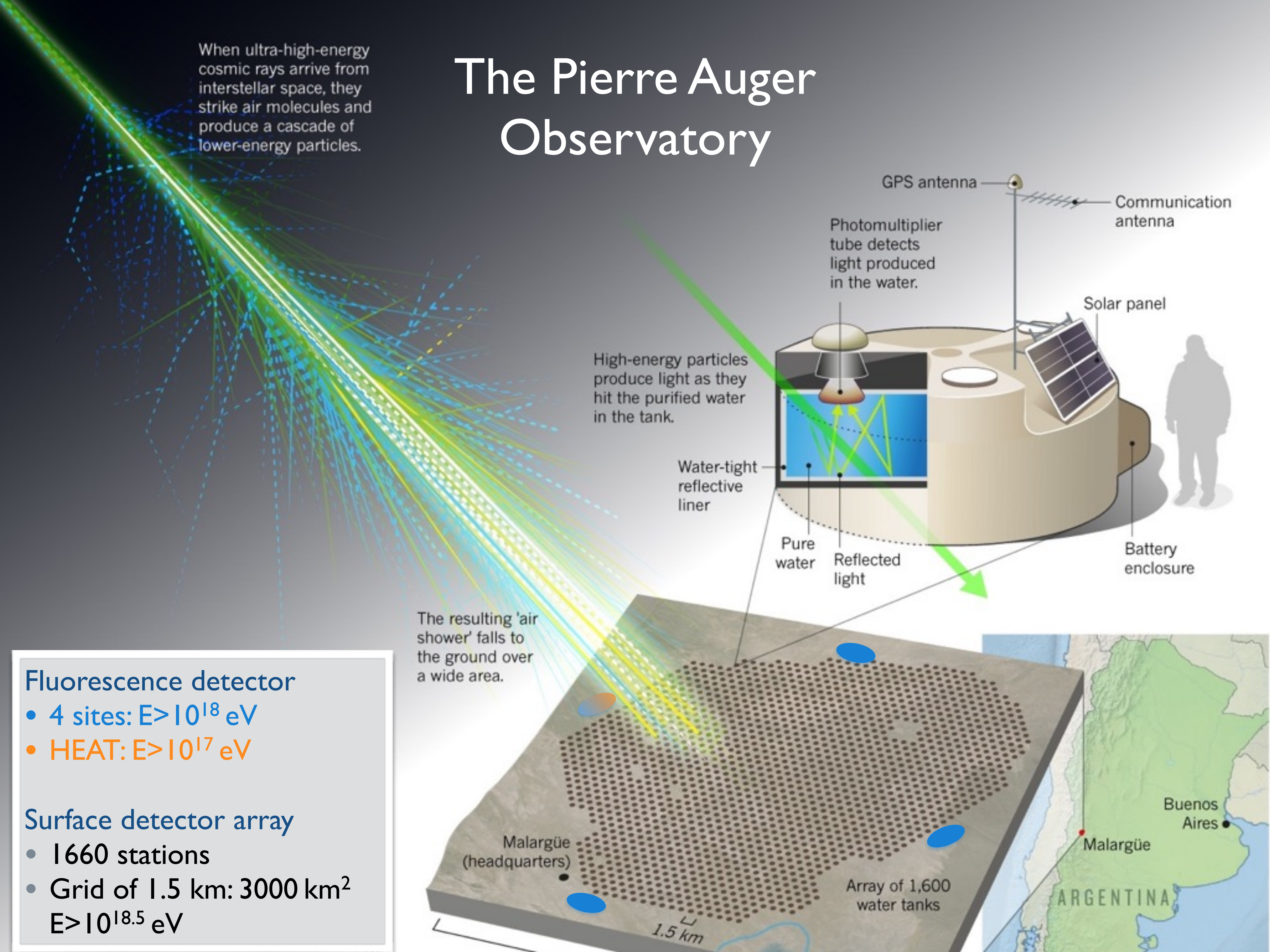
Composition Results from Auger

Markus Roth
Karlsruhe Institute of Technology (KIT)

The Pierre Auger Observatory



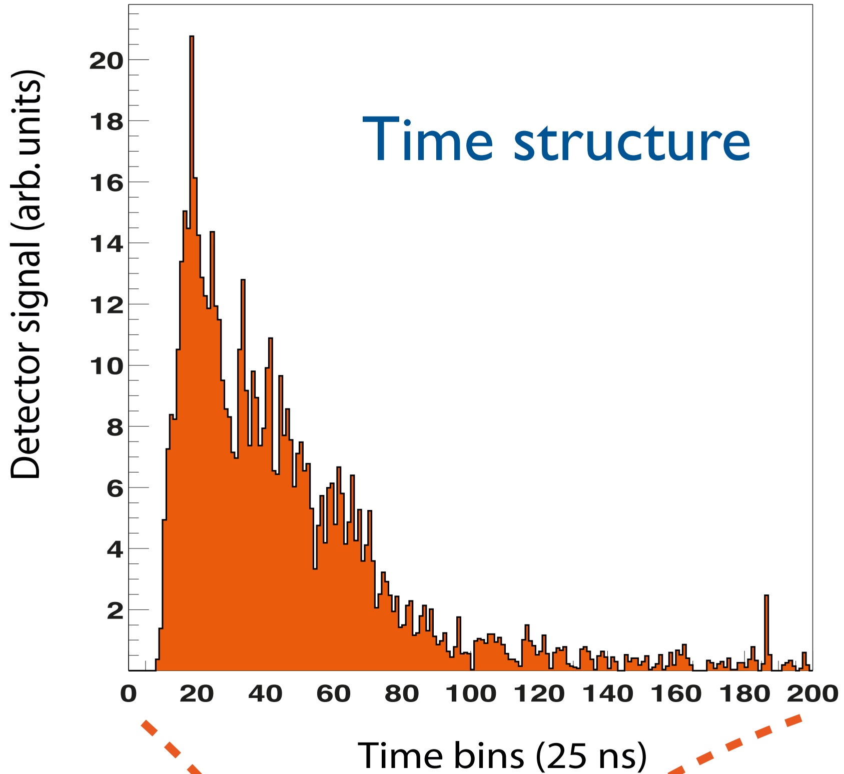
Fluorescence detector

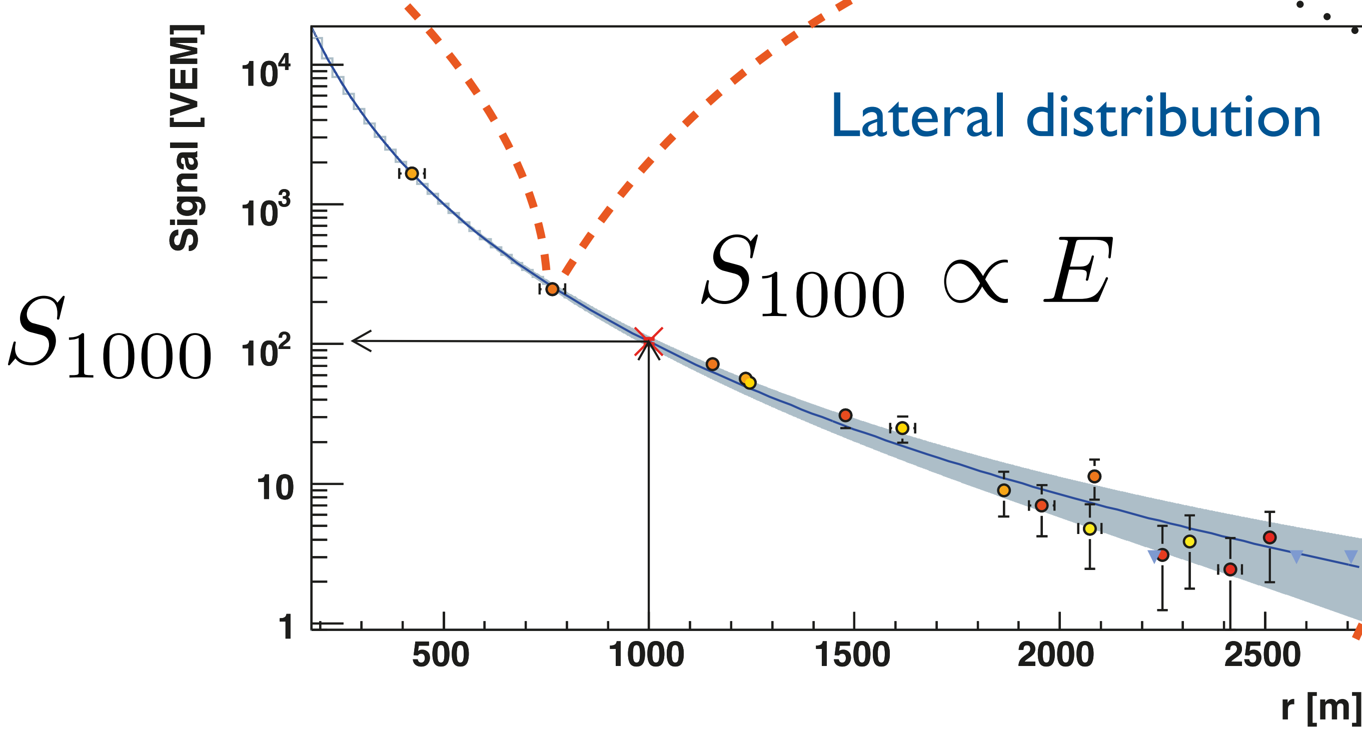
- 4 sites: $E>10^{18}$ eV
- HEAT: $E>10^{17}$ eV

