Energy Spectrum Measured by the Telescope Array Experiment

TELESCOPE ARRAY PROJECT

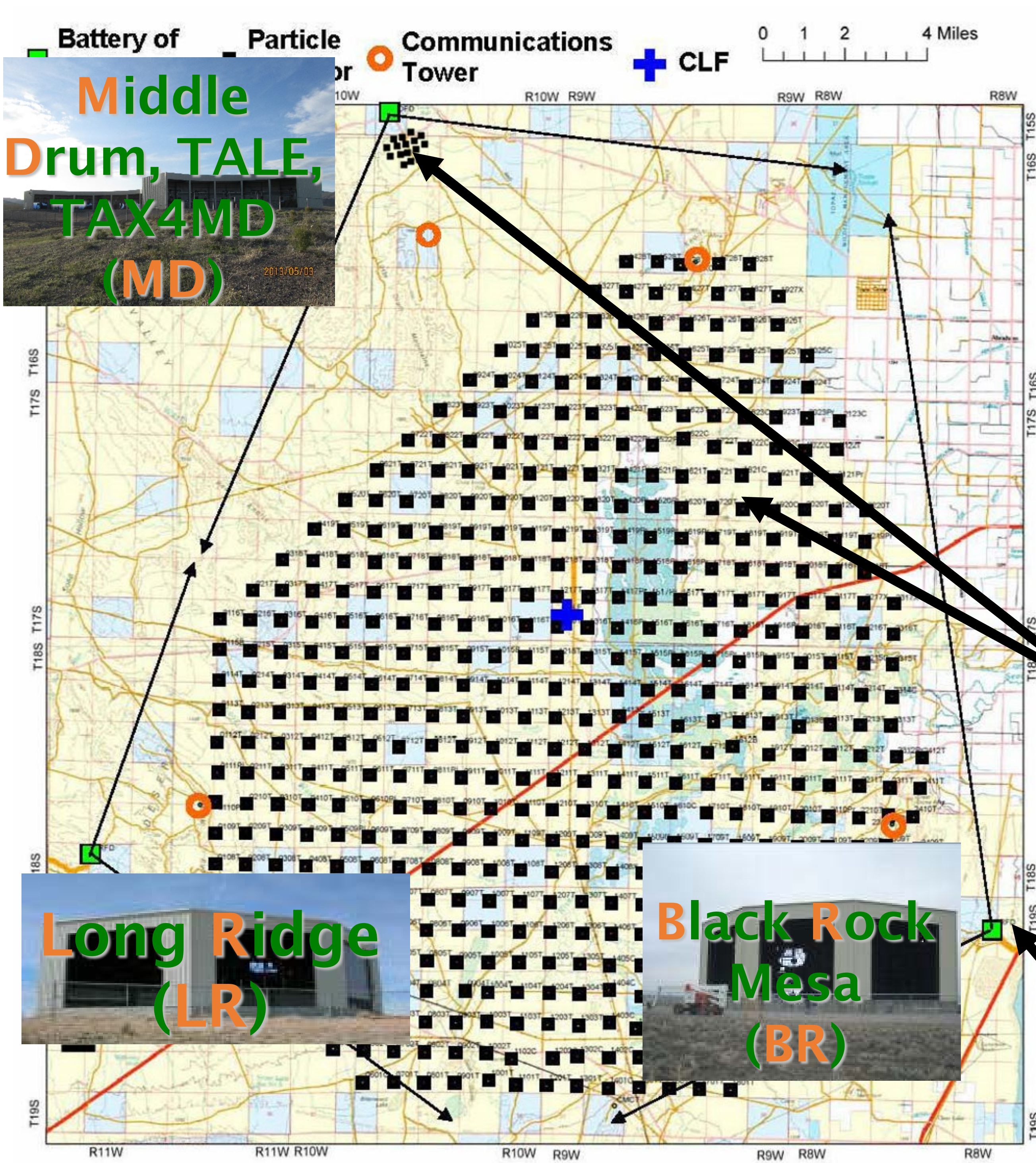
147 members, 36 institutions, from US, Japan, Belgium, Korea, Russia, and Czech Republic
http://www.telescopearray.org

ICRC2019
Madison, WI, USA

Dmitri Ivanov
University of Utah
07/27/2019 17:45-18:00
ICRCR 2019, Madison, WI, USA

Telescope Array

Hybrid detector



Millard County, UT

39.3˚ N , 112.9˚ W,

Alt. 1400m

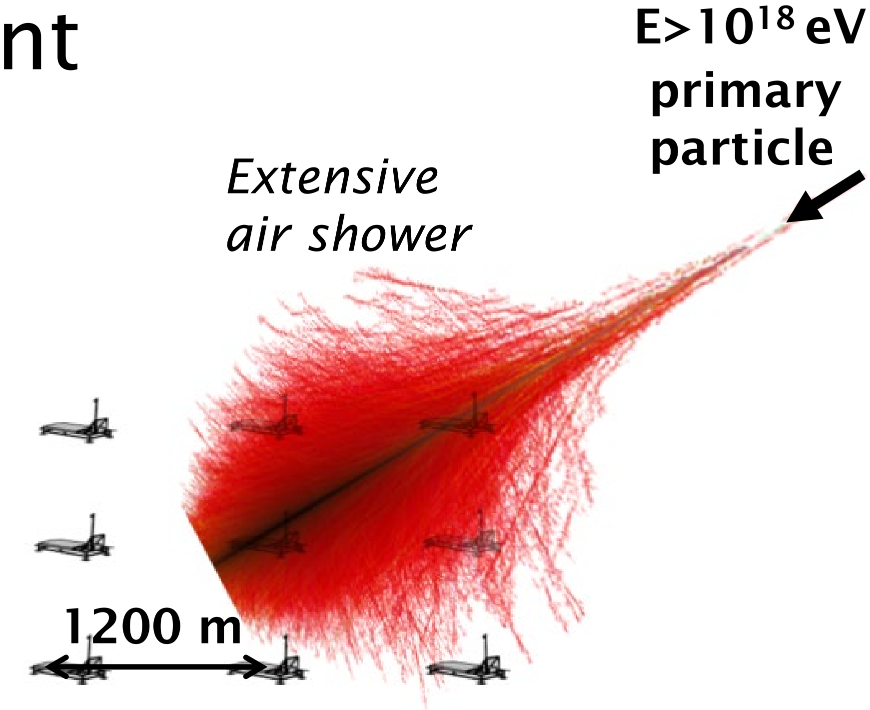
(~880g/cm^2 of air)

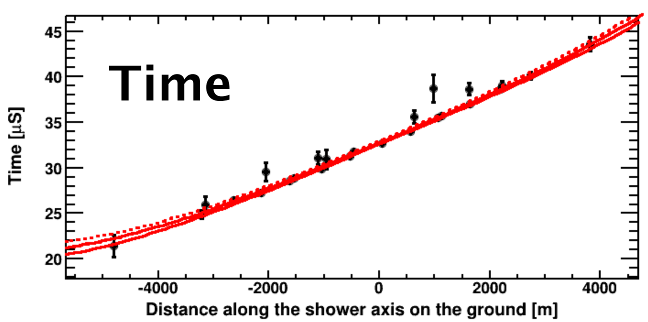
507 Surface Detector (SD) counters 1.2km apart +103 TALE infill array counters of 400m and 600m spacing

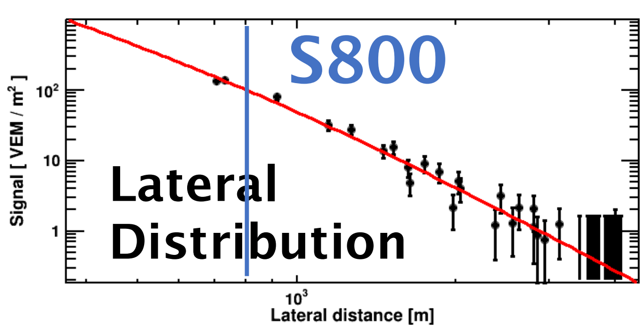
3 Fluorescence Detector sites (FD): BR, LR, and MD/TALE/TAX4MD

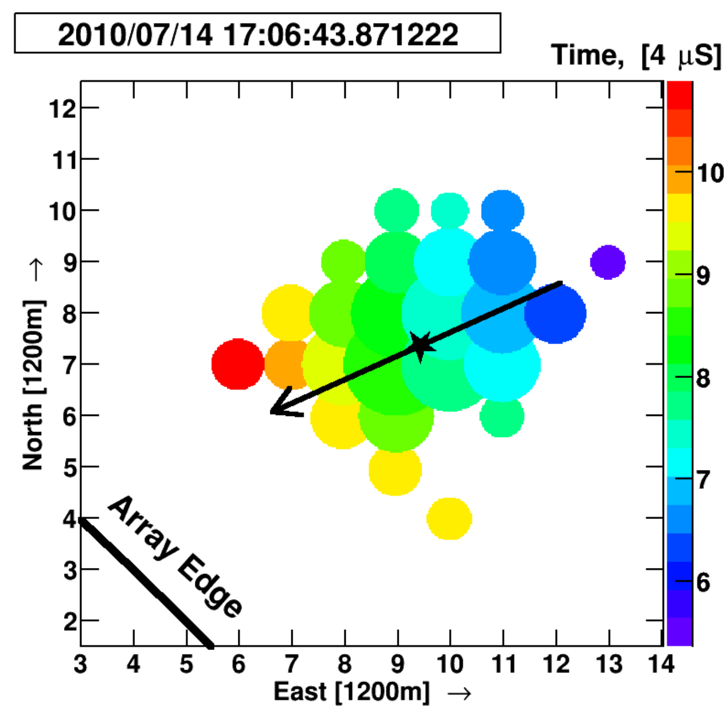
SD Event

- Plastic scintillation counters **sensitive to e±, γ, μ±, …**
- **Time fit** -> **primary particle trajectory**
- **Lateral distribution fit** -> Signal Size 800 m (**S800**) from shower axis -> **primary particle energy**

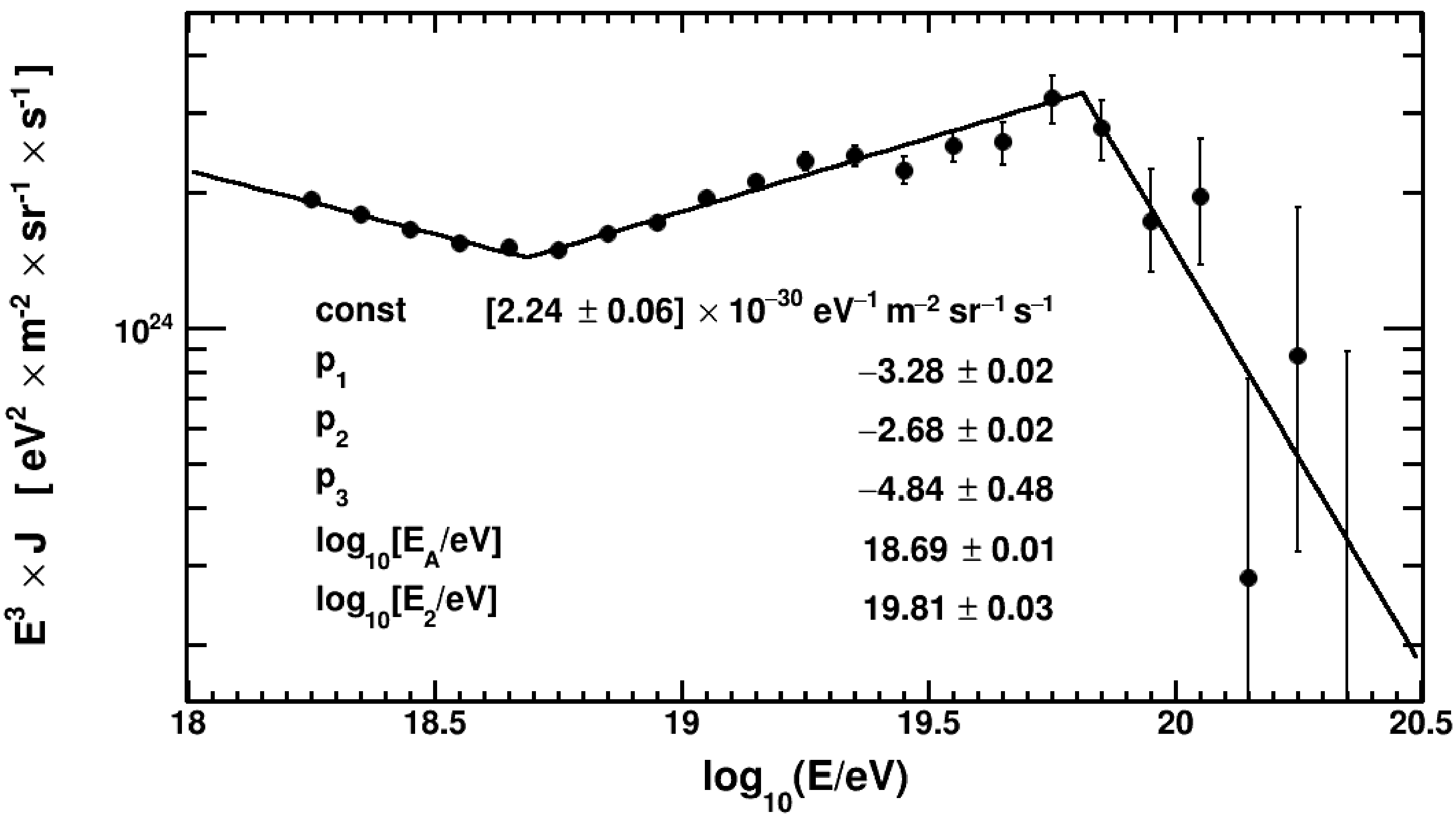








TA SD Spectrum (2008/05/11 – 2019/05/11)



TALE FD Monocular Events

Fluorescence event

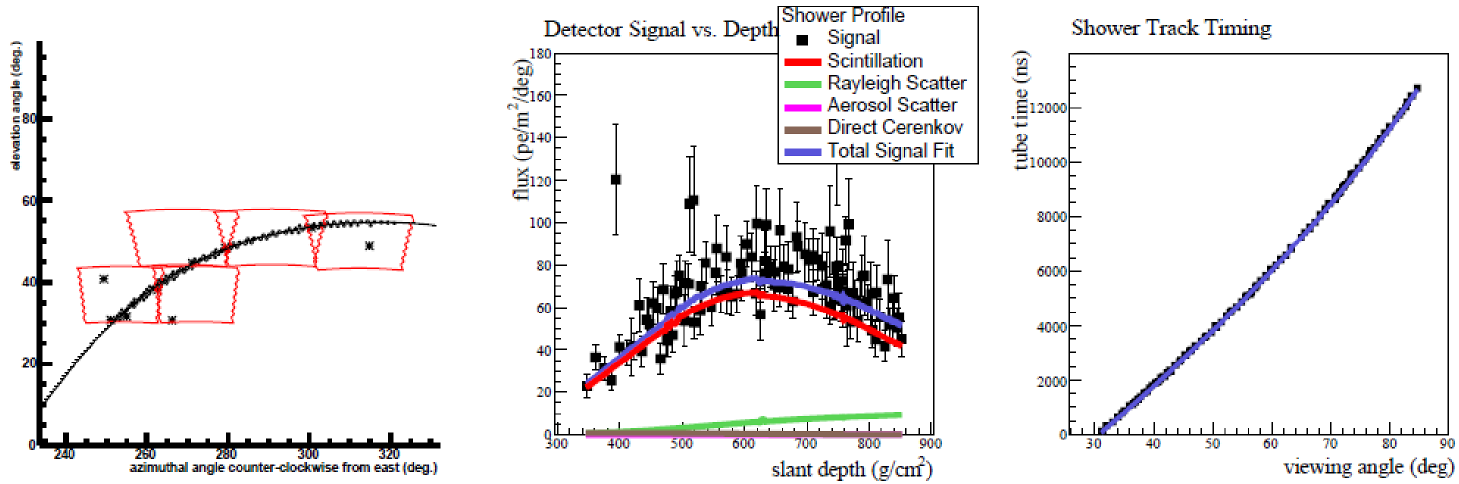


Figure 5: A five-telescope fluorescence event. The display panels show the event image (PMT trigger pattern), the reconstructed shower profile with relative contributions of FL/CL and scattered CL, and the time progression of triggered PMTs.

Cherenkov event, profile-constrained geometry fit.

