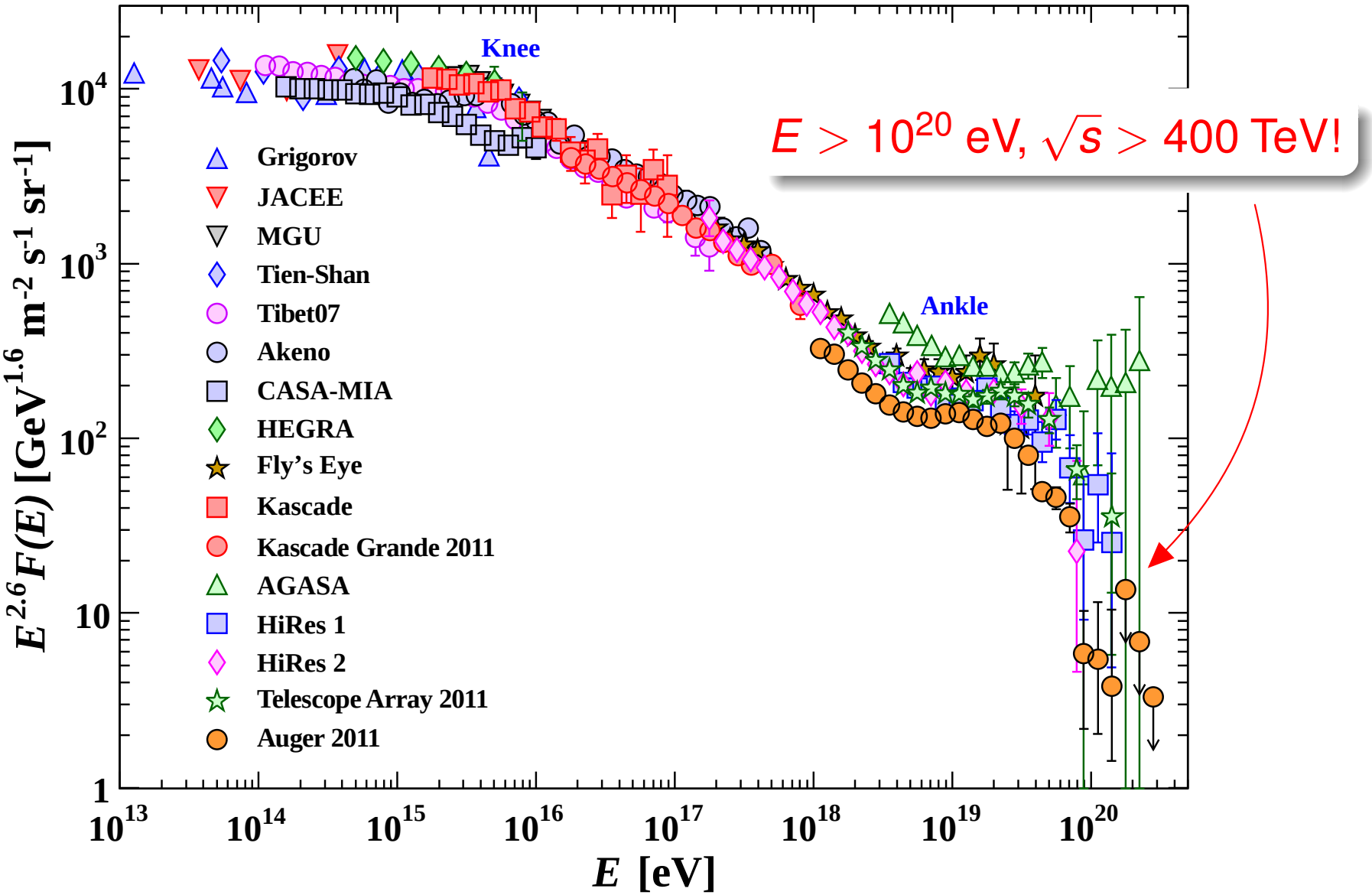
Ultra-High-Energy Cosmic Rays

Observations and Future Directions

Michael Unger
NYU&KIT

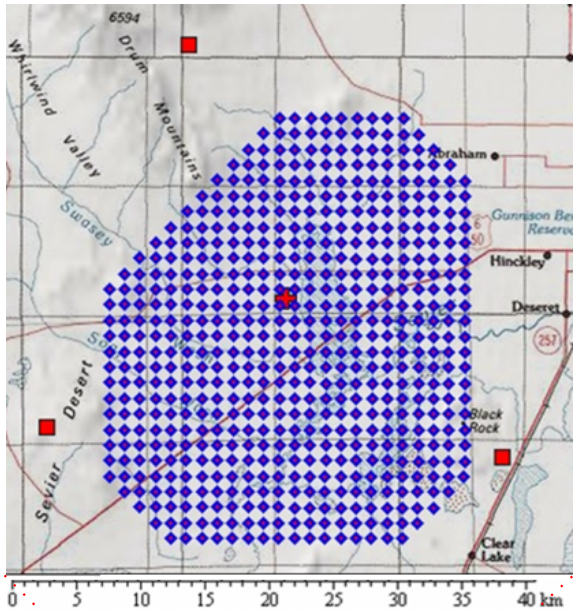
Ultra-High-Energy Cosmic Rays (UHECRs)

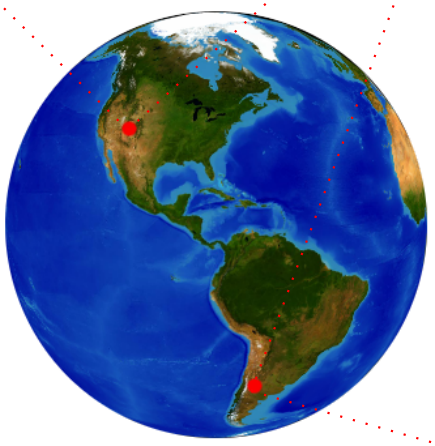


Particle Data Group 2011

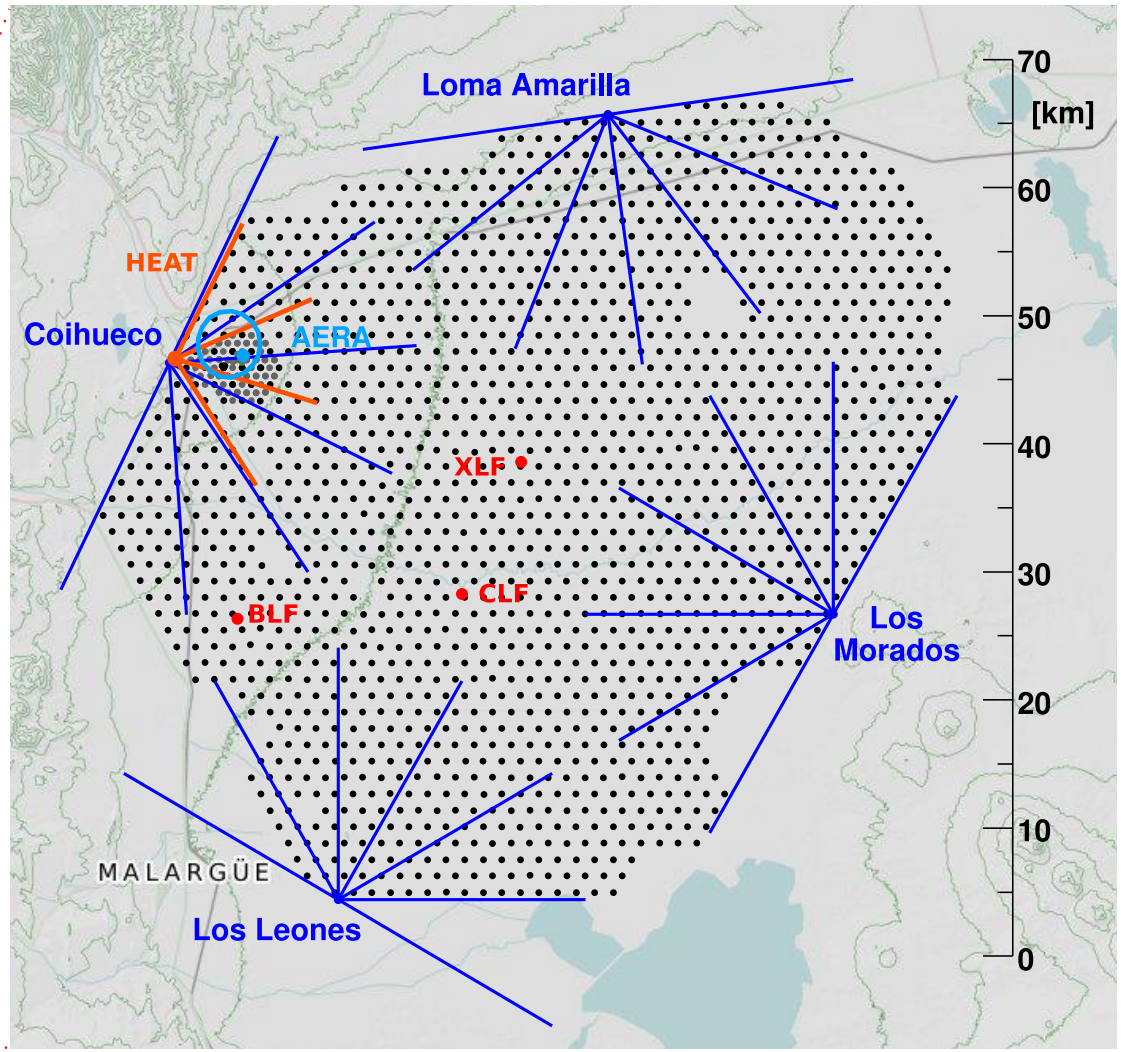
UHECR Observatories

Telescope Array





Pierre Auger Observatory



UHECR Observatories

Telescope Array

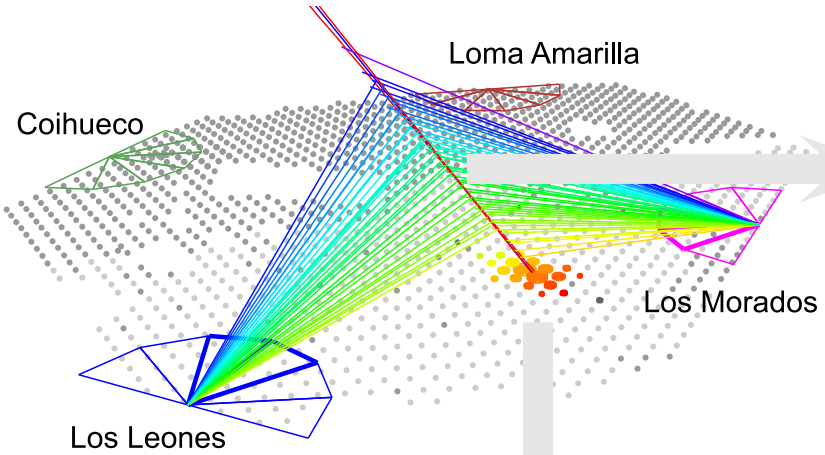
Pierre Auger Observatory

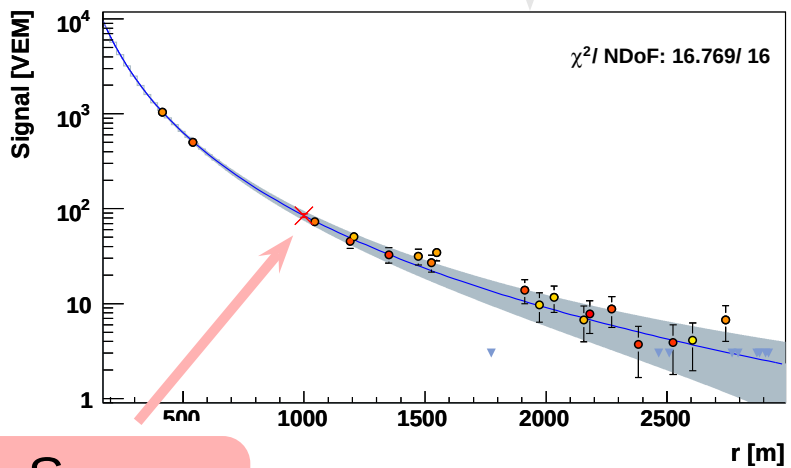
UHECR Working Groups

- **Spectrum** (TA+Auger)
- **Anisotropy** (TA+Auger)
- **Composition** (TA+Auger)
- **Hadronic Interactions** (IC+TA+Auger)
- **Multi-Messenger** (IC+Auger+TA)
- **Anisotropy** (IC+PAO+TA)

UHECR Symposium 2010, Nagoya

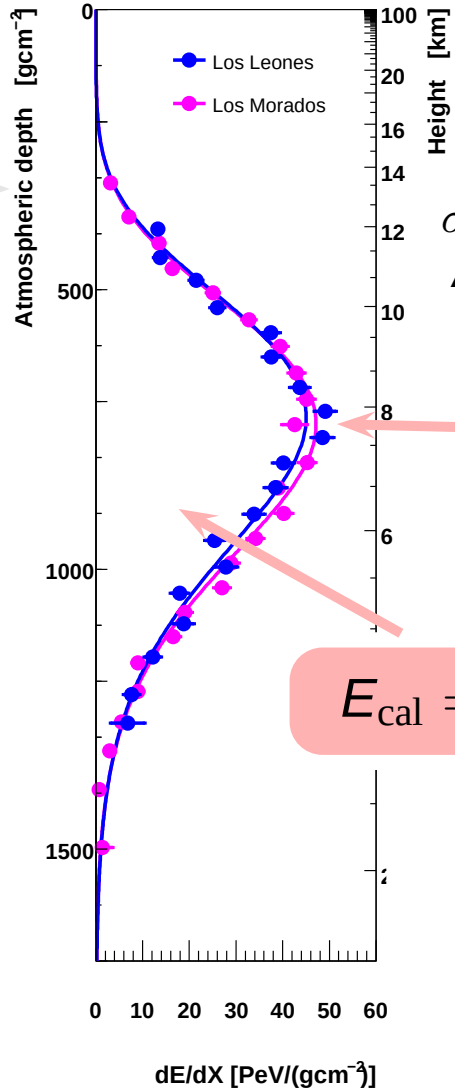
Air Shower Detection in the Hybrid Era





S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\max}} < 20\,\text{g/cm}^2$
$\Delta_{\text{sys}} \approx 15\,\text{g/cm}^2$

