Energy spectrum measured by the Telescope Array Surface Detectors

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on behalf of the Telescope Array Collaboration

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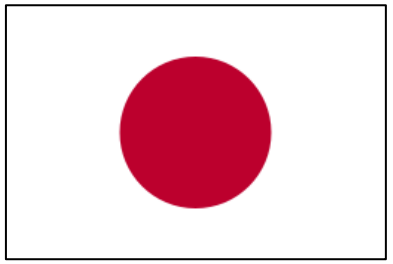
Outline

- Telescope Array Experiment
- Surface Detectors
- Event Reconstruction
- TA SD Energy Spectrum and Spectral Features
- Summary

Telescope Array Collaboration

USA



Japan

Korea

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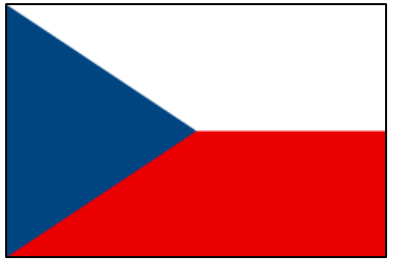
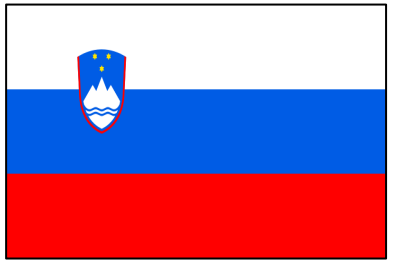
Russia

