AUGER-TA ENERGY SPECTRUM WORKING GROUP REPORT

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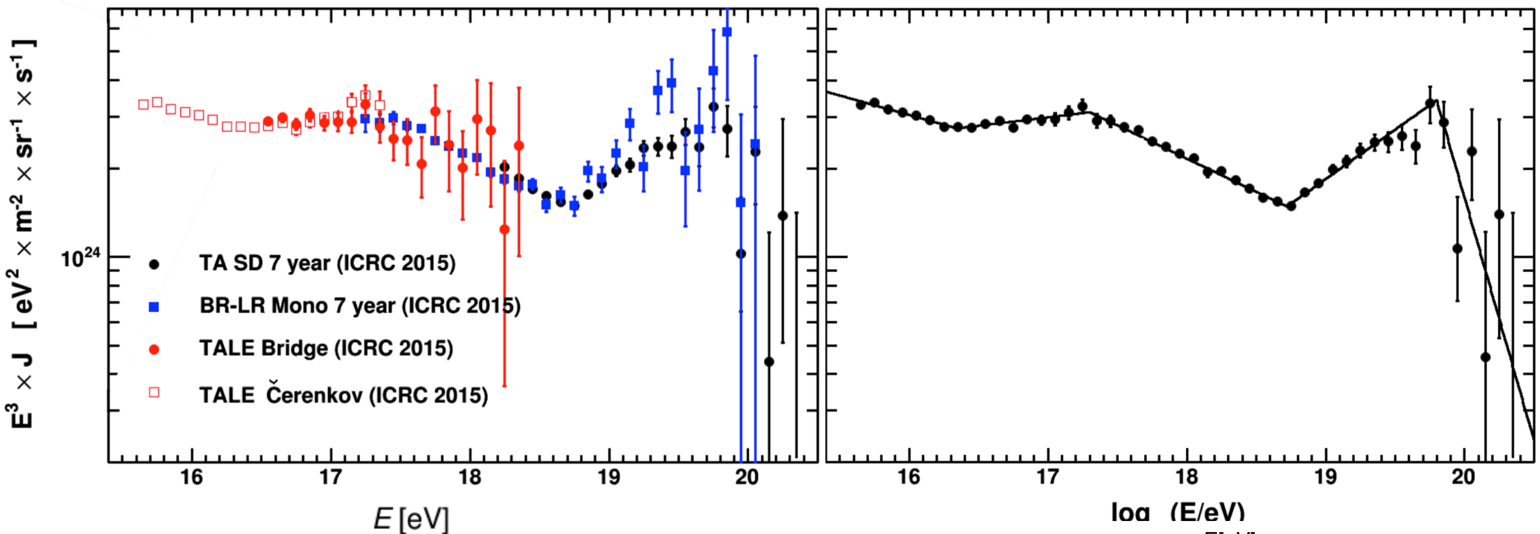
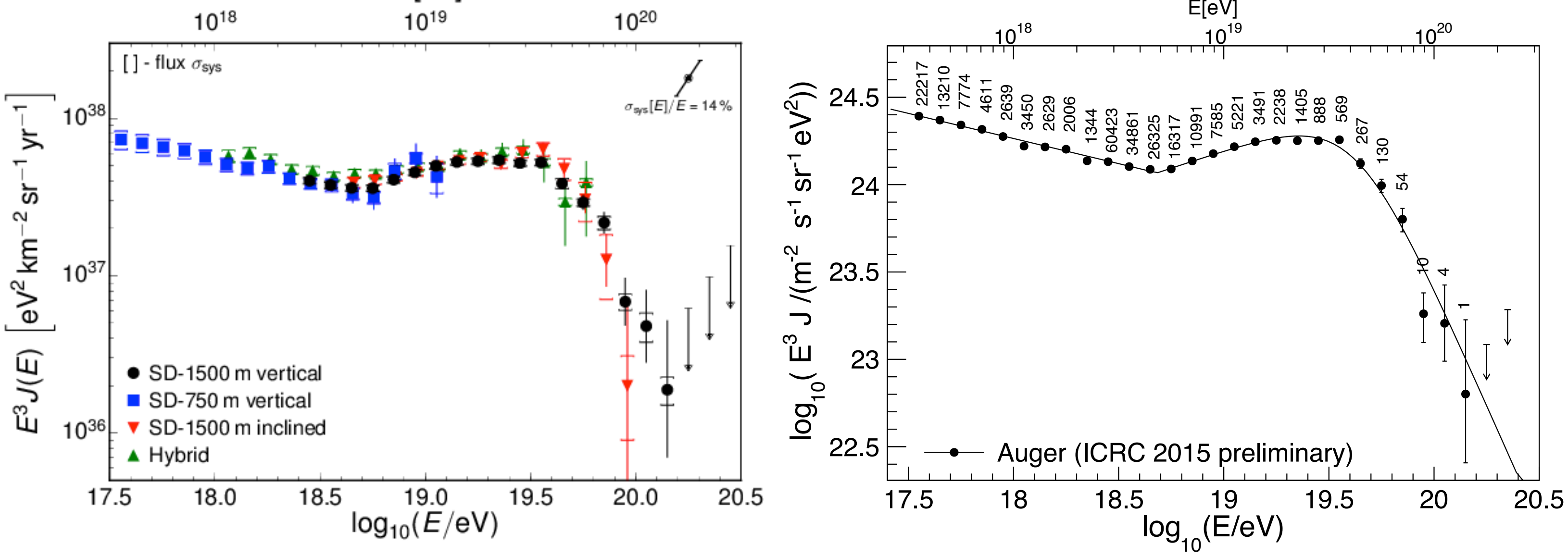
2016 International Conference on Ultra-High Energy Cosmic Rays
11 October 2016, Kyoto Research Park

- **First meeting in Nagoya (Japan) December 2010**
- **CERN, February 2012**
  First energy spectrum working group: HiRes, Yakutsk, Telescope Array and Auger
  → first systematic comparison between the measured spectra
- **Utah (USA) October 2014**
  Energy spectrum working group: Telescope Array and Auger
  → discussion on energy scale (improved determination of Auger)
  → first discussions on energy spectra in different regions of sky
- **this meeting**
  → use a larger exposure
  → setup the analysis methods to compare the energy spectra in the same declination band

TA energy spectrum (D.Ivanov)



Auger energy spectrum (M.Roth)

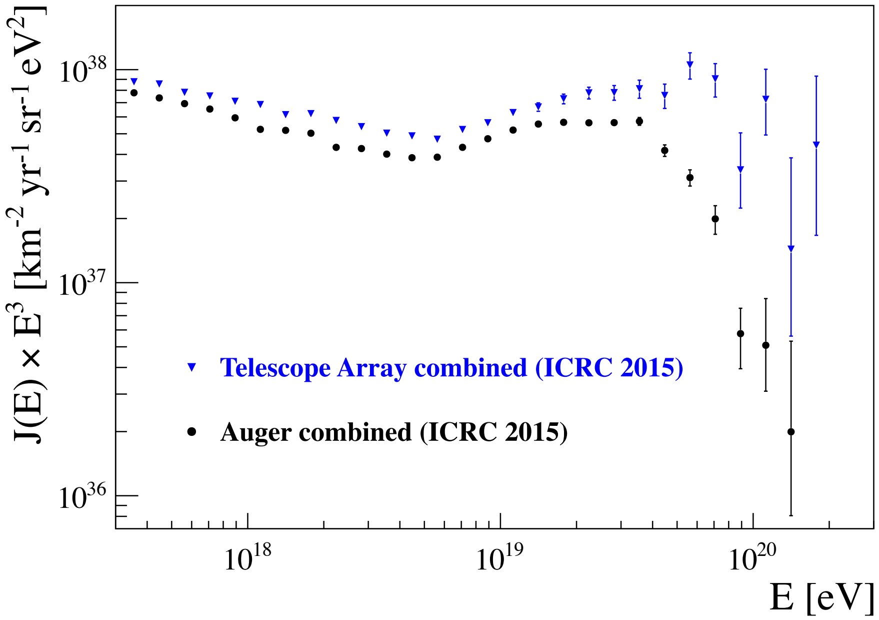


Both collaborations

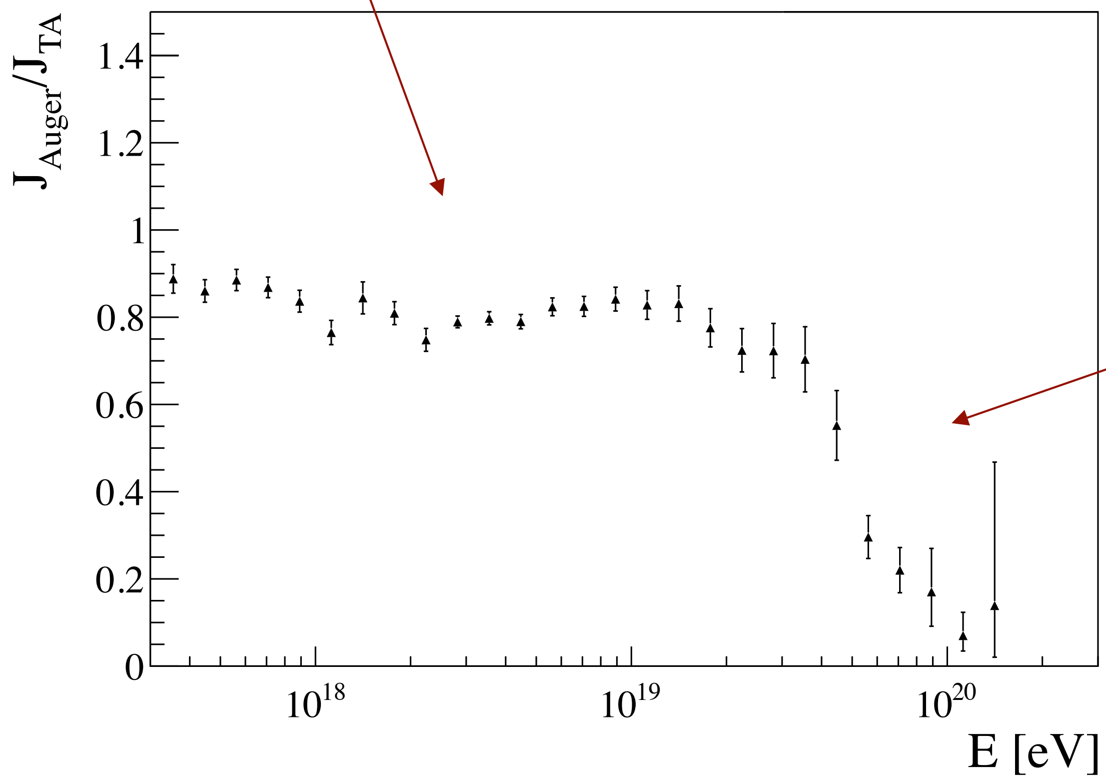
- consistency between measurements done with different analysis techniques (different systematics)
- all measurements have in common the same energy scale (from fluorescence measurements)

