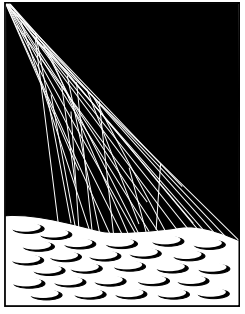
The muon component of extensive air showers above $10^{17.5}$ eV measured with the Pierre Auger Observatory



PIERRE AUGER OBSERVATORY

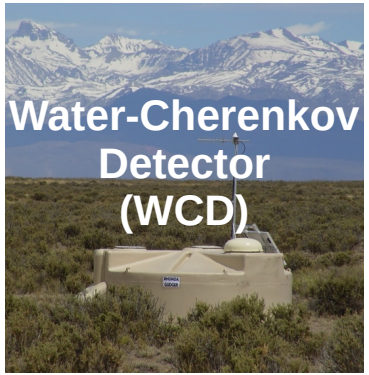
Federico Sánchez

for the Pierre Auger Collaboration

36th ICRC 2019

Madison

The Pierre Auger Observatory



Surface detector (SD)

100% duty cycle

SD-1500m
3000 km²
1600 WCDs

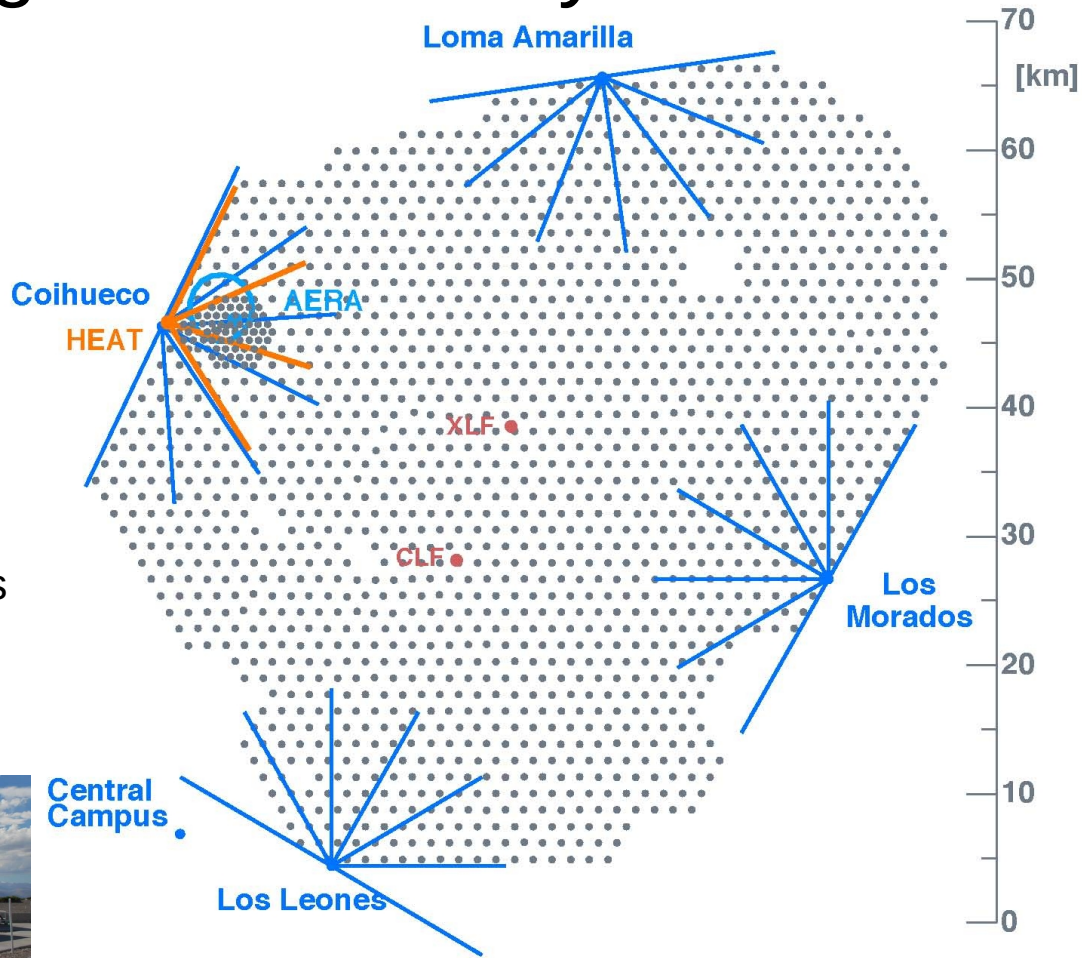
SD-750m
23.5 km²
61 WCDs

Fluorescence detector (FD)

