Auger-TA Energy Spectrum Working Group Report

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TA-Auger Spectrum Working Group Effort

1. UHECR 2010, Nagoya, Japan. Formed a working group aimed to compare and cross check the spectrum results.
2. UHECR 2012, Geneva, CERN. Auger and TA successfully cross-checked their methods for the first time.
3. UHECR 2014, Springdale, UT, USA. Detailed discussion of the energy scale systematic uncertainties. First discussions on searching for spectrum declination dependence.
4. UHECR 2016, Kyoto, Japan. Auger and TA spectra compared in the same region of sky (aka “common declination band”) for the first time.
5. ICRC 2017, Busan, Korea: A more systematic comparison of Auger and TA spectra in the common declination band using refined methods
6. **Now: checking TA and Auger spectra calculations using different techniques to understand the difference between Auger and TA in the common declination band**

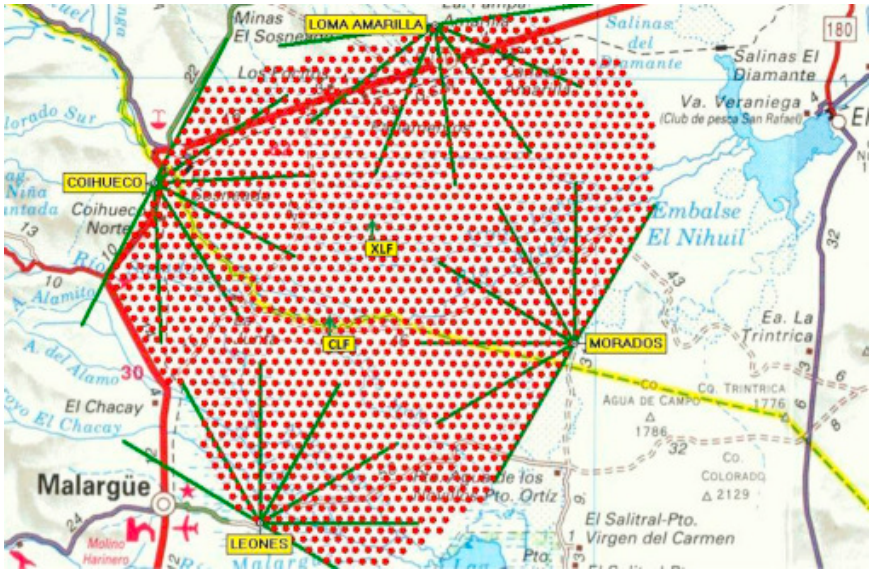
Outline

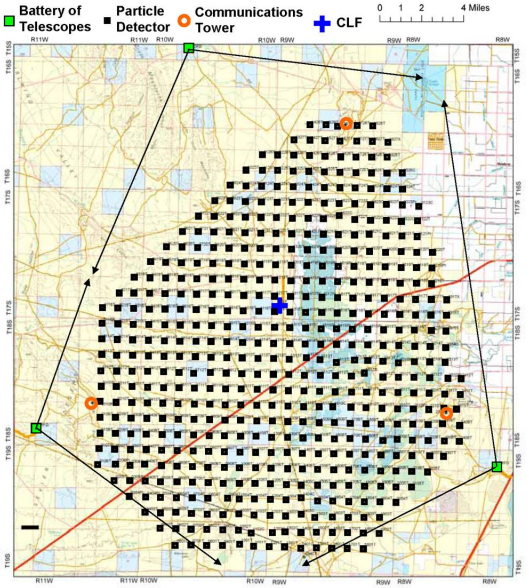
- Energy reconstruction methods of TA and Auger
- Energy scale of TA and Auger
- TA and Auger spectra in the common declination band
- Sources of possible energy nonlinearities for TA and Auger
- Check of TA and Auger spectrum calculations using alternative methods
- Summary and Outlook

TA and Auger Surface Detectors

Pierre Auger: **3000 km²**

Telescope Array: **700 km²**

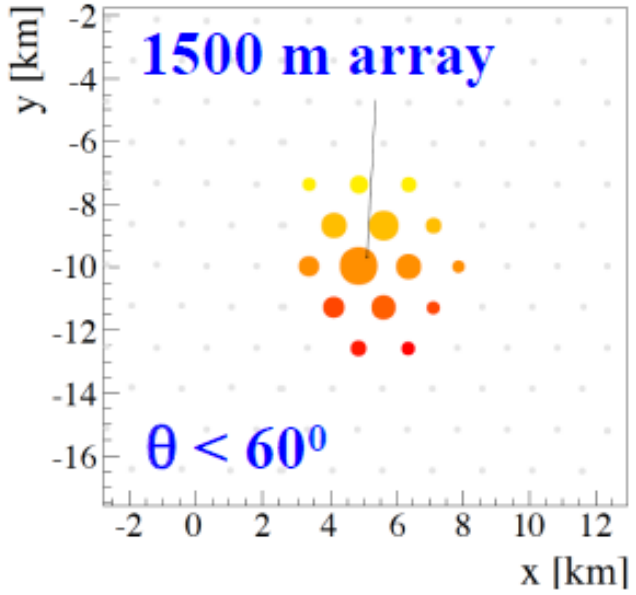


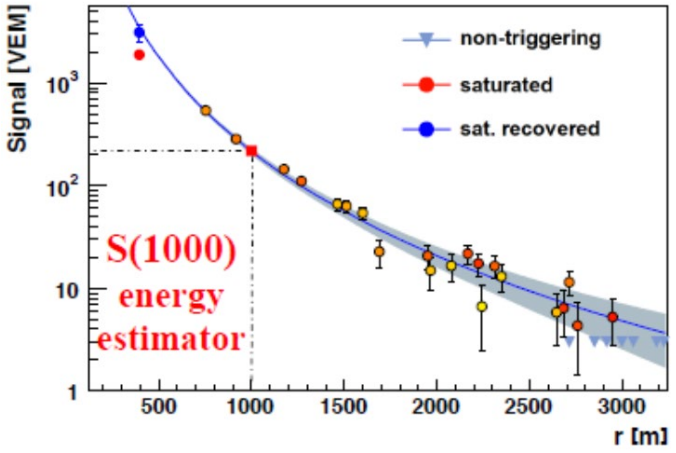


(not drawn to scale)

