Energy Spectrum Measured by the Telescope Array Surface Detector

TELESCOPE ARRAY PROJECT

RUTGERS
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OF NEW JERSEY

THE UNIVERSITY OF UTAH

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Piscataway, NJ, April 30, 2012

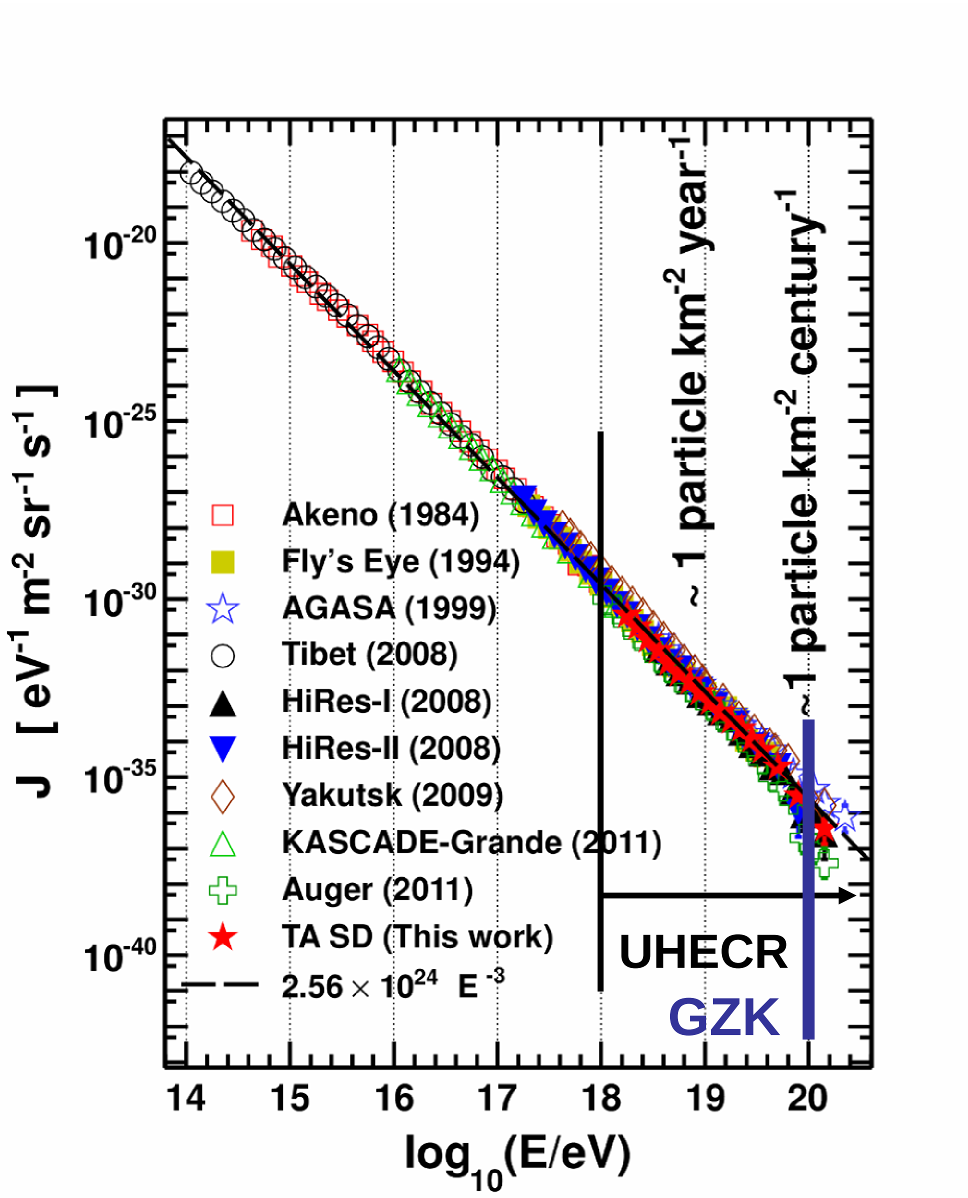
OUTLINE

- **U**ltra **H**igh **E**nergy **C**osmic **R**ays (**UHECR**)
- **G**reisen-**Z**atsepin-**K**uzmin **GZK** suppression
  - HiRes[1]-AGASA[2] contradiction
- **T**elescope **A**rray (TA)
- TA **S**urface **D**etector (**SD**)
- TA SD Event Reconstruction
- TA SD **M**onte-**C**arlo (**MC**) Simulation
- Energy Spectrum Result
- Conclusions

[1] **HiRes**: **H**igh **Res**olution Fly’s Eye (UHECR) experiment)

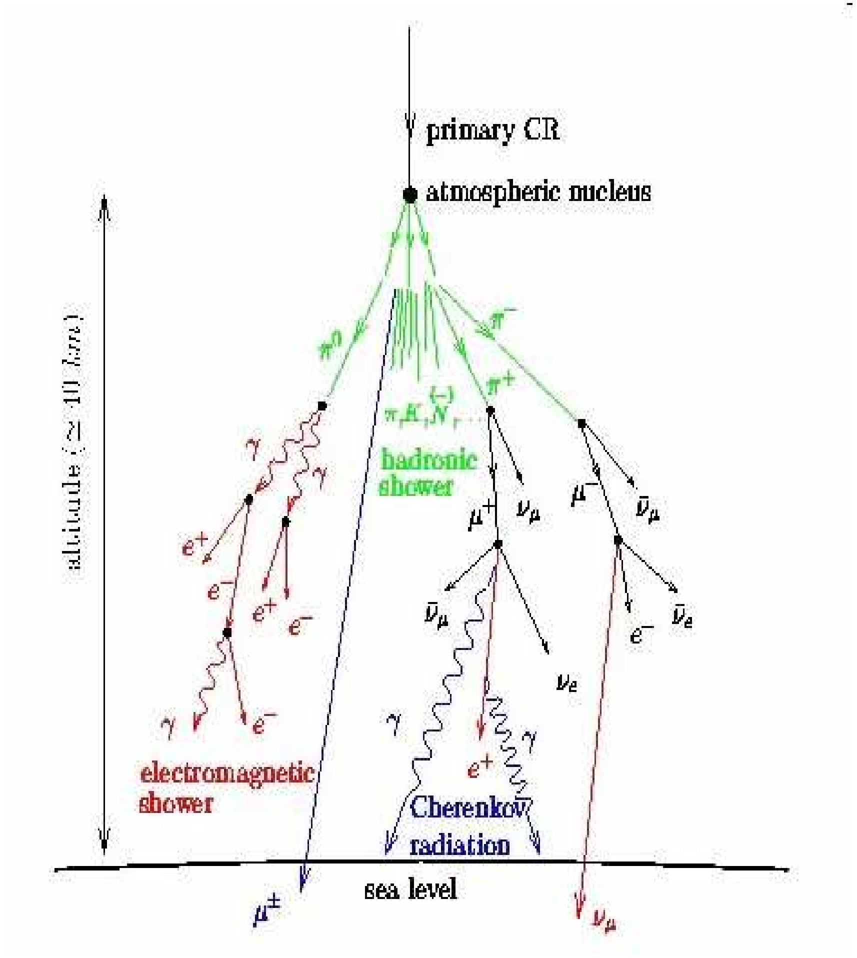
[2] **AGASA**: **A**keno **G**iant **A**ir **S**hower **A**rray (UHECR experiment)

Cosmic Rays



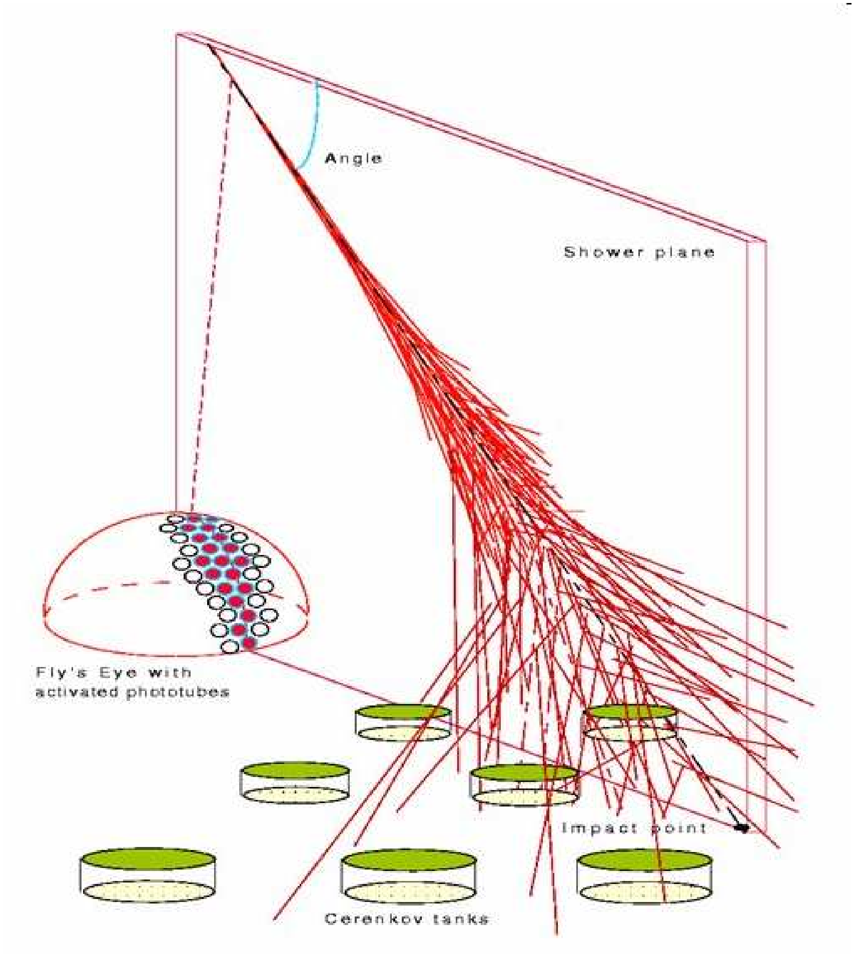
- Cosmic Rays
  - First discovered by V. Hess
  - Mostly charged particles
  - Flux = steeply falling power law → UHECR (E > 10^{18} eV) are **rare**
- E > 10^{18}eV, UHECR
  - Sources unknown
  - Produce extensive air showers in atmosphere (Auger)
  - Secondary particles reach the ground →Sparsely spaced ground array detectors (Rossi)
  - Volcano Ranch saw a first 10^{20} eV event (Linsley).

Extensive Air Showers



- Hadronic core
  - Baryons, π, K
- Electromagnetic component
  - Started by π^0 -> 2γ decays
  - Pair production
  - Bremmstrahlung
  - Ionization & Excitation losses
    - Produce Fluorescence and Cherenkov light
  - Compton scattering
- Muon component
  - Due to charged π and K decays
  - Muons are long-lived, penetrating, and reach the ground level

Extensive Air Showers (Contd.)



- Fluorescence detectors register fluorescence light due to the excitation of N_2 molecules by the electromagnetic component
- Ground Arrays register secondary particles from electromagnetic and muonic component

GZK Suppression

- A well known fact from accelerator experiments of ~0.5 GeV gamma + stationary proton:

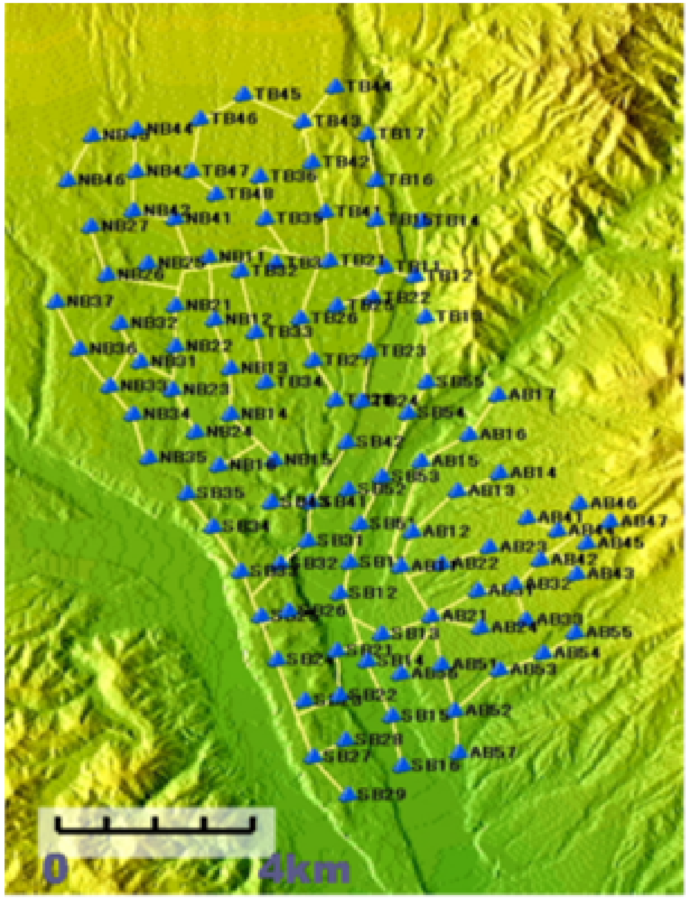
$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

- Cosmic Microwave Background
  - 2.7 K ~2 x 10^{-4}eV
  - 10^{20}eV protons should lose energy (efficiently) due to this **photopion** production → strong suppression in cosmic ray flux near 10^{20}eV (Greisen, Zatsepin, Kuzmin)

GZK Suppression (Contd.)

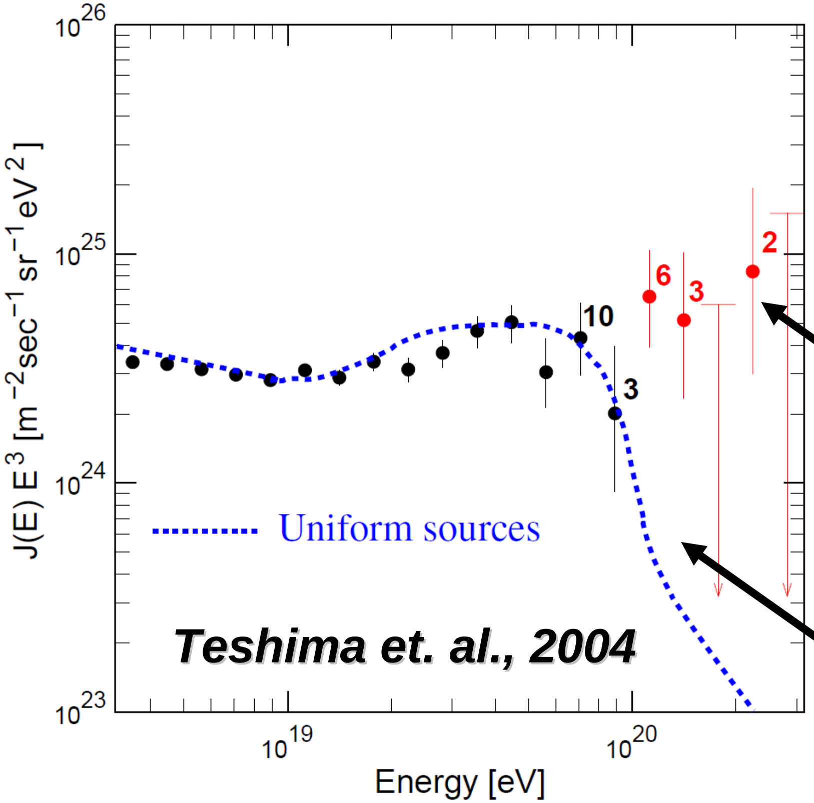
- But early ground array experiments reported seeing E ≥ 10^{20} eV events
  - Volcano Ranch, SUGAR, Yakutsk
- Fly’s Eye reported 3 x 10^{20}eV
  - Largest particle energy ever measured
  - Used Air-fluorescence technique
    - pioneered by University of Utah experiment
- The experiments were too small to conclusively rule out the GZK suppression
  - few tens of square kilometers
  - small (Area x Solid Angle x Observation Time) factors for measuring flux at E > 10^{19} eV

AGASA



- Akeno, Japan
- 1st experiment large enough to measure flux above 10^{19} eV
- Area ~ 100 km2
- ~ 1 km spacing
- 111 plastic scintillation counters
- 13 years of operation, 1991-2004
- ~120 km^2 sr aperture above 10^{19} eV

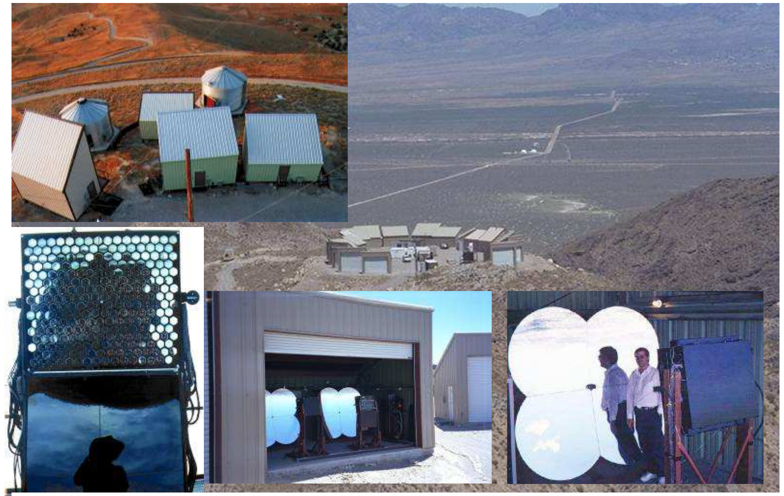
AGASA: No GZK effect

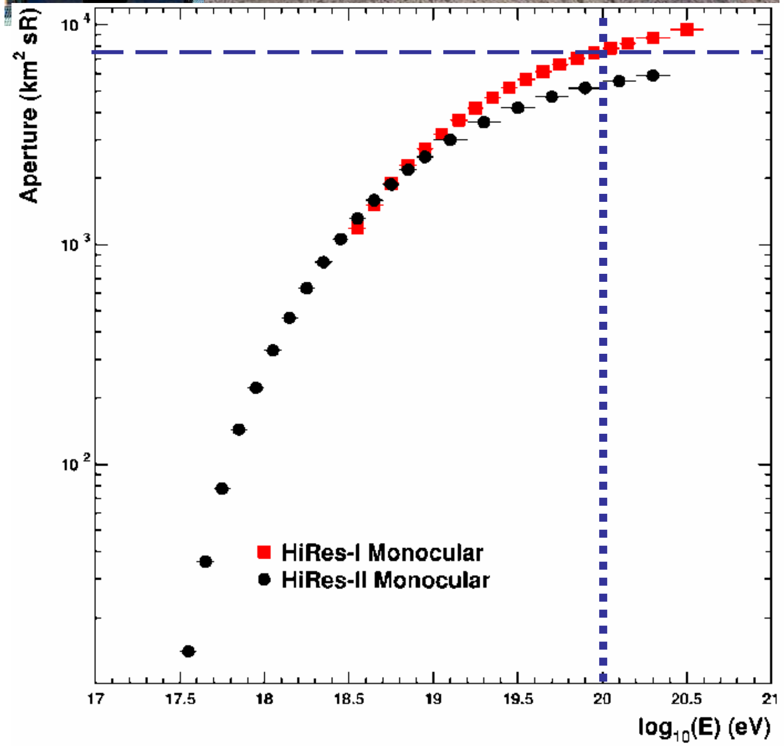


Dotted line = spectrum by uniform sources, propagated through cosmic microwave background

- 11 “super-GZK” events in AGASA data
- Flux limited by the rate at which sources can produce UHECR?
- GZK suppression ??