15% duty cycle

4 units x 6 telescopes
overlooking SD-1500m
FoV 30° x 30°
Minimum elevation 1.5°

1 units x 3 telescopes
overlooking SD-750m
FoV 30° x 30°
Minimum elevation 30°



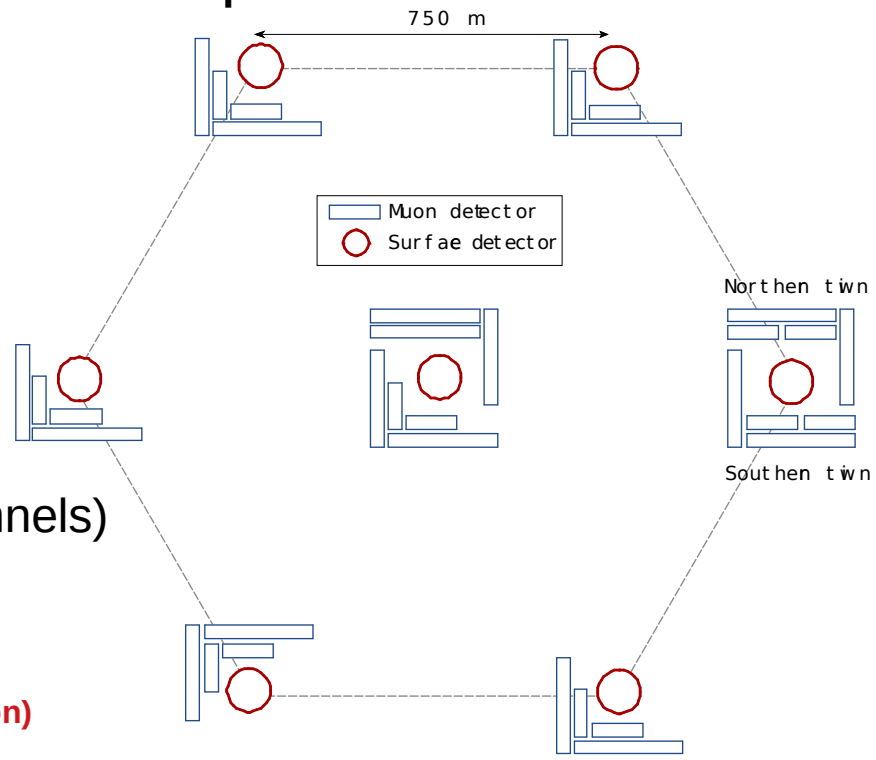
The Pierre Auger Observatory

Underground muon detector (UMD)

100% duty cycle

UMD-750m
23.5 km^2
61x30m^2 Plastic Scintillators
buried 2.3m triggering from WCDs

Engineering Array:
Operated until Nov. 2017



EA served for:
Validation of detection system (End-to-End)
Optimization of optical devices (PMT → SiPM)
Optimization of electronics (ASICs)
Optimization of dynamic range (2 extra analog channels)

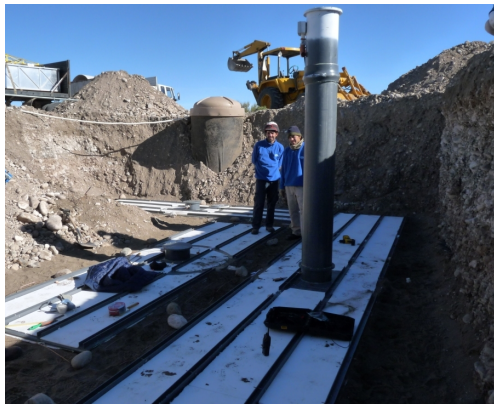
Physics observables are basically extracted from:

- **signal size → number of muon (this talk)**
- **signal timing → timing of muon (see PoS(202) poster session)**

1 year of data, 1742 event with energy 3 x 10^{17} – 2 x 10^{18} eV and zenith angle < 45^o

UMD: from raw traces to muons

Binary traces in raw (real) events



Highly **segmented** scintillators: 64 per unit

Signal in 32 strips

time	
0	00000000000000000000000000000000
⋮	
494	00000000000000000000**1**0000000000
495	000**1**00000000**1**00000000**1**0000000000
496	000**1**00000000**1**00000000**1**0000000**1**00
497	000**1**00000000**1**00000000**1**0000000000
498	00000000000**1**00000000**1**0000000000
499	00000000000**1**00000000**1**0000000000
500	00000000000000000000**1**0000000000
501	00000000000000000000**1**0000000000
⋮	
1024	00000000000000000000000000000000

