TA Spectrum

140 members, 34 institutions, from US, Japan, Belgium, Korea, Russia, and Czech Republic
http://www.telescopearray.org

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University of Utah
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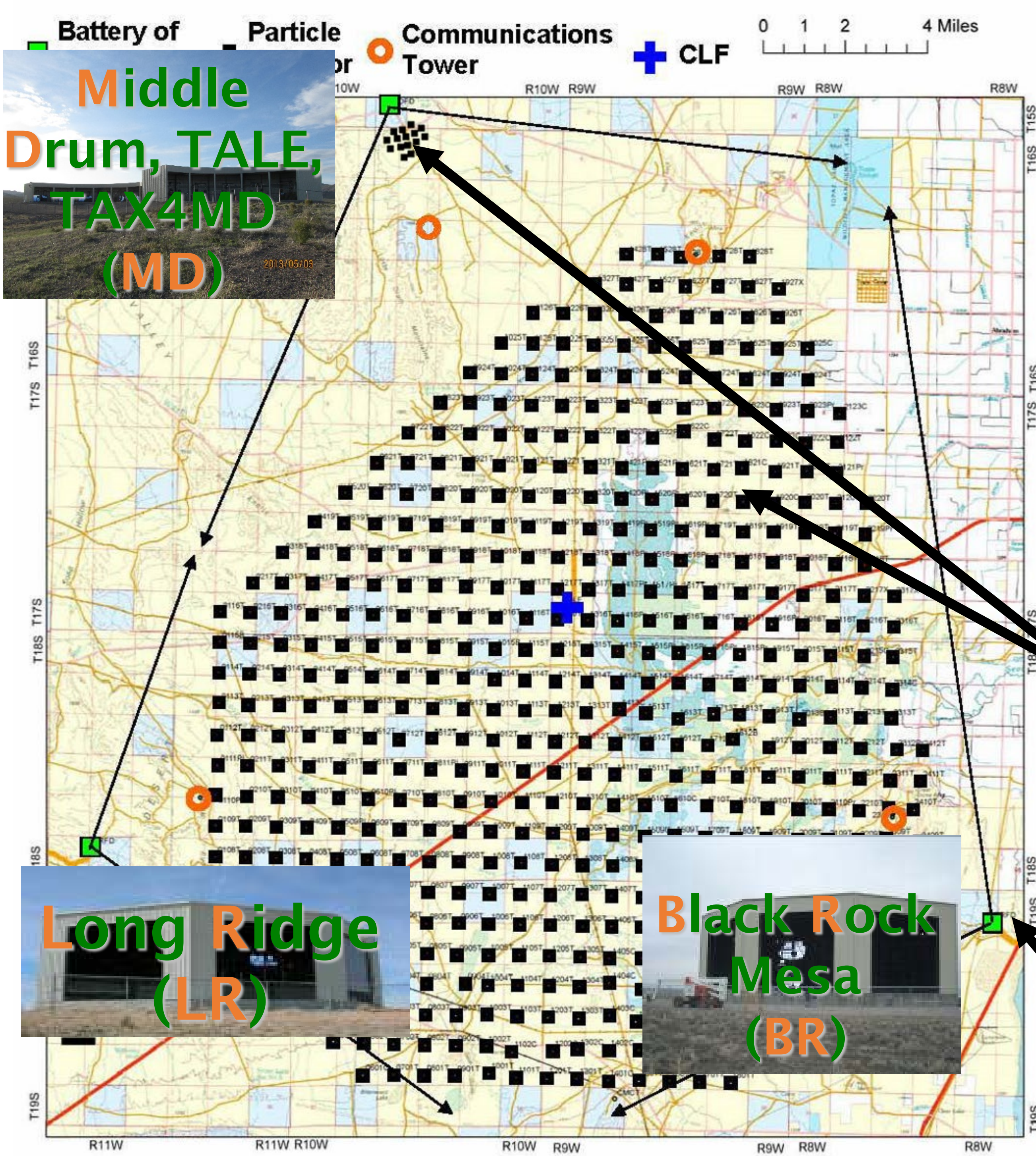
UHECR 2018, Paris, France

Outline

- Telescope Array (TA) Experiment
- TA Surface Detector Spectrum
- TA Fluorescence Detector Spectrum
- Check of SD Spectrum Using Constant Intensity Cuts Method
- Summary

Telescope Array

Hybrid detector



Millard County, UT

39.3° N , 112.9° W,

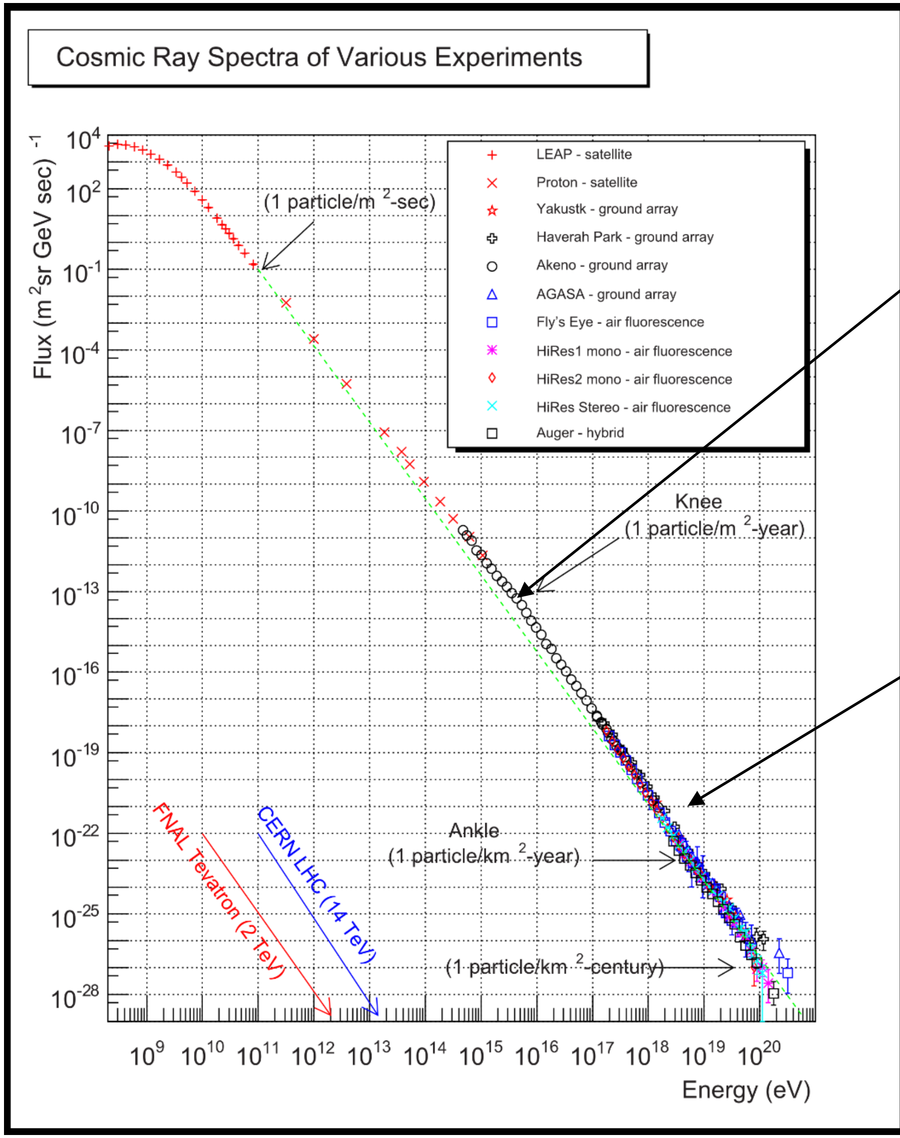
Alt. 1400m

($\sim$880g/cm^2 of air)

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

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

TA measurements

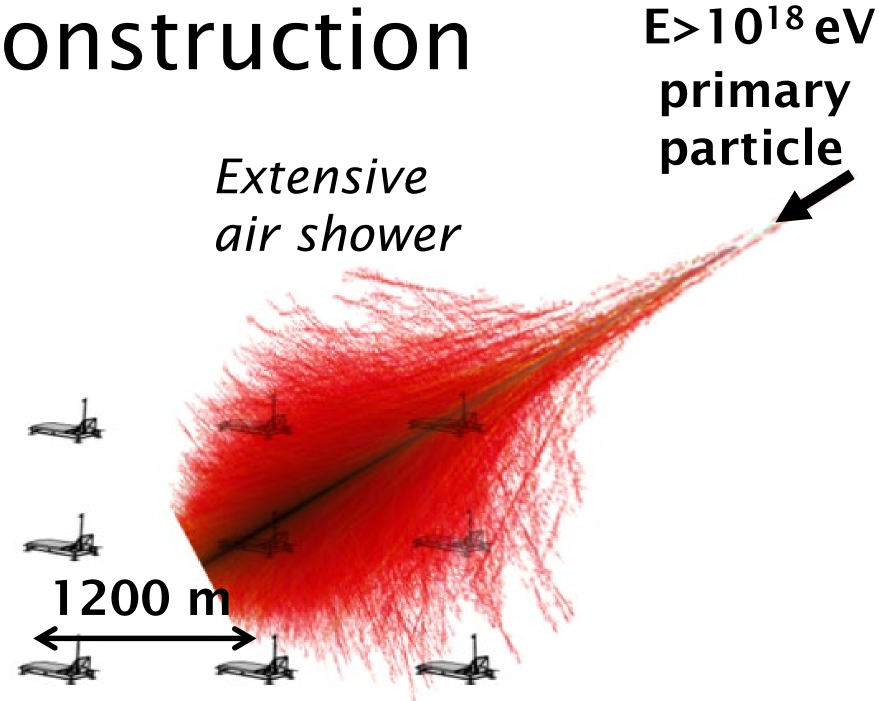


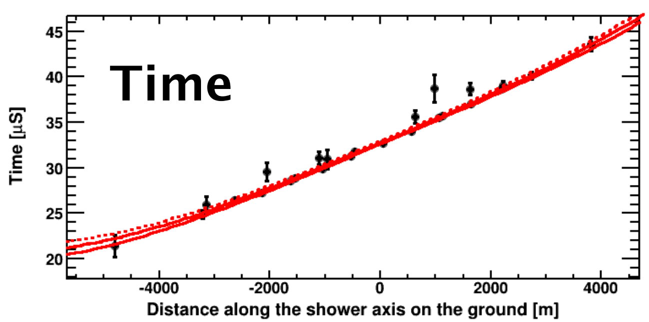
http://www.telescopearray.org/index.php/about/what-are-cosmic-rays

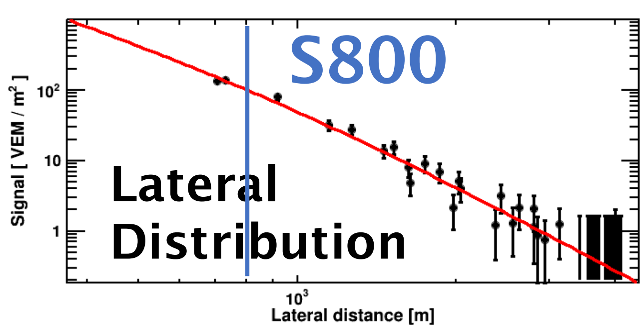
- TA Fluorescence Detector
  - Sensitive to cosmic rays from $10^{15.5}$ eV to 10^{20} eV and higher
  - Mass composition studies of cosmic rays by observing the cosmic ray shower maxima
  - Calorimetric energy estimation of cosmic rays, calibration of the surface detector
- TA Surface Detector (SD)
  - ~700 km^2 area on the ground, 100% duty cycle -> superior statistics at high energies ($10^{18.0}$, $10^{19.0}$, 10^{20} eV)
  - Best for anisotropy and energy spectrum studies where cosmic ray flux is small

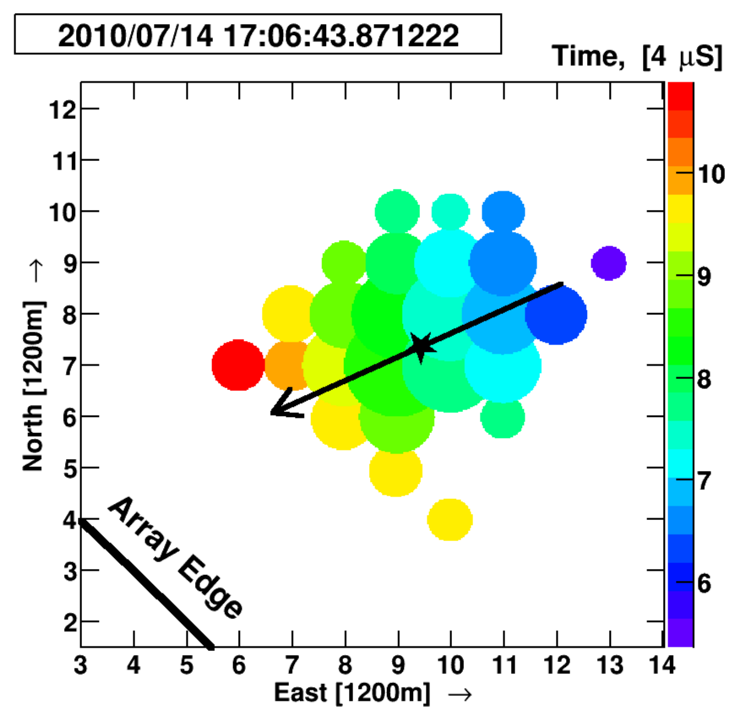
TA SD event reconstruction

- Cosmic Ray events produce Extensive Air Showers in the atmosphere
- Secondary particles (e±, γ, μ±, ..) detected by the TA SD counters
- Two fits to reconstruct primary particle
  - **Timing fit -> trajectory** of the primary particle
  - Counter signal **lateral distribution fit -> energy** of the primary particle

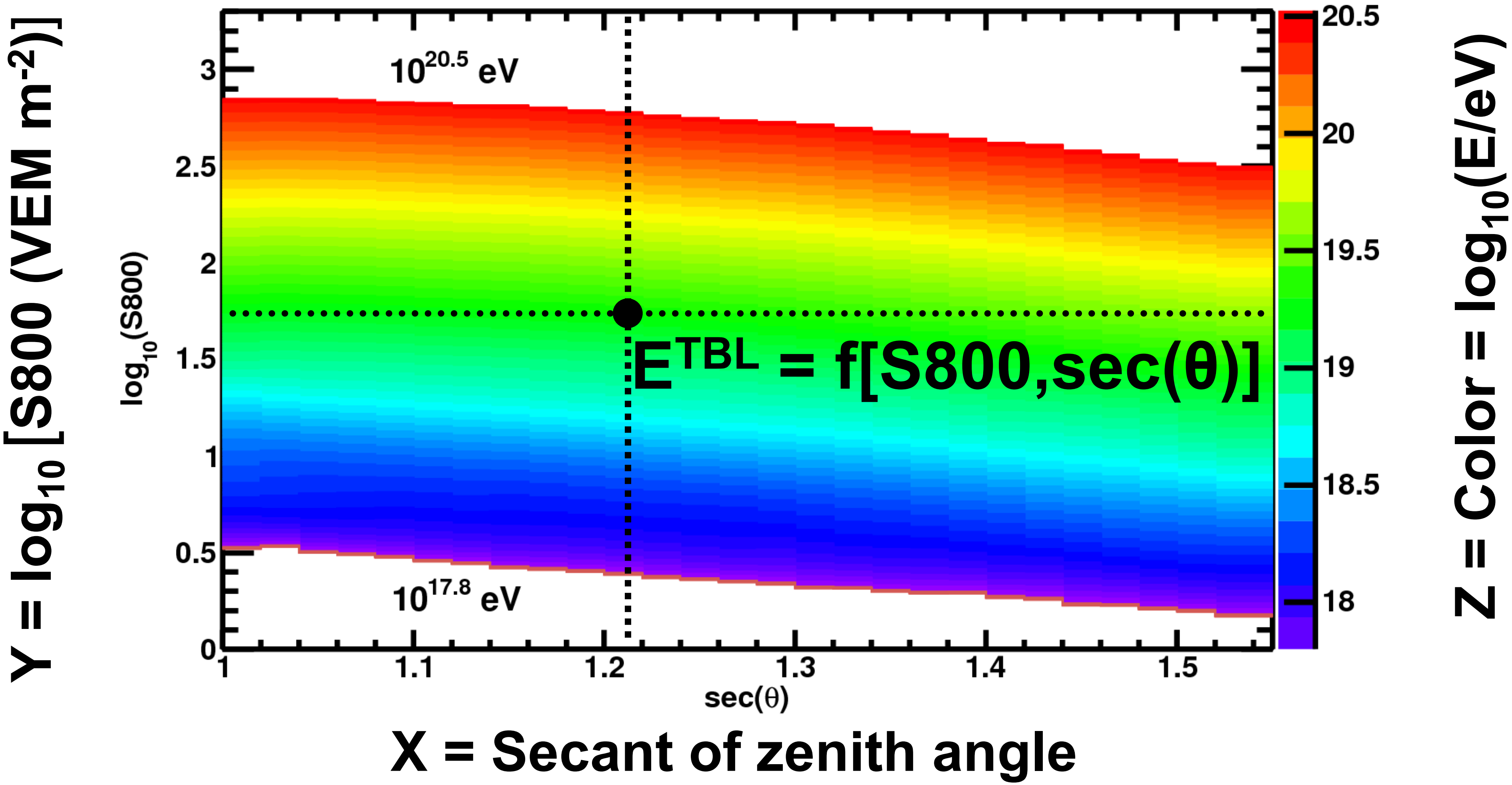






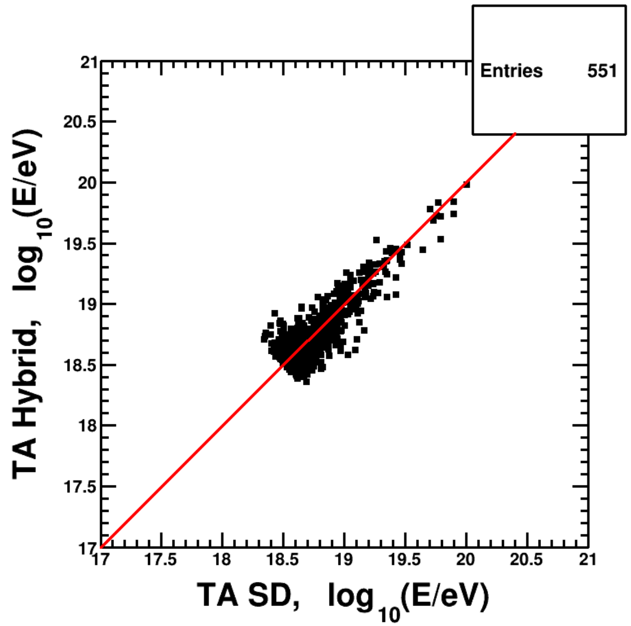


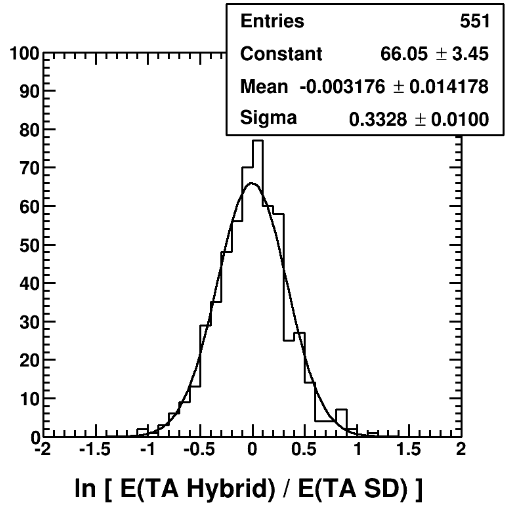
SD energy estimation



- First, a look-up table made from the Monte-Carlo
- Event energy (E^{TBL}) = function of *reconstructed* S800 and sec(θ)
- Energy reconstruction ←→ interpolation between S800 vs sec(θ) contours of constant values of E^{TBL}

