TAx4 Cosmic Ray Energy Spectrum

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What are cosmic rays?

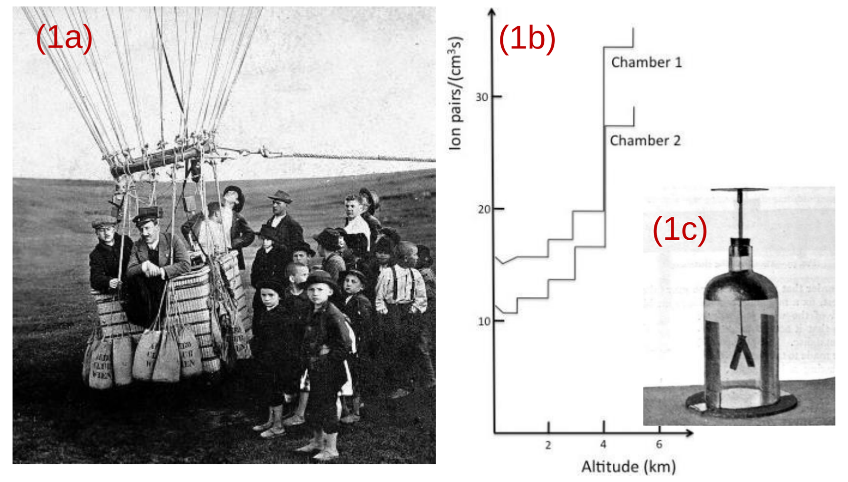


Figure 1: (1a) Victor Hess before a flight. (1b) Plot showing the increase in ionizing radiation as the altitude increases. (1c) Electroscope.

- 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 ~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!!

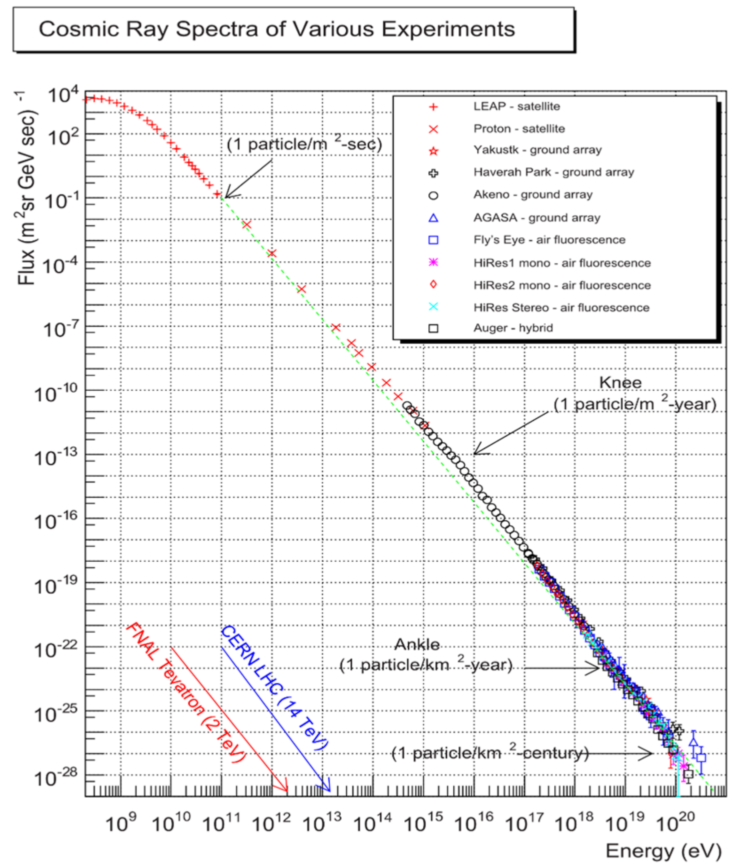


Figure 2: Comic ray spectra of various experiments.

