Measurement of the UHECR Flux by the TA FADC Fluorescence Detectors

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Ph. D. Defense

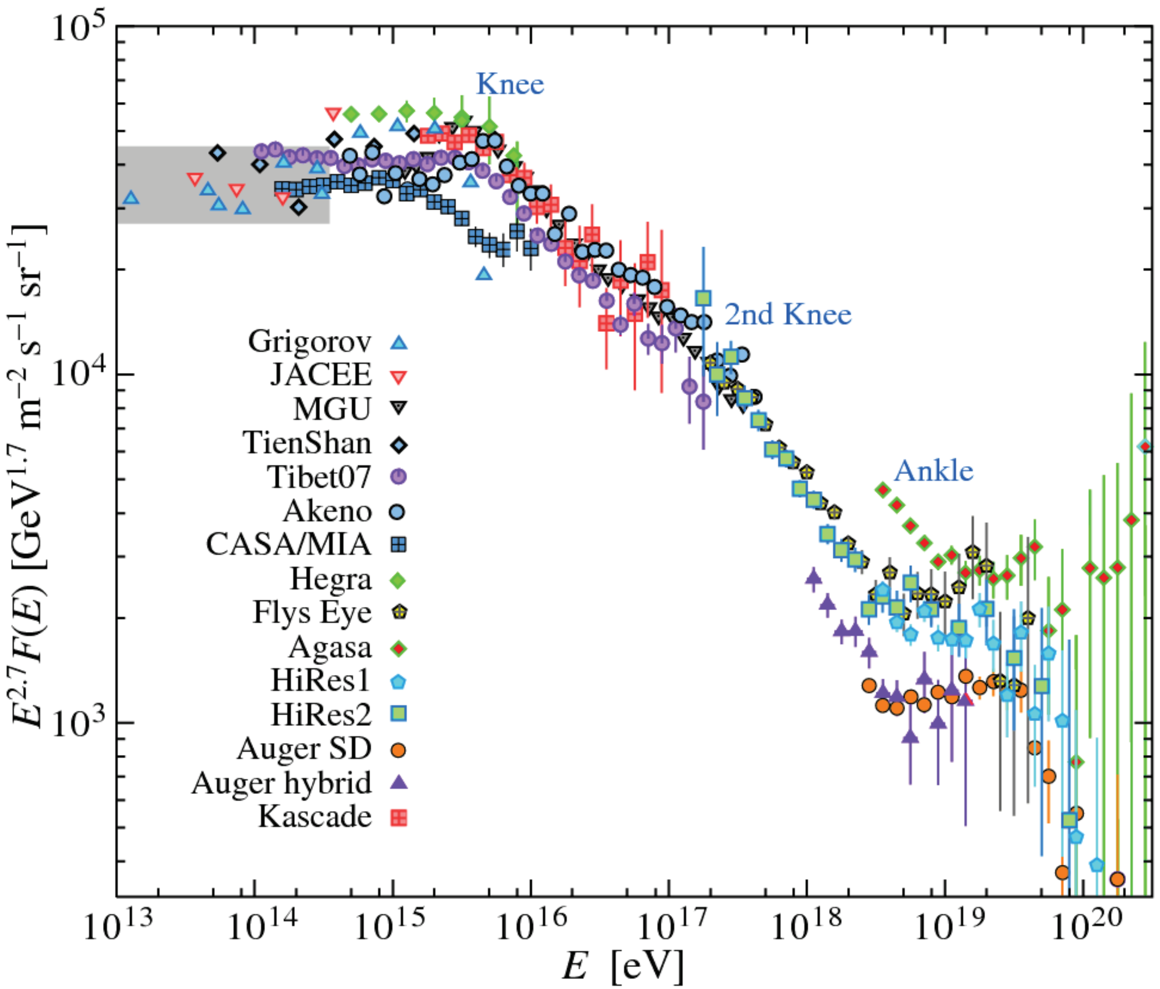
Contents

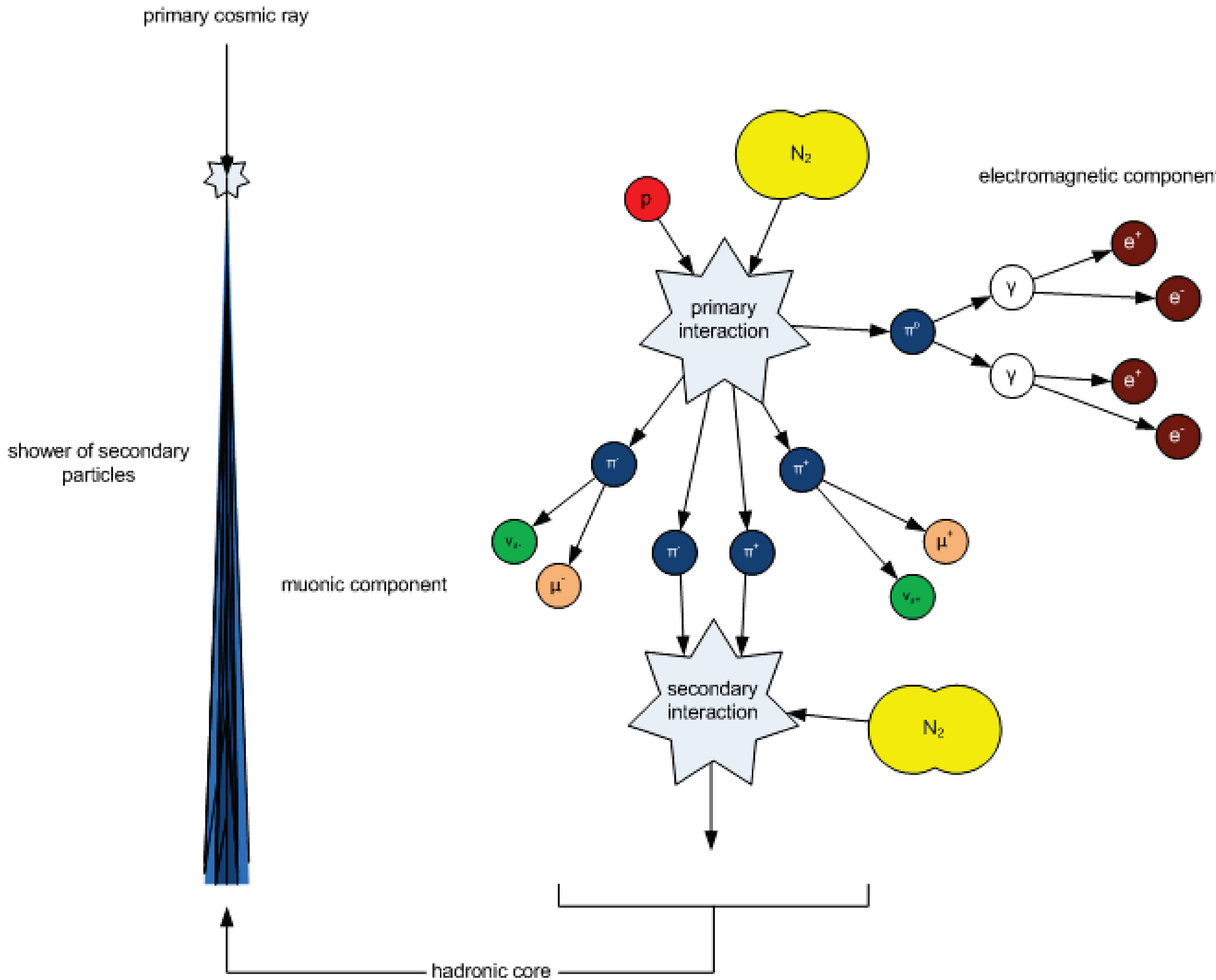
- Background
- The Telescope Array Project
- Monocular Measurement of the UHECR Flux
- Systematic Errors

Brief History of Cosmic Ray Physics

- 1912: Hess discovered ionizing radiation increased rapidly with altitude.
- 1934: Milikan dubs the term “Cosmic Rays”.
- 1934: Rossi & Auger measure coincidences in cosmic ray measurements, discover extensive air showers.
- 1934: Bethe & Heitler develop EM cascade theory.
- 1985: Fly’s Eye, the first successful air fluorescence detector.
- 1992: Beginning of AGASA
- 1999: High-Resolution Fly’s Eye complete
- 2004: First light at Pierre Auger Observatory
- 2007: All FD’s at Telescope Array on-line

Cosmic Ray Energy Spectrum

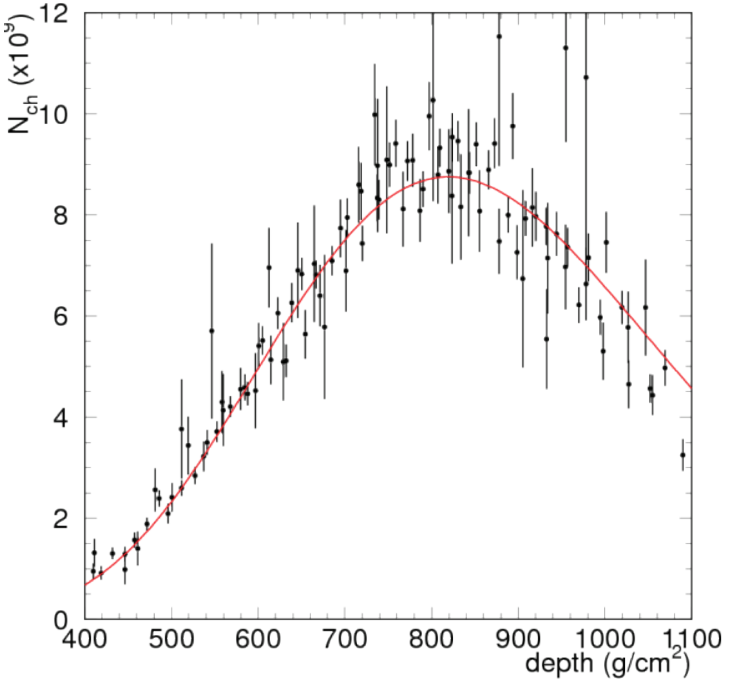


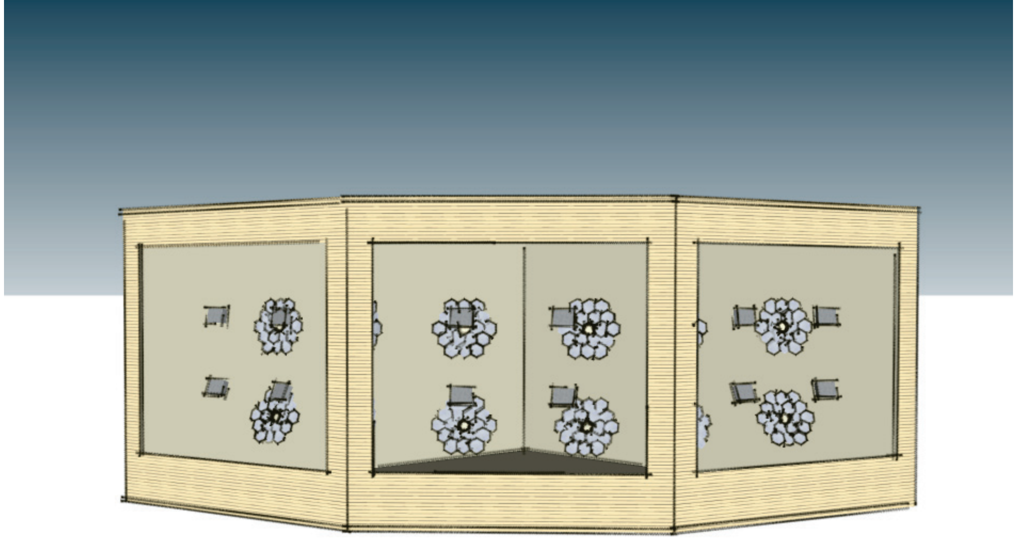

primary cosmic ray
shower of secondary particles
muonic component
electromagnetic component
p
N2
primary interaction
π0
γ
γ
e+
e-
e+
e-
π-
π-
π+
π+
μ-
μ+
secondary interaction
N2
hadronic core

Shower Profile

Gaisser & Hillas suggested that the number of particles in an extensive air shower as a function of atmosphere crossed should take the form:

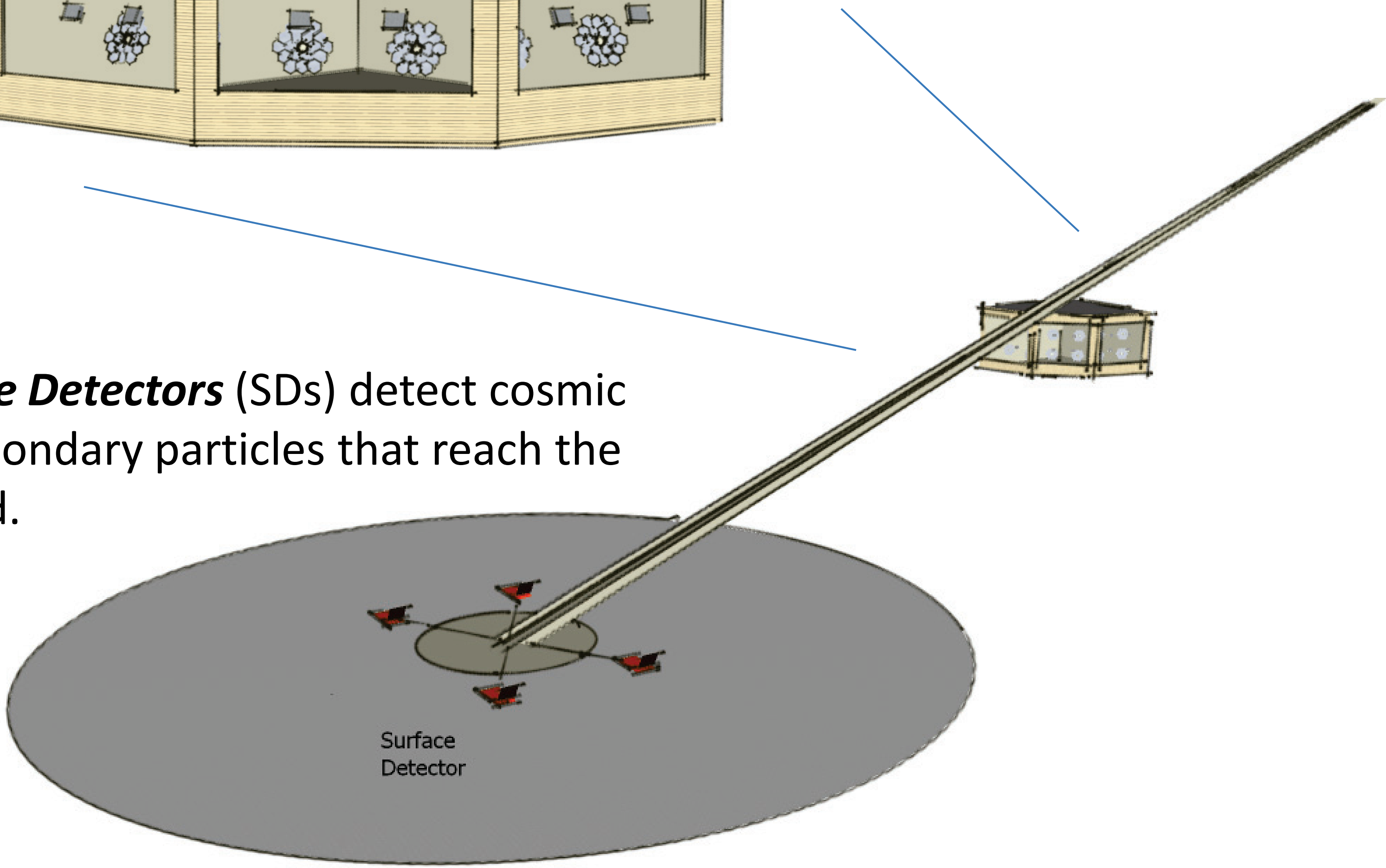
$$N(X) = N_{\max}\left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\Lambda}} \times e^{-\frac{X - X_{\max}}{\Lambda}}$$

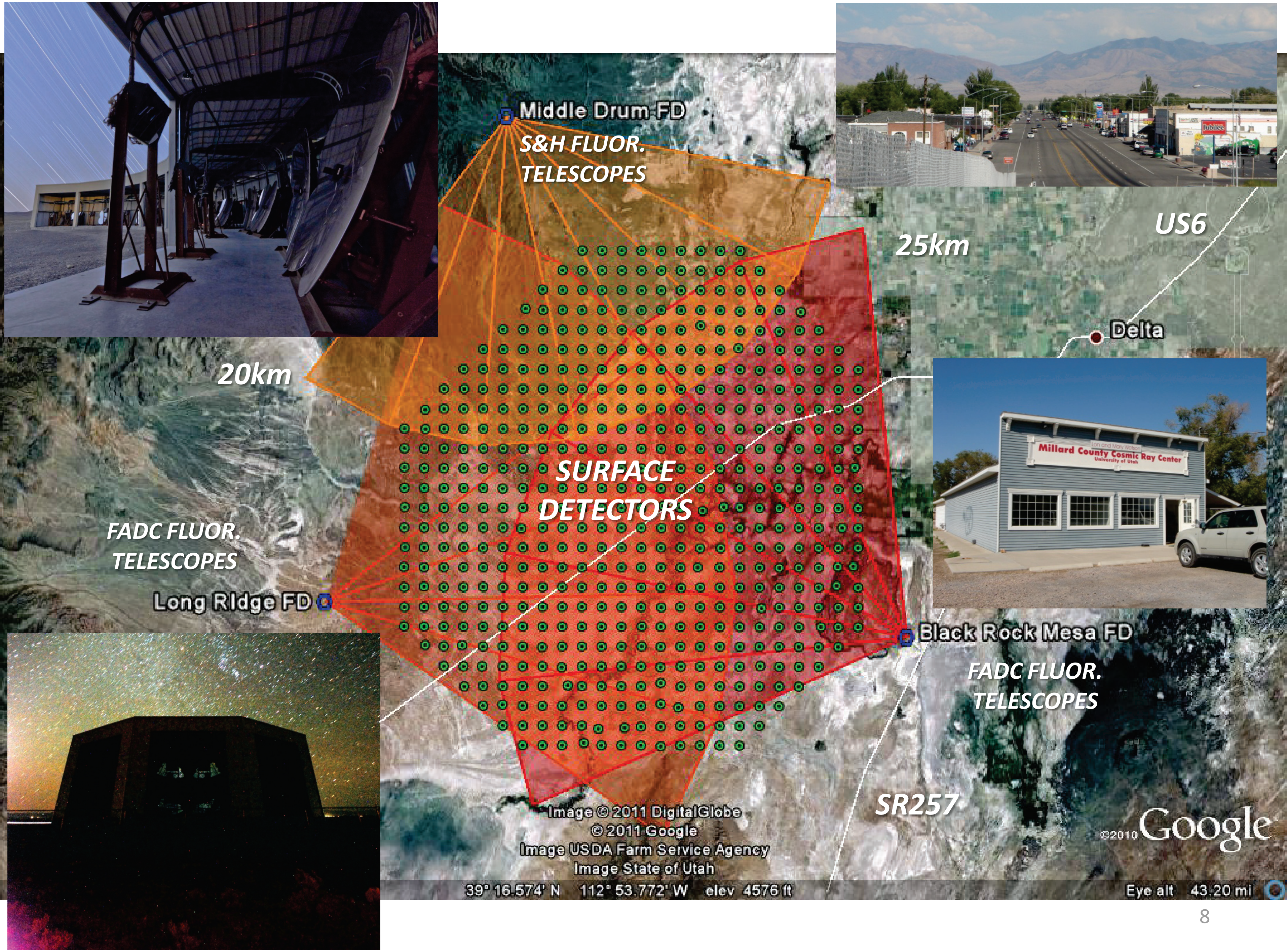




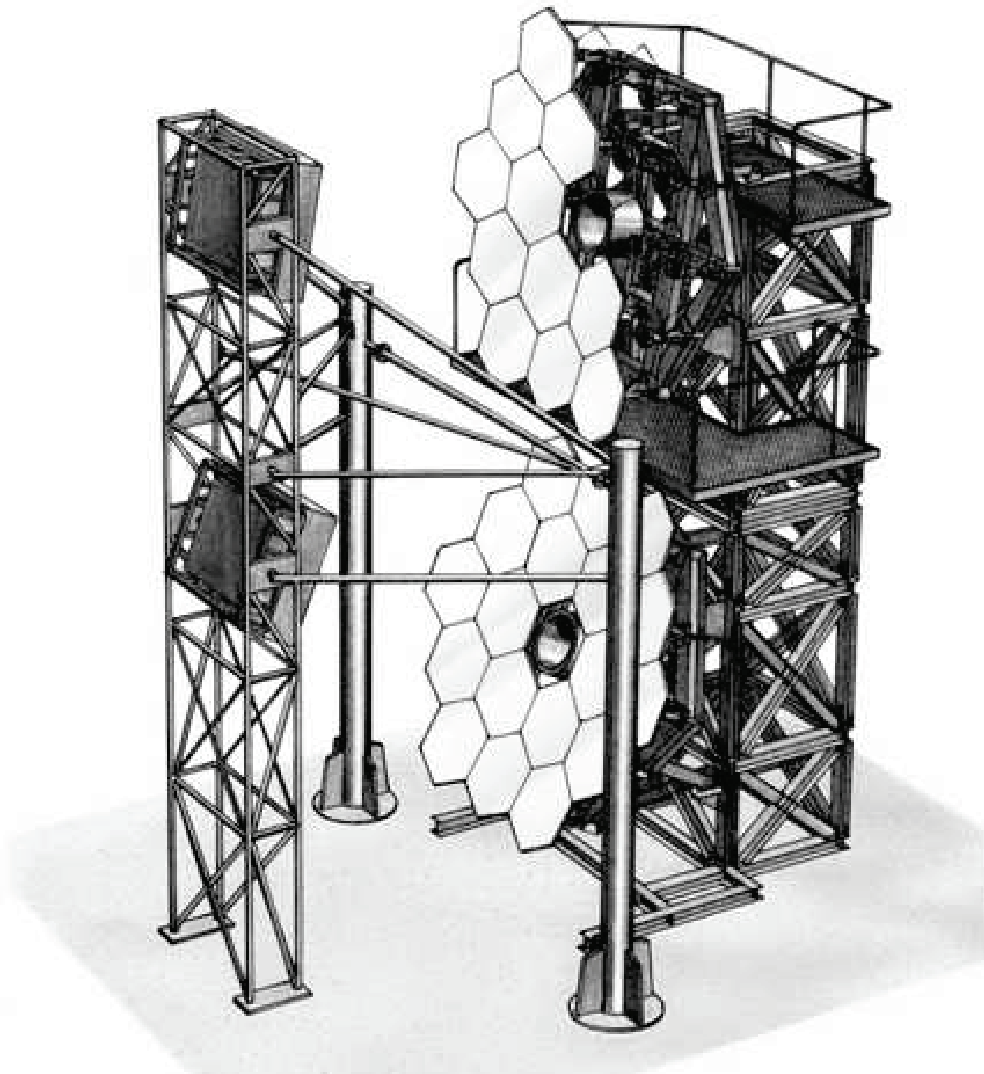
Fluorescence Detectors (FDs) detect the fluorescence light emitted as high-energy secondary particles ionize the atmosphere.

Surface Detectors (SDs) detect cosmic ray secondary particles that reach the ground.




Middle Drum FD
S&H FLUOR.
TELESCOPES
25km
US6
Delta
20km
SURFACE
DETECTORS
FADC FLUOR.
TELESCOPES
Long Ridge FD
Black Rock Mesa FD
FADC FLUOR.
TELESCOPES
Millard County Cosmic Ray Center
University of Utah
SR257
Image © 2011 DigitalGlobe
© 2011 Google
Image USDA Farm Service Agency
Image State of Utah
39° 16.574' N 112° 53.772' W elev 4576 ft
Eye alt 43.20 mi
©2010 Google

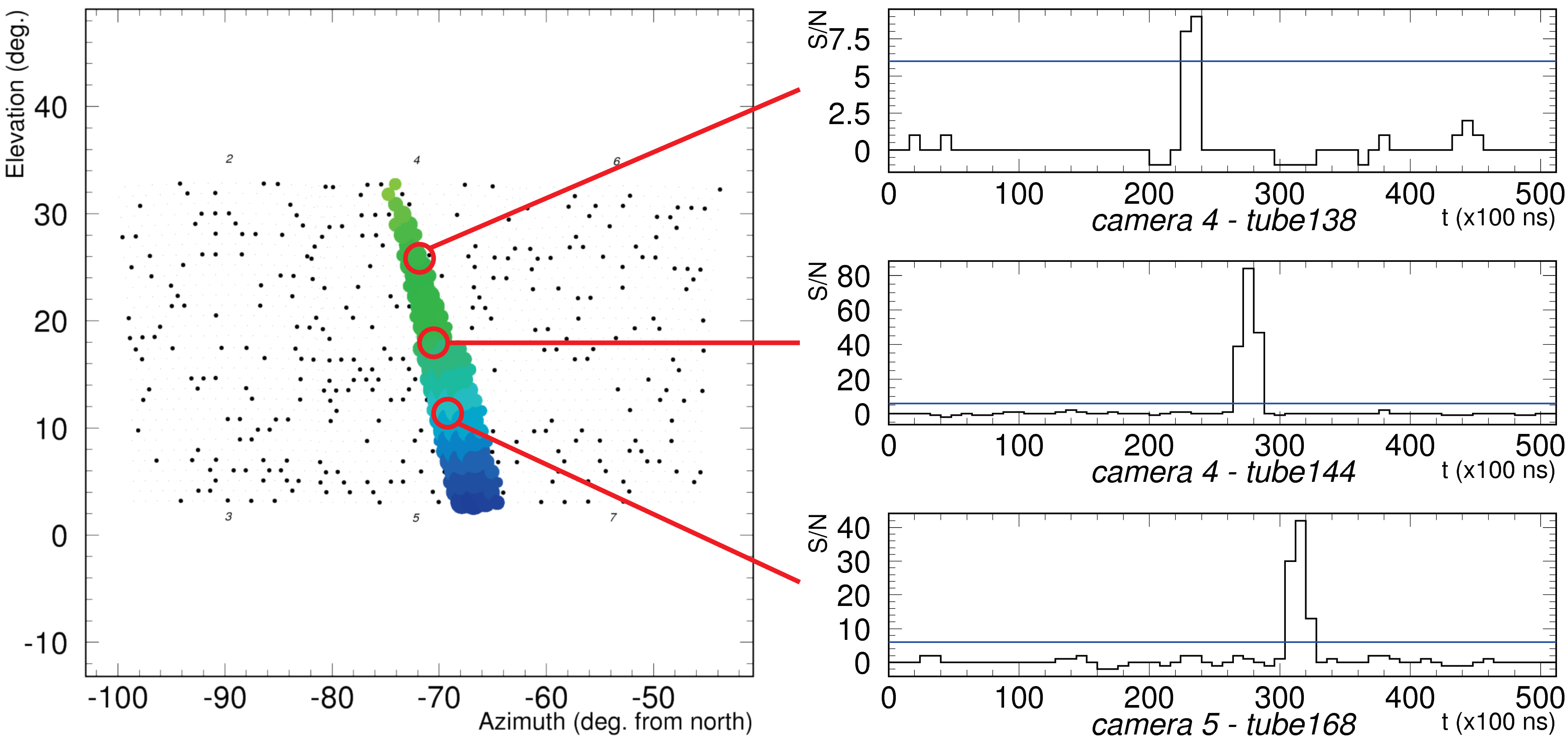
Fluorescence Detector



The FADC FDs consist of 18-segment spherical mirrors projecting onto 16x16 arrays of photomultiplier tubes.