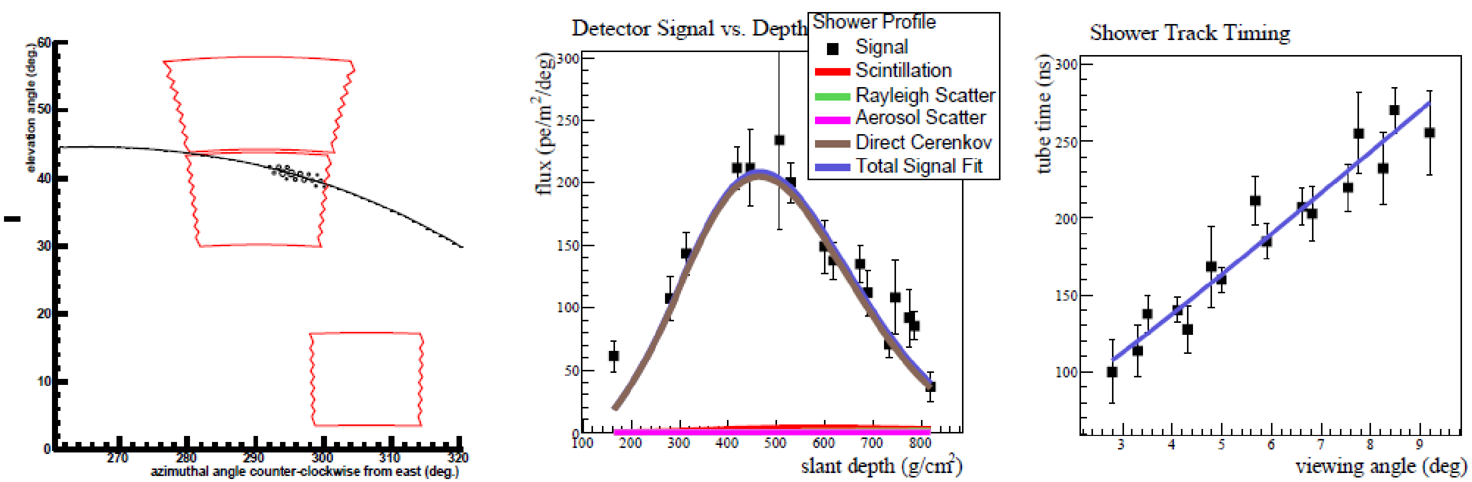
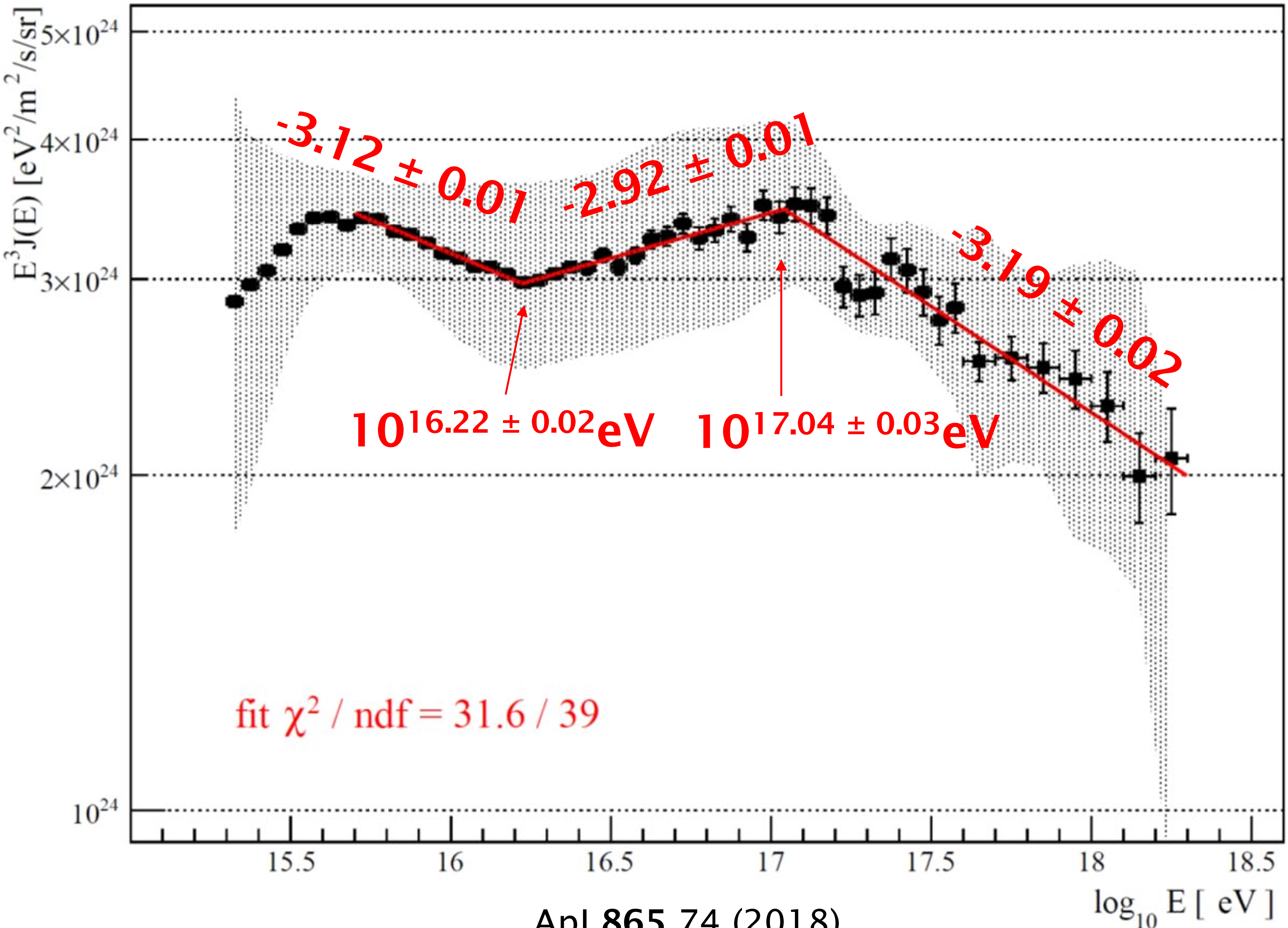


Figure 6: A one-telescope Cherenkov event. The display panels show the event image (PMT trigger pattern), the reconstructed shower profile with relative contributions of FL/CL and scattered CL, and the time progression of triggered PMTs.

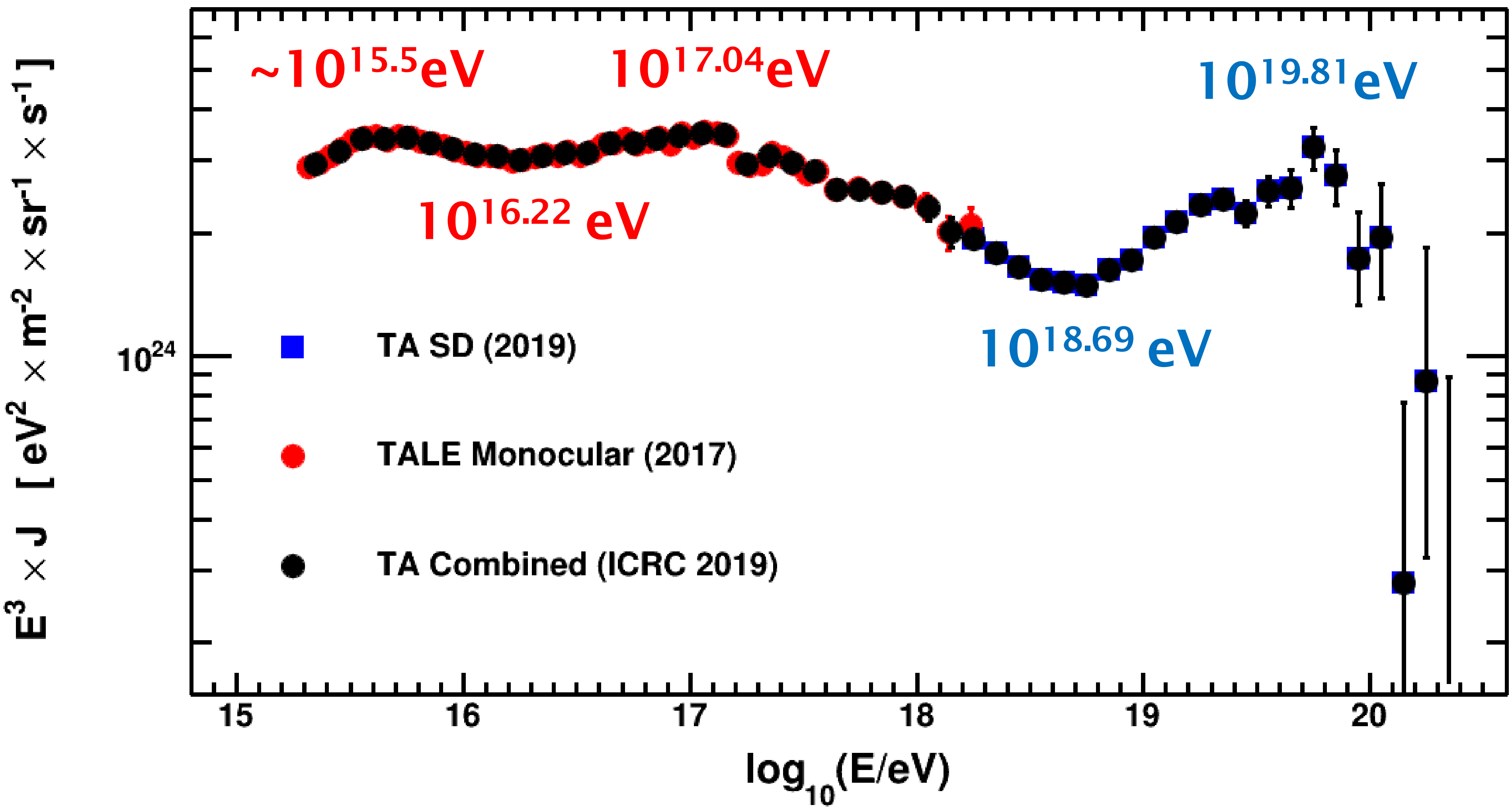
ApJ **865** 74 (2018)

TALE FD Monocular Spectrum

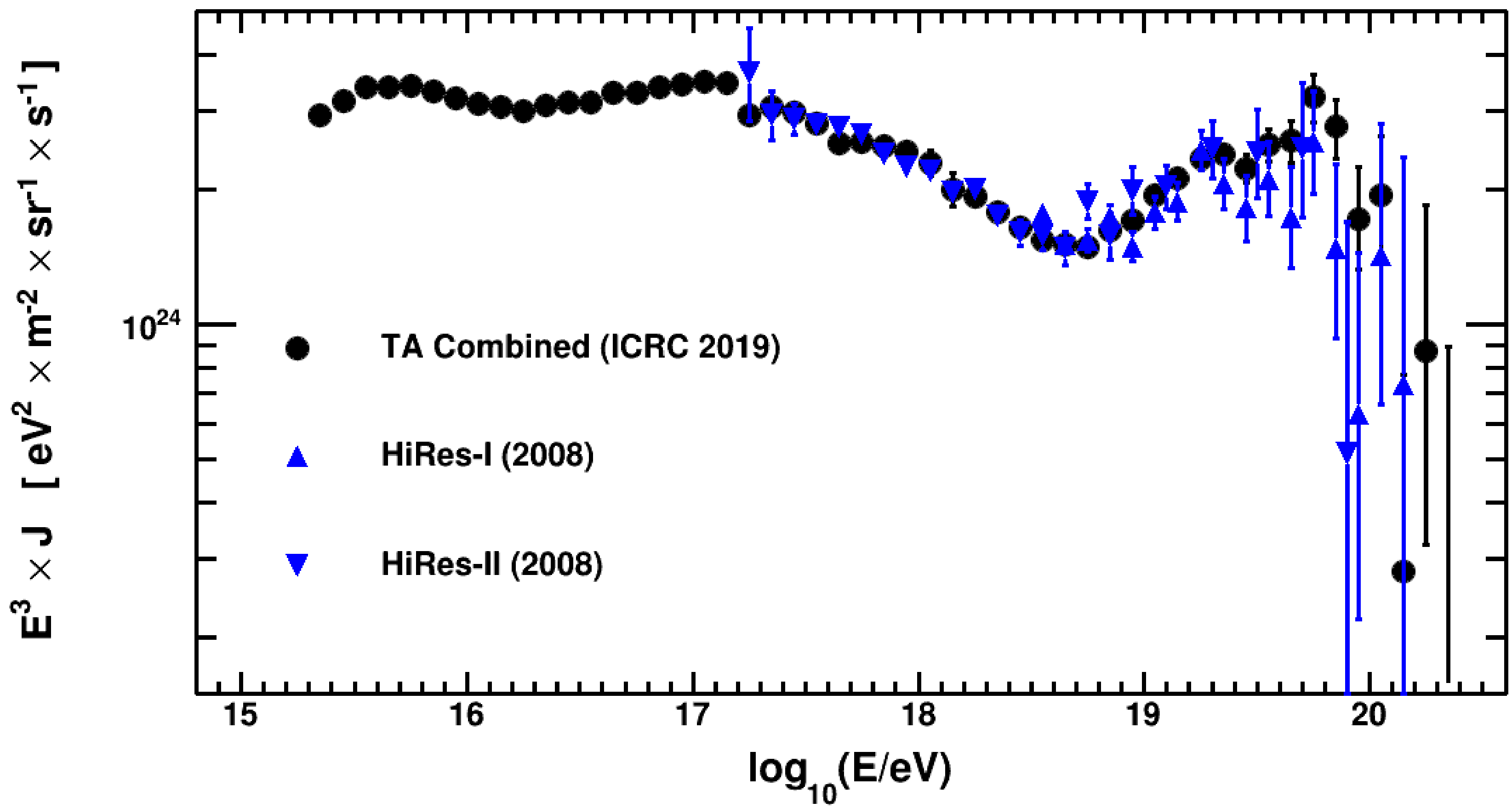


ApJ **865** 74 (2018)

