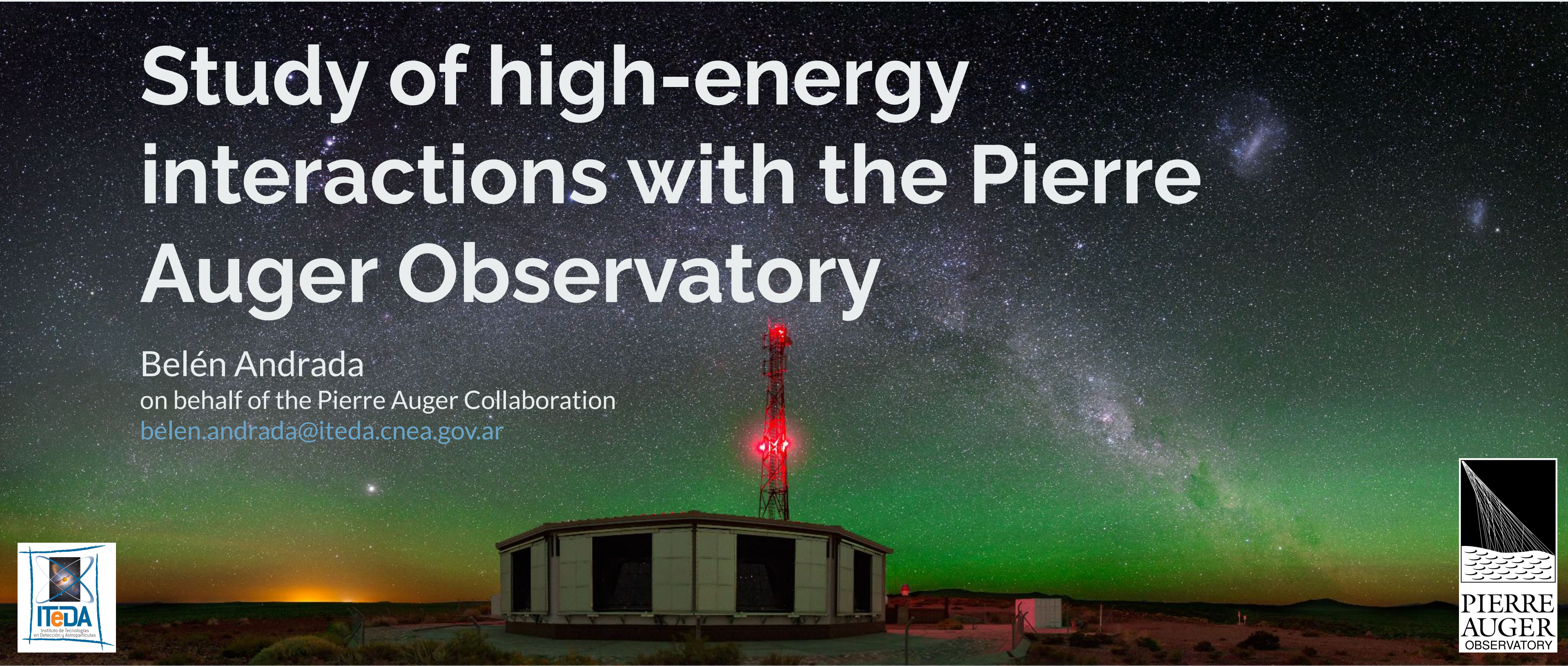

Study of high-energy interactions with the Pierre Auger Observatory

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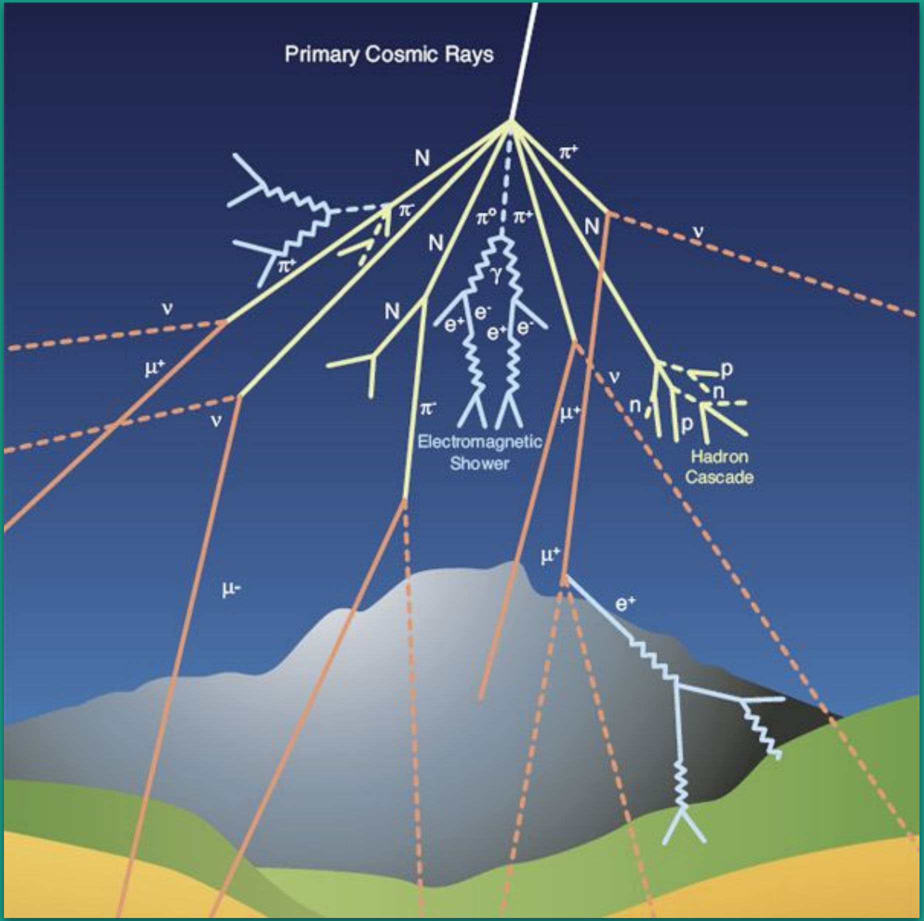
Outline

Introduction

Muon measurements @ Auger