Belgium



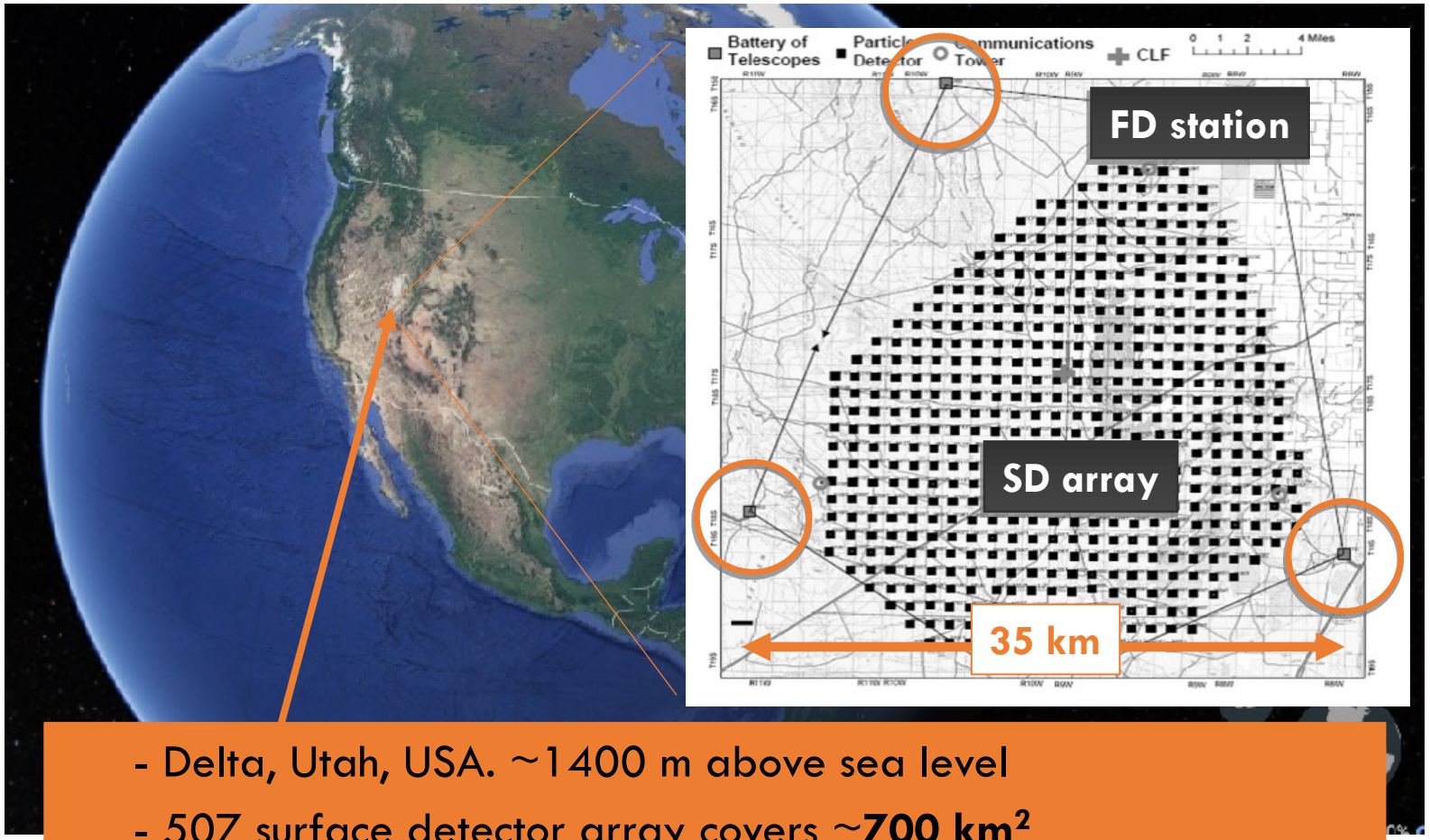
Czech Republic



Slovenia

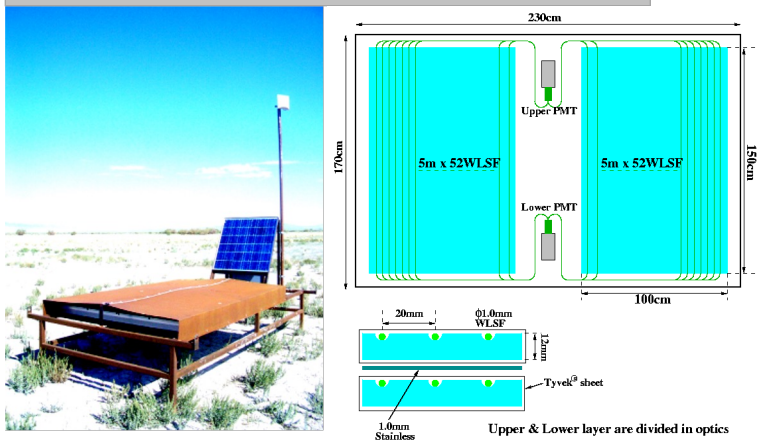
Telescope Array (TA) Experiment

- The largest cosmic ray observatory in the northern hemisphere



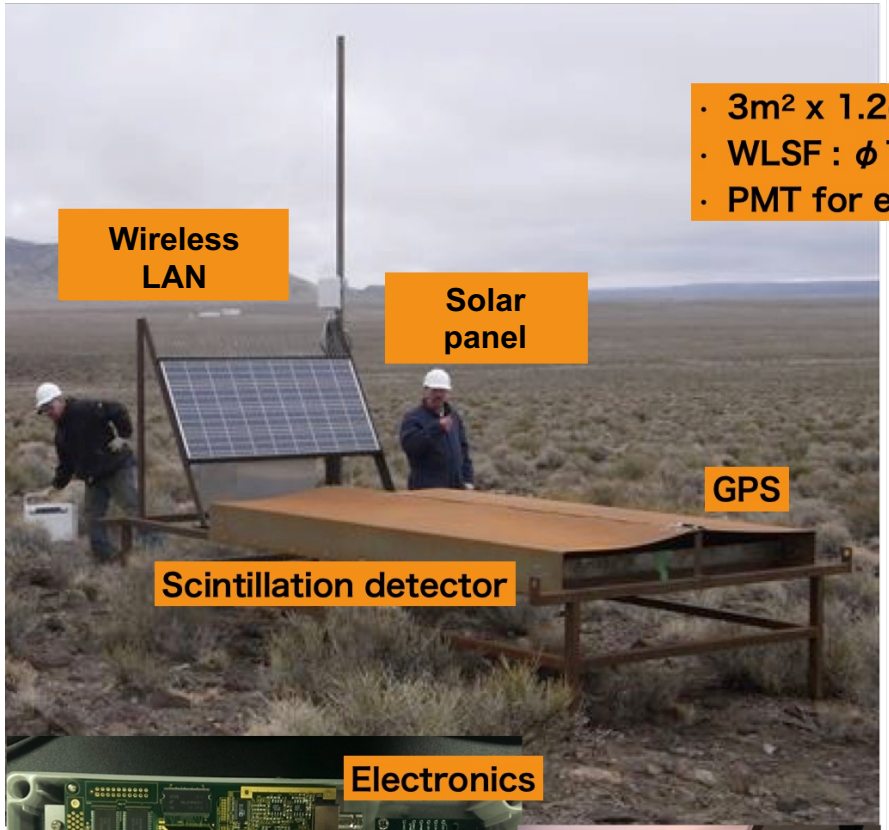
- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km²**
- 38 telescopes at 3 stations to observe the sky above the array

Surface Detector: Plastic Scintillator

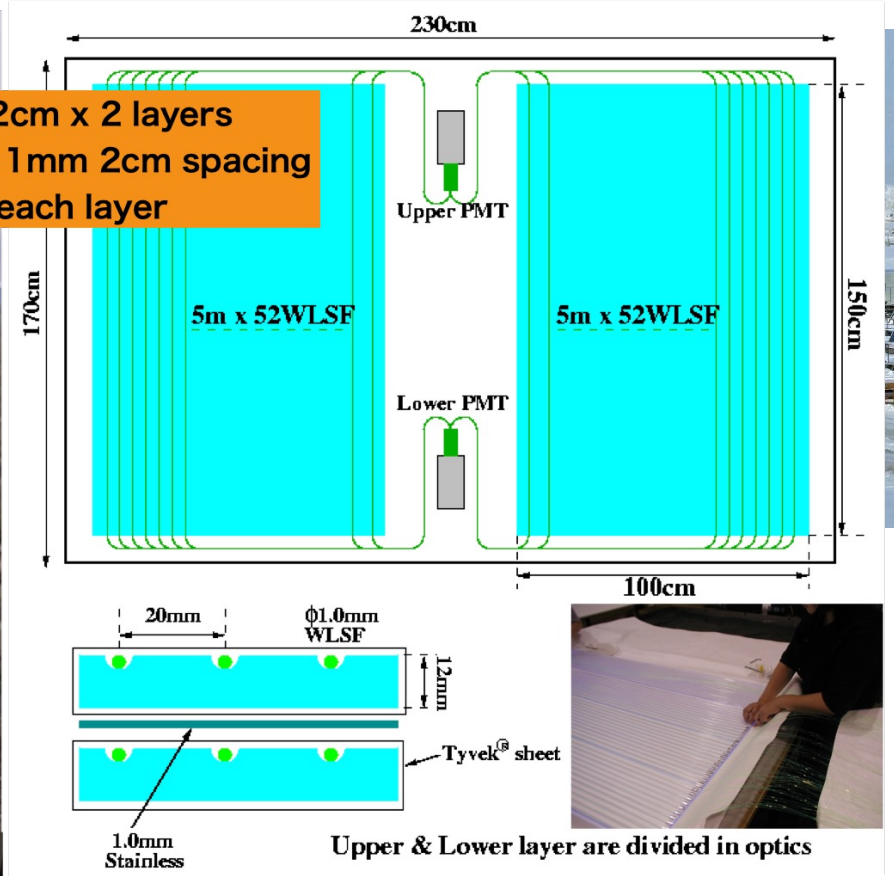


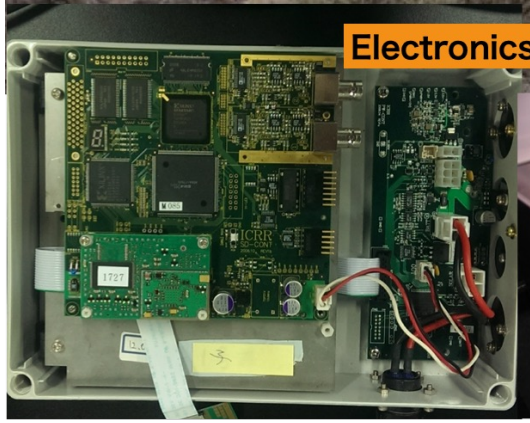
Fluorescence Detector: PMT camera

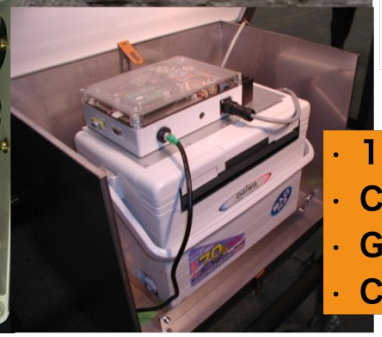
Scintillator Surface Detectors (SDs)



- 3m² x 1.2cm x 2 layers
- WLSF : ϕ1mm 2cm spacing
- PMT for each layer







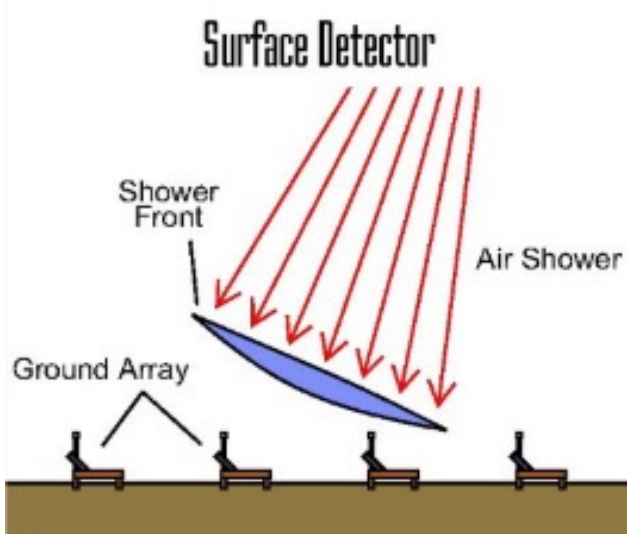
- 12bit 50MHz FADC x 2 layers
- CPU : Renesas SH4(25MHz)
- GPS, WLAN-modem
- Charge controller