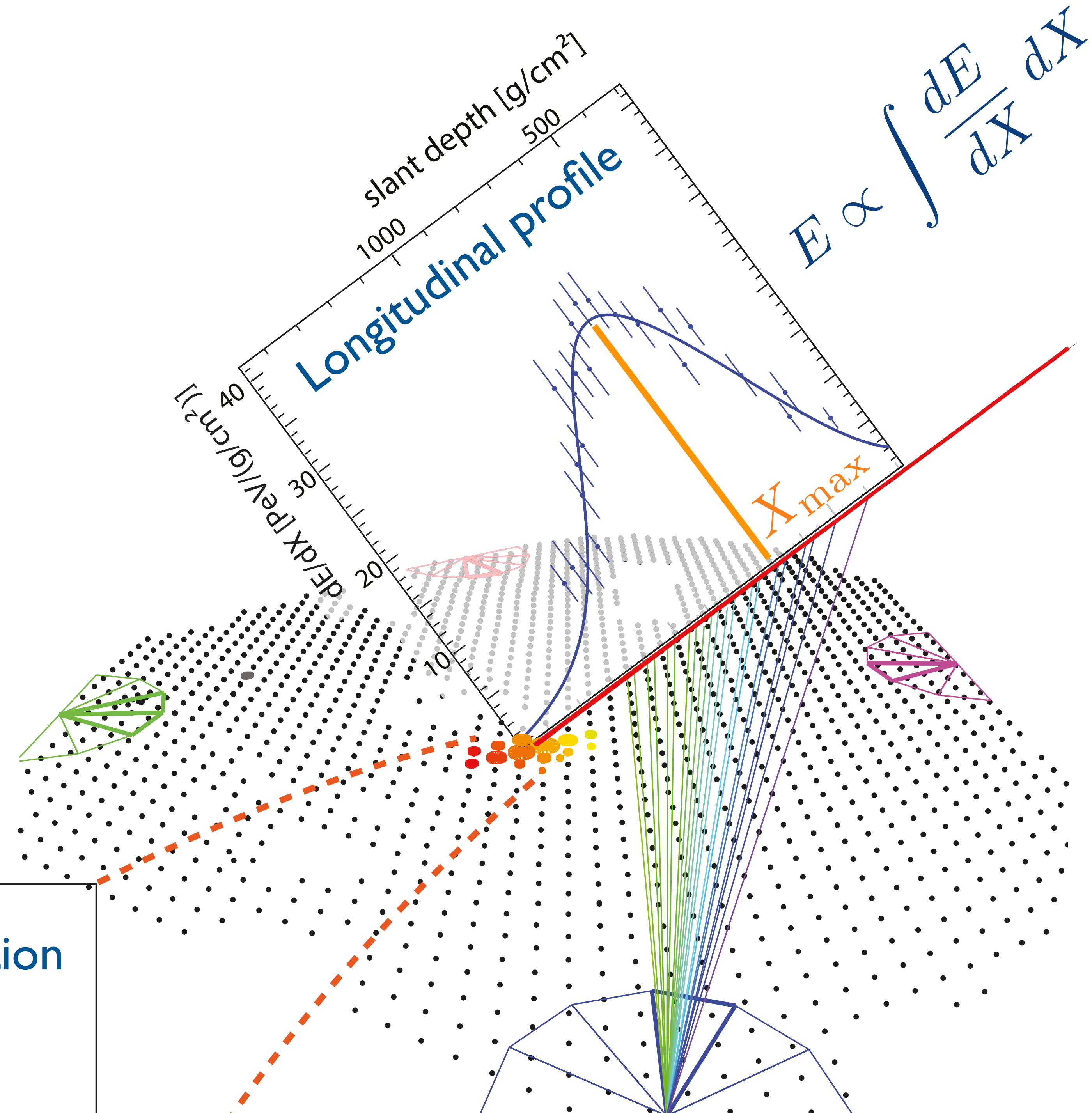
Surface detector array

- 1660 stations
- Grid of 1.5 km: 3000 km^2
  $E>10^{18.5}$ eV

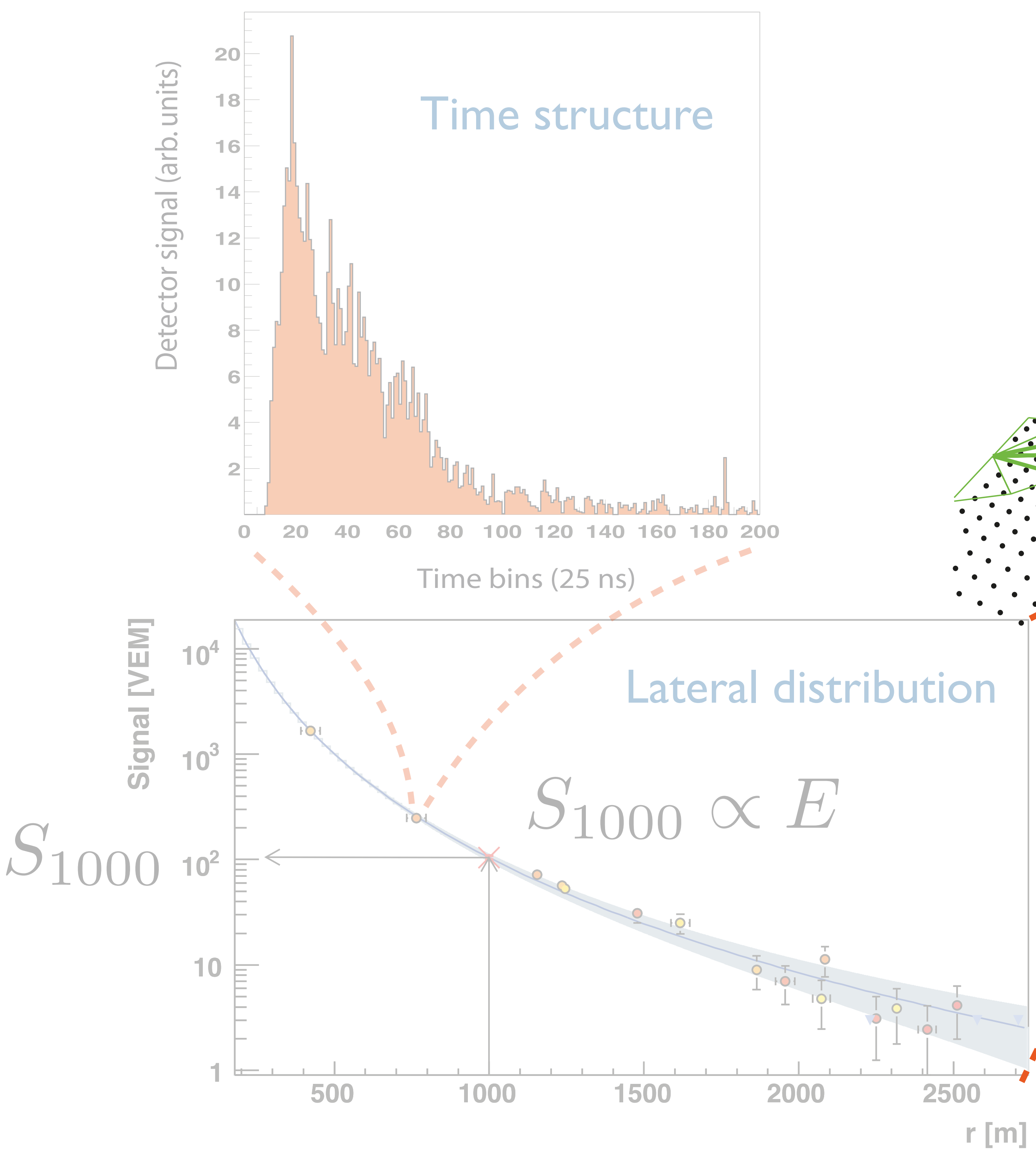
Shower observables recorded at Auger

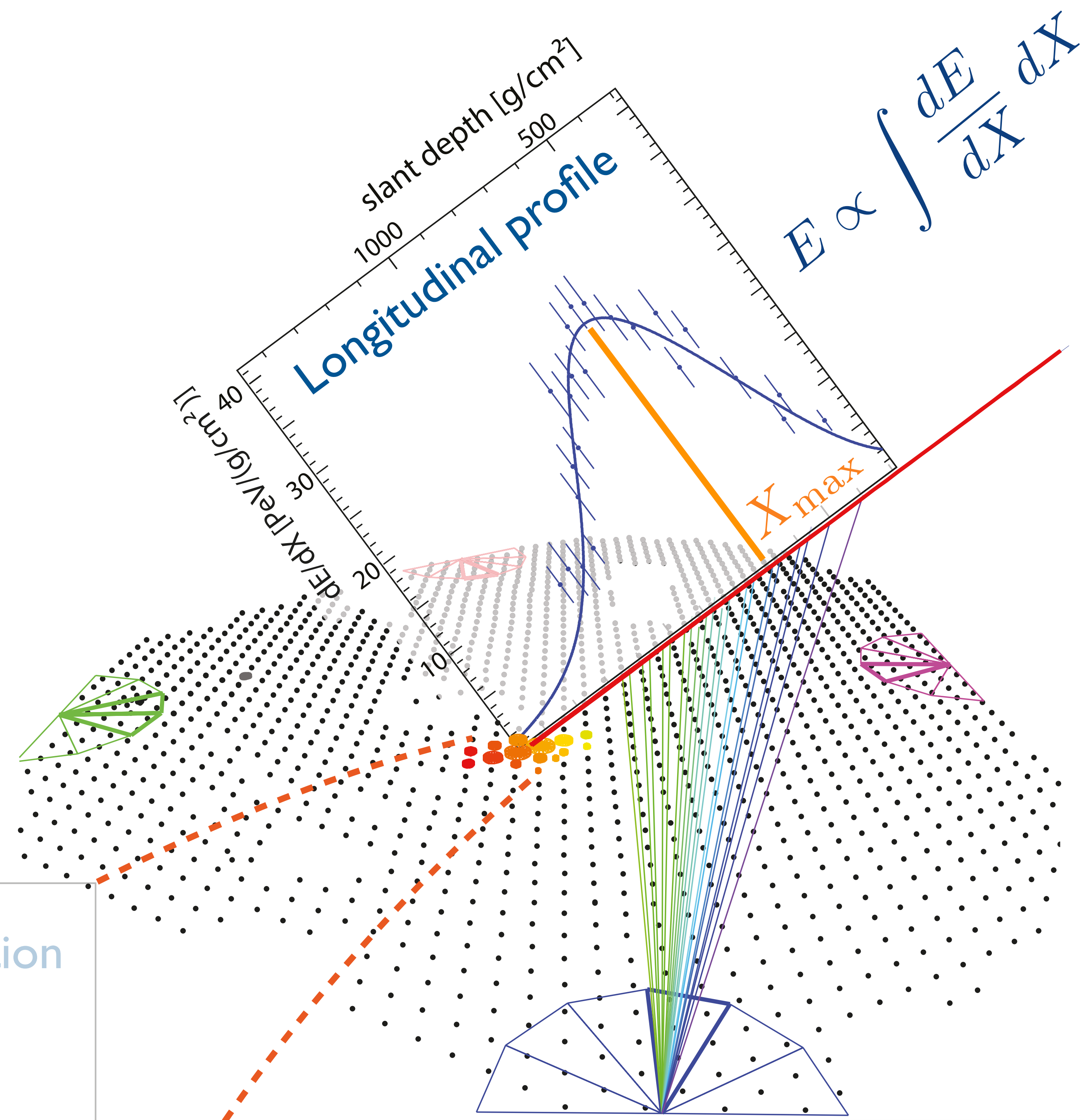




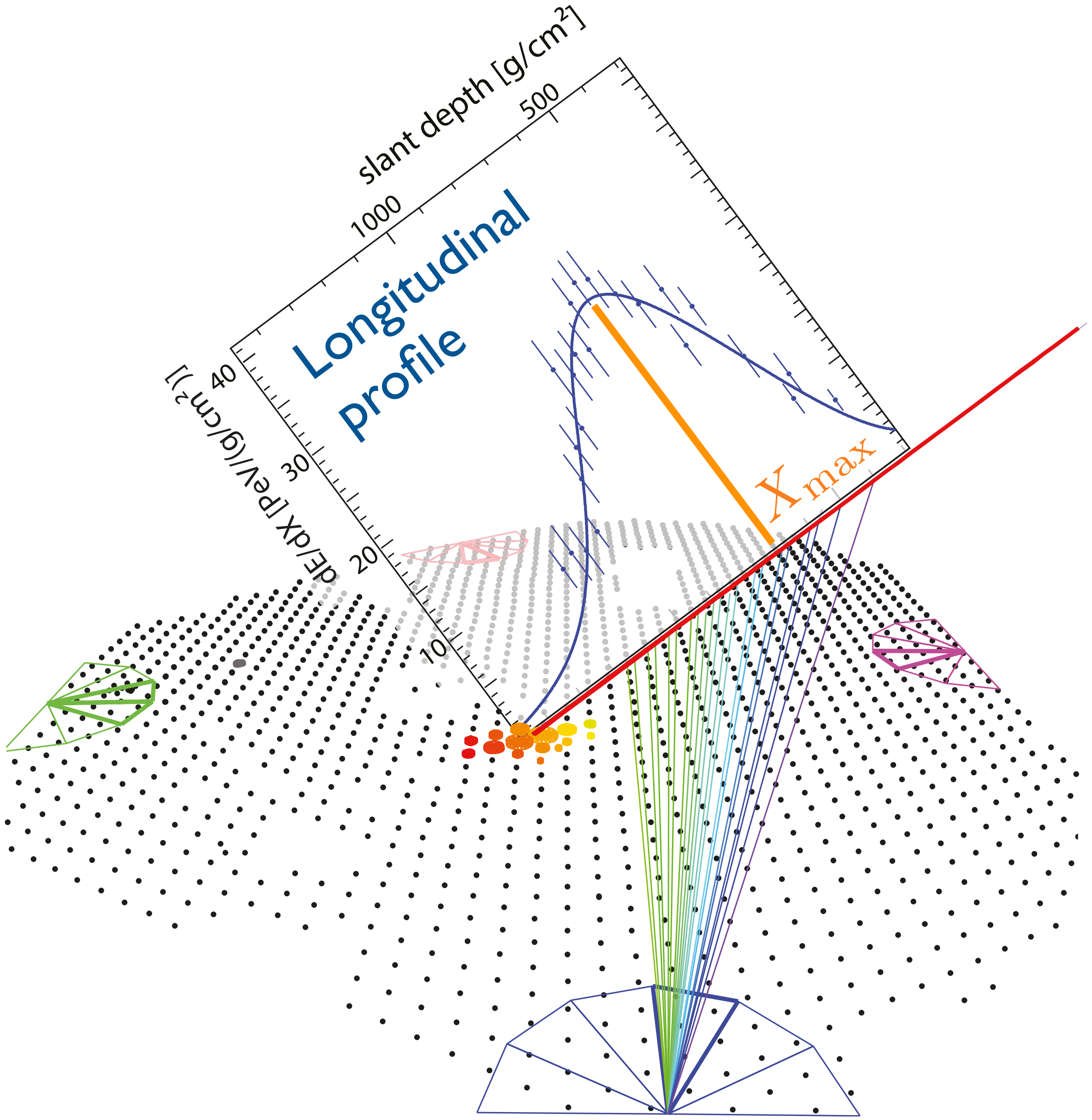


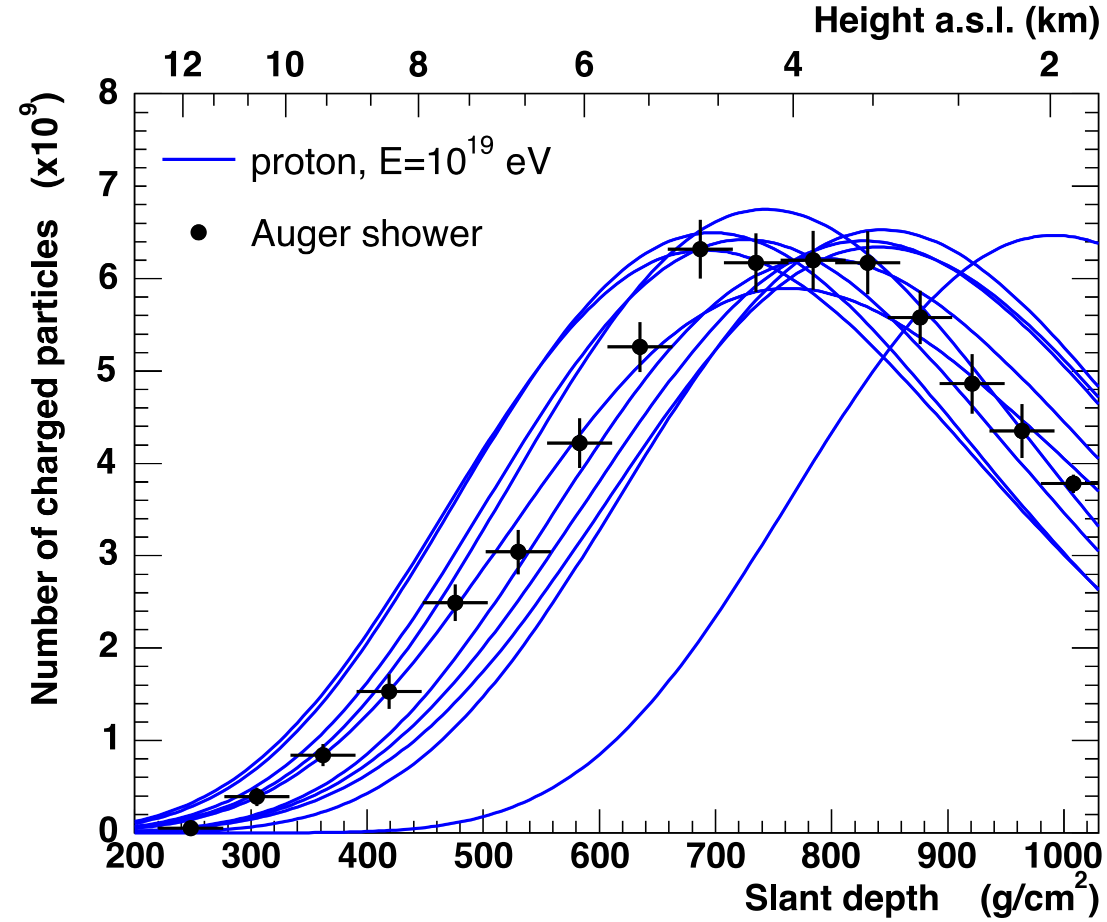
Shower observables recorded at Auger

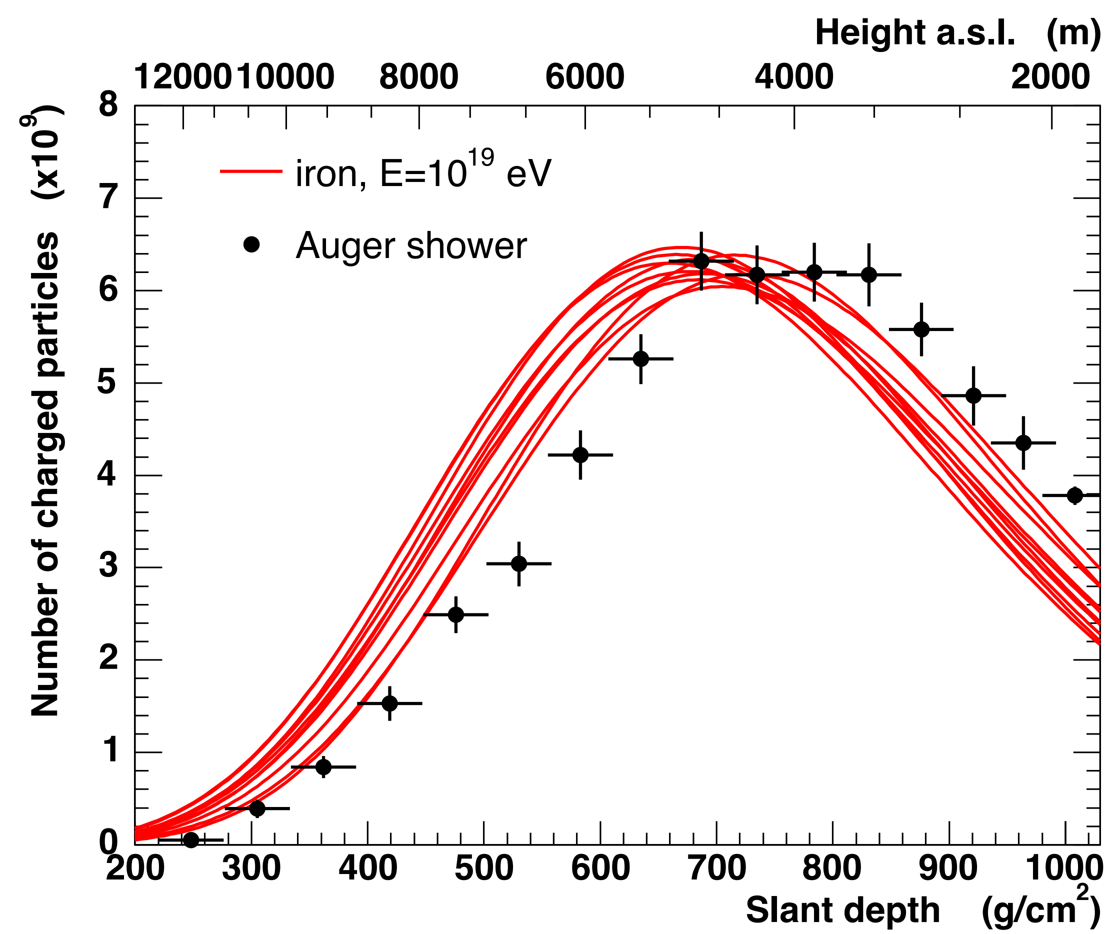




Primary mass and longitudinal shower profiles

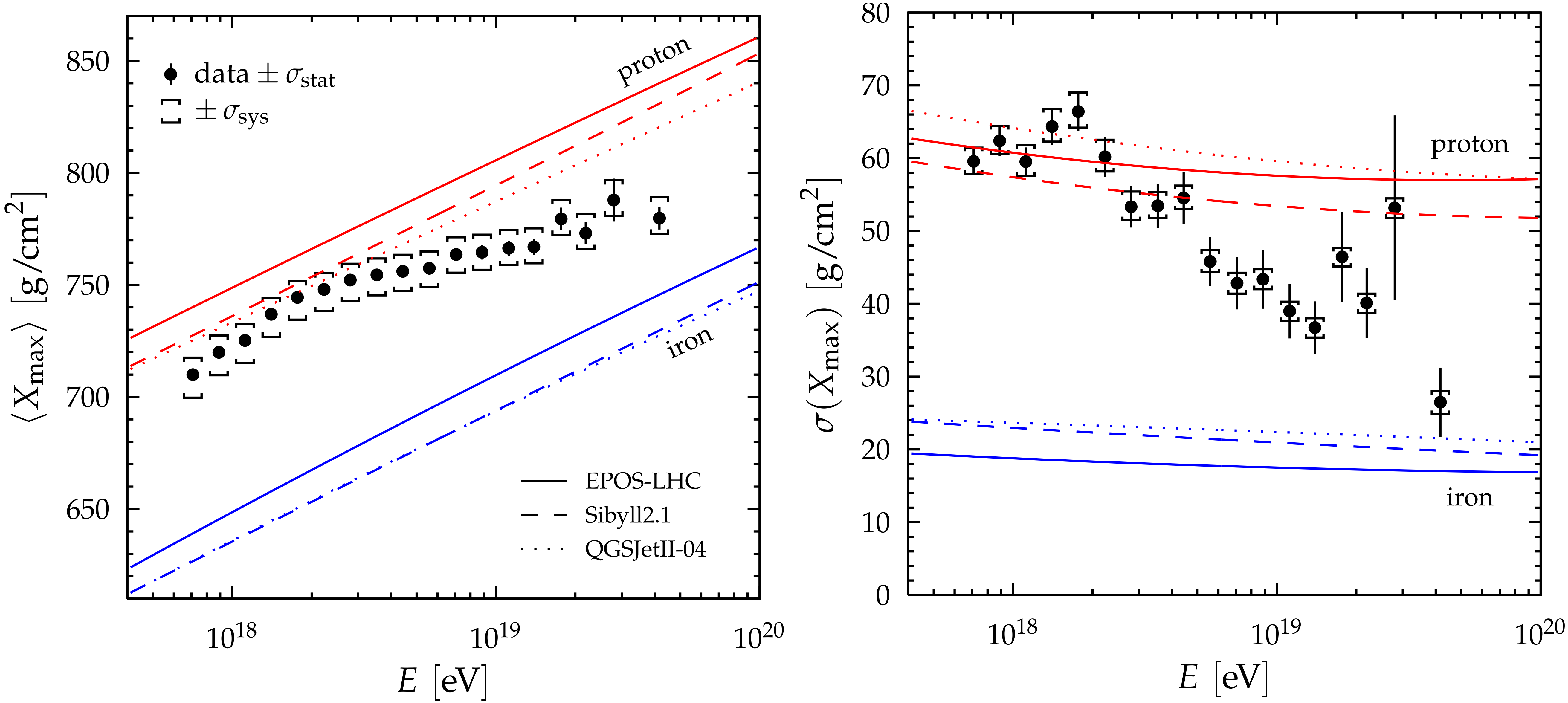






Mean depth of shower profiles and shower-to-shower fluctuations as measure of composition

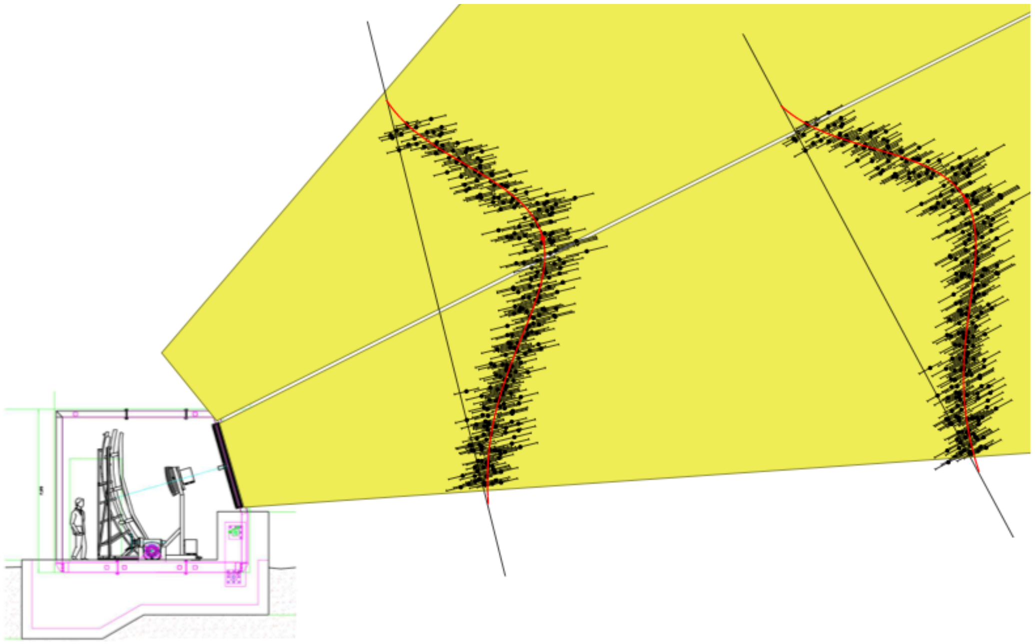
Average Shower Maximum

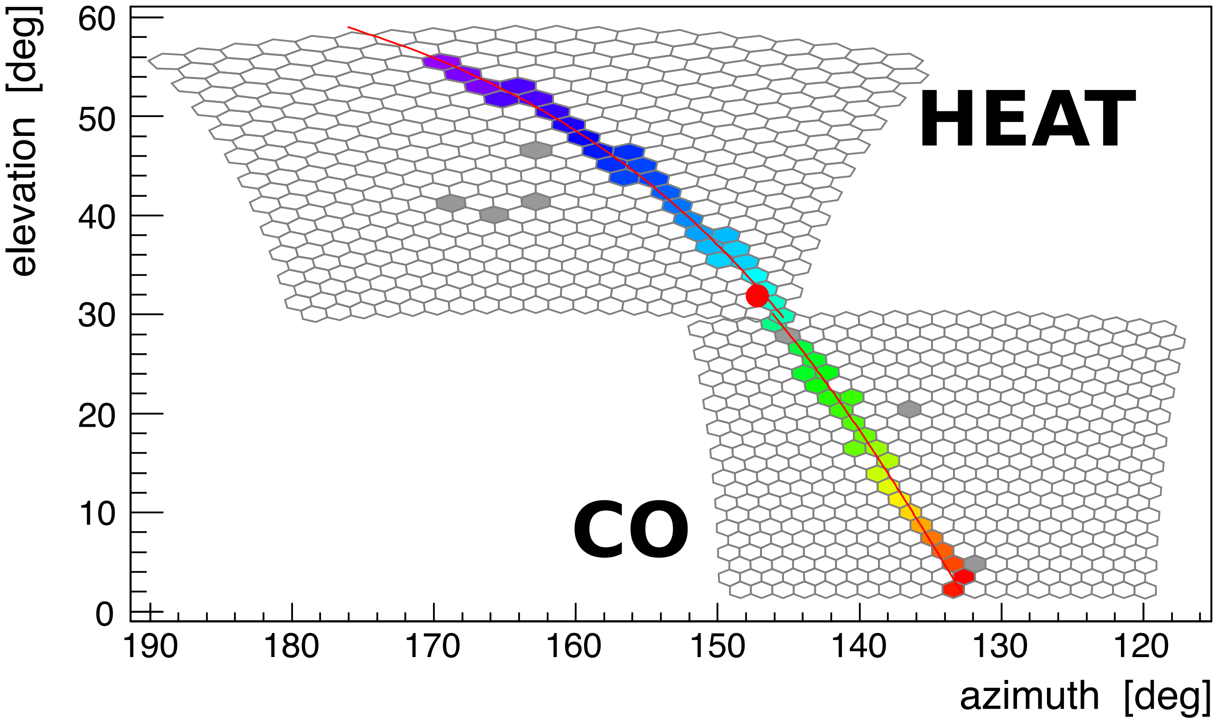


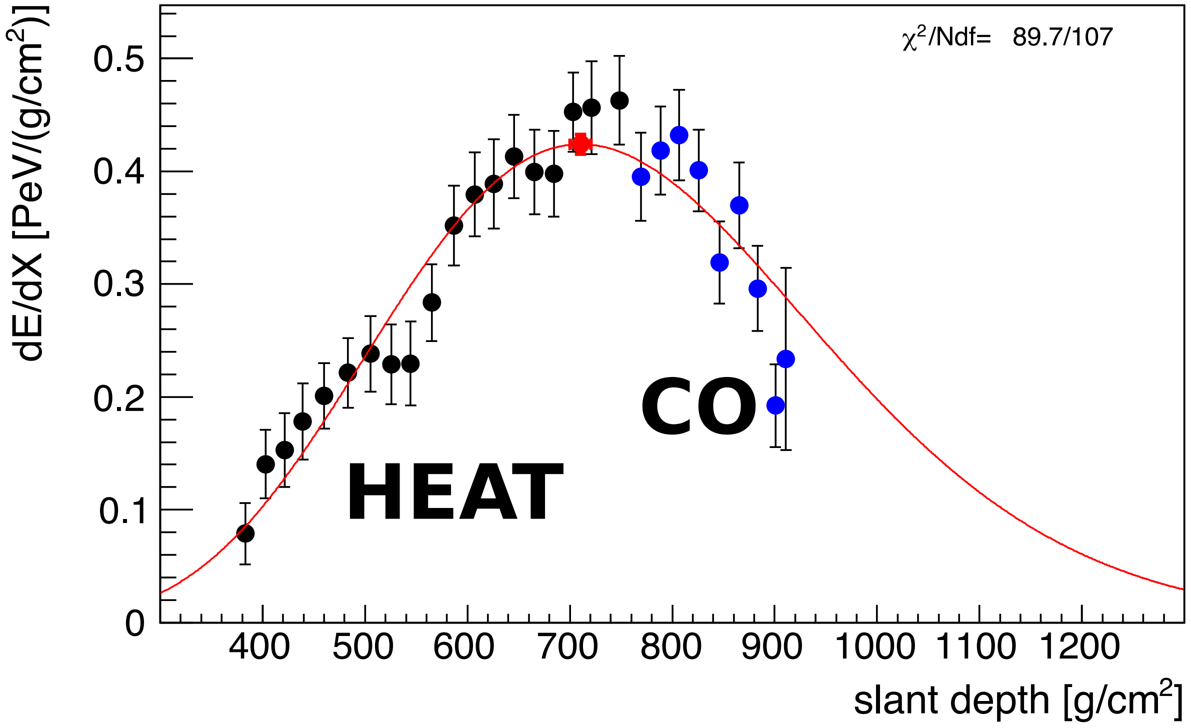
Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

HEAT+Coihueco telescopes: extended field of view

Coihueco: 2° - 30° FoV in elevation
HEAT: 30° - 60° FoV in elevation

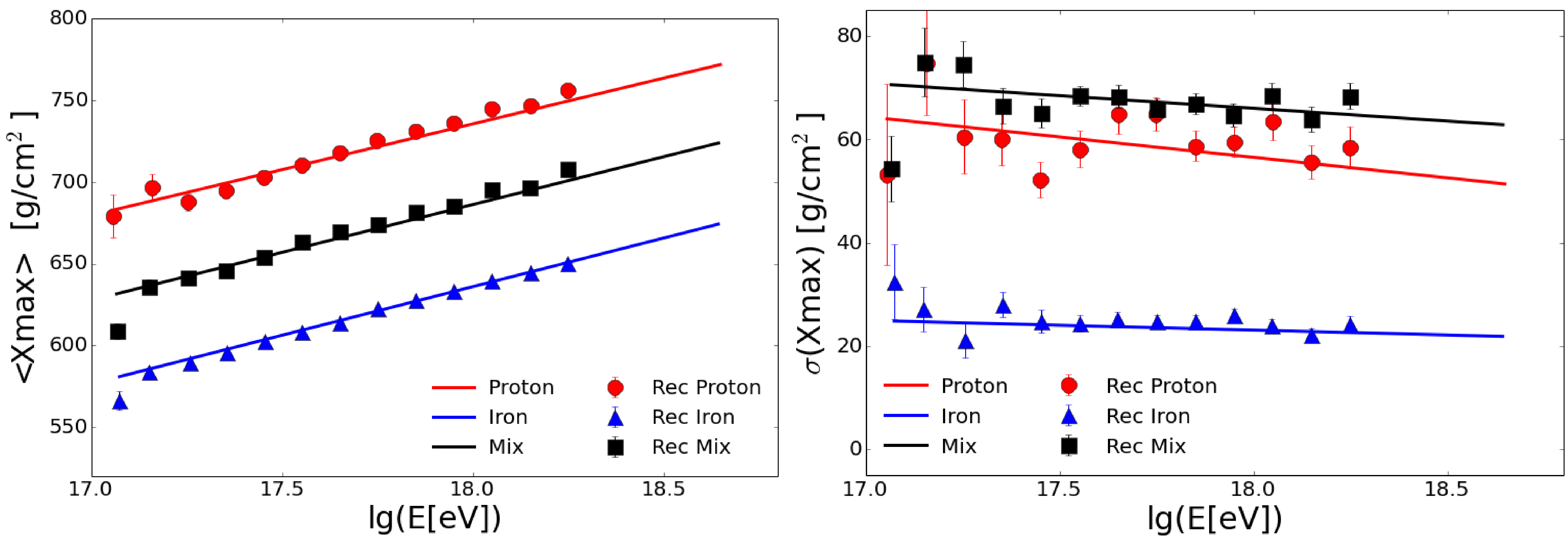






End to end cross-checks with MC simulations

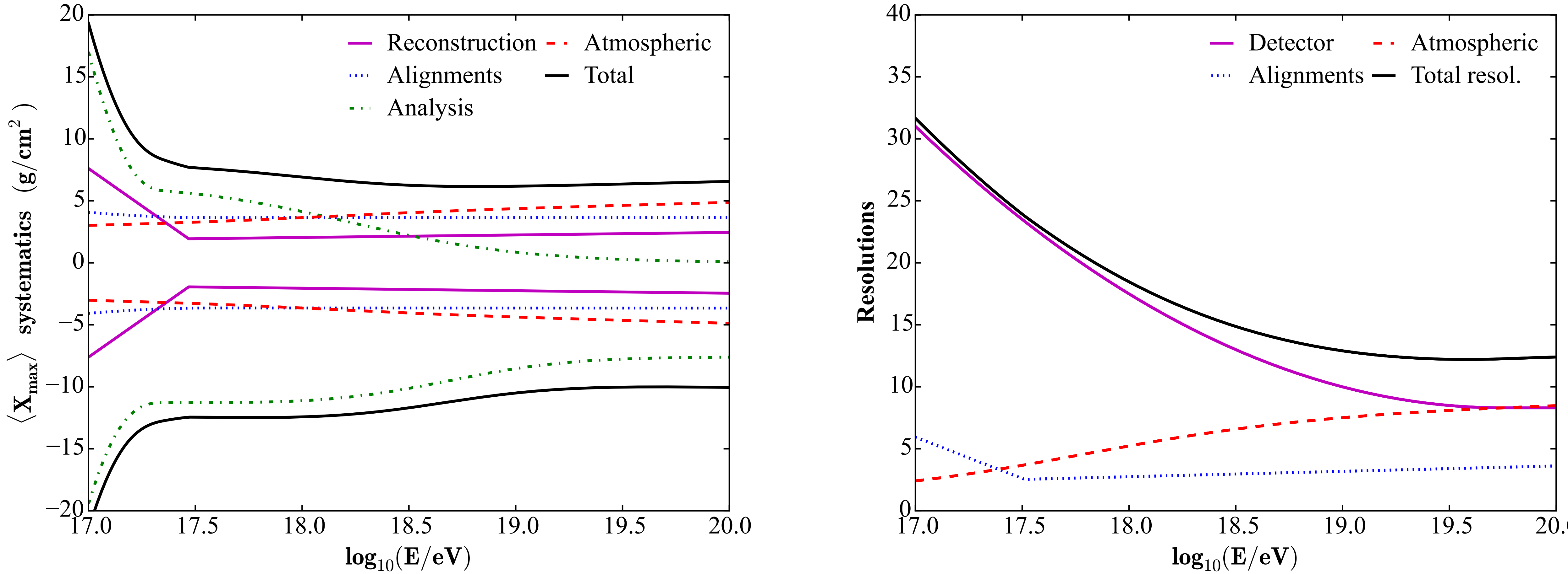
Proton, Iron and 50:50 mixture,
generated (lines) VS reconstructed (markers)



Generated and reconstructed MC data are compatible,
with residual bias in the lowest energy bin:

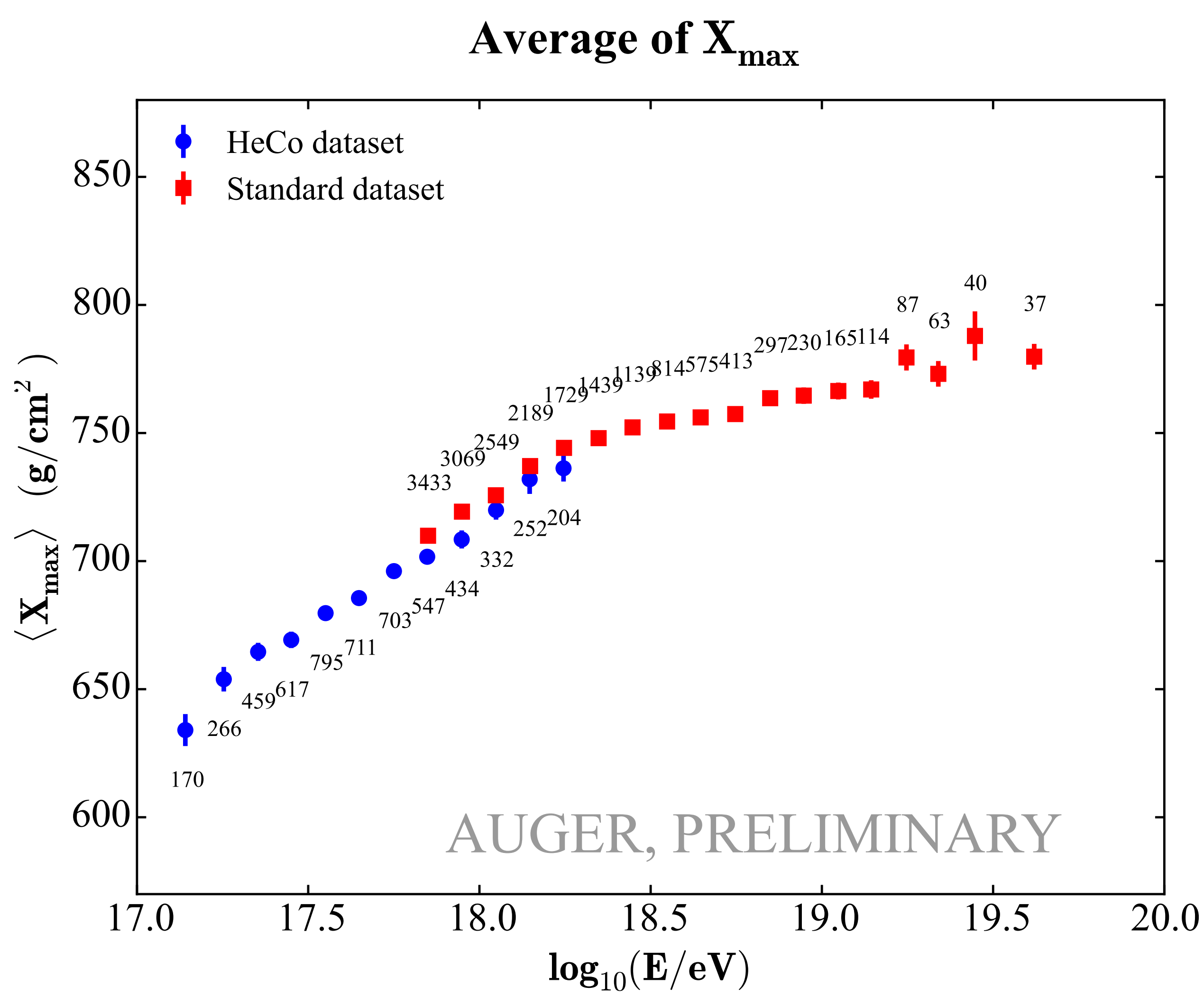
- correction using half of the 50:50 mixture,
- plus a symmetric systematic uncertainty accounted

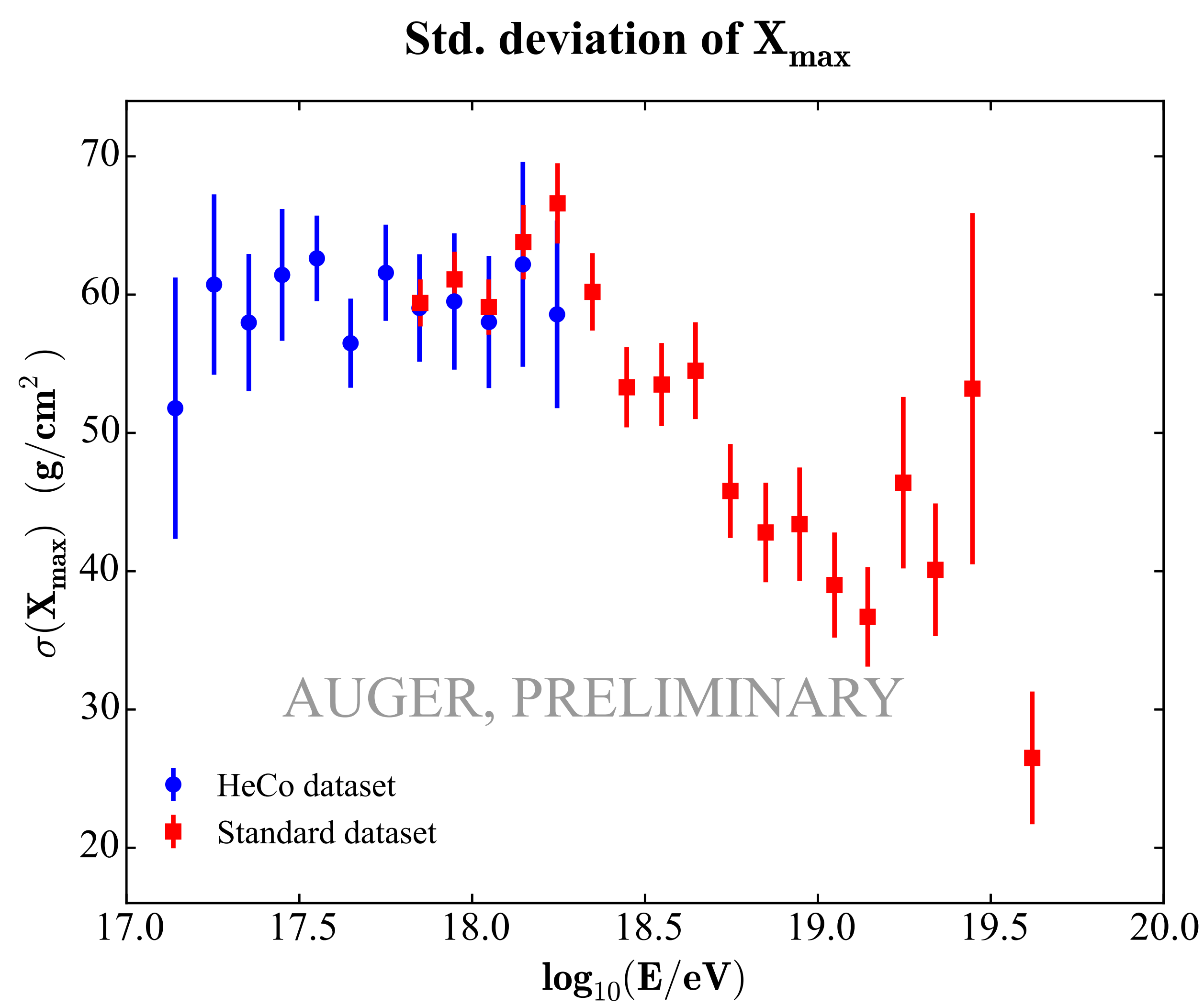
X_{max} systematic uncertainties & resolutions



- Reconstruction bias (only left) and detector resolution (right)
- Offset in time between SD-FD, calibration and telescopes alignment
- Analysis
- Atmospheric uncertainty in the geometry reconstruction and fluorescence light yield