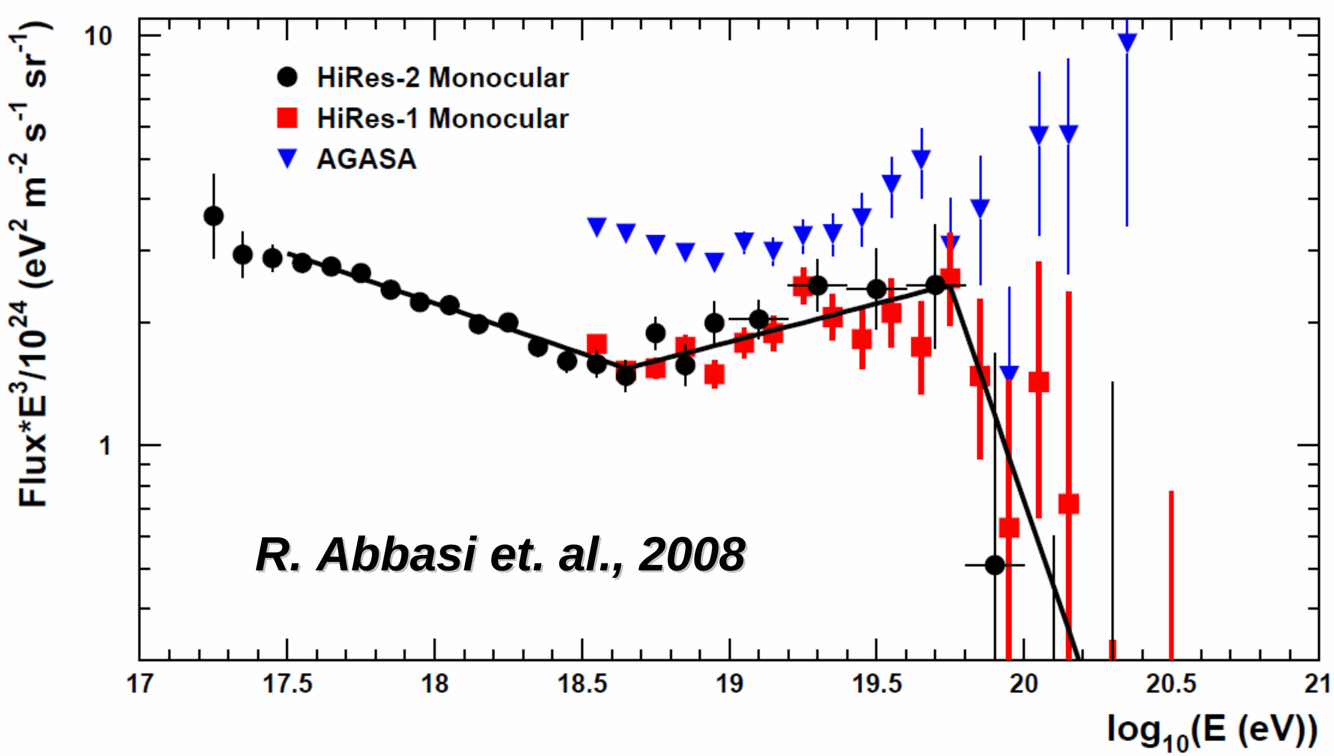
HiRes





- Dugway Proving Grounds, UT
- Two-site fluorescence detector
  - Spherical mirrors, 4.2m^2
  - 256 photomultiplier tubes / mirror
  - Each tube ~1 degree cone of the sky
  - **HiRes1**
    - 1 ring of 21 mirrors
    - 3 – 17 degree elevations
  - **HiRes2:**
    - 12.6 km South-West of HiRes1.
    - 2 rings x 42 mirrors
    - 3 – 31 degree elevations
- **9 years of operation 1997 – 2006**
  - **10% duty cycle**
- **Aperture ~7.5x10^3 km^2 sr at 10^{20} eV**

HiRes: GZK Cutoff Exists



- Fluorescence detector
  - First to observe GZK effect
    - Chance probability > 5 σ

HiRes vs AGASA

- Combine HiRes and AGASA experiments
  - AGASA-like array of scintillation counters
  - HiRes – like fluorescence detectors
- **Telescope Array** experiment
  - Deployed in 2007
  - Measure UHECR anisotropy, mass composition
  - Measure UHECR energy spectrum:
    - Using fluorescence detectors only
    - Using surface detectors only
      - large statistics above 10^{19} eV
      - **This work**
    - Using surface and fluorescence detectors (hybrid)

The Telescope Array (TA) Collaboration

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- 140 collaborators, 26 schools, 5 countries
- US, Japan, Korea, Russia, Belgium
- Many former HiRes & AGASA members

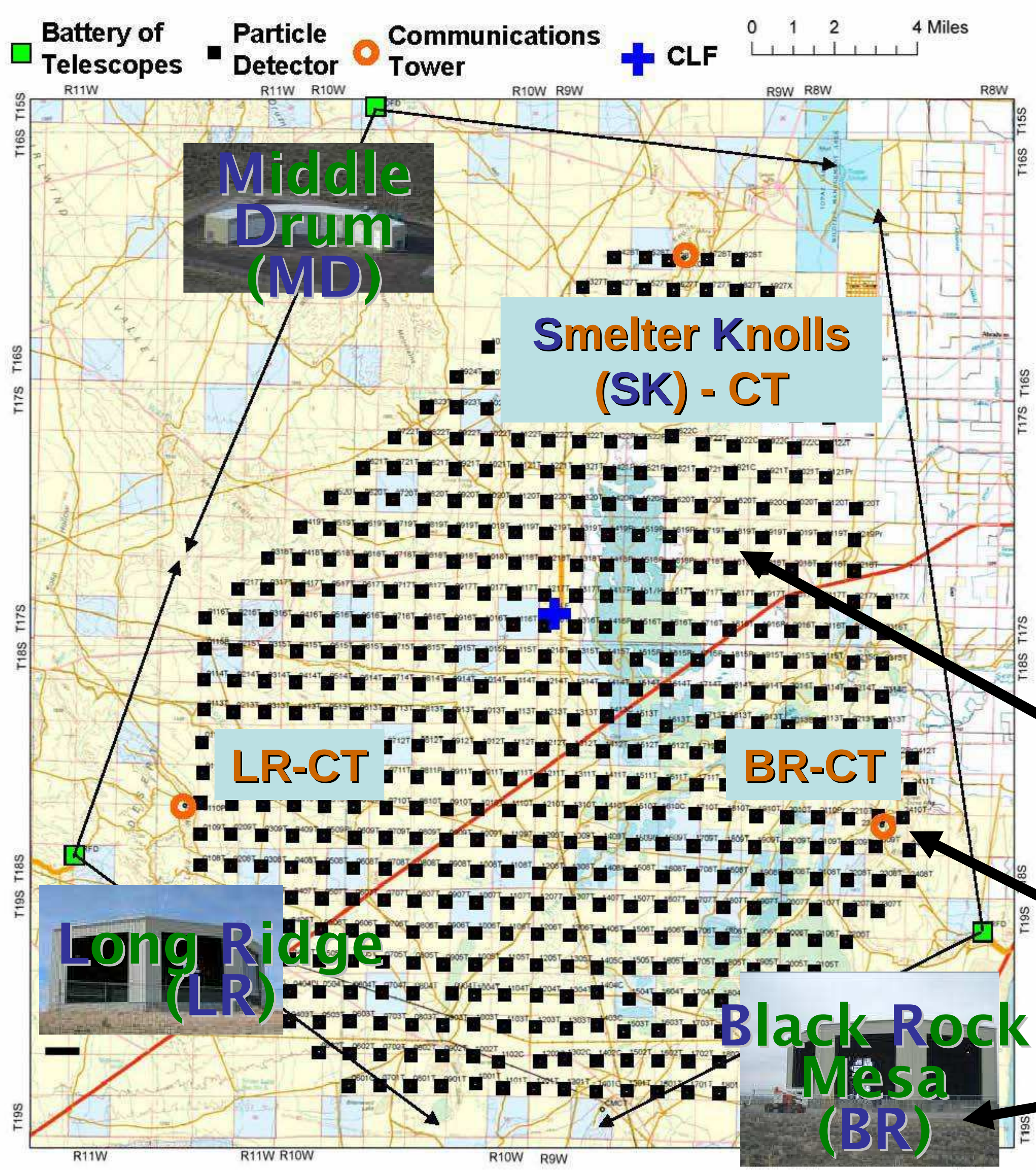
TA SD Spectrum Group

- Prof. Gordon Thomson - Faculty Supervisor
  - Dr. Benjamin Stokes - Post Doc
    - Detailed CORSIKA Monte-Carlo simulation of the TA SD
    - Circumvent problems due to approximations in CORSIKA
    - Solve computational performance issues
    - Simulate UHECR as they exist in nature
    - Include TA SD details: response, electronics, and calibration
  - Dmitri Ivanov - Graduate Student
    - Parsing and handling raw data, calibration
    - GEANT- 4 simulation of the detector response
    - Event reconstruction and quality cuts
    - Monte-Carlo validation (comparison with data)
    - Energy spectrum calculation and interpretation

Telescope Array

Hybrid detector

Millard County, UT
39.3° N , 112.9° W,
Alt. 1400m
~880g/cm^2



507 Surface Detector (SD) counters, 1.2km apart, cover 680km^2

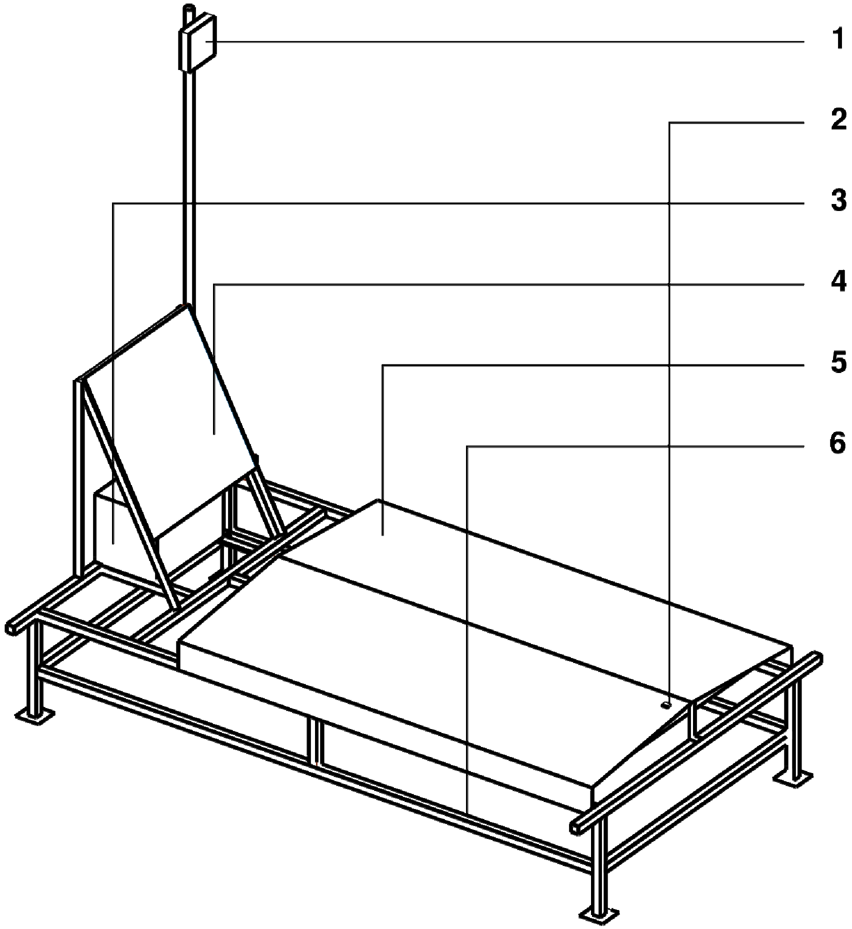
3 Communication Towers (CT):
BR,LR,SK

3 Fluorescence Detectors (FD):
BR,LR,MD

TA Surface Detector (**TA SD**)

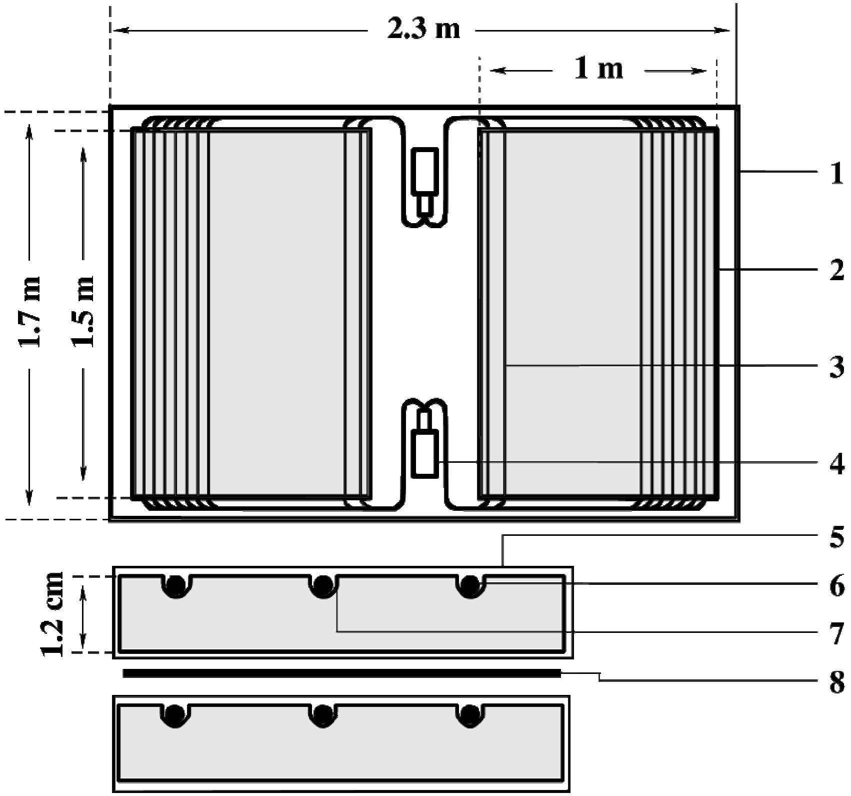
- Powered by solar cells; radio readout.
- Calibration using atmospheric muons.
- Energy deposition by secondary cosmic ray particles measured in **VEM** units (**V**ertical **E**quivalent **M**uon)
  - Energy deposited by a vertical minimum-ionizing muon

Exterior Parts



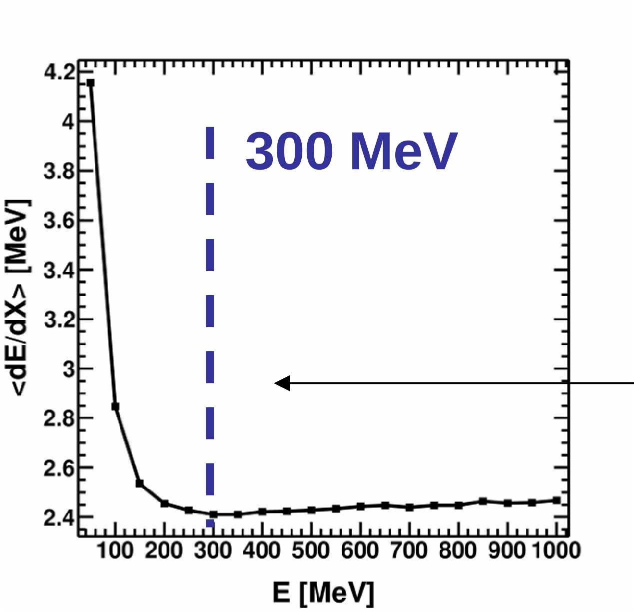
1. Wireless antenna
2. GPS receiver
3. Battery & electronics box
4. Solar panel
5. Iron roof
6. Supporting metal frame

