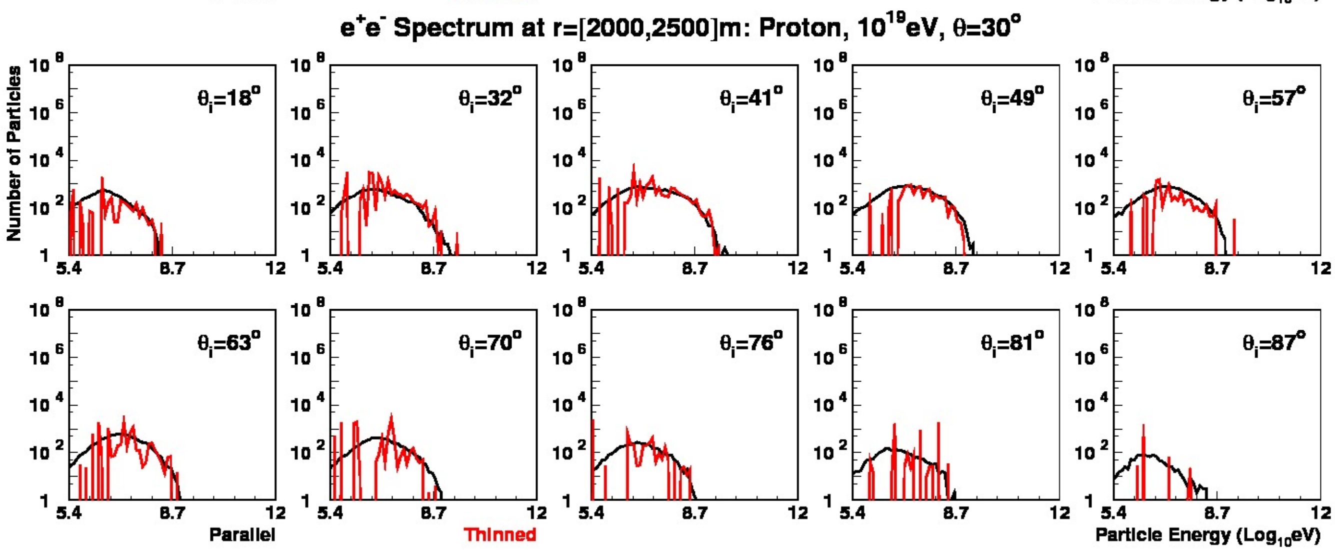
Secondary Particle Energy: 250keV to 1 TeV

Verifying Dethinning: Secondary e^+e^- Spectra



Dethinned
Non-thinned

Different Incident Angles

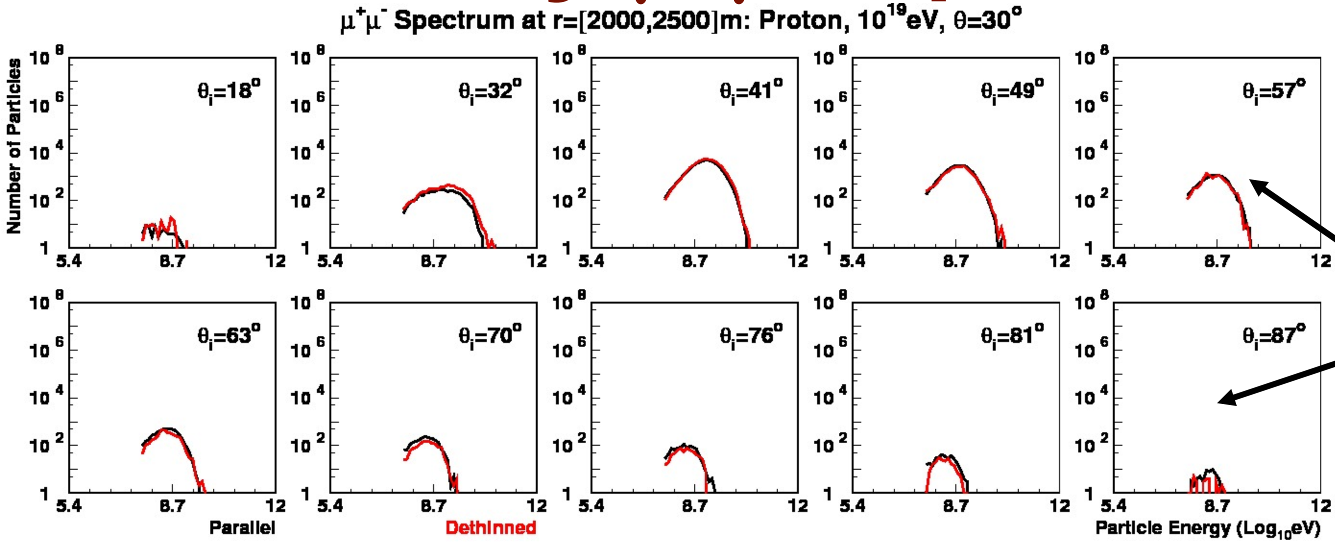


10^{-6} Thinning
Non-thinned

2-2.5km lateral distance *downstream* from shower core

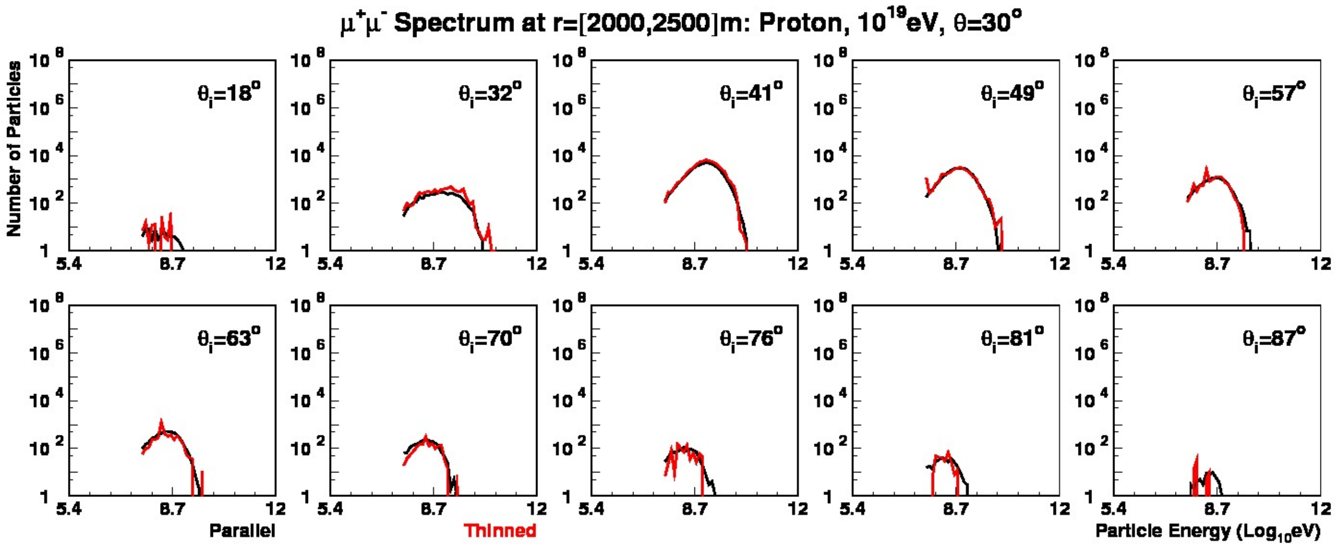
Secondary Particle Energy: 250keV to 1 TeV

