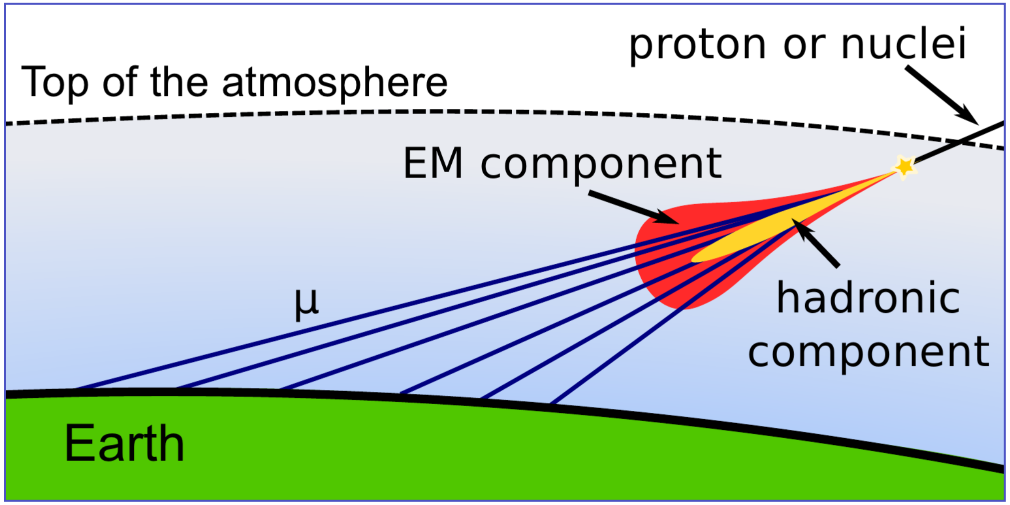
Energy spectrum derived from inclined air showers detected with the Pierre Auger Observatory

Inés Valiño Rielo
Univ. Santiago de Compostela, Spain
for the Pierre Auger Collaboration

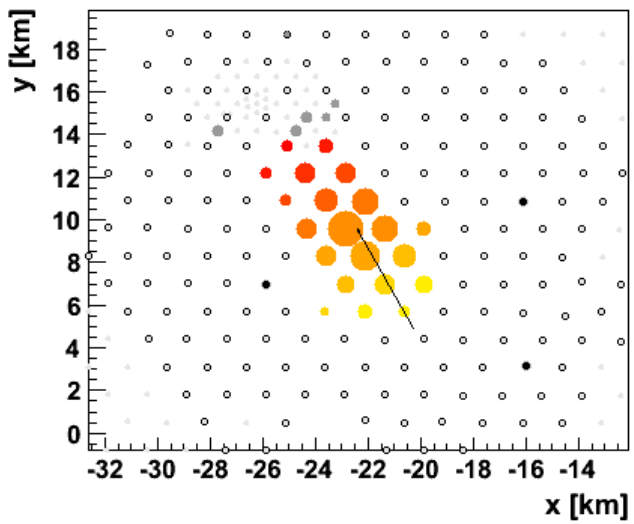
TA–Auger Workshop on the UHECR spectrum
Brussels 12-13 October 2017

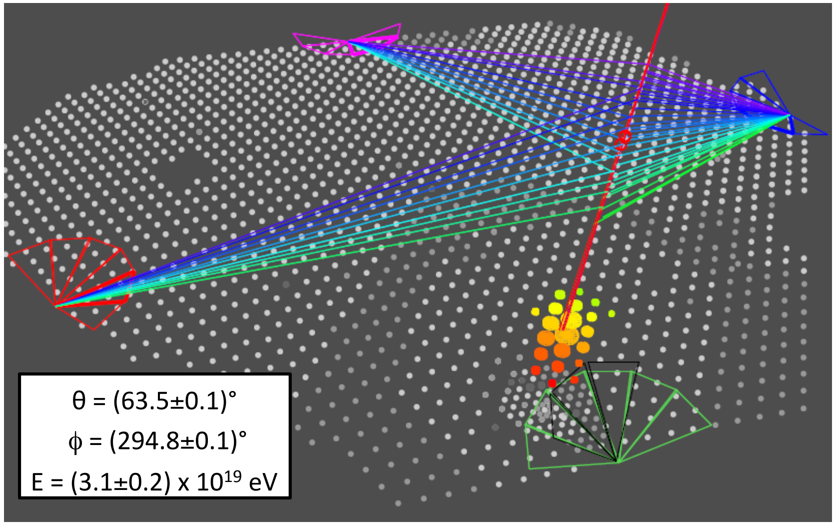
Inclined showers

- Induced by cosmic rays arriving with $\theta > 60°$
- Muons dominate at ground as the EM component is absorbed in the atmosphere
- Inclined showers generate asymmetric and elongated patterns in the SD array



Inclined showers at Auger





An inclined shower observed with the Surface Detector (left) and simultaneously with the Fluorescence Detector ("hybrid event", right)