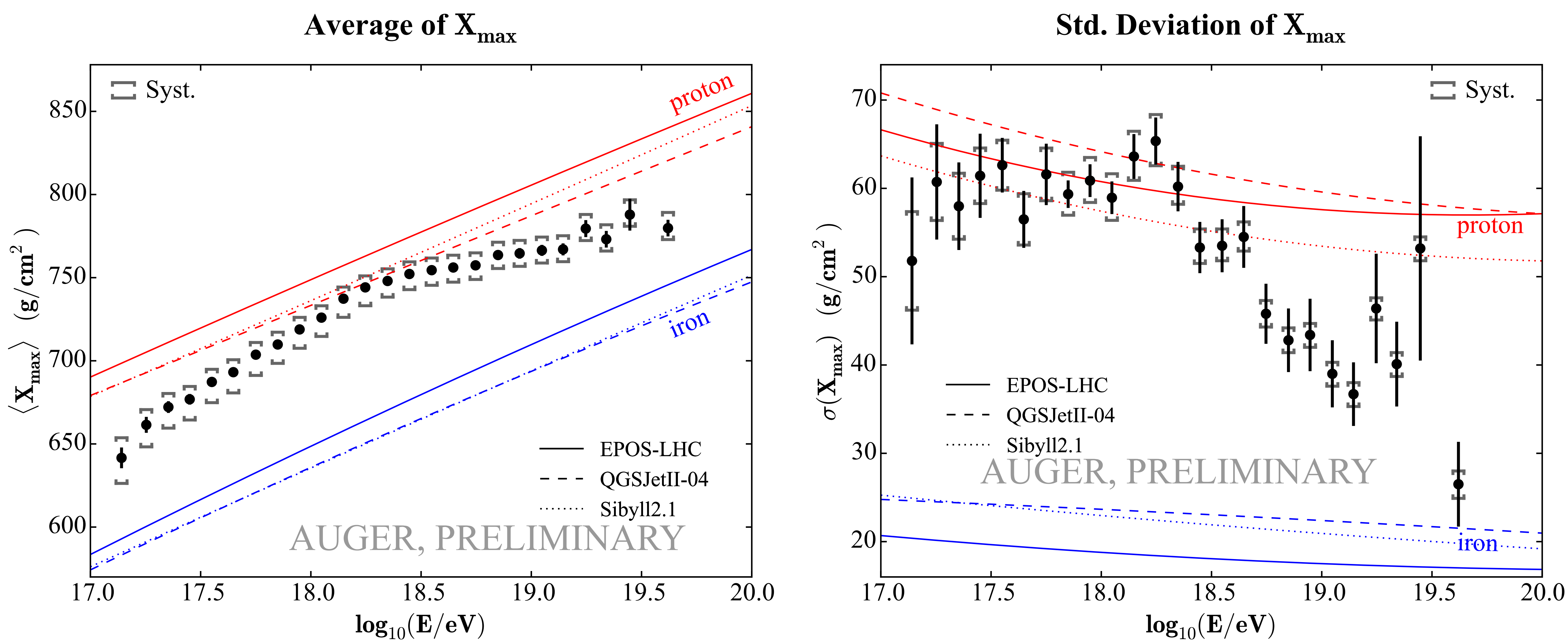
Standard FD vs HEAT+Coihueco





Compatible within expected uncorrelated systematic uncertainties (~ 7 g/cm^2)

Average shower maximum and RMS



Dip model (ankle due to pure proton flux) seems to be ruled out

Pierre Auger Collaboration, to be presented at ICRC15

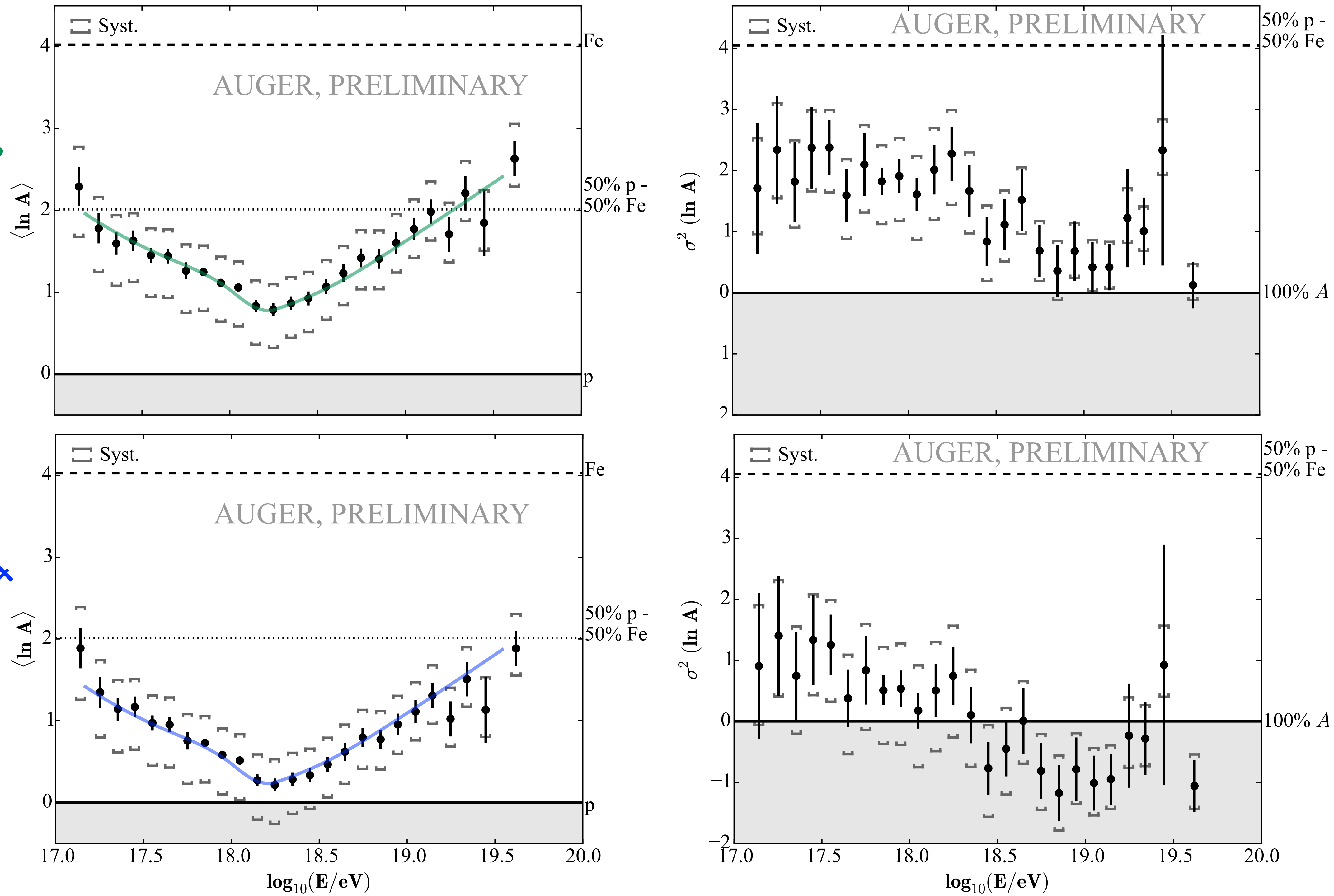
Statistical moments of ⟨ln A⟩

Mean

Variance

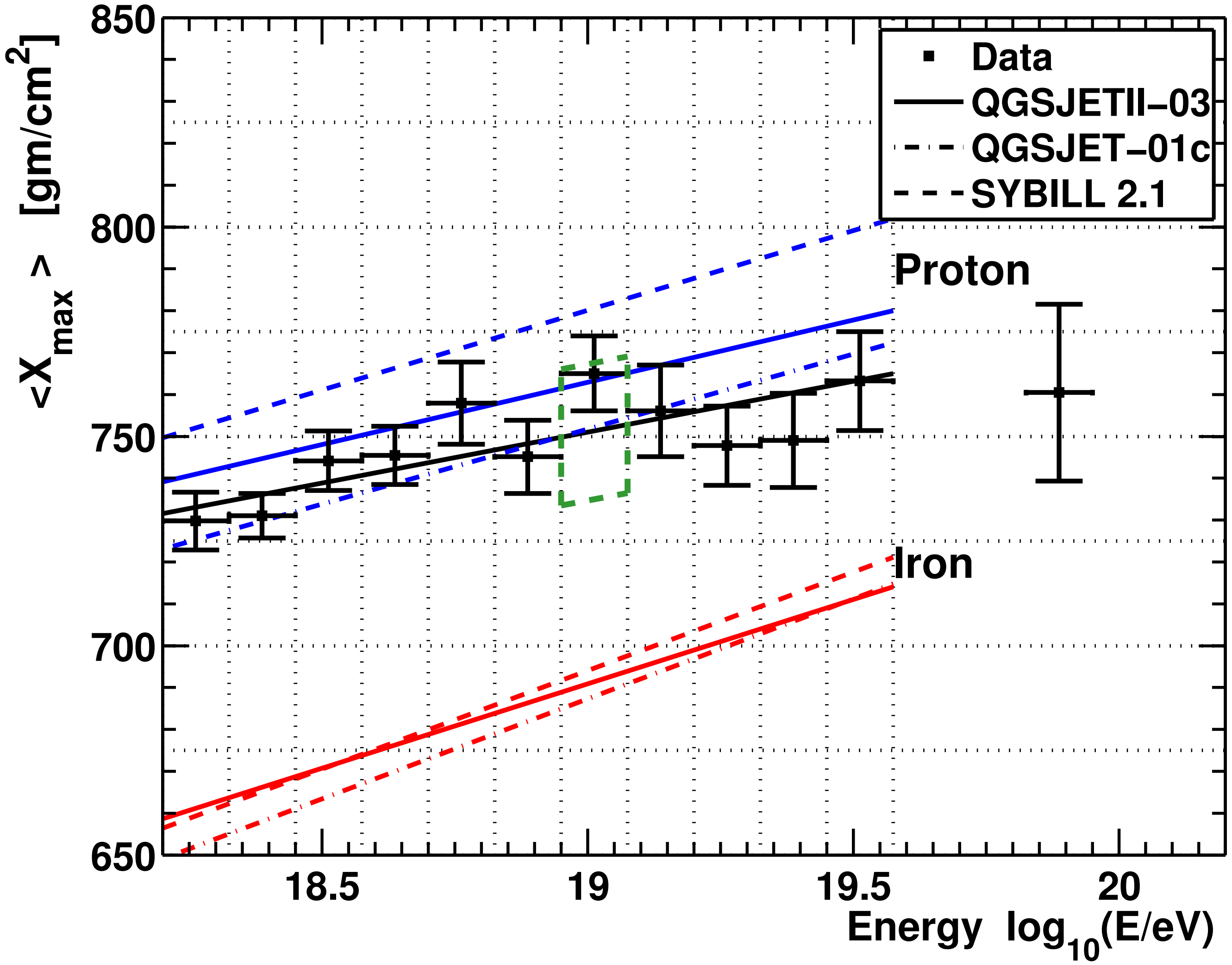
EPOS-LHC

QGSJetII-04

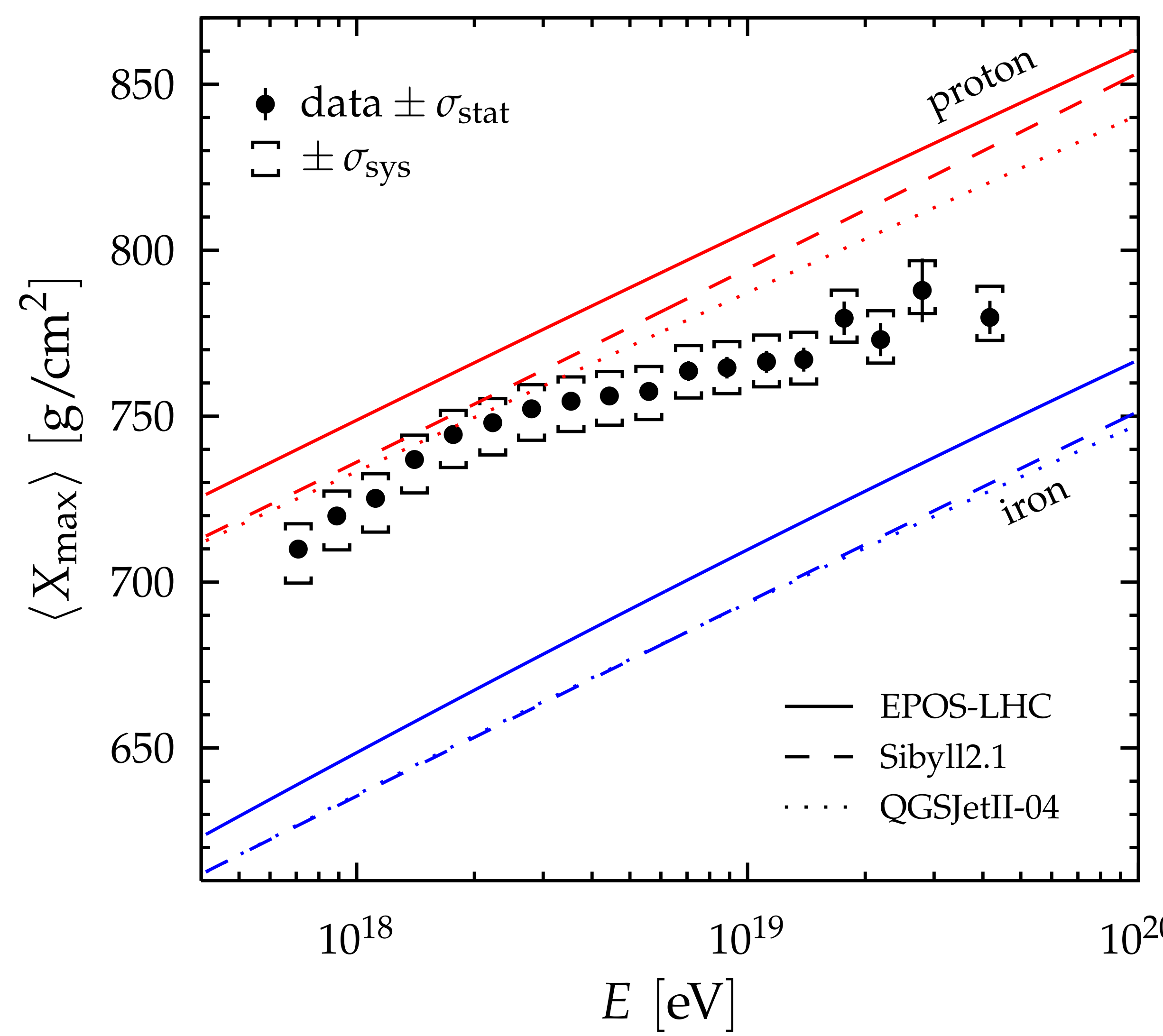


Average shower maximum

Telescope array



Auger



- EAS simulations are folded with detector response (det. resolution and bias introduced)
- Maximized statistics

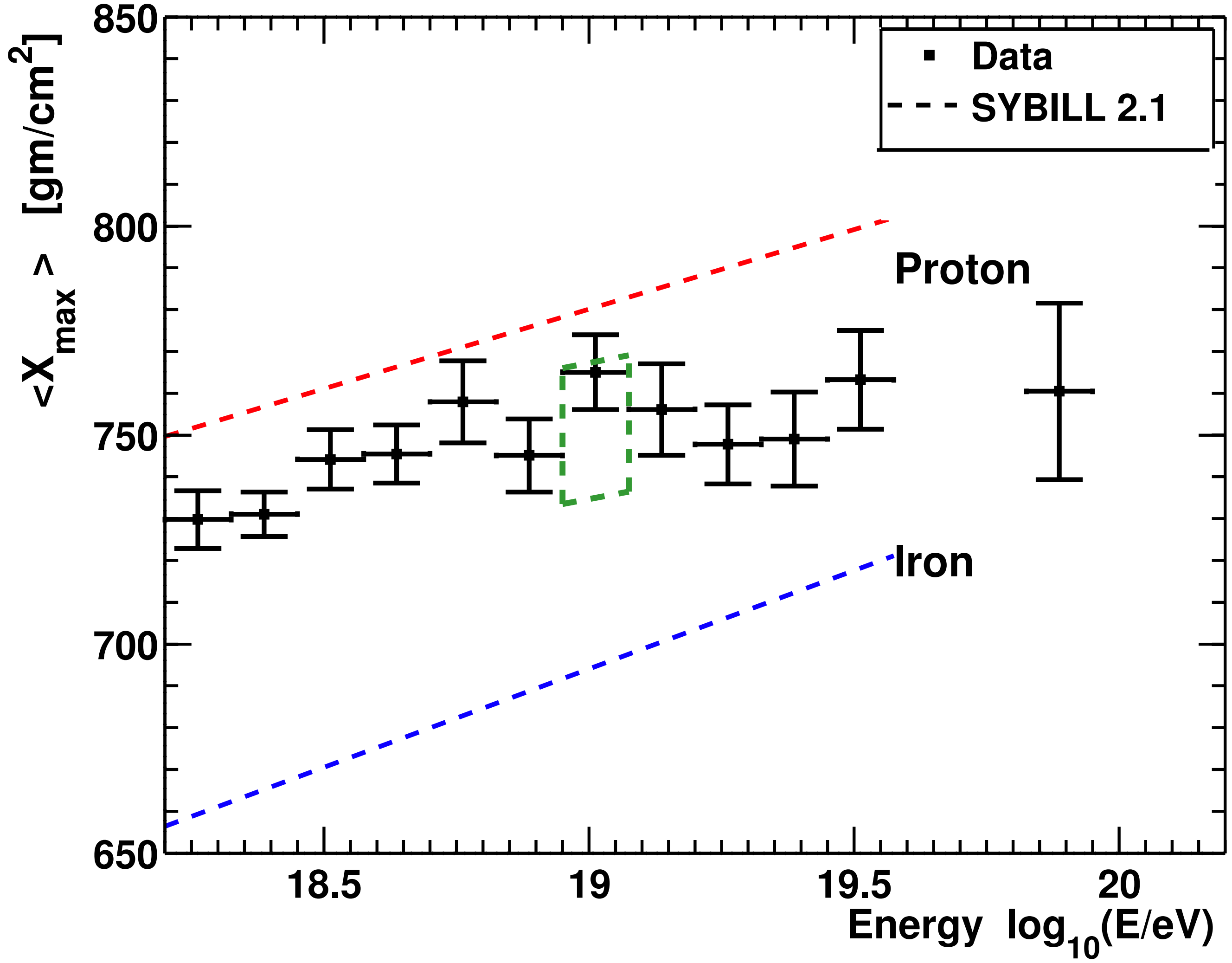
- Unbiased estimate of X_{max} and higher moments
- Reduced statistics

Telescope Array Collaboration, APP 64 (2014) 49

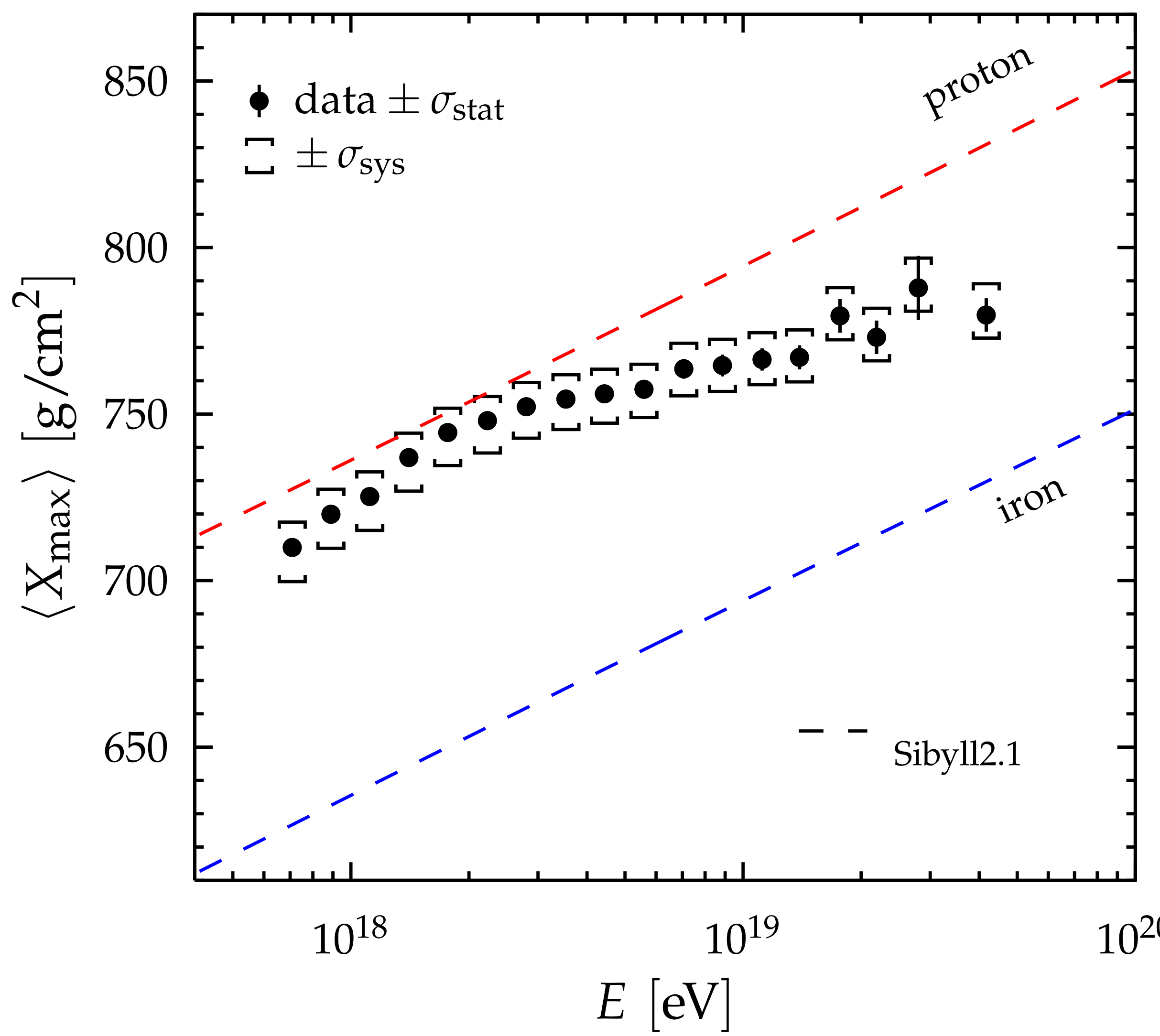
Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Average shower maximum

Telescope array



Auger



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- Maximized statistics

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Telescope Array Collaboration, APP 64 (2014) 49

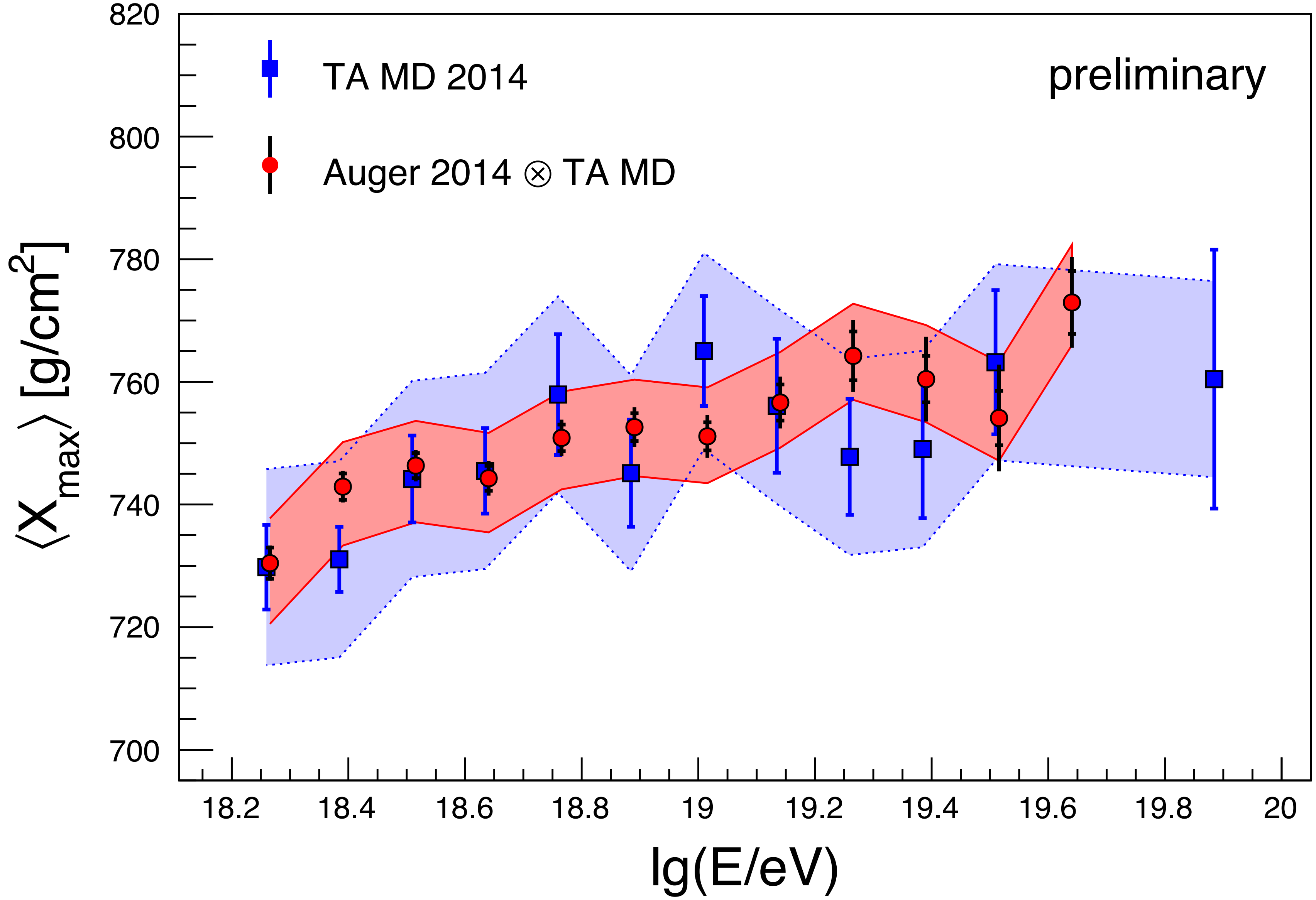
Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Average shower maximum

TA data from MD telescopes

Parameterized Auger data folded with the MD acceptance

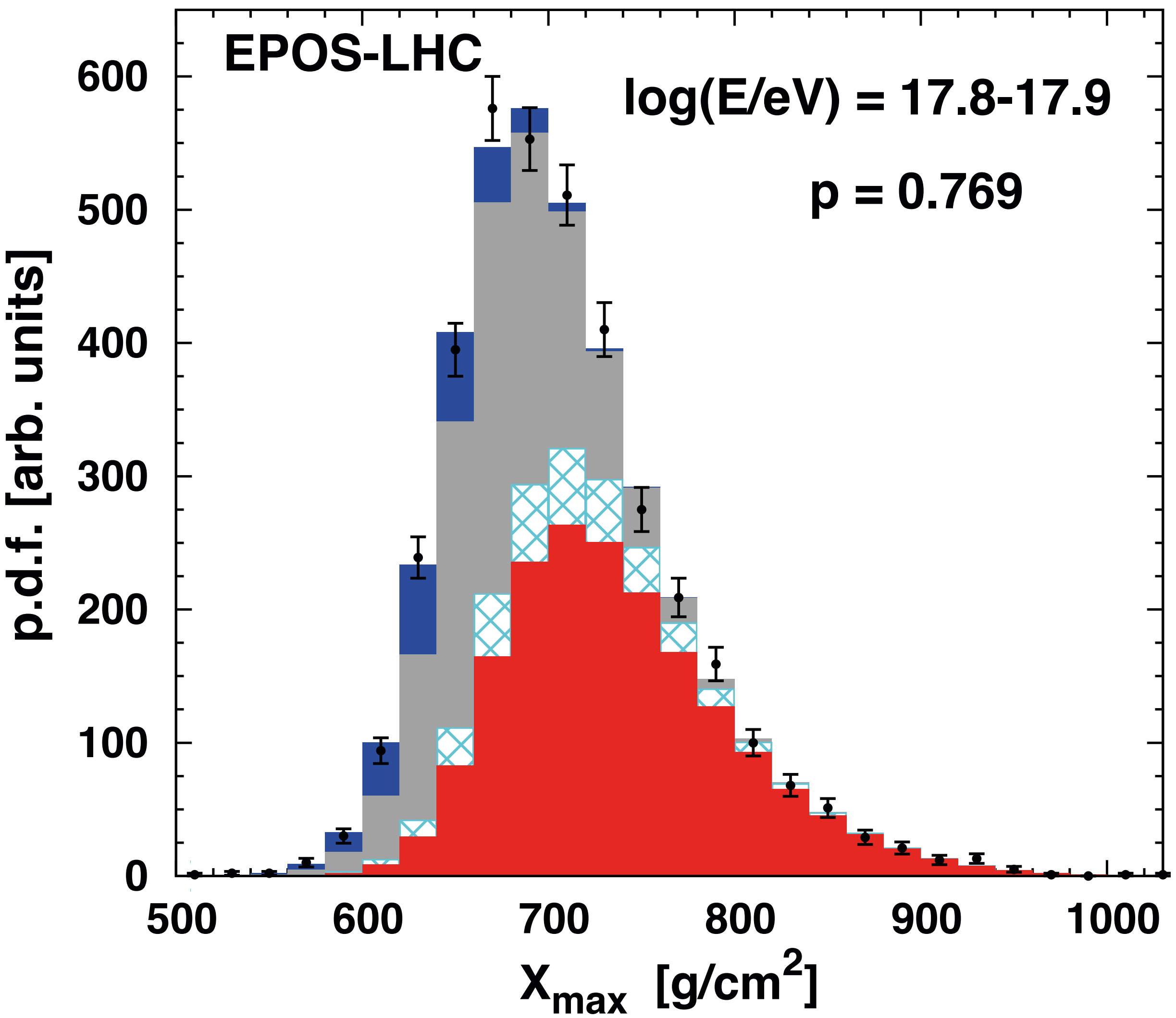
MD = Middle Drum
(site of one telescope station)