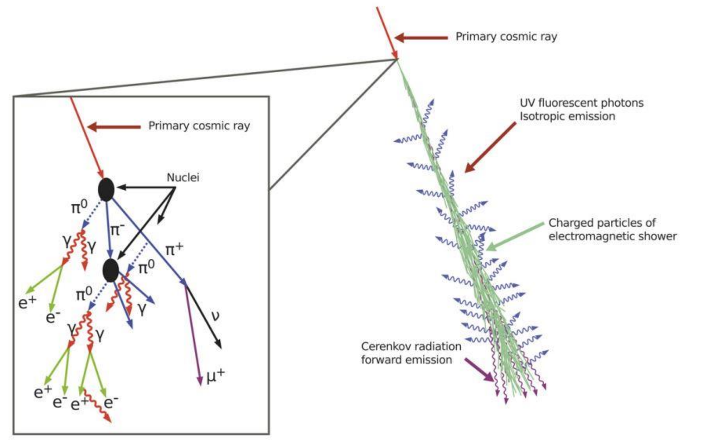


Figure 3: An extensive air shower, produces host of secondary particles, UV florescent photons, and forward directed Cerenkov radiation.

- 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.
- 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.

Motivations

- TA Hot Spot
  - The Telescope Array (TA) has seen indication of possible nearby source of ultrahigh energy cosmic rays
  - Cosmic Rays with E > 5.7×10^{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

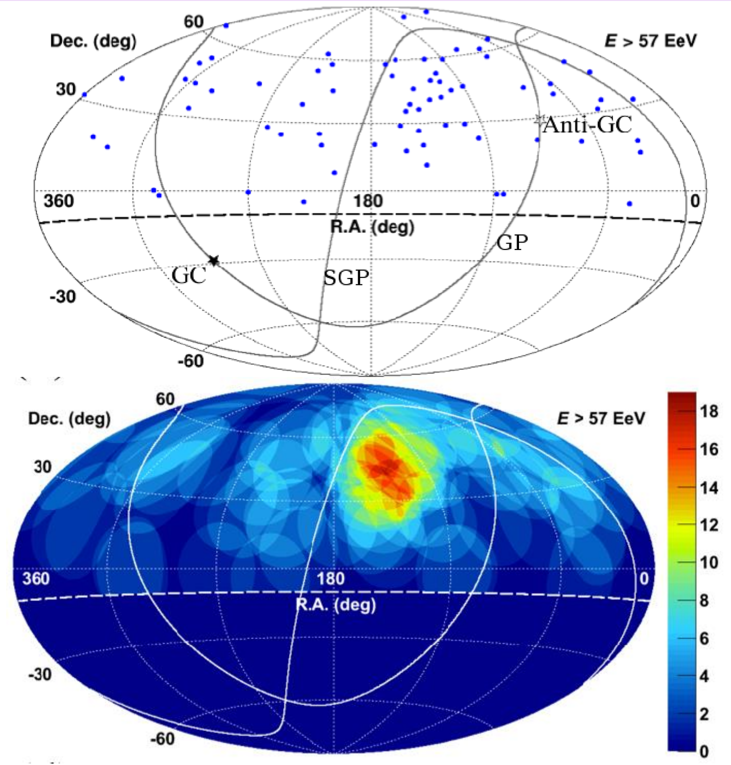


Figure 4: TA Hot Spot. (Top) All events above 57 EeV. (Bottom) Shows an excess of UHECE events where color is used to indicate density.

