TAx4 Monocular Cosmic Ray Energy Spectrum

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What are cosmic rays?

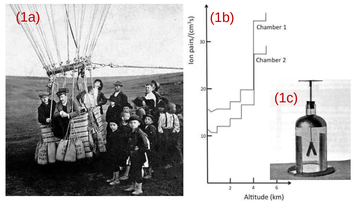


Figure 1: (1a) Victor Hess before a flight. (1b) Plot showing the increase in ionizing radiation as the altitude increases. (1c) Electroscope.

- Cosmic Rays are subatomic particles of extra-terrestrial origin.
- First discovered in 1912 by Victor Hess. Who measured radiation levels aboard a balloon that ascended up to 5300 meters during a near-total eclipse of the Sun. using two electroscopes.

- Cosmic ray energies span more than 11 orders of magnitude
- 6×10^{18} eV ~ 1 joule
- The highest energy cosmic rays ~10,000,000 times more energetic than Large Hadron Collider (LHC) protons
- Flux falls rapidly at $\sim E^{-3}$
  - Mostly Featureless except for a few breaks at certain energies
- At $E > 10^{17}$ eV, a 1 m^2, 2π Sr. detector sees < 1 event/50 yrs.
  - Direct measurement is impractical!!

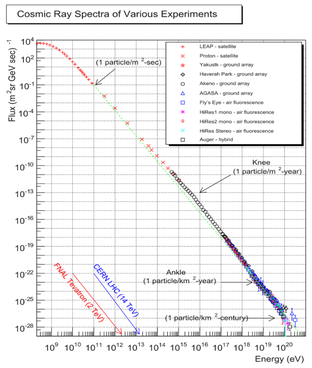


Figure 2: Comic ray spectra of various experiments.

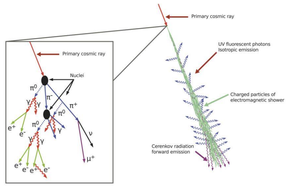


Figure 3: An extensive air shower, produces host of secondary particles, UV florescent photons, and forward directed Cerenkov radiation.

- An indirect way of measuring cosmic rays is to use the Earth's atmosphere as your detector.
- When the primary cosmic ray hits a nuclei in the atmosphere the energy of the collision sparks a cascading shower of particles that fall to earth, called an Extensive Air Shower (EAS).
- If you detect one or more of the products of an extensive air shower you can use these to get information on the primary cosmic ray.

Introduction to TA and TAx4

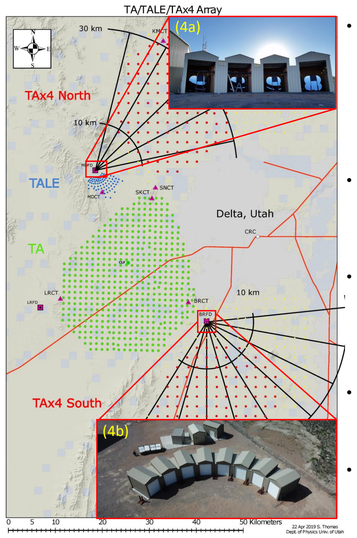


Figure 4: Telescope Array (TA) in Delta, Utah. (4a) TAx4 North at the Middle Drum (MD) site. (4b) TAx4 South at the Black Rock Mesa (BRM) site.

- TA Experiment (Figure 4) undertook the TAx4 upgrade to expand the area of our Surface Detectors (SD) by a factor of 4 and have added new Fluorescence Detector (FD) stations to view over the new SD arrays.
- Currently, TAx4 consists of 12 FDs and 257 SDs, of a planned 500, at a spacing of 2.08 km spread over two sites.
- TAx4 North (4 FDs), completed in 2018, views over the northern lobe of the new SDs, and TAx4 South (8 FDs), completed in 2019, views over the southern lobe.
- Both FD sites are in routine observation, with data being taken remotely at the TAx4 South site.
- On this poster, I will report on the performance of the TAx4 FD showing data/MC comparisons, detector resolutions, and a preliminary monocular energy spectrum for TAx4.

Procedure

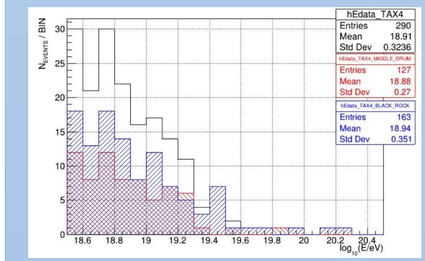
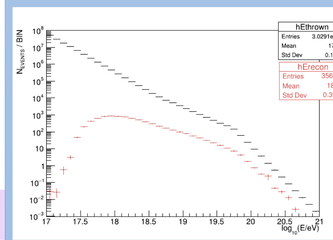


Figure 5: TAx4 histogram of reconstructed events with all cuts applied. The red histogram is TAx4 North, the blue histogram is TAx4 South, and the black histogram is the combined distribution for both sites.