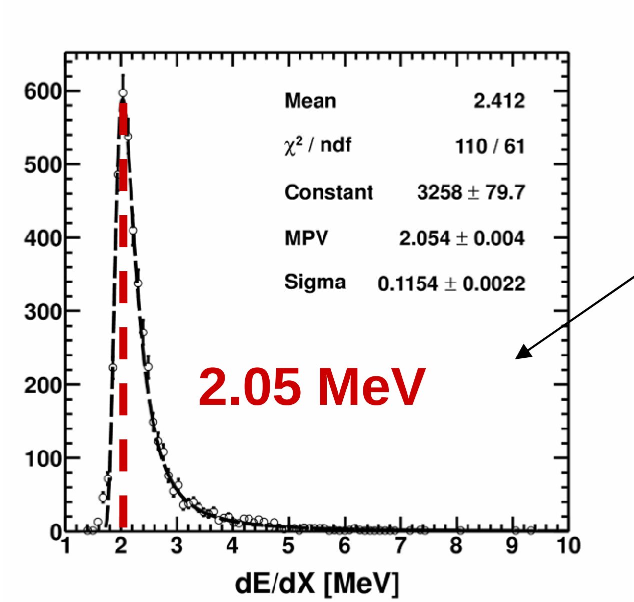
Sensitive Parts



1. Stainless steel box
2. Two layers of 1.5m x 2m plastic scintillators, 1.2cm thick each
3. **W**avelength **S**hifting **F**iber (**WLS**)
4. **P**hotomultiplier **T**ube (**PMT**)
    - Operate at ~1000 V
    - Gain ~ 2 x 10^6
    - One PMT for each (upper, lower) scintillator layer
5. Tyvek sheet
6. WLS (cross-sectional view)
7. WLS Grooves
8. Separator plate

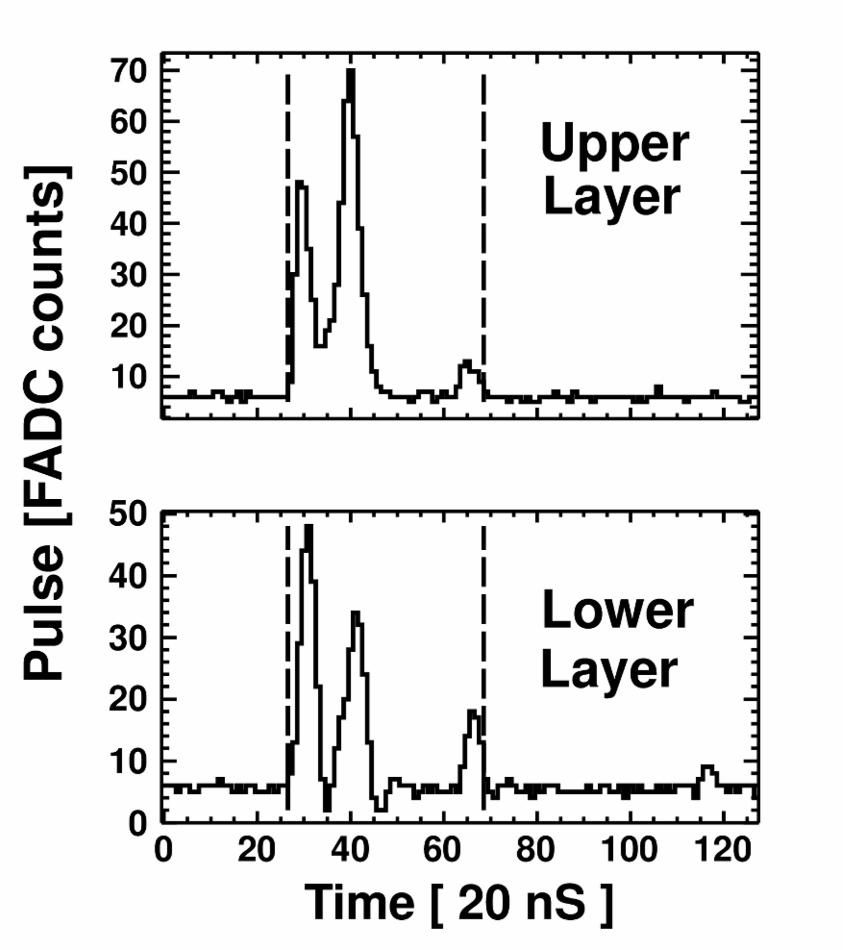
VEM Definition





- GEANT4 simulation:
  - – Minimum ionizing energy occurs at vertical muon (kinetic) energy of ~300 MeV
  - – Most probable value of dE/dX for a vertical 300 MeV muon is 2.05 MeV
- **1 VEM = 2.05 MeV**
- Varies slowly with increasing (kinetic) energy of muon

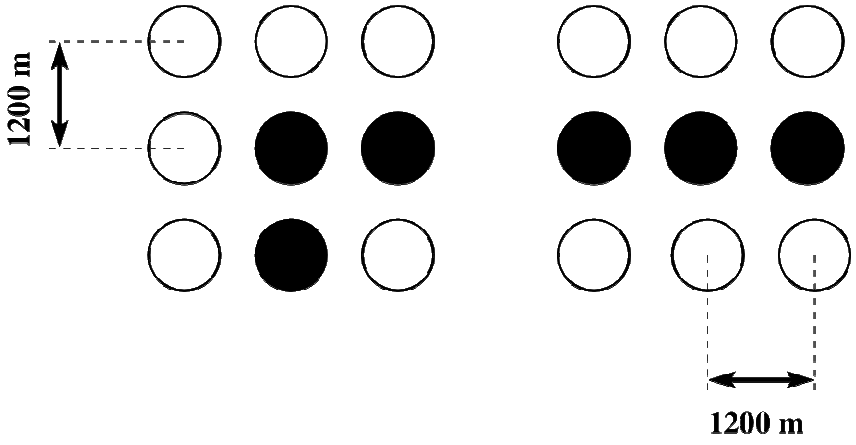
Electronics



Typical waveform reported by a counter (signal from an extensive air shower)

- Energy deposition in each counter is read out by two PMTs
  - upper, lower scintillator layers
- PMT output recorded by12 bit 50 MHz **F**lash-**A**nalog-to-**D**igital-**C**onverter (**FADC**)
- Waveforms (signal vs time) reported to the communication towers

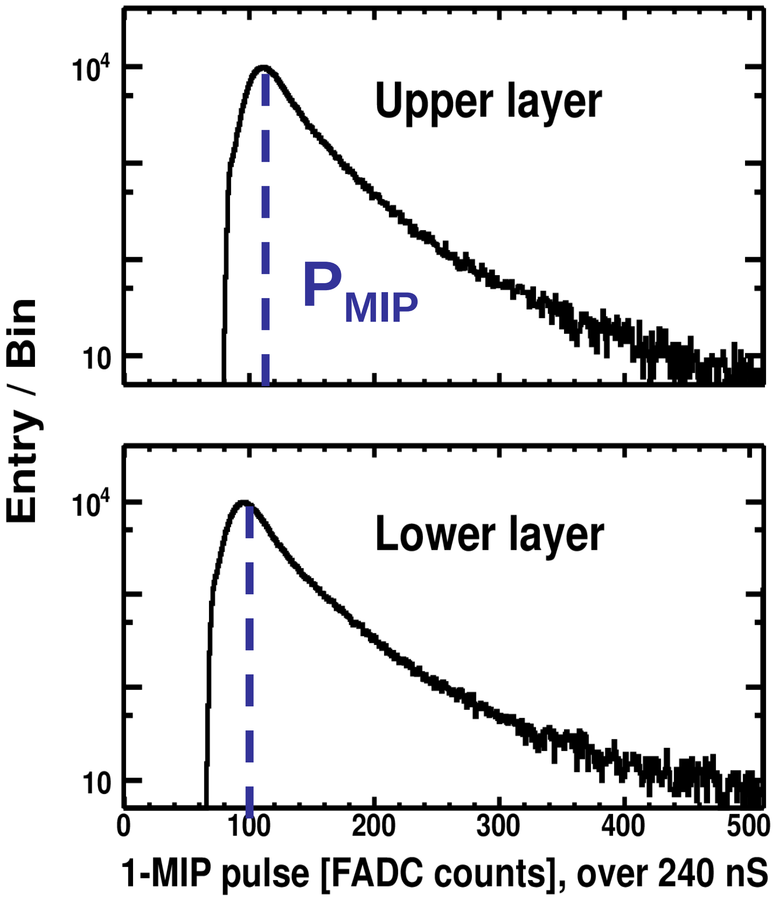
Trigger and Data Acquisition



Acceptable trigger patterns (up to rotations by 90°)

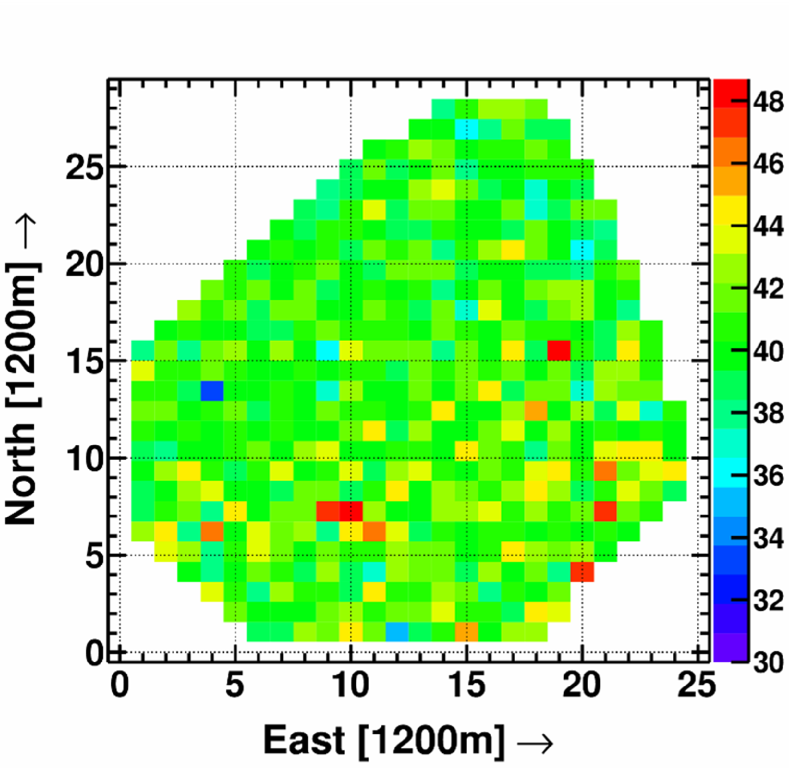
- Trigger issued by **C**ommunication **T**owers (**CT**) when:
  - 3 adjacent counters
  - ≥ 150 FADC counts each
  - Upper/lower layer coincidence
  - Within 8µS
- Data acquisition ←→ request waveforms from counters:
- ≥ 15 FADC counts each
  - Upper/lower layer coincidence
  - ± 32 µS of the trigger time
- Hybrid Trigger
  - FDs can send commands that prompt data acquisition
    - just like normal CT trigger

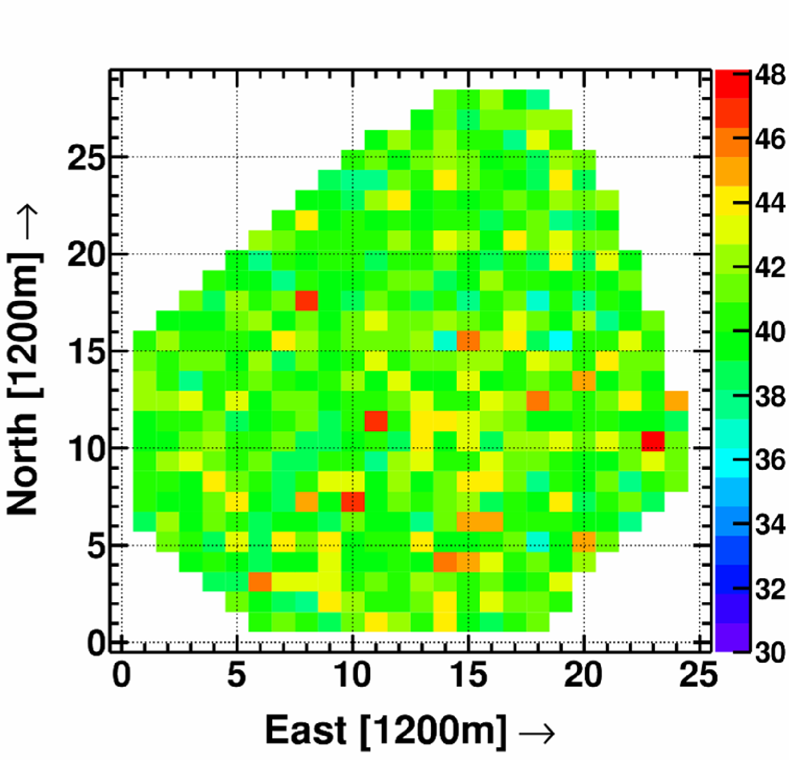
VEM Calibration



- Convert signal from [FADC] to [VEM]
- **M**inimum **I**onizing **P**article (**MIP**) pulses
  - ~700 Hz at a counter
  - Histogrammed over 10 minute periods by each counter
- Peak P_{MIP} of the histogram related to FADC counts per VEM (separately for each layer):
- $P_{MIP} \approx FADC_{VEM} \sec(30°)$
  - 30° is the effective zenith angle of particles
  - Detailed simulations of atmospheric particles give answers within 1.5%

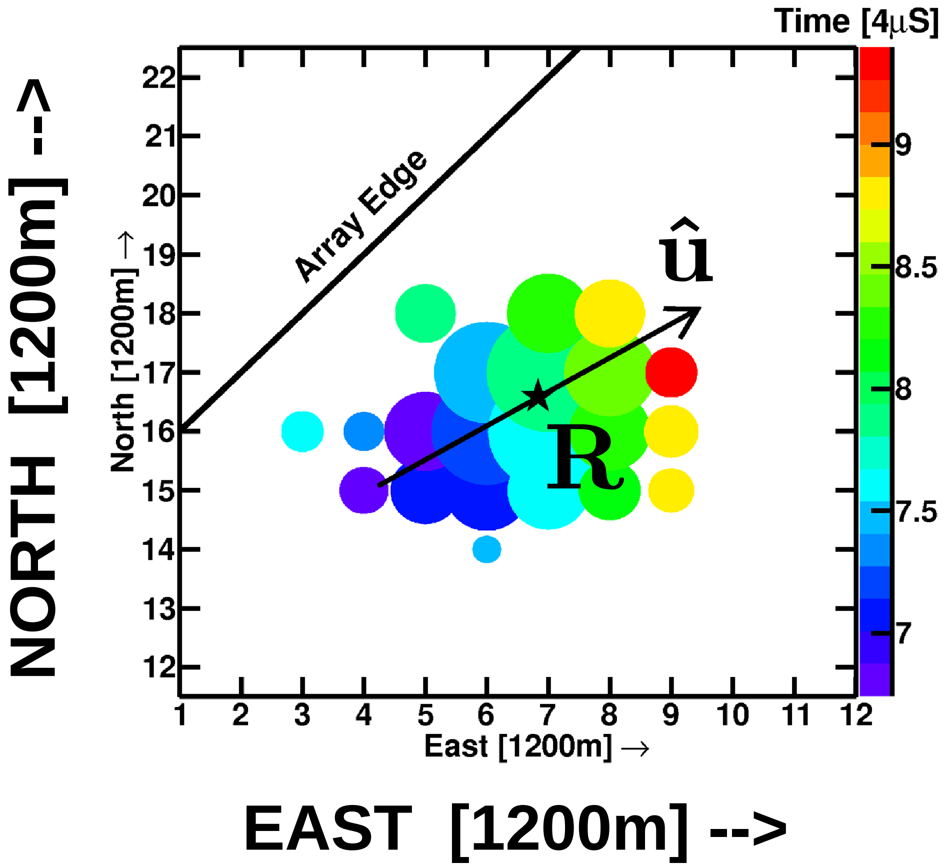
VEM Calibration (Contd.)





