Probing Hadronic Interactions with measurements from the Pierre Auger Observatory

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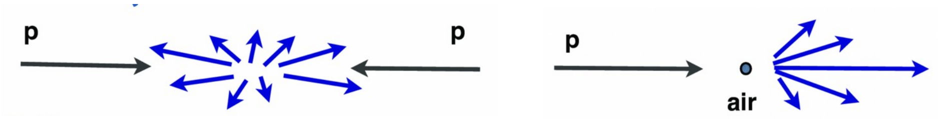
Cosmic Rays and Astrophysics – **ISMD**2021

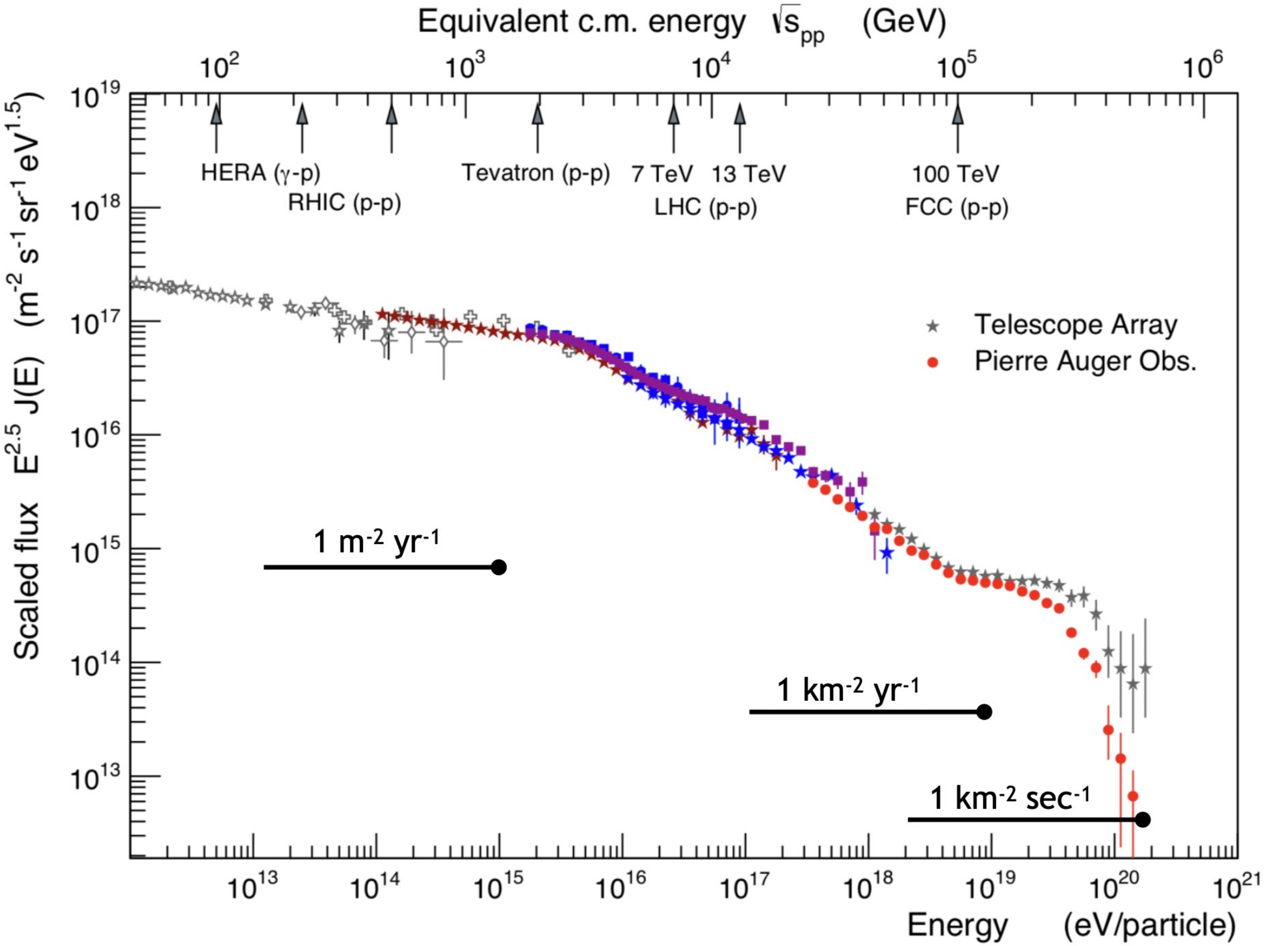
Outline:
- Cosmic rays and air showers
- The Pierre Auger Observatory
- Muon measurements with Auger
- Muon deficit: what about other experiments?

Ultra-high-energy cosmic rays

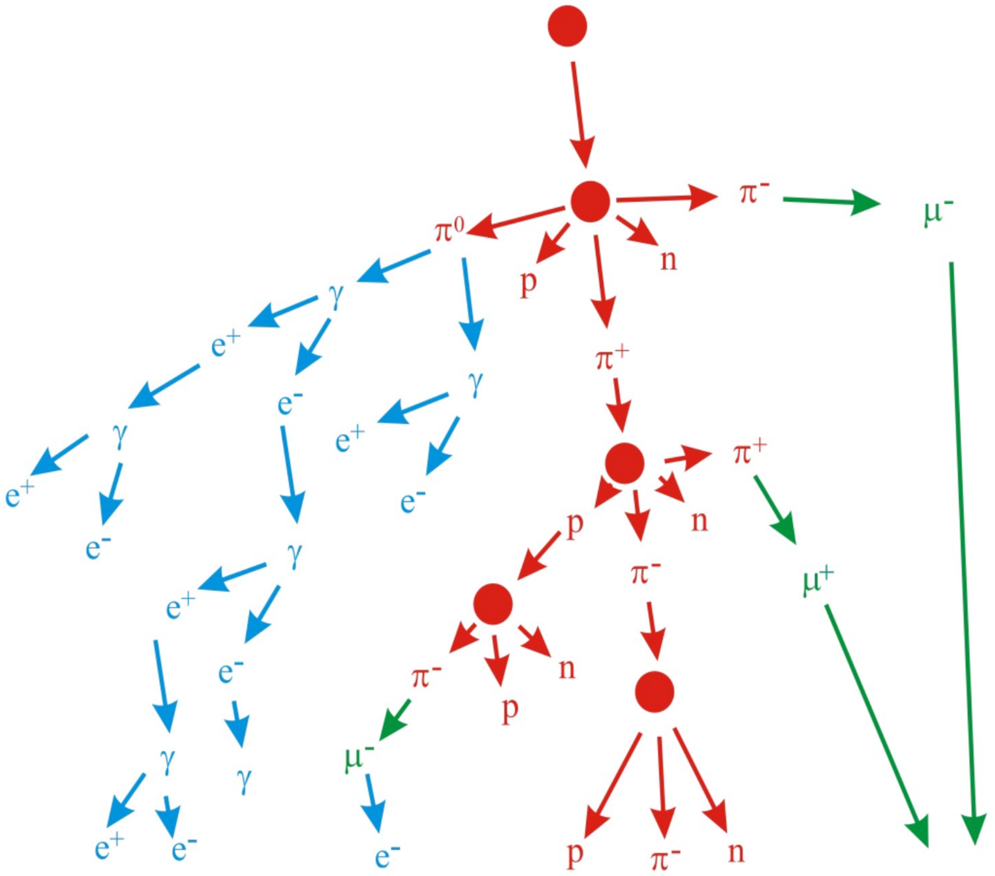


UHECR provide access to hadronic interactions at energies well beyond those achievable by human-made accelerators.

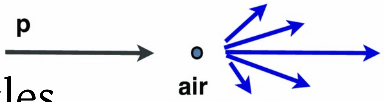
But cannot be measured directly...



