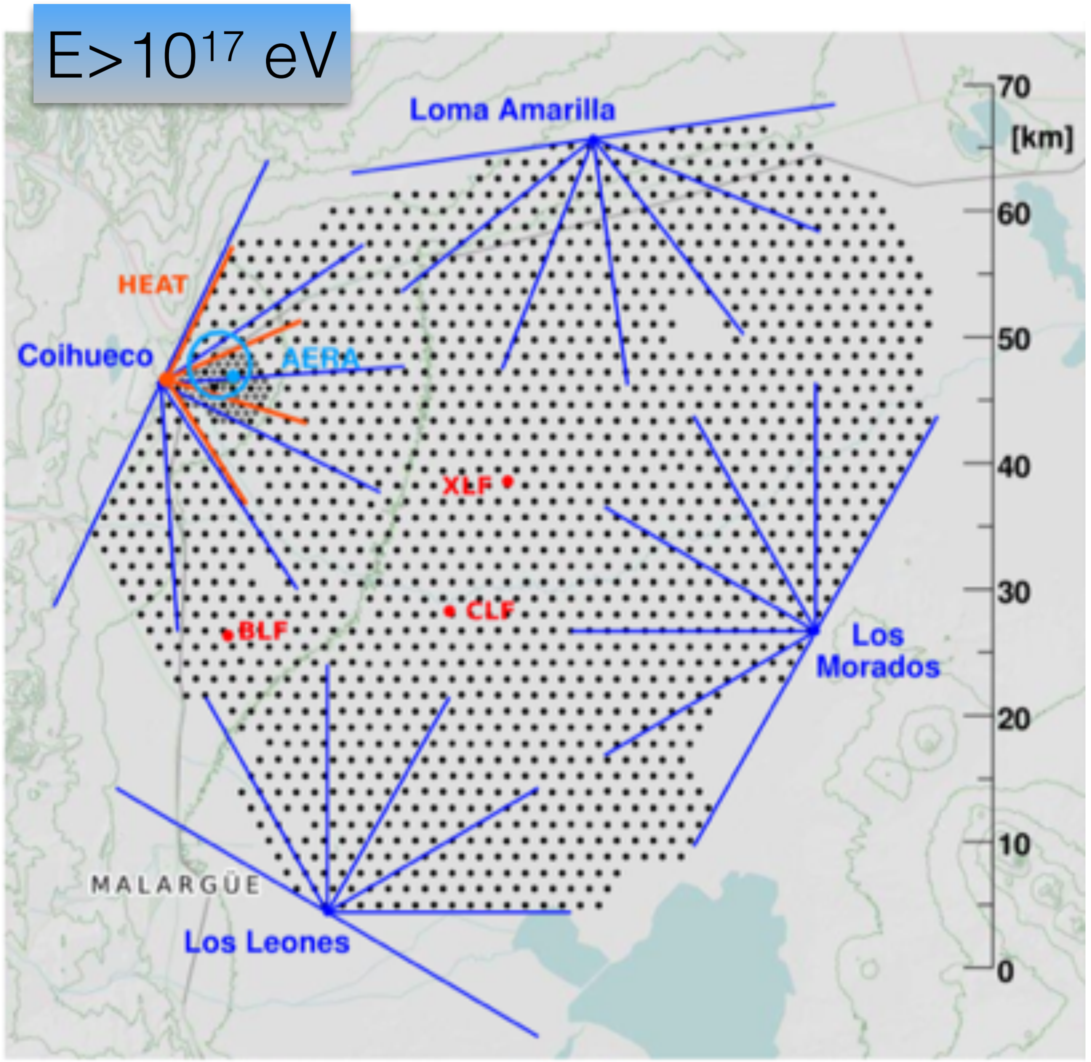
Mass composition and hadronic interactions of ultra-high energy cosmic rays at the Pierre Auger Observatory

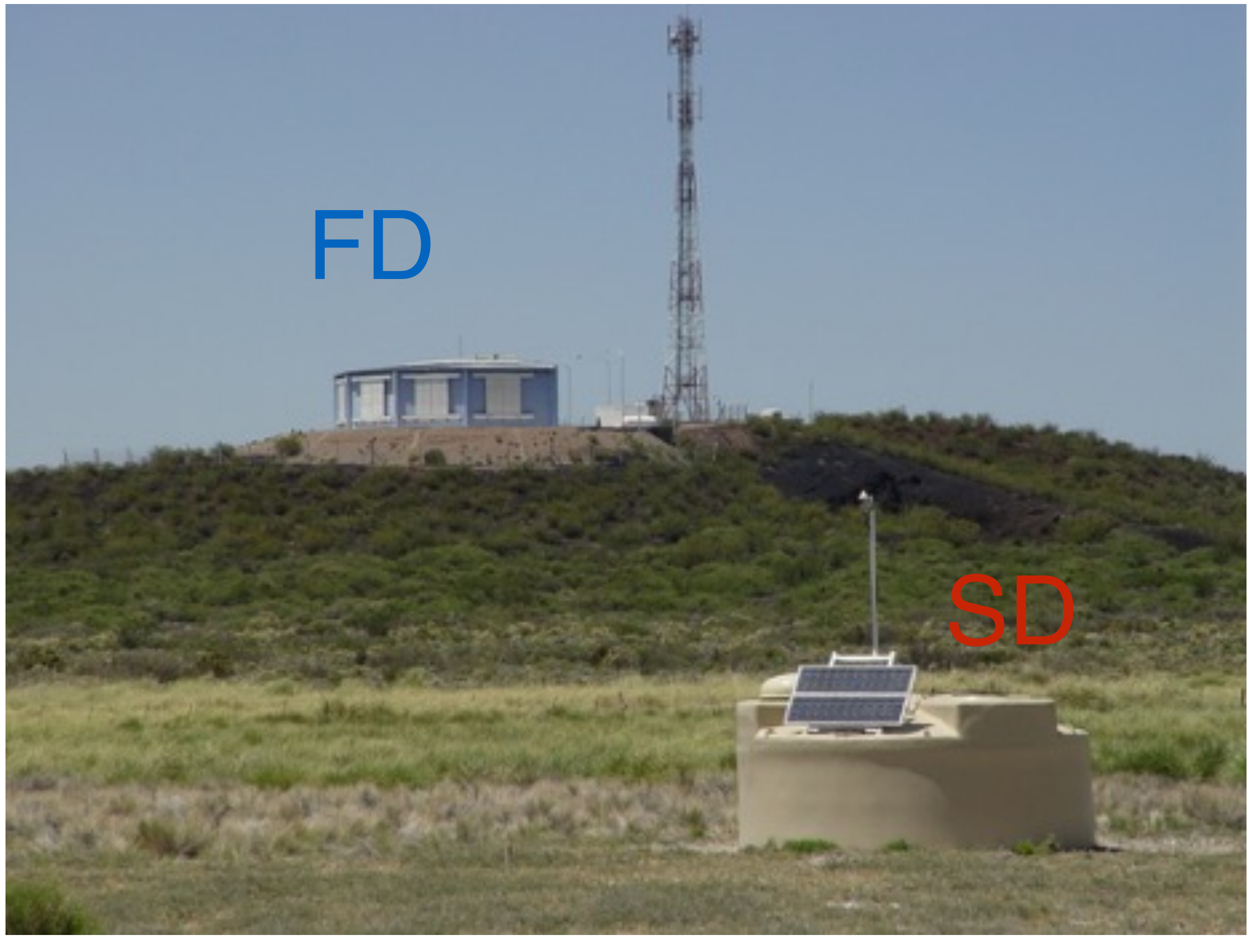
Laura Collica[1] for the Pierre Auger Collaboration[2]

[1]INFN Torino, Italy
[2] Av. San Martín Norte 304, 5613 Malargüe, Argentina
full author list: http://www.auger.org/archive/authors_2016_09.html

The Pierre Auger Observatory

Malargue, Argentina, ~1420 m a.s.l., ~870 g cm^{-2}



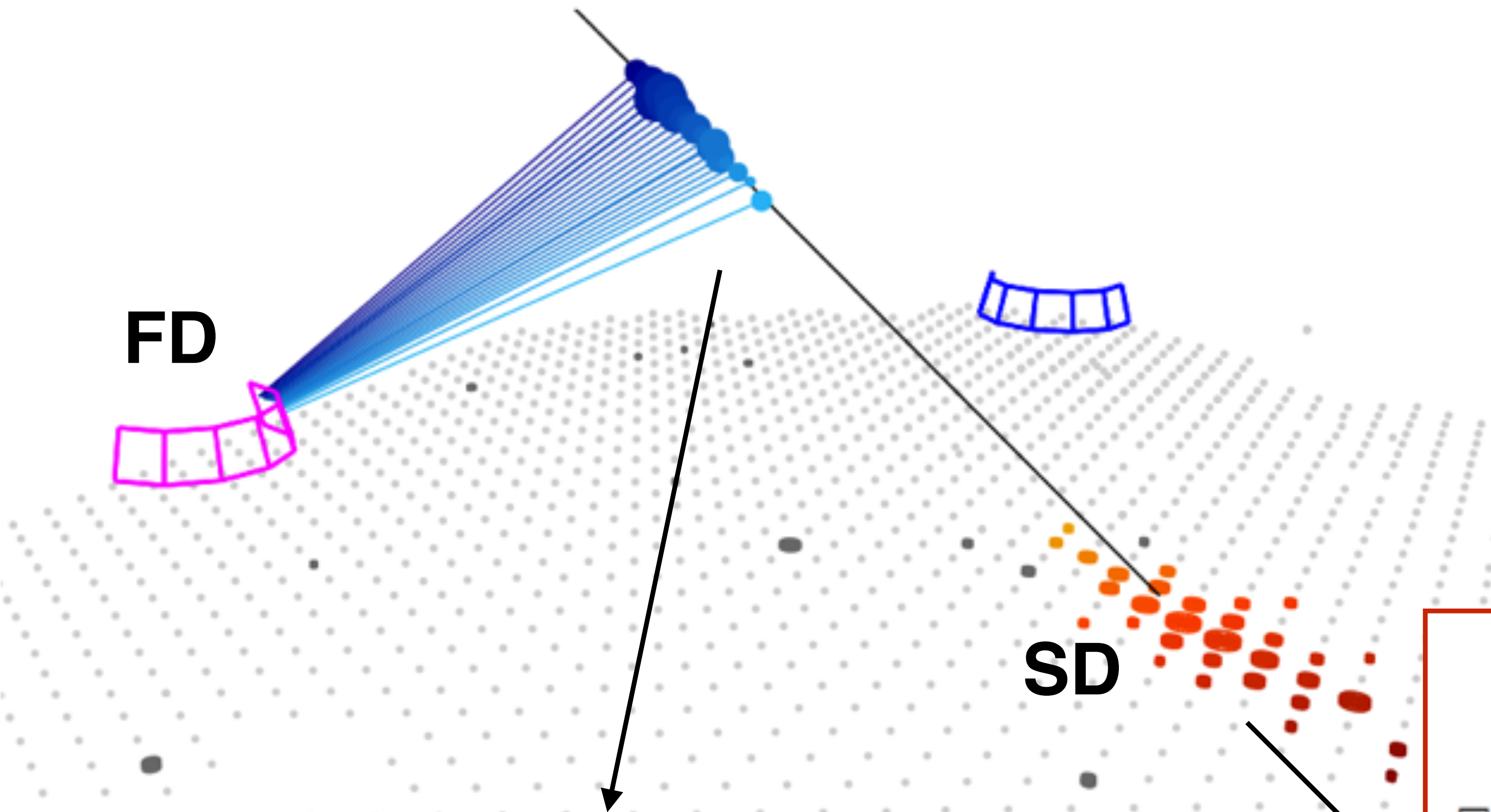


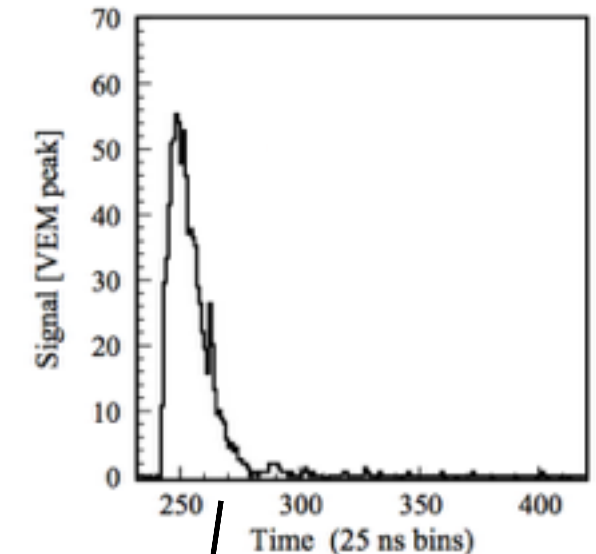
Surface Detector
1600+61(Infill) Water Cherenkov stations over 3000 km^2
<u>100% duty cycle</u>

Fluorescence Detector
24+3(HEAT) UV telescopes grouped in 4 buildings overlooking SD array
<u>15% duty cycle</u>

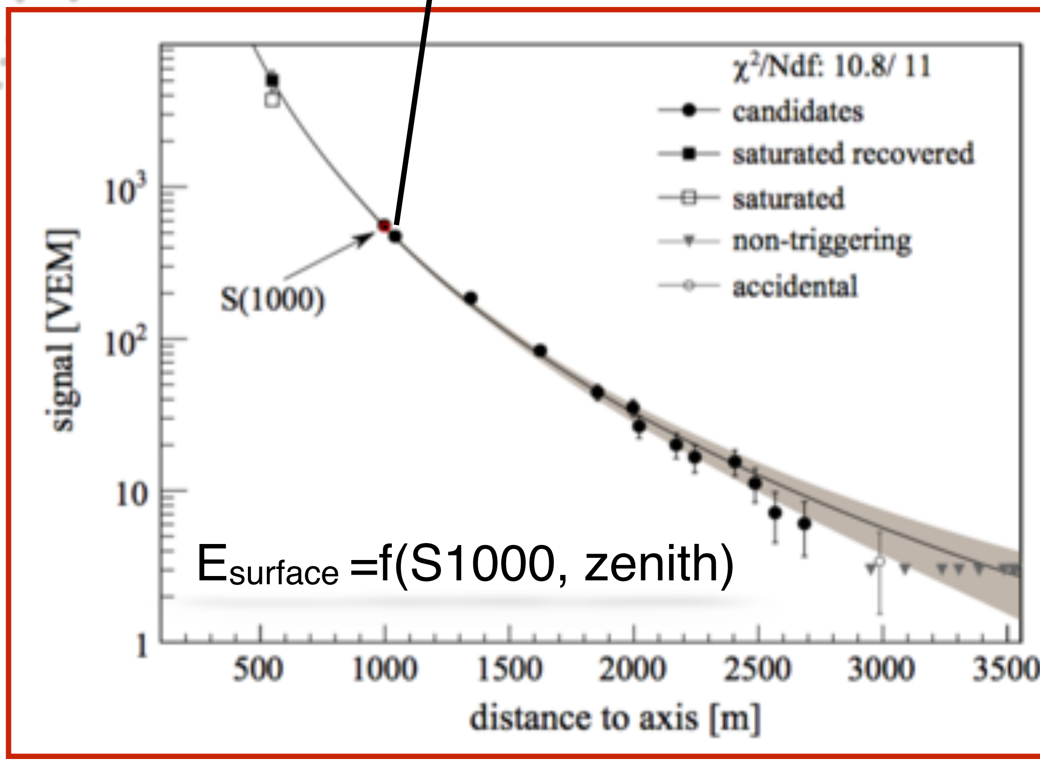
NIM A 798 (2015) 172–213

Hybrid detection of air showers

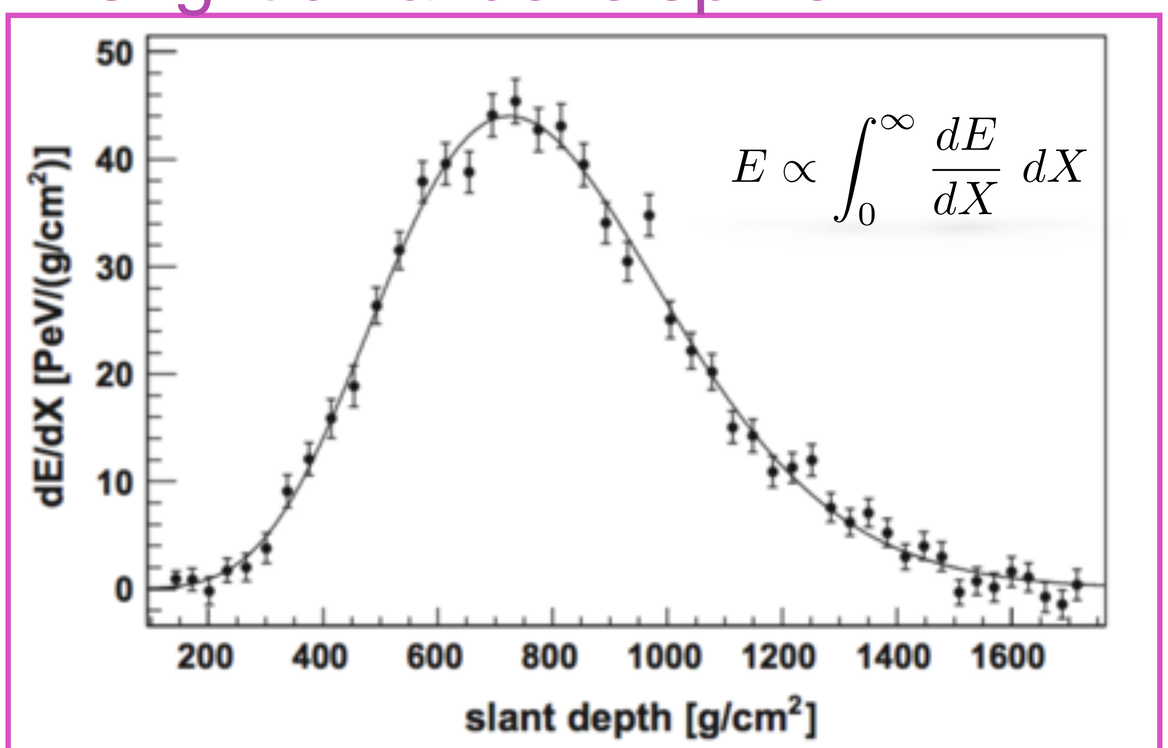




lateral distribution



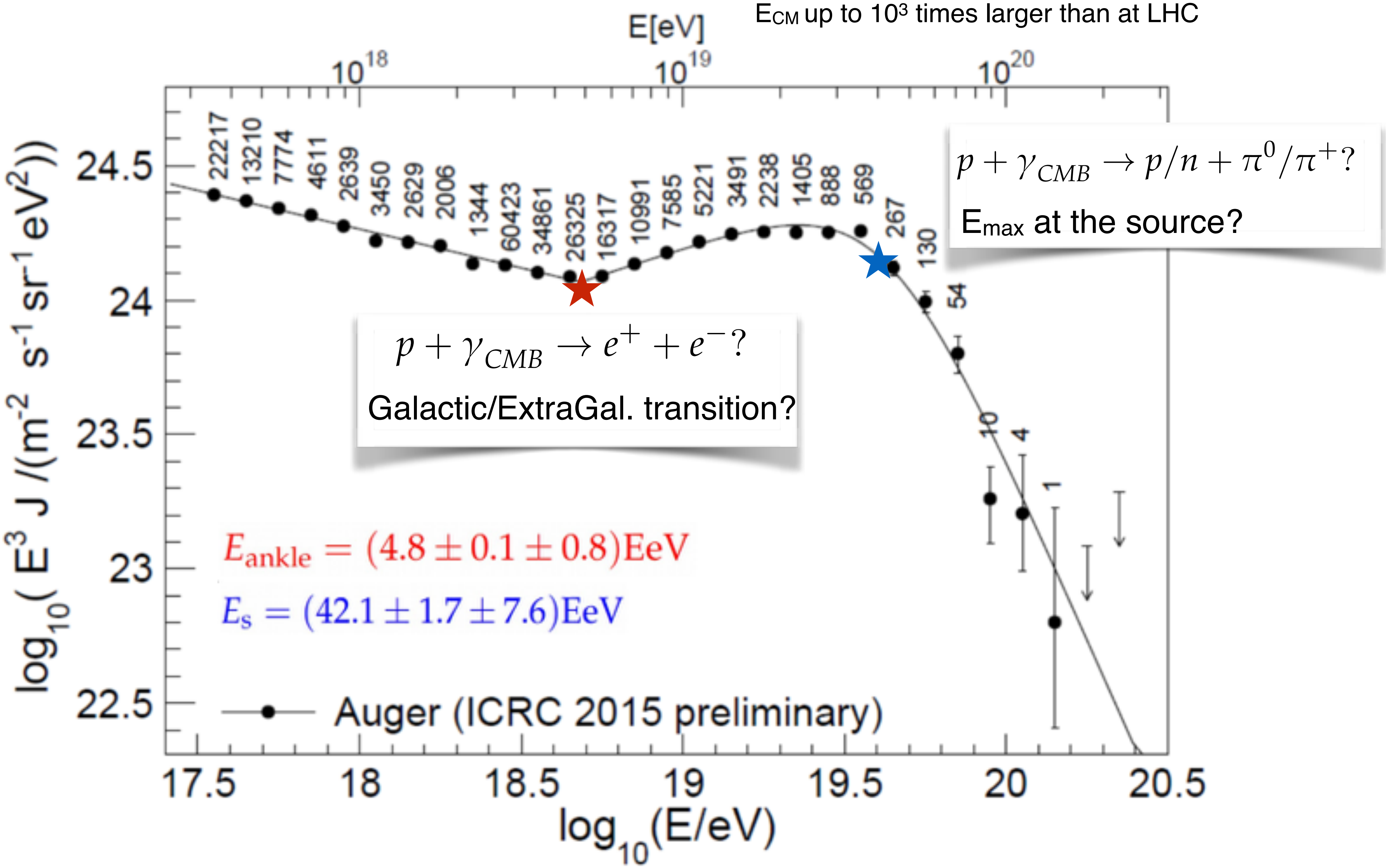
longitudinal development



Calorimetric measurement with FD, used to calibrate SD
systematic uncertainty on the energy scale: 14%

Energy spectrum of UHECRs

E_{CM} up to 10^3 times larger than at LHC



The origin of the spectral features (ankle, cut-off) at the highest energies is not clear yet

➜ **their properties cannot be disentangled by the spectrum alone: the knowledge of the UHECRs composition is needed**

Outline

Mass composition:

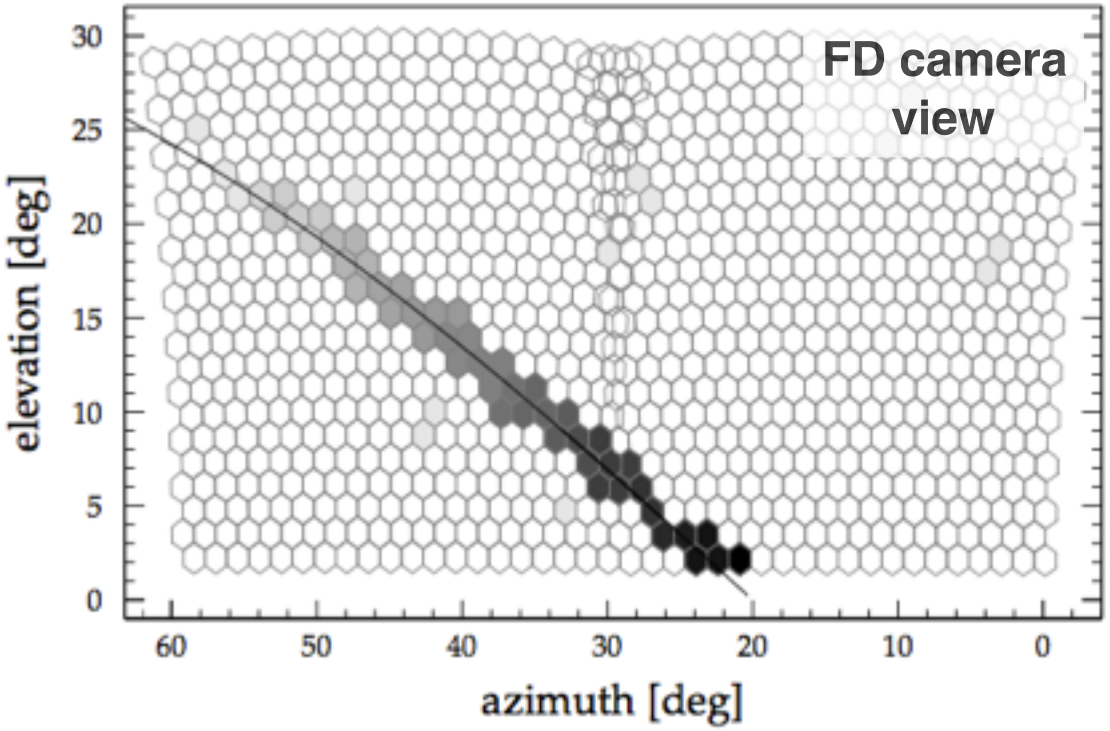
- Depth of the shower maximum
- Azimuthal asymmetry in the risetime

Hadronic interactions:

- Proton-air cross section
- Number of muons
- Muon production depth

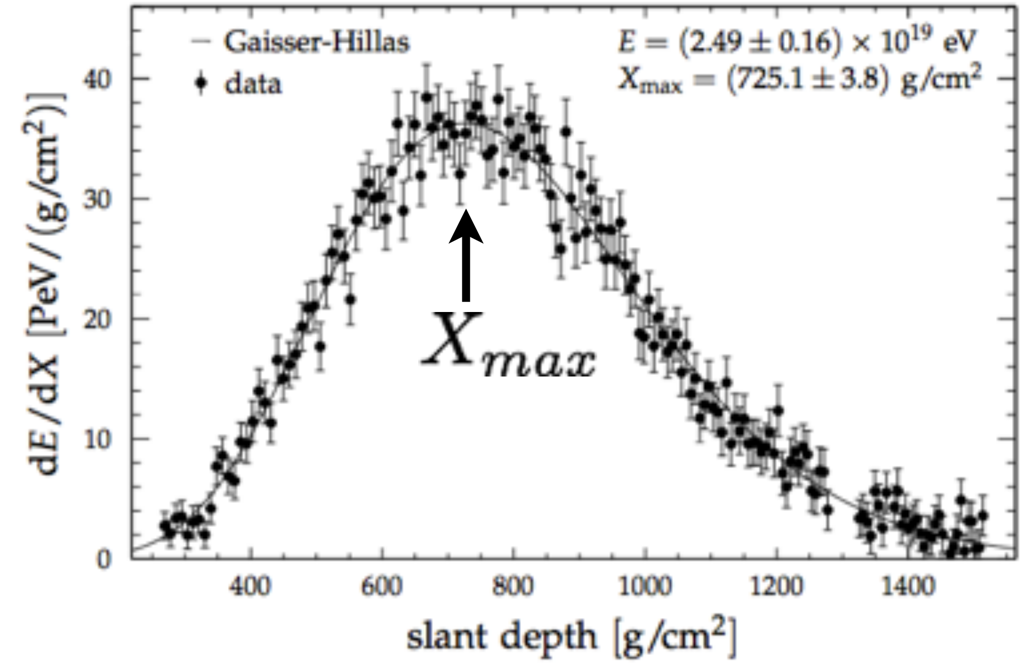
Measurement of the depth of the shower maximum with FD

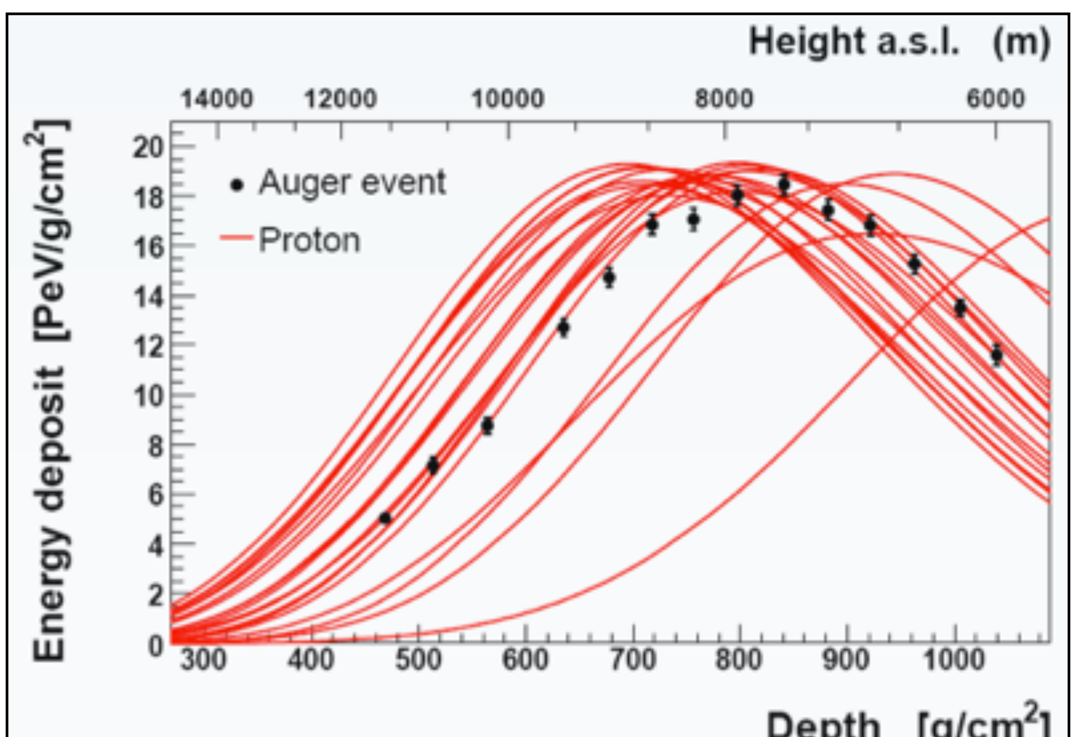
~ calorimetric energy measurement, weak dependence on hadronic models