Sampling @ 3.125 ns

25 ns

3 muons (“111” or “101” minimal pattern required) + 1 noise

UMD: efficiency and resolution

Efficiency
Resolution
} based on {
→ units of different areas (5m² & 10m²)
→ units of identical areas (30m² Vs 30m²)

Relative efficiency

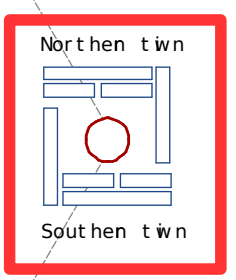
Ratio of counts per unit $r = \frac{\epsilon_1}{\epsilon_2} \cdot \frac{a_1}{a_2}$

where ϵ_i, a_i efficiency and area

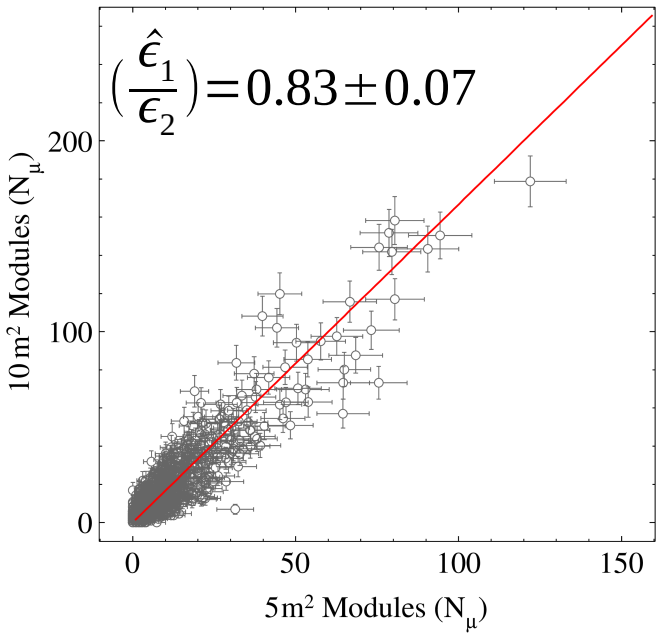
$$\left(\frac{\hat{\epsilon}_1}{\epsilon_2}\right) = \frac{a_1}{a_2} \cdot \frac{\langle N_2 \rangle}{\langle N_1 \rangle}$$

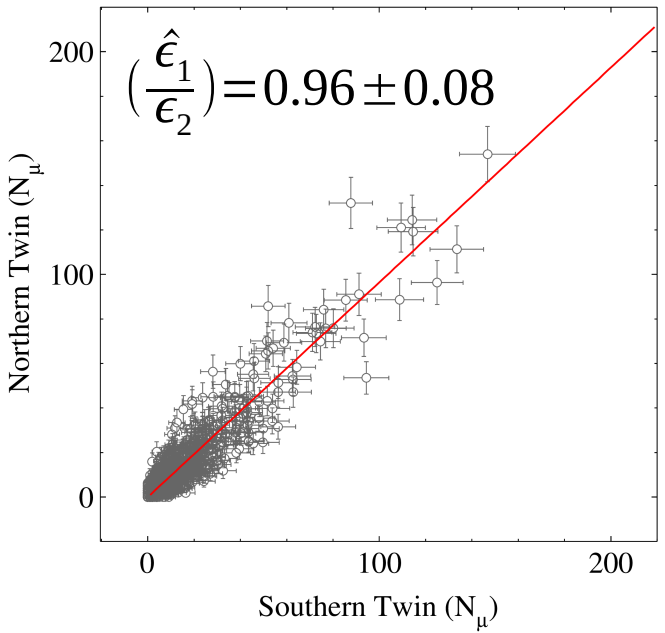
Rel. eff. estimator

***Twin* detectors:**
30m² North + 30m² South of same WCD highly segmented (4+4 units)



N-S separation
~ 20 m





UMD: efficiency and resolution

Efficiency
Resolution
} based on {
→ units of different areas (5m² & 10m²)
→ units of identical areas (30m² Vs 30m²)