Comparison of the combined energy spectra

constant energy shift does not explain the difference at the suppression

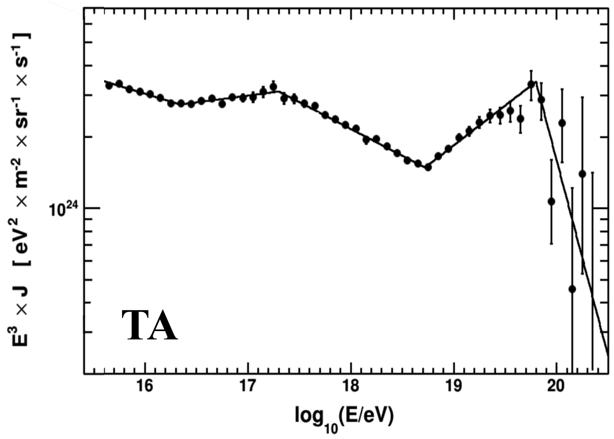


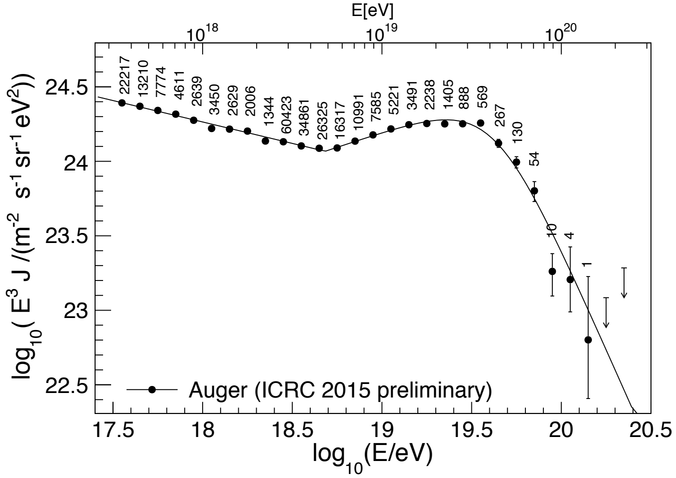
good agreement

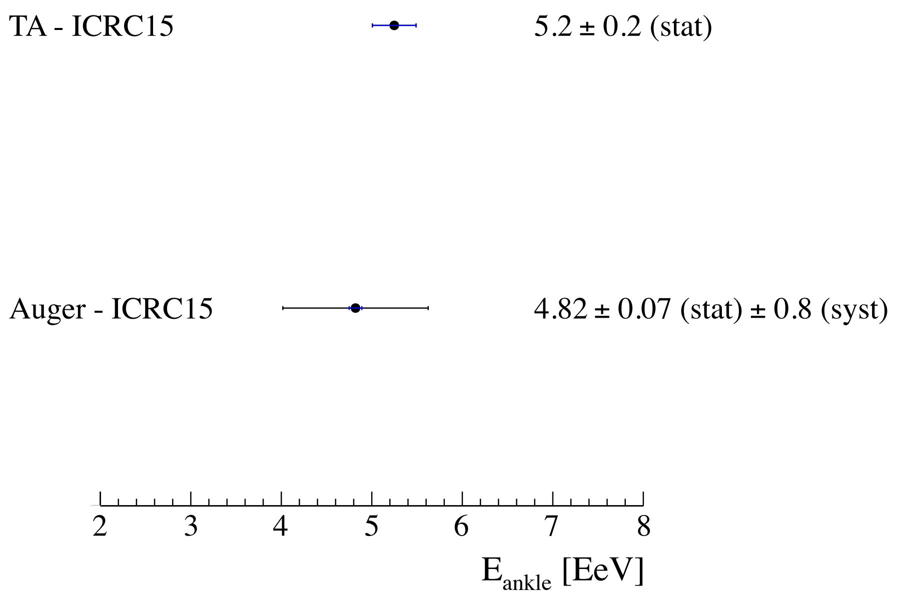


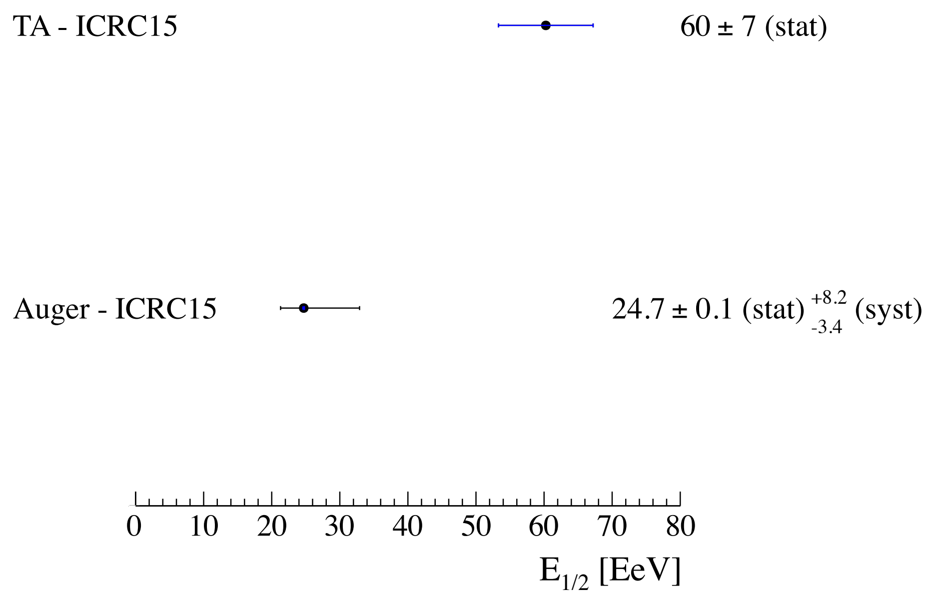
Is the difference at the highest energies due to experimental effects or to anisotropy signals?

Comparison of the combined energy spectra

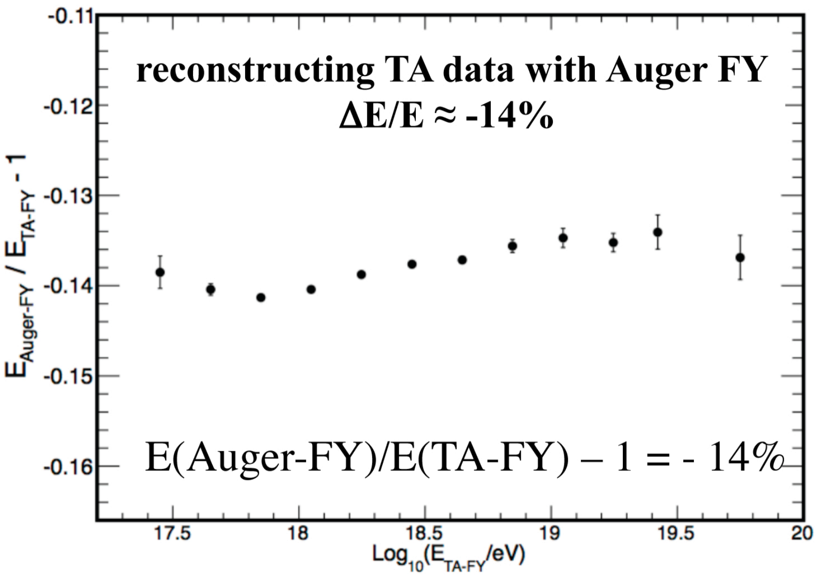


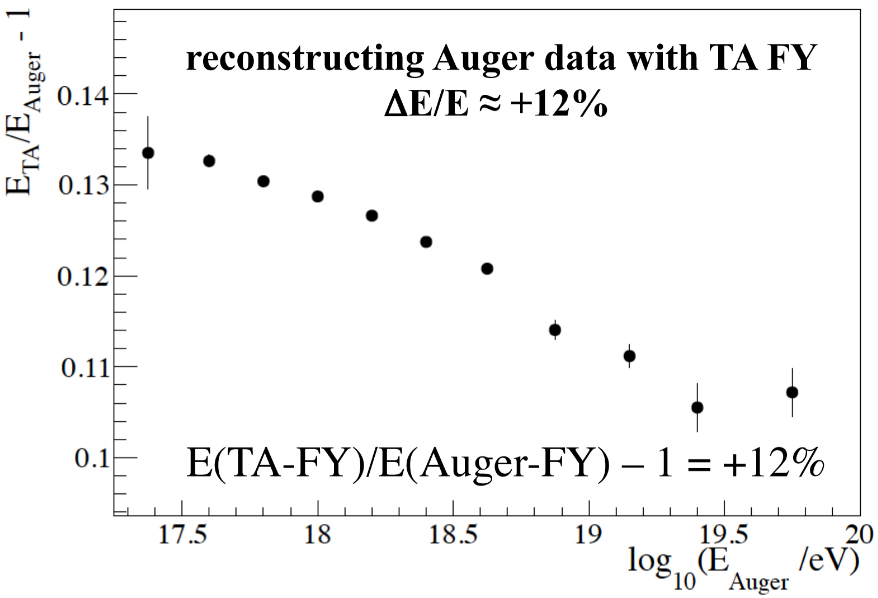






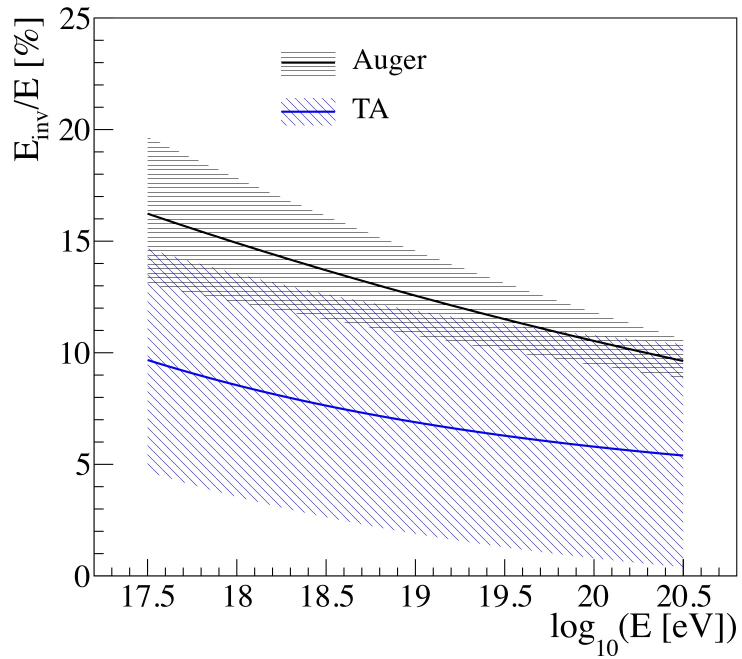
UHECR-2014: fluorescence yield and invisible energy





TA and Auger use different fluorescence yields and different invisible energy corrections

They produce an <u>almost constant energy shift</u> (between 5% and 10%)



Systematic uncertainties in the energy scale

Auger (ICRC13)

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

Telescope Array

T.Abu-Zayyad et al., In press on Astropart. Phys. (2014)
arXiv:1305.7273 [astro-ph.HE]

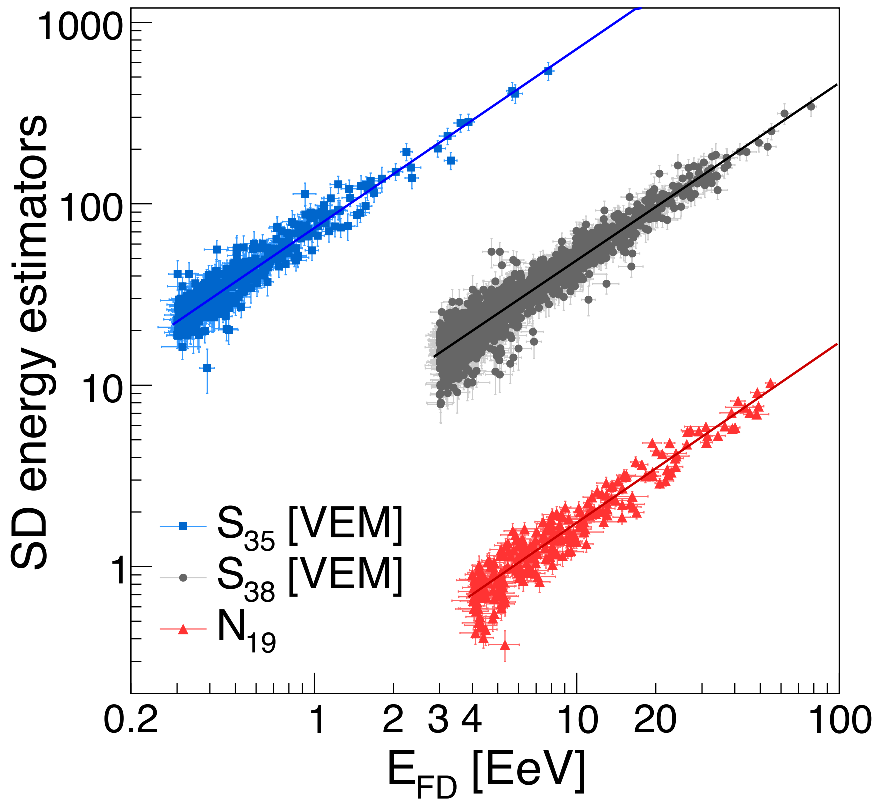
Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%) missing energy (5%)
Sum in quadrature	21	