- FADC$_{VEM}$ (color) plotted versus counter X, Y position
  - a randomly chosen 10 min monitoring cycle
- Typically, FADC$_{VEM}$ ≈ 40 FADC counts VEM^{-1}

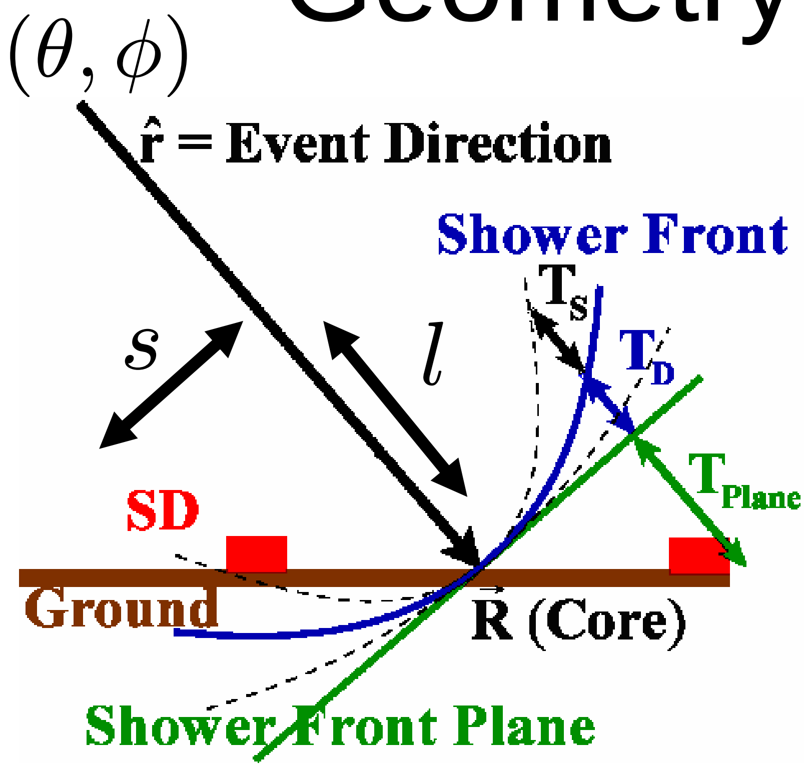
Event Reconstruction



- After pattern recognition
  - Pick out counters that are part of the event (remove random muons)

- Circle = a counter
- Color = counter time
- Circle size proportional to the log of the counter pulse height (in VEM)
- Star = shower impact position
- Arrow = projection of the event direction on the ground (the “u-axis”)
- Geometry reconstructed from the counter time
- Energy estimated from the lateral distribution of counter signals

Geometry Reconstruction



- **Event direction is found by minimizing:**

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

T_0 - Time of the core hitting ground

T_{Plane} - Time of the shower front plane

T_{D} - Time delay (next slide)

T_{S} - Fluctuation of the time delay

$\vec{\mathbf{R}}$ - Fitted (2D) core position

$\vec{\mathbf{R}}_{\text{COG}}$ - 2D core position found from the center of gravity of charge

- **6 parameters in the final fit:**
  - **Zenith and azimuthal angles**
  - **Core X, Core Y, Core time**
  - **Curvature of the front**

Time Structure of the Shower Front

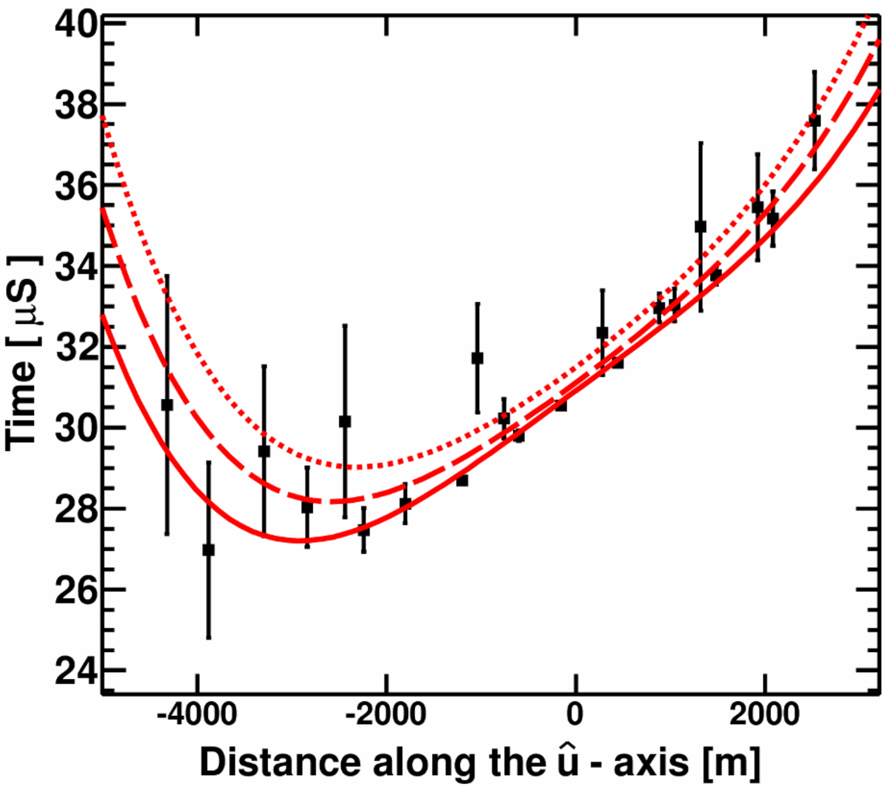
$$T_D = a\left(1 - \frac{l}{12\times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

$$T_S = (1.56\times 10^{-3}\mu\mathrm{S})\left(1.0 - \frac{l}{12\times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.5}\rho^{-0.3}$$

- T_D = Counter delay time due to the shower front curvature
- T_S = Fluctuation of the shower front time at the counter
- a = Curvature parameter
- l = Counter distance from the core along the (3D) shower axis
- s = Counter perpendicular distance from the shower axis
- ρ = Charge (pulse height) density at the counter, VEM m^{-2}

- Started with AGASA-Linsley formula
- Empirically adjusted using TA SD data only
- Tested that it works for Monte-Carlo also

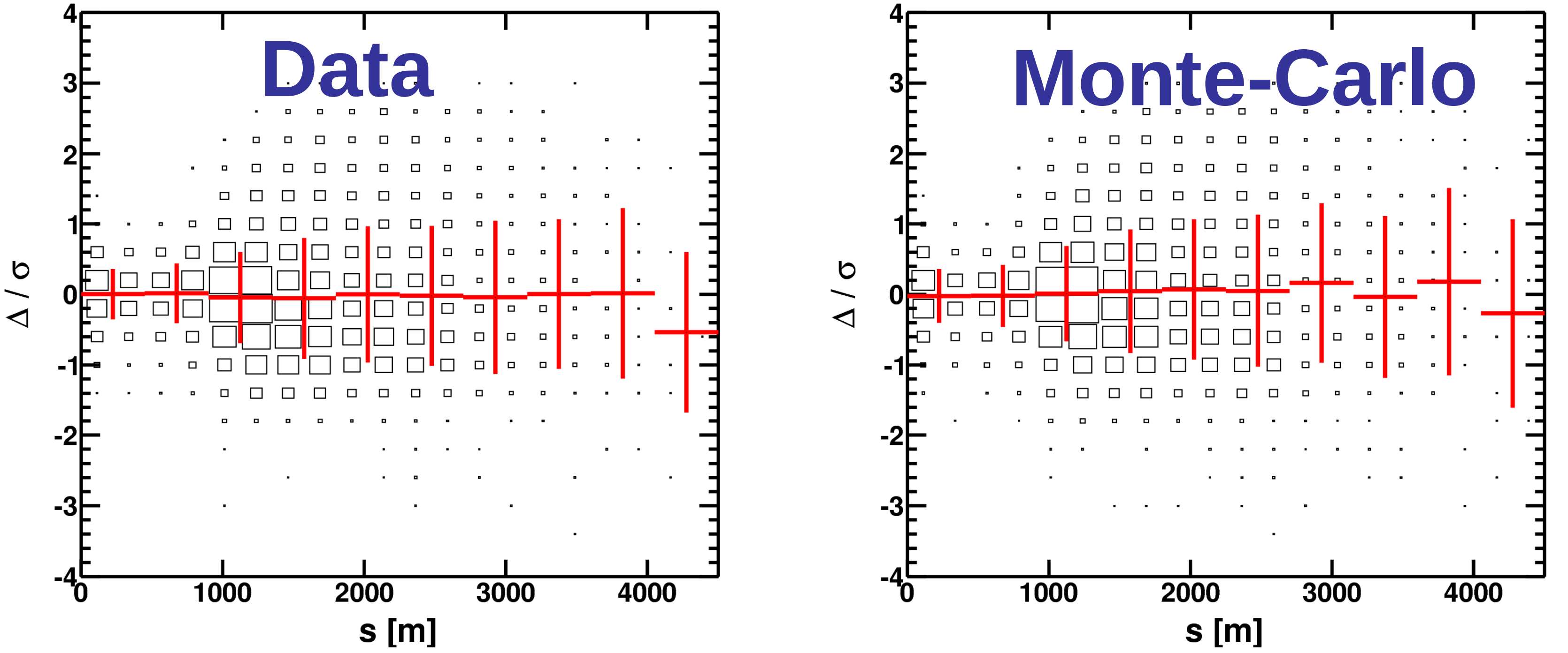
Time Fit



(**A 1D illustration of a multi-dimensional fit**)

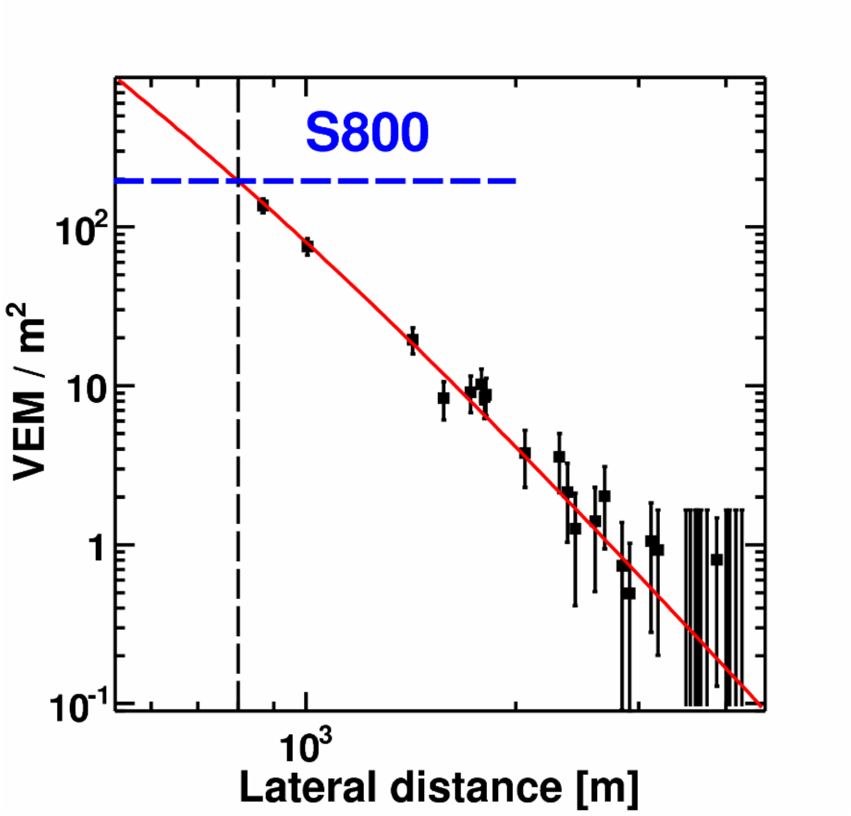
- Counter time plotted vs distance along the u-axis (points with error bars = data)
- Solid line = fit expectation time for counters on the u-axis
- Dashed line = fit expectation for counters 1km off the u-axis
- Dotted line = fit expectation for counters 2km off the u-axis

Time Fit Residuals



- Test the time fit formulas derived from the TA SD data
- Each entry = counter, plots are **over all counters and over all events**
- Normalized residual = (counter time – fit time) / T_S
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit in the same way

Lateral Distribution Fit



- Counter signal versus perpendicular (lateral) distance from the shower axis
- Fit to the AGASA **L**ateral **D**istribution **F**unction (LDF)
- Determine the **S**ignal **S**ize at **800**m (**S800**) from the shower axis

AGASA LDF:

$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

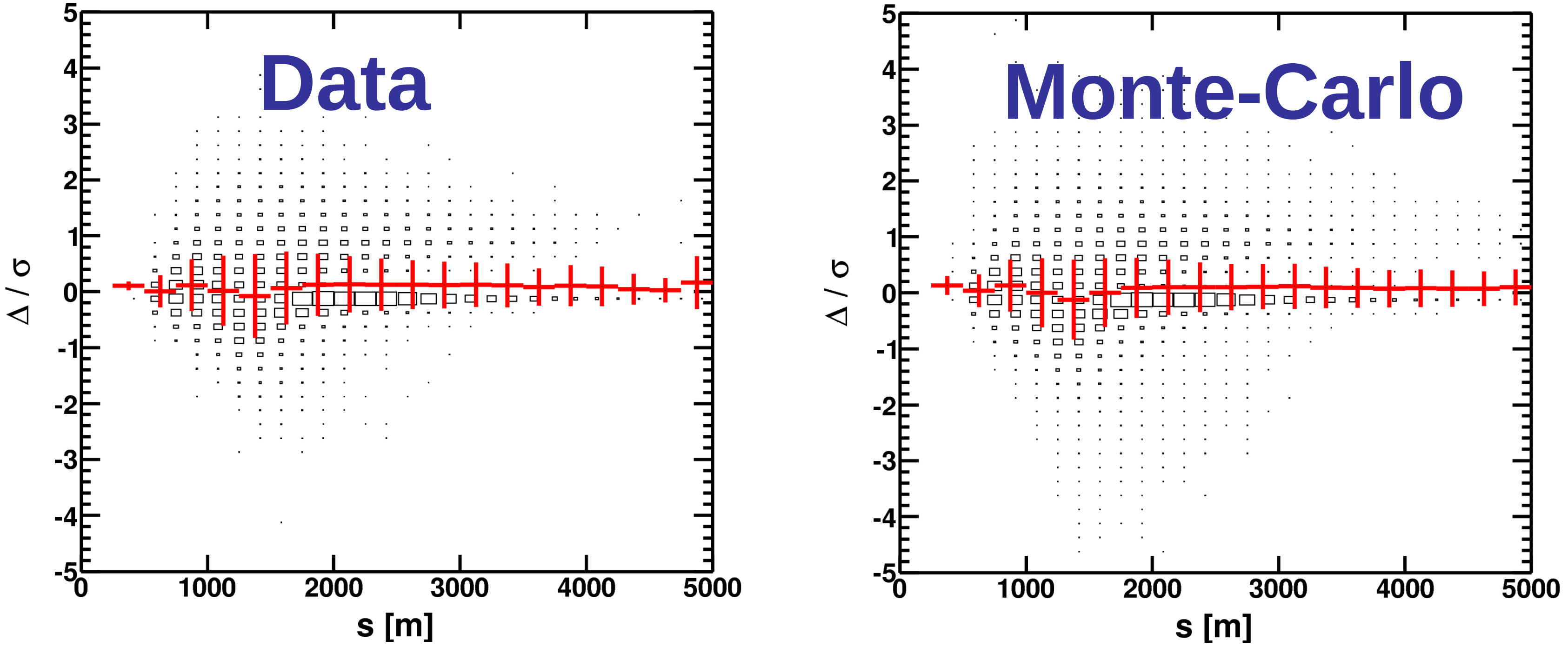
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta)-1\right]$$

$$\sigma_\rho = \sqrt{0.56\,\rho + 6.3\times10^{-3}\,\rho^2}$$

uncertainty on charge density ρ determined empirically from the TA SD data

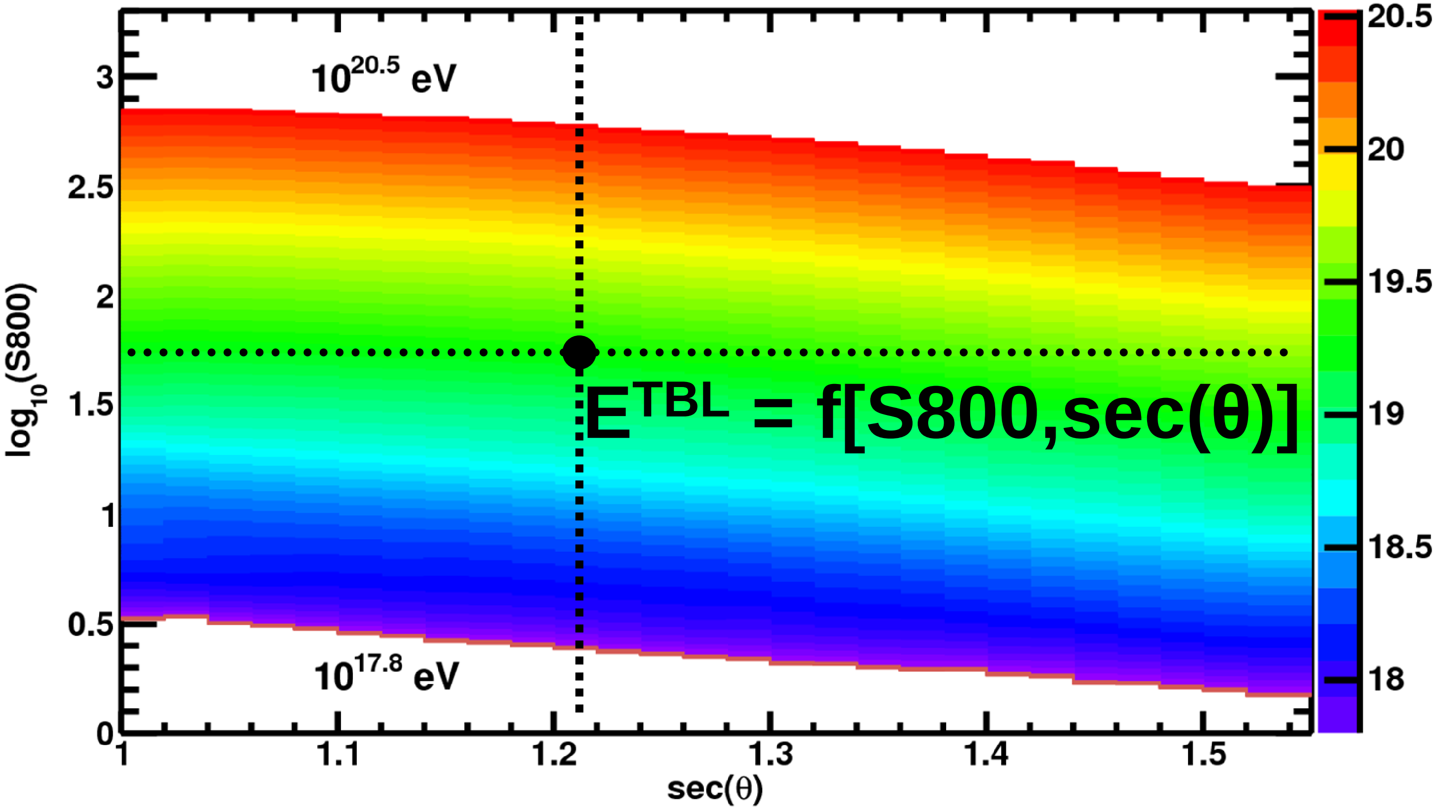
3 fit parameters: A, Core X, and Core Y

Lateral Distribution Fit Residuals



- Each entry = counter, plots are **over all counters and over all events**
- Normalized residual = (counter ρ – fit ρ) / σ_ρ
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit to the AGASA LDF in the same way