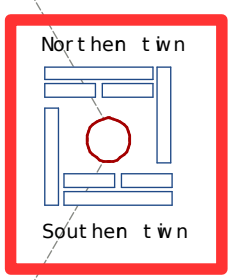
Resolution

Square ratio of mean and variance

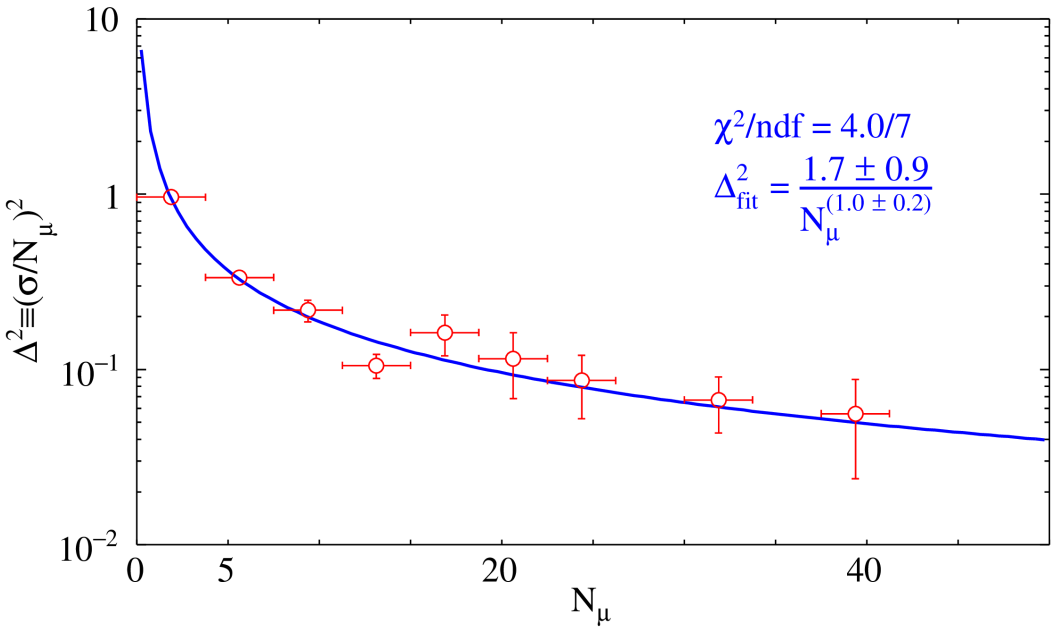
$$\left(\frac{\sigma}{\langle N\rangle}\right)^2 \Rightarrow \left(\frac{\hat{\sigma}}{\langle N\rangle}\right)^2 = 2\left(\frac{N_1 - N_2}{N_1 + N_2}\right)^2$$

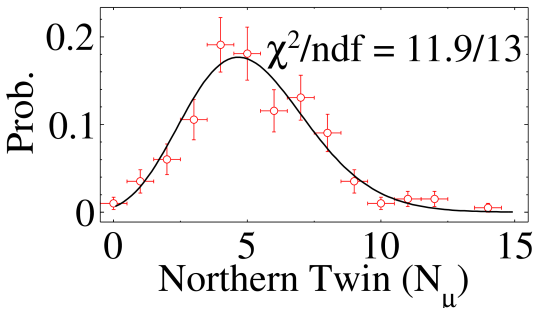
Resol. estimator

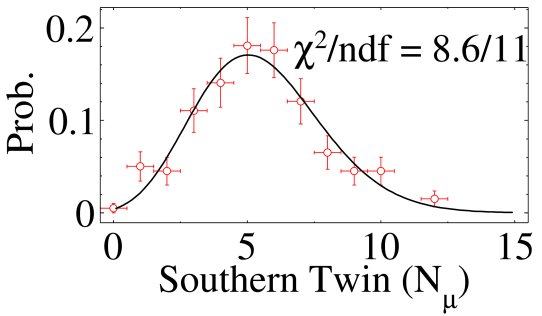
***Twin* detectors:**
30m² North + 30m² South of same WCD highly segmented (4+4 units)



N-S separation ~ 20 m







UMD: systematic uncertainties I

Sources of systematic uncertainty analyzed:

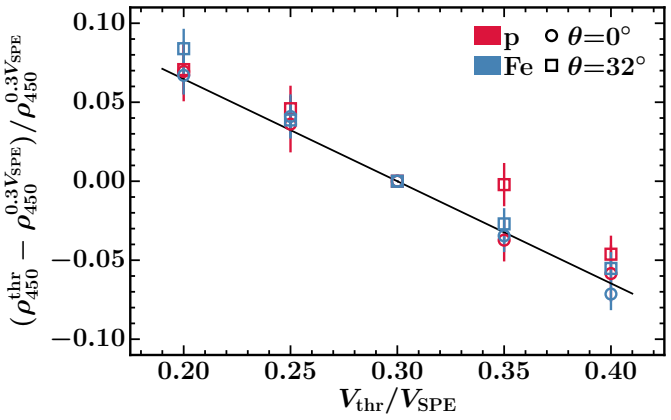
i. Calibration procedure → uncertainty in the “operation” point of each of 2240 electronic channels