The total uncertainty is energy independent

Calibration of SD energy estimators

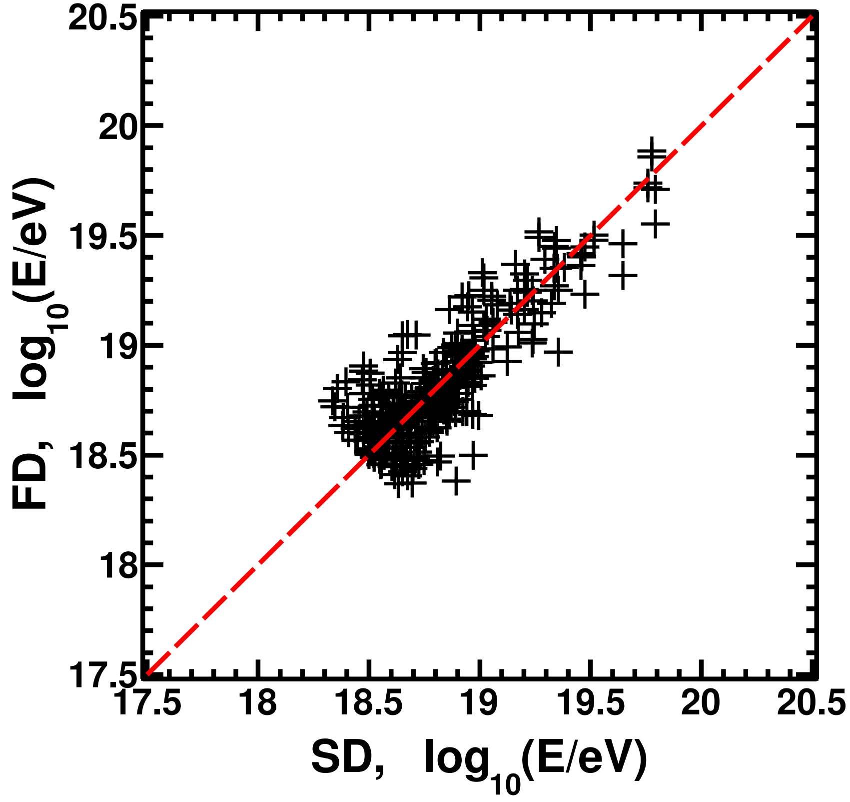
Auger

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



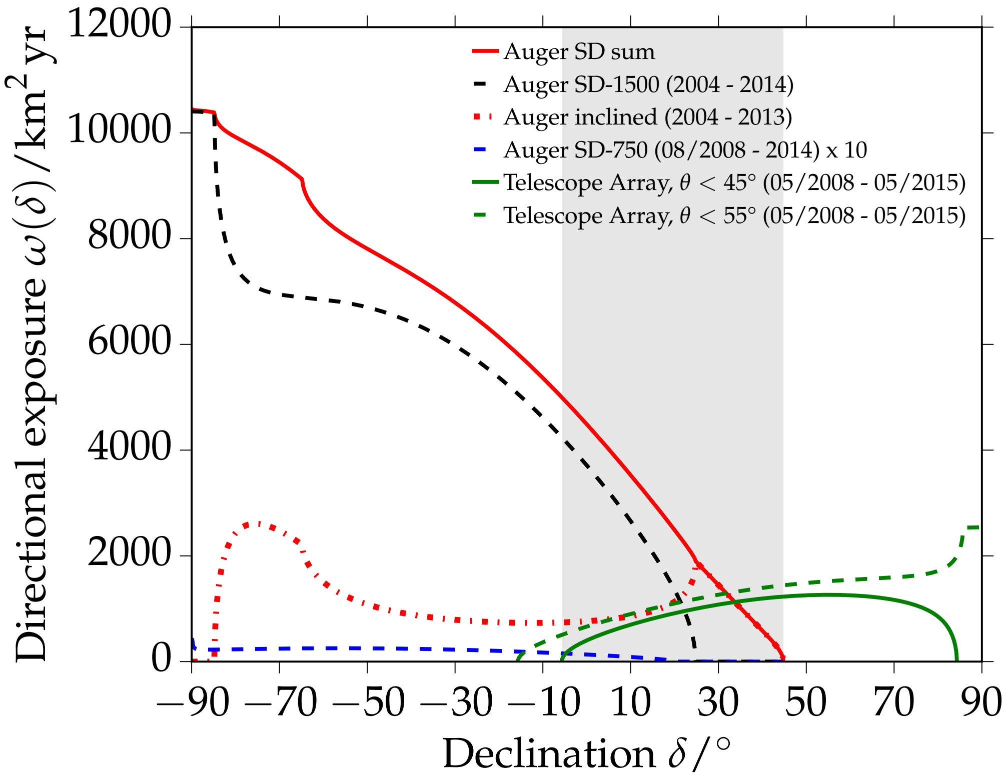
TA

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



Minimize the effect of anisotropies comparing the spectra in a declination band accessible by both experiments

Hot Spot
20^0 circular region
centered at ($\alpha=148.4^0$, $\delta=44.5^0$)



Common declination bands

[-5.7^0, 24.8^0] TA $\theta < 45^0$ vs Auger 'vertical' ← $\theta < 60^0$
[-5.7^0, 44.8^0] TA $\theta < 45^0$ vs Auger 'vertical' + 'inclined'
[-15.7^0, 24.8^0] TA $\theta < 55^0$ vs Auger 'vertical' ↖ $\theta > 60^0$
[-15.7^0, 44.8^0] TA $\theta < 55^0$ vs Auger 'vertical' + 'inclined'

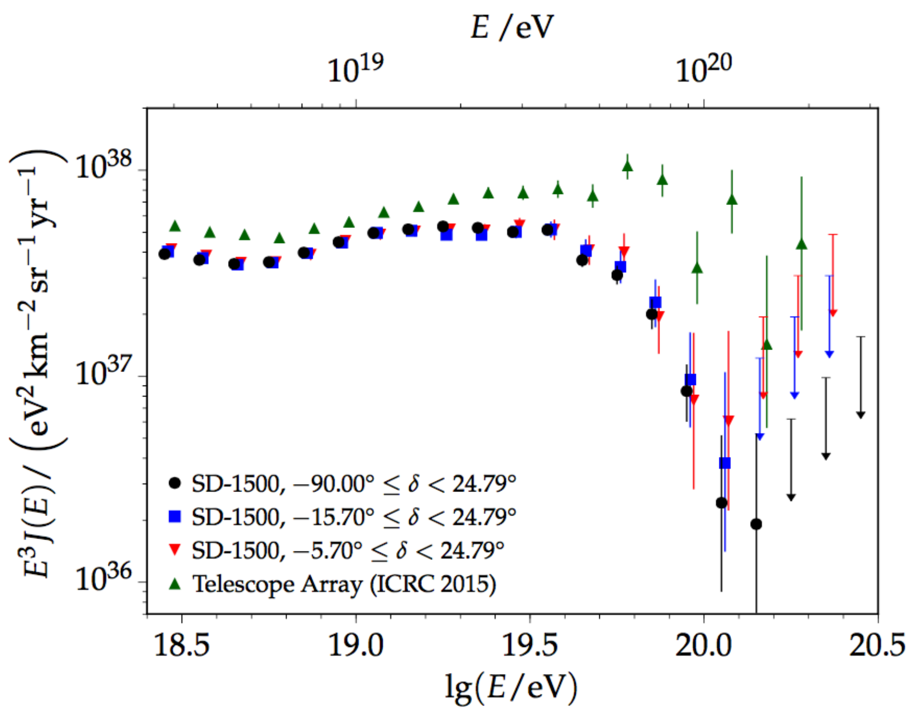
- **use Auger 'vertical' → $\delta < 24.8^0$**
- **use TA $\theta < 55^0$ (larger statistics) → $\delta > -15.7^0$**

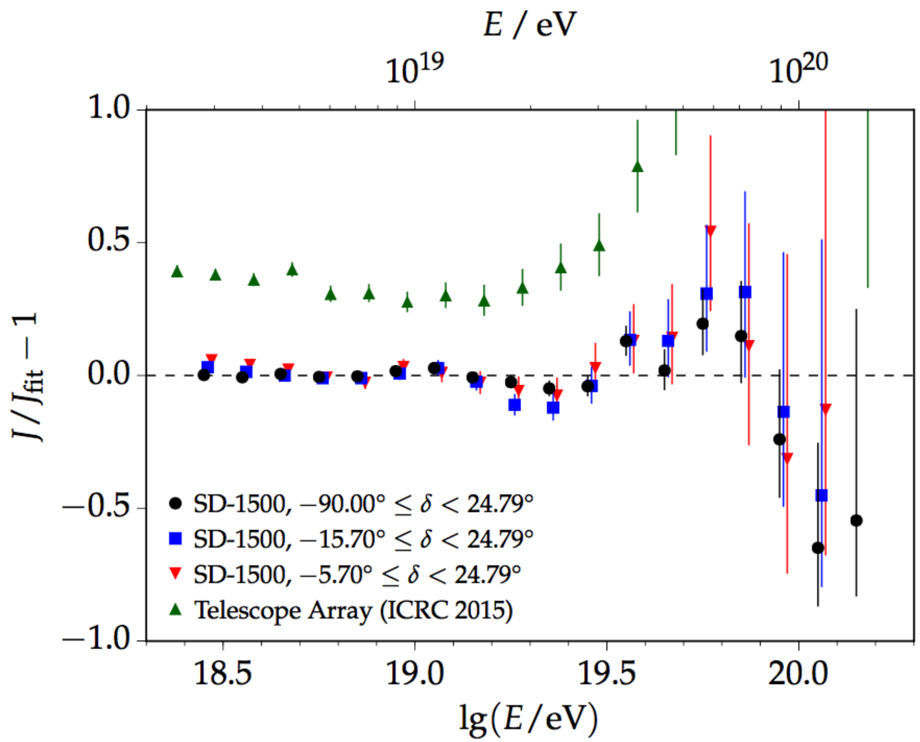
note: $\delta < 24.8^0$ is a good choice since it excludes the Hot Spot

Auger ‘vertical’ spectrum for δ in [-5.7^0, 24.8^0] and [-15.7^0, 24.8^0]