- Inclined showers generate asymmetric and elongated signal patterns in the SD array
- Asymmetry due to geometric and attenuation effects and geomagnetic deviations of muons.
- Inclined showers require specific reconstruction methods
- Full efficiency at E > 4 EeV
- Zenith-angle range: $60° < \theta < 80°$

Reconstruction of the SD energy estimator

Basic idea:

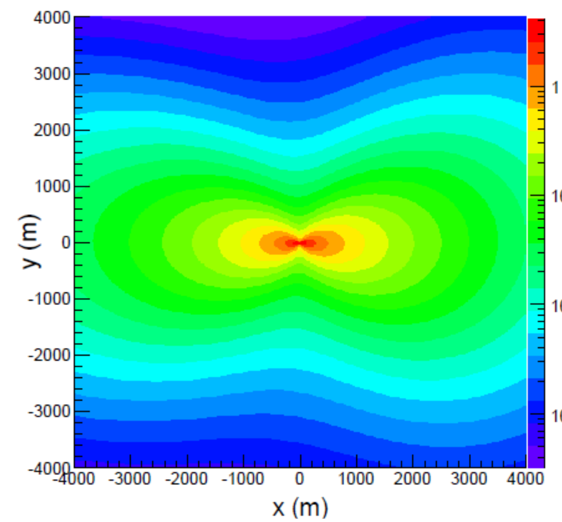
- shape of the muon distribution is approximately universal for a given shower direction and only its overall normalisation depends on the shower energy and primary mass
- Dependeces on E and mass are factorised out into the overall normalisation N_{19} (shower size) and dependence on the shower direction into the reference muon distribution

Measured signals fitted to the expected 2D muon distribution at ground:

$$\rho_\mu(\vec{r}) = N_{19}\,\rho_{\mu,19}(\vec{r};\theta,\phi)$$

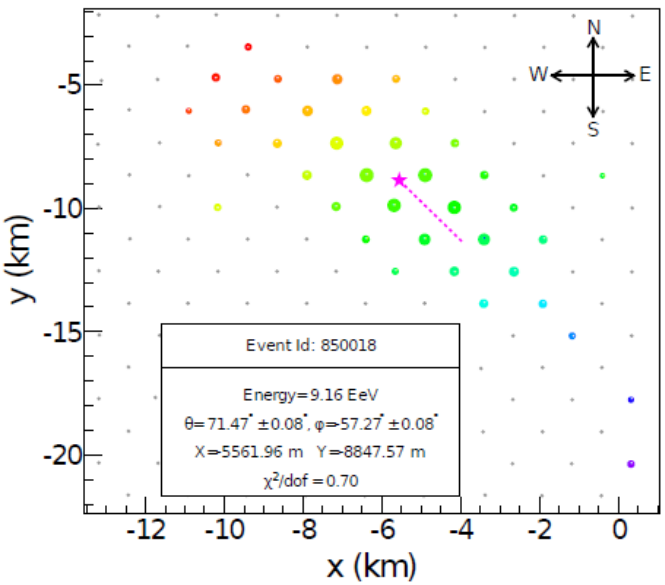
N_{19}: shower-size estimator

$\rho_{\mu,19}$: reference profile from parameterisation of muon density at ground for 10 EeV p showers simulated with QGSJetII-03.

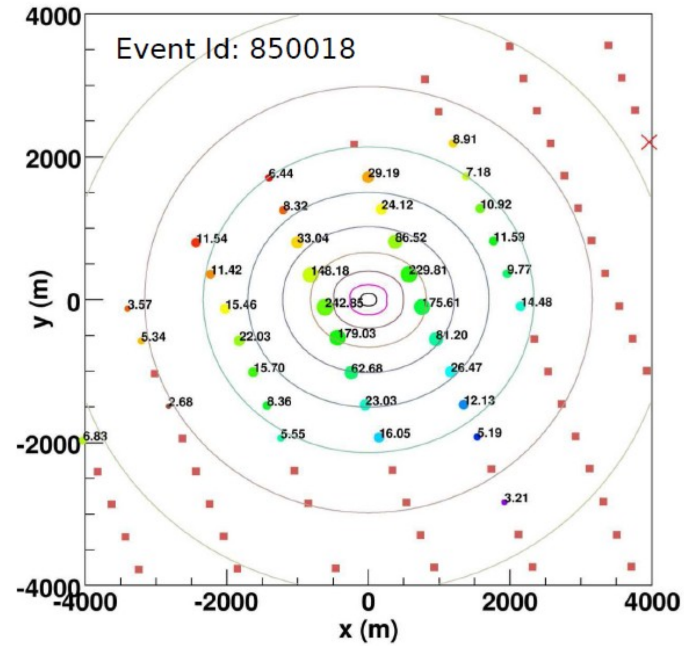


Example μ-distribution for 10 EeV proton showers with θ=80° and φ=0° simulated with QGSJetII-03

Example :