ii. Soil density variations → uncertainty in shielding by overburden

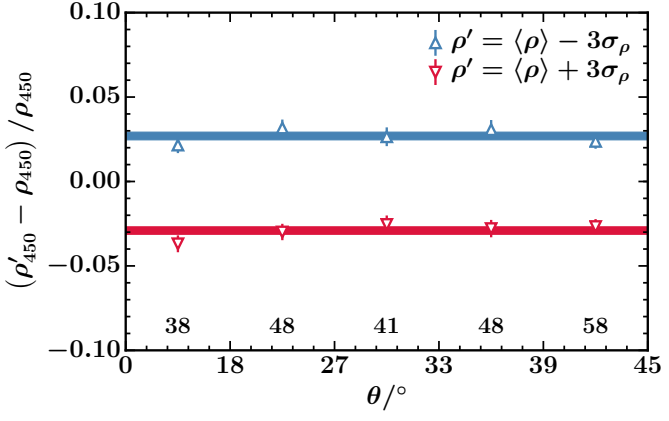
iii. Shape of muon lateral distribution function → slope $\beta(\theta)$ parametrization based on simulations

Simulation based

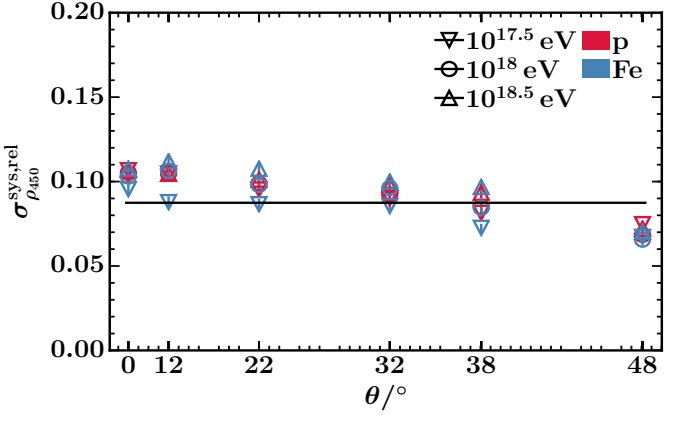
i.



ii.



iii.



σ/ρ_{450}	3.9%	2.8%	8.8%

UMD: systematic uncertainties II

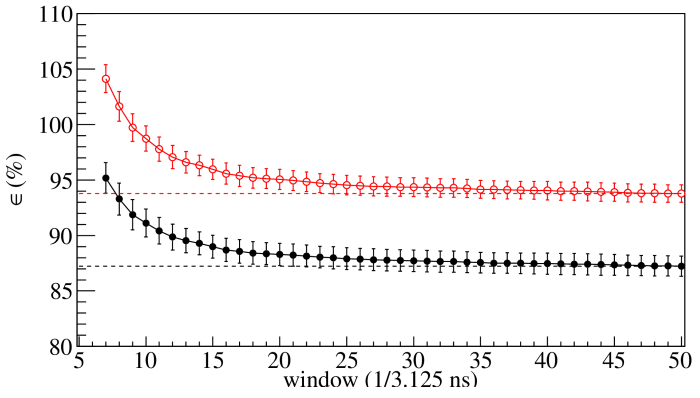
Sources of systematic uncertainty analyzed:

i. Efficiency correction → dependent time width selected to identify signals

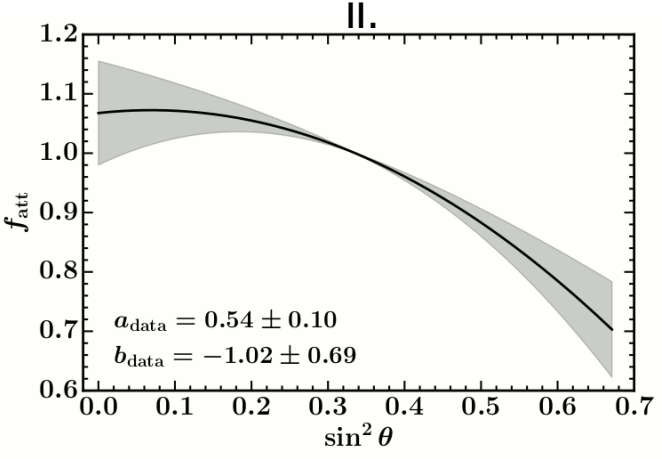
ii. Constant Intensity Cut (CIC) correction → uncertainty in parametrization

Data based

i.



ii.