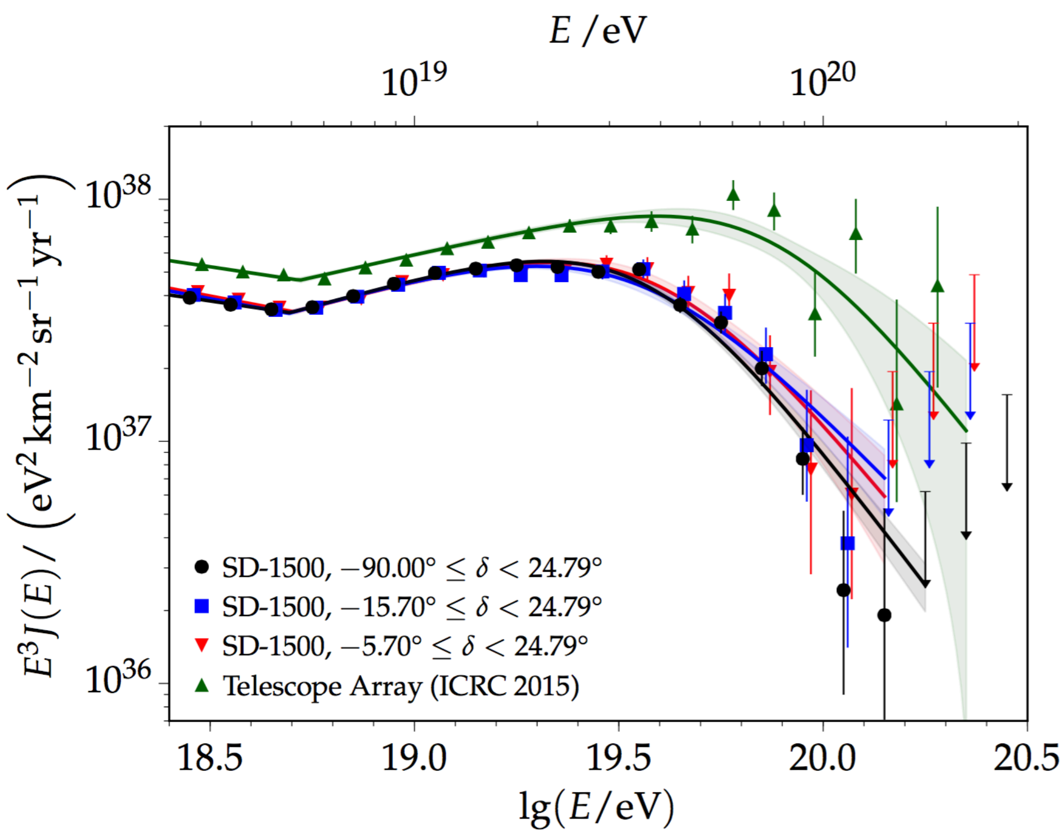
	N(>10 EeV)
• use 10 years SD-1500 data from 2004 to 2014 (ICRC15)	
• total exposure 42527 km^2 yr sr	10763
• 13595 km^2 yr sr for δ in [-15.7^0, 24.8^0]	3369
• 8575 km^2 yr sr for δ in [-5.7^0, 24.8^0]	2147

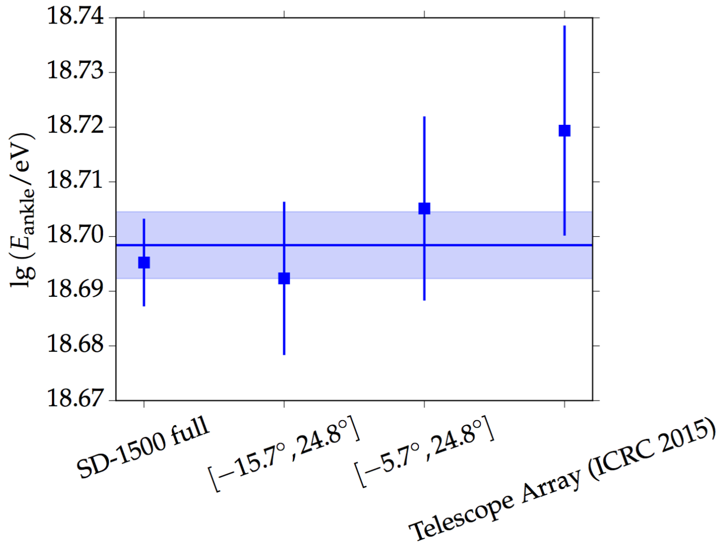
- correct the SD energy estimator for weather and geomagnetic effects (new)
- forward folding technique to correct for event migrations (same corrections for all δ bands)

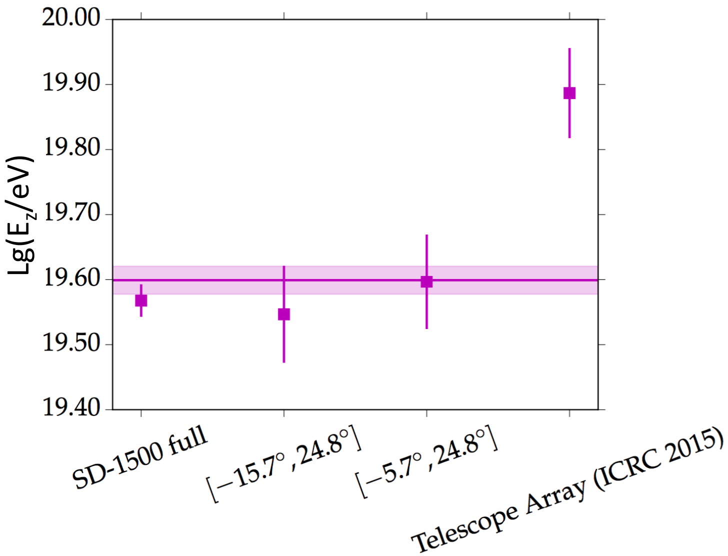




Auger ‘vertical’ spectrum for δ in [-5.7^0, 24.8^0] and [-15.7^0, 24.8^0]

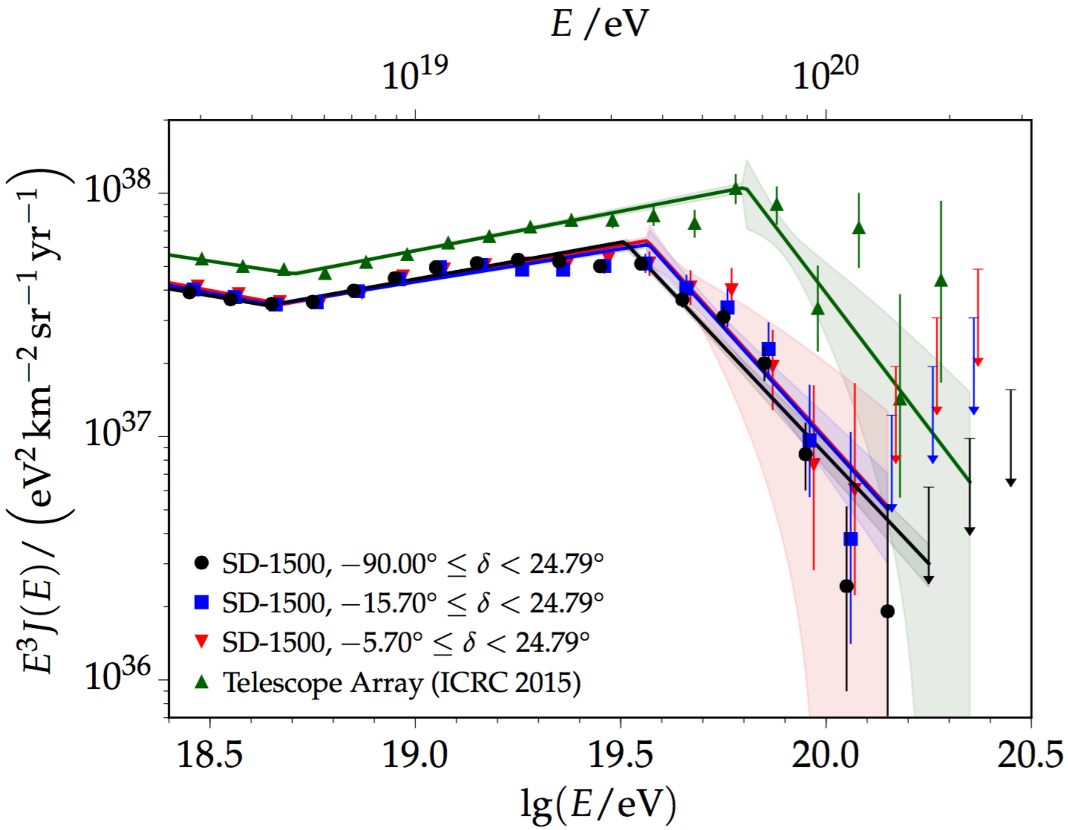


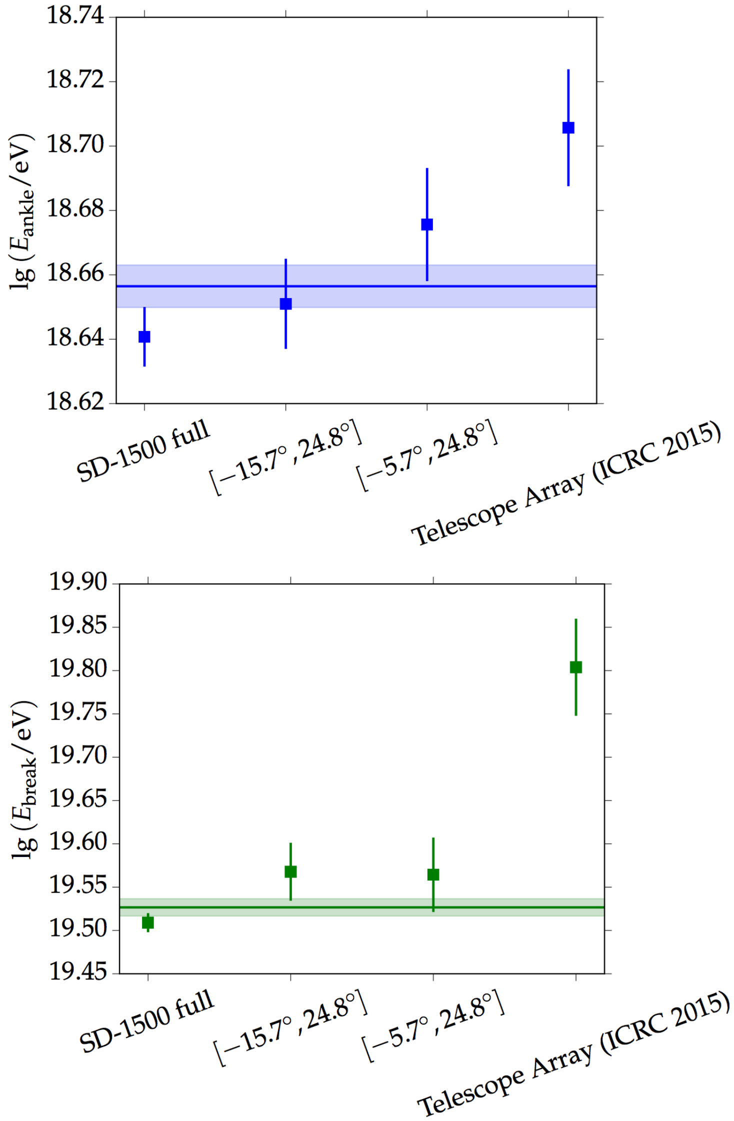




No declination dependence

Auger 'vertical' spectrum for δ in [-5.7^0, 24.8^0] and [-15.7^0, 24.8^0]