Verifying Dethinning: Secondary $\mu^+\mu^-$ Spectra



Dethinned
Non-thinned

Different Incident Angles



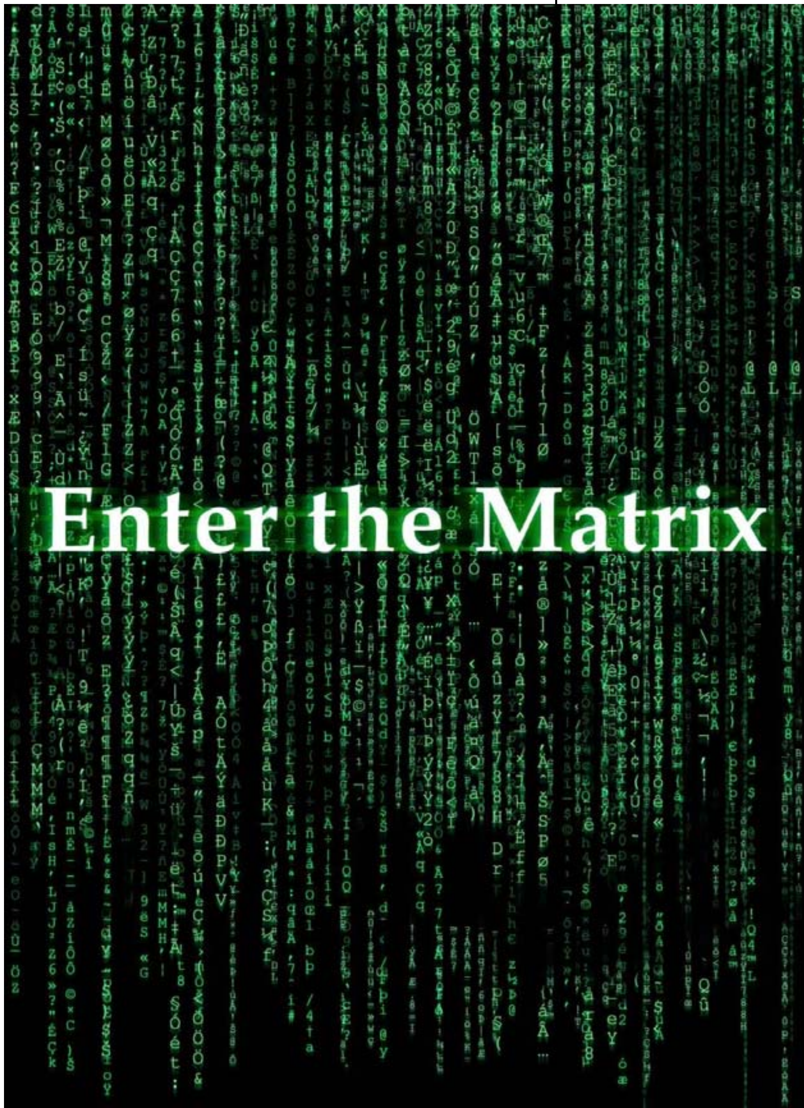
10^{-6} Thinning
Non-thinned

2-2.5km lateral distance *downstream* from shower core

Secondary Particle Energy: 250keV to 1 TeV

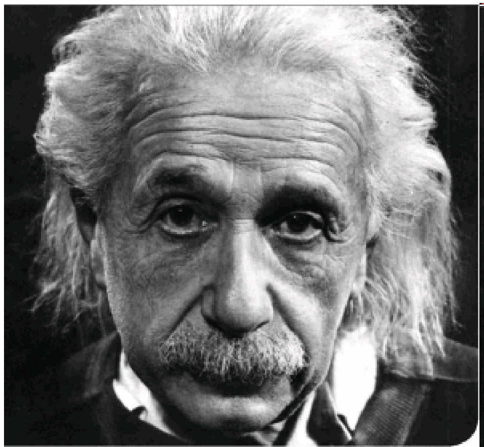
Simulation Program: Reproducing the Real Data Set

- CORSIKA shower library:
  - 33,000 dethinned showers
  - $10^{17.1}$ to $10^{20.5}$ eV
  - Isotropic distribution
- Calculate energy deposition for entire shower
  - GEANT4
- Simulate SD electronics repeatedly for each library element
- Select events for data set with respect to previously measured energy spectrum



SD Analysis:
A Careful Analysis Method

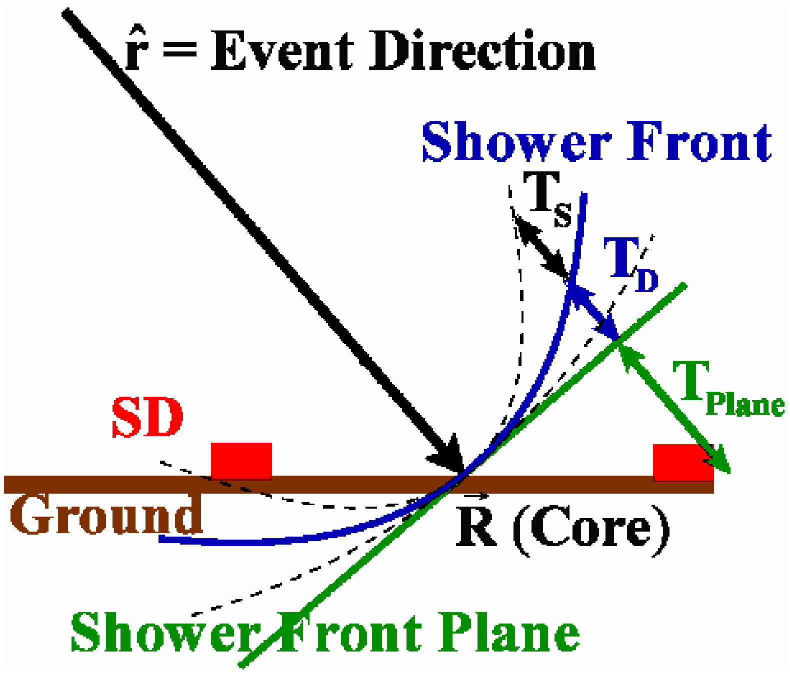
- Simulate the data the same way it is observed.
  - Write out the MC events in same format as data.
- Use fitting functions observed by previous experiments (i.e. AGASA) to ensure model independence.
  - Analyze the MC with the same programs used for data.
- *Test with data/MC comparison plots.*
- If they agree, say: “I understand my detector”; otherwise, ***work harder***.



SD Analysis: Geometric Fit

- Event direction is found by minimizing:

$$\chi^2 = \sum_{i=1}^{\text{nSDs}} \frac{\left(t_i - T_0 - T_{\text{Plane}} - T_{\text{D}}\right)^2}{T_{\text{S}}^{\,2}} + \frac{\left(\vec{\mathbf{R}} - \vec{\mathbf{R}}_{\text{COG}}\right)^2}{\left(180\text{m}\right)^2}$$



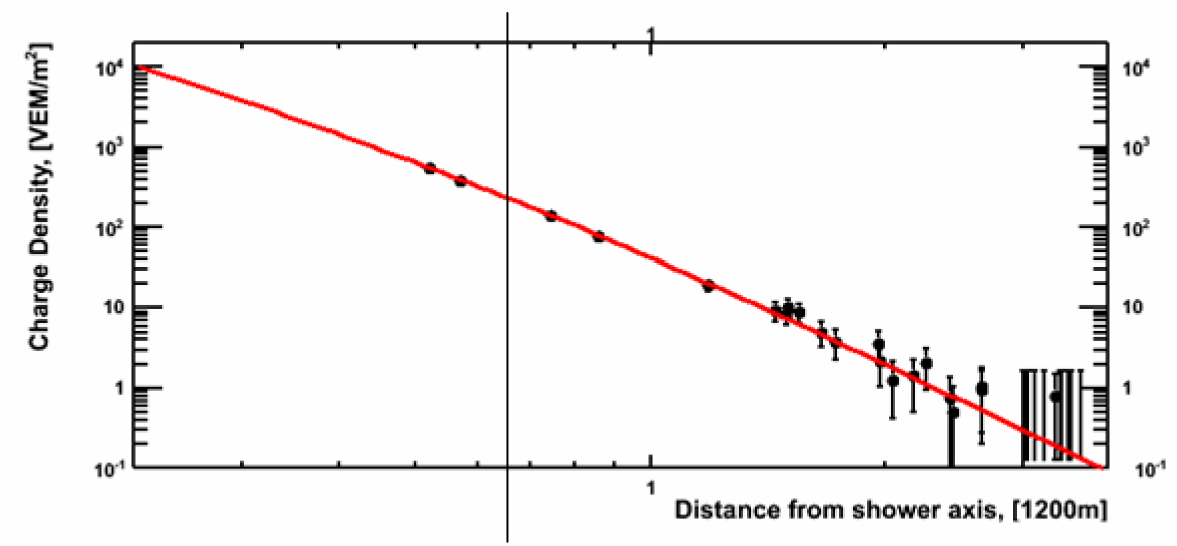
T_0	Time of the core hitting ground
T_{Plane}	Time of the shower front plane
T_{D}	Time delay (Modified Linsley)
T_{S}	Fluctuation of time delay (Modified Linsley)
$\vec{\mathbf{R}}$	(Fitted) core position
$\vec{\mathbf{R}}_{\text{COG}}$	Core position found from the center of gravity of charge