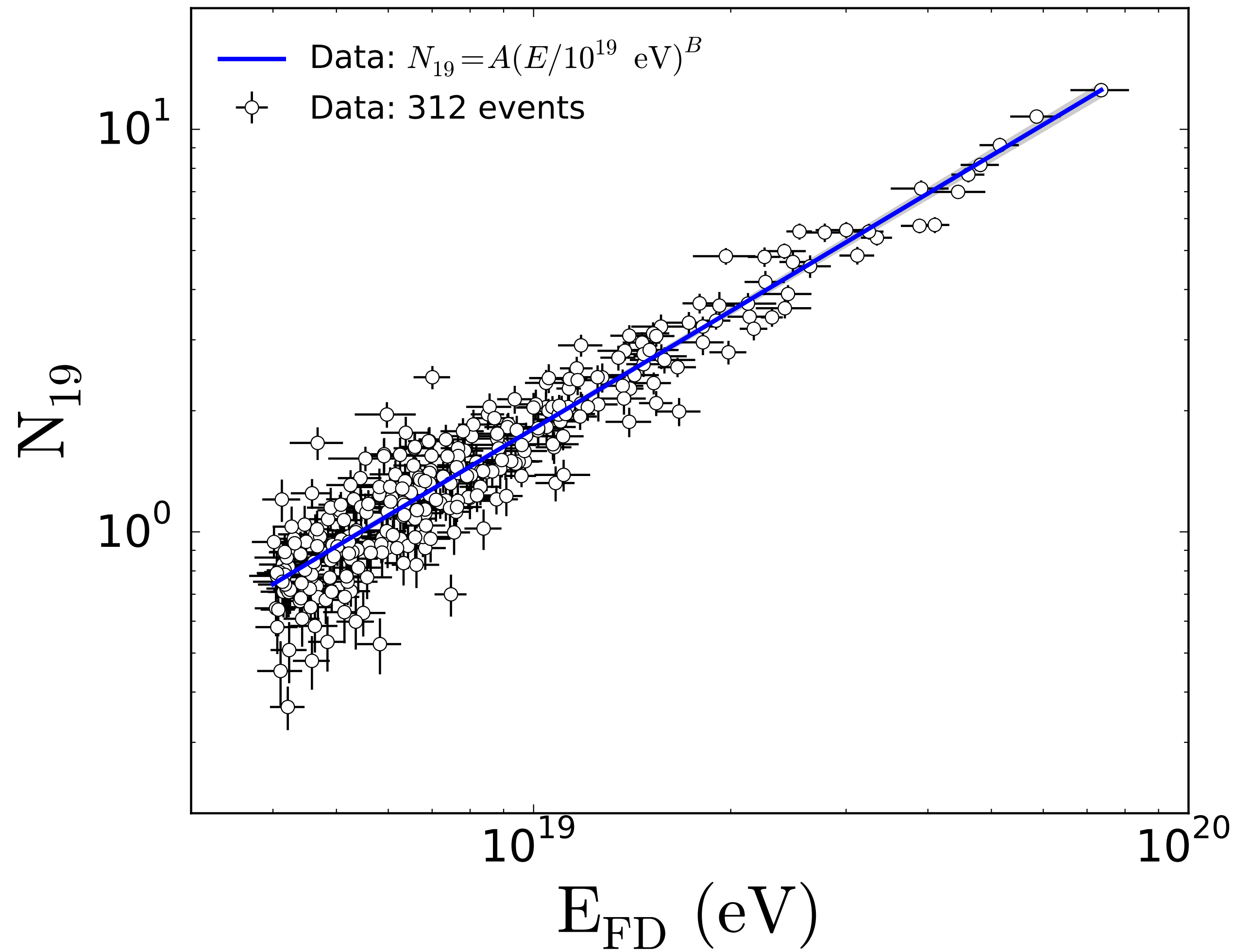
elongated and asymmetric



More details about “inclined” reconstruction in JCAP 08 (2015) 049

N_{19} uncert. associated with the unknown primary mass in data and hadronic model assumed for the reference distribution will be absorbed in the calibration procedure