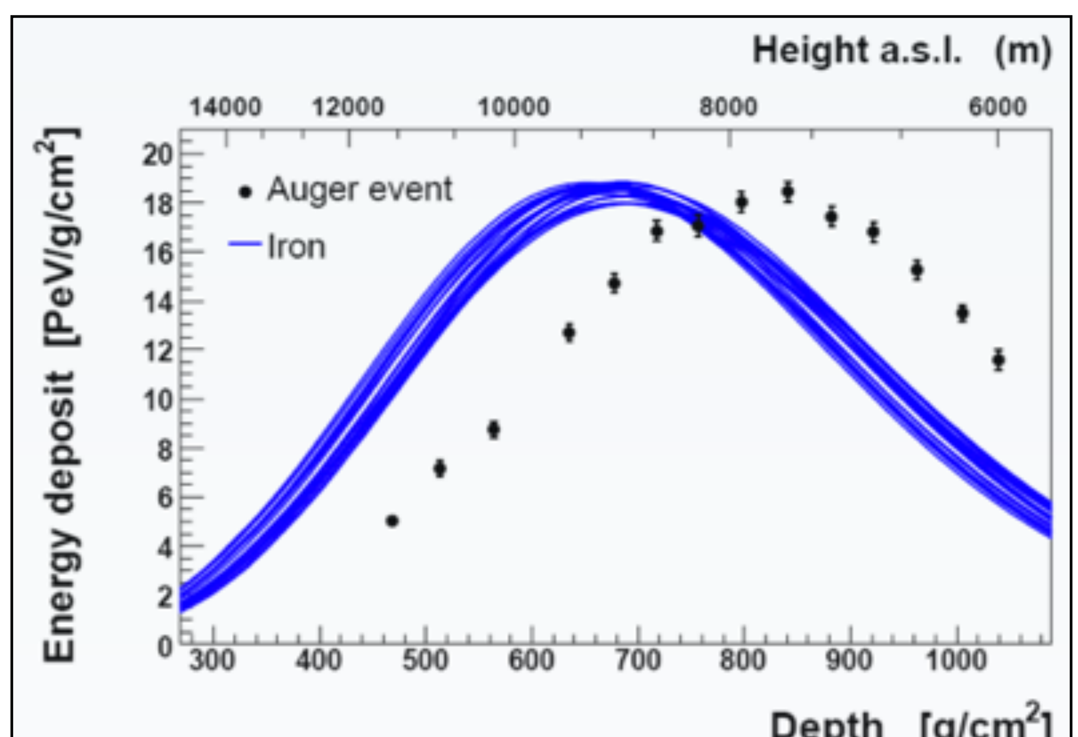


Hybrid reconstruction of geometry

Atmosphere attenuation and other light sources corrections



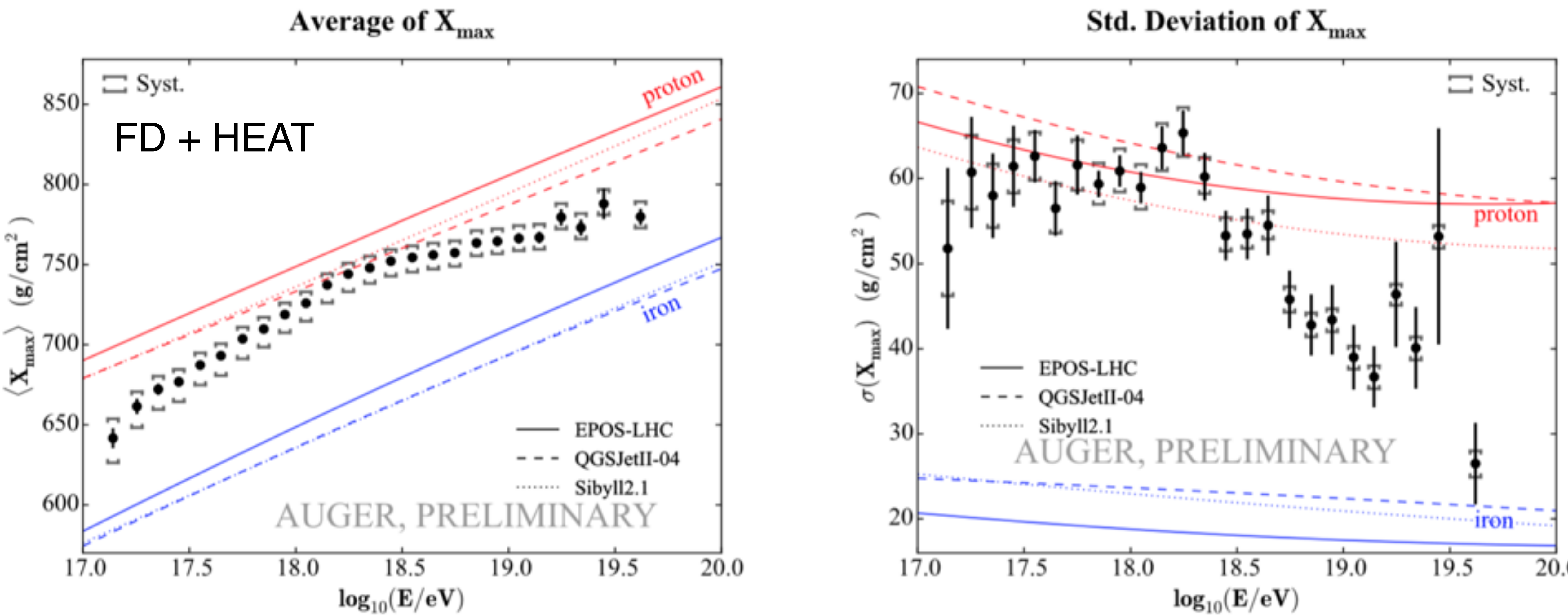




both $\langle X_{max} \rangle$ and $\langle \sigma(X_{max}) \rangle$ are sensitive to composition

First two moments of X_{max} distributions

uncertainties due to models << difference proton-iron



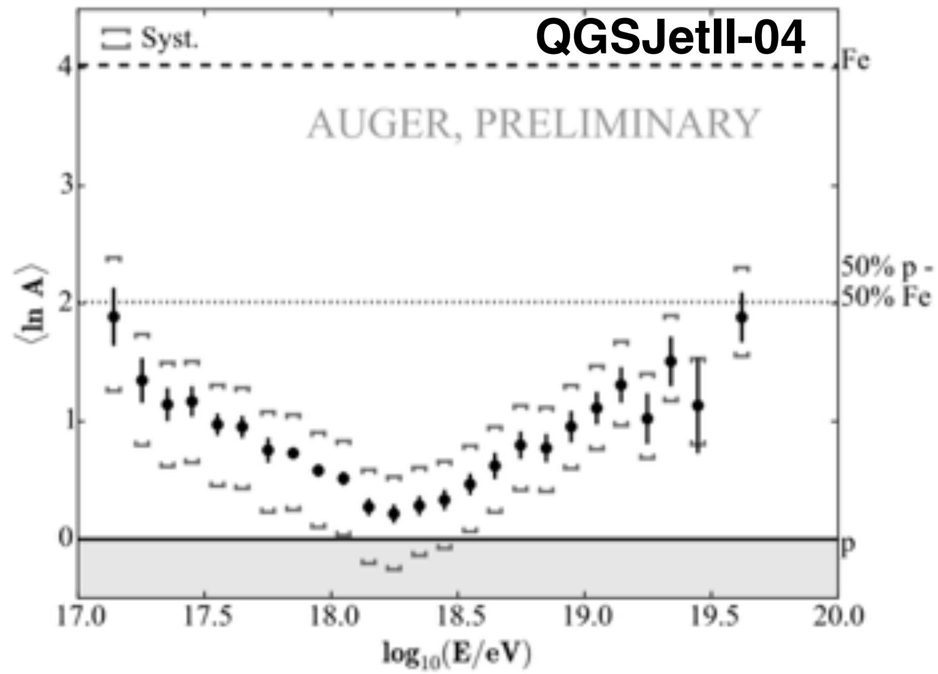
elongation rate not compatible with that expected from constant composition

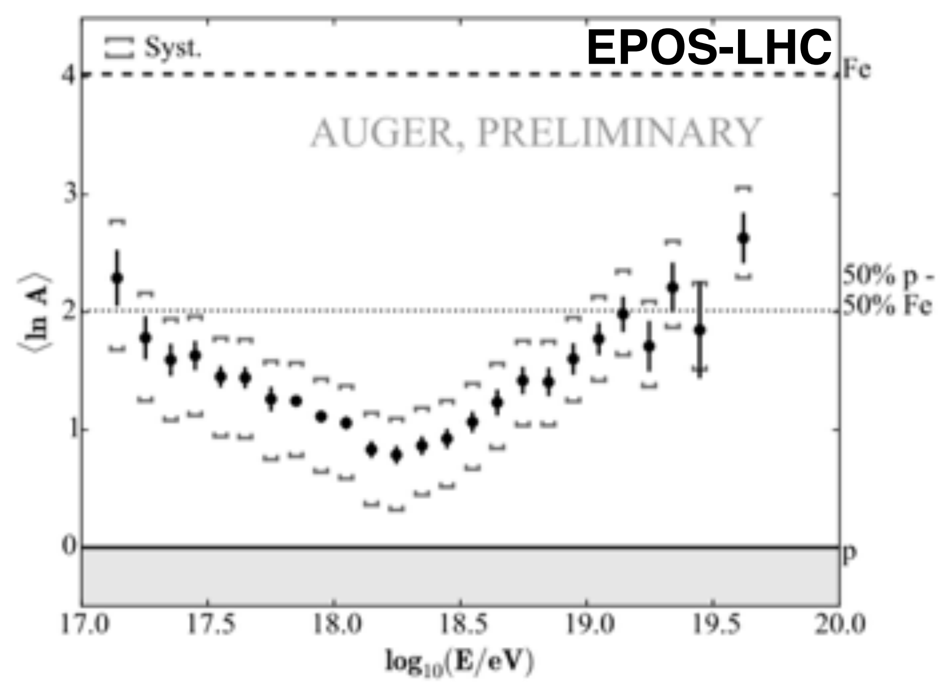
all models suggest heavier composition at lower energies, lightest around $10^{18.3}$ eV, heavier again towards highest energies

A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

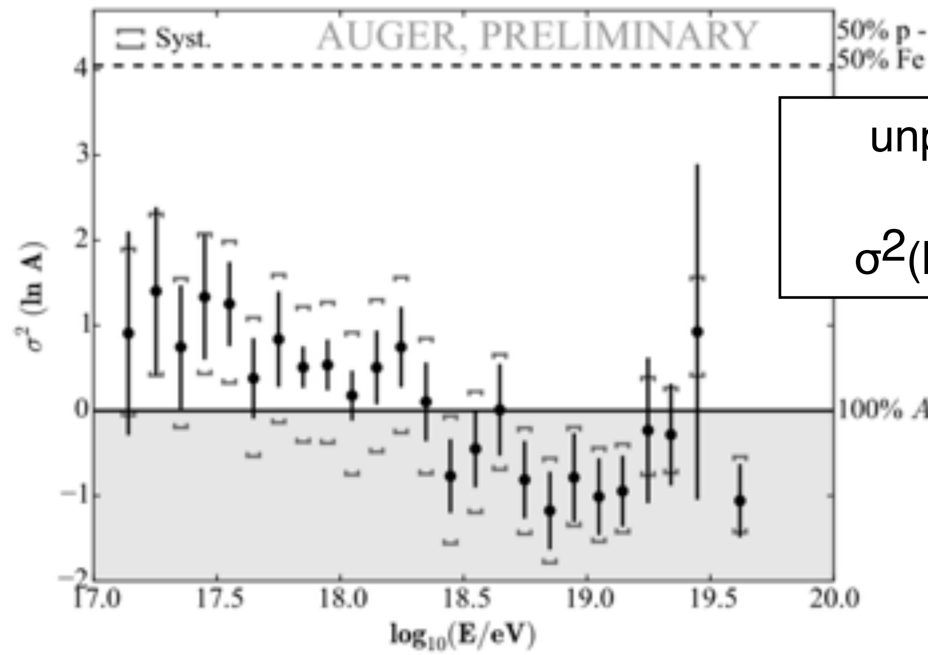
Conversion of X_{max} moments to lnA moments

lnA



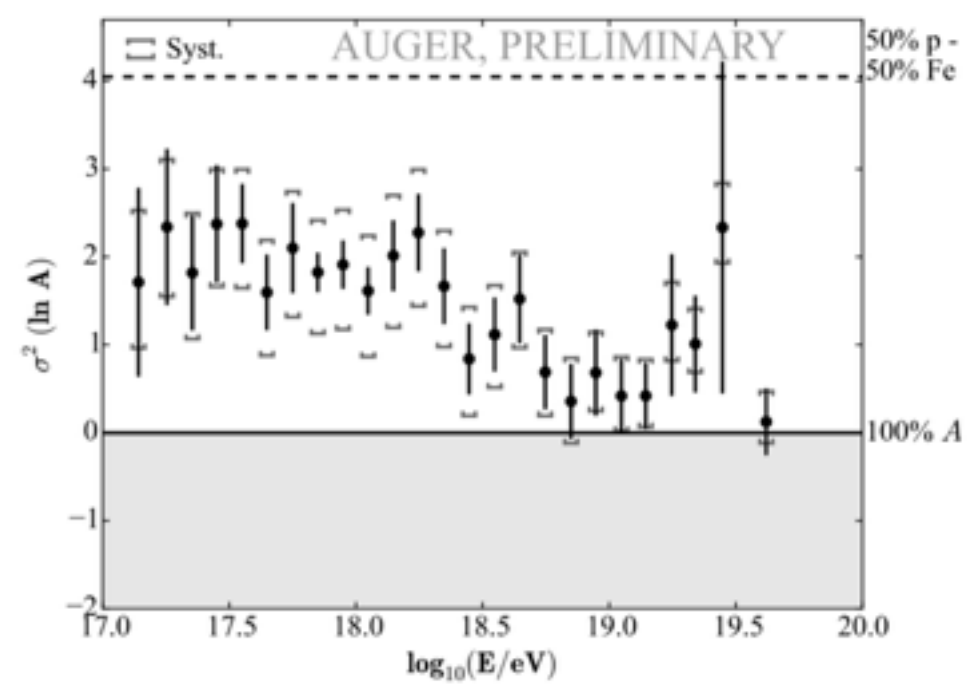


σ^2(lnA)



unphysical results for QGSJetII-04:

σ^2(ln A) < 0 (within 2σ)

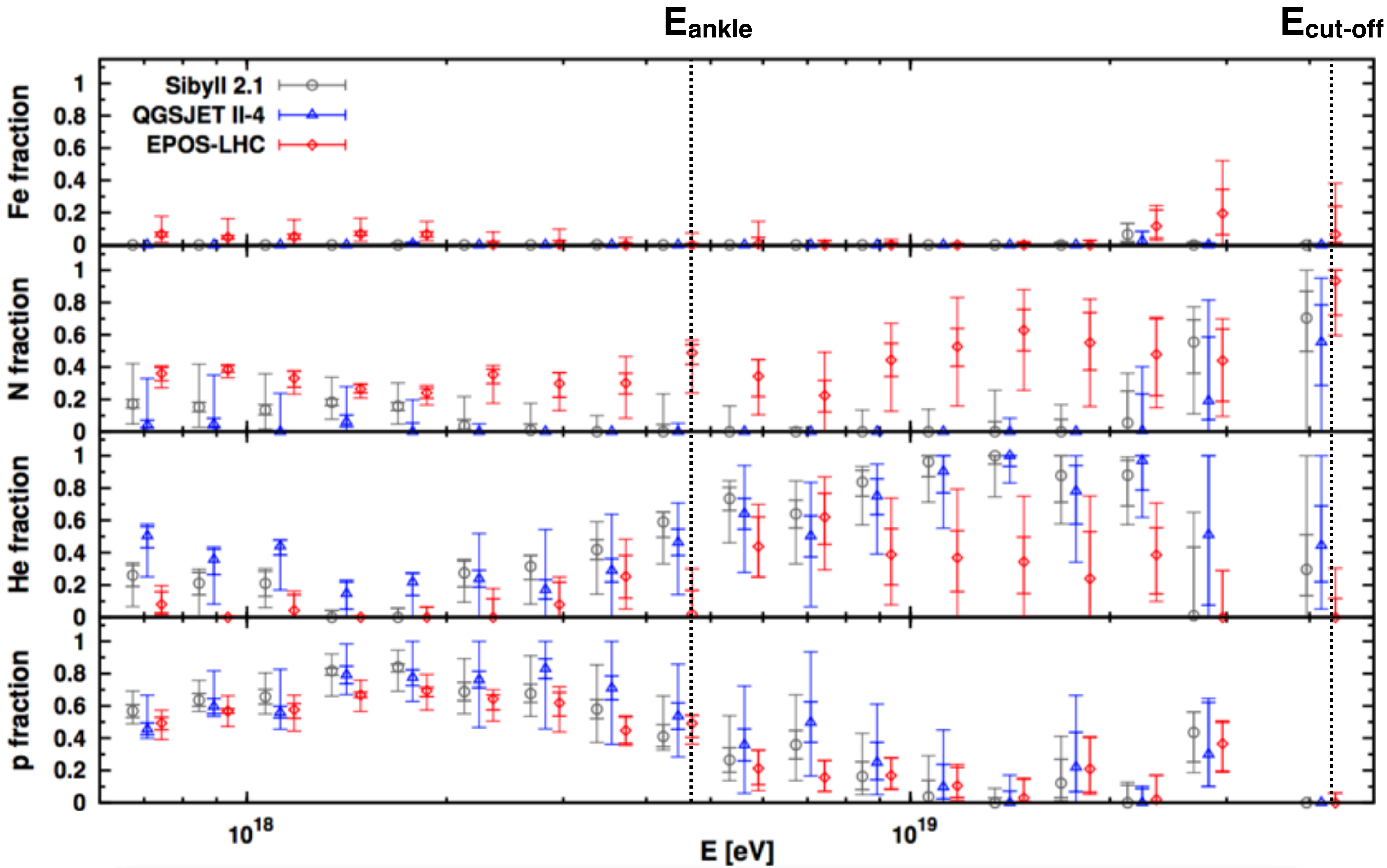


composition is lightest at around $10^{18.3}$ eV, gets heavier for higher energies

mass dispersion decreases with energy

A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Fractions of primary nuclei from fits of X_{max} distributions

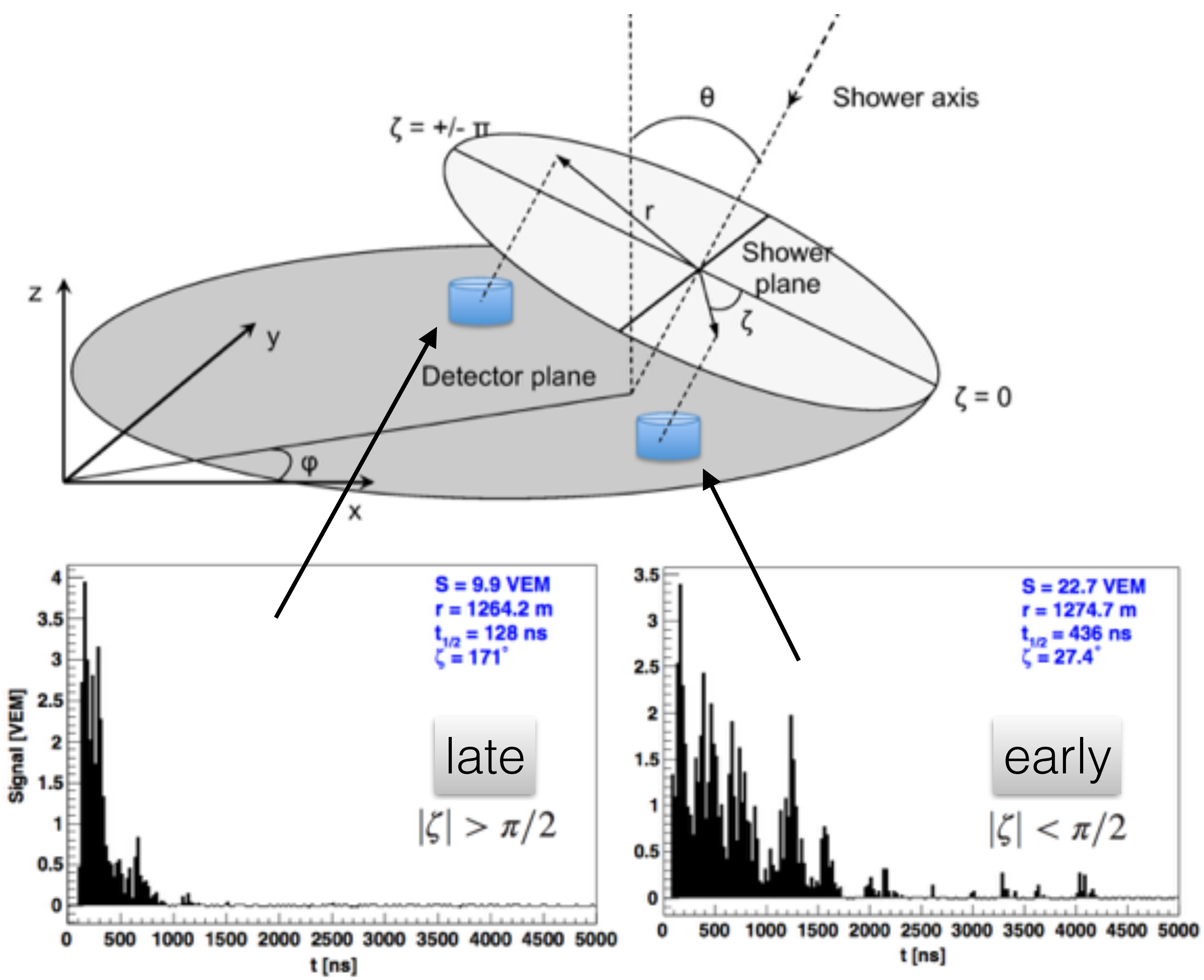


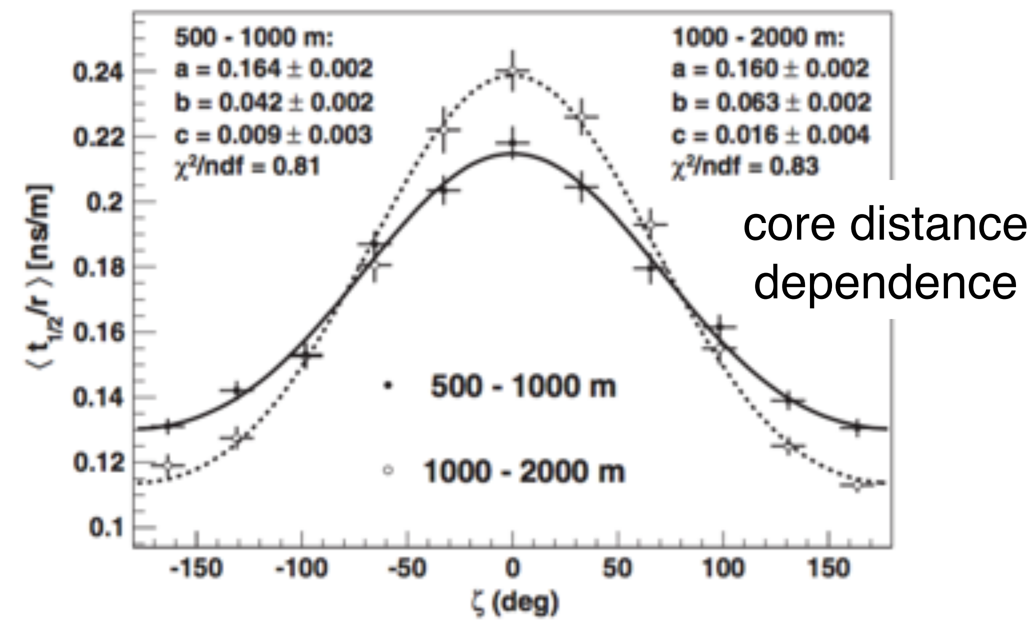
fractions of *p* and He change much with energy, Fe is almost absent (best fit obtained for EPOS-LHC)

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

Azimuthal risetime asymmetry in the SD signals

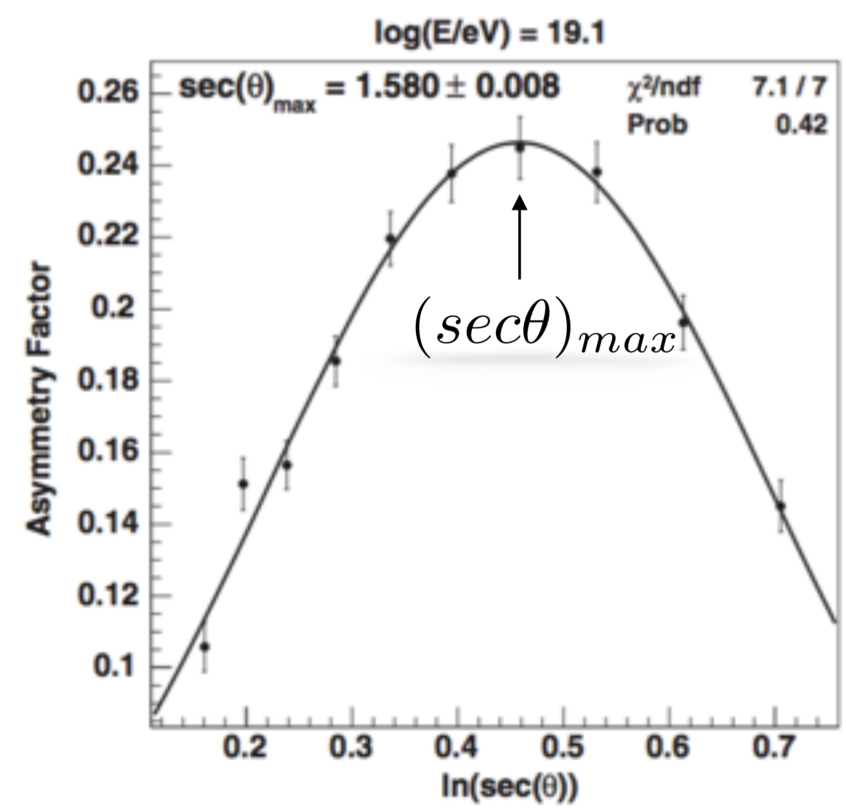
The asymmetry of $t_{1/2}$ ($T_{50} - T_{10}$) is related to the stage of the shower development at the ground





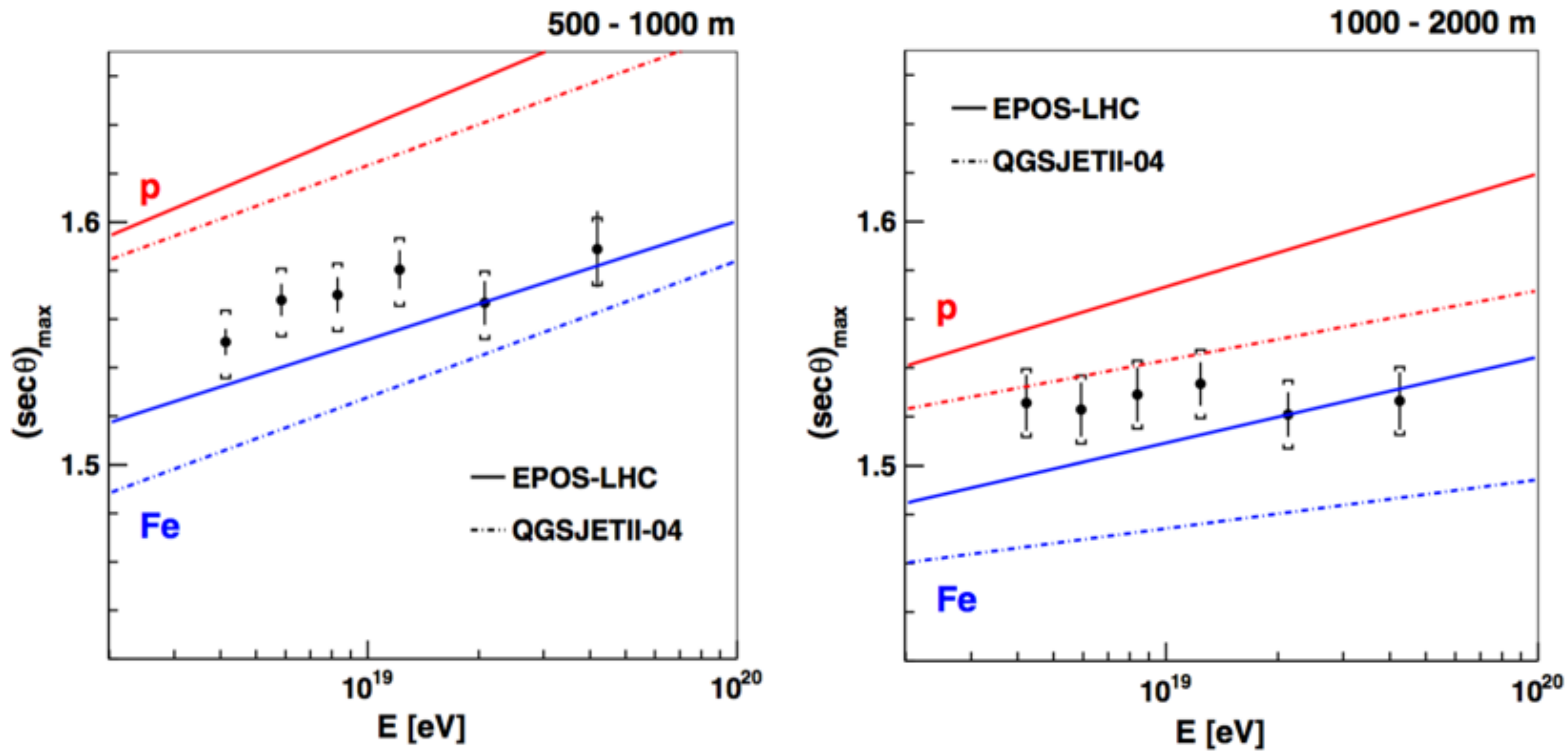
$$< t_{1/2}/r >= a + b\ cos\zeta + c\ cos^2\zeta$$

parametrised in E and θ (30°,62°)



the asymmetry factor b/(a+c) is maximum at a given θ: $(\sec\theta)_{max}$, which is sensitive to mass

$(\sec\theta)_{max}$ vs. energy



data bracketed between both models

data evolution is flatter than that predicted by models for both distance ranges, in line with X_{max} studies

The Pierre Auger Collaboration, PRD 93 (2016) 072006

Outline

Mass composition:

- Depth of the shower maximum
- Azimuthal asymmetry in the risetime

Hadronic interactions:

- Proton-air cross section
- Number of muons
- Muon production depth

Hadronic physics with Auger

EM shower particles:

- high energy interactions (HE γ from π^0 decay)
- longitudinal profile dominated by particles from secondaries in the first 100 interactions