SD Analysis:
Lateral Distribution Fit

- **Fit with AGASA LDF**

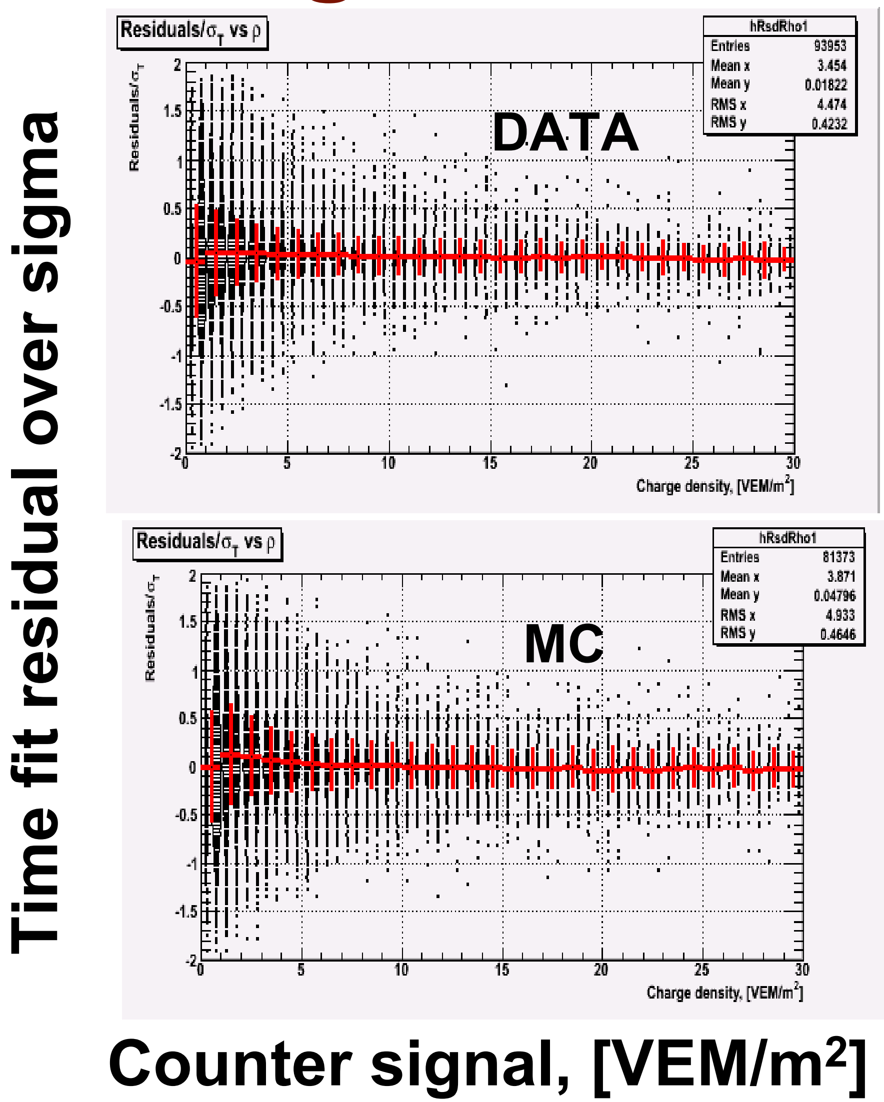
$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2}\left(1+\frac{r}{R_M}\right)^{-(\eta-1.2)}\left\{1+\left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

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



r = 800m

SD Analysis: Fitting Results



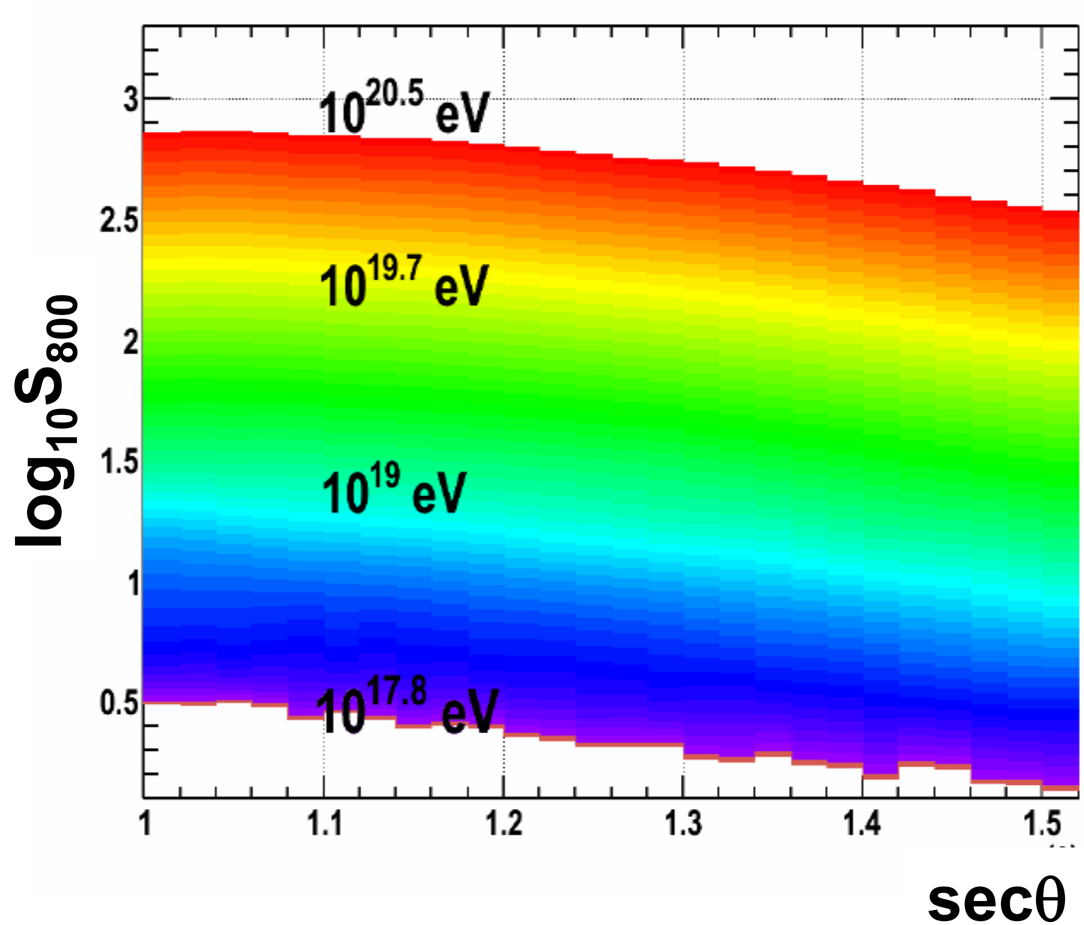
- Identical analysis routines are applied to data and Monte Carlo
- Fit results are compared between real and simulated events
- Monte Carlo fits the exact same way as the real data.
- Consistent for both geometric and lateral density fits.

SD Analysis: Data Quality Cuts

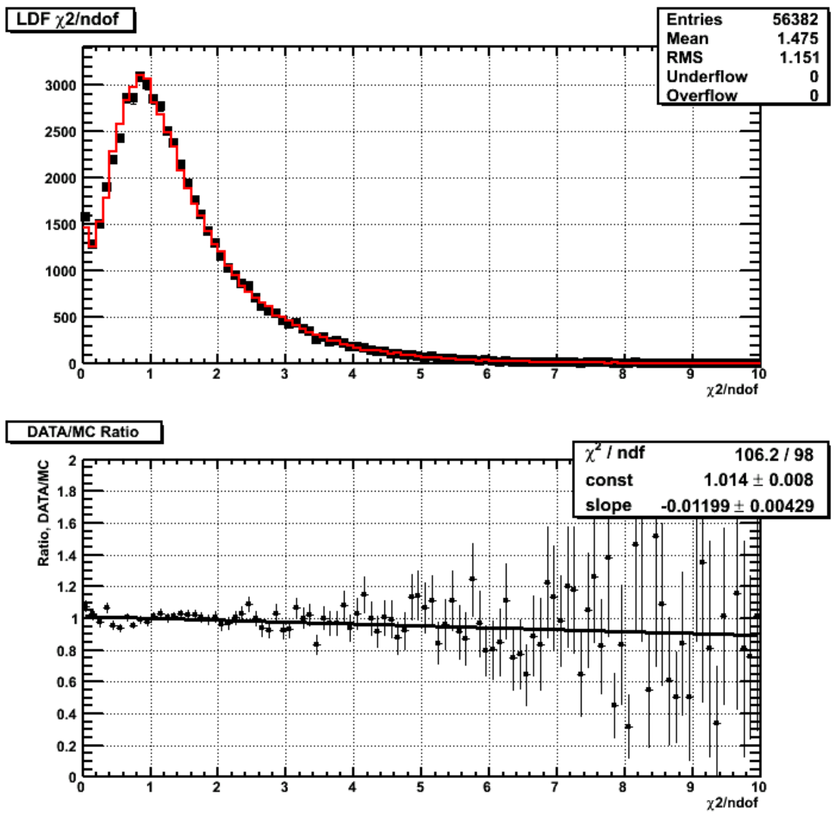
- Good data fits:
  - χ^2/d.o.f.: > 4.0
  - Pointing direction resolution: < 5^o
  - Fractional S800 uncertainty: < 25%
- Good shower geometry:
  - Border Cut > 1200m
  - Zenith Angle Cut: < 45^o
- **1.75 years, 6264 events.**