SD energy calibration: hybrid approach

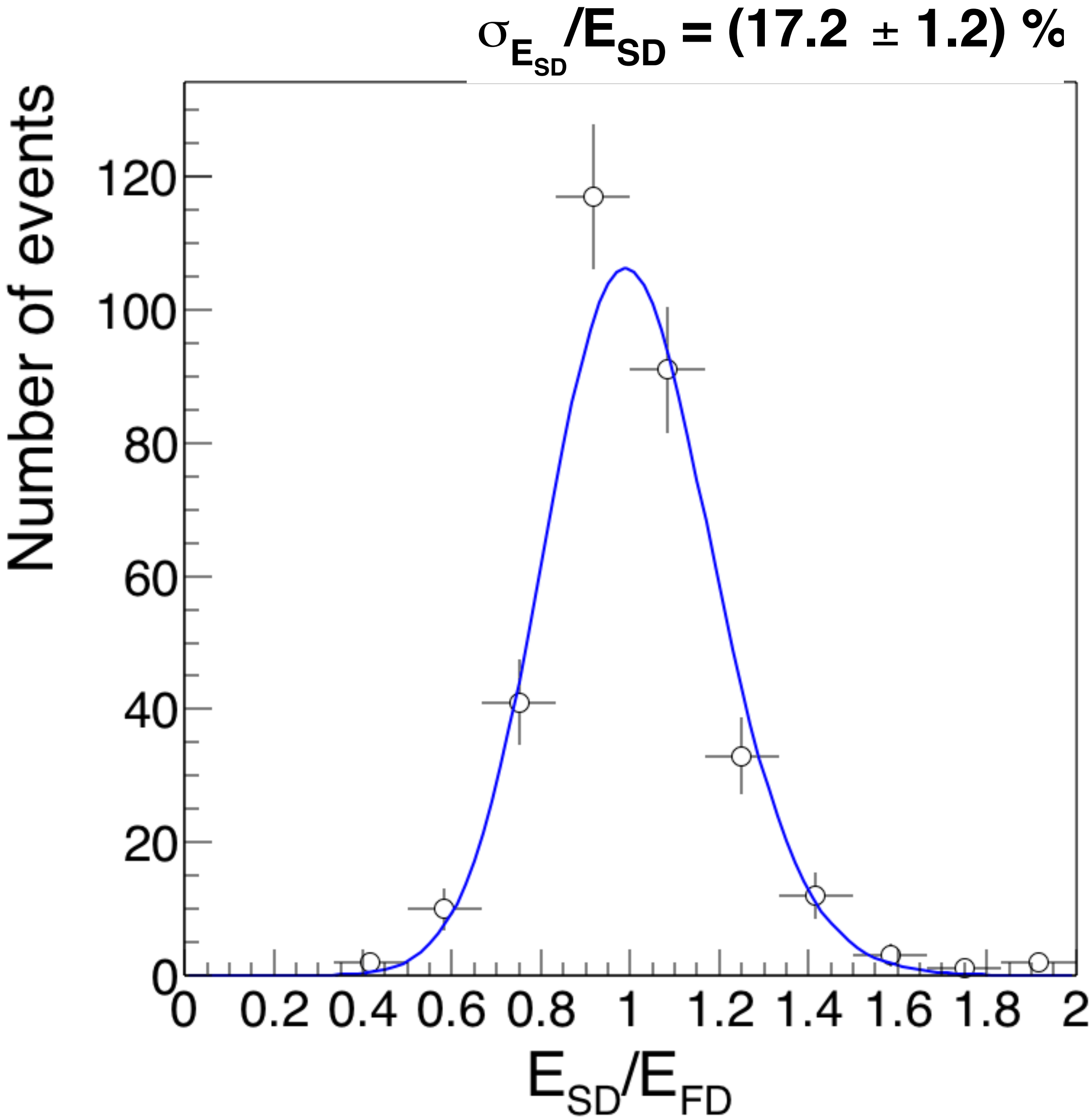


SD-energy scale

$$E_{SD} = A\,(N_{19})^B$$

A [EeV]	5.45 ± 0.08
B	1.03 ± 0.02

SD energy resolution



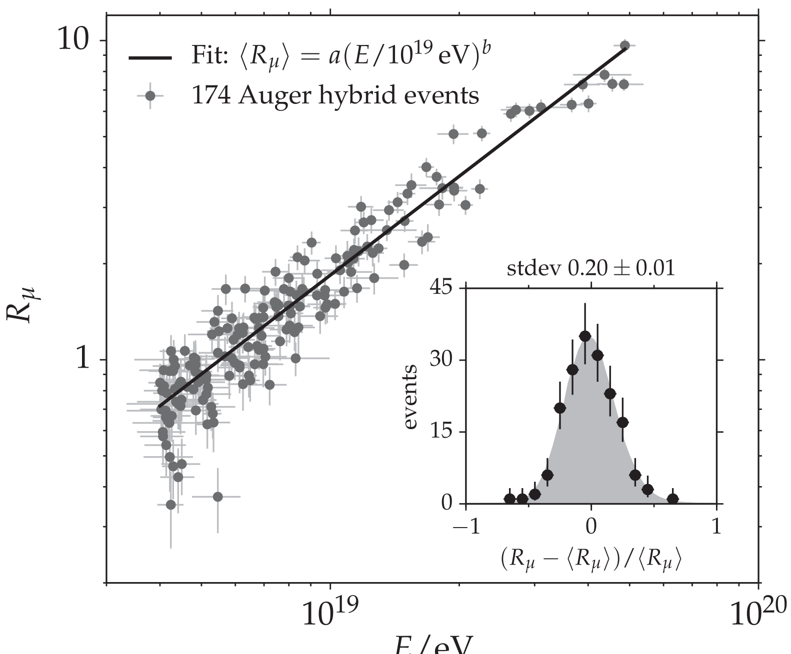
Muon content in inclined showers

The Pierre Auger Collaboration Phys. Rev. D 91 032003 (2015)

- Muon content is a powerful tracer of the primary mass

$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta \qquad \frac{\mathrm{d}\ln N_\mu}{\mathrm{d}\ln E} = \beta + (1-\beta)\frac{\mathrm{d}\ln A}{\mathrm{d}\ln E}$$