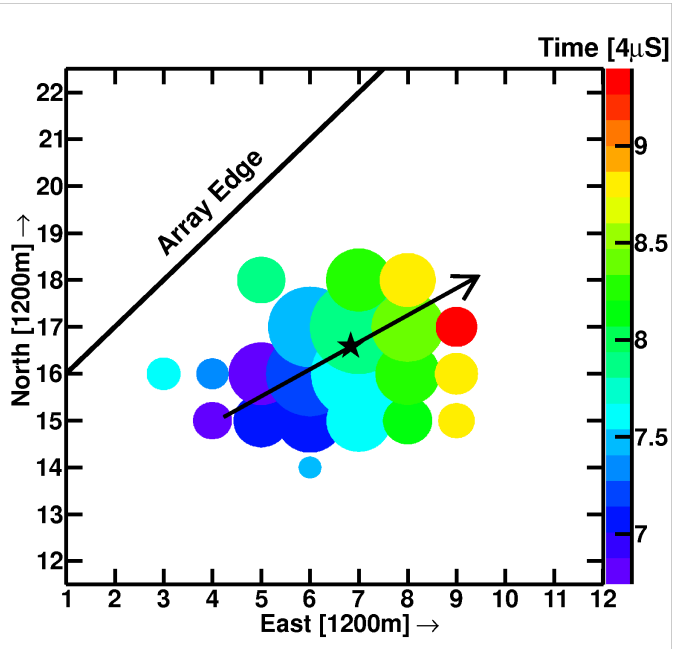
- 507 plastic scintillation counters
- 2 layers, 1.2 cm thick, 3 m^2 area
- 1.2 km square grid spacing covering

~700 km^2

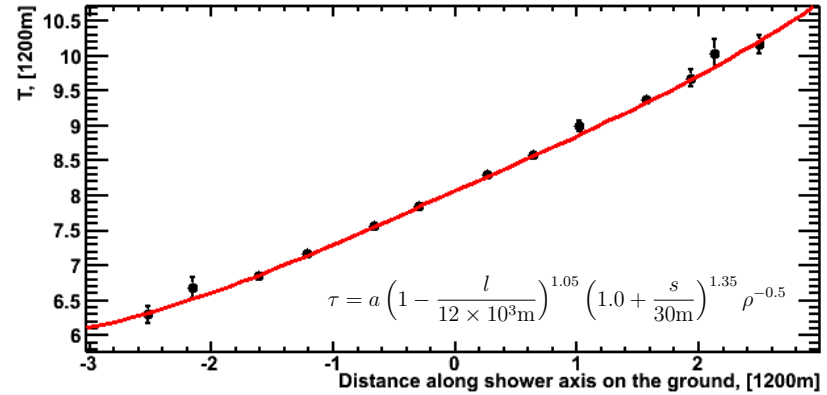
Event Reconstruction (1/2)

- Use counter location and timing to determine shower core and direction
- Fit counter signal size to find lateral distribution
- Signal size at 800 m, S800, is the energy indicator

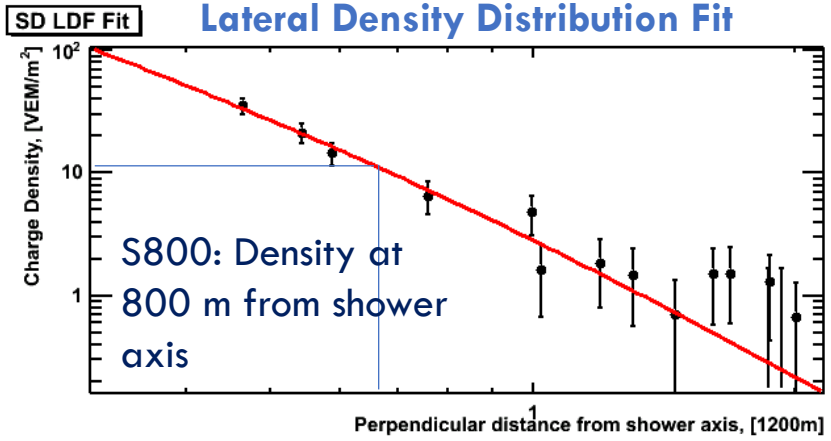




Geometry Fit (modified Linsley)



Lateral Density Distribution Fit

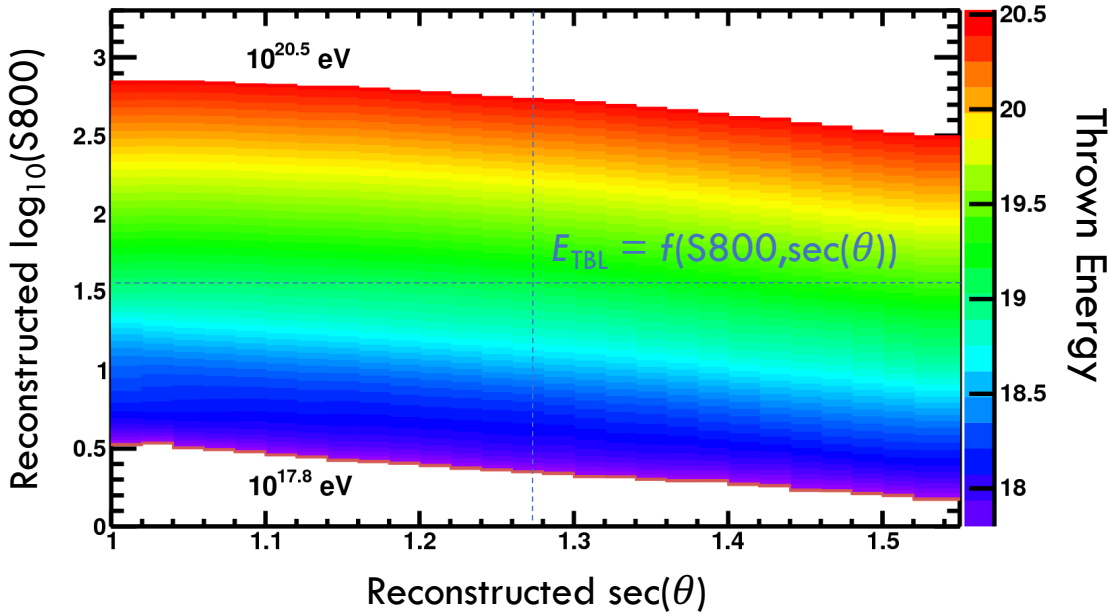


$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

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

Event Reconstruction (2/2)