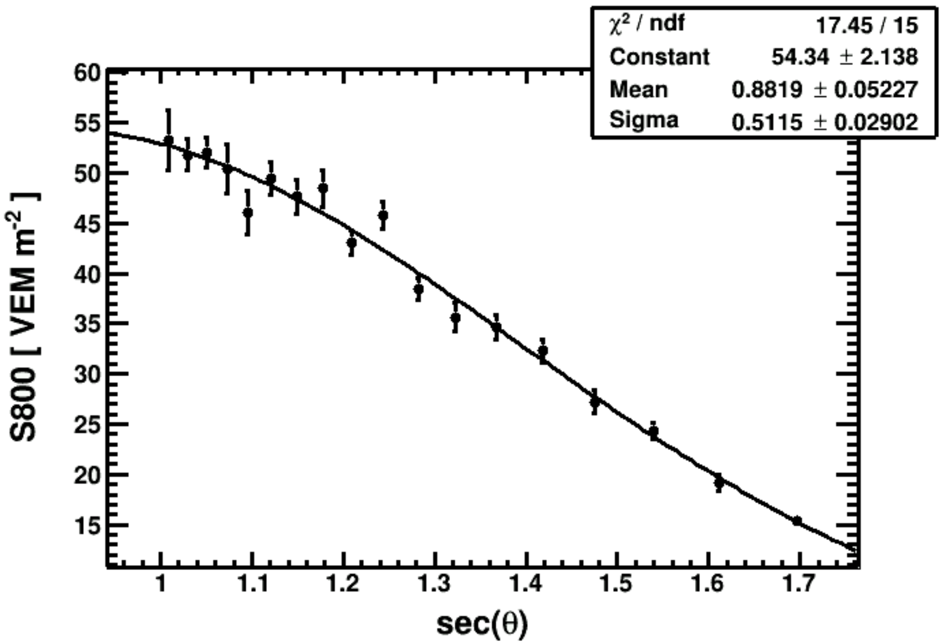
SD energy scale set to FD using hybrid events

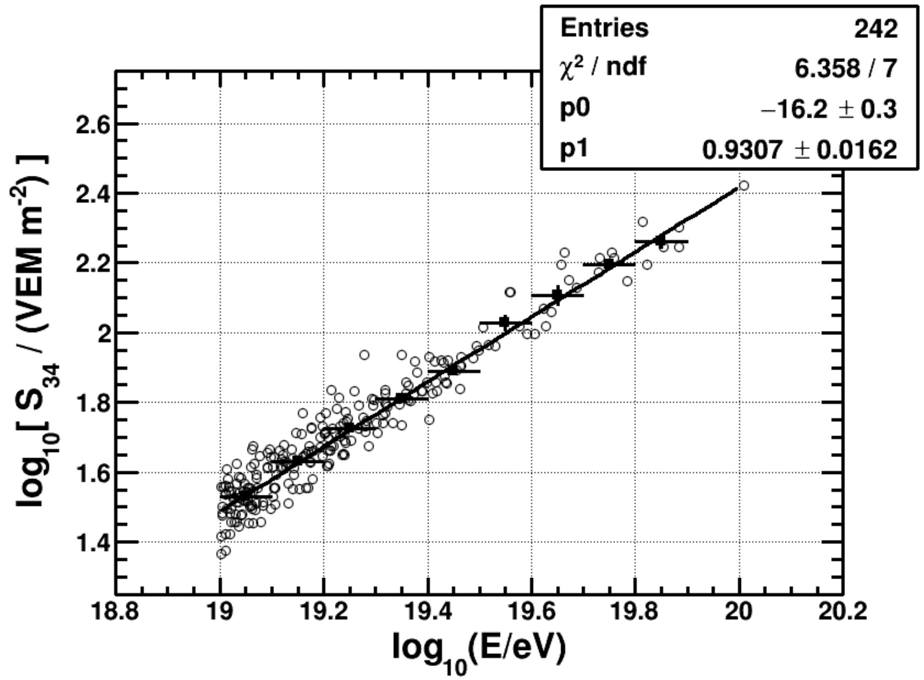


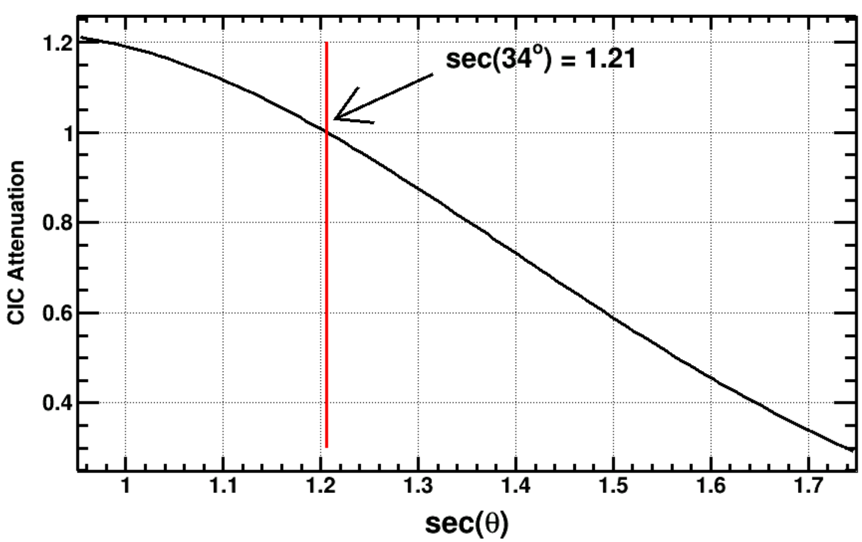


- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
  - $E^{FINAL} = E^{TBL} / 1.27$
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD}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

Constant Intensity Cuts (CIC) method as a check of SD spectrum



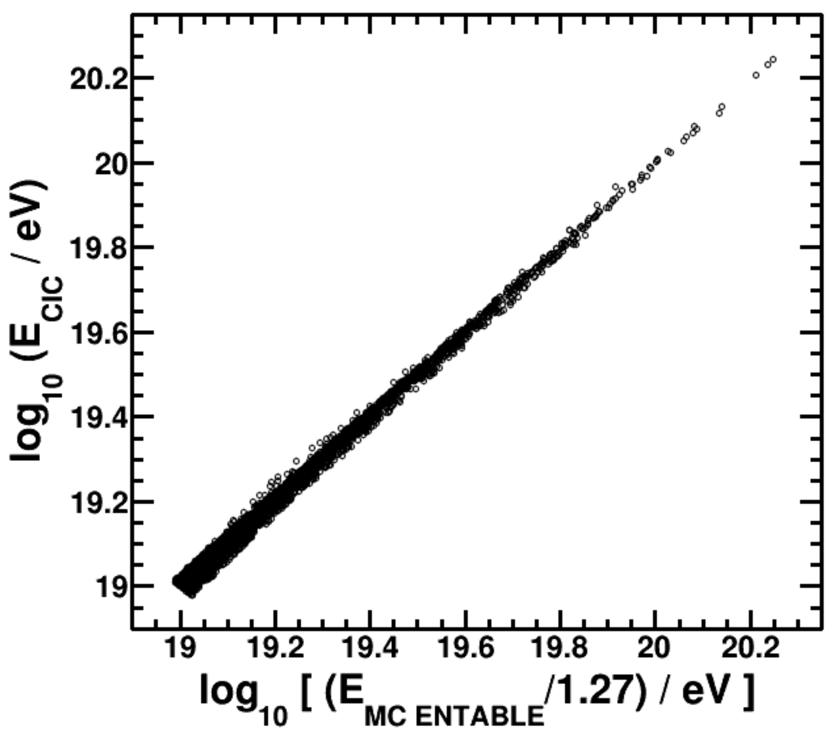


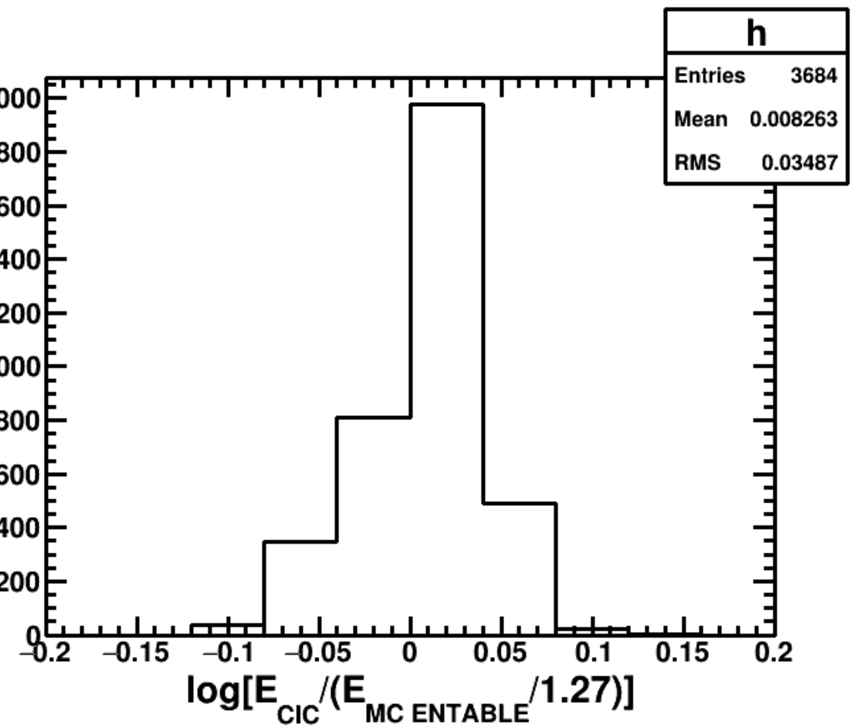


- Attenuation curve from the data
- Normalize at 34° zenith angle
- **S_{34} = S800 / CIC(θ)** is S800 of a shower of the same energy if it came at θ = 34°
- **Lock S_{34} to FD energy using hybrid events**

$$\log_{10} (E_{SD}^{CIC} / \mathrm{eV}) = ([16.2 \pm 0.3] + \log_{10} [S_{34} / (\mathrm{VEM\ m^{-2}})]) / (0.93 \pm 0.02)$$

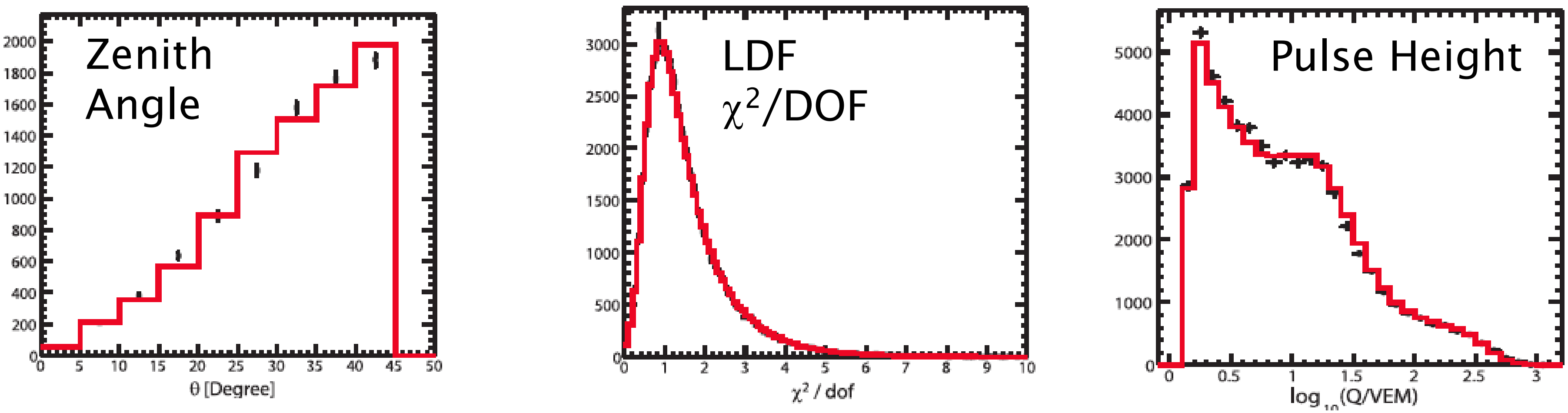
Compare the constant intensity cuts reconstruction and the original TA Monte Carlo - based energy reconstruction methods





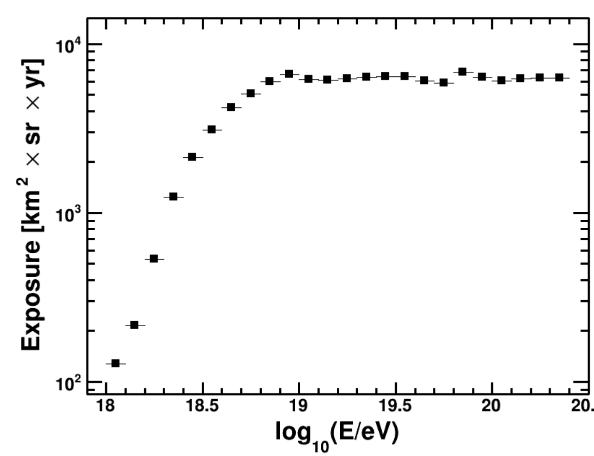
MC-based and Constant Intensity Cuts energy reconstruction methods agree at ~3% level

TA SD resolution and sensitivity by Monte Carlo simulation

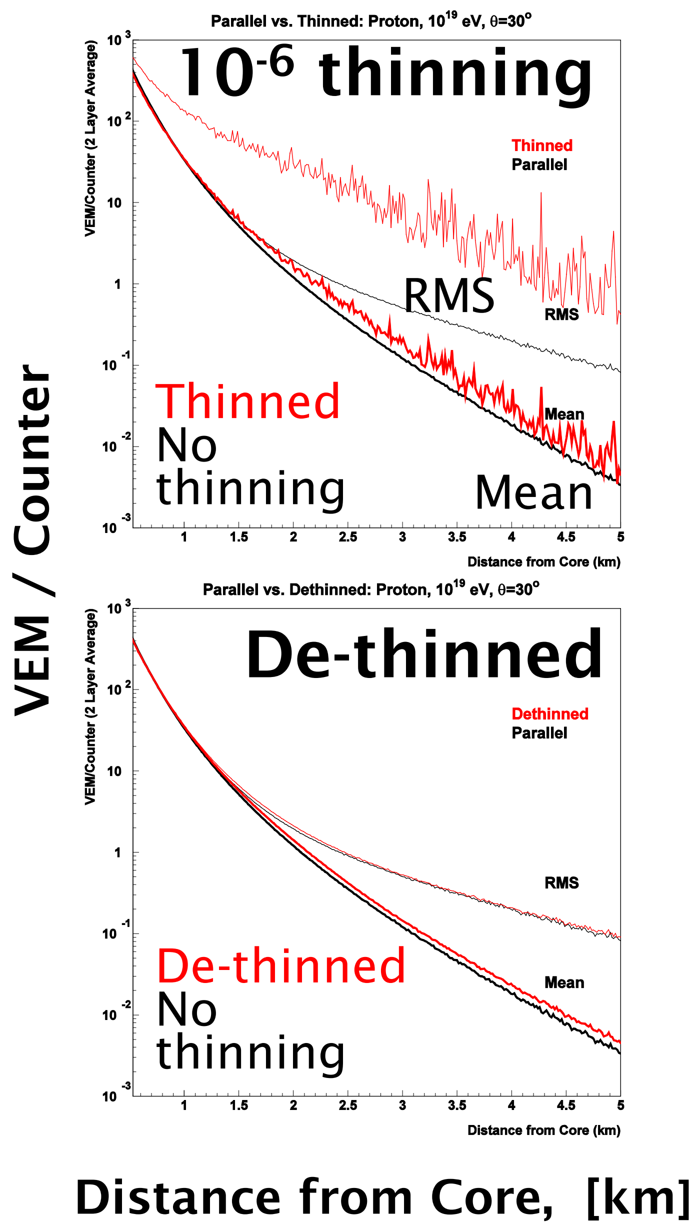


Comparison of distributions of the data (**black points**) and MC (red line)