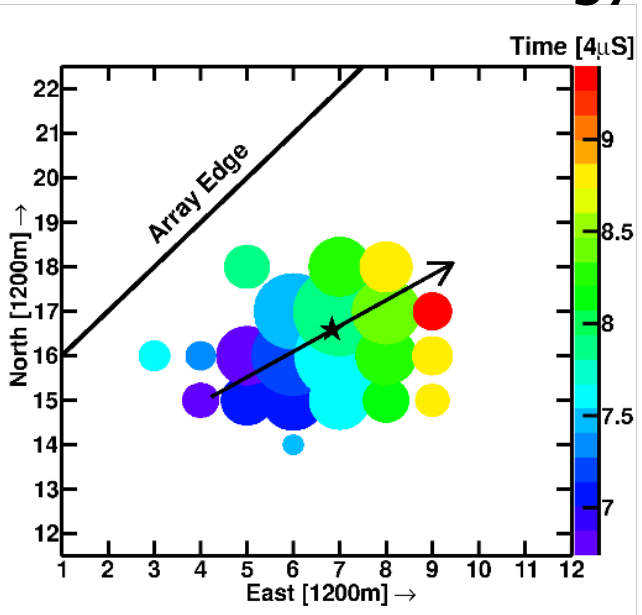
Surface Detector Event

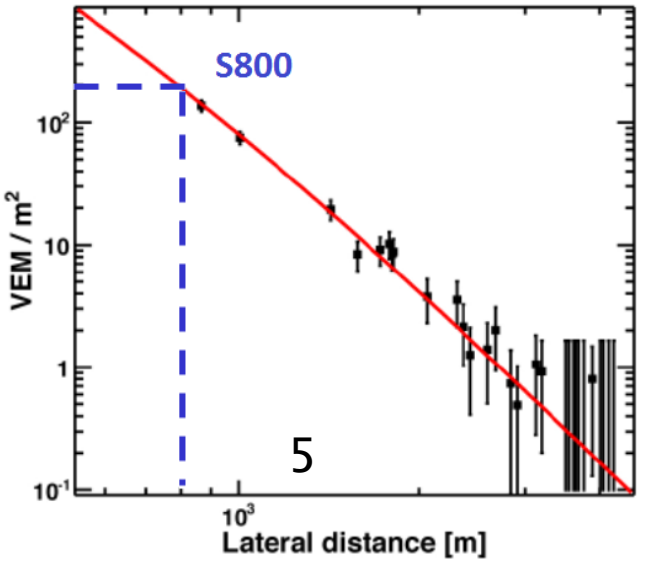
Auger: S1000-> event energy



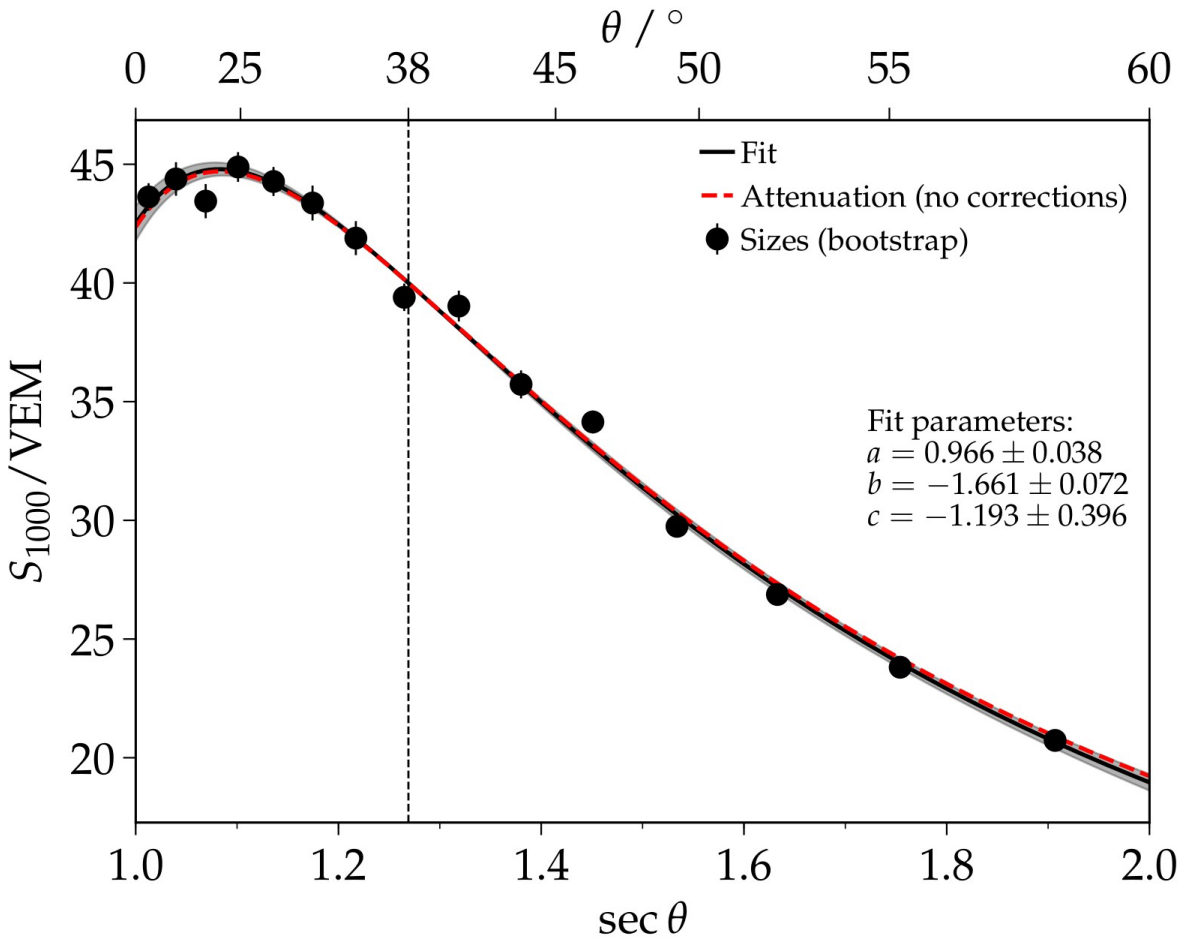


TA: S800 -> event energy



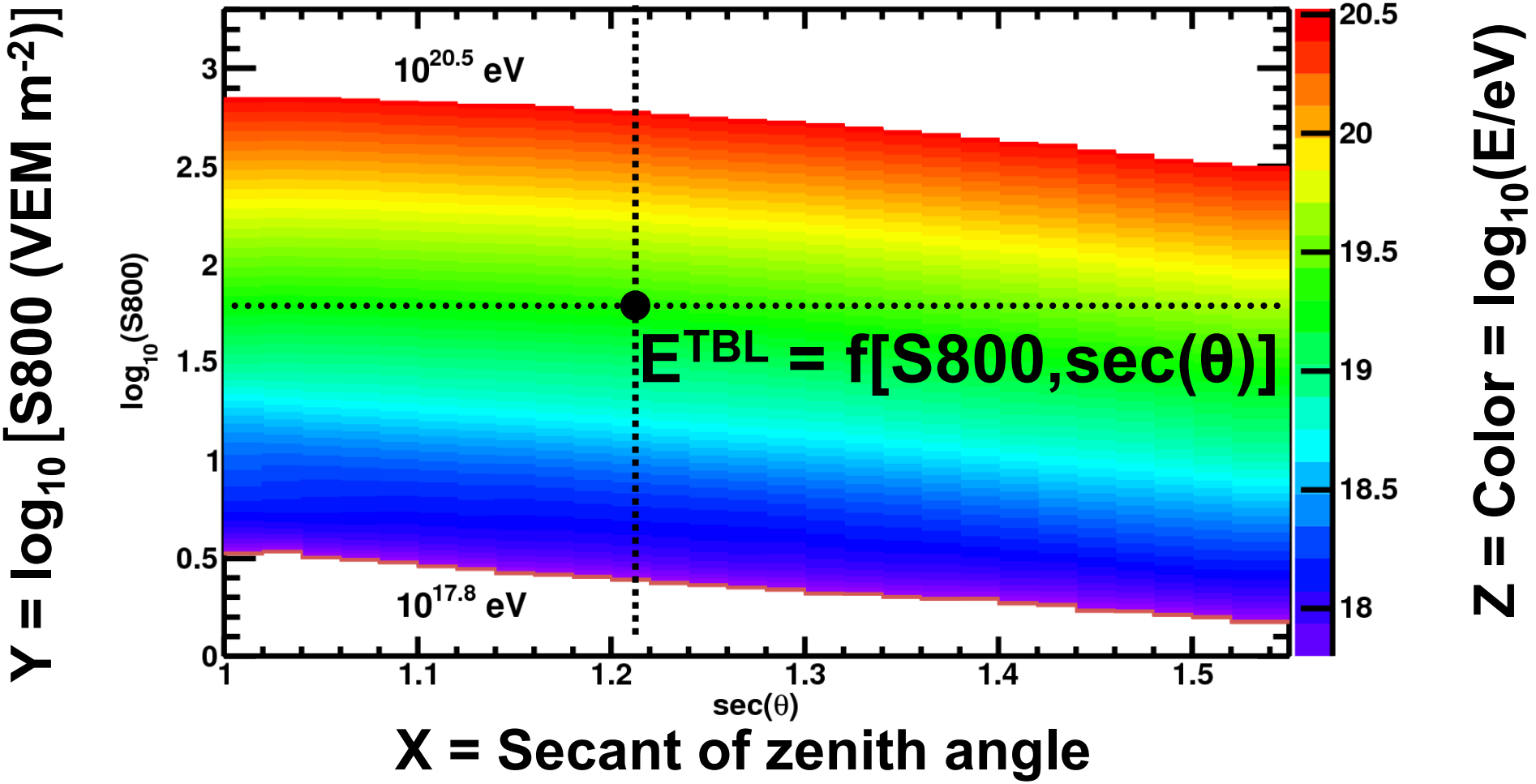


Auger: Energy Estimators Using Constant Intensity Cut Method



- S_{38} is S1000 for the shower if it had arrived at 38° in zenith angle

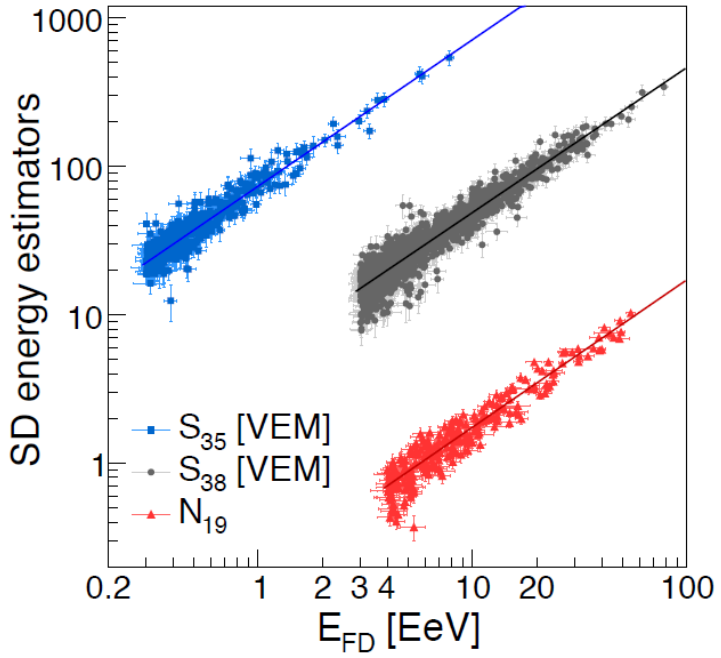
TA: Initial Energy Estimate from Monte Carlo

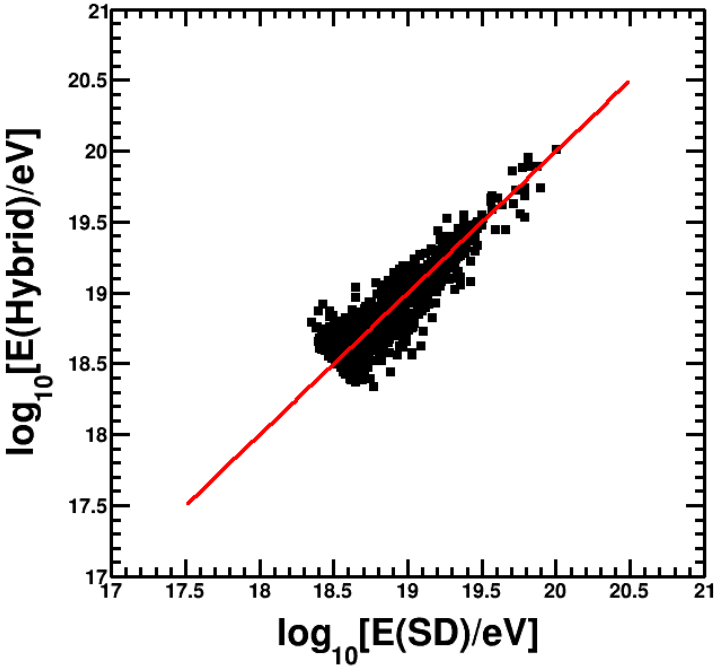


- Look-up table made from the Monte-Carlo
- Event energy (E^{TBL}) = function of *reconstructed* S800 and sec(θ)
- Energy reconstruction ←→ interpolation between S800 vs sec(θ) contours of constant values of E^{TBL}

Energy Scale

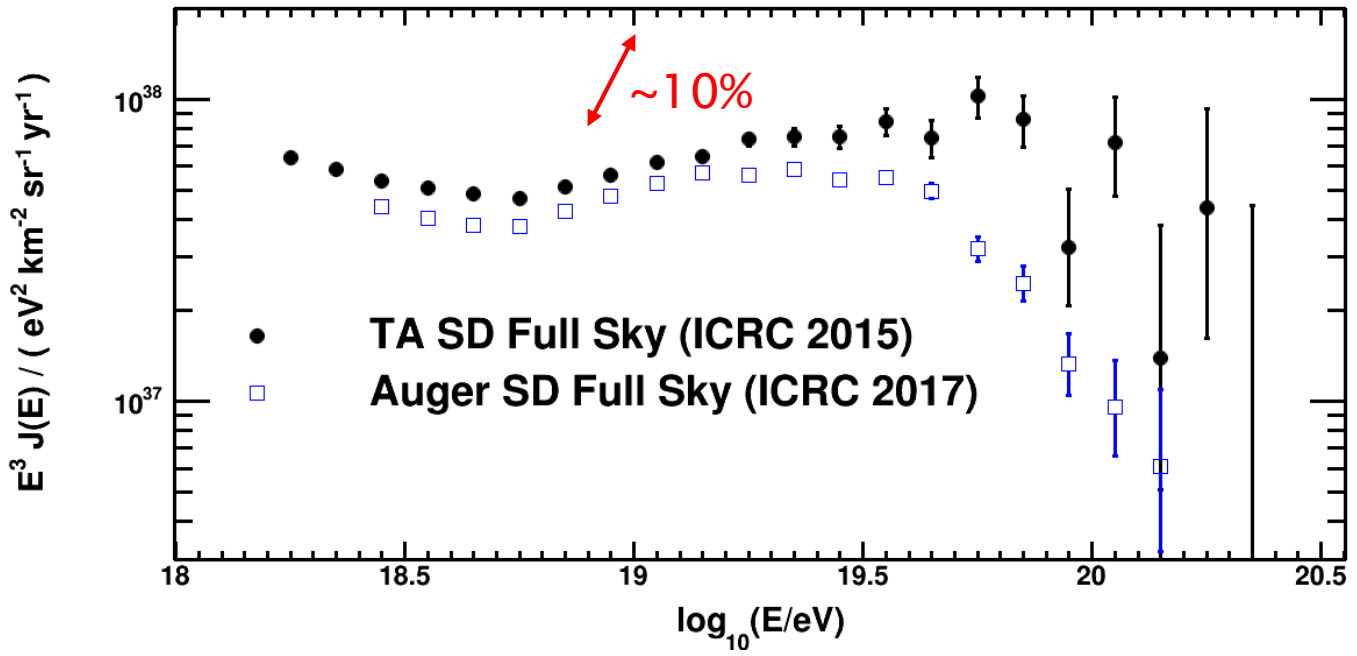
$$E = A\,(S_{38})^{B}$$





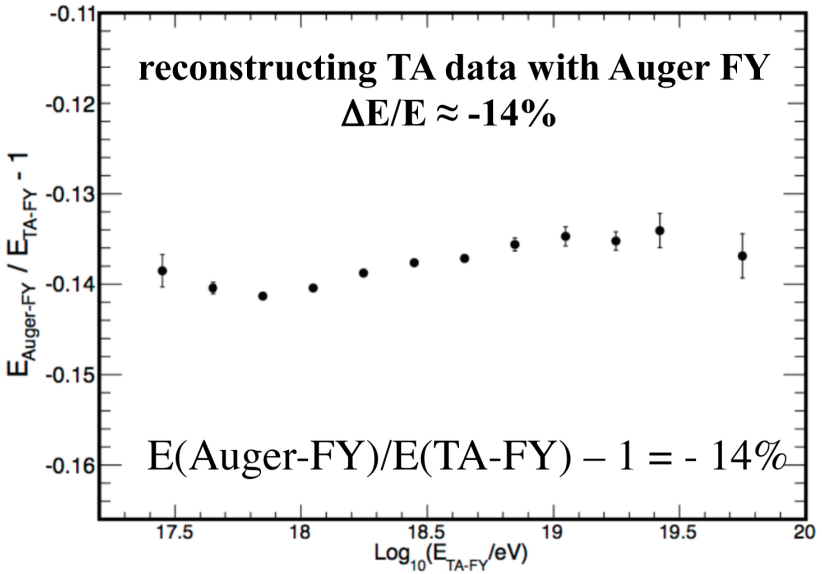
- Calibrate SD energy scale to that of fluorescence detectors (FD) using hybrid events => energy scale systematic uncertainty is that of the FD.
  - Auger: Apply constant intensity cut method to get S_{38} from S1000, then calibrate S_{38} to FD
  - TA: Initial energy estimate from (S800, zenith angle) using Monte Carlo then calibrate energy scale to FD

