OBSERVATION OF THE GZK SUPPRESSION WITH THE TELESCOPE ARRAY FLUORESCENCE TELESCOPES AND DEPLOYMENT OF THE TELESCOPE ARRAY EXPANSION

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Outline

- Introduction of Cosmic Rays and Extensive Air Showers
- Telescope Array (TA) Cosmic Ray Observatory
  - Indirection Detection of Cosmic Rays
  - Deployment of TAx4, the Expansion of TA
- Fluorescence Detection Event Reconstruction
- Weather Classification using Machine Learning
- Event Simulation (Monte Carlo)
  - Detector Aperture Calculation
  - Data/MC Comparisons
- TAx4 Preliminary Cosmic Ray Spectrum
- Monocular Combined Cosmic Ray Spectrum
  - Observation of the GZK Suppression

Introduction of Cosmic Rays and Extensive Air Showers

Cosmic Rays

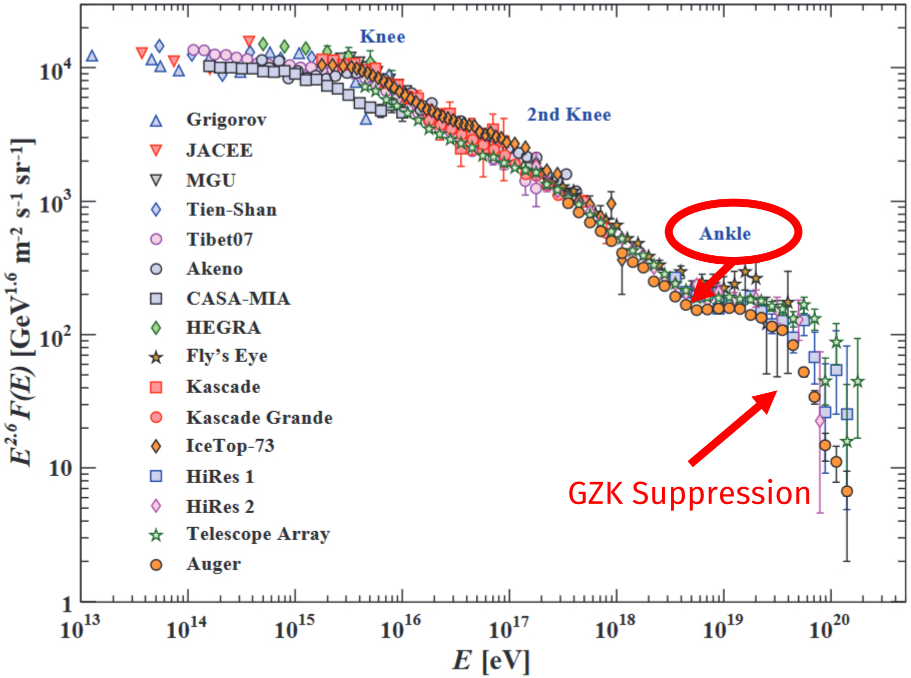
- Charged particles moving through the universe
  - Predominantly atomic nuclei
- Propagation is influenced by:
  - magnetic deflection
  - particle interactions
  - interactions with plasma clouds and astrophysical shock fronts
- Ultra-High Energy Cosmic Rays (UHECRs)
  - $E > 10^{18}$ eV

Fundamental Questions

- What is the composition of cosmic rays?
- What are the sources of cosmic rays?
- **What is the cosmic ray energy density in the universe?**
  - **Cosmic Ray Energy Flux Spectrum**

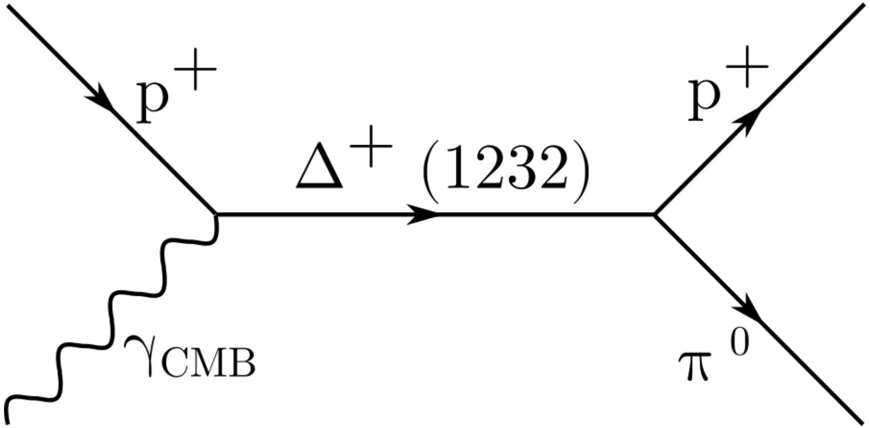
Cosmic Ray Energy Spectrum

- Differential flux of events
  - For UHECR, we expect 1 event per km^2 per century
- Two features above $10^{17.5}$ eV
  - *Ankle*, possibly caused by:
    - transition from galactic to the extragalactic cosmic ray populations
    - Proton pair-production energy losses
  - GZK Suppression



M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

GZK Suppression



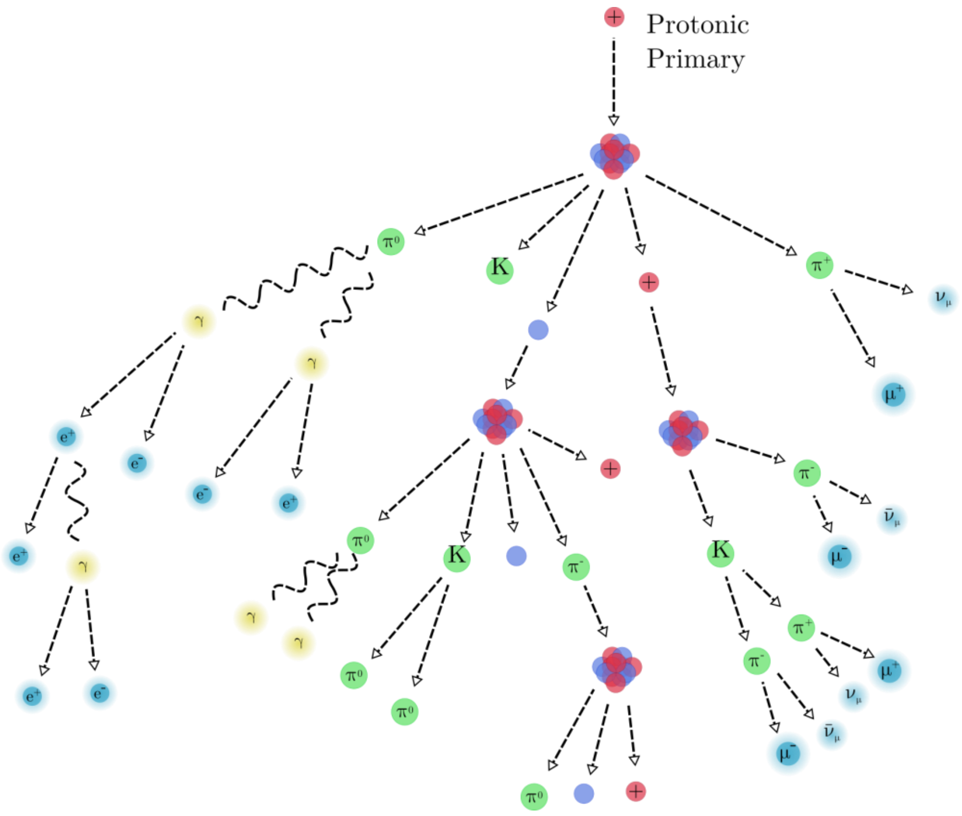
Particle Interactions :

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

Suppression of cosmic ray flux above the threshold due to the interaction of protons with the Cosmic Microwave Background photons :

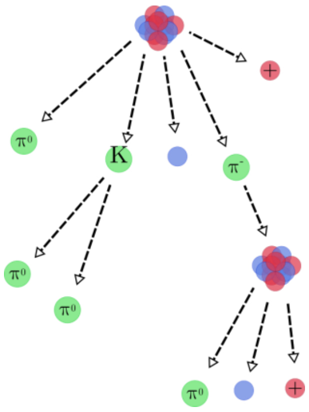
- Nucleon after interaction has less energy
- Threshold energy $E_{proton} > 6 \times 10^{19}$ eV
- First observed by the HiRes experiment
  - followed by Telescope Array surface detectors, and Pierre Auger surface detectors

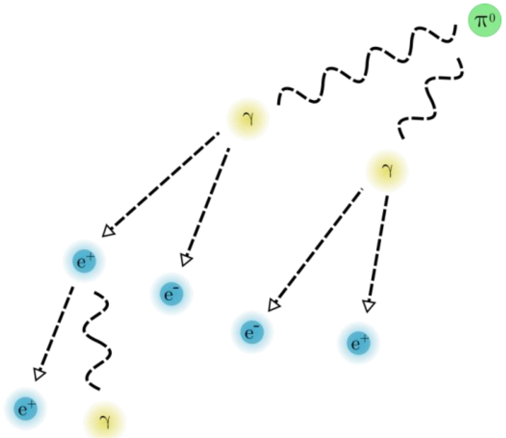
Extensive Air Showers (EASs)

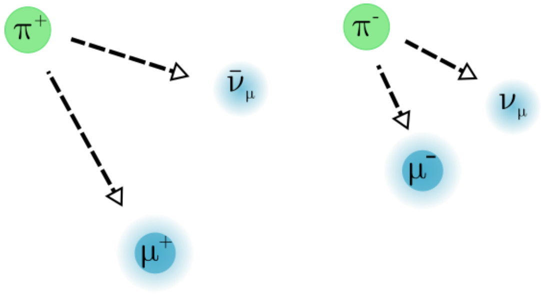


- Primary cosmic ray initiates a particle shower high in the atmosphere
- Shower continues until the energy is spread over many particles
- Shower has 3 main components

Extensive Air Showers Components







Hadronic Component :

- Core of the EAS
- Interaction of hadrons with the air molecule nuclei
- Feed into the other components

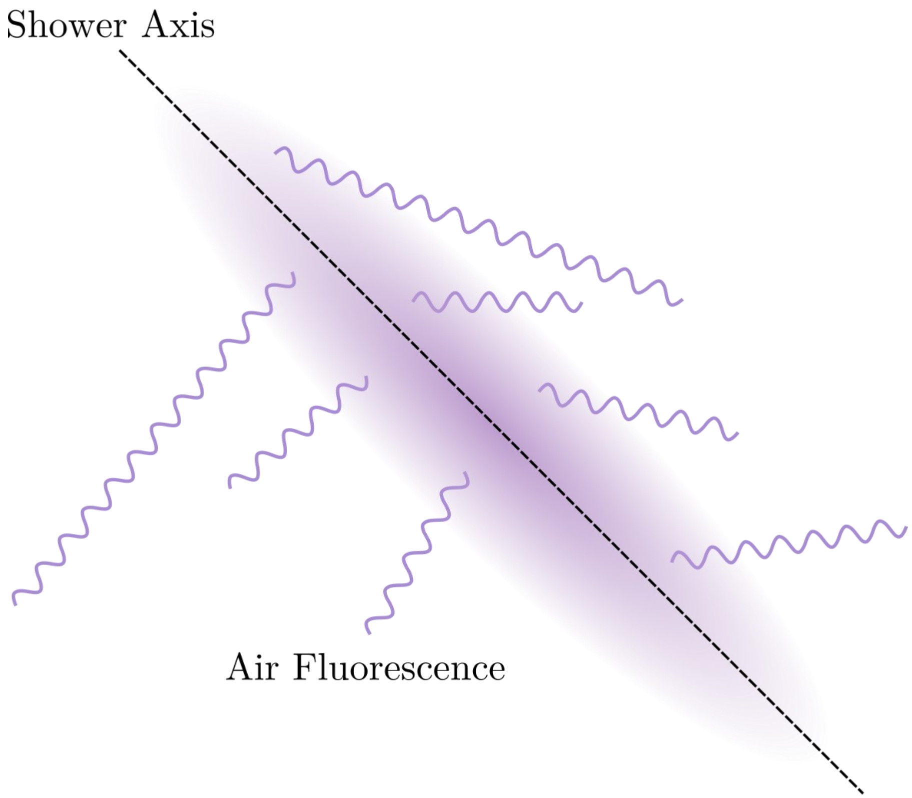
Electromagnetic (EM) Component :

- photons produced in the EAS from the decay of π^0
- Photons undergo pair-production
- Electrons undergo bremsstrahlung

Muonic Component :

- The $\pi^{\pm}$ may decay into muons and neutrinos
- Energy carried away from the EAS
  - Missing Energy of the EAS
  - Up to 10% of the primary cosmic ray energy

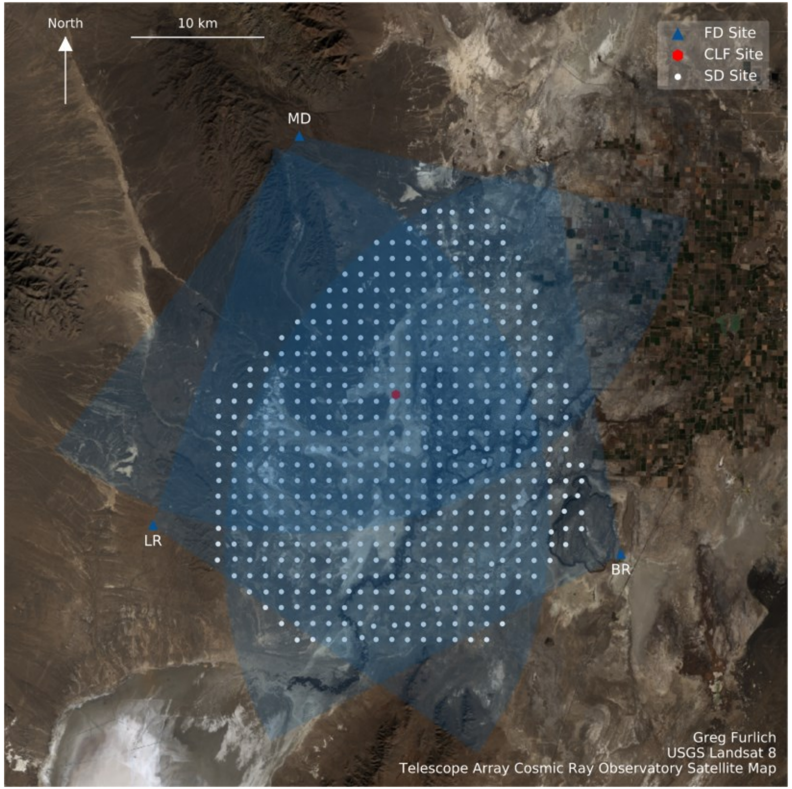
Air Fluorescence



- Charged particles in the EAS excite the molecular nitrogen in the atmosphere
- Molecular nitrogen recombines and emits UV light
- The amount of light generated is dependent on the number of charged particles in the EAS
- Amount of light observed is dependent on atmospheric scattering (Rayleigh and Mei) and ozone absorption

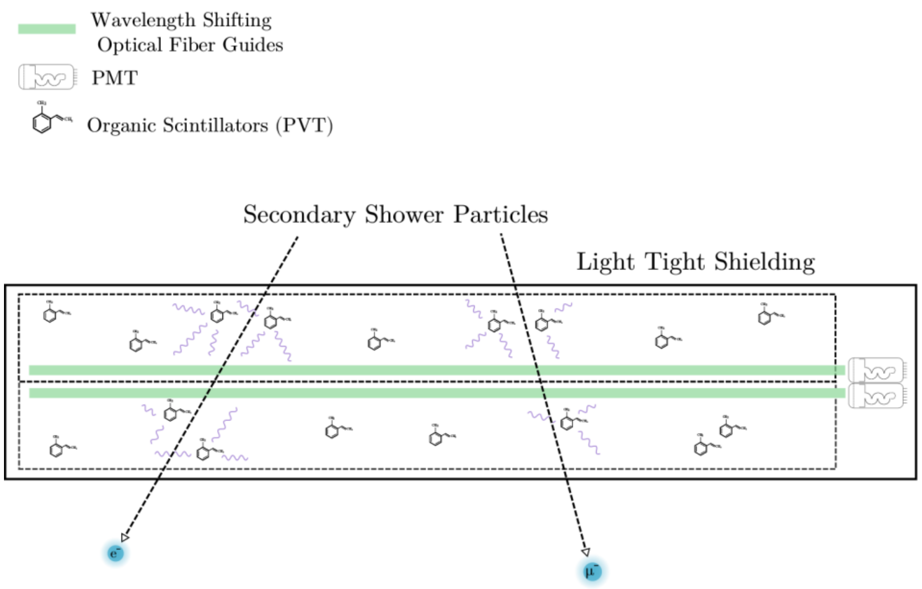
Telescope Array (TA) Cosmic Ray Observatory and Expansions, TAx4

Telescope Array (TA) Cosmic Ray Observatory



- Largest Cosmic Ray Observatory in the northern hemisphere
  - Covers 700 km^2 near Delta, UT
  - Hybrid detector for UHECRs
    - 507 Surface Detectors (SDs)
    - 3 Fluorescence Detectors (FDs) stations overlooking SD array
      - Black Rock (BR)
      - Long Ridge (LR)
      - Middle Drum (MD)

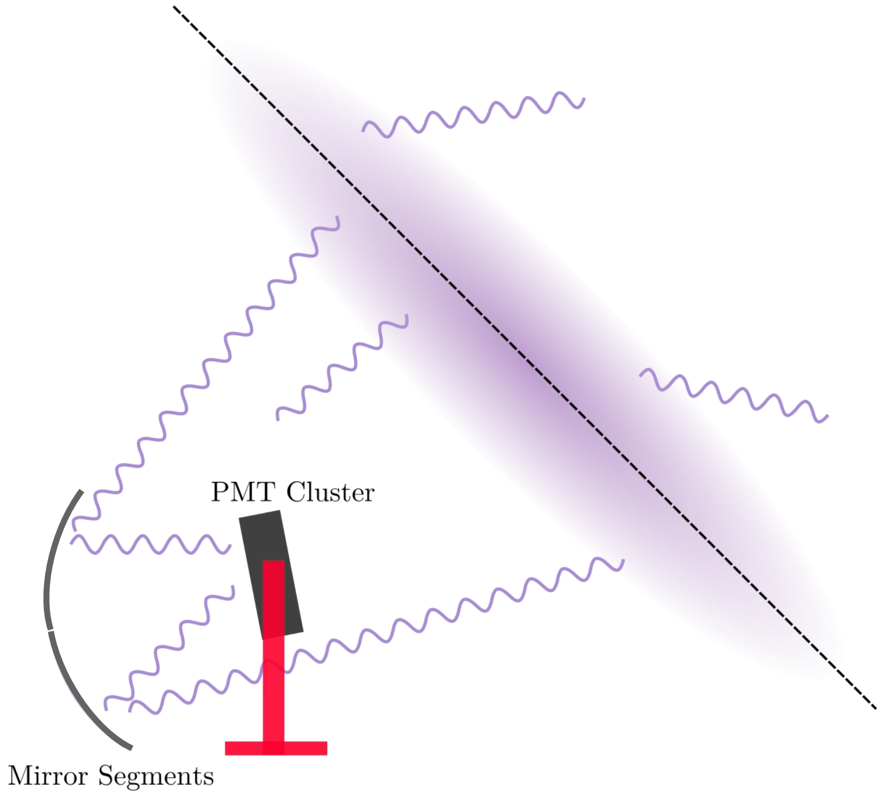
Surface Detectors (SDs)



- Two sheets of scintillating organic compound
- As charged particles pass through, the scintillating material produces light
- Amount of light is converted into a digital signal
- SDs sample the footprint of particles in the EAS
- Operate nearly 100% of time

TA SD in the Field

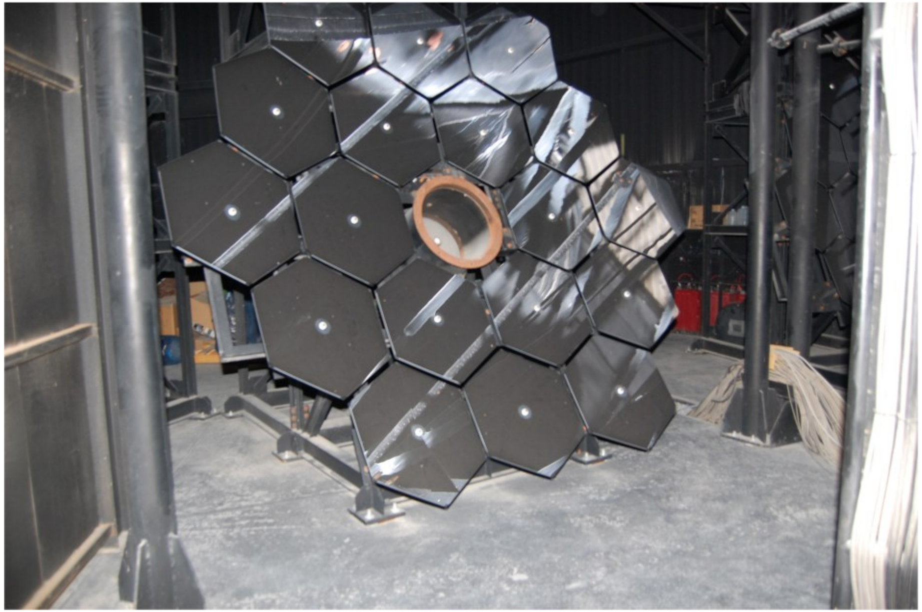
Fluorescence Detectors (FDs)