Extensive air showers



Primary CR + atmospheric nuclei
→ cascade of secondary particles

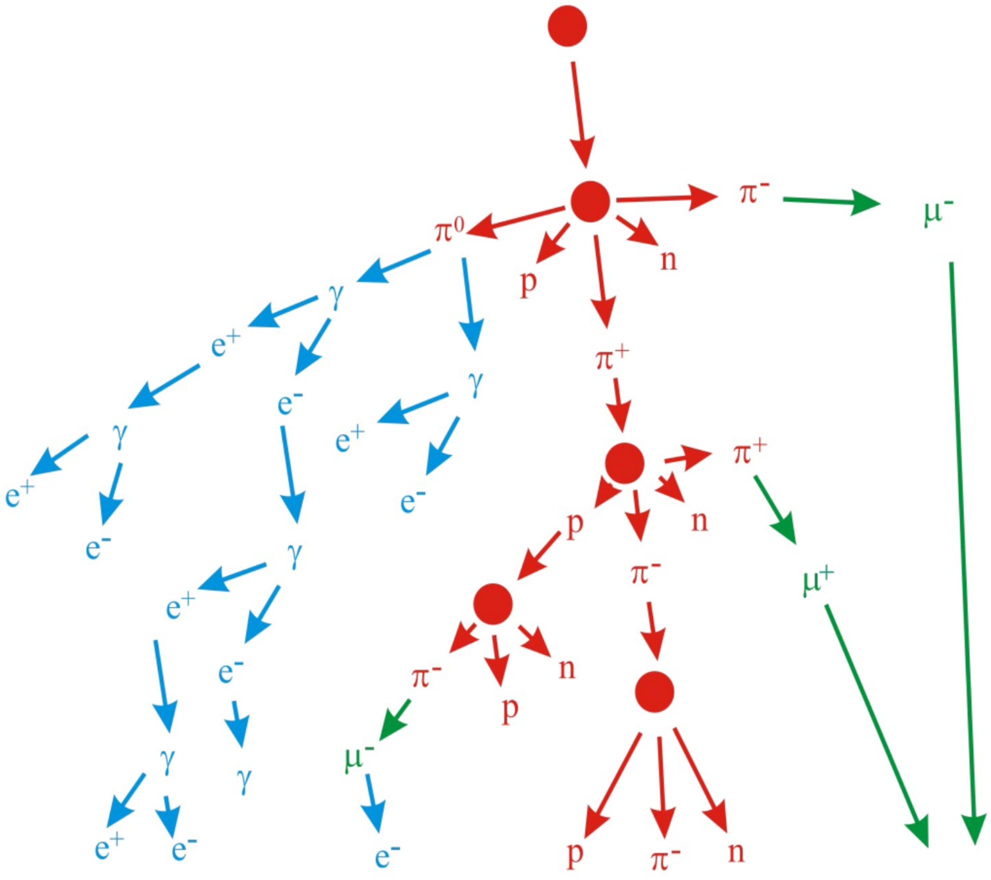


Components:

Muon mainly from the decay of charged pions
+ photo-production

EM mainly from the decay of neutral pions
+ muon decay
+ low energy pion decay

Extensive air showers



Primary CR + atmospheric nuclei
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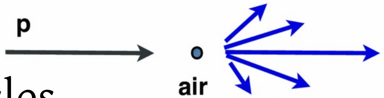


Components:

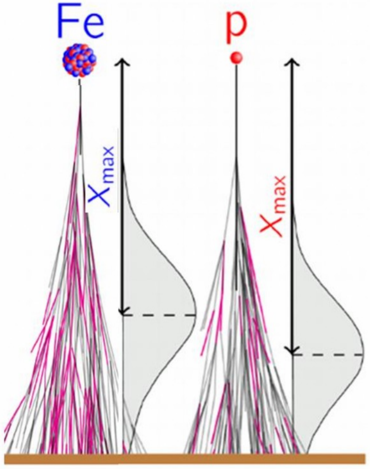
Muon mainly from the decay of charged pions
+ photo-production

EM mainly from the decay of neutral pions
+ muon decay
+ low energy pion decay

Observables:

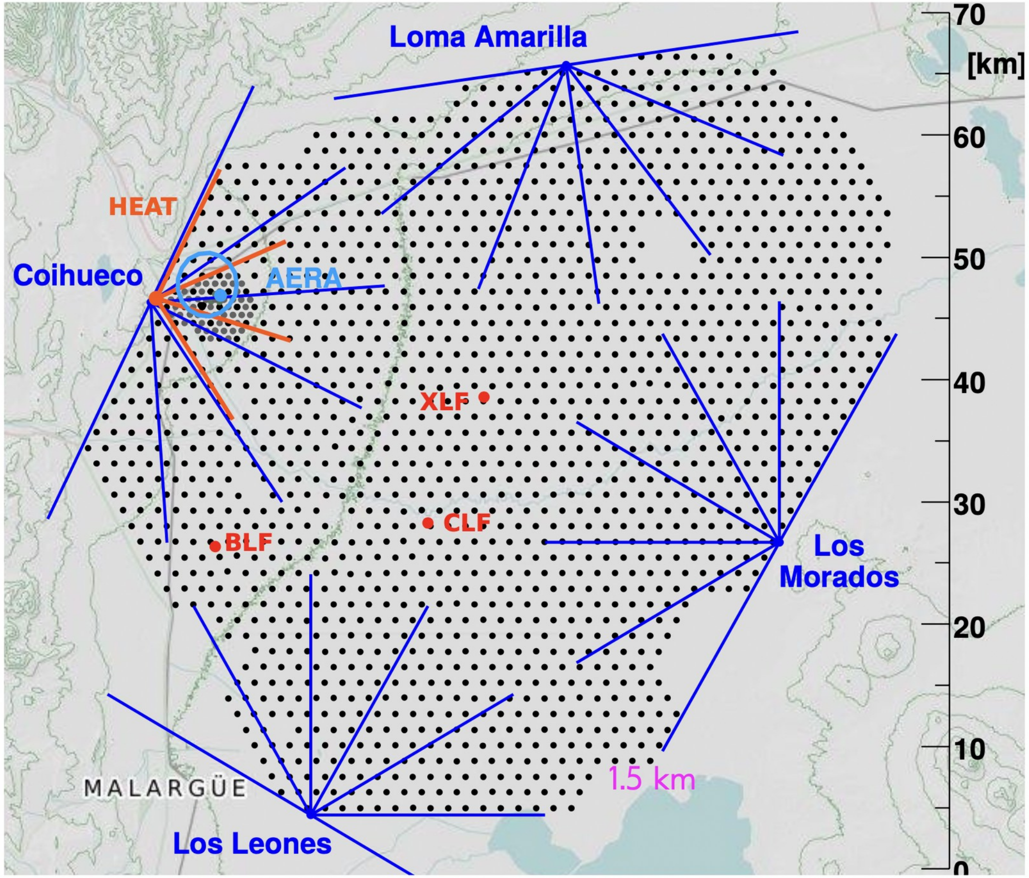
X_{max} – depth of maximum development of the shower in the atmosphere

N_μ – number of muons at ground



$N_\mu^{Fe} > N_\mu^{p}$

The Pierre Auger Observatory



Surface Detector (SD):
>1600 water Cherenkov det.
100% duty cycle

SD-1500
3000 km² – E > $10^{18.5}$ eV
SD-750
27 km² – E >$10^{17.5}$ eV
SD-433
1.9 km² – E >$10^{16.5}$ eV

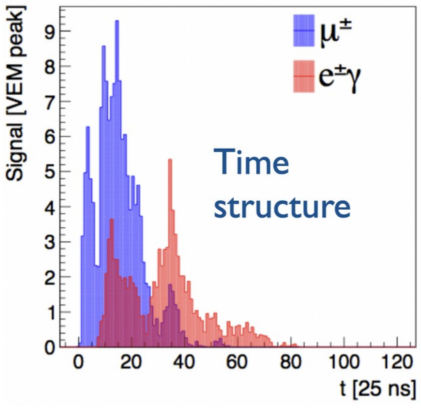
Fluorescence Detector (FD):
4 sites
27 telescopes
E > 10^{17} eV
15% duty cycle