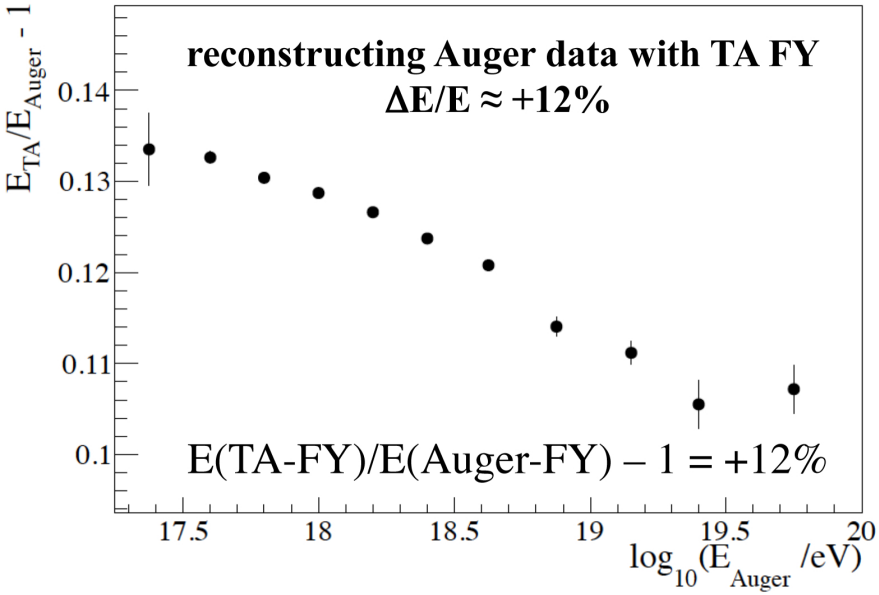
Auger and TA Surface Detector Spectra

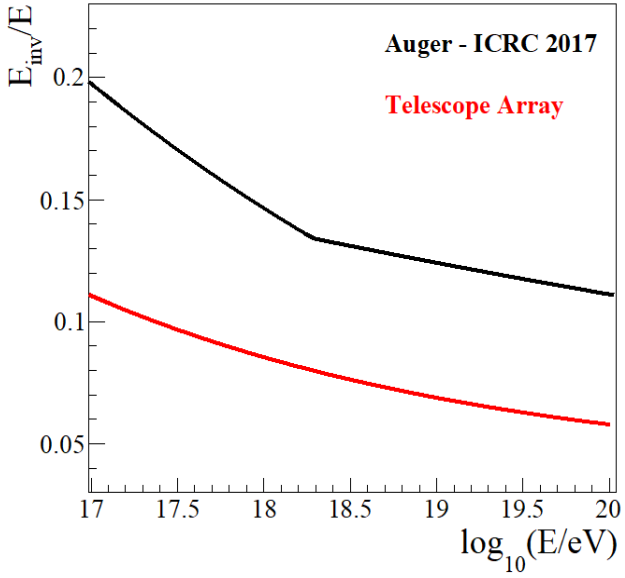


- Ankle at ~3 EeV, cutoff at ~40 to 60 EeV
- ~10% energy scale difference around ankle region
- **Large discrepancy in shape at E > ~$10^{19.4}$ eV**
  - Systematic uncertainties, reconstruction biases?
  - Anisotropies?

Fluorescence Yield and Missing Energy Correction Models

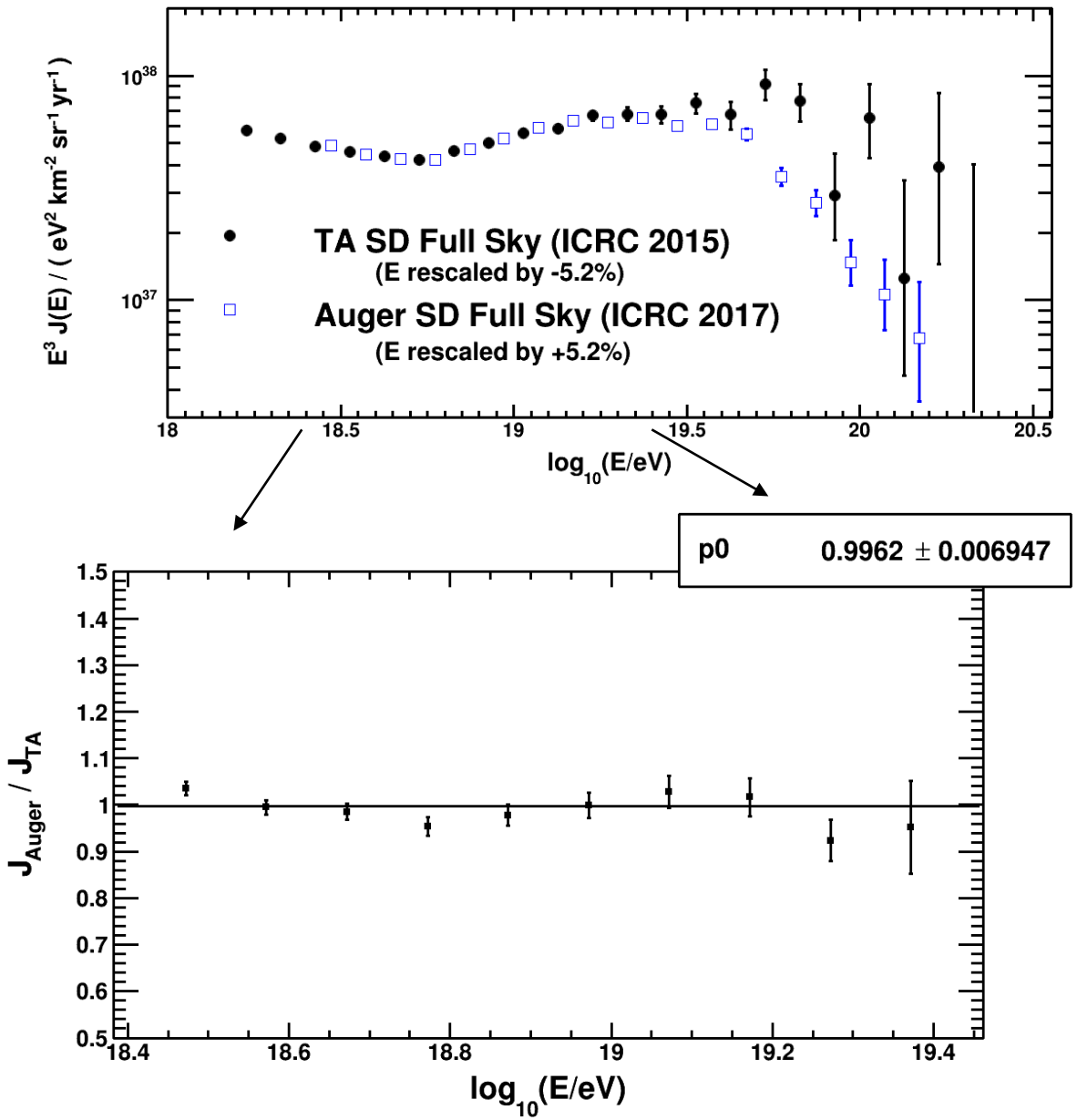






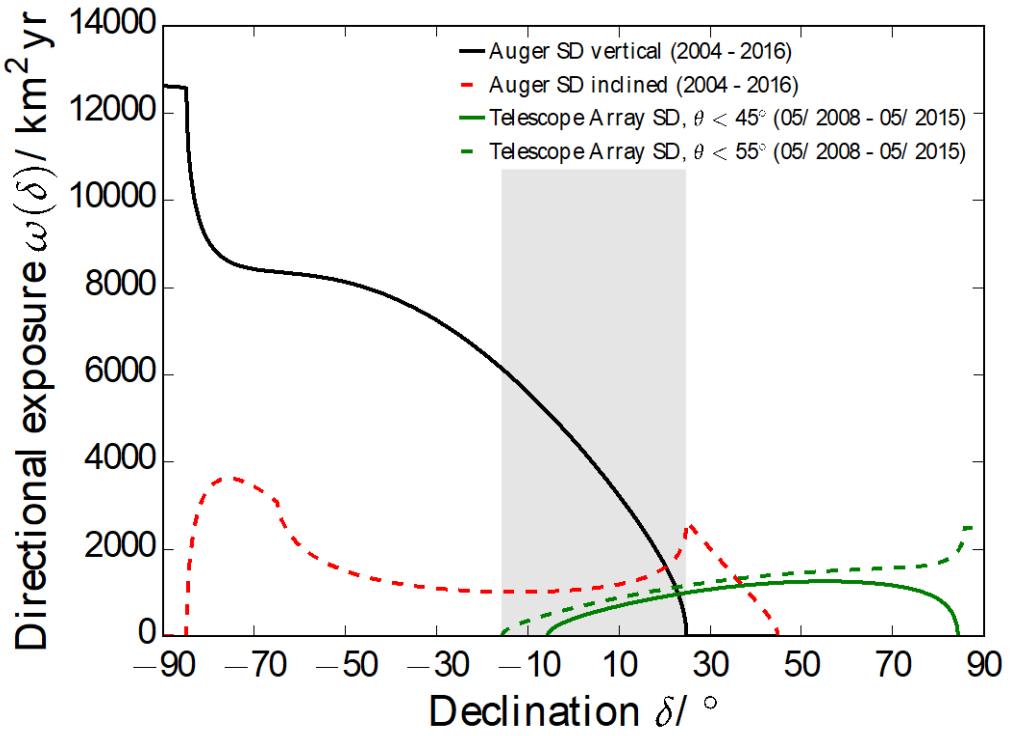
- Different fluorescence yield and missing energy correction models used
- 10% energy scale shift well within stated 14% (Auger) and 21% (TA) energy scale systematic uncertainties
- **Energy dependence of the shifts smaller than 1% above 10^{19} eV**

Rescale Auger and TA energies



- Constant rescaling factor of **5.2%**
  - From fitting ratio of fluxes Auger/TA into a unity in the ankle region
  - Auger energies *raised* by 5.2%
  - TA energies *lowered* by 5.2%
- Agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$eV after rescaling
- **Difference above $10^{19.4}$ eV persists after locking energy scales of experiments**