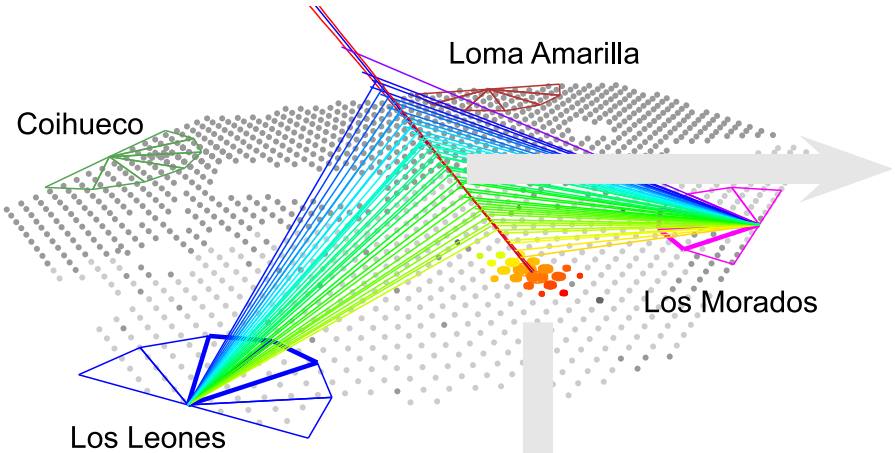
$X_{\max}$

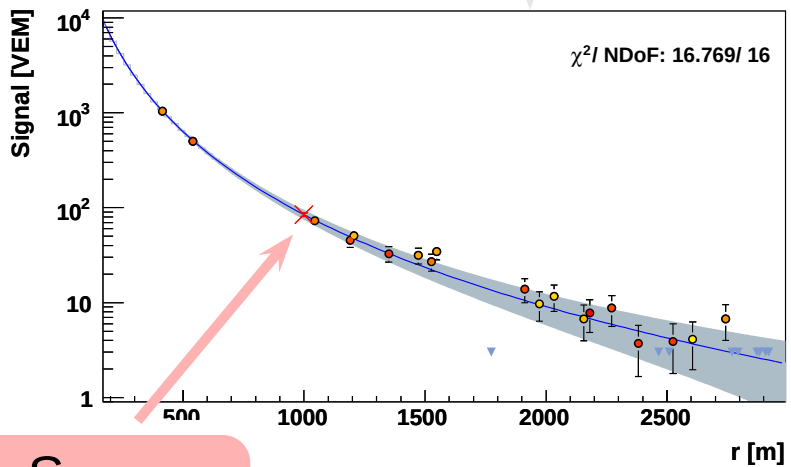
$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 22\,\%$