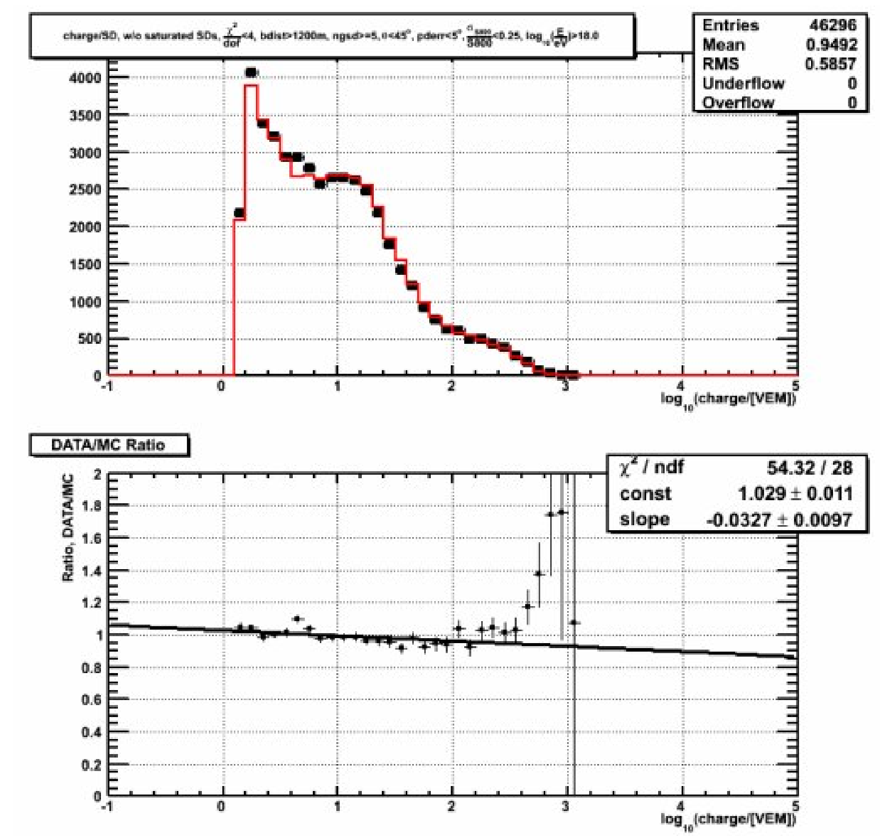
SD Analysis: Energy Determination

- Energy determination table is constructed from the fitting results of the Monte Carlo.
- First estimation of the event energy is done by interpolating between S_{800} vs. secθ isoclines.