- 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

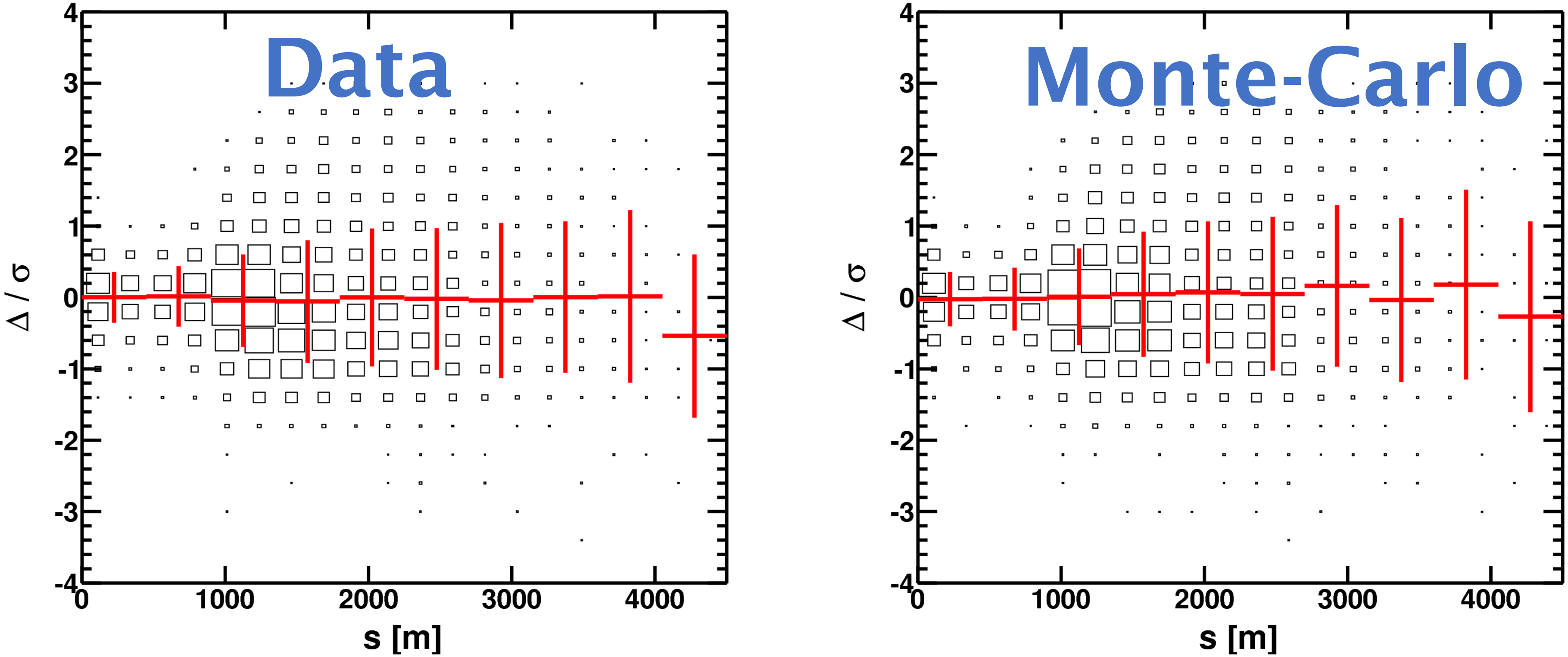


Simulation of the TA SD using CORSIKA



- Thinning in CORSIKA, used to save CPU time, removes particles from the shower and weights remaining ones. This loses information, particularly in transverse distribution at ground level.
- Use *dethinning* procedure that replaces lost particles, using weights (**Astropart.Phys. 35 (2012) 759-766**)
- Dethinning validated by comparing results with un-thinned CORSIKA showers, obtained by running CORSIKA in parallel mode.
- TA SD MC uses 10^{-6} – optimum-thinning CORSIKA + QGSJet II-3 proton showers that are dethinned
- We fully simulate the SD response, including FADC traces

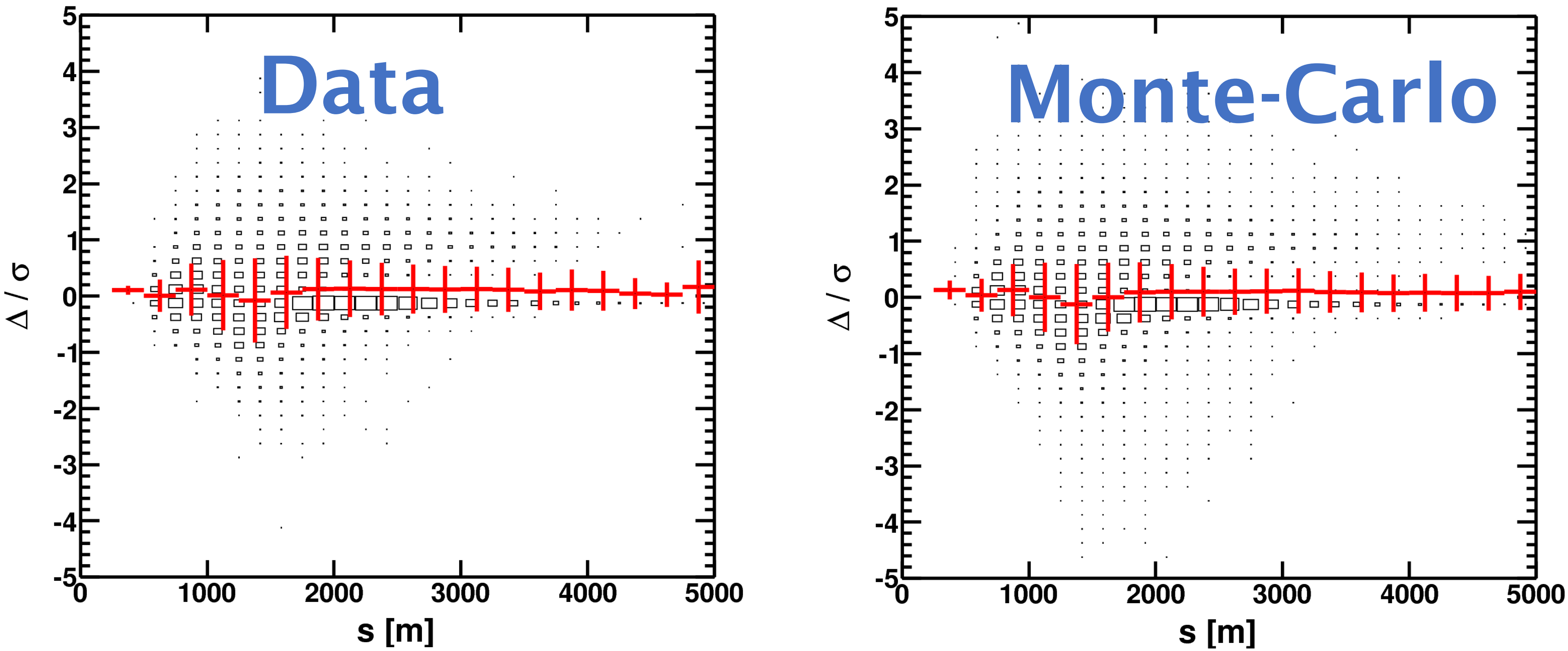
Monte Carlo check: time fit residuals



- 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

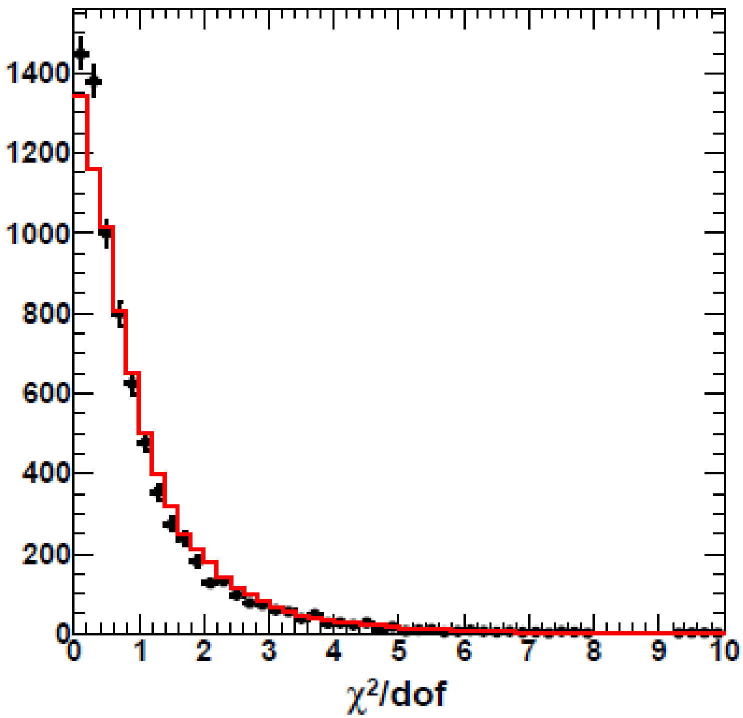
QGSJET-II.3 proton Monte Carlo

Monte Carlo Check: lateral distribution fit residuals

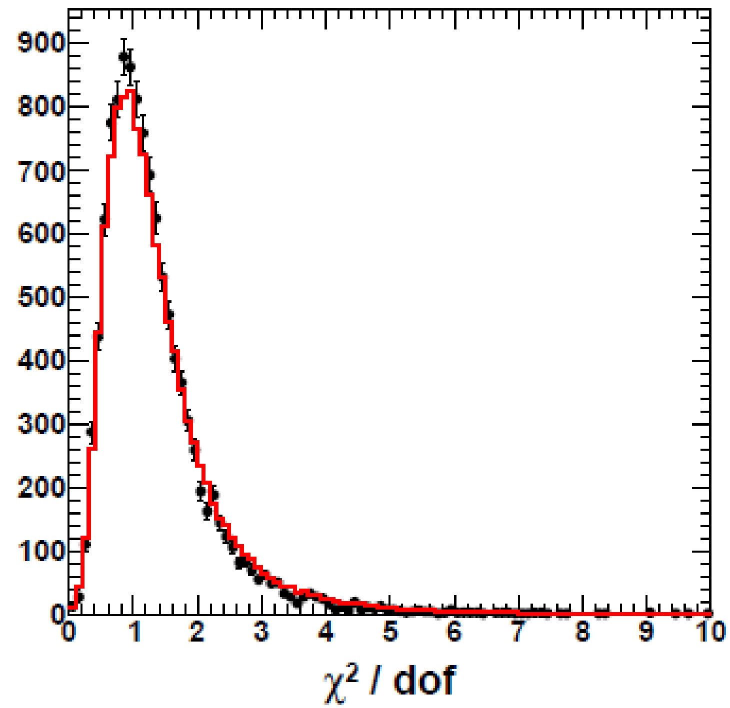


- Each entry = counter, plots are **over all counters and over all events**
- Normalized residual = (counter ρ – fit ρ) / σ_ρ
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit to the AGASA LDF in the same way

DATA and MC chi2/dof

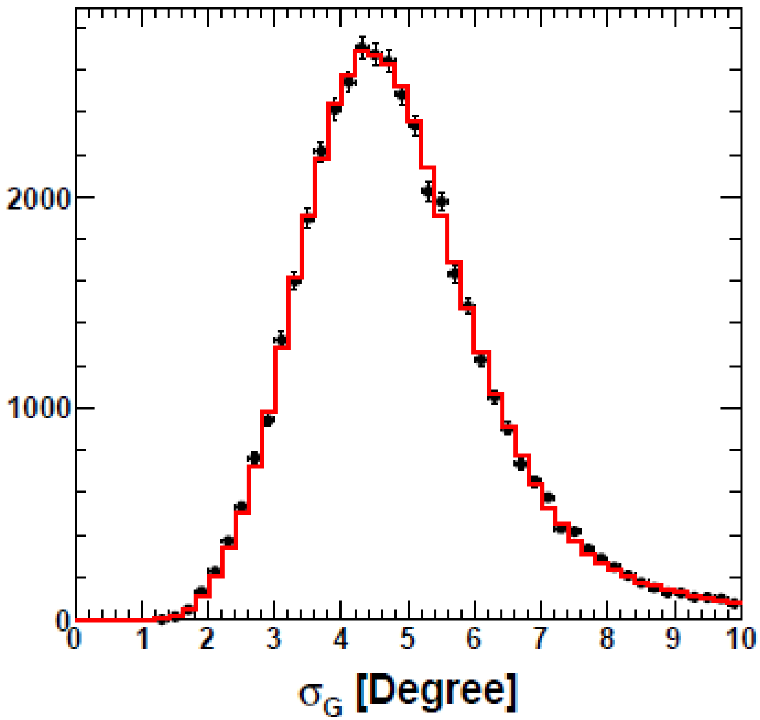


(a) χ^2/dof of the geometry fit.

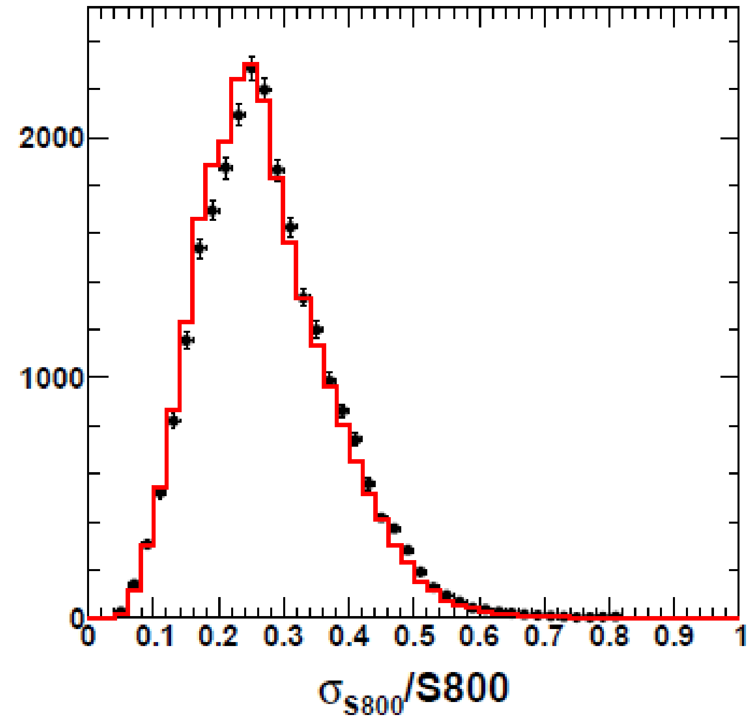


(b) χ^2/dof of the lateral distribution fit.

DATA and MC fitting uncertainties

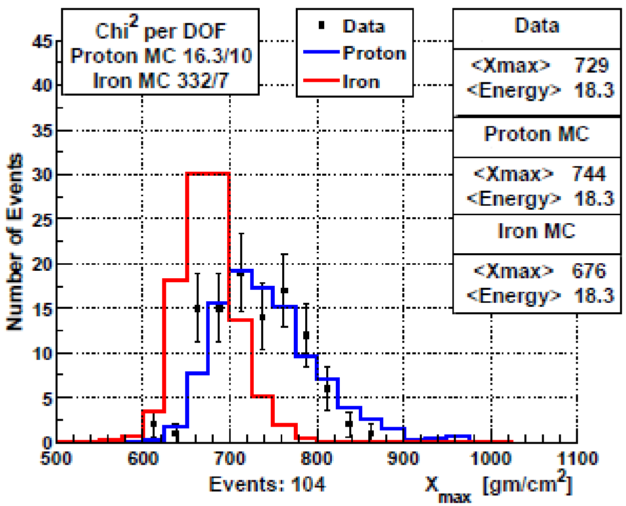


(c) Fit uncertainty of the event arrival direction.

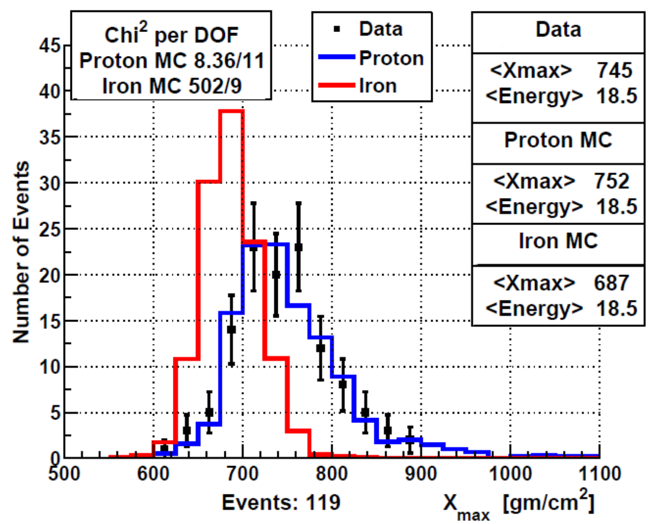


(d) Fractional uncertainty on (fitted) signal size 800 m from the shower axis.