Each FD ***station*** contains 12 telescopes arranged with six viewing from 3-18° elevation and the rest viewing from 18° to 33°.

Signal-Finding



The Signal Digitizer/Finder (SDF) scans the waveforms of each photomultiplier channel. A channel is flagged as "hit" if the SDF finds a S/N ratio greater than 6 within a 25.6 µs time window.

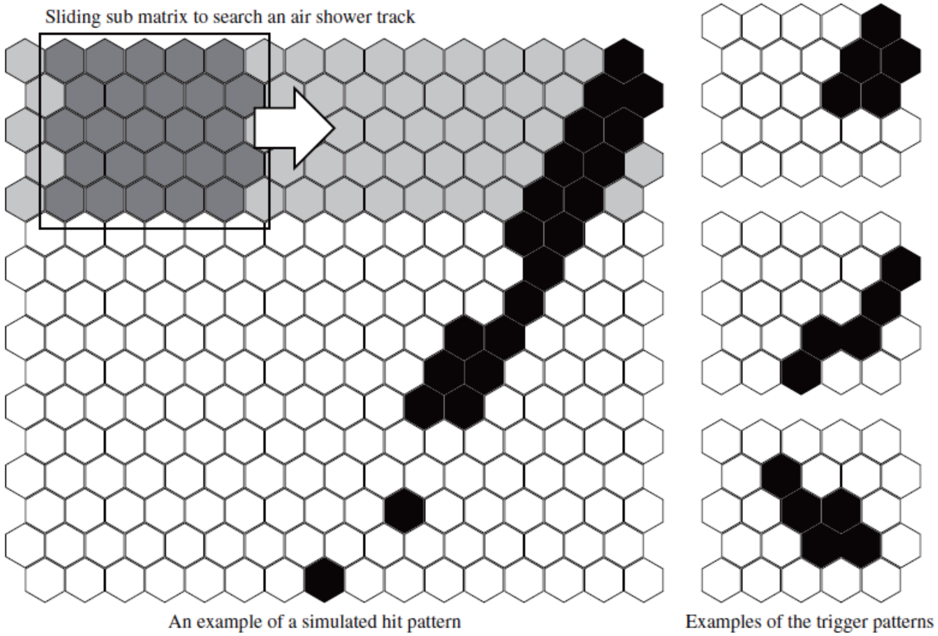


Fig. 4. Schematic diagram of the track finding process.

The Track Finder (TF) continuously scans for patterns of "hit" PMT channels. When a pattern is matched in either a 5x5 window in 1 camera (left) or a 4x4 pattern in two adjacent cameras (below), the FADC buffer from every channel of every camera in the site is read out.

Each FD station triggers at a rate of ~2Hz, producing ~1TB of raw data per observation period (~100 hours of on-time).

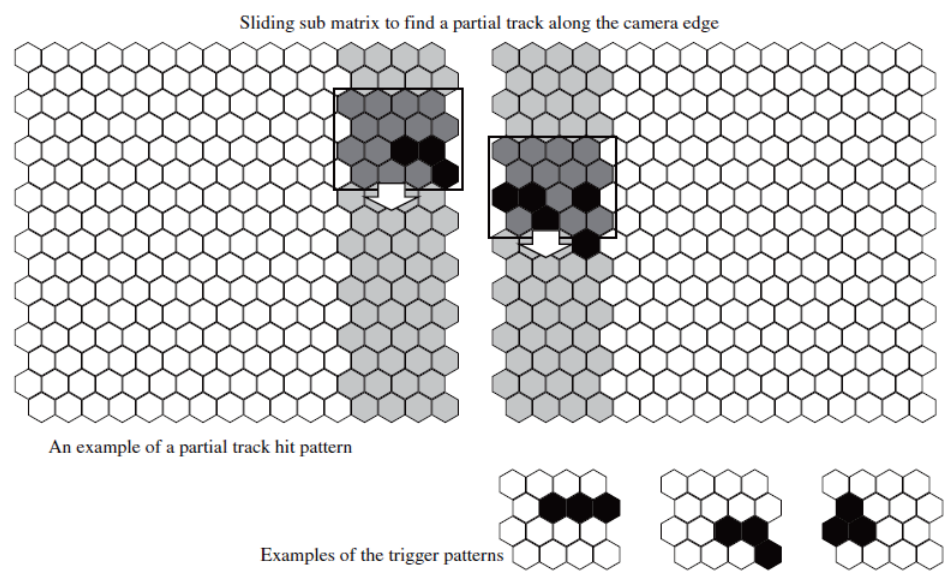


Fig. 5. Schematic diagram of the partial track search near the boundary of a camera.

Calculating the UHECR Flux

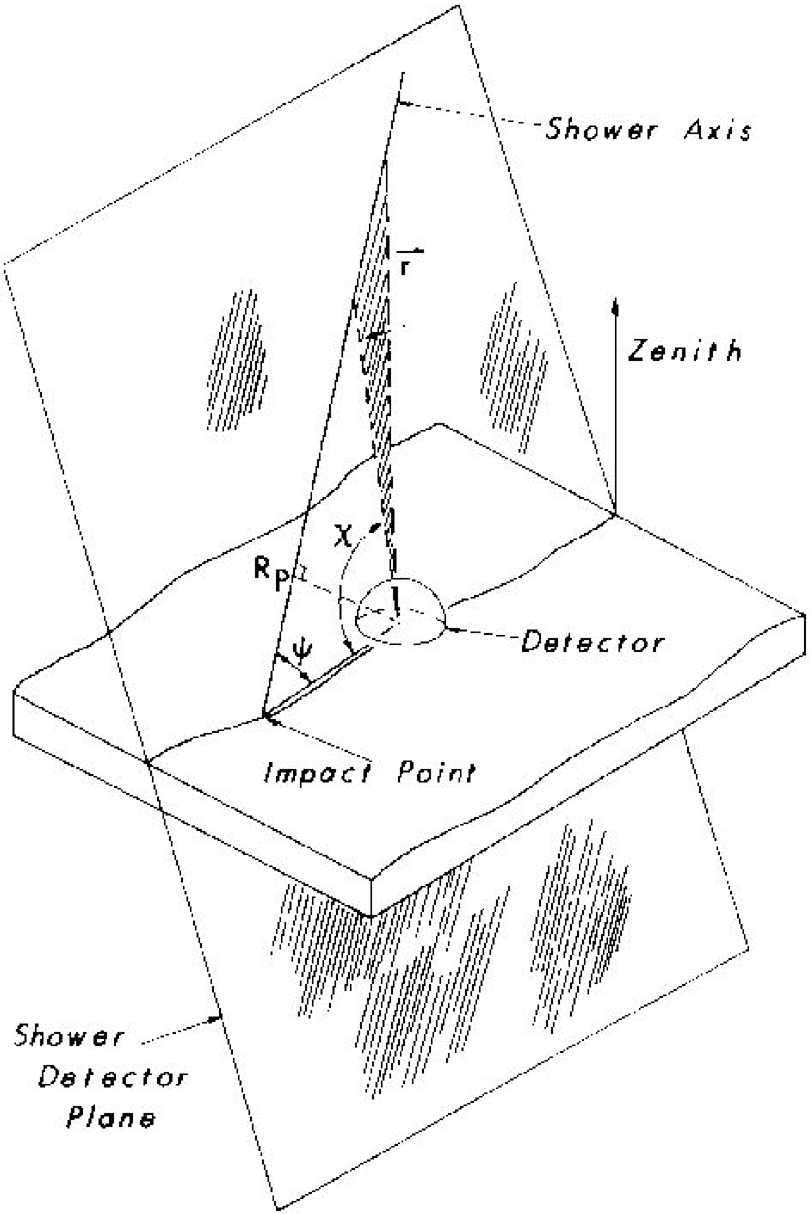
Distribution of observed event energies

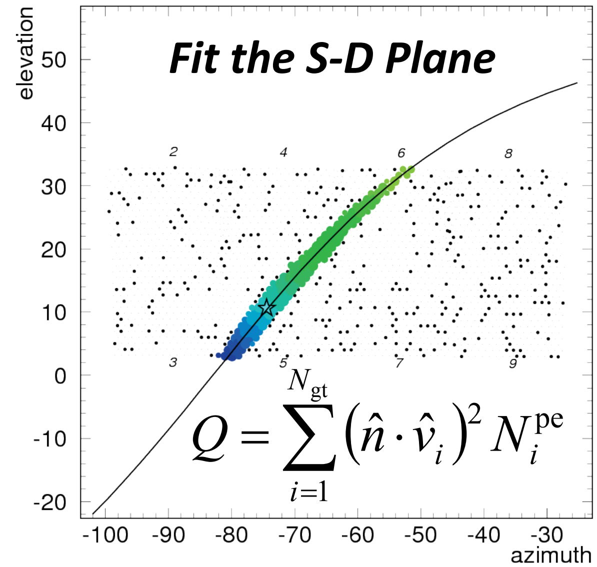
$$J(E_i) = \frac{1}{\Delta E_i} \frac{N(E_i)}{T} \frac{1}{\mathrm{Ap}(E_i)}$$

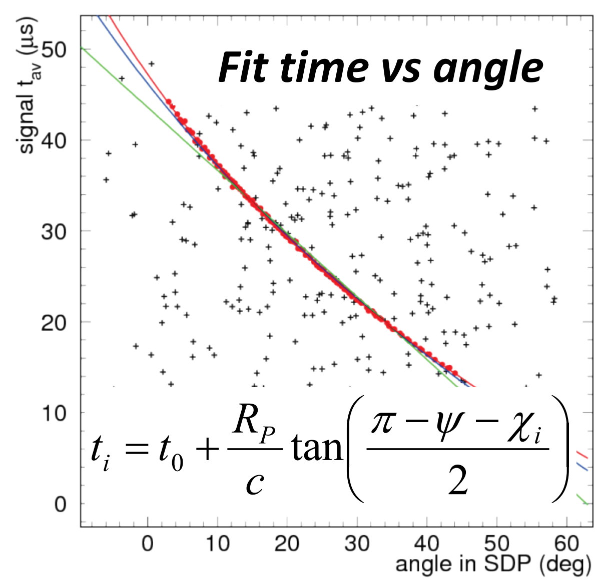
Net detector ***on-time***

Aperture –
Computed using the Monte Carlo method

Shower Geometry Fit

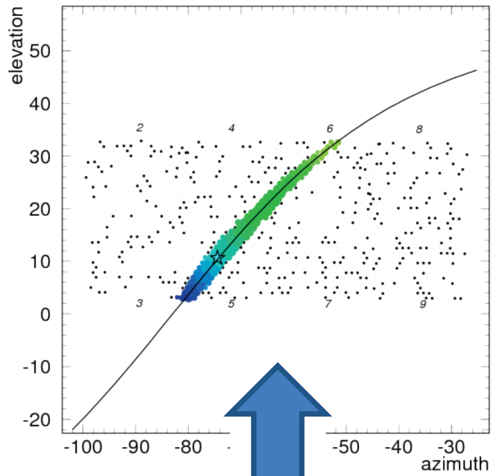




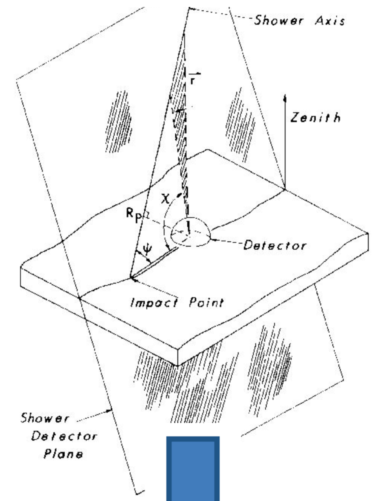


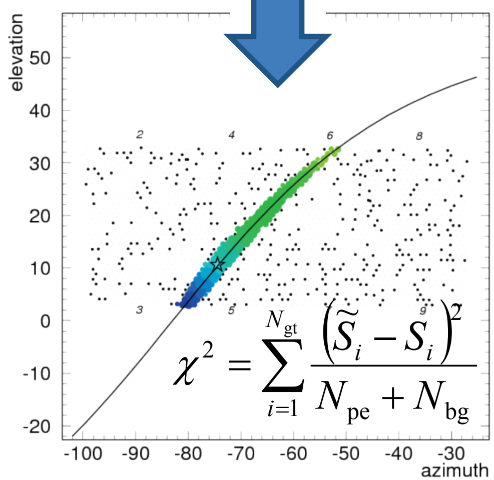
Shower Profile Fit

Observed Event



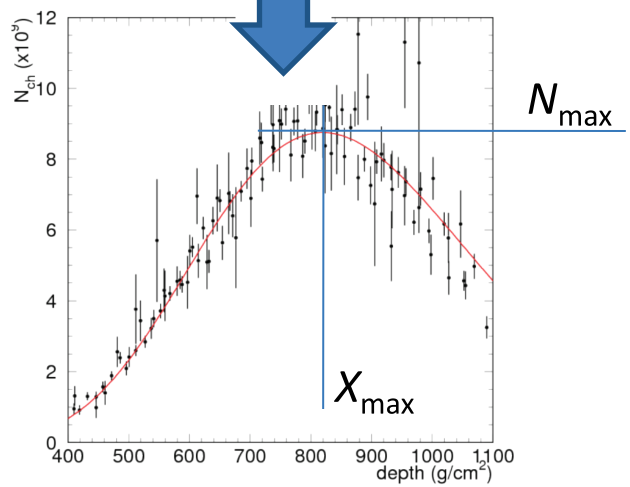
Use Best-fit Geometry



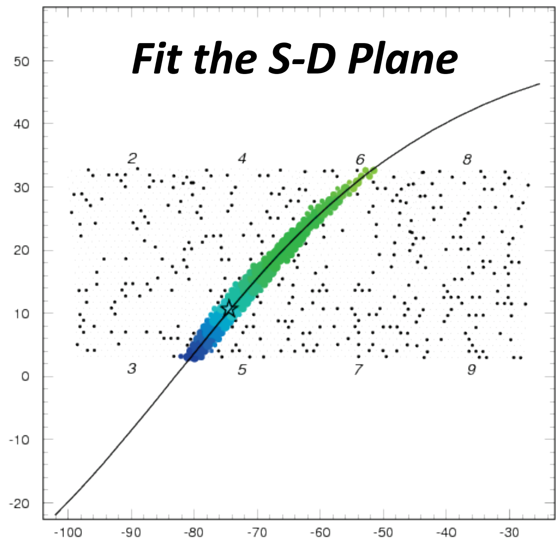


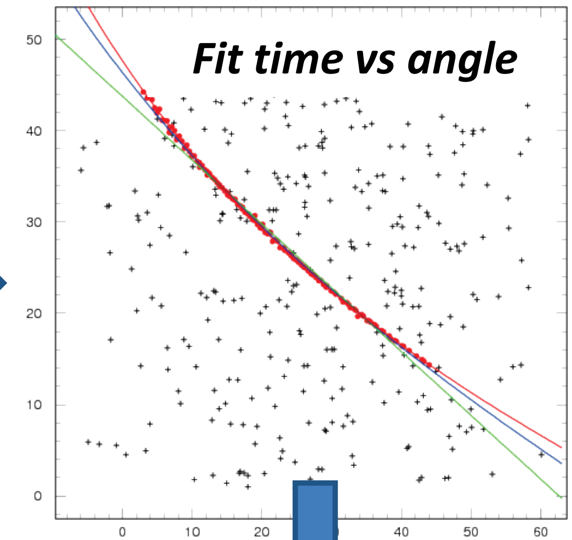
$$\chi^2 = \sum_{i=1}^{N_{gt}} \frac{\left(\widetilde{S}_i - S_i\right)^2}{N_{pe} + N_{bg}}$$