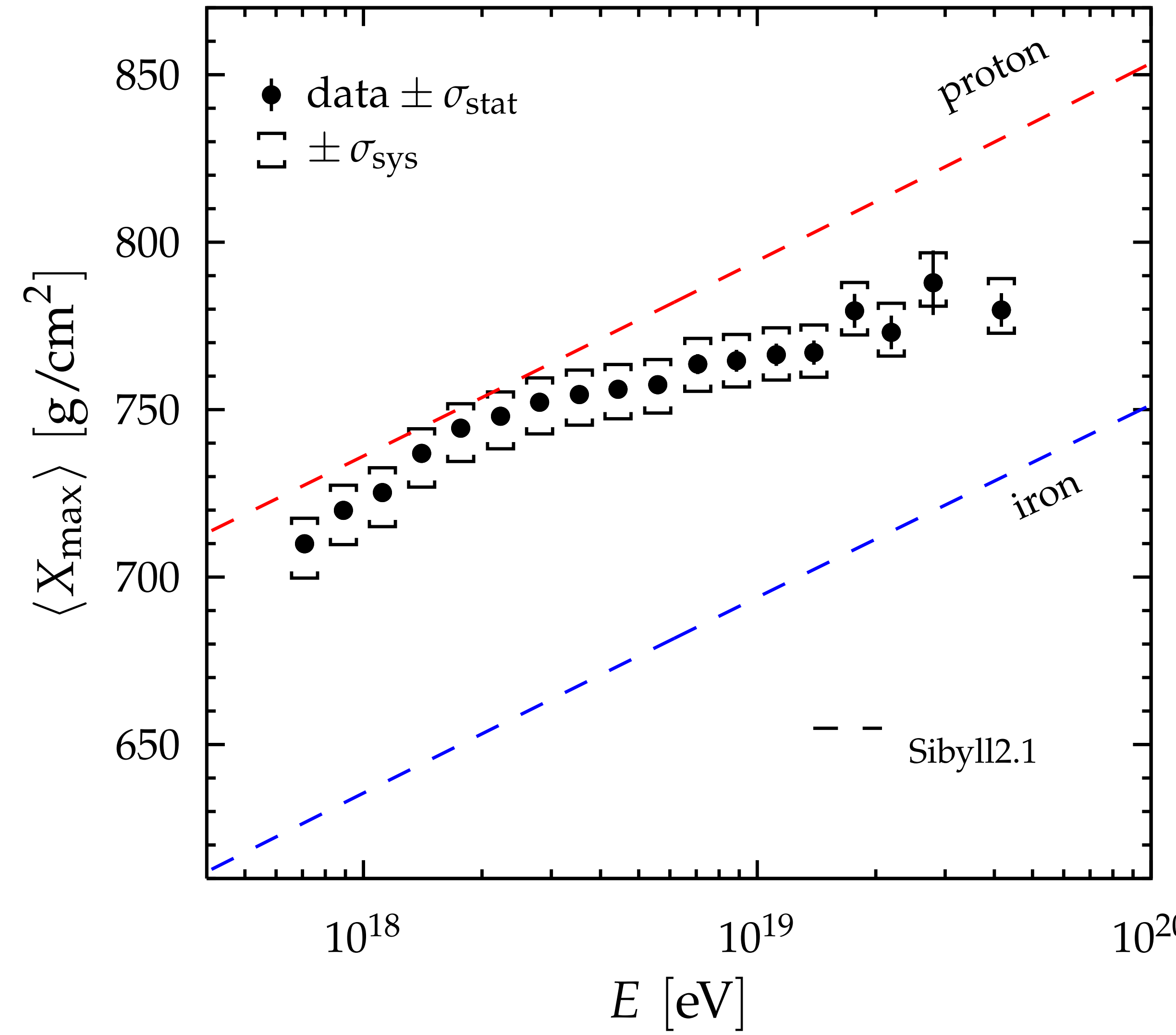


$\langle \Delta \rangle$ = (2.9 ± 2.7 (stat.) ± 18 (syst.)) g/cm^2

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

Composition fit of the whole distribution

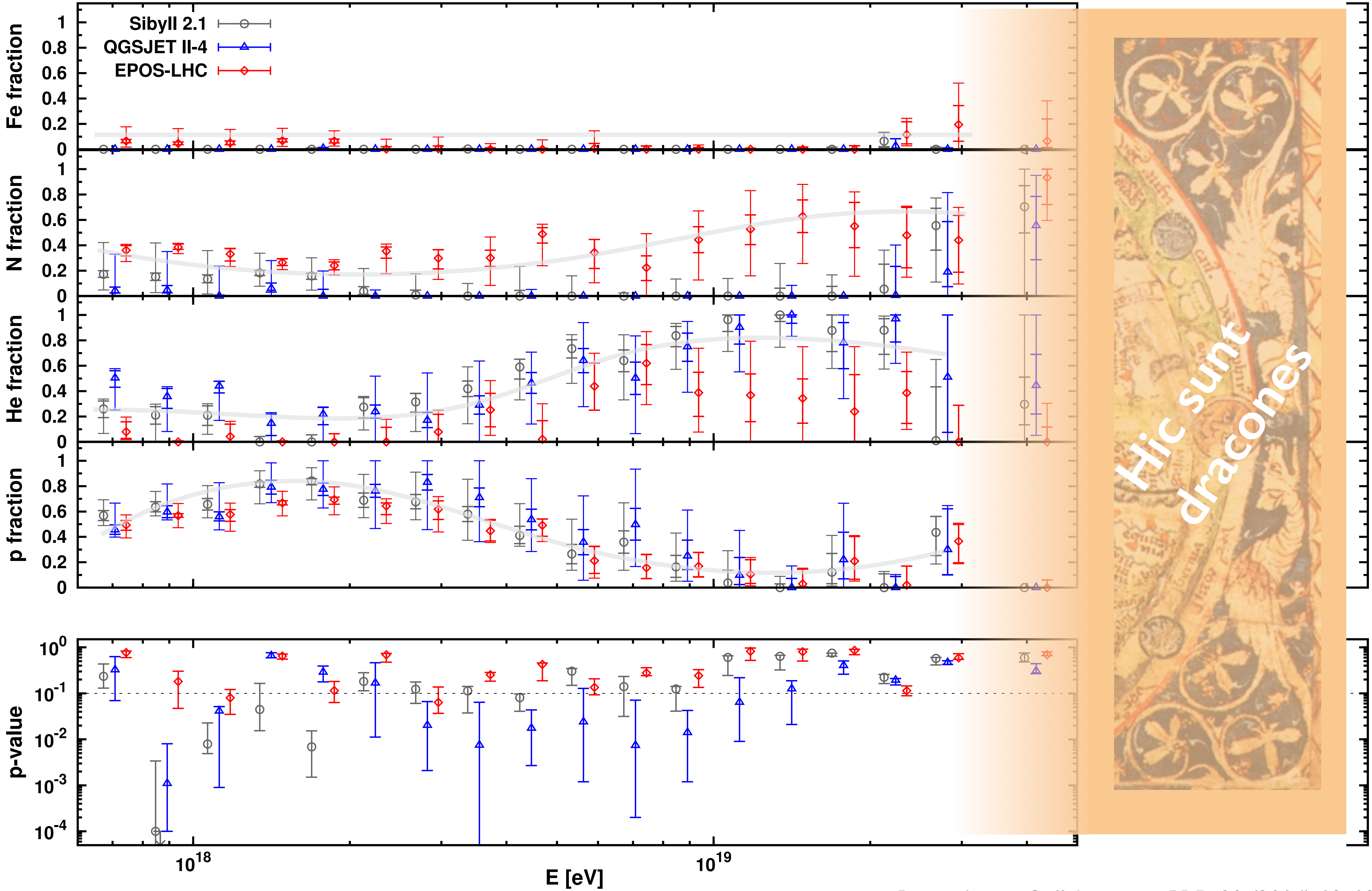




Pierre Auger Collaboration, PRD 90 (2014) 12, 122006

Composition Fit (X_{max} distribution)

Data available only up to < 5×10^{19} eV



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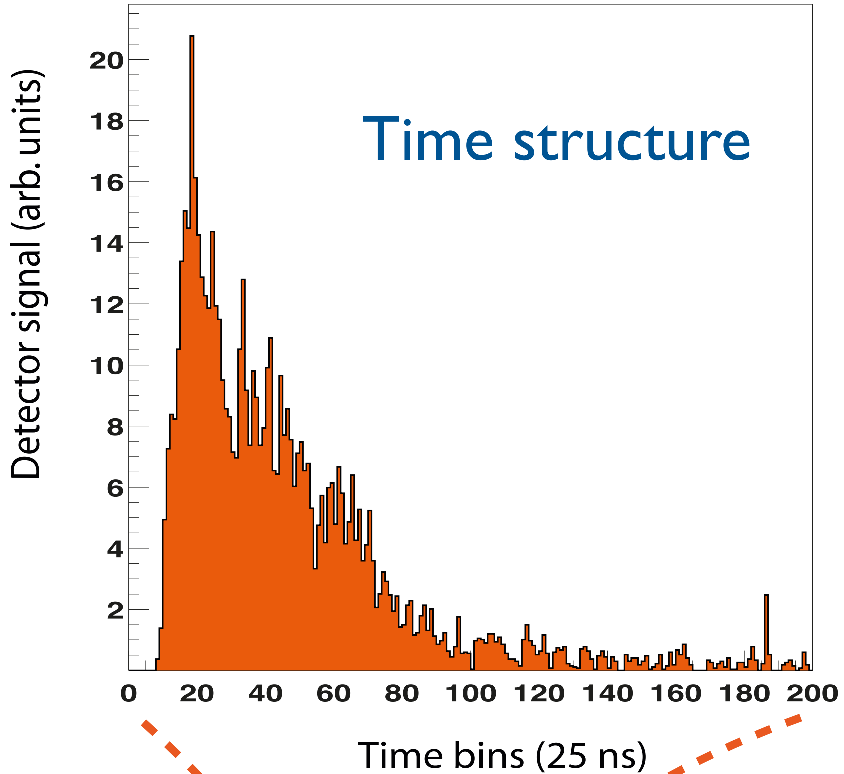
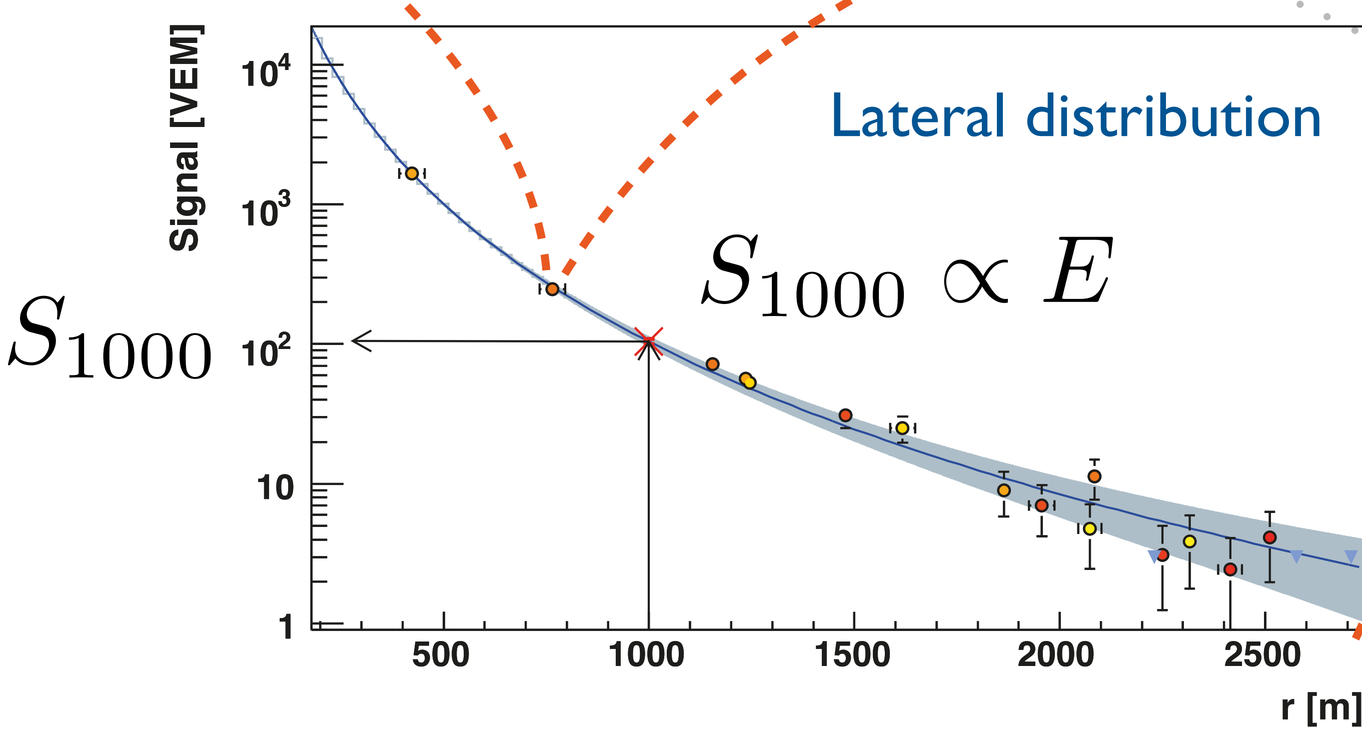
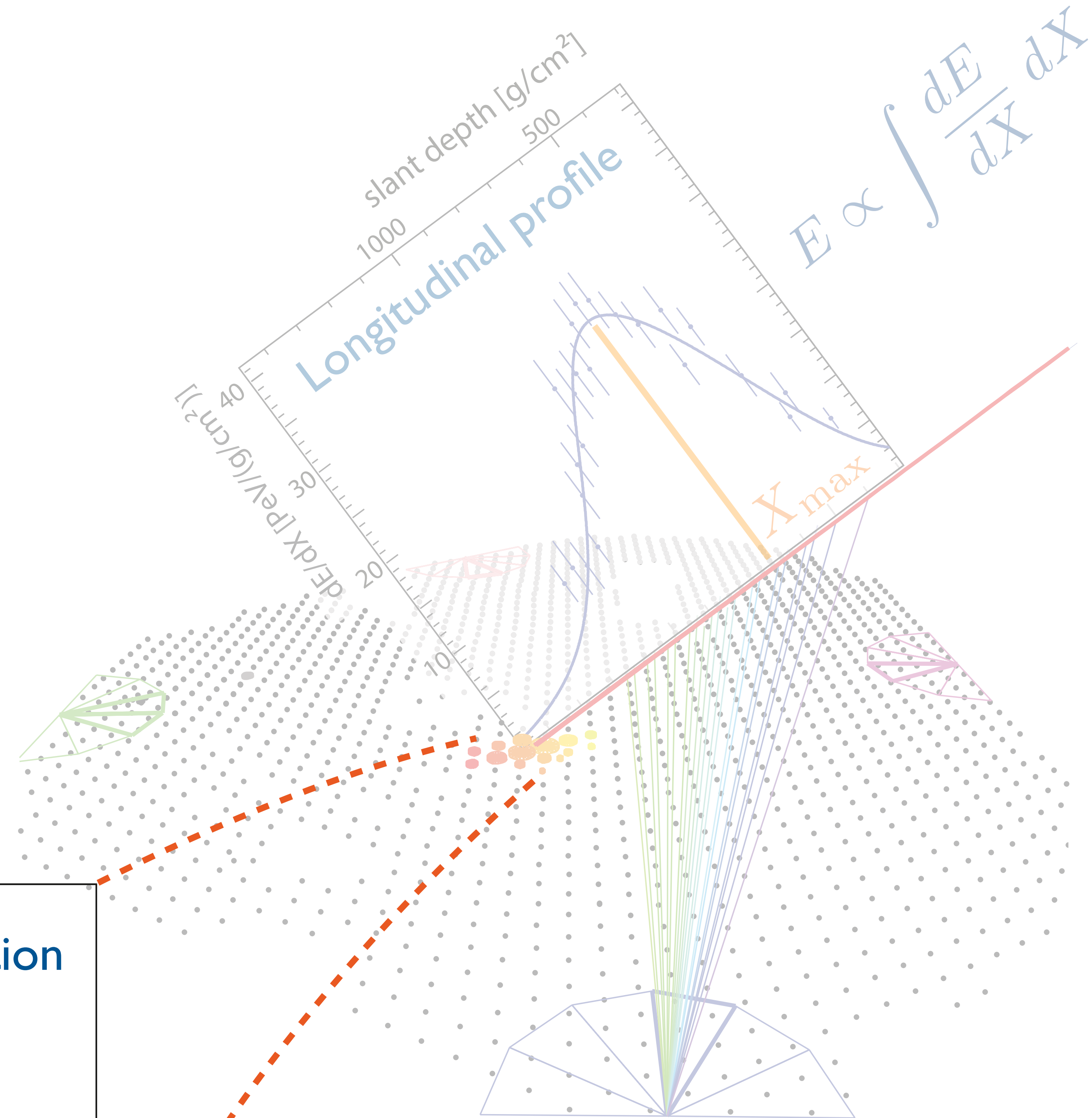
Shower observables recorded at Auger







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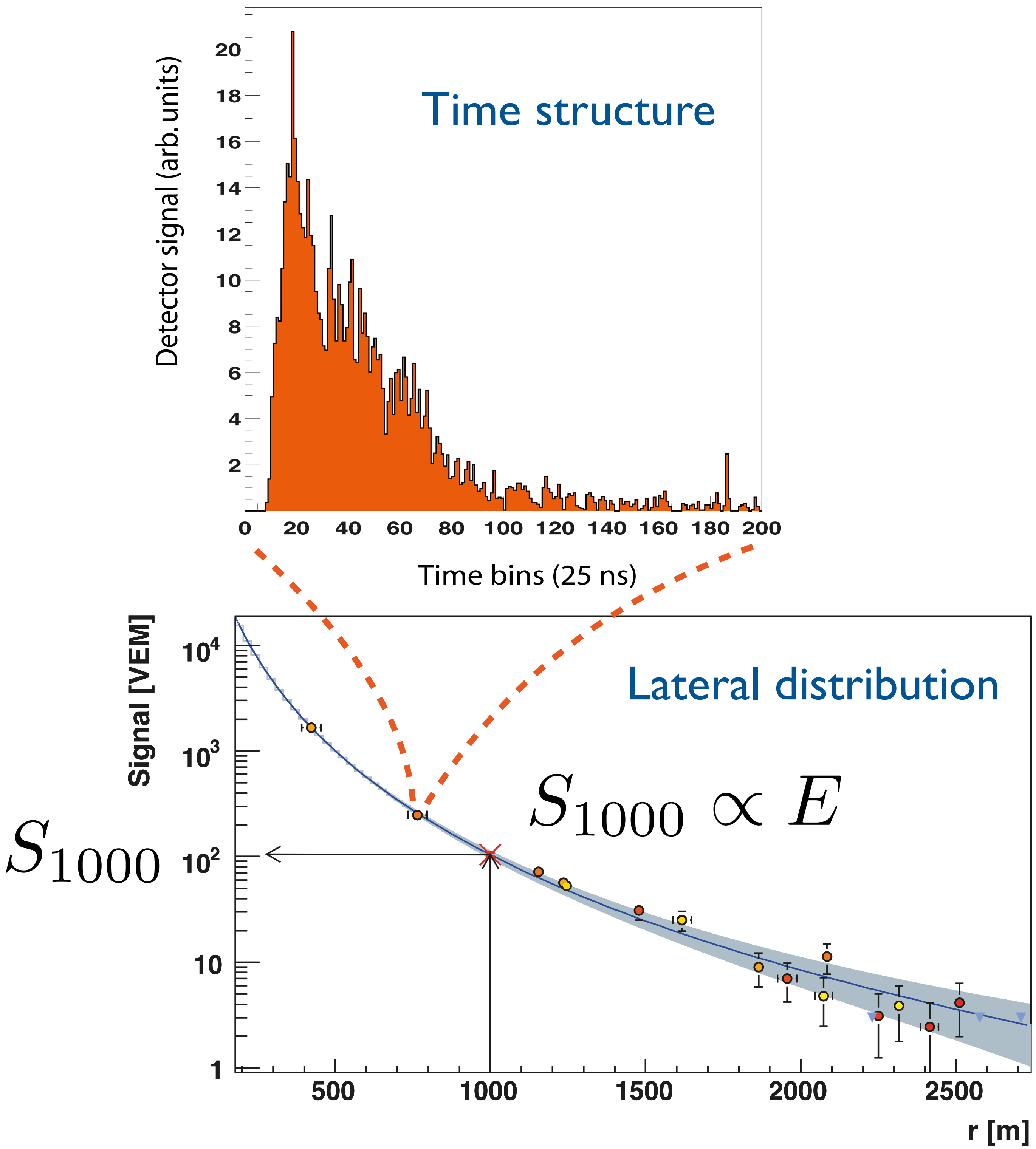
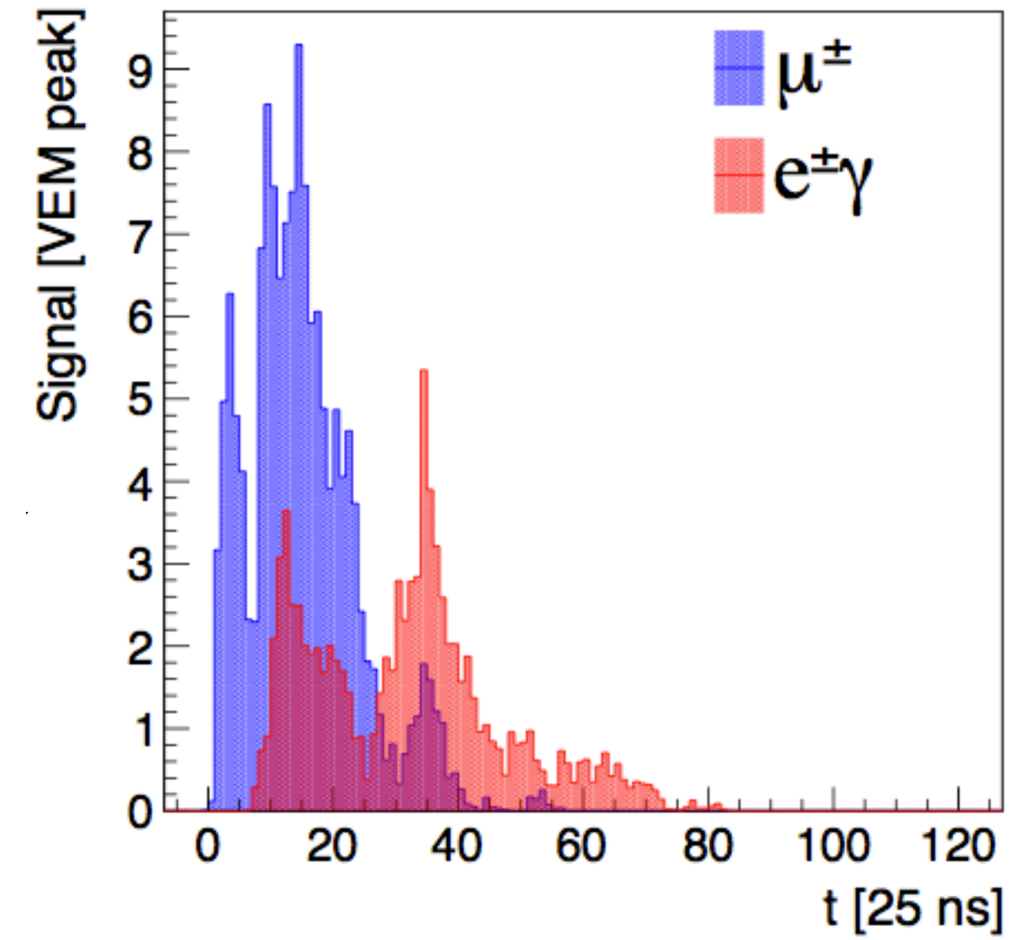
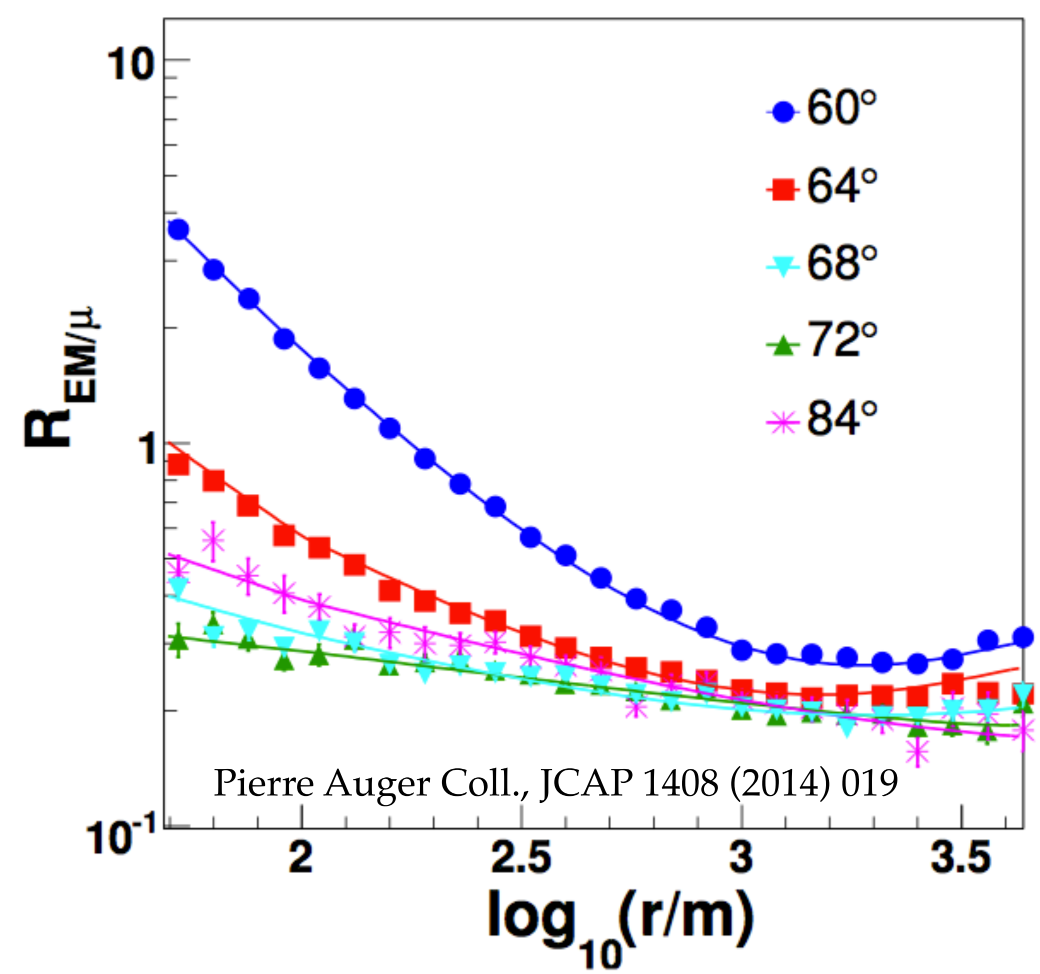
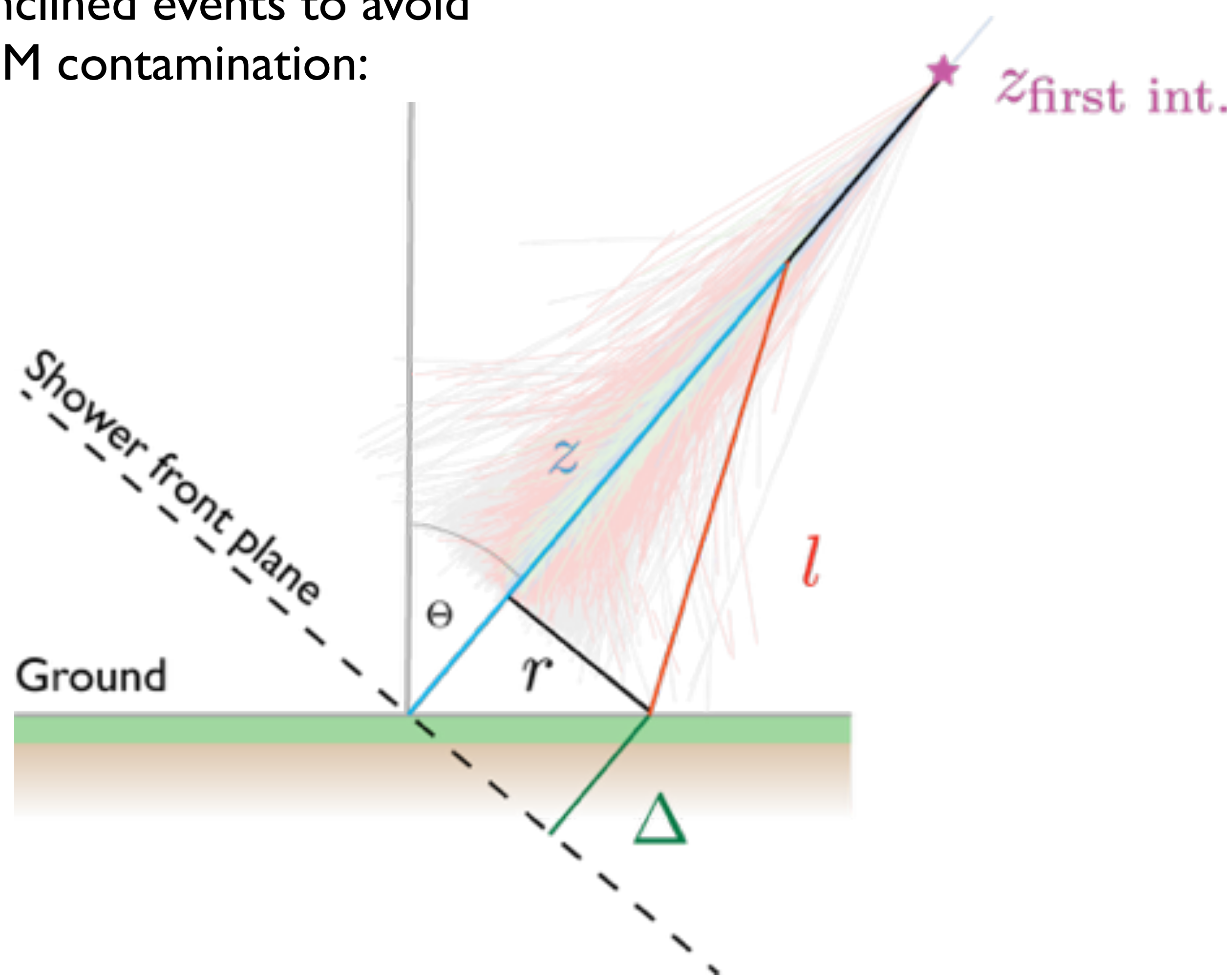