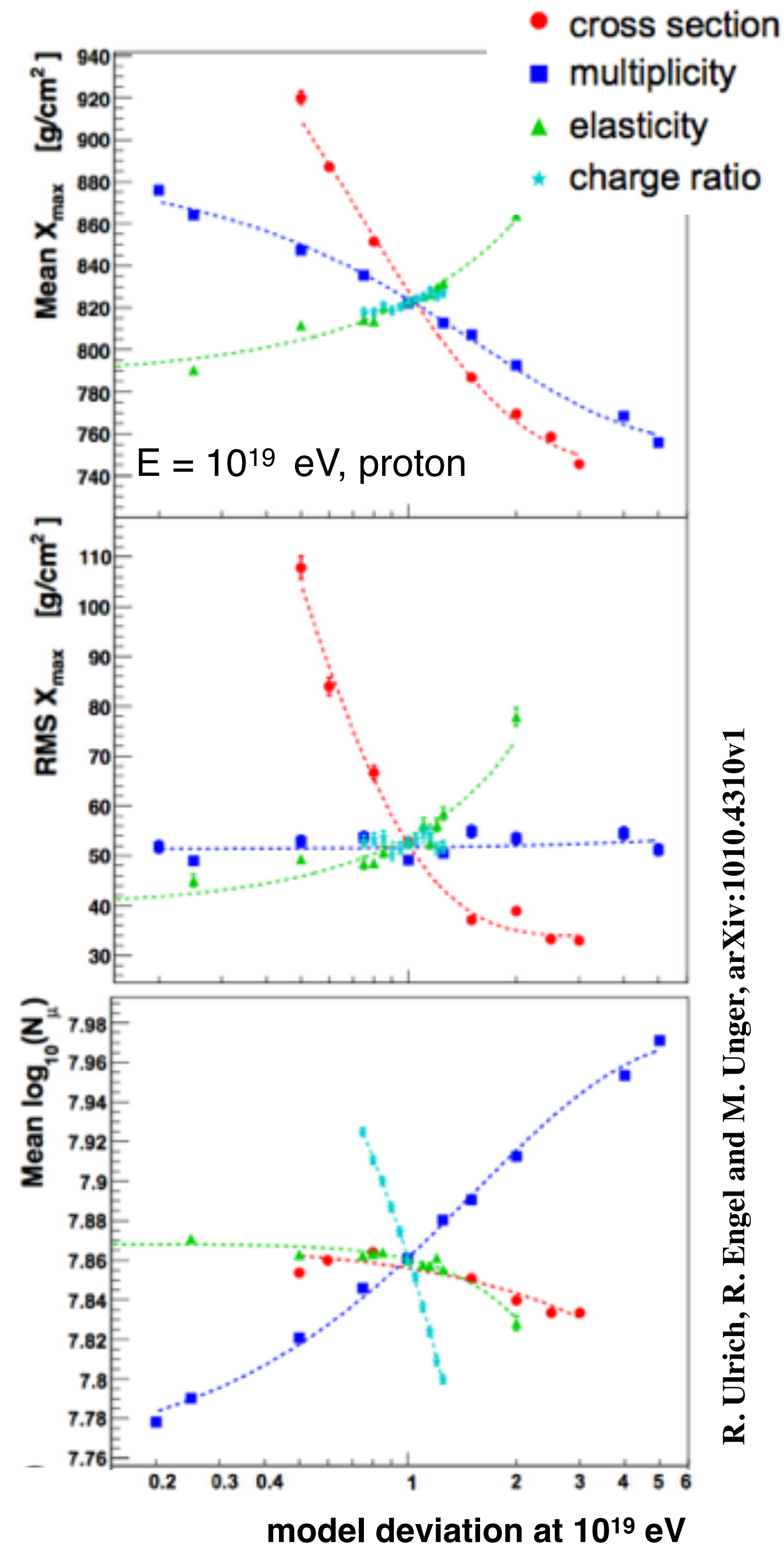
→ X_{max}, $\sigma(X_{max})$, long. profile

Muons:

- low energy interactions (from the $\pi^{+/-}$ decay)
- negligible fraction from the first interactions

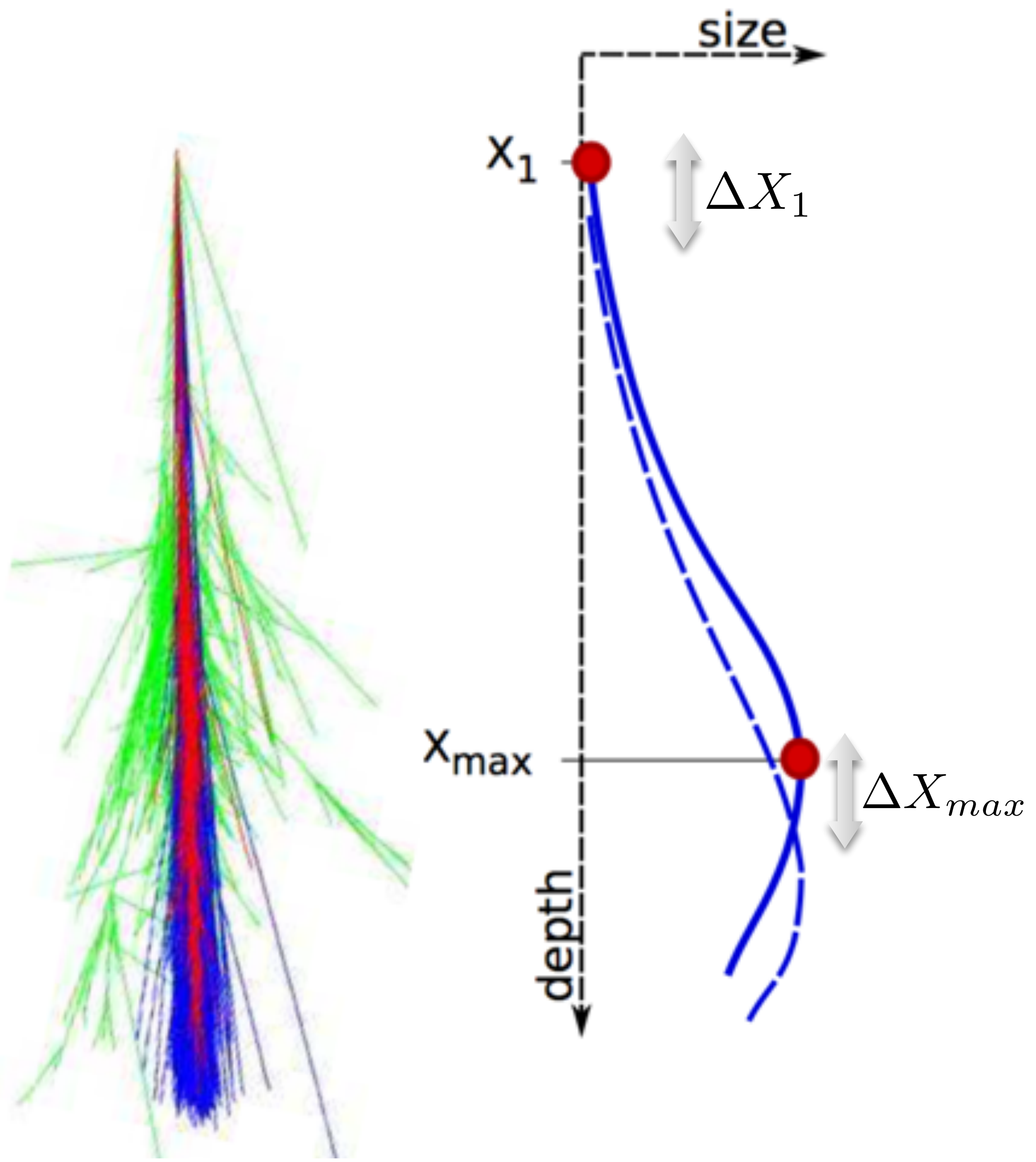
→ N_μ, X^μ_{max}, long. and lat. profile

With unknown mass composition, hadronic interactions can only be tested using various observables which should give consistent mass results



R. Ulrich, R. Engel and M. Unger, arXiv:1010.4310v1

Measurement of the proton-air cross section



select 20%(η=0.2) of the deepest events
to increase proton fraction

energy range $10^{17.8}$ - $10^{18.5}$ eV
<25% He contamination

Distribution of the depths of first interaction

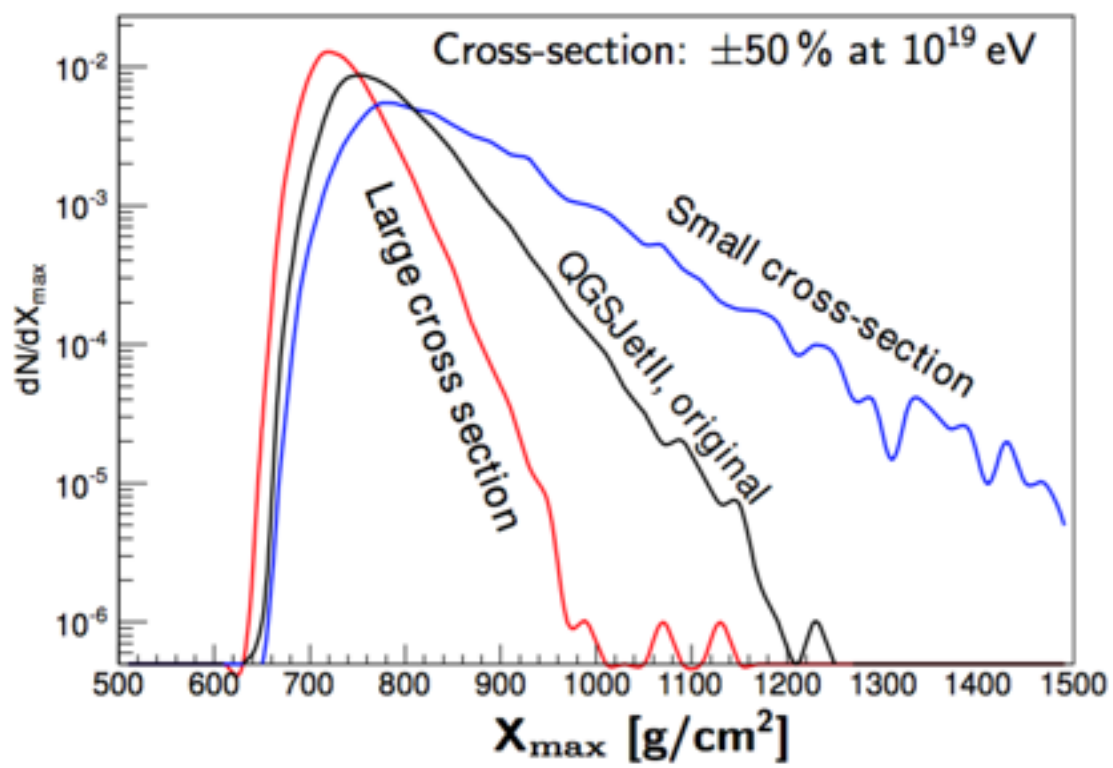
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{int} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

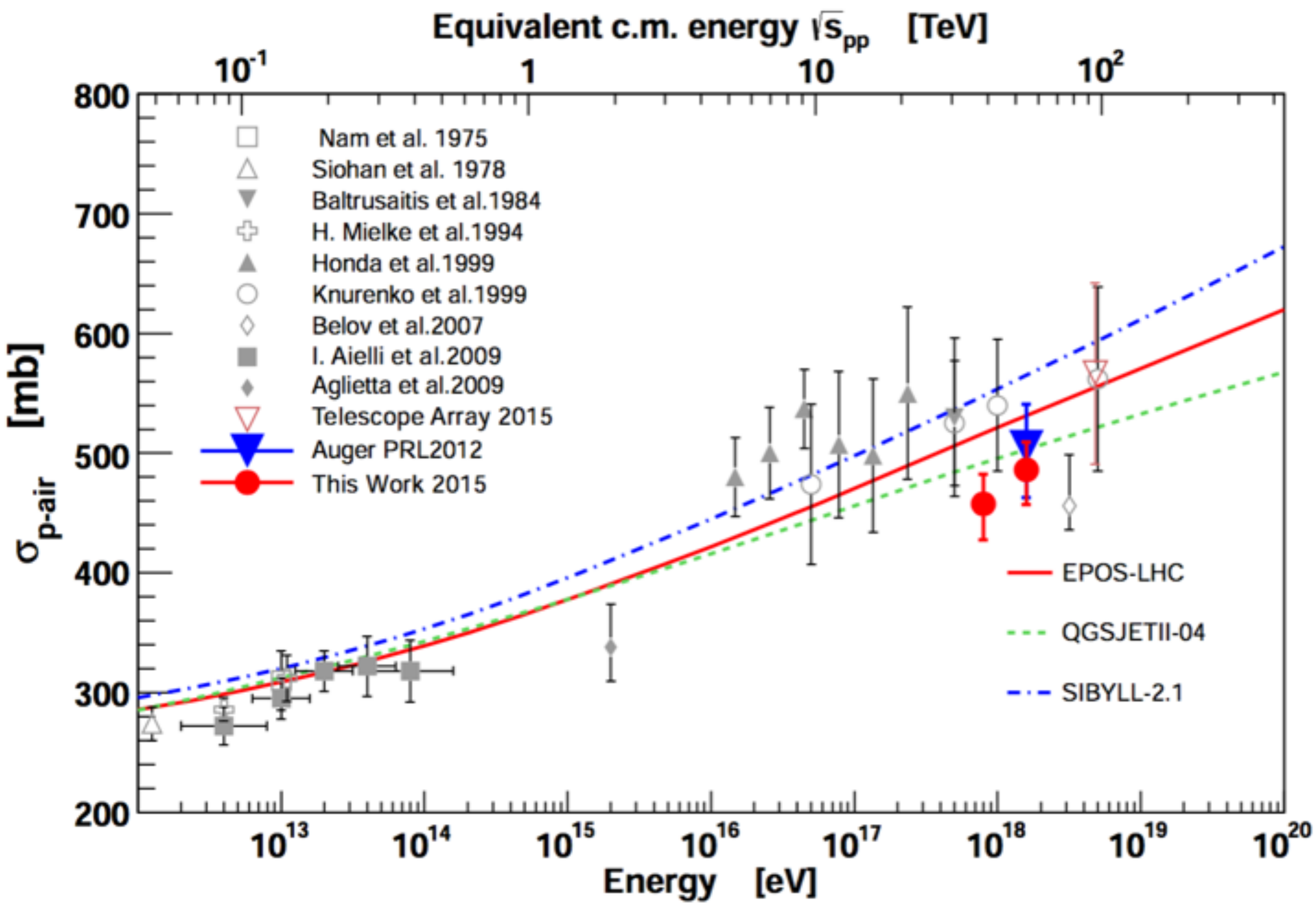
The tail of the X_{max} distribution is sensitive to the p-Air cross section

$$\frac{dN}{dX_{max}} \propto e^{\frac{-X_{max}}{\Lambda_\eta}}$$

$$\Lambda_\eta \propto \lambda_{int}$$



Proton-air cross section



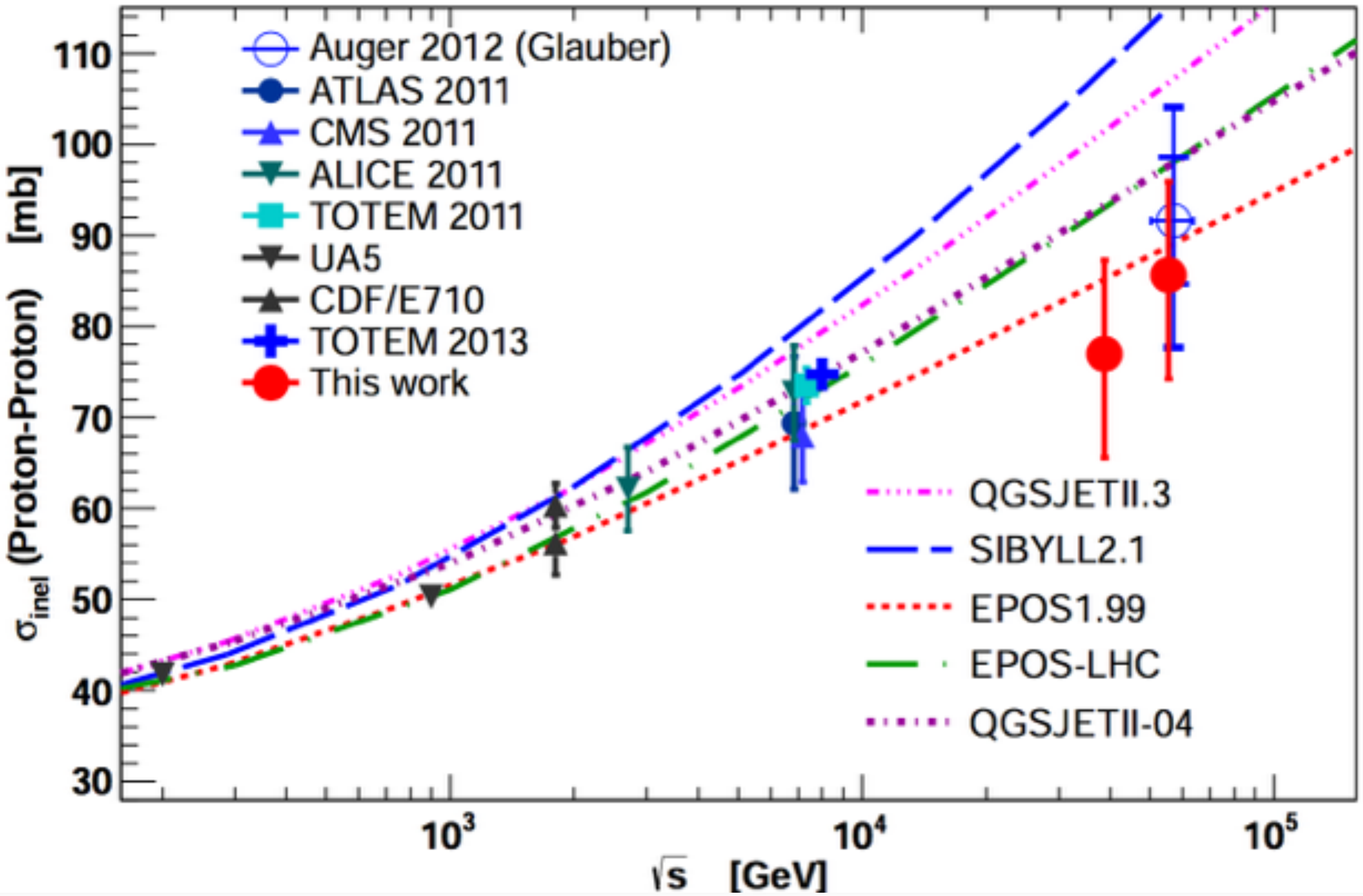
$$\sigma_{p-air} = [458 \pm 18_{\rm stat}\ (^{+19}_{-25})_{\rm sys}]\ \text{mb at } 10^{17.8}\ \text{eV} \leq E < 10^{18}\text{eV}$$

$$\sigma_{p-air} = [486 \pm 16_{\rm stat}\ (^{+19}_{-25})_{\rm sys}]\ \text{mb at } 10^{18}\ \text{eV} \leq E < 10^{18.5}\text{eV}$$

R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Inelastic proton-proton cross section

Extended Glauber conversion with inelastic screening + propagation of modeling uncertainties



$$\sigma_{pp}^{inel} = [77 \pm 6_{\rm stat}\ (^{+5}_{-7})_{\rm sys} \pm 7_{\rm Glauber}]\ \text{mb at } \sqrt{s_{\rm pp}} = 39 \pm 3\ \text{TeV}$$
$$\sigma_{pp}^{inel} = [86 \pm 6_{\rm stat}\ (^{+6}_{-7})_{\rm sys} \pm 7_{\rm Glauber}]\ \text{mb at } \sqrt{s_{\rm pp}} = 56 \pm 4\ \text{TeV}$$

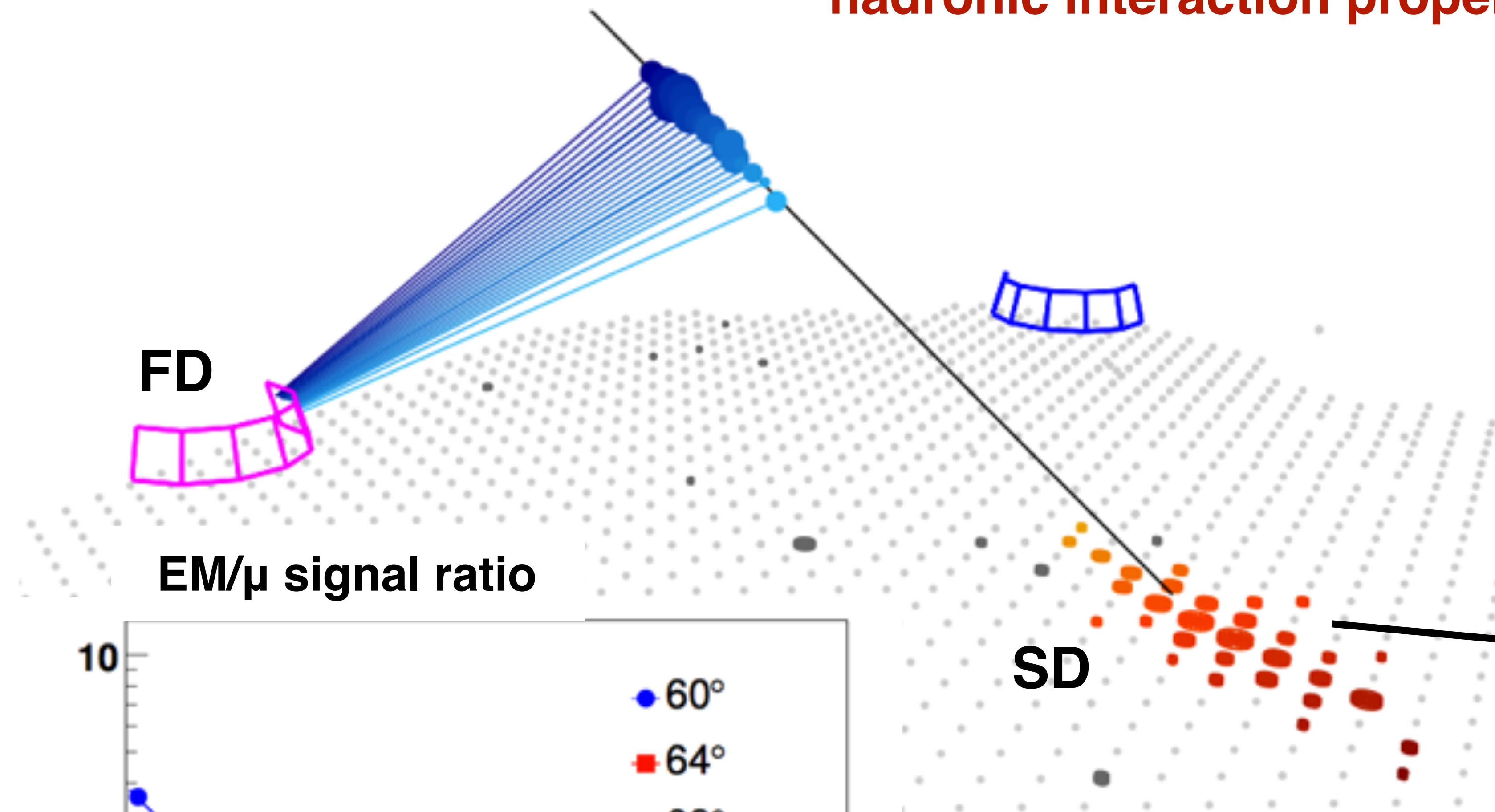
(Model uncertainties may be underestimated, since there are other theoretical models available for the conversion)

Data consistent with a rising cross-section with E

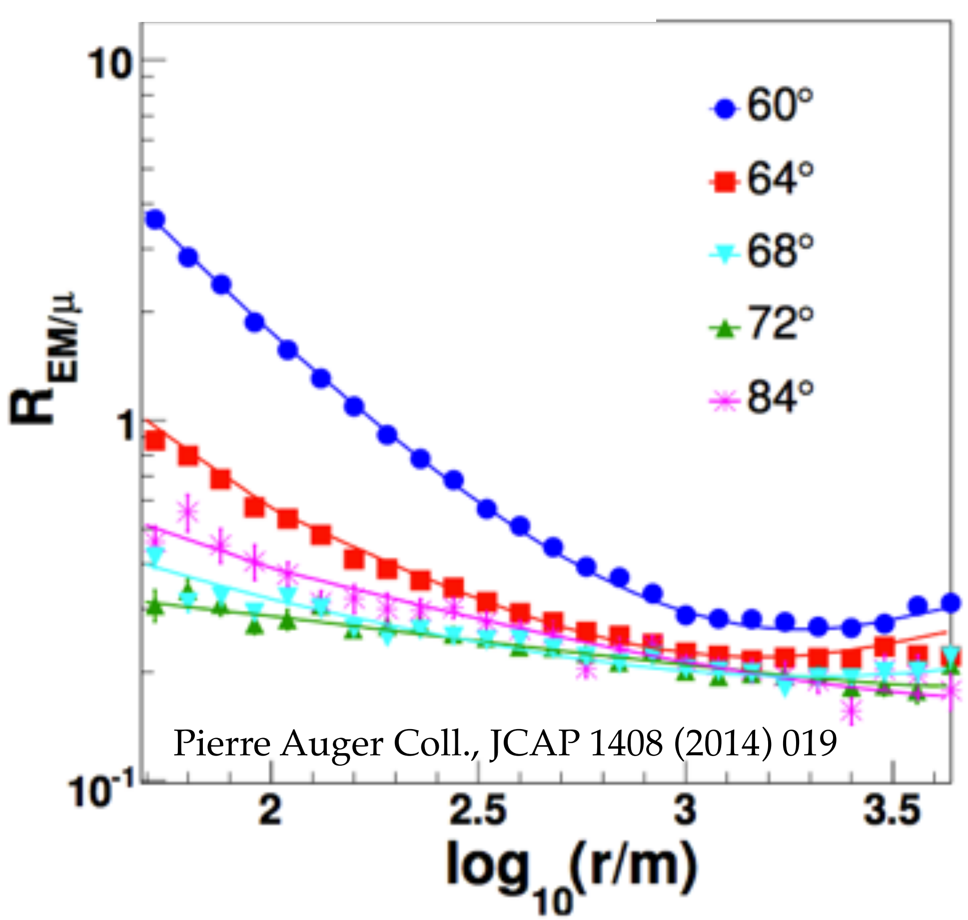
R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

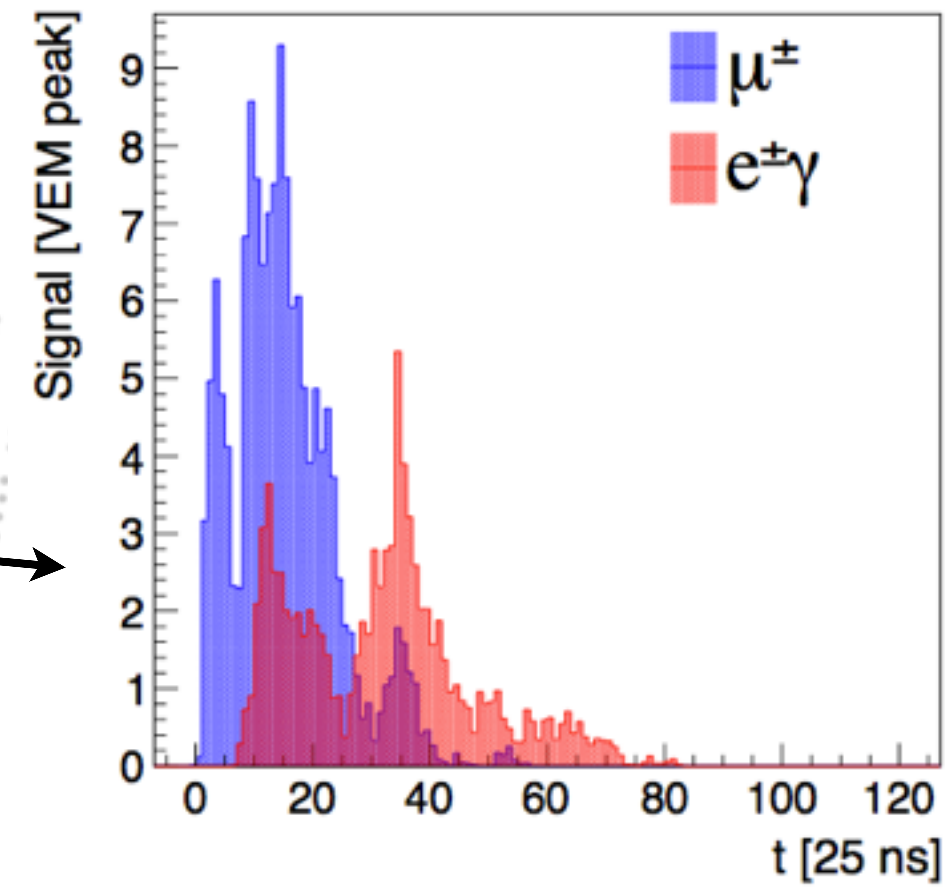
Measuring muons with Auger SD

The muon content of EAS is sensitive to the primary composition and to the hadronic interaction properties



EM/μ signal ratio





- in inclined showers the EM component is largely absorbed before reaching the ground

- the EM signal decreases with the distance from the core

Muon studies with inclined hybrid events (62°,80°)

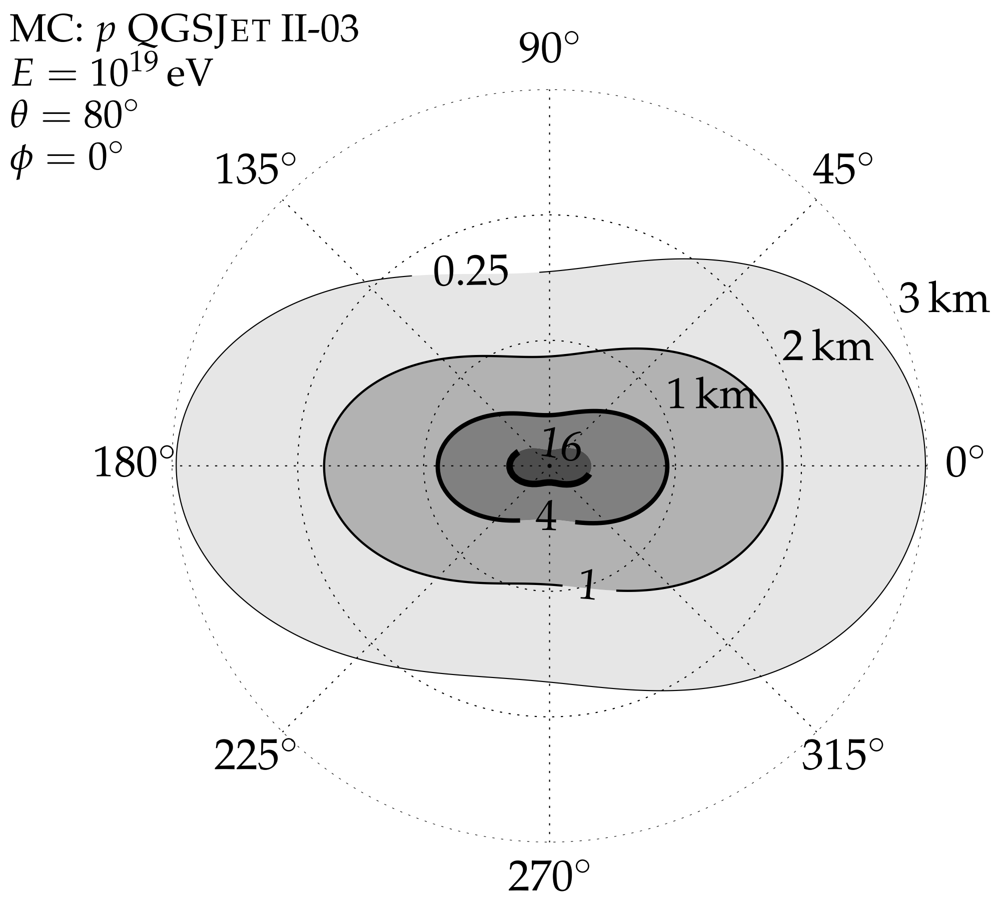
The number of muons per unit area at the ground level has a shape which is almost independent of energy, composition or hadronic model