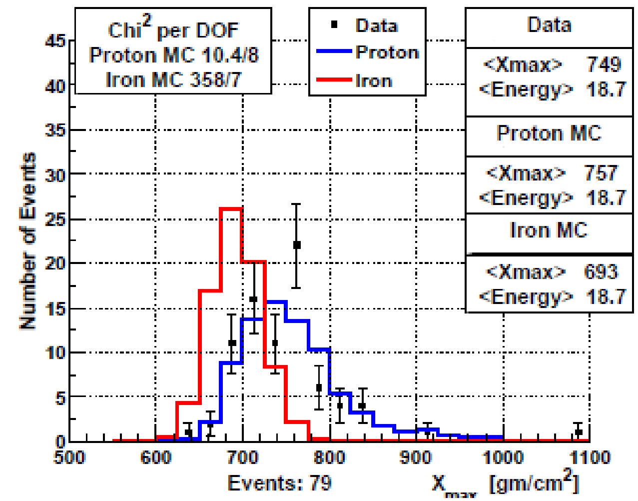
QGSJET-II.3 proton MC Xmax agrees with TA data



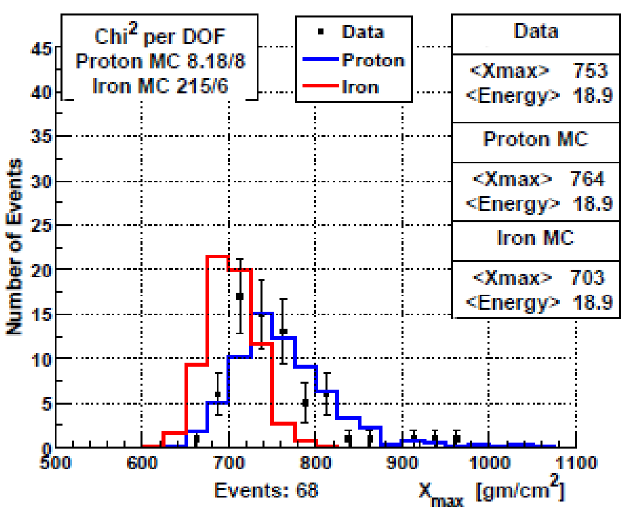
$10^{18.2} < E < 10^{18.4}$ eV



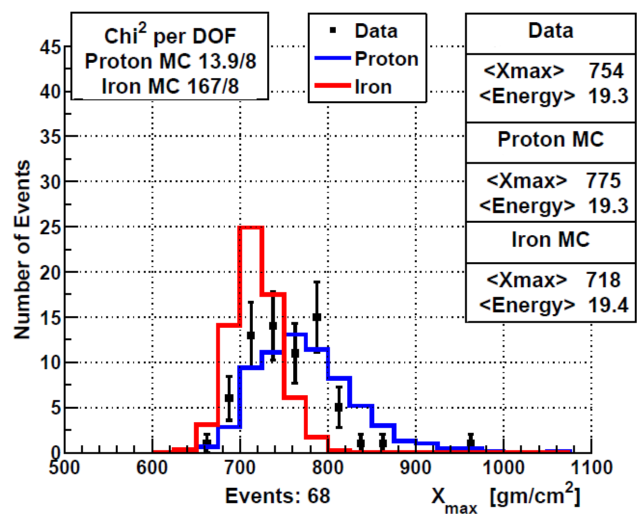
$10^{18.4} < E < 10^{18.6}$ eV



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



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

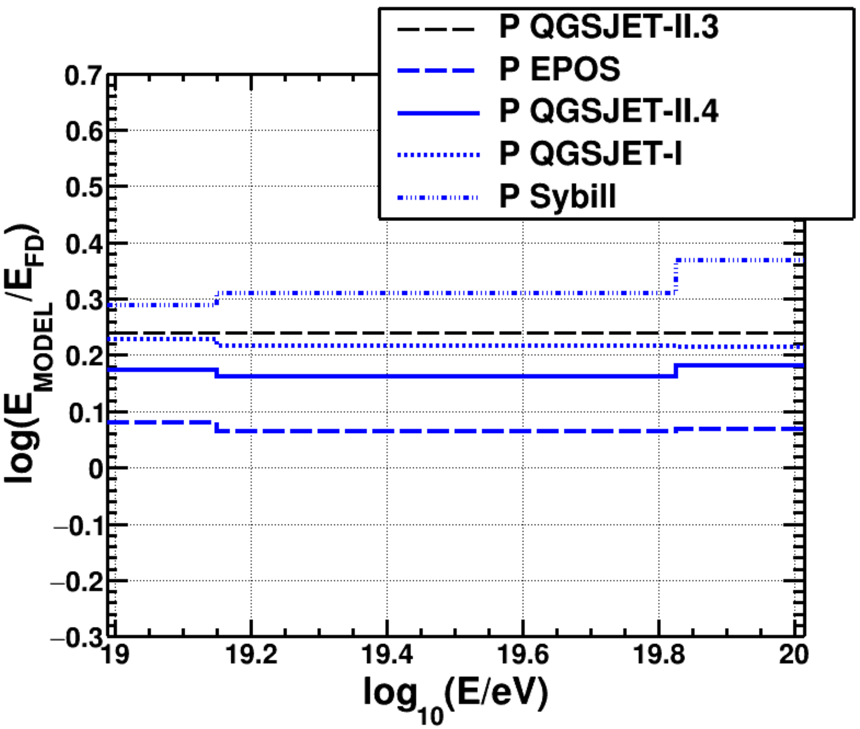


$E > 10^{19}$ eV

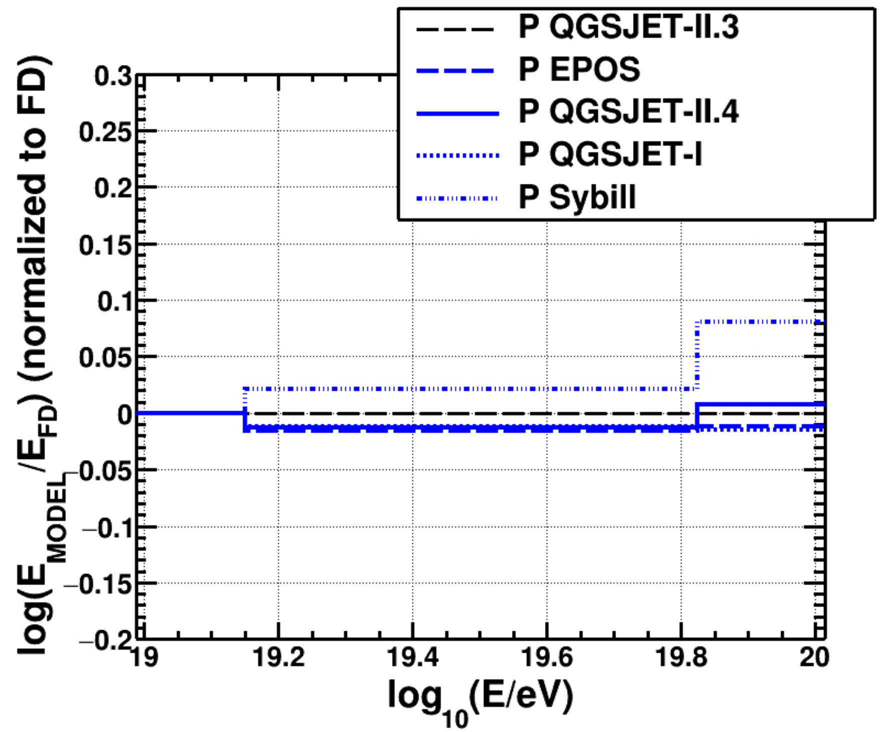
(Astropart. Phys. 64 (2015) 49-62)

Looking at other hadronic models

SD energy from the hadronic models relative to the FD



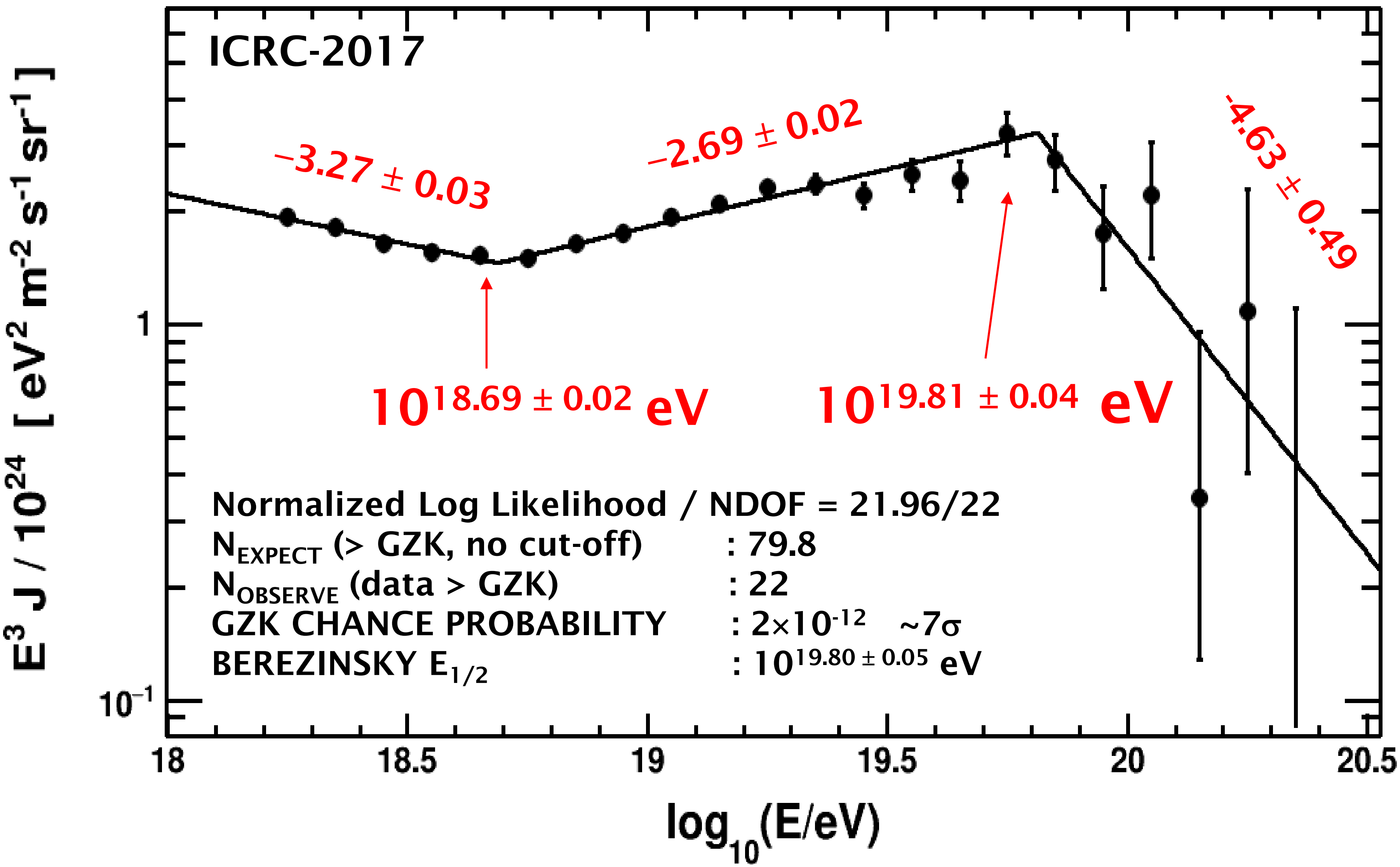
SD energy from the hadronic models after normalization at 10^{19} eV



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

1. Implementing newest EPOS-LHC for TA SD, almost ready
2. **TA SD results not sensitive to hadronic models above 10^{19} eV**

TA SD spectrum (2008/05/11-2017/05/11)



TALE FD event reconstruction

Fluorescence event

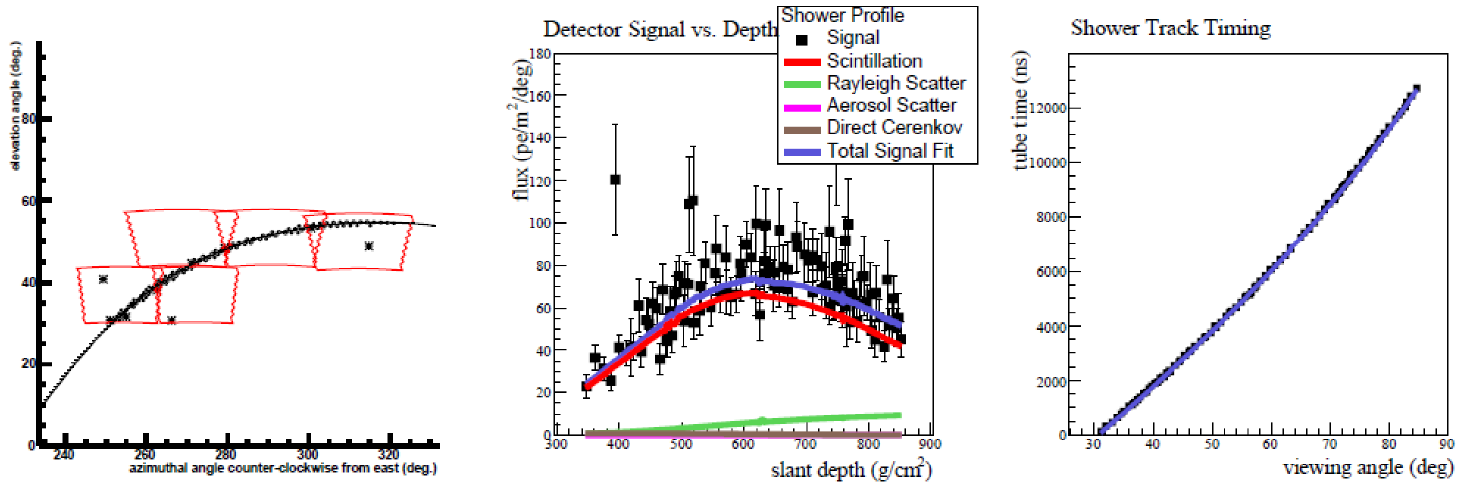


Figure 5: A five-telescope fluorescence event. The display panels show the event image (PMT trigger pattern), the reconstructed shower profile with relative contributions of FL/CL and scattered CL, and the time progression of triggered PMTs.

Cherenkov event, profile-constrained fit.

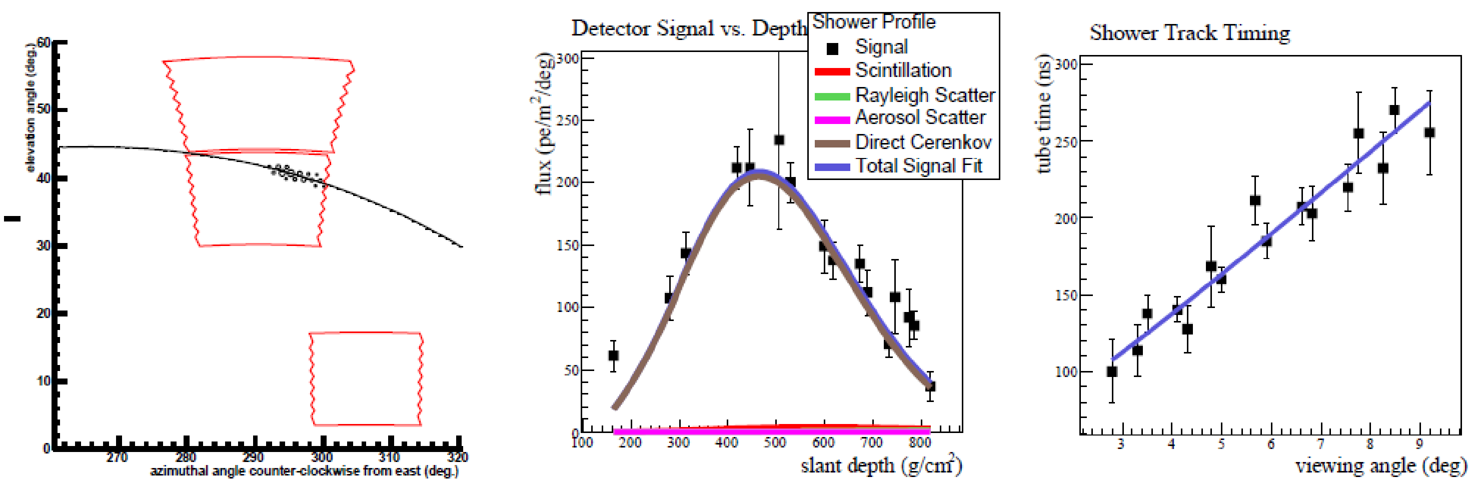
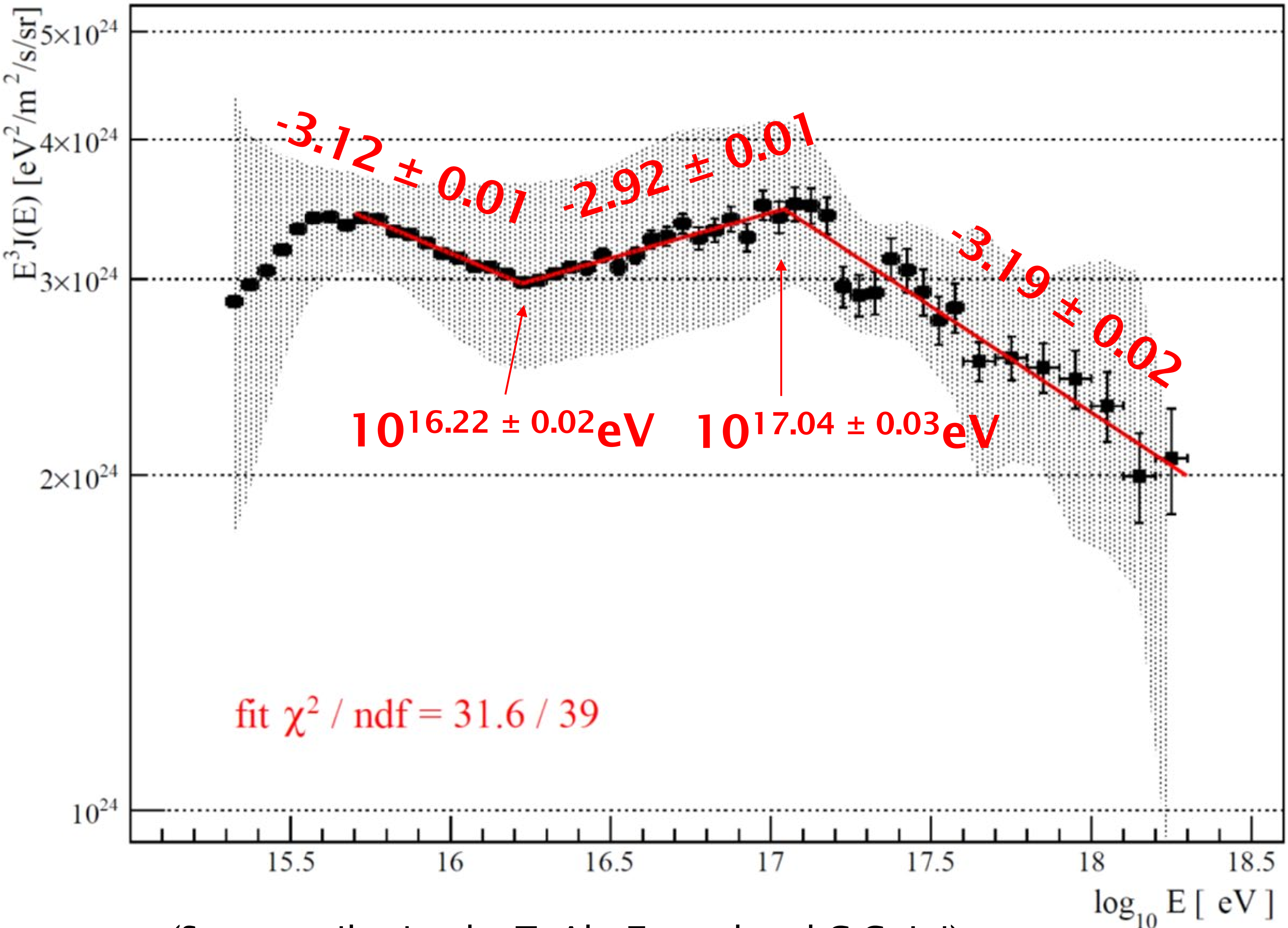