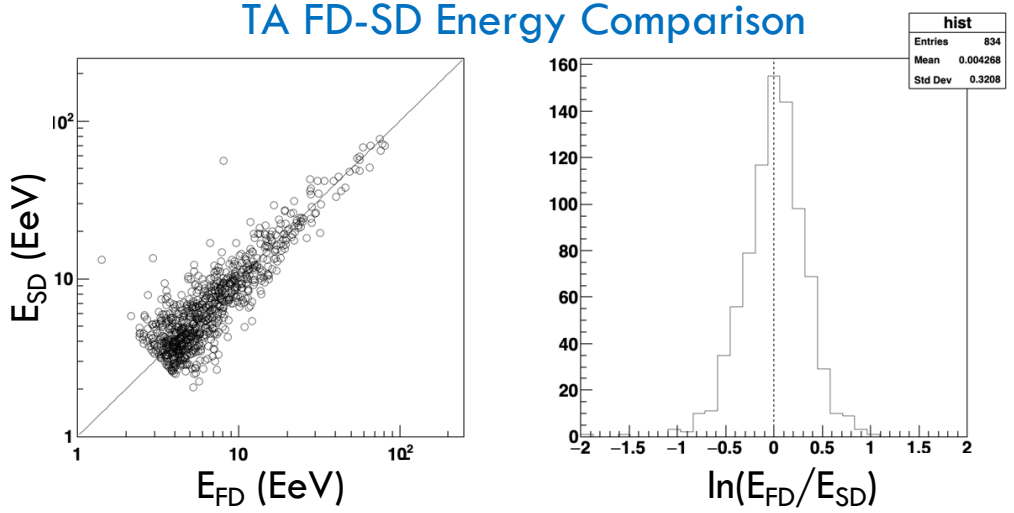
- Use S800 and zenith angle to look up energy (from CORSIKA-produced table)



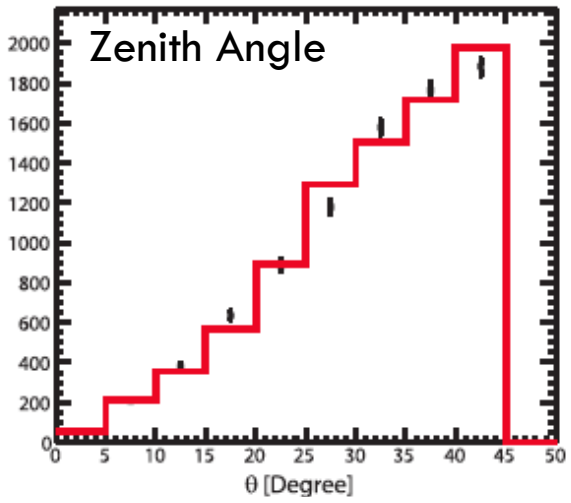
- Scaled to the calorimetric energy/FD

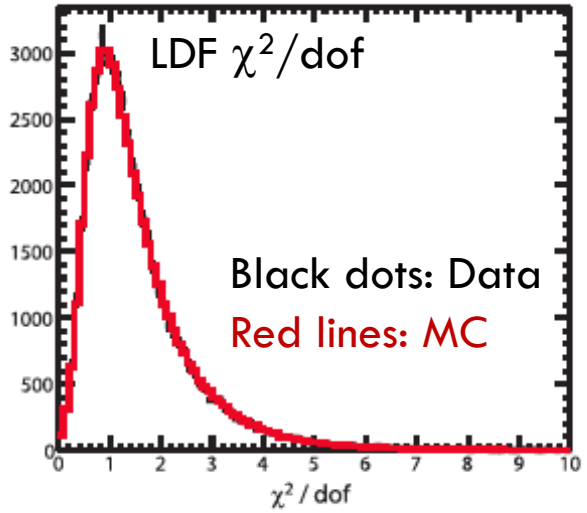
$$E_{Final} = E_{TBL}/1.27$$

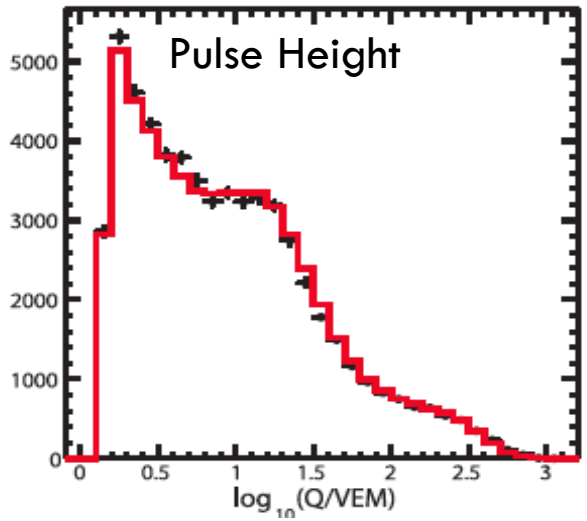
TA FD-SD Energy Comparison



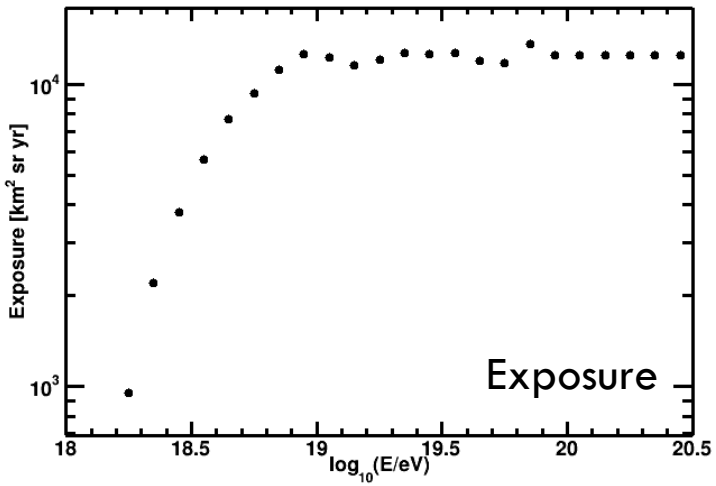
Resolution and Sensitivity by Monte Carlo Simulation





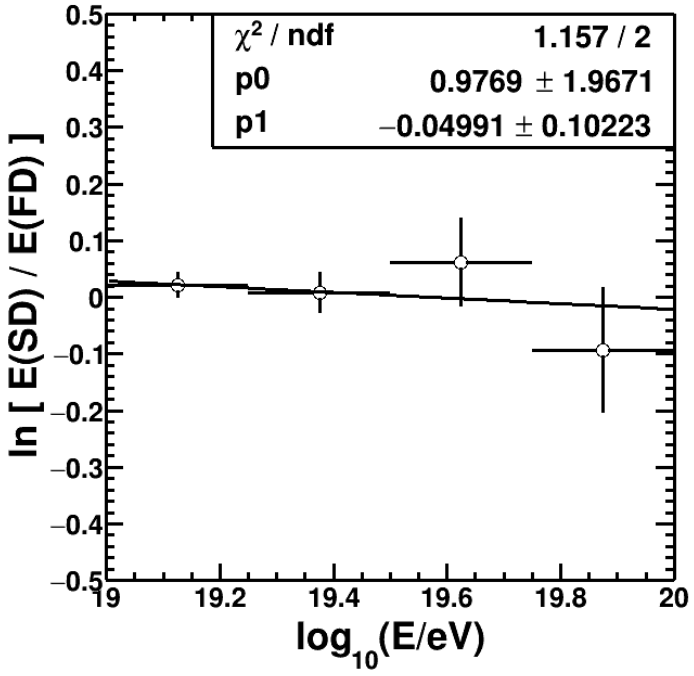


- Monte Carlo based on CORSIKA program used for resolution and exposure calculations.
- TA SD Resolution:
  - 20% energy, 1.4° angular, $E \geq 10^{19.0}$ eV
  - 29% energy, 2.1° angular, $10^{18.5}\text{eV} \leq E < 10^{19.0}$ eV
  - 34% energy. 2.4° angular, $10^{18.0}\,\text{eV} \leq E < 10^{18.5}$ eV