Auger Event Display

Air Shower Detection in the Hybrid Era

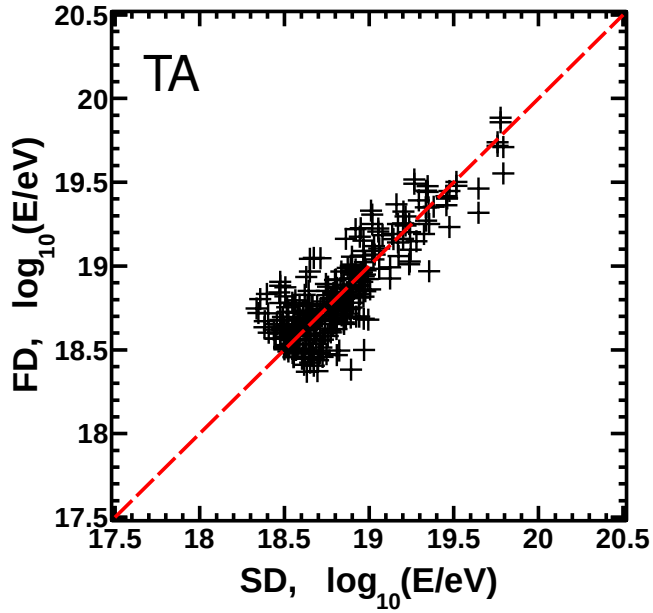


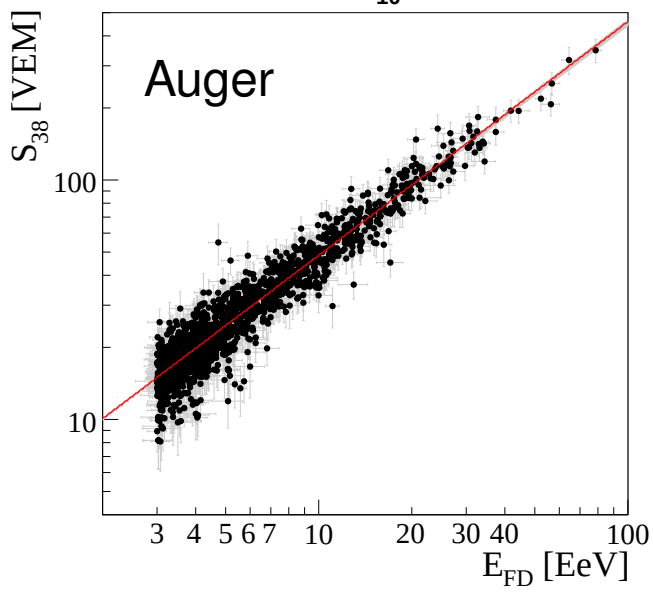


S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$

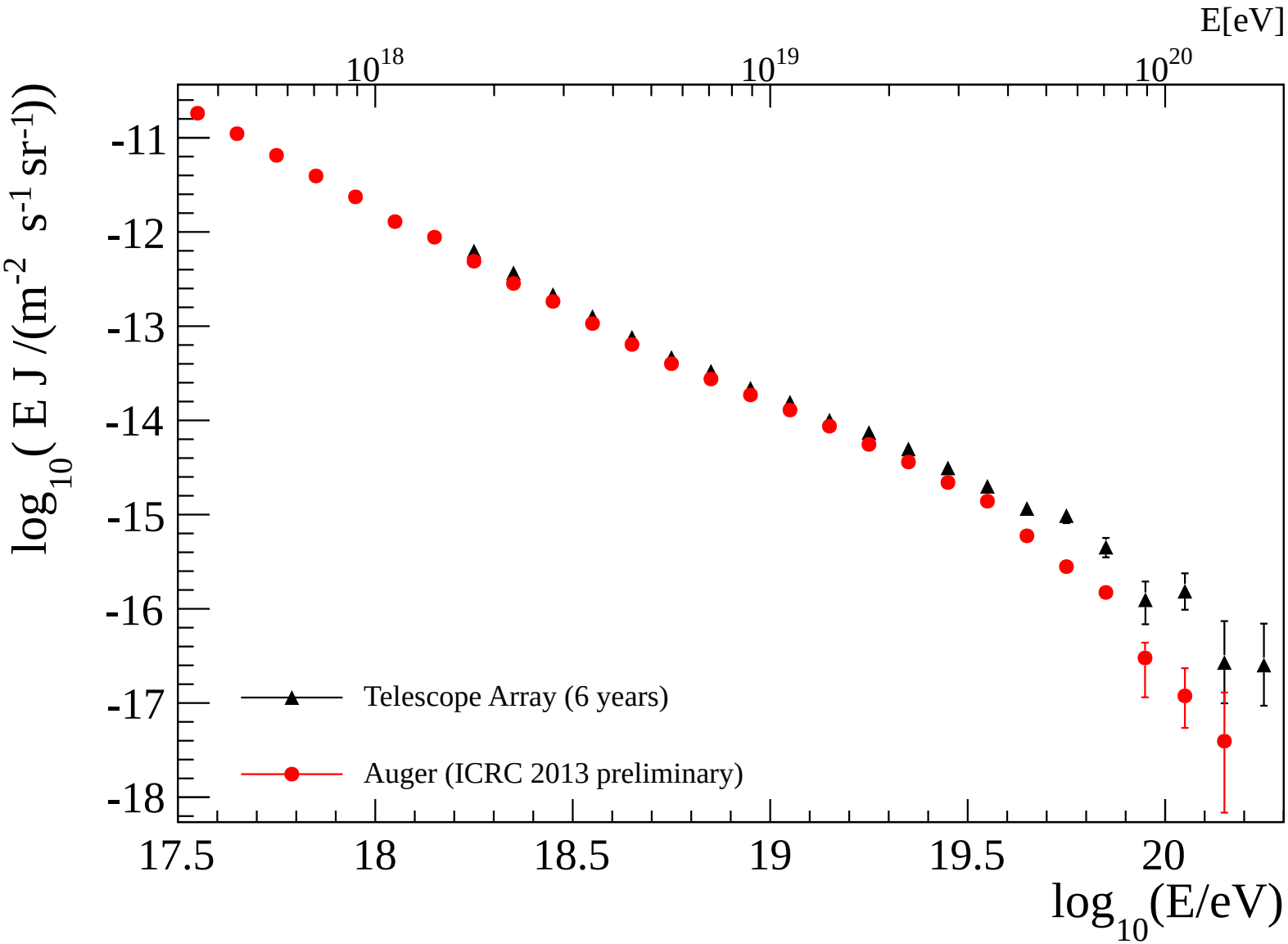
$E \sim$ **model-independent!**





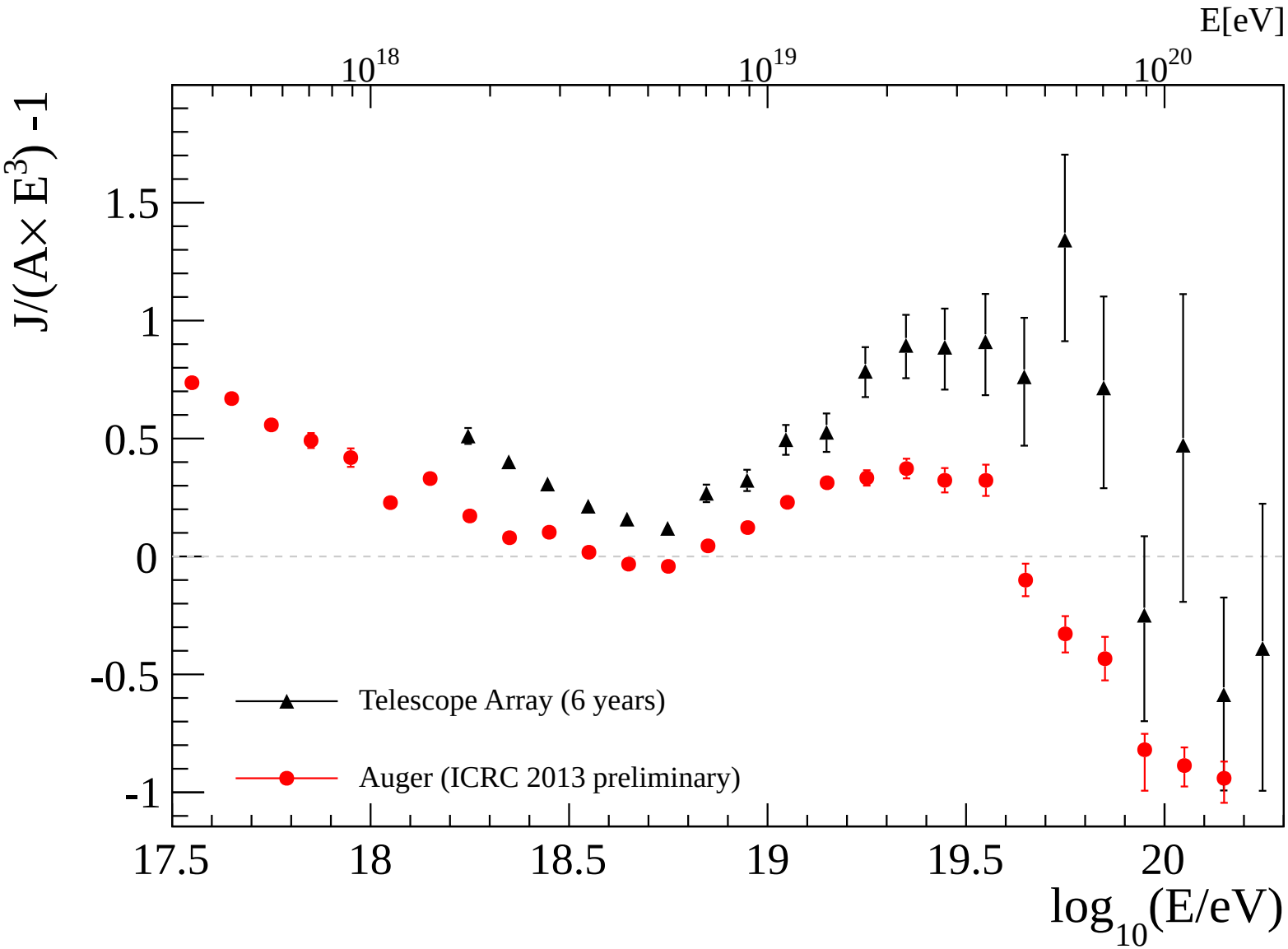
Auger Event Display

UHE Energy Spectrum



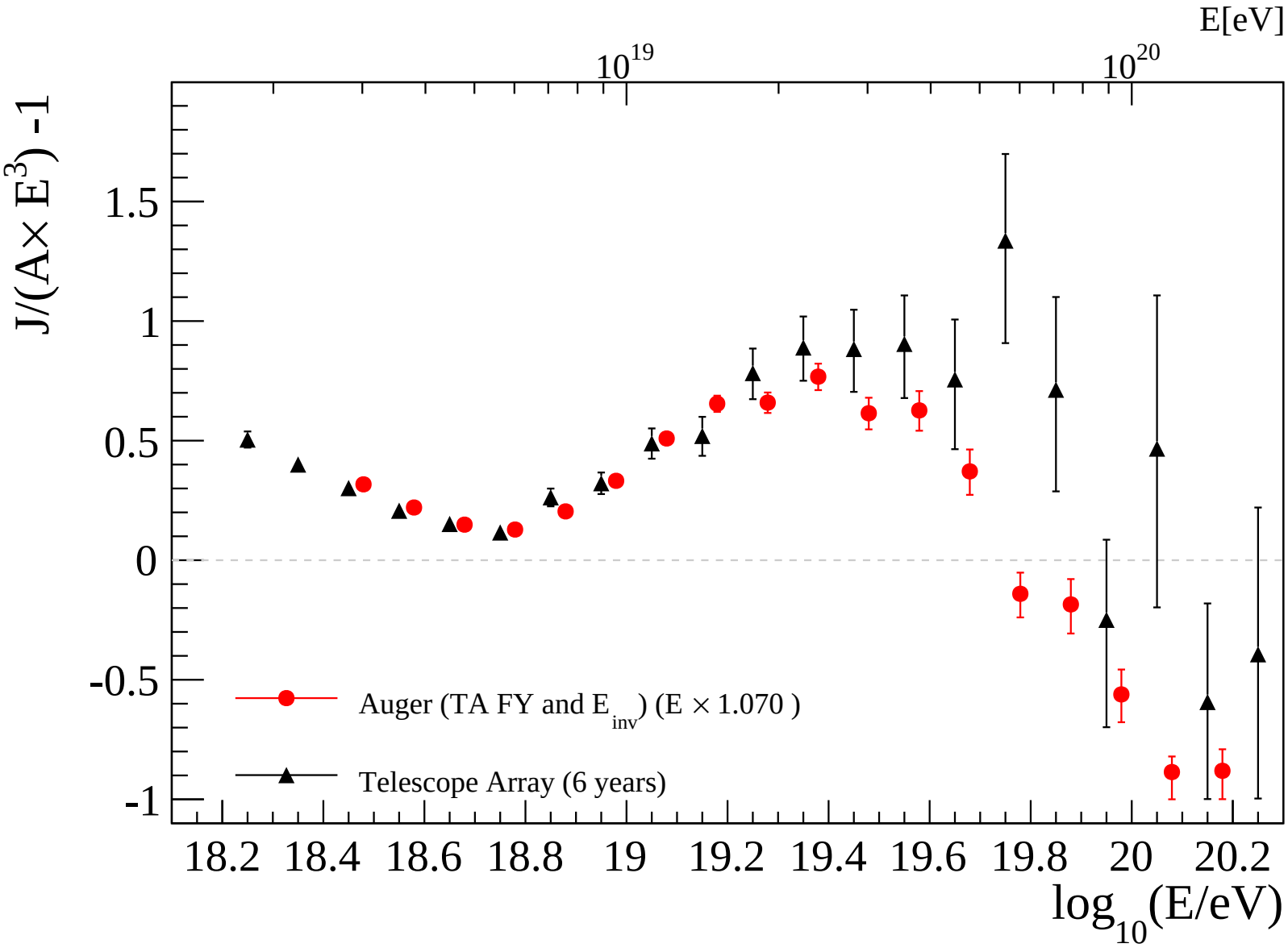
Spectrum WG Report, UHECR14

UHE Energy Spectrum



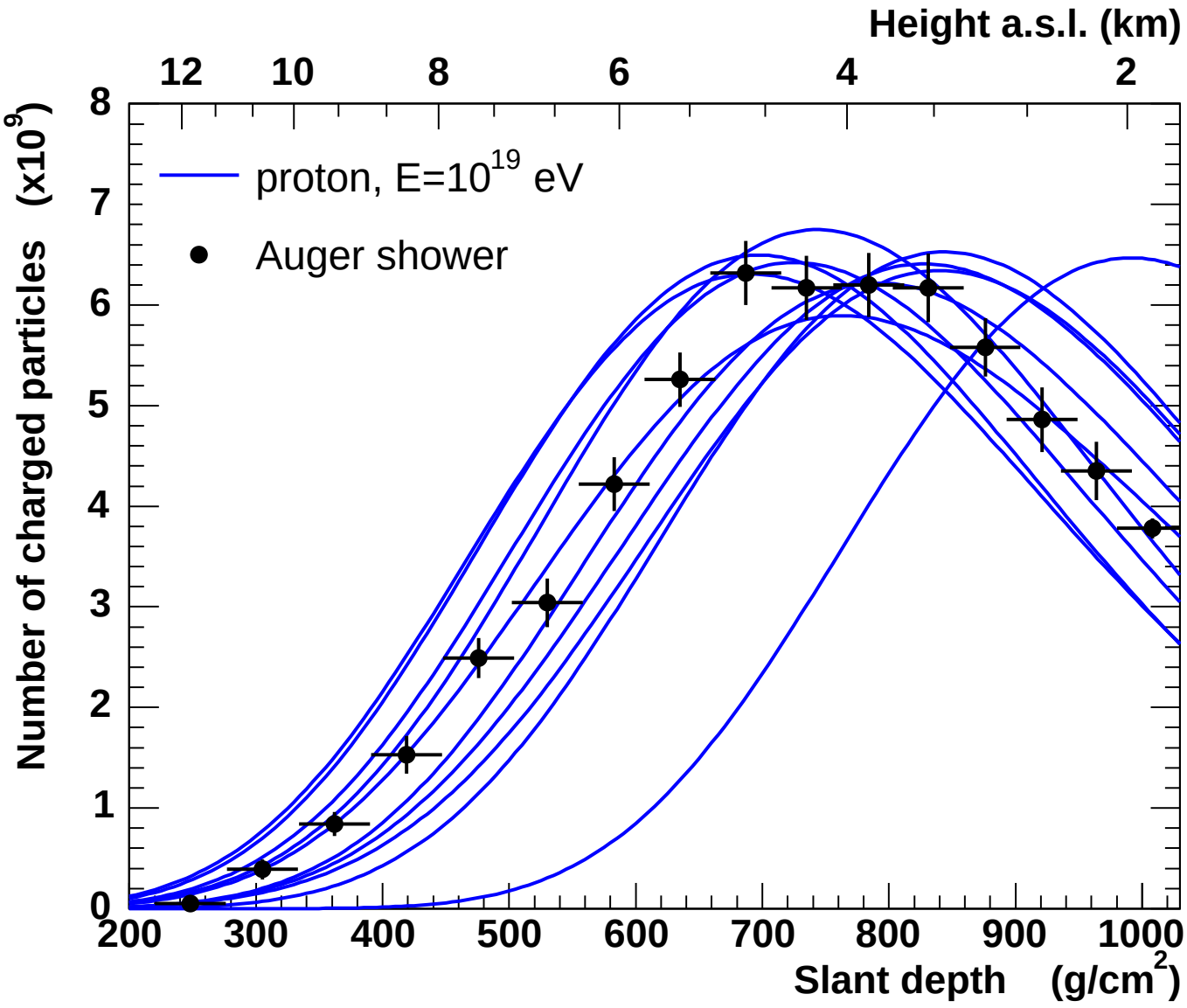
Spectrum WG Report, UHECR14

UHE Energy Spectrum

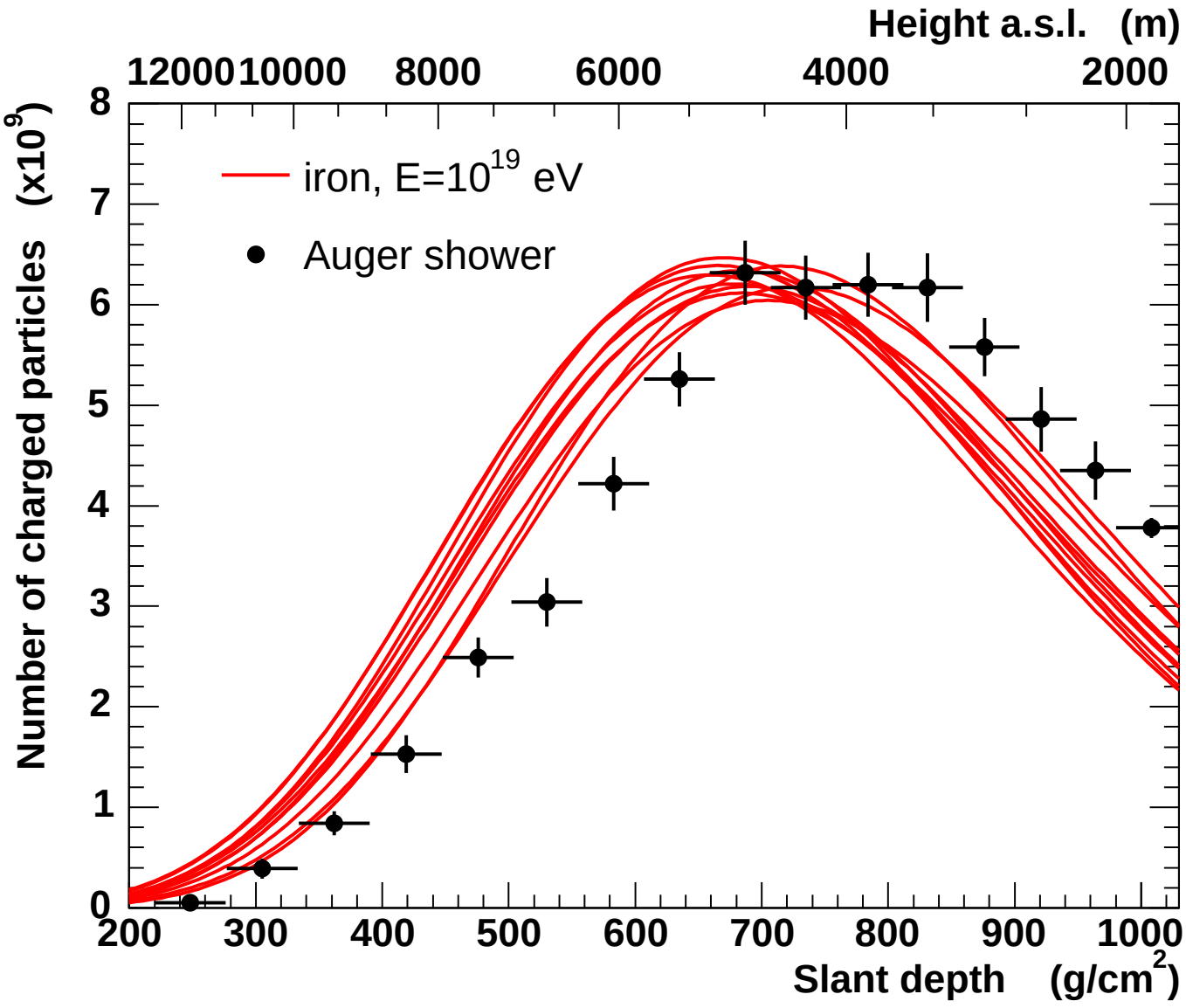


using same fluorescence yield and invisible energy + 7% shift

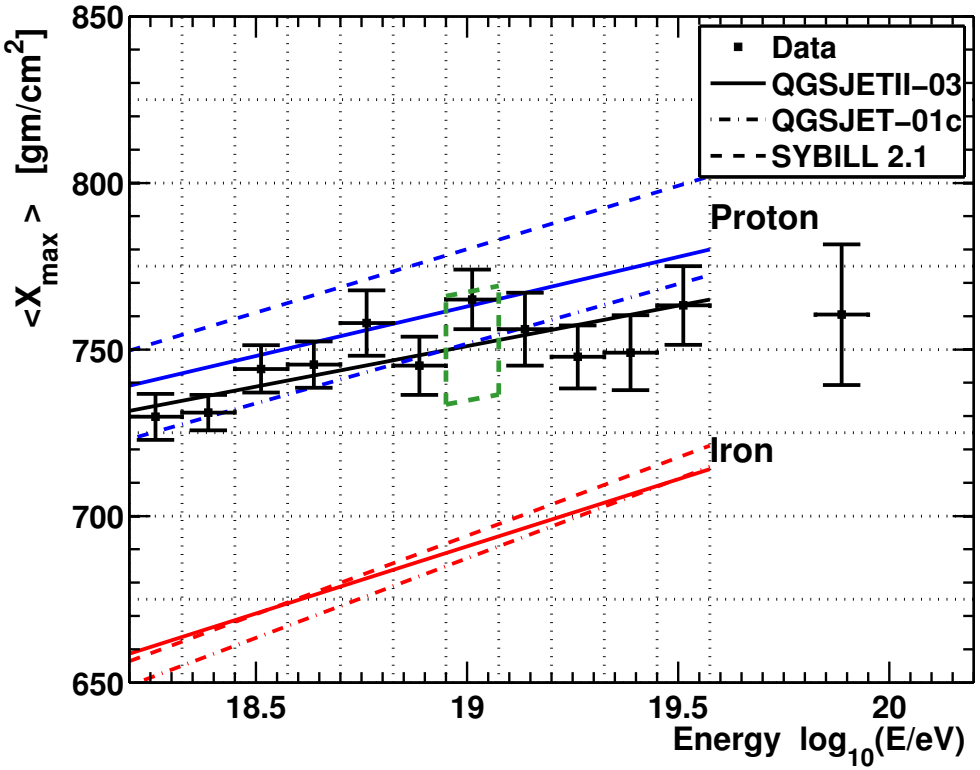
Primary Mass and Longitudinal Shower Profiles



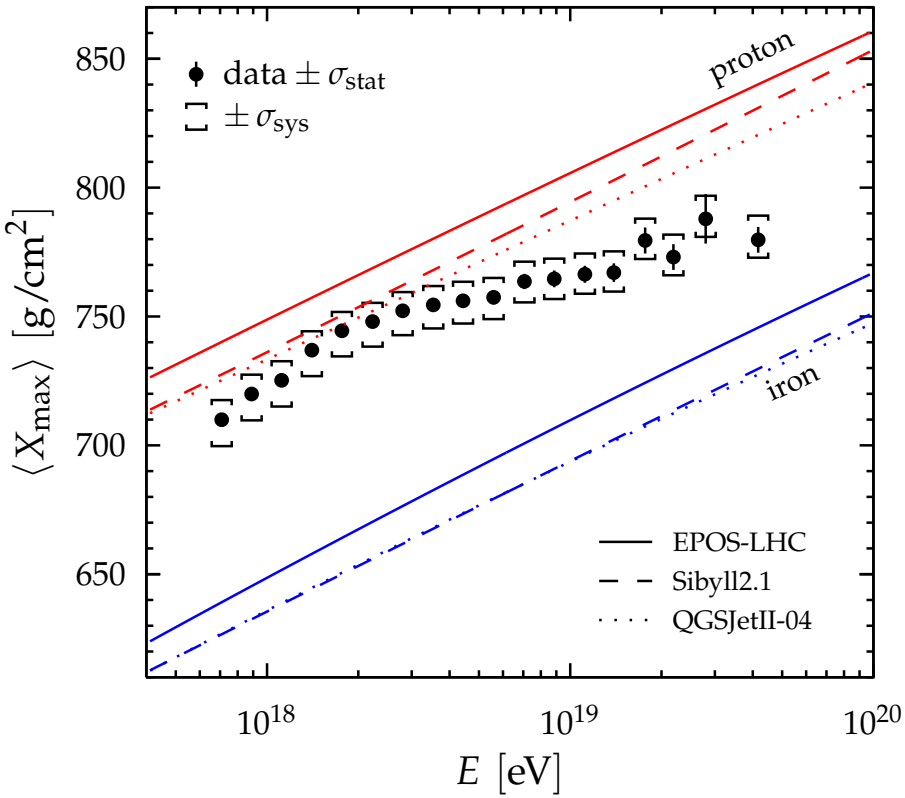
Primary Mass and Longitudinal Shower Profiles