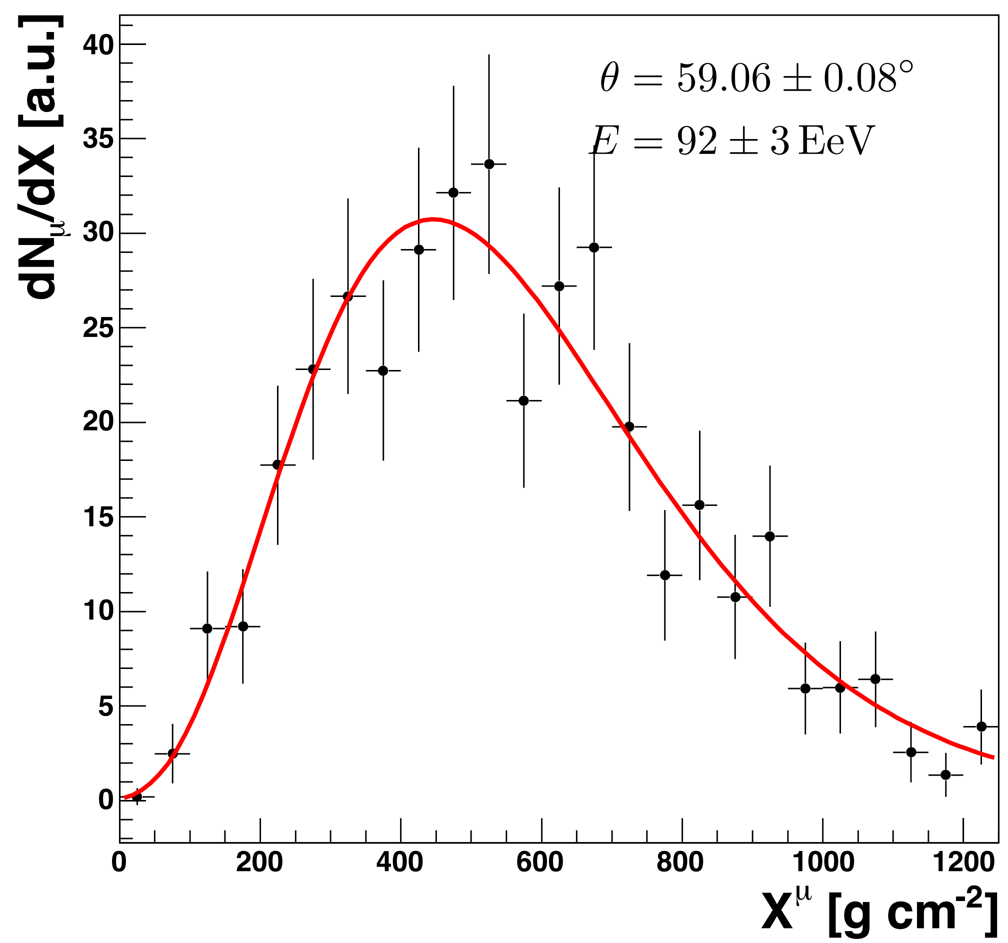




Muon Production Depth
distribution (MPD) in a nutshell

Inclined events to avoid EM contamination:





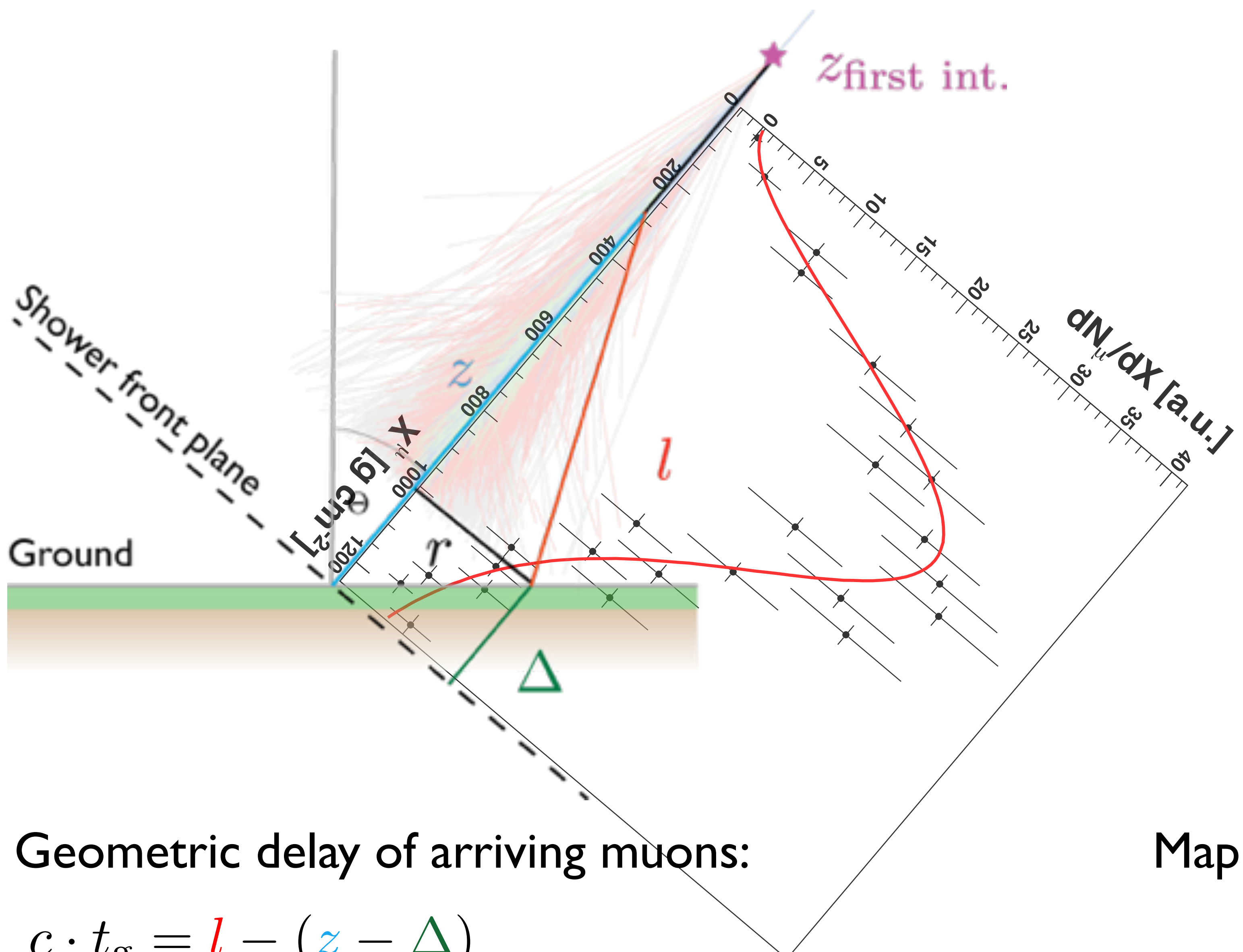
Geometric delay of arriving muons:

$$c \cdot t_g = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta)$$

Mapped to muon production depth:

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

Muon Production Depth
distribution (MPD) in a nutshell



Geometric delay of arriving muons:

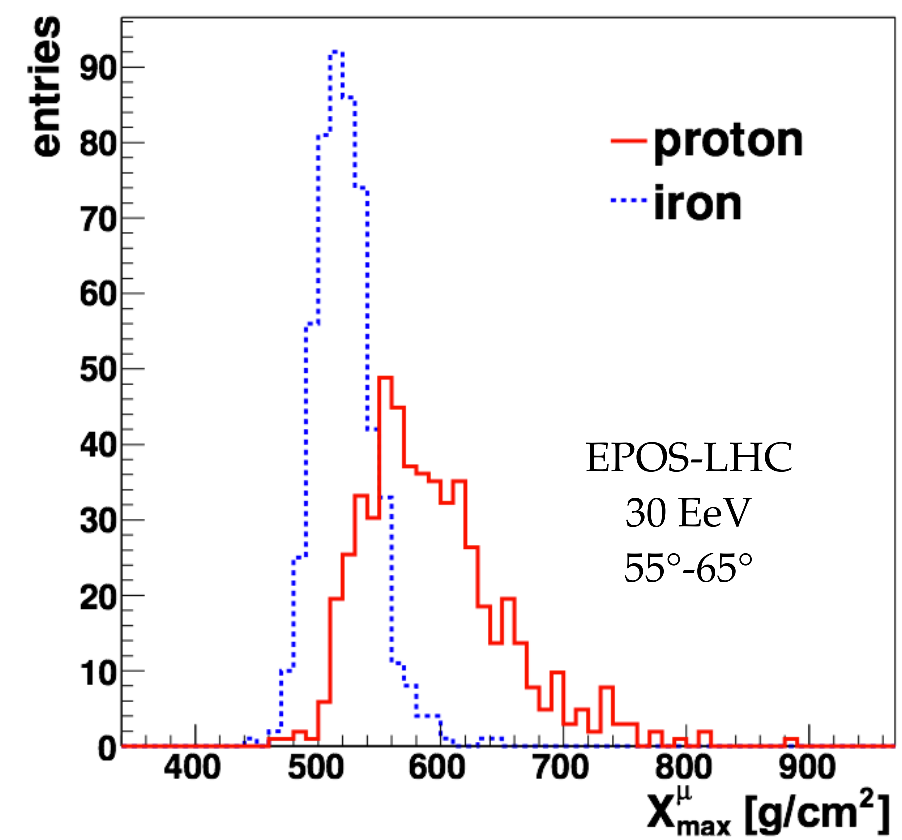
$$c \cdot t_{\rm g} = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

Mapped to muon production depth:

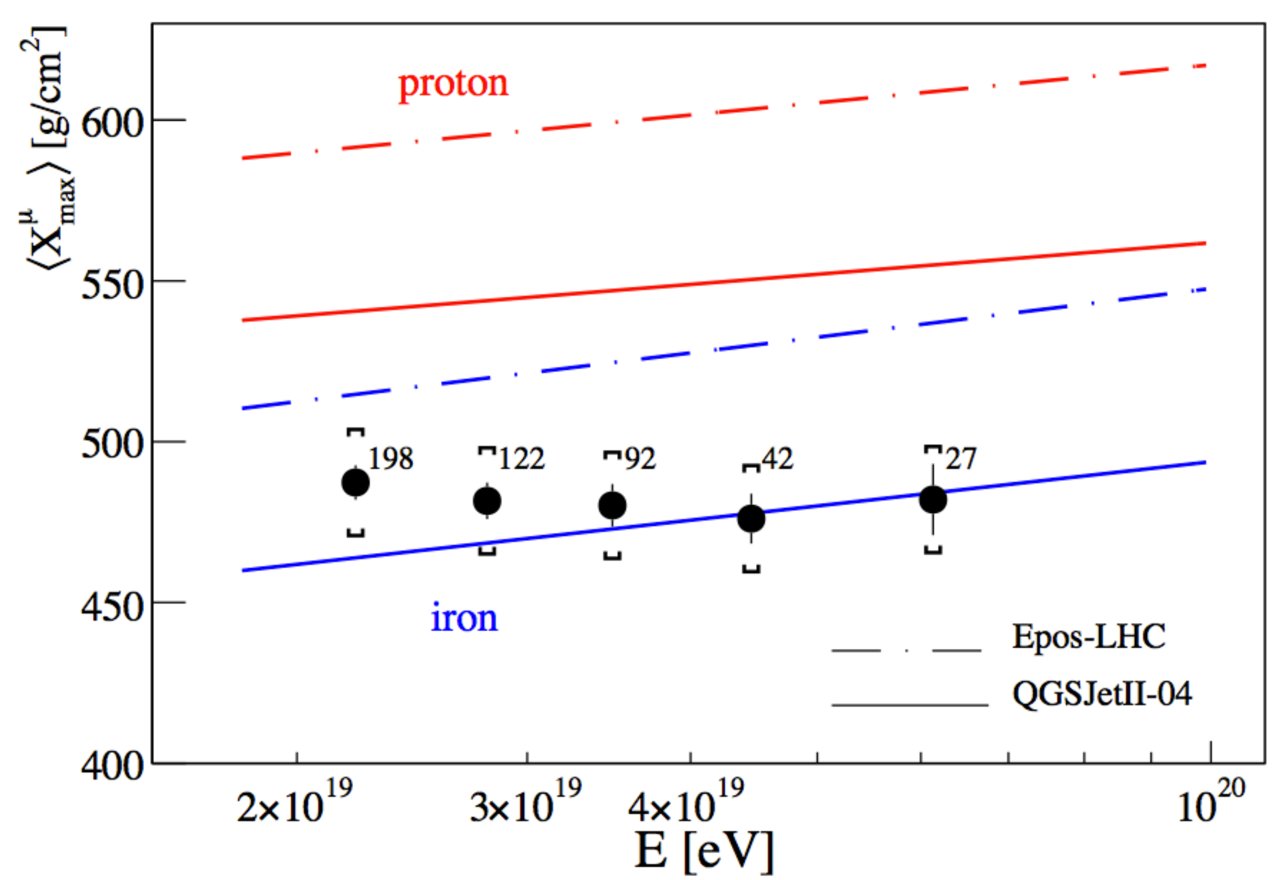
$$z = \frac{1}{2}\left(\frac{r^2}{ct_{\rm g}} - ct_{\rm g}\right) + \Delta$$

Muon Production Depth

Data set: 01/2004 - 12/2012
E > $10^{19.3}$ eV (more muons/event)
Zenith angles [55°,65°] (low EM contamination)
Distances from the core [1700 m, 4000 m]
481 events after quality cuts
Systematic uncertainties: 17 g/cm^2



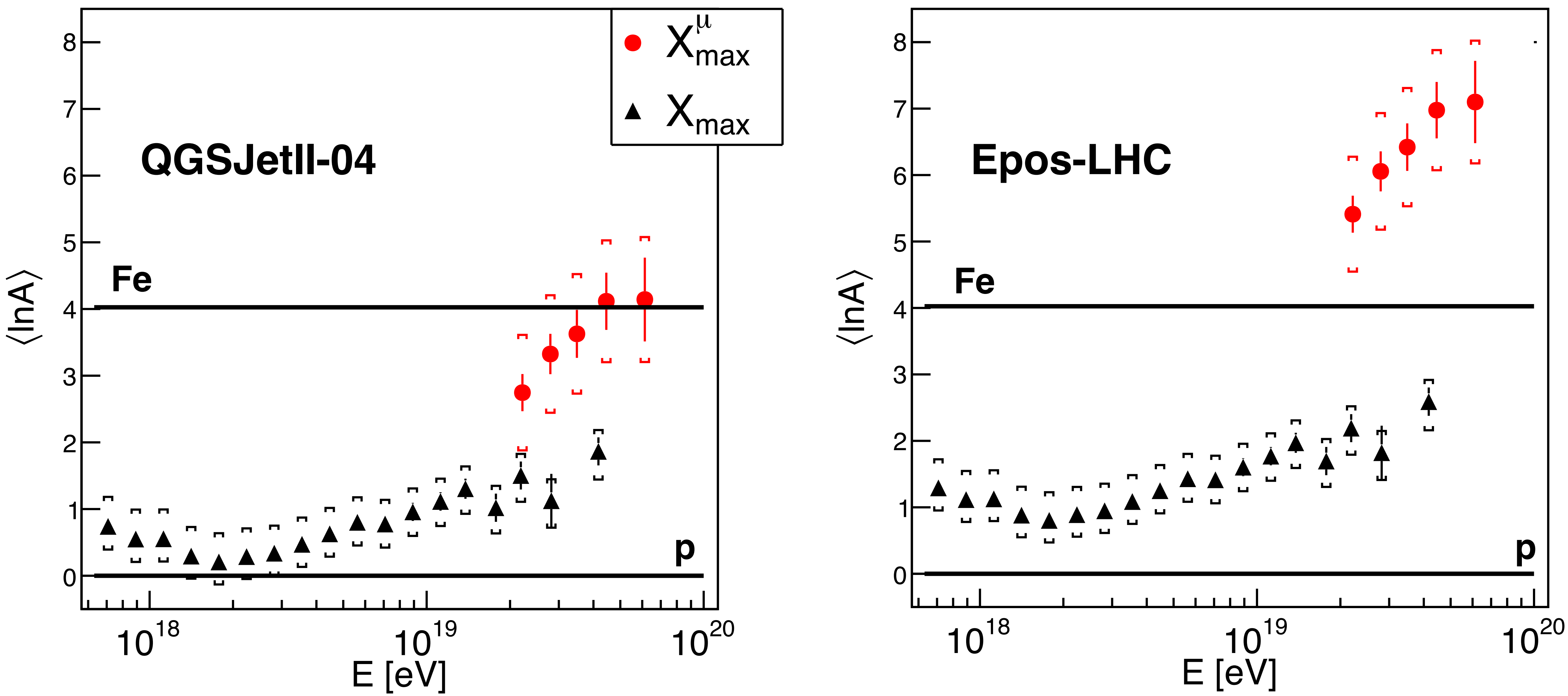
Resolution:
100 (80) g/cm^2 at $10^{19.3}$ eV for p (Fe)
50 g/cm^2 at 10^{20} eV



QGSJetII-04: data bracketed by predictions
EPOS-LHC: predictions above data

Comparison of ⟨ln A⟩ from X^{μ}_{max} and X_{max}

lnA (FD) from *Phys. Rev.* D 90 (2014) 12



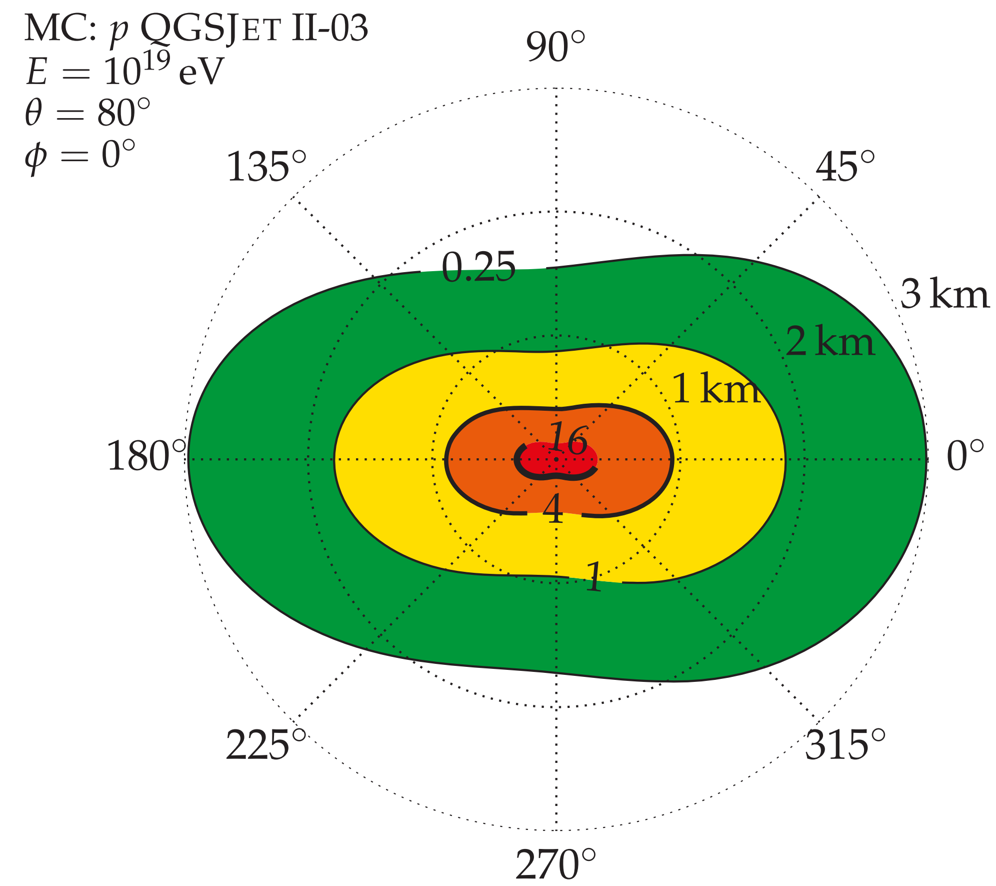
QGSJetII-04: Compatible values within 1.5 σ
EPOS-LHC: Incompatibility at a level of at least 6 σ

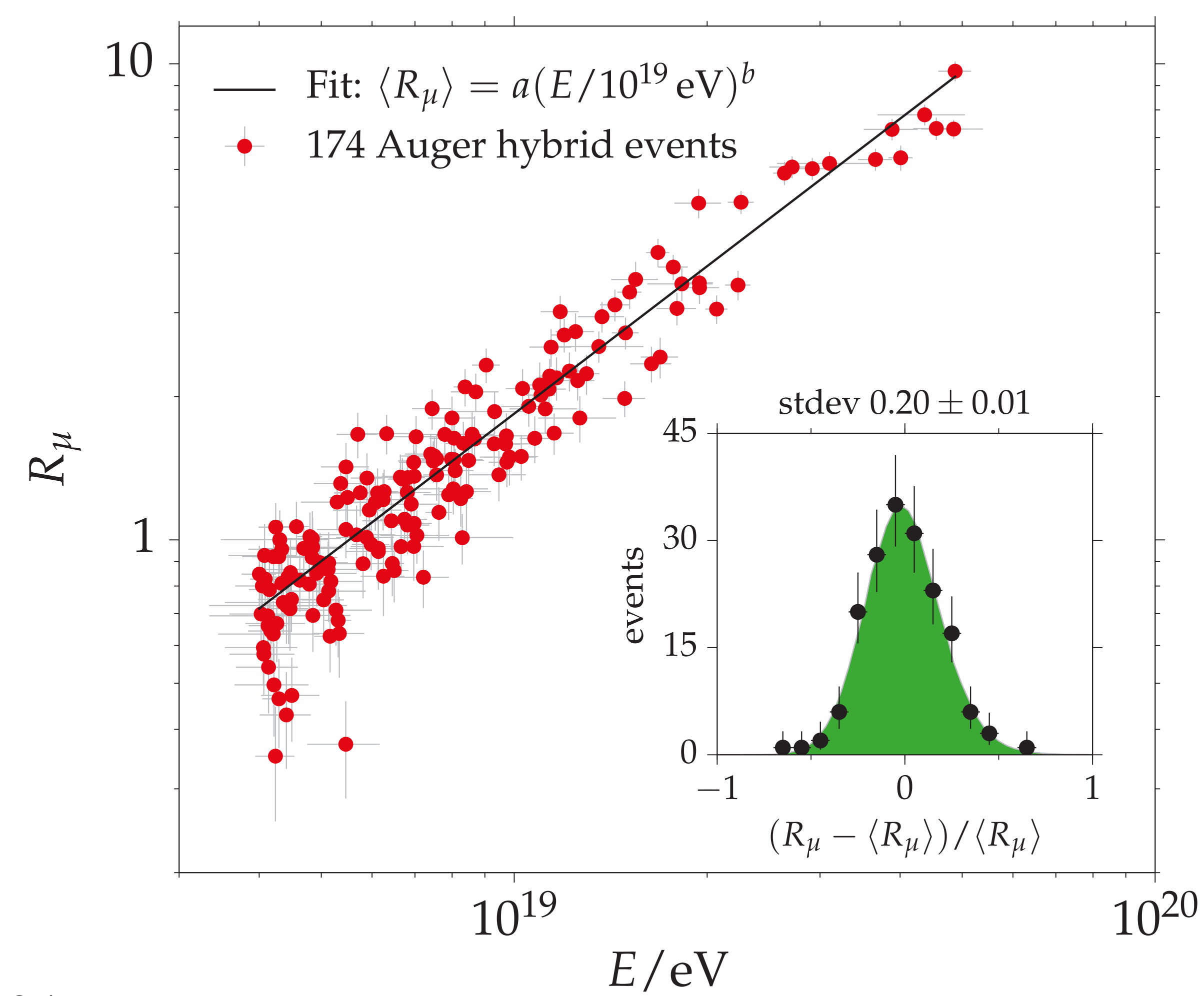
Muons in highly inclined events

$$\rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

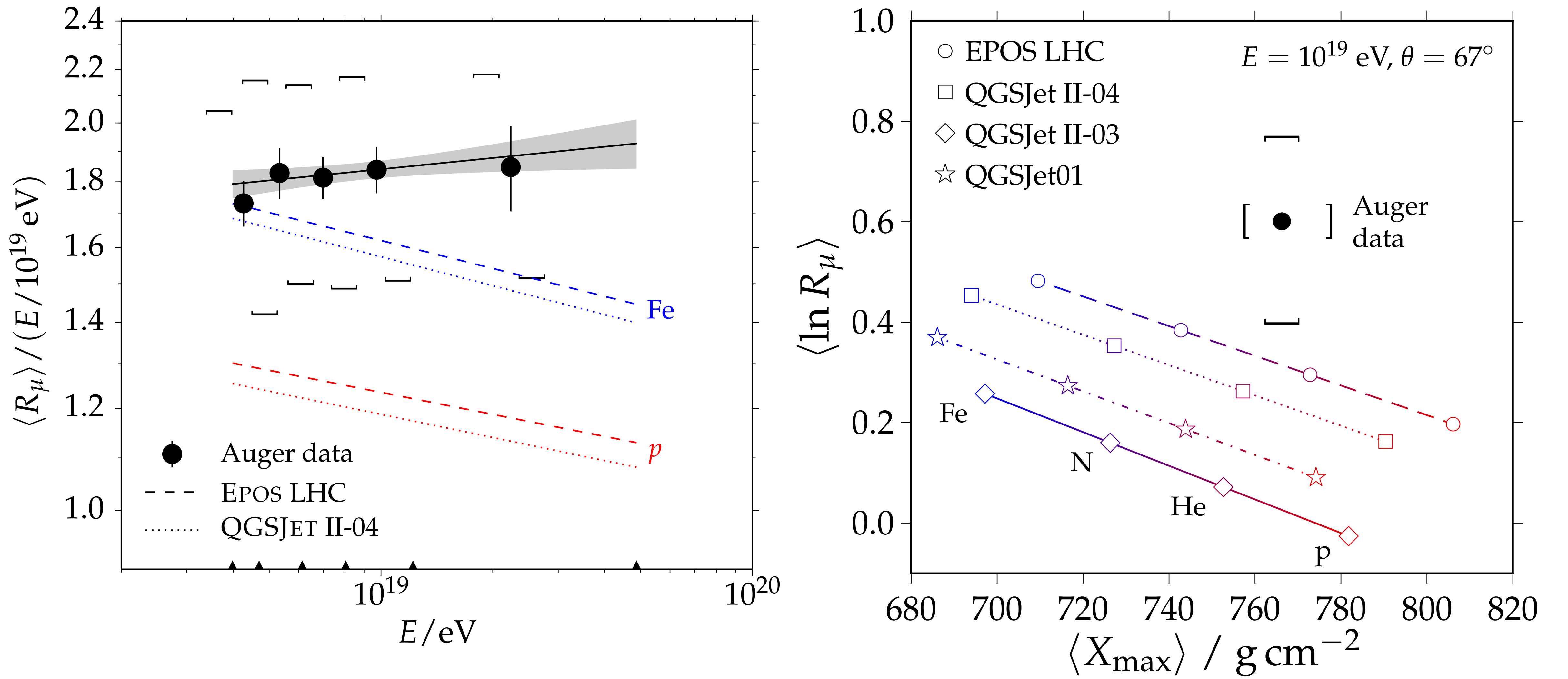
$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