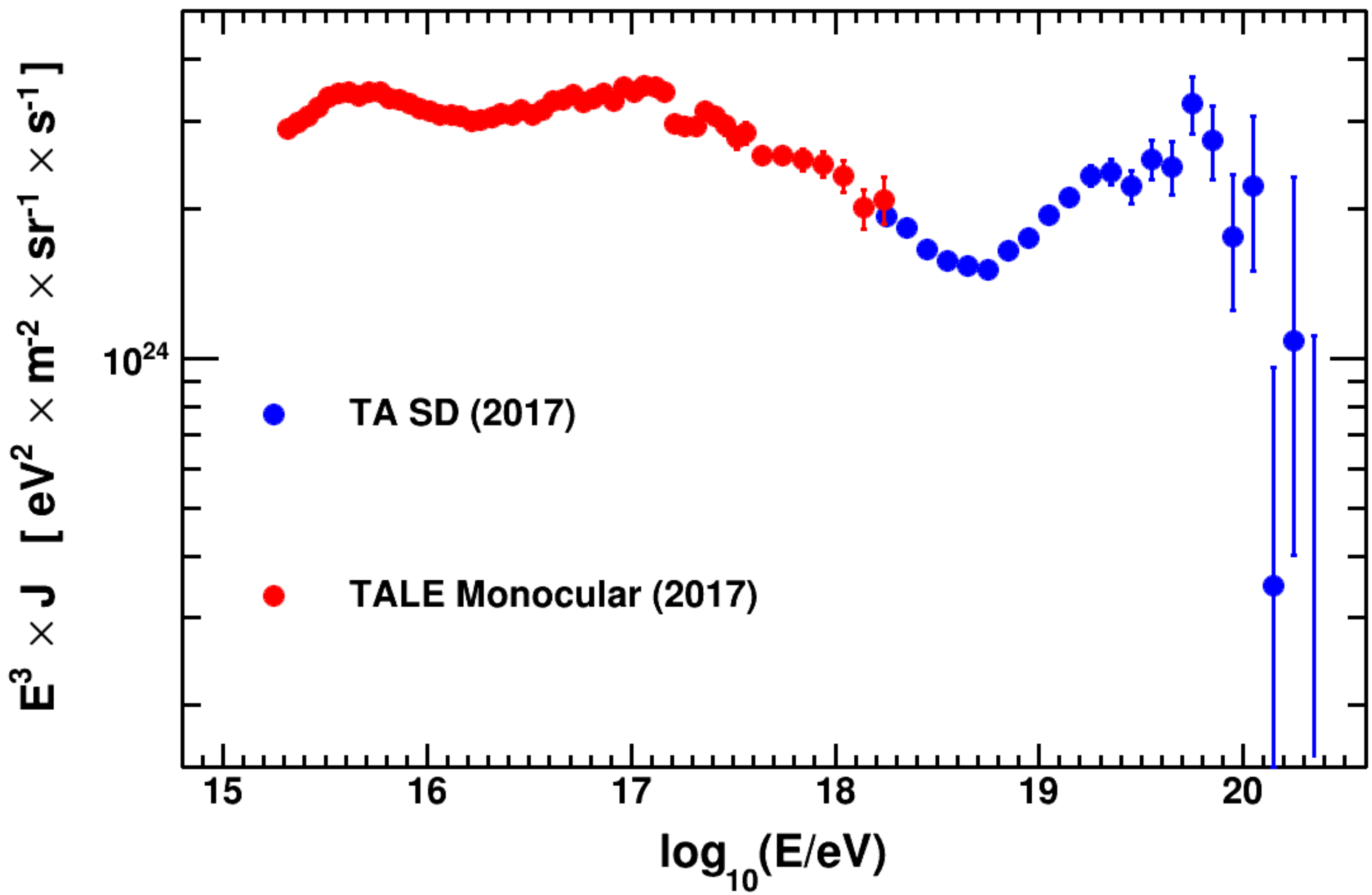
Figure 6: A one-telescope Cherenkov event. The display panels show the event image (PMT trigger pattern), the reconstructed shower profile with relative contributions of FL/CL and scattered CL, and the time progression of triggered PMTs.

TALE FD spectrum

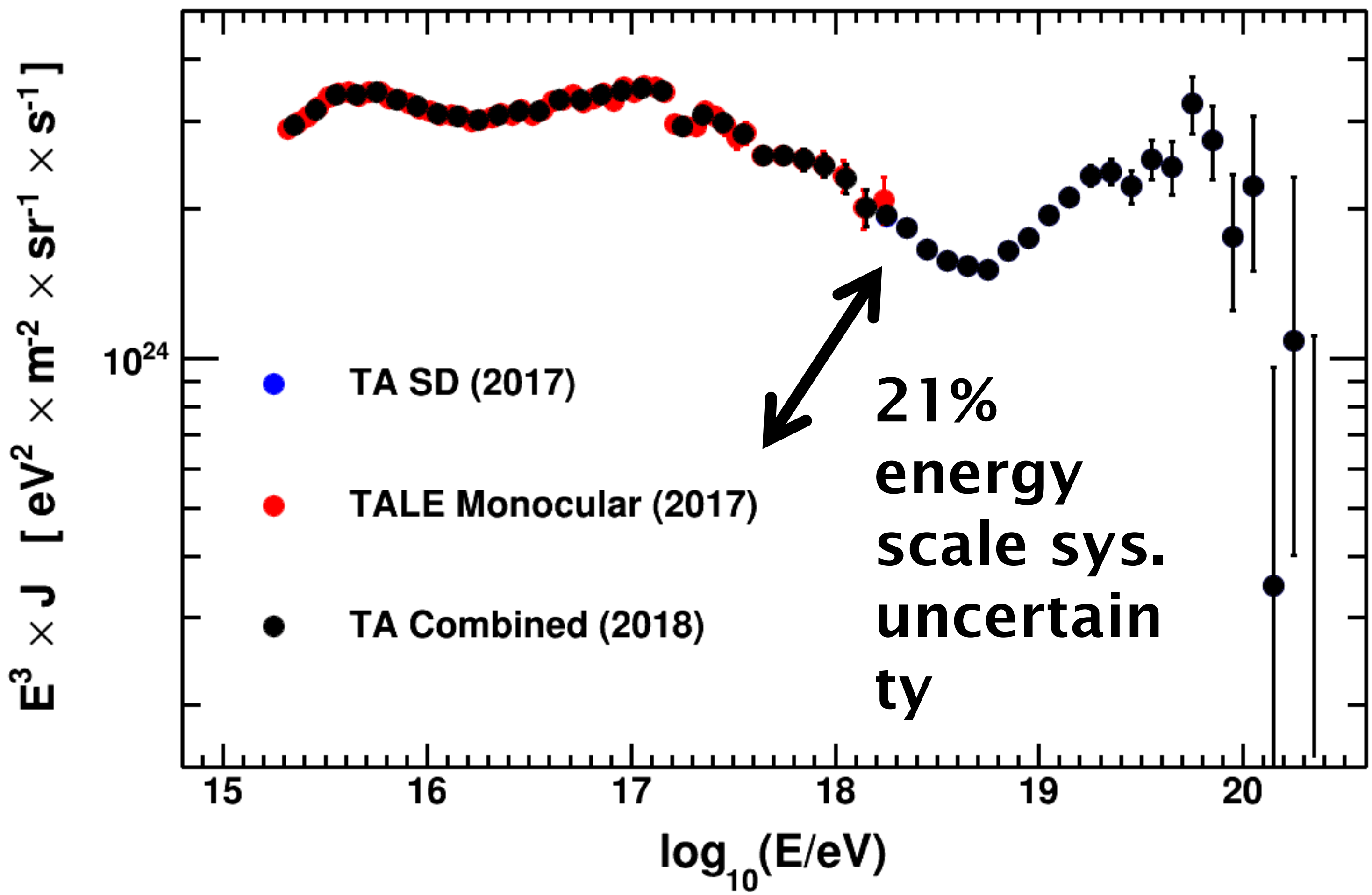


(See contribution by T. AbuZayyad and C.C. Jui)

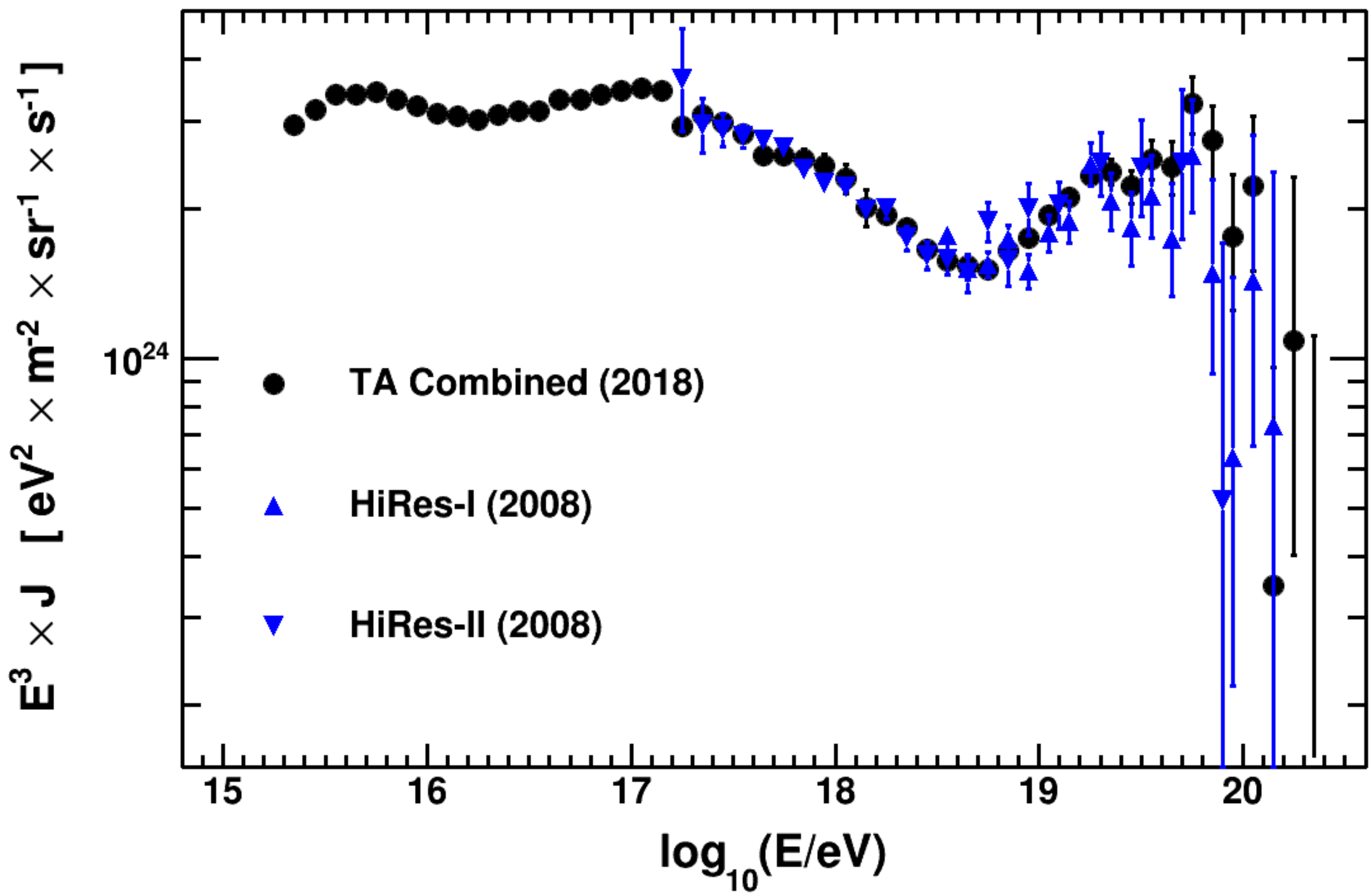
TA/TALE spectrum



Combined TA spectrum

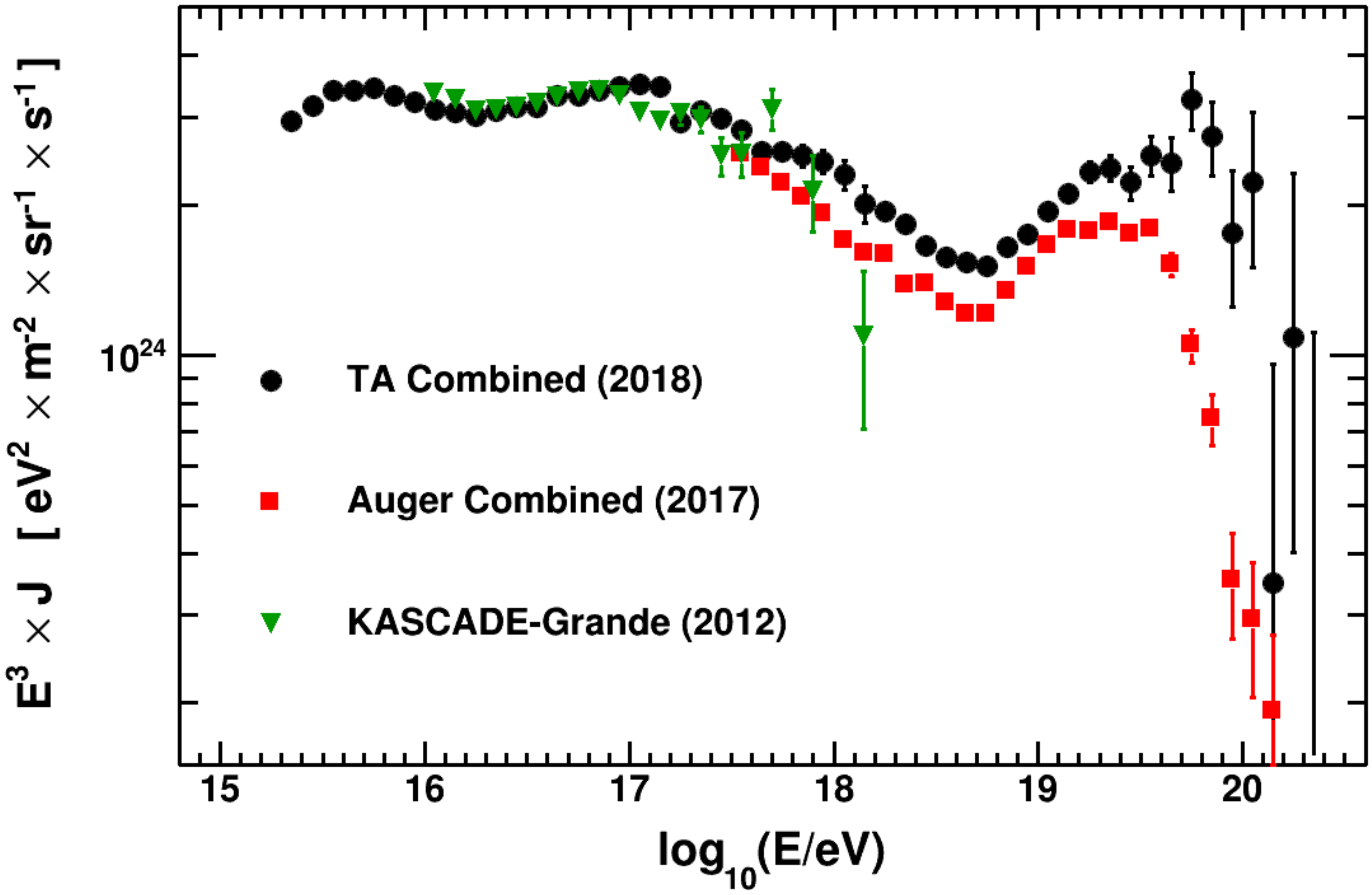


TA and HiRes

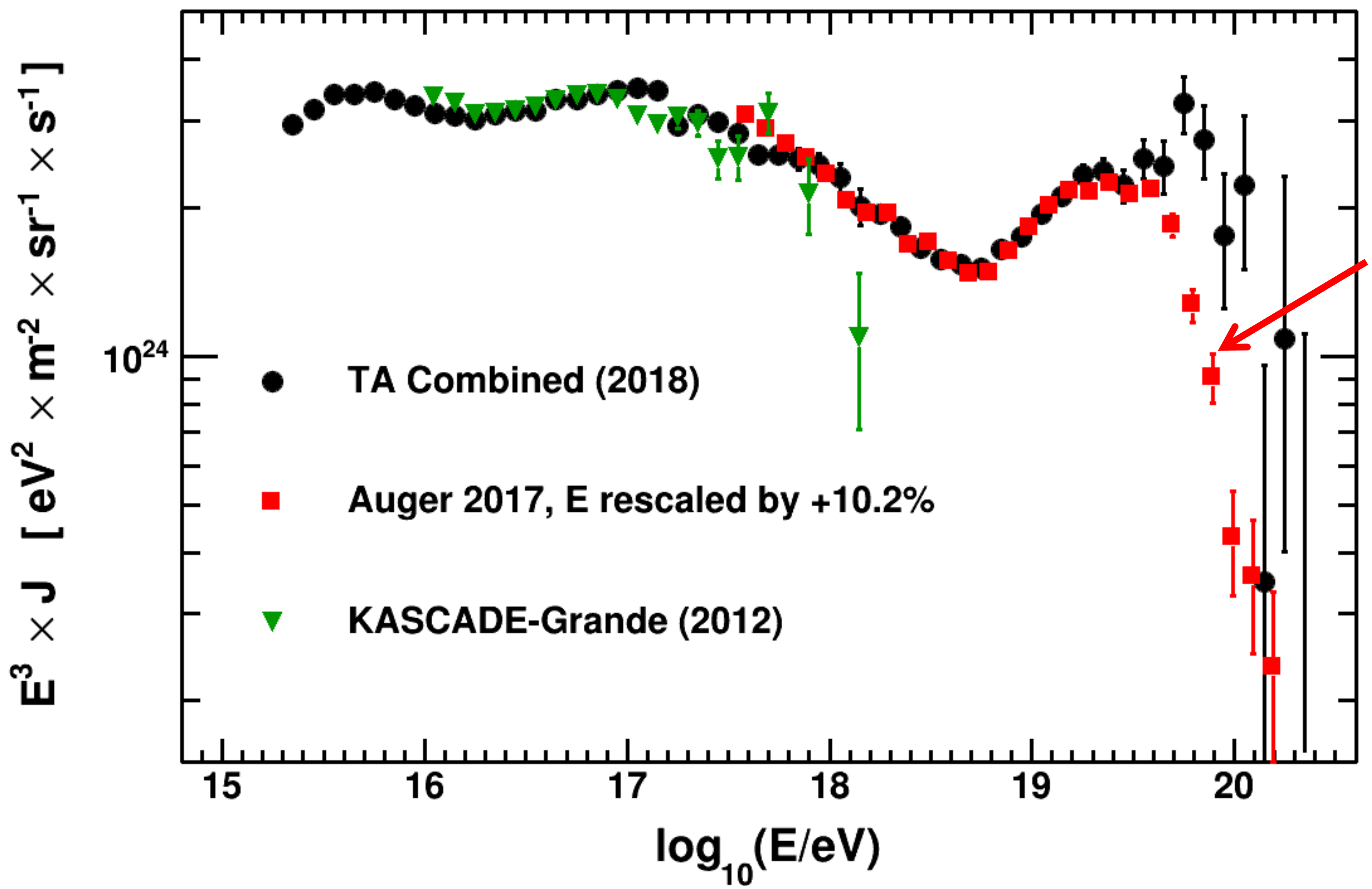


$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
TA Combined (2018)
HiRes-I (2008)
HiRes-II (2008)
15
16
17
18
19
20
$\log_{10}(E/eV)$