Average Shower Maximum

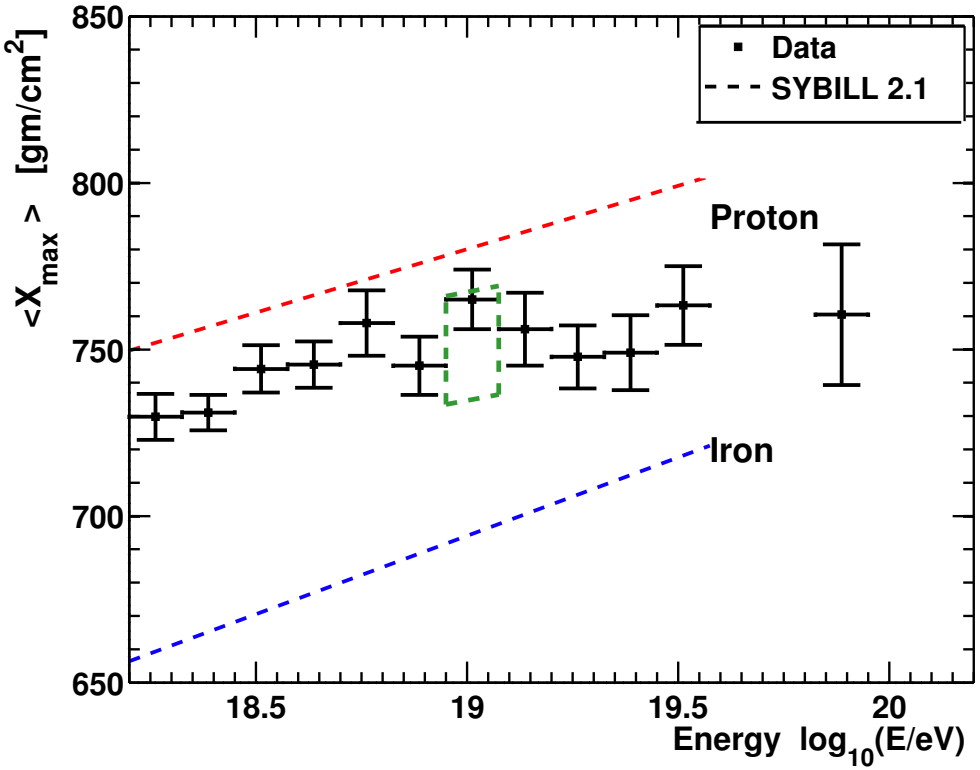


Telescope Array Collaboration, APP **64** (2014) 49

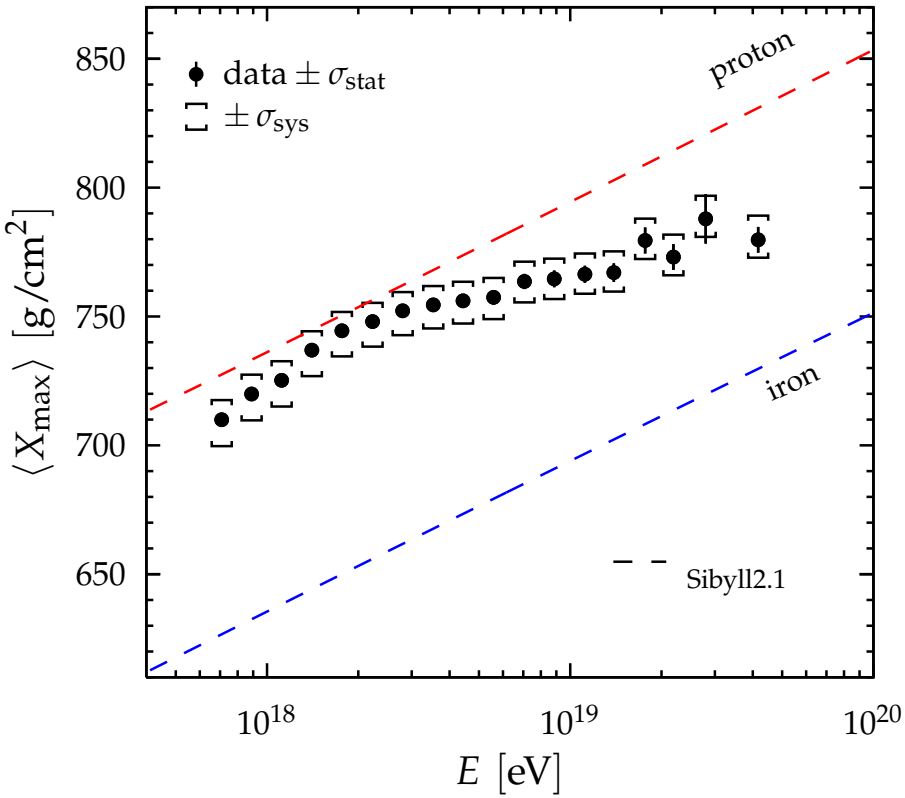


Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

Average Shower Maximum

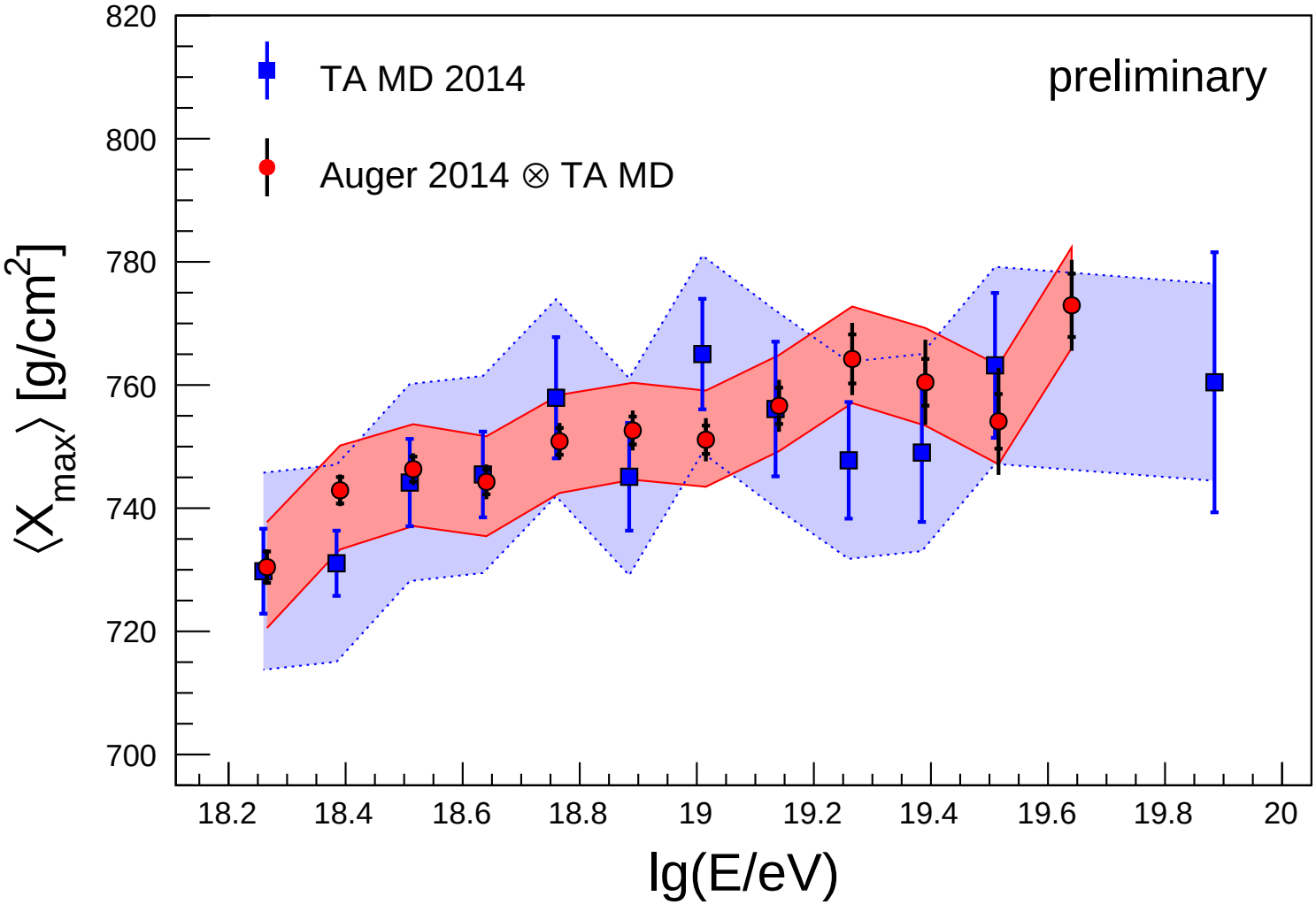


Telescope Array Collaboration, APP **64** (2014) 49



Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

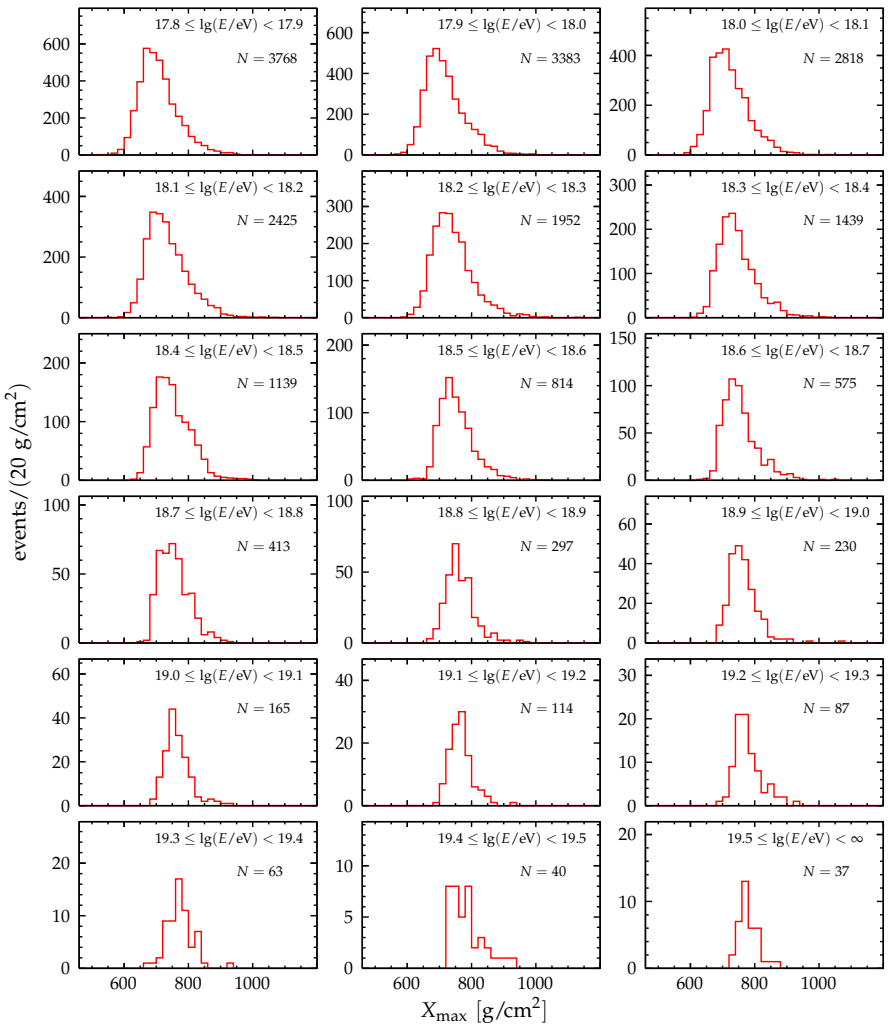
Average Shower Maximum



$$\langle \Delta \rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$$

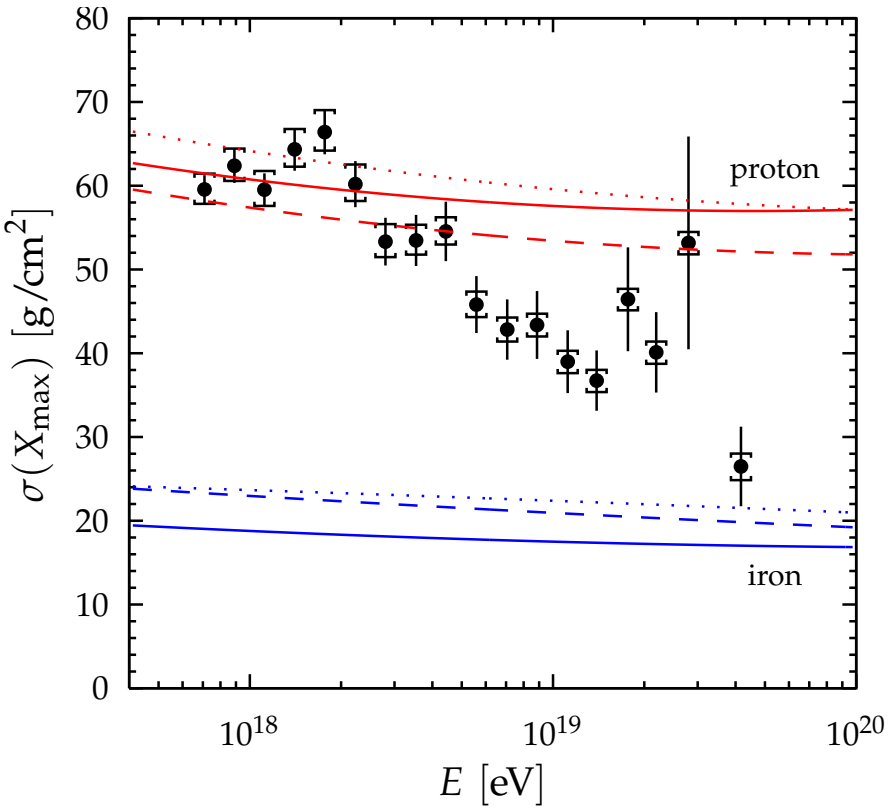
Pierre Auger and TA Collaborations, Proc. UHECR 2014, arXiv:1503.07540

X_{max} Distributions



http://auger.org/data/xmax2014.tar.gz

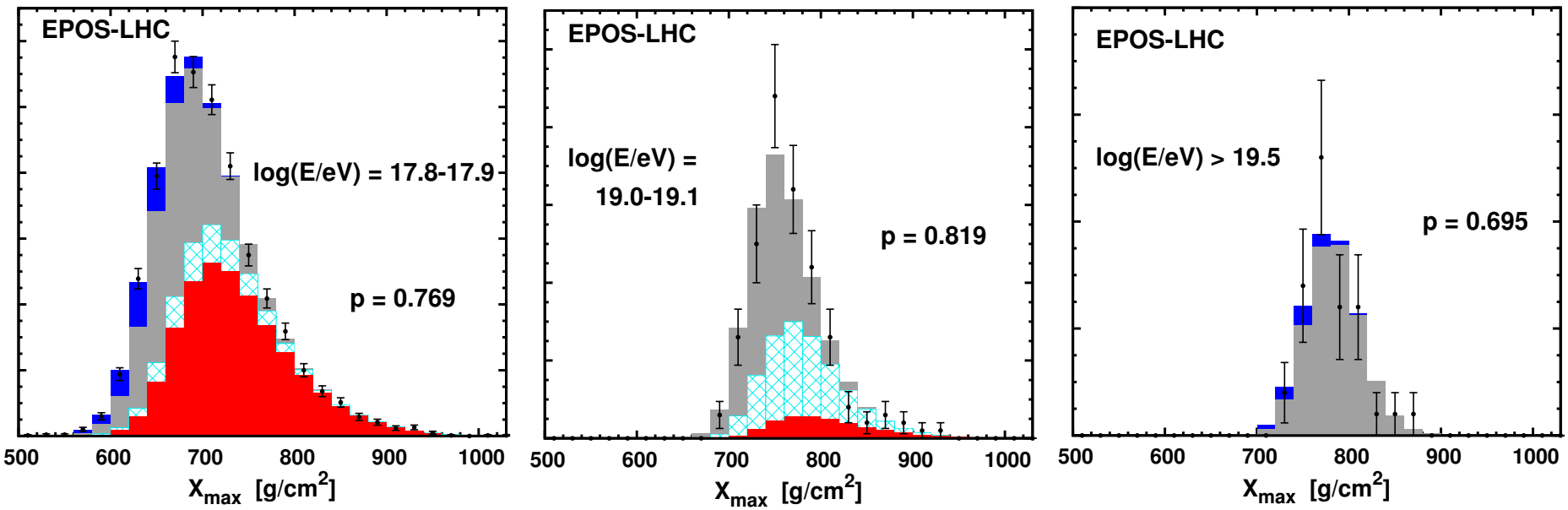
standard deviation of distributions:



Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

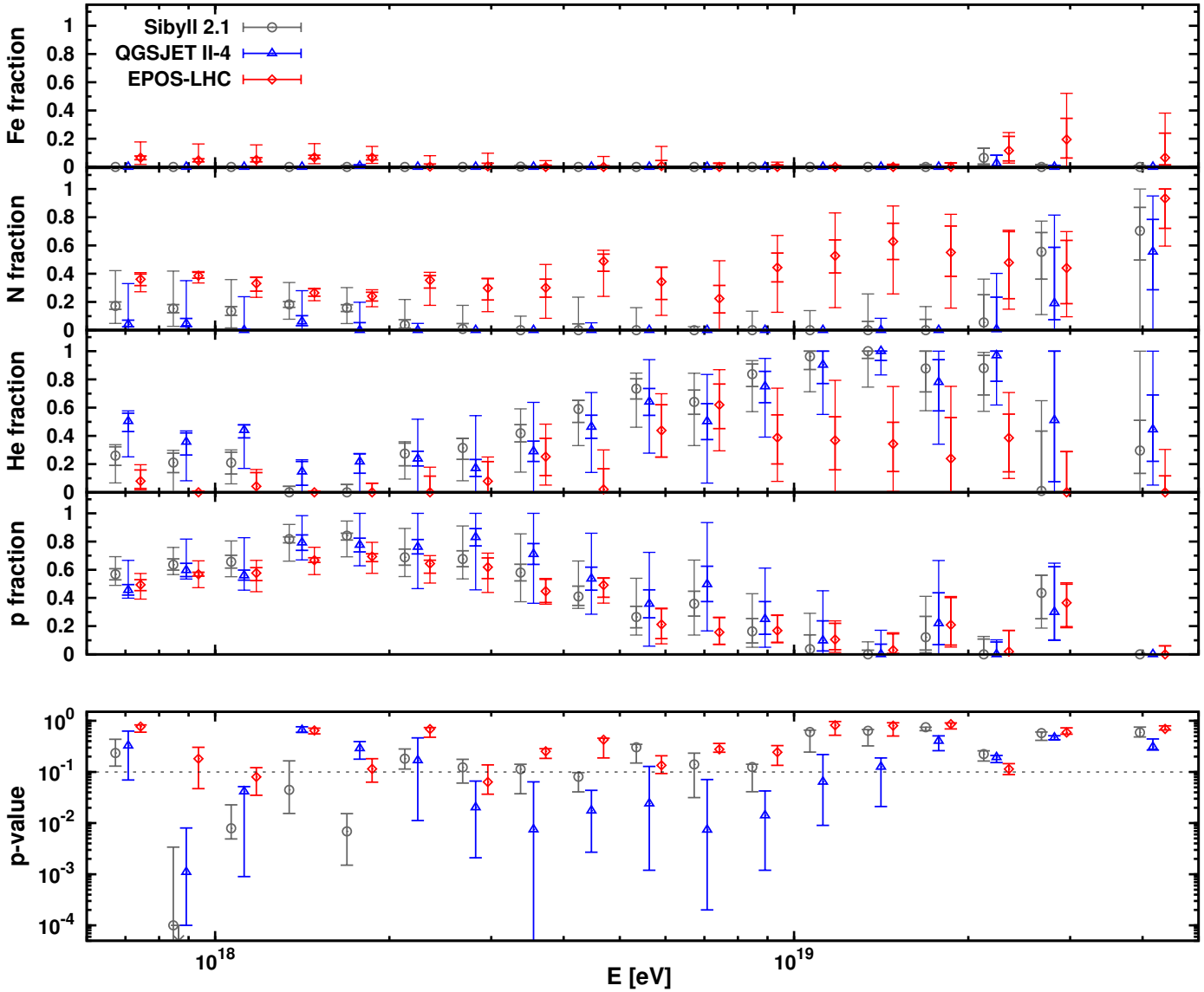
Composition Fit (X_{max} distribution)

proton, helium, nitrogen, iron



Pierre Auger Collaboration, PRD **90** (2014) 12, 122006

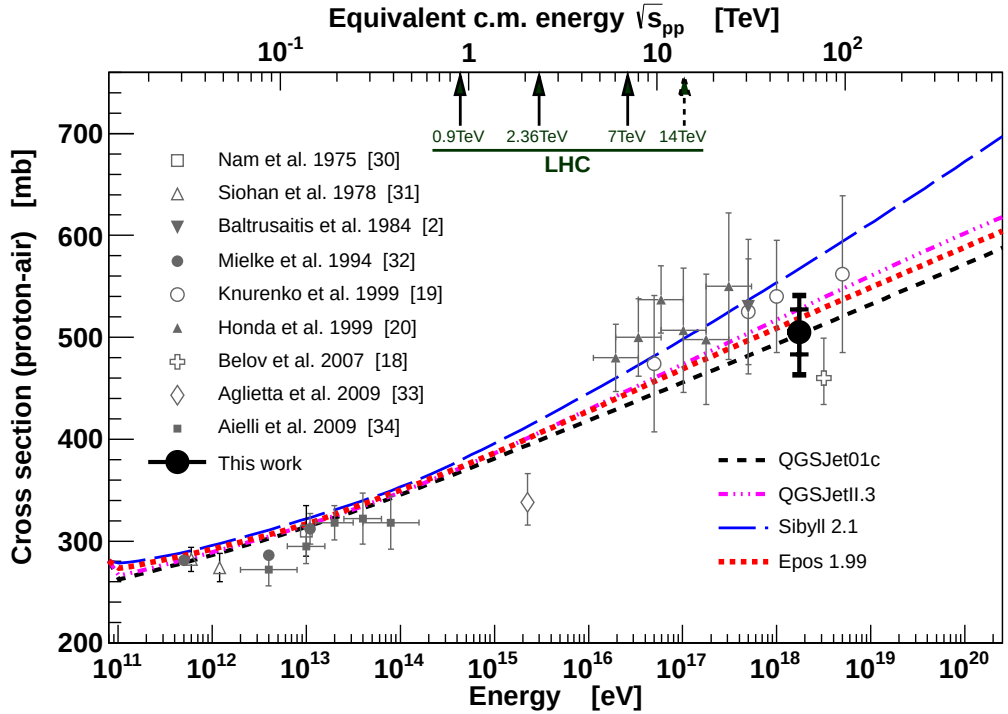
Composition Fit (X_{max} distribution)



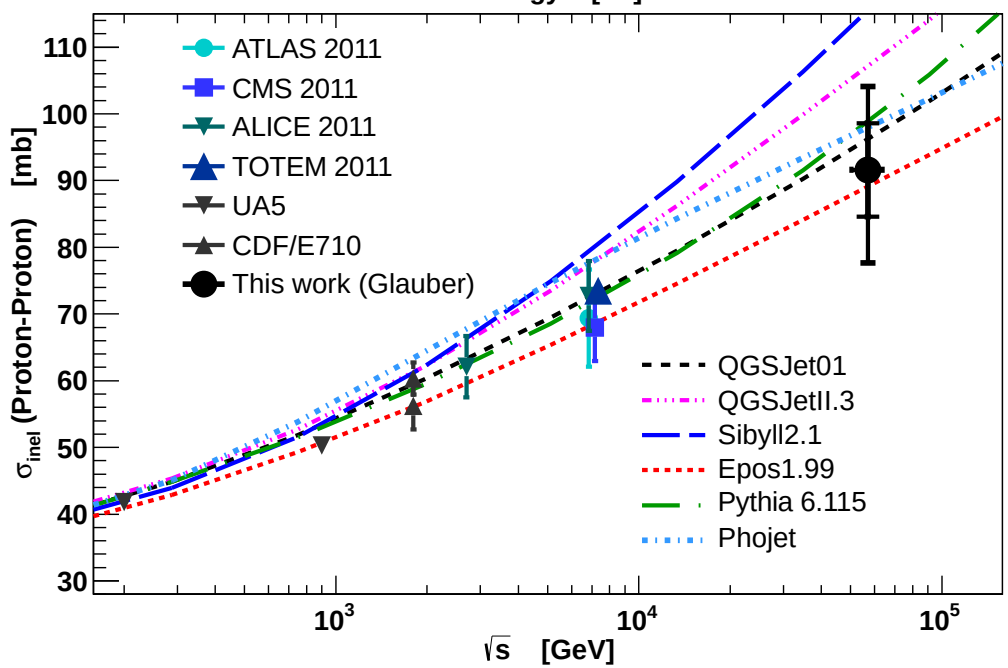
Pierre Auger Collaboration, PRD **90** (2014) 12, 122006

Hadronic Interactions

$\sigma(p + \text{air})$ at 1.7 EeV:



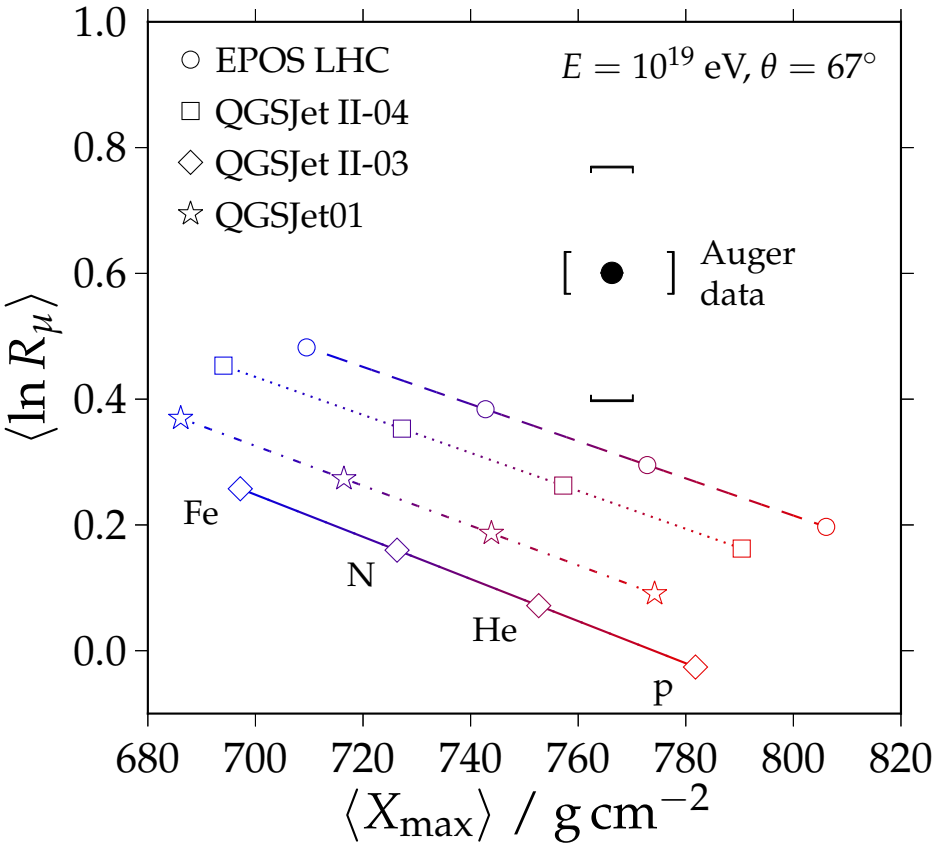
$\sigma(p + p)$ at $\sqrt{s} = 57$ TeV:



Pierre Auger Collaboration, PRL **109** (2012) 062002

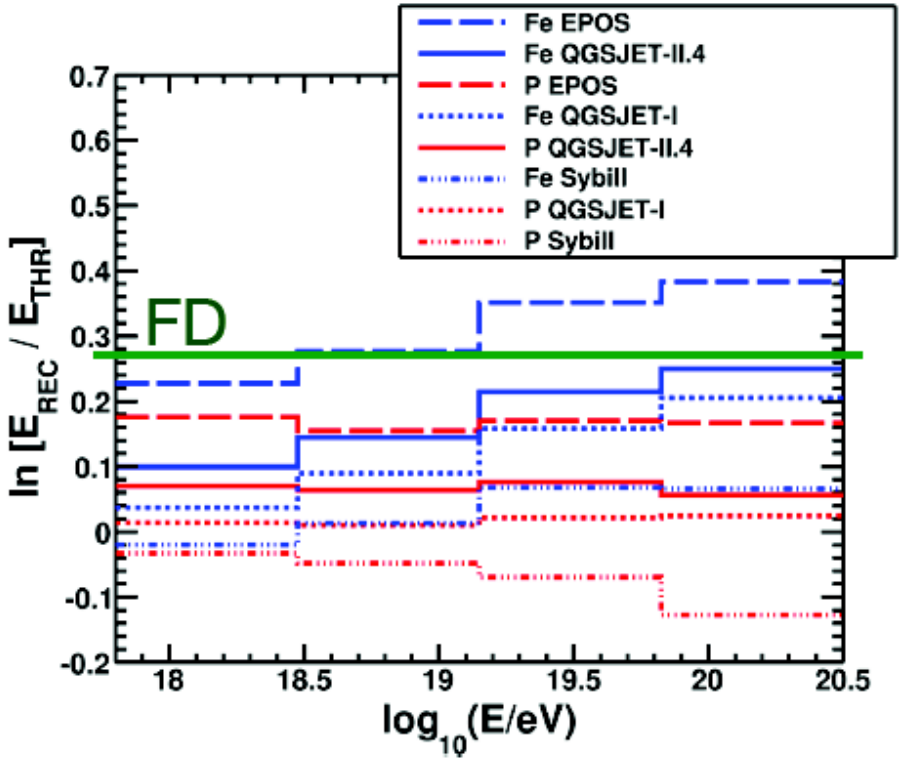
Hadronic Interactions

muon number:



Pierre Auger Collaboration, PRD91 (2015) 3, 032003

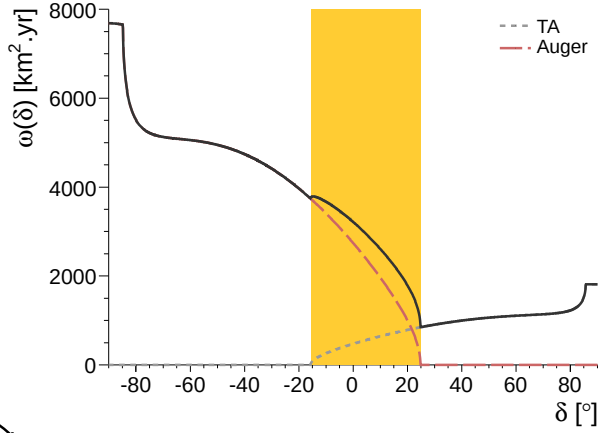
MC energy scale:

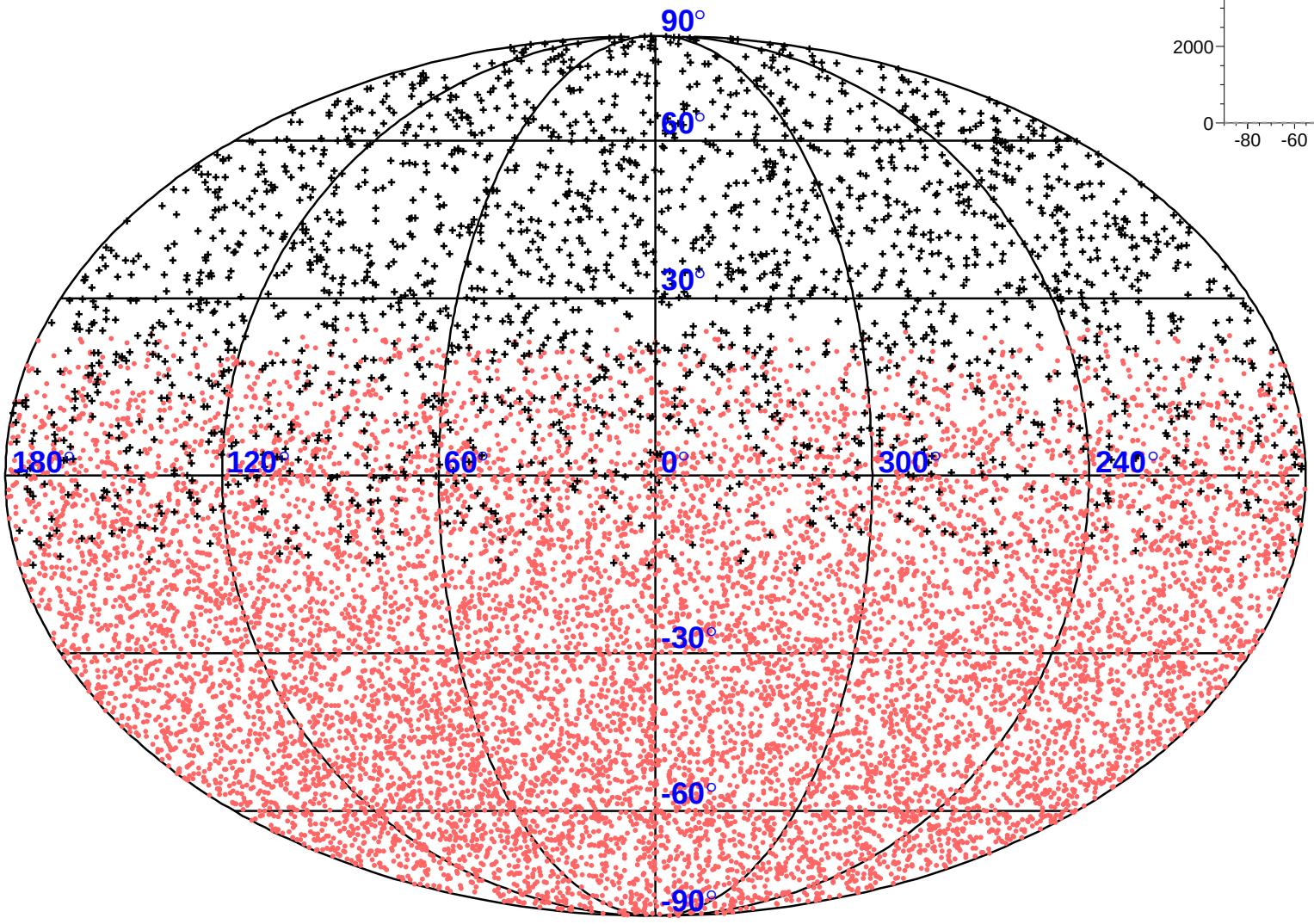


FD: -27%
QGSJet II.04: -5%
EPOS: -20%
Sibyll: +5-1-%

Telescope Array Collaboration, UHECR14 Symposium

The UHECR Sky above 10 EeV

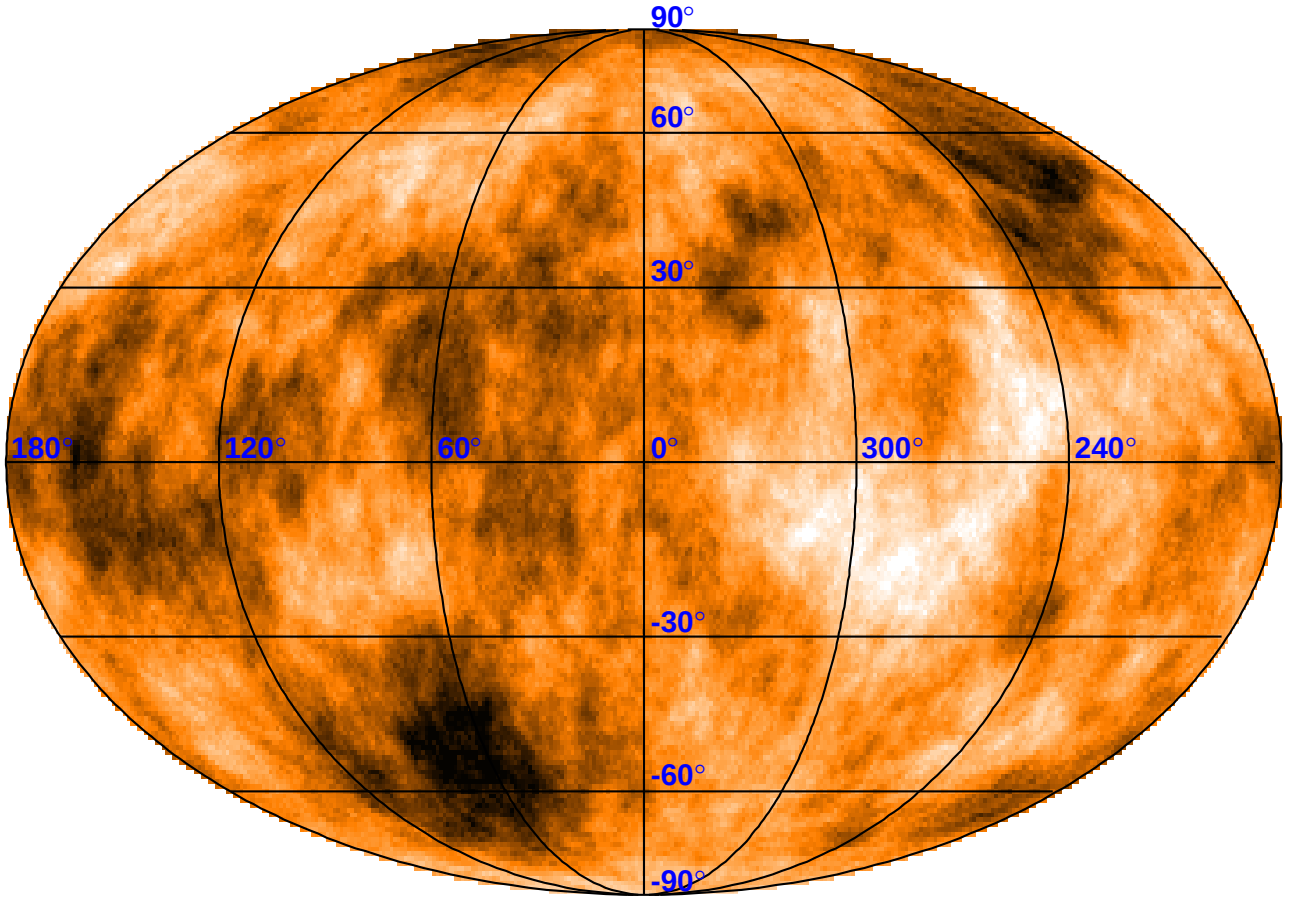


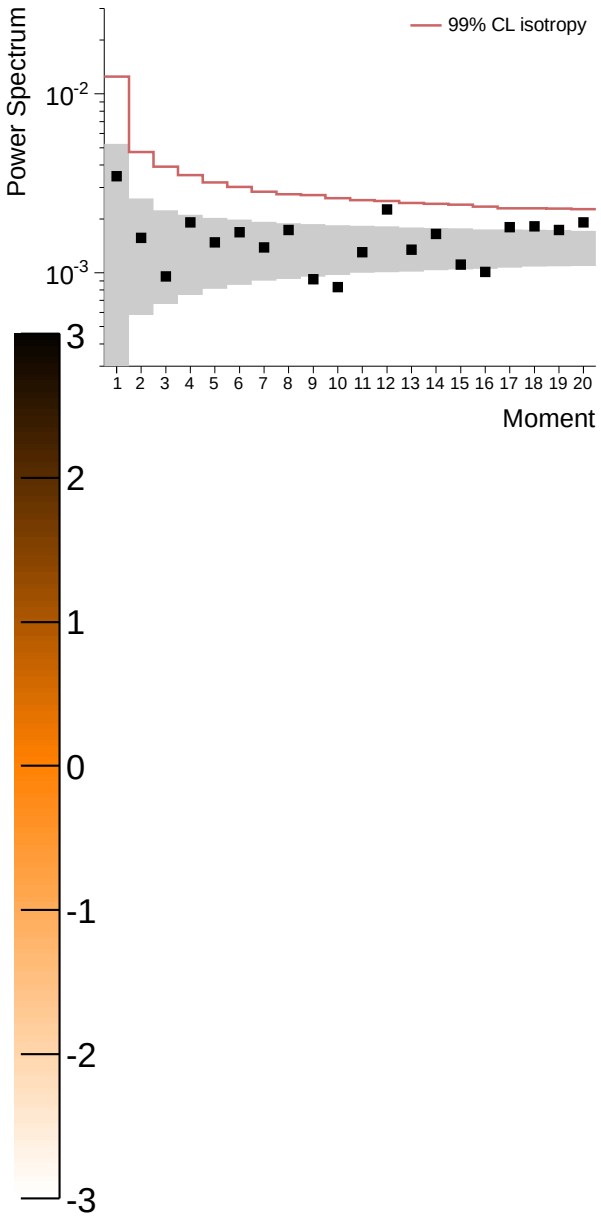


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

The UHECR Sky above 10 EeV

significance map:



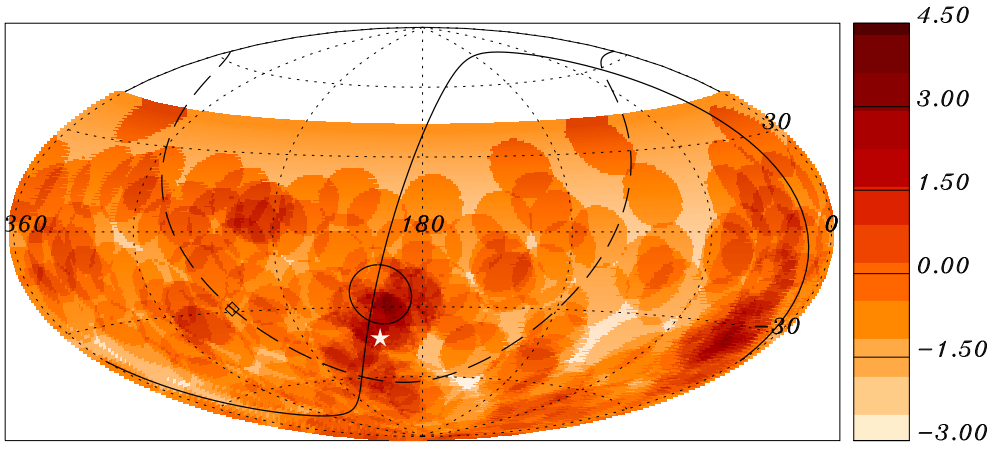


Pierre Auger and TA Collaborations, APJ **794** (2014) 2, 172

Searches for a Localized Excess of UHECRs

Auger:

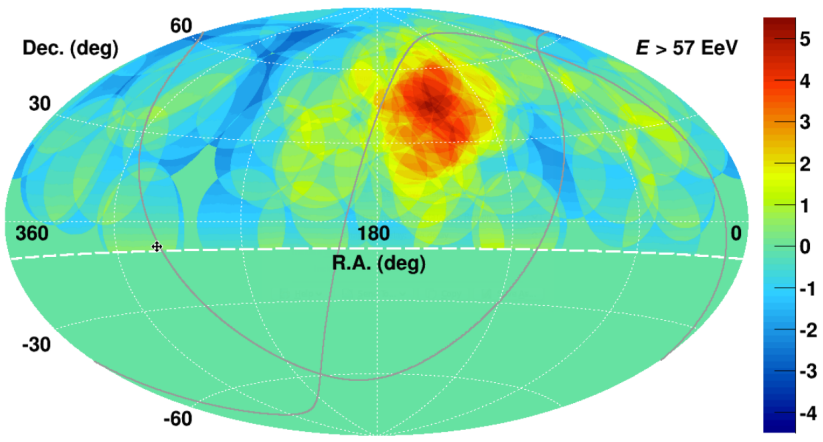
- $r = 1^\circ - 30^\circ$, $\Delta r = 1^\circ$
- $E = 40 - 80$ EeV, $\Delta E = 1$ EeV



- $r = 12^\circ$, $E = 54$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 14/3.23
- pre-trial: 4.3 σ
- post-trial: $P = 69\%$

TA:

- $r = 15^\circ - 35^\circ$, $\Delta r = 5^\circ$
- $E = 57$ EeV



- $r = 20^\circ$, $E = 57$ EeV
- $n_{\rm obs}/n_{\rm exp}$ = 23/5.49
- pre-trial: 5.55 σ
- post-trial: 4 σ

Auger Coll., APJ **804** (2015) 1, 15; TA Coll., APJ **790** (2014) L21, 6-year update at UHECR14.

Summary Observations, E $> 10^{19}$ eV

Spectrum

- flux suppression at $E \gtrapprox 5 \times 10^{19}$ eV
- UHE shape different in Northern and Southern hemisphere? (cosmic variance?)