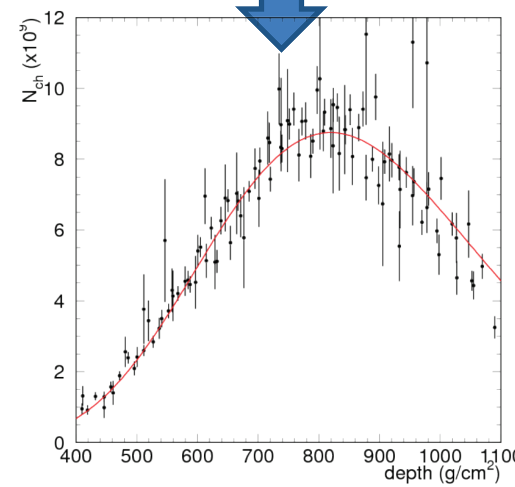
Compare



Simulate Event







Fit the Profile

Integrate to find E_{cal}

$$E_{\text{cal}} = \int_0^{\infty} \left\langle \frac{dE}{dX} \right\rangle N(X)\, dX$$

$$E_0 = A + B \log E_{\text{cal}} + C\left(\log E_{\text{cal}}\right)^2$$

Correct for "missing energy"

Quality Cuts

Geometry Cuts

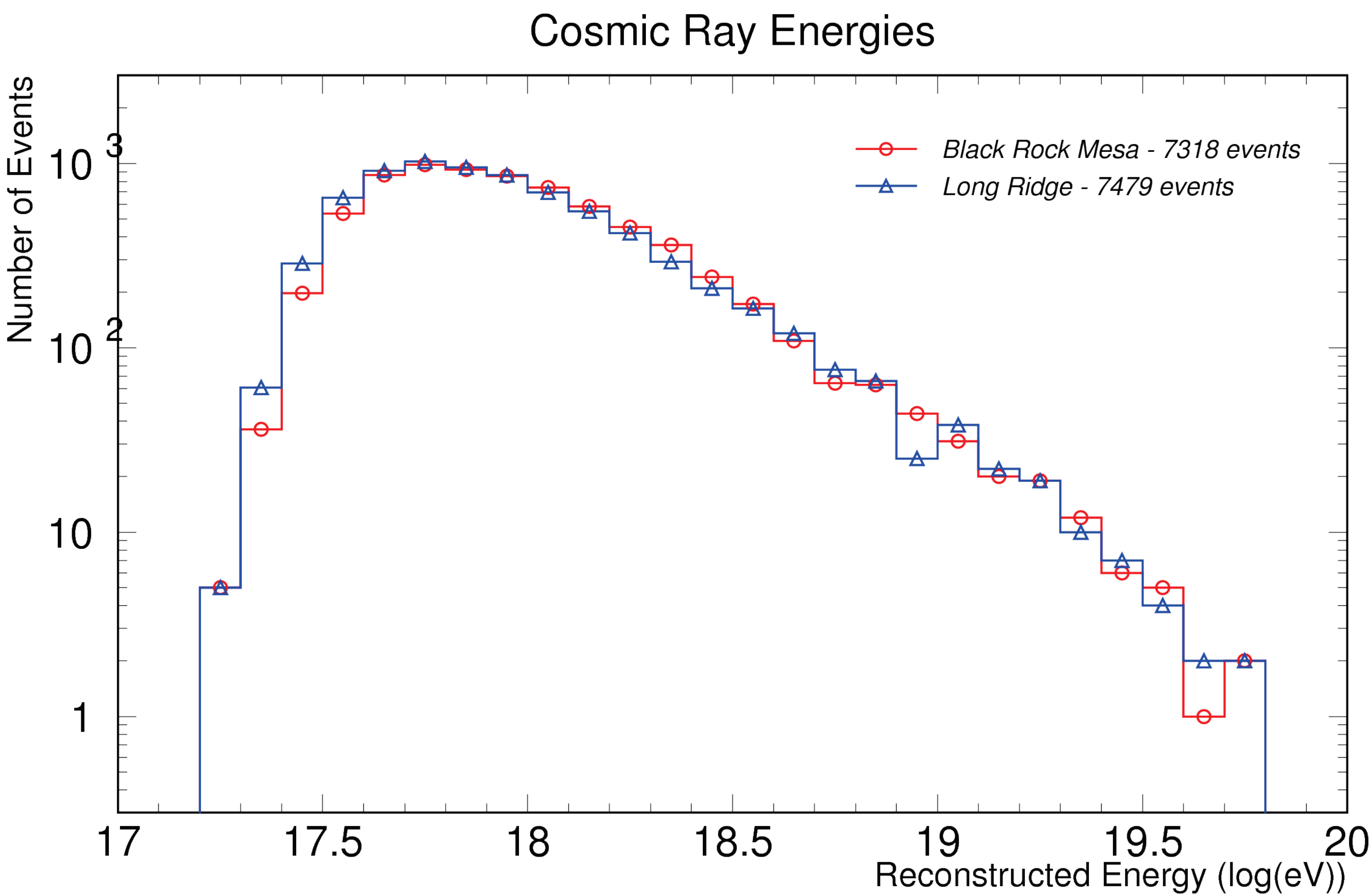
- Geometry fit failed or is not downward event
- N_{GT}/N_T<3.5% (good tube fraction)
- $N_{PE}/\Delta\chi$<25 deg^{-1}
- pseudo-distance <1.5 km
- $\cos^{-1}n_z$>80° (SDP angle)
- R_P<500 m
- Ψ>130°
- Δt<6.5 µs
- $\delta\Psi$>36°
- tangent fit χ^2>10
- $\Delta\chi$<7° (10° if R_P seen in ring 2)
- ϑ>70°
- t_0>25.6 µs
- R_P<5 km *and* Δt<6 µs

Profile Cuts

- Profile fit failed to converge
- X_1<150 g/cm^2 *or* X_1>1200 g/cm^2
- ΔX<150 g/cm2
- X_{max} not directly observed (bracketing cut)

Data Set

	Black Rock Mesa	Long Ridge
Observation Period	3/29/2008 – 9/6/2011	3/30/2008 – 8/8/2011
# Good Weather Nights	436	417
# Good Runs	4581	3793
Gross On-Time	2077.00 hr	1727.27 hr
Dead Time Fraction	7.6%	8.7%
# Triggers	17.3M	16.2M
# Downward Events	835,195	806,597
# Good Geometry	10,983	10,441
# Good Events	7318	7479

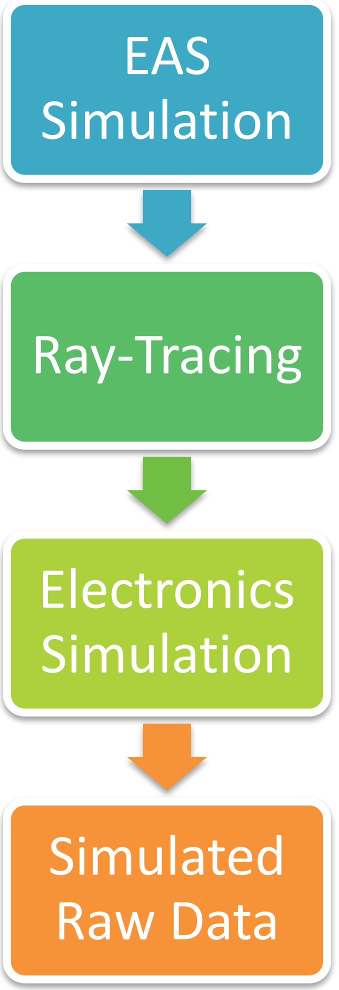

Cosmic Ray Energies
Number of Events
Reconstructed Energy (log(eV))
Black Rock Mesa - 7318 events
Long Ridge - 7479 events
17
17.5
18
18.5
19
19.5
20
1
10
10 2
10 3

Monte Carlo is Used For...

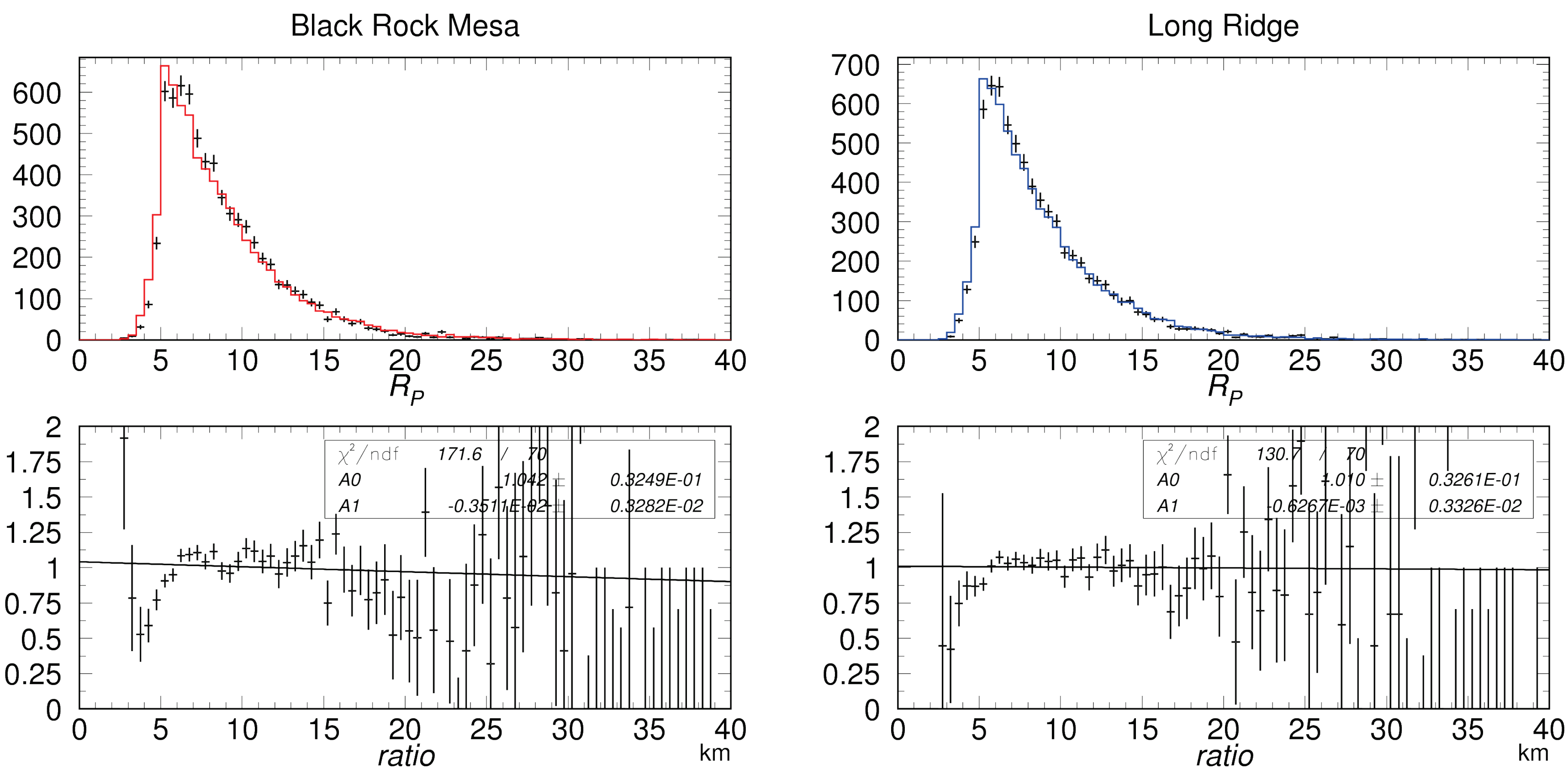
- ...calculating aperture
- ...fitting N_{max} & X_{max} (IMC)
- ...measuring parameter resolution