Auger-TA Common Declination Band Spectrum Analysis

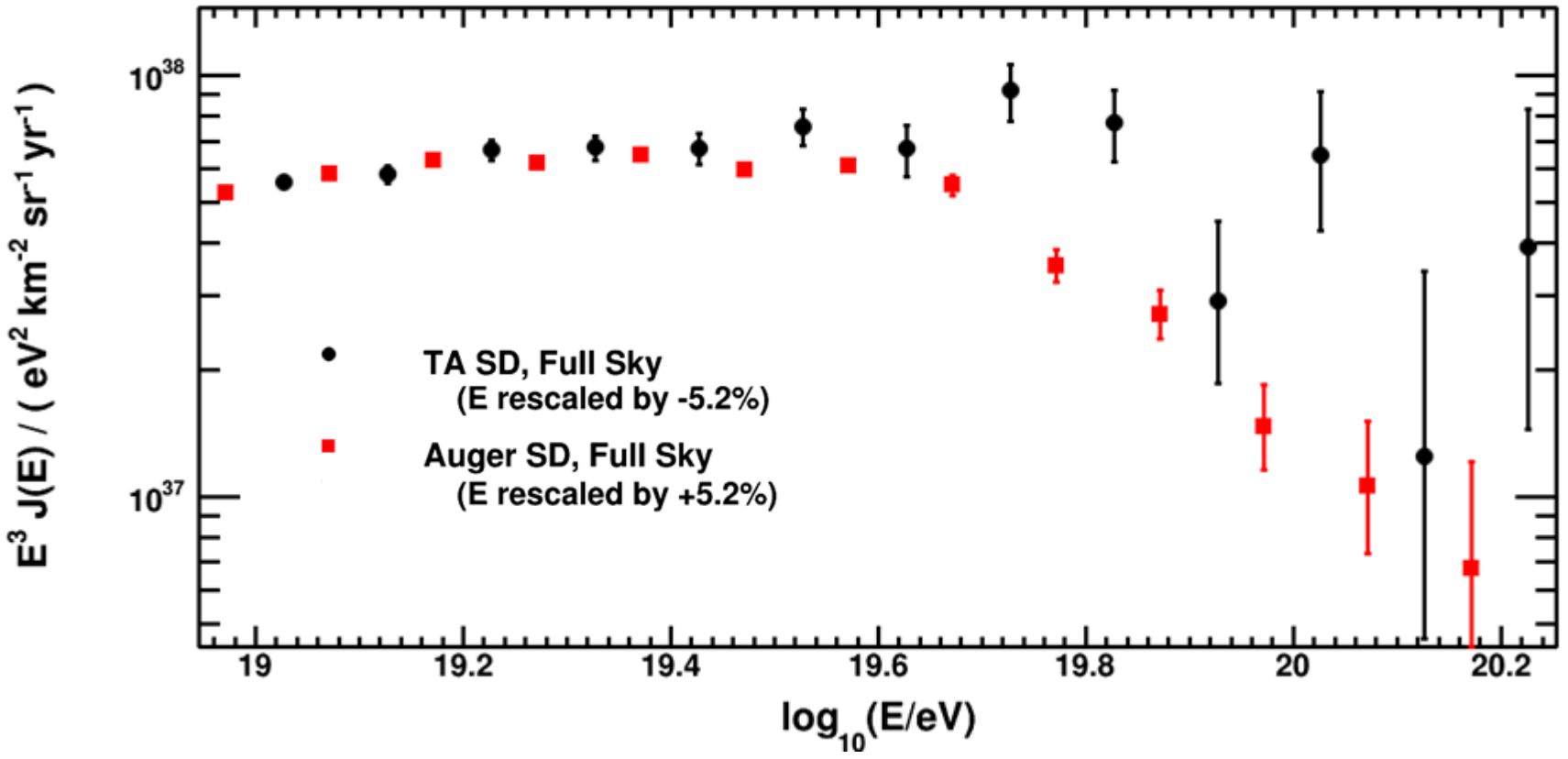


- Restrict δ to [-15º ,24.8º] range
  - Excludes TA hot spot
- Independence of exposure on declination (aka "1/ω method"):

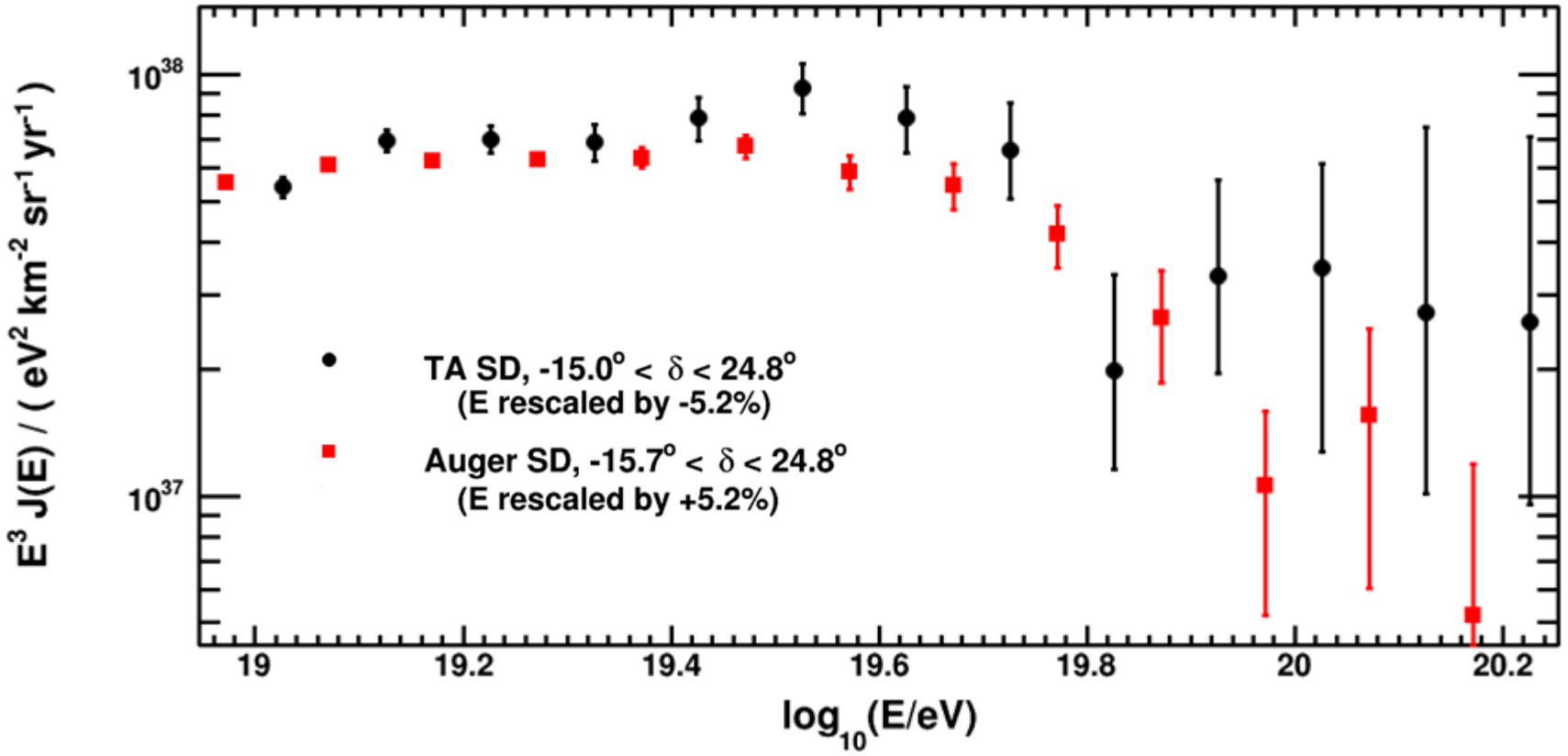
$$J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\delta_i)}$$

(UHECR 2016 proceedings)

Entire Sky Spectra

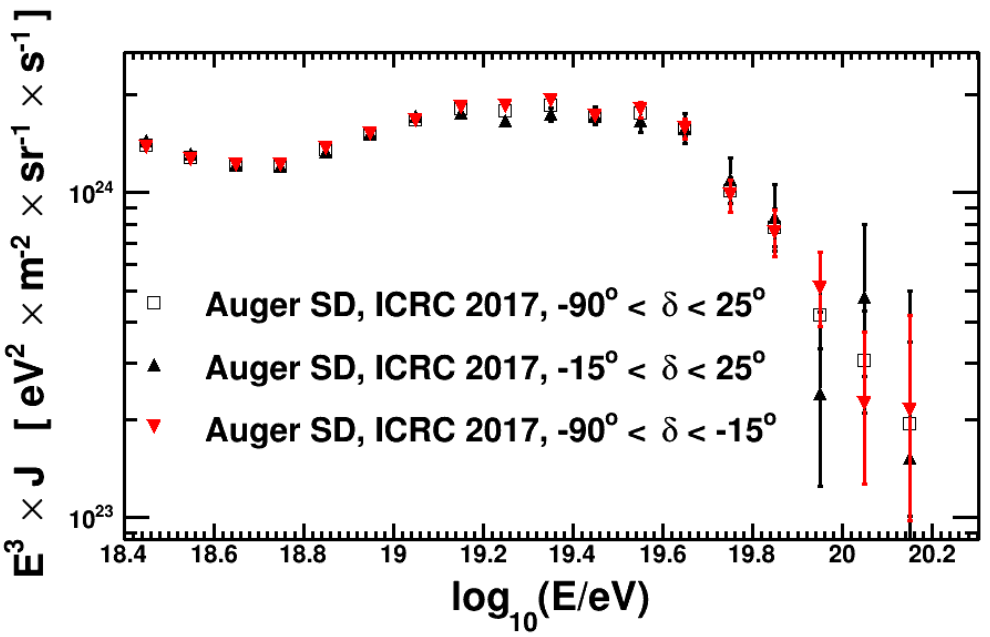


Common Declination Band

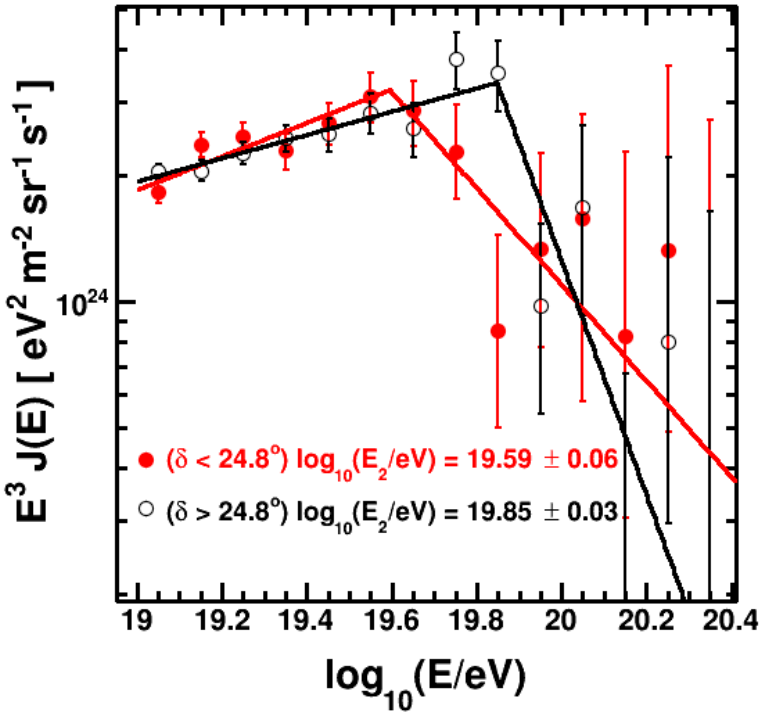


Better agreement between TA and Auger in the common declination band

Declination Dependence in TA



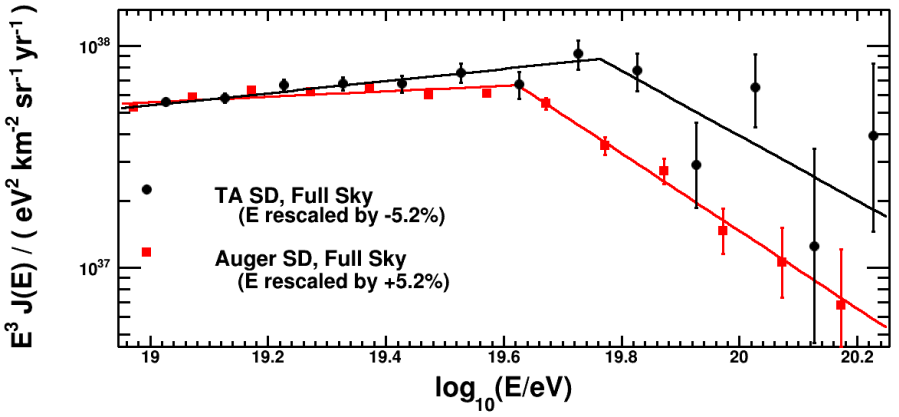
Auger: no apparent declination dependence



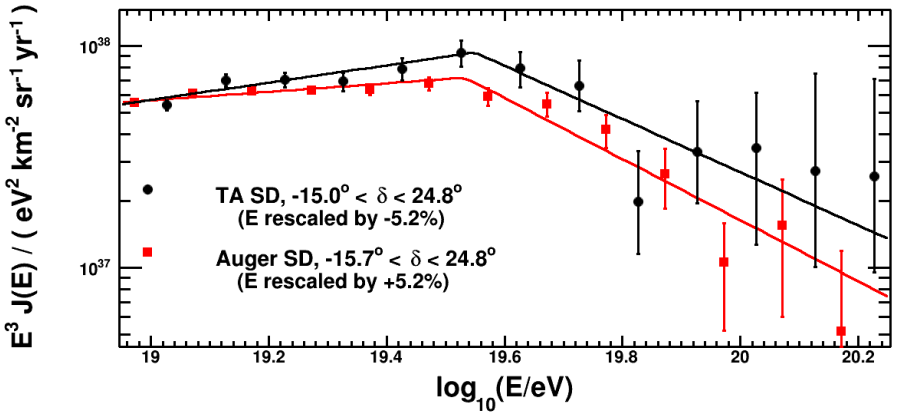
TA: Second break points above and below the declination of 24.8° are 4σ different