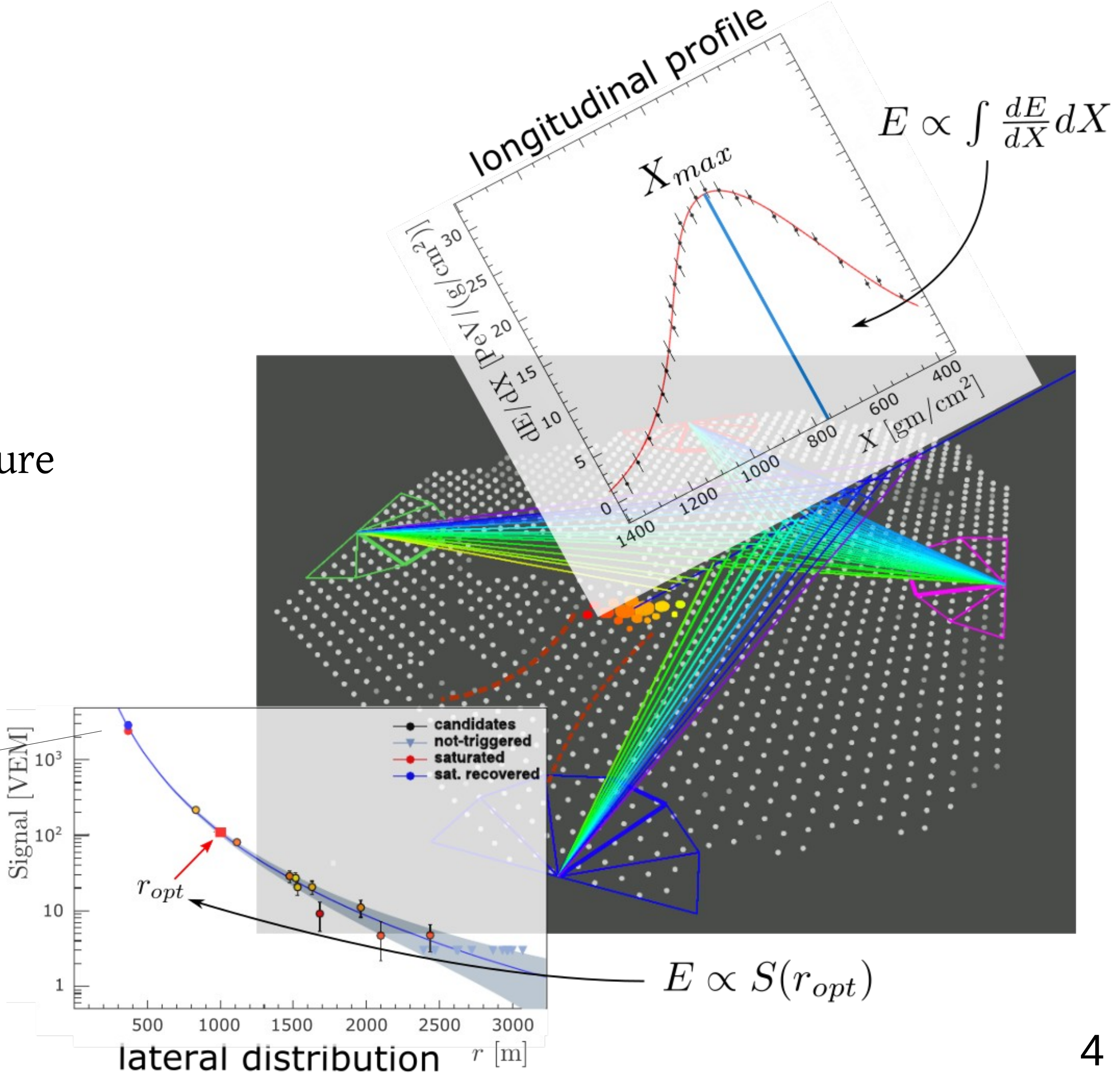
Location: Malargüe, Mendoza, Argentina.

Hybrid detector

FD: - calorimetric measurement of E
- direct measurement of X_{max}

SD: - energy estimator via $S(r_{opt})$
- composition sensitive time structure



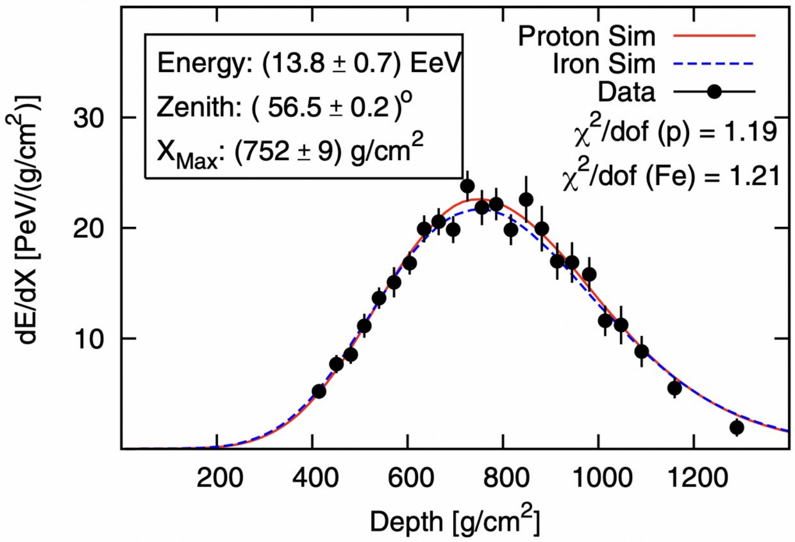


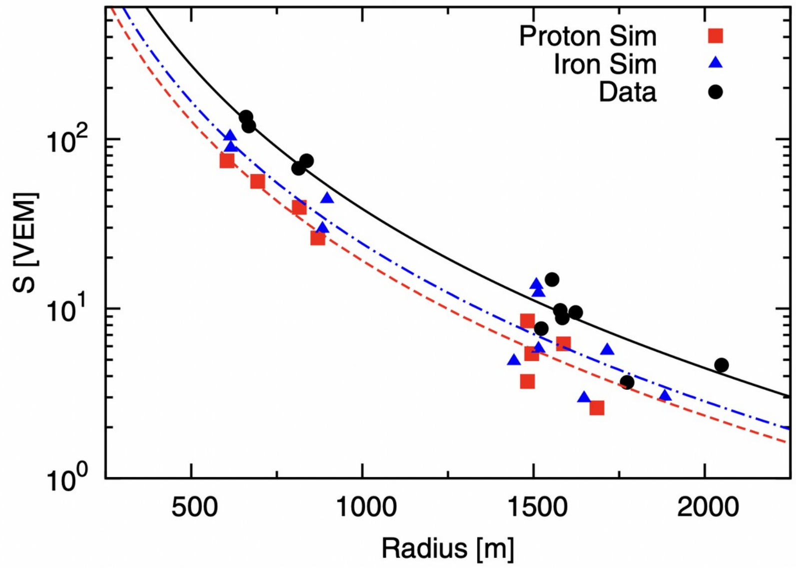
Hybrid muon measurement

Energy: $10^{18.8} - 10^{19.2}$ eV
Zenith angle: 0° – 60°
411 high quality events

Longitudinal profile (EM):
well reproduced by simulations

Lateral distribution (EM + Muon):
simulations produce systematically smaller signals than those found in data





Phys. Rev. Lett. 177, 192001 (2016)

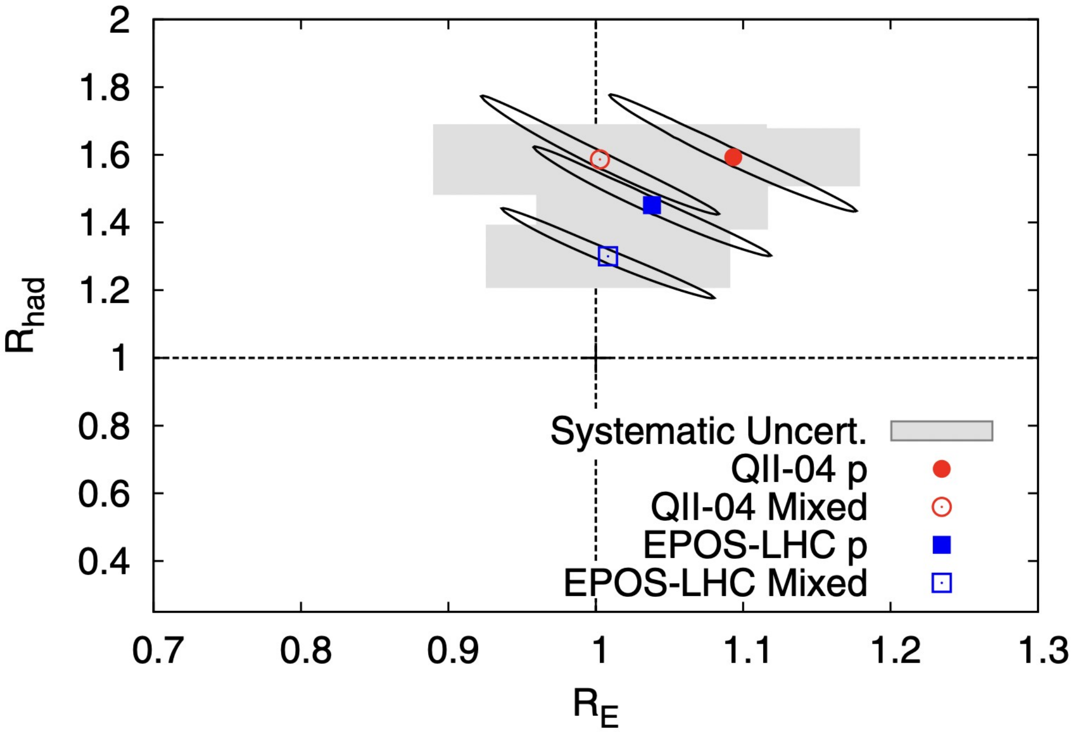
Hybrid muon measurement

ML fit adjusting the EM and Muon contributions to the signal

$$S_{\text{resc}} = R_E\, S_{\text{EM}} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had}}$$

$$\alpha \simeq 0.9$$

$$R_\mu \approx 0.93\, R_E^{0.9}\, R_{\text{had}} + 0.07\, R_E$$



Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

- No energy rescaling is needed

- Observed muon signal larger than predicted by models (1.3 – 1.6)