Energy Determination, Step 1/2



$E^{TBL} = f[S800,\sec(\theta)]$

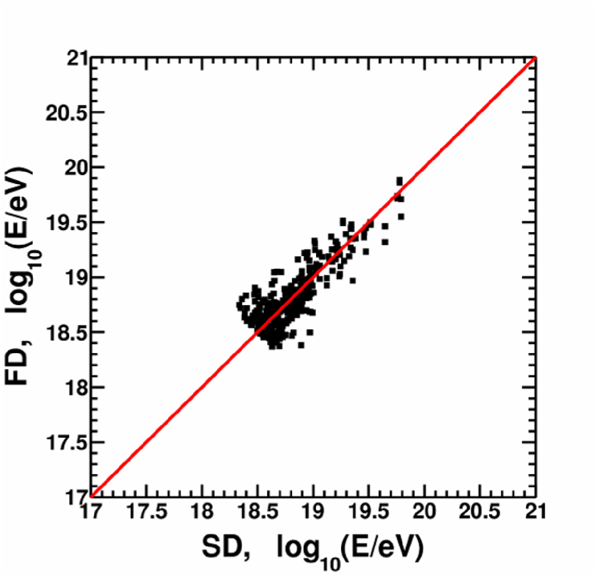
$Y = \log_{10}[S800\ (VEM\ m^{-2})]$

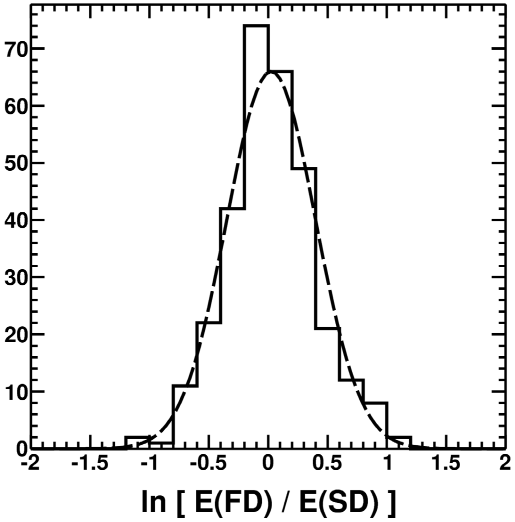
Z = Color = $\log_{10}(E/eV)$

X = Secant of zenith angle

- A look-up table made from the Monte-Carlo
- Event energy (E^{TBL}) = function of *reconstructed* S800 and sec(θ)
- Energy reconstruction ←→ interpolation between S800 vs sec(θ) contours of constant values of E^{TBL}

Energy Determination, Step 2/2



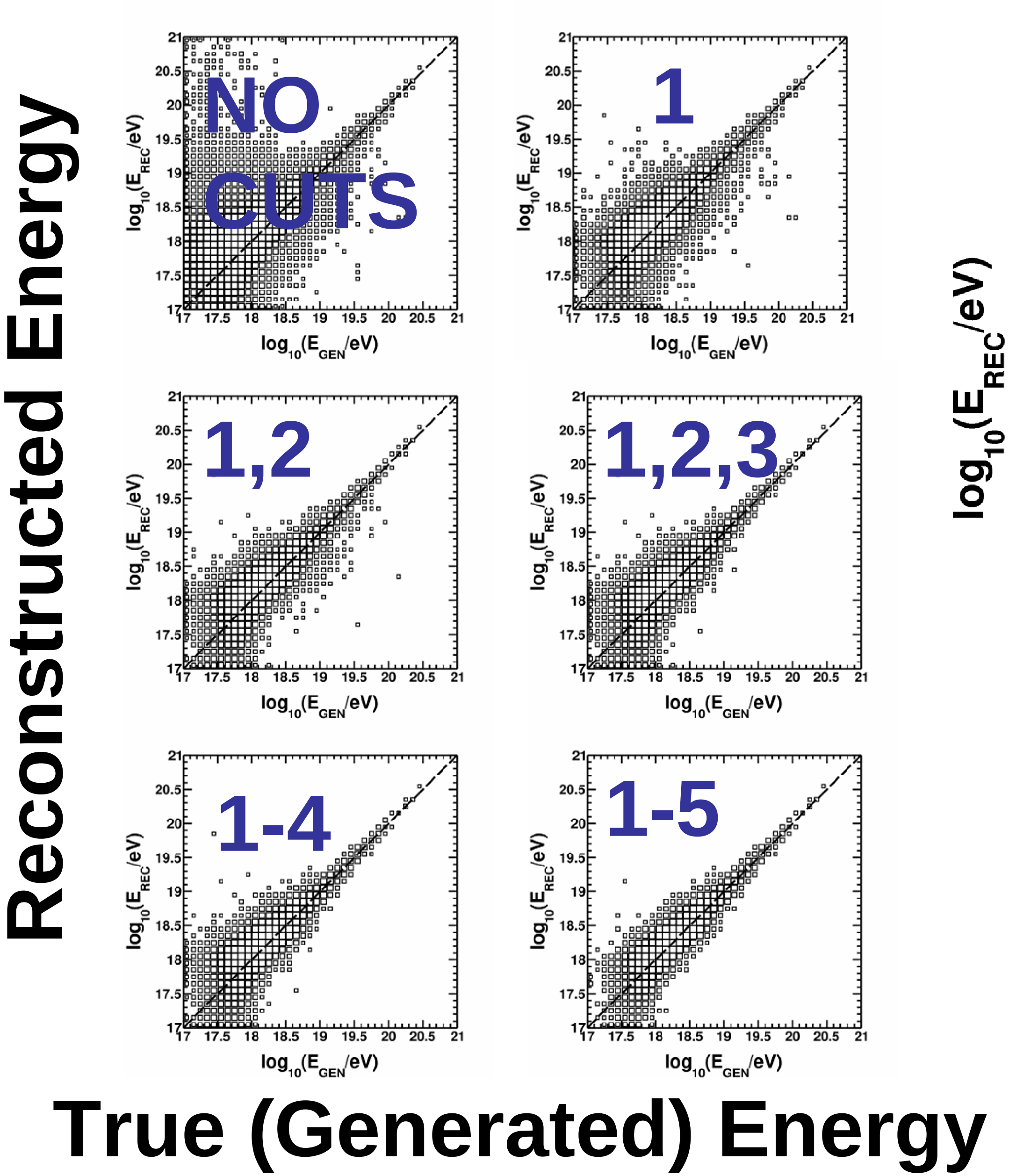


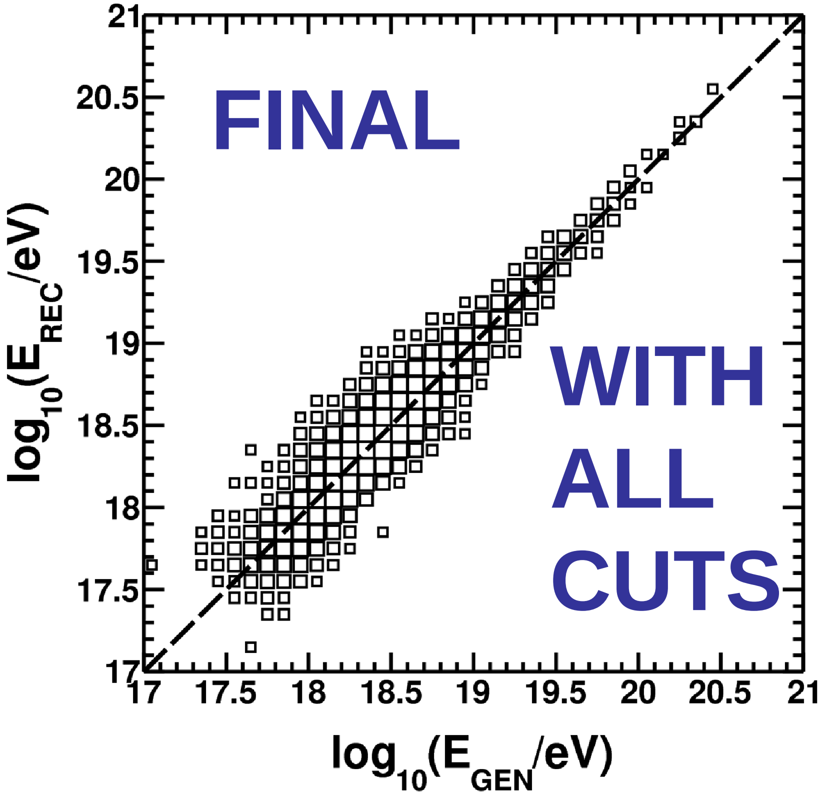
- Energy scale locked to the TA FD to reduce the systematic due to the model
- Used well-reconstructed events seen in common by the TA SD and TA FD:
  - TA SD ∩ [BR U LR U MD]
  - $E^{FINAL} = E^{TBL} / (1.27 \pm 0.02)$
- Energy scale systematic uncertainty is now same as that of the TA FD, which is 21%
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD} ratio

List of Quality Cuts

- Remove events reconstructing with bad resolution, otherwise may “miss” important features in the energy spectrum.
- Quality cuts:
    1. **$N_{SD} \geq 5$** : minimum number of counter / event
    2. **$\theta < 45^{o}$** : maximum zenith angle
    3. **$D_{Border} \geq 1200m$** : minimum core distance from the edge of the array
    4. **χ^2 / d.o.f. < 4** : maximum χ^2 per degree of freedom of time and LDF fits.
    5. **$\sigma_G < 5^{o}$** : maximum pointing direction uncertainty (from the time fit)
    6. **σ_{S800} / S800 < 0.25** : maximum fractional uncertainty of S800 (from the LDF fit)
- Next page shows the effects on the energy resolution of incrementally applying cuts 1 through 6

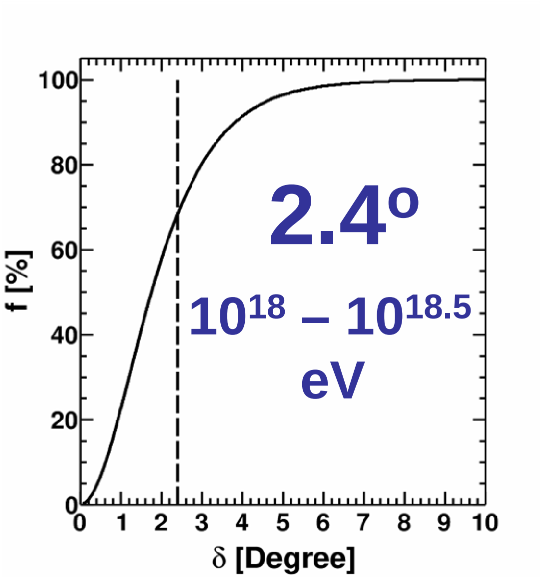
Effect of Quality Cuts

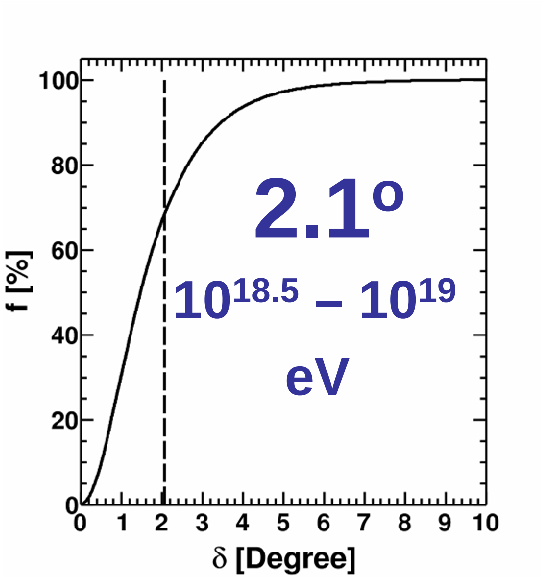


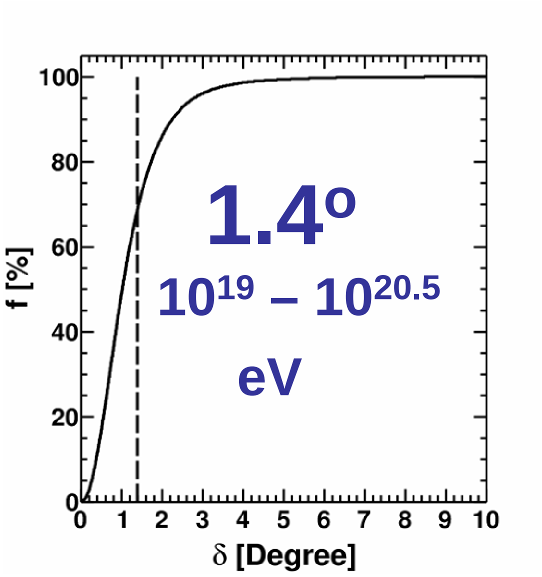


- Used a detailed Monte-Carlo to develop quality cuts

Angular Resolution

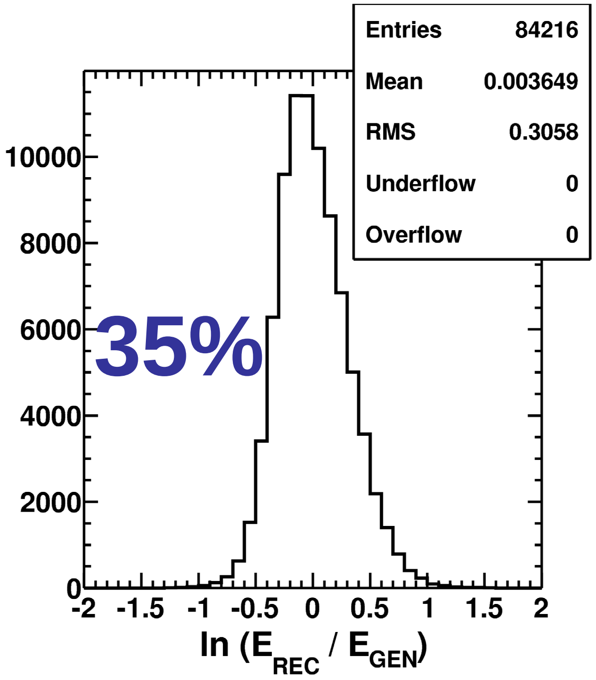




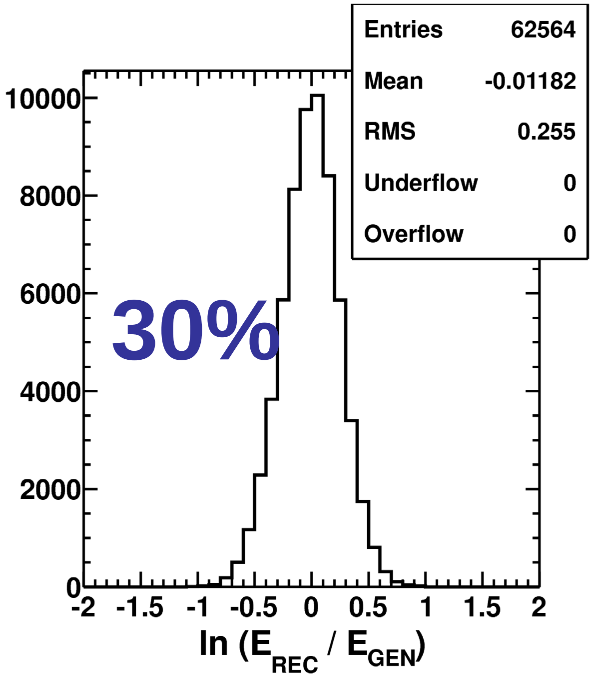


- Determined from the Monte-Carlo
- Cumulative distribution (f = fraction of events) of the opening angle between the true and reconstructed event directions (δ)
- Quoted 68% confidence limits:
  - values of δ that contain 68% of events (f = 68%)