- 3.5σ (post-trial significance) effect in TA
- Auger sees no significant declination dependence

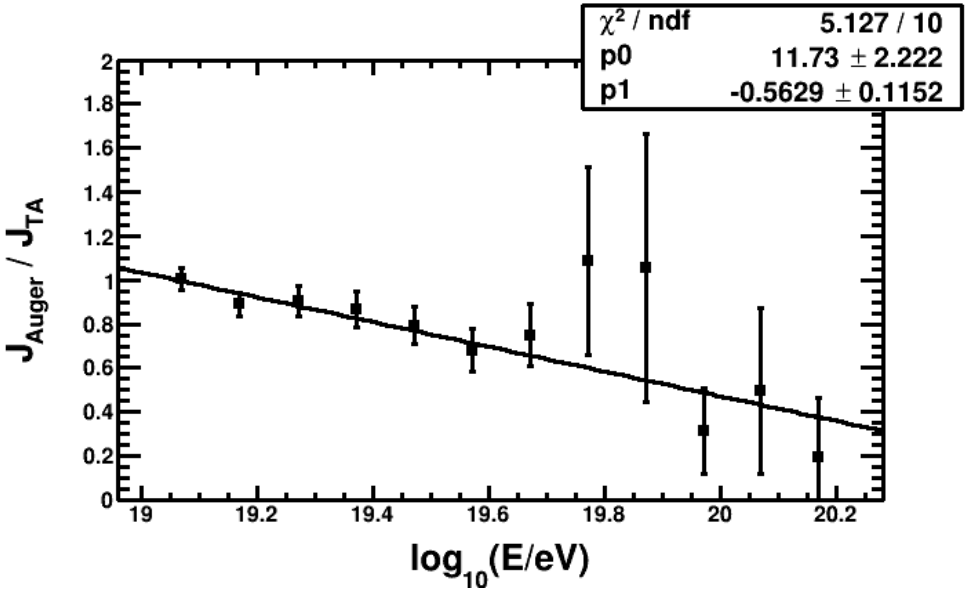
Entire skies of Auger and TA



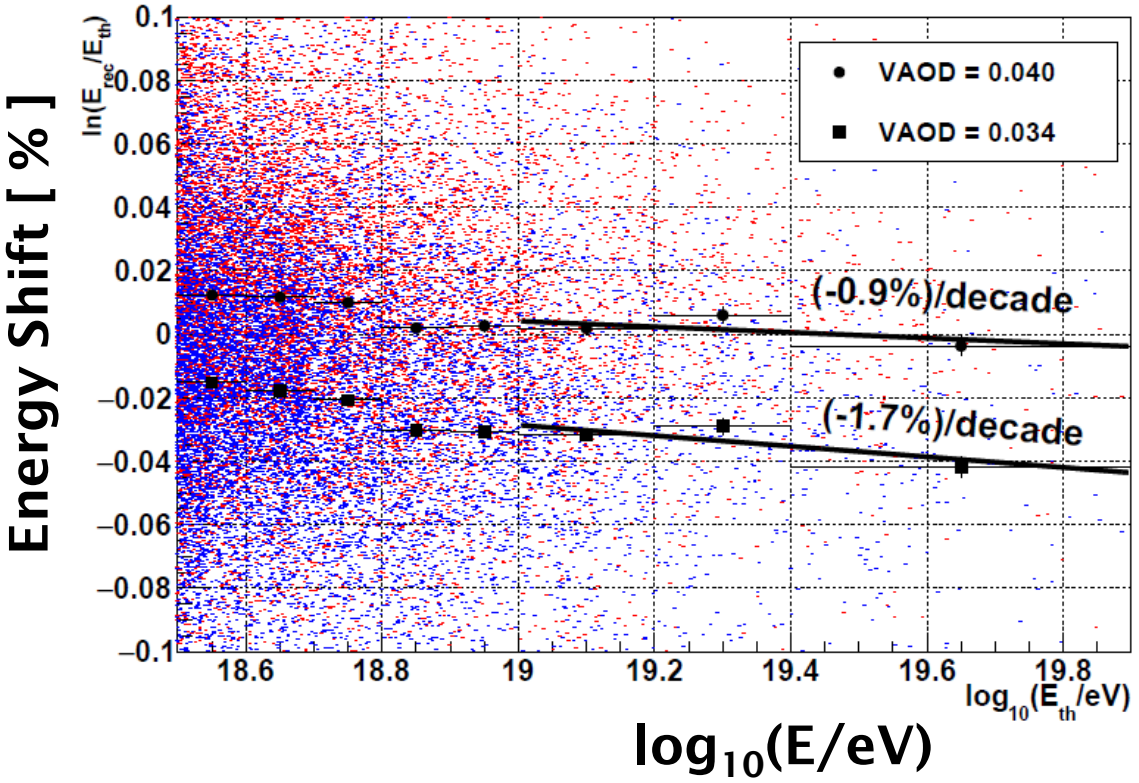
Common declination band



- Second break points are roughly in agreement in the common declination band
- Smaller but significant difference remains in the common declination band

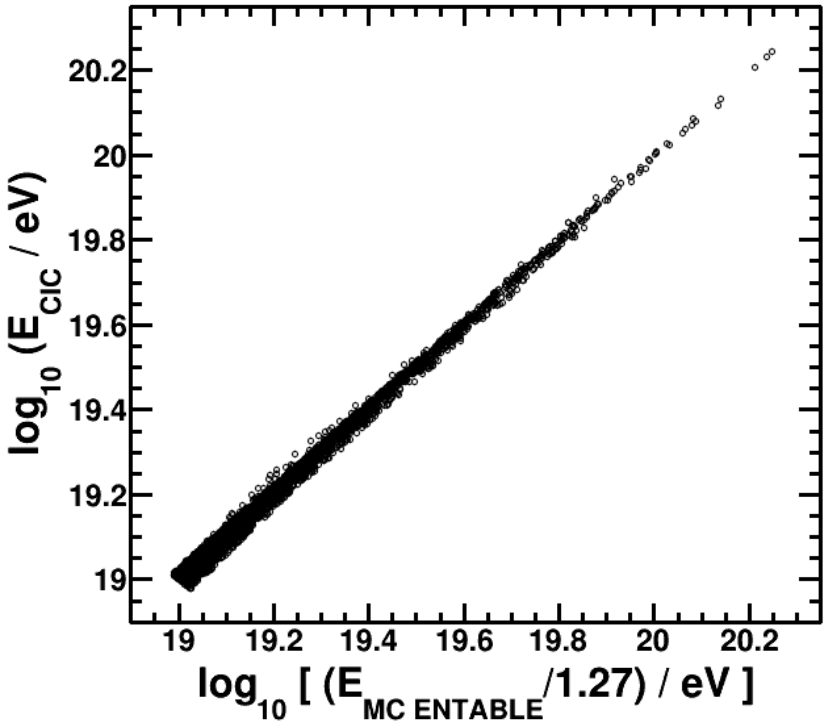


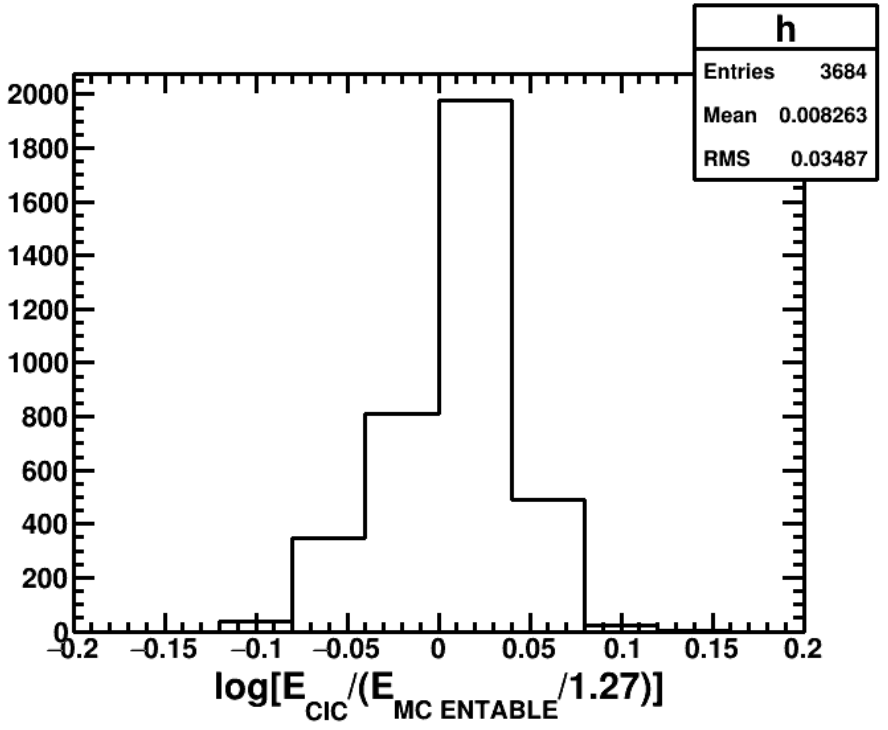
TA Energy Uncertainties Due to Aerosols



- Possible energy-dependent reconstruction bias in TA due to the aerosols is 1.7% per decade of energy in extreme scenario cases

Compare TA Constant Intensity Cut and TA Original Monte Carlo Based Energy Reconstruction Methods