Composition

- good agreement of Auger and TA $X_{\rm max}$ data
- mixed composition (model dependent!), but poor statistics above 3×10^{19} eV

Arrival directions

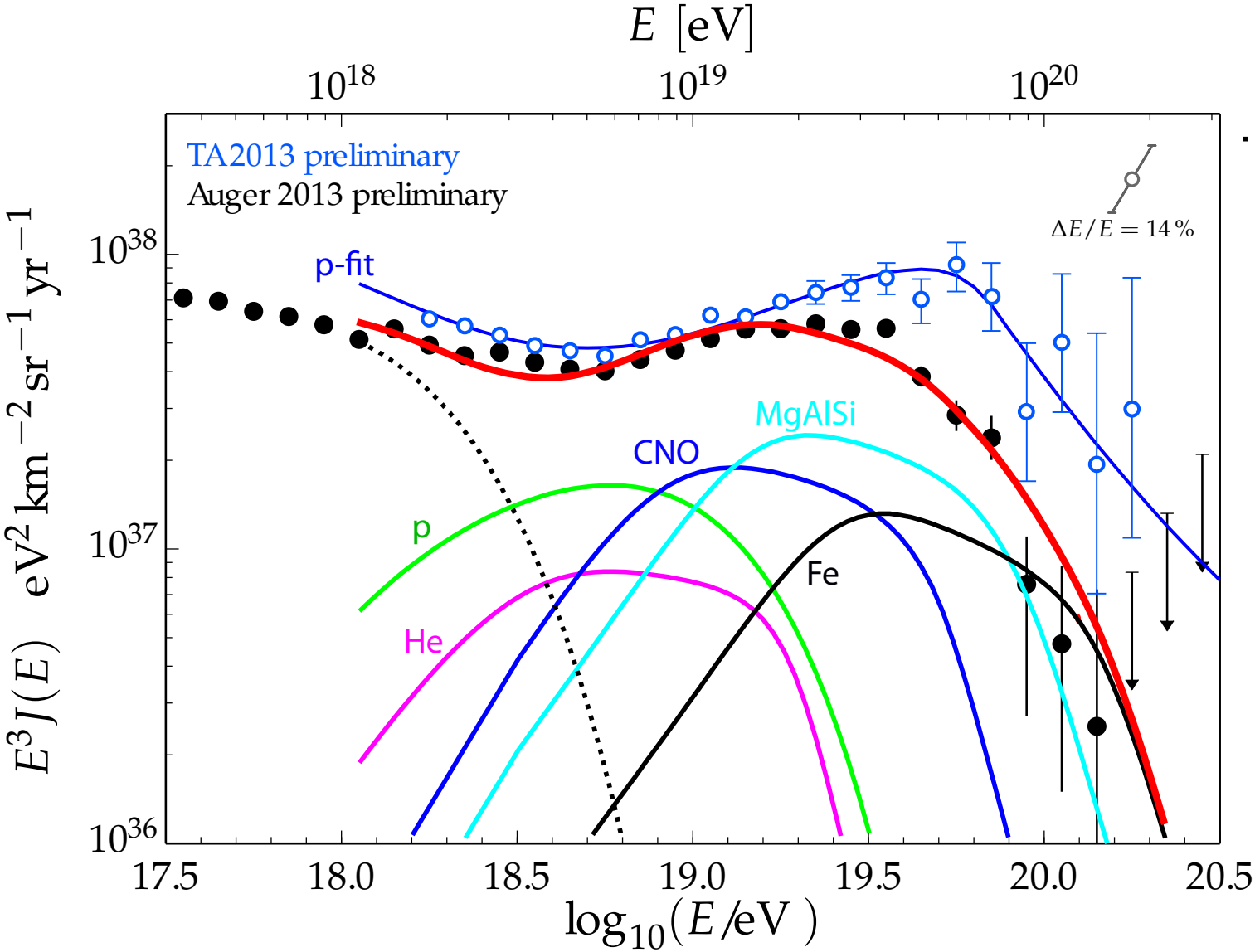
- $E_{\rm thr} = 10$ EeV: CR sky isotropic
- no significant signal from catalog-based searches
- 'hot spot' in Northern hemisphere, $E_{\rm thr} = 57$ EeV, $4\,\sigma$
- 'warm spot' around CenA, $E_{\rm thr} = 57$ EeV, $P = 1.4\%$ (a posteriori)

Hadronic Interactions

- particle deficit at ground level

+photon limits, neutrino limits, muon production depth, ...

Origin of Ankle and Flux Suppression?

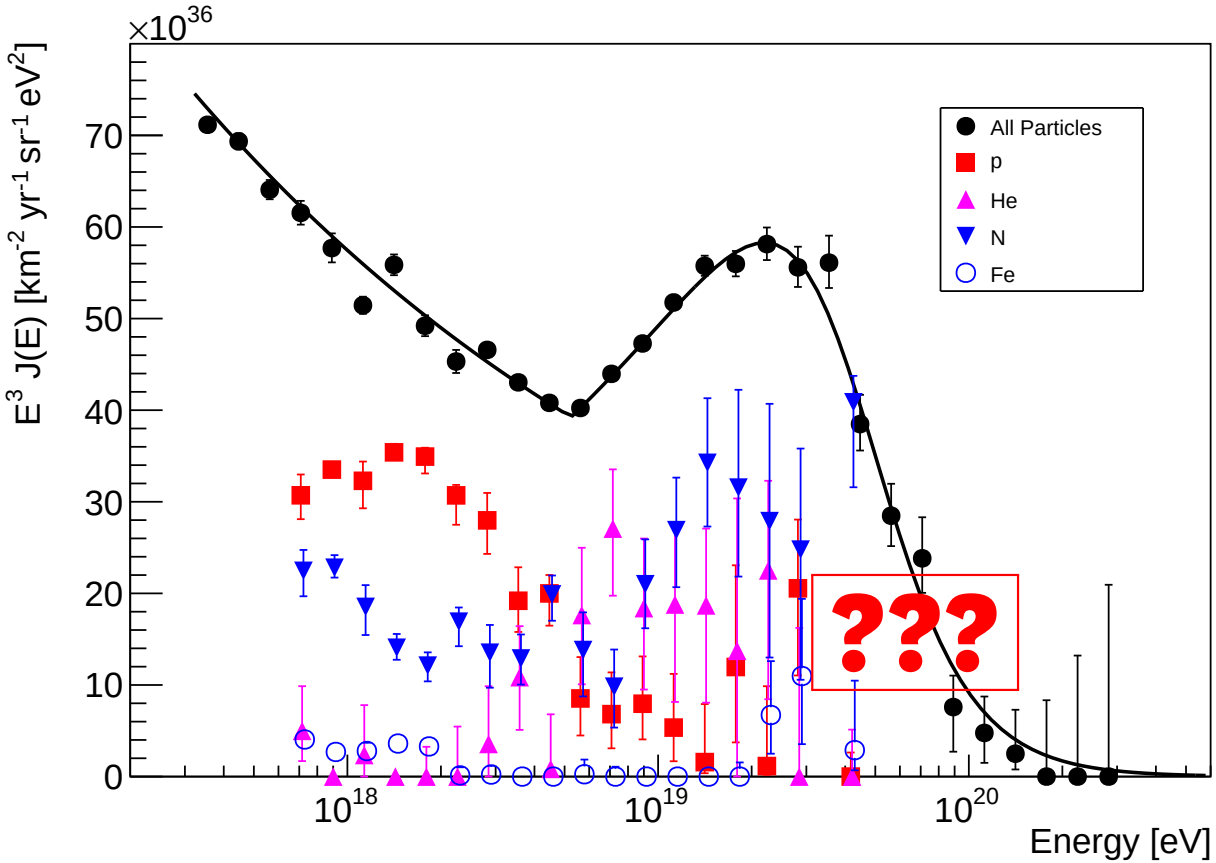


Kampert&Tinyakov, CRP **15** (2014) 318; Aloisio, Berezinsky & Blasi, JCAP 1410 (2014) 10, 02

see also L. Anchordoqui talk this afternoon!

Upgrade of the Pierre Auger Observatory

- origin of flux suppression?
- proton fraction at UHE?
- hadronic physics above $\sqrt{s} = 140$ TeV



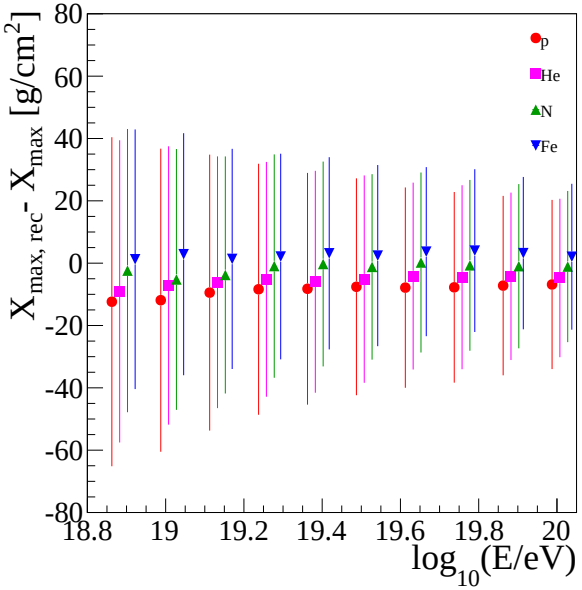
V. de Souza for the Pierre Auger Collaboration, Proc. UHECR14

Upgrade of the Pierre Auger Observatory

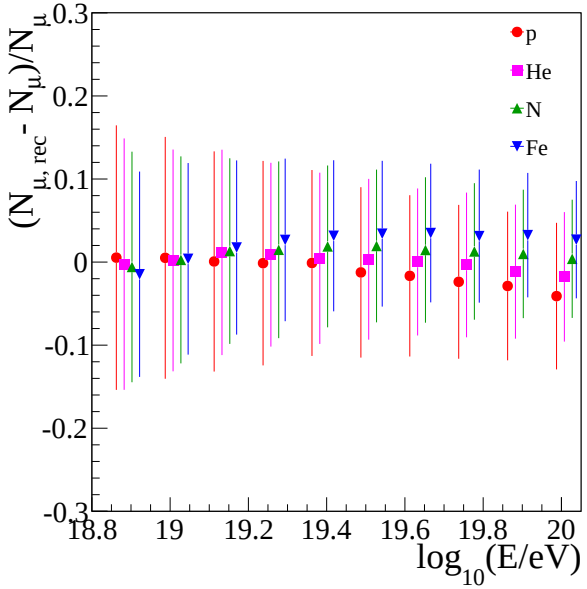
additional scintillators (4 m^2)

→ event-by-event mass estimate with 100% duty cycle

X_{max} determination:



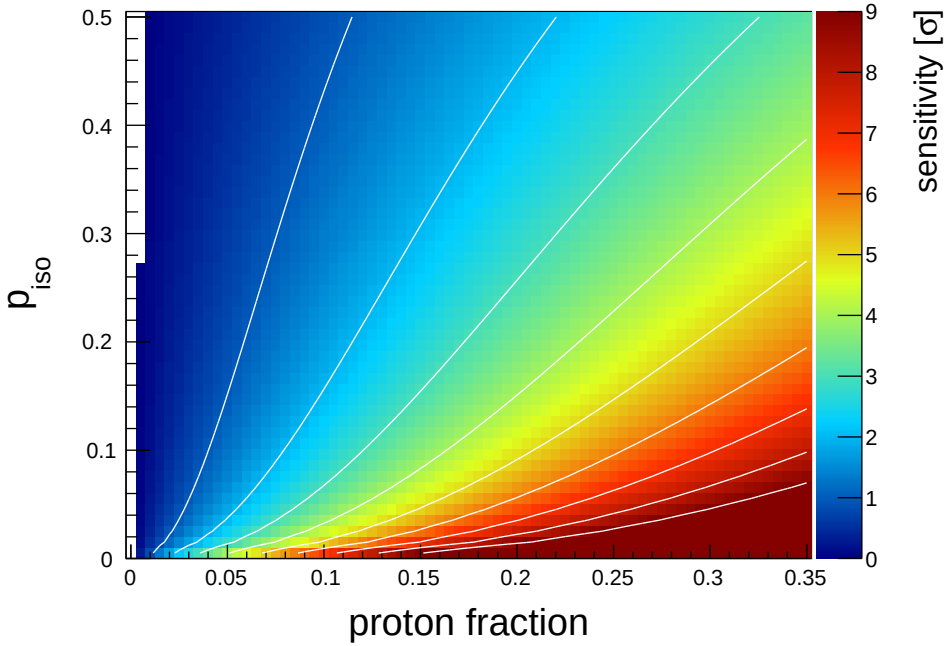
muon determination:



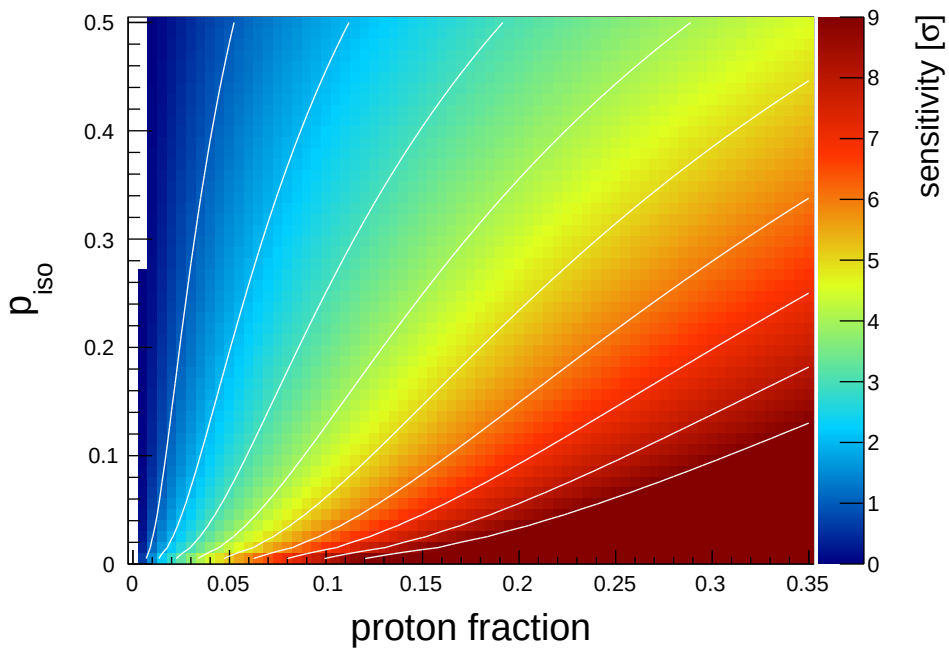
Upgrade of the Pierre Auger Observatory

low-Z particle astronomy

no mass determination:



p-Fe separation merit factor: 1.5

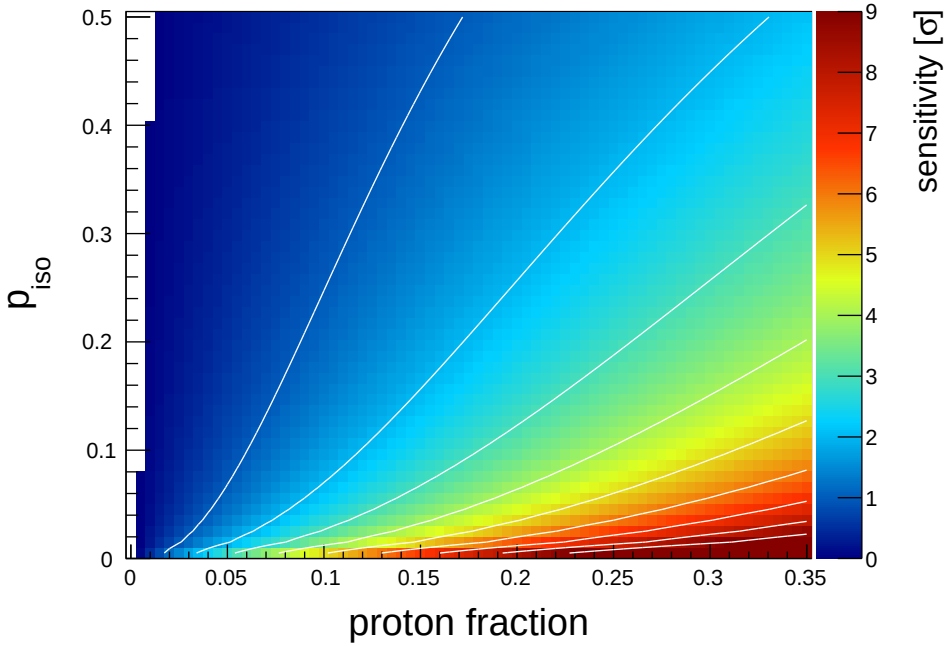


(isotropic background: 25%)