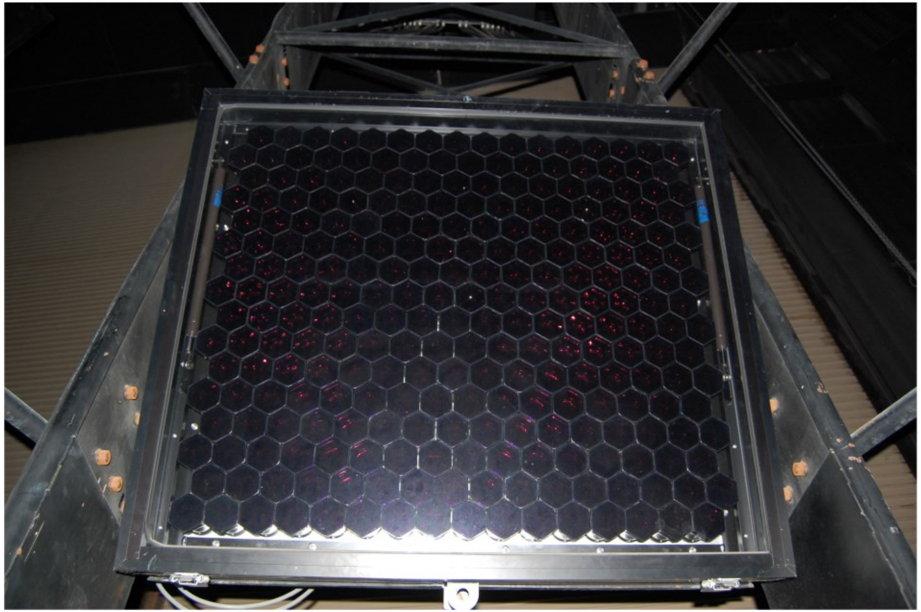
- EAS excites the molecular nitrogen in the atmosphere which emits light in the near UV (300-420 nm)
- The fluorescence light is collected using an array of mirrors onto a cluster of Photomultiplier Tubes (PMTs)
- Intensity of the light signal along the EAS track allows for reconstruction of the EAS charged particle profile
- Observes the energy deposited by the EAS in the atmosphere
- Operate roughly 10% of the time

Black Rock Fluorescence Telescopes

Primary Mirror



16x16 PMT Cluster



Black Rock FD Station

Expansion of Telescope Array, TAx4

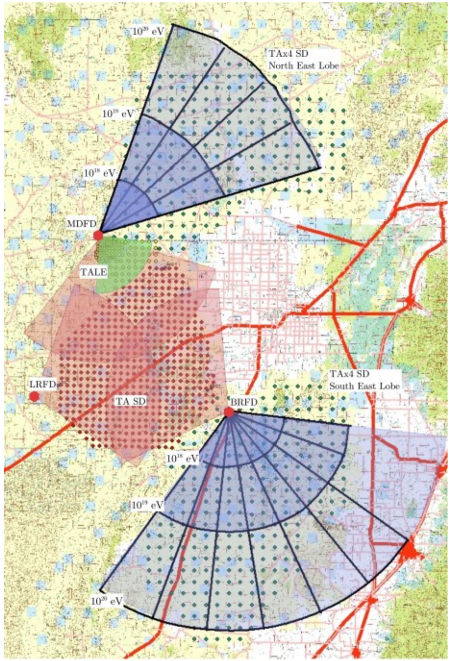
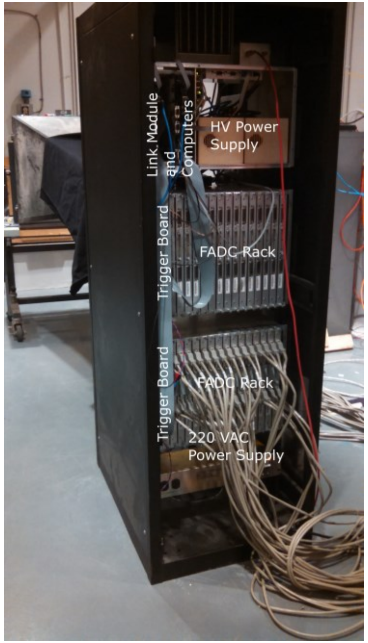


Image adapted from Bob Cady

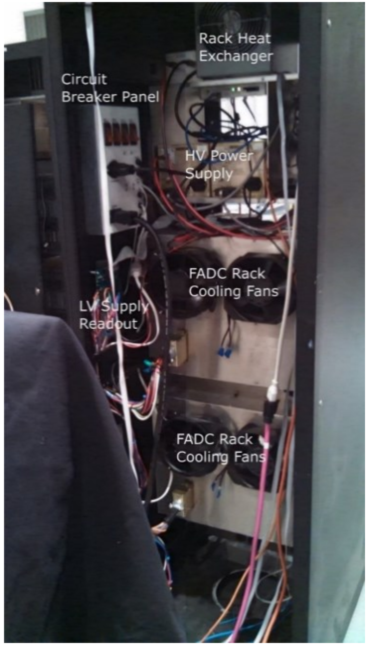
- Better observe a possible anisotropy of cosmic ray with E > 57 EeV in the northern hemisphere
- Quadruple the detection aperture of TA
- 500 new SDs
- Expansion of the Middle Drum (MD) and Black Rock (BR) FD stations overlooking the new surface detector array
  - 4 new telescopes at MD
  - 8 new telescopes at BR

Refurbishing and Testing the TAx4 FD Electronics Racks

Front



Back



- Refurbished 7 HiRes-II Fast Analog Digital Converters (FADCs) electronics racks
  - Control the operation, triggering, and read out of events in the telescopes
  - Upgraded components of the racks
- Tested racks in a darkroom with UVLED
- Tested 14 HiRes PMT clusters

TAx4 FD Deployment

Installing a PMT Cluster

Image Credit: John Matthews,
Telescope Array

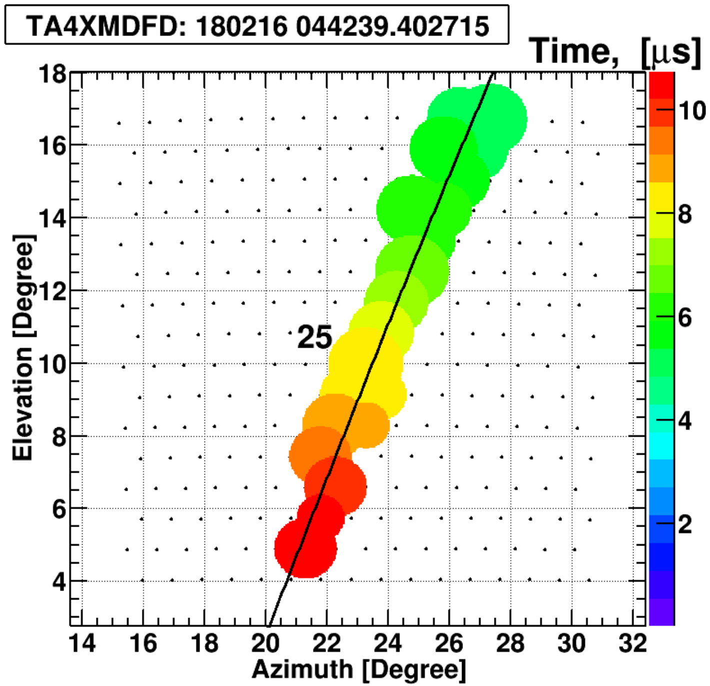
Wiring up the PMT Cluster

Wiring up the Refurbished Electronics Racks

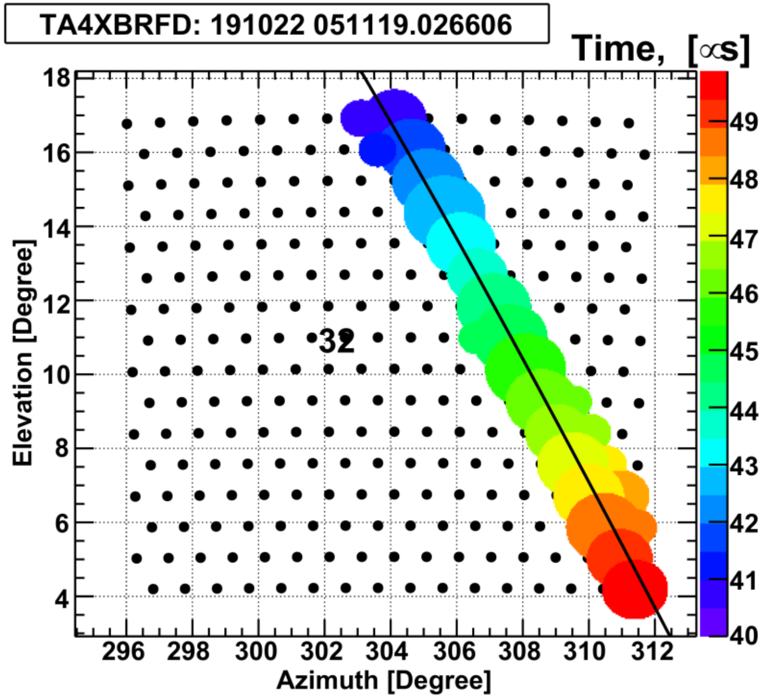
TAx4 Middle Drum FDs

TAx4 MD and BR FD First Light

TAx4 MD First Light

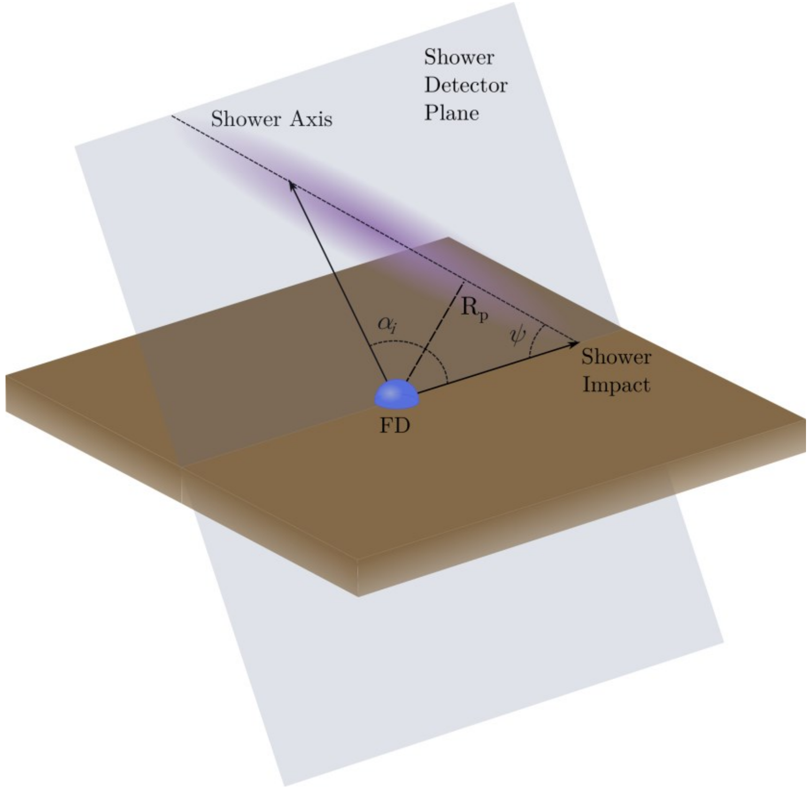


TAx4 BR First Light



Fluorescence Detection Event Reconstruction

Geometry Reconstruction



Shower Detector Plane (SDP) Calculation:

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{good}}} (\hat{n} \cdot \hat{v}_i)^2 N_{\mathrm{pe},i}$$

n : SDP normal vector

v : PMT pointing direction

N_{PE} : Photo-electrons per PMT

Timing Fit:

$$t_i = t_o + \frac{R_p}{c} \tan\left(\frac{\pi - \psi - \alpha_i}{2}\right)$$

R_p : Impact parameter

Ψ : Inclination angle in SDP

α : PMT pointing direction in the SDP

Charged Particle Profile

Shower Parameterization of Shower Charged Particles with the Gaisser-Hillas Function:

$$N_{\mathrm{ch}}(X) = N_{\max}\left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max}-X_0}{\lambda}} \exp\left(\frac{X_{\max} - X}{\lambda}\right)$$

N_{ch} : Charged Particles in EAS at depth X

N_{max} : maximum number of particles the shower creates

X_{max} : depth of shower maximum

X_0 : approximate start of the shower

λ : shower decay length.

Slant Depth:

$$X = \int \rho(r)dr$$

Calorimetric Energy Reconstruction

Shower Energy Deposition:

$$\frac{dE_{\mathrm{dep}}(X)}{dX} = \alpha(X)_{\mathrm{eff}} N_{\mathrm{ch}}(X)$$

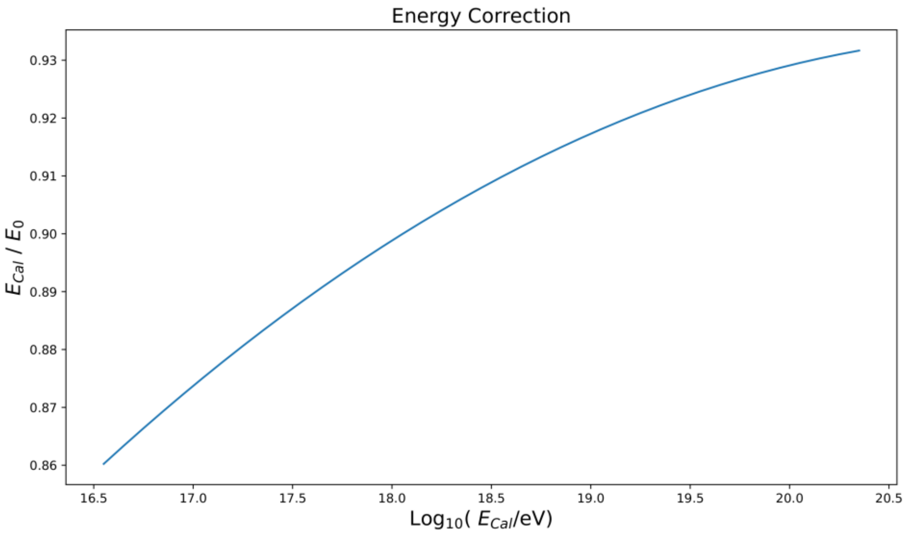
$\alpha(X)_{\mathrm{eff}}$: mean ionization energy loss of the charged particles to the atmosphere

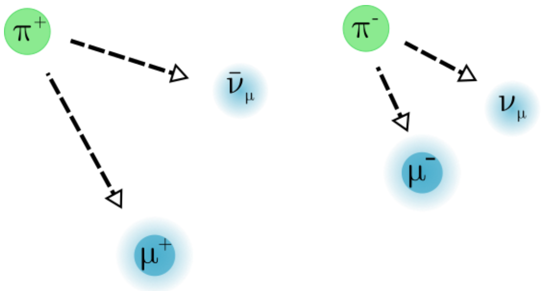
Calorimetric Energy:

$$E_{\mathrm{cal}} = \int_{X_0}^{\infty} \frac{dE_{\mathrm{dep}}(X)}{dX} dX$$

Missing Energy Correction

Account for energy carried away from EAS in muons and neutrinos and was not deposited in the atmosphere.

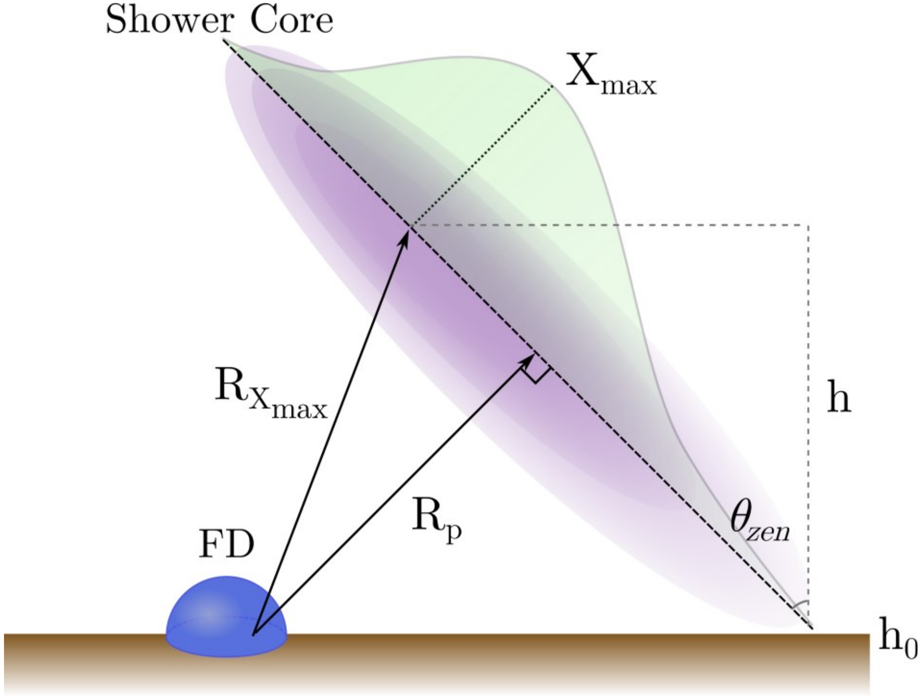




Energy Correction Function:

$$\frac{E_{\mathrm{cal}}}{E_0} = -0.5717 + 0.1416 \log_{10}(E_{\mathrm{cal}}/\mathrm{eV}) - 0.003328 \log_{10}(E_{\mathrm{cal}}/\mathrm{eV})^2$$

Distance to Shower Max, R_{Xmax}



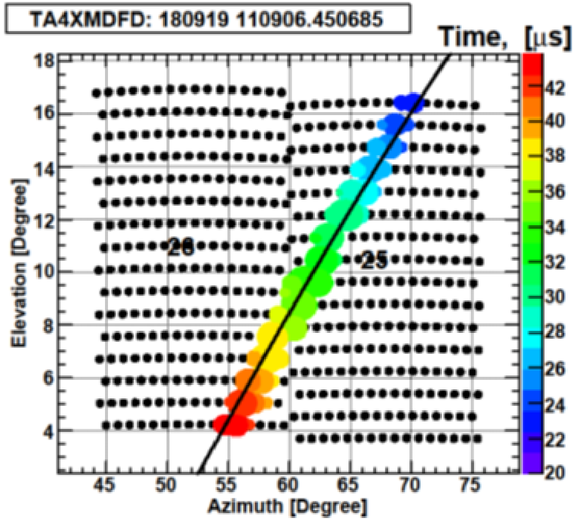
- R_p is a construct of the geometry reconstruction
- X_{max} is the depth where the EAS is maximally developed
- R_{Xmax} is a new parameter to gauge the detector's sensitivity to the shower brightness

$$h(X_{\max}, \theta_{\text{zen}}, h_o) = X^{-1}[X_{\text{top}} - X_{\max}\cos(\theta_{\text{zen}})] - h_0$$

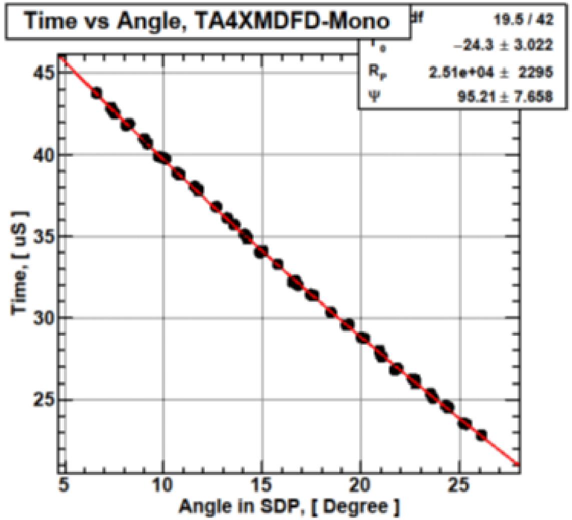
X_{top} = 1033.2 g/cm^2

TAx4 Good Event

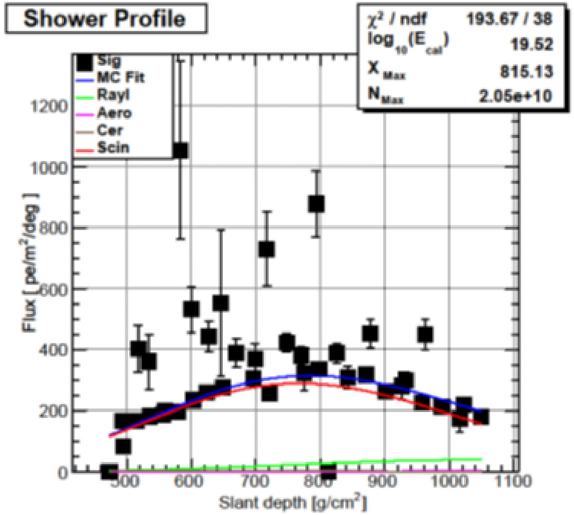
EAS Track



Event Timing



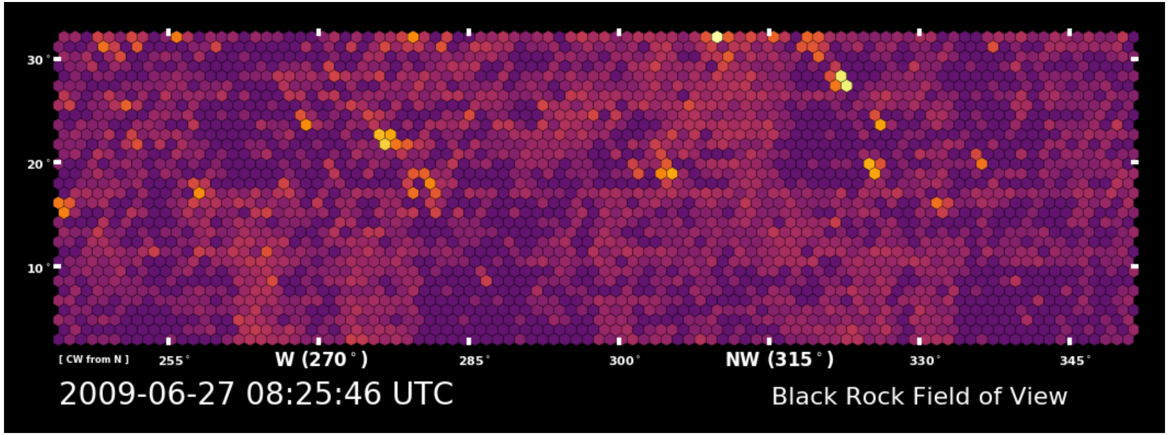
Event Profile



Novel Machine Learning Weather Classification

Weather Classification using FADC Pedestals

- Previous weather classification method is having operators at MD station go outside every hour and observe the night sky.
  - Assumed weather was identical at all 3 FD stations
- Implement a novel method that uses the BR and LR PMT FADC pedestals of each PMT to create false color animations of the night sky for each FD data part.