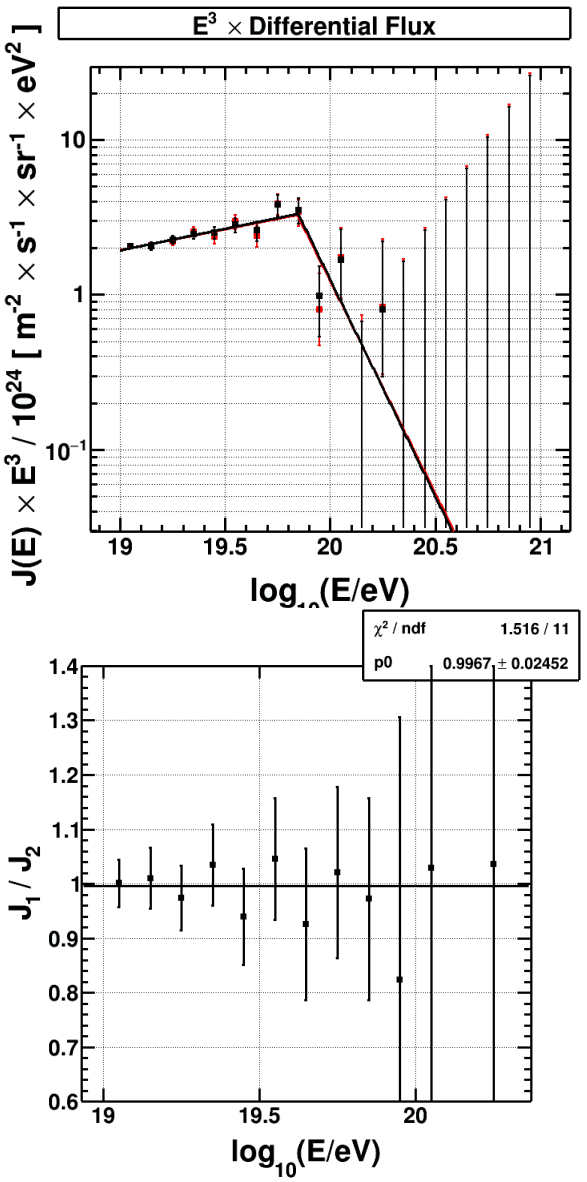




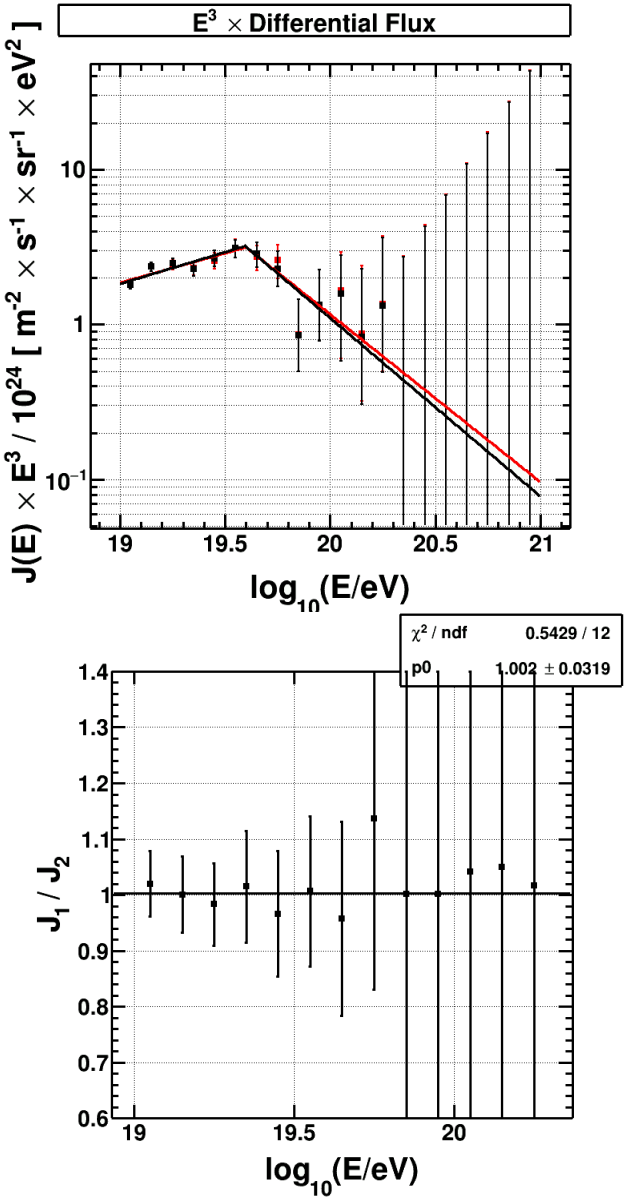
TA MC-based and Constant Intensity Cut energy reconstruction methods agree at ~3% level

Check of TA Spectrum Using Constant Intensity Cut Method

24.8° < δ < 90°



-15° < δ < 24.8°

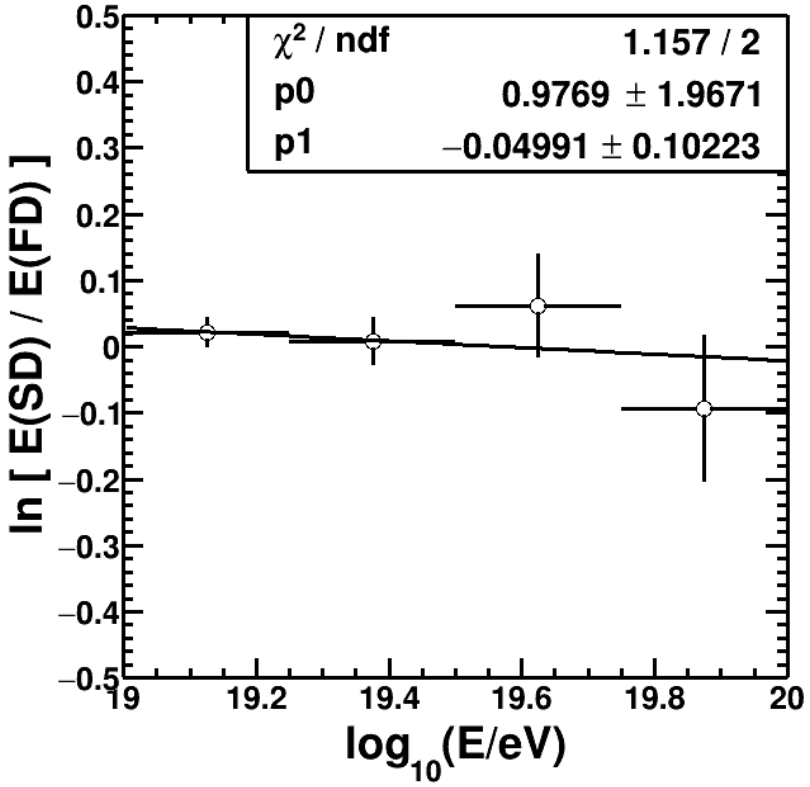


(**RED**) TA spectrum, in two declination bands, calculated using constant intensity cut method

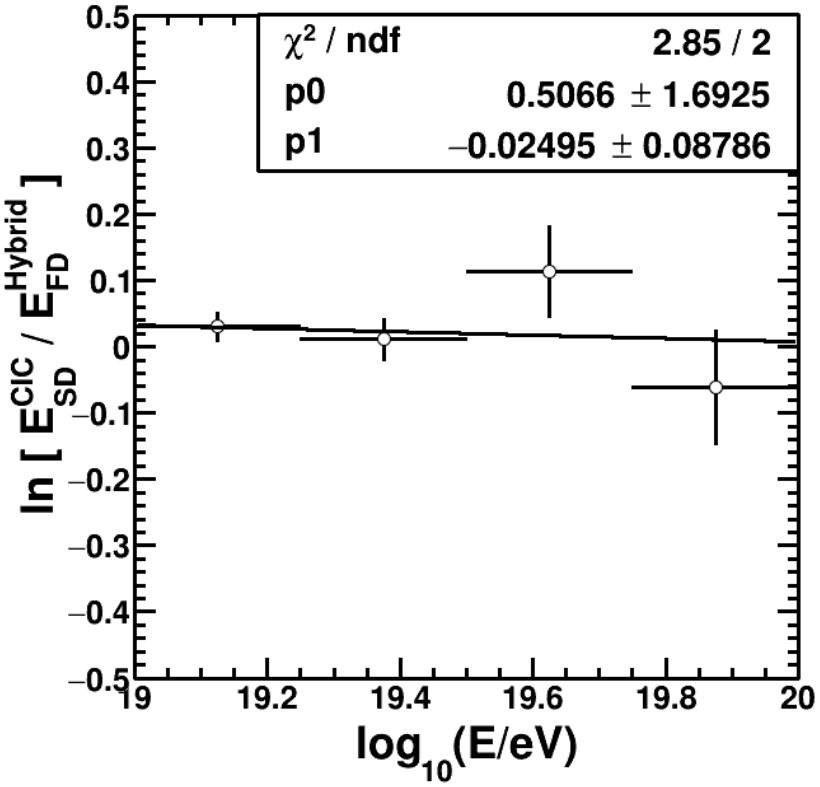
(**BLACK**) TA spectrum calculated using Monte Carlo – based energy reconstruction approach

Systematics of the TA Energy: Check SD Energies with Hybrid

TA SD Monte Carlo - based energy reconstruction



TA SD constant intensity cut - based reconstruction

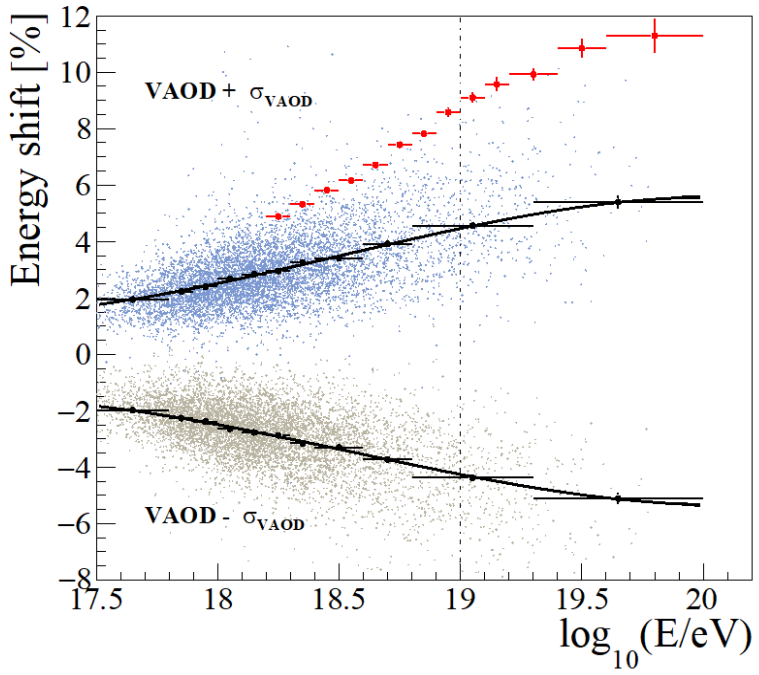


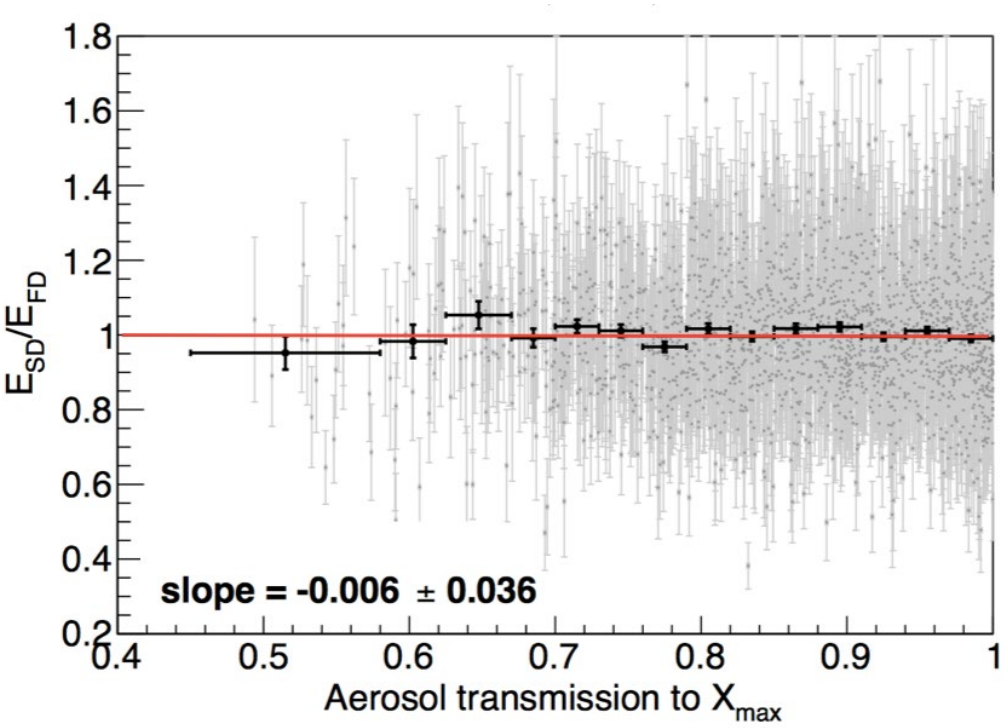
Possible TA energy - dependent energy reconstruction bias:
2 ± 9% / decade

Sources of Energy-Dependent Energy Reconstruction Bias 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%**

Auger Energy Uncertainties Due to Aerosols





Nonlinearities induced by the uncertainties on the aerosols:

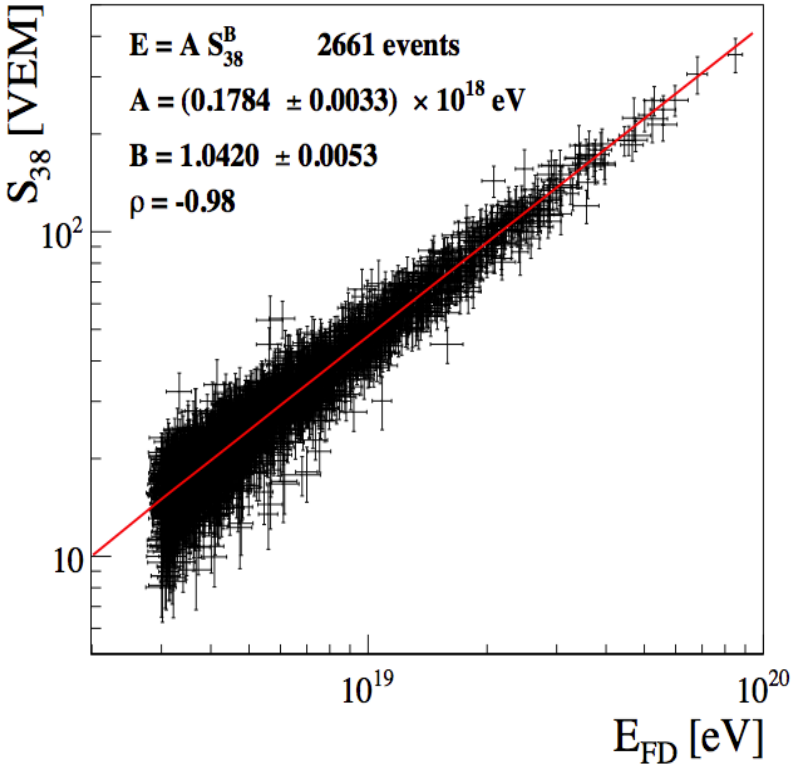
- 1% above 10 EeV
- extreme scenario: 2%

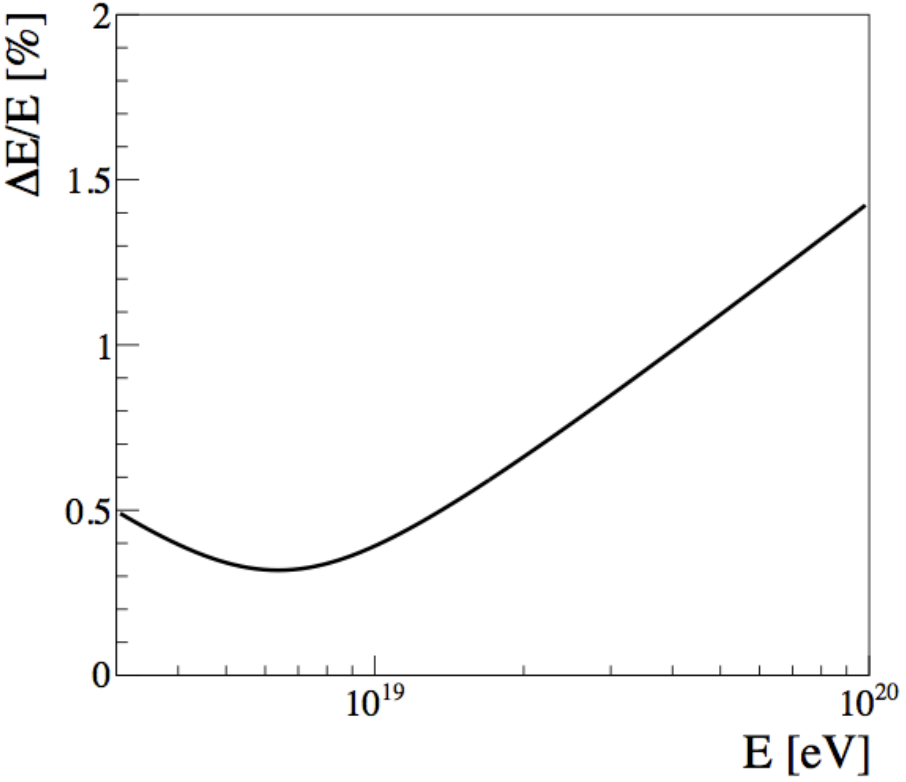
Internal consistency of the data:

- Slope compatible with 0

NB:
- Slope>0 ⇒ overestimation of the aerosols
- Slope<0 ⇒ underestimation of the aerosols

Auger Energy Calibration Uncertainties



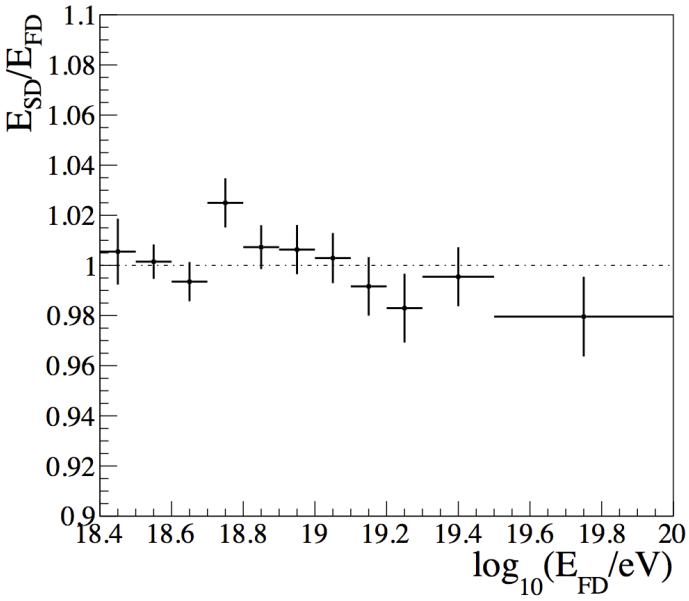


Nonlinearities from the stat. uncertainties on the calibration parameters:

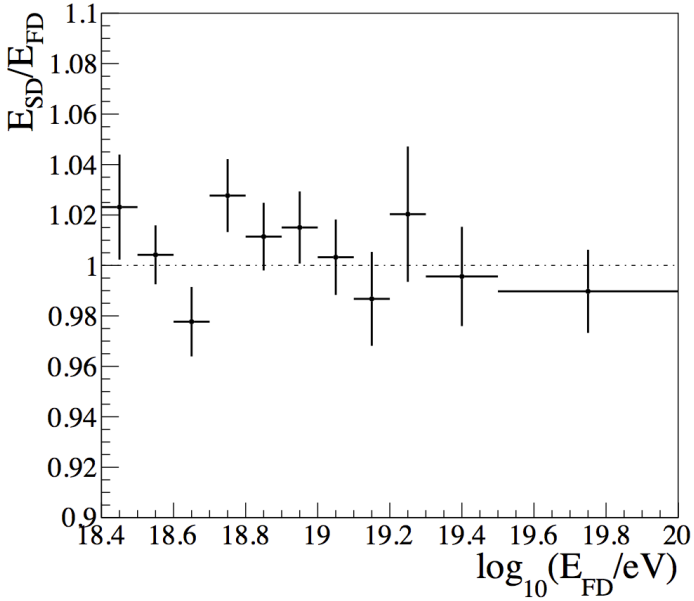
→ 1% above 10 EeV

Systematics of the Auger Energy: Check SD Energies with Hybrid

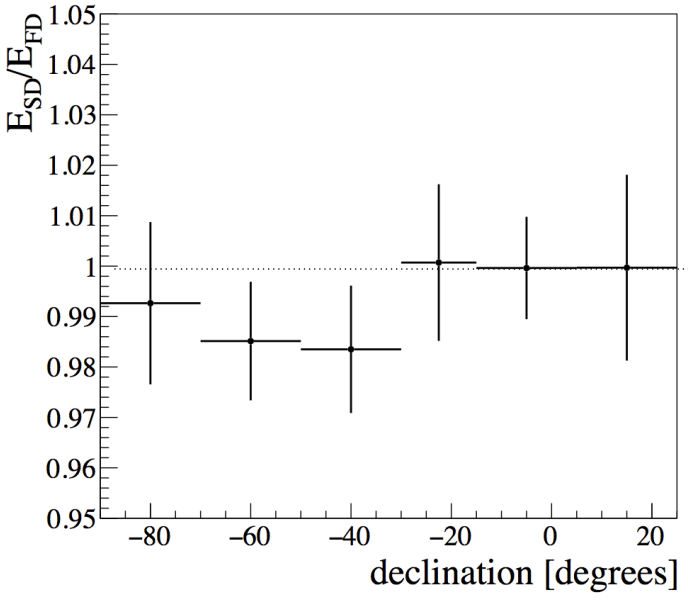
Auger f.o.v.