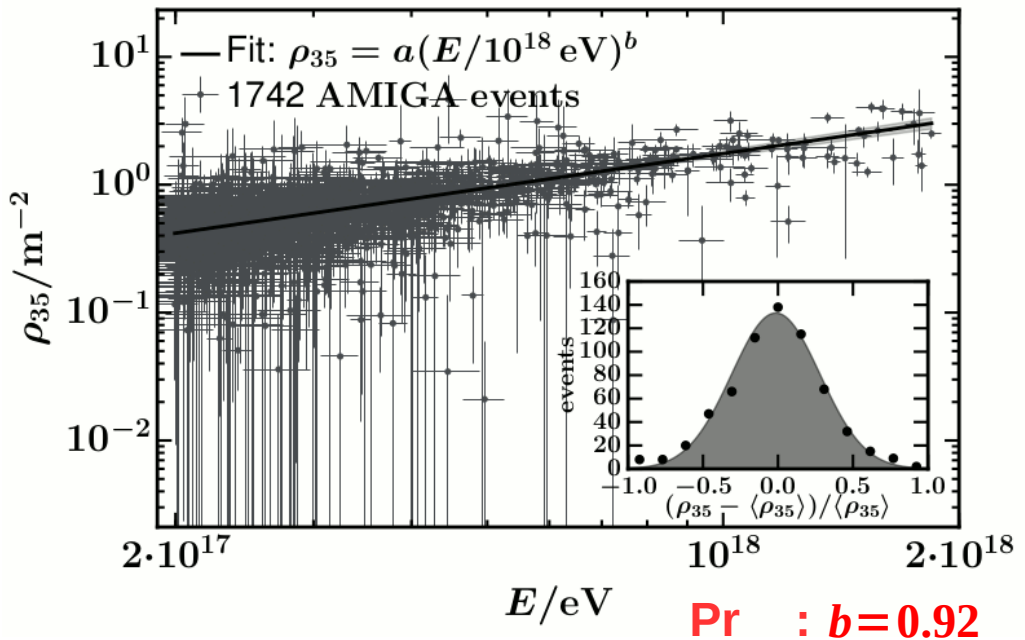
Total uncertainty:	
σ/ρ_{35}	14.3%

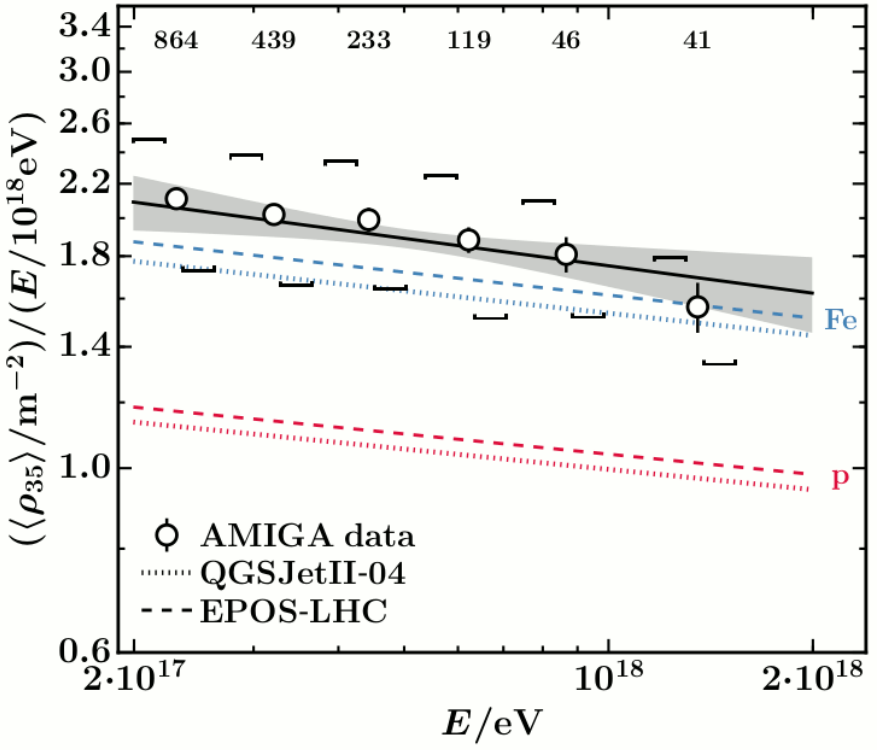
σ/ρ_{450}	9.9%	2.3%

Muon densities Vs energy $\Rightarrow \rho_{35}(E)$

First direct measurement of the muon densities at energies $10^{17.3}$ eV < E < $10^{18.3}$ eV