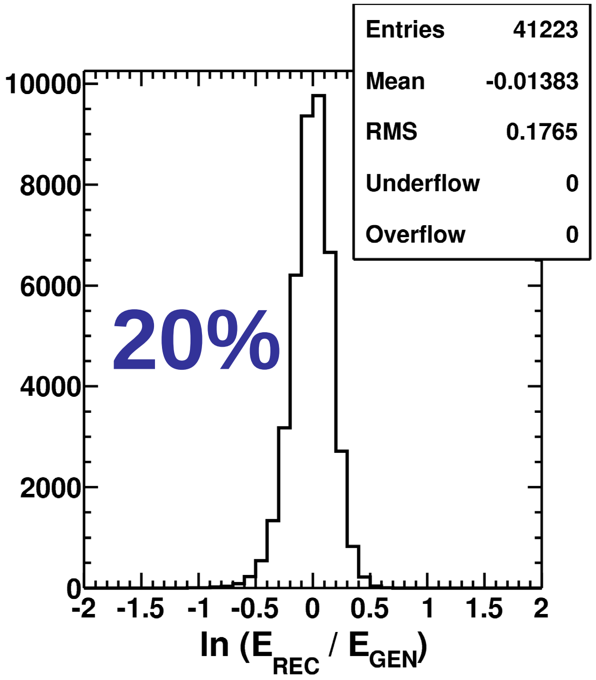
Energy Resolution



$10^{18} – 10^{18.5}$ eV



$10^{18.5} – 10^{19.0}$ eV



$10^{19.0} – 10^{20.5}$ eV

- Determined from the Monte-Carlo
- Histogram (natural logarithm) of reconstructed over generated (true) energies
- Use the root-mean-square (RMS) of the distribution to determine the energy resolution in percent of the true energy

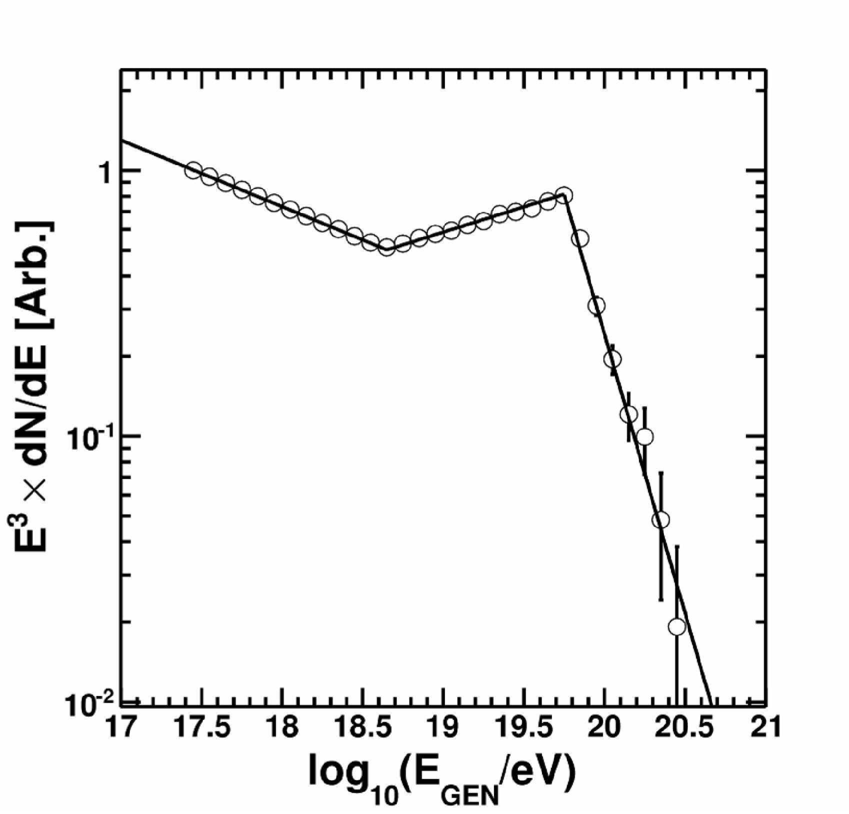
Reconstruction Summary

- Two fits:
  - Time fit → event geometry
  - Lateral distribution fit → S800 (Signal 800m from shower axis)
  - Fitting procedure and formulas adjusted using data only →avoid model dependences
- Energy determination:
  - Reconstructed (S800, sec θ) + Monte-Carlo → initial estimate of energy
  - FD energy scale(1/1.27 rescaling of look-up table values) →reduce model dependence
  - Quality cuts →improve resolution

TA SD Monte-Carlo Approach

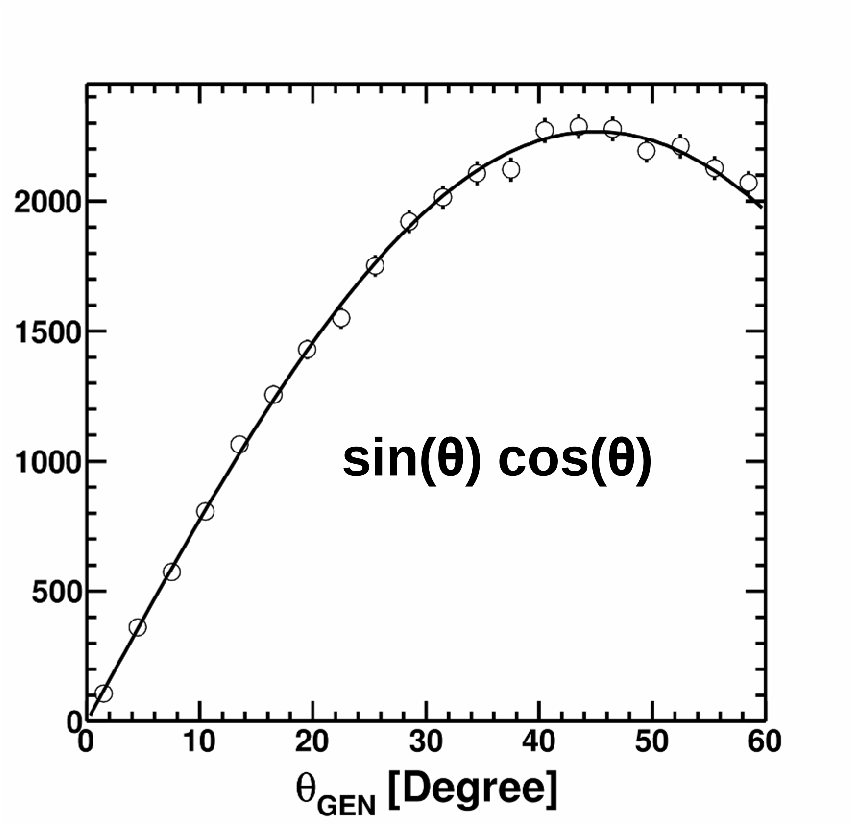
- Simulate UHECR as they exist in nature
  1. Primary particle type
     - Proton, mass composition measurement by HiRes
  2. Energy spectrum
     - previously measured by HiRes
  3. Angular distribution
     - Isotropic in local sky
  4. Shower impact parameter
     - Distributed randomly in a large circular area surrounding the Telescope Array experiment

Generated Energy Distribution

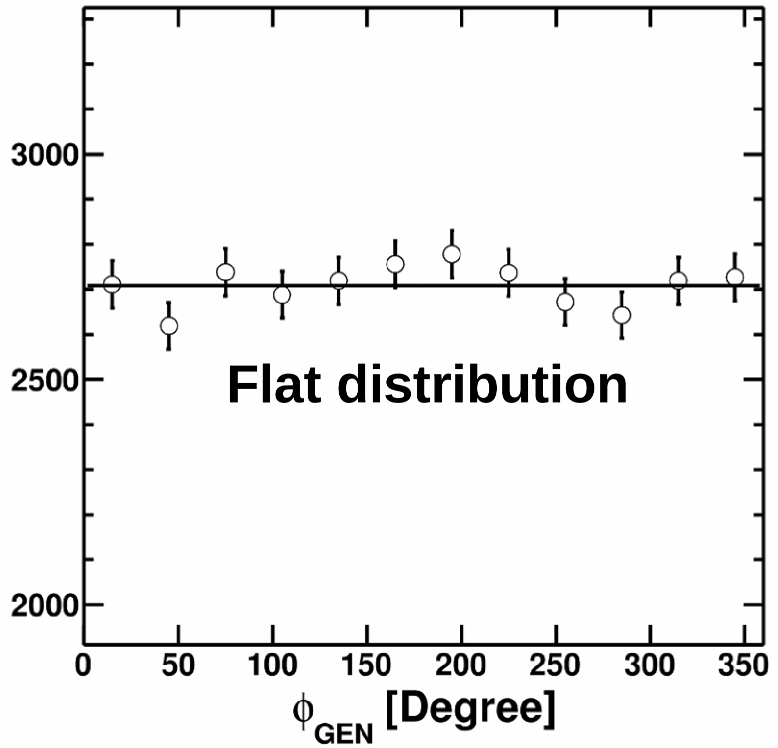


- Generated MC energy histogram displayed using format:
  - 0.1 $\log_{10}(E/eV)$ bins
  - Each bin content
  - divided by the (linear) bin size in energy
  - Multiplied by E^3 (energy of the bin center)
  - Normalized so that the first bin is unity
- Solid line = HiRes spectrum, parameterized by a broken power law function

Generated Angular Distribution

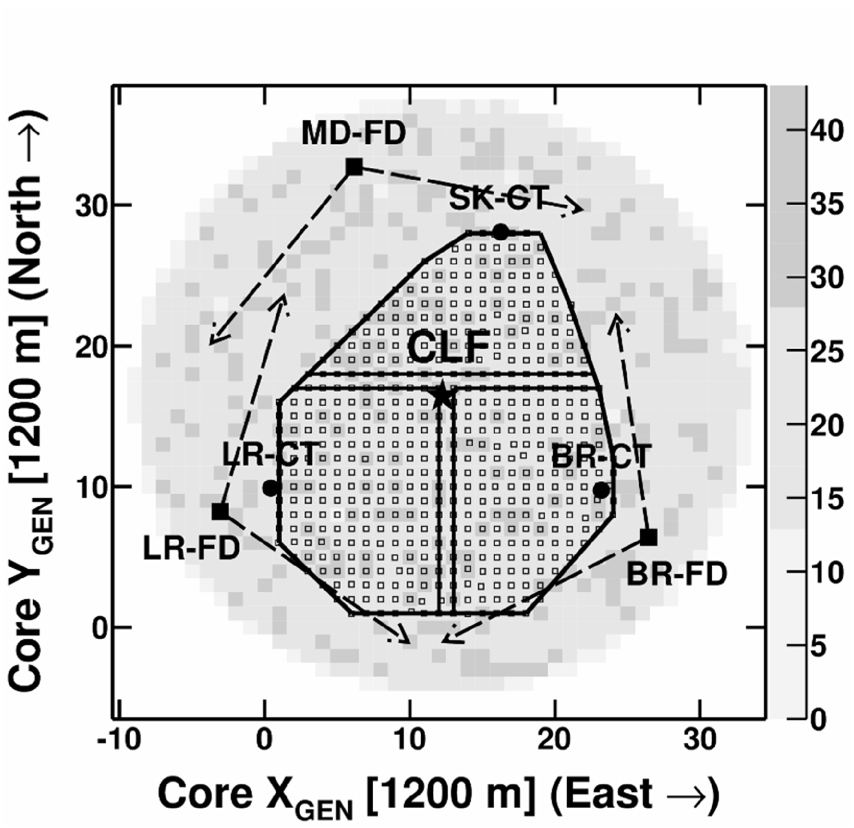


Zenith Angle



Azimuthal Angle

Generated Impact Position



- Random point inside a circle
  - radius = 25 km
  - centered at the **C**entral **L**aser **F**acility (**CLF**)
  - Encircles entire experiment

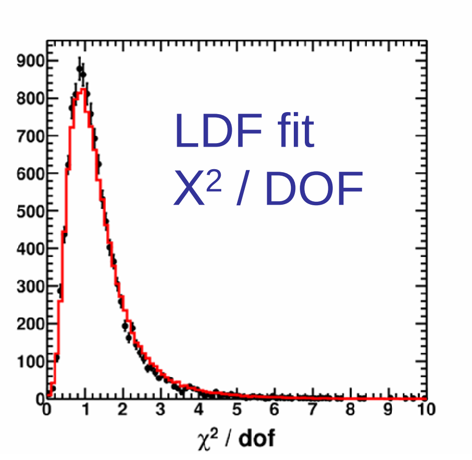
TA SD Monte-Carlo Procedures

- Simulate Extensive Air Showers
  - Use CORSIKA:
    - QGSJET-II high energy hadronic model
    - EGS4 electromagnetic model
    - FLUKA low energy hadronic model
  - Include atmospheric muon flux
  - Simulate detector response to secondary particles by GEANT4
    - Including γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, p, n
  - Use real-time detector calibration and life-time
  - Simulate the trigger and electronics
  - Write events in the same format as data, reconstruct with the same programs, apply same quality cuts
- Validate the Monte-Carlo by comparing the distributions of reconstructed variables with data

DATA / MC Comparisons

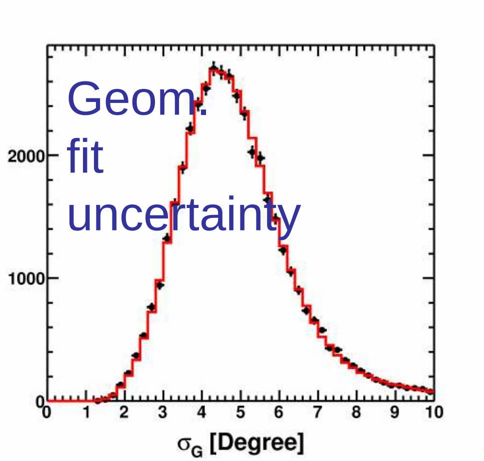
Points with error bars = DATA histograms

Solid line = MC histograms normalized to the data histograms by area

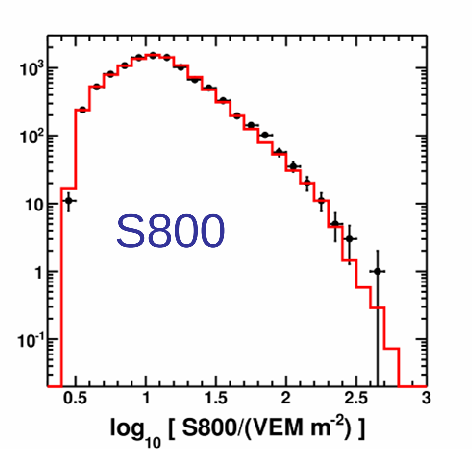


LDF fit

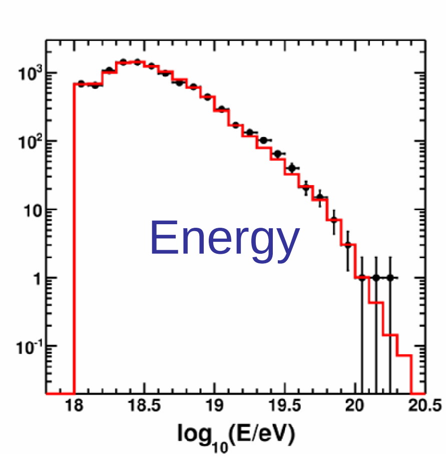
X^2 / DOF



Geom. fit uncertainty



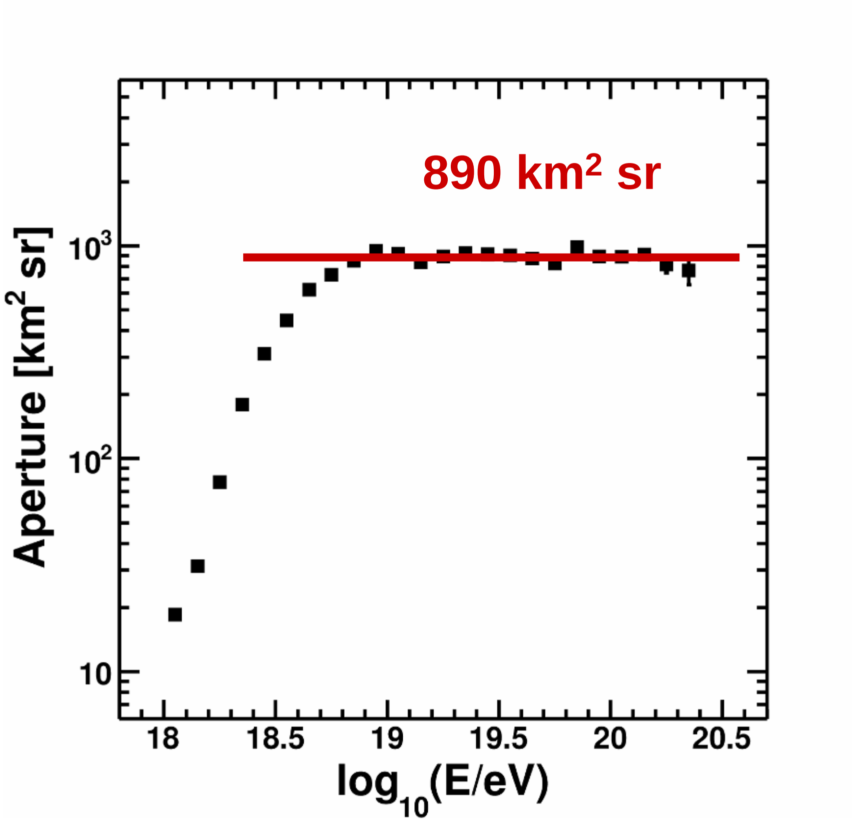
S800



Energy

1 to 2 % agreement between the DATA and MC in most variables

Next Step: Aperture



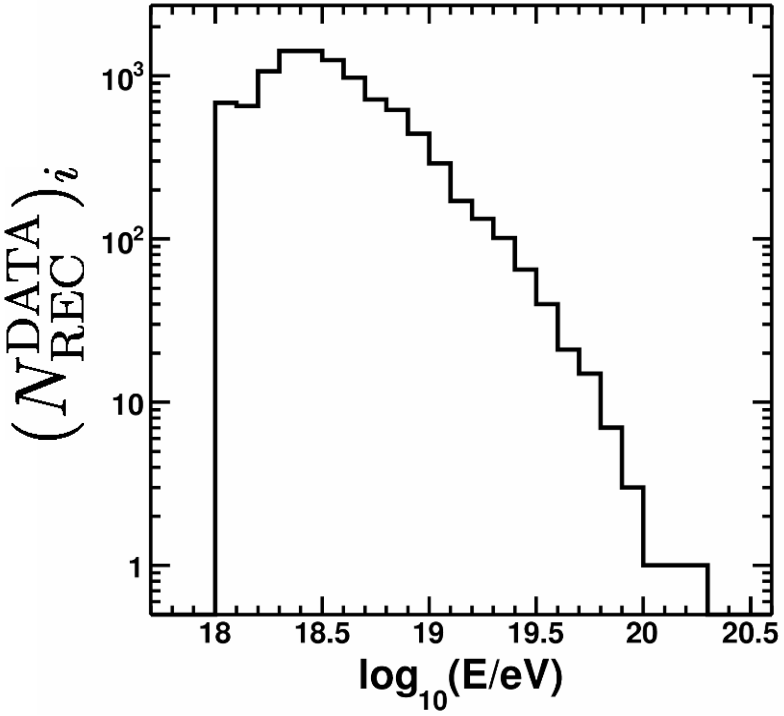
(Efficiency plateaus at E ~10^{19} eV)