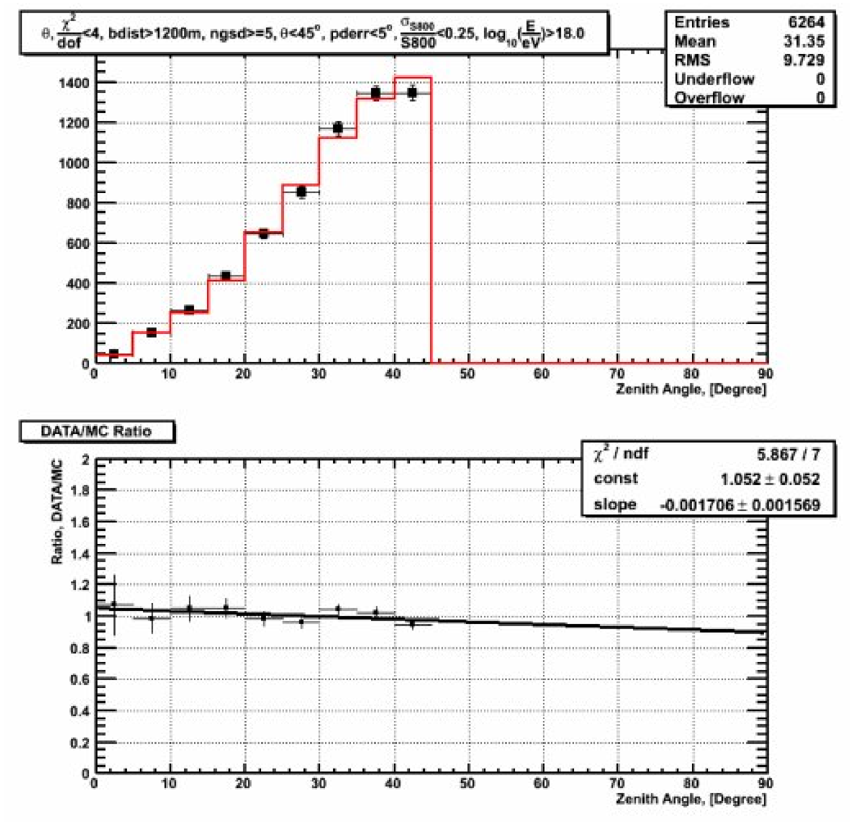
SD Analysis: Data/MC Comparisons

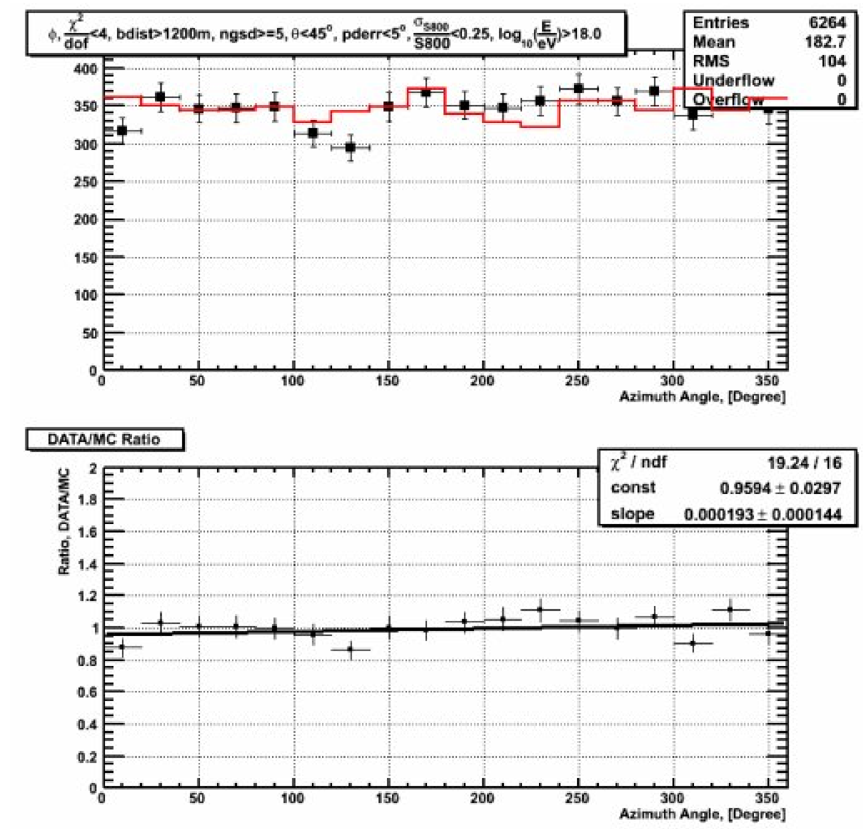




LDF fit χ^2/dof **VEM / counter**

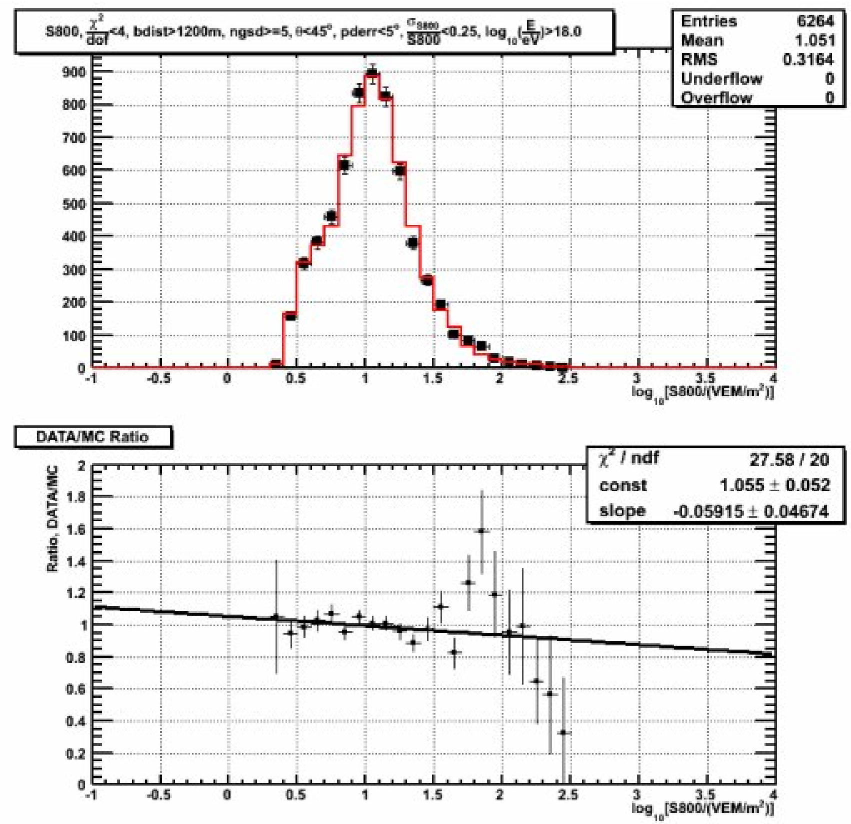
SD Analysis: Data/MC Comparisons



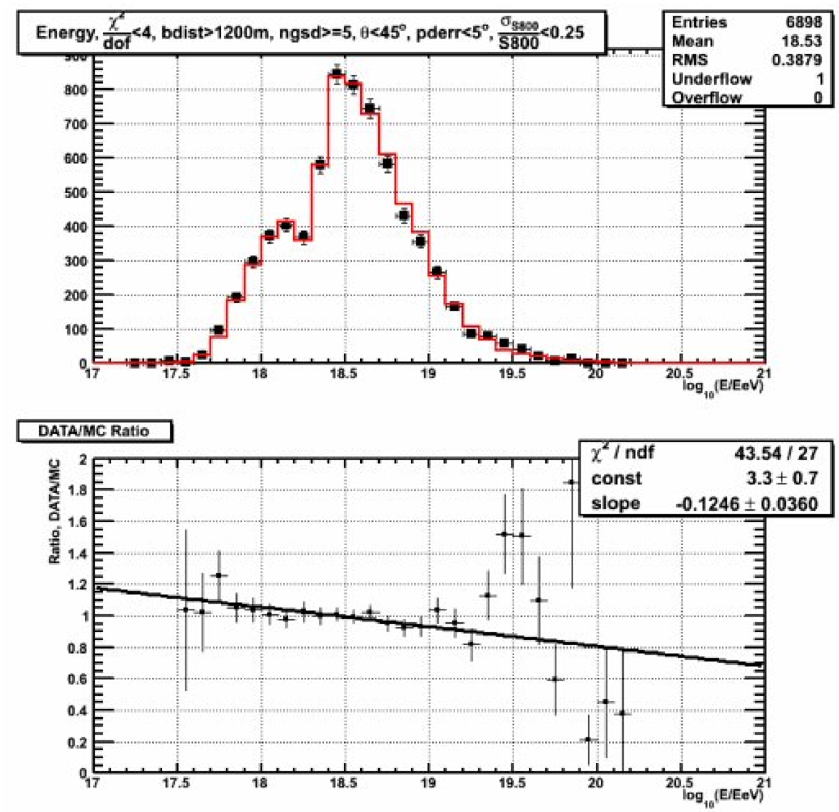


Zenith angle **Azimuthal angle**

SD Analysis: Data/MC Comparisons

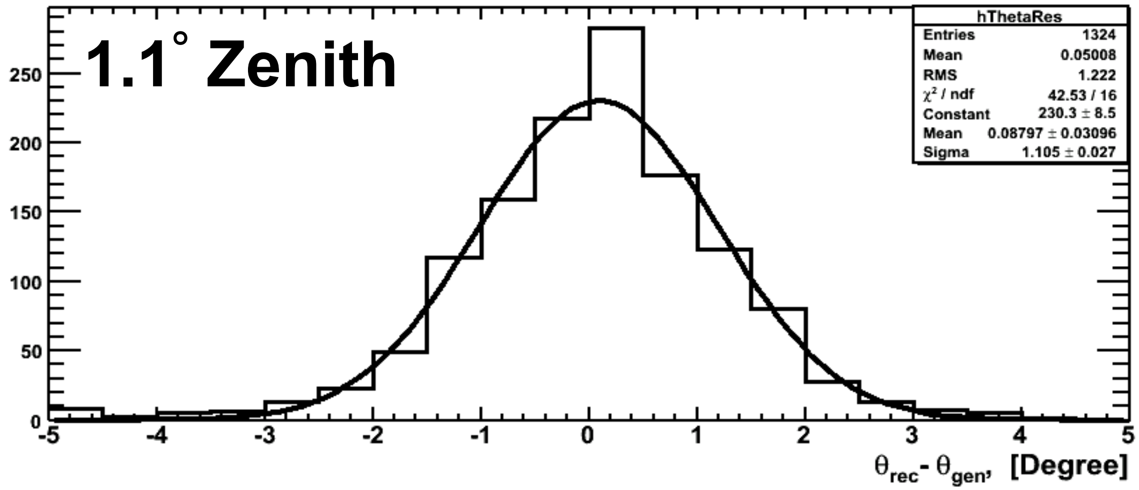


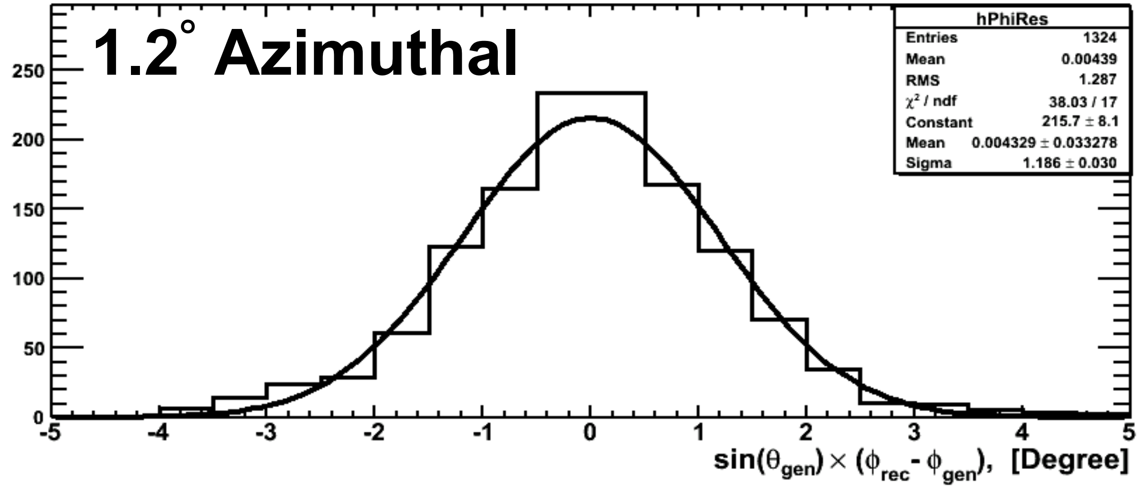
S_{800}



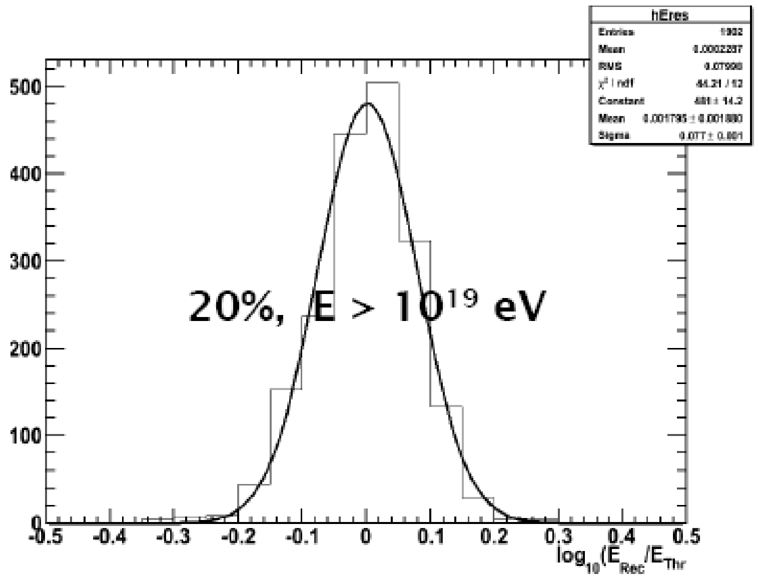
Energy

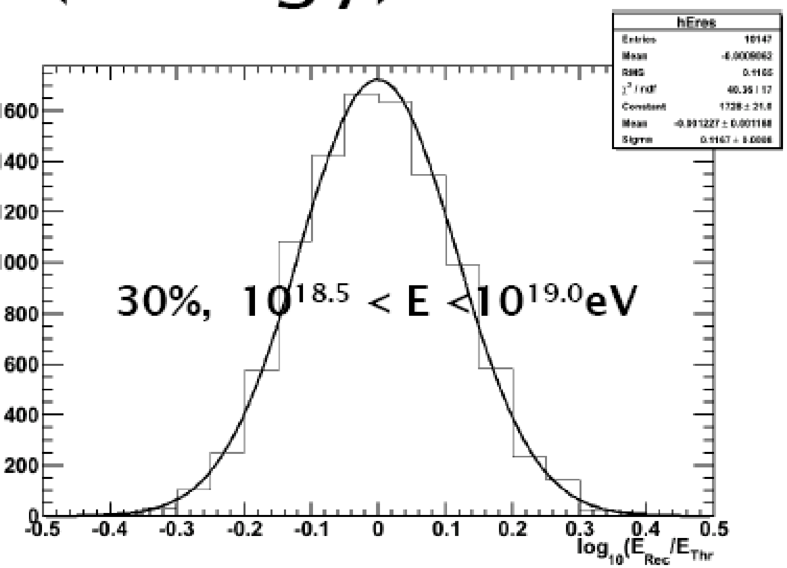