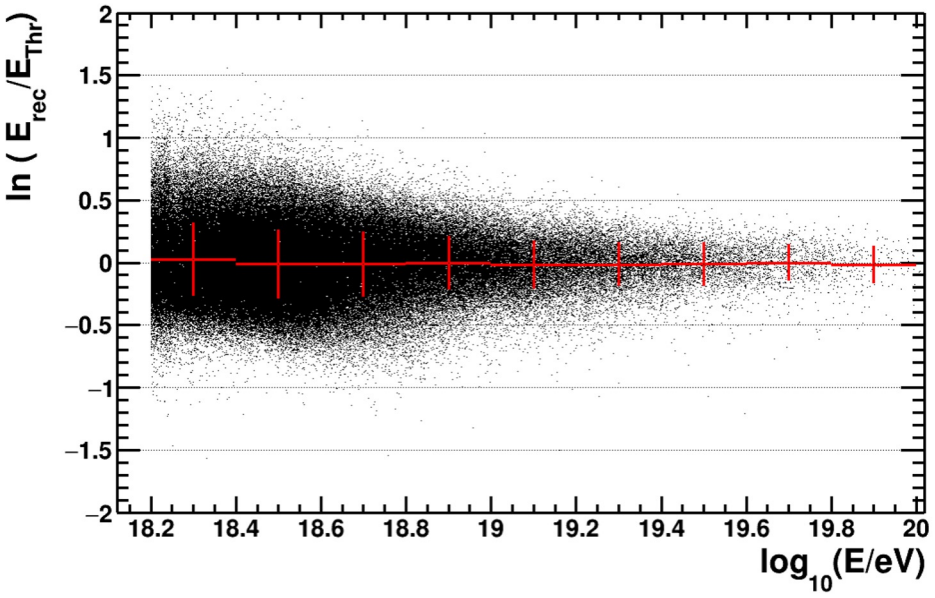


Linearity in Energy Reconstruction D. Ivanov, ICRC2019

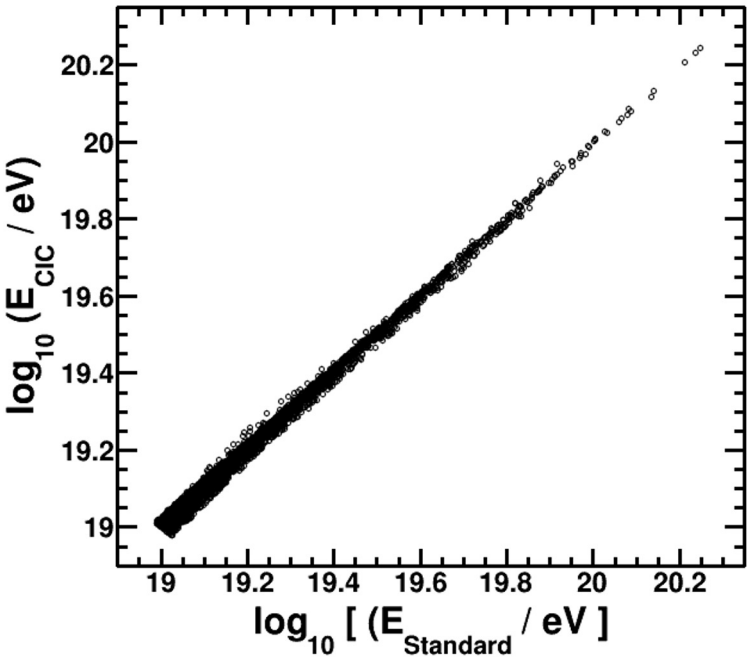
Standard TA SD and FD using hybrid events