Procedure

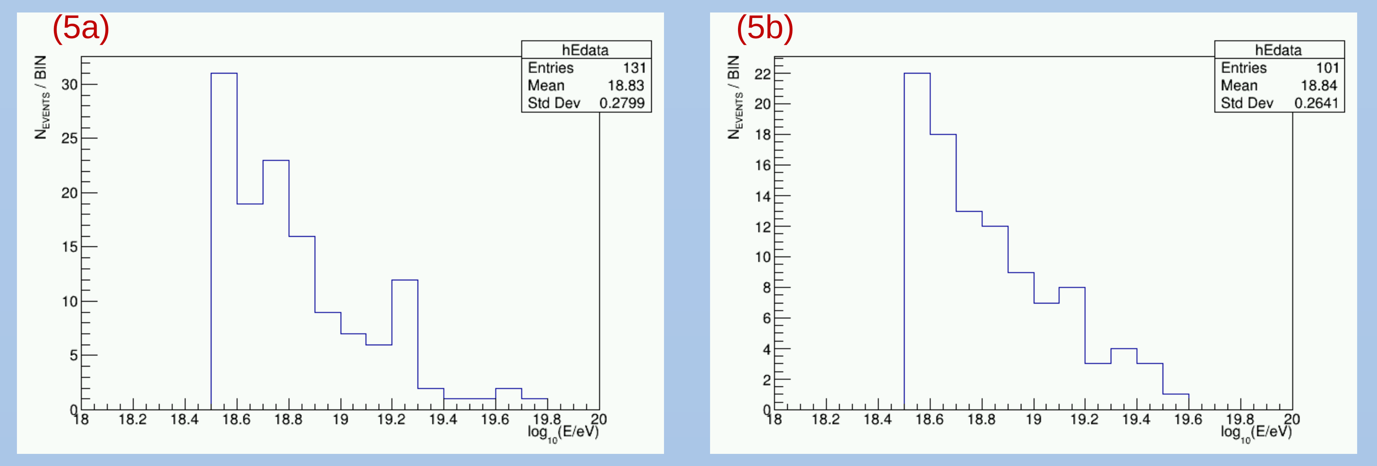


Figure 5: TAx4 histogram of reconstructed events with all cuts applied. (5a) TAx4 MD (5b) TAx4 BR

- Reconstruct the shower parameters from the real data and histogram the energy of the reconstructed events. (Figure 5)
- Throw Monte Carlo (MC) simulations for each data part and reconstruct it using the same reconstruction program as the real data (Figure 7).
- Apply the same cuts to all reconstructed events to ensure quality. (Figure 6)
- Calculate the ontime of the detector (Figure 8) and apply weather cuts
  - TAx4 MD: no overhead clouds and no horizon clouds to the north and east
  - TAx4 BR: no overhead clouds and no horizon clouds to the south and east

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	$\Delta\theta > 7.9°$
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	$X_1 \leqslant 1200\ \text{g/cm}^2$

Figure 6: TAx4 event reconstruction quality cuts.