Combined TA Spectrum

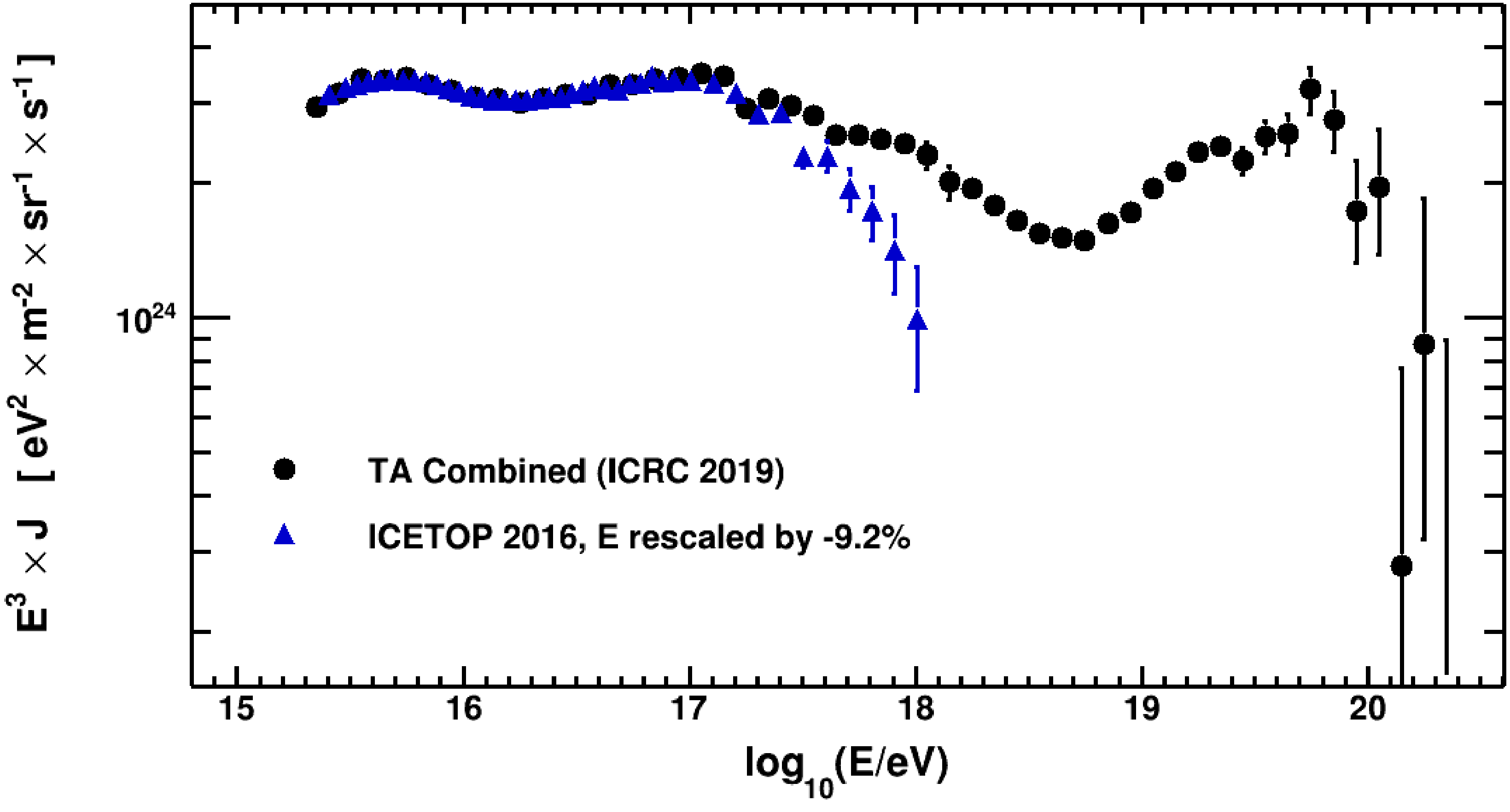


Compare with HiRes

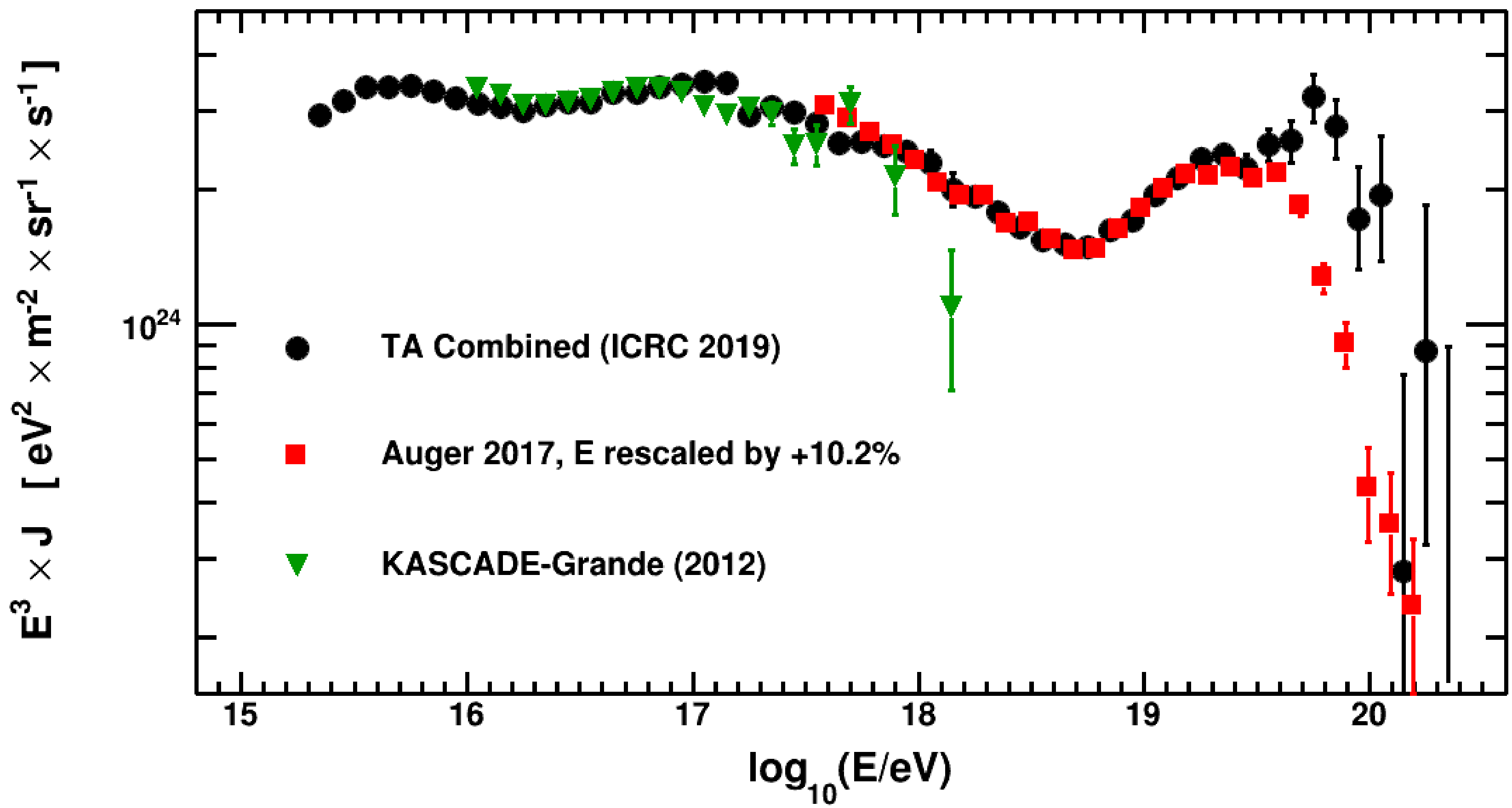


Compare with IceTop

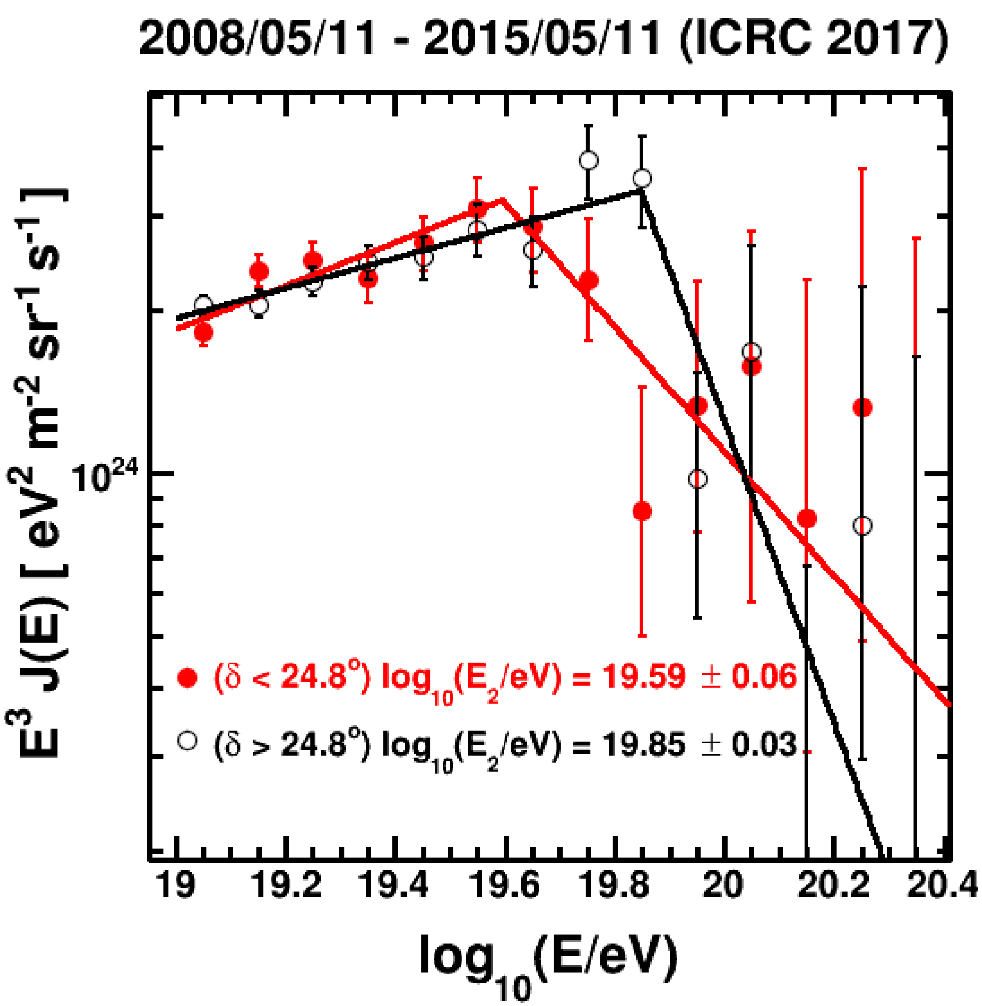
Good agreement up to ~$10^{17.4}$ eV



Compare with KASCADE-Grande and Auger

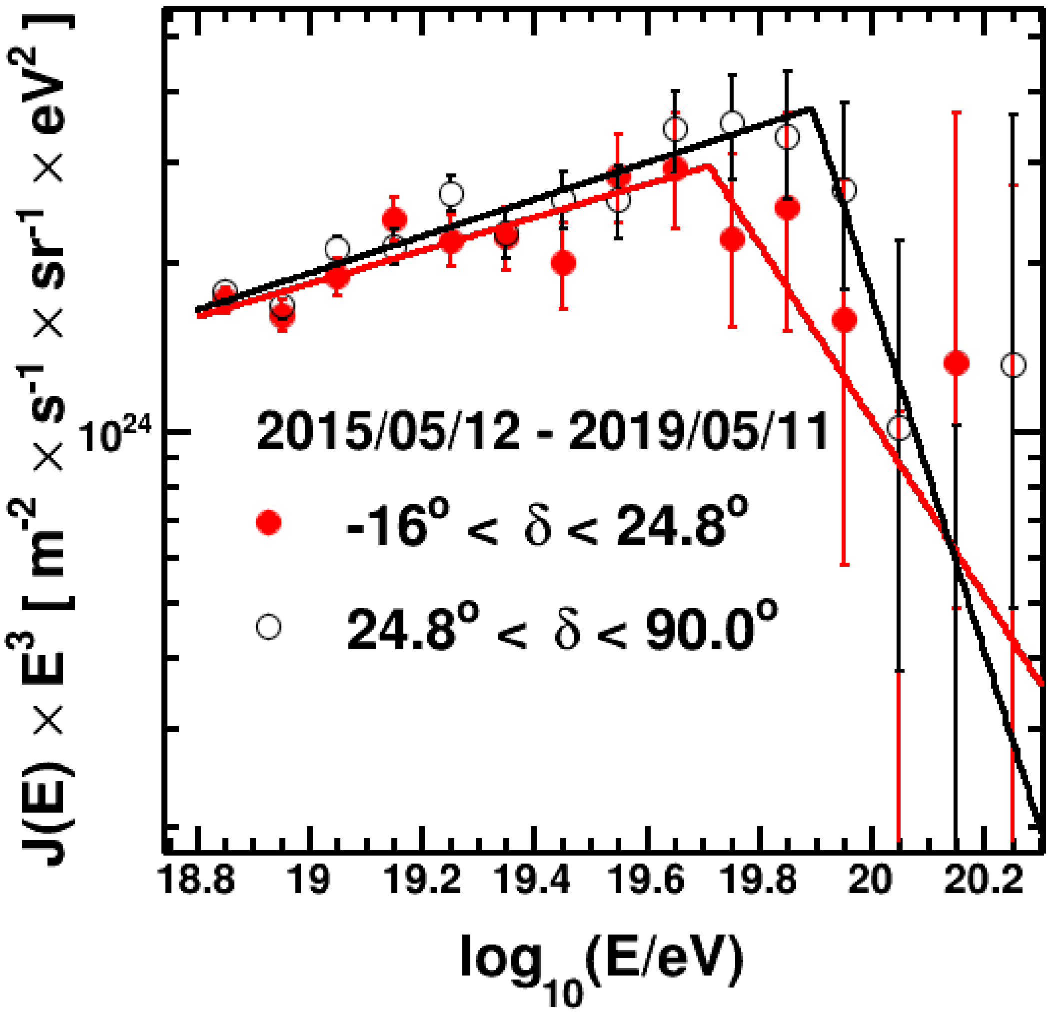


TA Spectrum Declination Dependence



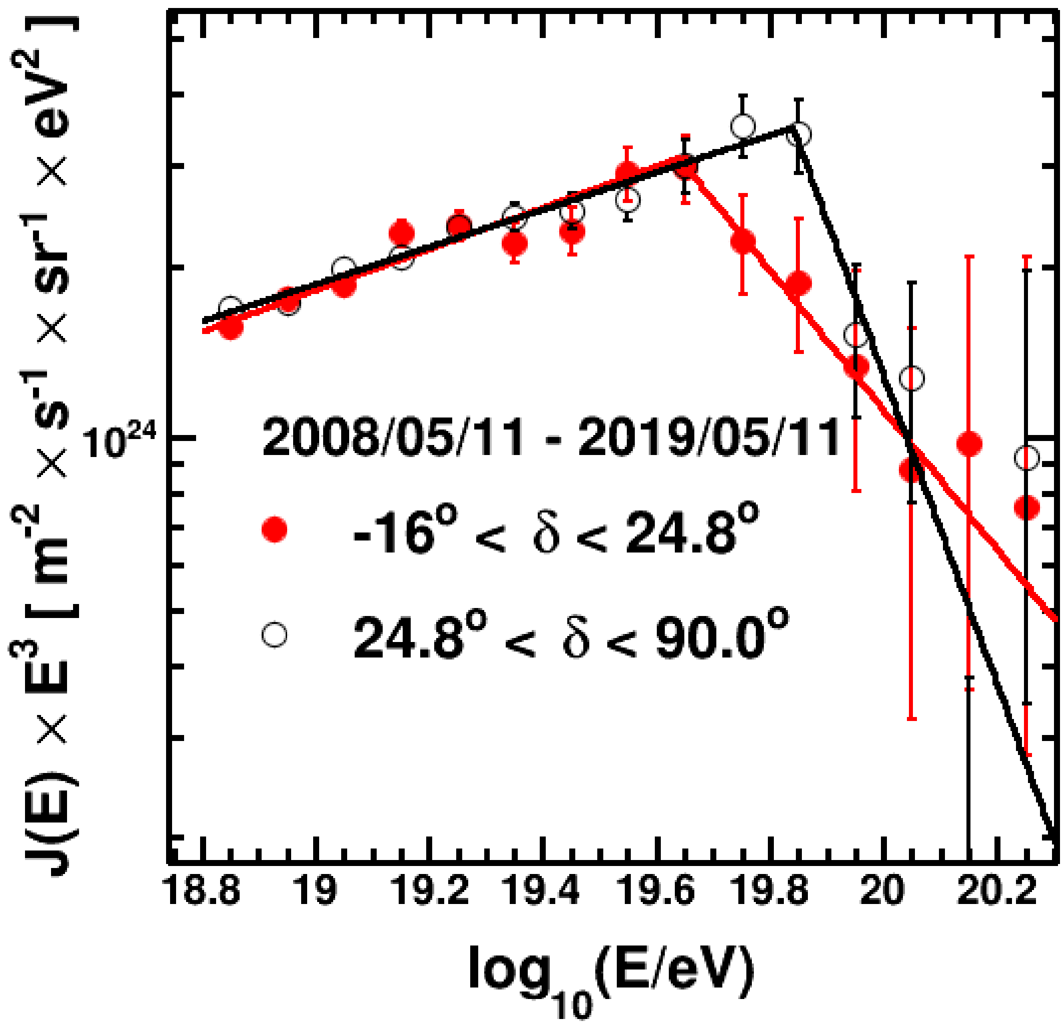
- UHECR2016, ICRC2017 result that uses 7 years of TA SD data
- 3.9 σ difference in the cutoff energies between TA lower and higher declination band spectra
- TA and Auger cutoff energies within 0.5 σ in the TA-Auger Common Declination Band
  - (-15.7° < δ < 24.8°)

4 years of independent TA SD data



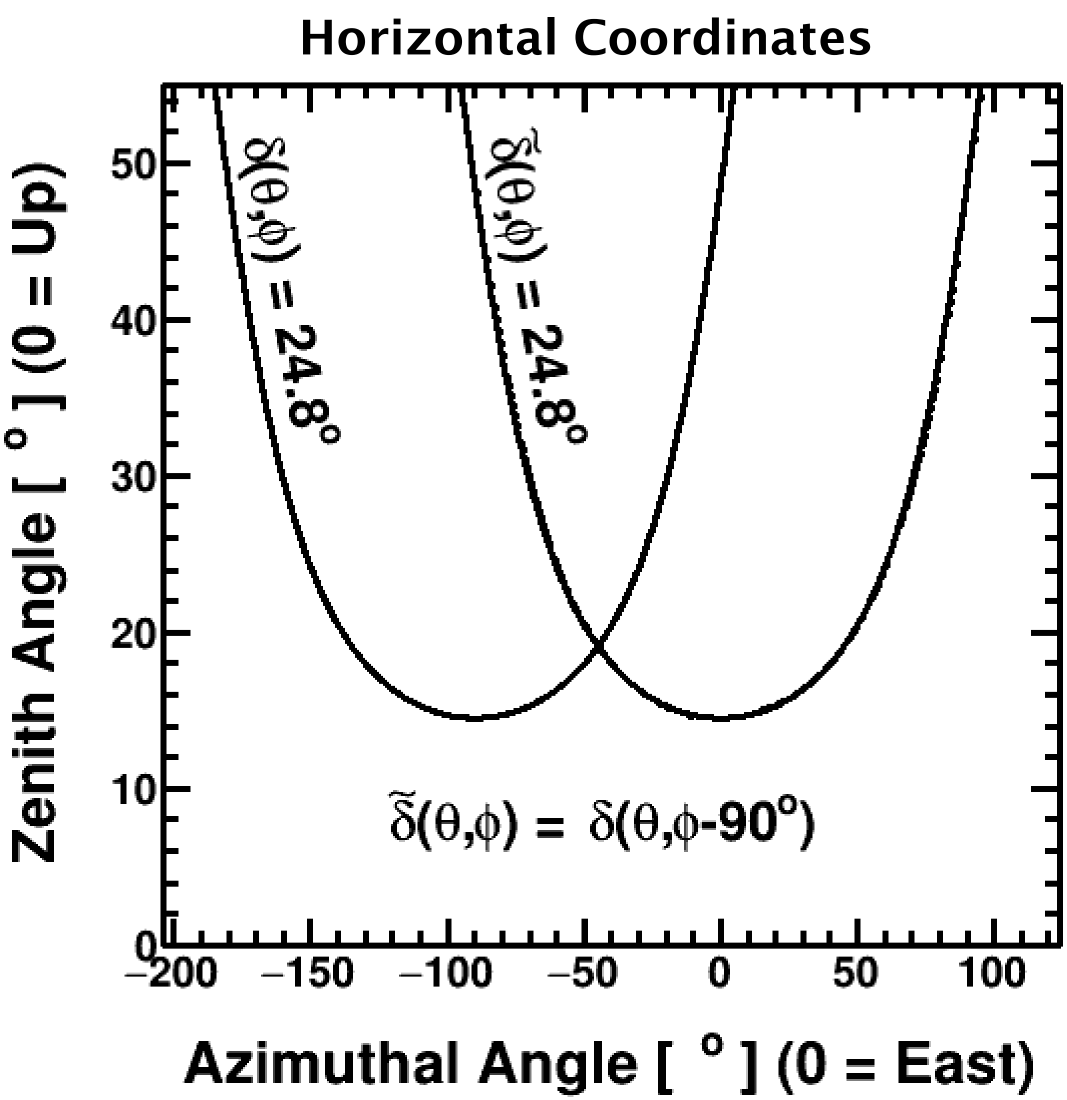
Effect persists in an independent 4-year data set

Using 11 years of SD data



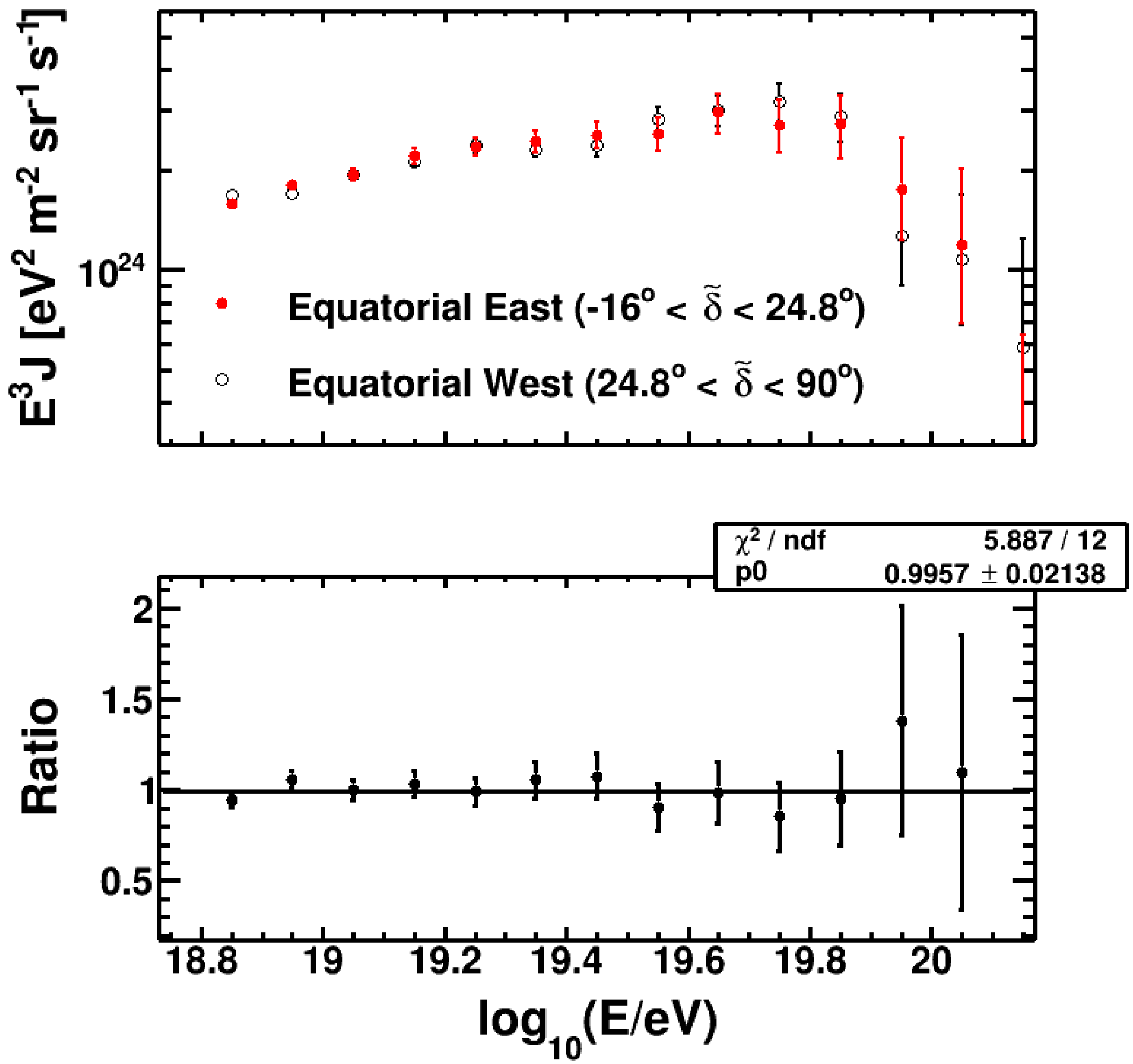
- Cutoff energies in lower and higher declination bands now 4.7 σ different.
  - **4.3 σ global chance probability of the effect**
- **Strong evidence of cosmic ray spectrum declination dependence in the Northern Hemisphere**

Could it be caused by a systematic uncertainty?