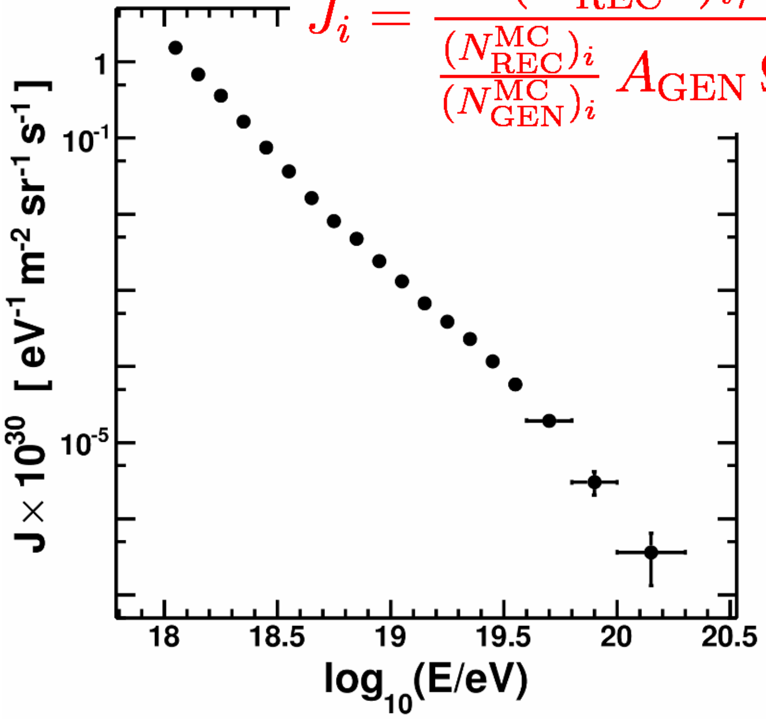
- Calculated from the MC
- Including:
  - Effects of quality cuts
  - Effects of energy resolution

$$\alpha_i = A_{\mathrm{GEN}}\,\Omega_{\mathrm{GEN}}\,(N^{\mathrm{MC}}_{\mathrm{REC}})_i/(N^{\mathrm{MC}}_{\mathrm{GEN}})_i$$

$A_{\mathrm{GEN}}\,\Omega_{\mathrm{GEN}}$	MC generation aperture, 4626 km^2 sr
$(N^{\mathrm{MC}}_{\mathrm{REC}})_i$	Number of MC events reconstructing in the i$^{\mathrm{th}}$ energy bin
$(N^{\mathrm{MC}}_{\mathrm{GEN}})_i$	Number of MC events generated in the i$^{\mathrm{th}}$ energy bin

Measured UHECR Flux

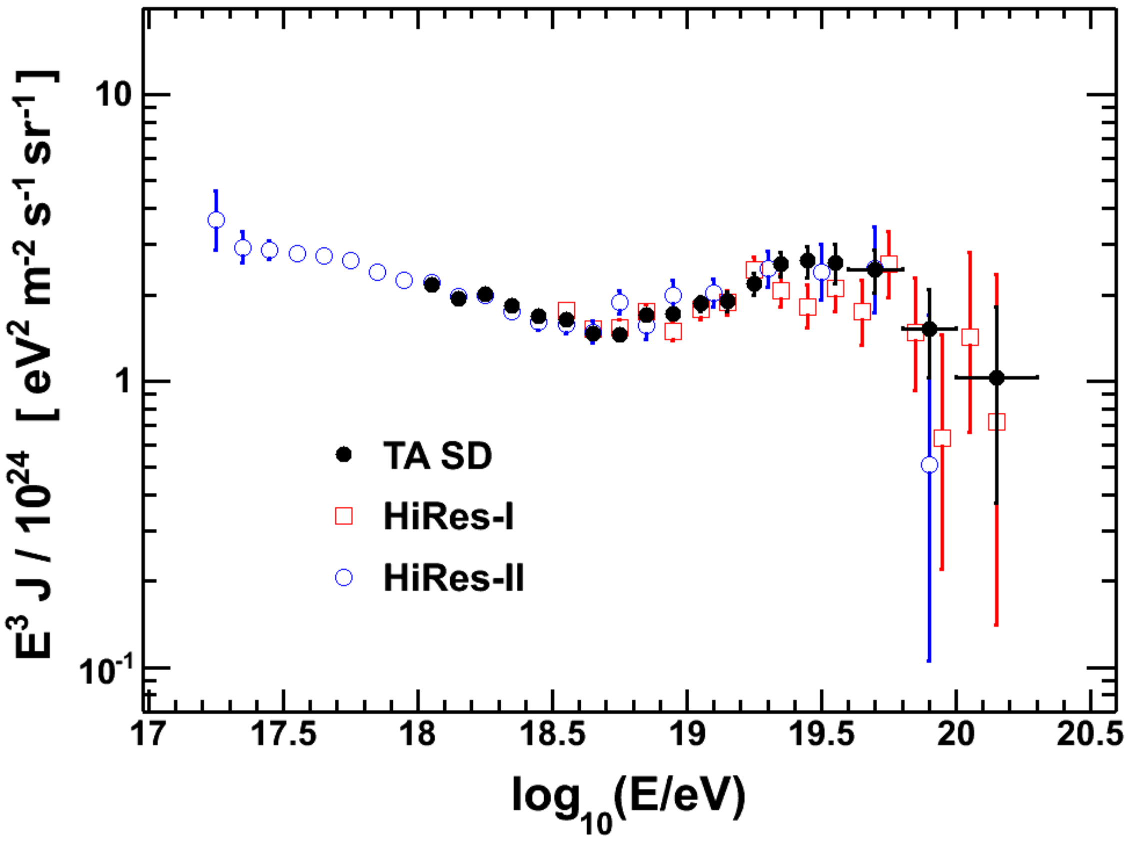




$$J_i = \frac{(N^{\rm DATA}_{\rm REC})_i/\Delta E_i}{\frac{(N^{\rm MC}_{\rm REC})_i}{(N^{\rm MC}_{\rm GEN})_i}\, A_{\rm GEN}\, \Omega_{\rm GEN}\, T}$$

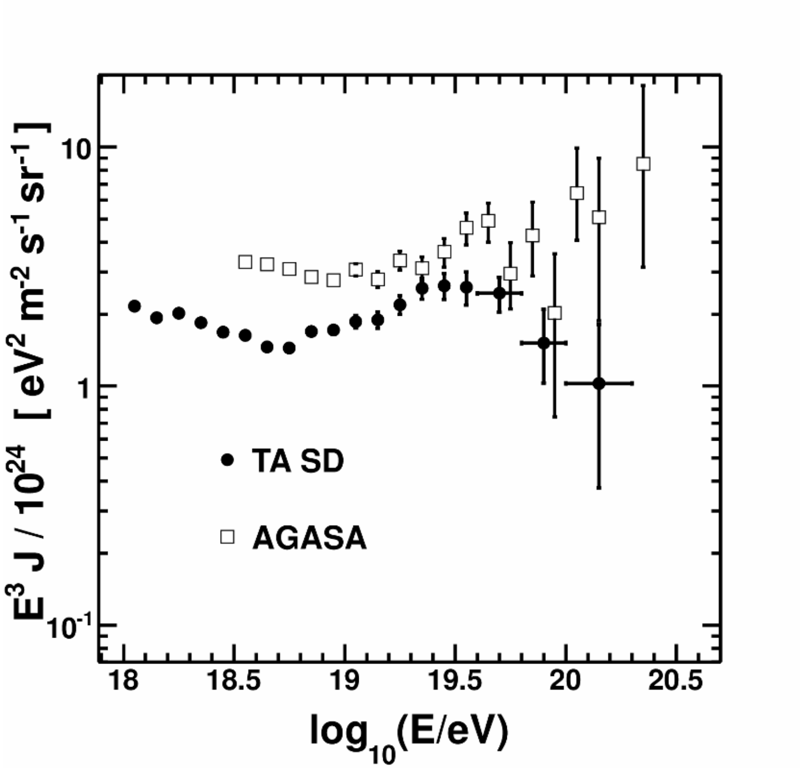
- 2008/05/11 – 2011/04/25 (T ~ 3 yr)
- Systematic uncertainties
  - 21% on energy scale (controlled by the FD) → ~35% on J
  - 2% due to the acceptance (14% below $10^{18.2}$ eV)
  - 2 % due to the resolution unfolding

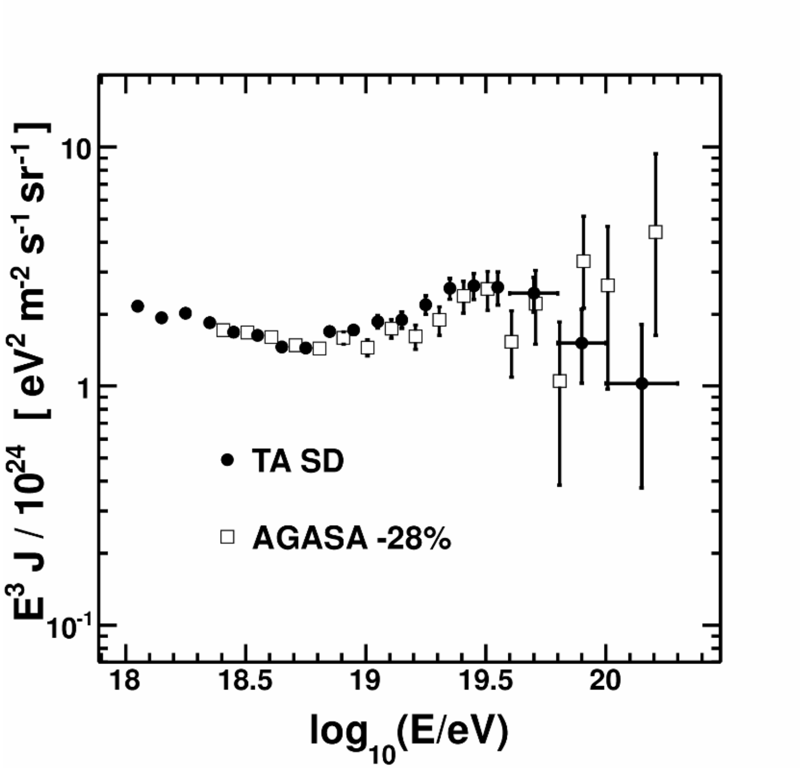
Comparison with HiRes



- Different detection techniques, excellent agreement
- Both experiments clearly see the ankle feature near $10^{18.7}$ eV
- TA SD confirms the existence of the break at $10^{19.7}$ eV

Comparison with AGASA





- Clear disagreement
- (RIGHT) Accounting for AGASA – TA energy scale difference
  - Doesn’t explain discrepancy above $10^{19.7}$ eV

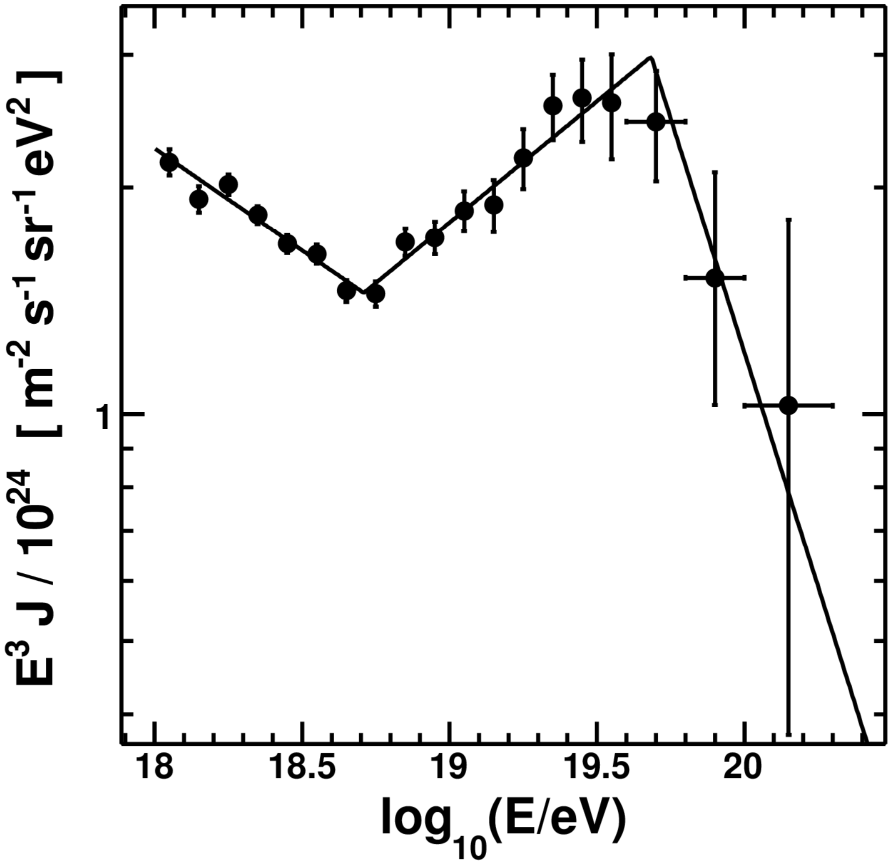
TA SD Flux Fit

- Differential flux is described by the **B**roken **P**ower **L**aw formula (**BPL**):

$$J(E) = K \times \begin{cases} E^{k}, E < E_{ANK} \\ E_{ANK}^{k-l} E^{l}, E_{ANK} \leq E < E_{GZK} \\ E_{ANK}^{k-l} E_{GZK}^{l-m} E^{m}, E \geq E_{GZK} \end{cases}$$

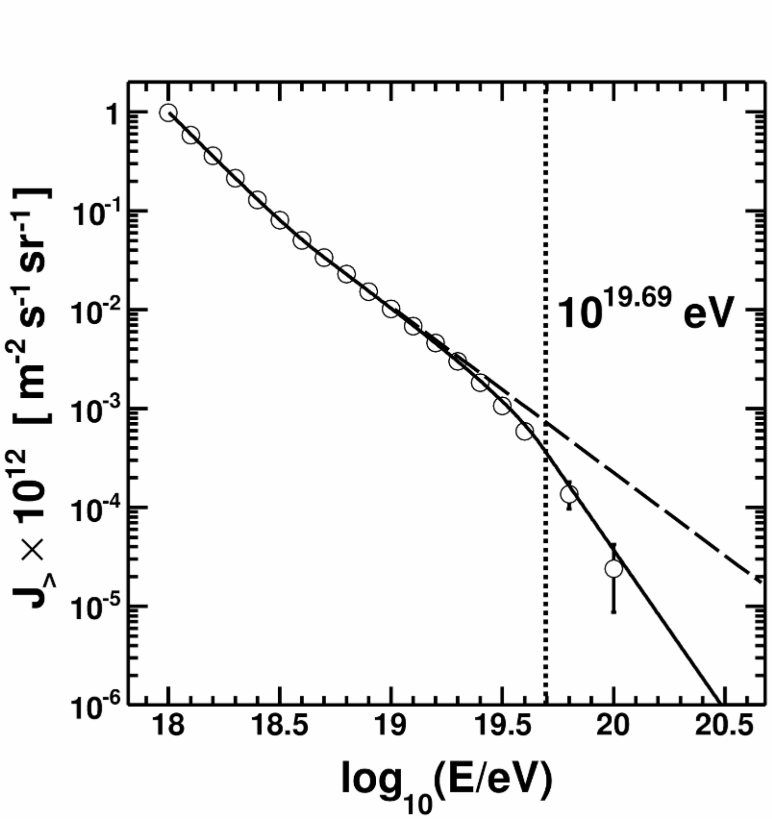
- 6 Fit parameters:
  - K = normalization factor
  - k, l, m (negative) spectral indices
  - E_{ANK} – 1st break point
  - E_{GZK} – 2nd break point

TA SD Flux Fit (Contd.)