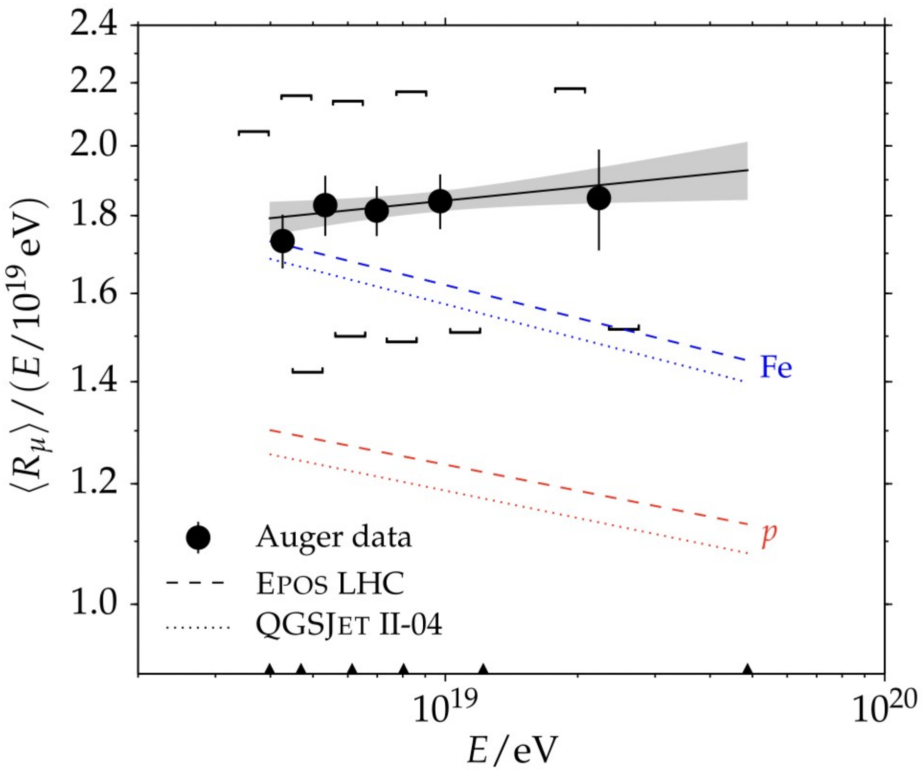
Phys. Rev. Lett. 177, 192001 (2016)

Muons in highly inclined showers

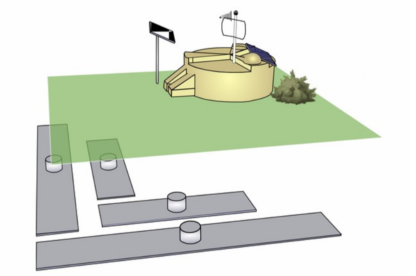
Energy > 4×10^{18} eV
Zenith angle: 62° – 80°
174 hybrid events

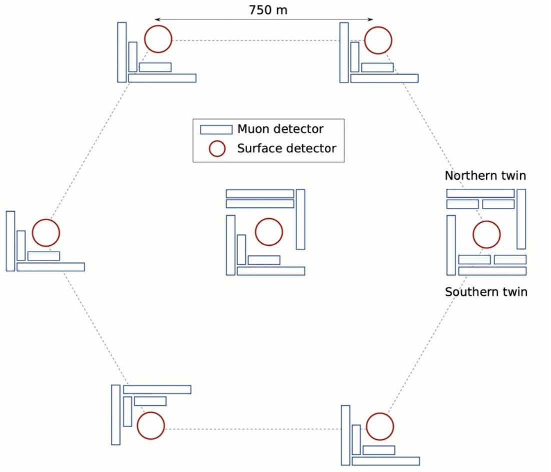
- EM component mostly absorbed in the atmosphere
- Muon component measured with the SD
- Energy measured with the FD

Higher abundance of muons in data than in predictions from hadronic models.
Compatible with iron primaries.



Direct measurements with the AMIGA Underground Muon Detector



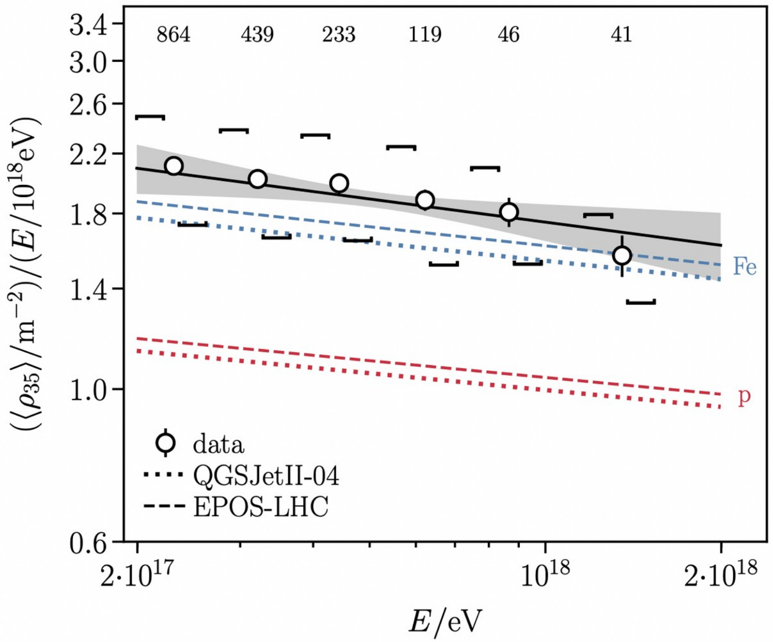


30 m^2 scintillators buried at 2.3 m underground at 7 SD locations.

Energy: 2x10^{17} – 2x10^{18} eV
Zenith angle: 0° – 45°
1742 events

- Lower energy measurements (closer to LHC data)
- First direct measurement of the muon content

Larger muon content in data than in predictions from hadronic models, but compatible with iron primaries.



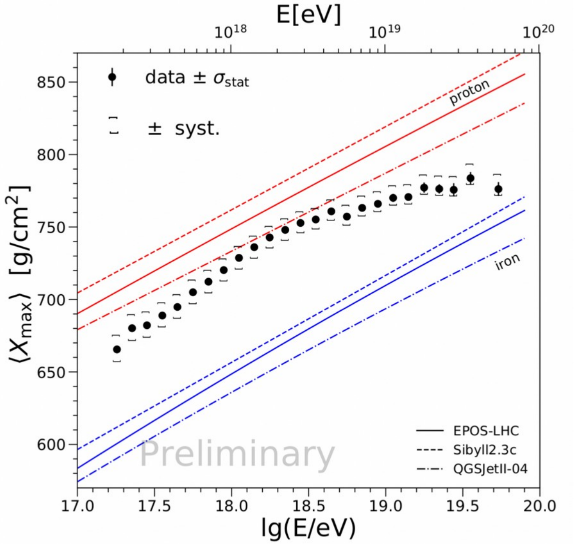
Eur. Phys. J. C 2020 80:751

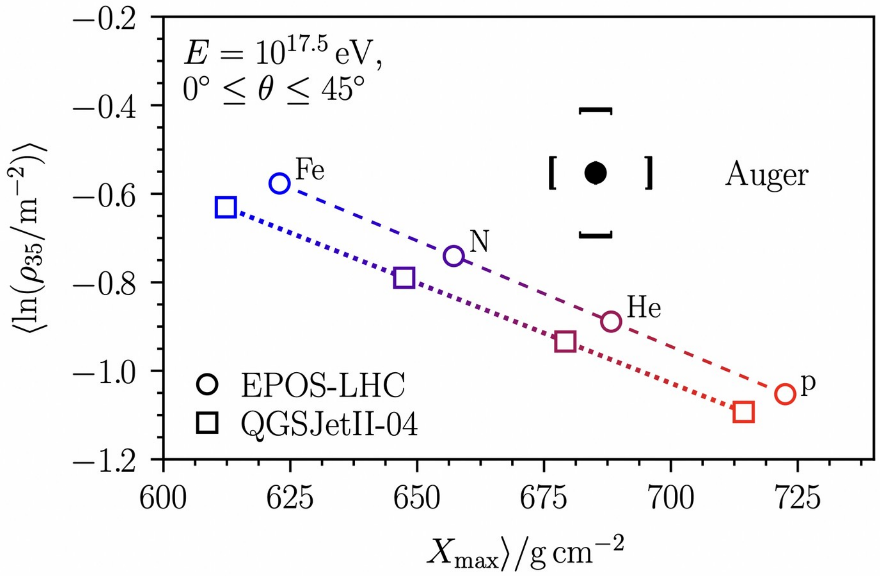
What about composition information?

Highly inclined events + UMD measurements

Composition information can be inferred from depth of shower maximum X_{max} measurements (FD) via hadronic interaction models.

Data is in tension with all model predictions.