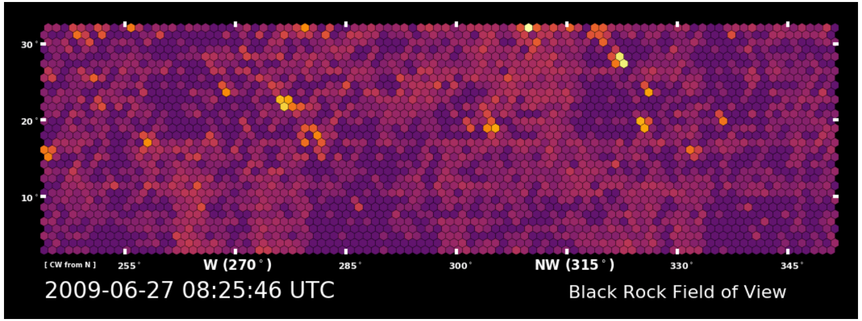
Big Dipper

Machine Learning Weather Classification

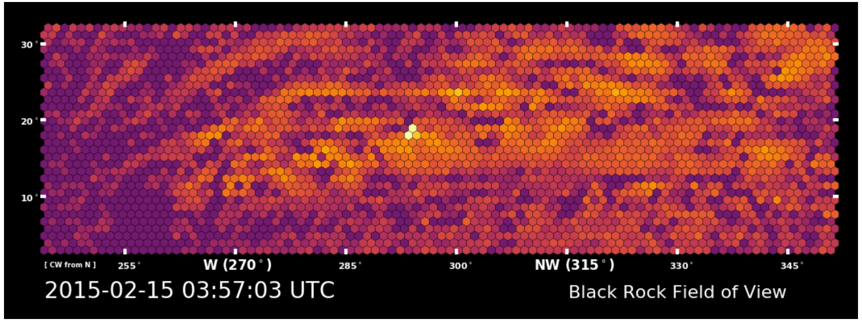
- Each FD data part was fed through a trained neural network for classification for both BR and LR.
    - Uniform classification method
    - Better timing resolution
- Designed four neural networks with increasing complexity to better match the input data
    - Recurrent Convolution Neural Network (RCNN)
        - Convolution layers train on spatial information in the animations
        - Recurrent Layers train on temporal information in the animations

Weather Classes

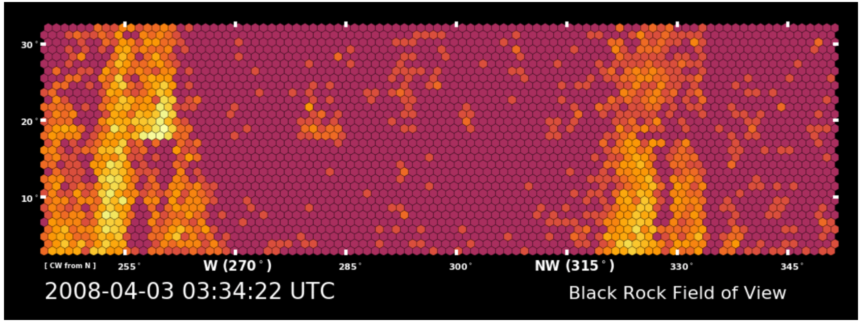
Clear



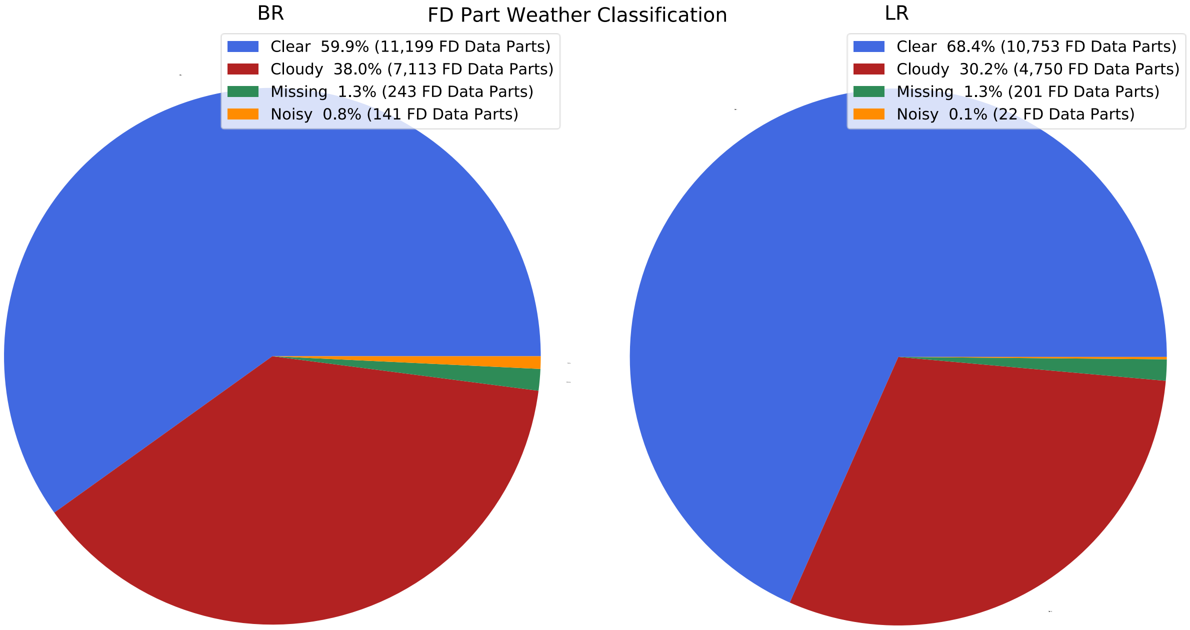
Cloudy



Noisy

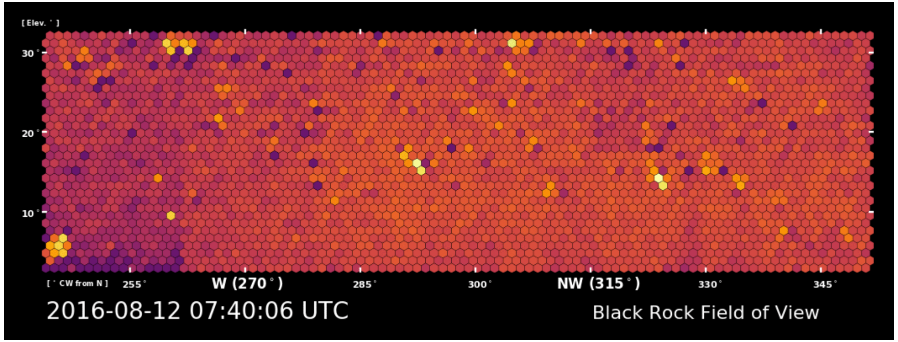


Data Parts Weather Classification Results

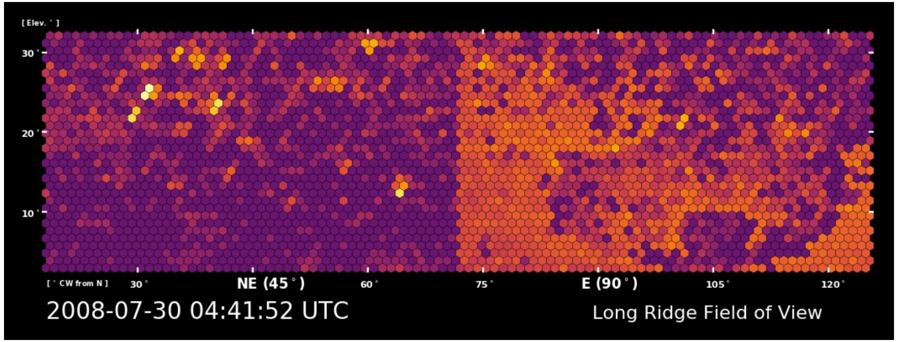


LR has 10% more Clear FD data parts than BR

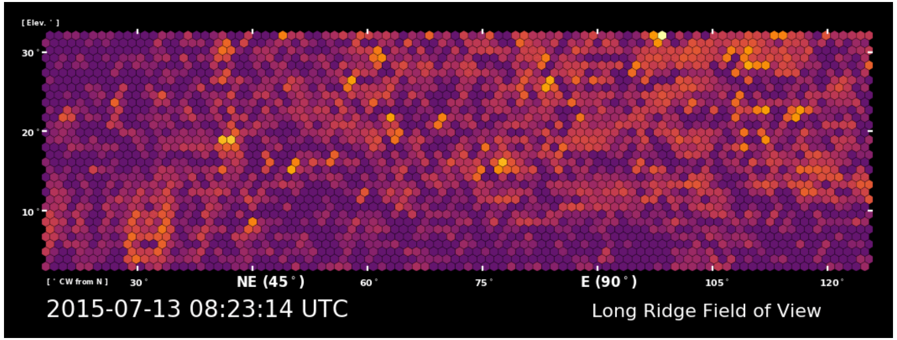
Other Interesting Pedestal Events



2016 Perseid Meteor Shower



Transient Luminous Event called ELVES



Aurora Borealis

Monte Carlo (MC) Simulated Events

Monte Carlo (MC) Simulated Events

- MC events are populated with random geometry, energy, and compositions according to selection distributions and are *thrown* around the detector
- MC has two purposes:
  - Event reconstruction resolution of comparing the thrown *true* values to the reconstructed values
  - Determine the detection aperture
    - Good Data/MC comparisons to justify that the MC events represent the observed events

Acceptance

$$\text{Acceptance(E)} = \frac{N(E)_{\text{Recon.}}}{N(E)_{\text{Thrown}}}$$

Aperture

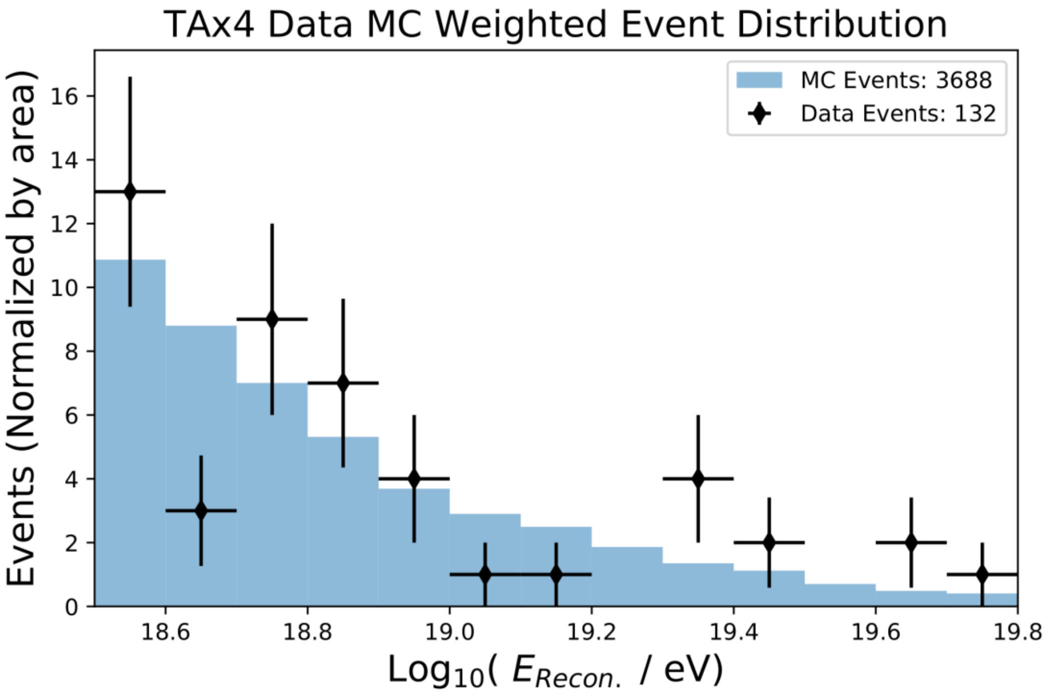
$$A\Omega(E) = A_0\Omega_0 \times \text{Acceptance}(E)$$

MC Simulation Procedure

I. Set MC configuration (thrown volume, calibration, etc.)
II. Set MC event parameters (energy, geometry, shower profile) and throw event
III. Simulate light production
IV. Simulate light propagation
V. Simulate detector optics
VI. Simulate detector electronics and triggering
VII. Read out triggered MC events

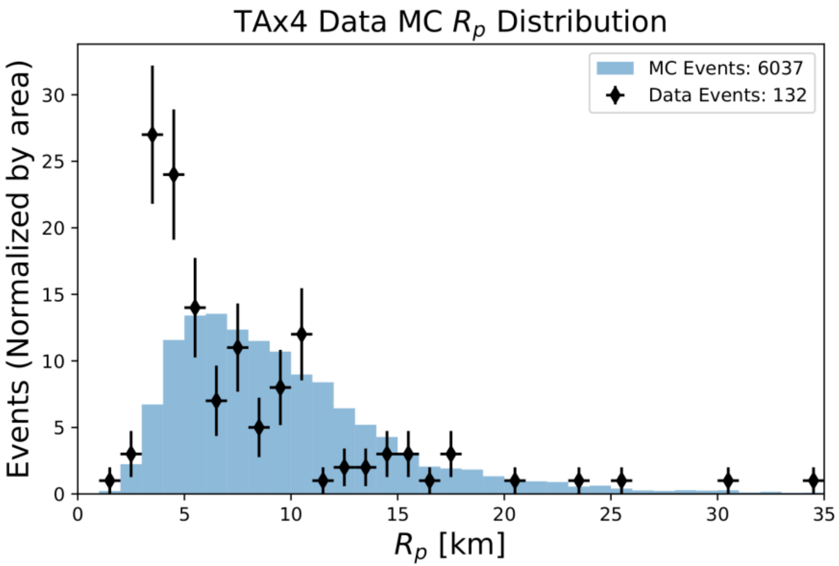
TAx4 Data/MC (1/2)

Energy



TAx4 Data/MC (2/2)

R_p



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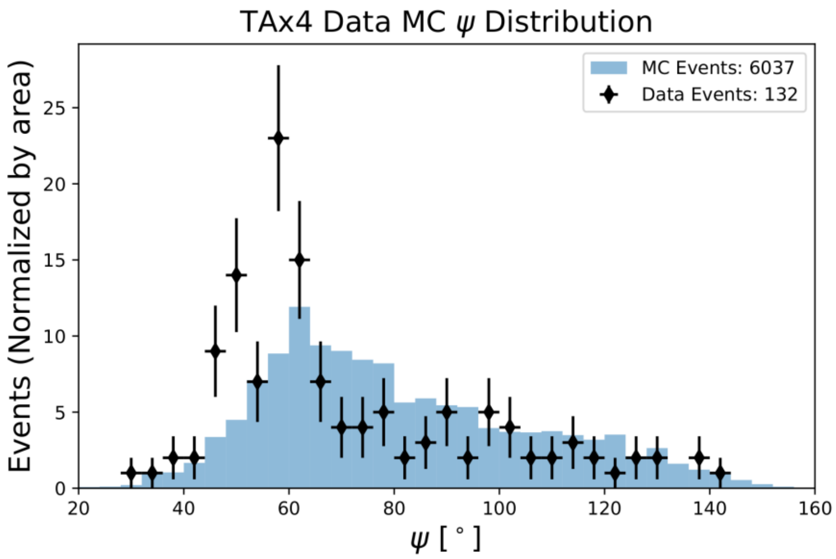
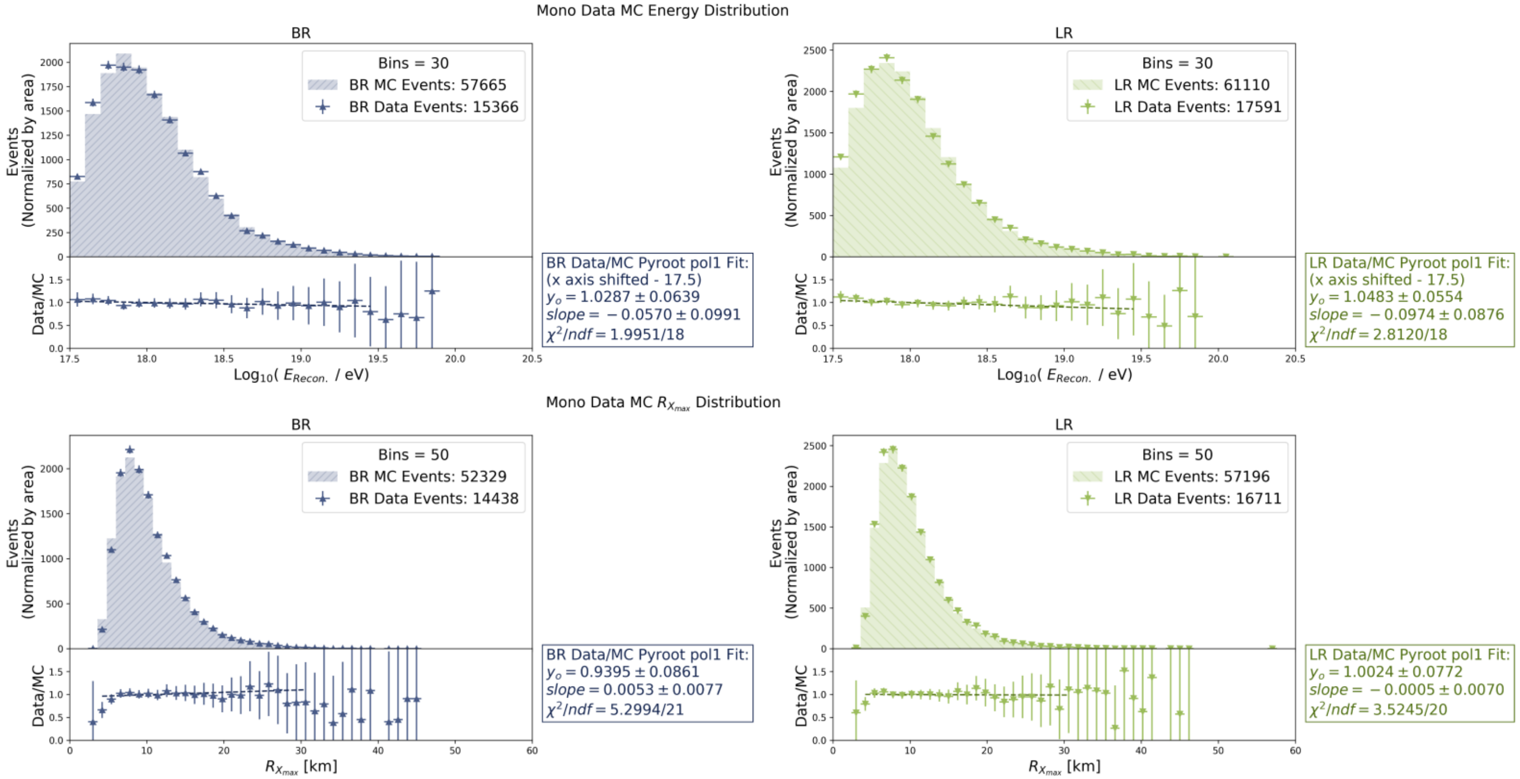


BR and LR Data/MC (1/2)

Energy

R_{Xmax}



BR and LR Data/MC (2/2)

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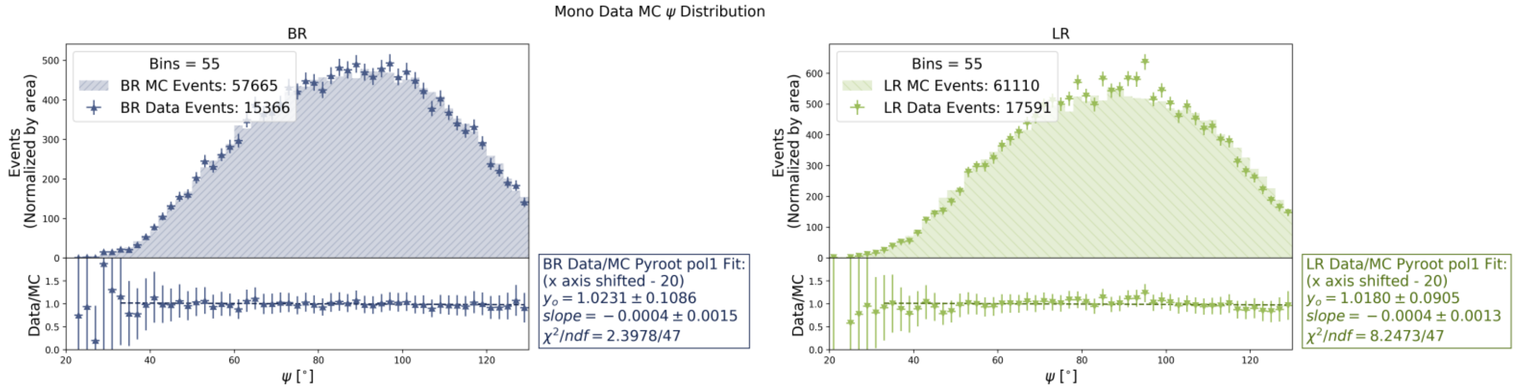
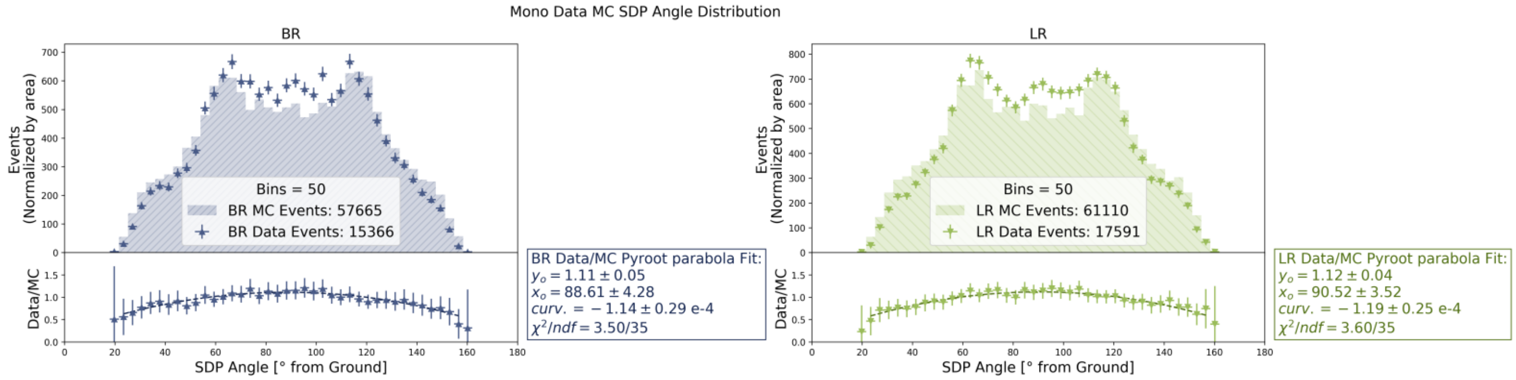