- Data set: 01/2004 - 12/2013
- E > 4 x 10^{18} eV (100% SD trigger)
- Zenith angles [62°, 80°] (low EM contamination)
- 174 hybrid events after quality cuts
- Systematic uncertainty on R_μ: 11%





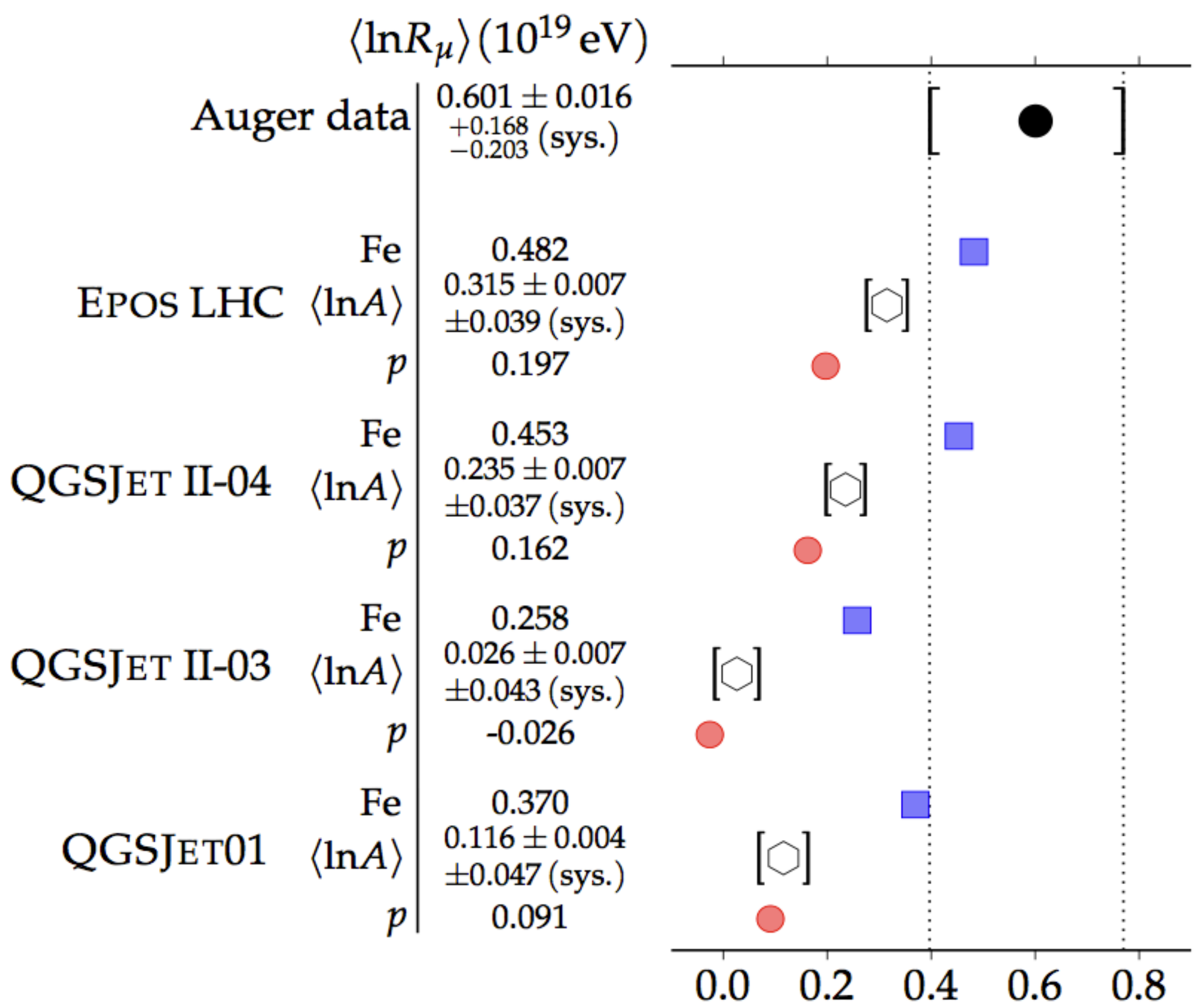
Hadronic interactions
Data at variance with simulations

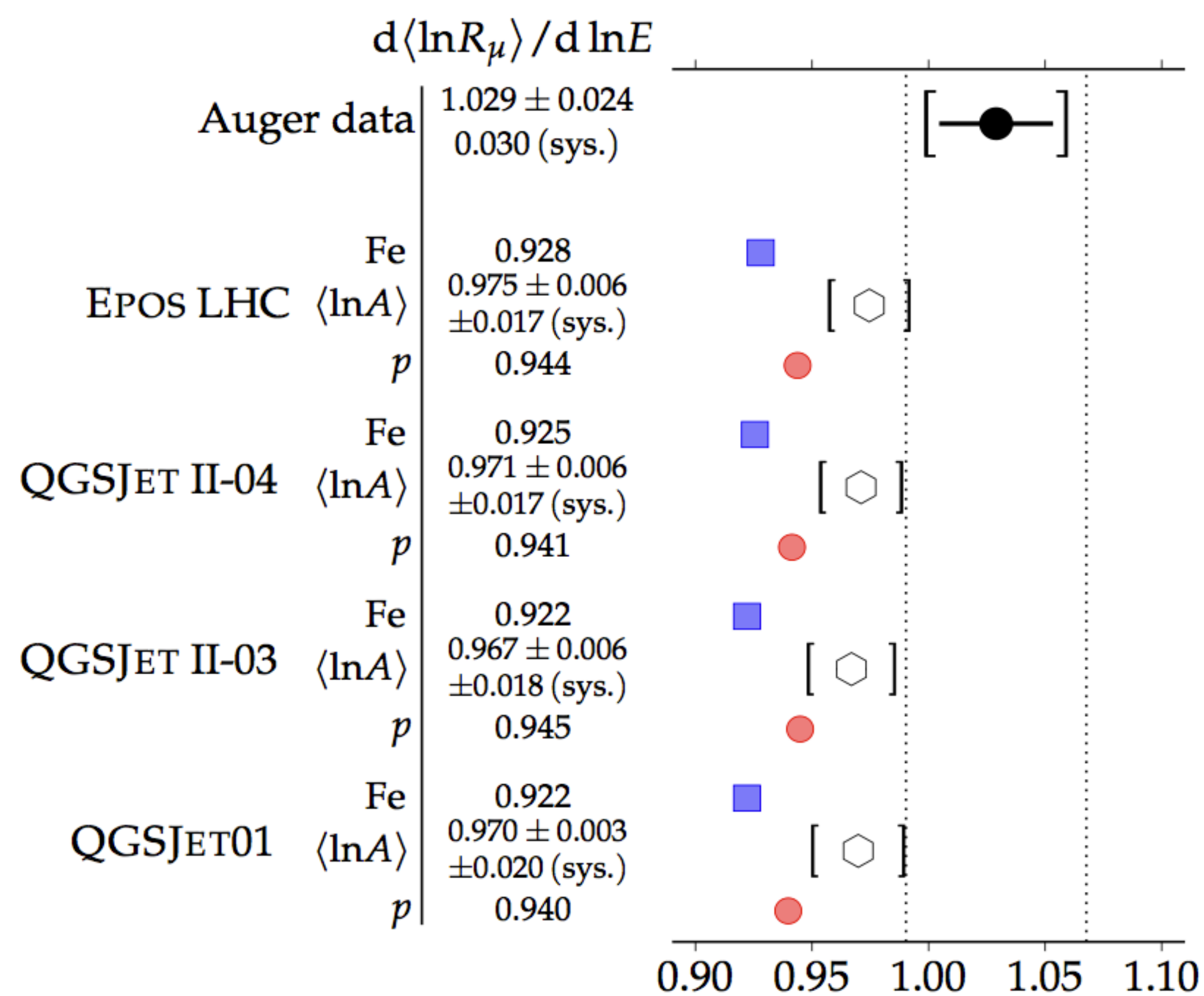


- $\langle R_\mu \rangle$ higher than MC iron predictions
- Tension between the X_{max} and muon measurements
- Older versions of QGSJet model are at odds with data taking into account the large systematic uncertainty

Pierre Auger Collaboration, PRD91 (2015) 3, 032003

The average muon content and the muon gain with energy

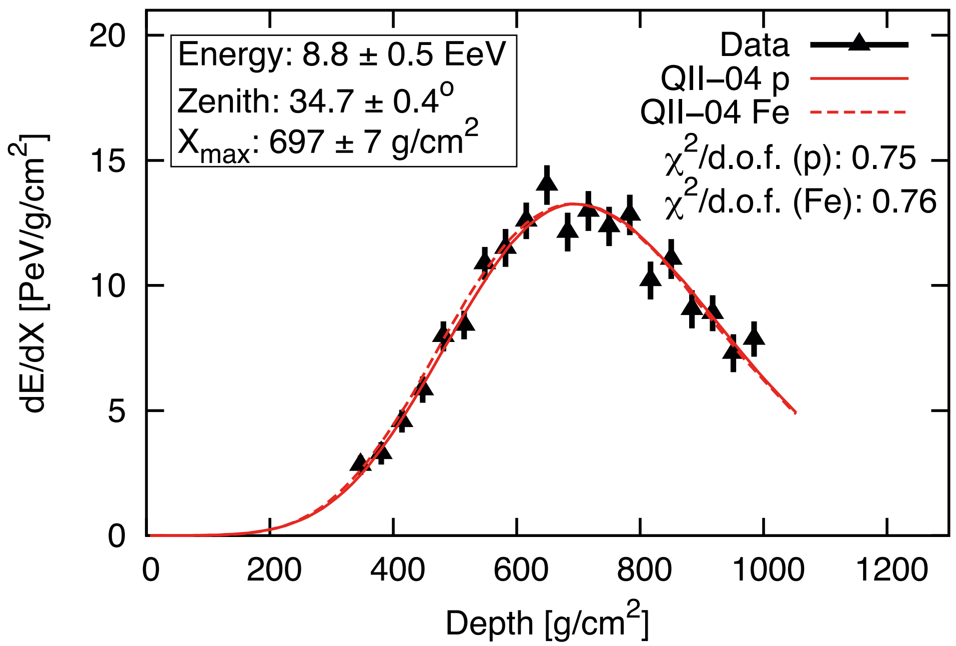


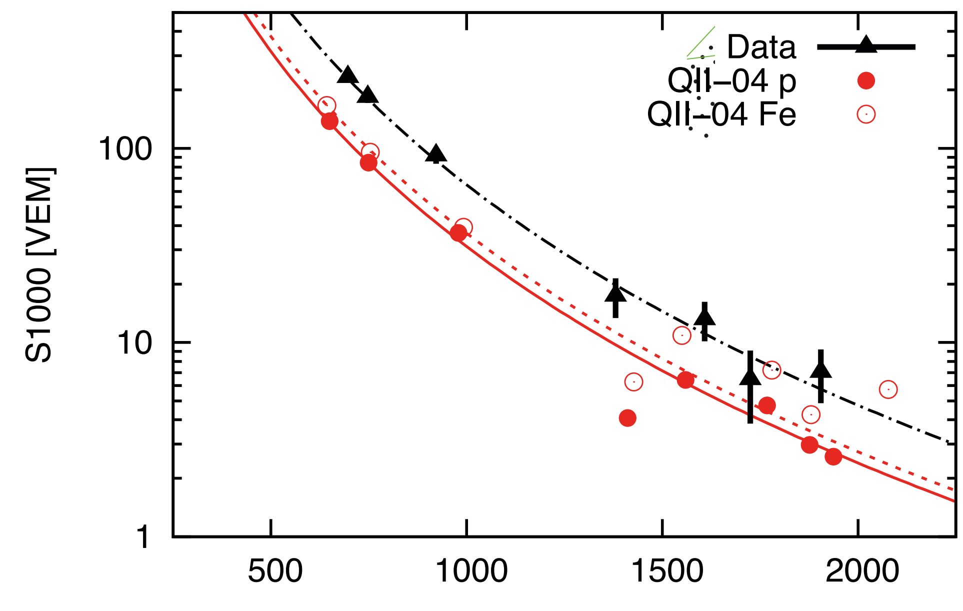


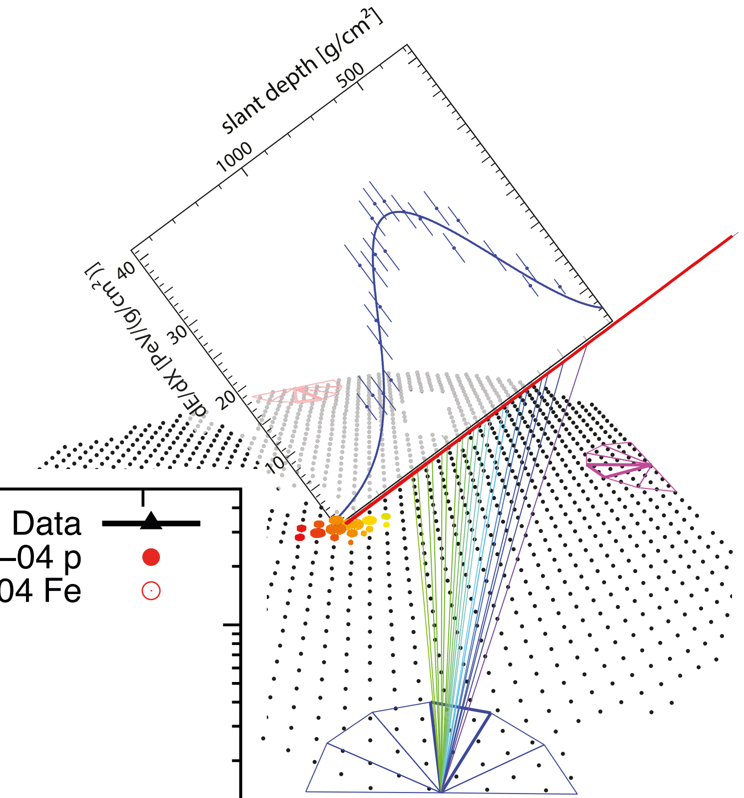
Muon deficit from 30% to 80% at 10^{19} eV depending on the model:
Best case for EPOS-LHC
(minimum deviation of 1.4 σ)

Deviations from a constant proton (iron) composition observed at the level of 2.2 (2.6) σ

Muon number in hybrid events with θ<60°



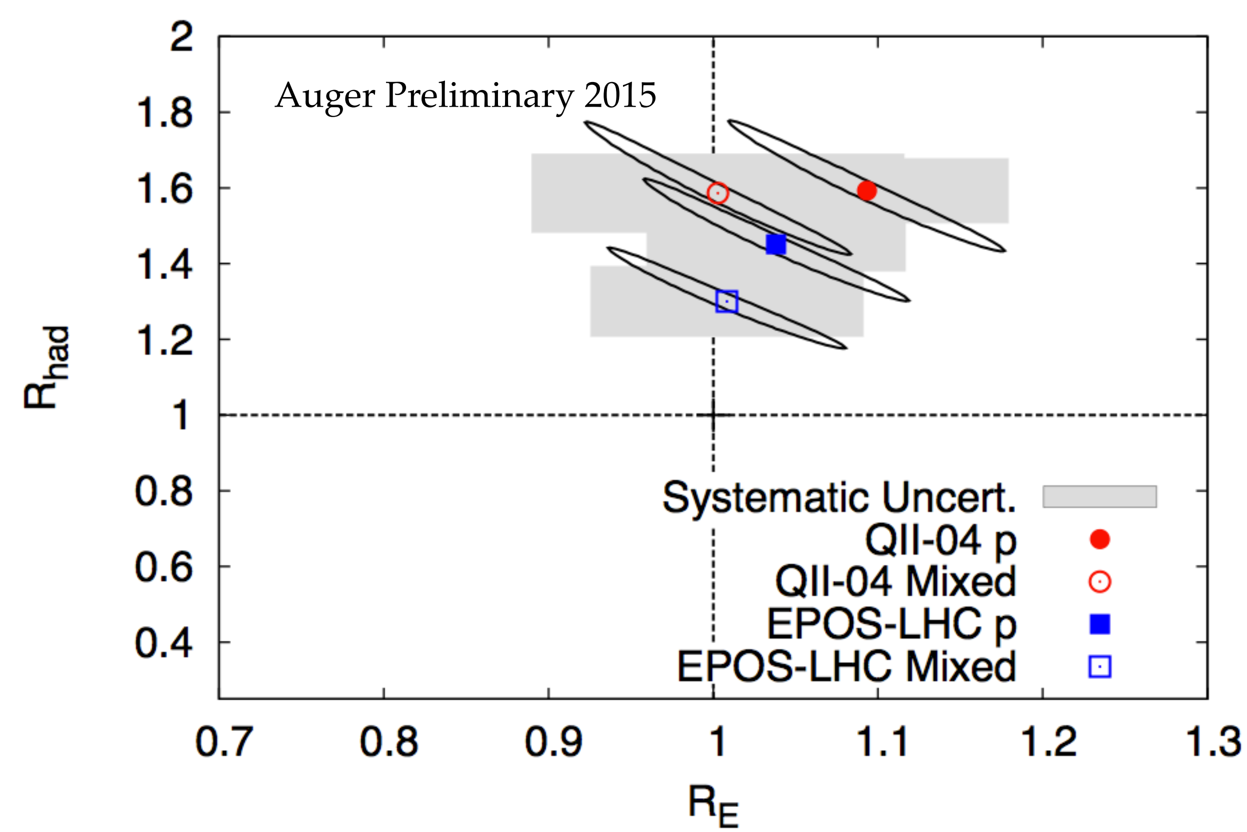




Ratio R_{had}

Data set: 01/2004 - 12/2012

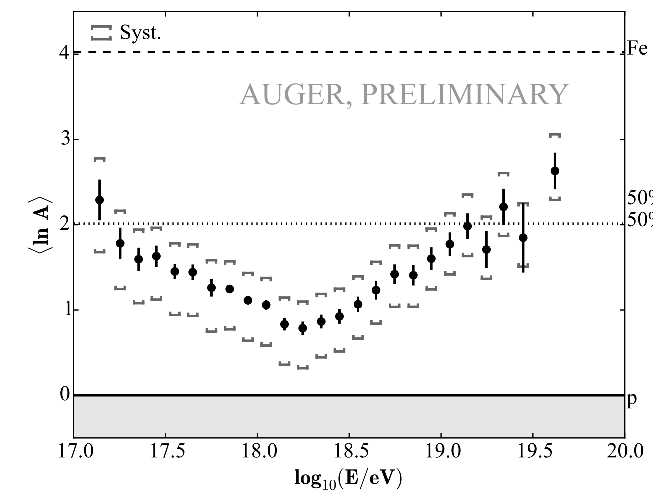
- E = $10^{18.8}$ - $10^{19.2}$ eV
- Zenith angles [0°, 60°]
- 411 hybrid events after quality cuts
- Systematic uncertainties on R_E and R_{had}: 10 %



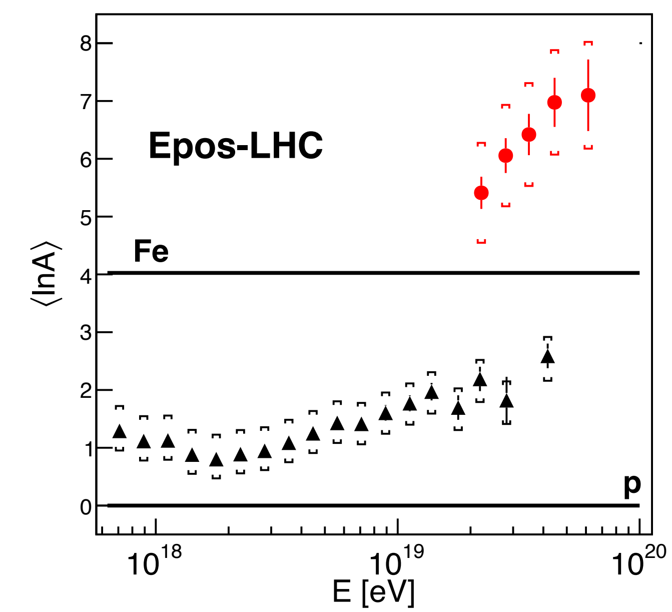
ML fit adjusting EM and muonic contribution to S1000

Summary

- X_{max}:
  - Measured in ~ 3 decades of energy down to 10^{17} eV
  - ⟨lnA⟩ vs $\log_{10}$(E/eV): Non-constant composition; Lightest at ~ $10^{18.4}$ eV
- **Muon measurements:**
  - Muon deficit in simulations
  - Strong model dependence
  - Conclusions on composition cannot be drawn but discrepancy with models large enough to put new constrains on hadronic interactions

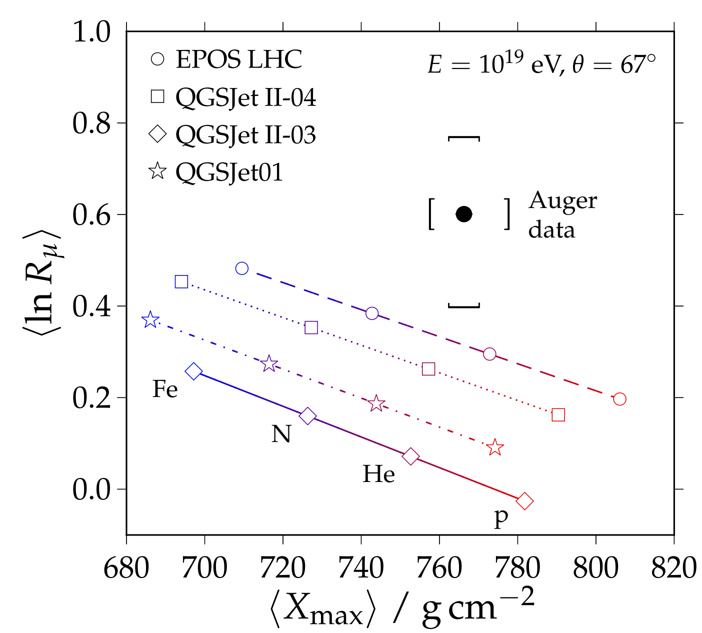


X_{max}



X^{μ}_{max}

X_{max}



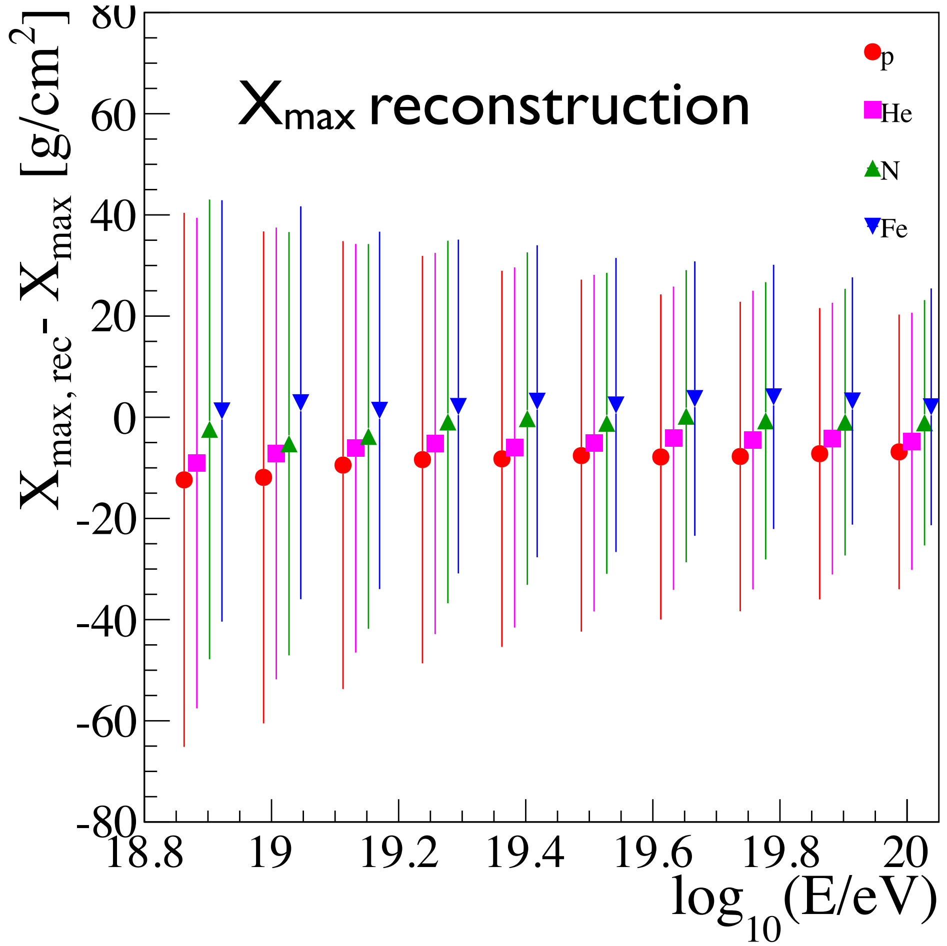
R_{μ}

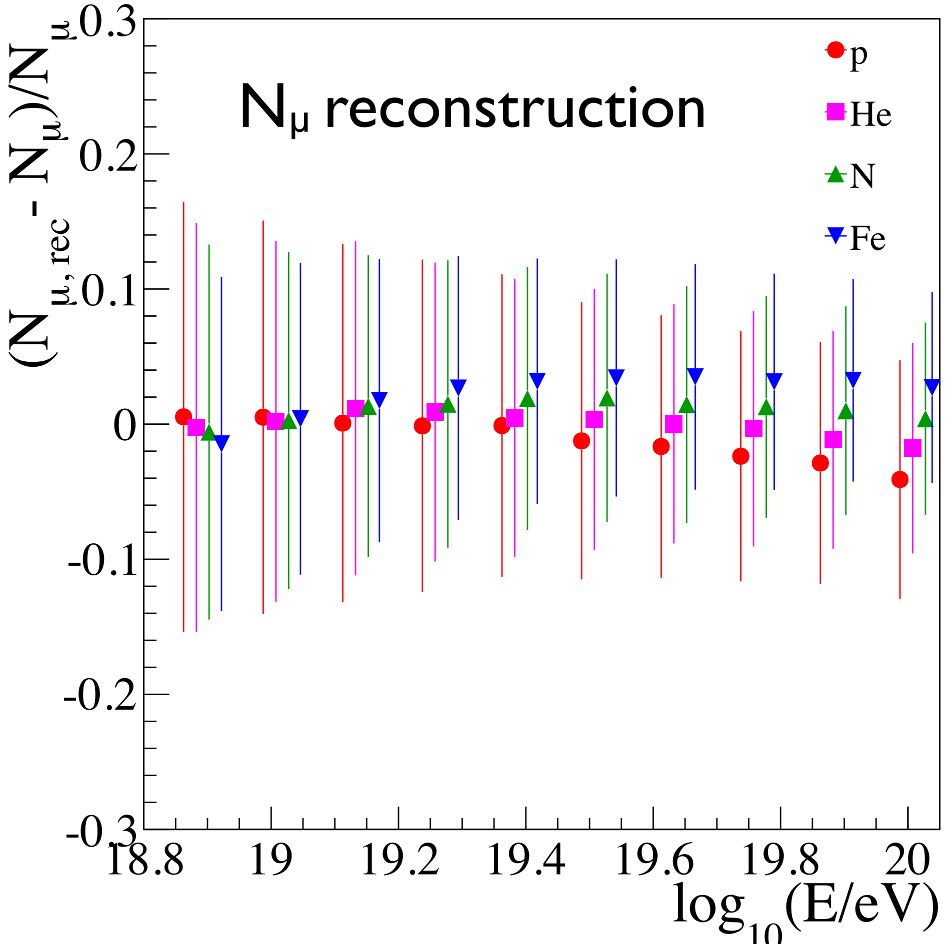
None of the interaction models recently tuned to LHC data provides a consistent description of both the EM and muonic shower profiles as measured by Auger