SD Analysis
Angular Resolution

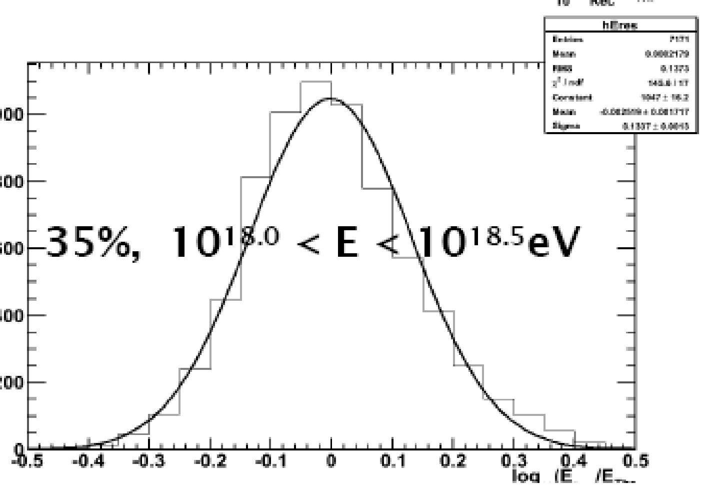


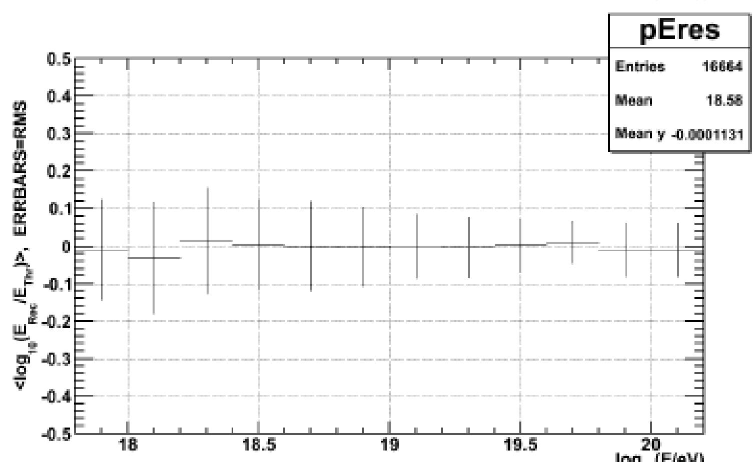


SD Analysis: Energy Resolution

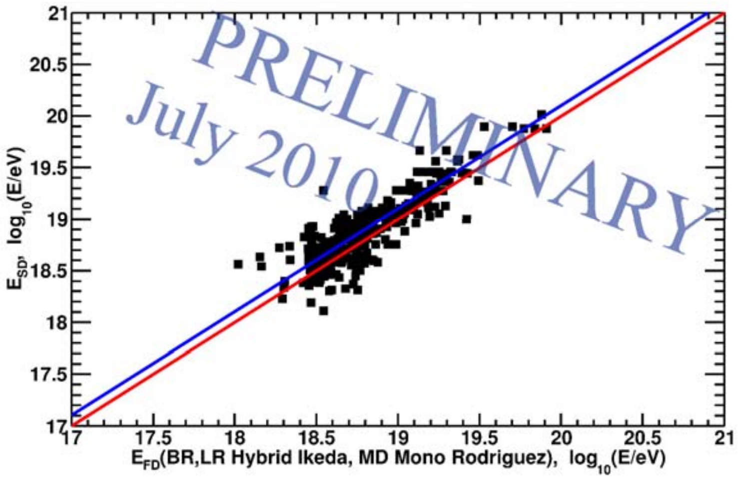


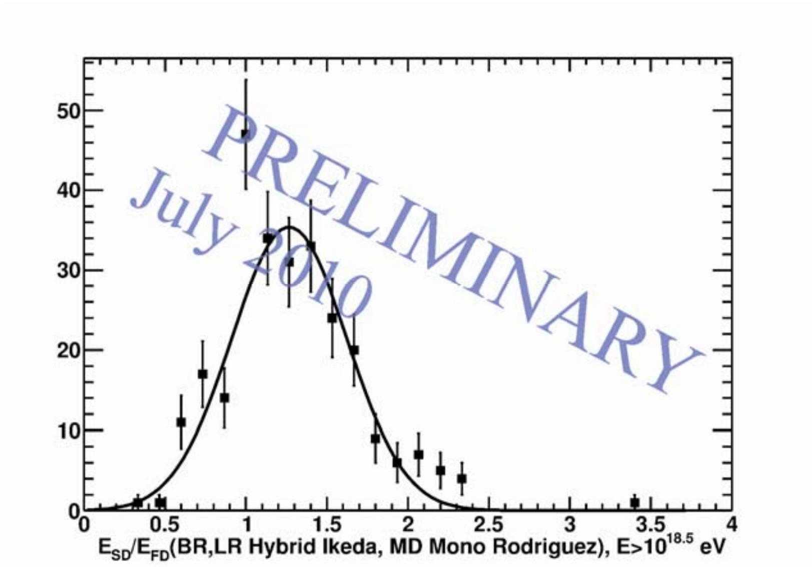






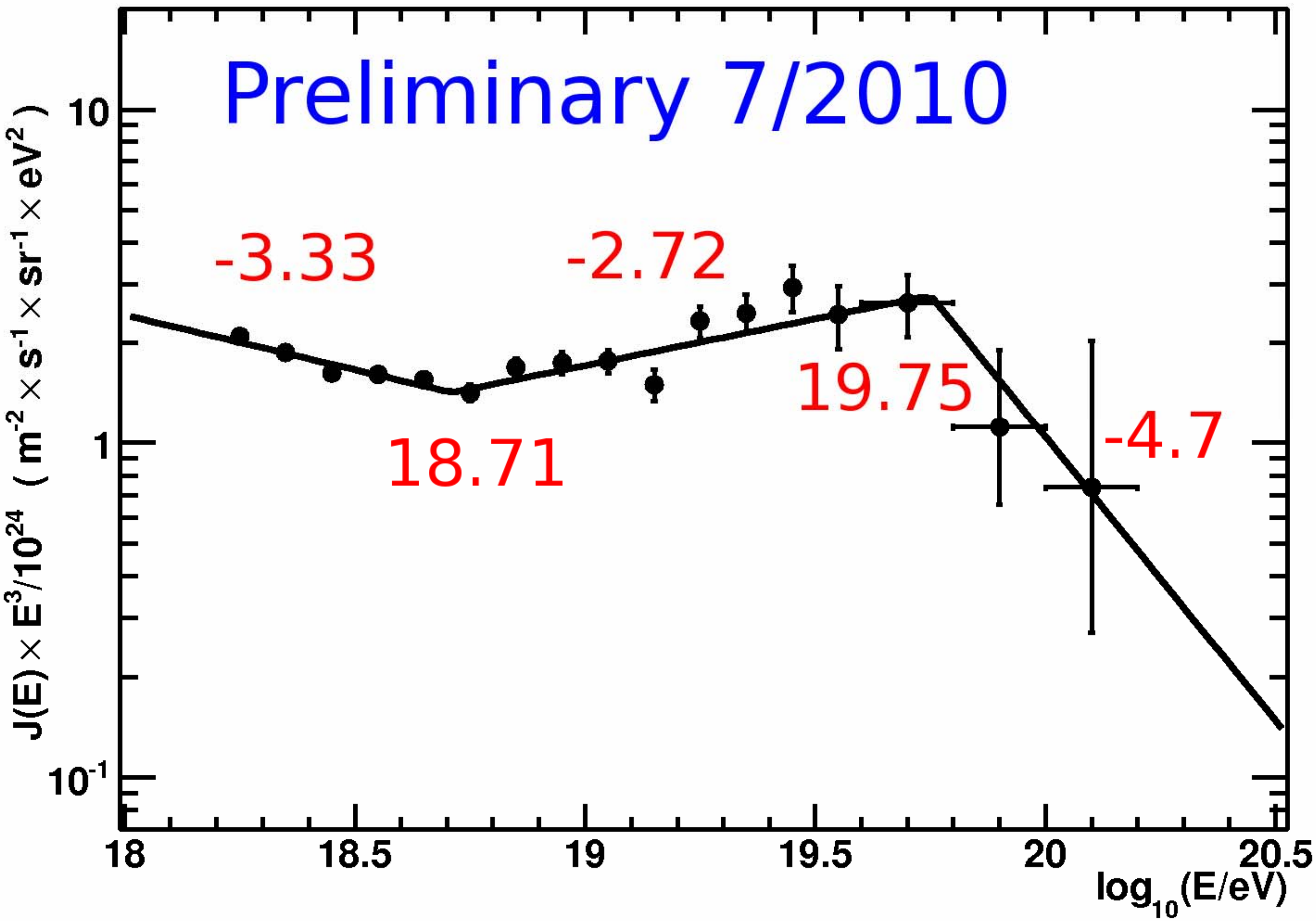
SD Analysis: Energy Scale



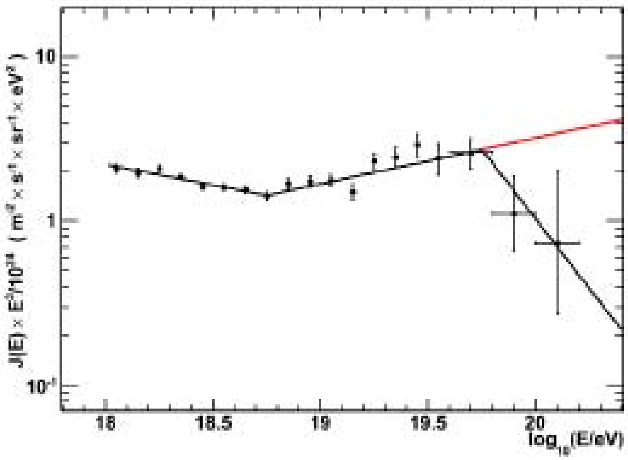


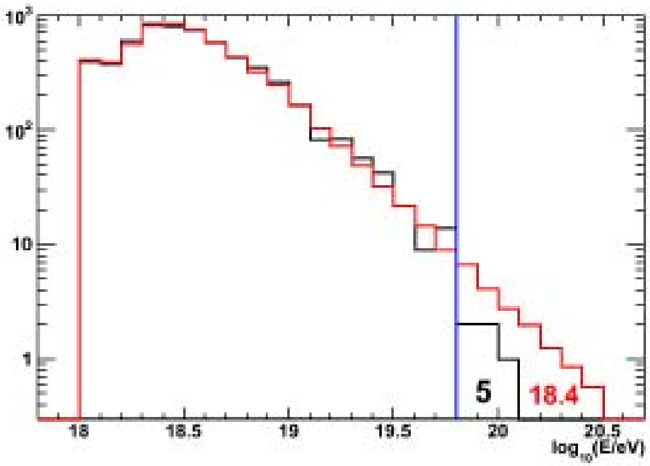
- Energy scale is more accurately by FD than by simulation