Auger/TA common band



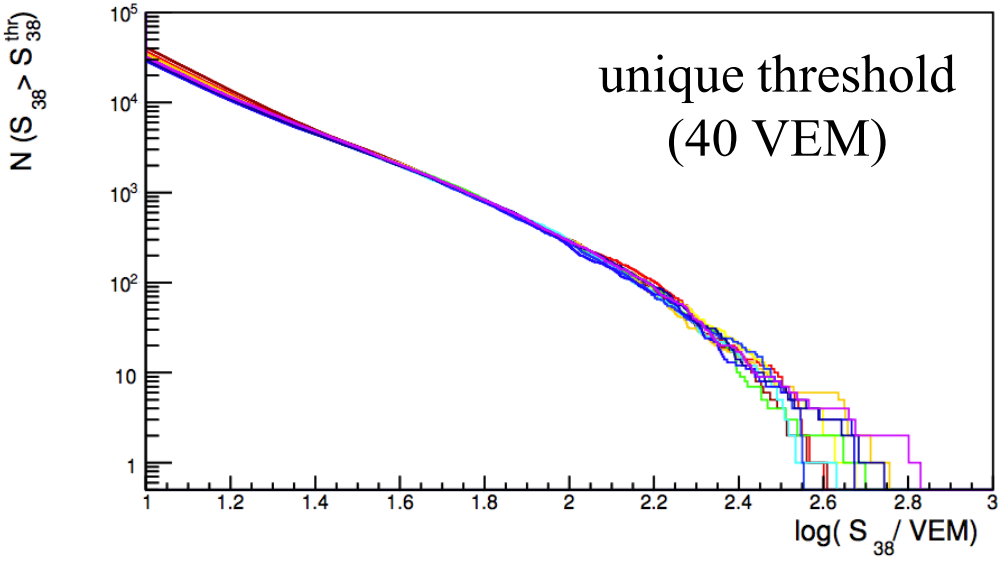
E > 10 EeV

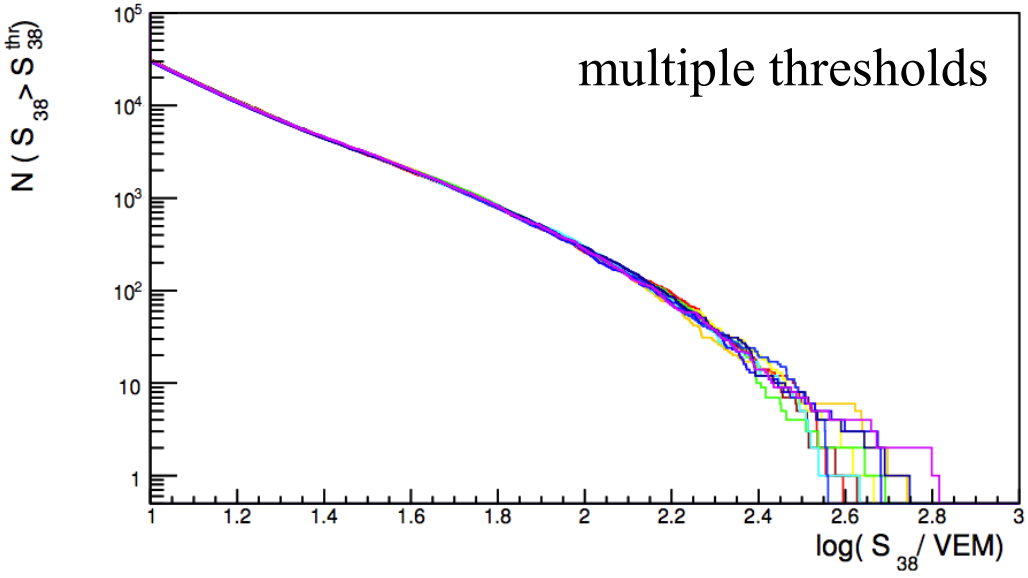


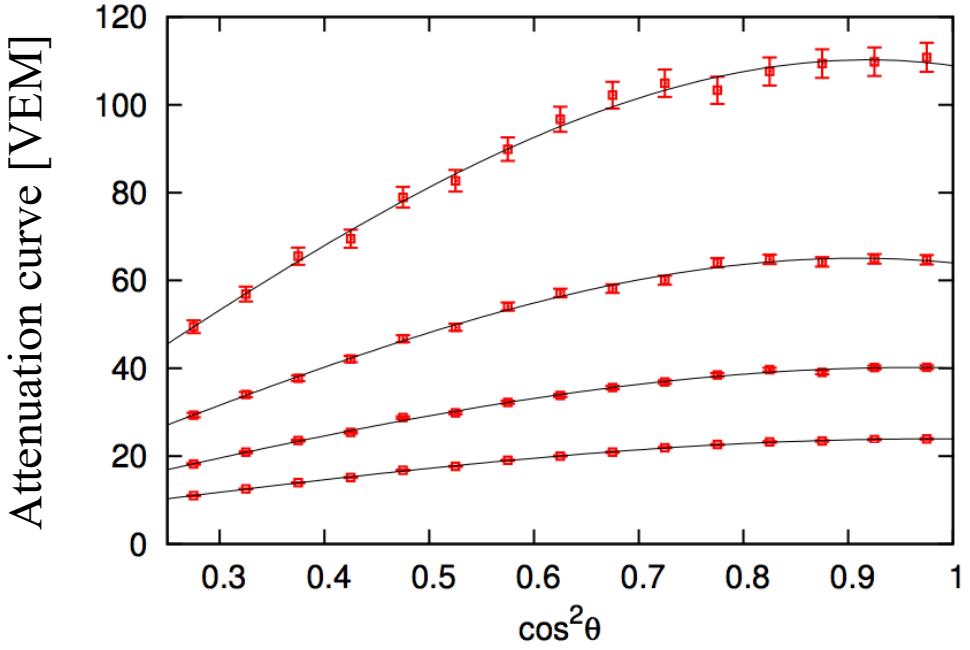
Nonlinearities from the fitting procedure: < 2%/decade

Declination stability: <1%

Auger: Check Constant Intensity Cut Attenuation Curve at Different Energy Thresholds

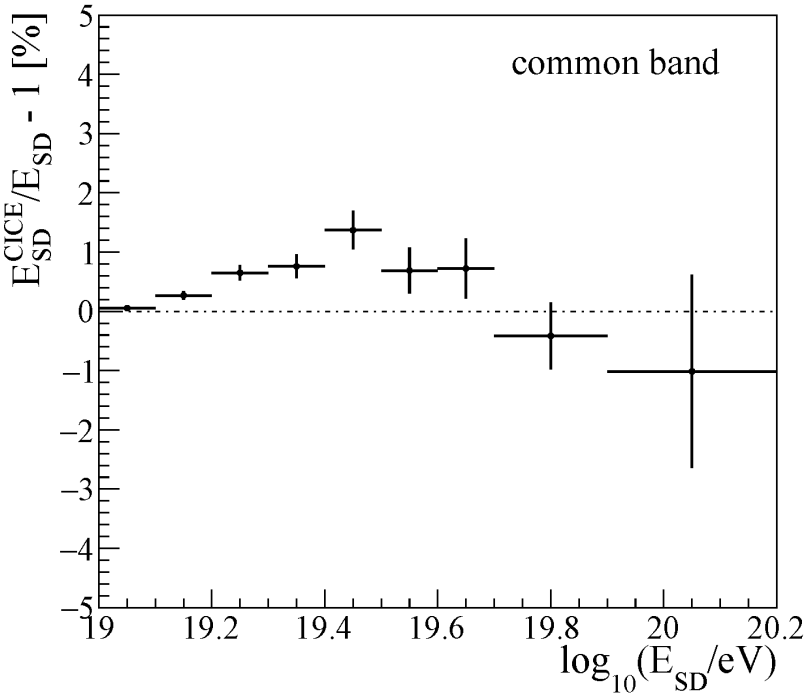


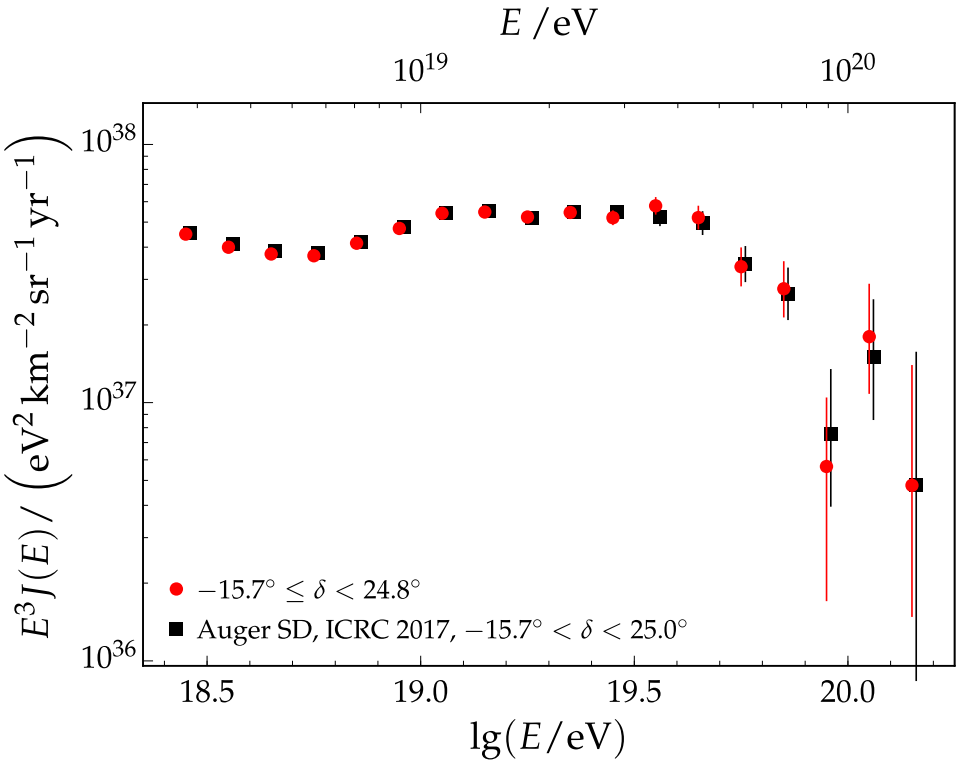




→ Possibility to measure/use attenuation curves between ~4 and ~20 EeV

Systematics of the Auger Spectrum: Compare Energy Spectra Calculated Using Energy Dependent CIC and Energy Independent CIC



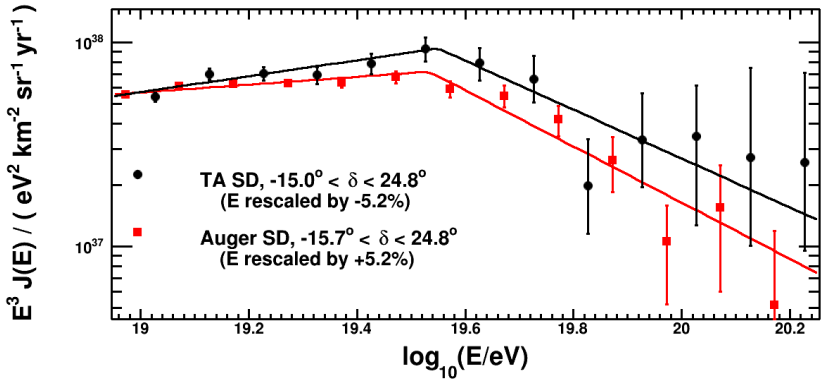


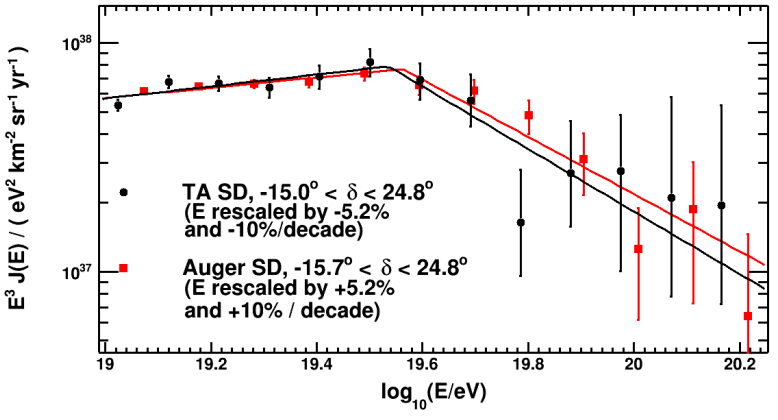
- Energy spectrum very stable w/o energy-dependent CIC
- Nonlinearities: 2%/decade

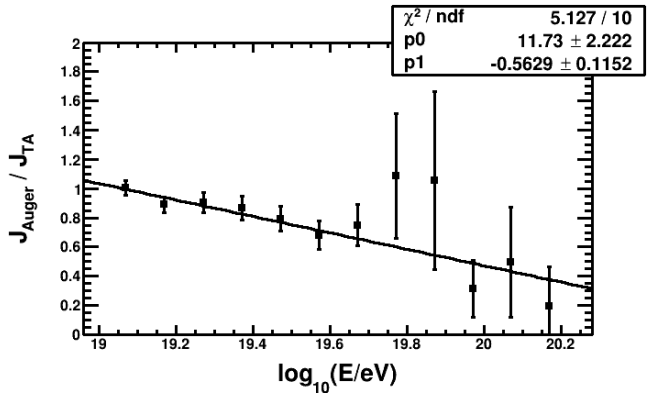
Sources of Energy-Dependent Energy Reconstruction Bias in Auger

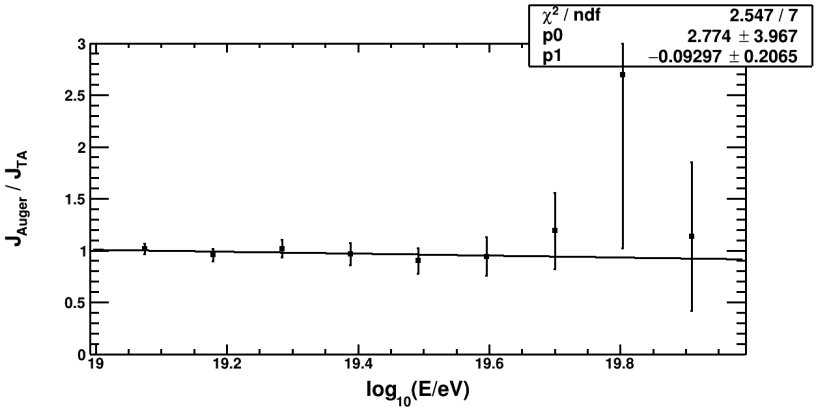
Sources of nonlinearities	**% per decade > 10 EeV**
Aerosols	± 1%
stat. uncertainties calib. param.	± 1%
check with hybrids SD/FD comparison	± 2%
energy dependent CIC	± 2%
Net	**≈ ± 3%**

TA-Auger Difference









- Agreement in the common declination band after a correction of Auger energies by +10% per decade, and TA by -10% per decade, starting at 10^{19} eV
- TA energy-dependent bias: -0.3 +/- 9% per decade of energy, and SD reconstruction checked using Monte Carlo and constant intensity cut reconstruction methods.

- Auger energy-dependent bias: within 3% per decade of energy and SD reconstruction checked using two different constant intensity cut methods.

Summary and Outlook

- TA and Auger agree in the ankle region after 10% relative energy scale shift, which is within the systematic uncertainties of the two experiments
- We have checked the TA and Auger spectrum calculations using alternative methods and we have carefully examined the sources of possible energy non-linearities in both TA and Auger. We have not identified the source of the remaining TA and Auger spectrum difference yet.
- Will perform further studies of the systematic uncertainties in TA and Auger
- Try using Auger detectors at the TA site for understanding the SD response (see Sarazin and Covault)
- Reduce statistical uncertainties with the future TA x 4 expansion and continuous Auger data taking
- Compare the scintillator – only SD fluxes between AugerPrime and TA
- Combine study with the lower energy experiments TALE, Auger Infill, IceCube, HAWC, Tunka, Kascade-Grande