Auger is going to extend the composition measurements up to highest energies by means of SD: AugerPrime
⇒ Refined analysis procedures needed

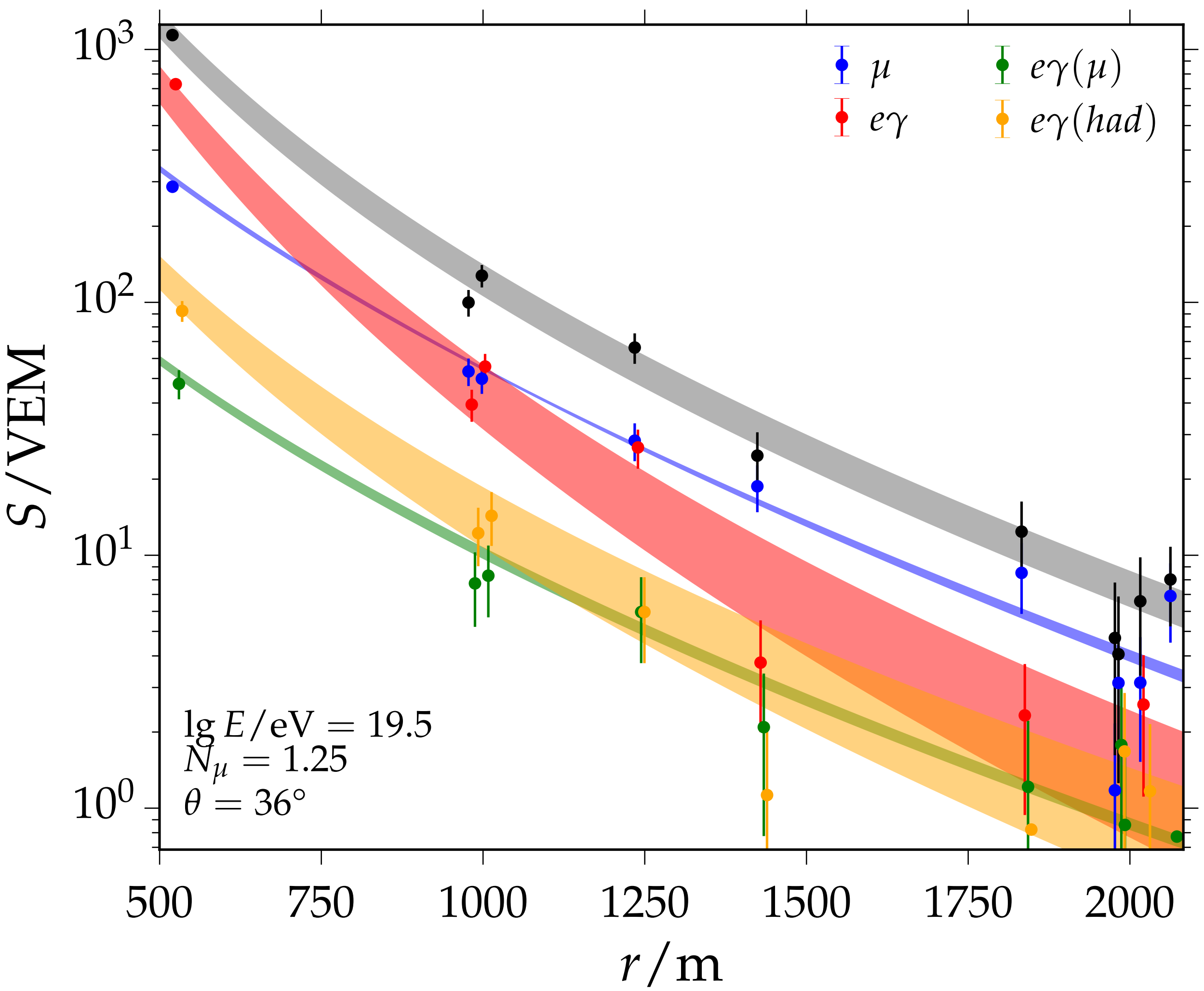
Upgrade of the Pierre Auger Observatory

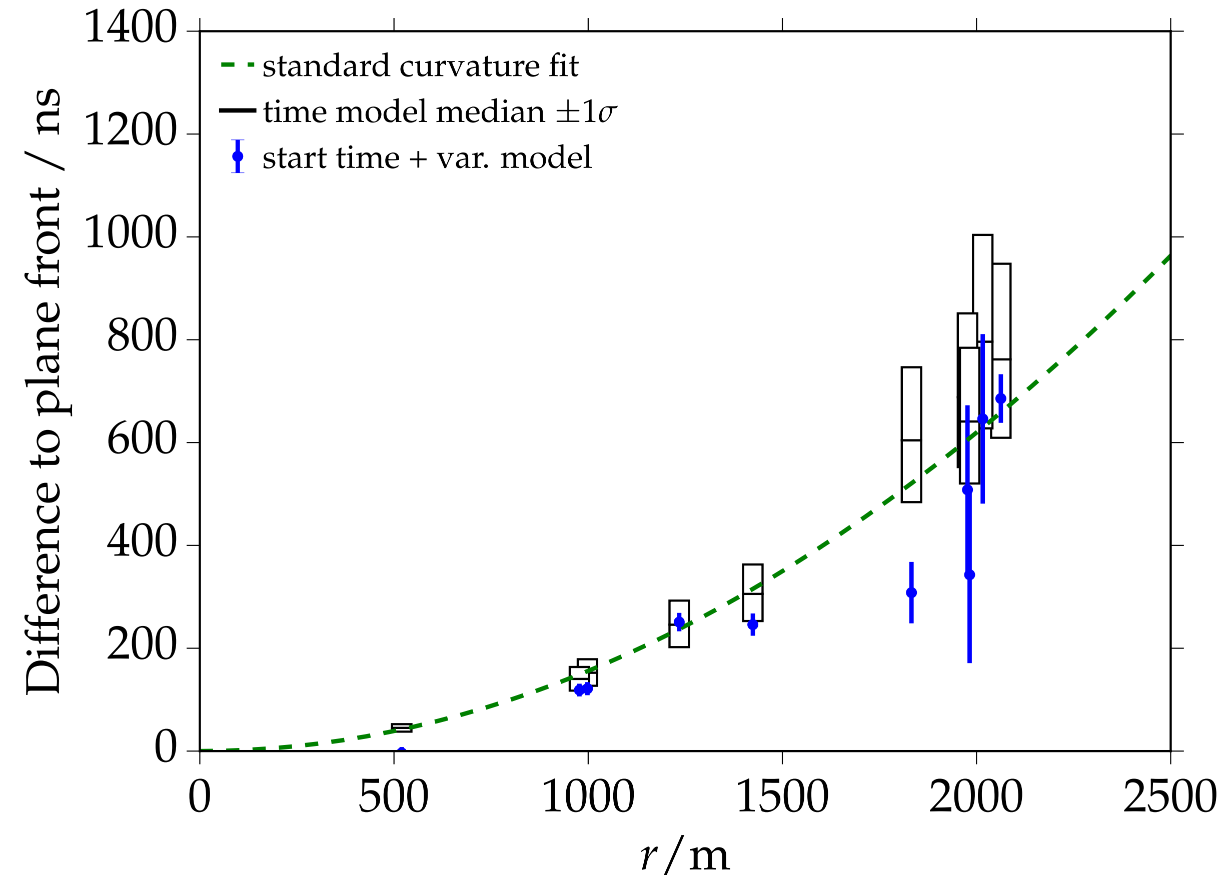
- Additional scintillators (4 m²)
- Event-by-event mass estimate with 100% duty cycle instead of 15% for FD

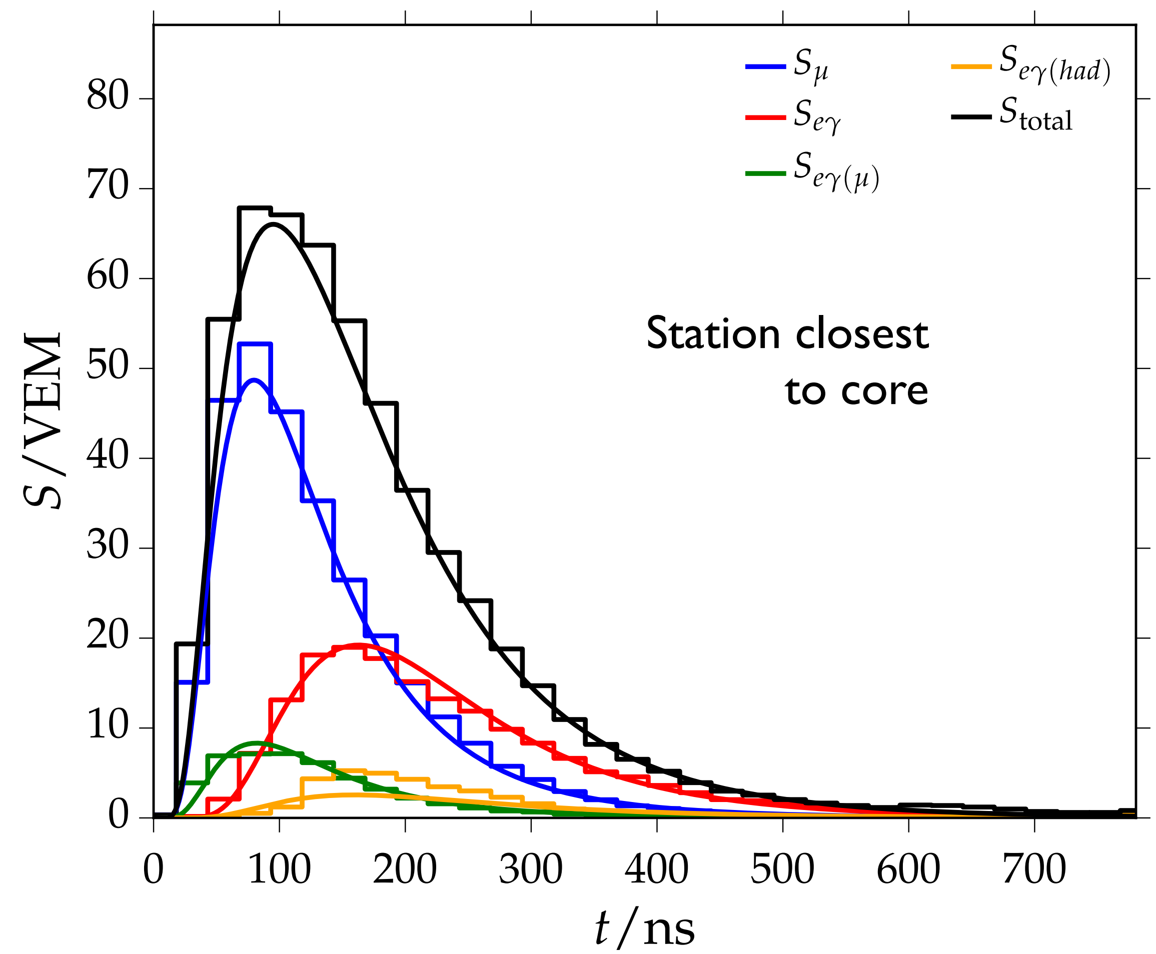




Universality fitting procedure
Fitting of a single event





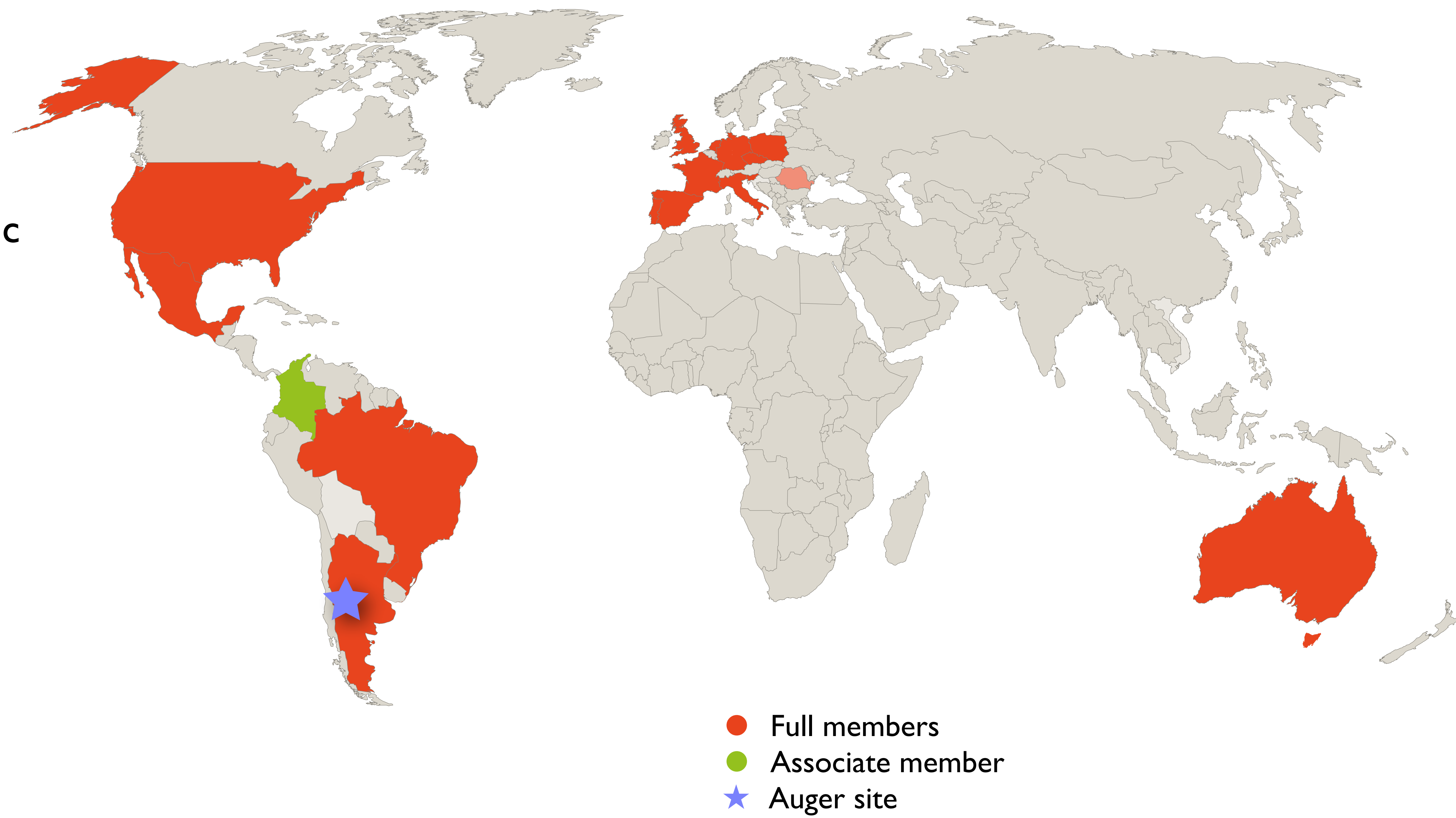


Colored bands indicate corrections for up- and downstream asymmetry, e.g. different ΔX, ground screening, detector response

The world‘s largest cosmic ray observatory

About 500 members from 16 countries

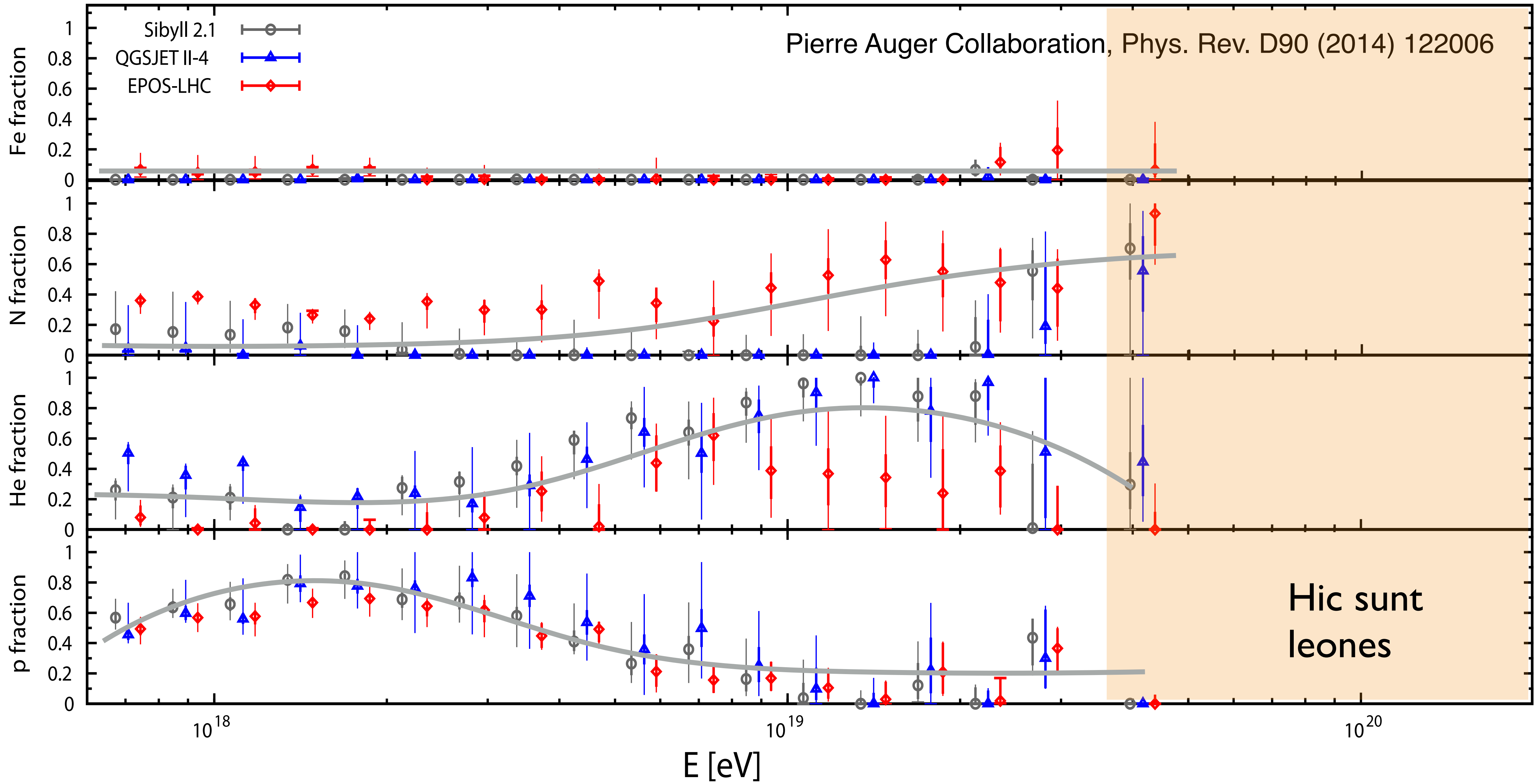
Argentina
Australia
Brazil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA



*Associated

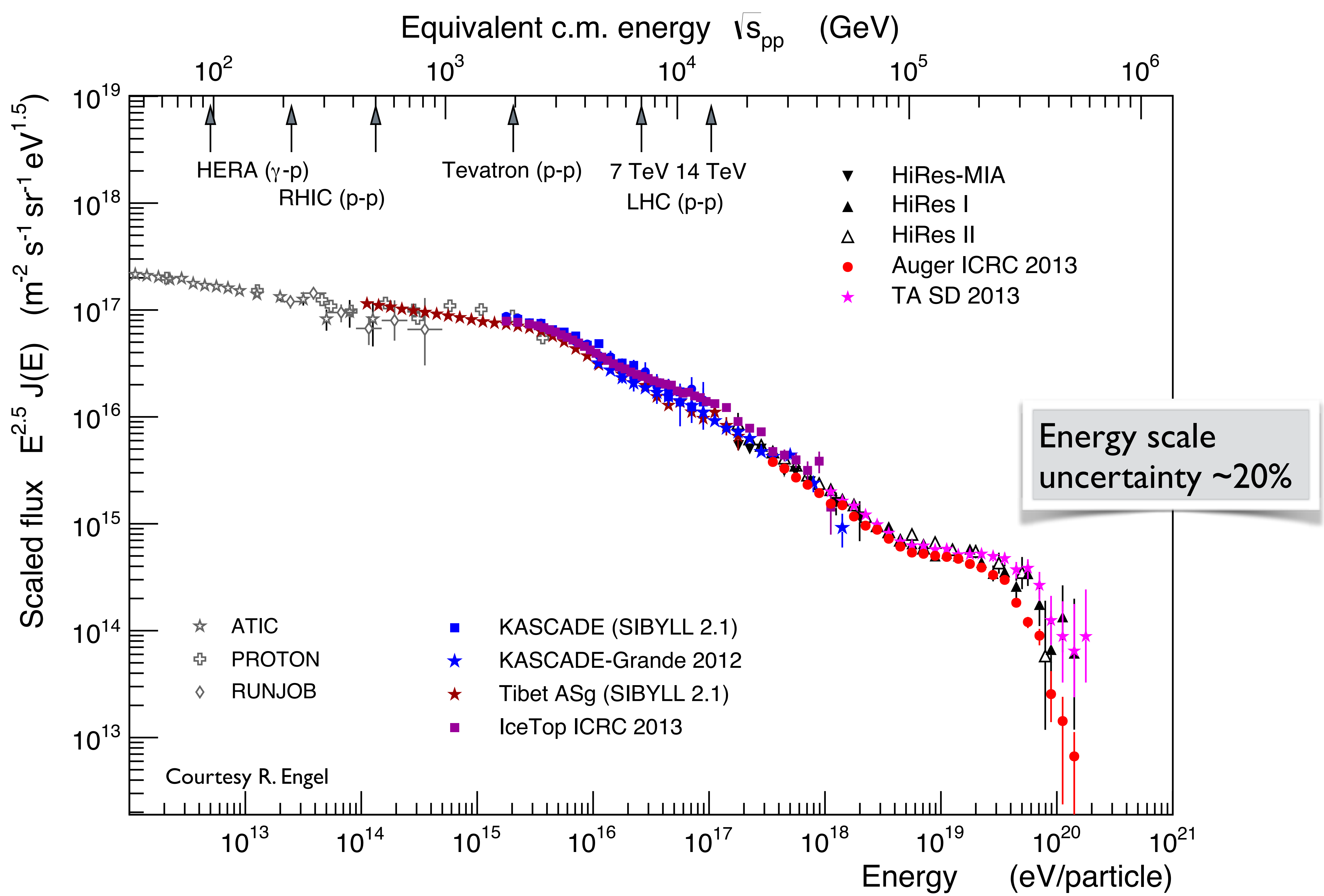
Composition Fit (X_{max} distribution)

Data available only up to < 5×10^{19} eV



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

Unambiguously detected flux suppression

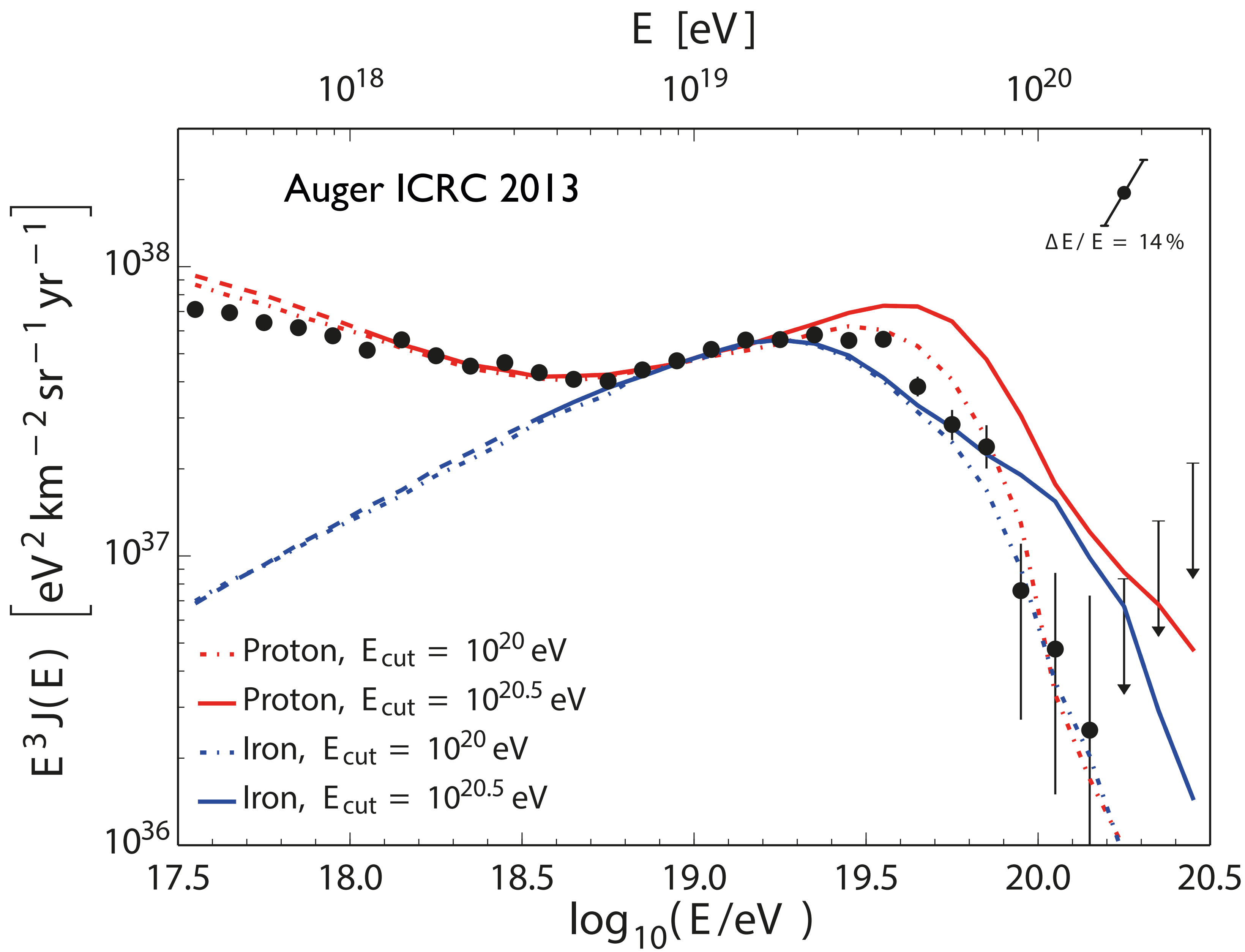


Flux suppression due to GZK energy-loss?