- Set SD energy scale to Middle Drum (i.e. HiRes-I) FD energy scale using well-reconstructed events seen by both detectors:
- **27% renormalization.**

TA Surface Detector Energy Spectrum



SD Energy Spectrum: GZK Feature



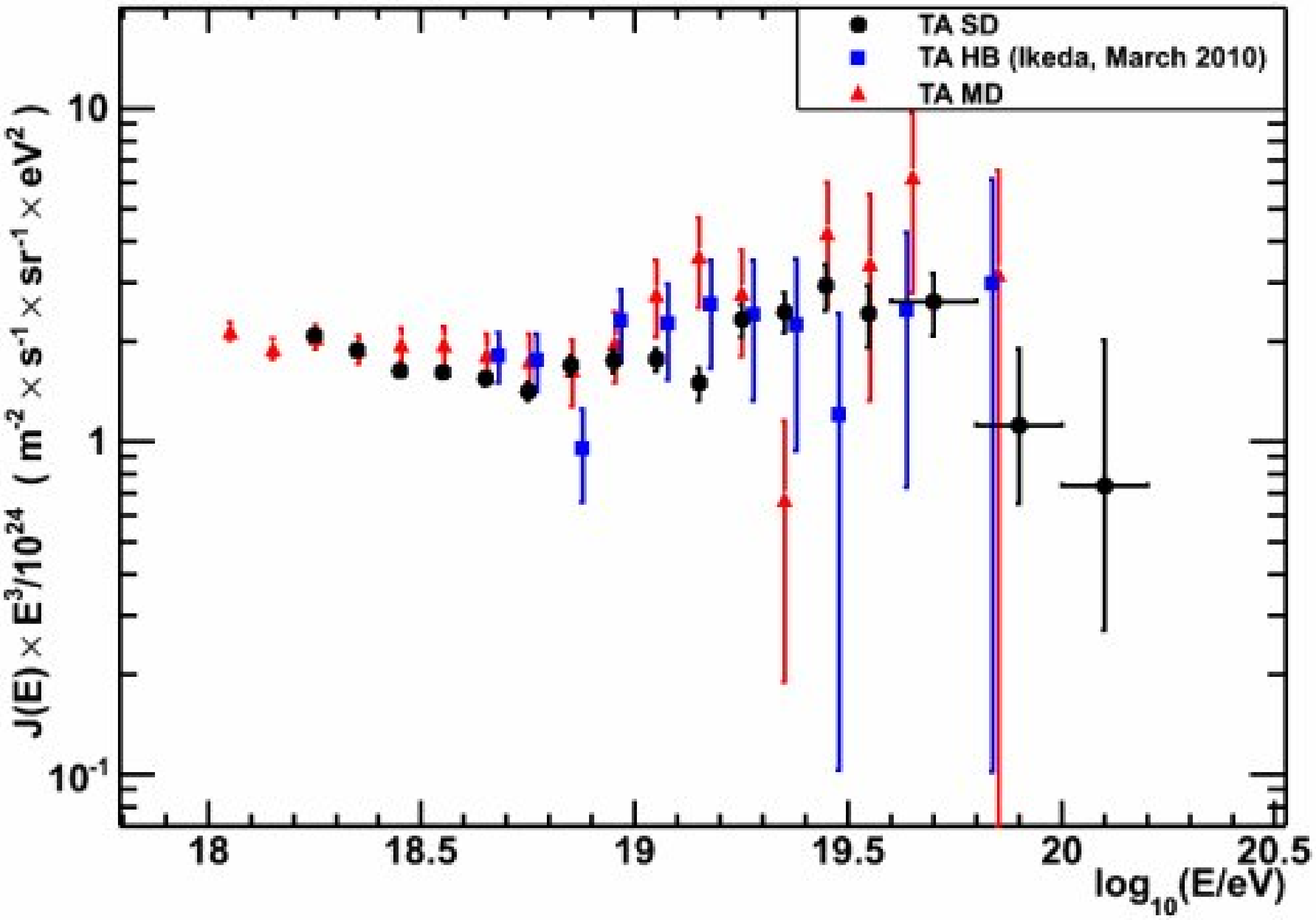


- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TASD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}E$ bins after $10^{19.8}$eV bin:
  - $N_{EXPECT} = 18.4$
  - $N_{OBSERVE} = 5$

$$\text{PROB}=\sum_{i=0}^{5} Poisson(\mu = 18.4; i) = 2.41 \times 10^{-4}$$

(3.5σ)