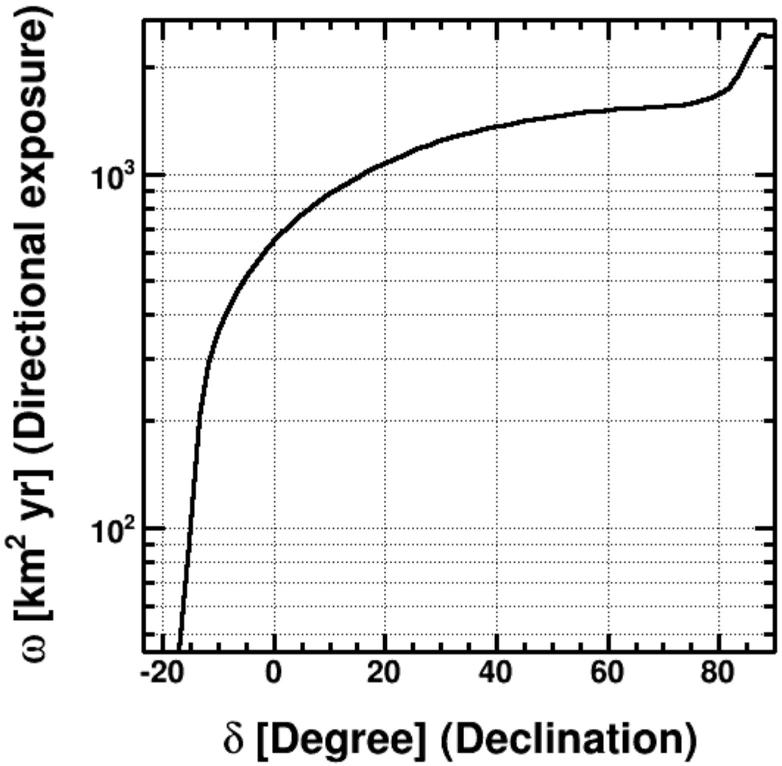


No declination dependence

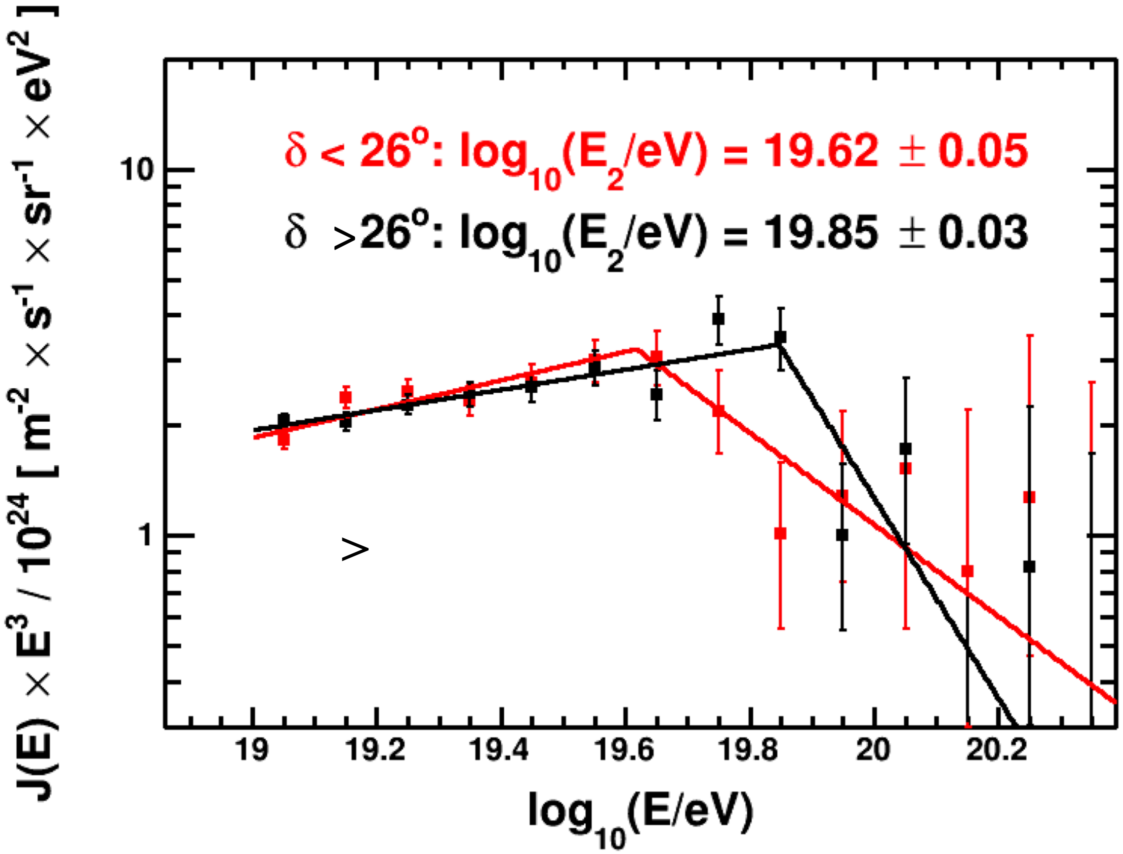
Note: power laws with breaking points describe the Auger spectrum poorly

TA SD data set ($\theta < 55^0$)

- 7 Years of TA SD Data 2008/05/11-2015/05/11
- Cuts
  - Zenith angle < 55 degrees
  - N_{SD} >= 5
  - Distance of the shower core from the border of the array > 1200m
  - Geometry, LDF Chi2 / d.o.f. < 4
  - Pointing direction uncertainty < 5 degrees
  - S800 fractional uncertainty < 25%
- Using E > 10 EeV only
  - Exposure 8300 km^2 sr yr
  - 2890 events
- Resolution from MC
  - Angular resolution ~1.5 degree above 10 EeV
  - Energy resolution ~20% or better above 10 EeV

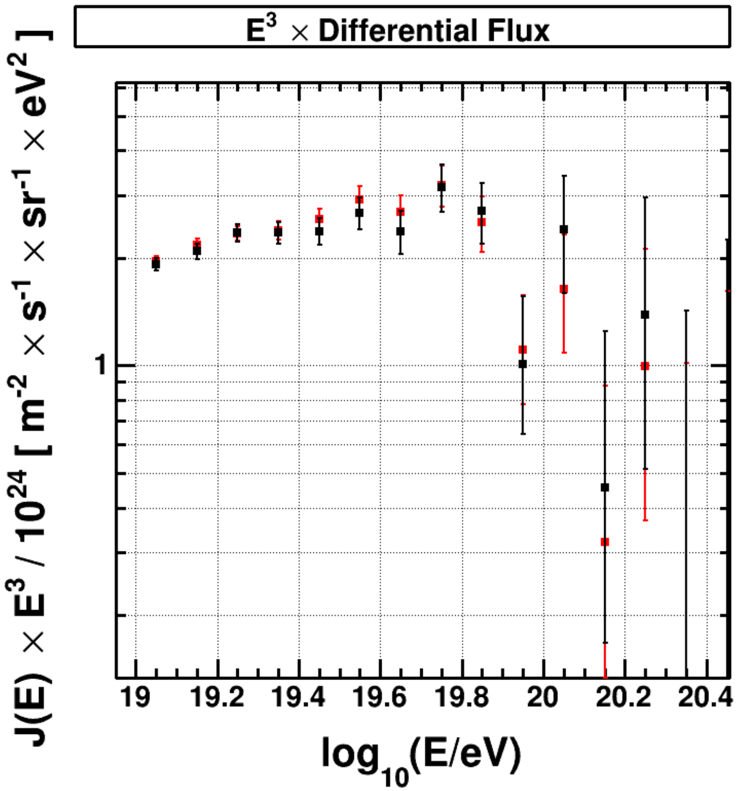


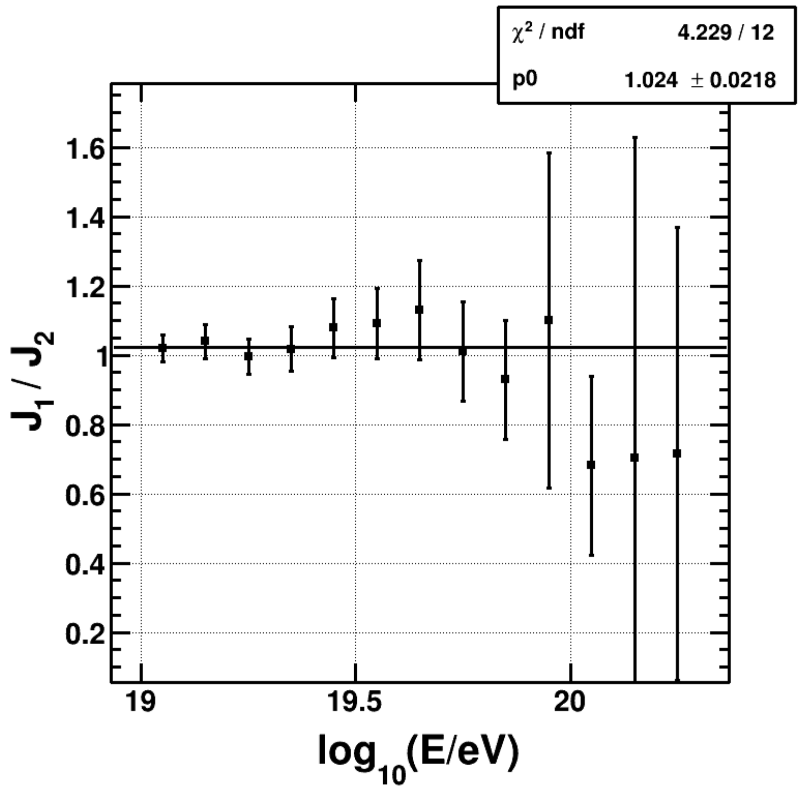
Declination dependence of TA spectrum ($\theta < 55^0$)



difference ($\approx 3.9\ \sigma$) in the position of the 2nd break point

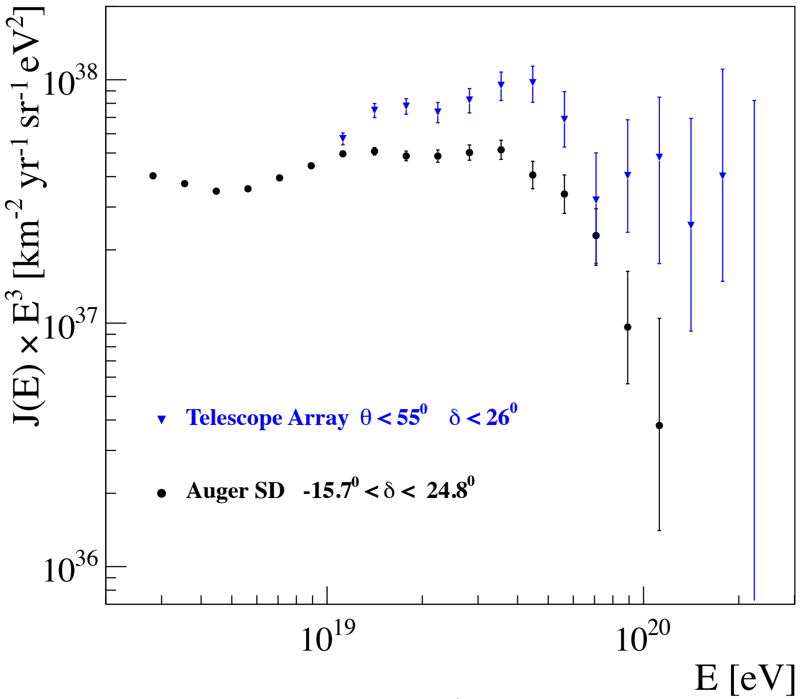
Check of the TA SD spectrum calculation



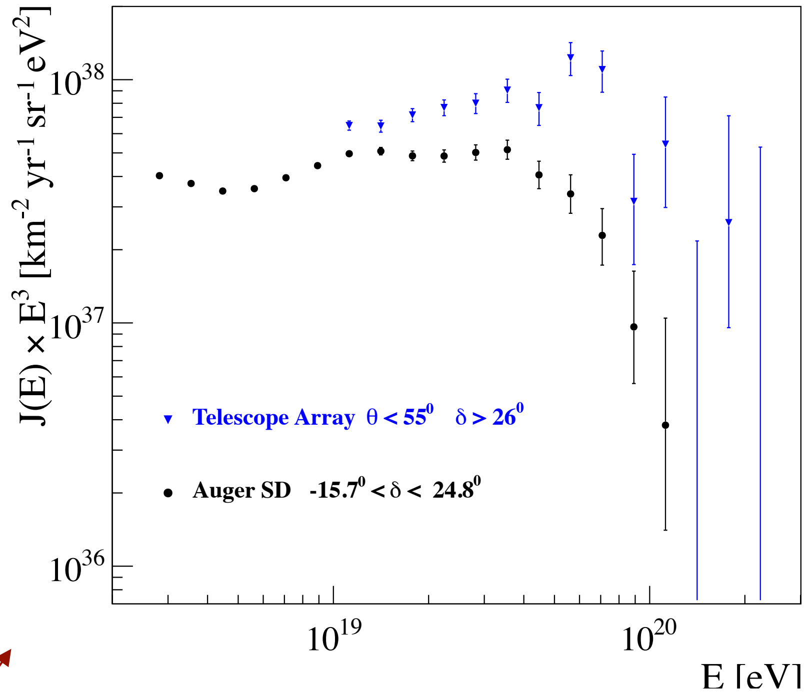


Spectrum calculated using this data set (RED) agrees with standard TA SD spectrum (BLACK) above 10^{19} eV