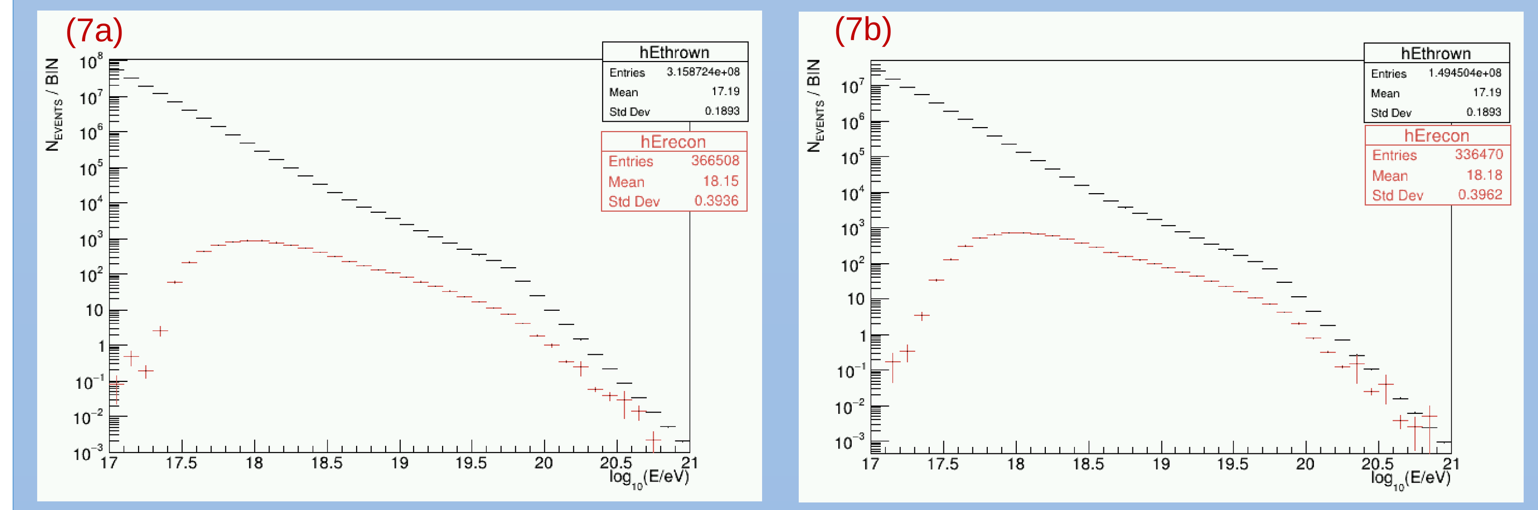


Figure 7: Monte Carlo thrown (black) and reconstructed (brown) distributions (7a) TAx4 MD (7b) TAx4 BR

- Compare the MC to the data to ensure that your reconstruction results agree (Figure 9)
- Using the MC calculate the aperture [eq.2]
- Scale the aperture with the detector's good weather ontime to get exposure [eq.3]

- 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 10)

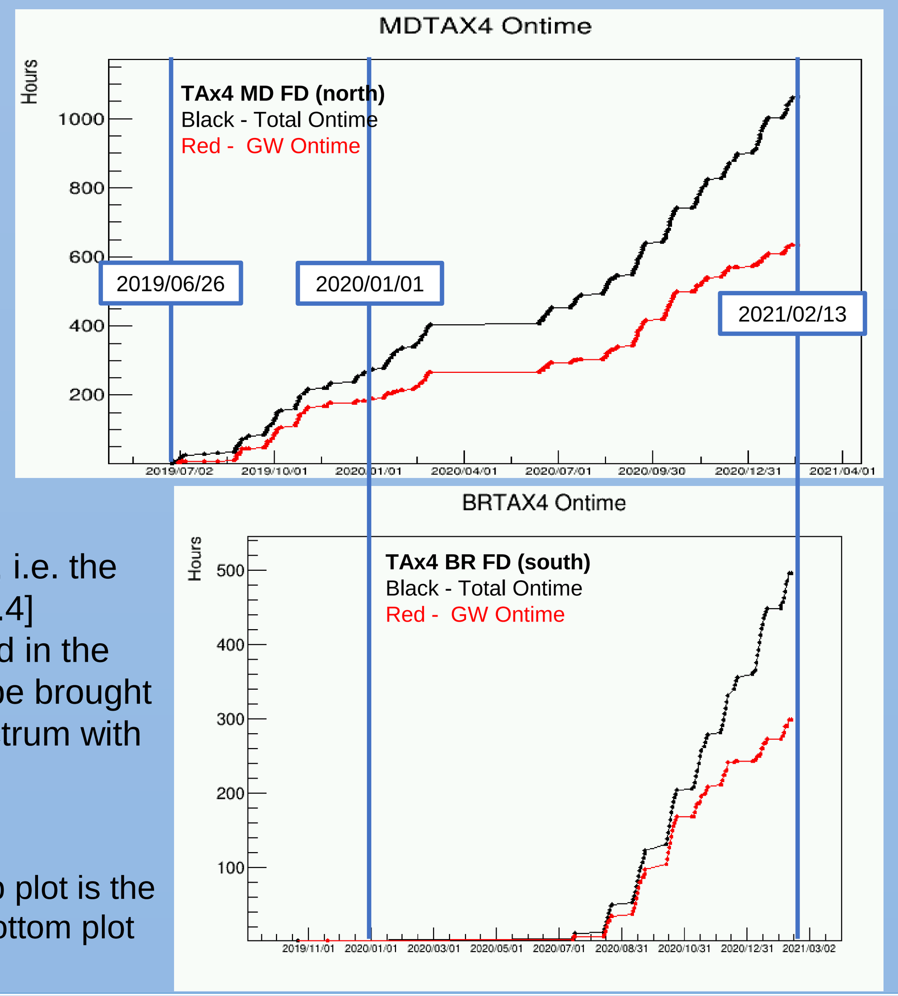


Figure 8: TAx4 ontime plot. The top plot is the northern array TAx4 MD, and the bottom plot is the southern array TAx4 BR.