MC Thrown energy and reconstructed energy

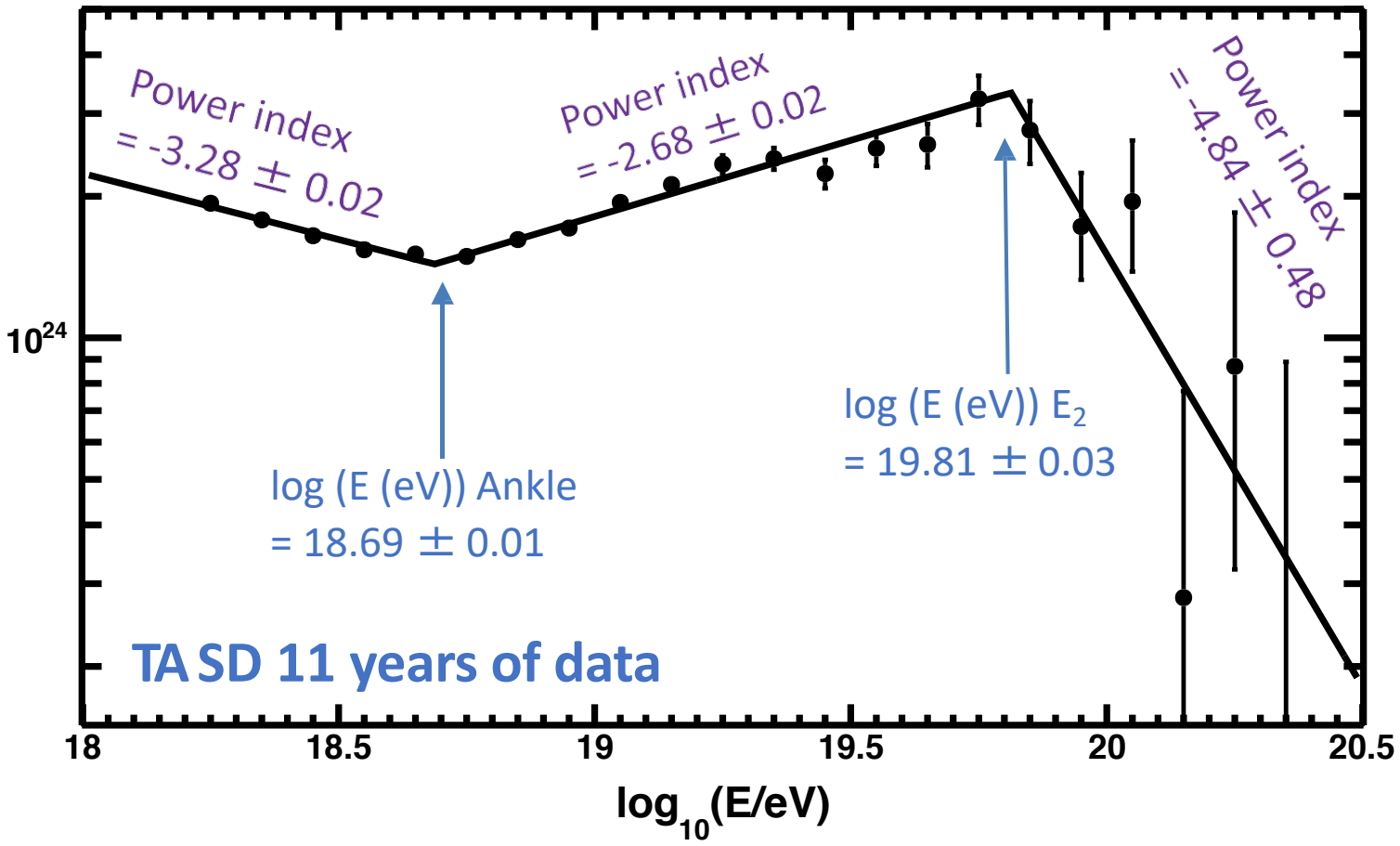


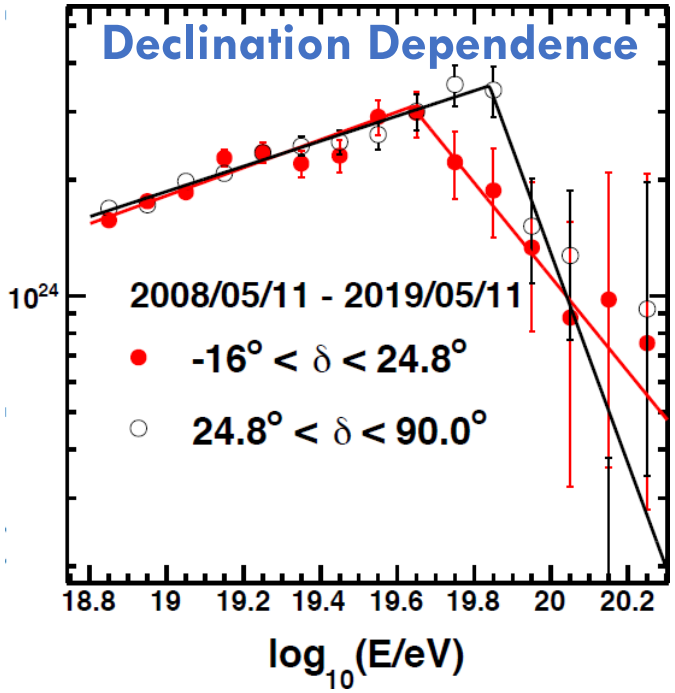
Constant intensity cut and standard TA SD reconstruction



These show the linearity of the standard TA SD energy reconstruction.

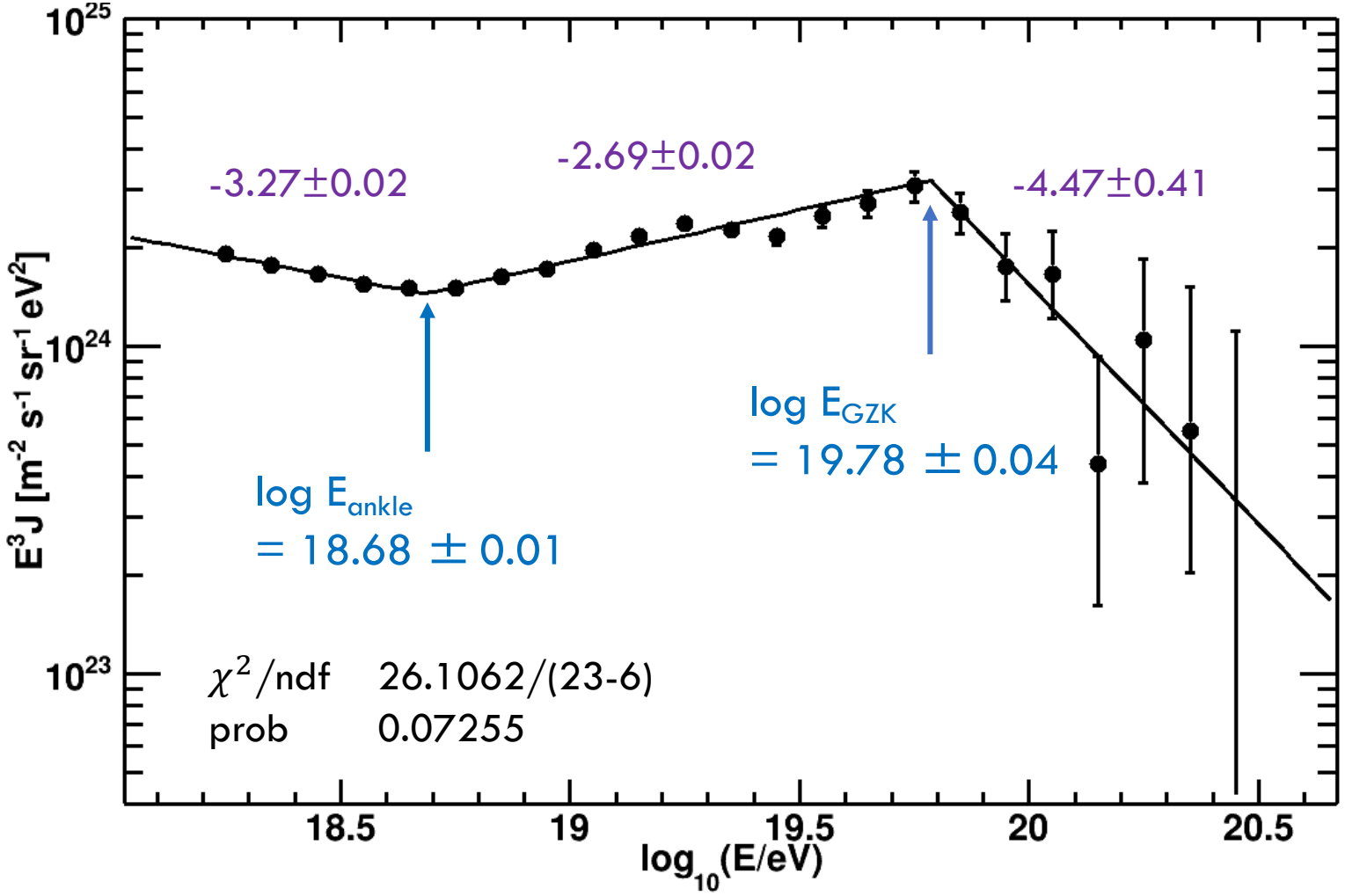
Previous Results using 11-year Data (2008-05-11 to 2019-05-11)



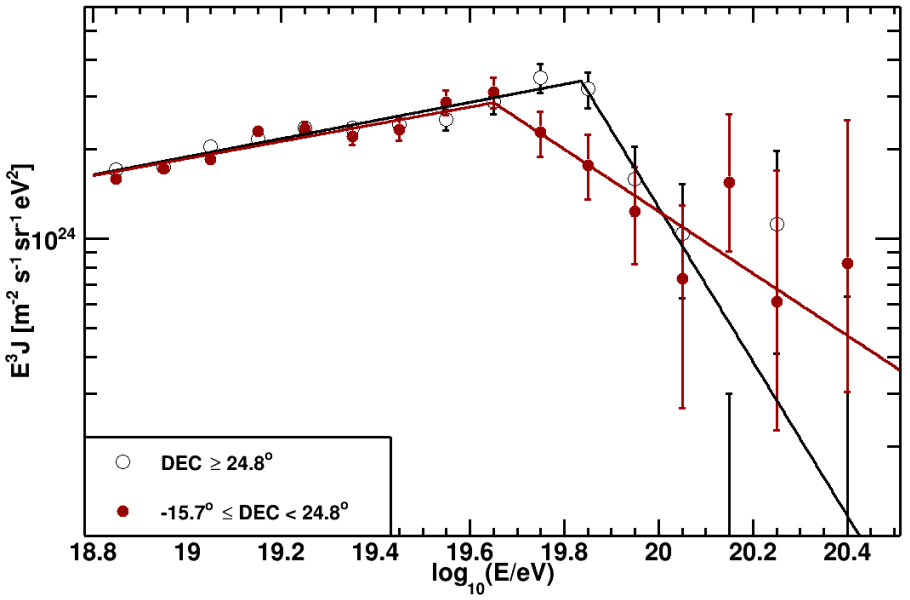


- Differences in the cutoff energies
  - log(E/eV)=**19.84 ±0.02** for (24.8°–90°)
  - log(E/eV)=**19.64 ±0.04** for (-16°–24.8°)
- The global significance of the difference is estimated to be **4.3σ.**