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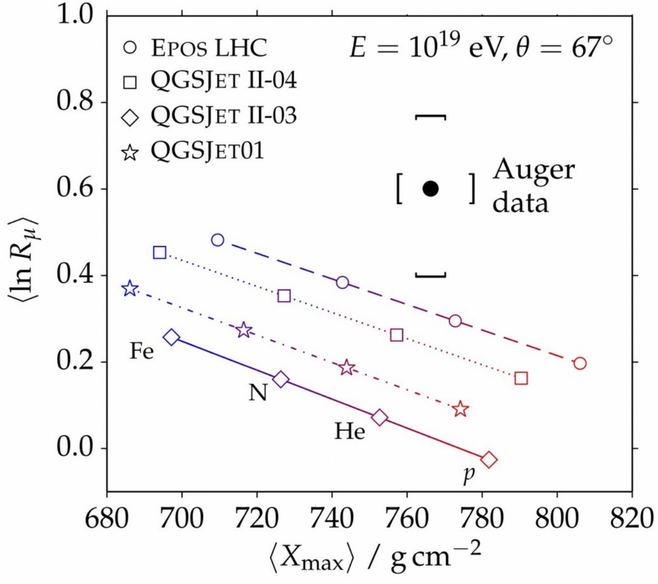


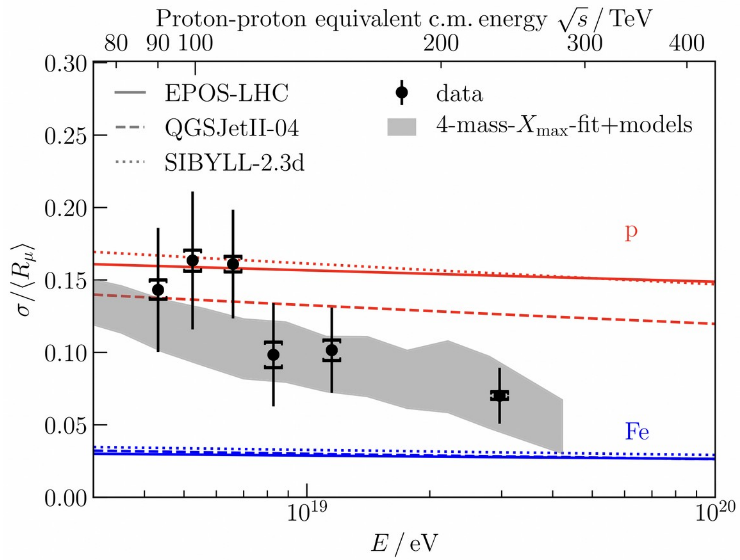
Phys. Rev. D 91, 032003 (2015)

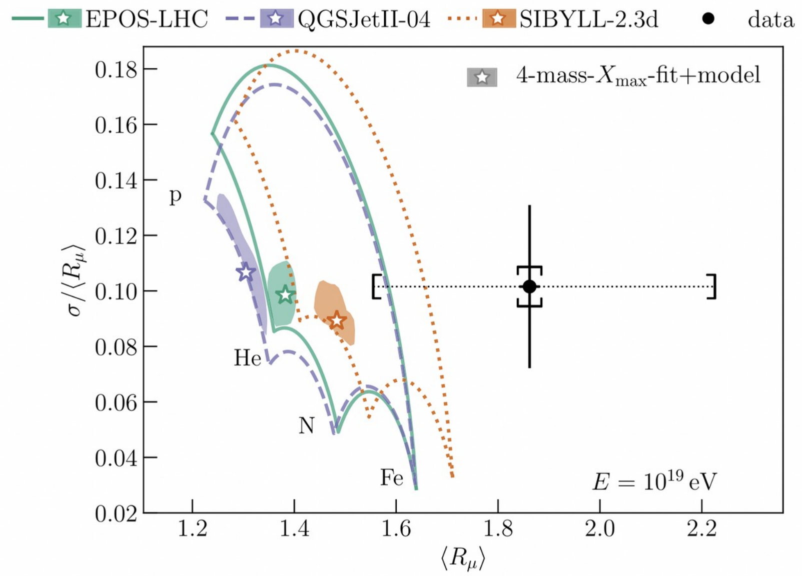
Fluctuations in the number of muons

Energy > 4×10^{18} eV
Zenith angle: 62° – 80°
281 hybrid events

Fluctuations in the number of muons are well reproduced by models.

All the available information points to a small effect at every stage of the shower (rather than a discrepancy in the first interaction).

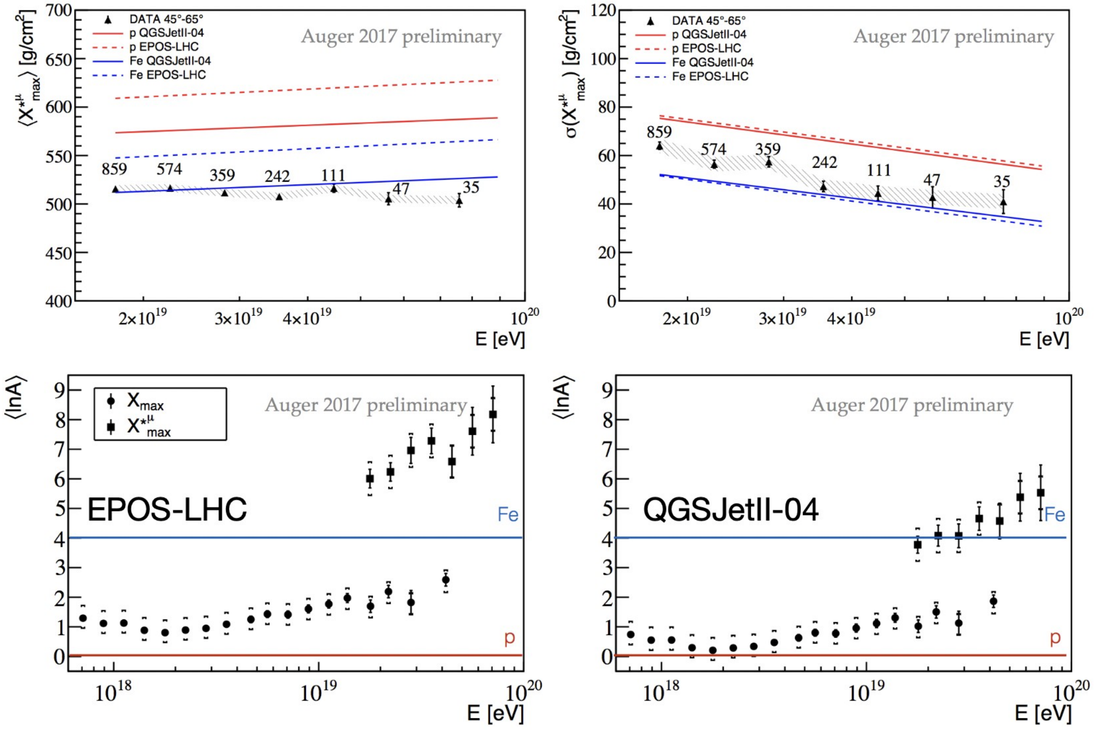




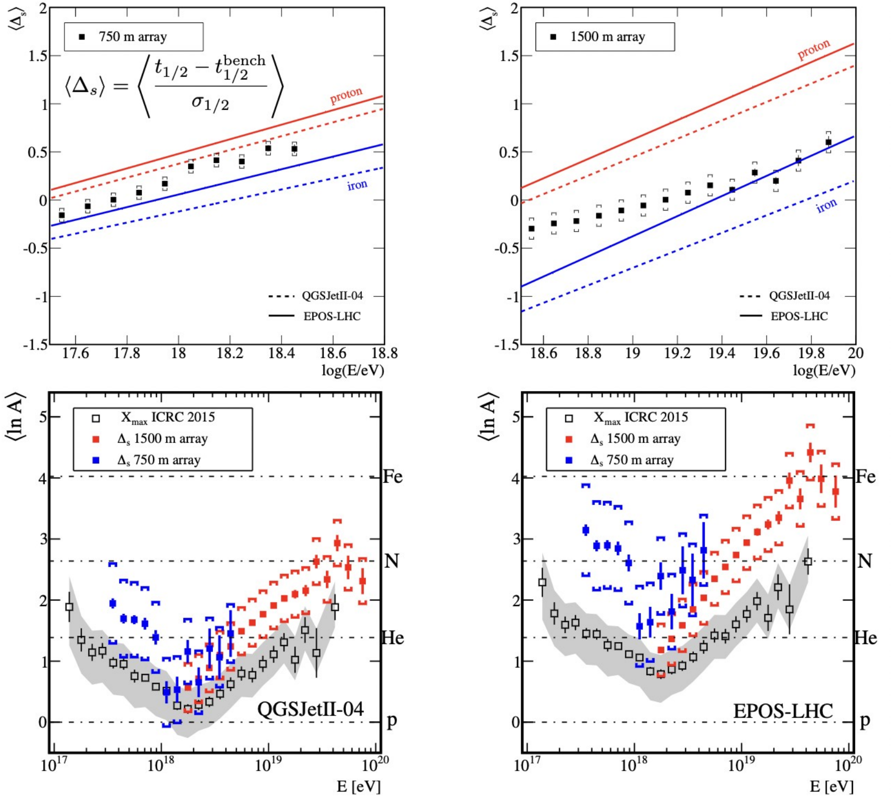
Phys. Rev. Lett. 126, 152002 (2021)