θ_{SDP}

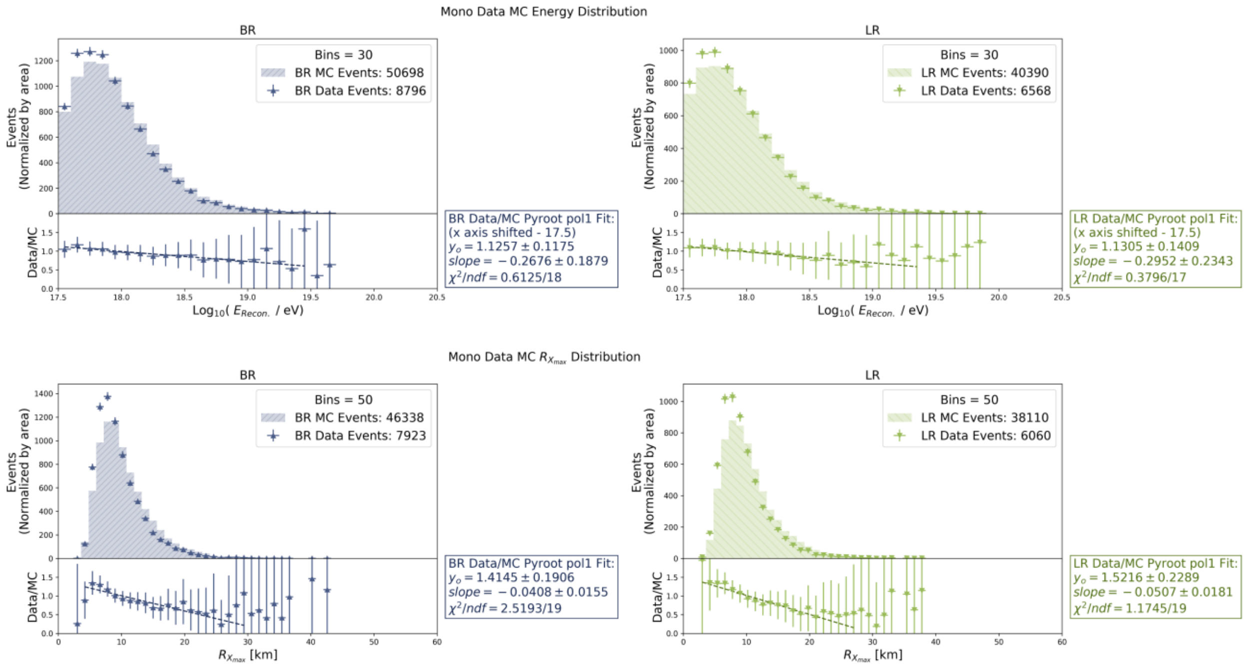


BR and LR Bad Weather Data/MC

Using the machine learning weather classifications and selecting only the bad weather events for a Data/MC comparison.

Energy

R_{Xmax}



TAx4 Preliminary Spectrum

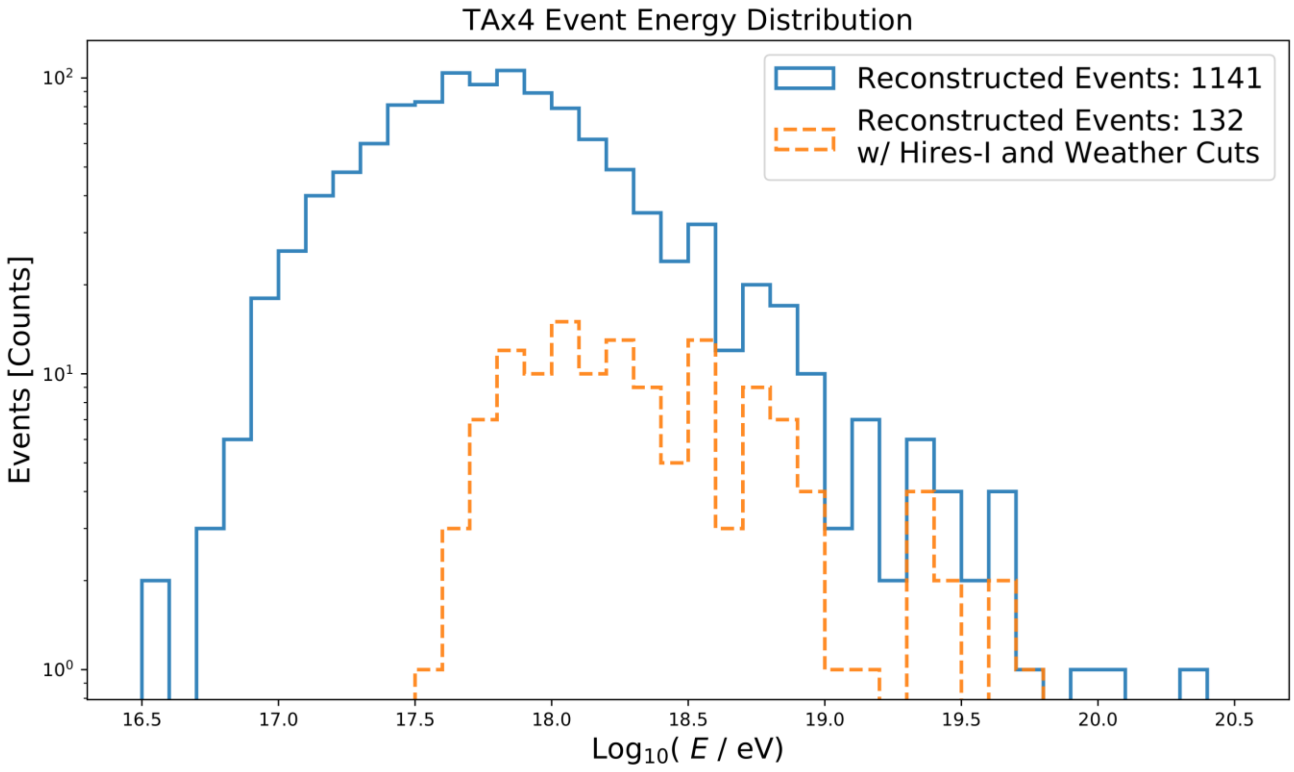
Cosmic Ray Spectrum

- Differential flux of particles as a function of energy
- Represents the energy density of cosmic rays in the universe
- Features in the spectrum are insight into cosmic ray populations

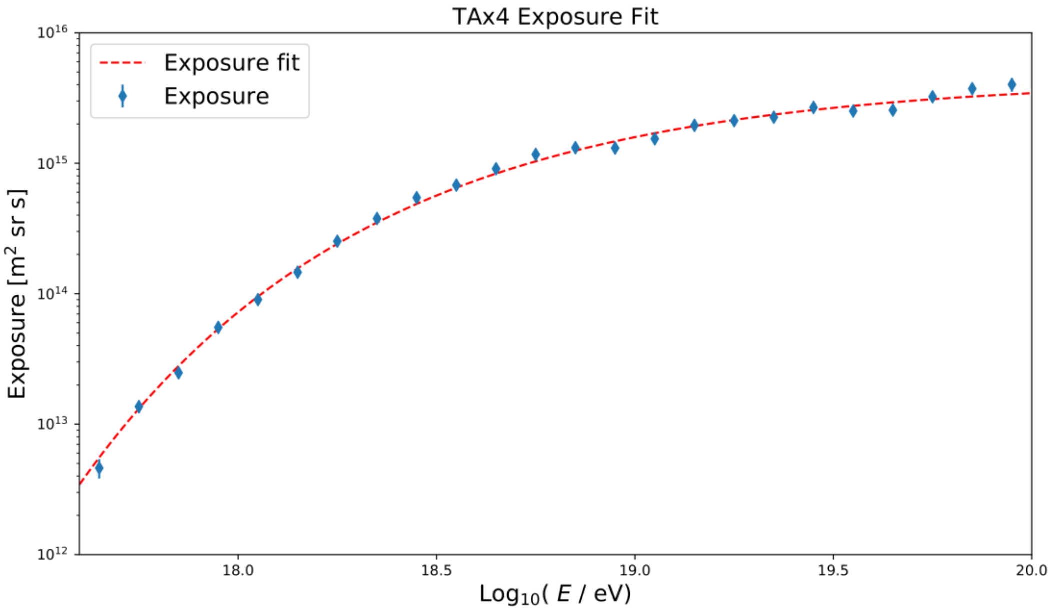
$$J(E_i) = \frac{N(E_i)}{\Delta E_i \, A\Omega(E_i) \, T}$$

$N(E_i)$:	Event Distribution
ΔE_i :	Bin Size
$A\Omega(E_i)$:	Detector Aperture
T :	Detector Ontime
$\xi(E_i) = A\Omega(E_i)T$	Detector Exposure

TAx4 Event Distribution



TAx4 Exposure

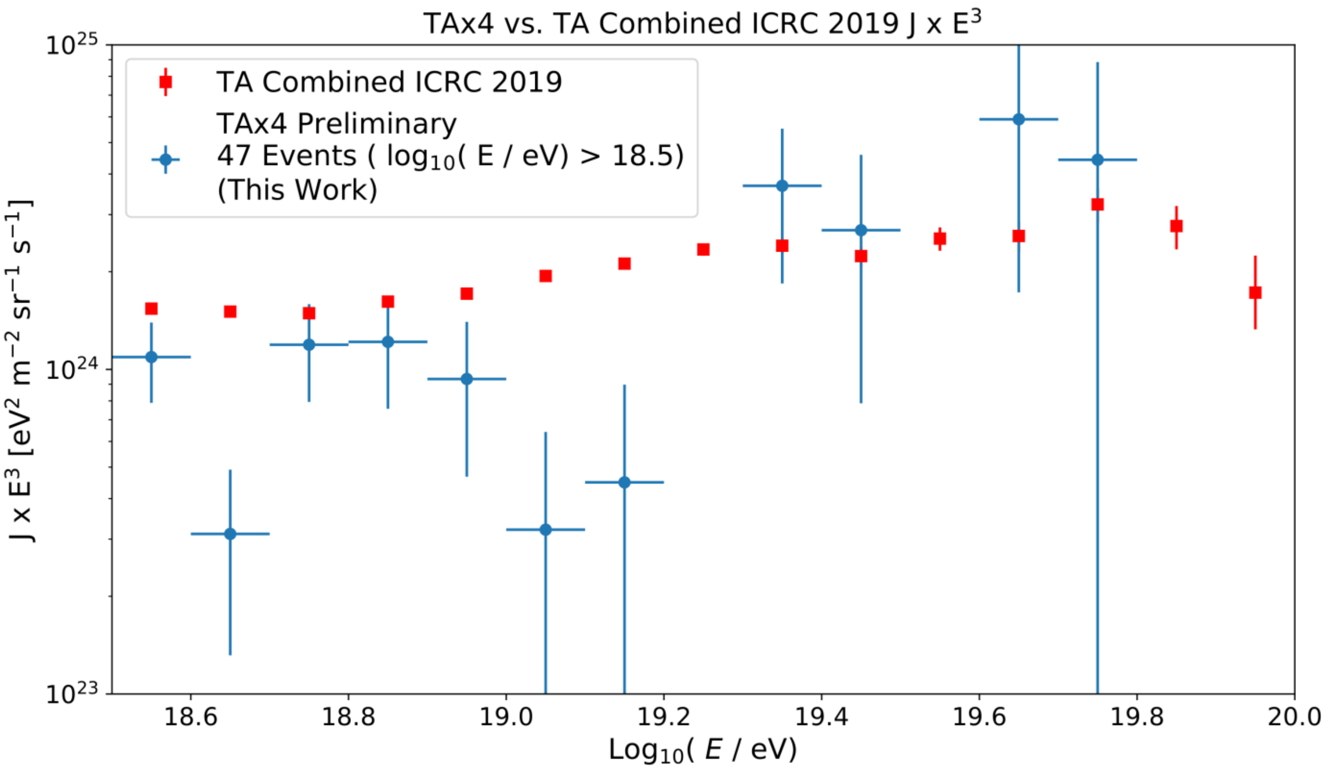


Exposure Fit Function

$$\log_{10}\xi(E) = p_1\left(1 - \exp\left[-\frac{\varepsilon - p_2}{p_3}\right]\right)$$

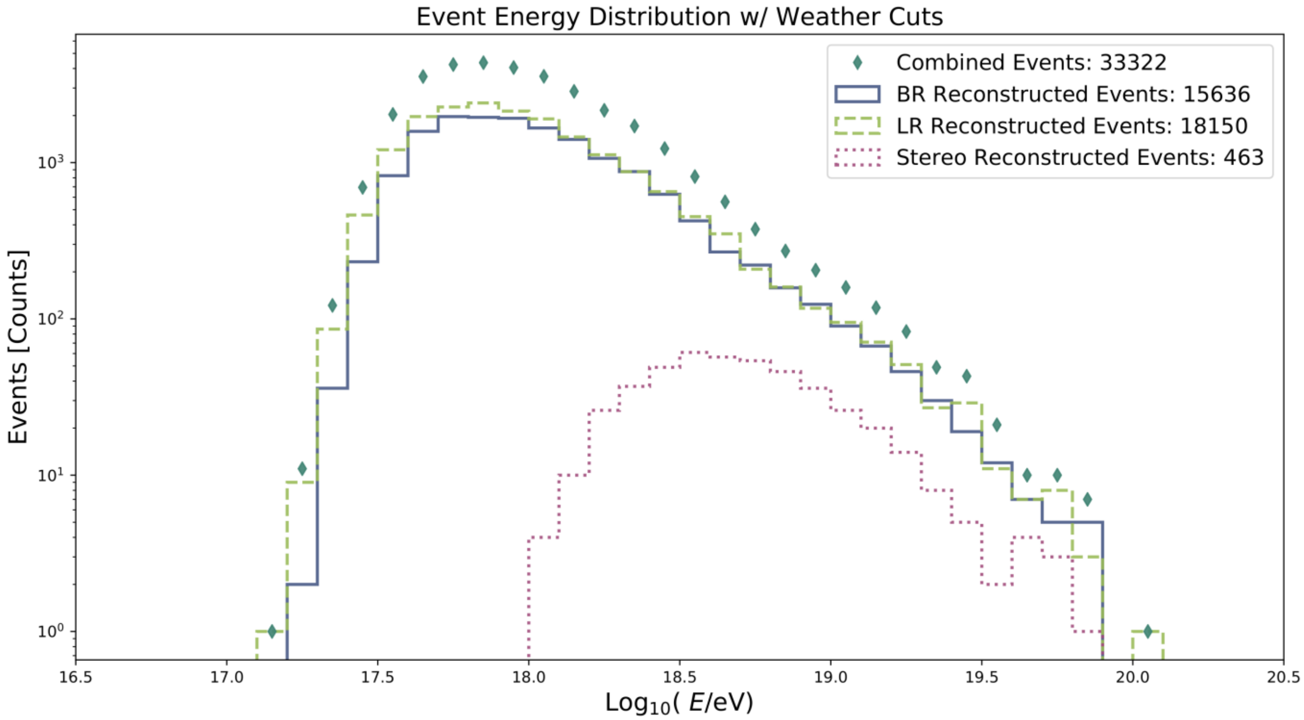
$$\varepsilon = \log_{10}(E/\mathrm{eV})$$

TAx4 Preliminary Spectrum



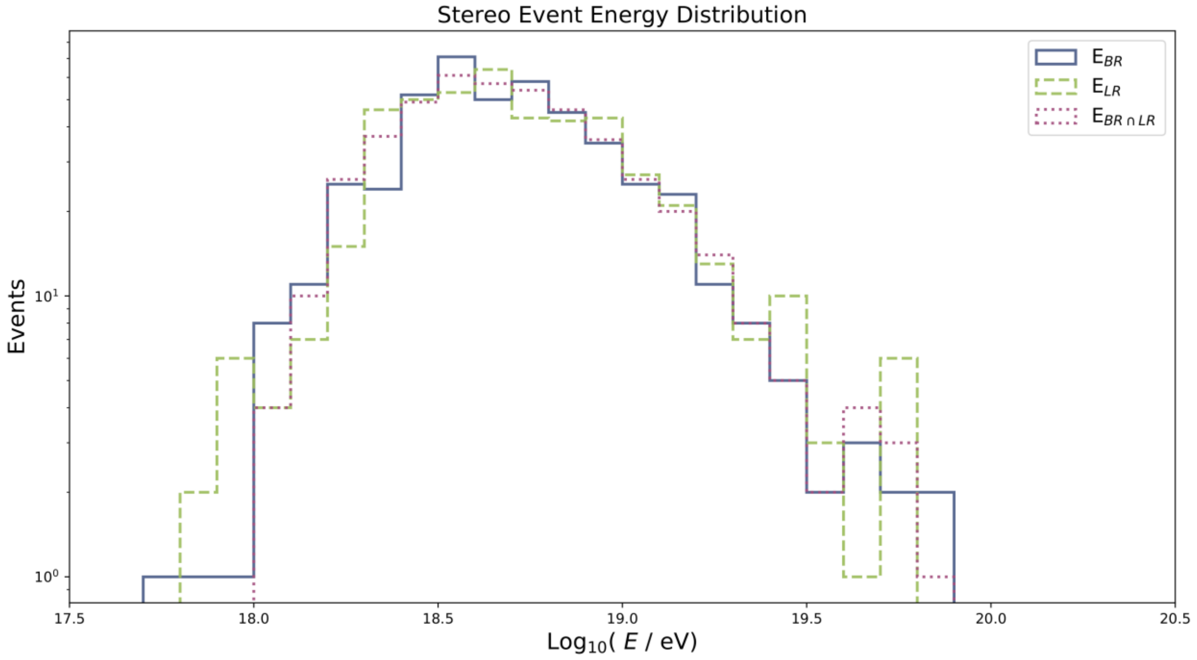
10 year BR and LR Monocular Combined Spectrum and Observation of the GZK Suppression

Mono Combined Event Distribution



$$N(E_i)_{\text{Combined}} = N(E_i)_{\text{BR}} + N(E_i)_{\text{LR}} - N(E_i)_{\text{BR}\cap\text{LR}}$$

Stereo Events

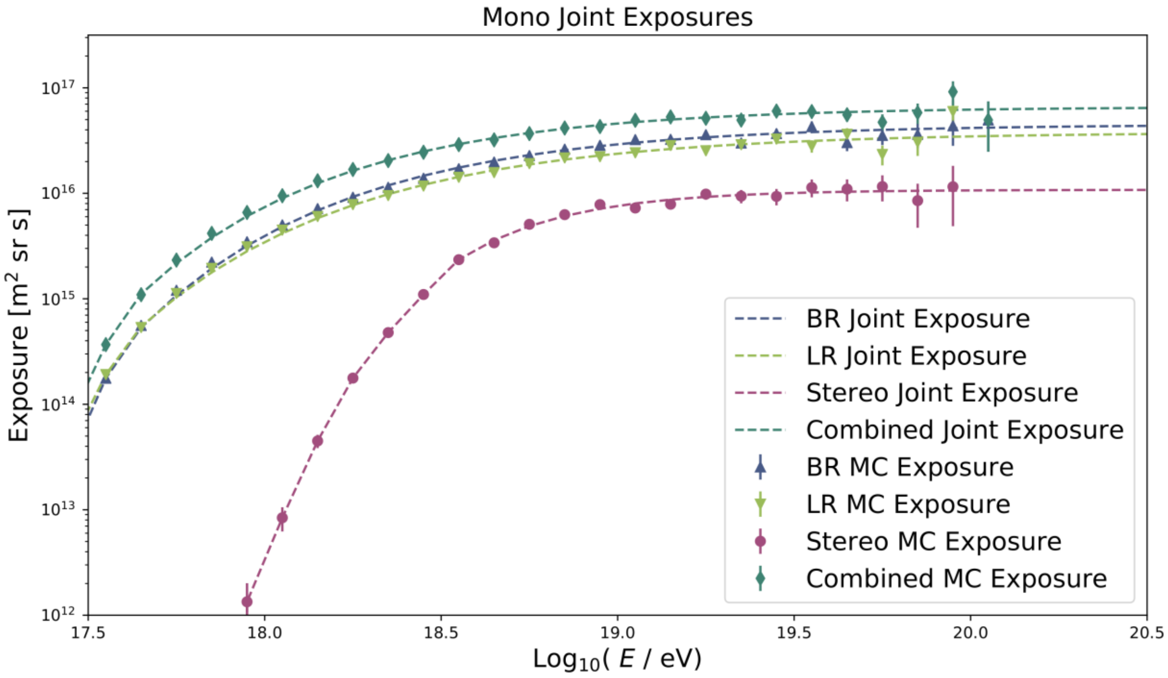


Stereo Energy

$$E_{\text{Stereo}} = E_{\text{BR}\cap\text{LR}} = \sqrt{E_{\text{BR}} \times E_{\text{LR}}}$$