- ✔ Geometry & Energy from SD alone
- ✔ Event core contained in UMD hexagon
- ✔ Zenith < 45°





$$\rho_{35}(E) = a \cdot \left(E/10^{18}\,eV\right)^b$$

Pr : $b = 0.92$

Fe : $b = 0.91$ → 8% (EPOS) – 14% (QGSJet) below measurements

Data: $b = 0.89 \pm 0.04(stat) \pm 0.04(sys)$

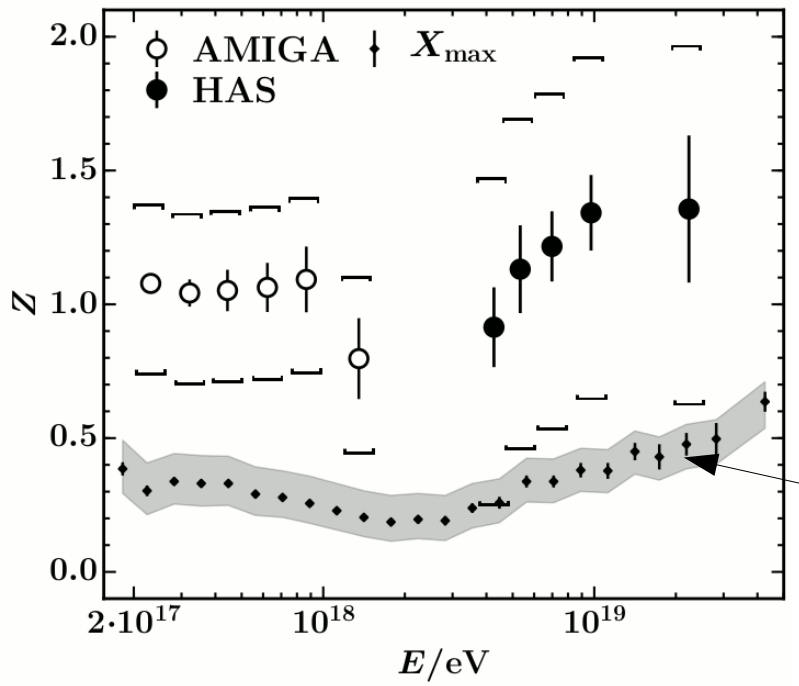
Comparison with other Auger measurements I

$$z_\alpha = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_p}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_p}$$

same composition sensitive observable for

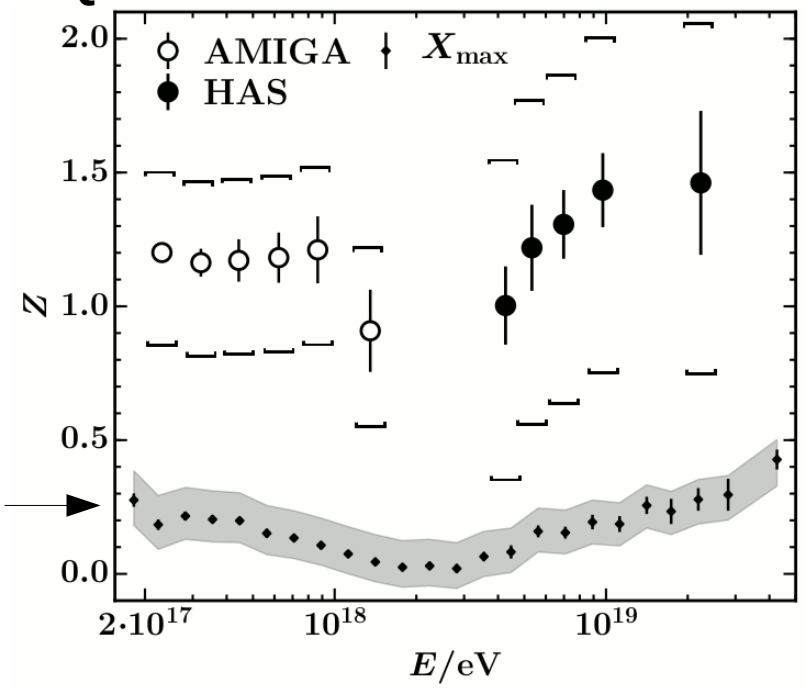
- SD → R_μ
- FD → X_{max}
- UMD → ρ_{35}