Other Auger results on Muon Deficit

Muon Production Depth



Risetime measurement



Phys. Rev. D 90, 012012 (2014)

Phys. Rev. D 96, 122003 (2017)

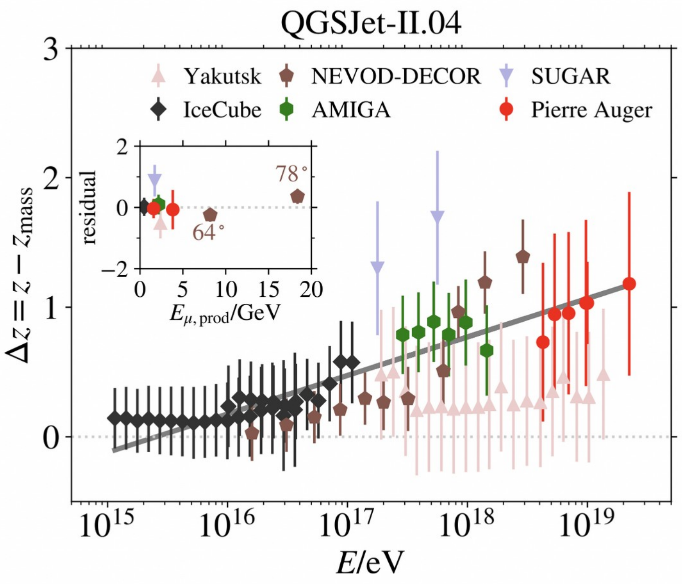
What about other experiments?

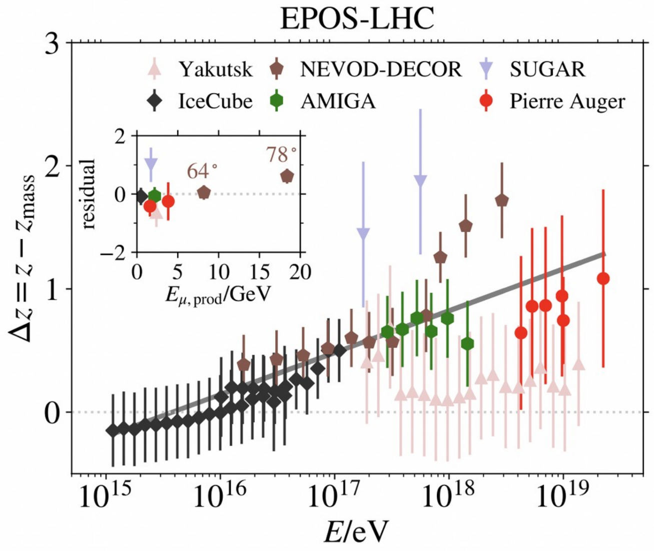
A **W**orking Group on **H**adronic **I**nteractions and **S**hower **P**hysics (WHISP) was created in 2018.

Combined analysis of Muon Density measurements from air shower experiments with different:
- measurement techniques
- zenith angle ranges
- energy thresholds

$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p}$$

Growing muon deficit in the simulations above 10^{16} eV (8σ significance).





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Summary

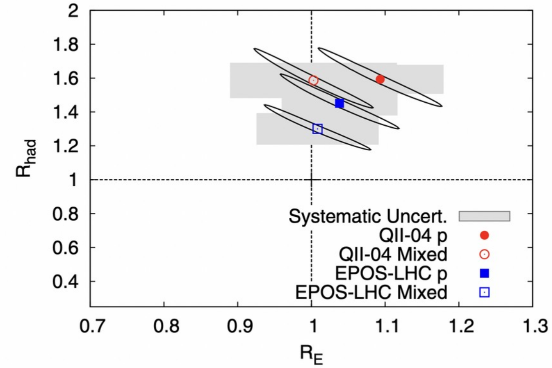
- UHECR allow access to interactions in high energy regions unavailable at human-made accelerators.

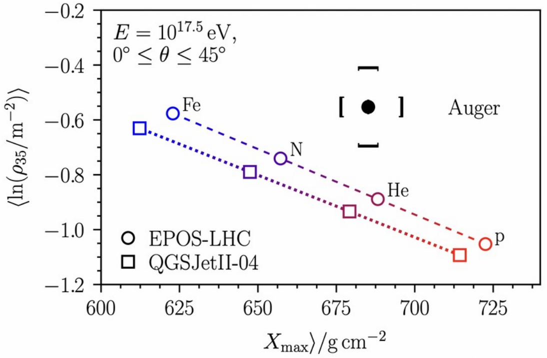
- Auger's hybrid design enables measurements from both EM and Muon components of air showers.

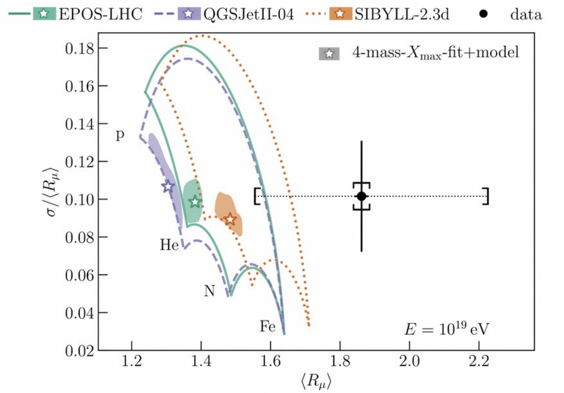
- Estimates of mass composition from EM component are in conflict with measurements more sensitive to the Muon component
  → muon deficit in simulations (from up to date hadronic interaction models)

- **AugerPrime:** upgrade of the Auger Observatory to disentangle EM and Muon components
  → increase sensitivity to hadronic interactions and mass composition.

arXiv:1604.03637







Thanks!