TA, Auger, KASCADE-Grande

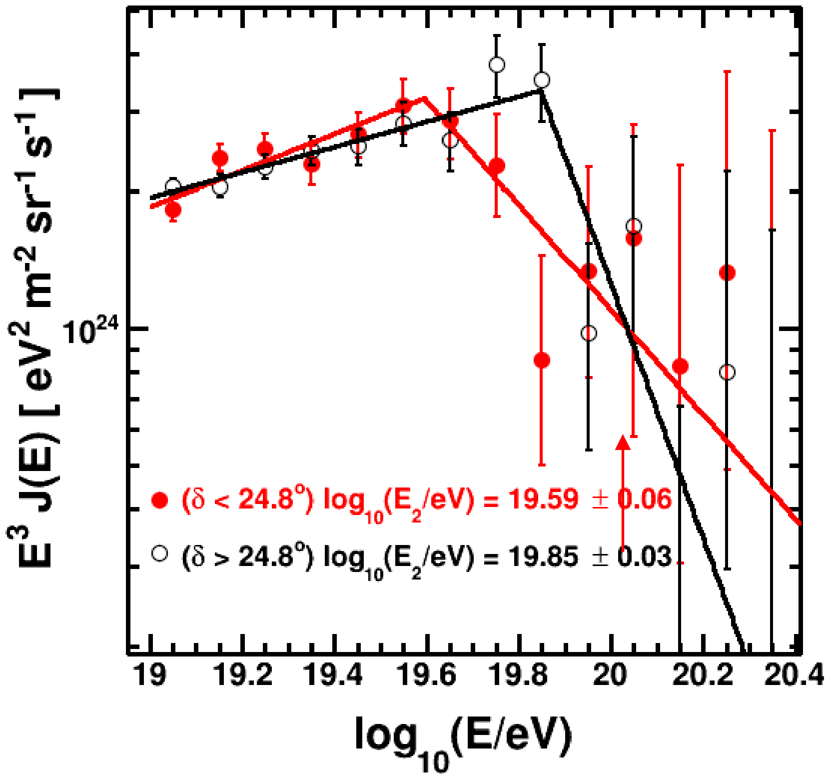


TA, Auger, KASCADE-Grande

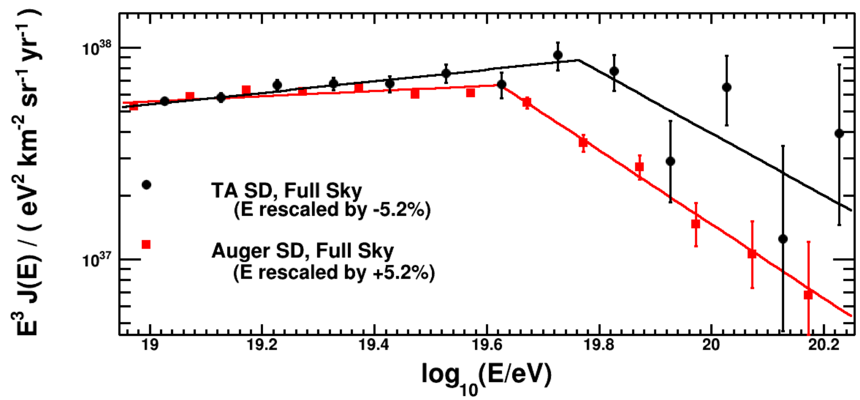


Discrepancy between TA and Auger investigated further

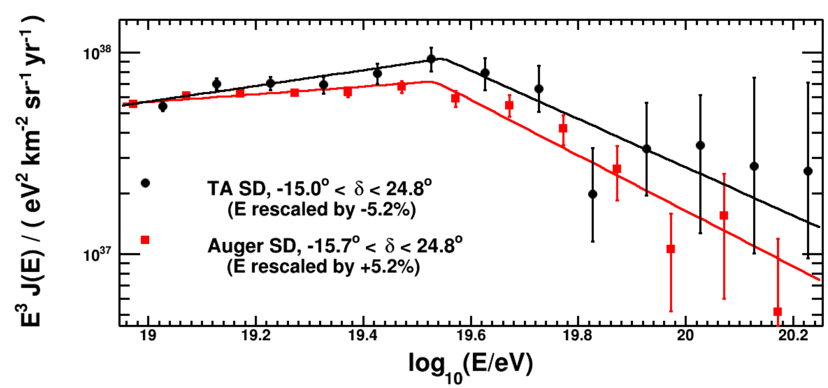
Declination dependence above 10^{19} eV



TA: Break points above and below the declination of 24.8º are 4σ different



Restrict to common declination band -15.0º to 24.8º

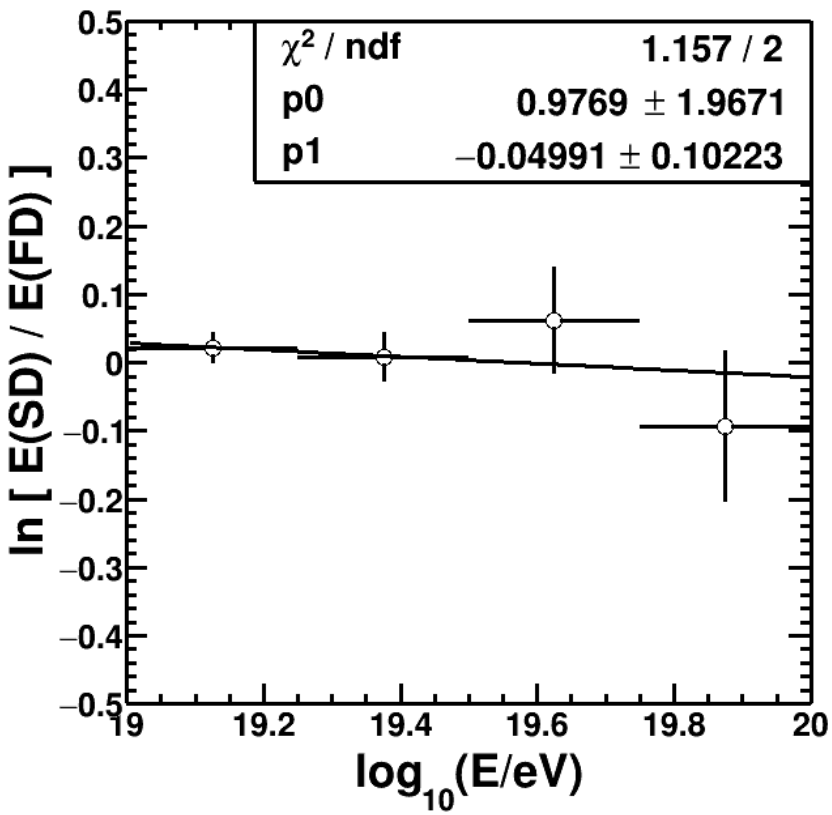


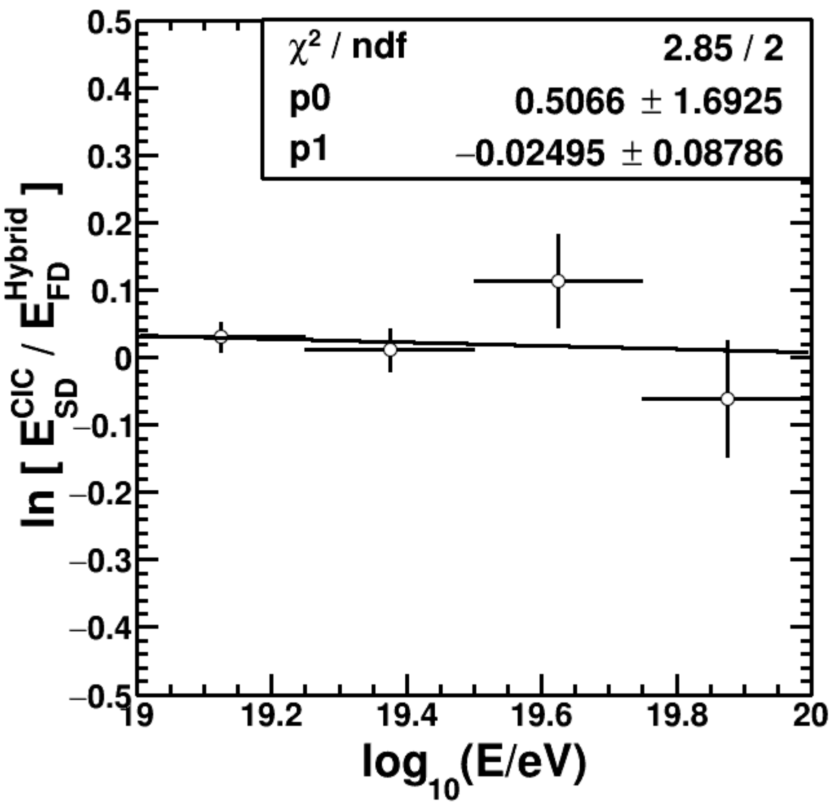
Second break points of TA and Auger agree to within 0.5 σ in the common declination band

Post - trial significance: 3.5σ

https://arxiv.org/abs/1801.07820

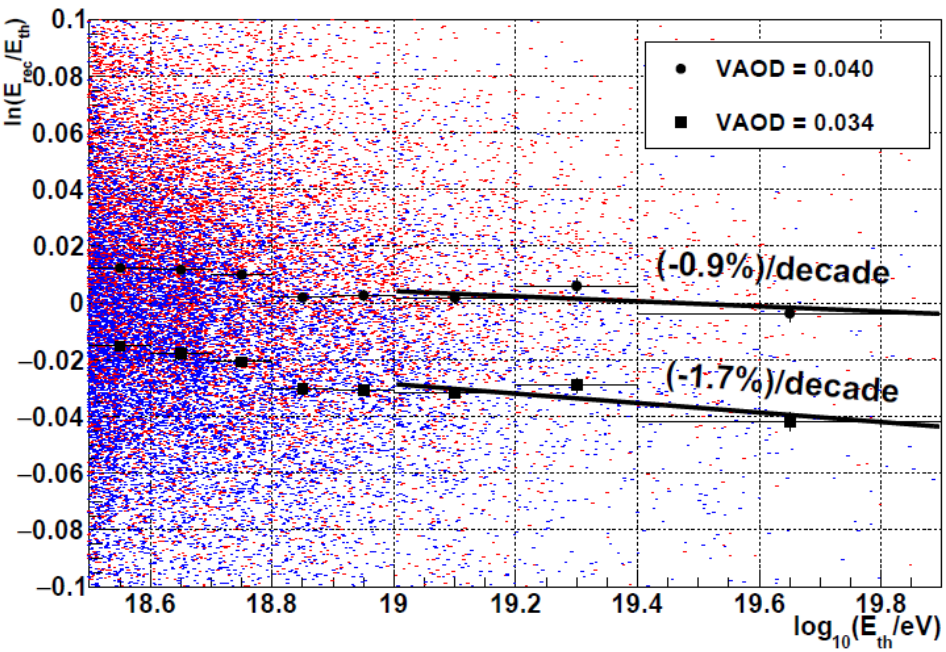
Linearity check of SD with FD using hybrid events: no evidence of nonlinearity





1. **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.**

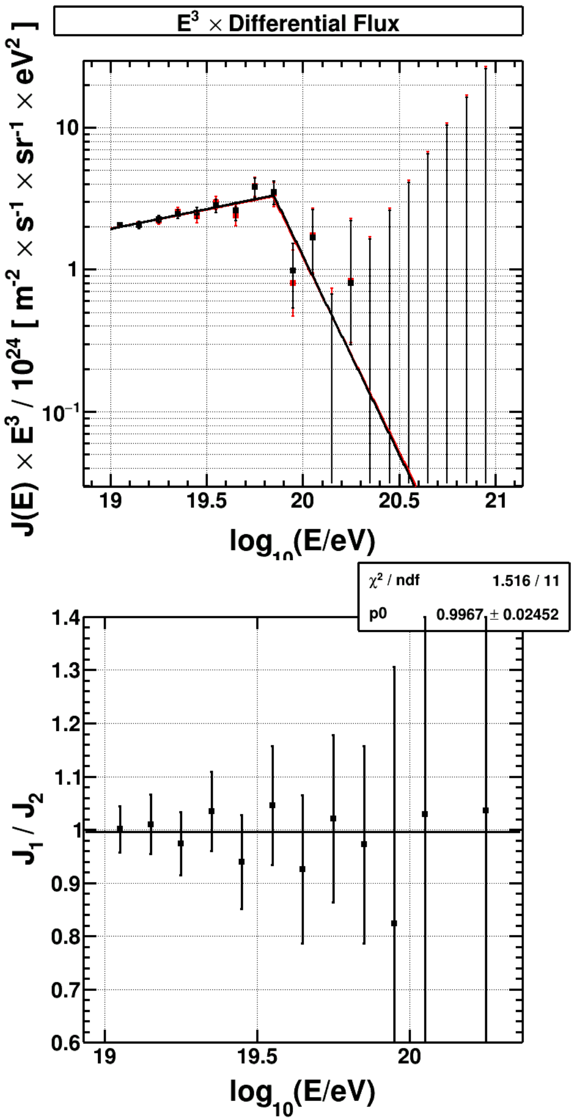
Check of FD energies



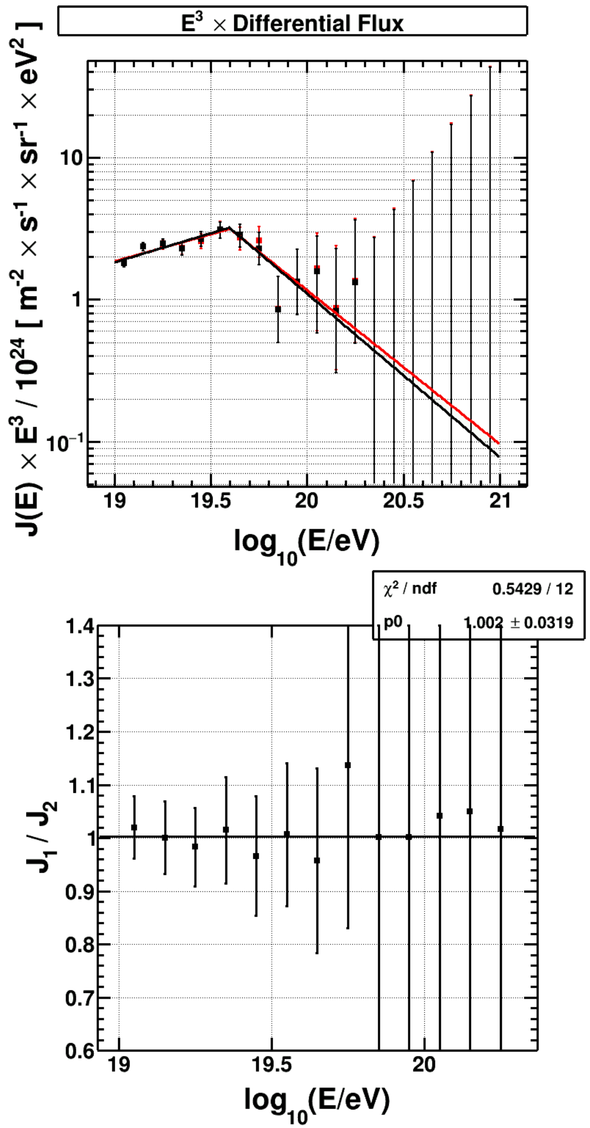
- Maximum possible non-linearity effects of atmospheric conditions are 1.7% per decade

Constant intensity cuts and **MC energy estimation table** methods for TA SD give same results in the two declination bands