TRUMP

- ***T***elescope Array ***R***eversible and ***U***pdateable ***M***onte Carlo ***P***rogram
- Library of Gaisser-Hillas fits to air showers simulated with ***CORSIKA***
- *dE*/*dX* from ***Nerling*** (2006)
- Fluorescence Yield from ***Kakimoto*** (1996) and ***FLASH*** (Abbasi, 2000)
- Composition from ***HiRes/MIA*** (Abbasi, 2005)
- Input energy spectrum from the UHECR flux measured by ***HiRes*** (Abbasi, 2008)

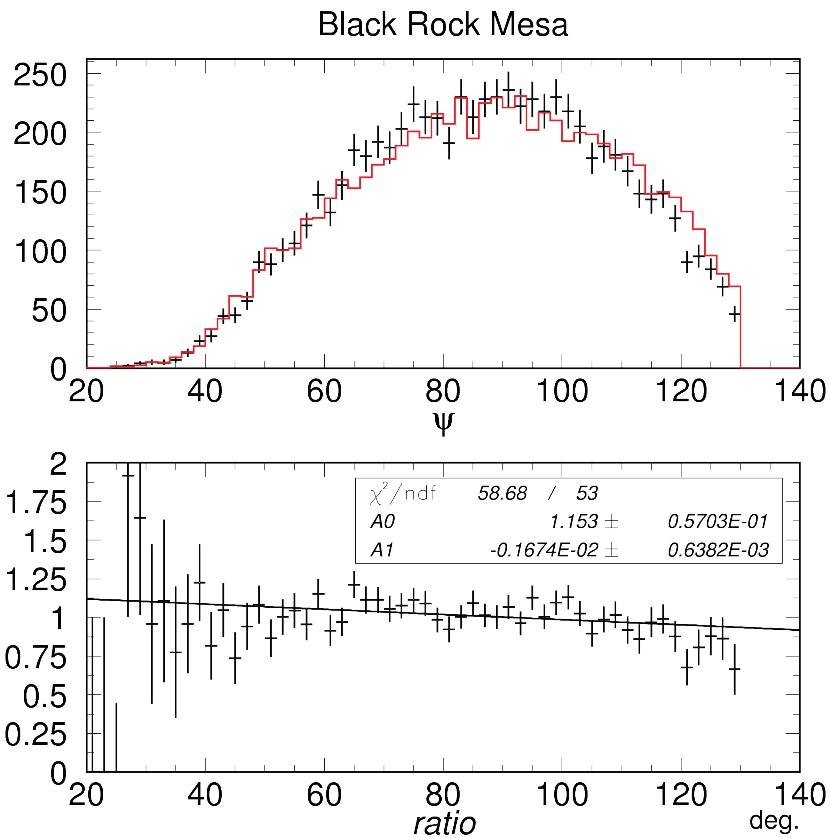


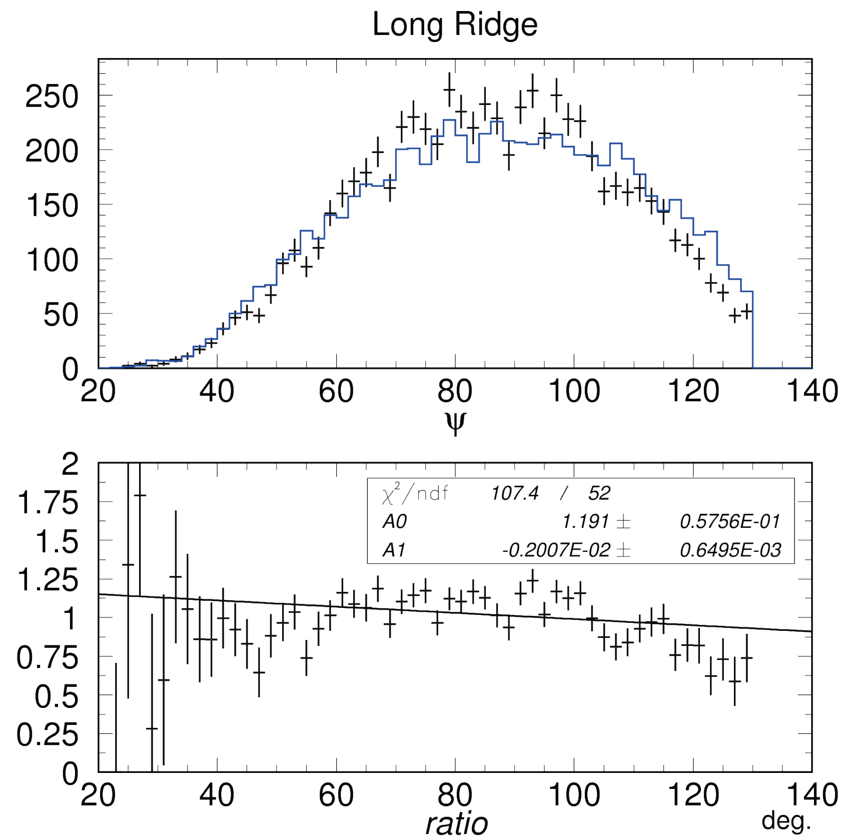
R_P Data/MC Comparison



Reconstructed energy > $10^{17.5}$ eV.

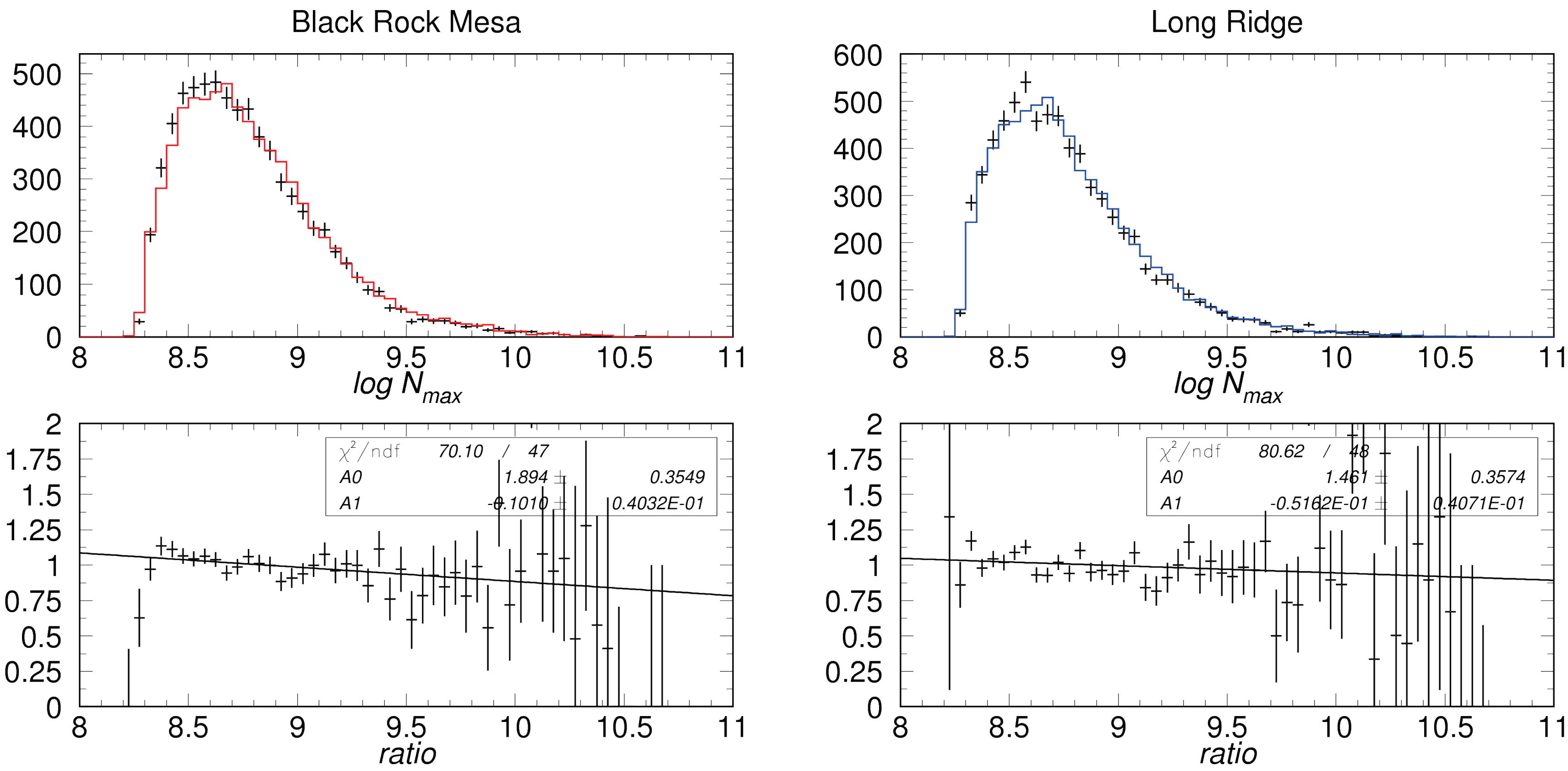
ψ Data/MC Comparison





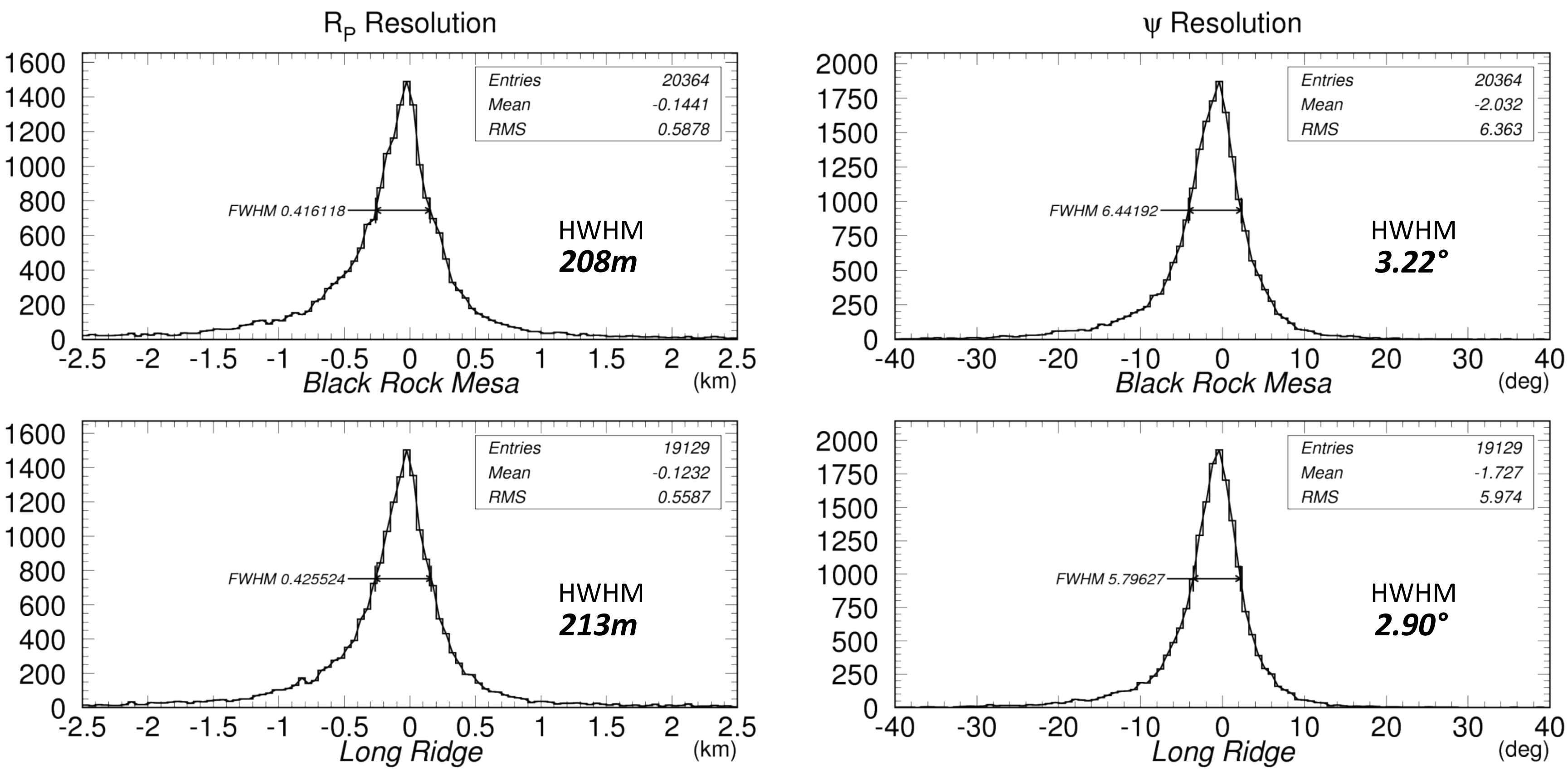
Reconstructed energy > $10^{17.5}$ eV.