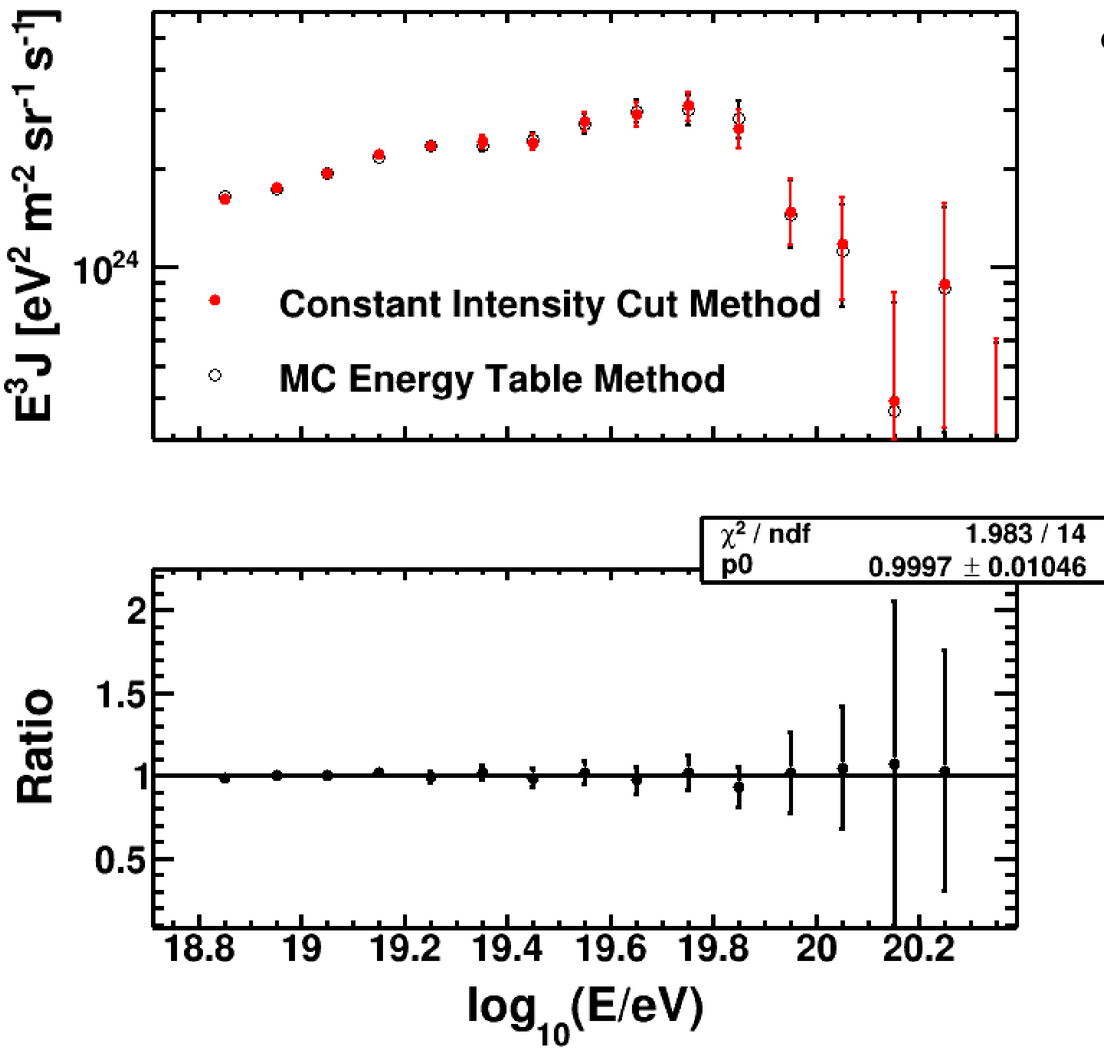
- Instead of looking North and South (δ<24.8° and δ>24.8°), compare equatorial east and west spectra averaged over time ($\tilde{\delta}$<24.8° and $\tilde{\delta}$>24.8°)
- If there are no systematic biases with respect to local horizontal coordinates, **must measure identical spectra**

Result



- Time averaged equatorial east and west spectra have same power laws, same cutoff energies, and their ratio is 1.00 ± 0.02
- **Stringent test of systematics uncertainties**

Also: Check Using Constant Intensity Cut (CIC) Reconstruction Method



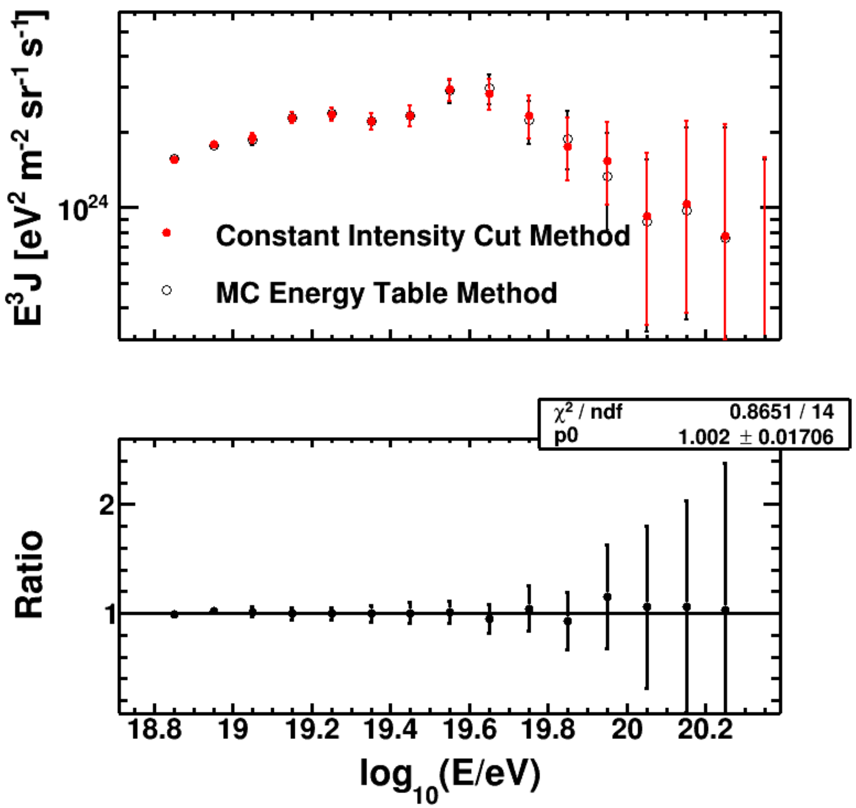
TA SD Full Sky Spectrum

(-16° < Declination < 90°)

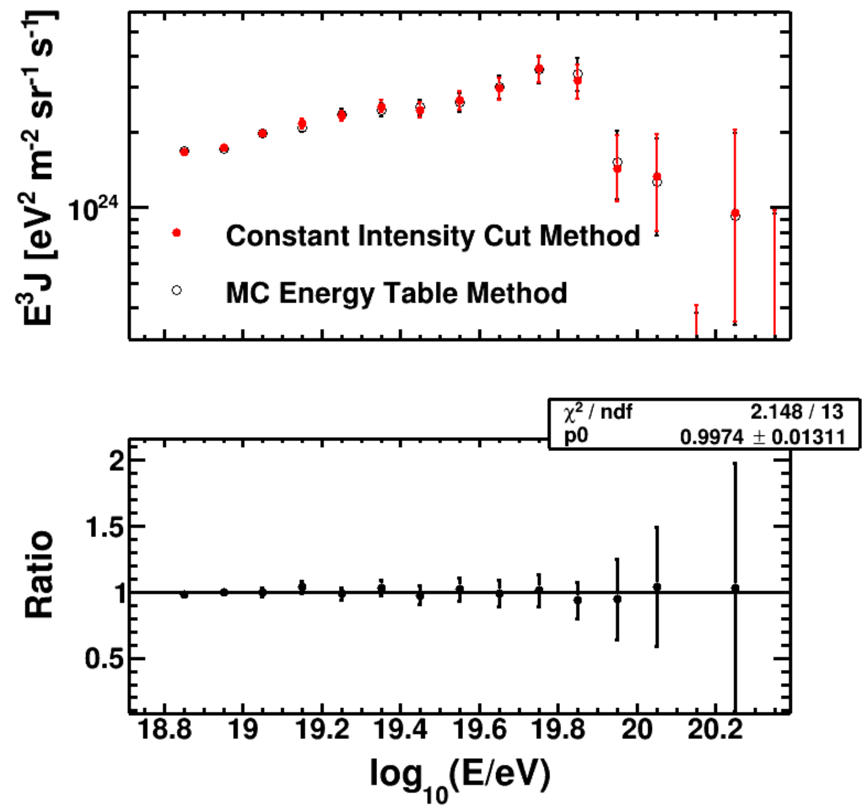
- Energy spectra derived by TA Standard and CIC methods agree: their ratio is 1.00 ± 0.01

In Declination Bands, Constant Intensity Cut vs TA Standard Methods

-16º < δ < 24.8º



24.8º < δ < 90º



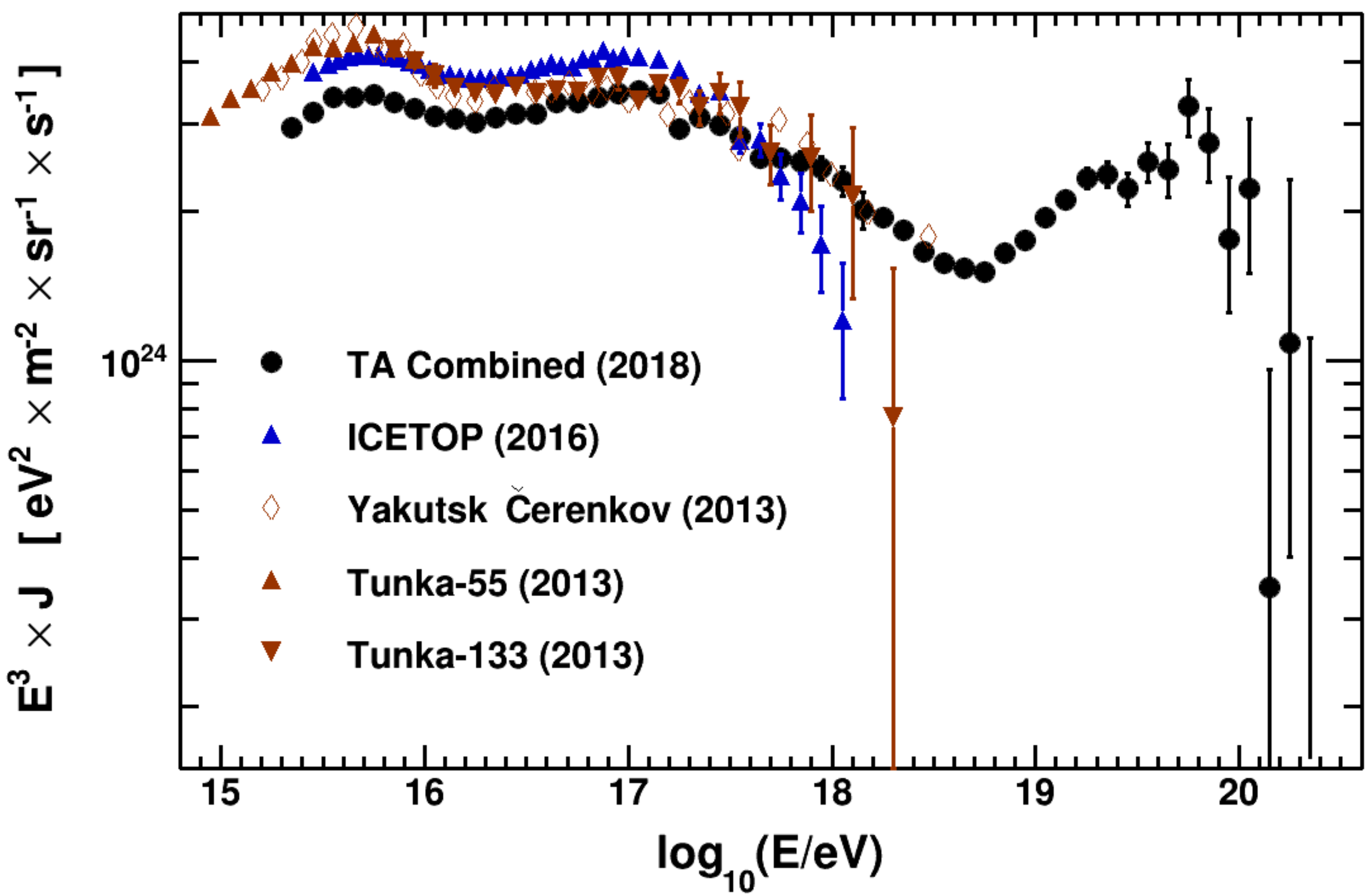
Ratio of the two methods is 1.00 ± 0.02

Summary

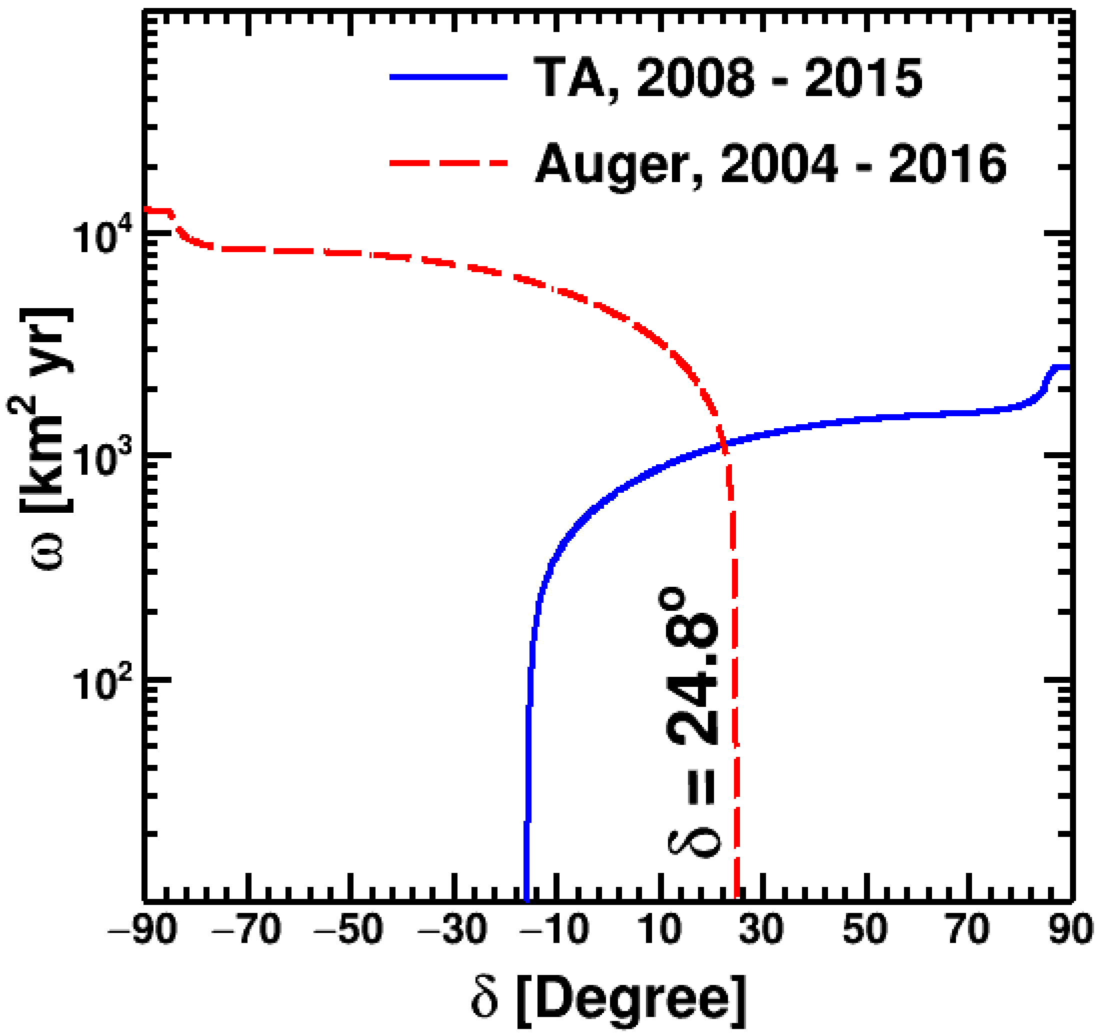
- Cosmic ray spectrum measured over 5 orders of magnitude in energy by TA and TALE
- Detected 5 spectral features
- Strong evidence of the spectrum anisotropy in the Northern hemisphere (4.3 σ global chance probability) at the highest energies, which cannot be explained by systematic uncertainties
  - Stringent equatorial east/west systematics check performed and possible systematic effects restricted to ±2%
  - Alternative model-independent energy reconstruction method used to cross-check the results, ±2% agreements over different declination bands

Backup Slides

TA, ICETOP, Yakutsk, and Tunka

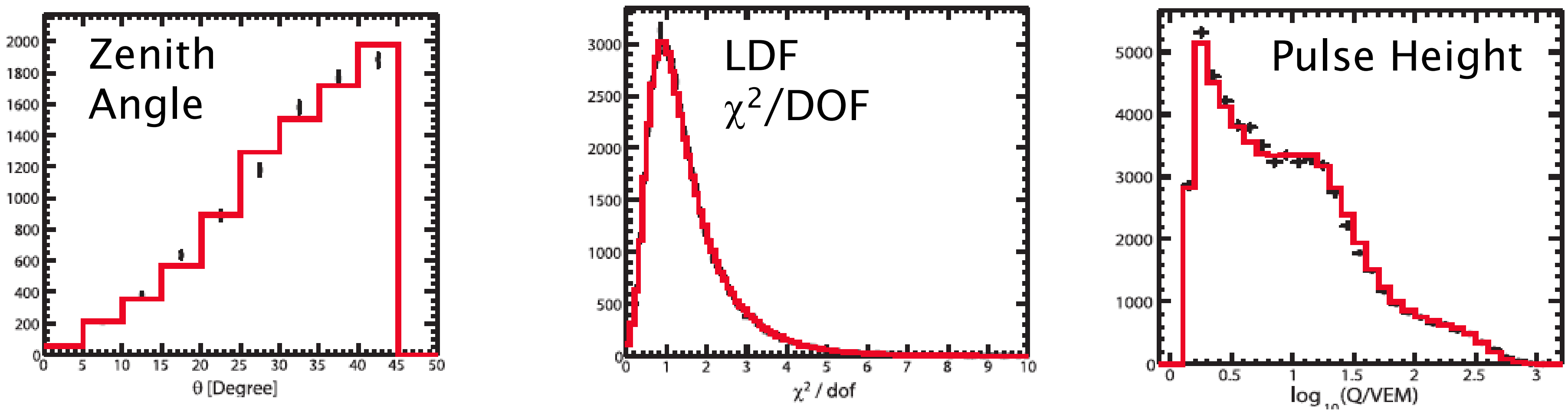


Auger-TA Common Declination Band



- First proposed at UHECR 2014
- Upper limit of Auger vertical SD analysis is δ=24.8°
- Splits TA data into lower and higher declination bands at δ=24.8°
- *Auger-TA Common Declination Band* consists of a declination range (-15.7° < δ < 24.8°)