Energy Spectrum using 14-year Data (2008-05-11 to 2022-05-11)

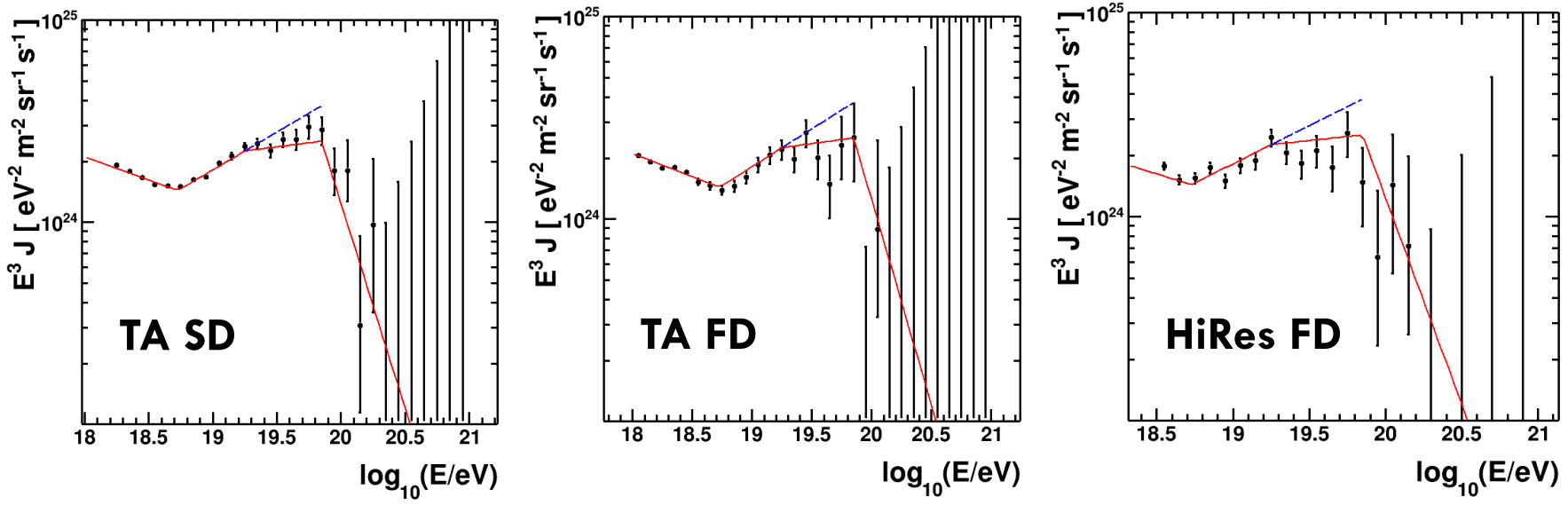


Declination Dependence



- Differences in the cutoff energies
  - log(E/eV)=**19.84 ±0.02** for (24.8°–90°)
  - log(E/eV)=**19.65 ±0.002** for (-16°–24.8°)