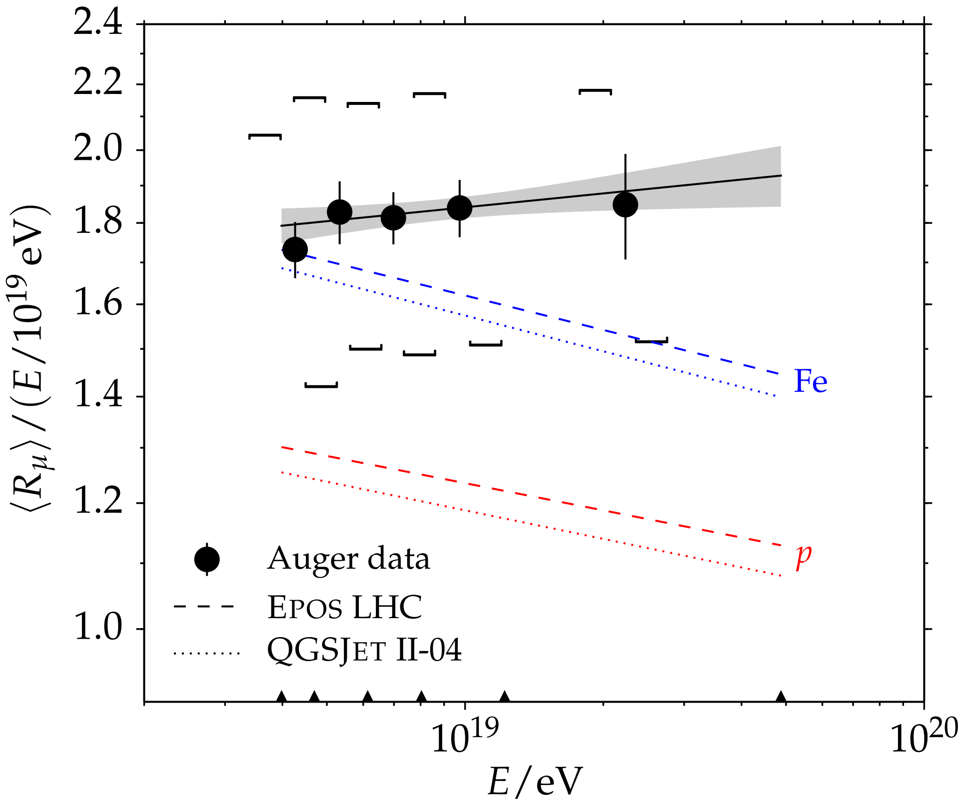
- N_{19} provides a direct measurement of the relative muon number with bias < 5% (tested with MC):
  - Rμ defined as the measured N_{19} after correction for an average bias

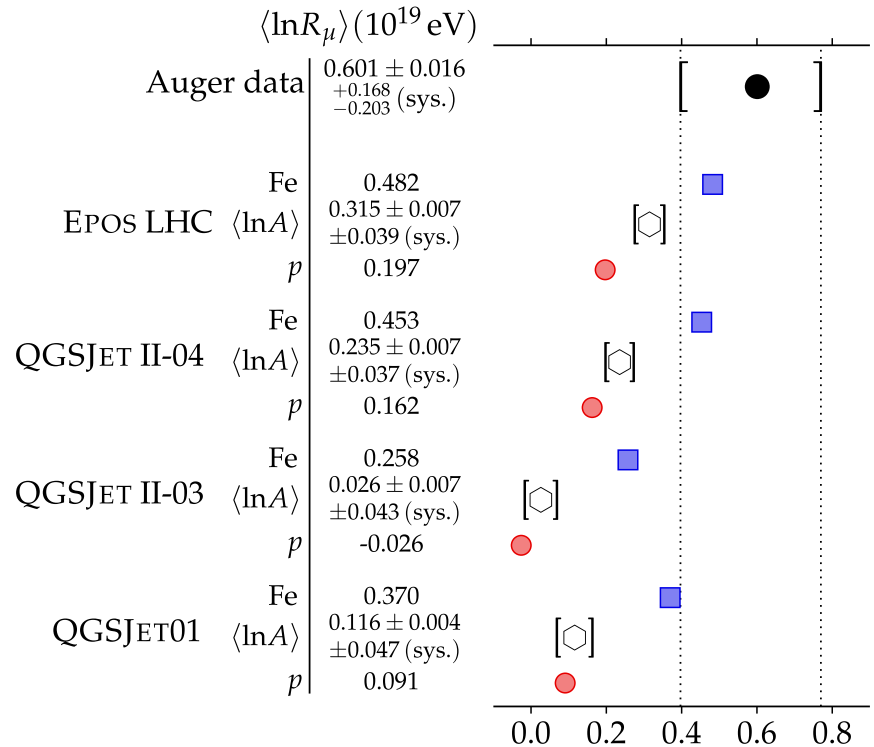


$$a = \langle R_\mu\rangle(10^{19}\ \mathrm{eV}) = (1.841 \pm 0.029 \pm 0.324(\mathrm{sys})),$$

$$b = \mathrm{d}\langle\ln R_\mu\rangle/\mathrm{d}\ln E = (1.029 \pm 0.024 \pm 0.030(\mathrm{sys}))$$