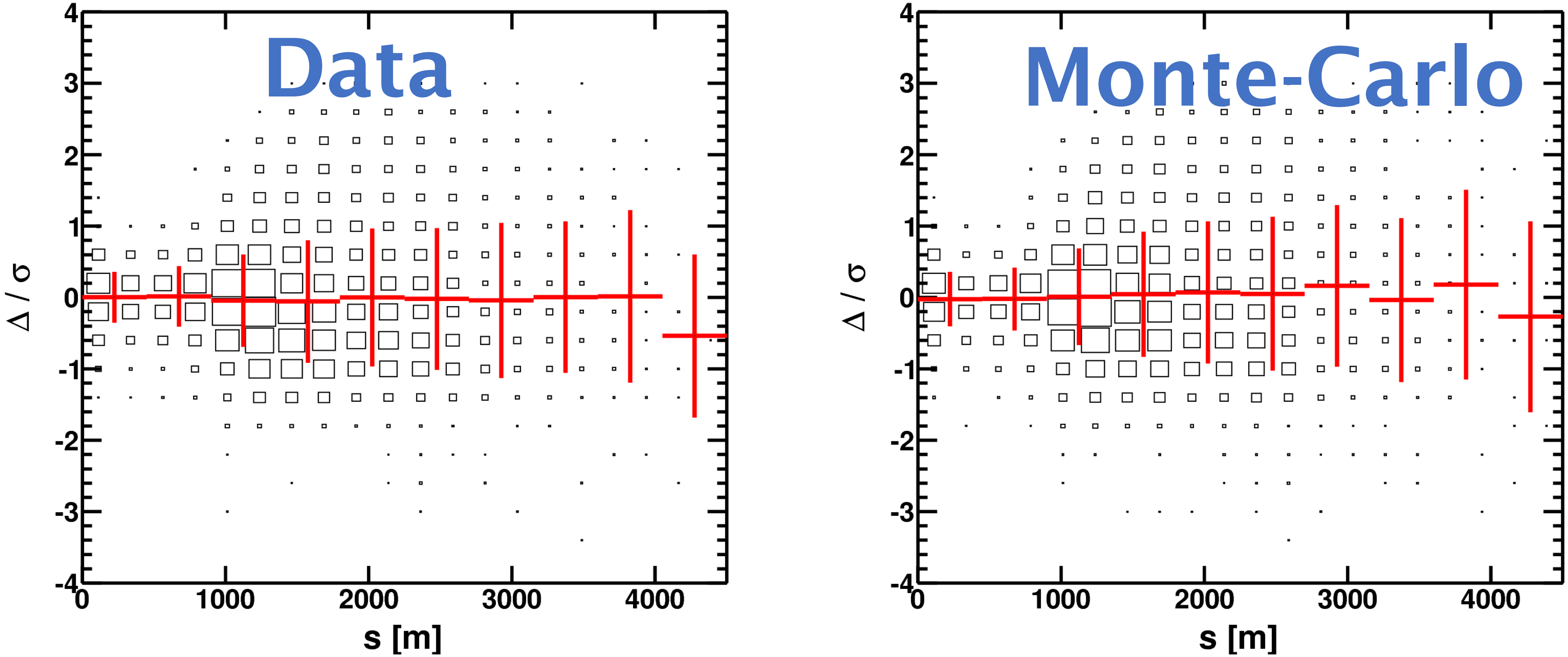
TA SD Resolution and Sensitivity by Monte Carlo Simulation



Comparison of distributions of the data (**black points**) and MC (red line)

- Detailed Monte Carlo based on CORSIKA program used for resolution and exposure calculations
- TA SD Resolution:
  - 19% energy, 1.5° angular, $E > 10^{19.0}$ eV
  - 29% energy, 2.1° angular, $10^{18.5}$ eV $< E < 10^{19.0}$ eV
  - 36% energy. 2.4° angular, $10^{18.0}$ eV $< E < 10^{18.5}$ eV

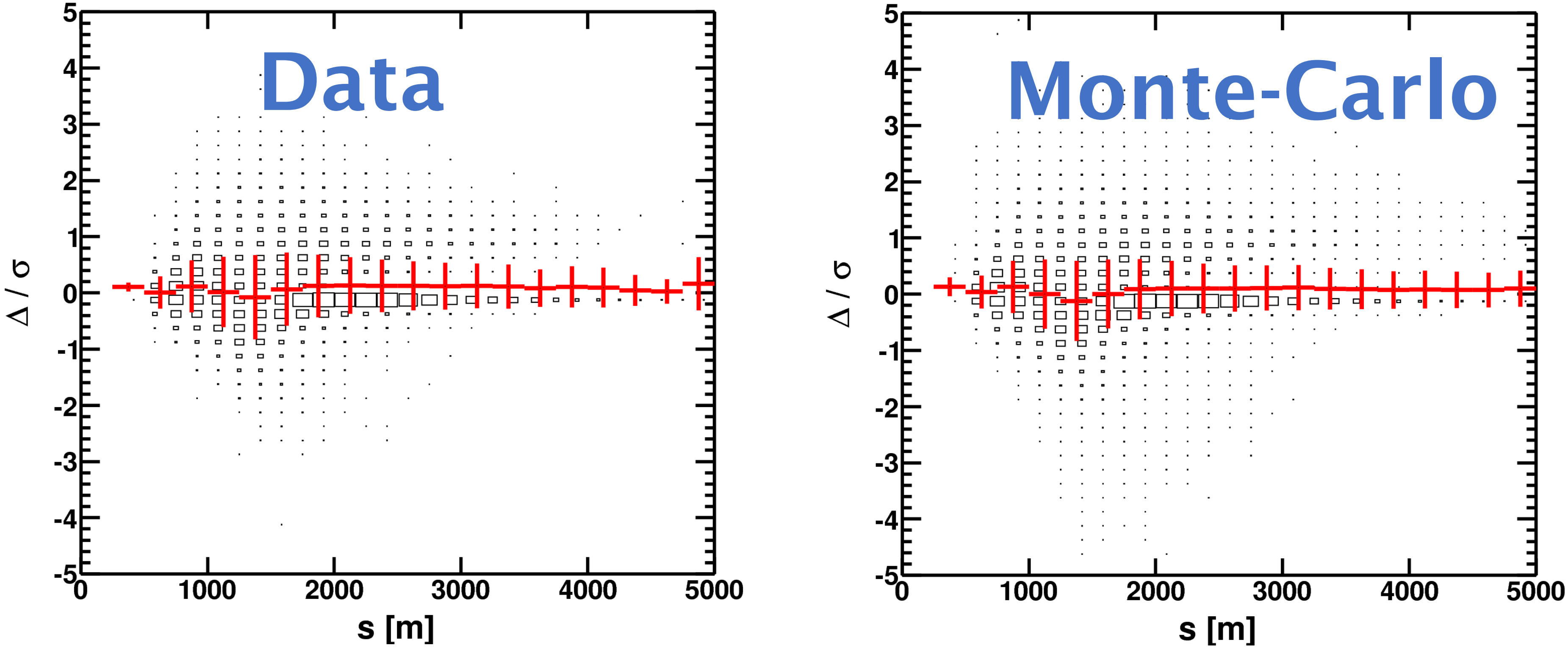
Monte Carlo check: time fit residuals



- Test the time fit formulas derived from the TA SD data
- Each entry = counter, plots are **over all counters and over all events**
- Normalized residual = (counter time – fit time) / T_S
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit in the same way

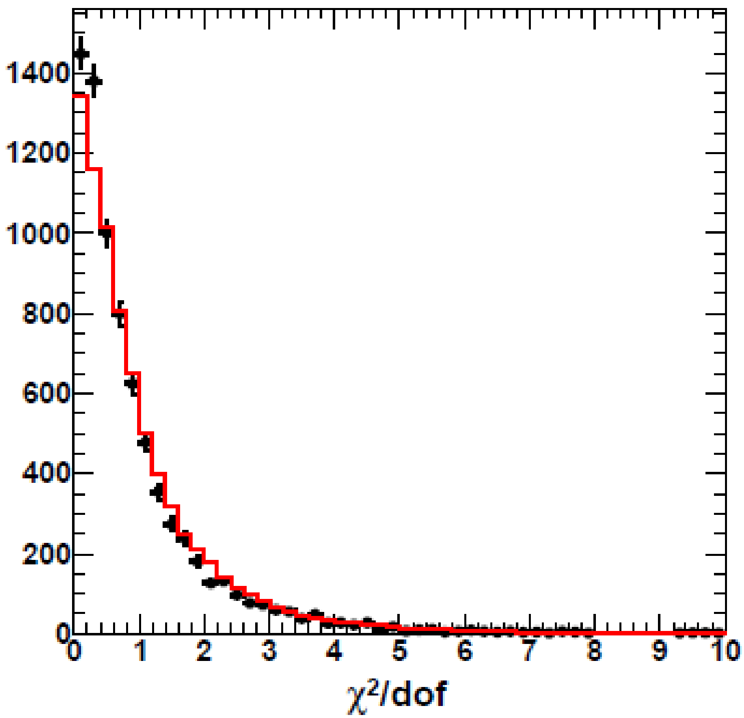
QGSJET-II.3 proton Monte Carlo

Monte Carlo Check: lateral distribution fit residuals

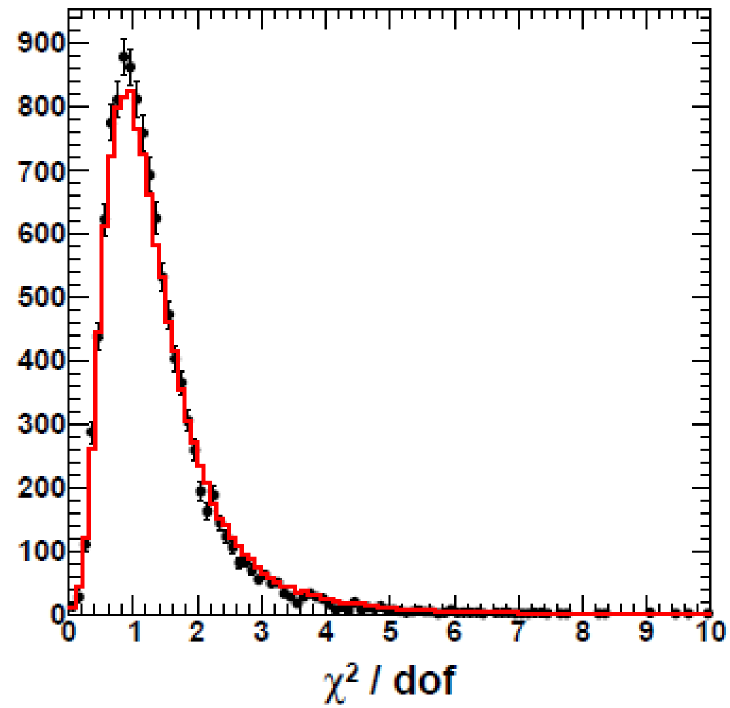


- Each entry = counter, plots are **over all counters and over all events**
- Normalized residual = (counter ρ – fit ρ) / σ_ρ
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit to the AGASA LDF in the same way

DATA and MC chi2/dof

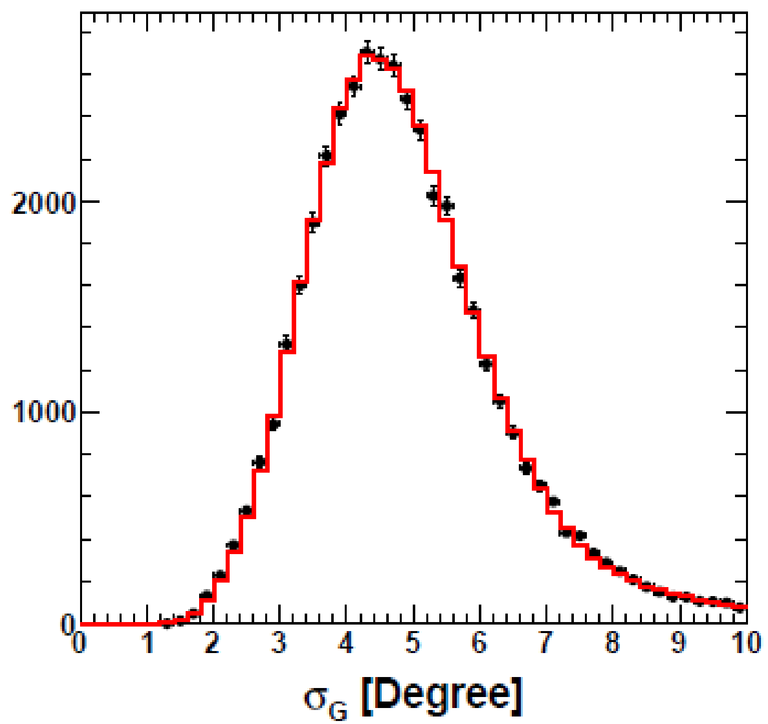


(a) χ^2/dof of the geometry fit.

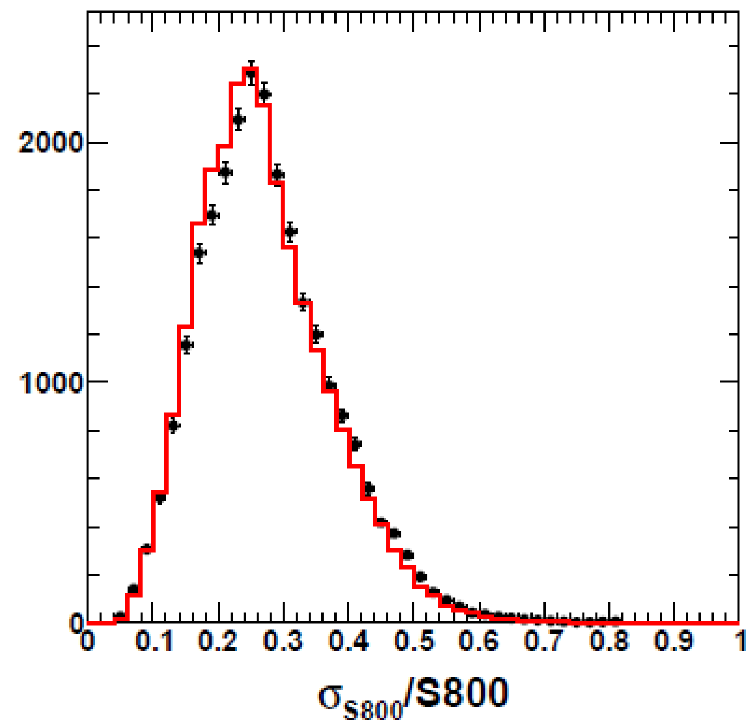


(b) χ^2/dof of the lateral distribution fit.

DATA and MC fitting uncertainties

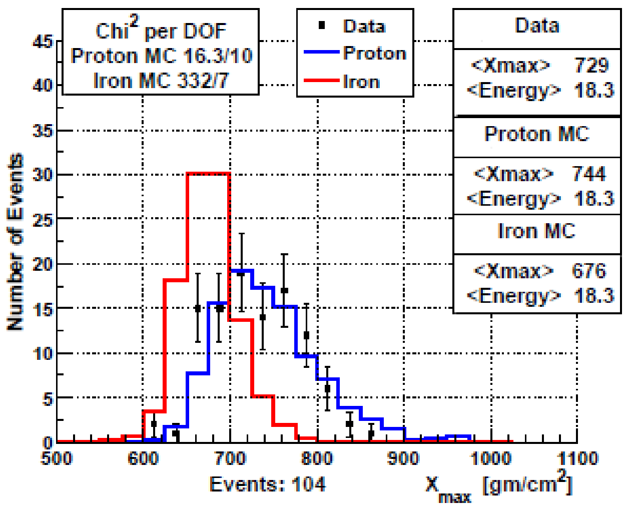


(c) Fit uncertainty of the event arrival direction.

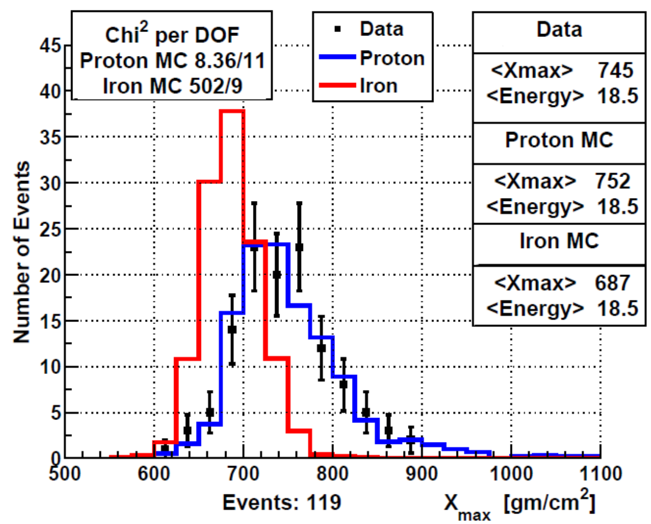


(d) Fractional uncertainty on (fitted) signal size 800 m from the shower axis.