24.8° < δ < 90°



-15° < δ < 24.8°

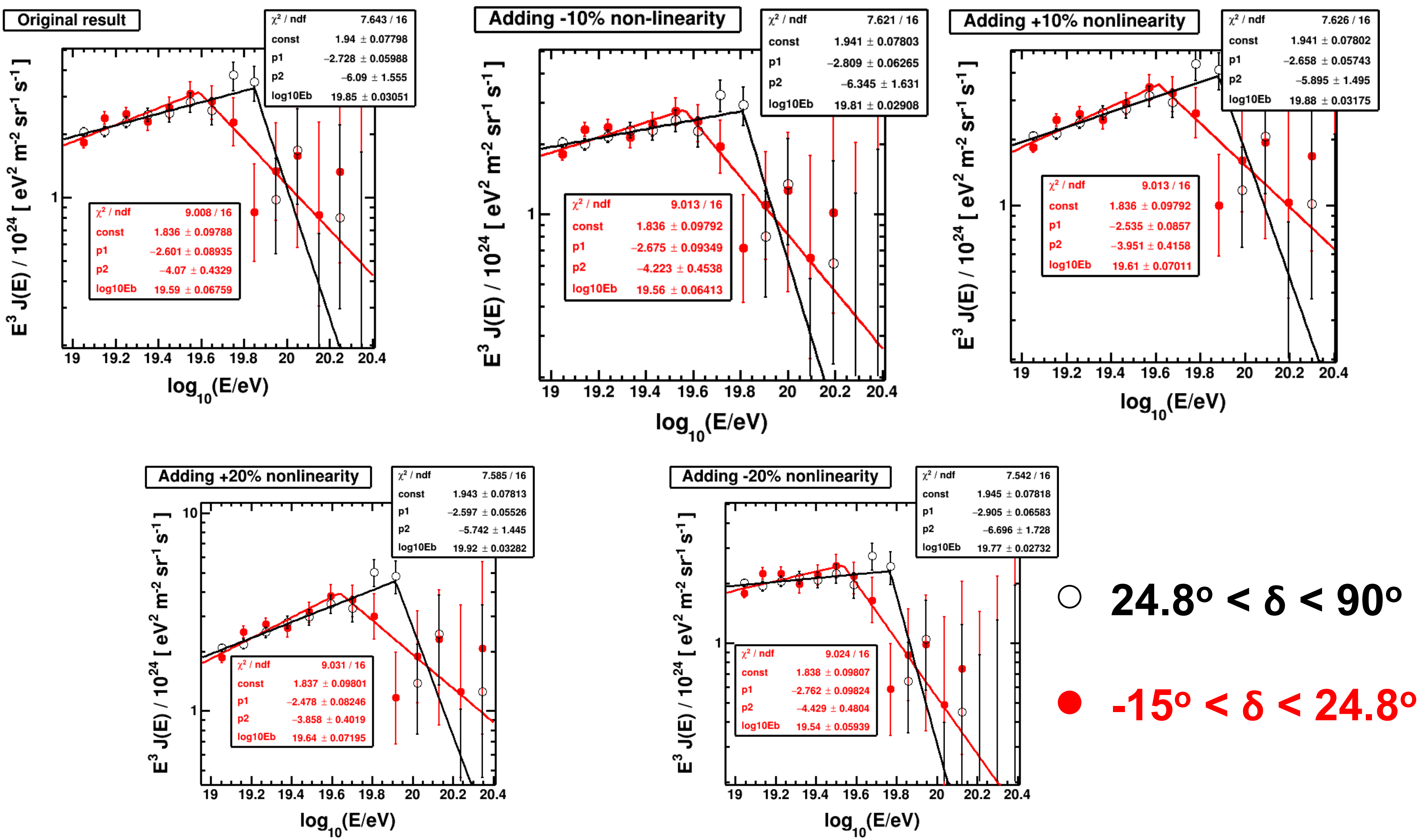


- **Constant Intensity Cuts Method**
- **MC Energy Estimation Method**

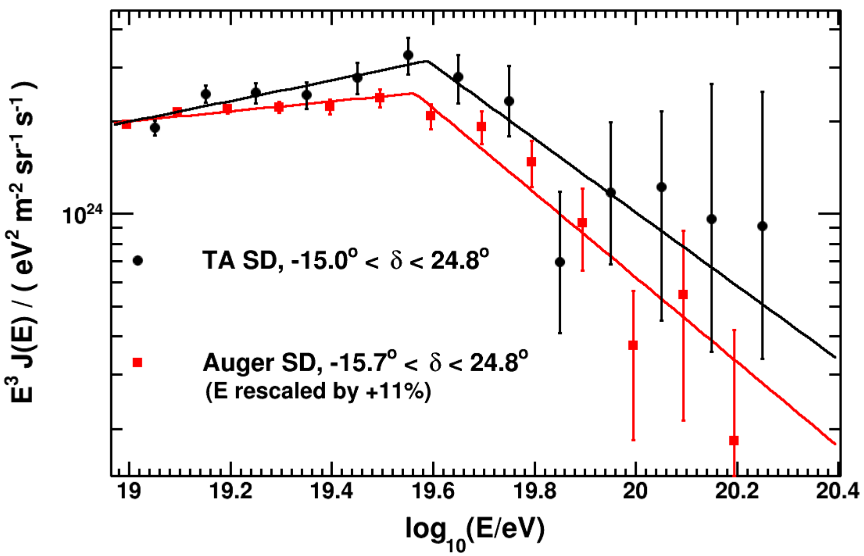
Nonlinearity sources above 10^{19} eV in TA

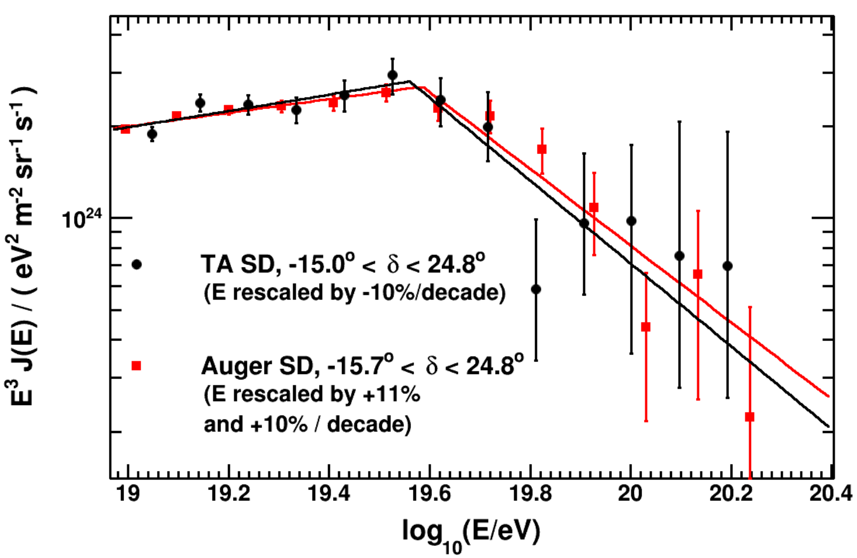
Source of Nonlinearity	Amount (percent per decade above 10^{19} eV)
FD missing energy correction	1% +/- 1%
FD Fluorescence Yield Model	-1% +/- 1%
FD Atmospheric Conditions	1.7% +/- 1%
SD and FD comparison:	-2% +/- 9%
Net	**-0.3% +/- 9%**

But result is robust under nonlinearity shifts of +/- 20% per decade of energy



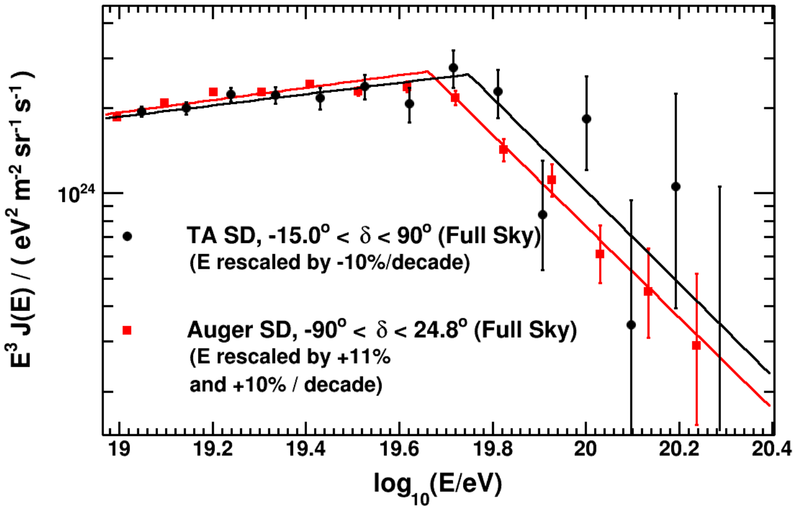
Remaining difference with Auger in the common declination band

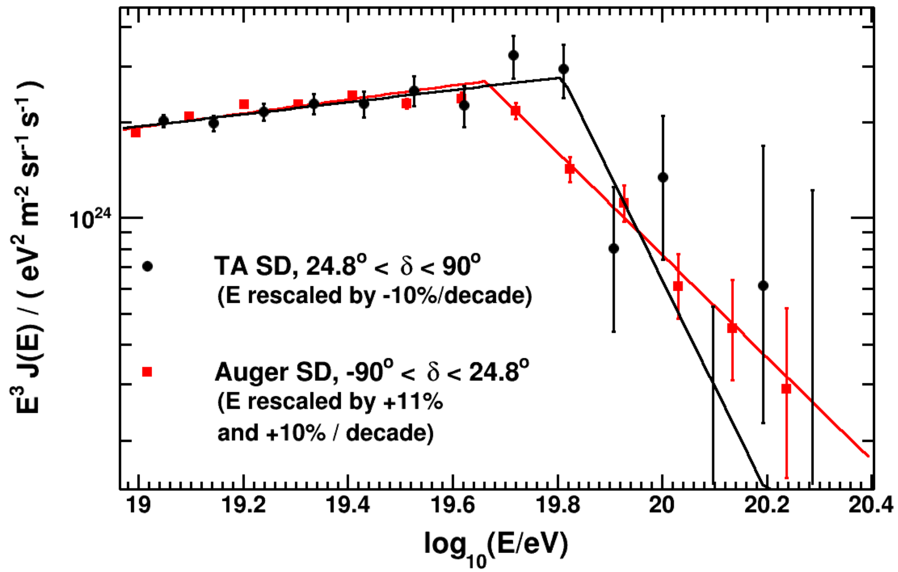


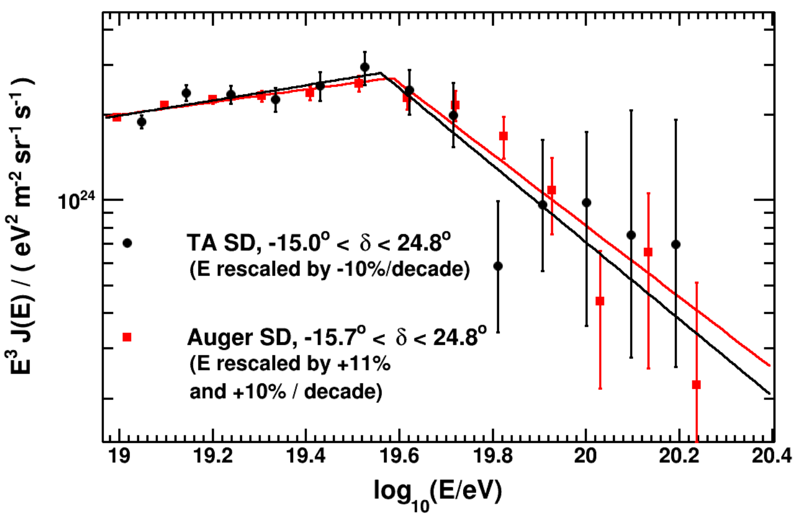


- TA and Auger spectra can be brought to agreement after a correction of Auger energies by +10%, and TA energies by -10% per decade, starting at 10^{19} eV.
  - Second break points of Auger and TA would then be ($\log_{10}$ (E/eV)): 19.58 +/- 0.03 for Auger and 19.56 +/- 0.06 for TA
- **TA energy estimation 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 ?







- 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.**

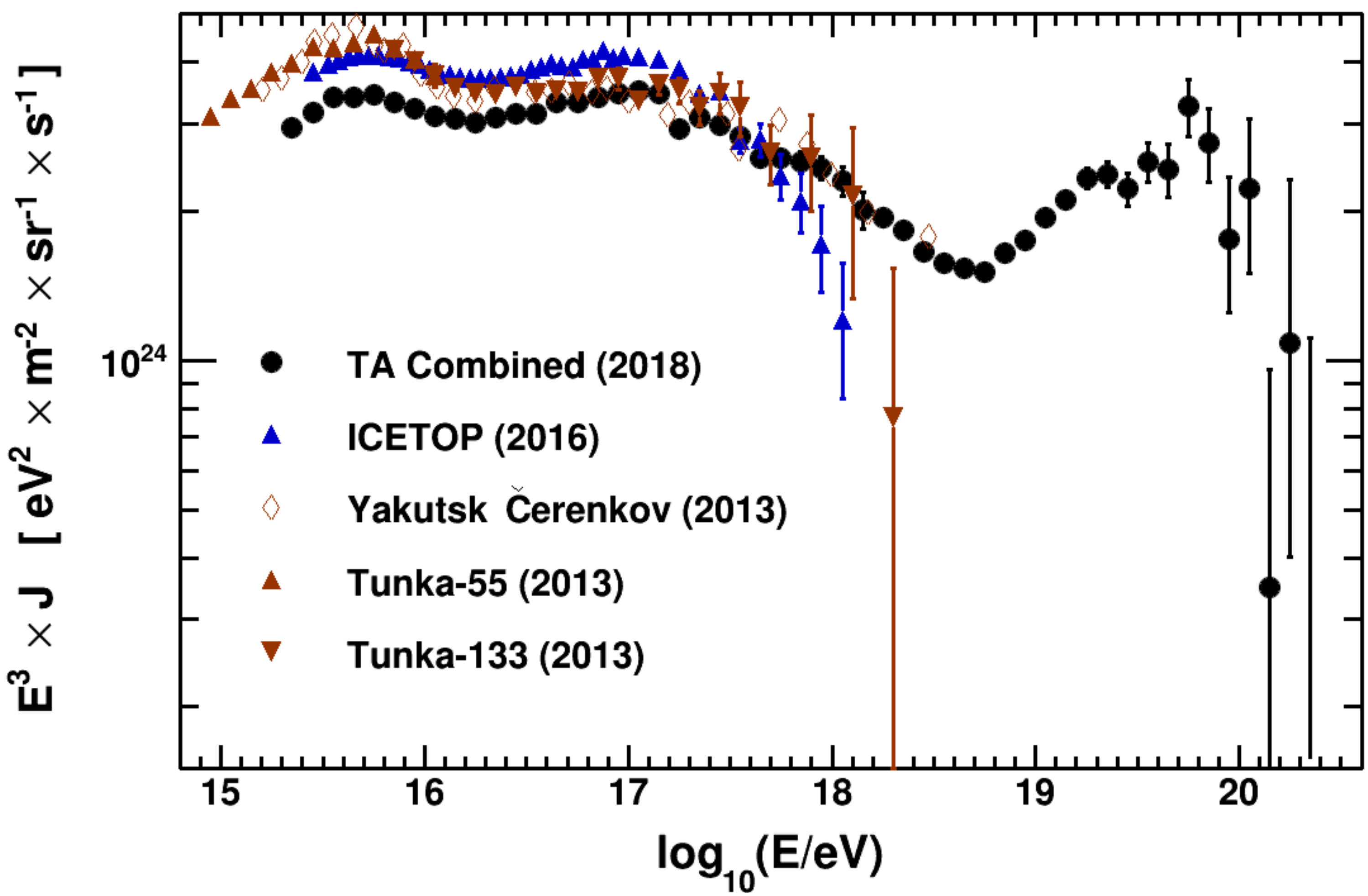
→ For the TA - Auger spectrum working comparison purposes we will mostly use TA spectra in the TA-Auger common declination band, -15°, 24.8°

Summary

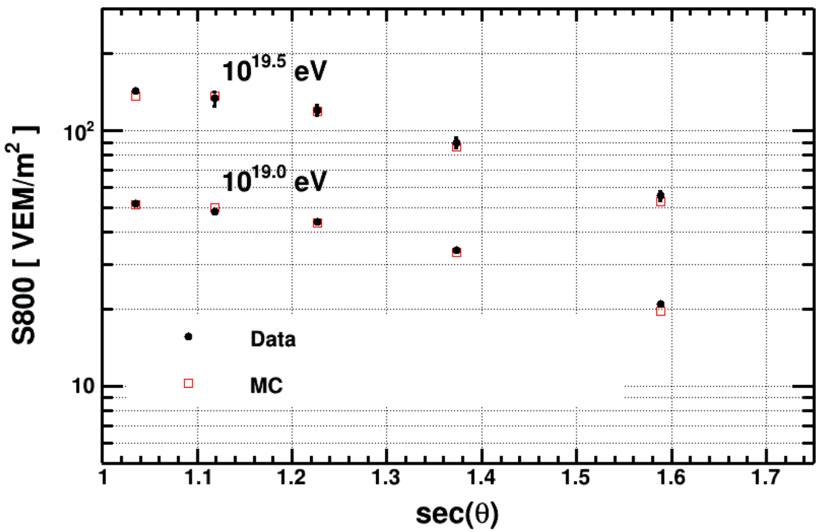
- TA uses advanced simulation and reconstruction techniques, TA Monte Carlo carefully validated by comparisons with the data.
- TA SD spectrum shows indications of anisotropies above 10^{19} eV, see TA anisotropy talk (see contributions by K. Kawata, J.P. Lundquist, A. di Matteo et al.)
- TA SD spectrum is robust and it has been checked by reconstructing TA SD energies using either Monte Carlo or constant intensity cuts methods
- TALE has extended sensitivity of TA by 3.5 orders of magnitude, see TALE talk (see contribution by T. AbuZayyad and C.C. Jui)
    - Low energy ankle at $10^{16.22}$ eV, and the second knee at $10^{17.04}$ eV all consistent with He, Fe Peters cycle.
- TA X 4 extension is under construction, it will increase statistics above 10^{19} eV that is needed for the spectrum, mass composition, and anisotropy measurements
- For the further comparisons with Auger, see the TA-Auger spectrum working group talk.