Testing hadronic models with Rμ



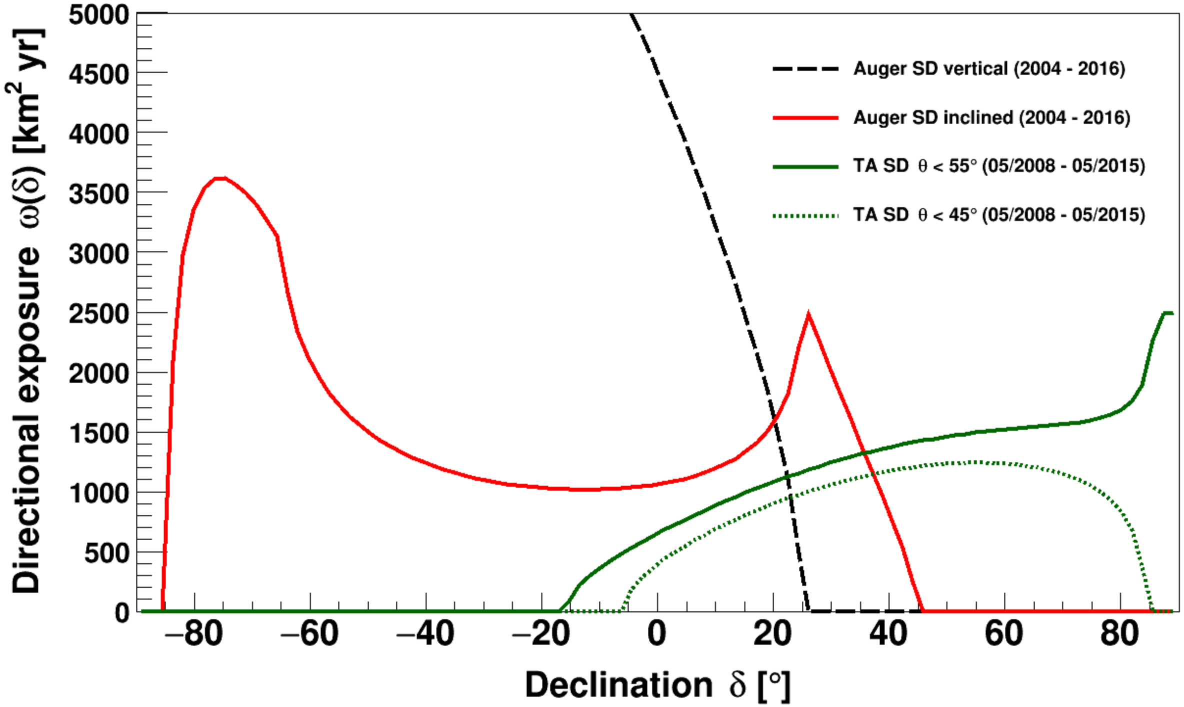


Muon deficit in simulations of 30 to 80% at 10^{19} eV, depending on the model

Hypothesis of a constant proton