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

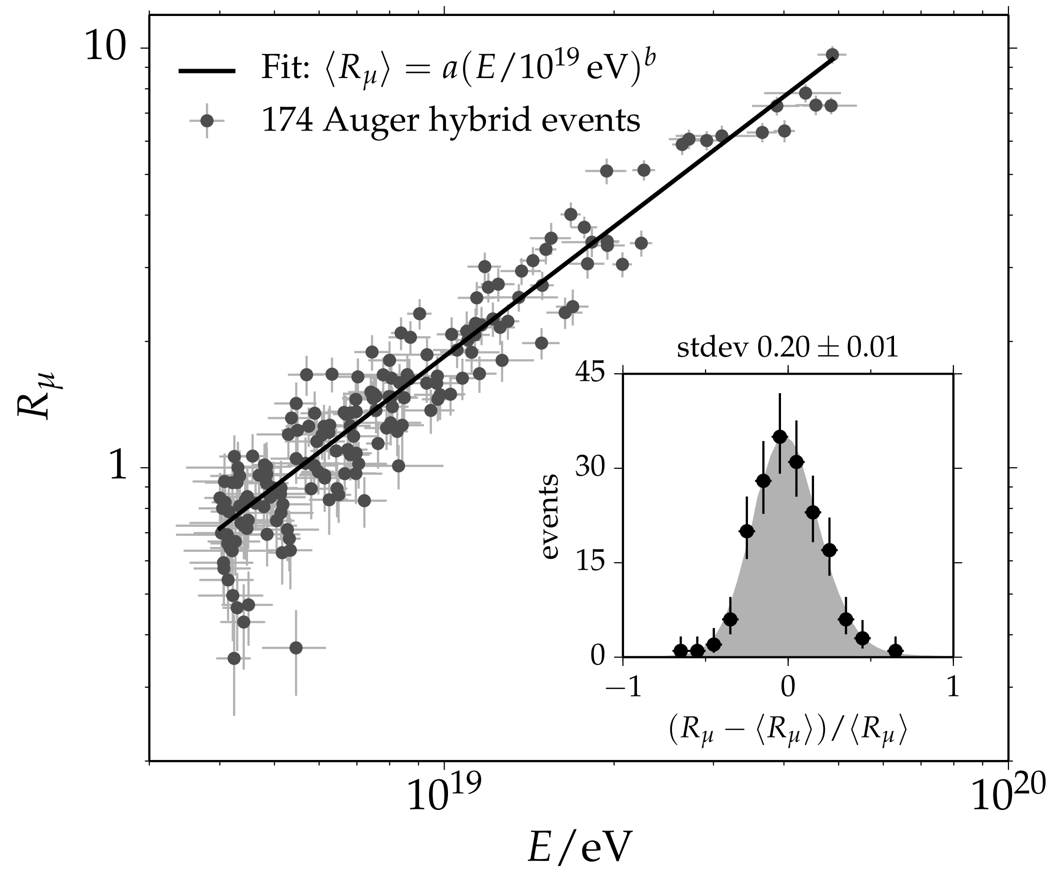
N_{19}: scale factor measured/reference density profiles

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

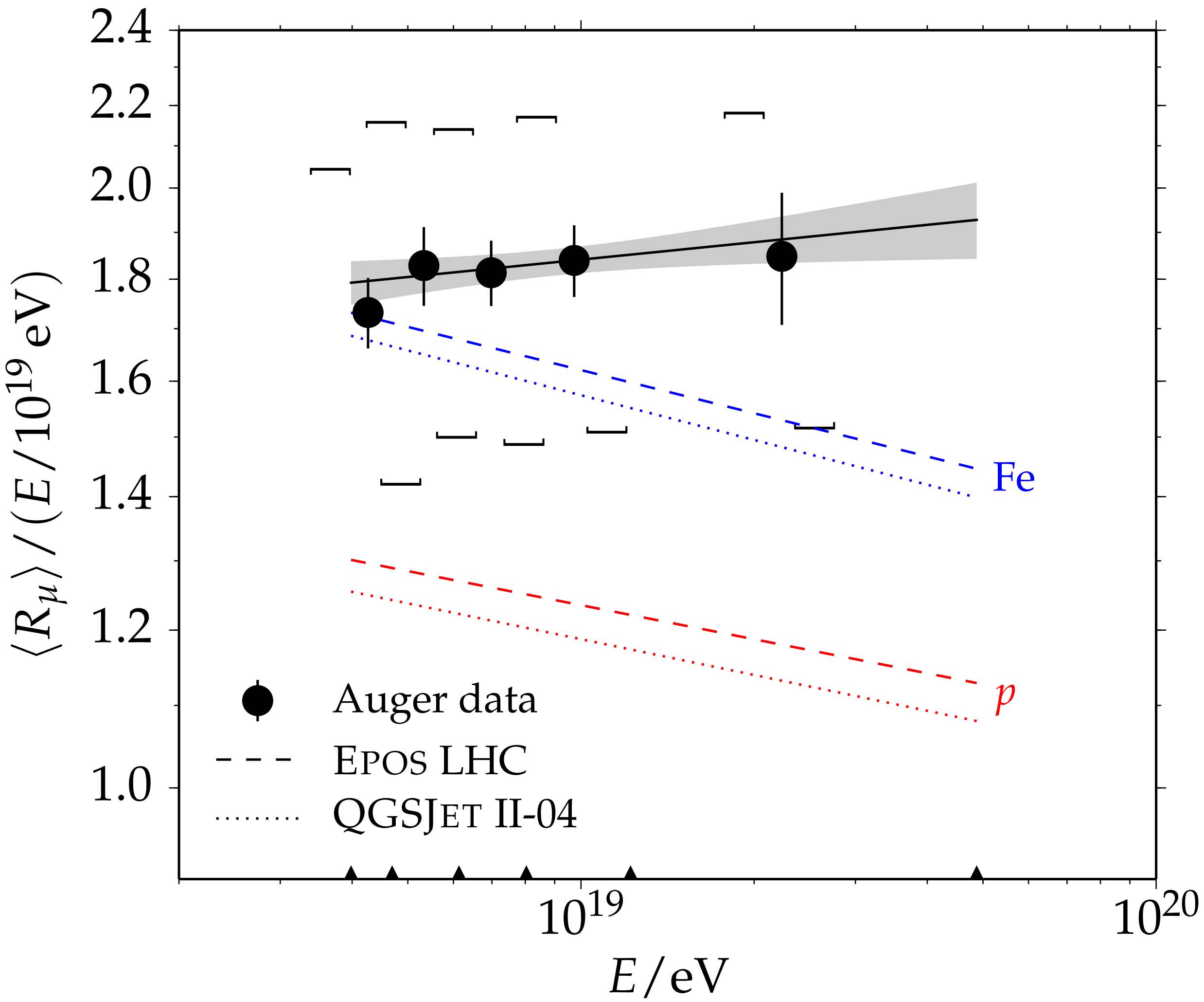
reference density profile $\rho_{\mu,19}$ [hits/station]



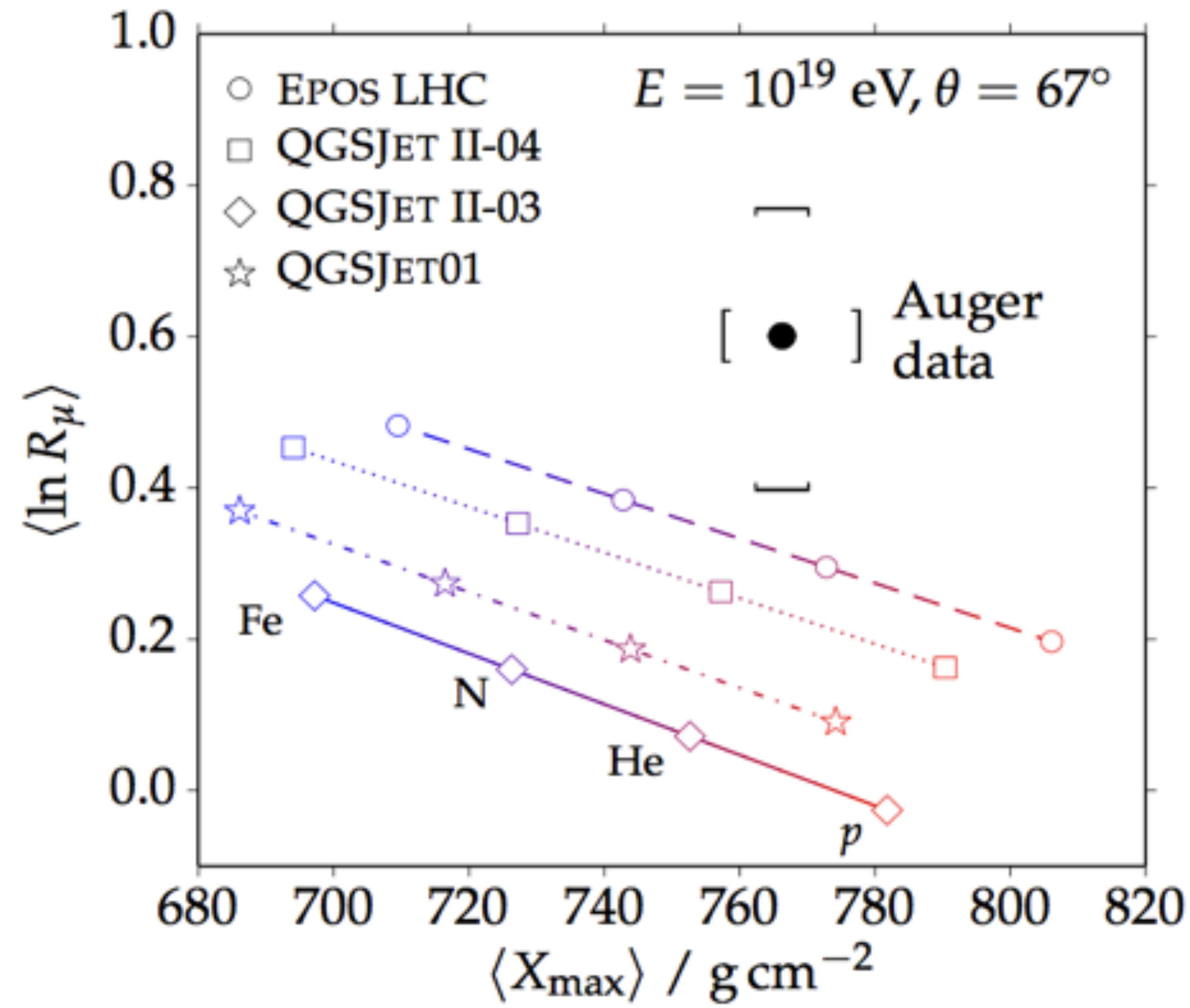
R_μ calibration for hybrid events



Mean Muon Scale $\langle R_\mu \rangle$



systematic uncertainty inherited from the energy scale

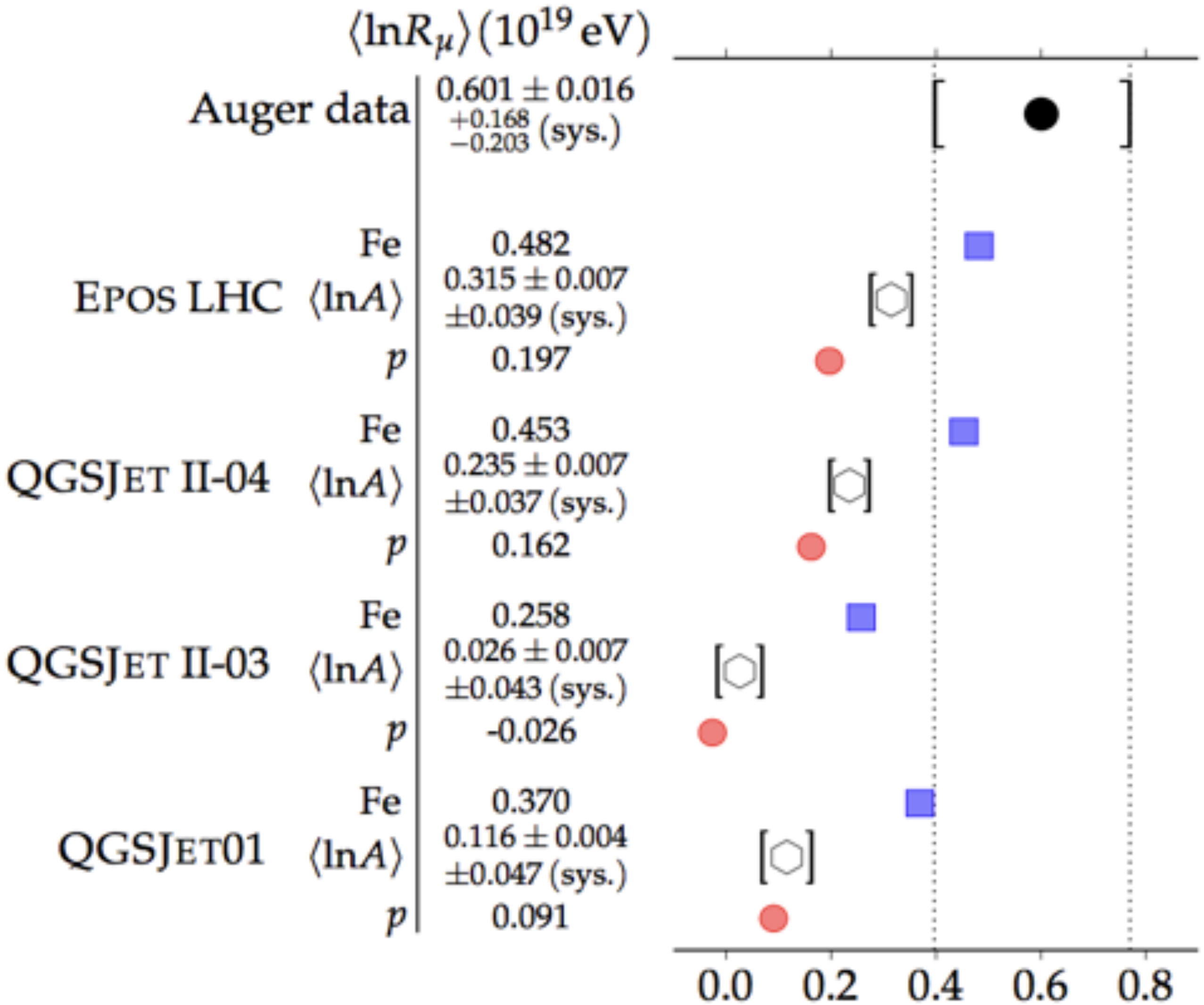


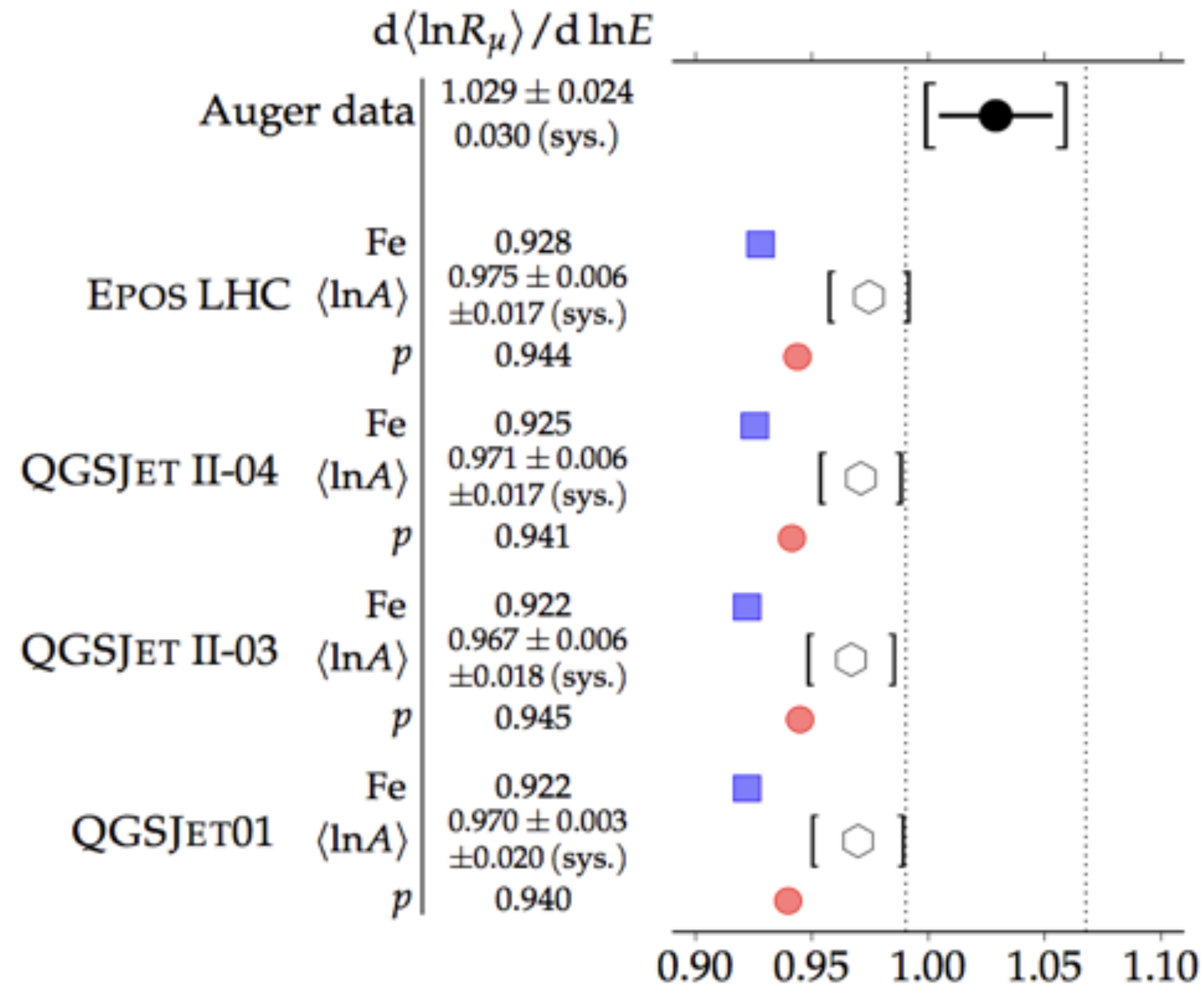
$\langle R_\mu \rangle$ higher than iron predictions

tension among the X_{max} and muon measurements

The Pierre Auger Collaboration, PRD 91 (2015) 032003; PRD 91 (2015) 059991

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)

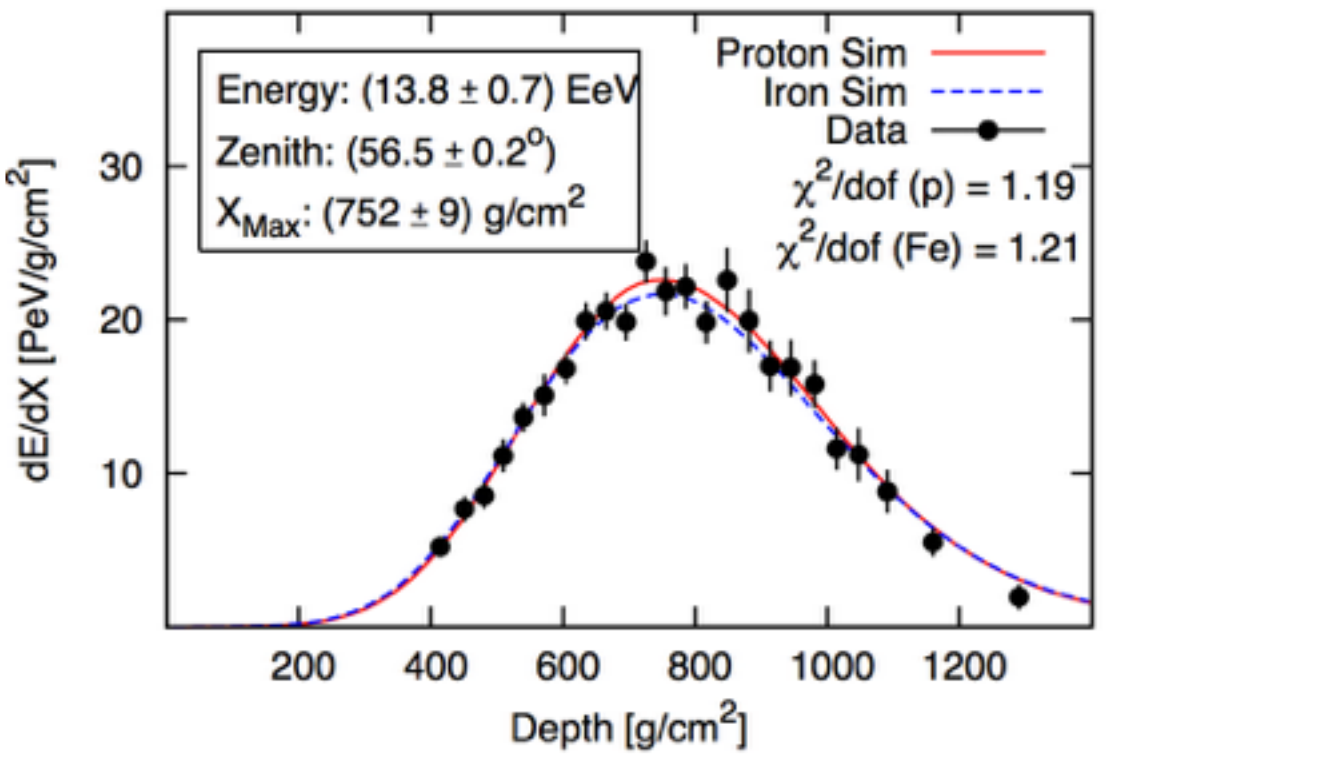
deviations from a constant proton (iron) composition observed at the level of 2.2 (2.6) σ

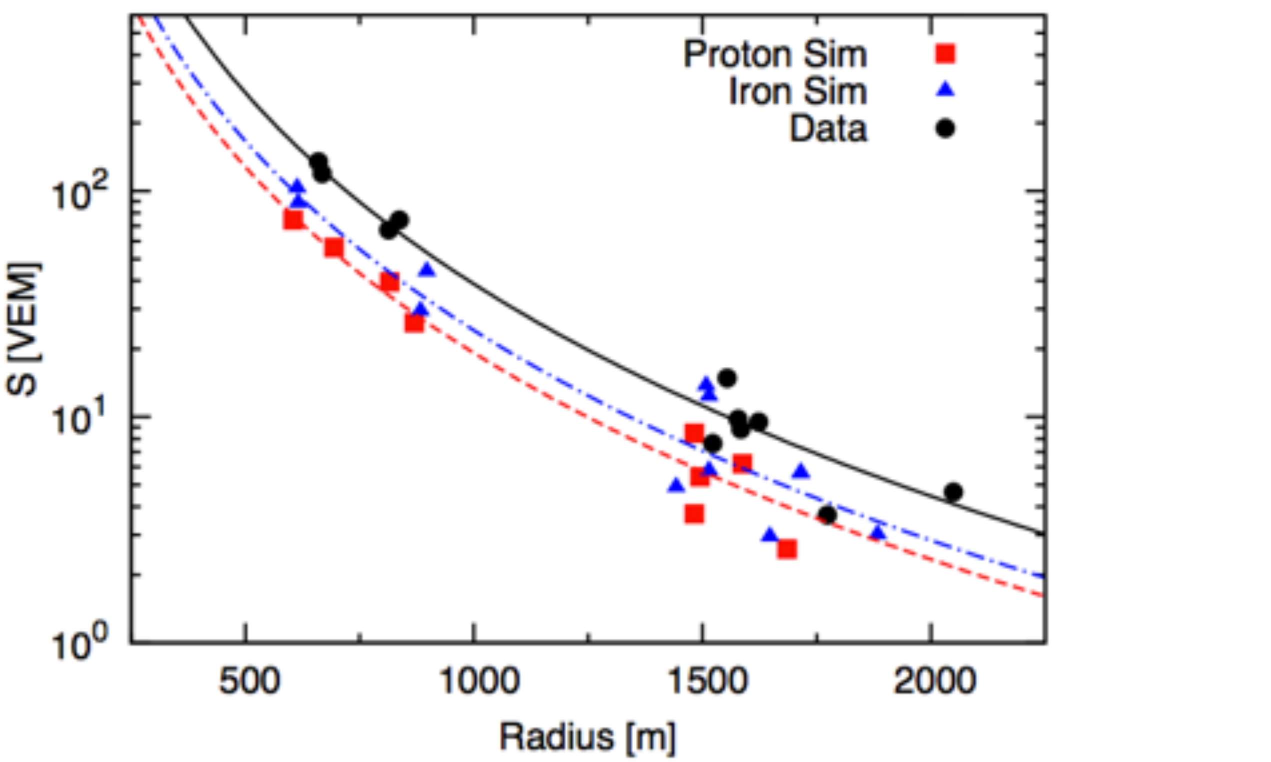
The Pierre Auger Collaboration, PRD 91 (2015) 032003; PRD 91 (2015) 059991

Muon studies with vertical hybrid events (0°,60°)

- MC events selected to match the measured longitudinal profile

- Ground signal components rescaled to fit data (lateral profile)



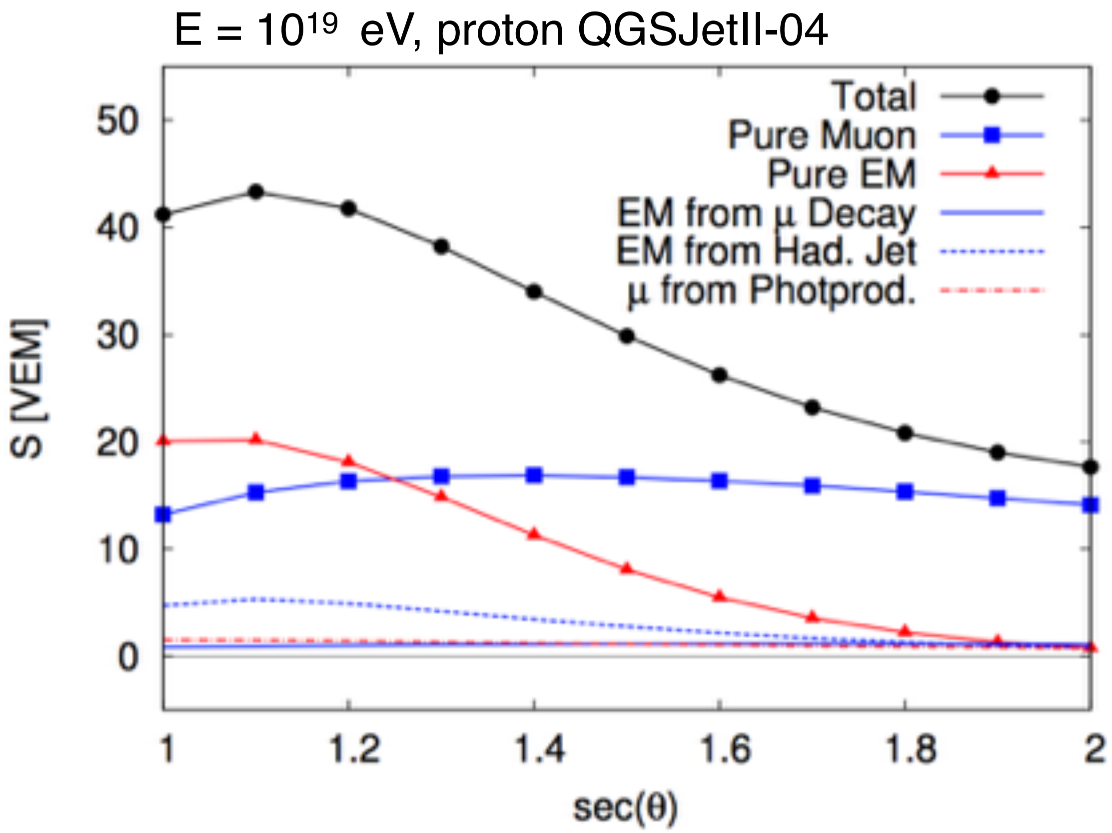


Rescaling factors:

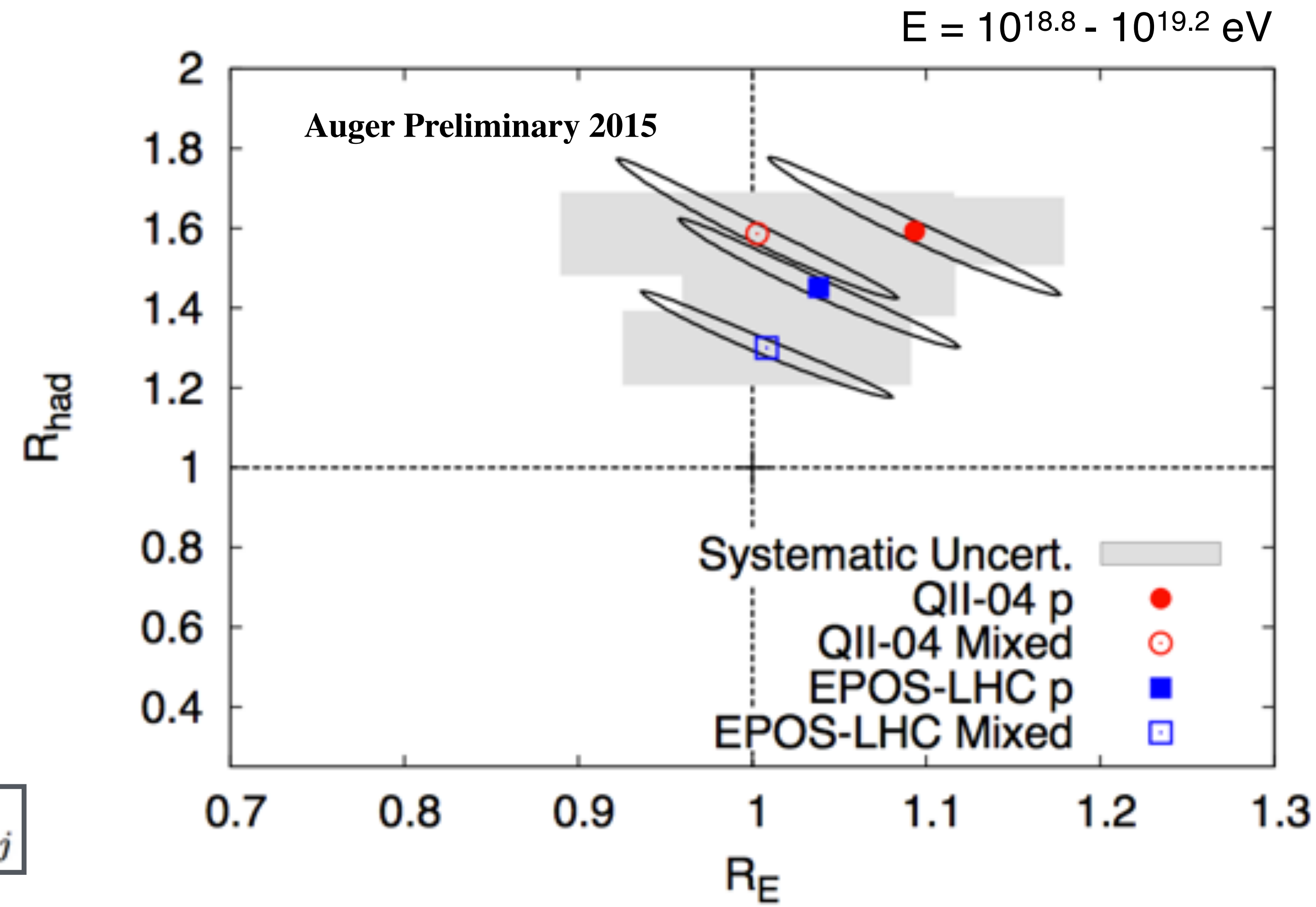
R_E → primary energy

R_{had} → hadronic contribution to the ground signal

Muon studies with vertical hybrid events (0°,60°)



$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\mathrm{had}}\, R_E^{\alpha}\, S_{\mathrm{had},i,j}$$



no energy rescaling is needed

the observed muon signal is a factor 1.3 to 1.6 larger than predicted by models best case for EPOS-LHC with mixed composition (minimum deviation of 1.9 σ)