1. Reconstruct the shower parameters from the real data, apply quality cuts (Figure 6), and histogram the energy of the reconstructed events. (Figure 5)
2. Throw Monte Carlo (MC) simulations for each data part and reconstruct it using the same reconstruction program as the real data (Figure 7).
3. Calculate the ontime of the detector (Figure 8) and apply weather cuts.TAx4's good weather condition is no overhead clouds and no horizon clouds in the field of the view of the detector.

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

Figure 6: TAx4 event reconstruction quality cuts.



MC input parameter	Value
$R_{p,min}$	100 m
$R_{p,max}$	50 km
θ_{max}	70°
E_{min}	10^{17} eV
E_{max}	10^{21} eV
Spectral index, γ	2
Hadronic Model	QGSJetII-03, proton

Figure 7: Monte Carlo thrown (black) and reconstructed (red) distributions after reweighing. The table represents the MC parameters that were chosen to create these distributions.

4. Compare the MC to the data to ensure that your reconstruction results agree (Figure 9).
5. Determine the resolution of your MC (Figure 10).
6. Using the MC calculate the aperture [eq.2].
7. Scale the aperture with the detector's good weather ontime to get detector exposure [eq.3].
8. Calculate the energy spectrum, i.e. the flux as a function of energy [eq.4]. The spectral features found in the cosmic ray spectrum can be brought out by multiplying the spectrum with energy cubed (Figure 11).

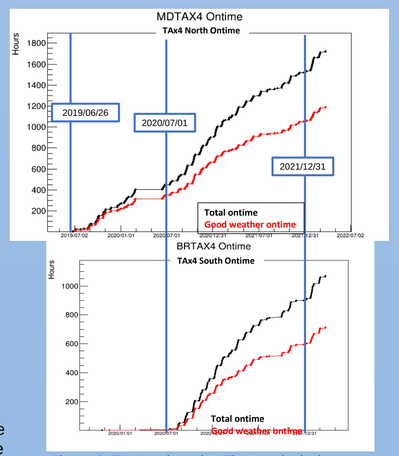


Figure 8: TAx4 ontime plot. The top plot is the northern array TAx4 North, and the bottom plot is the southern array TAx4 South.

Results

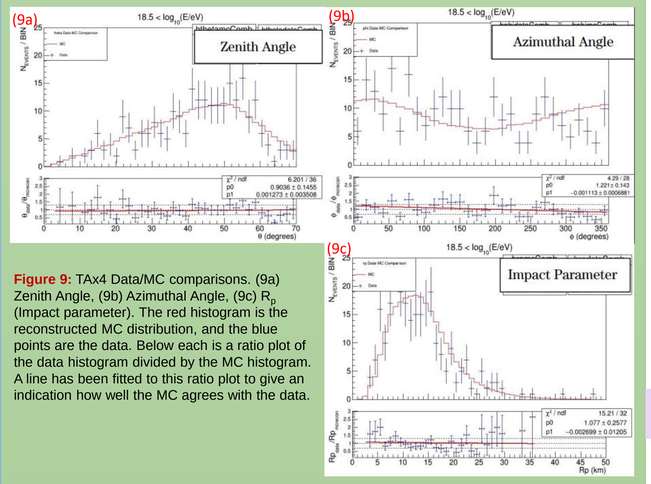
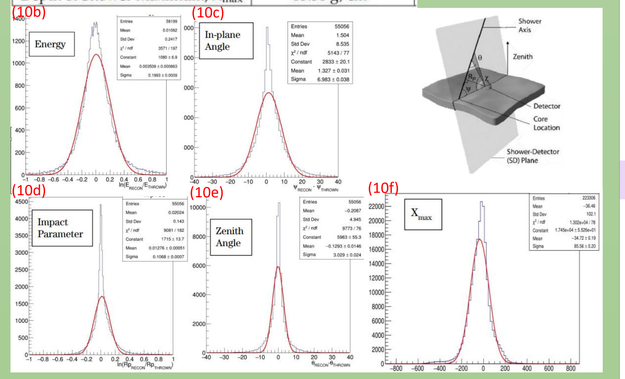


Figure 9: TAx4 Data/MC comparisons. (9a) Zenith Angle, (9b) Azimuthal Angle, (9c) R_p (Impact parameter). The red histogram is the reconstructed MC distribution, and the blue points are the data. Below each is a ratio plot of the data histogram divided by the MC histogram. A line has been fitted to this ratio plot to give an indication how well the MC agrees with the data.