(standard TA SD spectrum has $\theta<45^0$ and goes down to $10^{18.2}$ eV) same declination band



declination bands don't overlap

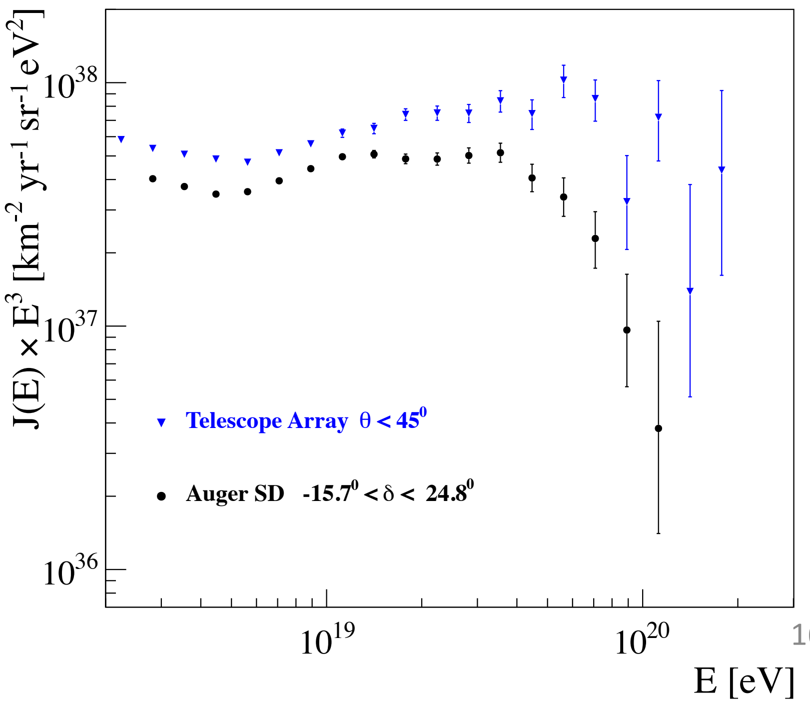


Auger vs TA($\delta < 26^0$)

Auger vs TA($\delta > 26^0$)

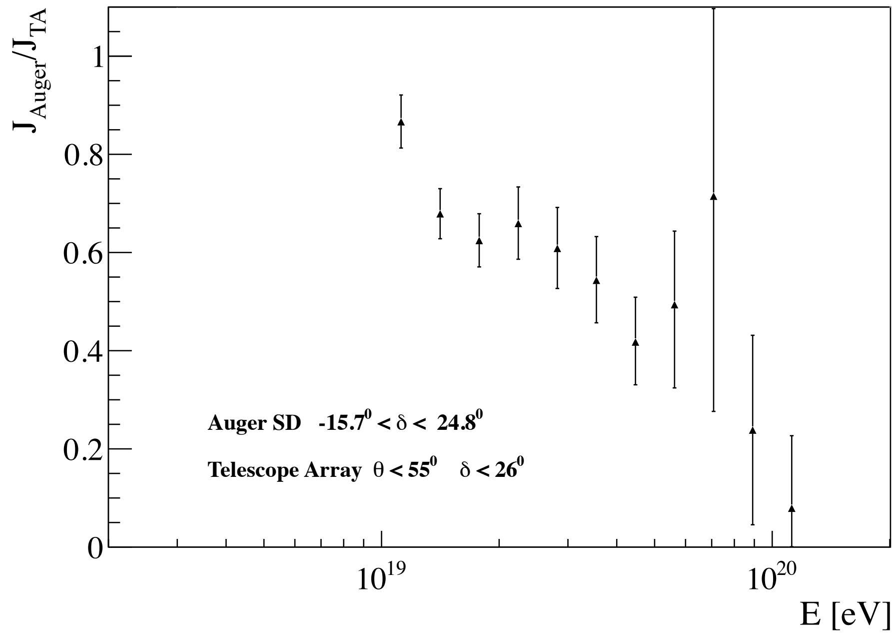
Auger vs TA($\theta < 45^0$)

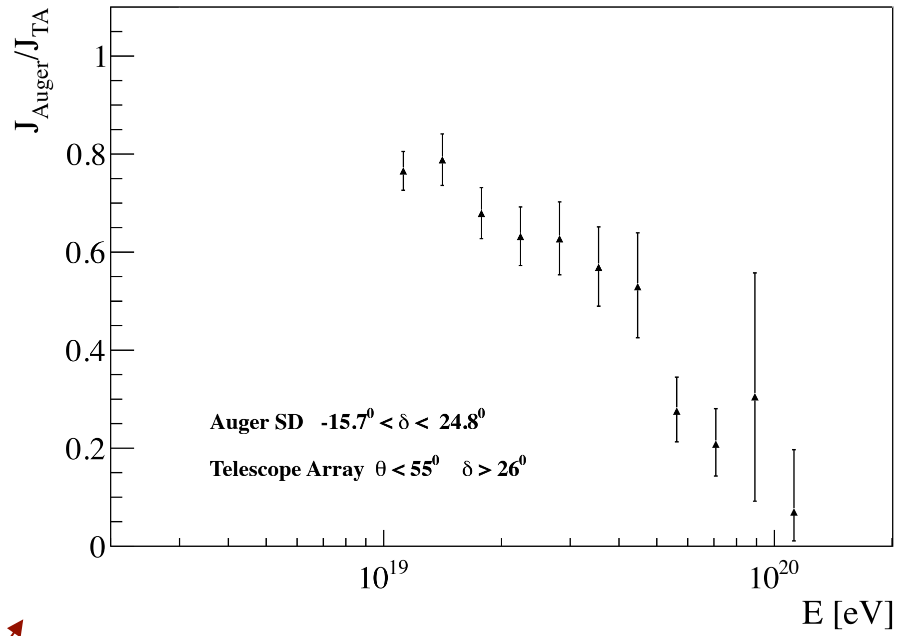
$-15.7^0 < \delta < 24.8^0$

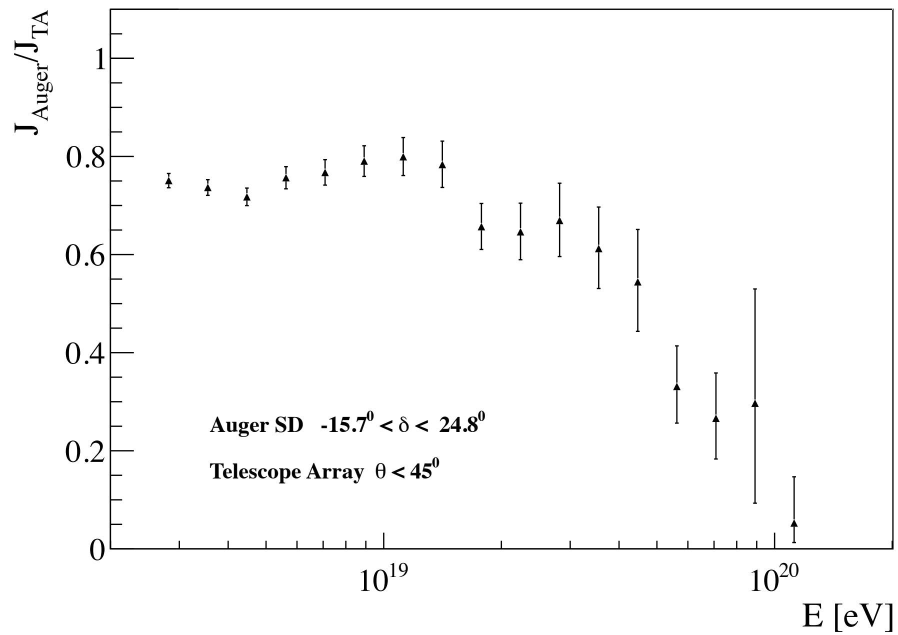


same declination band

declination bands don't overlap







Auger vs TA($\delta < 26^0$)

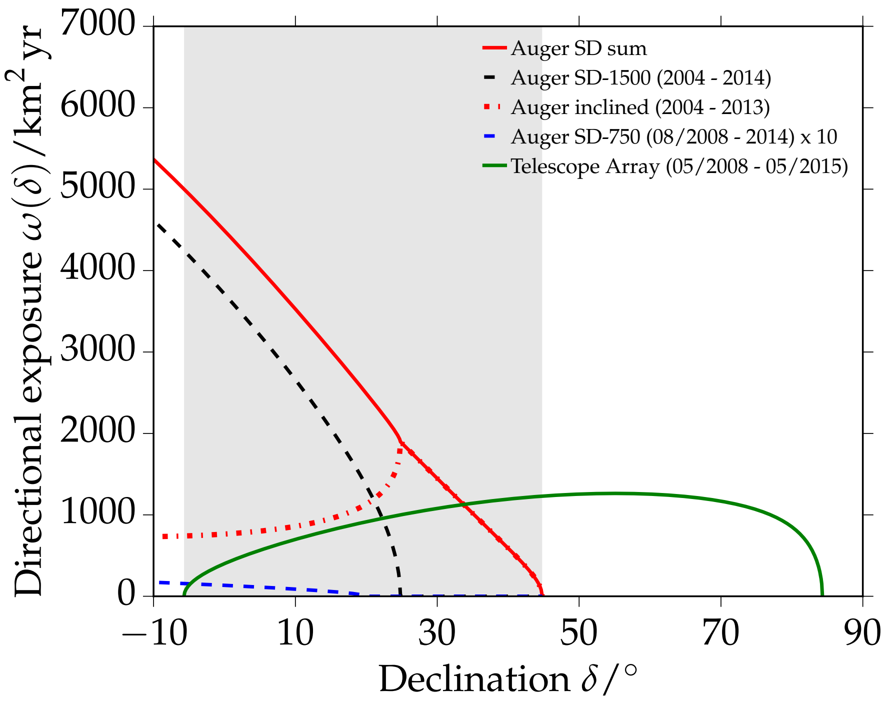
Auger vs TA($\delta > 26^0$)

Auger vs TA($\theta < 45^0$)

$-15.7^0 < \delta < 24.8^0$

Different shape of the directional exposure functions:

- Auger ‘vertical’ very different from TA
- Auger ’inclined’ more similar to TA, but analysis not yet ready



Anisotropy Auger-TA WG: compare a flux measurement insensitive to anisotropies

$$\langle\Psi_{\Delta E}\rangle_{\Delta\Omega} = \int \frac{\mathrm{d}\Omega}{\omega(\delta)} \frac{\mathrm{d}N}{\mathrm{d}\Omega}(\Delta E) = \sum_{\text{events}} \frac{1}{\omega(\delta_i)} \qquad \text{in [km}^{-2}\text{ yr}^{-1}]$$

the measurements of the two observatories should agree within the uncertainties

$$\langle\Psi_{\Delta E}\rangle_{\Delta\Omega} = \int \mathrm{d}\Omega\, \Psi_{\Delta E}(\alpha,\delta) \qquad \frac{\mathrm{d}N}{\mathrm{d}\Omega}(\Delta E) = \omega(\delta)\int_{\Delta E} \mathrm{d}E\, \Phi(\alpha,\delta,E) \equiv \omega(\delta)\Psi_{\Delta E}(\alpha,\delta)$$