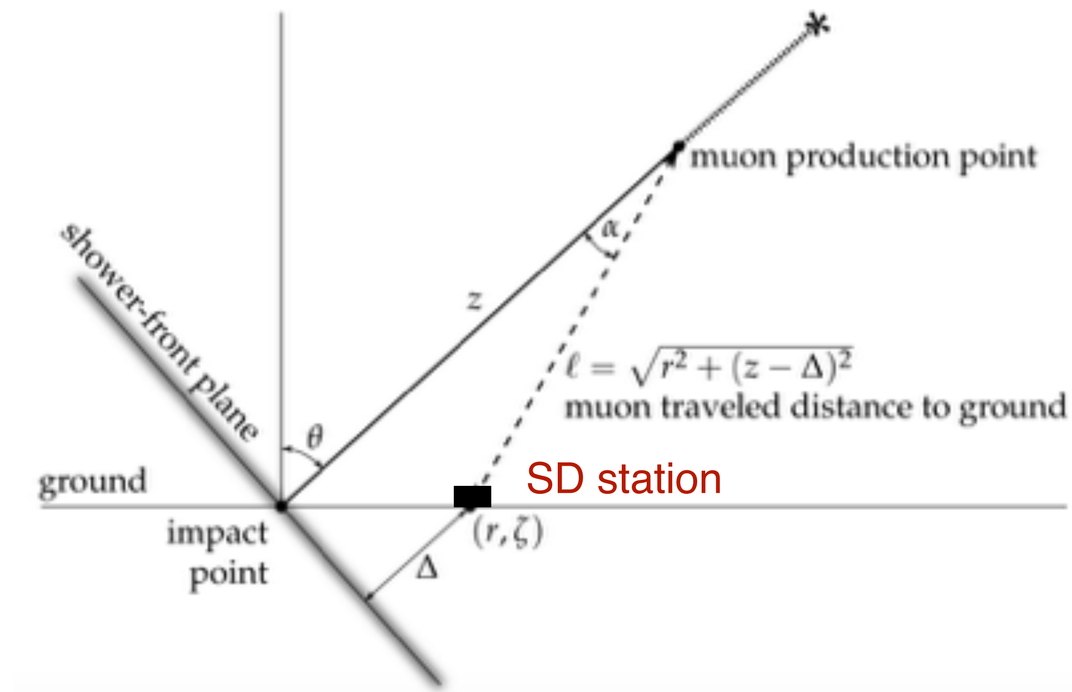
L. Collica for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

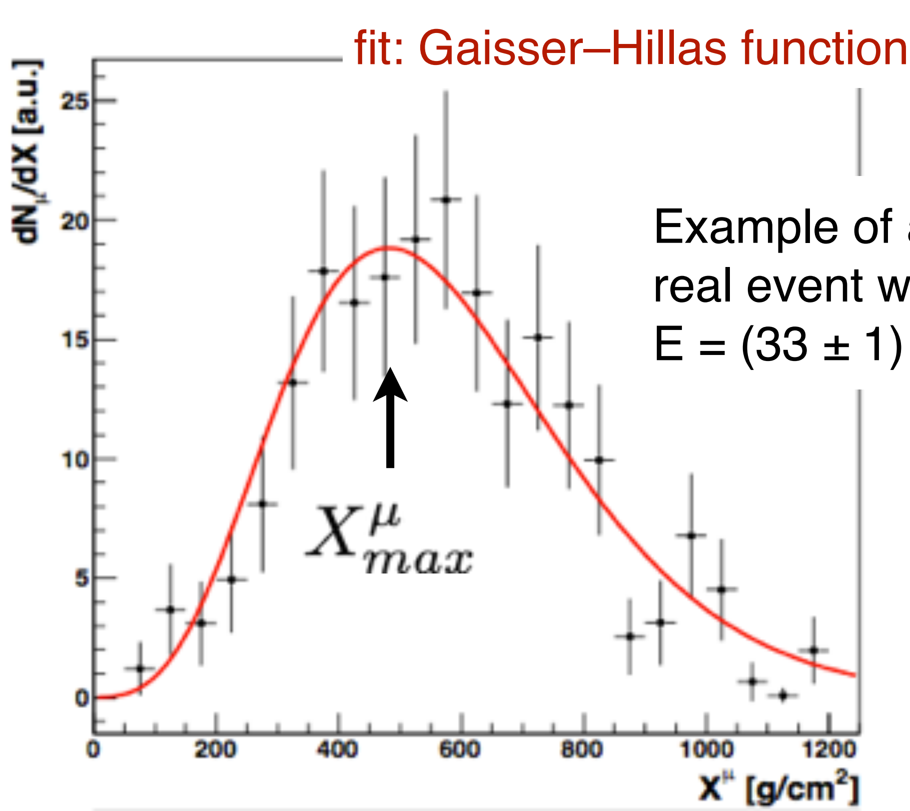
Muon Production Depth (MPD)

The muon longitudinal profile could be estimated from the muon arrival times at the ground

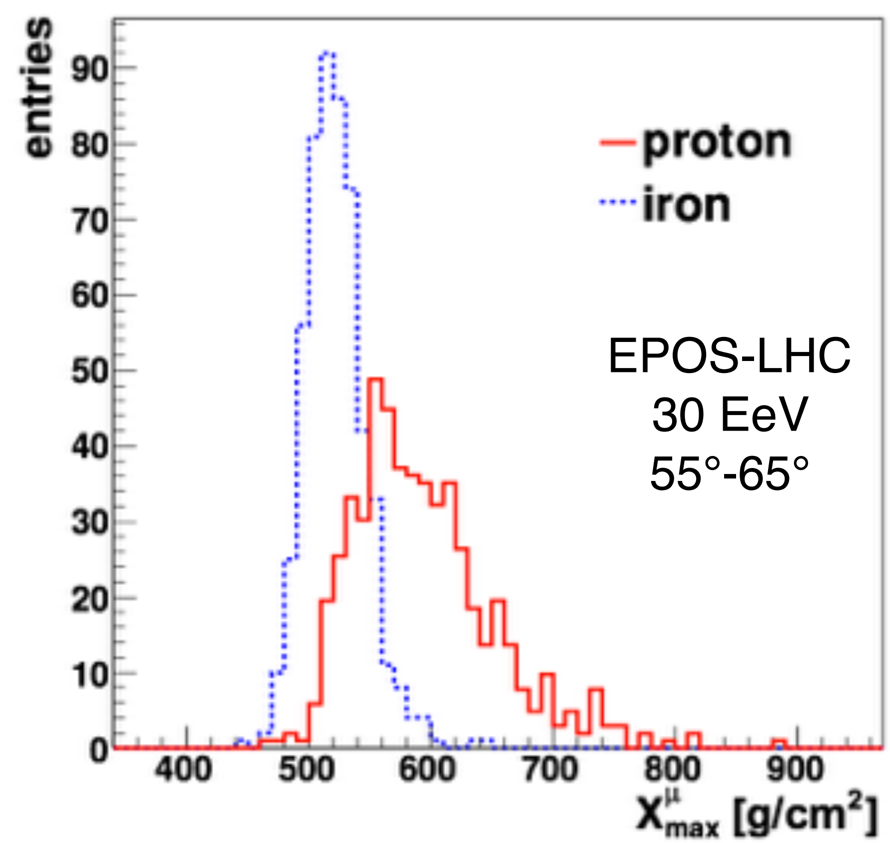
$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t-\langle t_\epsilon \rangle)} - c(t-\langle t_\epsilon \rangle)\right) + \Delta - \langle z_\pi \rangle$$

→ MPD $X^\mu = \int_z^\infty \rho(z')dz'$





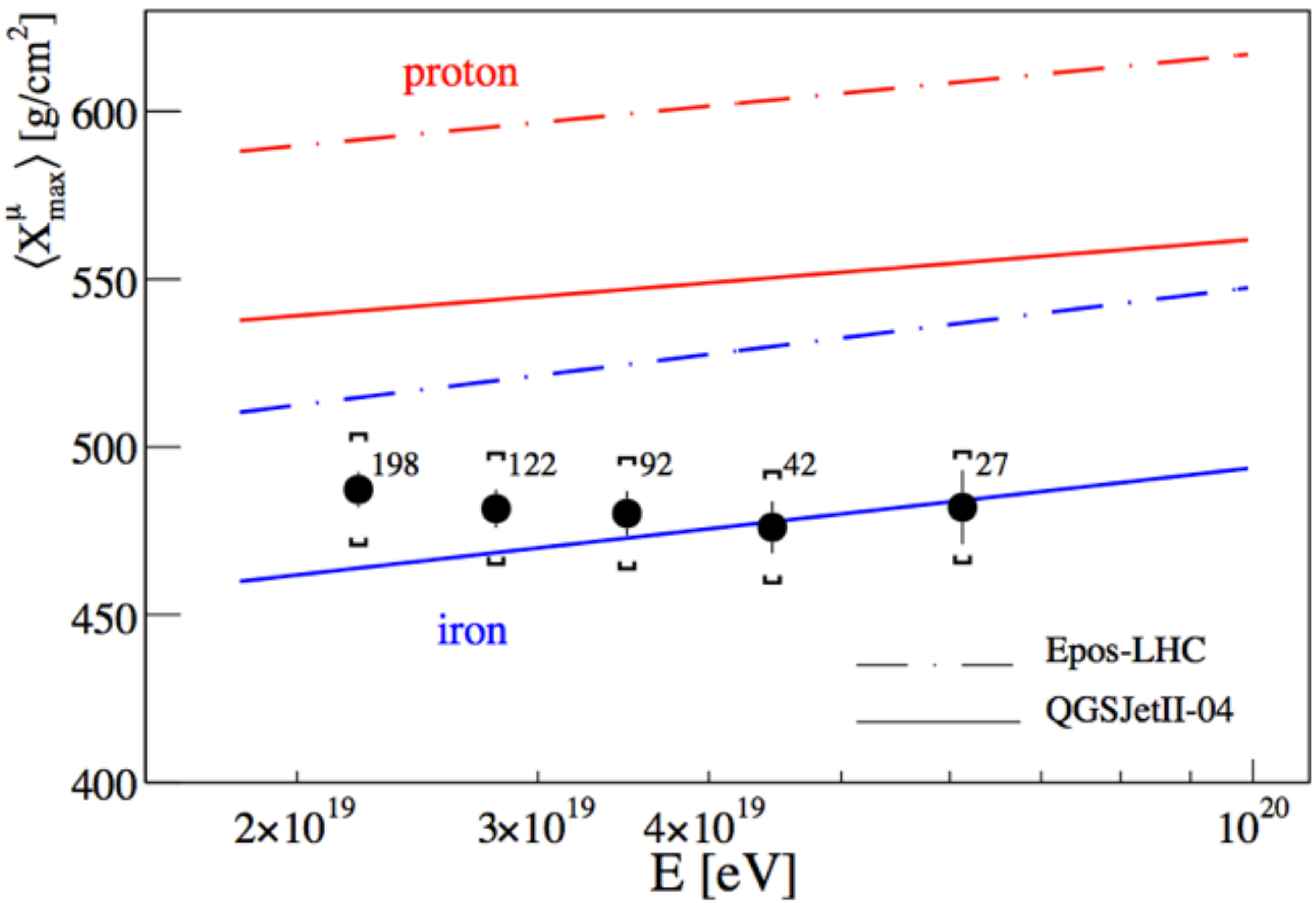
Example of a real event with:
E = (33 ± 1) EeV



Muon-rich stations:

- zenith angles [55°,65°]
- distances from the core [1700 m, 4000 m]

X^{μ}_{max} vs. energy

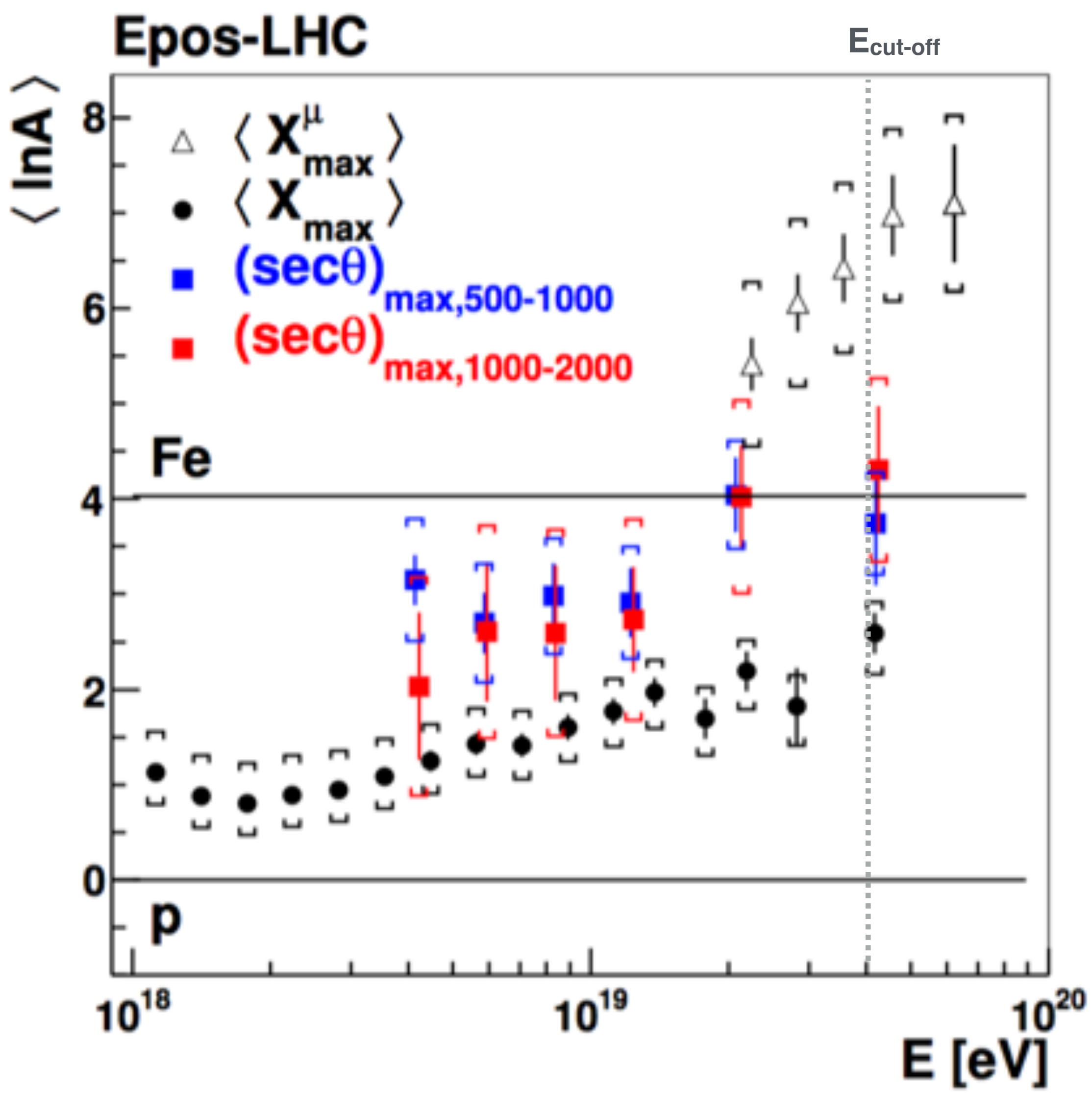


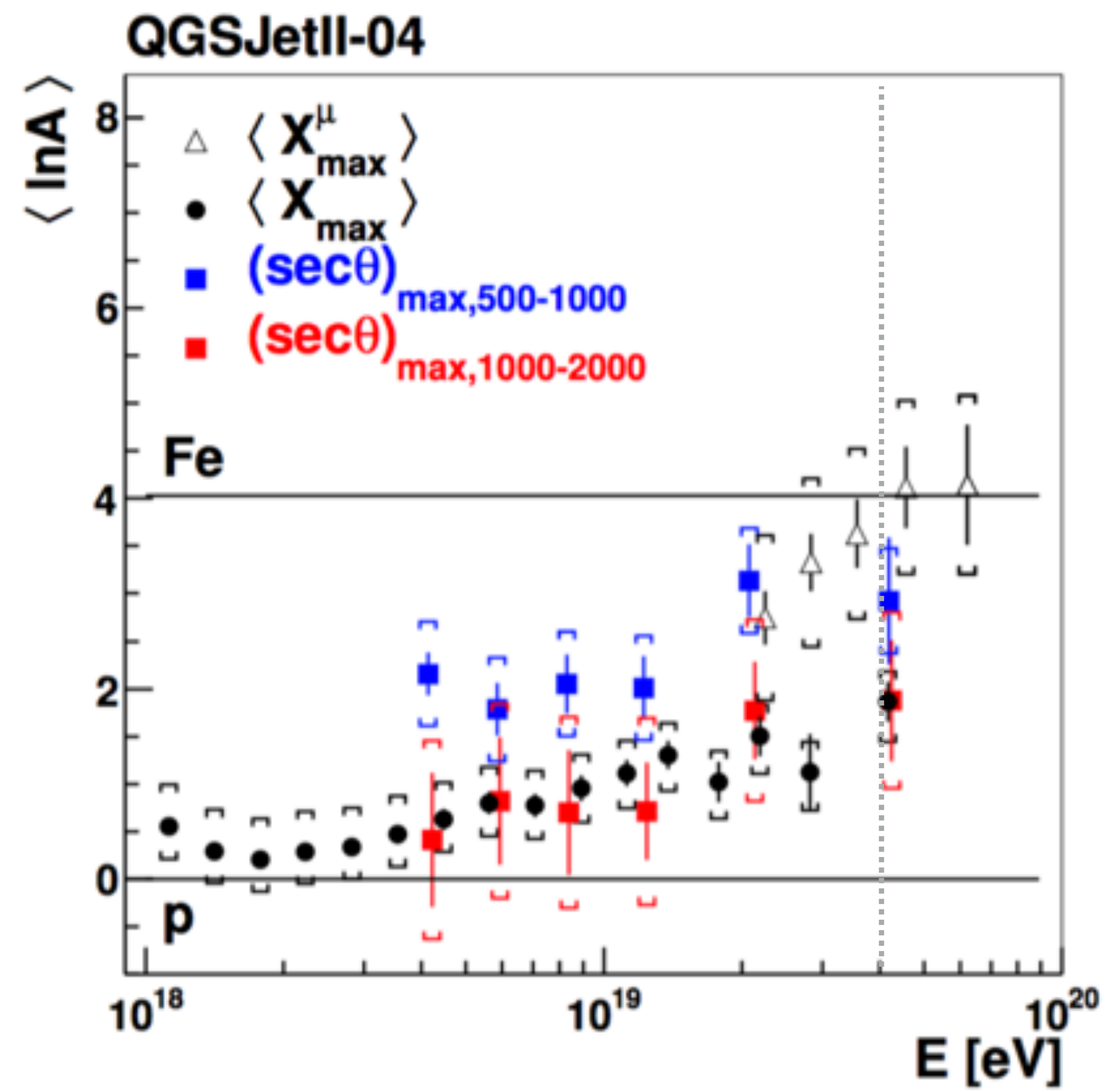
data bracketed by QGSJetII-04 predictions, below EPOS-LHC predictions

muonic elongation rate flatter than pure p or Fe in both models

The Pierre Auger Collaboration, PRD 90 (2014) 012012; PRD 92 (2015) 019903

Comparison of <lnA> from X_{max}, X^{μ}_{max} and $(\sec\theta)_{max}$





EPOS-LHC:
X^{μ}_{max} and X_{max} values incompatible at a level of > 6 σ
$(\sec\theta)_{max}$ consistent in the two distance ranges

QGSJetII-04:
X^{μ}_{max} and X_{max} values compatible within 1.5 σ
$(\sec\theta)_{max}$ not consistent in the two distance ranges

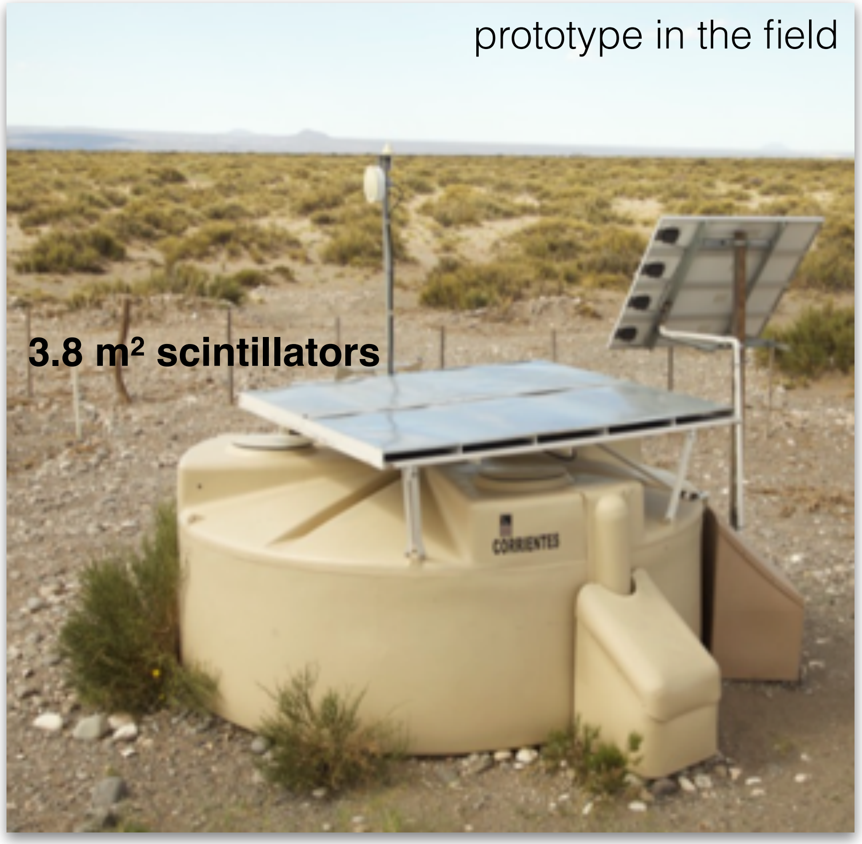
these results provide constraints on hadronic interaction models

The Pierre Auger Collaboration, PRD 93 (2016) 072006

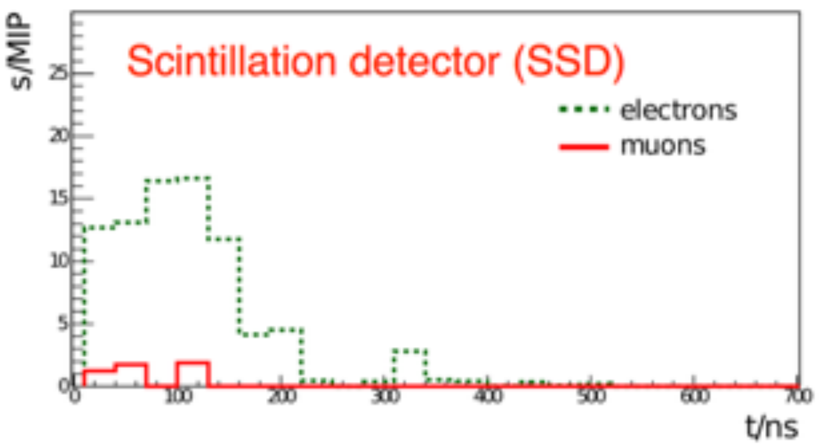
AugerPrime: the upgrade of the Pierre Auger Observatory

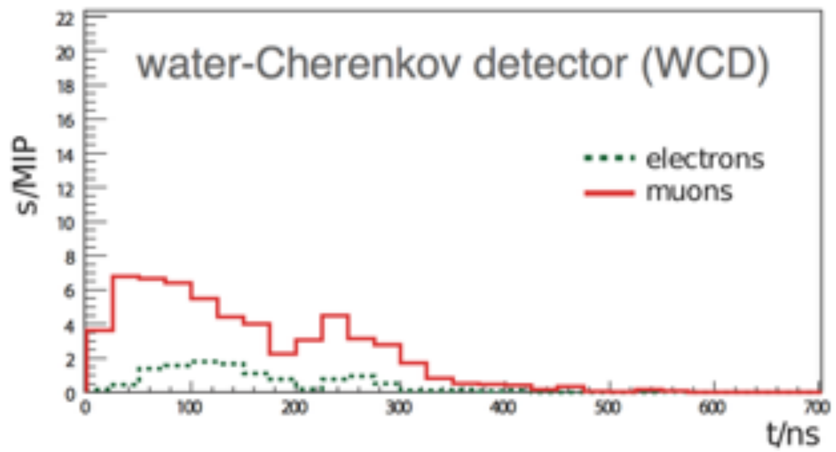
- Understand the origin of the flux suppression
- Do composition enhanced anisotropy studies
- Study EAS properties and hadronic interactions

Composition sensitivity at and above the suppression region is needed:



Scintillator (SSD) on top of a WCD:
complementarity of particle response used to discriminate EM and muonic components





$S_{\mu,WCD} = a\, S_{WCD} + b\, S_{SSD}$

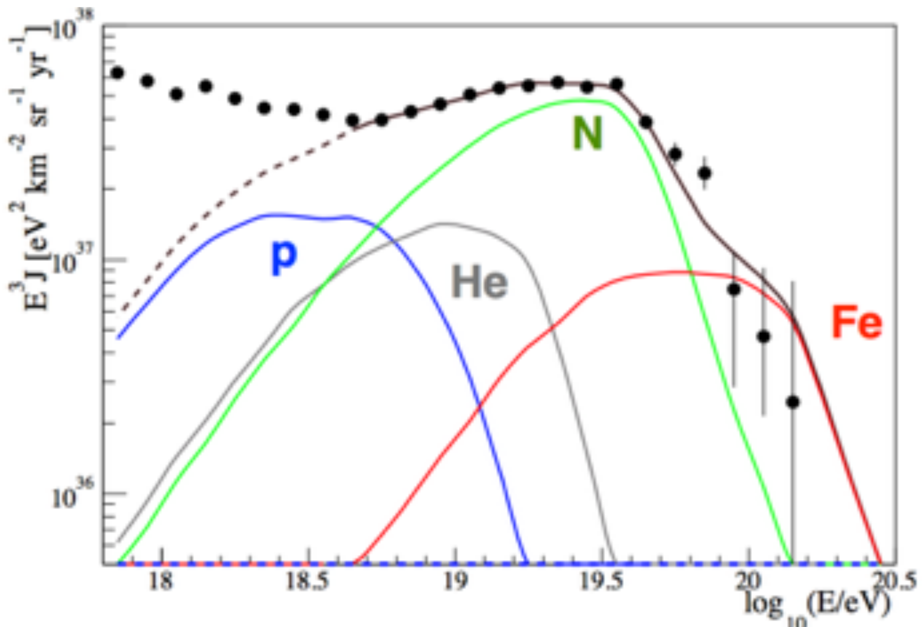
a and b from simulations, weak dependence on the primary type and energy

EA currently under construction
construction: 2017-2019
data taking up to 2024

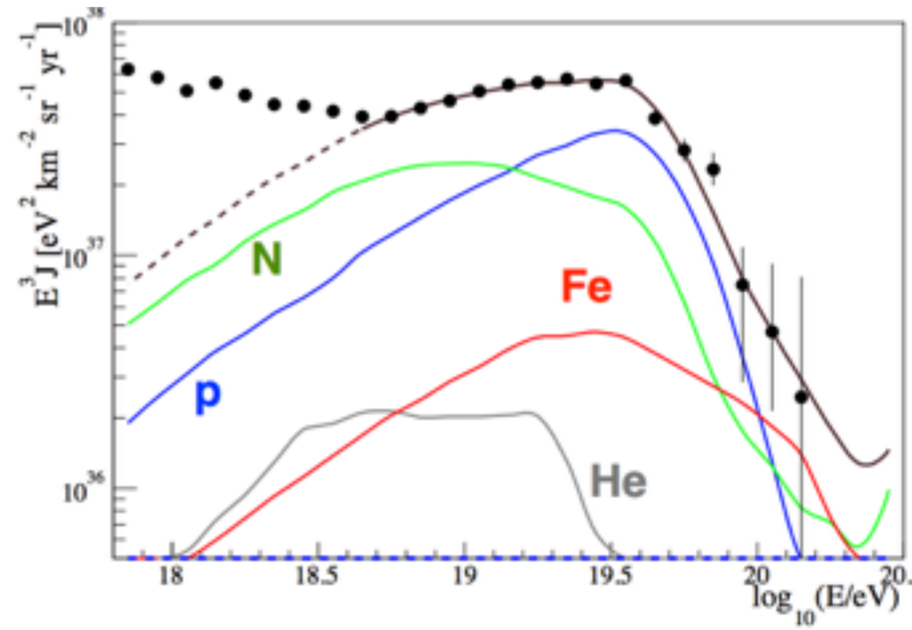
+ new electronics, underground muon detectors, extension of the FD duty cycle

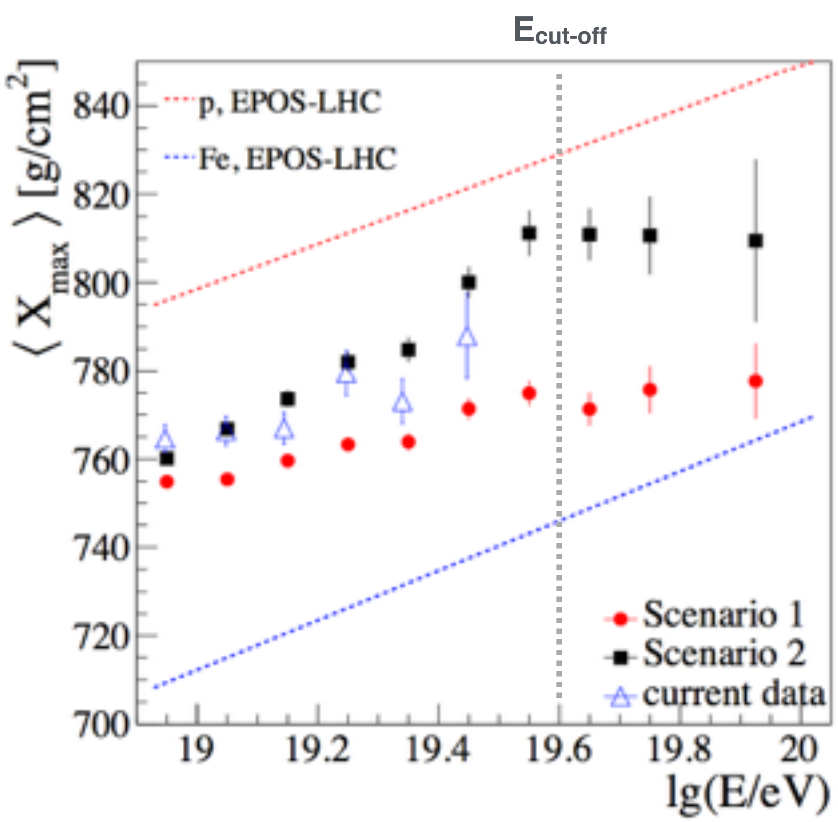
AugerPrime:
mass sensitivity and discrimination of scenarios