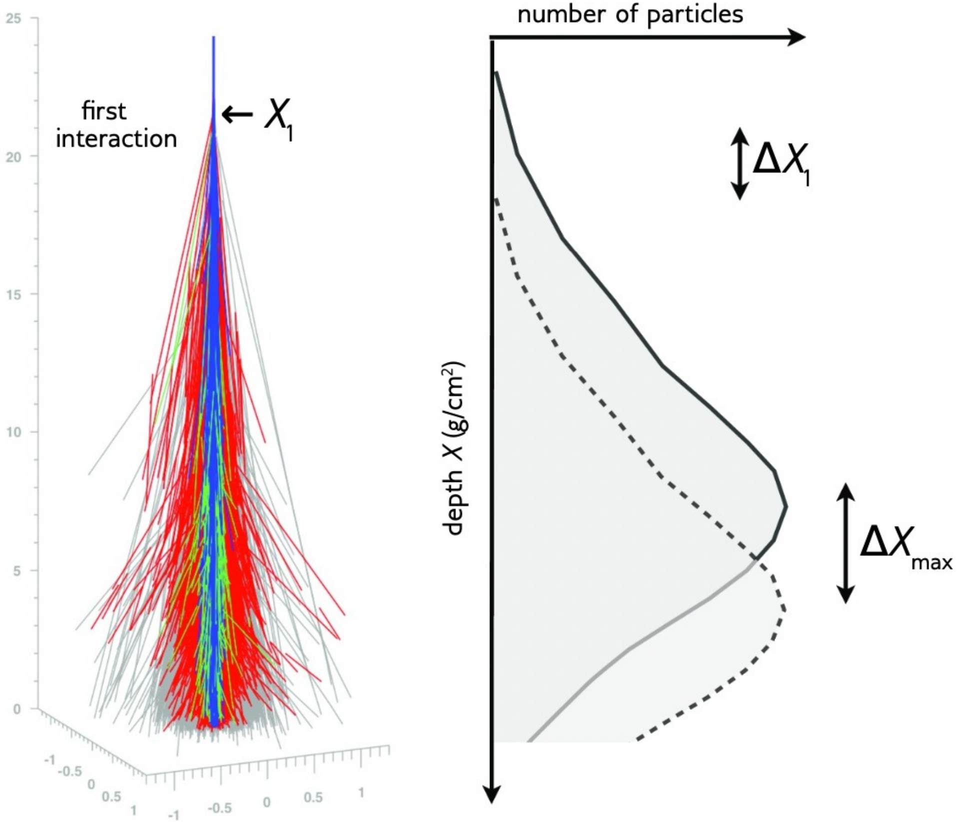
BACKUP

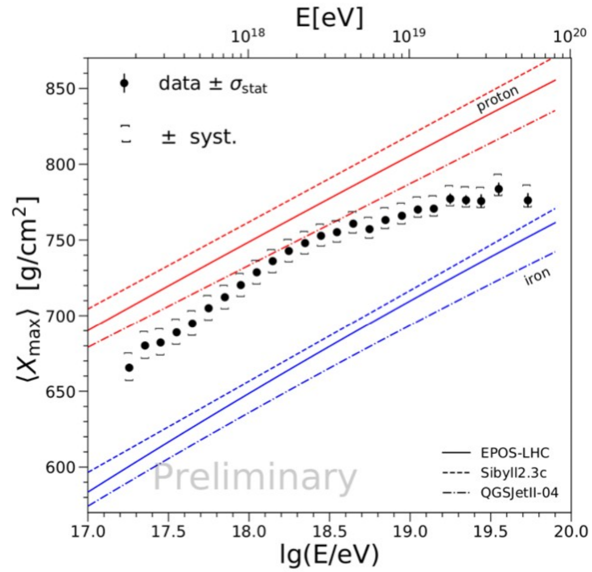
X_{max} measurements

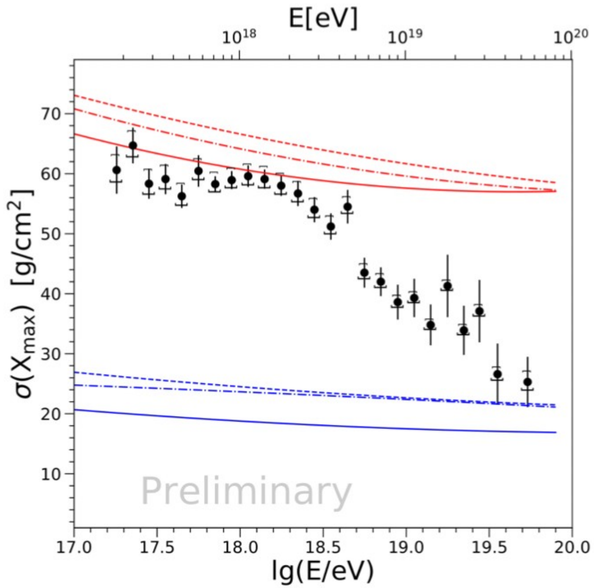
FD – most direct measurement of

→ depth of shower maximum

→ fluctuations



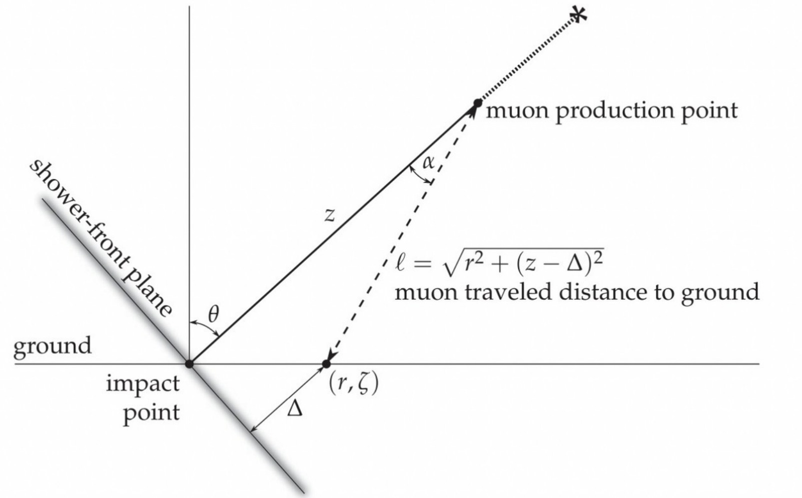


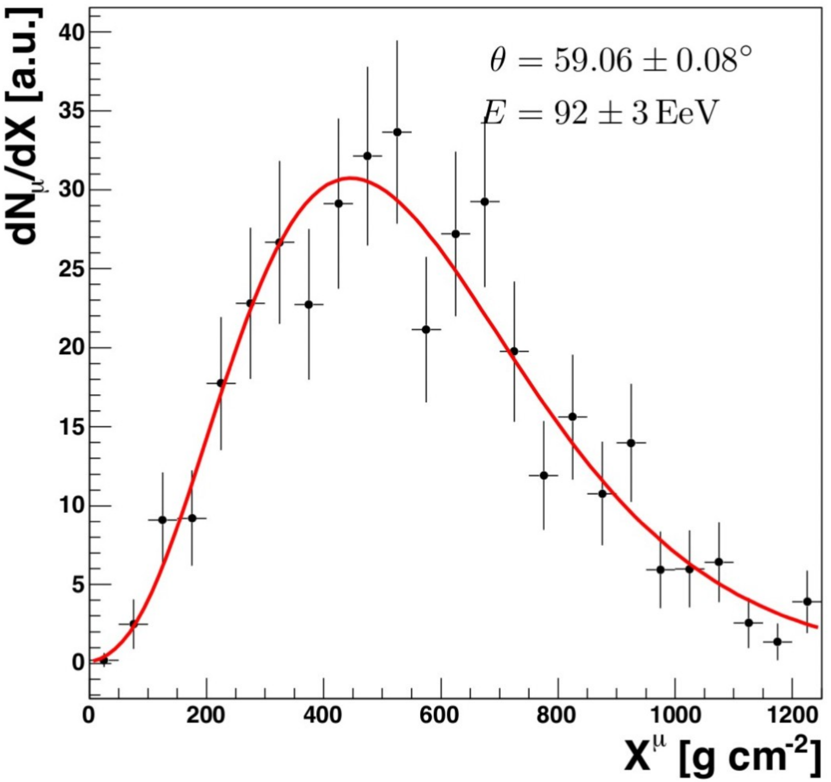


Muon Production Depth

Assumptions:
- muons are produced along the shower axis
- muons have straight trajectories

Given shower geometry and arrival times, muons can be mapped to its production depth.





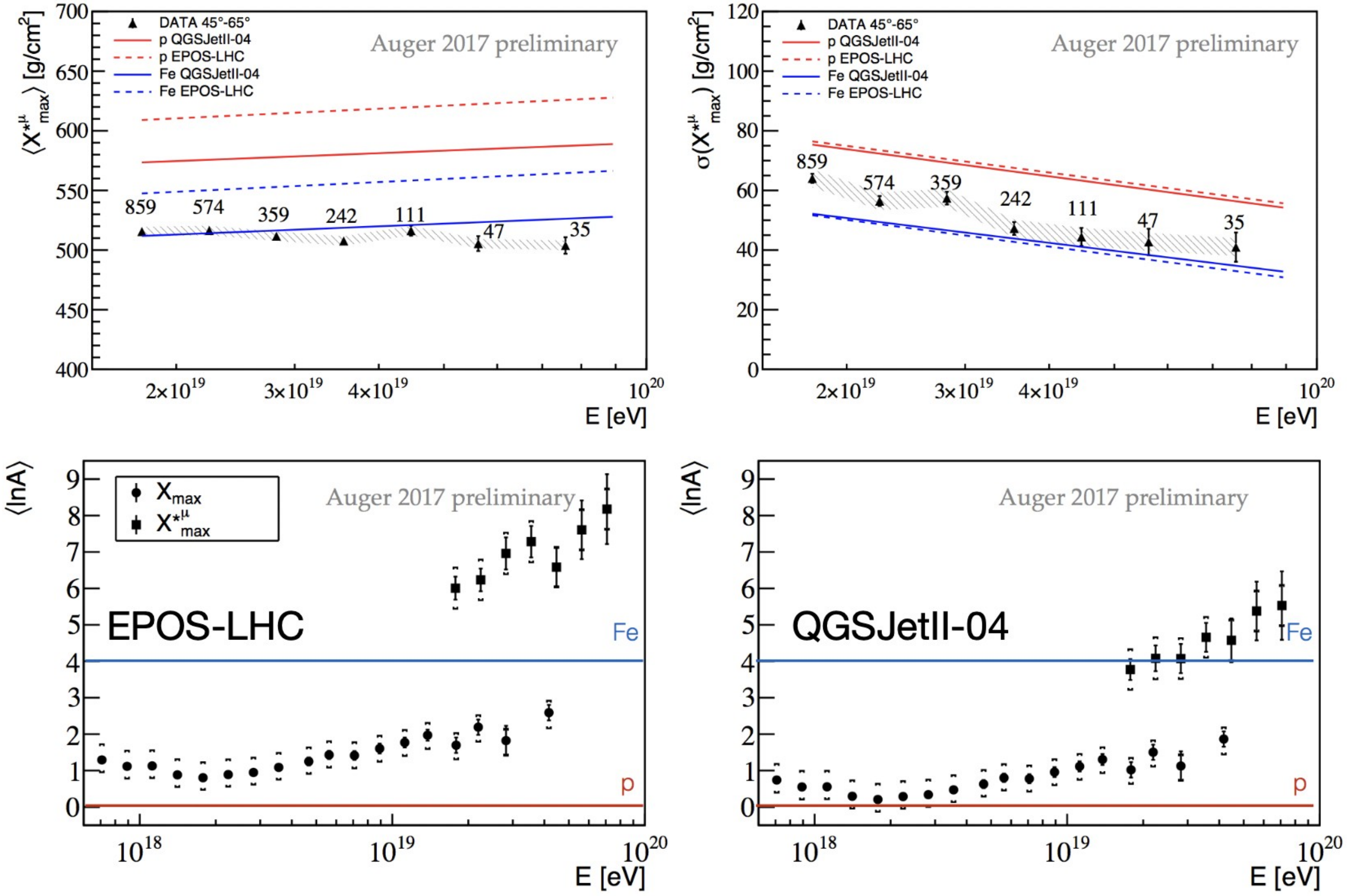
Phys. Rev. D 90, 012012 (2014)

Muon Production Depth

Energy > 2×10^{19} eV
Zenith angle: 55°- 65°
481 SD events

Data shows a flatter trend than pure primaries.
X^{μ}_{max} can be used to constrain the models.