EPOS



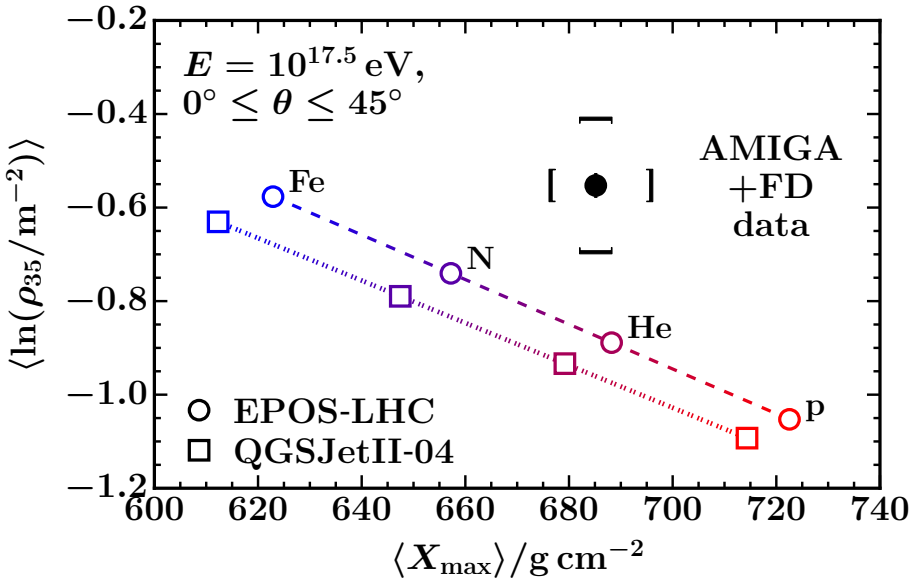
$$z_{X_{max}} = \frac{\langle \ln(A) \rangle}{\ln(56)}$$

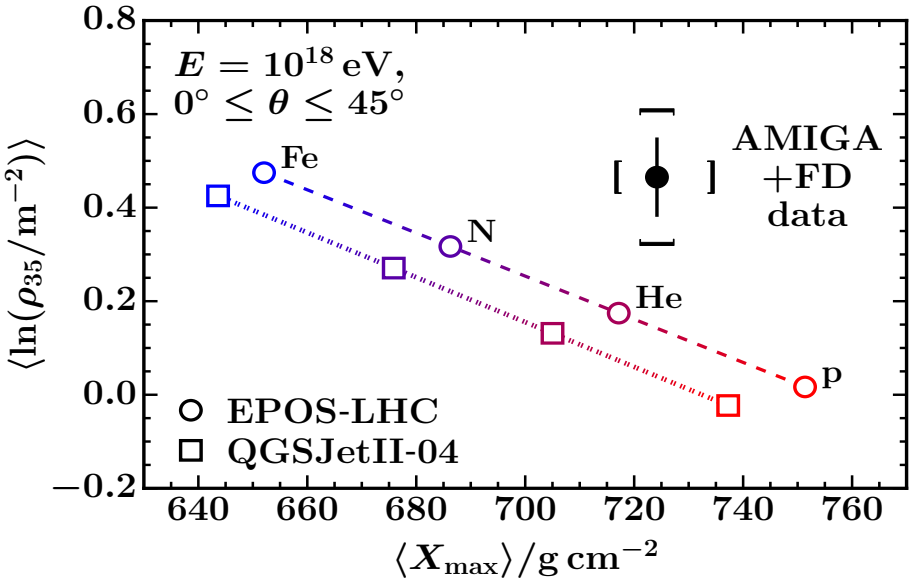
QGSJet



Comparison with other Auger measurements II

Bi-parametric analysis: X_{max} , ρ_{35}





muon deficits in LHC-tuned hadronic models

@$10^{17.5}$ eV **EPOS 38%** **QGSJet 50%**

@$10^{18.0}$ eV **EPOS 38%** **QGSJet 53%**

Final remarks

- An engineering array for the Underground Muon Detector (UMD) was fully operative at the Pierre Auger Observatory and was used to thoroughly validate the detection system
- For the production phase several hardware improvements were implemented (see PoS(ICRC2019)202 in the poster session)
- The first direct observations of a device dedicated exclusively to measuring the muonic component of EAS were presented
- In the energy range 3×10^{17} eV to 2×10^{18} eV simulations fail to reproduce muon densities even for LHC-tuned hadronic interaction models
- Compared to data, the combined analysis of X_{max}, ρ_{35} showed a discrepancy ranging from 38% to 53% depending on the model
- The combined muon analysis at high (SD) and low (UMD) energies match the trend in composition observed with the FD in the whole energy range