Parameter	Value
K	$2.25 \pm 0.06 \times 10^{-30}$ eV^{-1}m^{-2}s^{-1}sr^{-1}
E_{ANK}	$10^{18.70\pm0.03}$ eV
E_{GZK}	$10^{19.68\pm0.09}$ eV
k	-3.27 ± 0.03
l	-2.68 ± 0.04
m	-4.2 ± 0.7

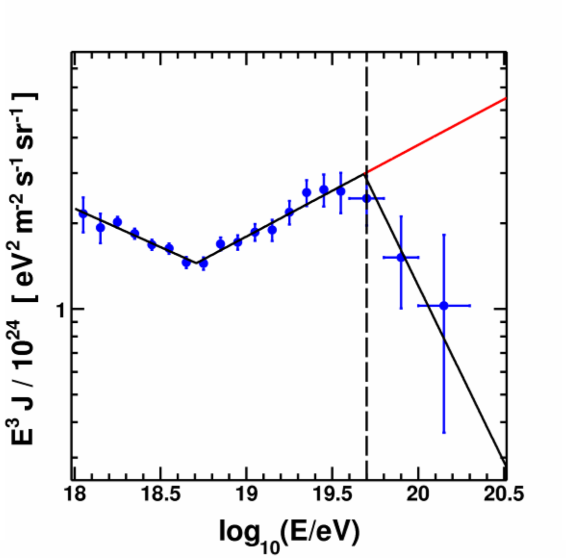
Measured GZK cutoff

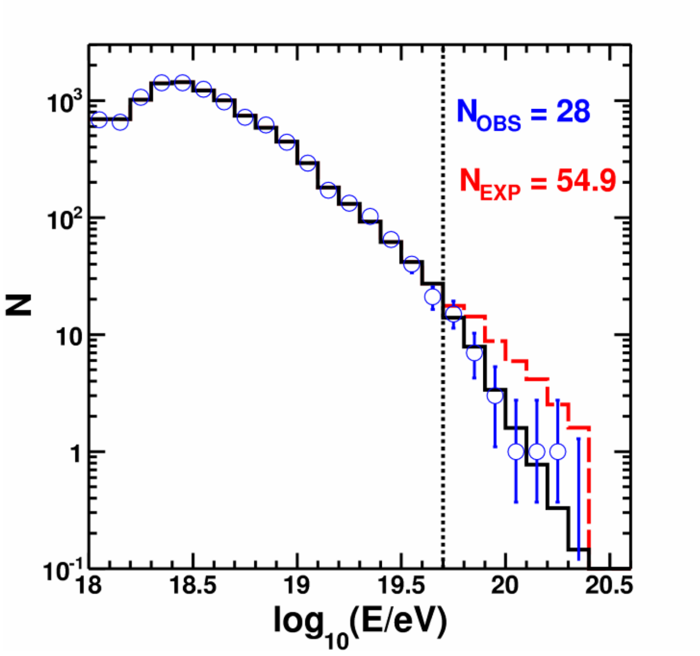


$$J_> = \int_E^\infty \mathrm{d}E'\, J(E')$$

- Quantify position of the break by $E_{1/2}$ (Berezinsky et. al)
  - Integral flux becomes ½ of the flux obtained by linear extrapolation beyond the GZK break
- TA SD measures
  - $\log_{10}(E_{1/2})$ = **19.69 ± 0.10**
- Berezinsky calculates for proton primaries propagating in cosmic microwave background
  - $\log_{10}(E_{1/2}^{\mathrm{THEORY}})$ = **19.72**
- TA SD measurement fits the extra-galactic proton model

Significance of the GZK cutoff



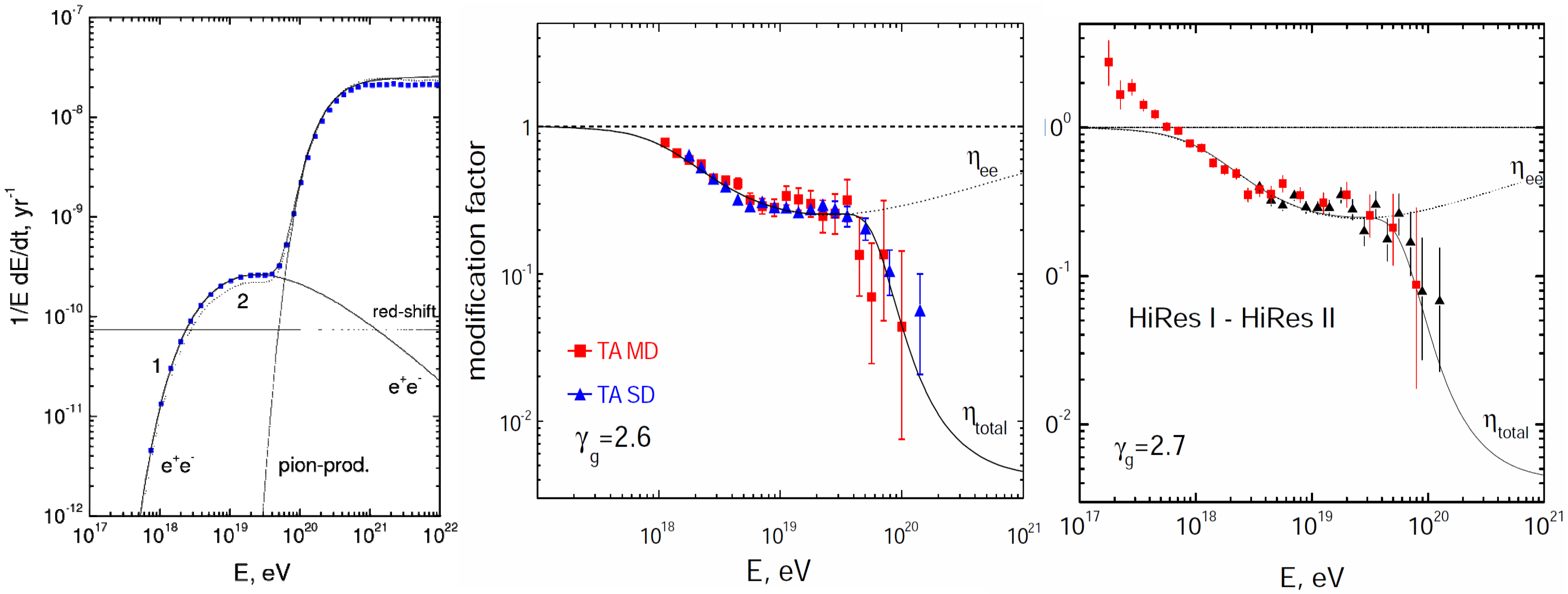


- Assume no GZK cutoff and extend the broken power law fit beyond the break
- Apply this extended flux formula to the actual TA SD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10}E$ bins after $10^{19.7}$eV bin:
  - N_{EXPECT} = 54.9
  - $N_{OBSERVE}$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

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

(3.9σ)

Recent - UHECR 2012



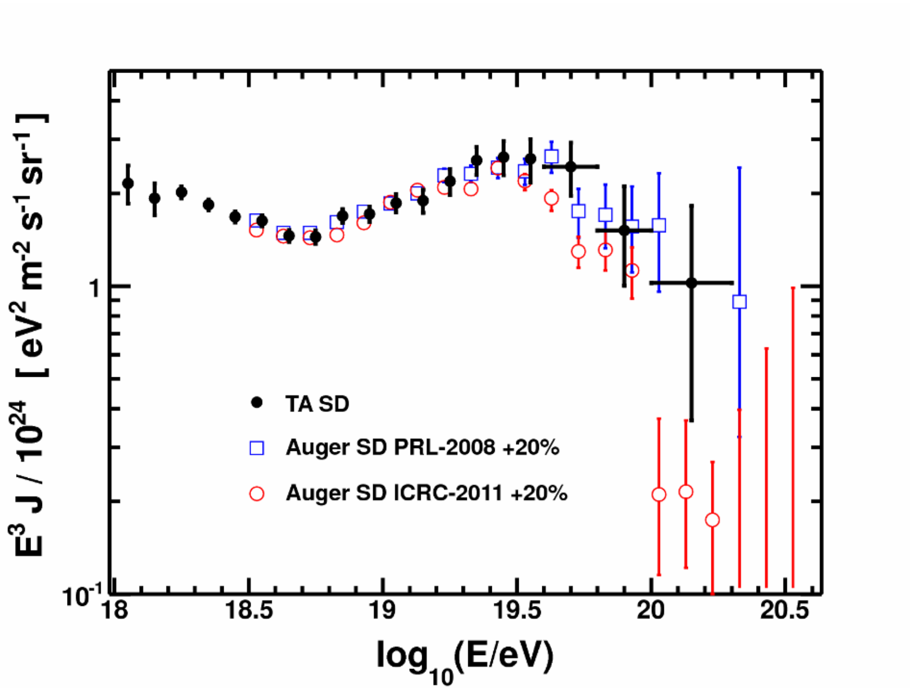
- Fits to extragalactic proton model made by V. Berezinsky
  - UHECR-2012 Conference, Feb. 2012, CERN
- Both TA and HiRes consistent with model of extragalactic proton propagation in Cosmic Microwave Background

Conclusions

- Telescope Array combined measurement techniques used by the AGASA and HiRes experiments
  - Fit formulas derived starting with AGASA functions, tuned to fit the TA SD data
  - DATA / MC analysis used, just like in HiRes experiment (excellent control of systematic uncertainties)
  - Energy scale locked to the FD to avoid large systematic uncertainties due to the hadronic models
- Existence of the GZK cutoff is verified, for the first time, by an array of scintillation counters
- Measurement suggests extra-galactic proton interpretation (Berezinsky *et. al.*)

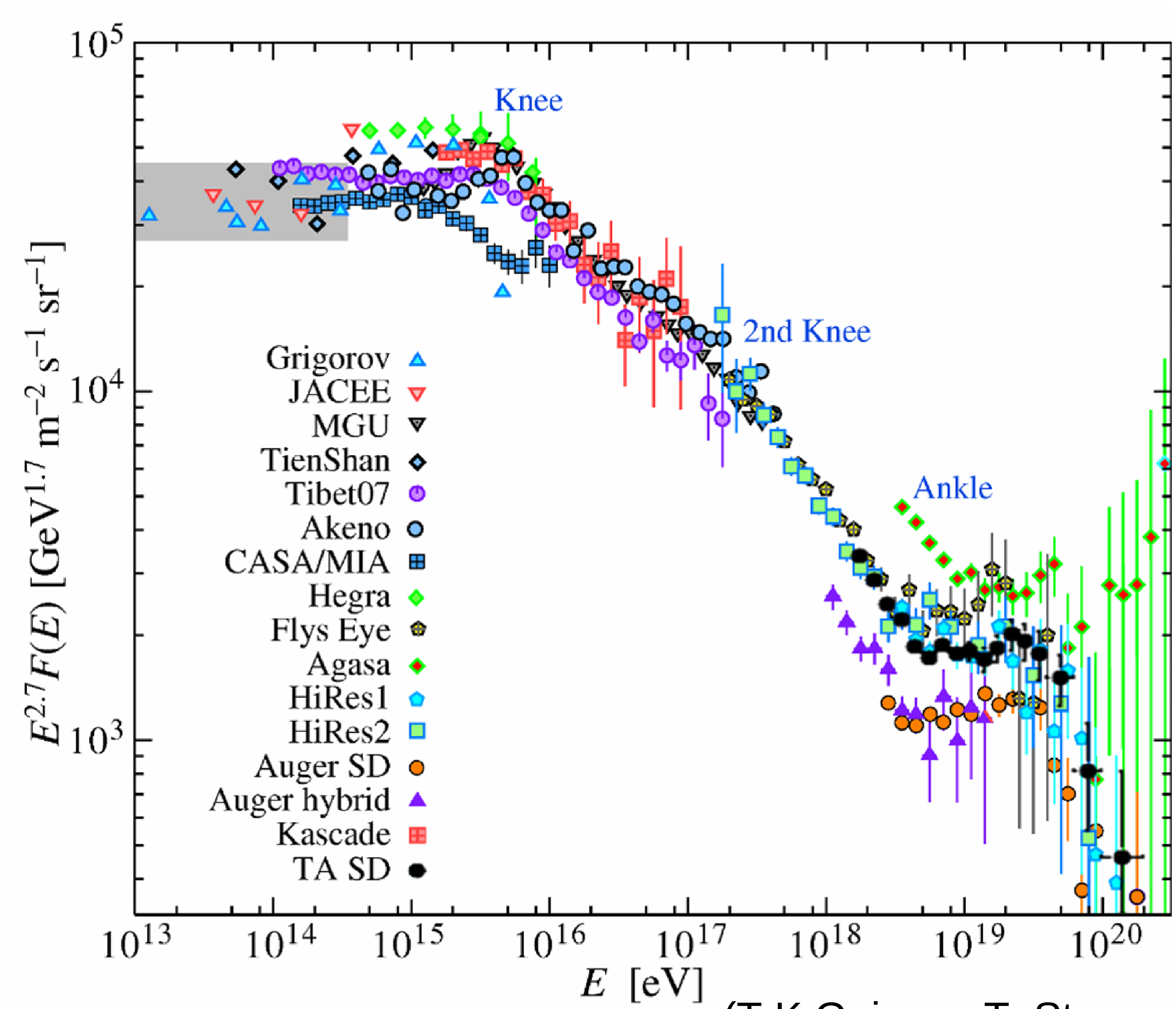
Fin

Comparison with Pierre Auger Observatory

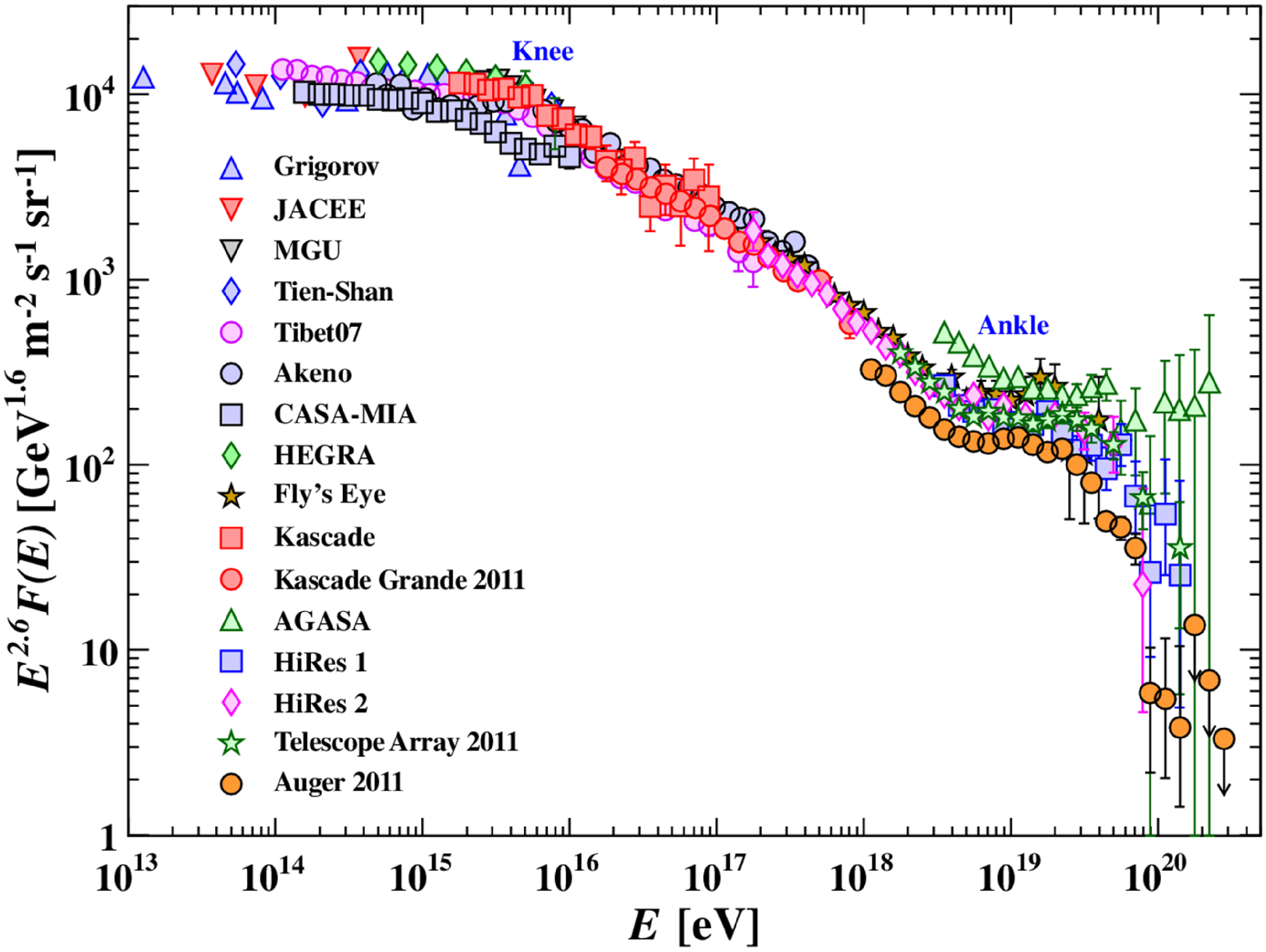


- ~20% energy scale difference
  - Comes from the FD
- Same power laws (within fitting errors)
- Position of the second break (E_{GZK}) different
- Most recent Auger result (ICRC-2011)
  - Auger ~27% lower
  - After taking energy scale into account

Compare with other CR experiments



(T.K Gaisser, T. Stanev, 2009)


Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande 2011
AGASA
HiRes 1
HiRes 2
Telescope Array 2011
Auger 2011
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
E [eV]