Proton dominated flux
- Ankle: e+e– pair production
- Suppression: delta resonance

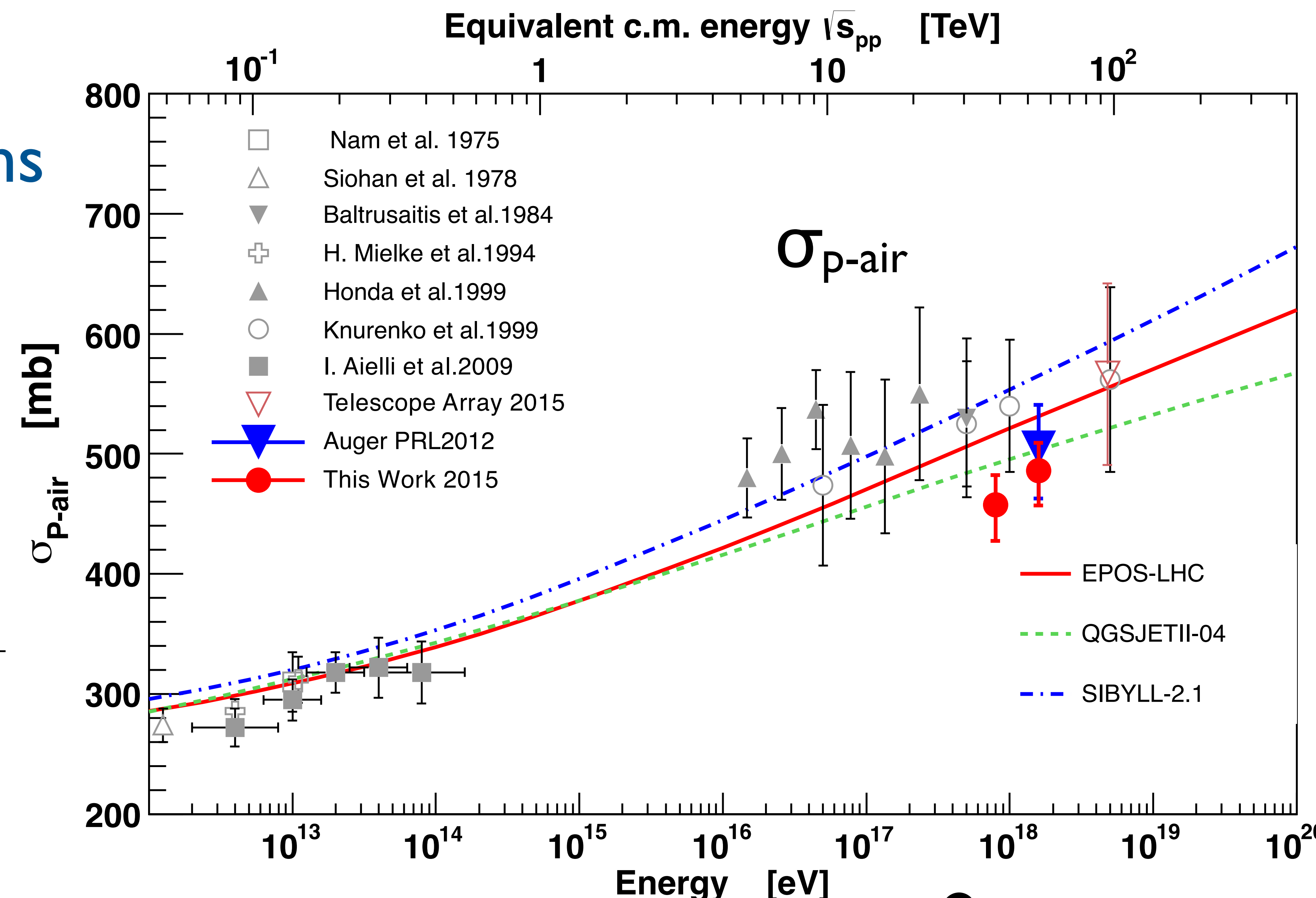
(Dip model by Berezinsky et al.)

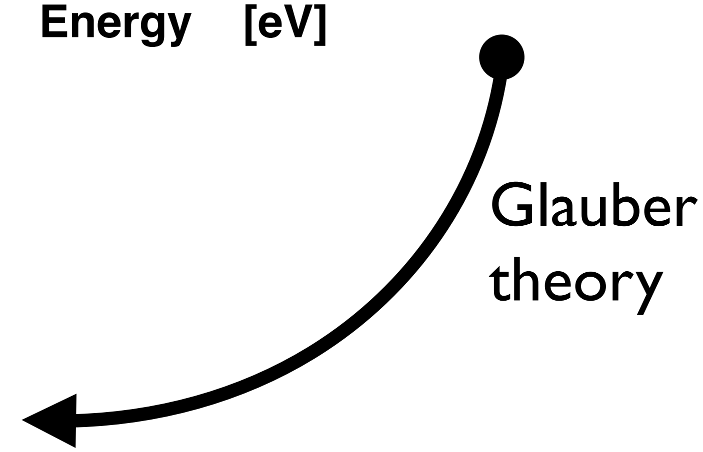
Iron dominated flux
- Ankle: transition to galactic sources
- Suppression: giant dipole resonance

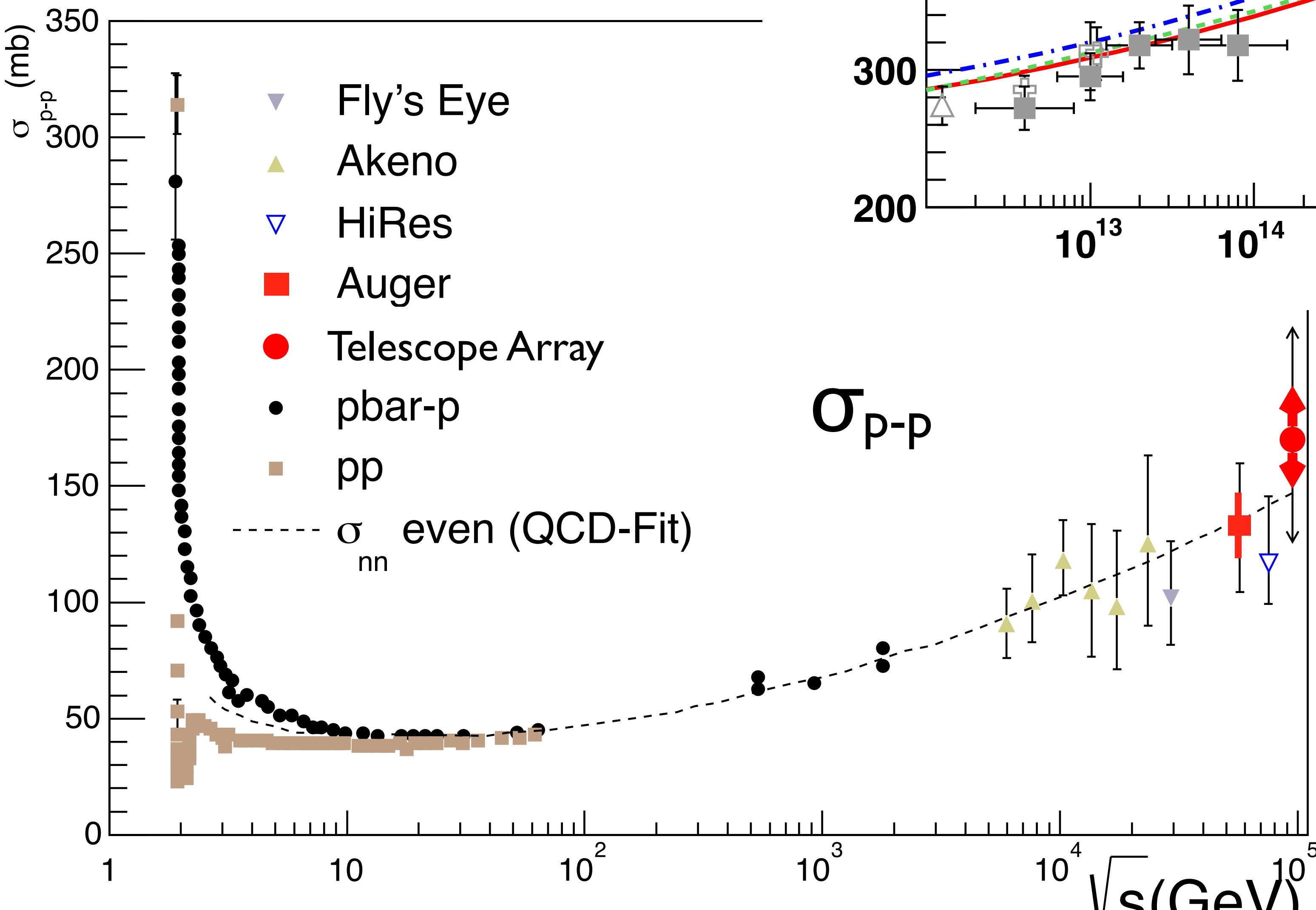


Spectral information is not enough to decide upon

Hadronic interactions

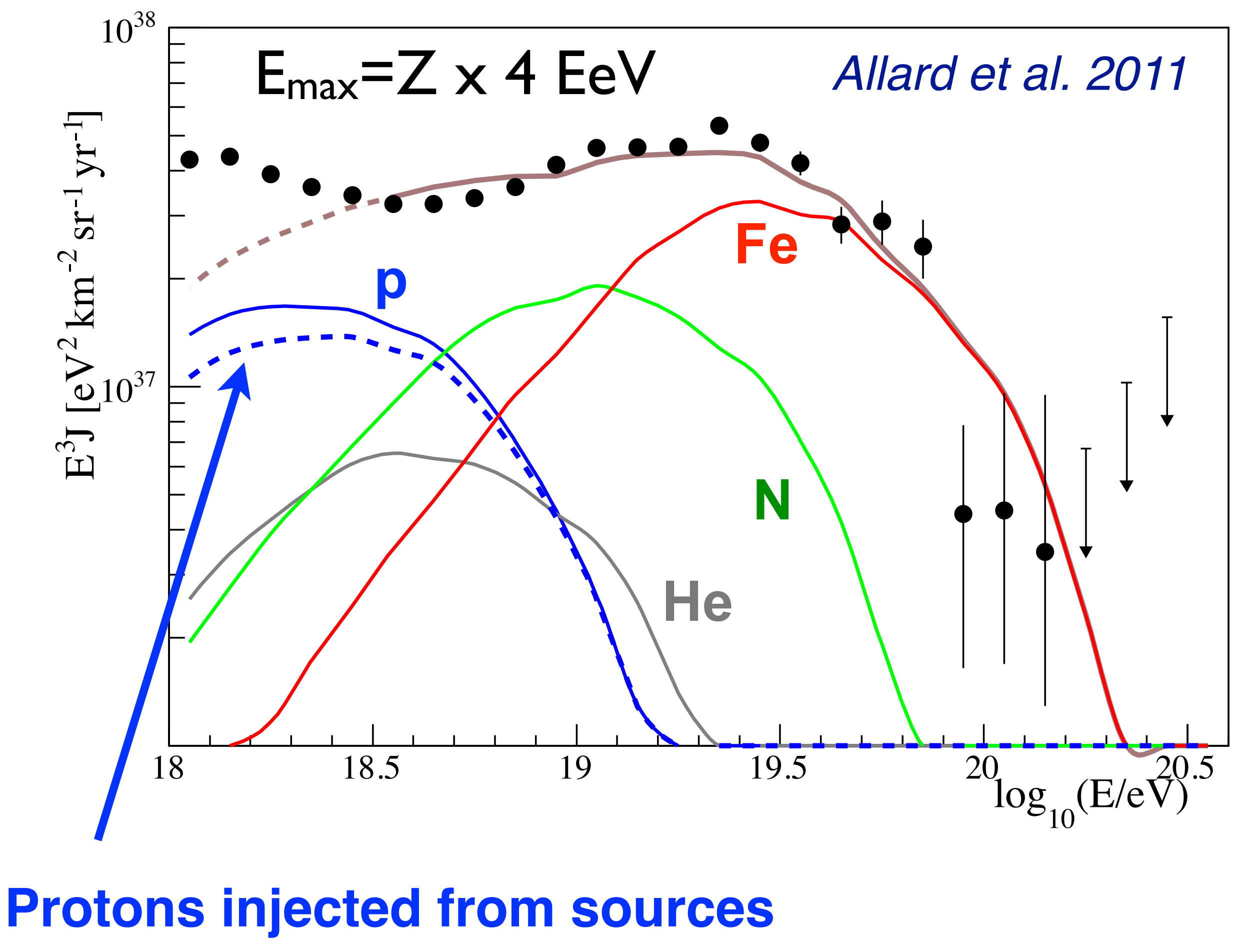




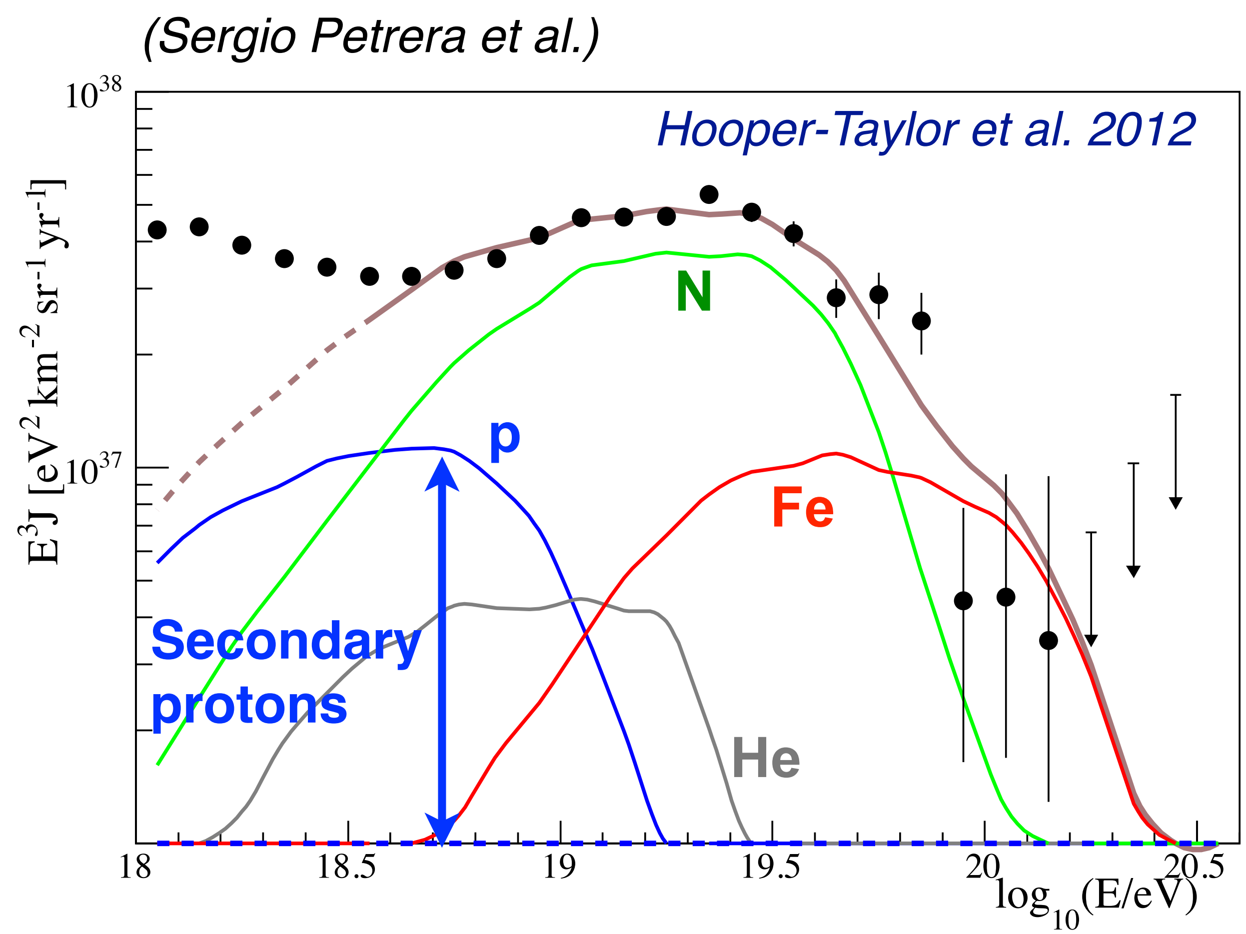


TA collaboration, arXiv:1505.01860v1
Pierre Auger Collaboration, PRL 109 (2012) 062002

Maximum-energy or GZK energy-loss?
Hard injection spectrum?



Injection: Galactic composition with enhanced heavy elements



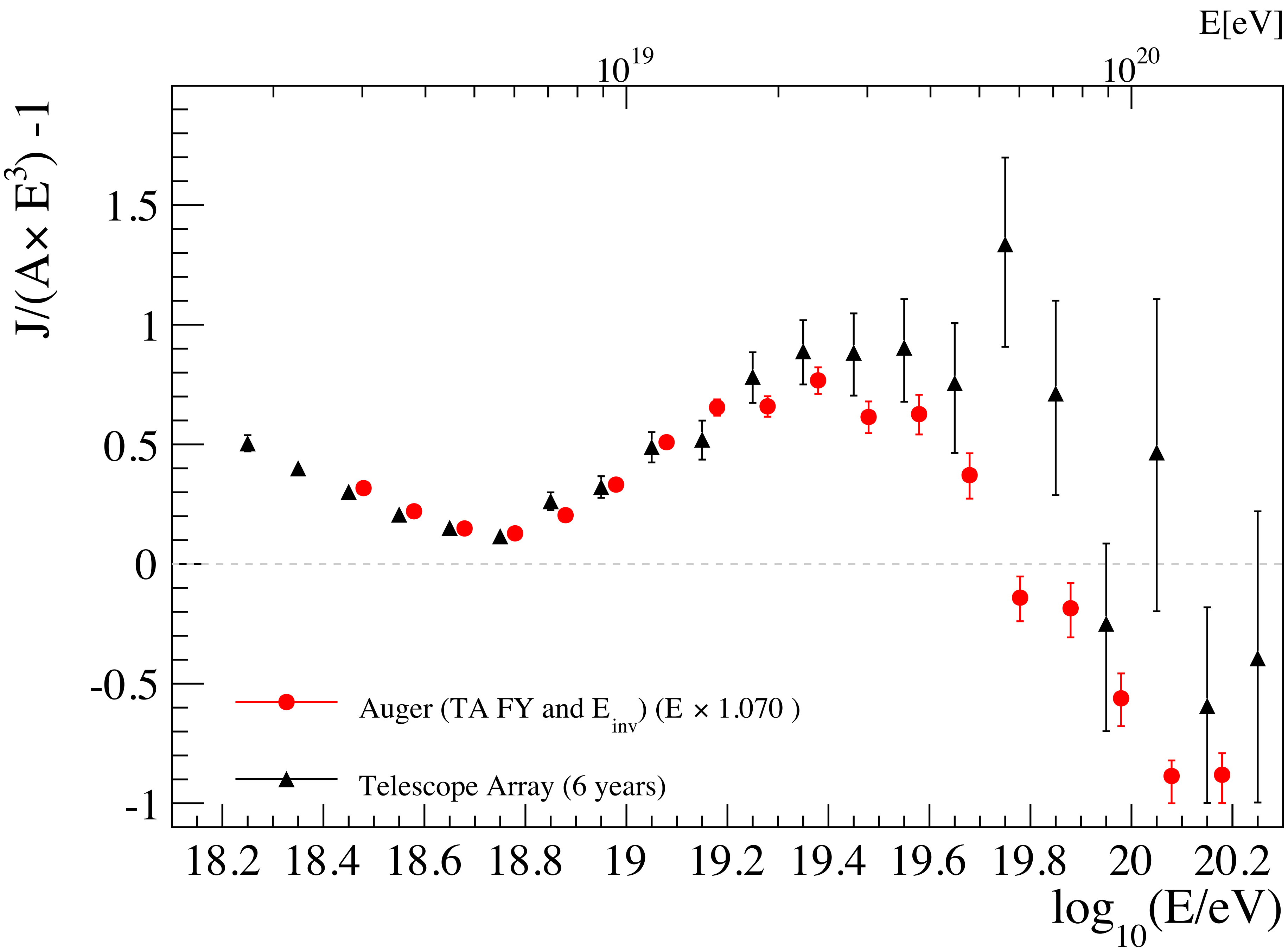
Injection: ~70% N or Si (almost no light elements)

Difference: Scaling with charge Z or mass number A
Both scenarios: Hard injection spectrum, $\gamma \approx$ -1 … 1.7, and heavy source composition (Astrophysics: very exotic result!)

(Shaham & Prian, Phys. Rev. Lett. 110, 2013)

Flux suppression not universal?

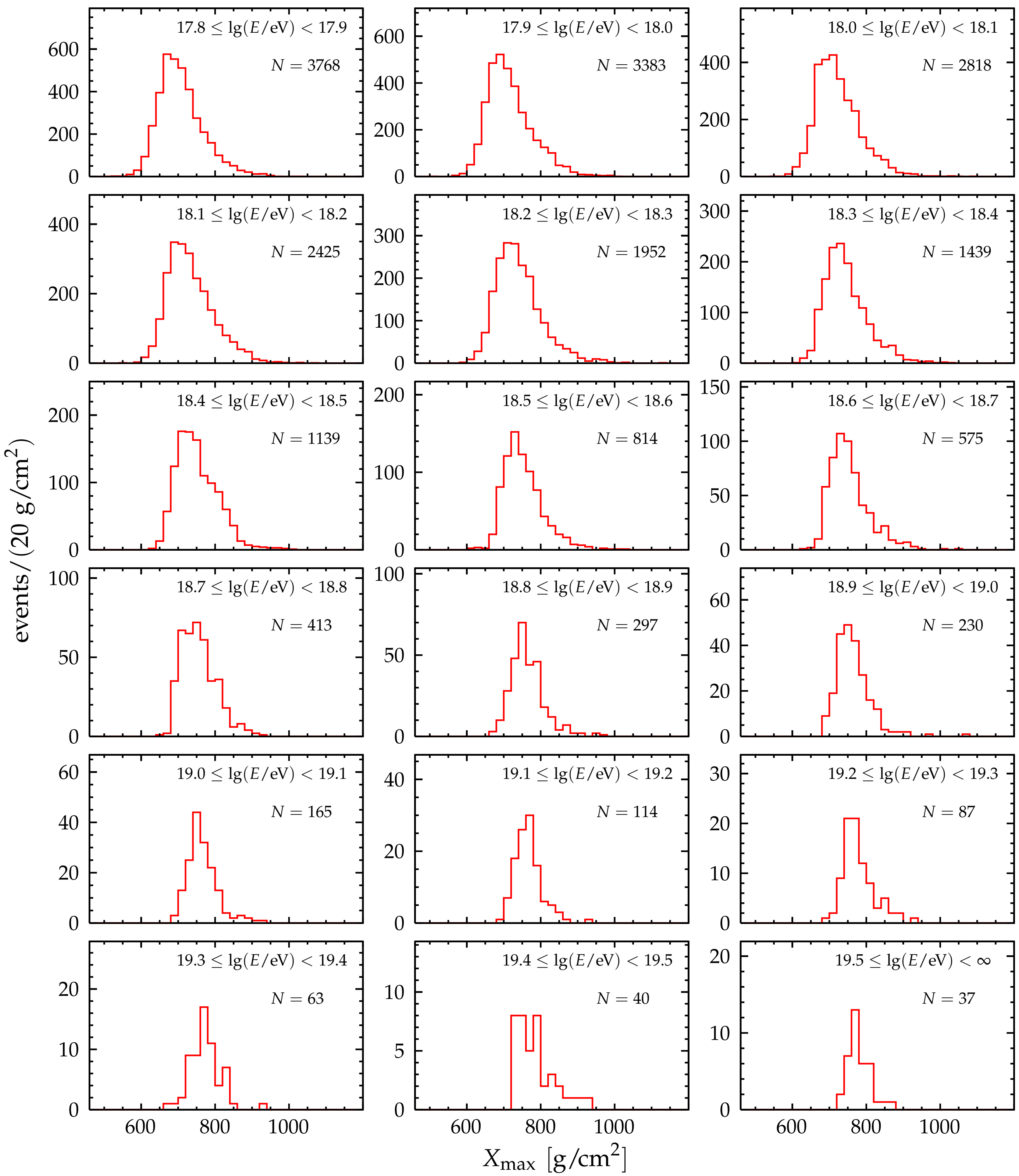
Suppression different in northern and southern hemisphere?

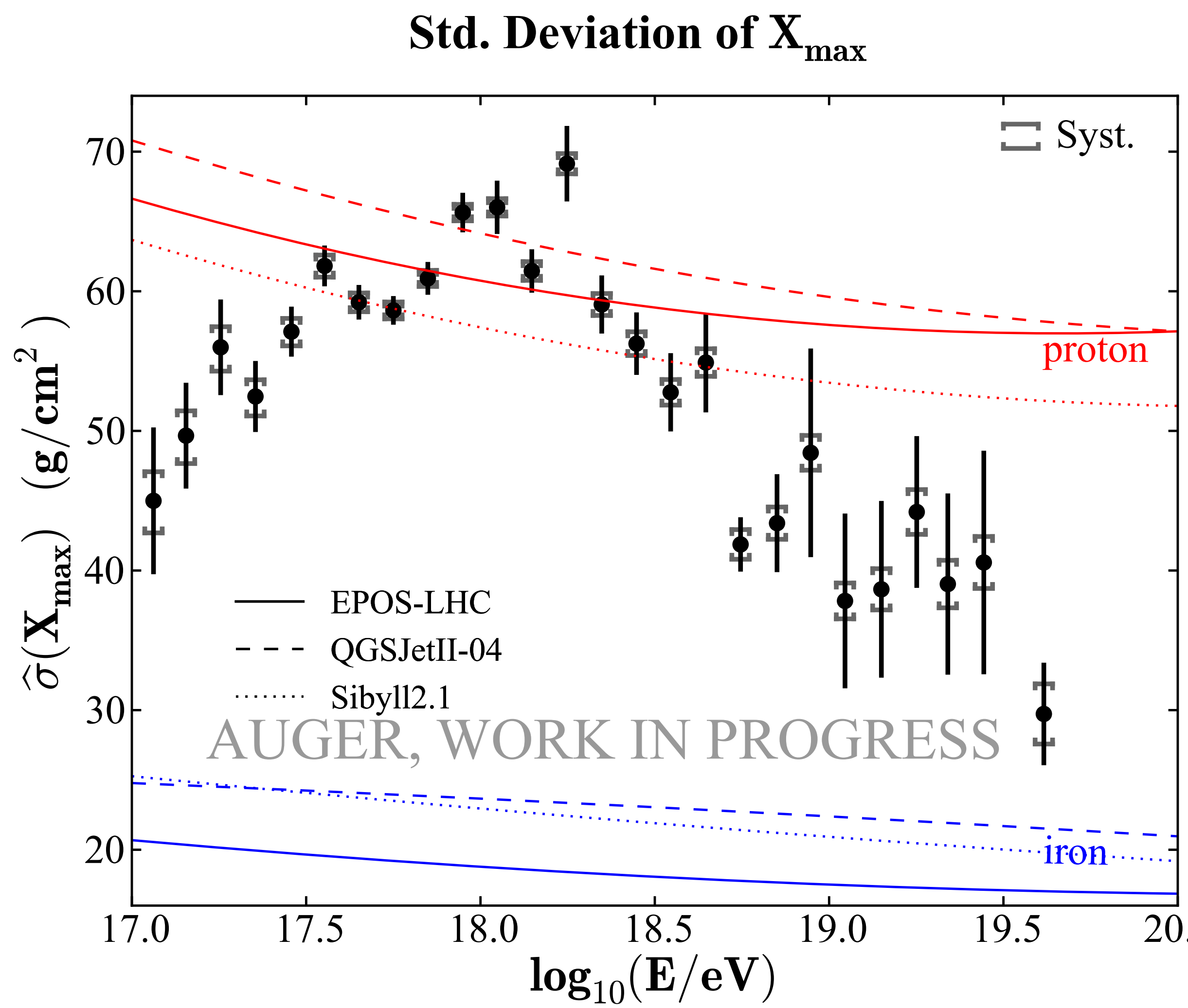


Using same fluorescence yield and invisible energy + 7% shift

Spectrum working group report, UHECR14

Average shower maximum and RMS





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