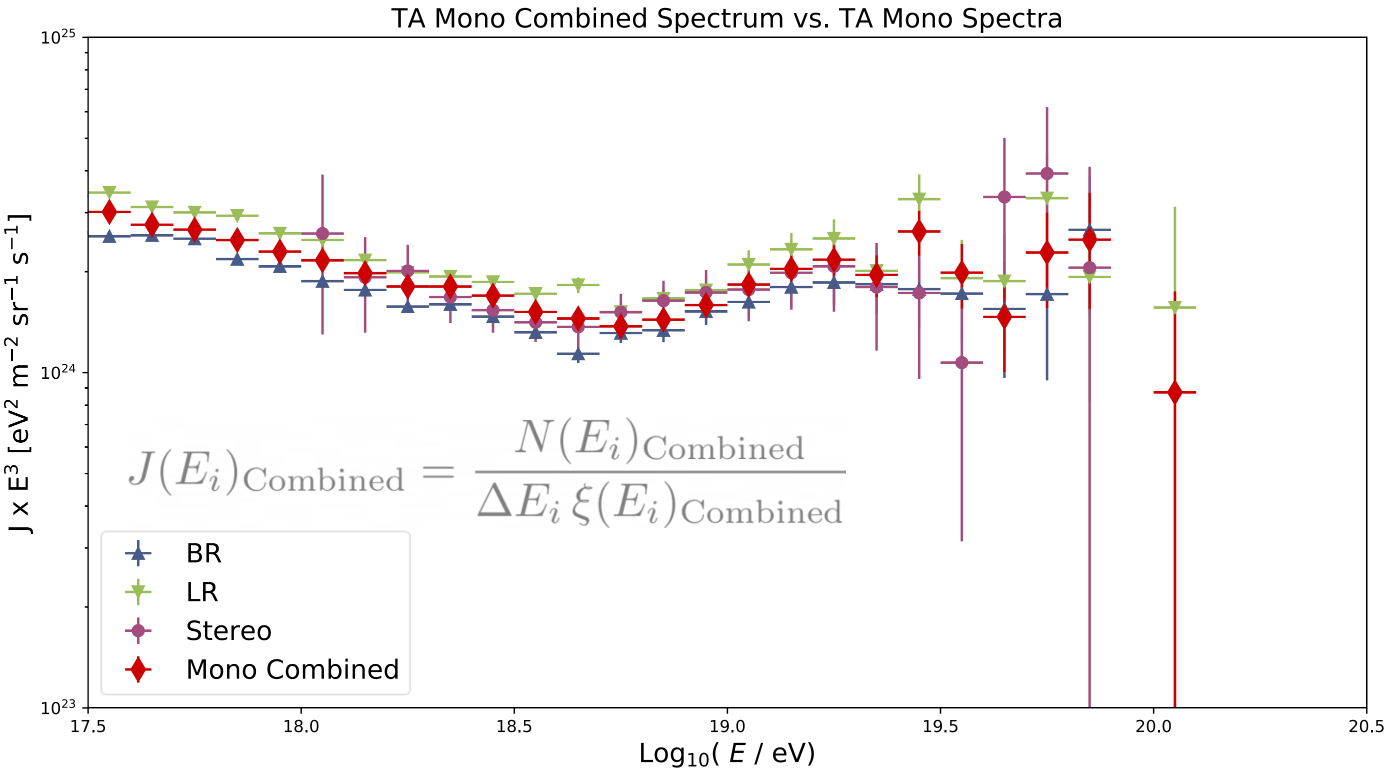
Mono Combined Exposure

Joint exposure using calculated exposure and fit exposure

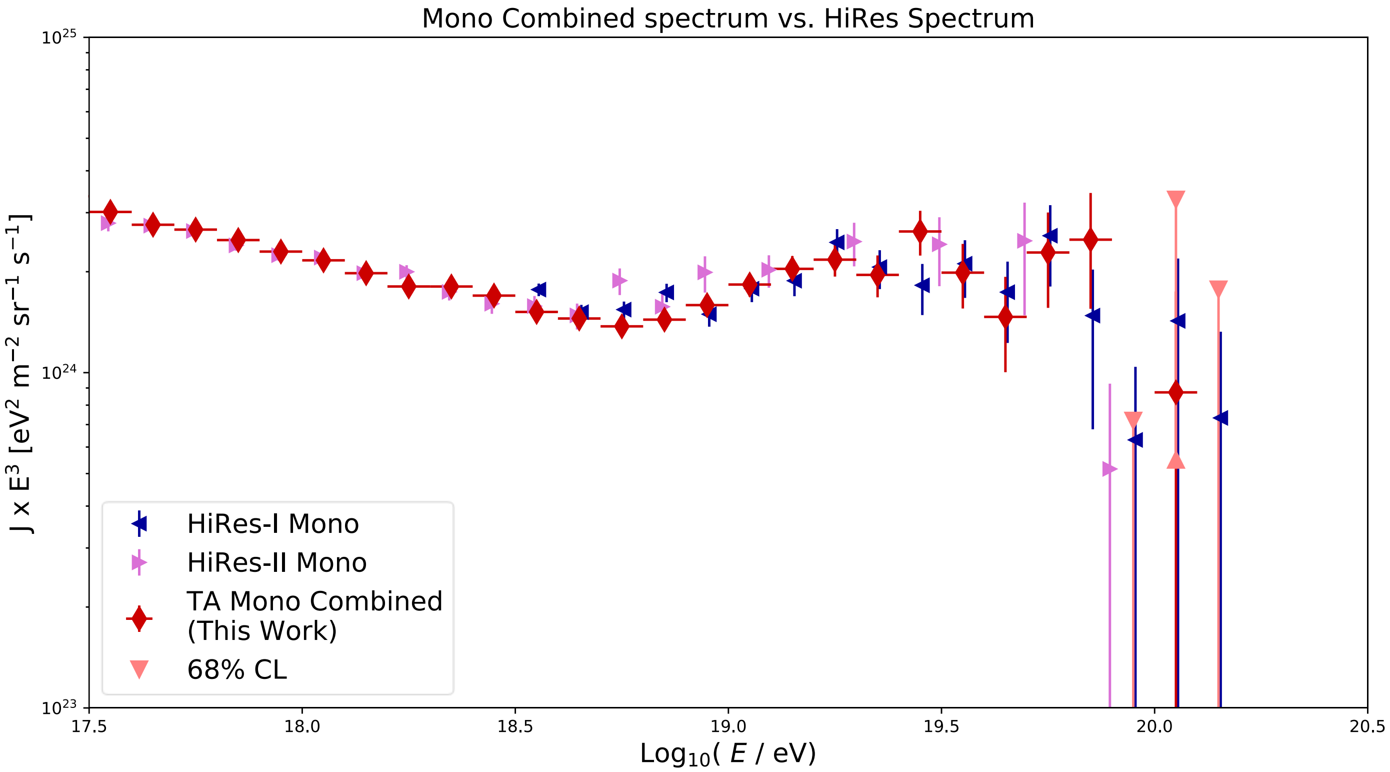


$$\xi(E)_{\mathrm{Combined}} = A\Omega(E_i)_{\mathrm{BR}}\,T_{\mathrm{BR}} + A\Omega(E_i)_{\mathrm{LR}}\,T_{\mathrm{LR}} - A\Omega(E_i)_{\mathrm{BR}\cap\mathrm{LR}}\,T_{\mathrm{BR}\cap\mathrm{LR}}$$

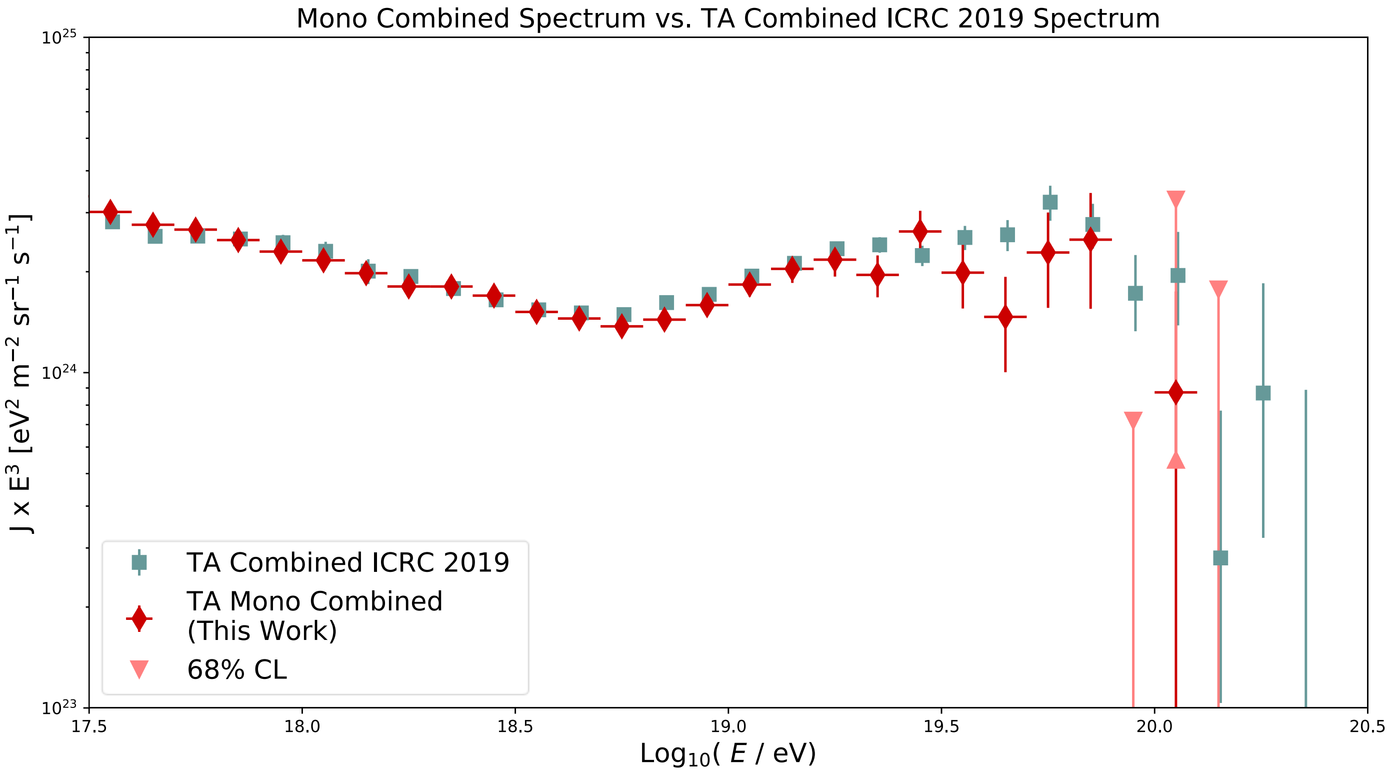
Mono Combined Spectrum vs Mono Spectra



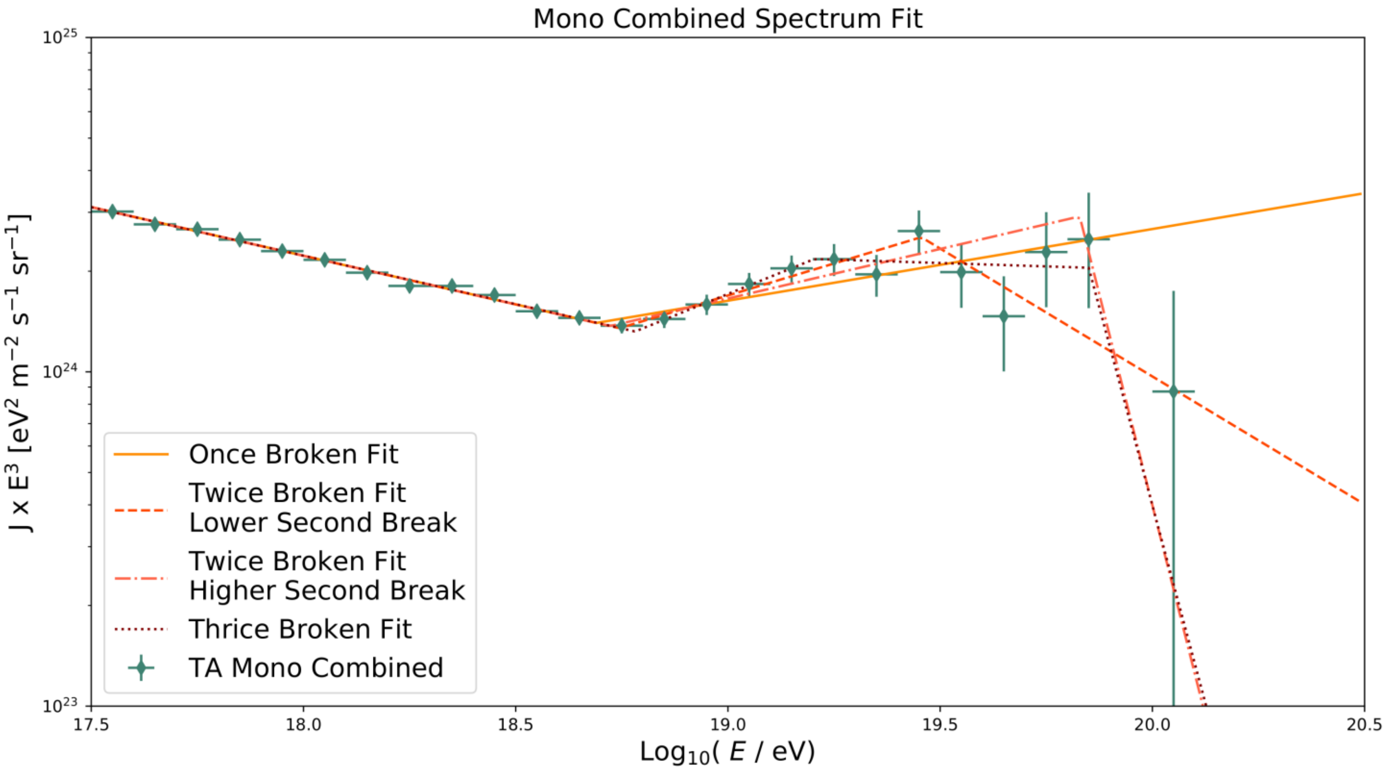
Mono Combined Spectrum vs. HiRes



Mono Combined Spectrum vs. TA Combined ICRC 2019



Fitting the Spectrum with Broken Power Laws



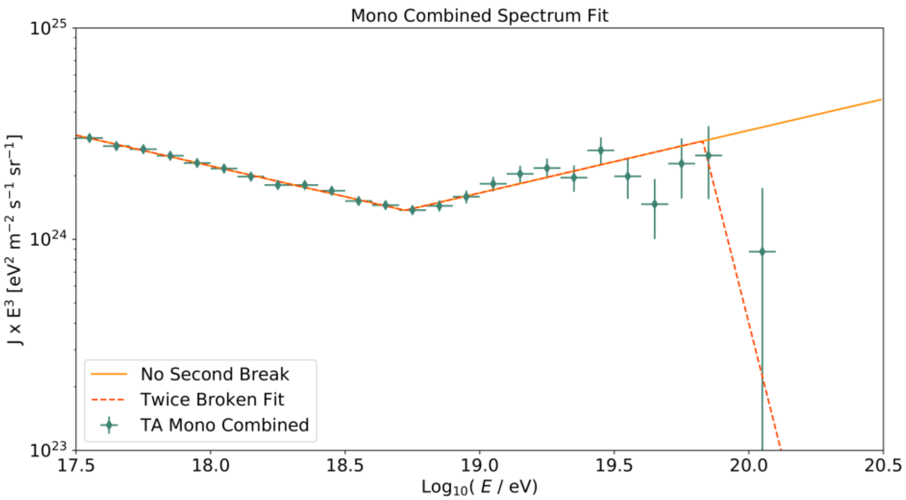
Spectrum Broken Power Law Fit Results

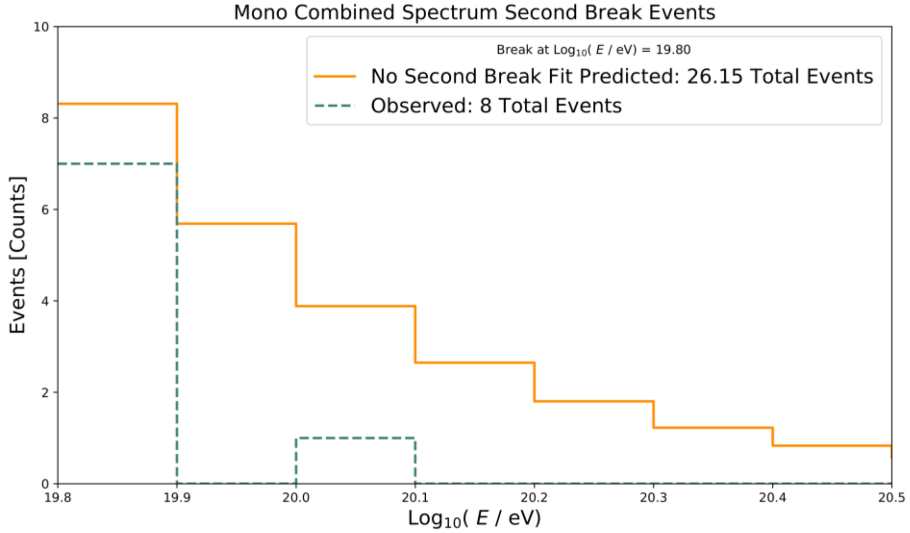
	$J(E)_{\text{Once Broken}}$	$J(E)_{\text{Twice Broken}}$, Lower E_2	$J(E)_{\text{Twice Broken}}$, Higher E_2	$J(E)_{\text{Thrice Broken}}$
$J(\text{E} = 10^{18}$ eV)	2.22 ± 0.01	2.22 ± 0.01	2.22 ± 0.01	2.23 ± 0.01
$\times 10^{-30}$ eV^{-1} m^{-2} sr^{-1} s^{-1}				
γ_1	-3.29 ± 0.01	-3.29 ± 0.01	-3.29 ± 0.01	-3.29 ± 0.01
$\log_{10}(E_1$ / eV)	18.68 ± 0.04	18.74 ± 0.03	18.72 ± 0.05	18.78 ± 0.04
γ_2	-2.79 ± 0.05	-2.62 ± 0.06	-2.70 ± 0.05	-2.49 ± 0.15
$\log_{10}(E_2$ / eV)	-	19.46 ± 0.10	19.83 ± 0.04	19.20 ± 0.11
γ_3	-	-3.77 ± 0.41	-8.04 ± 2.74	-3.04 ± 0.19
$\log_{10}(E_3$ / eV)	-	-	-	19.850 ± 0.001
γ_3	-	-	-	-7.74 ± 2.43
$\text{D}_{\text{Poisson}}$ / ndf	43.45 / 26	22.69 / 24	23.29 / 24	17.74 / 22

- $J(E)_{\text{Twice Broken}}$ higher E_2 agrees with previous measurements
- $J(E)_{\text{Thrice Broken}}$ has the best deviance compared to the other fits.
  - Suggests another break besides the ankle and GZK suppression at $\log_{10}(E\ /\text{eV}) = 19.2$

Observation of the GZK Suppression

Using the higher E_2 twice broken power law fit since it is in agreement with previous results





GZK Suppression Significance

Poisson Probability

$$P_{\mathrm{GZK}} = \sum_{n=0}^{N_{\mathrm{Observed}}} P_{\mathrm{Poisson}}(n, N_{\mathrm{Expected}})$$

Two-tailed Sigma significance

$$1 - P_{\mathrm{GZK}} = F(\mu + n\sigma) - F(\mu - n\sigma) = \mathrm{erf}\left(\frac{n}{\sqrt{2}}\right)$$

F is a normal distribution of mean , μ, and standard deviation σ

	$J(E)_{\mathrm{Twice\ Broken}}$ Lower E_2	$J(E)_{\mathrm{Twice\ Broken}}$ Higher E_2
$\log_{10}(\mathrm{E}_2 / \mathrm{eV})$	19.46 ± 0.10	19.83 ± 0.04
N_{Expected}	96.88	26.15
N_{Observed}	49	8
P_{GZK}	5.82×10^{-8}	3.37×10^{-5}
σ_{GZK}	5.42	4.15

Integral Flux and $E_{1/2}$

Cosmic Ray Integral Flux :

$$I(E) = \int_E^\infty J(E')dE'$$

$E_{1/2}$ calculation:

$$\log_{10}(\mathrm{E}_{1/2} / \mathrm{eV}) = \log_{10}(\mathrm{E}_2 / \mathrm{eV}) + \frac{1}{\gamma_2 - \gamma_3}\log_{10}\left(2\frac{\gamma_2 + 1}{\gamma_3 + 1}\right)$$

$E_{1/2}$ is where the integral flux has halved compared an unbroken integral flux past E_2.
Provides an astrophysical interpretation of the GZK suppression energy threshold.

	$J(E)_{\text{Twice Broken}}$ Lower E_2	$J(E)_{\text{Twice Broken}}$ Higher E_2	TA SD ICRC 2019	HiRes
$\log_{10}(\mathrm{E}_{1/2} / \mathrm{eV})$	19.51 ± 0.12	19.77 ± 0.04	19.79 ± 0.04	19.73 ± 0.07

Conclusion – Give me a (spectrum) break!