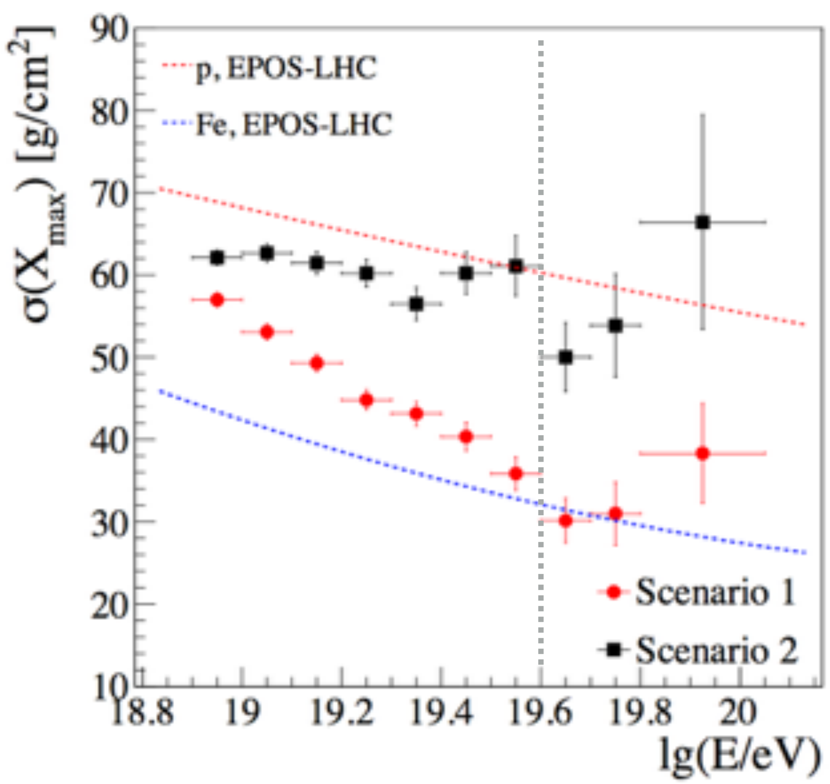
Scenario 1: no protons at high energy

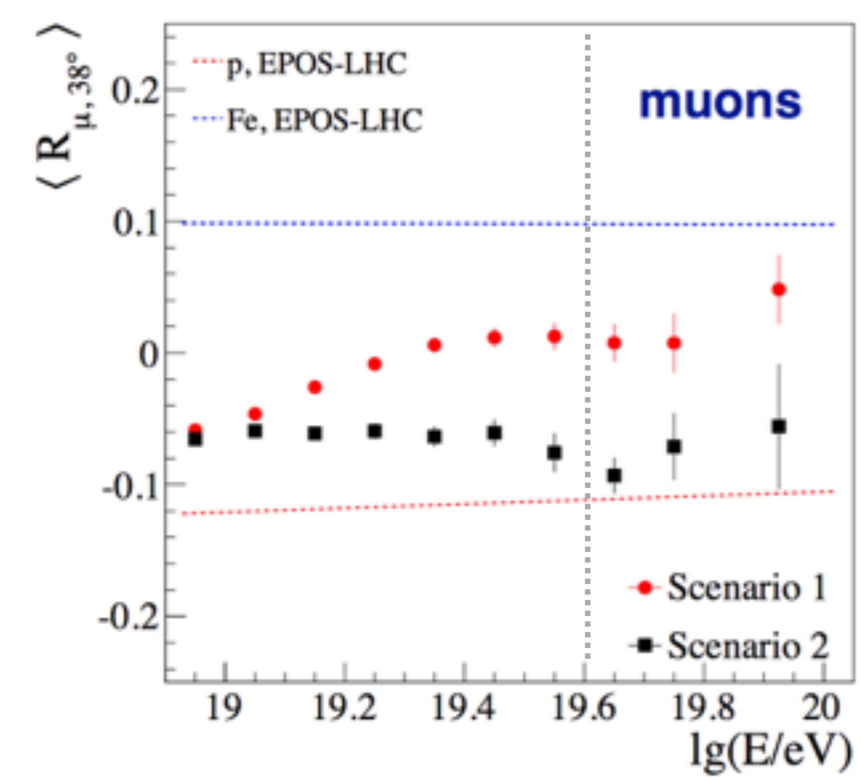


Scenario 2: scenario 1 with 10% protons added







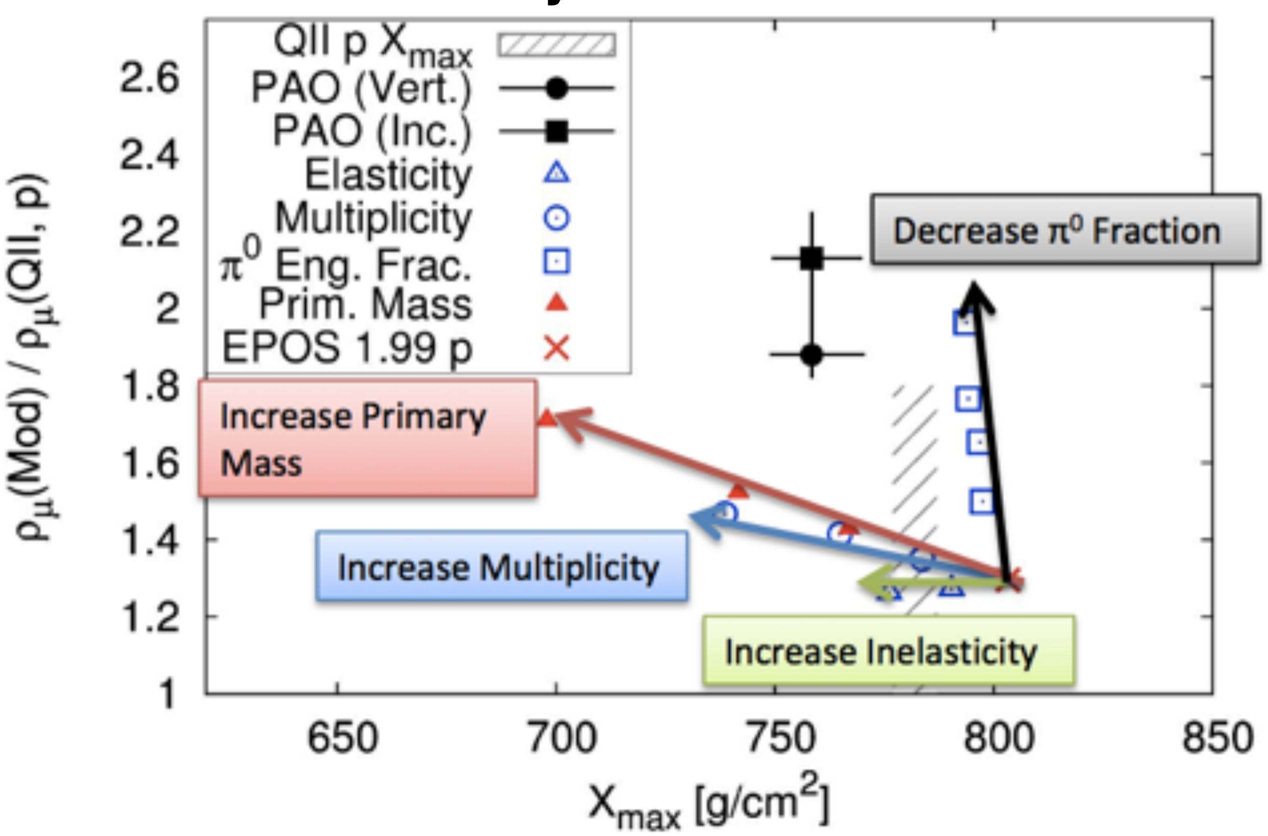


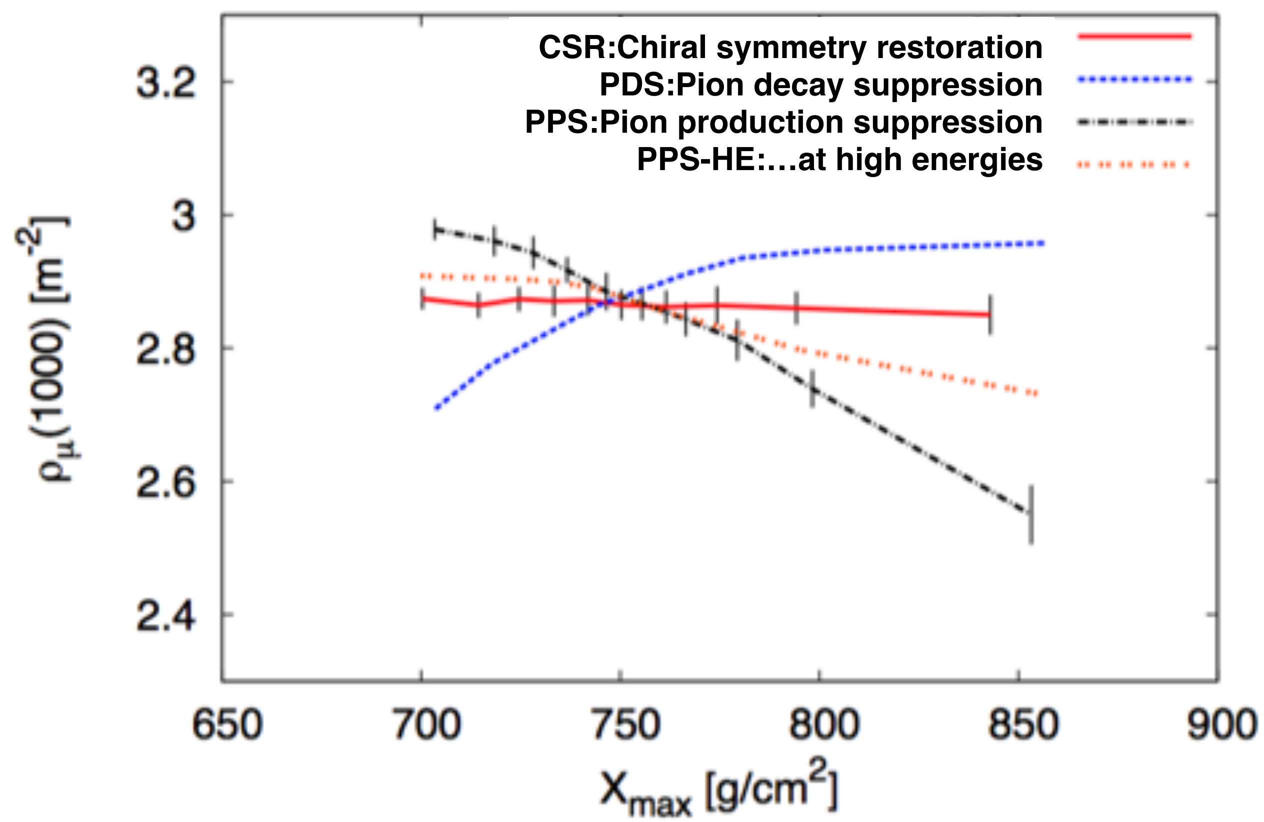
X_{max} and N_{μ} reconstructed from SD data only!

The Pierre Auger Collaboration, arXiv:1604.03637

AugerPrime: particle physics

Muon density vs. X_{max}





different scenarios of modified hadronic interactions can be distinguished if the event-by-event correlation of N_{μ} and X_{max} can be measured

J. Allen and G. Farrar (2014) arXiv1307.7131v1

The Pierre Auger Collaboration, arXiv:1604.03637

Summary

Mass composition:

- **elongation rate, X_{max}, $\sigma(X_{max})$**:
  mixed composition around and above the ankle
- **fits of X_{max} distributions:**
  less proton/more helium above 10^{19} eV, iron fraction is close to zero for all energies
- **azimuthal risetime asymmetry**:
  results in agreement with X_{max} studies, can be used to constrain models

Hadronic interactions:

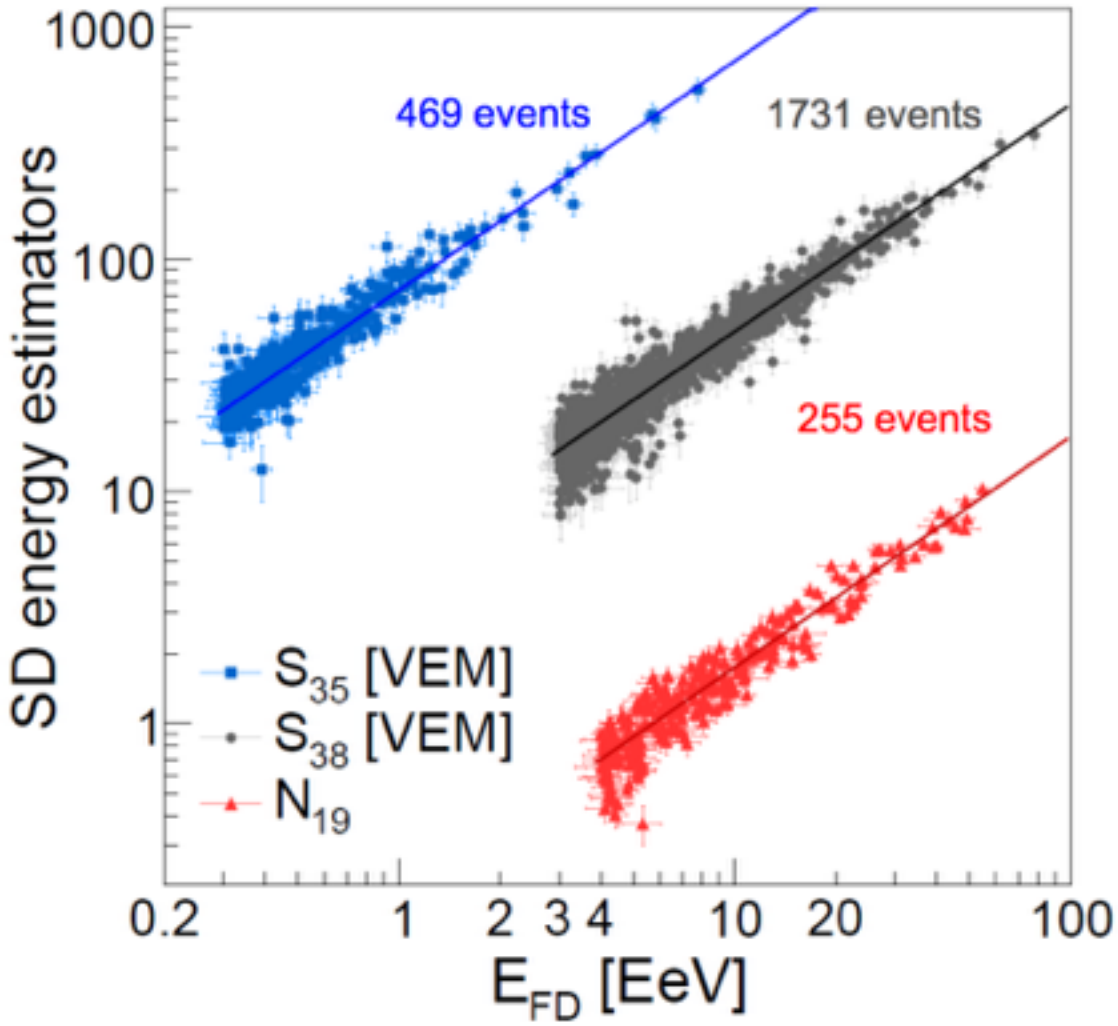
- **p-Air cross section:**
  consistent with a cross-section rising with energy
- **Number of muons:**
  significant muon deficit in the simulation, light composition disfavoured at 10^{19} eV
- **Muon production depth**:
  X^{μ}_{max} below prediction for iron EPOS-LHC, marginally compatible with QGSJetII-04
  results indicate that the muon component is not well described in models

Future: AugerPrime will extend the composition measurements up to 10^{20} eV

Please check arXiv:1509.03732 for the complete list of recent Auger results!

backup slides

Energy calibration at Auger

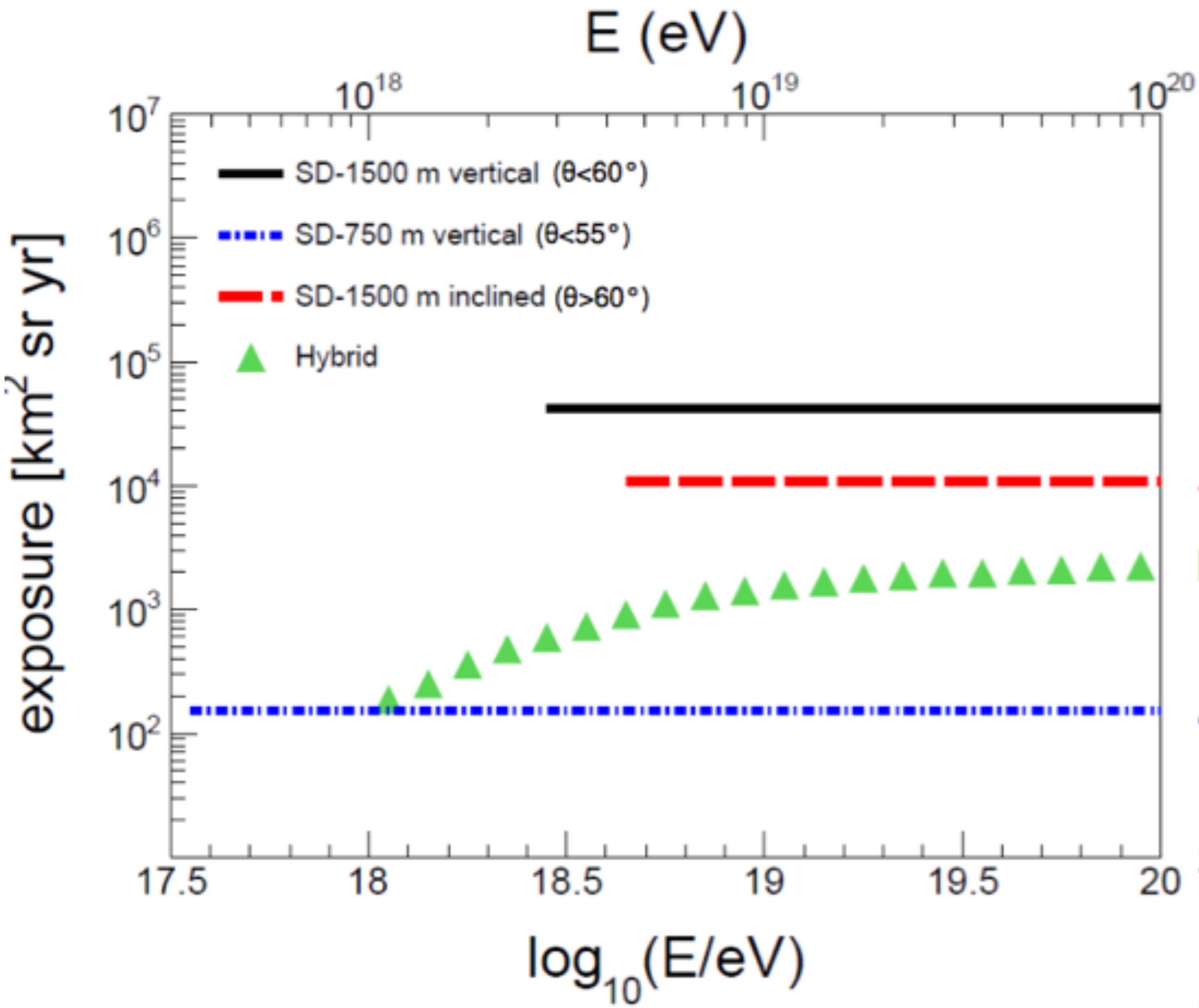


Calibration function : $E_{\rm FD} = A\,(\hat{S})^B$

- SD-1500 m "vertical" (S_{38}):
  - A = (0.1871± 0.004) EeV
  - B = 1.023 ± 0.006
  - energy resolution (E > 3 EeV)= (15.3 ± 0.4)%
- SD-1500 m "inclined" (N_{19}):
  - A = (5.71± 0.09) EeV
  - B = 1.01 ± 0.02
  - energy resolution (E > 4 EeV)= (19 ± 1)%
- SD-750 m (S_{35}):
  - A = (12.87± 0.63) PeV
  - B = 1.013 ± 0.013
  - energy resolution (E > 0.3 EeV) = (13 ±1)%

Systematic uncertainty on energy scale	**14%**
Fluorescence yield	3.6%
Atmosphere	3.4-6.2%
FD calibration	9.9%
FD profile reconstruction	6.5-5.6%
Invisible energy	3.0-1.5%
Stability of energy scale	5%
…..	

Auger exposure



Exposure [km² sr yr]

Jan 2004 - Dec 2014:	42500
Jan 2004 - Dec 2013:	10900
Nov 2005 - Dec 2013:	1500 at 10 EeV
Aug 2008 - Dec 2014:	150

SD: based on geometrical calculation

Hybrid: based on time-dependent MC simulations

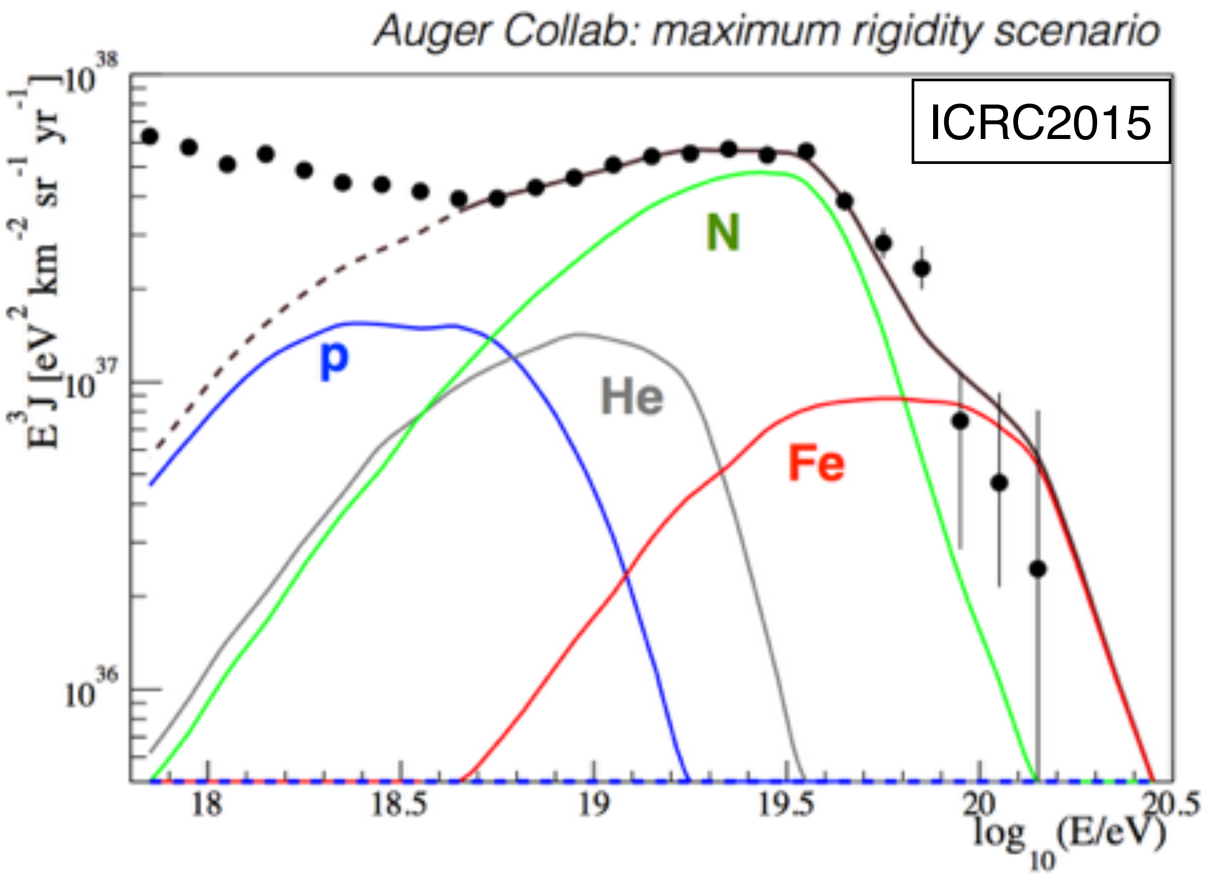
Interpretation of the Auger Spectrum

Propagation Scenario: UHECR interaction with the cosmic microwave background (CMB)

GZK effect: for distances ≥ 50 Mpc only protons and iron nuclei survive at UHECR energies a two components composition is assumed

Source Scenario: we may observe the upper-limit of the accelerator power $E_{max} = Ze(v/c)RB$

(Simple) Model of UHECR to reproduce the Auger spectrum and X_{max} distributions at the same time



best fit:

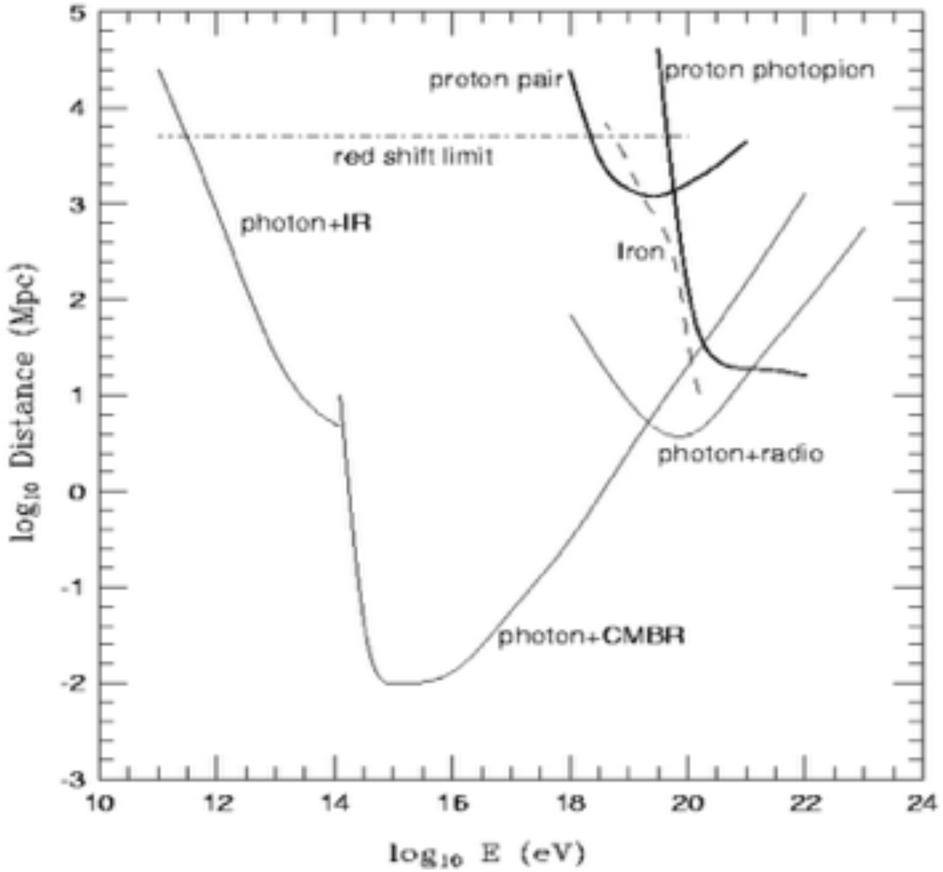
SPG prop. model, EPOS-LHC air interactions

Interpretation:

model scenario without GZK preferred, many alternative scenarios

crucial to know the proton contribution at UHE

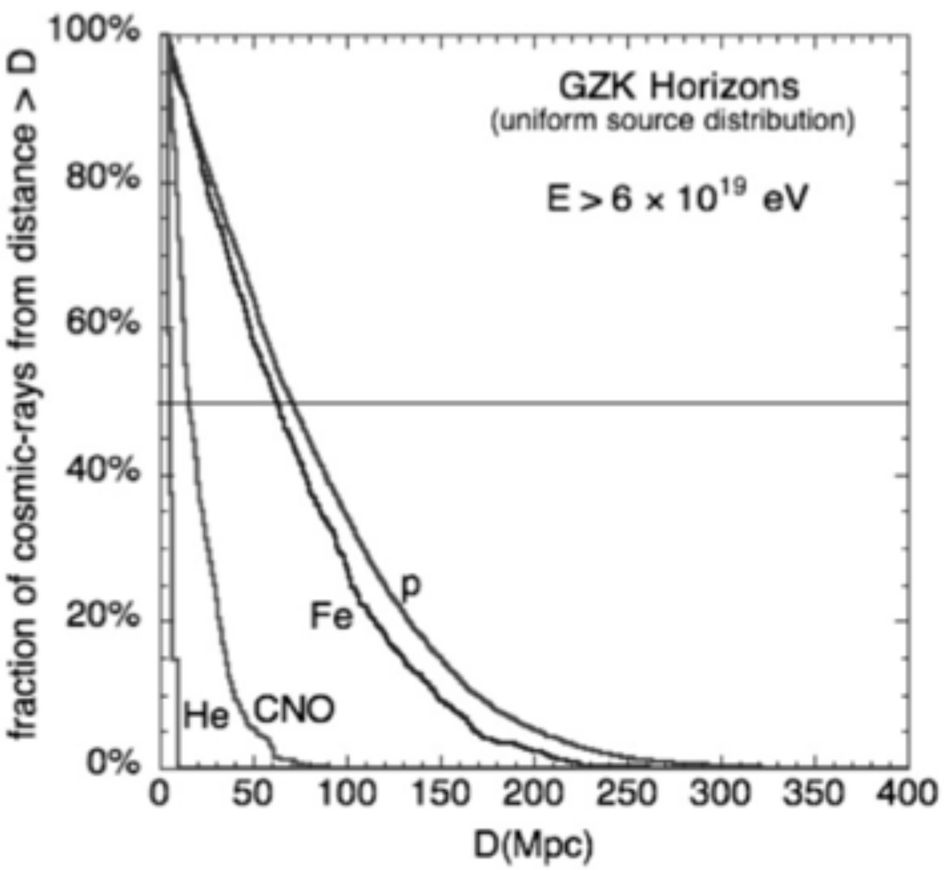
GZK effect



Greisen Zatsepin Kuz'min effect (1966): interaction with the cosmic microwave background

protons:

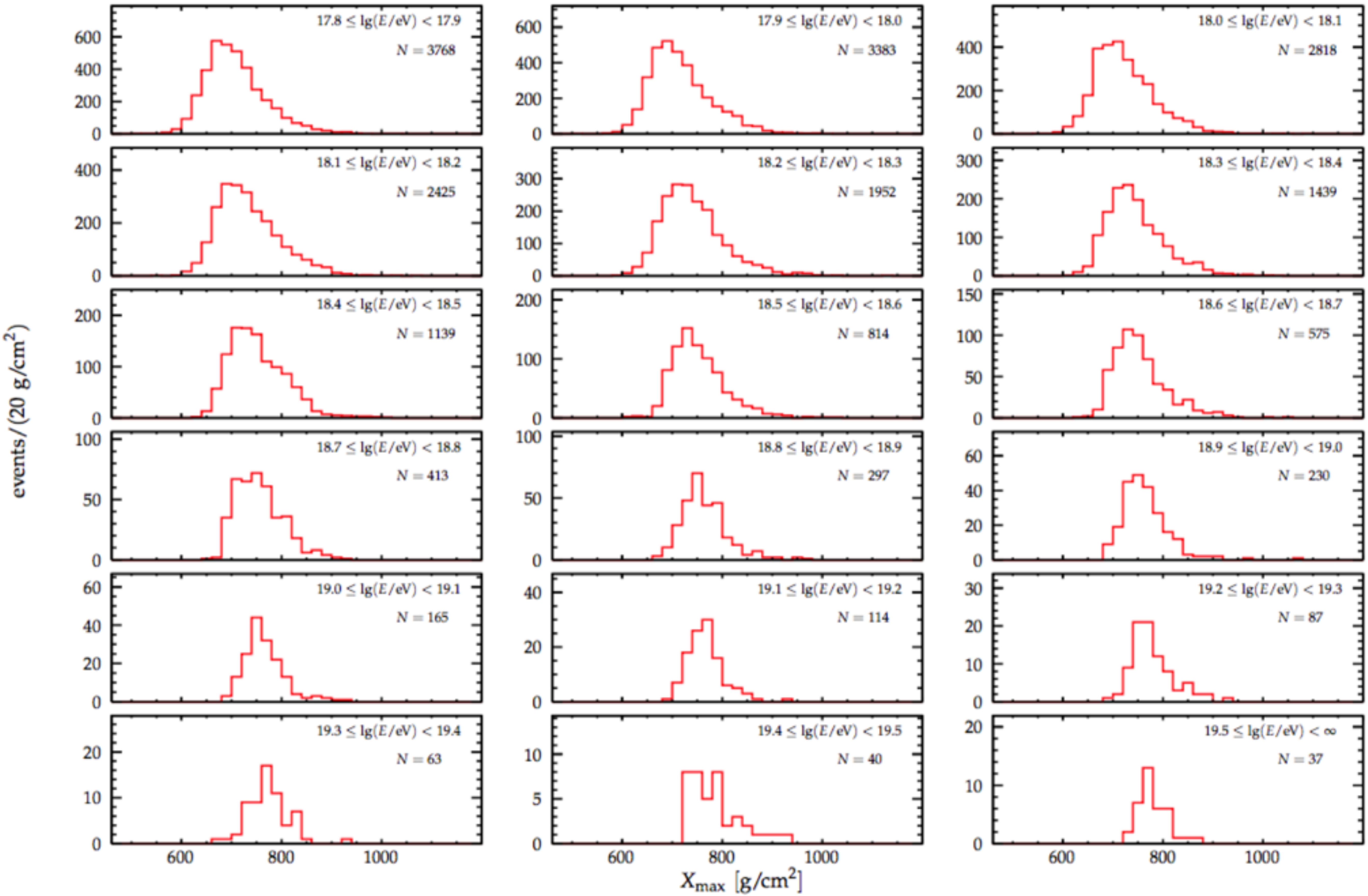
$$p + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$
$$p + \gamma_{CMB} \rightarrow p + \pi^{0}$$
$$p + \gamma_{CMB} \rightarrow n + \pi^{+}$$



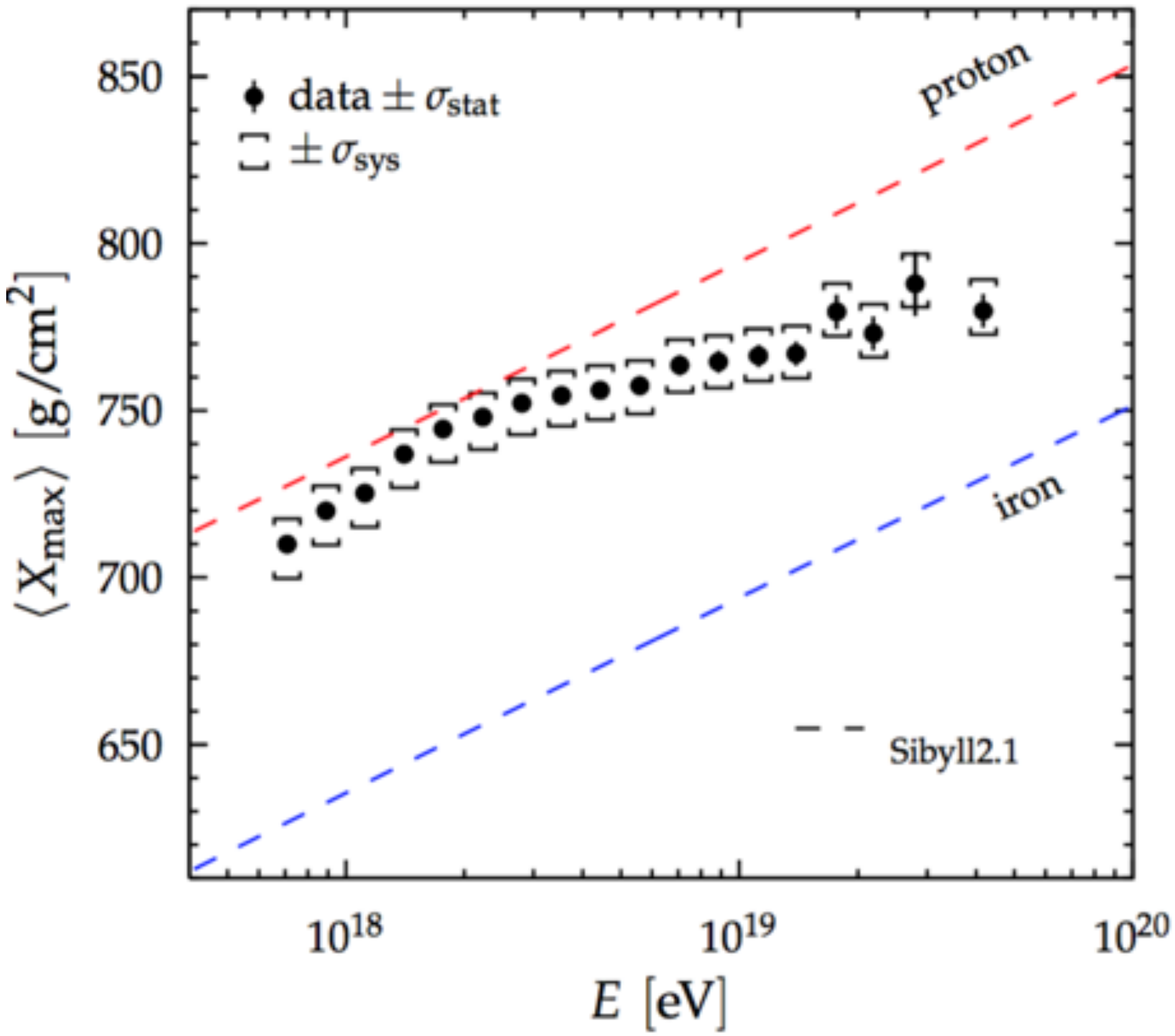
nuclei:
photo-disintegration and pair-production on CMB (RB IR)

“horizon” (p and iron) ~ 100 Mpc (~10^{20} eV)

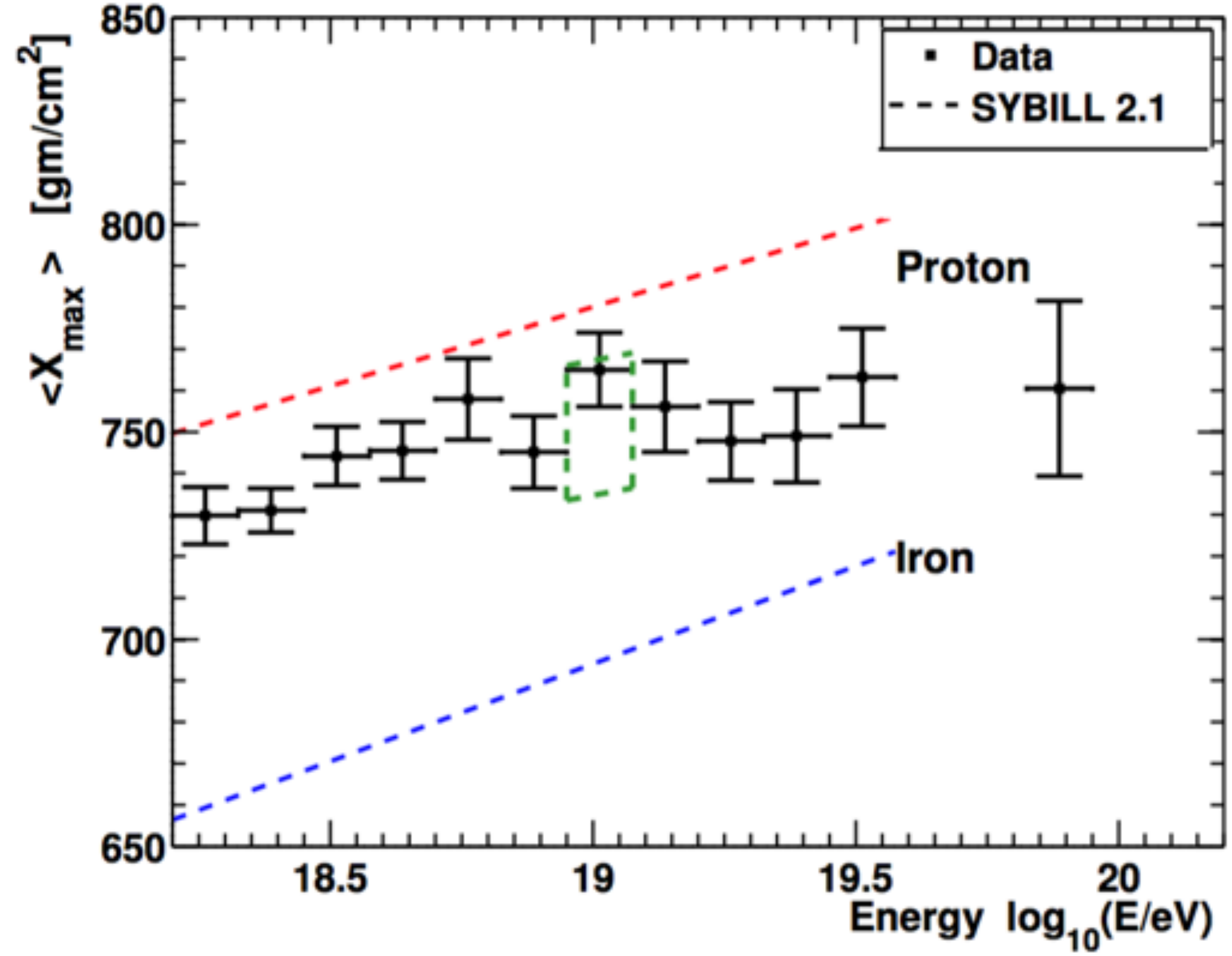
X_{max} distributions



X_{max}: Auger vs. TA



Pierre Auger Coll., PRD **90** (2014) 12, 122005



Telescope Array Coll., APP **64** (2014) 49

Minimize bias

Unfolded <Xmax>

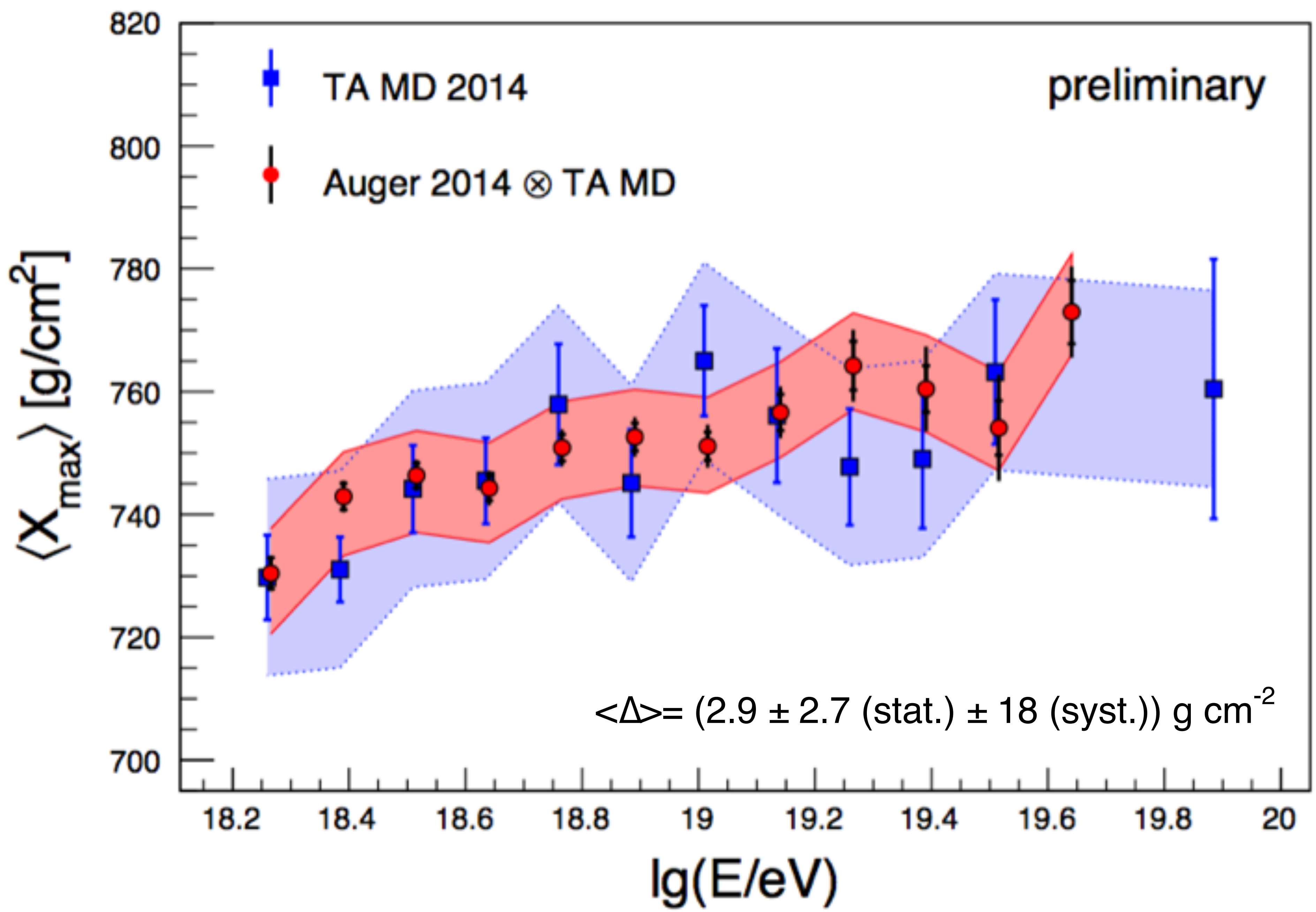
Simulation as generated

Maximize statistics

Measured <Xmax>

Simulation includes detector

X_{max}: Auger vs. TA

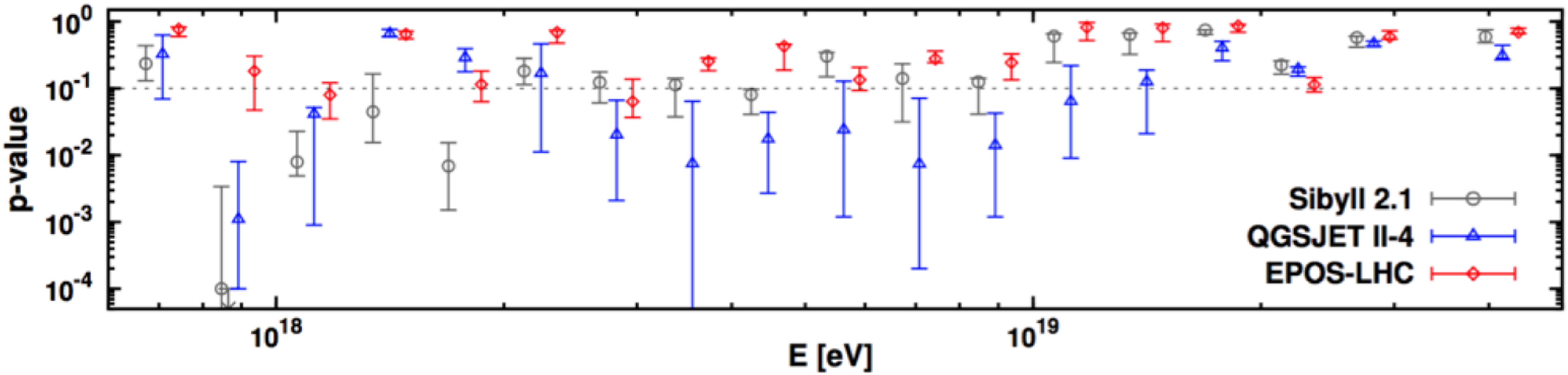


The two results are in good agreement within systematic uncertainties

TA cannot distinguish between pure proton or mixed composition with the current level of uncertainty

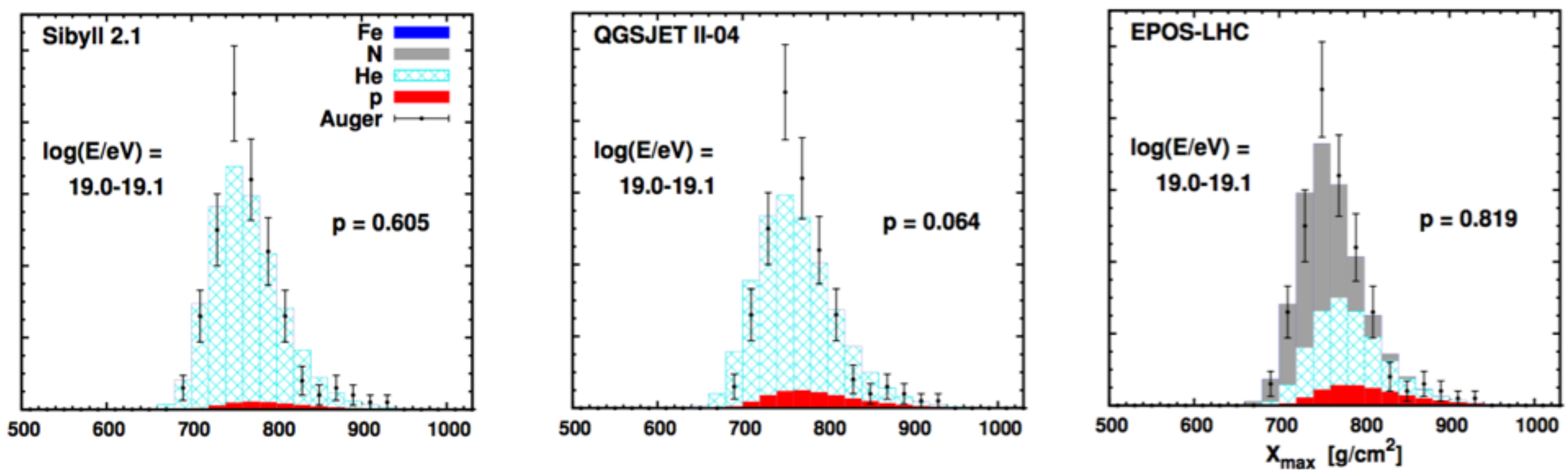
Abundances fits

EPOS-LHC fits data the best

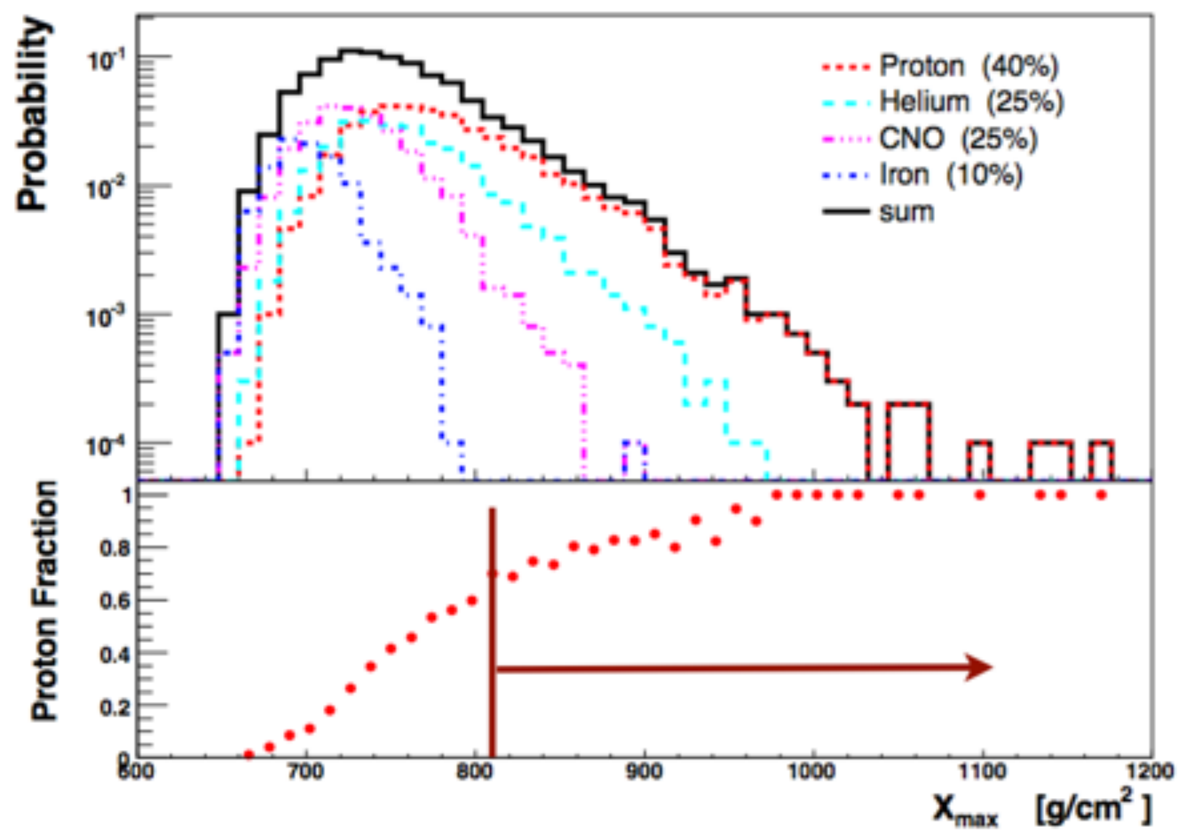


QGSJetII-04 produces poor fits for most of the energies

in particular distributions are too wide, in line with conclusions about $\sigma^2(\ln A) < 0$



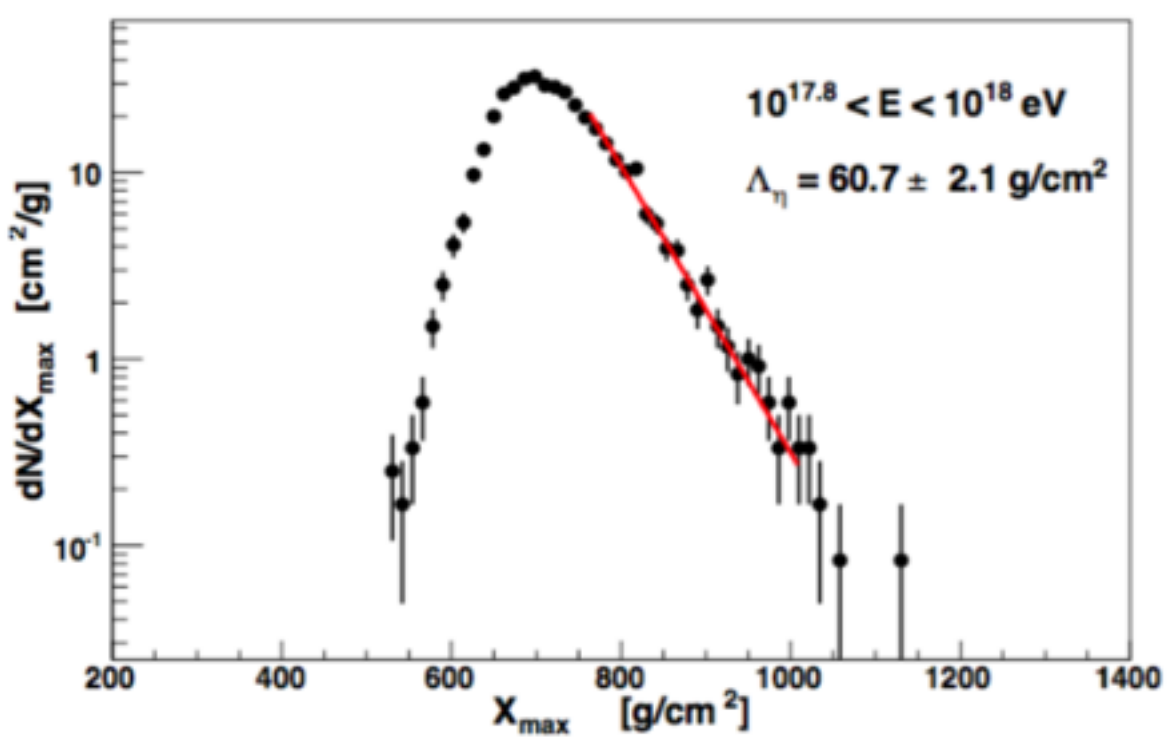
Measurement of UHE p-Air cross section

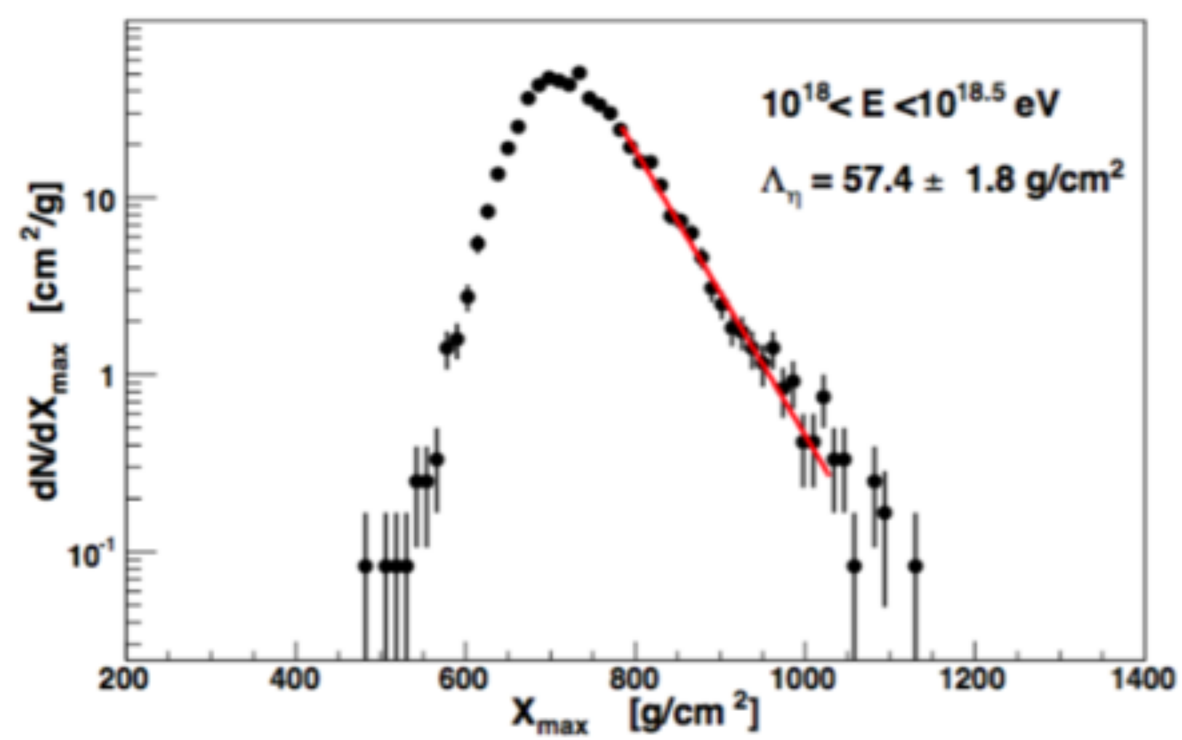


Example of distribution of X_{max} for mixed composition

Only deep showers are used in analysis to enhance proton fraction in data sample

Tail of X_{max} distribution:

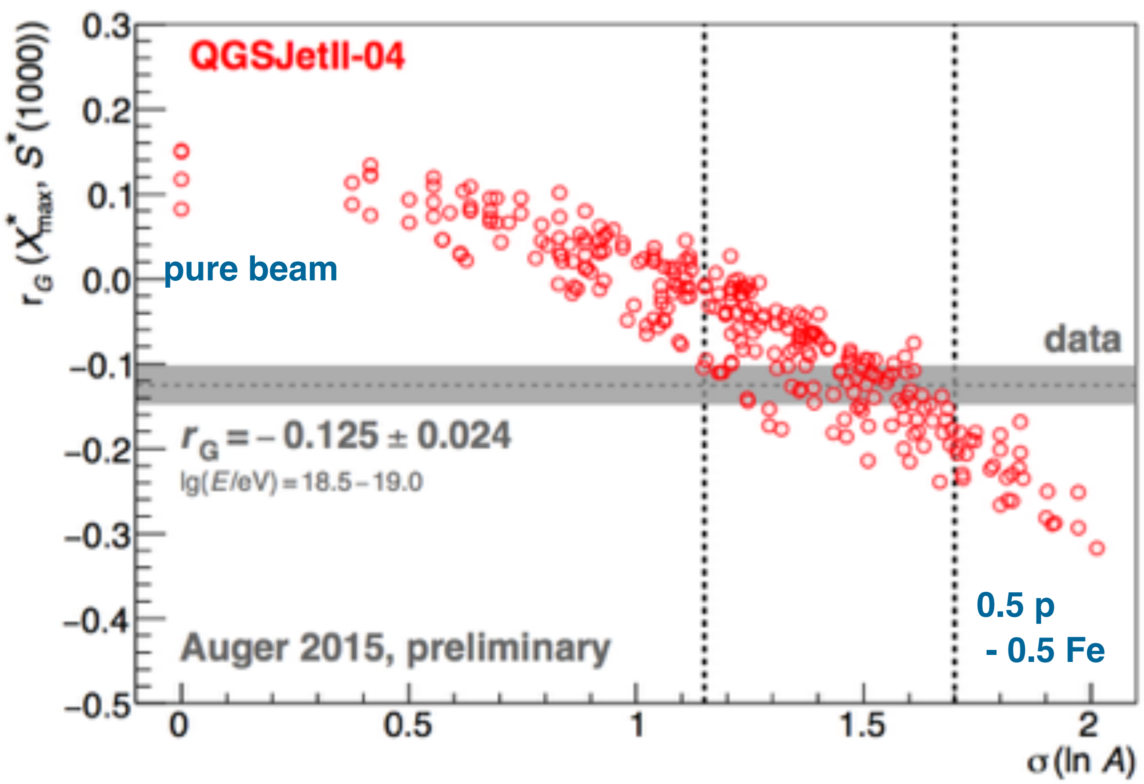


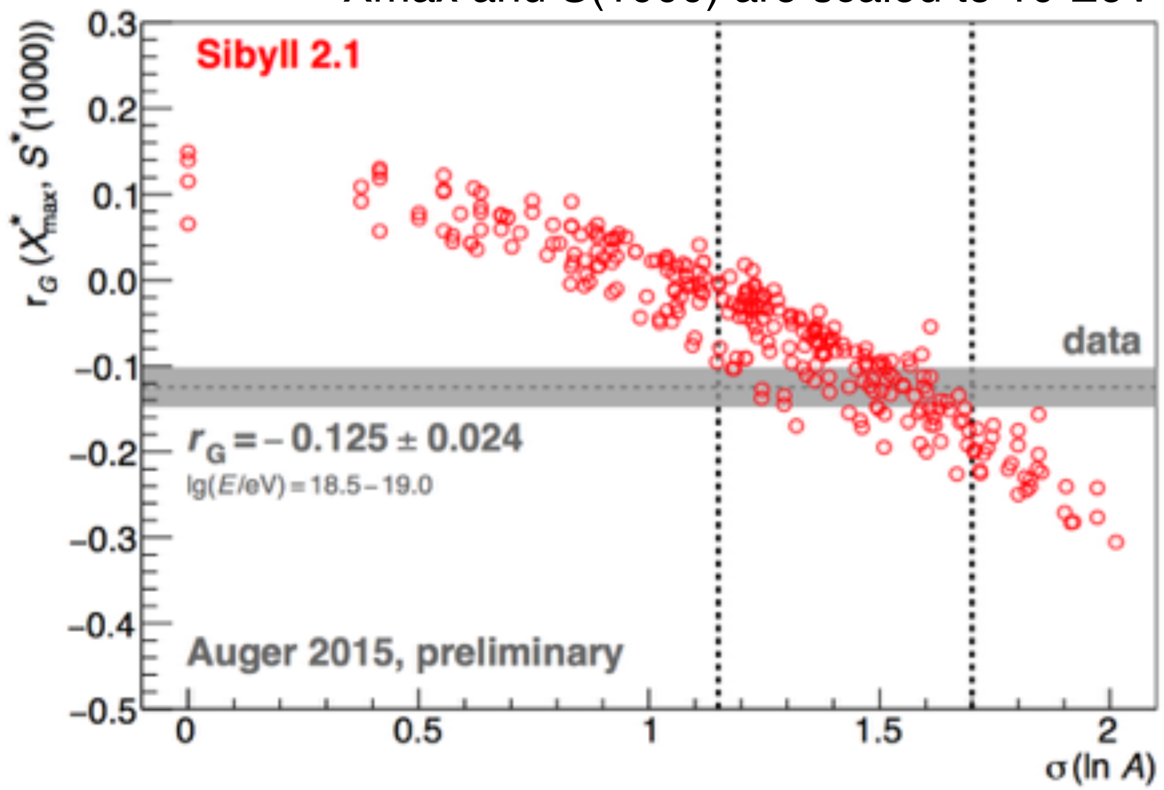


Correlation of ground signal with X_{max}

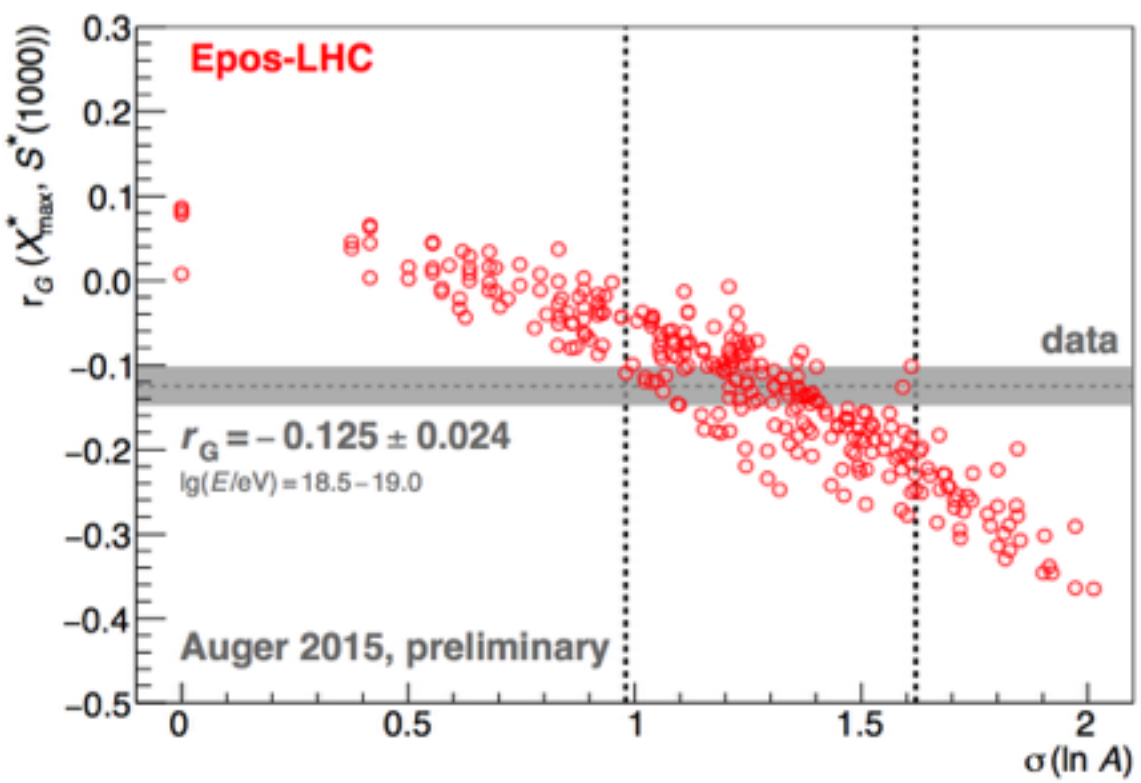
heavier nuclei produce showers with smaller X_{max} and larger signal at the ground (more muons)

Xmax and S(1000) are scaled to 10 EeV





Pure compositions ⇒ correlation > 0



difference to pure beams is > 5σ:
the primary composition around the “ankle” is mixed

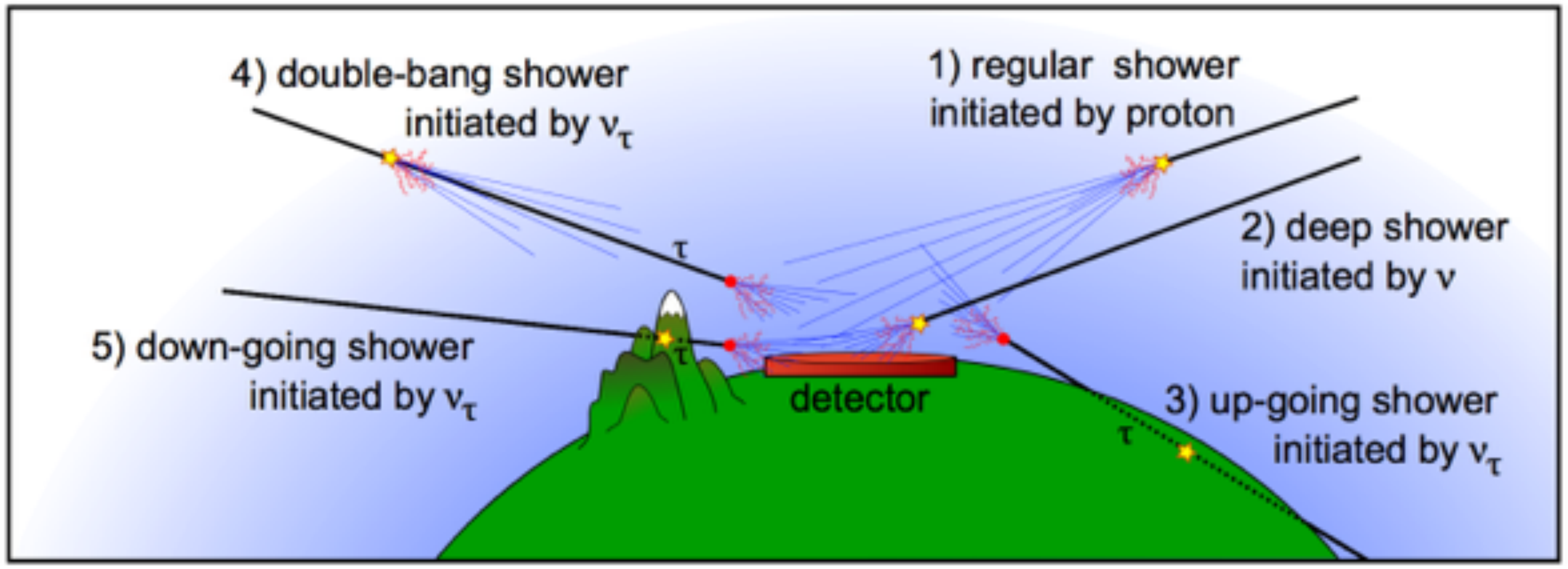
data are compatible with 1.0< σ(ln A) <1.7

results are robust against experimental uncertainties on X^*_{max} and $S^*(1000)$ and moderate modifications of hadronic interactions

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

UHE neutrino and photon searches

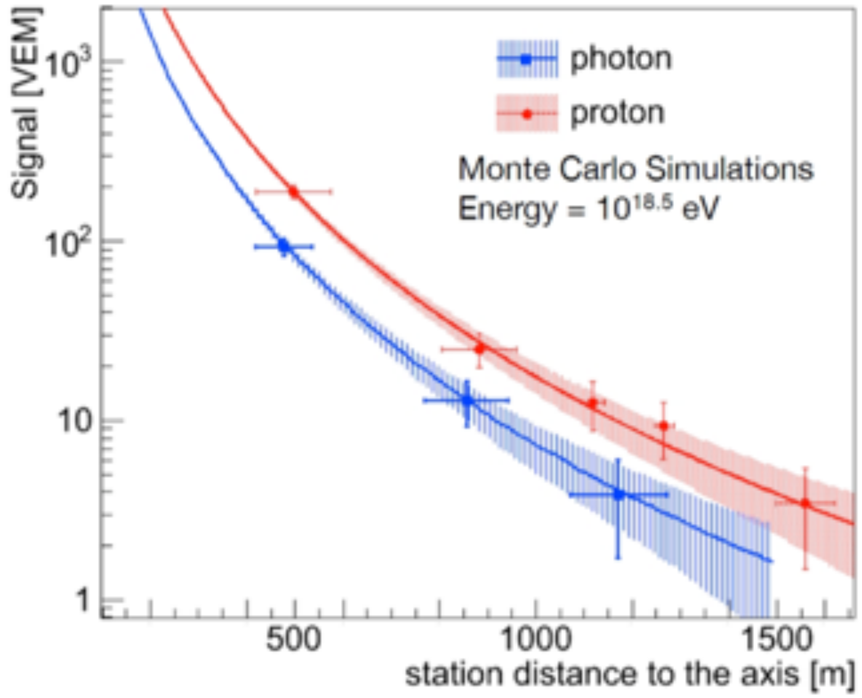
neutrino and photon showers can be identified through the time structure of the SD signals: broader time structure expected due to the larger EM component

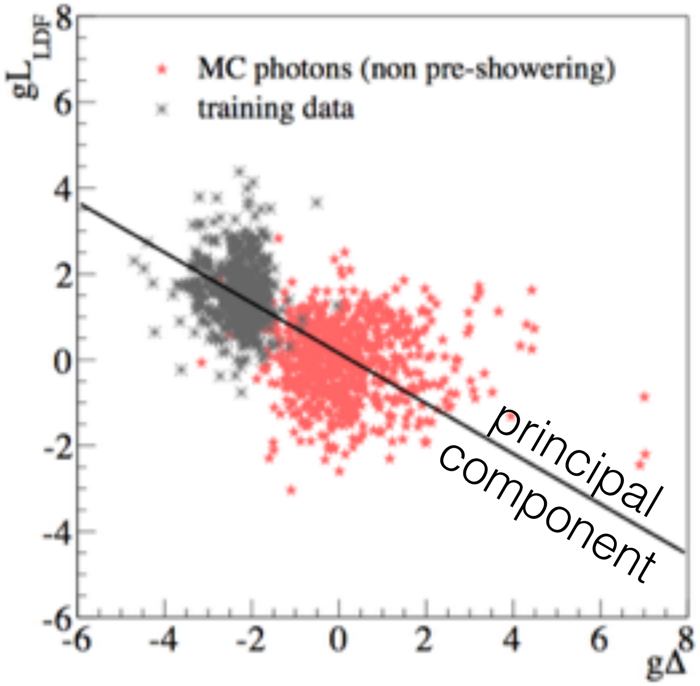


Observables to select neutrinos: very inclined showers (θ>60˚) with EM component at the ground, signals extended in time

E>10^{18} eV

no neutrino candidates found in D-G or E-S searches





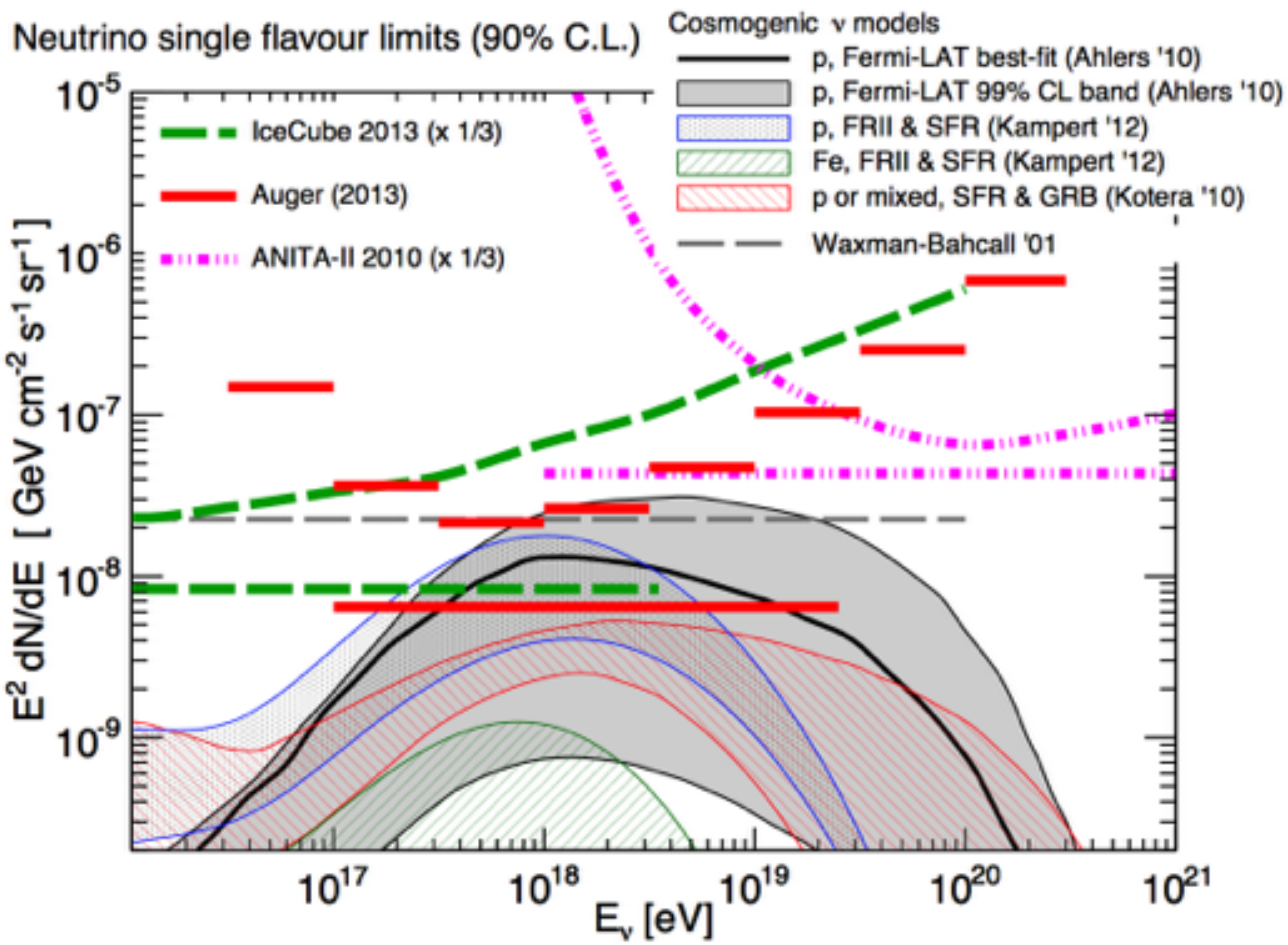
Observables to select photons: showers with 30<θ<60˚, steep LDF and large risetimes

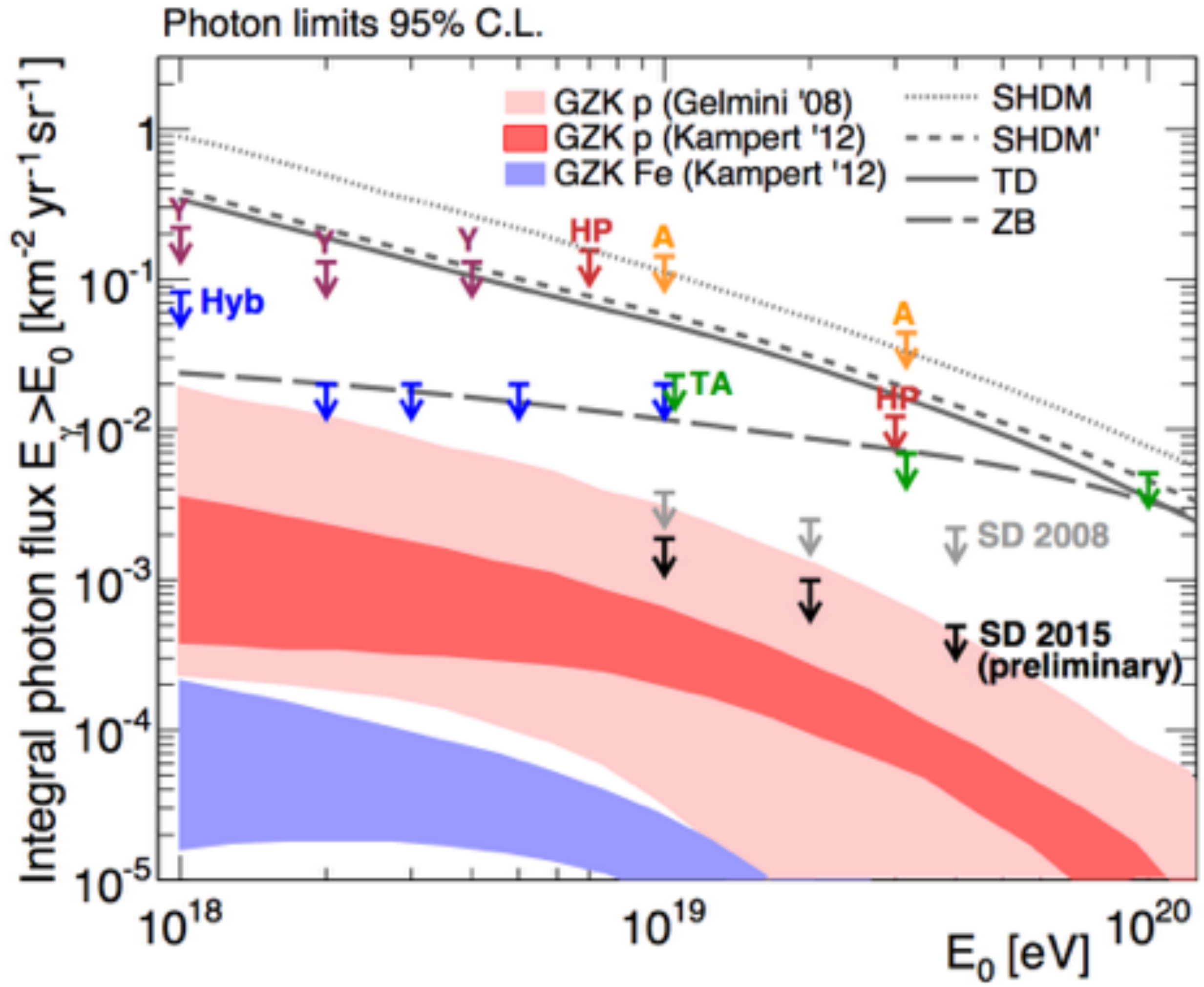
E>10^{19} eV

4 photon candidates, compatible with background expectation

C. Bleve for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Neutrino and photon limits at EeV energies





$dN/dE = k\,E^{-2} \rightarrow k \sim 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

F_γ (E_γ > 10, 20, 40 EeV) < 1.9, 1.0, 0.49 $\times 10^{-3}$ km^{-2} yr^{-1} sr^{-1}

First limit from an EAS array below WB bound

Cosmogenic model with pure p composition at the source disfavoured

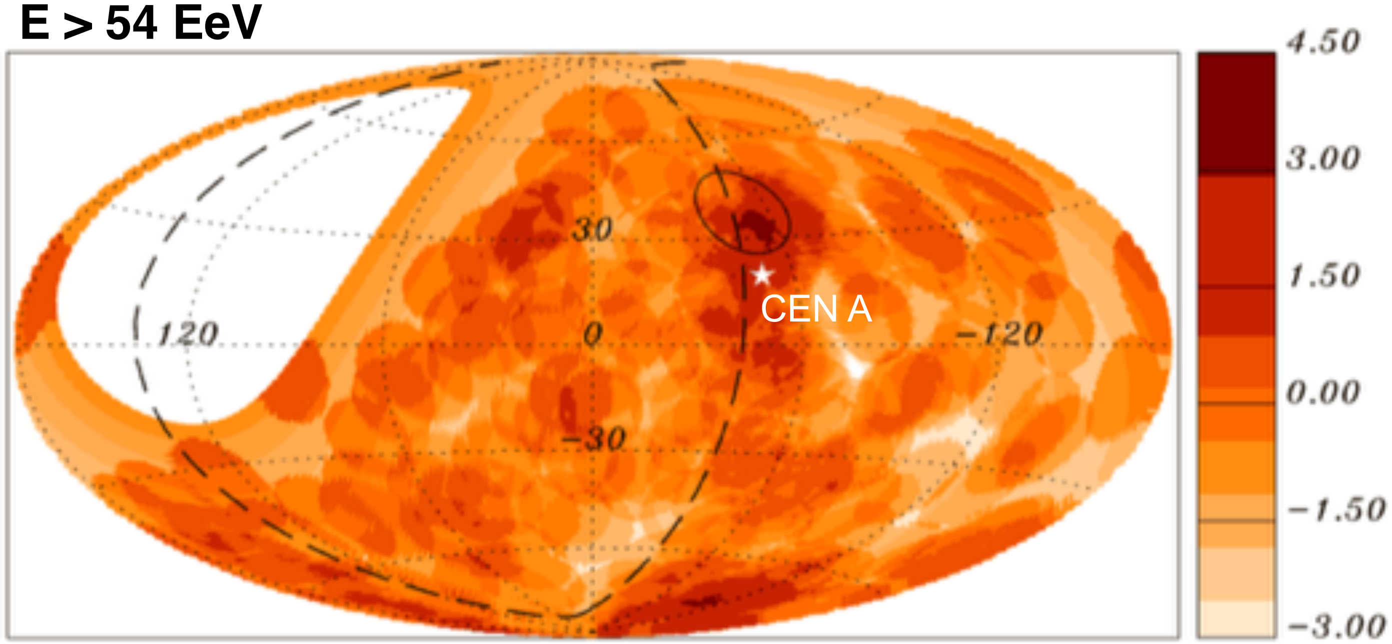
Top-down models strongly disfavoured

Updated limits closing on GZK predictions

C. Bleve for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Anisotropy tests

E > 54 EeV



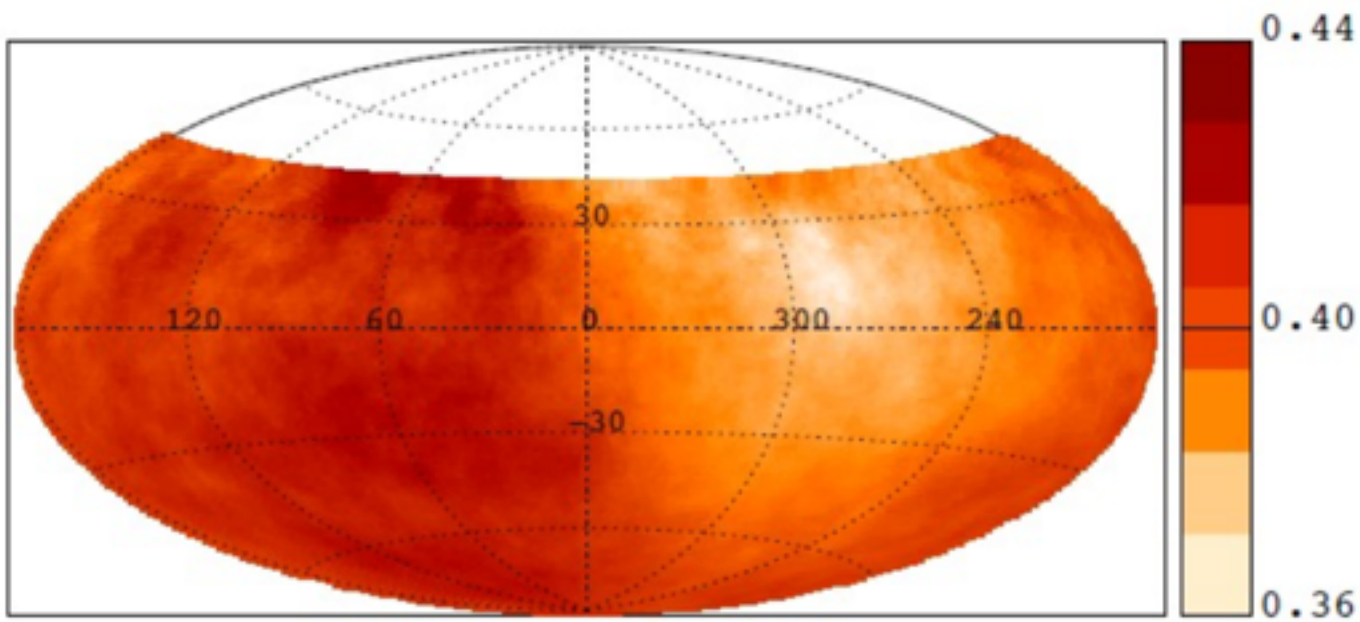
most significant excess (4.3σ): 18° from CenA
post-trial probability : 69%

At small/intermediate scales: no evidence of anisotropies

No statistically significant deviation from isotropy in none of the tests: the most significant deviations from isotropy are at intermediate scales

J. Aublin for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Sky map of the CR flux **E > 8 EeV**



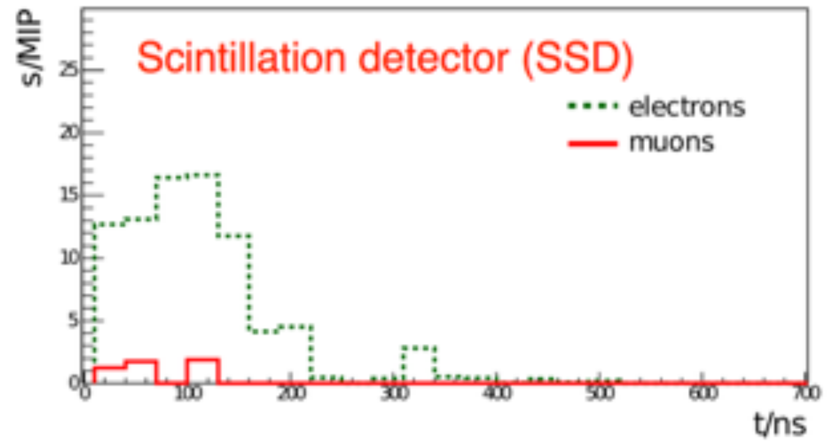
Dipole Amplitude: 7.3 ± 1.5% ($p=6.4\times10^{-5}$)
Pointing to (a, d) = (95˚±13˚, -39˚±13˚)

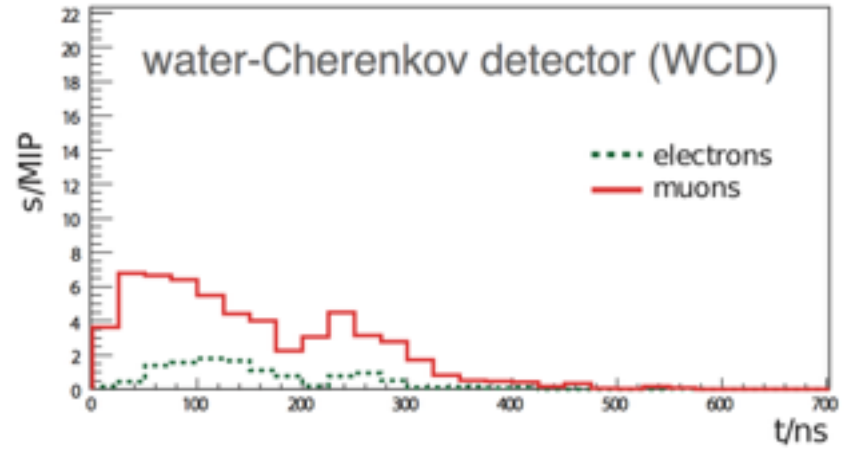
At large scales: indication of a dipole at E>8 EeV

challenging the original expectations of isotropy at these energies

I. Al Samarai for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

AugerPrime: event reconstruction

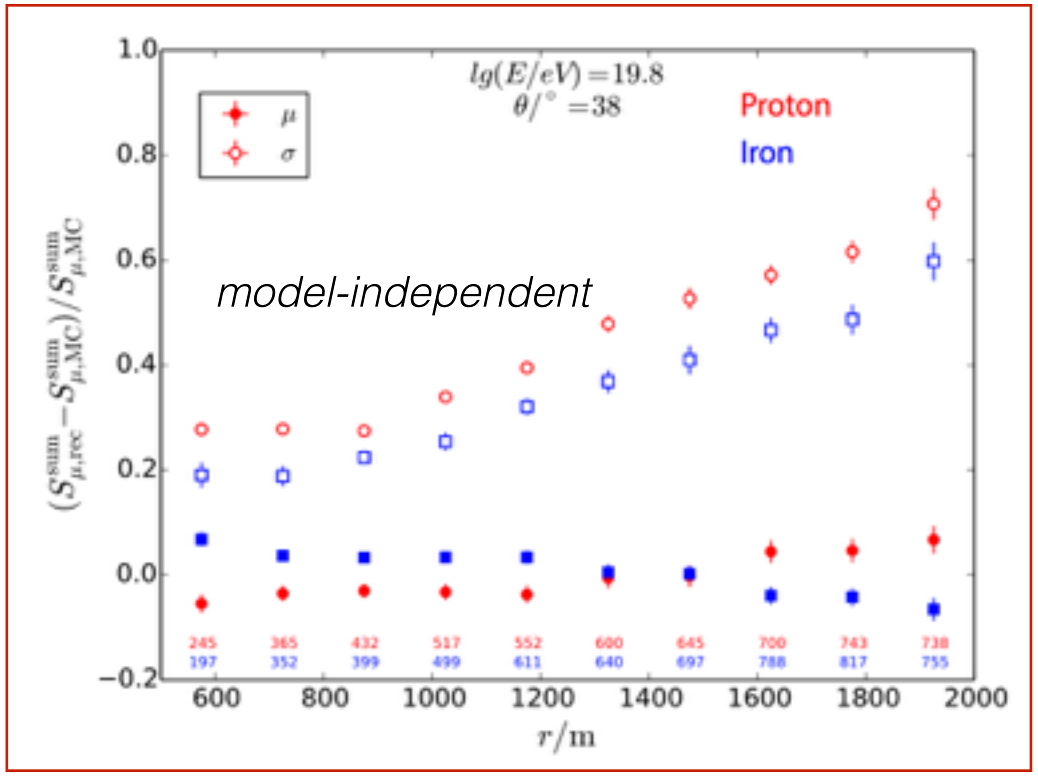




$$S_{muonic}\,(WCD) = a\ S(WCD) + b\ S(SSD)$$

a and b from simulations, weak dependence on the primary type and energy

Matrix-based muon reconstruction



Universality-based event reconstruction