Results

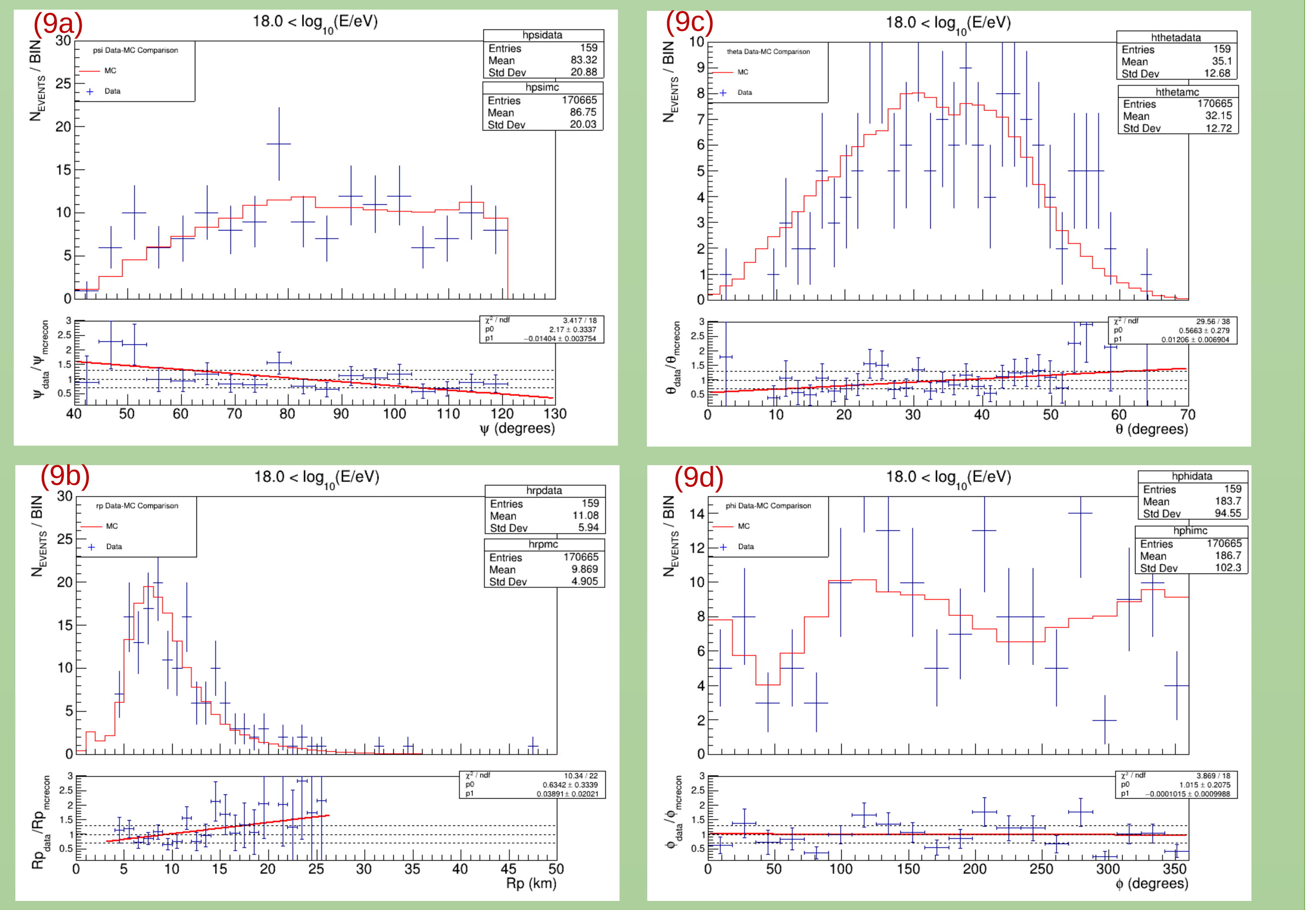


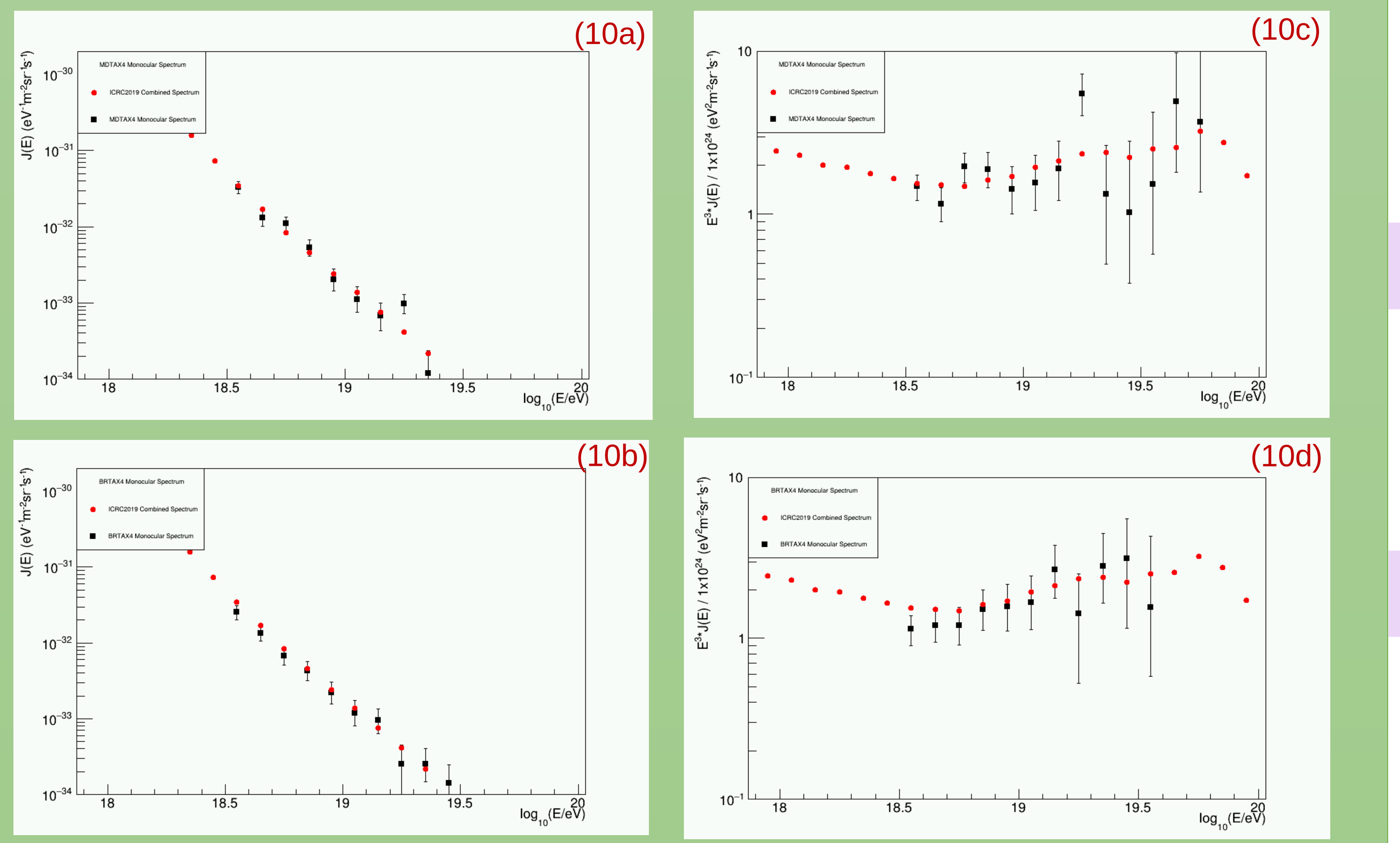
Figure 9: TAx4 MD Data/MC comparisons. (9a) Psi (9b) R_p (Impact parameter) (9c) Theta (9d) Phi