N_{max} Data/MC Comparison



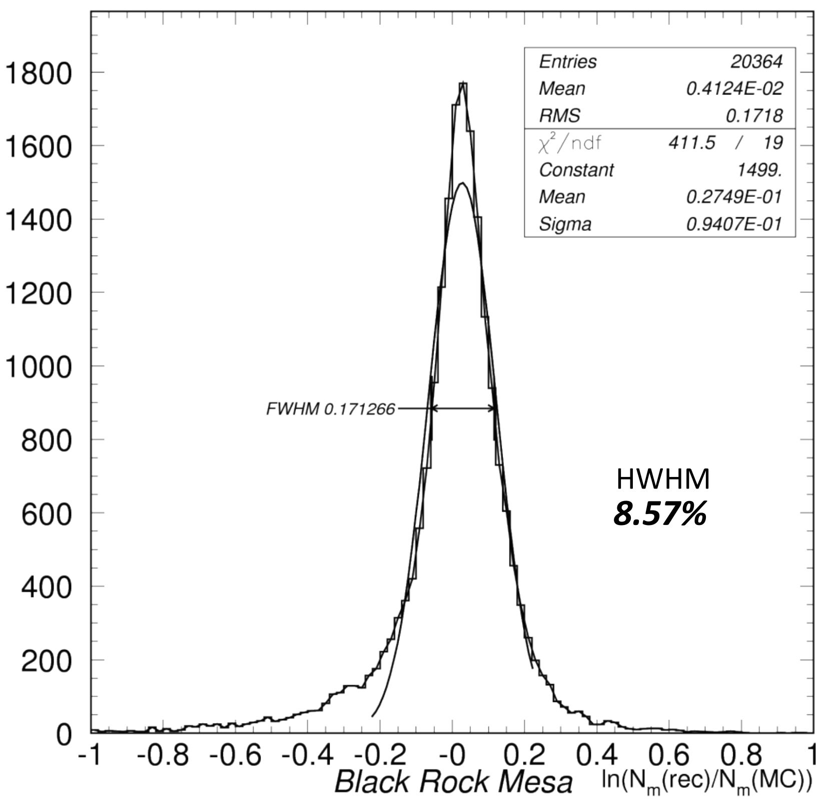
Reconstructed energy > $10^{17.5}$ eV.

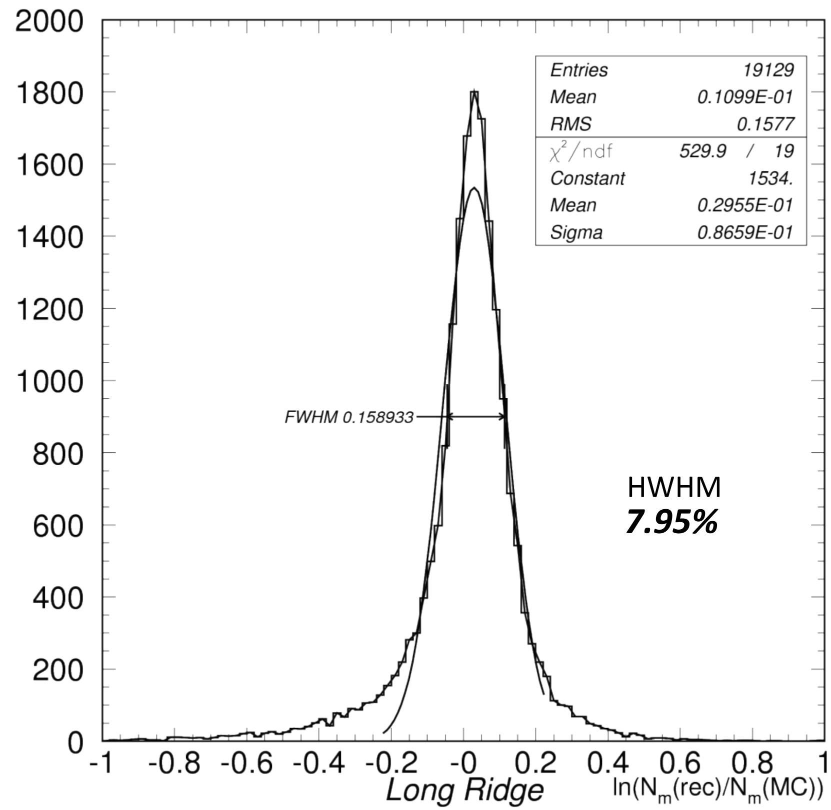
R_P and Ψ Resolution



Reconstructed energy > $10^{17.5}$ eV.

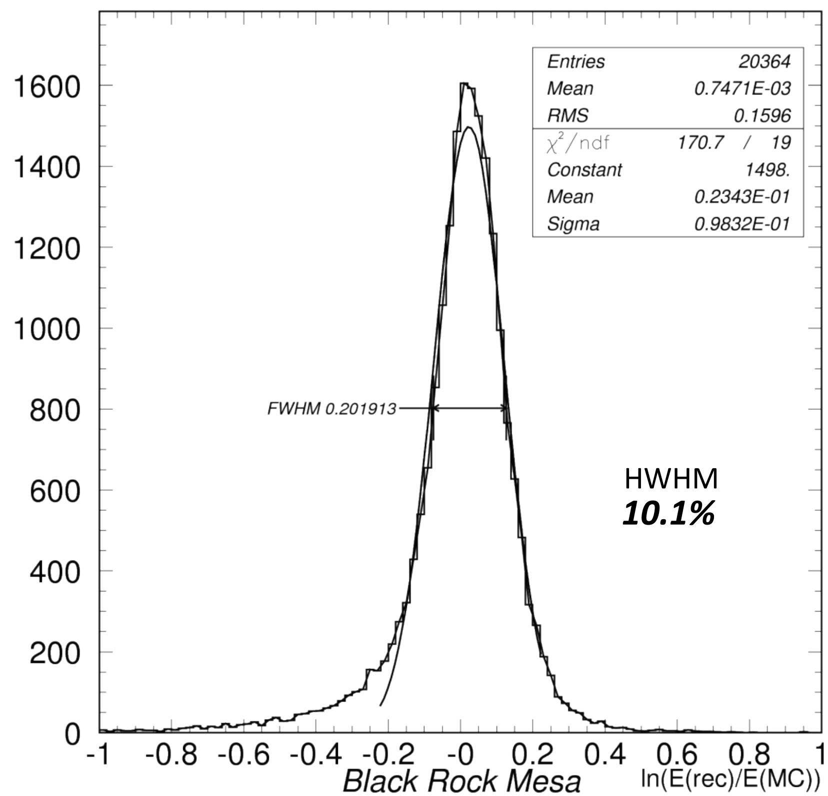
N_{max} Resolution

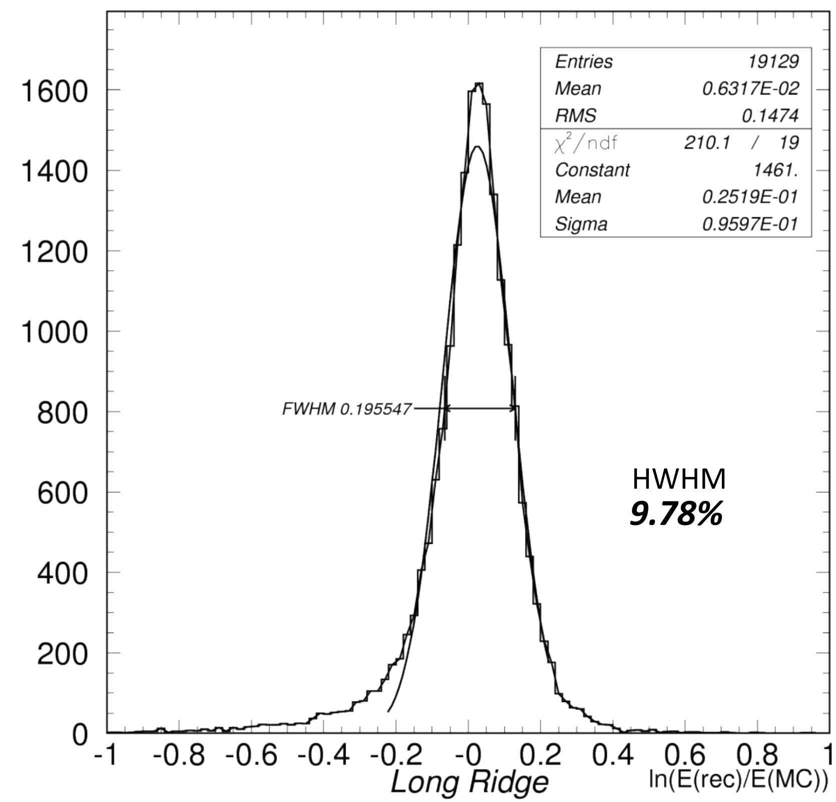




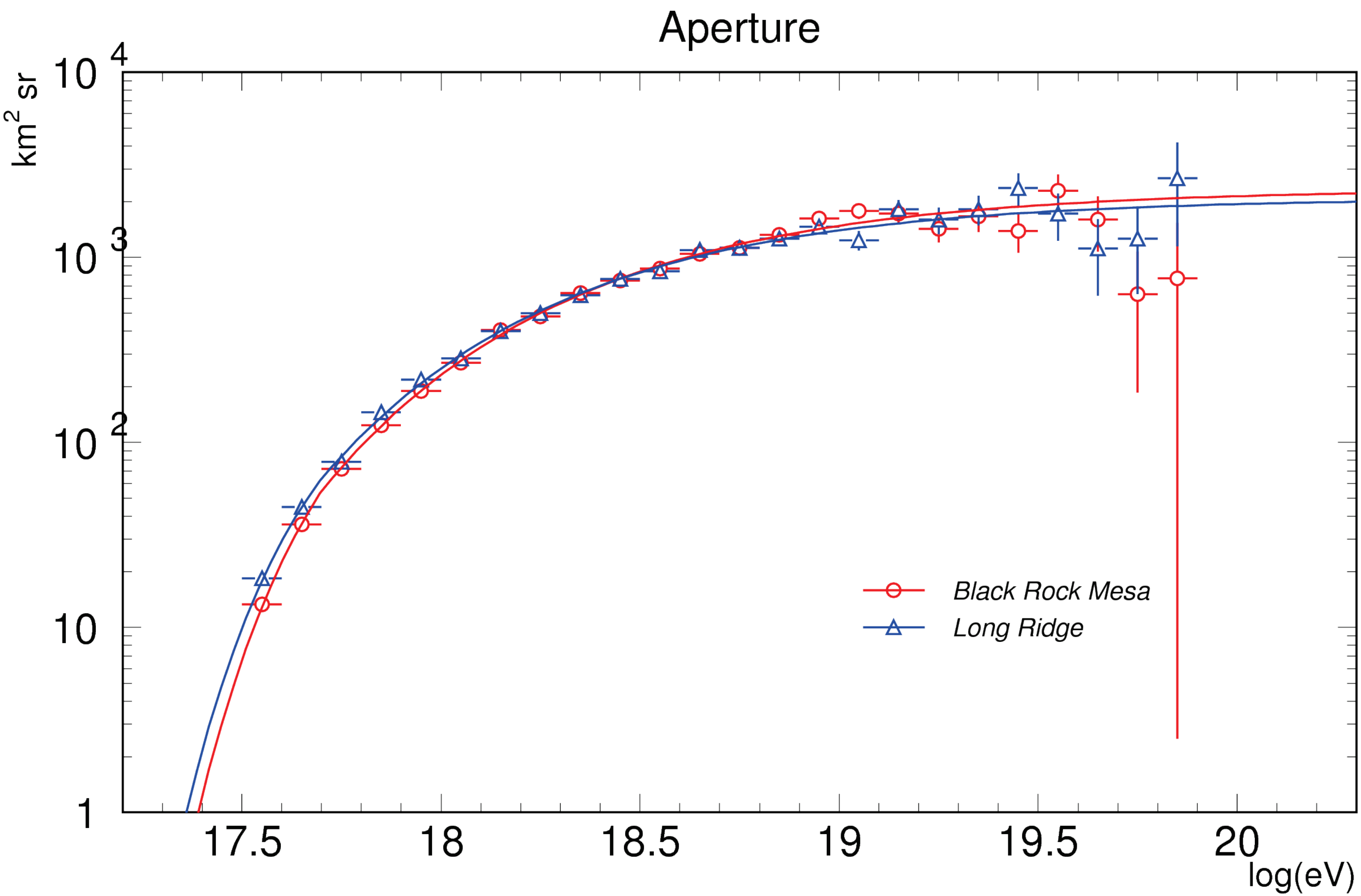
Reconstructed energy > $10^{17.5}$ eV.

Energy Resolution

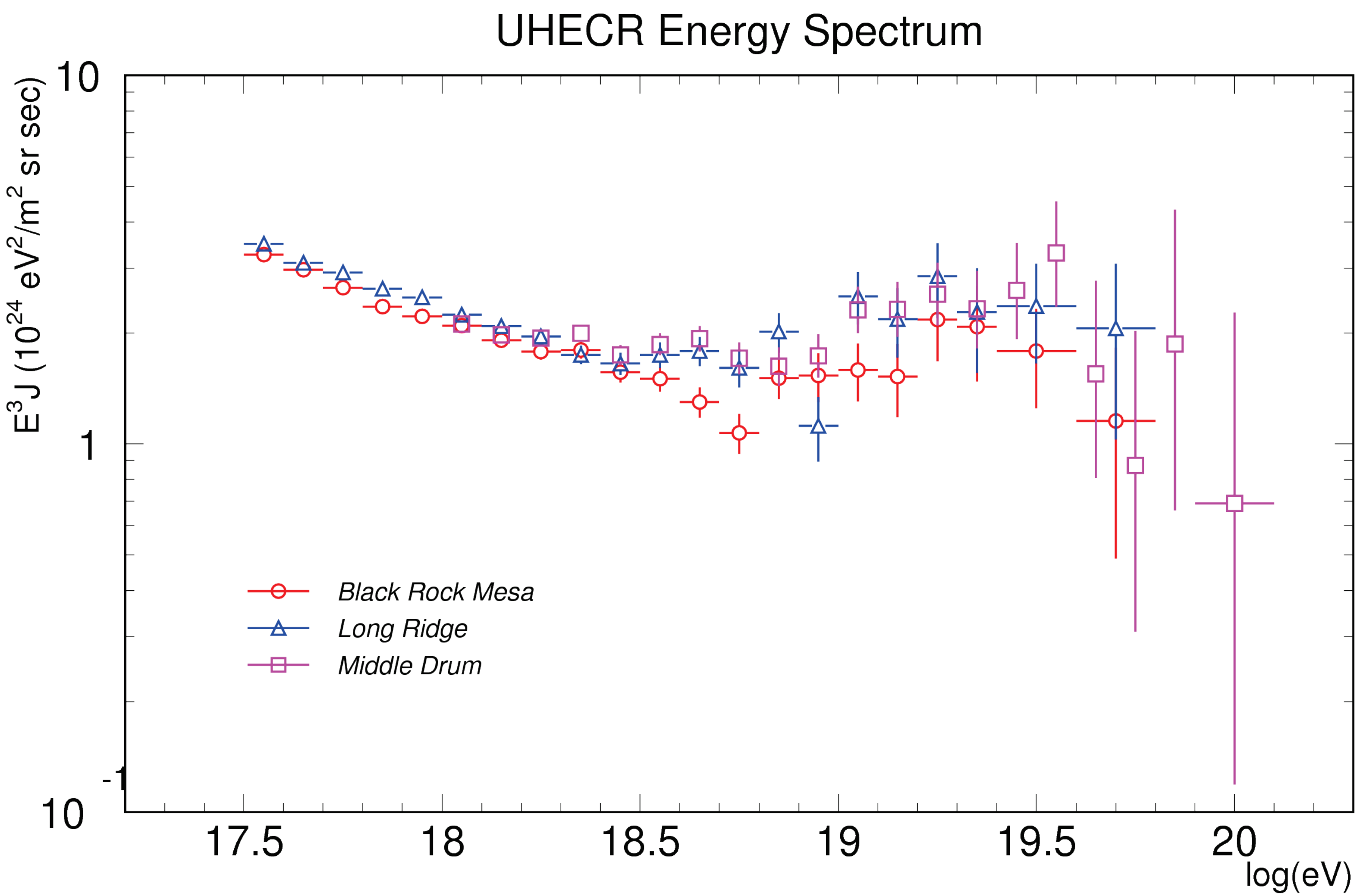




Reconstructed energy > $10^{17.5}$ eV.