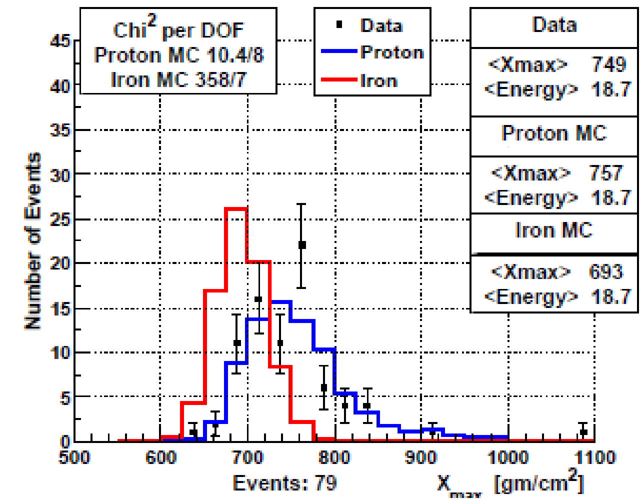
QGSJET-II.3 proton MC Xmax agrees with TA data



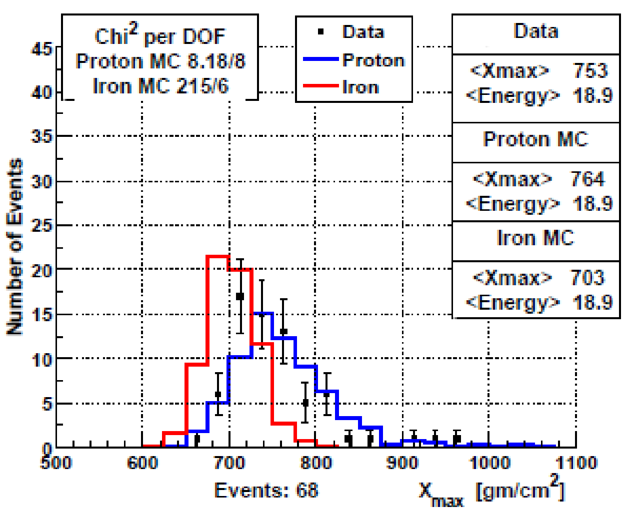
$10^{18.2} < E < 10^{18.4}$ eV



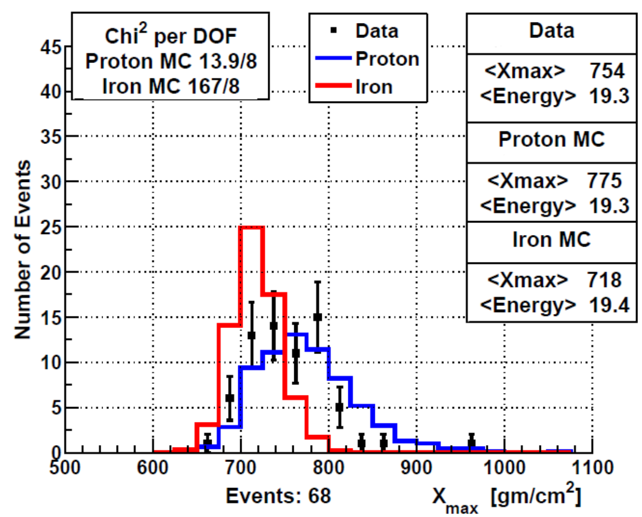
$10^{18.4} < E < 10^{18.6}$ eV



$10^{18.6} < E < 10^{18.8}$ eV



$10^{18.8} < E < 10^{19}$ eV

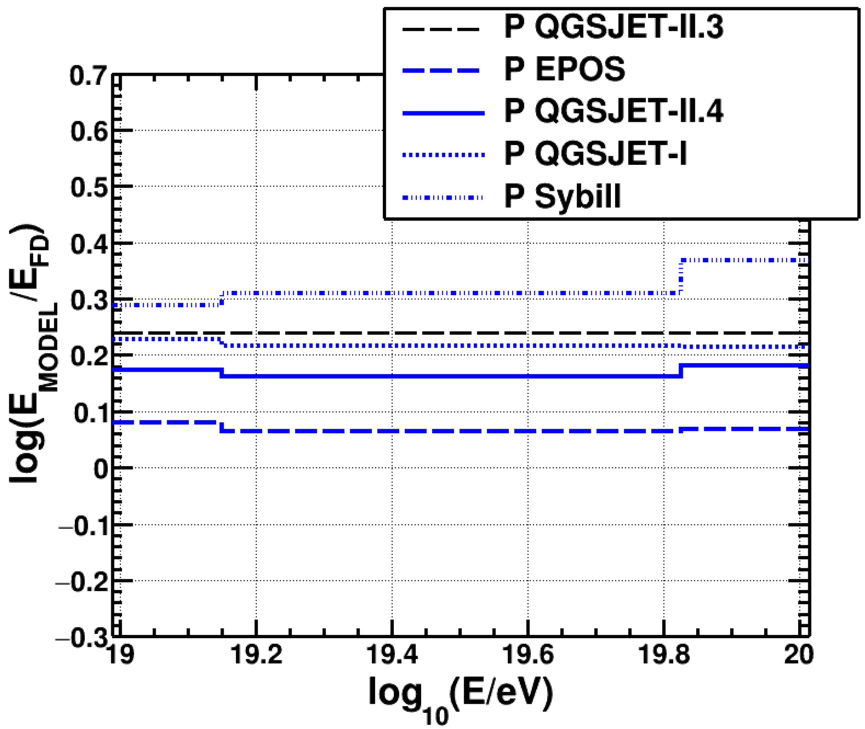


$E > 10^{19}$ eV

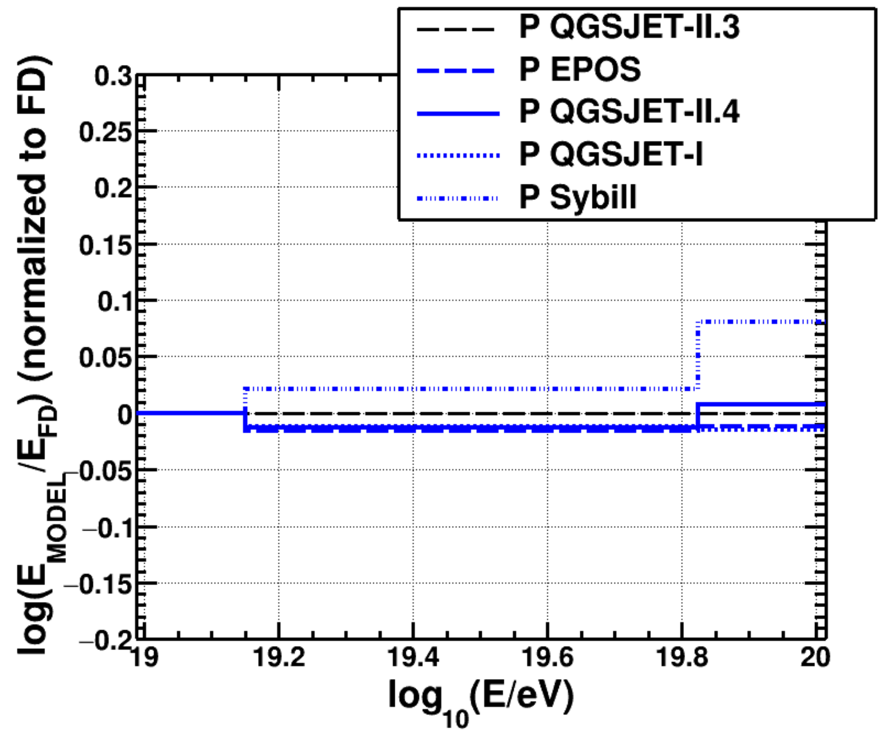
(Astropart. Phys. 64 (2015) 49-62)

Looking at other hadronic models

SD energy from the hadronic models relative to the FD



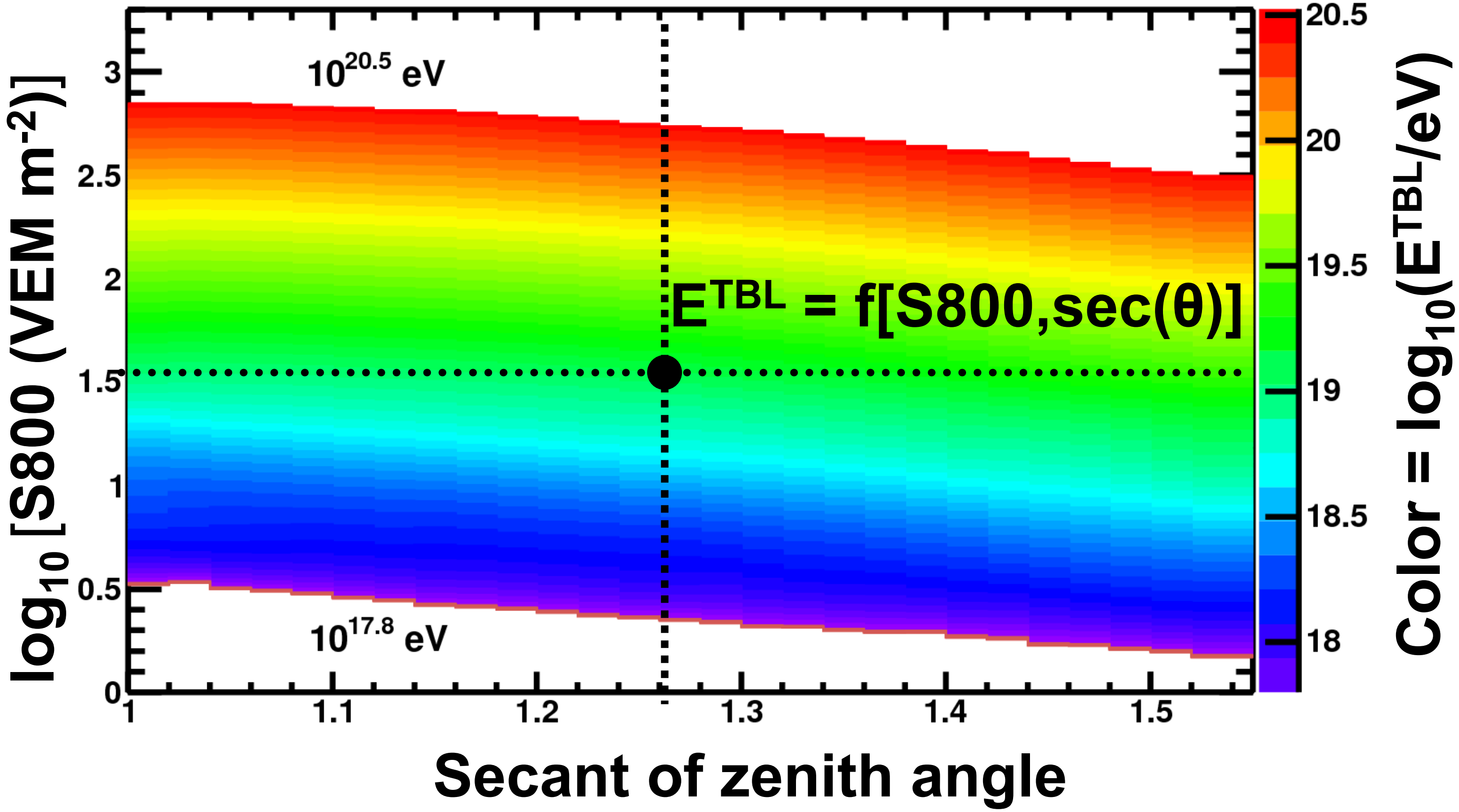
SD energy from the hadronic models after normalization at 10^{19} eV



(B.T. Stokes, D. Ivanov study made for ICRC-2013)

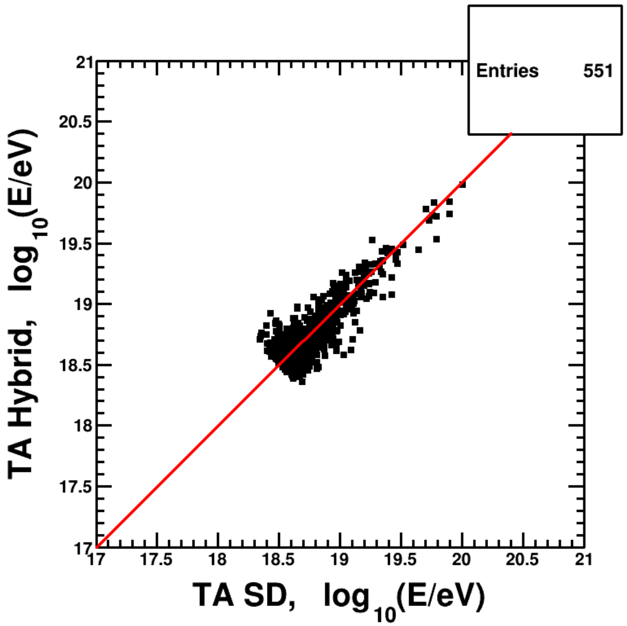
TA SD results not sensitive to hadronic models above 10^{19} eV

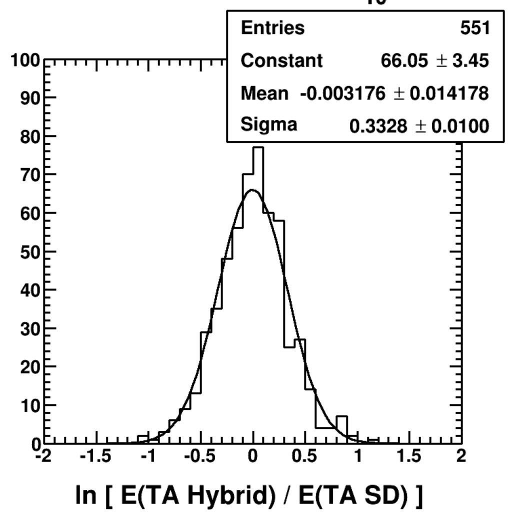
SD Energy Reconstruction - Standard TA Method



- Look-up table made from Monte-Carlo
- Energy (E^{TBL}) is a function of *reconstructed* S800 and sec(θ)
- Calibrate to FD using *constant* scaling factor: $E = E^{TBL}/1.27$

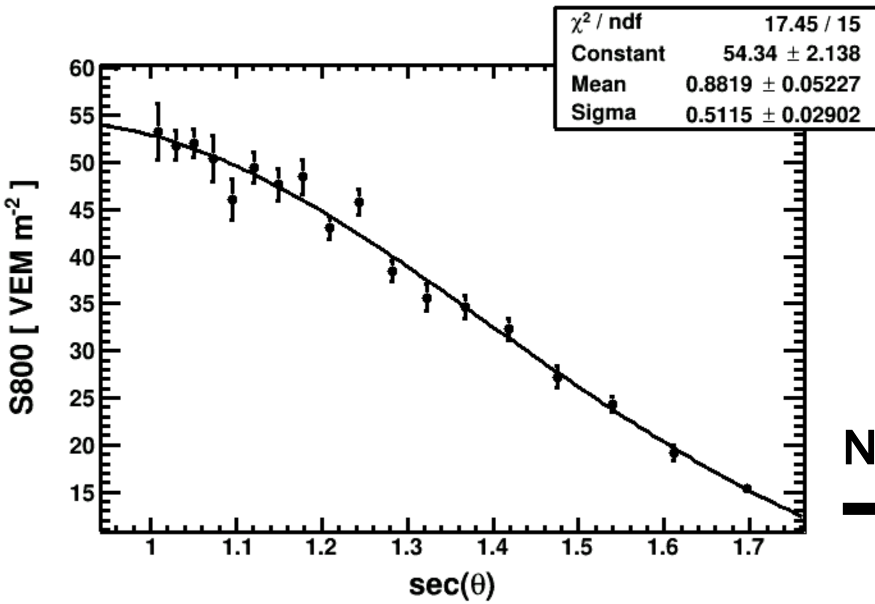
SD energy scale set to FD using hybrid events



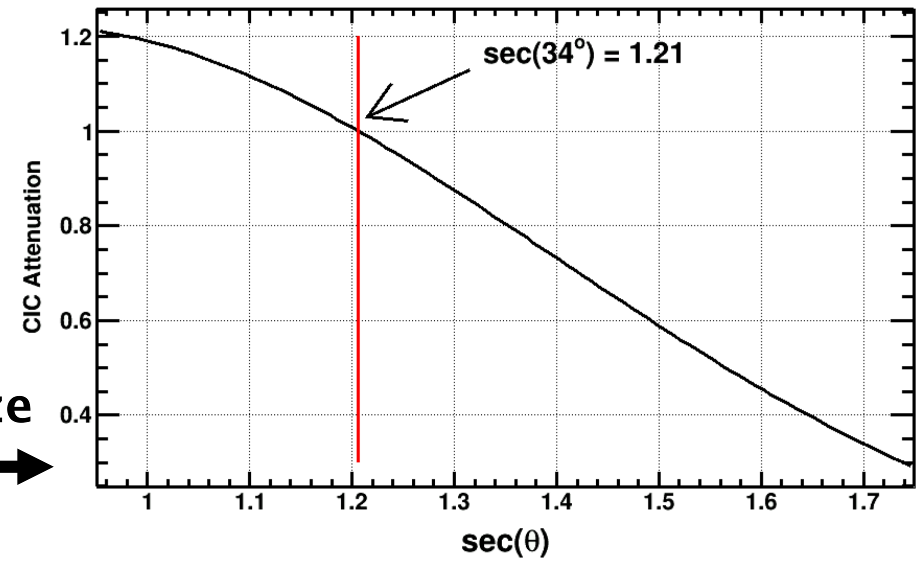


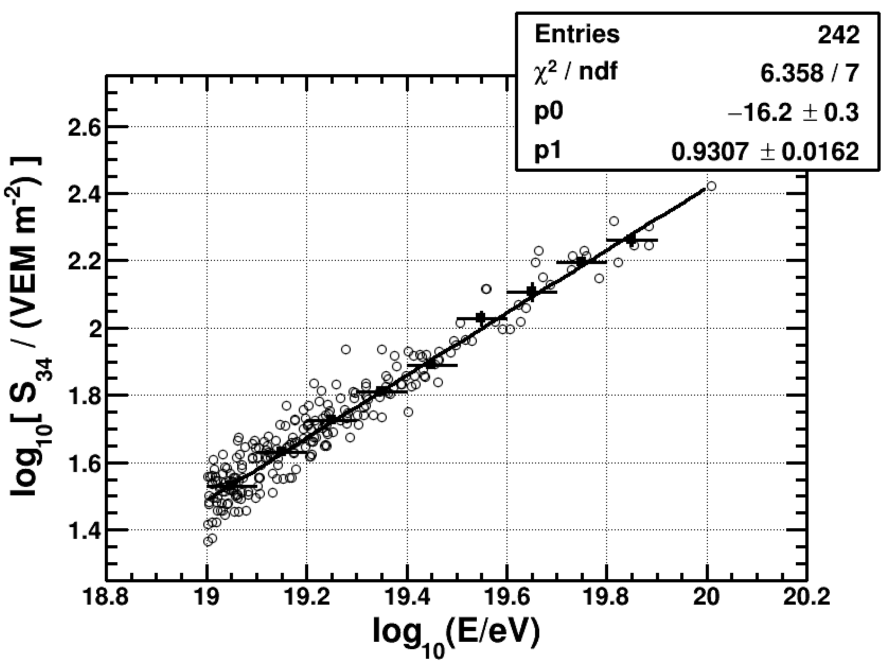
- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
- $E^{FINAL} = E^{TBL} / 1.27$
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD} ratio

SD Energy Reconstruction - Constant Intensity Cuts (CIC) Method



Normalize





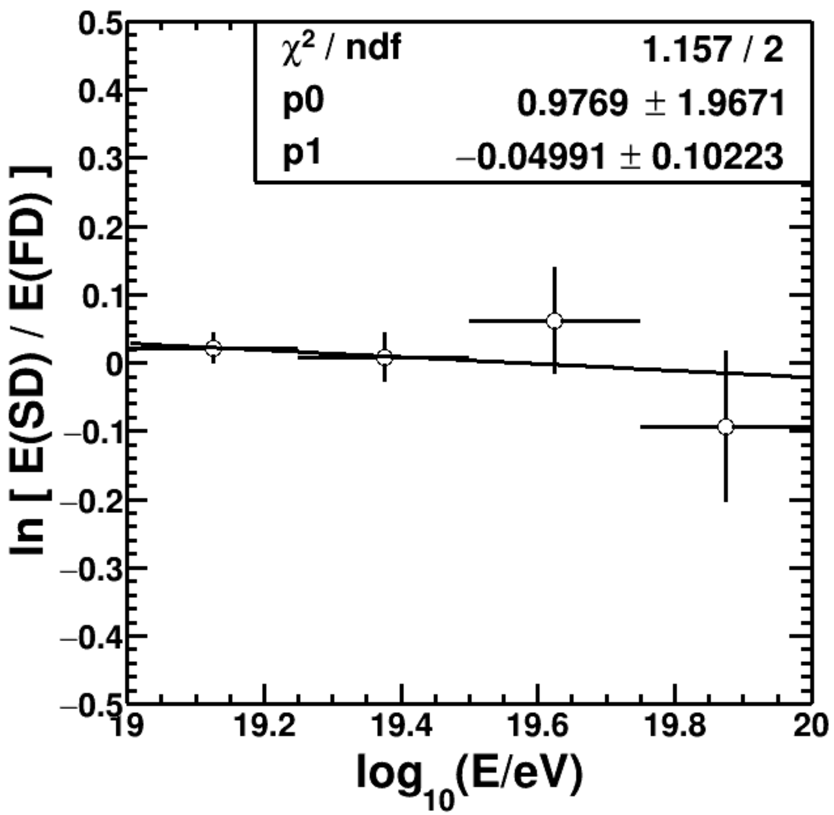
- Attenuation curve from SD data
- S_{34} = S800 / CIC(θ) is S800 of a shower of the same energy if it came at θ = 34°
- Lock S_{34} to FD energy using hybrid events