(10a)

Parameter	Monocular Resolution
Energy, E	19.93%
Zenith Angle, θ	3.03°
In-plane Angle, ψ	6.98°
Impact Parameter, R_p	10.68%
Depth of Shower Maximum, X_{max}	85.56 g/cm²

Figure 10: TAx4 Resolutions. (10a) Table of resolutions. Histogram of resolutions (10b) Energy, (10c) In-plane Angle, (10d) R_p (Impact parameter), (10e) Zenith Angle, (10f) X_{max}.



$$[eq.1]\ A_0\Omega_0 = 2\pi^2(R_{pmax}^2 - R_{pmin}^2)(1-\cos\theta_{max})$$

$$[eq.2]\ Aperture = A\Omega = A_0\,\Omega_0 \cdot \frac{N_{recon}}{N_{thrown}}$$

$$[eq.3]\ Exposure = A\Omega \cdot t$$

$$[eq.4]\ Flux = J(E) = \frac{N(E)}{\Delta E \cdot A\Omega \cdot t}$$

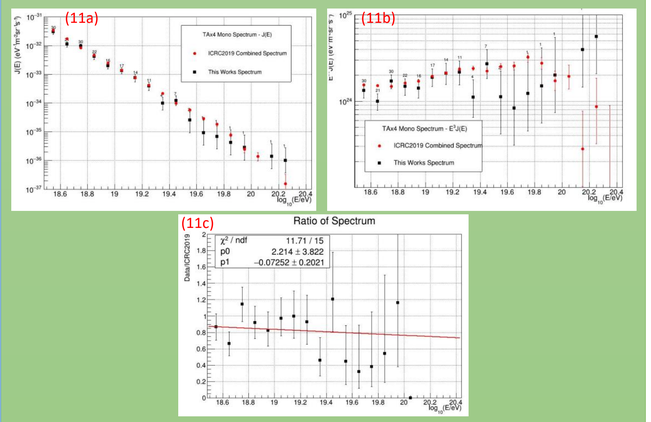


Figure 11: TAx4 monocular energy spectrum results. Numbers above data points indicate how many events are in each bin.

Motivations

- TA Hot Spot
  - The Telescope Array (TA) has seen indication of possible nearby source of ultrahigh energy cosmic rays
  - Cosmic Rays with $E > 5.7\times10^{19}$ eV can't have traveled much further than 100-300 million light years
- Composition
  - TA composition measurements are consistent with light mass composition at $E < 10^{19}$ eV
  - Currently there is insufficient statistics to make claims of composition at $E > 10^{19}$ eV
- Determine TAx4 resolutions
- Calculate energy spectrum laying the groundwork for composition and anisotropy analyses

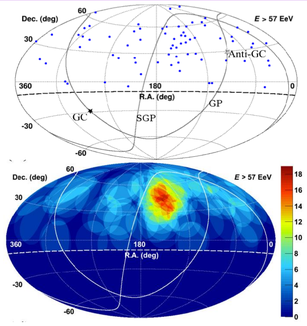


Figure 12: TA Hot Spot. (Top) All events above 57 EeV. (Bottom) Shows an excess of UHECE events where color is used to indicate density.

Monocular TAx4 Event

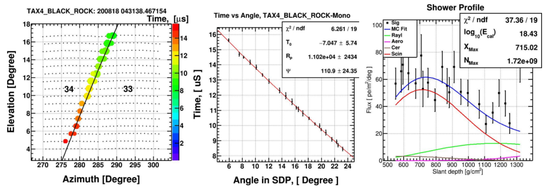


Figure 13: Typical monocular event captured by TAx4 South. (Left) FD event display. (Middle) Time verses angle fit. (Right) Shower profile plot. All the parameters have been extracted from the statistic boxes and displayed on the table to the right.

$E = 2.7\times10^{18}$ eV
$R_p = 11.02$ km
$\Psi = 110.9°$
$X_{max} = 715.02$ g/cm²
$N_{max} = 1.72\times10^9$ particles

Conclusions and Future Analysis

- TAx4 is working as intended. We are getting the number of events that we expect.
- The TAx4 monocular resolutions are consistent other TA results.
- The TAx4 MC and data appear to be in reasonable agreement.
- This work's monocular spectrum measured by TAx4 are in reasonable agreement with the TA's energy spectrum.
- **This energy spectrum paves the way for future composition and anisotropy analyses.**

Acknowledgements

I want to thank everyone working with TA for making TAx4 possible! I have learned so much and had a lot of fun working with them all.