Aperture
km^2 sr
10^4
10^3
10^2
10
1
17.5
18
18.5
19
19.5
20
log(eV)
Black Rock Mesa
Long Ridge


UHECR Energy Spectrum
$E^3 J$ (10^{24} eV^2/m^2 sr sec)
10
1
10^{-1}
17.5
18
18.5
19
19.5
20
log(eV)
Black Rock Mesa
Long Ridge
Middle Drum

Combining Data Sets

- To improve statistics, the BR and LR data sets may be combined.
- The sites are separated by more than 30 km, but there is some overlap in their exposures above 10^{19} eV.
- A tandem-stereo MC is needed.

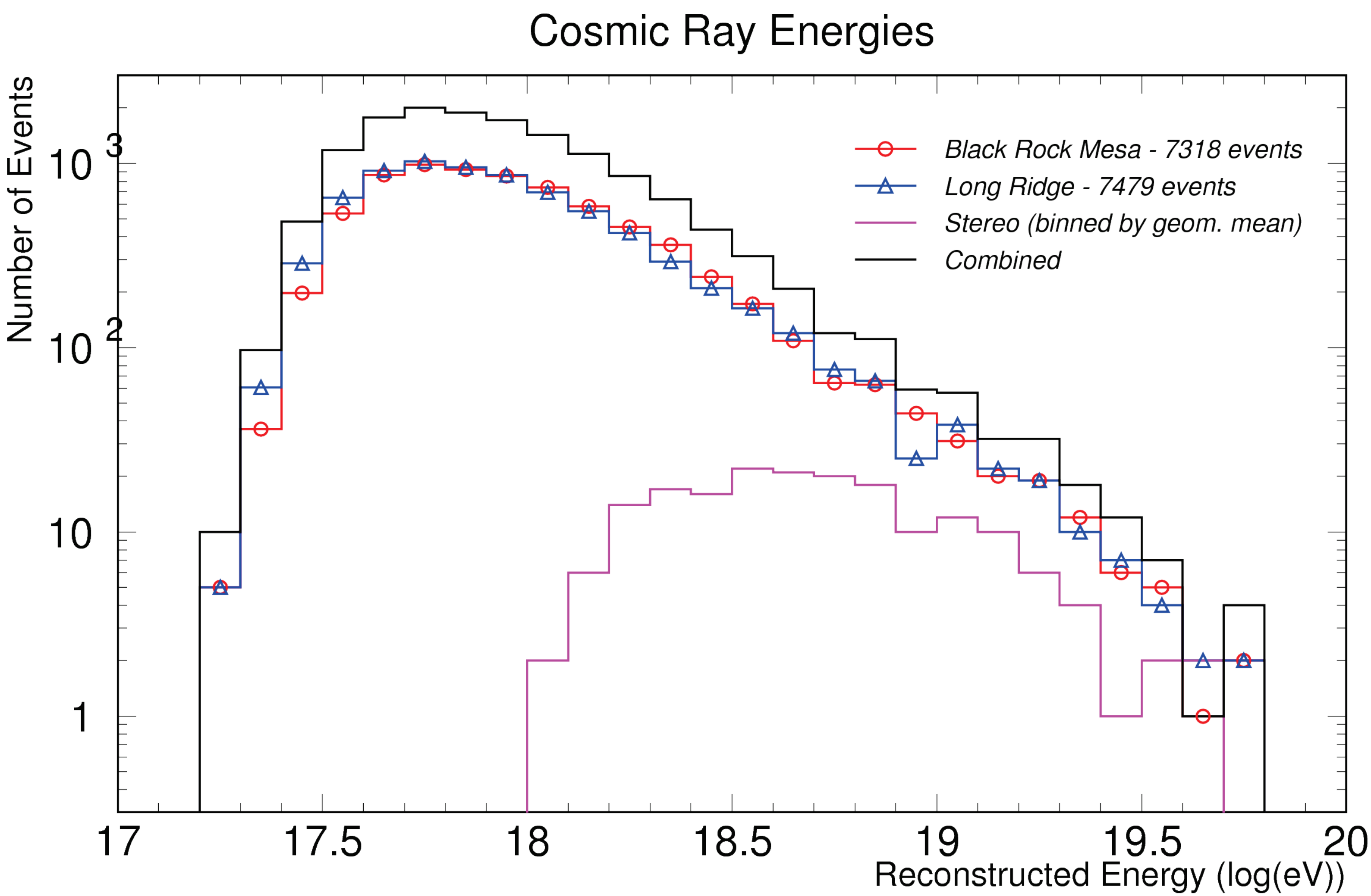
Combining Data Sets

The total number of unique events observed by BR & LR will come from the union of their exposures.

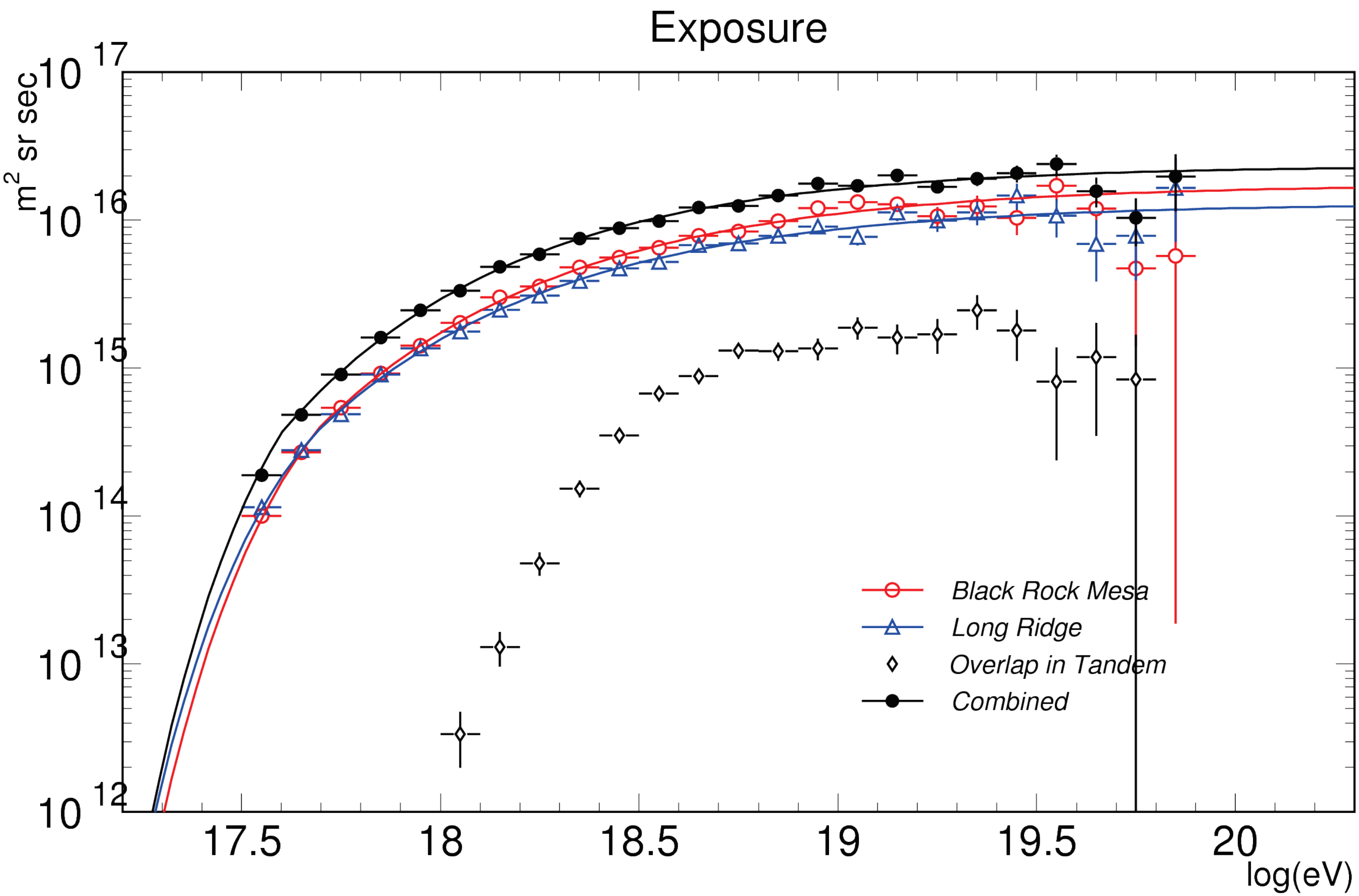
$$N_{\mathrm{BR}\cup\mathrm{LR}}(E) = \mathrm{X}_{\mathrm{BR}\cup\mathrm{LR}}(E) \cdot J(E)$$

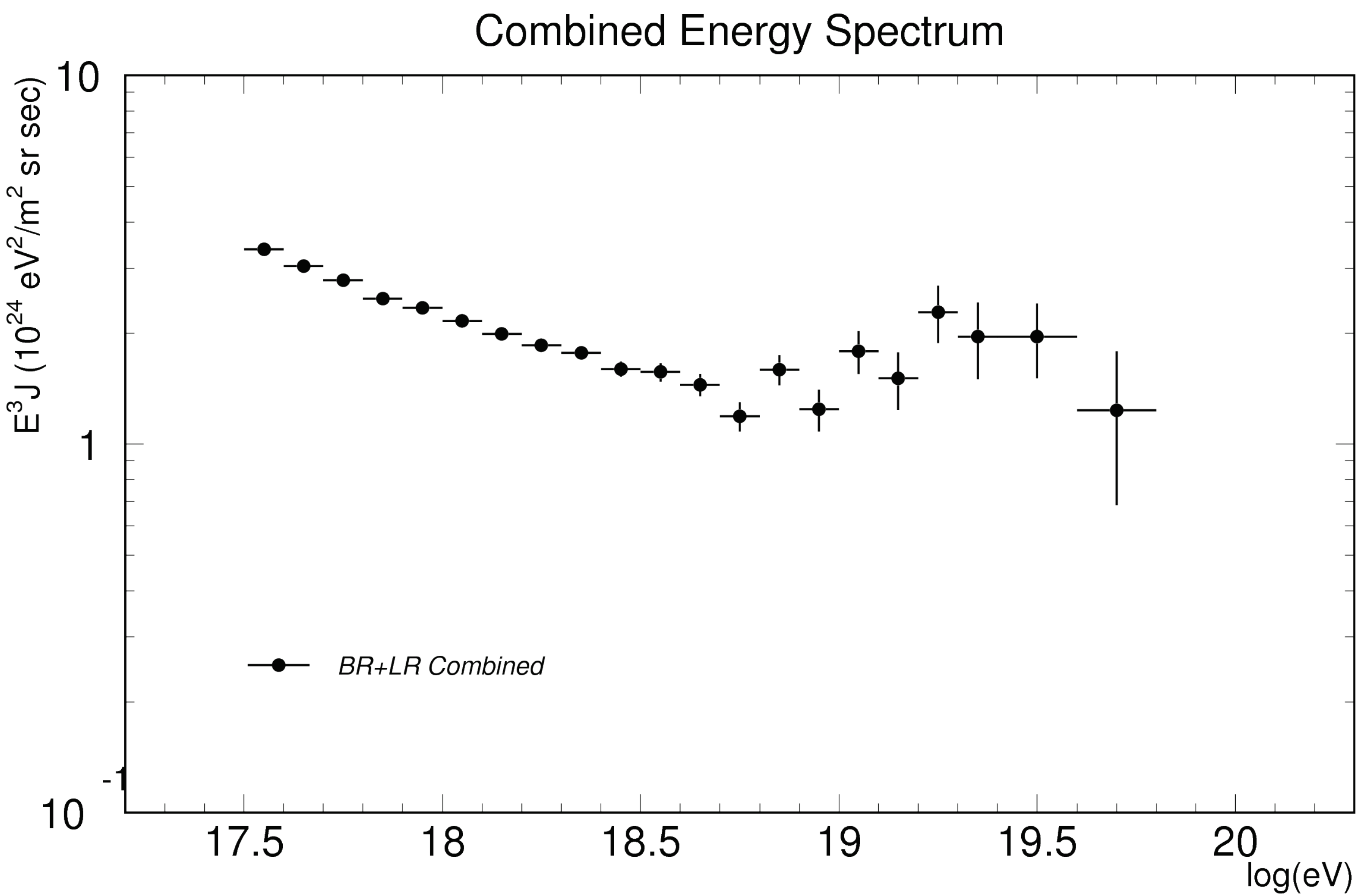
$$N_{\mathrm{BR}\cup\mathrm{LR}} = N_{\mathrm{BR}} + N_{\mathrm{LR}} - N_{\mathrm{BR}\cap\mathrm{LR}}$$

$$\mathrm{X}_{\mathrm{BR}\cup\mathrm{LR}}(E) = \mathrm{Ap}_{\mathrm{BR}}(E) \cdot T_{\mathrm{BR}} + \mathrm{Ap}_{\mathrm{LR}}(E) \cdot T_{\mathrm{LR}} - \mathrm{Ap}_{\mathrm{BR}\cap\mathrm{LR}}(E) \cdot T_{\mathrm{BR}\cap\mathrm{LR}}$$