Spectral Feature in 10^{19}–$10^{19.5}$ eV D. Ivanov, ICRC2021

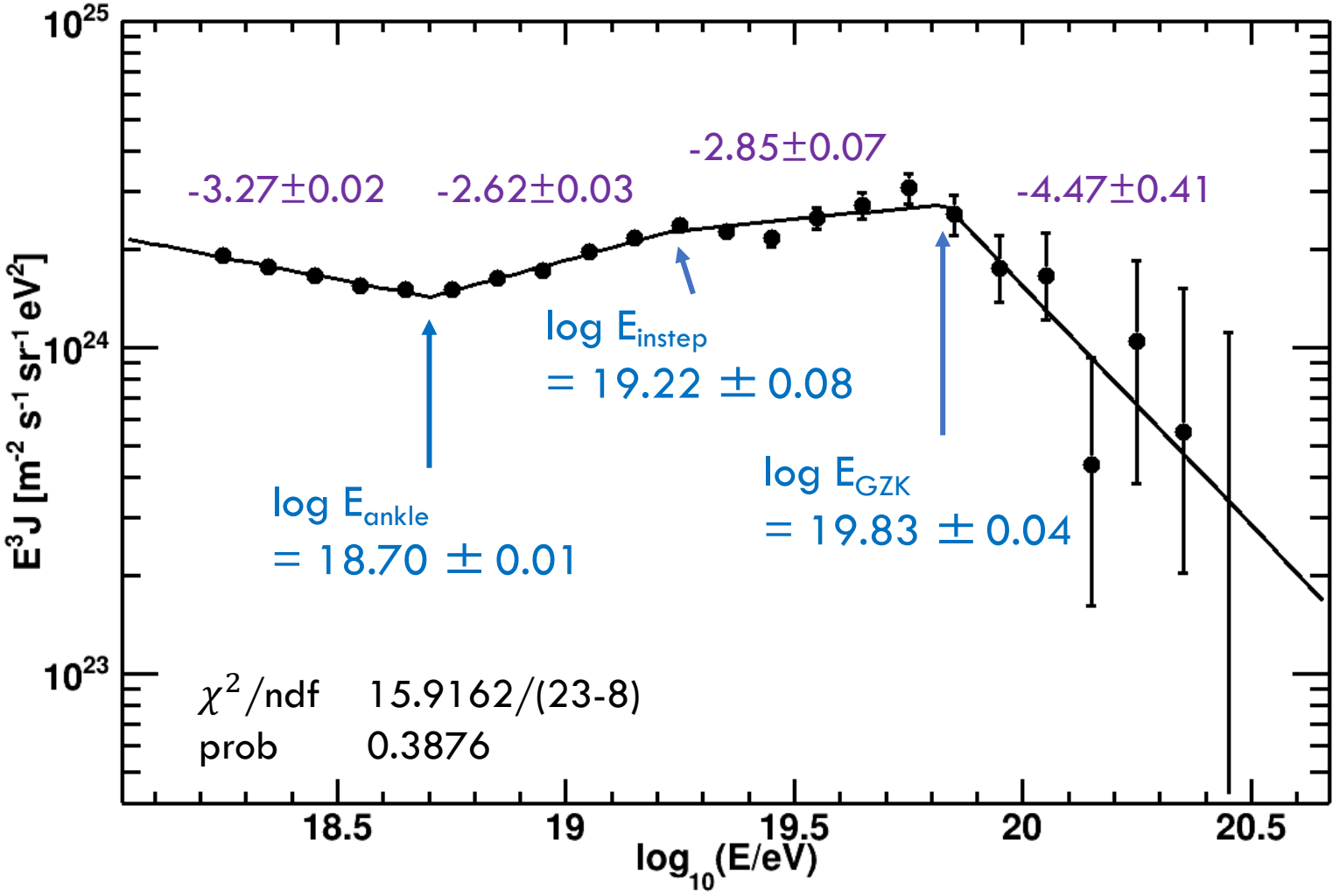


Fit parameter	HiRes—TA	Pierre Auger
p_1	-3.23 ± 0.01 (stat)	-3.29 ± 0.02 (stat)
p_2	-2.63 ± 0.02 (stat)	-2.51 ± 0.03 (stat)
p_3	-2.92 ± 0.06 (stat)	-3.05 ± 0.05 (stat)
p_4	-5.0 ± 0.4 (stat)	-5.1 ± 0.3 (stat)
$\log_{10}[E_{\rm ANKLE}/{\rm eV}]$	18.73 ± 0.01 (stat)	18.70 ± 0.01 (stat)
$\log_{10}[E_{\rm SHOULDER}/{\rm eV}]$	19.25 ± 0.03 (stat)	19.11 ± 0.03 (stat)
$\log_{10}[E_{\rm GZK}/{\rm eV}]$	19.85 ± 0.03 (stat)	19.66 ± 0.03 (stat)

- Pierre Auger found a new spectral feature in 10^{19}–$10^{19.5}$ eV (*instep* feature).

- We observed the same softening feature in the northern hemisphere but at $10^{19.25\pm0.03}$ eV with a 5.3σ significance.

Spectral Feature in 10^{19}–$10^{19.5}$ eV using 14-year Data

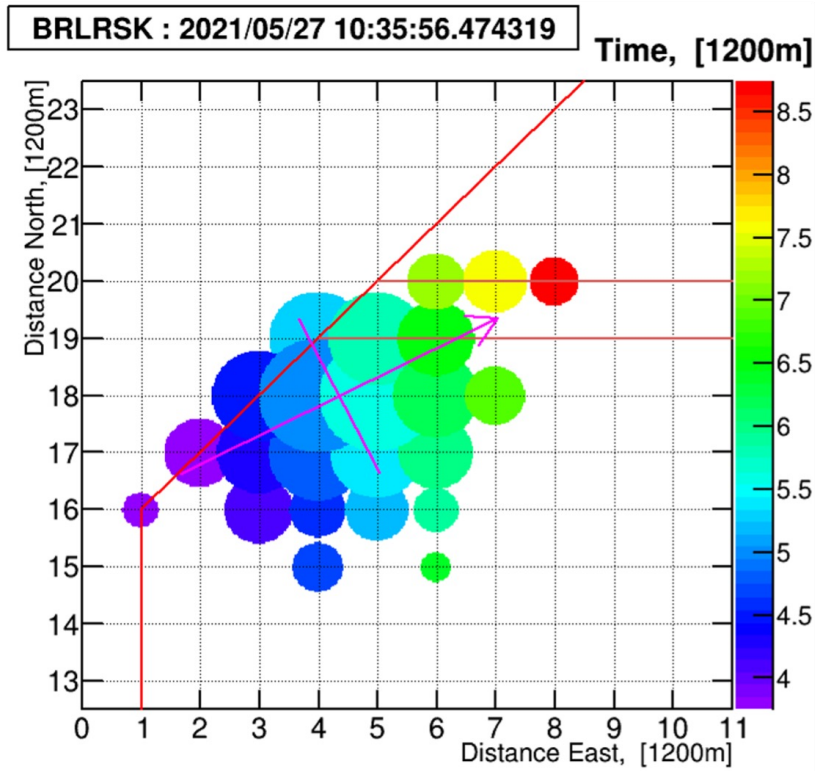


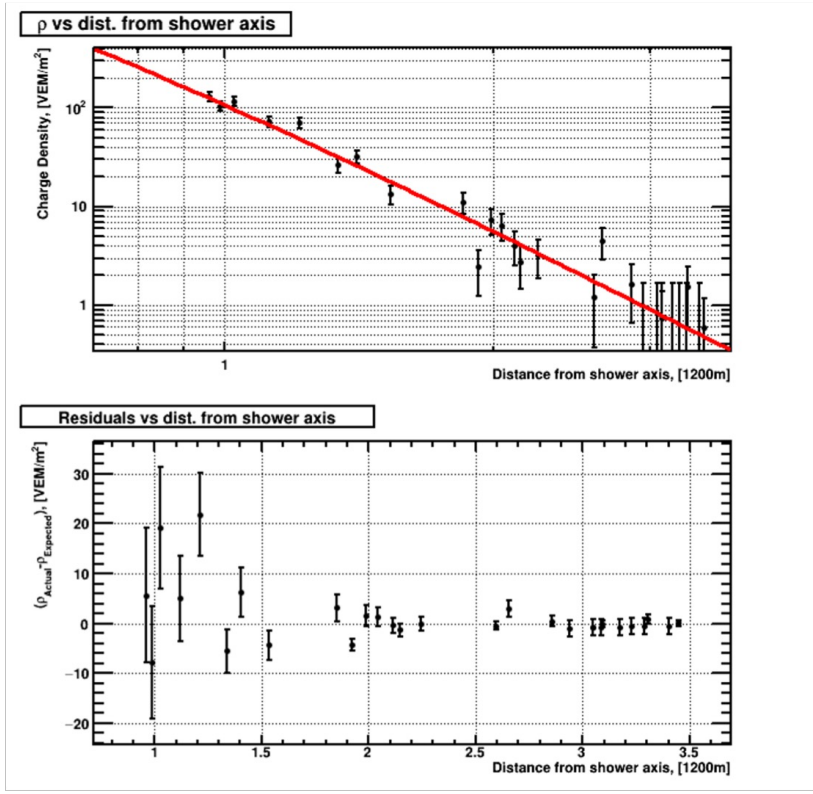
- N_{exp} (no softening) : 1898.9
  N_{obs} : 1725
  Chance probability : 2.7×10^{-5}, $\sim4.0\sigma$

- TA SD observed the same softening feature in the northern hemisphere but at $10^{19.22\pm0.08}$ eV with a 4.0σ significance.

Highest energy event @ May 27, 2021

Figure 5.8: **Left:** SD display of the highest energy event seen by TA, at $10^{20.4}$ eV. The circle size represents the SD integrated signal, while the color represents the relative time. The shower core and direction are shown by the cross. **Right:** The longitudinal profile of the event. The two counters closest to the core of the shower were saturated and are not included. The value of $S(800)$ is 530 VEM/m^2.





Snowmass 2021 white paper, https://arxiv.org/abs/2205.05845)

Summary

- Have validated Monte Carlo carefully by comparing it with the distribution of the data.
- TA SD energy reconstruction is robust. It has been checked using 1) FD/SD comparison, 2) Monte Carlo, and 3) Constant intensity cut methods.
- TA SD spectrum has shown the spectral features (ankle, *instep*, and GZK cutoff) with 14 years of data.
- Declination dependence of spectrum seen in the up-to-date dataset.

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Abstract submission will open in December or January.
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