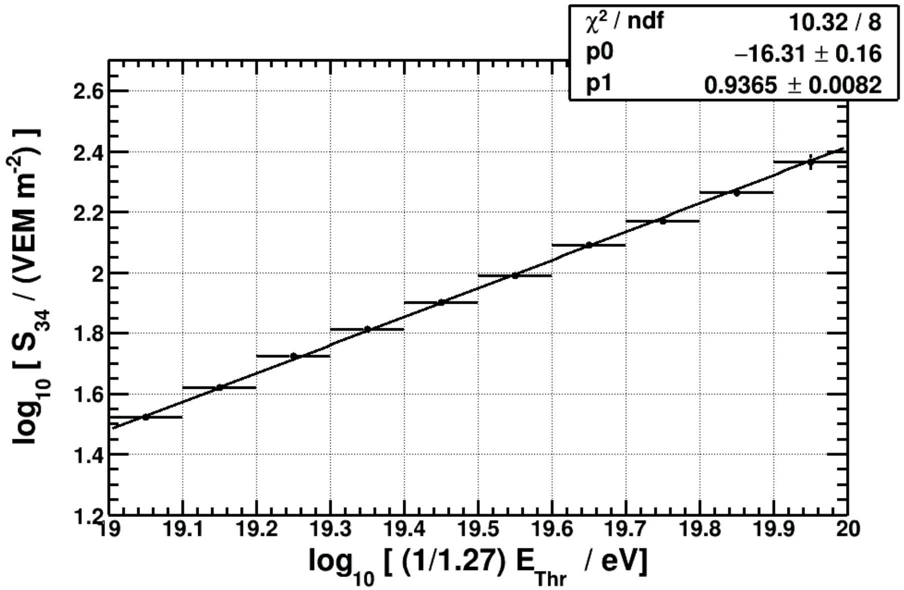
Back up slides

TA, ICETOP, Yakutsk, and Tunka



Check constant intensity cuts method using TA SD Monte Carlo

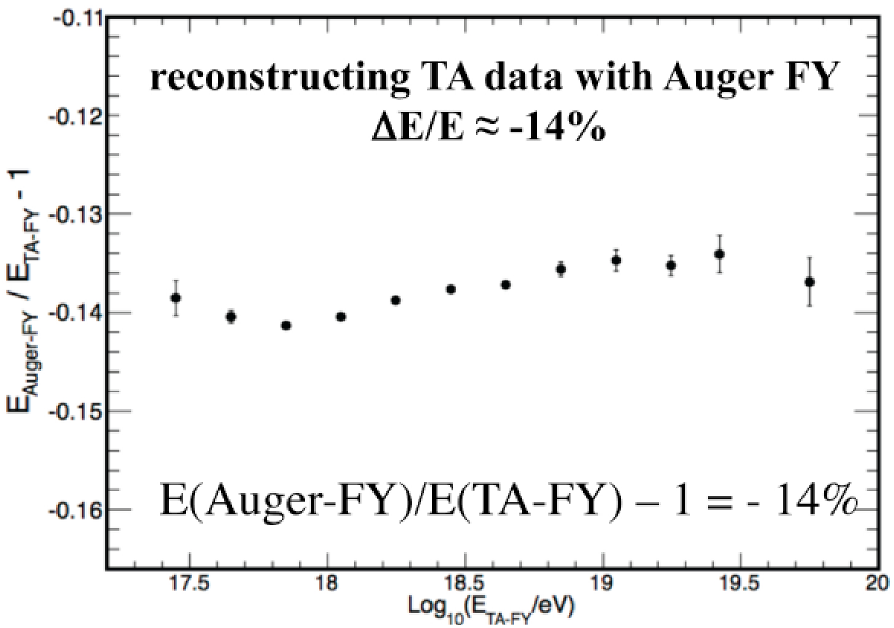


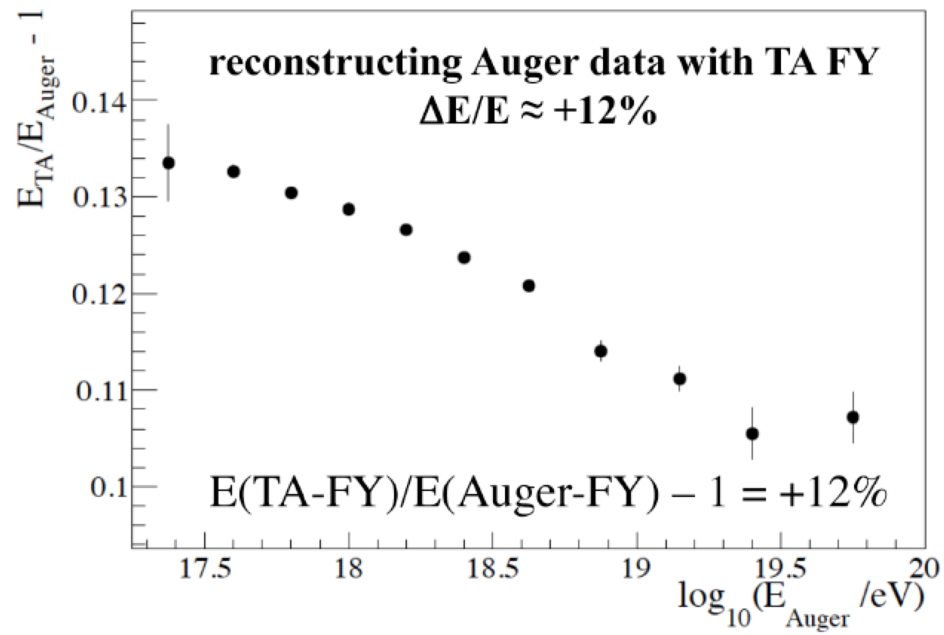


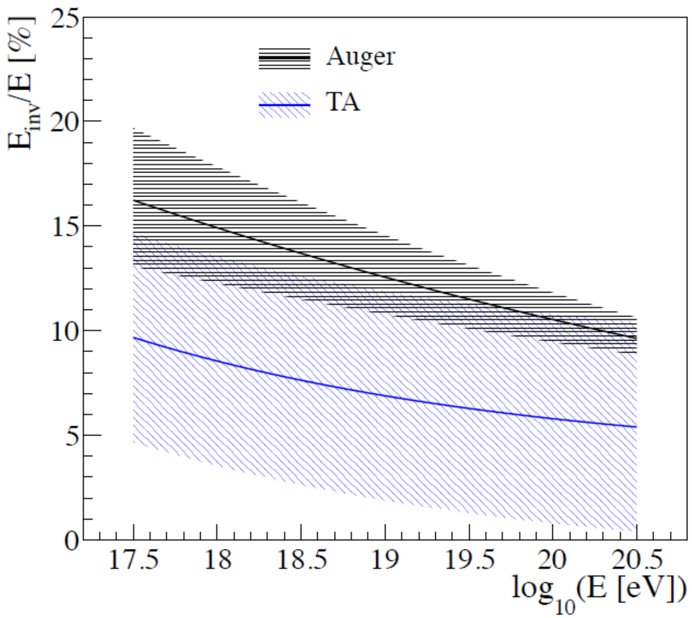
LEFT: **TA SD Monte Carlo** has the same CIC attenuation as the **data**

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

More FD checks



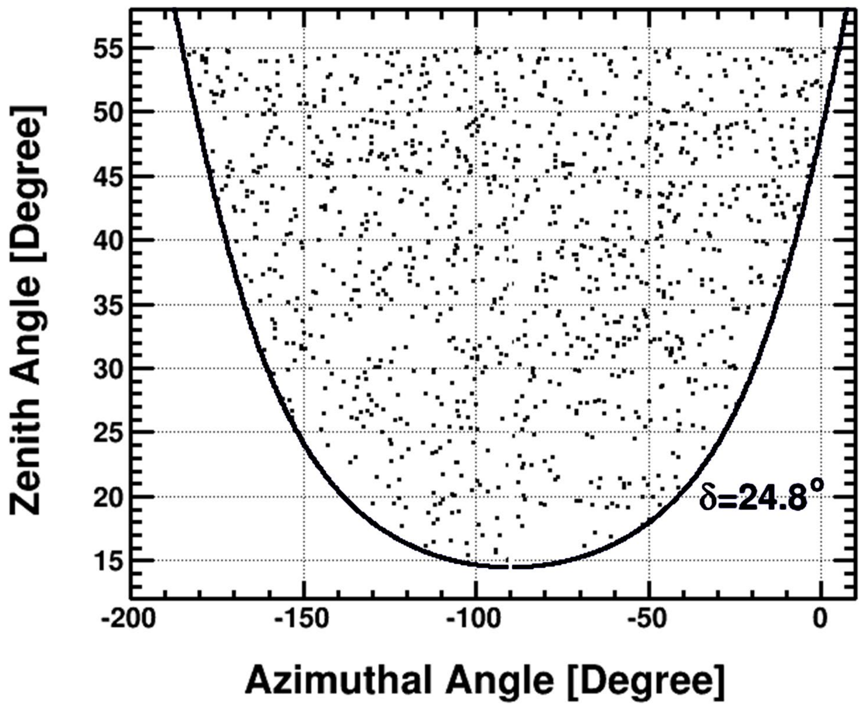




- UHECR 2016: It was shown that non-linearity effects of the fluorescence yield and missing energy correction are within 1% per decade above 10^{19} eV

SD Spectrum Declination Dependence Checks

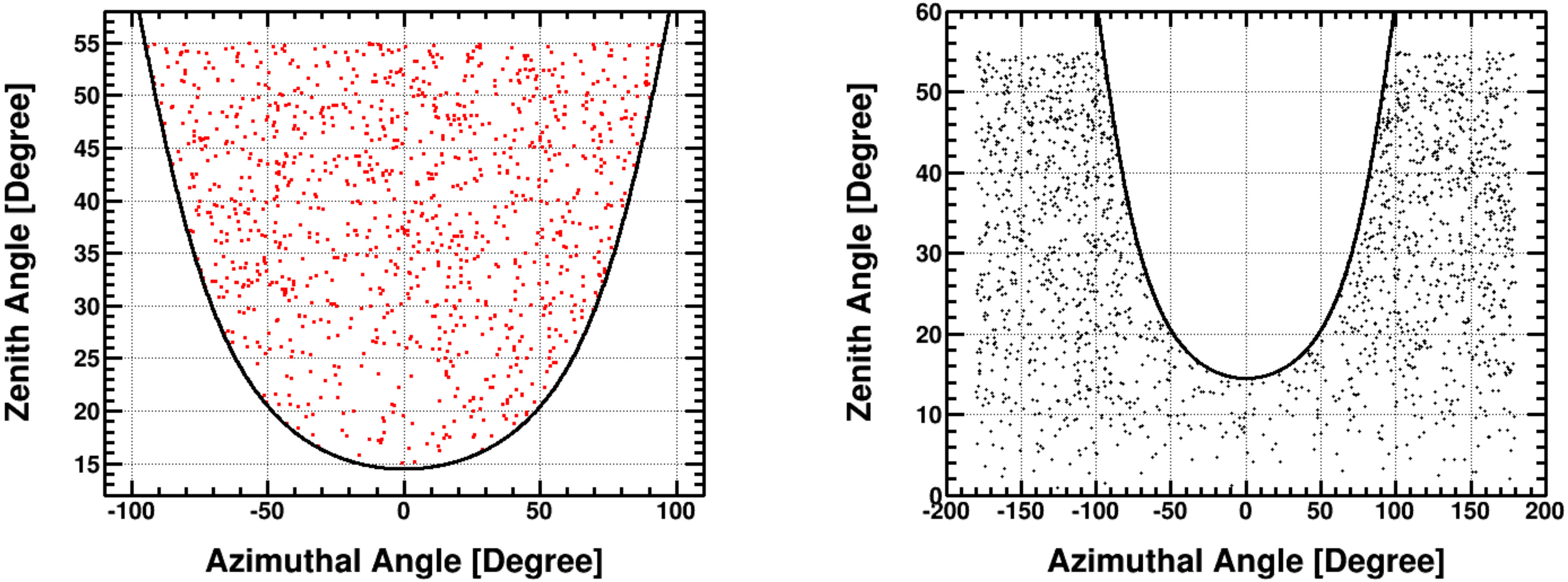
Check by cutting on theta vs phi phase space (1/4)



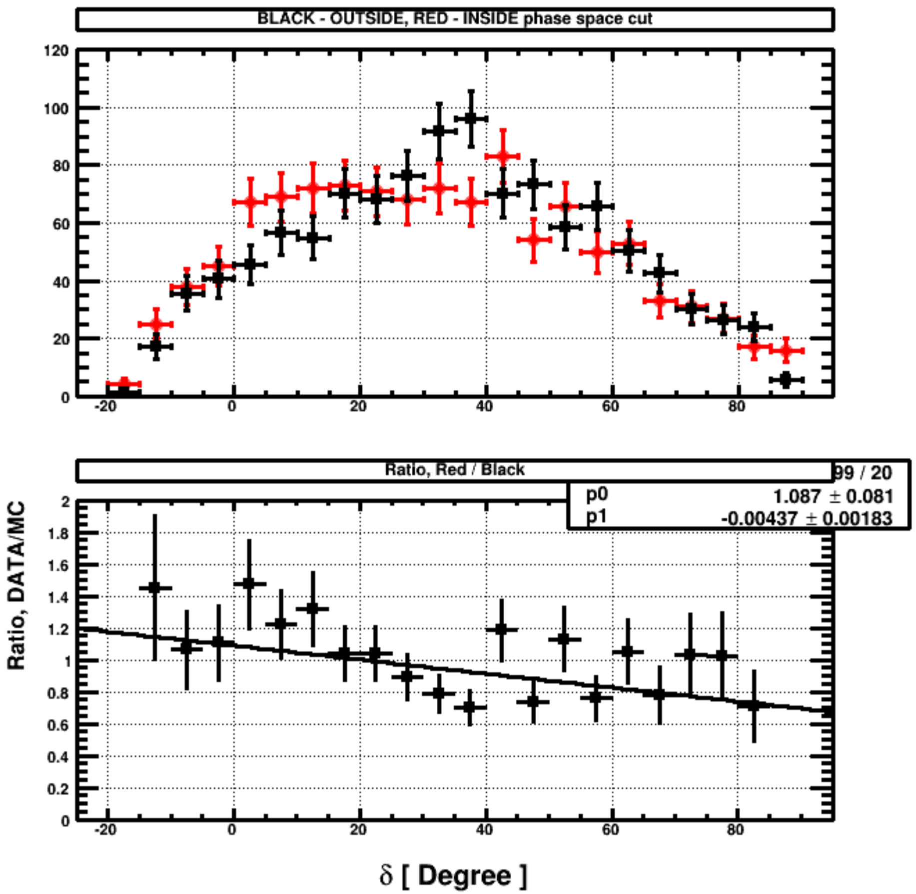
- Cutting on points above and below the contour line is mathematically equivalent to cutting on declination below and above 24.8^o, respectively

Check by cutting on theta vs phi phase space (2/4)

- Artificially move the curve by +90 degrees to the right in phi. Call the data sets inside the u-shaped region **S_1** and outside the u-shape region **S_2**.
- Cutting on points above and below the blue line will not be the same thing as cutting on declination below and above 24.8 degrees.

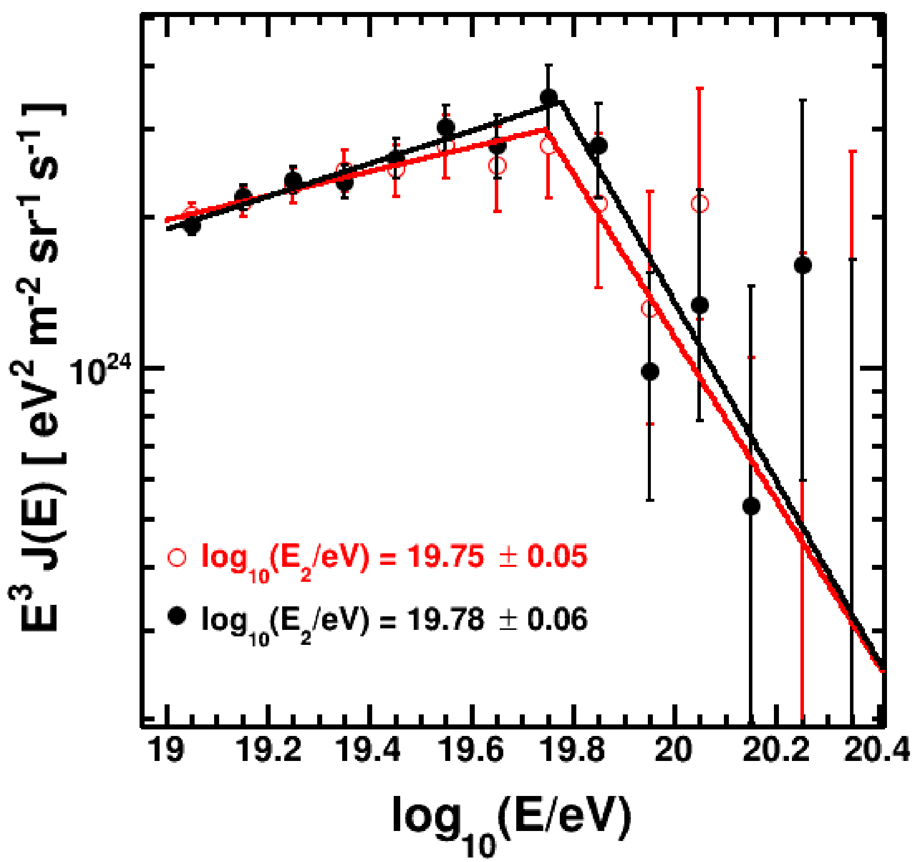


Check by cutting on theta vs phi phase space (3/4)



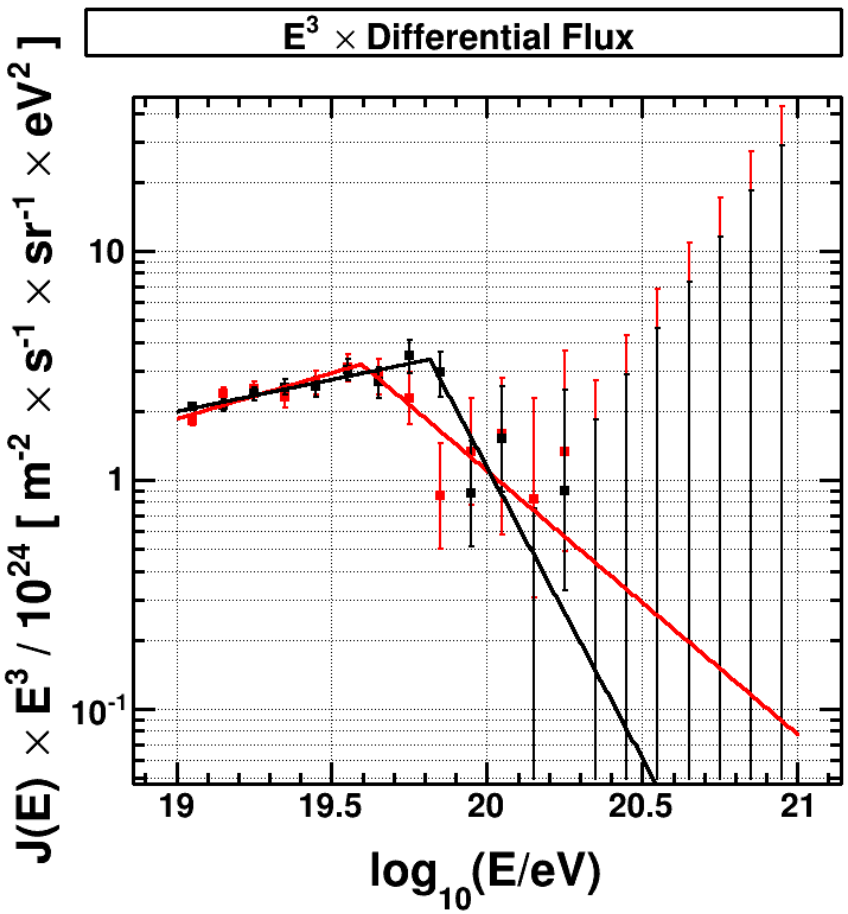
- Declination histograms of the two sets of events (S_1 and S_2) are nearly similar
- If the effect is due to cutting on declination and there is no instrumental effect associated with cutting on theta, phi, the energy spectrum should be the same for the two data sets.

Check by cutting on theta vs phi phase space (4/4)



- Result: spectra made using these data sets (S_1 and S_2) are consistent with each other and with the full sky TA SD spectrum: 2nd break point occurs at $10^{19.75}$ eV

Declination dependence of the spectrum without the TA Hot Spot



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