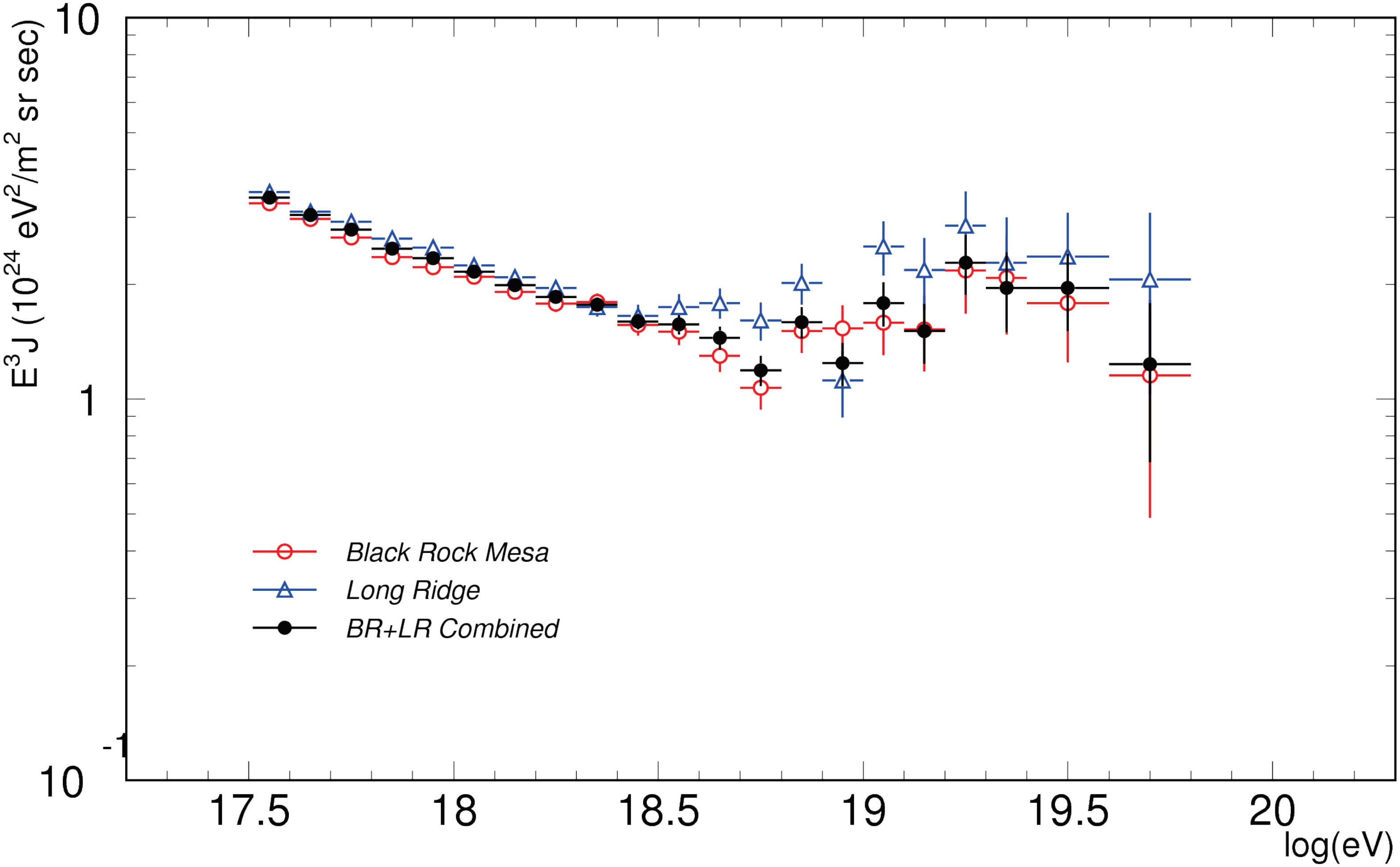
Cosmic Ray Energies
Number of Events
10^3
10^2
10
1
17
17.5
18
18.5
19
19.5
20
Reconstructed Energy (log(eV))
Black Rock Mesa - 7318 events
Long Ridge - 7479 events
Stereo (binned by geom. mean)
Combined

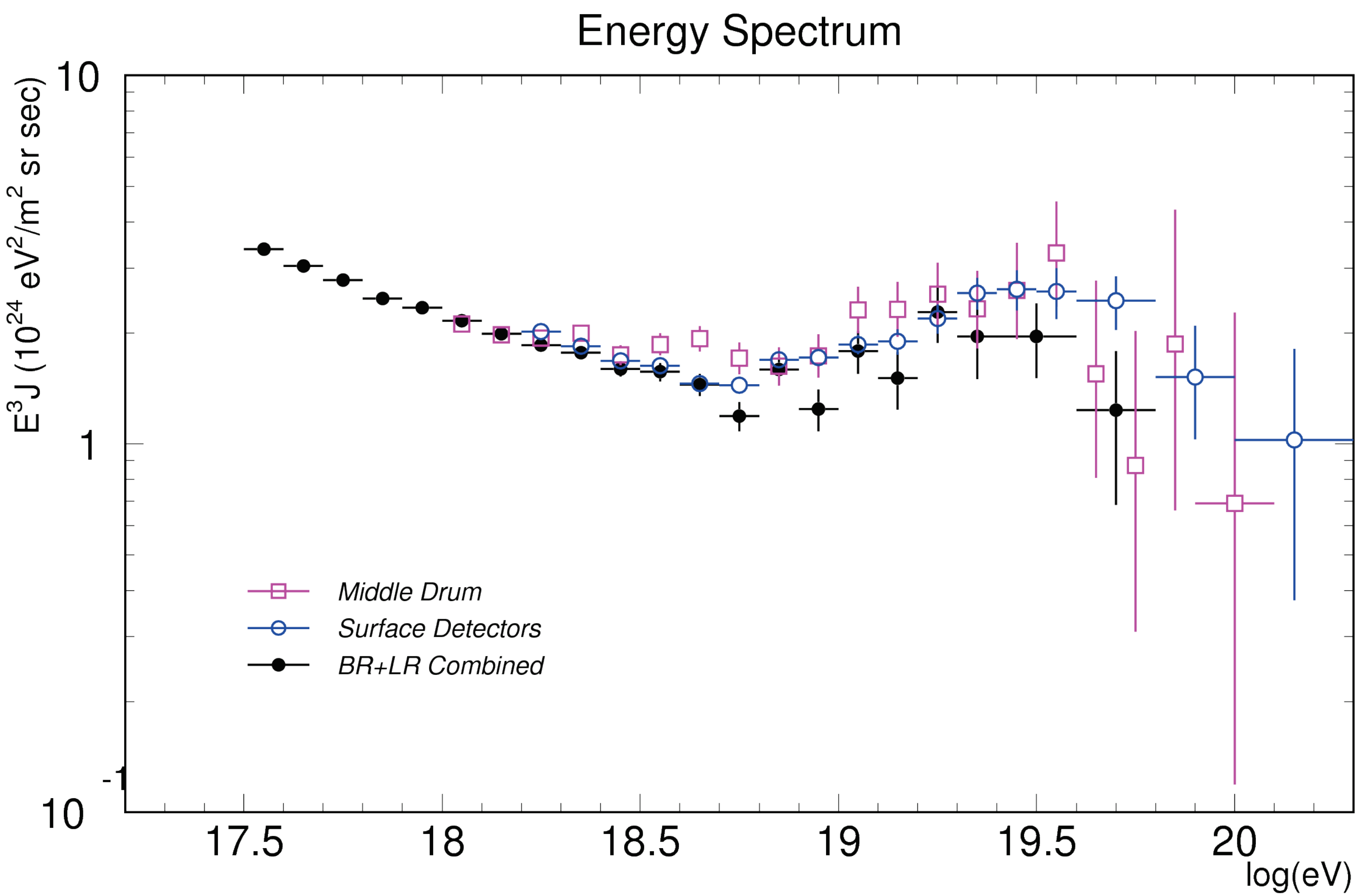

Exposure
m^2 sr sec
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
17.5
18
18.5
19
19.5
20
log(eV)
Black Rock Mesa
Long Ridge
Overlap in Tandem
Combined



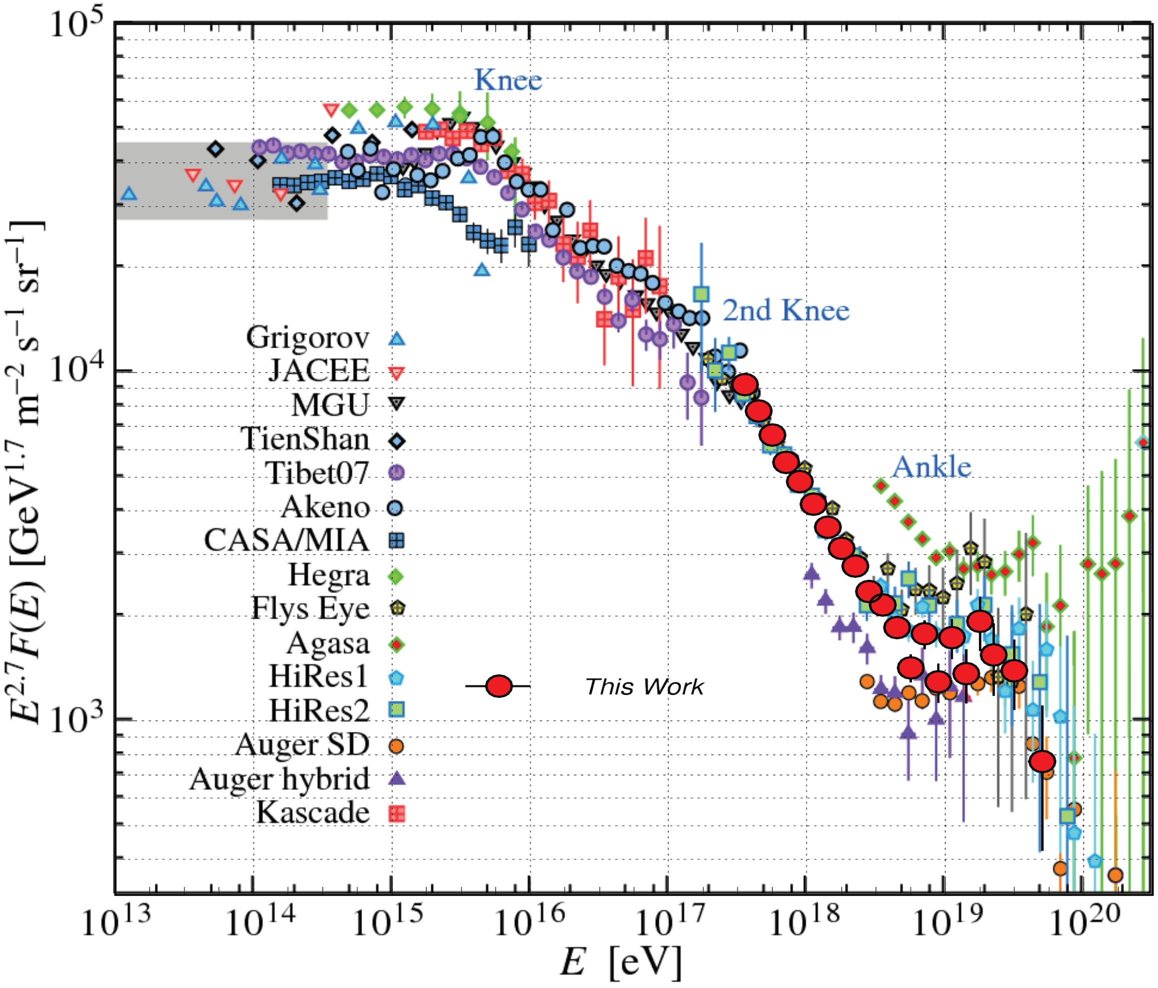
Combined Energy Spectrum
E^3J (10^{24} eV^2/m^2 sr sec)
10
1
10^{-1}
17.5
18
18.5
19
19.5
20
log(eV)
BR+LR Combined

Combined Energy Spectrum




Energy Spectrum
$E^3 J$ (10^{24} eV^2/m^2 sr sec)
10
1
10^{-1}
17.5
18
18.5
19
19.5
20
log(eV)
Middle Drum
Surface Detectors
BR+LR Combined

Cosmic Ray Energy Spectrum



Sources of Systematic Error

Uncertainty from Experimental Apparatus	
Detector Optics	10%
Electronics	10%
Detector On-Time	1%
Uncertainty from “Laboratory” Environment	
Attenuation by Aerosols	10%
Uncertainty from Physics Models	
Fluorescence Yield	10%
Mean *dE*/*dX*	1%
Missing Energy Correction	5%
Total Systematic Uncertainty in Energy Estimates	21%
Systematic Uncertainty in Flux Measurement	**35%**

Summary

- This dissertation focuses on data collected by the FADC-driven FDs at BR & LR.
- FD sensitivity is calculated using TRUMP, a Monte Carlo simulation program.
- The UHECR flux shown here is in agreement with other measurements within Telescope Array as well as with previously published measurements.

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