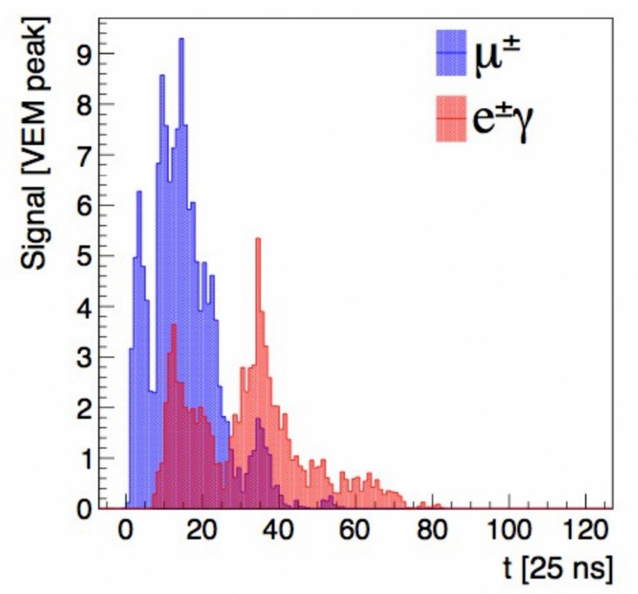
X_{max} and X^{μ}_{max} results are incompatible.
No model provides a consistent description of EM and MPD profiles.

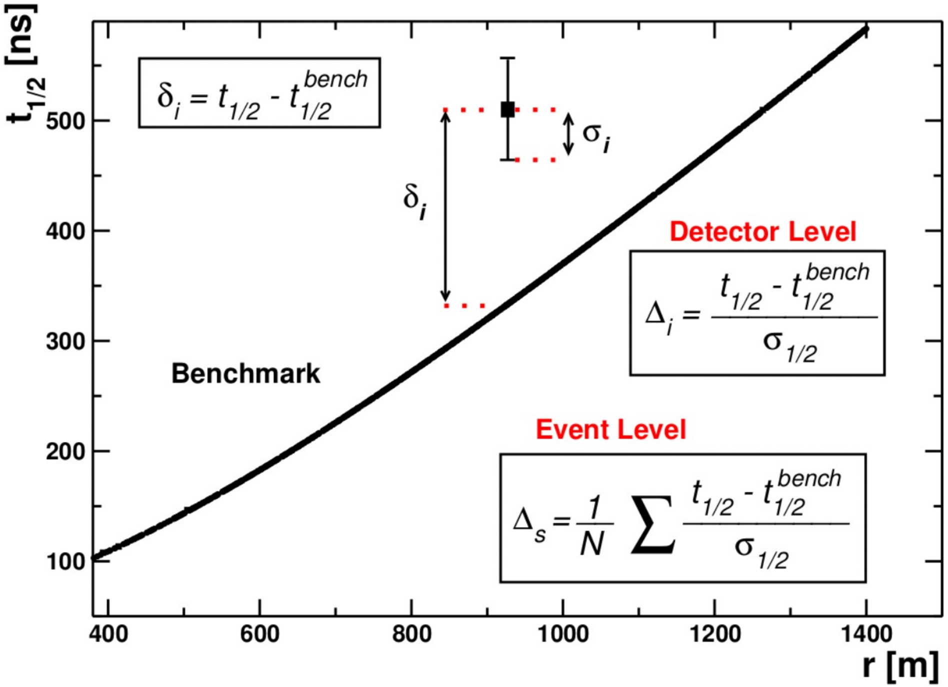


Phys. Rev. D 90, 012012 (2014)

Risetime Measurement

- SD signals in vertical events.
- Risetime = time between signal reaching 10% and 50% of total signal used.
- Sensitive both to EM and Muon components





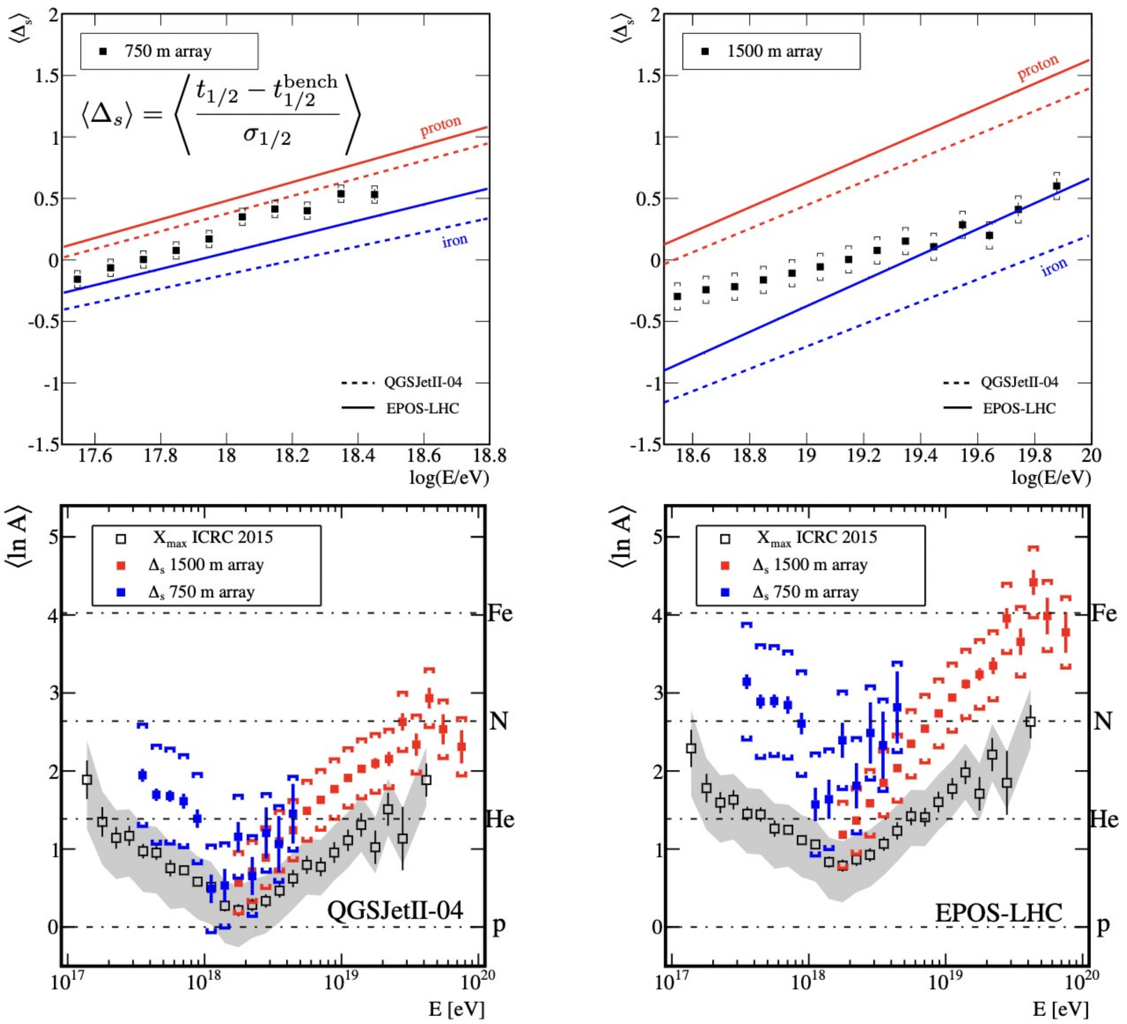
Phys. Rev. D 96, 122003 (2017)

Risetime Measurement

Energy > $10^{17.5}$ eV
Zenith angle < 45°
481 SD events

Measurements suggest an increase of the mean mass with energy (if hadronic models are correct).

Composition from X_{max} (EM) and risetime measurements (EM+Muon) differ but follow a similar trend.



Phys. Rev. D 96, 122003 (2017)