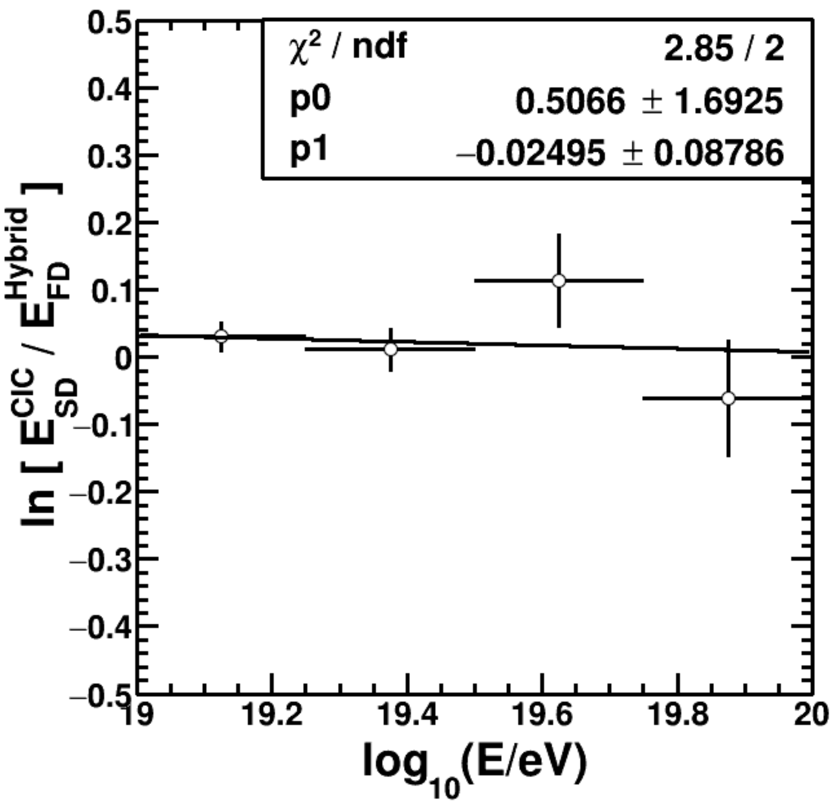
Use reconstruction method independent of Monte Carlo to cross-check SD energy spectrum

Nonlinearity sources above 10^{19} eV in TA

Source of Nonlinearity	Amount (percent per decade above 10^{19} eV)
FD missing energy correction	1% +/- 1%
FD Fluorescence Yield Model	-1% +/- 1%
FD Atmospheric Conditions	1.7% +/- 1%
SD and FD comparison:	-2% +/- 9%
Net	**-0.3% +/- 9%**

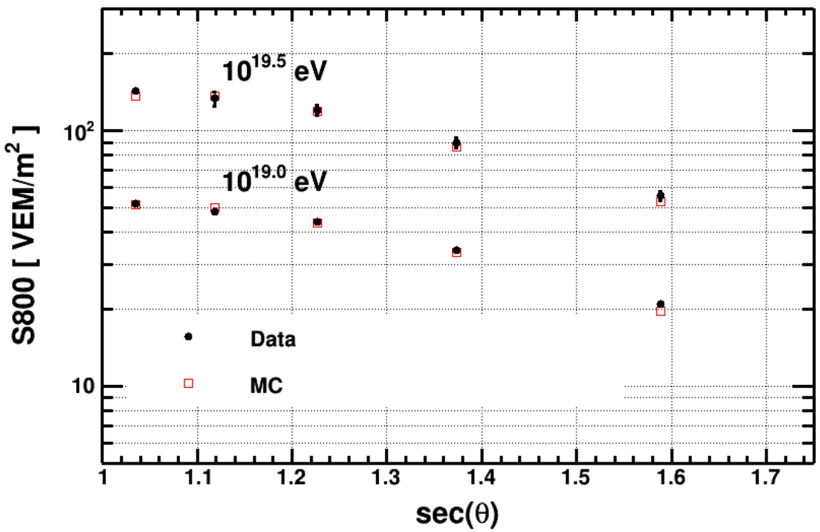
Linearity check of SD with FD using hybrid events: no evidence of nonlinearity

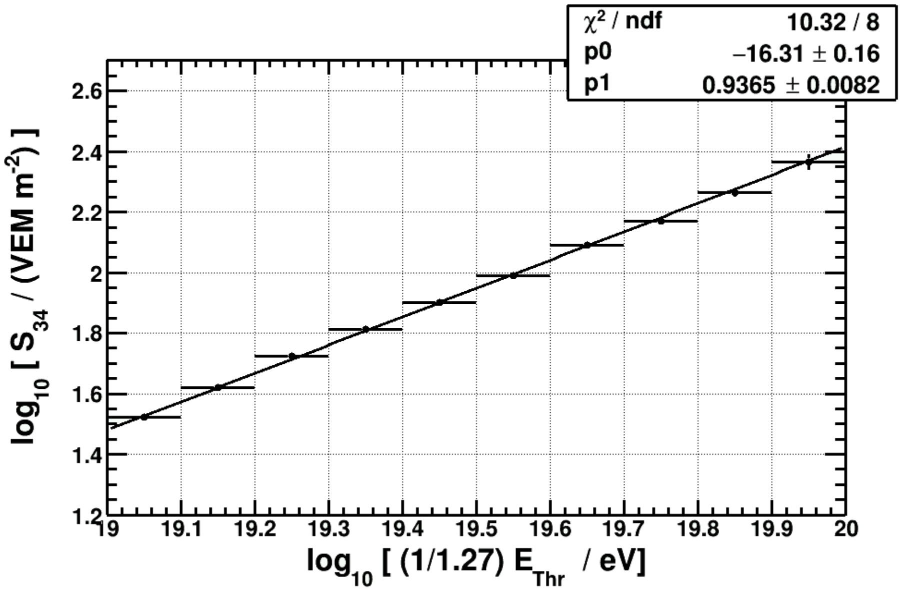




Comparison of SD energies reconstructed using either QGSJET-II.3 proton model or Constant Intensity Cut method to FD shows no evidence of nonlinearity: the slopes of the linear fits are within their fitting uncertainties.

Check constant intensity cuts method using TA SD Monte Carlo

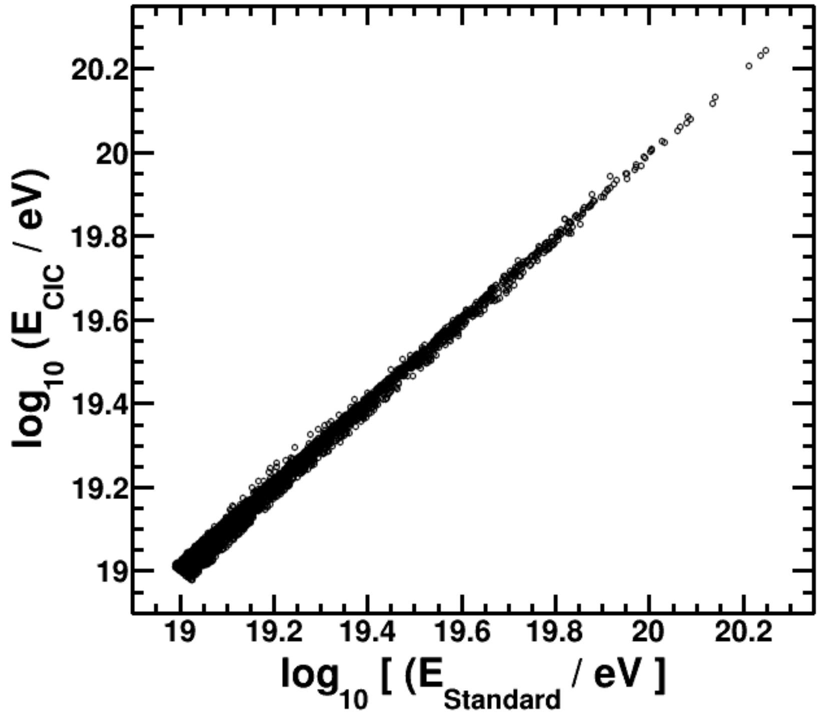


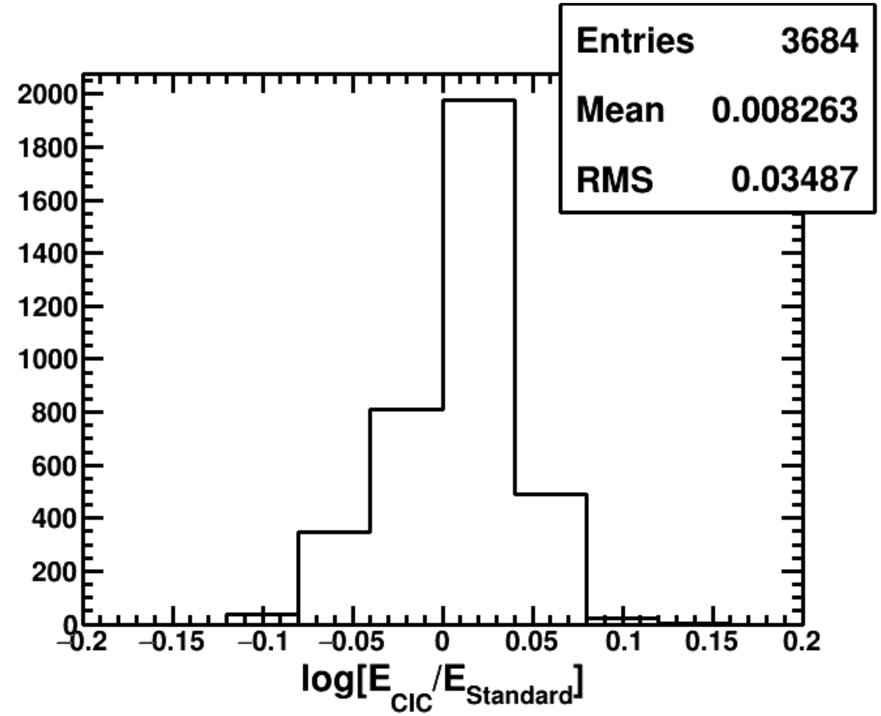


LEFT: **TA SD Monte Carlo** has the same CIC attenuation as the **data**

RIGHT: S_{34} and energy relation is the same in TA SD Monte Carlo as that between the TA SD and TA FD data

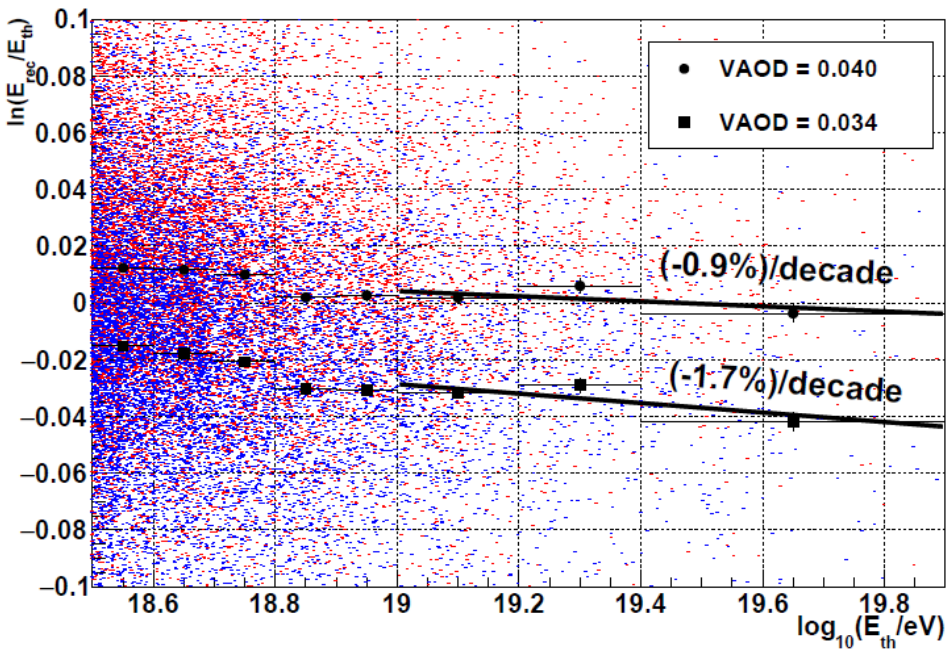
Energy Comparison between Constant Intensity Cut and Standard TA Reconstructions





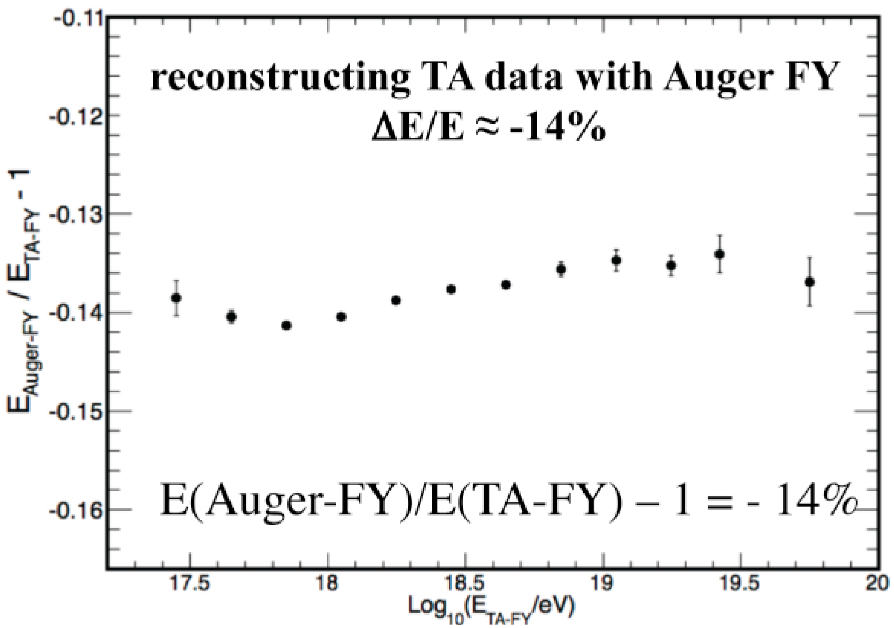
Individual event energies reconstructed by the standard TA and the Constant Intensity Cut methods agree at ~3% level

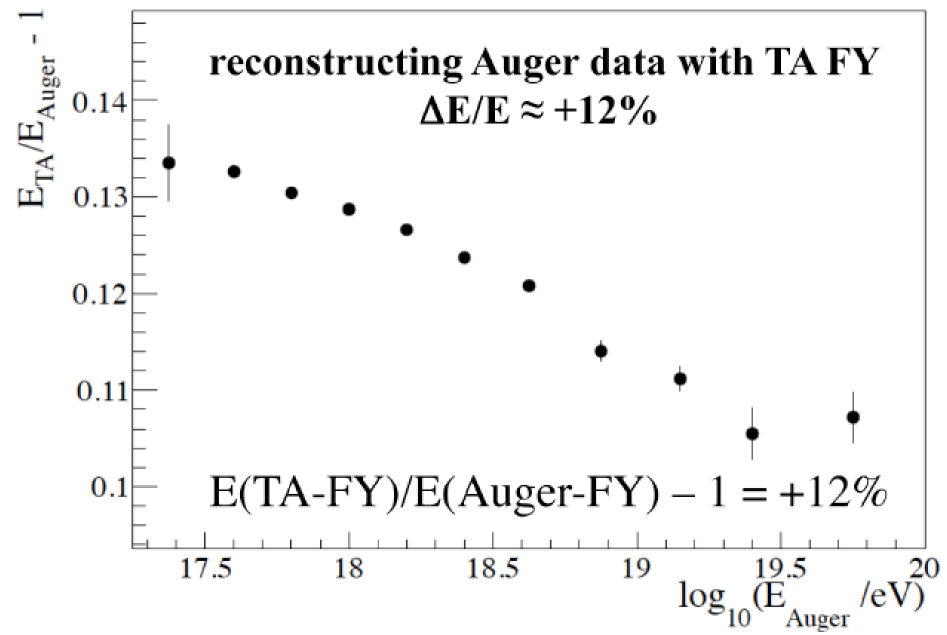
Check of FD energies

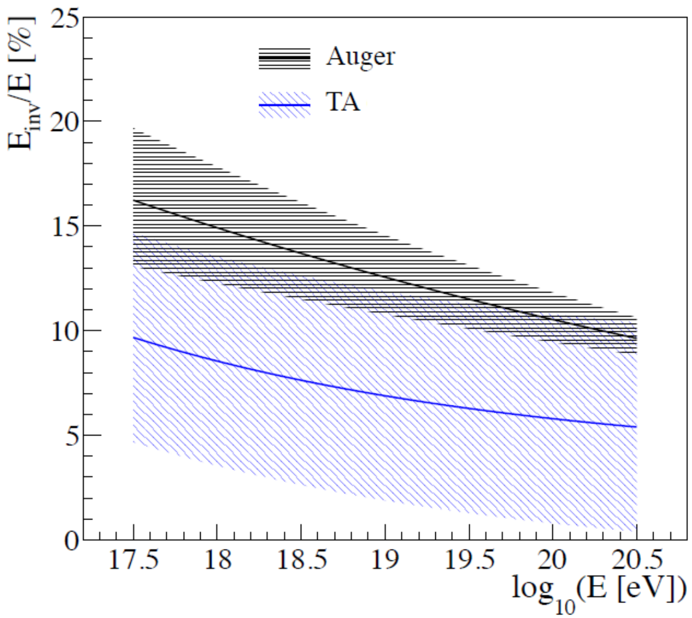


- Maximum possible non-linearity effects of atmospheric conditions are 1.7% per decade