- TAx4 FD was refurbished, tested, deployed, and first light was collected
- A preliminary spectrum using the first year of TAx4 MD FD data was calculated
  - Agreement with previous measurements
  - TAx4 FD will work well for calculating the TAx4 SD energy scale with hybrid events
- A novel machine learning weather classification method was implemented for BR and LR
- A 10 year combined energy spectrum was calculated
  - Excellent agreement with previous results
  - Thrice broken power law fits suggests a break at $\log_{10}(E / \text{eV}) = 19.2$
  - The GZK suppression was observed above 4σ significance
  - The effective GZK energy, $E_{1/2}$, agrees with previous measurements
  - 4th observation of the GZK suppression

Telescope Array Collaboration

Telescope Array Collaboration, Winter 2019 Meeting in Korea
100+members from USA, Japan, Korea, Russia, Belgium, and Czech Republic

Acknowledgements

- My Advisor, Douglas Bergman
- Members of the Telescope Array Collaboration: Charlie Jui, Shochi Ogio, John Matthews, Frank Misak, Stan Thomas, Jeremy Smith, Robert Cady, Tom Stroman, Dmitri Ivanov, Tareq Abu Zayyad, Jon Paul Lundquist, JiHee Kim, Gary McDonough, Patrick Wright, Matt Potts, Yoshiki Tsunesada, Toshihiro Fujii, Eiji Kido, and many more
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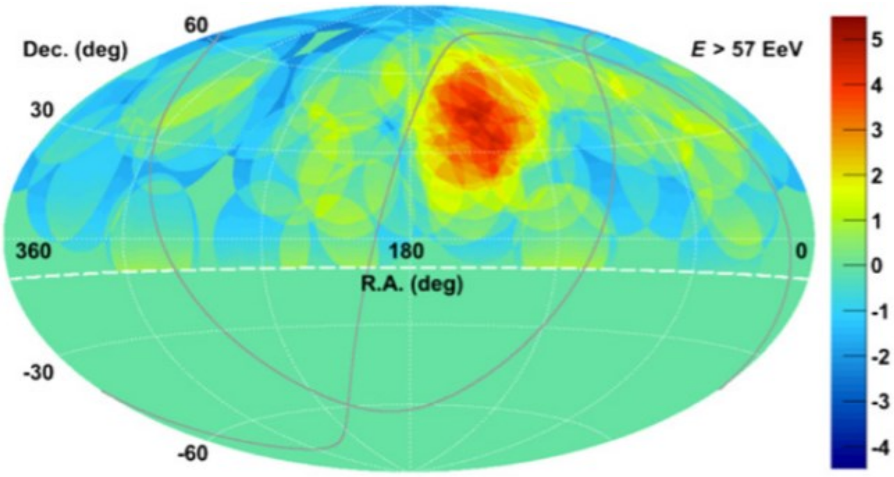
- Center for High Performance Computing (CHPC) for use of their computational clusters at the University of Utah
- My Family: Stephan, Paula, Jon, Emily, Chris, Eric, Bonnie, Ginny, Freddy, Skip, Cheryl, Oliver, Robert, Valerie, Sonny, and in memory of Frank and Vicky.
- My Friends: Flo Doval, Nels Evenson, Rosa (the dog), Paul Bergeron, Jessica Galbraith-Frew, JiHee Kim, and Jackson Remington and many more
- My Wife, Kiley

Thank You!

Questions?

Backup Slides

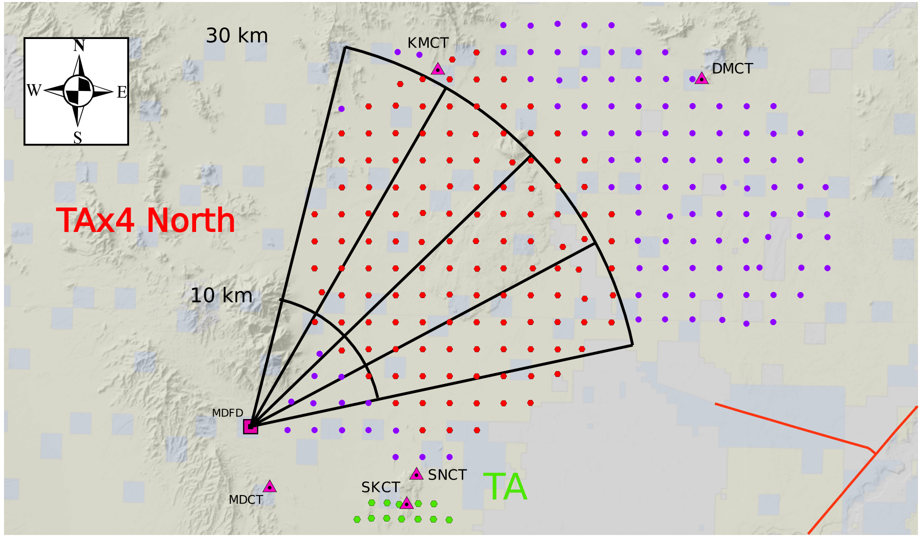
Evidence for a Cosmic Ray Anisotropy



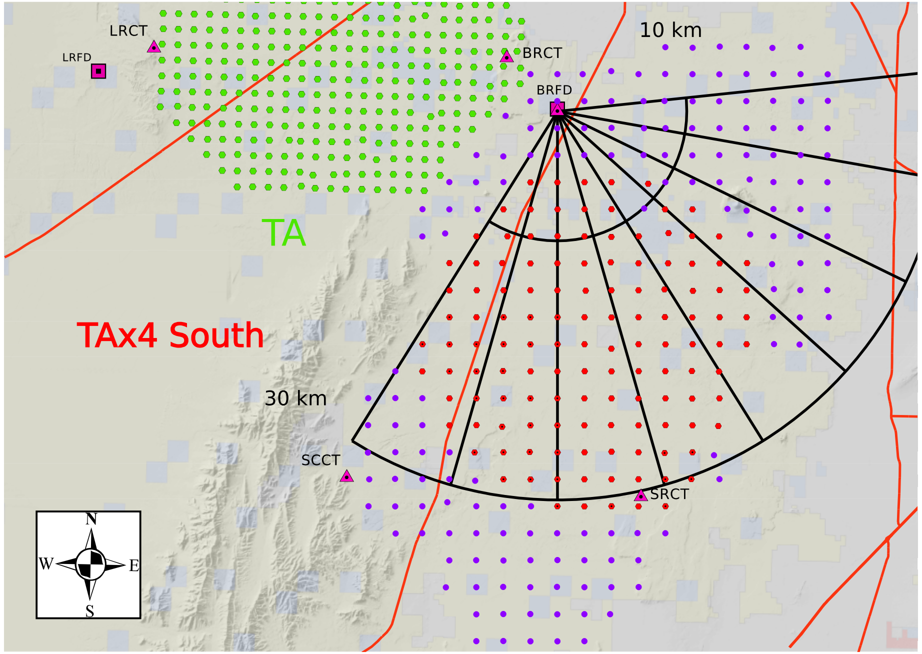
The Astrophysical Journal Letters, Volume 790, Issue 2, article id. L21, 5 pp. (2014).

TAx4 SD Expansion

Northern Lobe



Southern Lobe



TAx4 Deployment - SDs

Photo taken by ICRR PR Office in February, 2019

Testing the TAx4 FDs

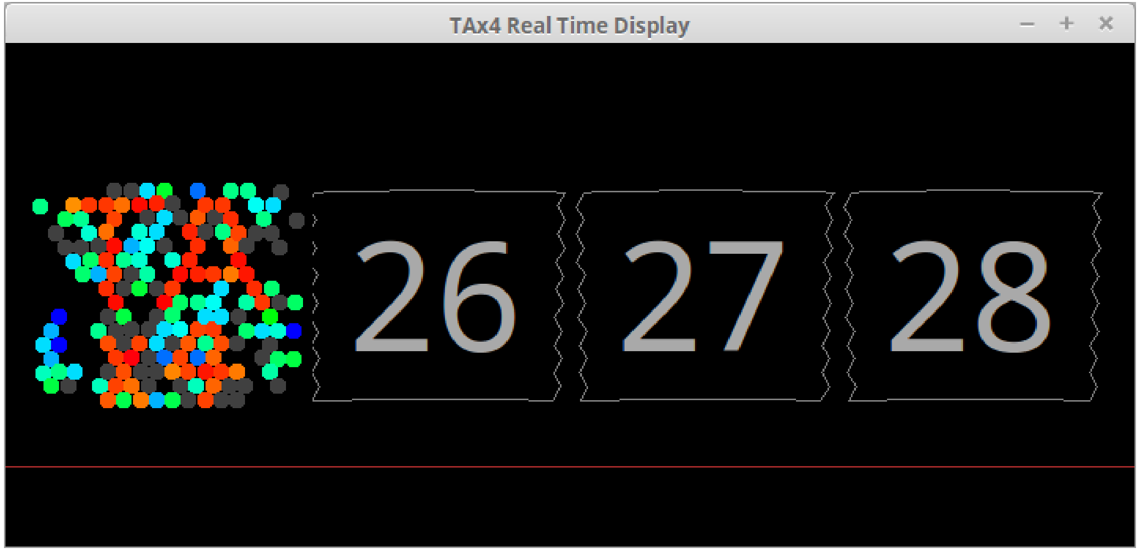
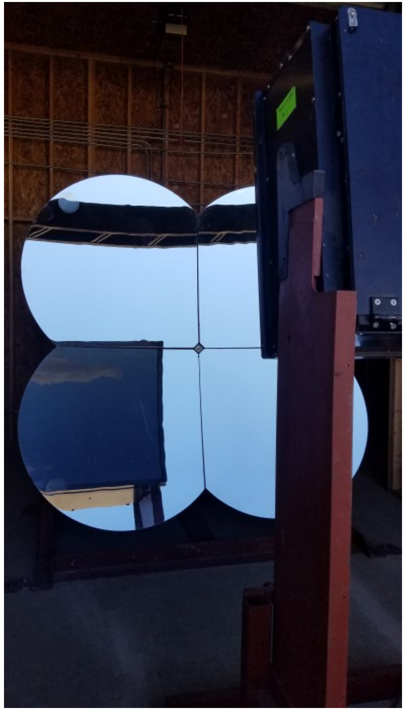


Image Credit: Stan Thomas

TAx4 Fluorescence Telescope

HiRes Ring 1 “Clover-leaf” Primary Mirror



HiRes 16x16 PMT Cluster

TAx4 FD Epochs

Epoch 0 (2018/06/08 - 2019/04/09):

The initial TAx4 MD FD epoch since the FD became fully operational and started collecting data every night.

Epoch I (2019/04/24 - 2019/06/08):

The column thickener daughter board was added to the trigger-host board for each telescope.

Epoch II (20190625 - Present):

The intermirror trigger was enabled in the TAx4 operations software.

Event Quality Cuts

BR and LR Monocular :

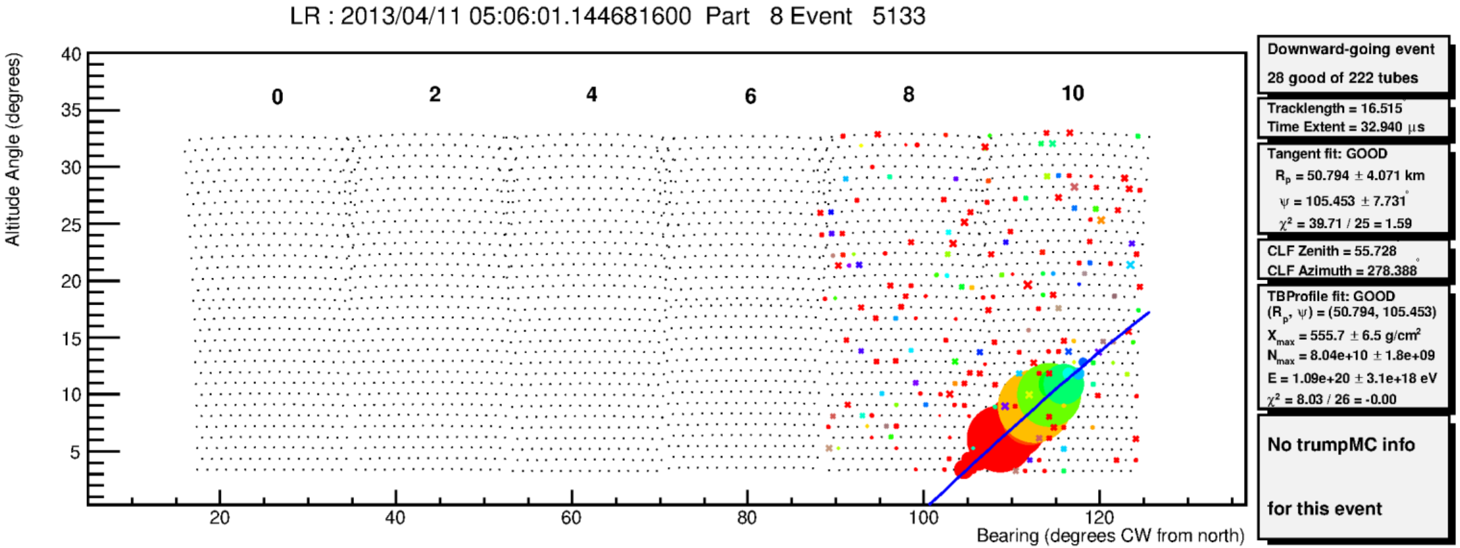
Event Geometry Reconstruction Cuts	
Good PMT Fraction	$N_{\text{Good PMT}}/N_{\text{PMTs}} \geqslant 3.5\%$
Number Good PMTs	$N_{\text{Good PMT}} \geqslant 6$ Tubes
NPE per Degree	$N_{\text{pe}}/\Delta\theta > 25$ NPE / deg.
Pseudo Distance (angular speed of EAS)	$r_p > 1.5$ km
SDP Angle	$\leqslant 80°$
R_p	$R_p \geqslant .5$ km
ψ	$\psi < 130°$
ψ fit uncertainty	$\sigma_\psi < 36°$
	Successful Timing Fit
Timing Fit	$\chi^2/\text{ndf} < 10$
Track Length 1 Ring	$\Delta\theta_{\text{Ring 1}} > 7°$
Track Length 2 Ring	$\Delta\theta_{\text{Ring 2}} > 10°$
Zenith Angle	$\theta_{\text{zen}} < 70°$
Crossing Time	$t_0 < 25.6\,\mu$s
Time Duration	$\Delta t > 6\ \mu$s (for $R_p < 5$ km)

Event Profile Reconstruction Cuts	
	Successful Profile Fit
First Depth	$150\ \text{g/cm}^2 \leqslant X_1 \leqslant 1200\ \text{g/cm}^2$
Observed Depth Extent	$\Delta X \geqslant 150\ \text{g/cm}^2$
X_{max} Bracketing	X_{max} *is contained within the FOV*

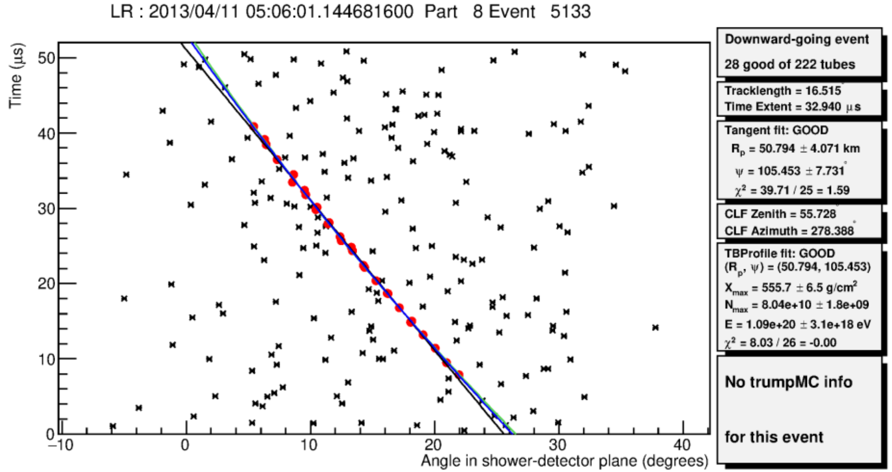
TAx4 MD FD (Based on HiRes-I):

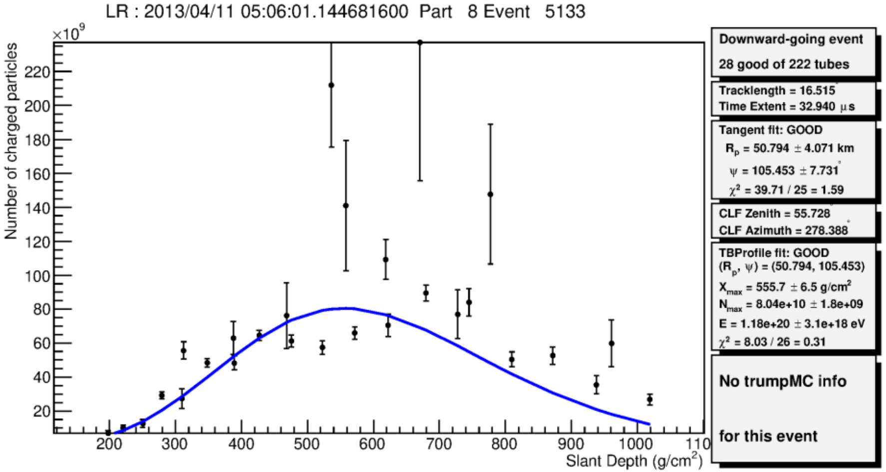
Event Reconstruction Cuts	
Rayleigh Filter	$P_{\log_{10}} \geqslant 2$
Brightness Cut	$\Sigma N_\gamma/N_{\text{Good PMTs}} \geqslant 200$
	$\Sigma N_{\text{pe}}/N_{\text{Good PMTs}} \geqslant 55$
Track Length	$\Delta\theta > 7.9°$
Track Width RMS	$\theta_{\text{RMS}} \leqslant 1°$
Angular Speed	$5.73°/\mu s$
	Successful Geometry Fit
	Successful Profile Fit
Profile Fit	$\chi^2/\text{ndf} < 14$
Cerenkov Fraction	$f_{\text{Cerenkov}} < 20\%$
First Interaction	$X_1 \leqslant 1200\ \text{g/cm}^2$

LR Highest Energy Event Track



LR Highest Energy Event Timing and Profile



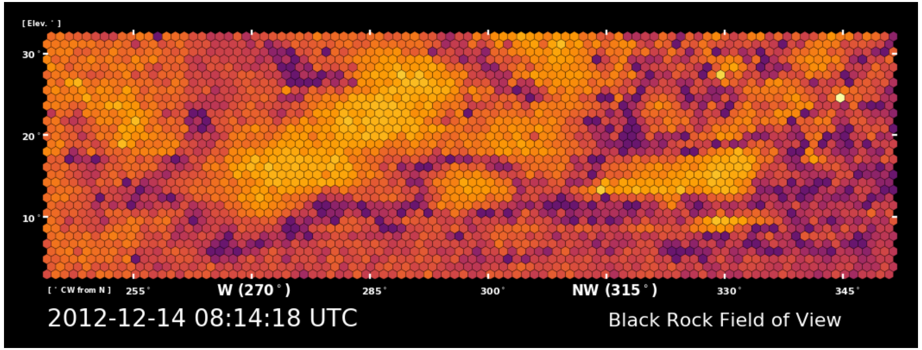


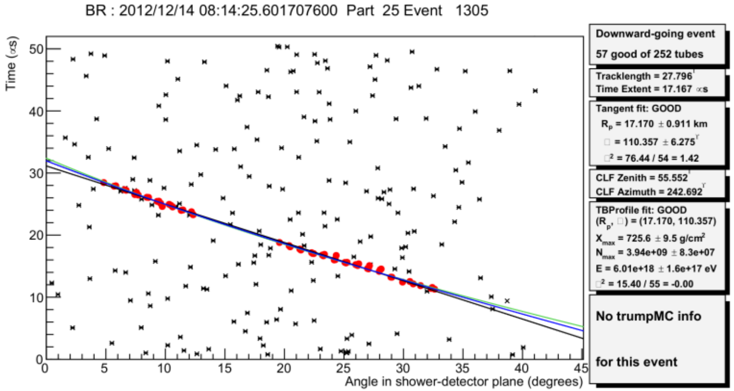
LR Highest Energy Event

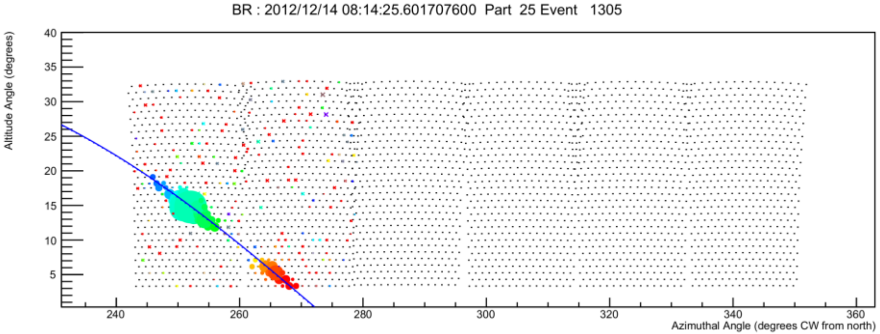
Event Reconstruction Parameters		
Date		2013-04-11
Time		05:06:01.144682 UTC
Good Tubes		22 out of 222 PMTs
Track Length	$\Delta\theta$	16.515°
Time Extent	Δt	32.940μs
Impact Parameter	R_p	50.749 ± 4.071 km
SDP Inclination Angle	ψ	$105.453 \pm 7.731°$
Shower Max	$X_{\max}$	$555.7 \pm 6.5 g/cm^2$
	$N_{\max}$	$(8.04 \pm .18) \times 10^{10}$
Calorimetric Energy	E_{cal}	$(1.089 \pm .031) \times 10^{20}$ eV
Primary Energy	E_0	$(1.171 \pm .032) \times 10^{20}$ eV
		117 ± 3.2 EeV
		18.7 J

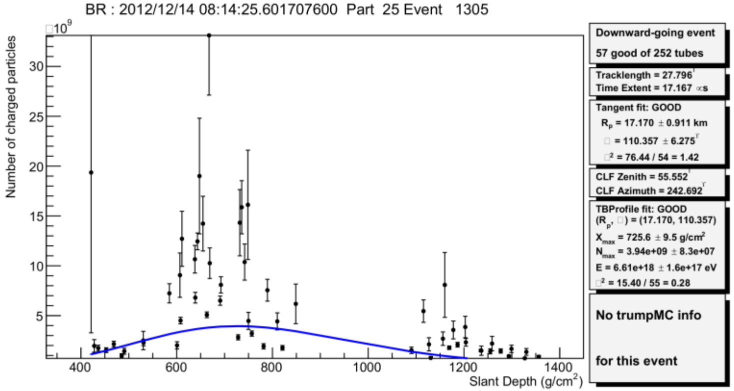
- The “Oh-My-God particle” particle had energy 2.7 times greater and the maximum development at 800 g/cm2.
- Fly’s Eye observed the “Oh-My-God particle” event at about 18 km with Rp
- LR observed this event at about the edge of TA’s detection area with Rp = 50.7 ± 4 km.