SD Energy Spectrum: Comparison

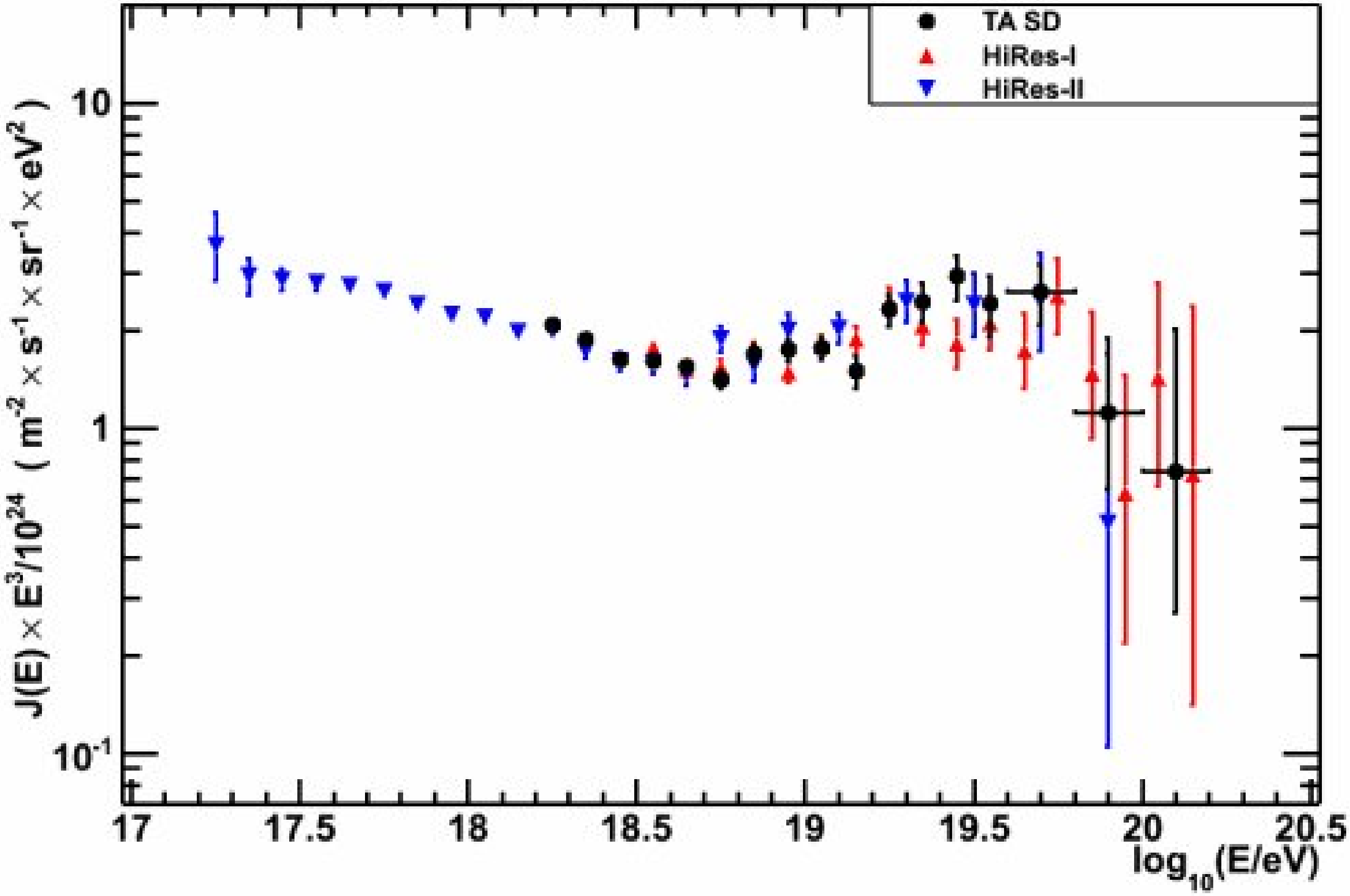


● TA SD

■ TA Hybrid

▲ TA MD

SD Energy Spectrum: Comparison

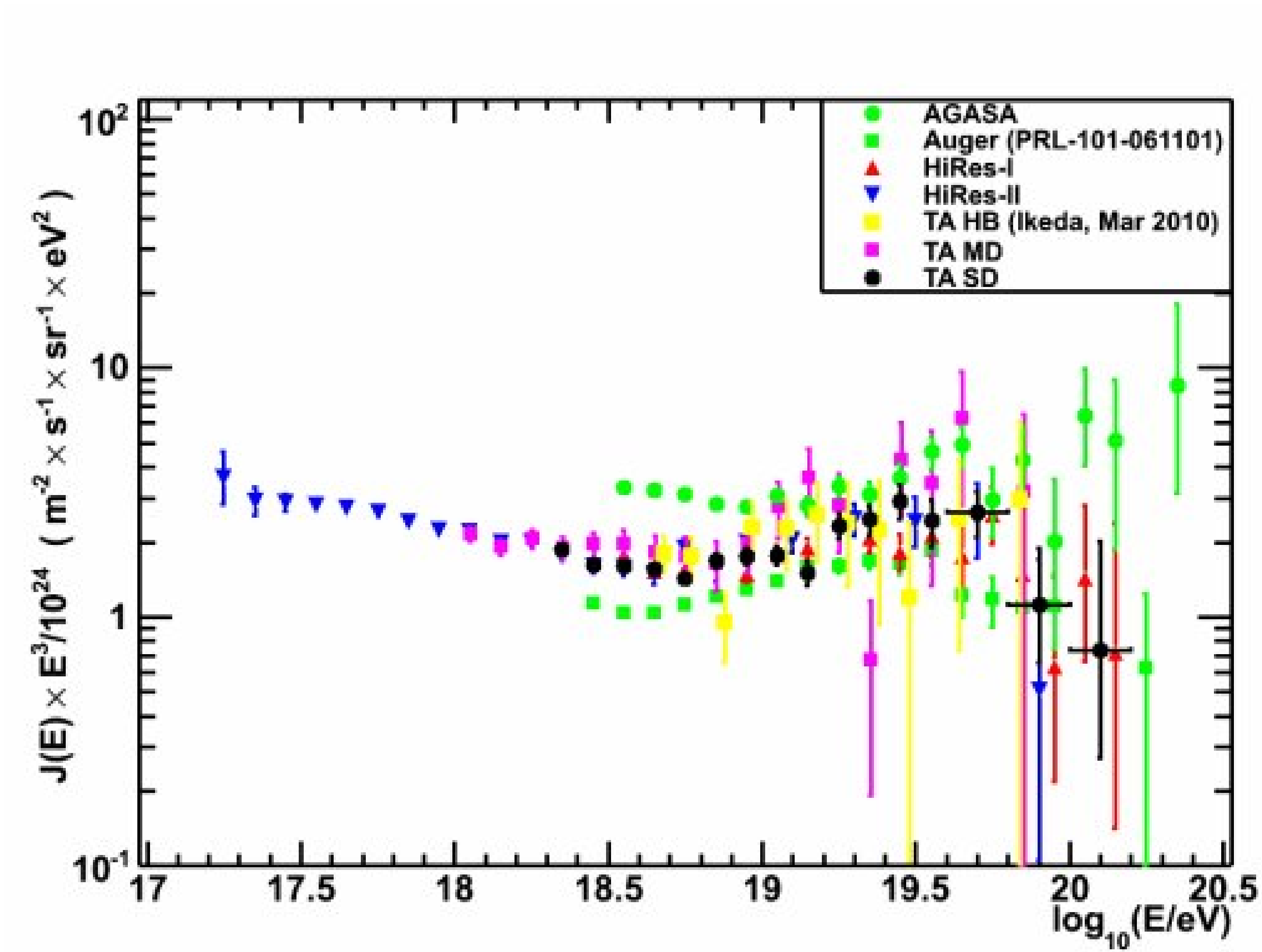


● TA SD

▲ HiRes-I

▼ HiRes-II

SD Energy Spectrum: Comparison



AGASA

Auger

HiRes-I

HiRes-II

TA Hybrid

TA MD

TA SD

Conclusion: A Work in Progess

- TA possesses the largest aperture for UHECR’s in the Northern Hemisphere.
- SD energy spectrum measurement shows good agreement with results previously reported by HiRes.
- Data collection is ongoing.

Acknowledgments

文部科学省
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NATIONAL • SCIENCE • FOUNDATION

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MINISTRY OF EDUCATION, SCIENCE AND TECHNOLOGY

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