Compare $<\Psi_{\Delta E}>_{\Delta\Omega}$ for E > 10 EeV

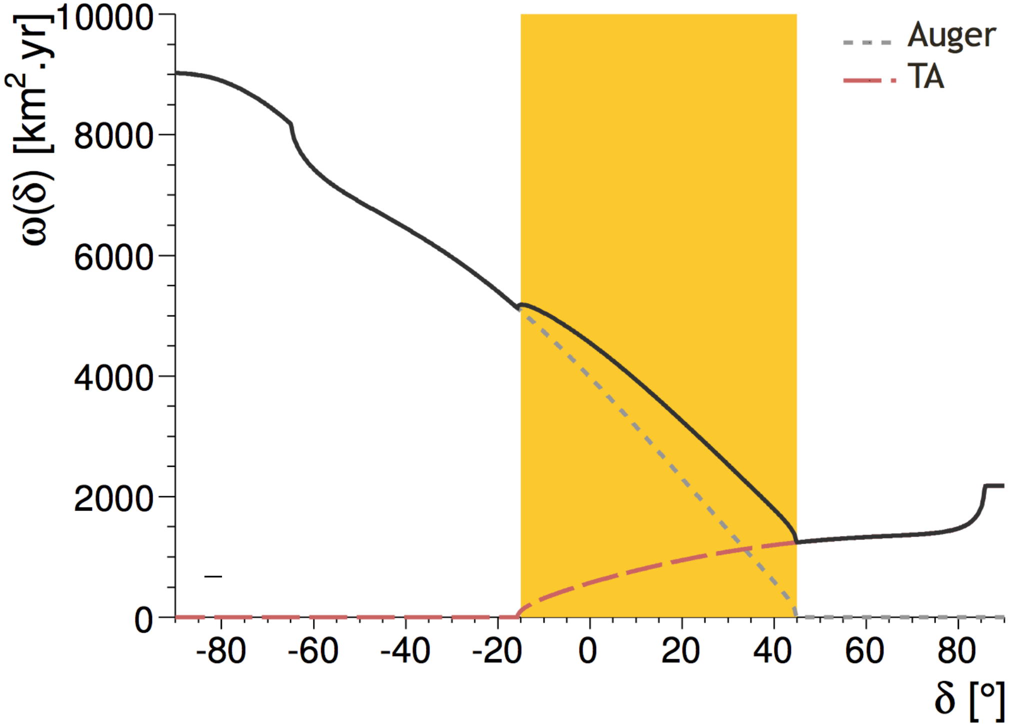
Data set

Auger 'vertical' + 'inclined'

TA $\theta < 55^0$ – cuts for anisotropy analyses

E > 10 EeV

δ in $[-15^0, 40^0]$



$$\frac{<\Psi_{>10\ \mathrm{EeV}}>_{\Delta\Omega}\ (\mathrm{Auger})}{<\Psi_{>10\ \mathrm{EeV}}>_{\Delta\Omega}\ (\mathrm{TA})} \approx 0.75 \pm 0.02\ (\mathrm{stat.\ unc.})$$

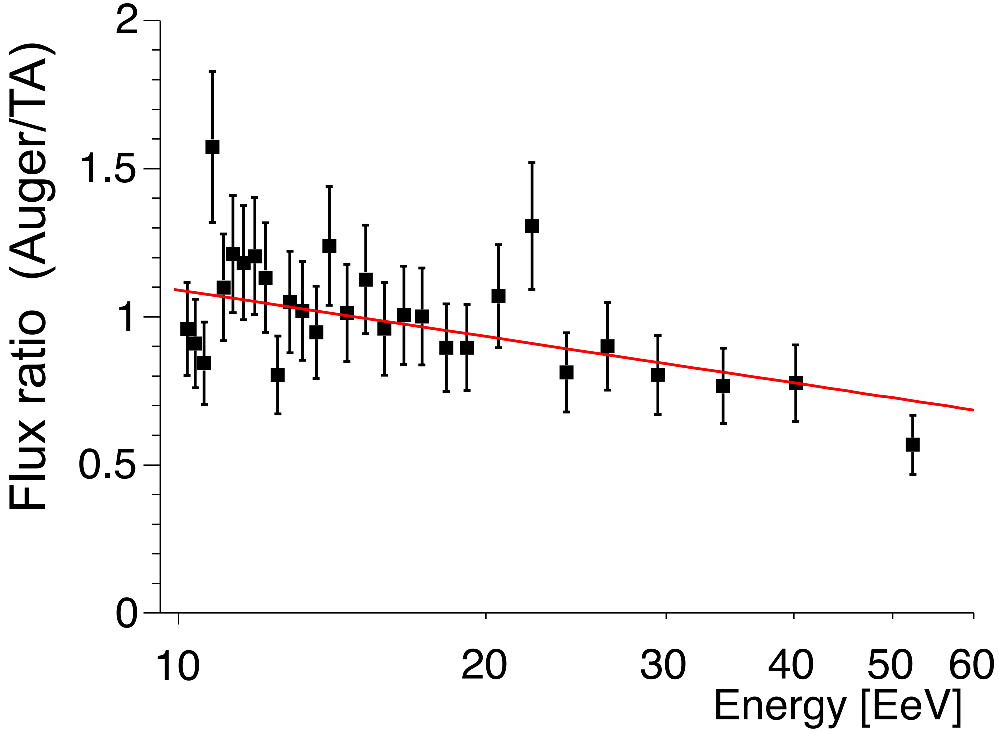
for Auger, in order to get the same value of $<\Psi_{>10}>_{\Delta\Omega}$ measured by TA, the energies have to be increased by ~15% (8.55 EeV → 10 EeV)

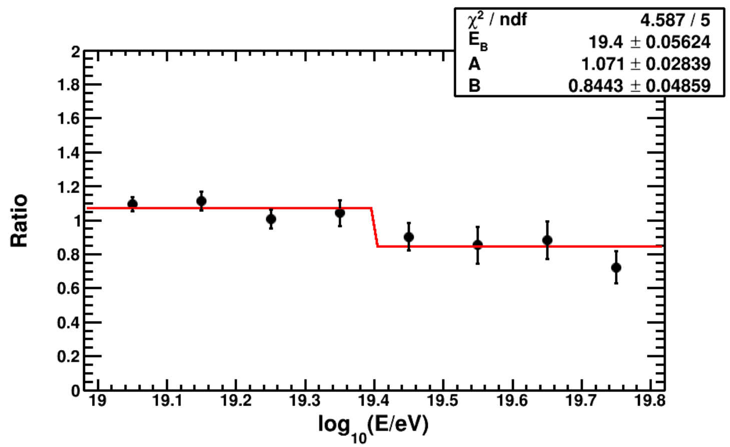
agreement within the systematic uncertainties

Compare $<\Psi_{\Delta E}>_{\Delta\Omega}$ for different energies

Comparison of $<\Psi_{\Delta E}>_{\Delta\Omega}$ in independent energy bins (E > 10 EeV)   δ in [-15^0,40^0]

- bins such that there are 100 events in total in TA data set
- ~30 independent energy bins
- note: Auger energies shifted to match $<\Psi_{>10}>_{\Delta\Omega}$ of TA



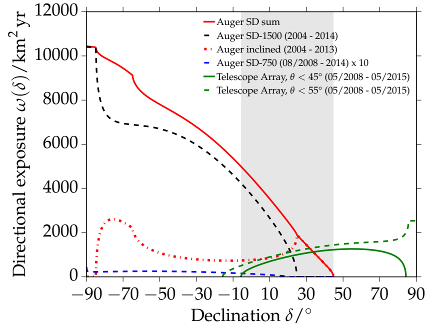


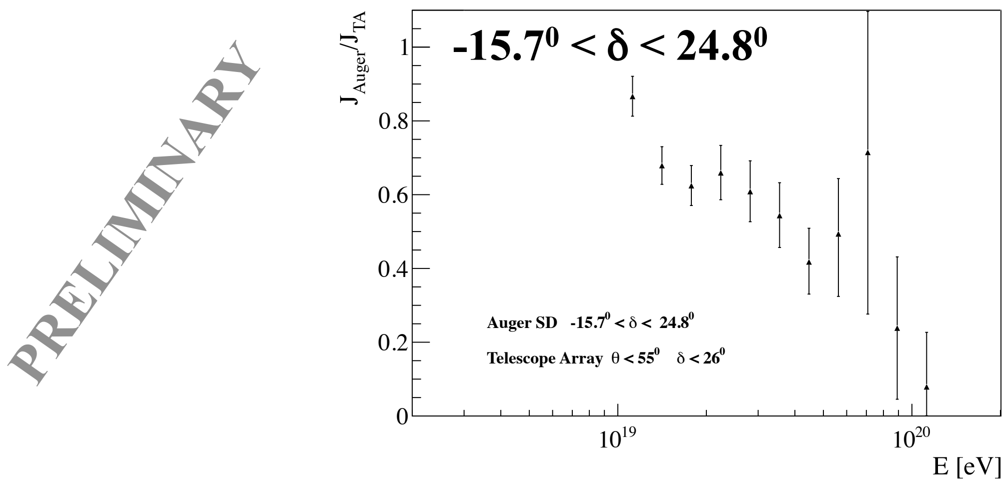
Working in progress to make cross checks with 'standard' spectrum calculations

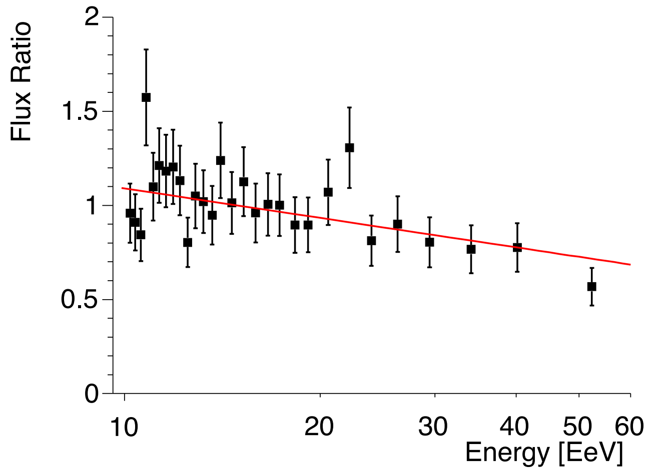
Outlook

- **Address if the difference between Auger and TA spectra at the highest energies is due to anisotropy signals or to experimental effects**

- **Analysis tools to study the flux in the common declination bands**
  - **comparison of the energy spectra**
  - **comparison of a flux measurement insensitive to anisotropies (in collaboration with the anisotropy WG)**