Cloudy Weather affect on Reconstruction

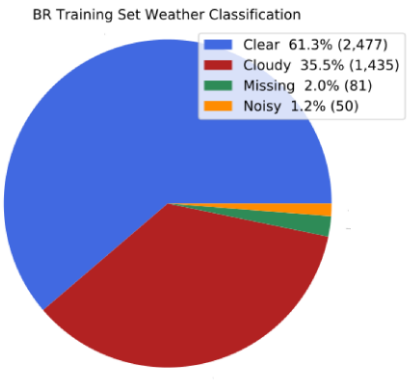


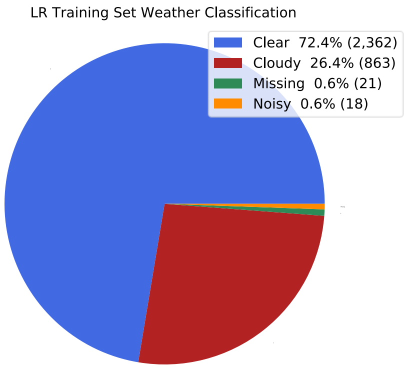


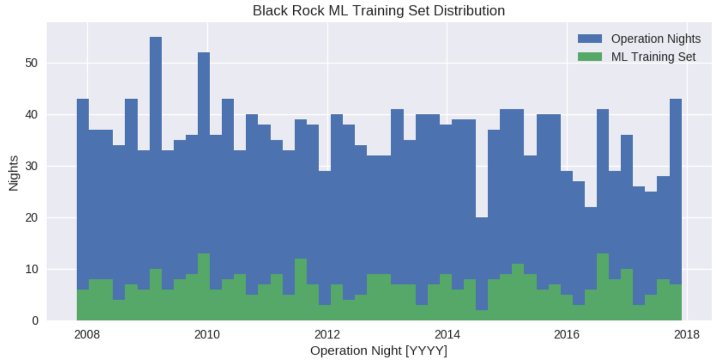




Training and Validation Set







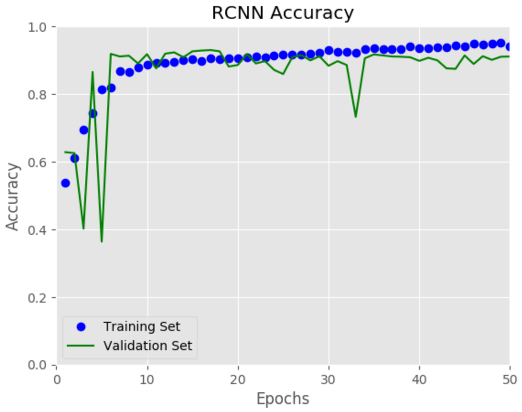
20% of nights from overall data for FD site uniformly sampled over all time for training and validation set

RCNN Architecture

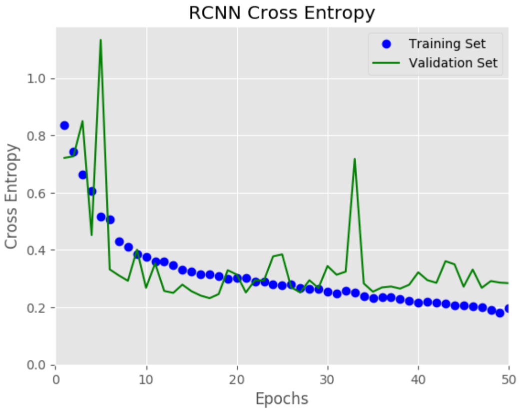
RCNN Layers	
Input Layer	$\text{Input}_{dim} = t_{\max}$ x 32 rows x 96 columns of pixels
1^{st} Time Distributed Convolution Layer	8 4x4 Convolution Filters
2^{nd} Time Distributed Convolution Layer	8 4x4 Convolution Filters
1^{st} LSTM Layer	48 Nodes
2^{nd} LSTM Layer	6 Nodes
Output Layer	3 Output Nodes

Recurrent Convolution Neural Network Performance

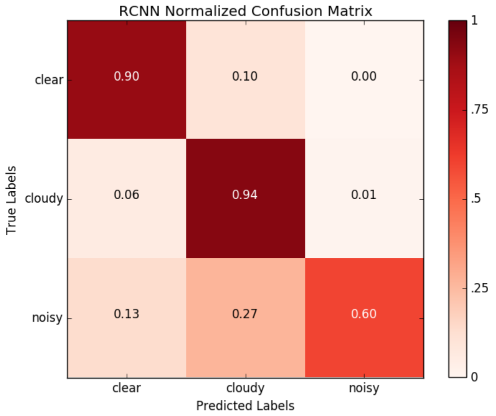
Training Accuracy



Training Cross Entropy



Validation Confusion Matrix



Neural Network Results

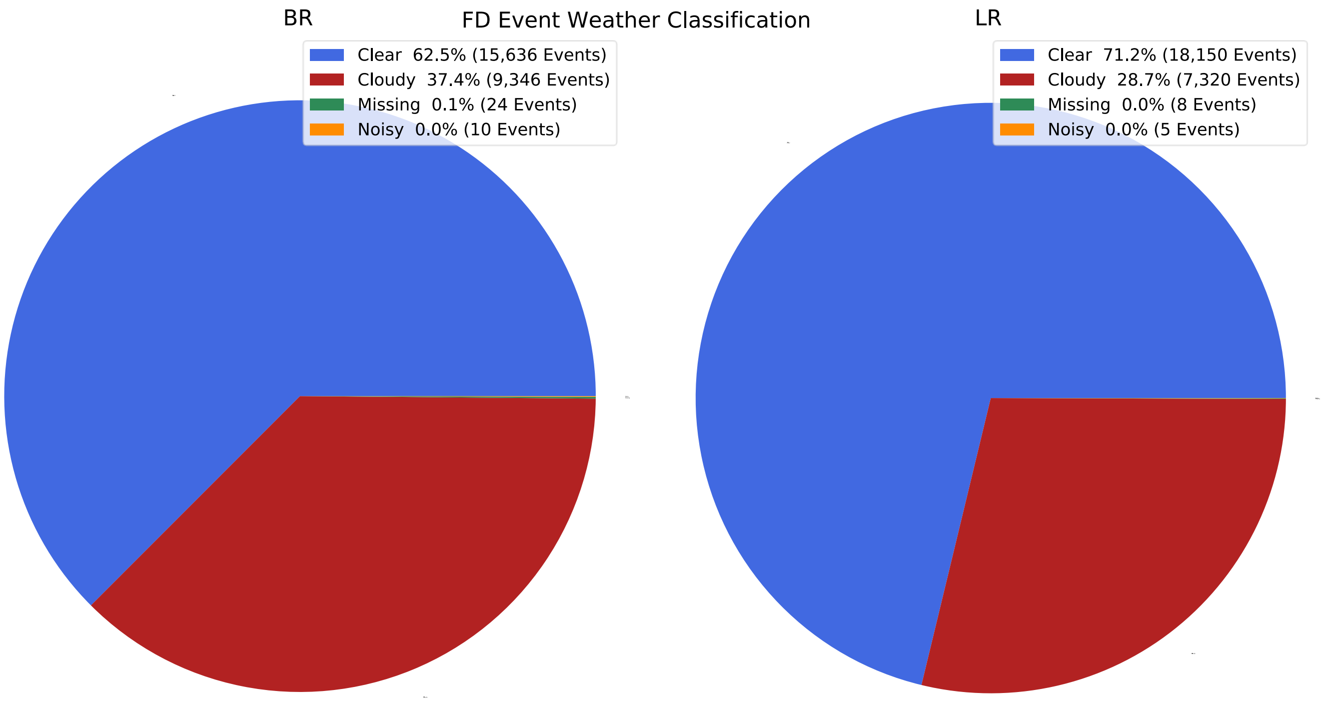
BR Neural Network Results

Model	Training Epochs	Optimizer	Computation Time	Validation Accuracy	Validation Cross Entropy
DNN	75	Adadelta	0:21:49 hours	76.79 %	.58
CNN	75	Adadelta	0:09:06 hours	86.09 %	.42
RNN	75	Adadelta	1:06:02 hours	87.65 %	.35
RCNN	50	Adagrad	2:16:11 hours	90.93 %	.29

LR RCNN Results

Model	Training Epochs	Optimizer	Computation Time	Validation Accuracy	Validation Cross Entropy
RCNN	50	Adagrad	0:36:57 hours	94.31 %	.19

Event Weather Classification Results



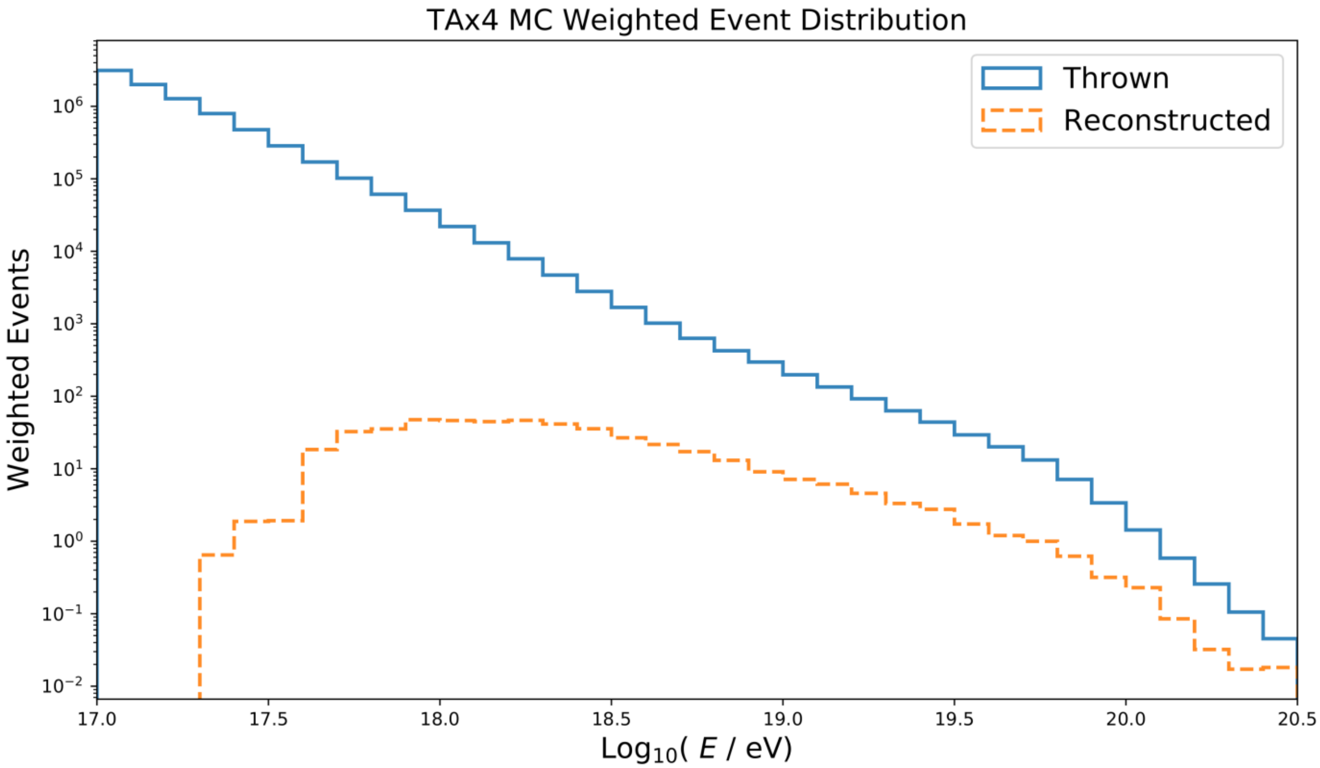
TAx4 Reconstruction Resolution

Parameter	Resolution	Resolution ($\log_{10}(E/\mathrm{eV}) > 18.5$)
E	21%	18%
R_p	12%	10%
ψ	6.8°	6.1°
X_{max}	70 g/cm^2	65 g/cm^2
N_{max}	25%	21%
θ_{zenith}	2.6°	2.3°
ϕ_{azimuth}	7.1°	6.7°

BR and LR Reconstruction Resolution

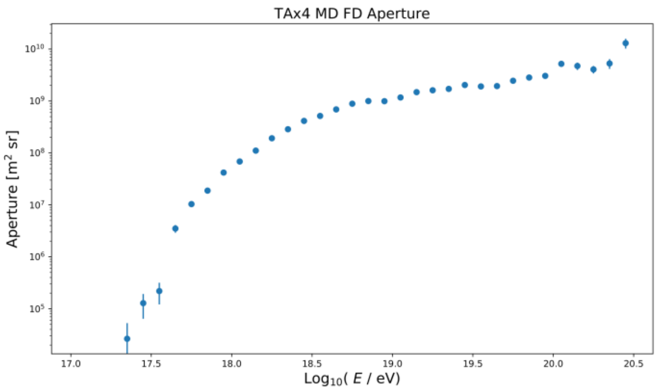
Parameter	BR Resolution	LR Resolution
E	11%	11%
R_p	3.9%	3.8%
ψ	3.6°	3.6°
X_{max}	37 g/cm^2	38 g/cm^2
N_{max}	11%	11%
θ_{zenith}	1.5°	1.6°
ϕ_{azimuth}	4.5°	4.3°
$R_{X_{\mathrm{max}}}$	6.9%	6.9%

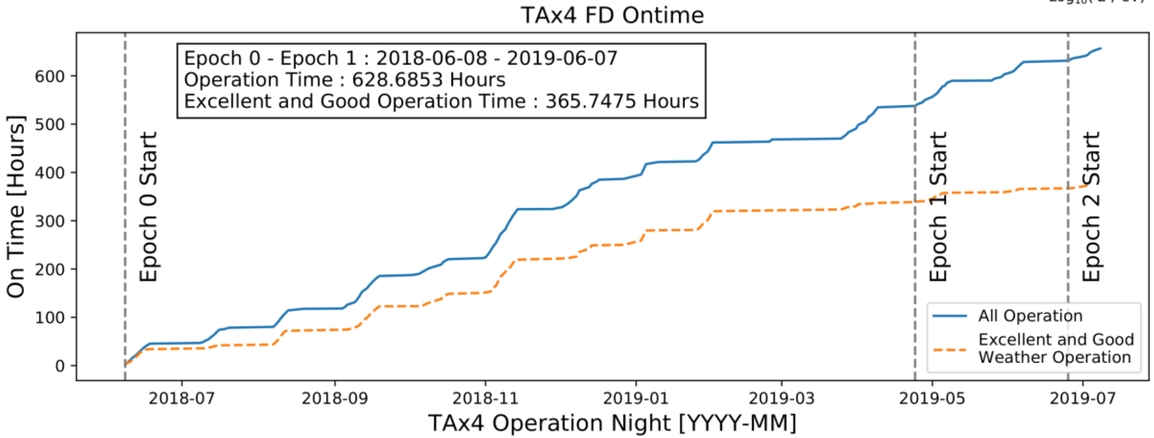
TAx4 MC Event Distribution



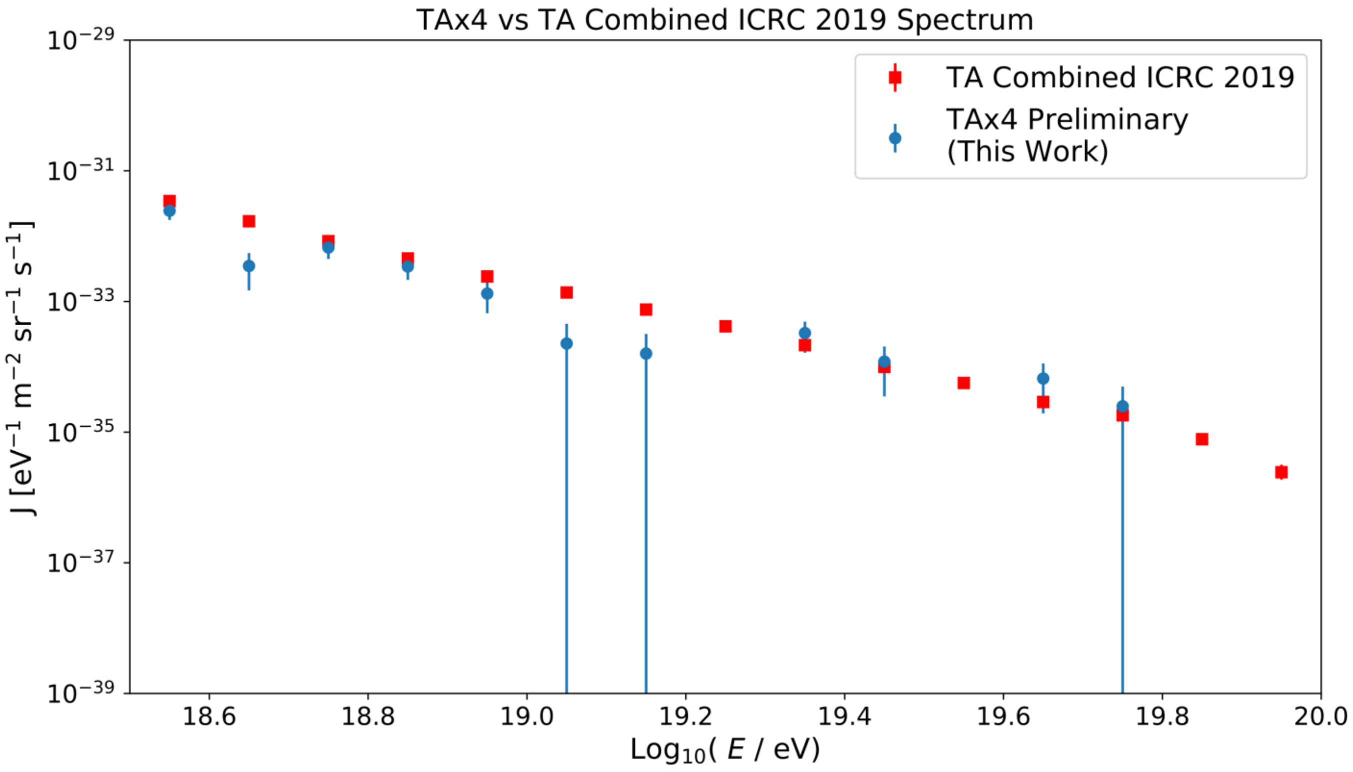
TAx4 Aperture and Ontime

$$A_0 = \pi(R_{p\ \mathrm{max}}^2 - R_{p\ \mathrm{min}}^2)$$
$$\Omega_0 = 2\pi(1 - \cos(\theta_{\mathrm{zenith\ max}}))$$
$$A_0\Omega_0 = 3.24698 \times 10^{10}\ \mathrm{m}^2\ \mathrm{sr}$$