composition disfavored at the level of 2.2σ

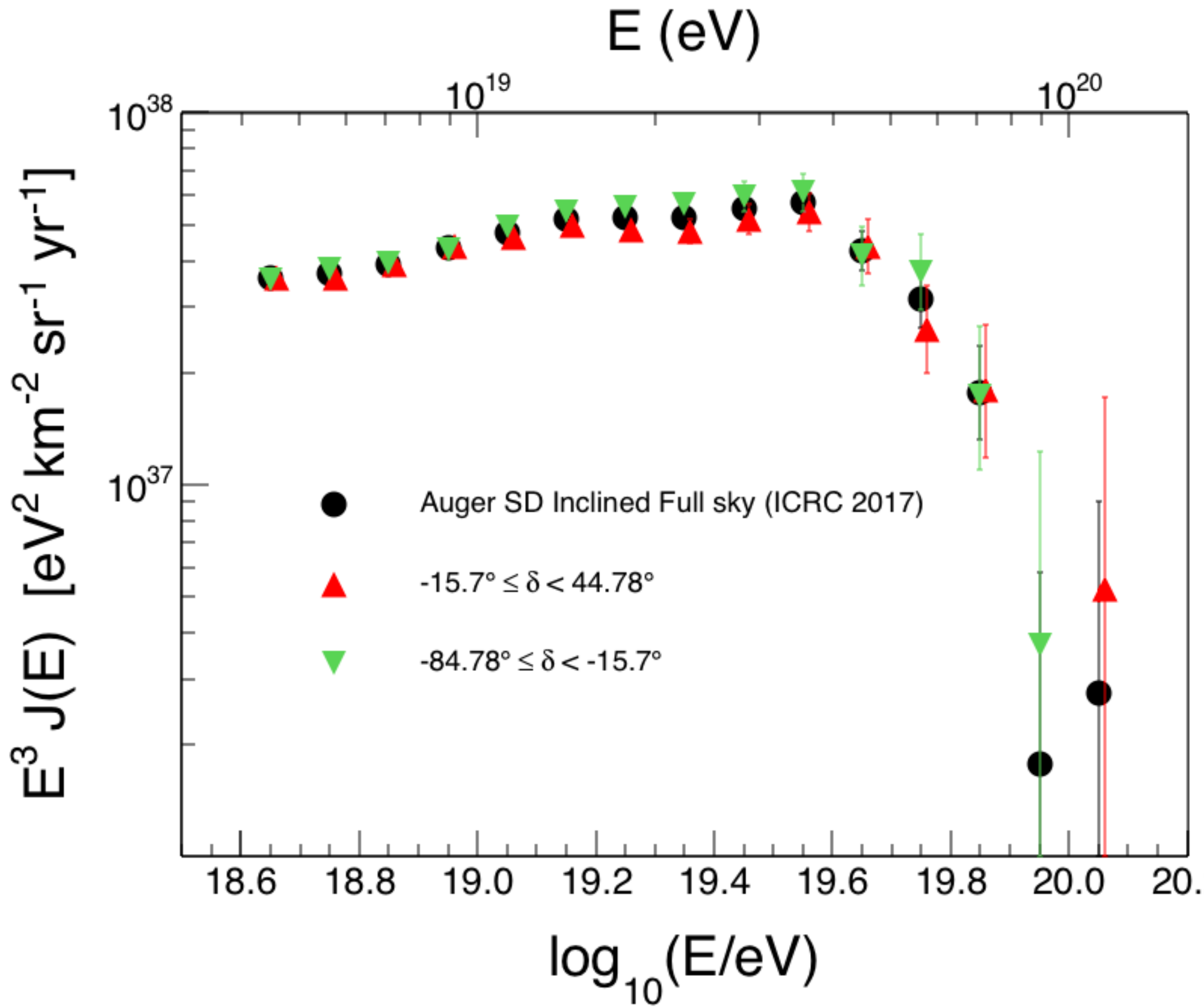
Inclined spectrum for our declination studies:

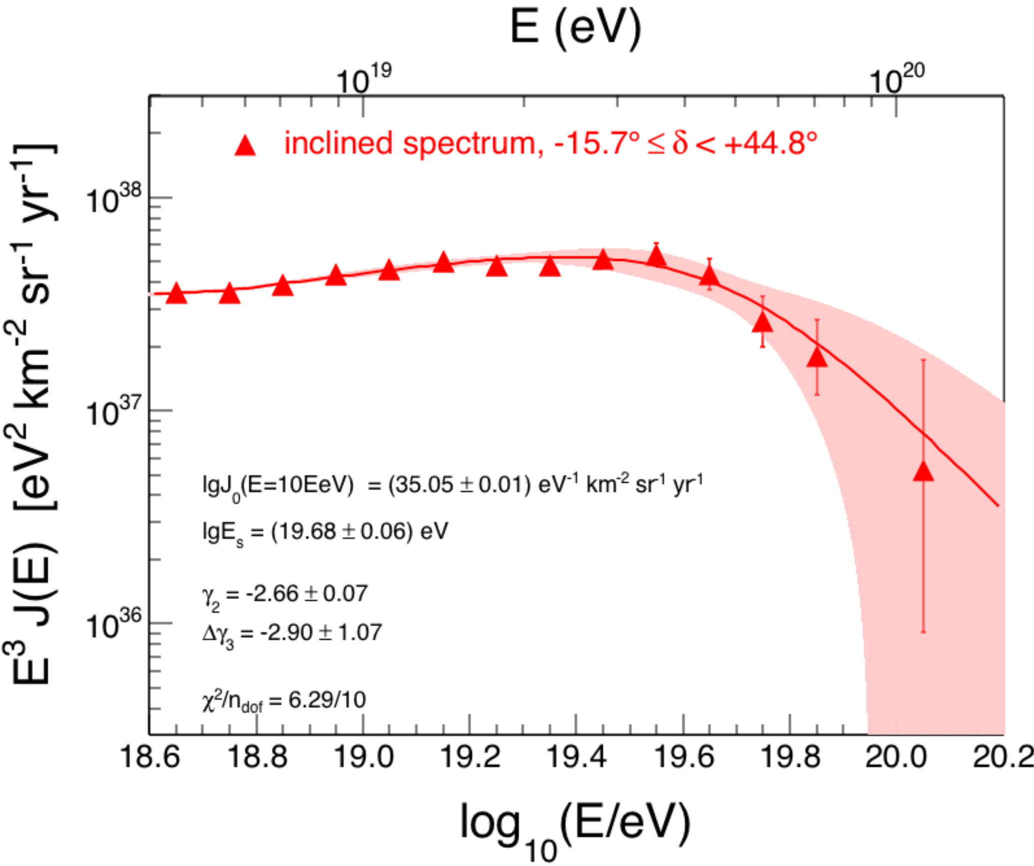
all are advantages!