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

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

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

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



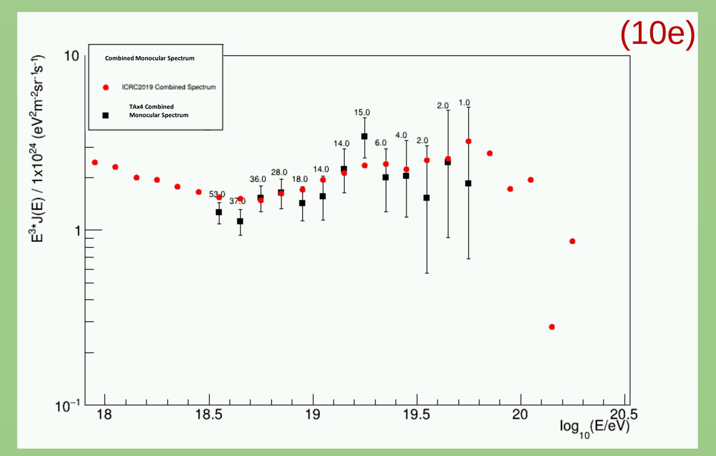


Figure 10: TAx4 monocular energy spectrum results. (10a,10c) TAx4 MD (10b,10d) TAx4 BR (10e) Combined monocular spectrum for TAx4. Numbers above data points indicate how many events are in each bin.

Introduction

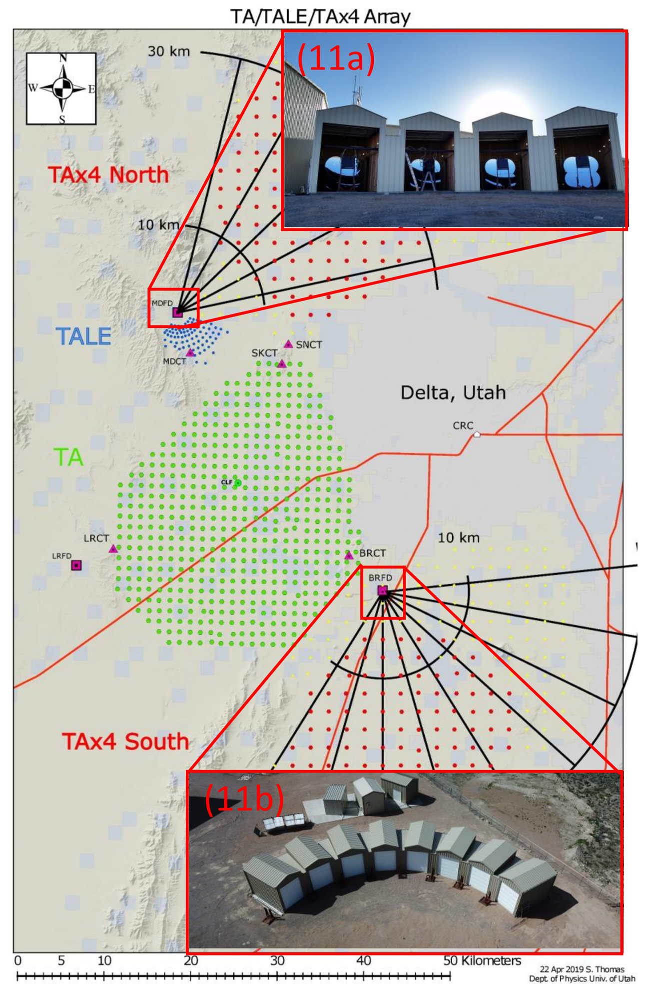


Figure 11: Telescope Array (TA) in Delta, Utah. (11a) TAx4 MD at the Middle Drum (MD) site. (11b) TAx4 BR at the Black Rock Mesa (BRM) site.

- TA Experiment (Figure 11) 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 MD (4 FDs), completed in 2018, views over the northern wing of the new SDs, and TAx4 BR (8 FDs), completed in 2019, views over the southern wing.
- Both FD sites are in routine observation, with data being taken remotely at the TAx4 BR site.
- My role with TAx4
  - The first step before a composition study can be pursued, is a energy spectrum must be calculated.
  - On this poster, I will report on the performance of the TAx4 FD showing data/MC comparisons, a preliminary monocular energy spectrum for each detector, and a preliminary combined monocular spectrum for TAx4.

References

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Future Analysis

I am working towards creating a hybrid energy spectrum. Which means instead of just using the FD information, a hybrid spectrum would use both FD and SD information to improve the accuracy of the reconstruction.

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.