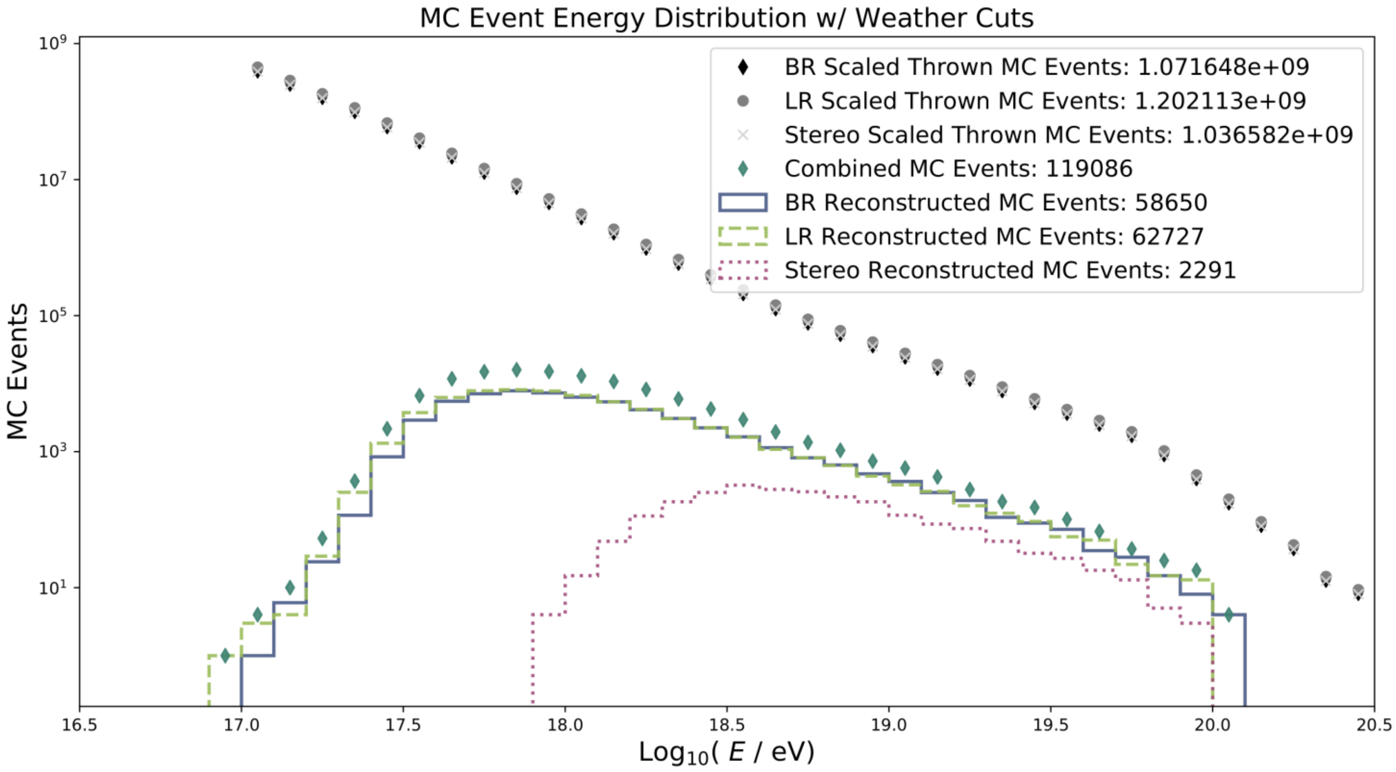




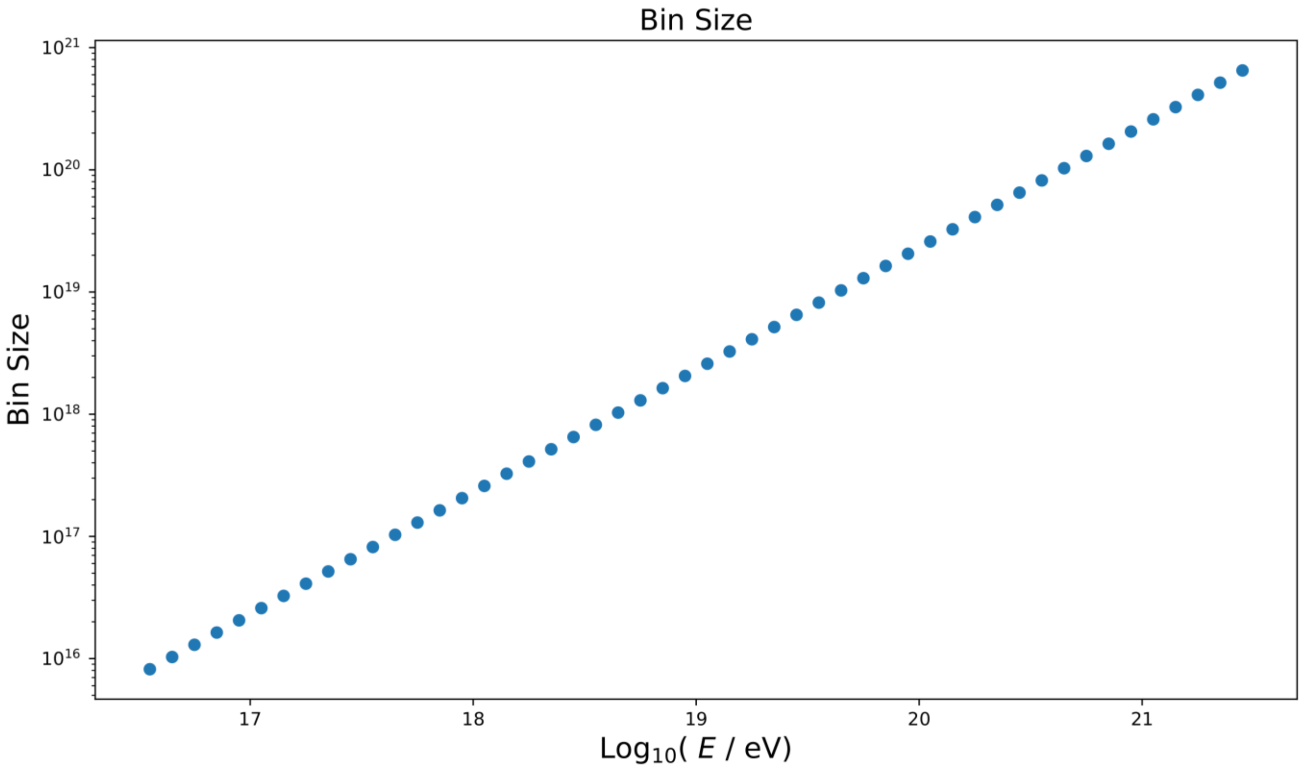
TAx4 Preliminary Spectrum



Mono MC Event Distribution



Spectrum Energy Bin Size

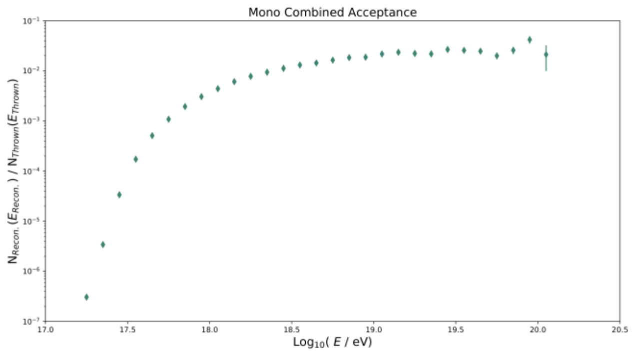


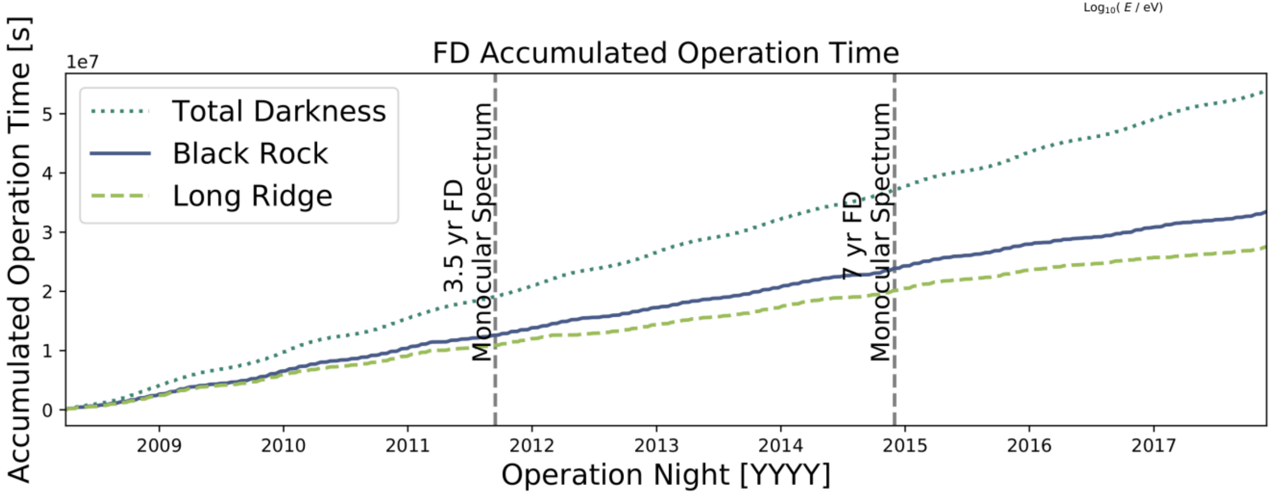
Mono Combined Acceptance, Aperture, and Ontime

BR and LR Geometric Aperture

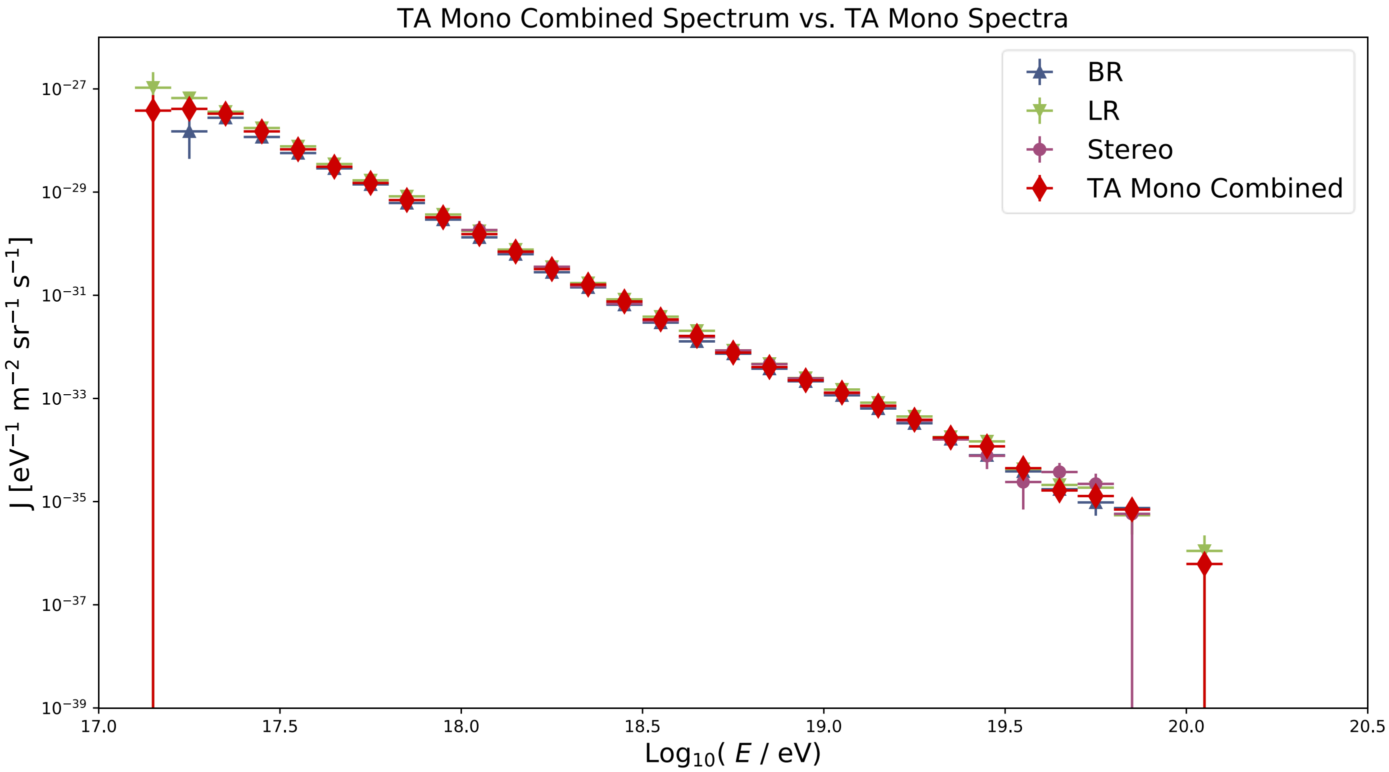
$$A_0 = 2\pi \int_{0^\circ}^{1^\circ} R_{\text{Earth}}^2 \sin(\alpha) d\alpha$$

$$\Omega_0 = 2\pi \int_{0^\circ}^{80^\circ} \sin(\theta)\cos(\theta)\, d\theta$$





Mono Combined Spectrum vs Mono Spectra



Broken Power Law Fits

Once Broken Fit

$$J(E)_{\text{Once Broken}} = A \begin{cases} E^{\gamma_1} & E < E_1 \\ E_1^{\gamma_1-\gamma_2} E^{\gamma_2} & E_1 \leq E \end{cases}$$

Twice Broken Fit

$$J(E)_{\text{Twice Broken}} = A \begin{cases} E^{\gamma_1} & E < E_1 \\ E_1^{\gamma_1-\gamma_2} E^{\gamma_2} & E_1 \leq E < E_2 \\ E_1^{\gamma_1-\gamma_2} E_2^{\gamma_2-\gamma_3} E^{\gamma_3} & E_2 \leq E \end{cases}$$

Thrice Broken Fit

$$J(E)_{\text{Thrice Broken}} = A \begin{cases} E^{\gamma_1} & E < E_1 \\ E_1^{\gamma_1-\gamma_2} E^{\gamma_2} & E_1 \leq E < E_2 \\ E_1^{\gamma_1-\gamma_2} E_2^{\gamma_2-\gamma_3} E^{\gamma_3} & E_2 \leq E < E_3 \\ E_1^{\gamma_1-\gamma_2} E_2^{\gamma_2-\gamma_3} E_3^{\gamma_3-\gamma_4} E^{\gamma_4} & E_3 \leq E \end{cases}$$

Poisson Deviance

$$D_{\text{Poisson}} = 2 \sum_i \left[N(E_i)_{\text{Expected}} - N(E_i)_{\text{Observed}} + N(E_i)_{\text{Observed}} \ln \left(\frac{N(E_i)_{\text{Observed}}}{N(E_i)_{\text{Expected}}} \right) \right]$$

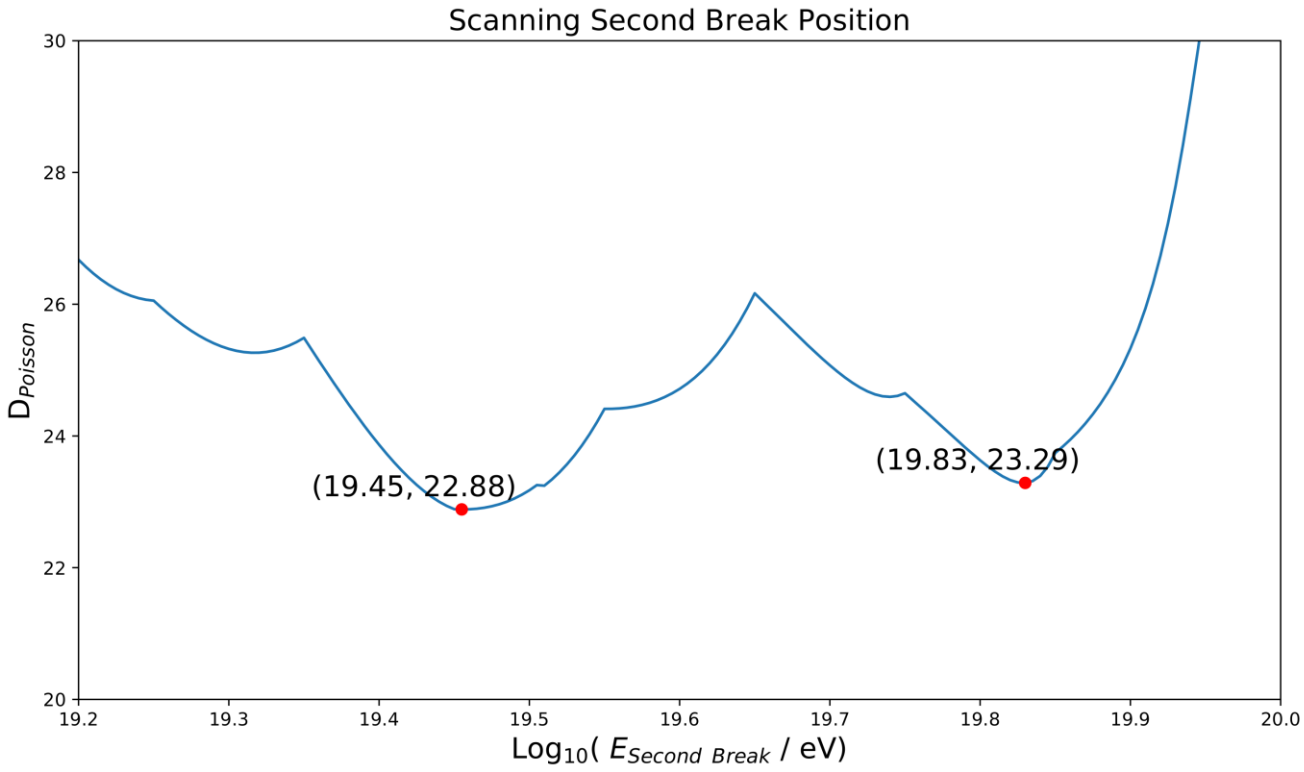
Expected Events

$$N(E_i)_{\text{Expected}} = J(E_i)_{\text{Fit}} \, \Delta E_i \, \xi(E)$$

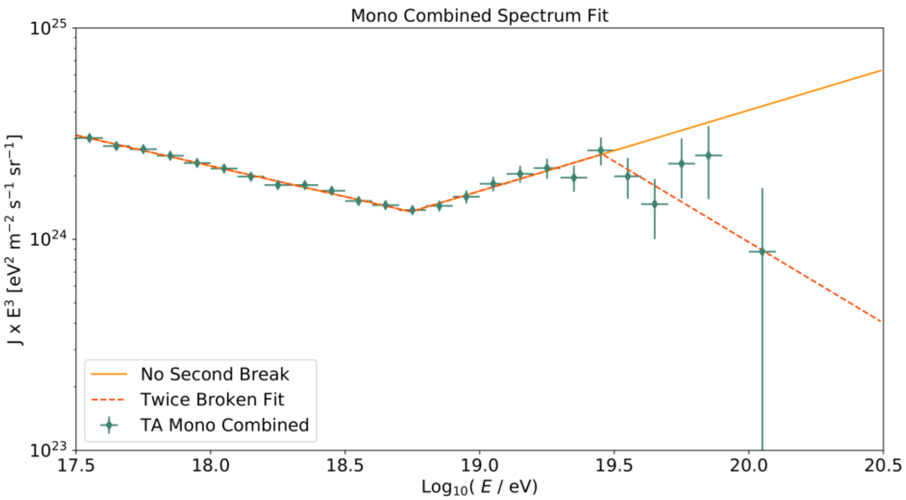
Twice Broken Power Law Fit Results Compared to Previous Measurements

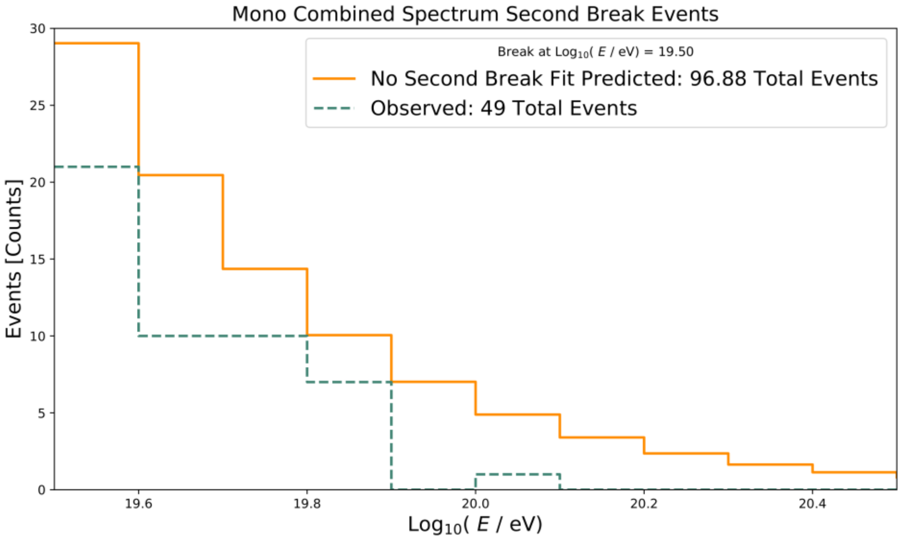
	This Work, Higher E_2	HiRes	TA SD ICRC 2019
$J(\mathrm{E} = 10^{18}$ eV)	2.22 ± 0.01	-	2.24 ± 0.06
$\times\ 10^{-30}$ eV^{-1} m^{-2} sr^{-1} s^{-1}			
γ_1	-3.29 $\pm$ 0.01	-3.25 $\pm$ 0.01	-3.28 $\pm$ 0.02
$\log_{10}(E_1$ / eV)	18.72 $\pm$ 0.05	18.65 $\pm$ 0.05	18.69 $\pm$ 0.01
γ_2	-2.70 $\pm$ 0.05	-2.81 $\pm$ 0.03	-2.68 $\pm$ 0.02
$\log_{10}(E_2$ / eV)	19.83 $\pm$ 0.04	19.75 $\pm$ 0.04	19.81 $\pm$ 0.03
γ_3	-8.04 $\pm$ 2.74	-5.1 $\pm$ 0.7	-4.84 $\pm$ 0.48

Two Twice Broken Power Law Fits

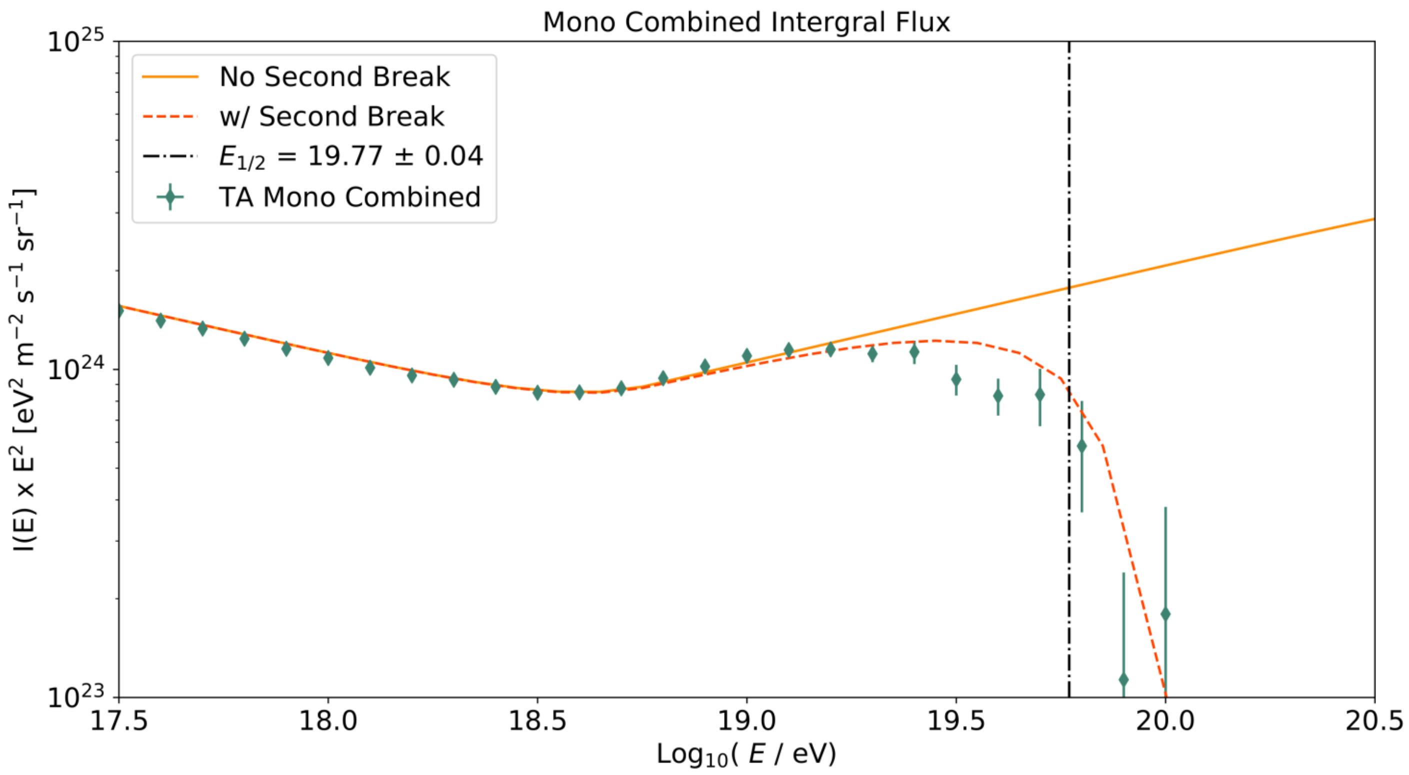


Observation of the GZK Suppression Lower E_2





Mono Combined Integral Flux



Mono Combined Integral Flux
Lower E_2