More FD checks

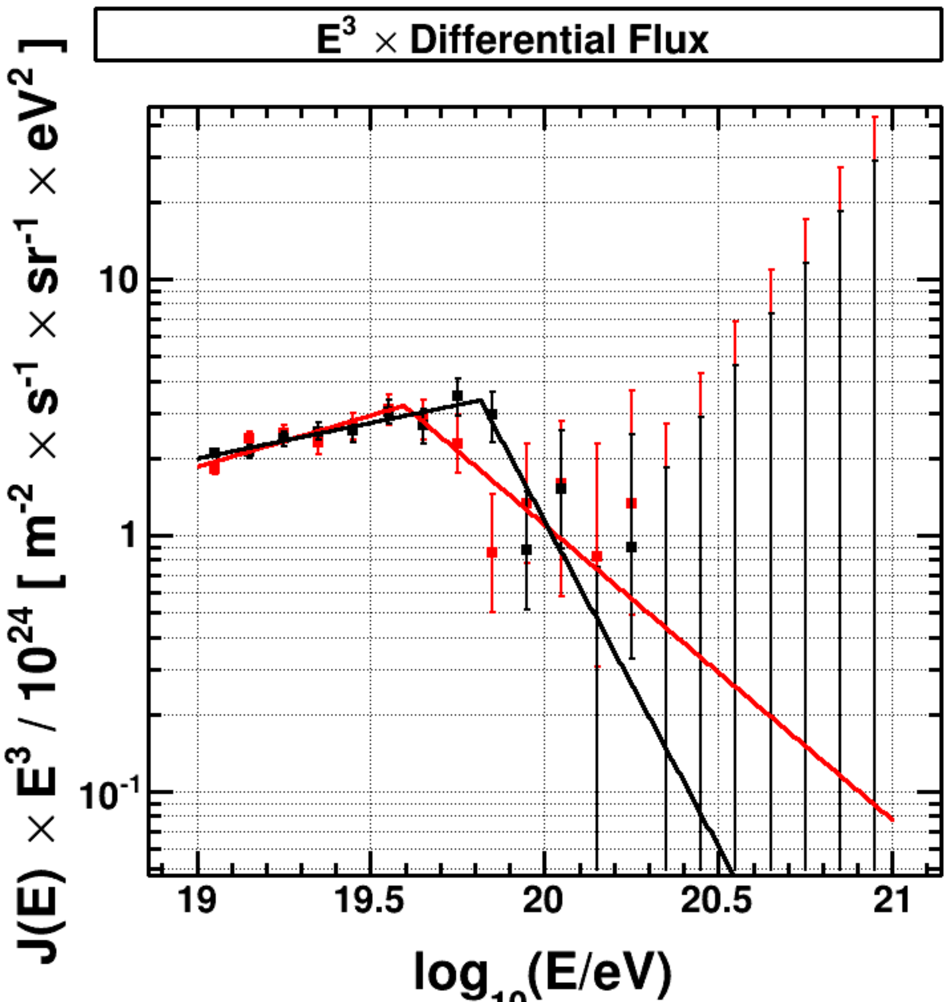






- UHECR 2016: It was shown that non-linearity effects of the fluorescence yield and missing energy correction are within 1% per decade above 10^{19} eV

Declination Dependence of the Spectrum Without the TA Hot Spot

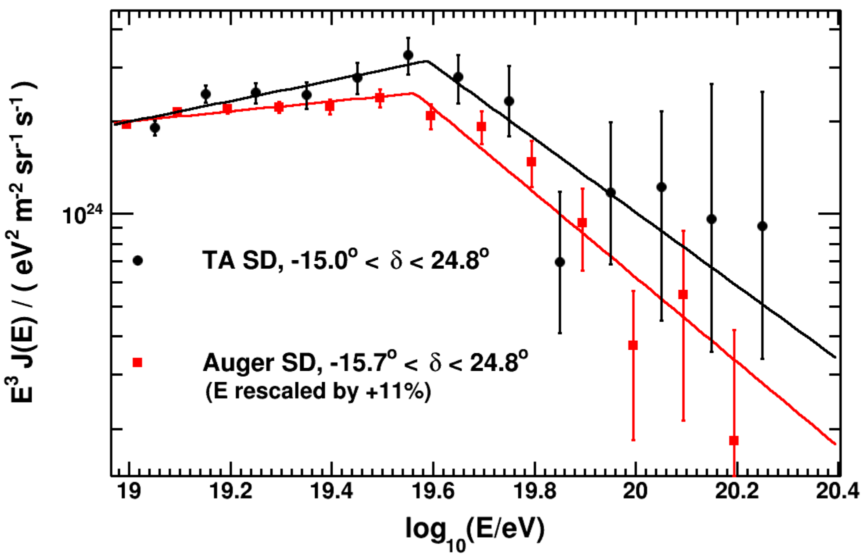


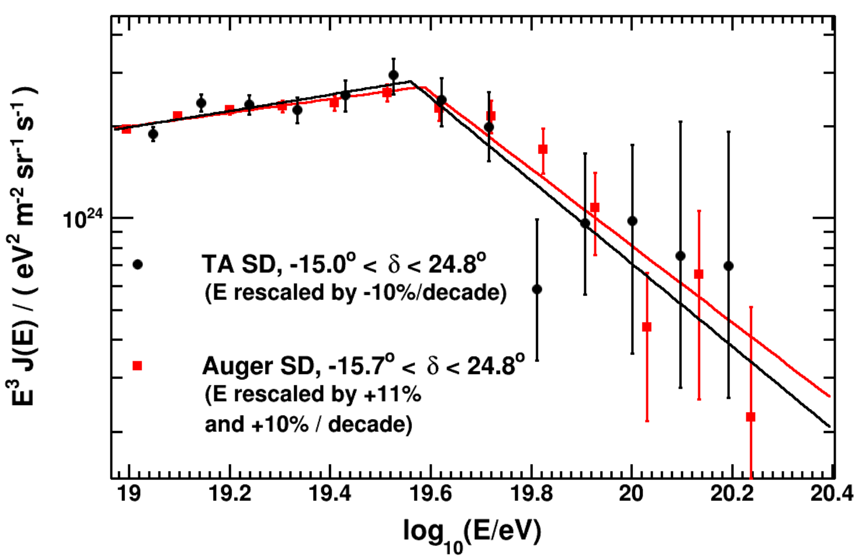
Using 7 years of TA SD data (2008/05/11-2015/05/11)

- Exclude a 20° region around TA Hot Spot RA,DEC=(148.4°,44.5°)
- Result: second break points
  - 19.59 ± 0.06 (below 24.8° in declination)
  - 19.81 ± 0.04 (above 24.8° in declination)
- Consistent with what we've found previously but the difference is less significant (~3 σ instead of 3.9 σ)

Remaining difference with Auger in the common declination band

(7 years SD data)

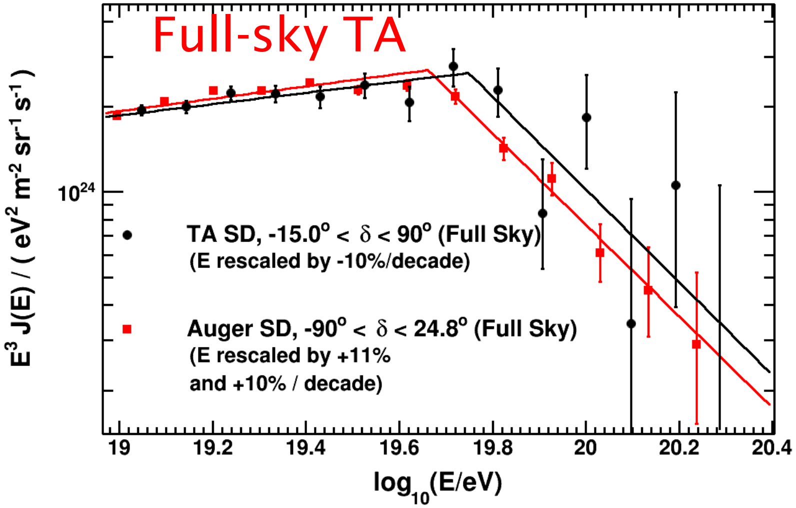




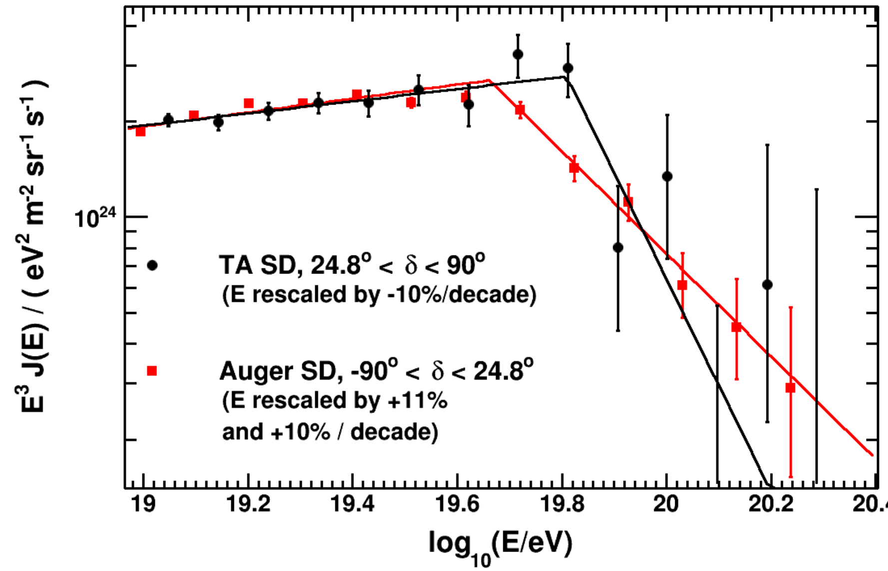
- TA and Auger spectra can be brought to agreement after a correction of Auger energies by +10%, and TA energies by -10% per decade, starting at 10^{19} eV.
  - Second break points of Auger and TA would then be ($\log_{10}$ (E/eV)): 19.58 +/- 0.03 for Auger and 19.56 +/- 0.06 for TA
- **TA energy estimation nonlinearity evaluated as -0.3 +/- 9% above 10^{19} eV and spectrum has been checked using two different reconstruction methods.**

Q. What about the TA and Auger **full sky spectra** (not just in common declination band) when ± 10% correction is applied to TA and Auger in opposite directions ?

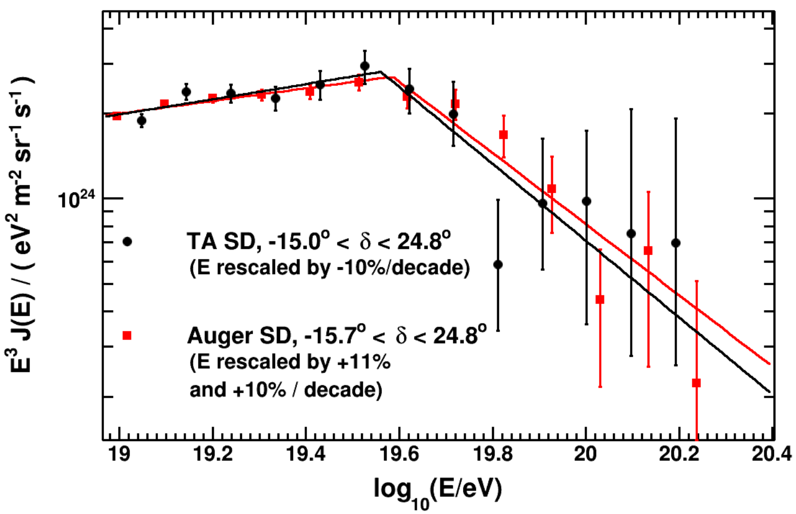
(7 years SD data)



Higher declination band TA



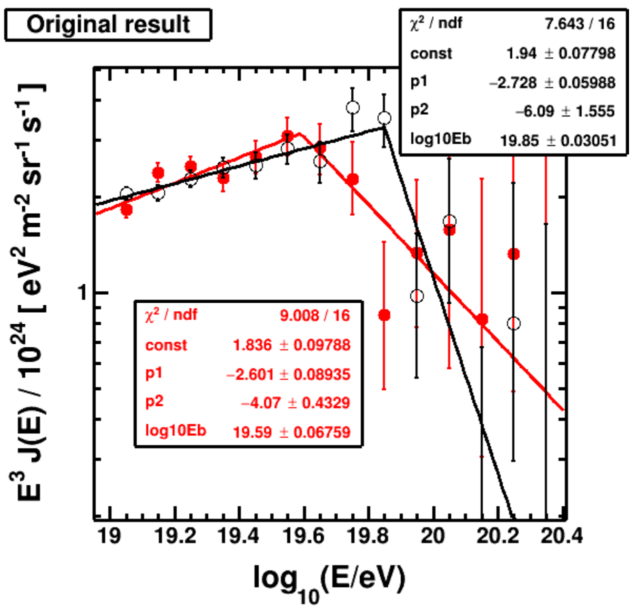
Common declination band TA

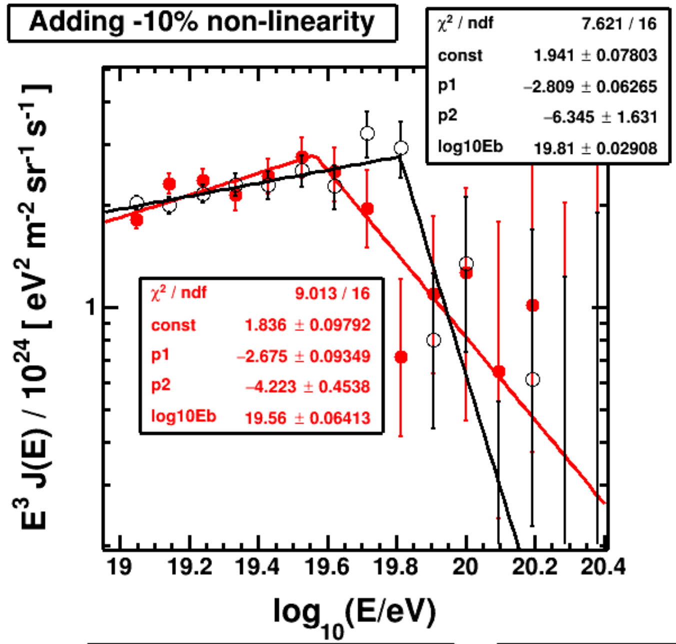


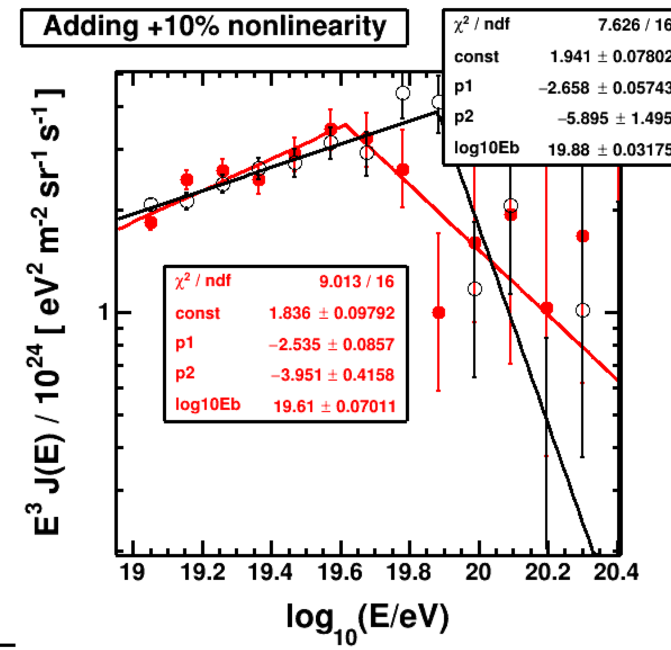
- Small difference in full sky TA and Auger spectra persists because TA and Auger view different skies and there is an evidence of declination-dependent anisotropy in TA.
- **The difference becomes more visible when one compares Auger full sky spectrum to the TA spectrum above 24.8° degrees in declination.**

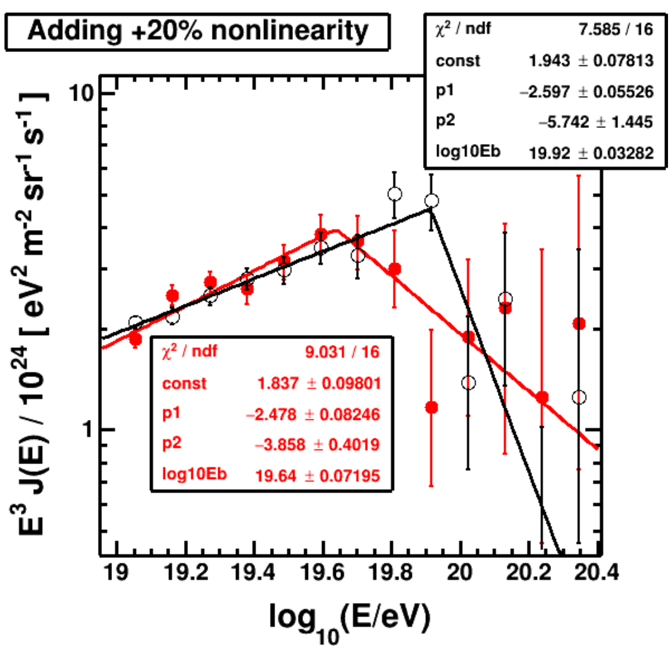
→ For the TA - Auger spectrum working comparison purposes we use TA spectrum in the TA-Auger common declination band (-15.7°, 24.8°)

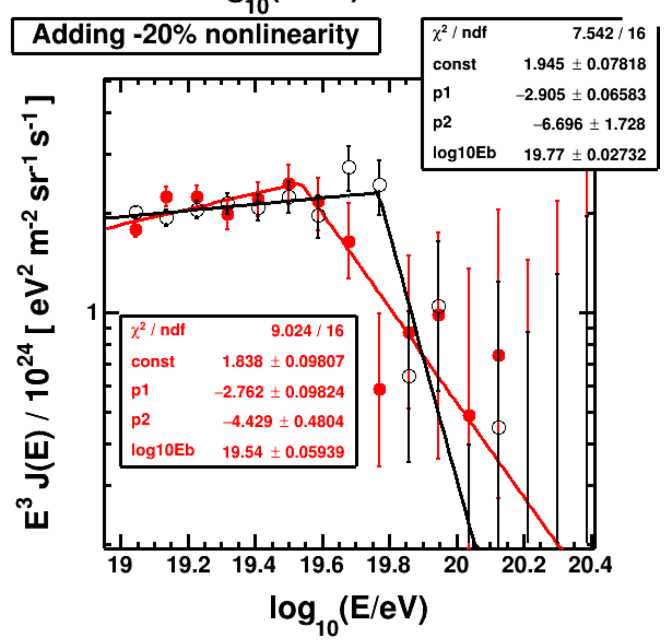
Result robust after nonlinearity shifts up to ±20% per decade of energy











○ **24.8° < δ < 90°**

● **-15° < δ < 24.8°**

(7 years SD data)