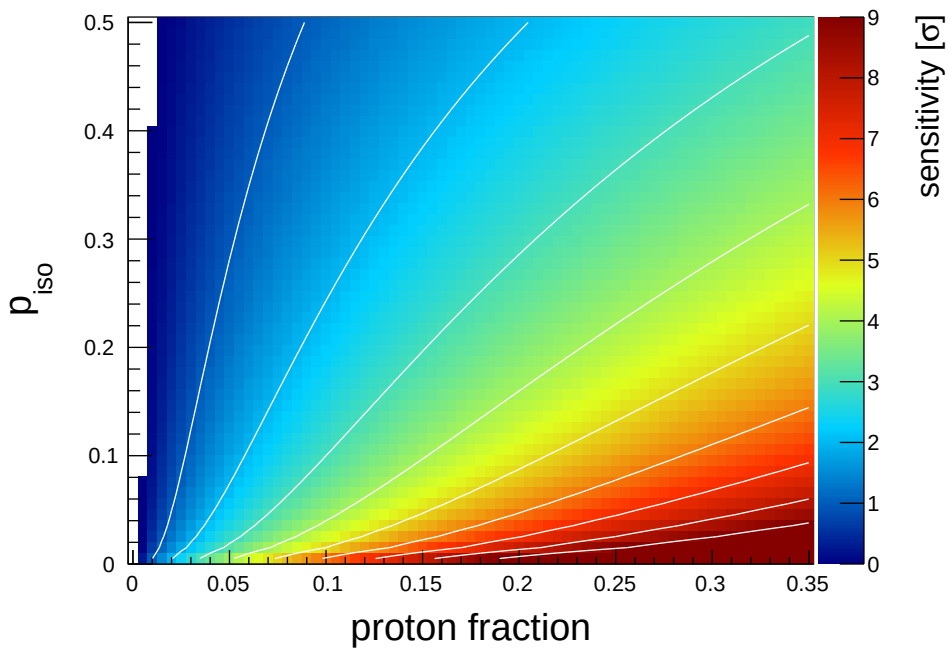
Upgrade of the Pierre Auger Observatory

low-Z particle astronomy

no mass determination:

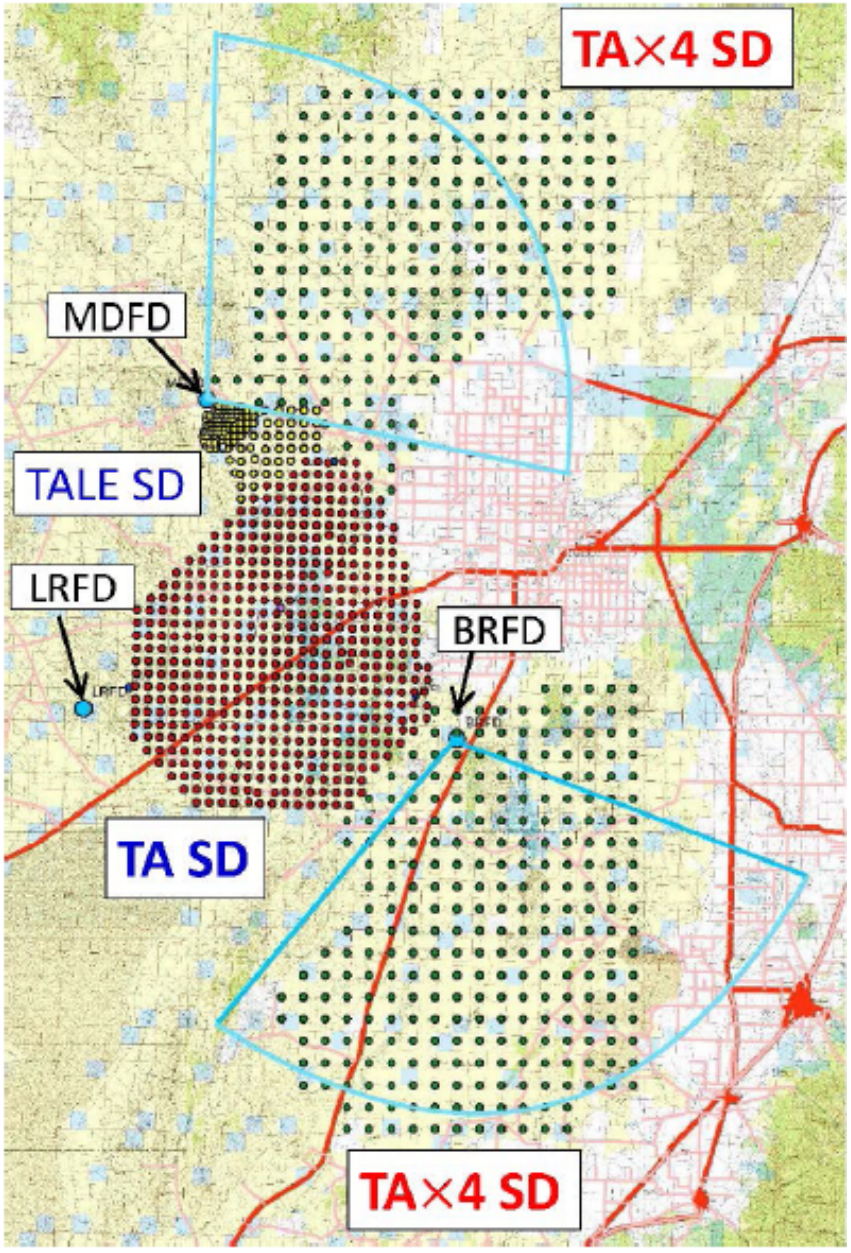


p-Fe separation merit factor: 1.5



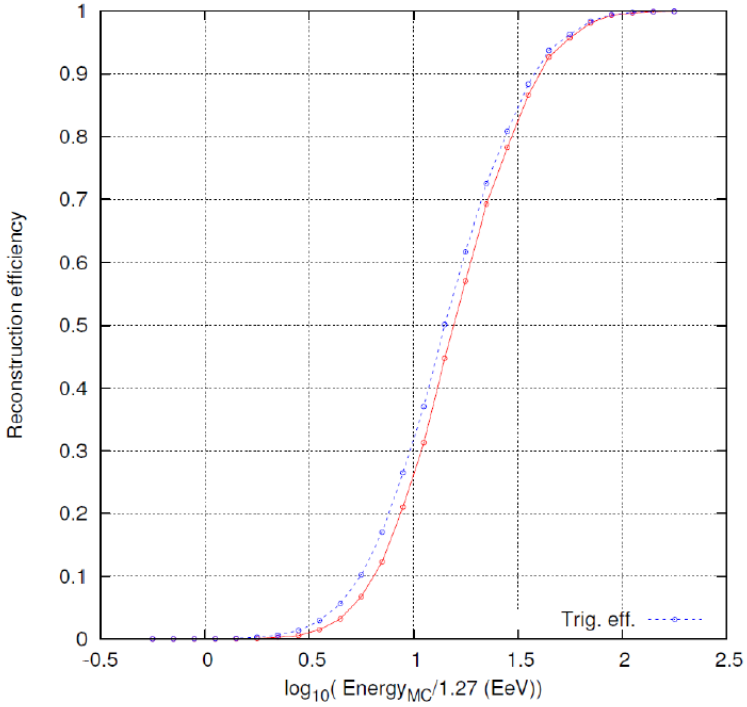
(isotropic background: 50%)

TAx4



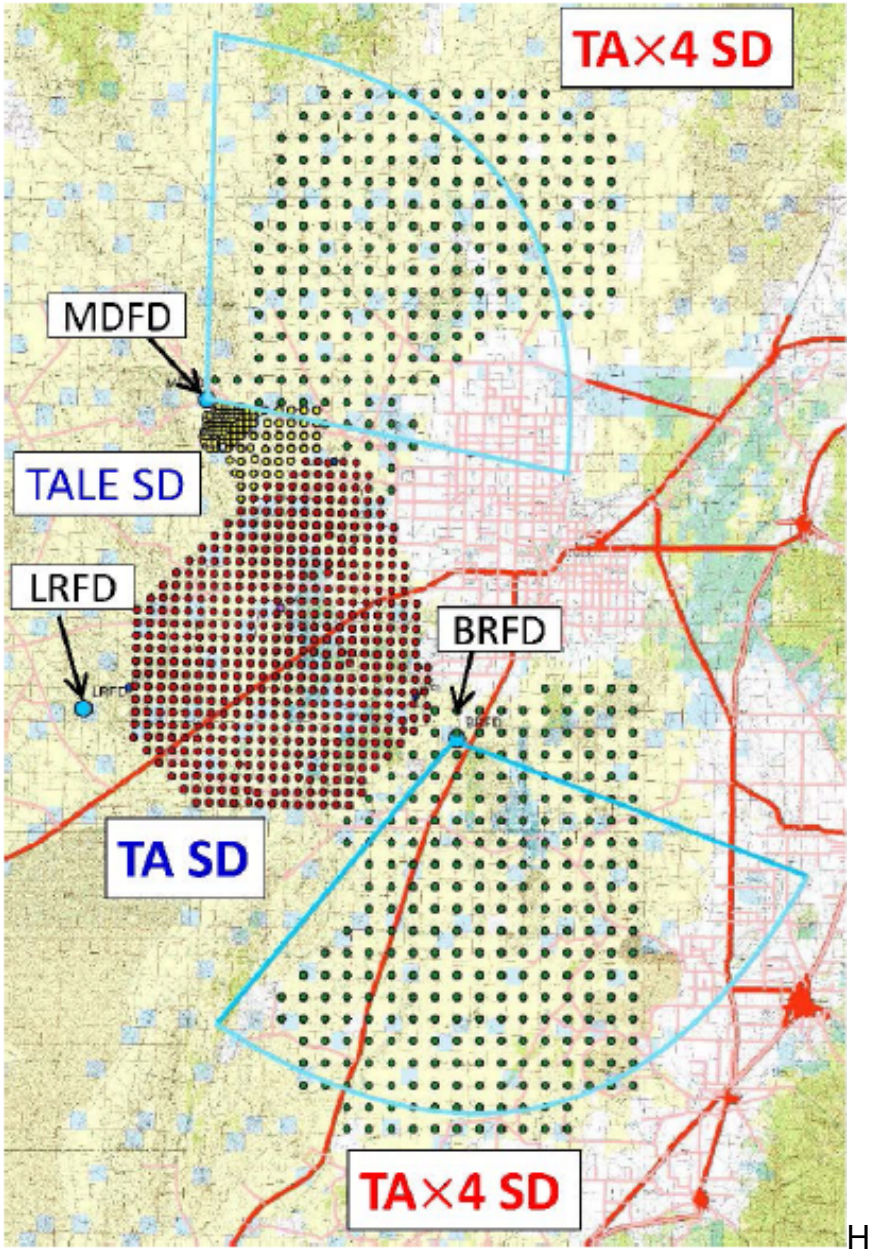
quadruple acceptance:

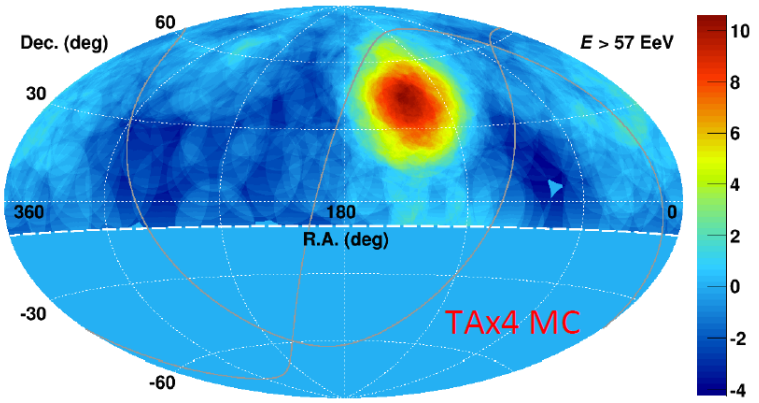
- 500 add. SDs
- 2.1 km spacing
- 2 add. FD stations

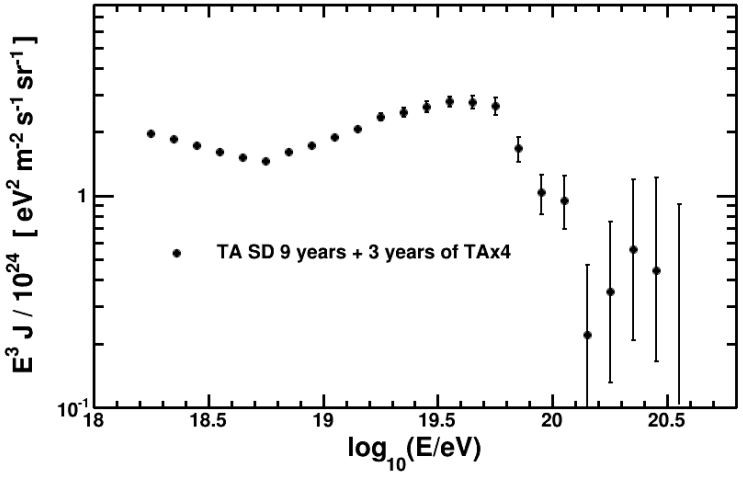


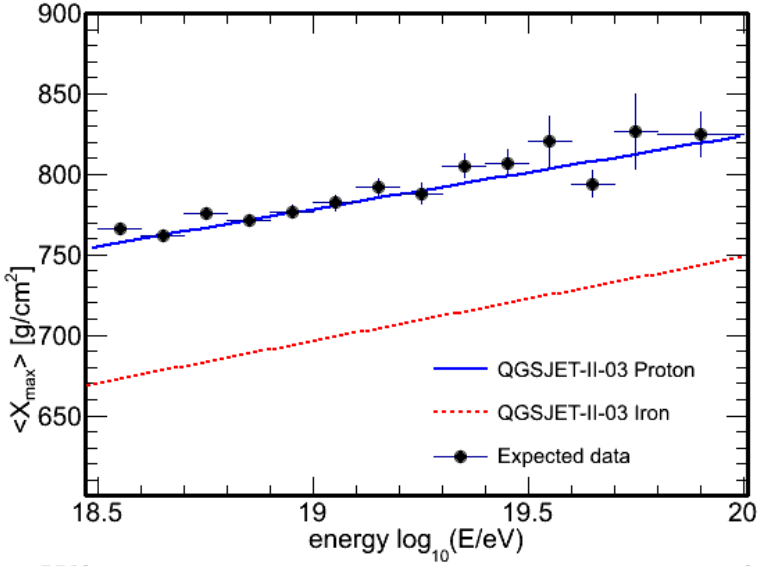
H. Sagawa for TA, UHECR14.

TAx4









H. Sagawa for TA, UHECR14.

Outlook

- TA & Auger Upgrades:
  - study nature of flux suppression
  - prospects for particle astronomy
  - R&D for Next Generation Observatory
- fluorescence detection from space
  - KLYPVE, Mini-EUSO (K-EUSO), EUSO
- radio detection of air showers
  - ground-based hybrid detectors (radio&surface)
  - high-altitude antennas (see talk A. Vieregg)
- LHC restart
  - $\sqrt{s} = 14\ TeV$ ($E_{\mathrm{CR}} = 10^{17}$ eV), p+O collisions?