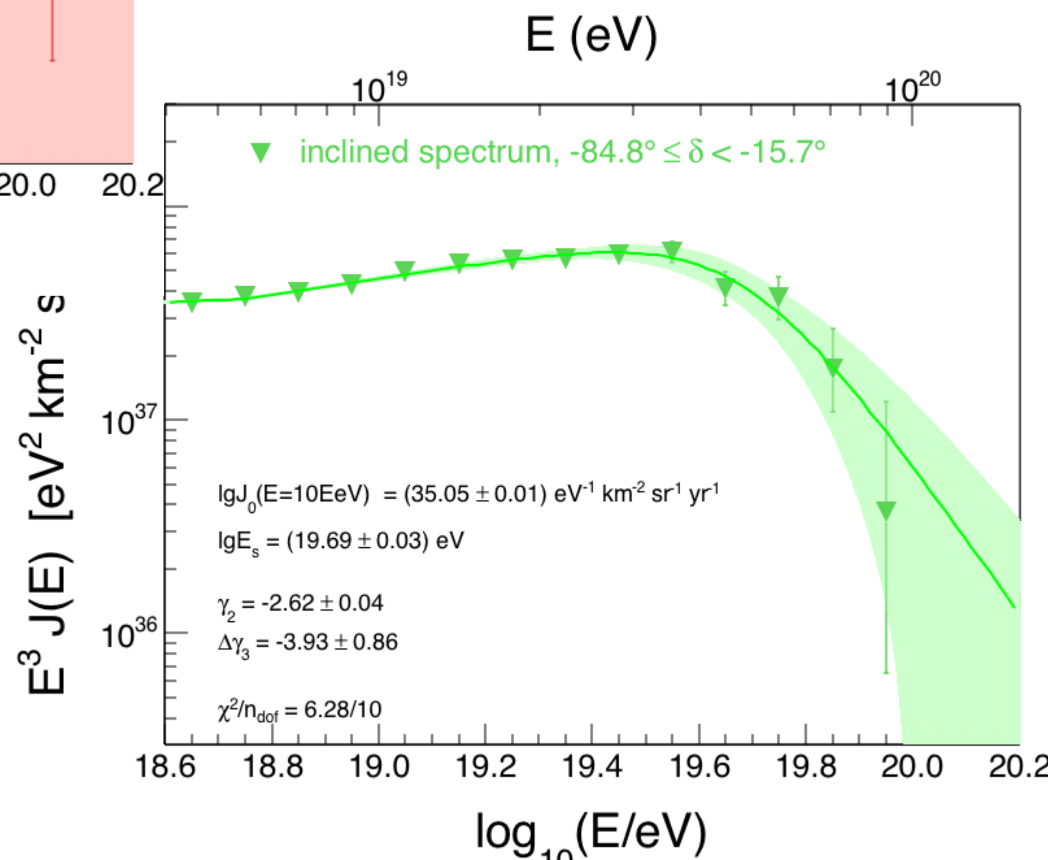
- To enlarge the common band in δ from (-15.7°, 24.8°) to **(-15.7°, 44.8°)** **: ~ +50 %**
- The statistics of Auger data sample is increased by a ~ 30%
- Directional exposure has a similar shape to the TA one.

Inclined spectrum in and out common region with TA





E (eV)
10^{19}
10^{20}
inclined spectrum, -15.7° ≤ δ < +44.8°
E^3 J(E) [eV^2 km^{-2} sr^{-1} yr^{-1}]
10^{38}
10^{37}
10^{36}
lgJ$_0$(E=10EeV) = (35.05 ± 0.01) eV^{-1} km^{-2} sr^{-1} yr^{-1}
lgE$_s$ = (19.68 ± 0.06) eV
γ_2 = -2.66 ± 0.07
$\Delta\gamma_3$ = -2.90 ± 1.07
χ^2/n_{dof} = 6.29/10
18.6 18.8 19.0 19.2 19.4 19.6 19.8 20.0 20.2
log_{10}(E/eV)



E (eV)
10^{19}
10^{20}
inclined spectrum, -84.8° ≤ δ < -15.7°
E^3 J(E) [eV^2 km^{-2} s
10^{37}
10^{36}
lgJ$_0$(E=10EeV) = (35.05 ± 0.01) eV^{-1} km^{-2} sr^{-1} yr^{-1}
lgE$_s$ = (19.69 ± 0.03) eV
γ_2 = -2.62 ± 0.04
$\Delta\gamma_3$ = -3.93 ± 0.86
χ^2/n_{dof} = 6.28/10
18.6 18.8 19.0 19.2 19.4 19.6 19.8 20.0 20.2
log_{10}(E/eV)

PROPOSAL TO THE WG:

to use the inclined spectrum for our future studies

Number of HAS events in the δ -range [24.8°,44.8°]

$\log_{10}E$	# events
19.25	100
19.35	54
19.45	33
19.55	27
19.65	18
19.75	5
19.85	2