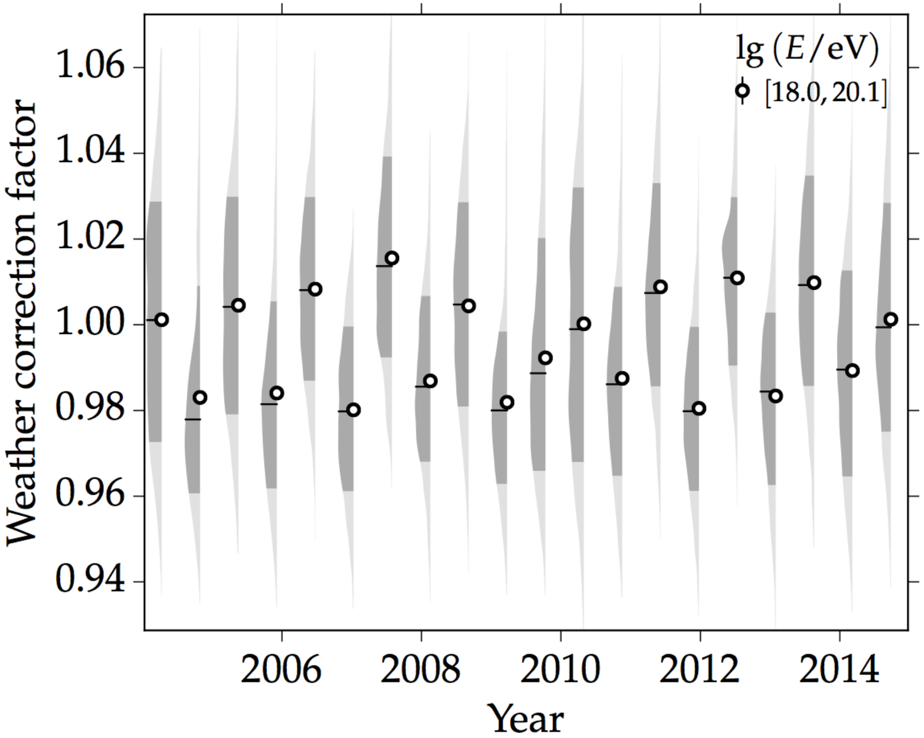


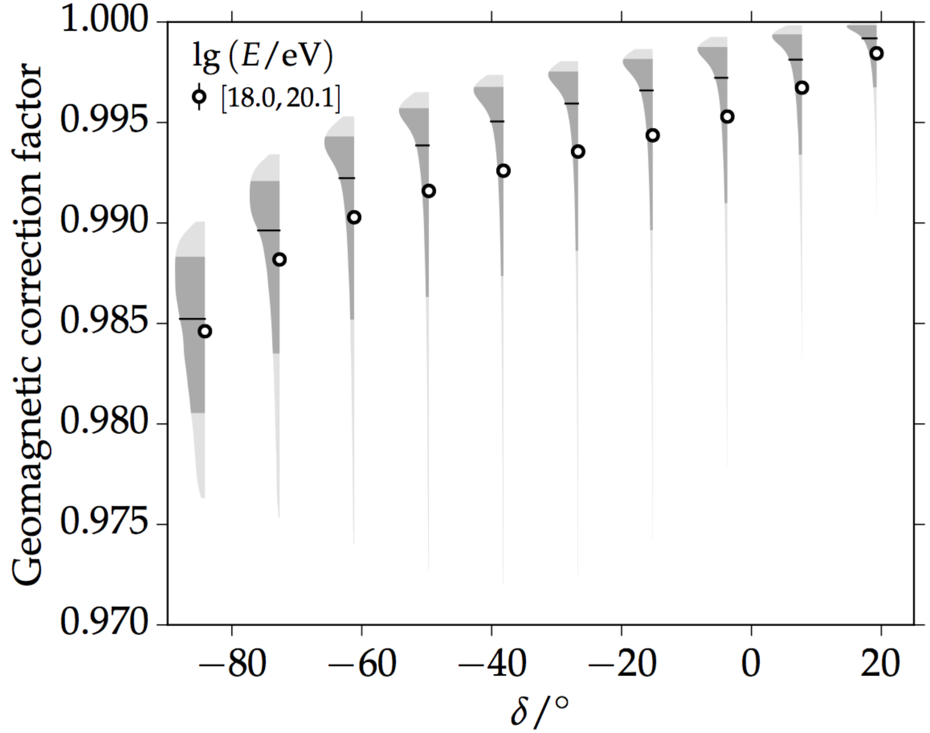


- **<u>This is only a starting point</u>: refine the analyses tools, cross checks, systematics, ...**

- **Include the measurement of the energy spectrum with the Auger 'inclined' events ($\theta > 60^0$)**

back-up slides

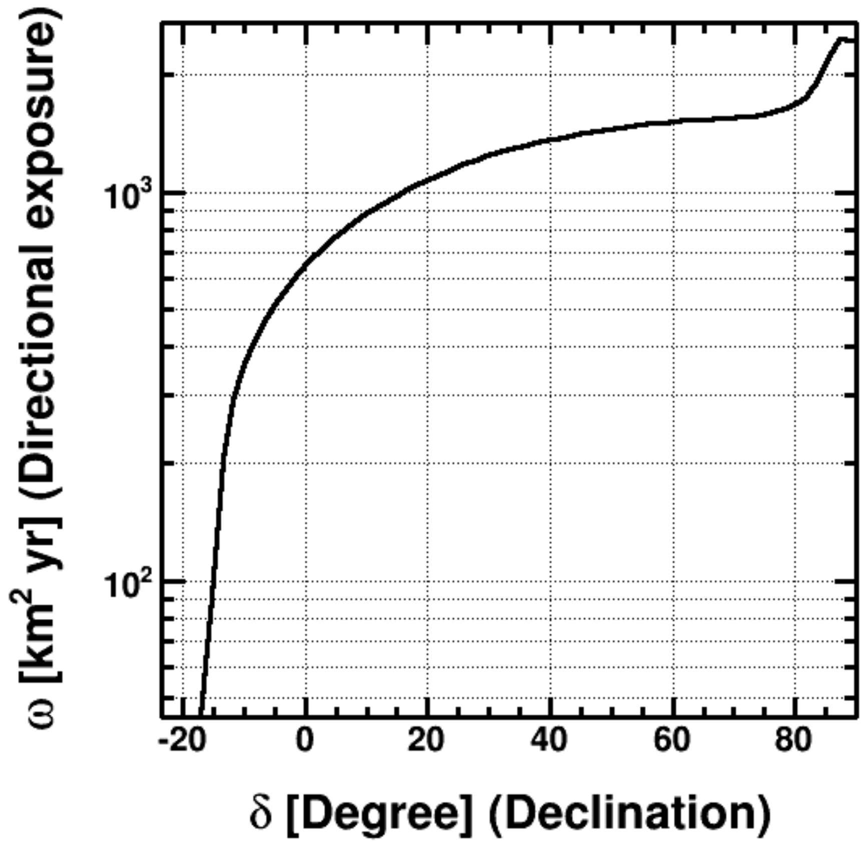

lg (E/eV)
[18.0, 20.1]
Weather correction factor
1.06
1.04
1.02
1.00
0.98
0.96
0.94
2006
2008
2010
2012
2014
Year


lg (E/eV)
[18.0, 20.1]
Geomagnetic correction factor
1.000
0.995
0.990
0.985
0.980
0.975
0.970
−80
−60
−40
−20
0
20
δ/°

TA SD spectrum in the common declination band using the '1/ω method' developed by the anisotropy WG

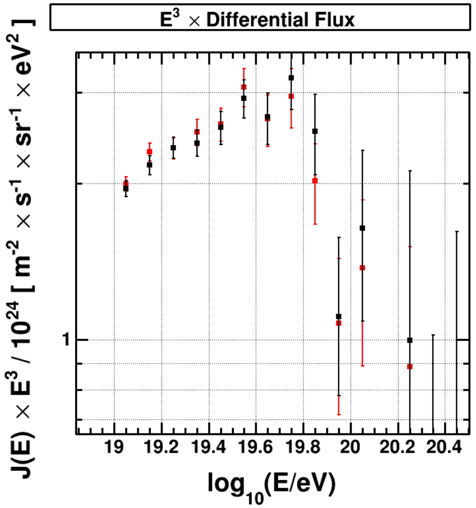
- directional exposure calculated for the TA SD data set $\theta<55^0$, normalized to 8300 km^2 sr yr

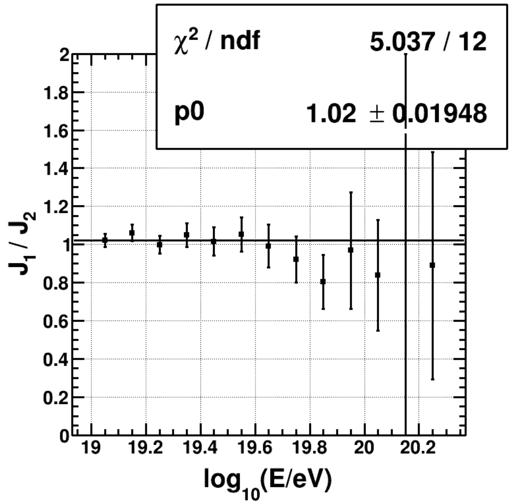
- use exposure normalization calculated by MC for each individual energy bin (0.1 log10(E/eV) binning)



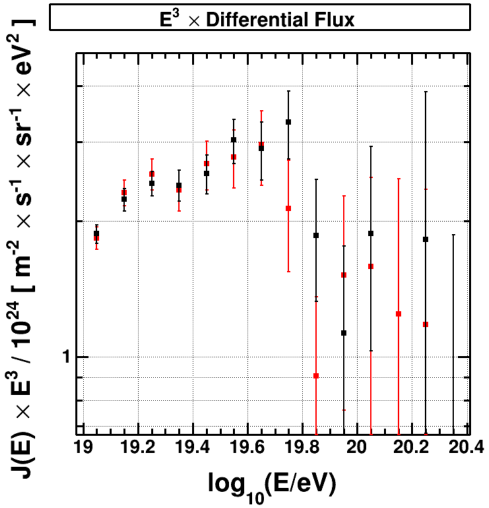
TA check: compare the spectra calculated with ‘1/ω method’ (red) with full TA SD MC (black)

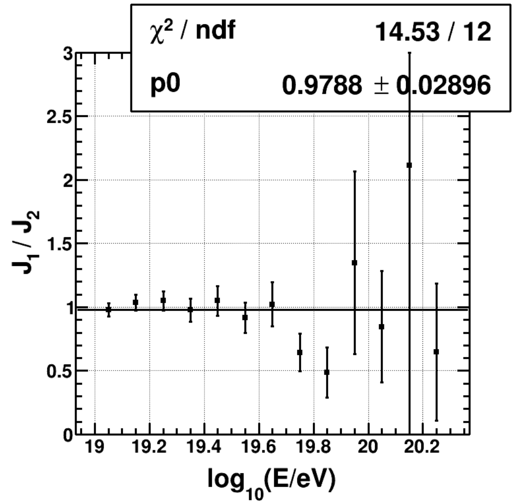
δ in [-16^0,90^0]



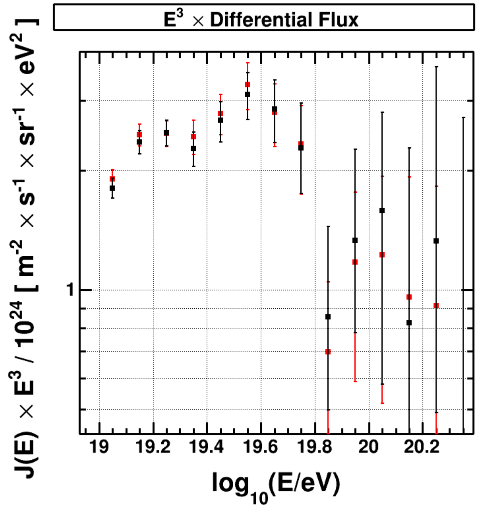


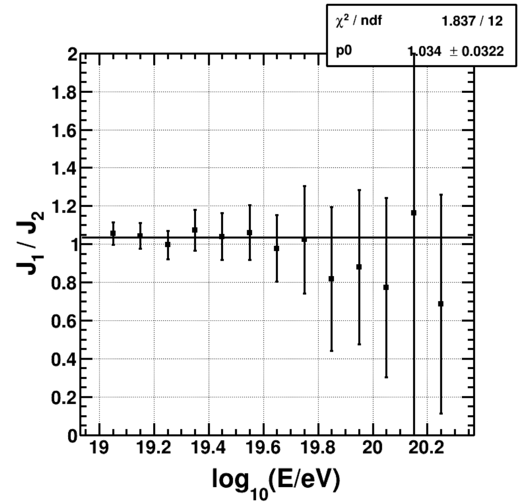
δ in [-6^0,24.8^0]





δ in [-15^0,24.8^0]





good agreement in all declination bands