Other muon studies

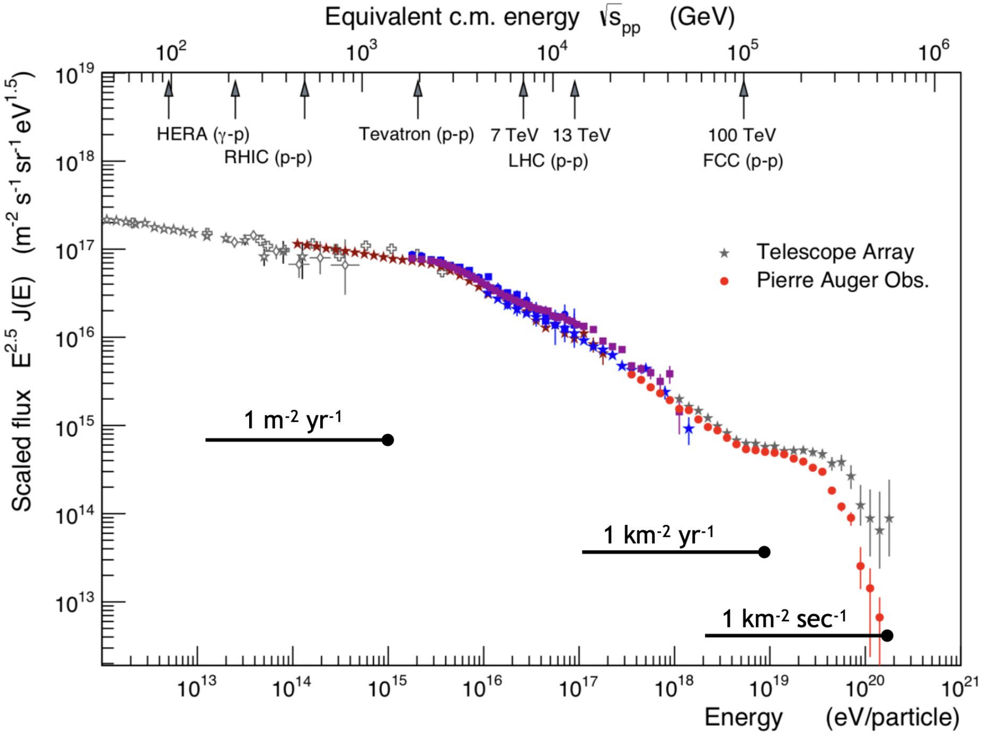
Introduction



Ultra high energy cosmic rays

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

But their flux is so low that they can't be measured directly
→ **extensive air showers**



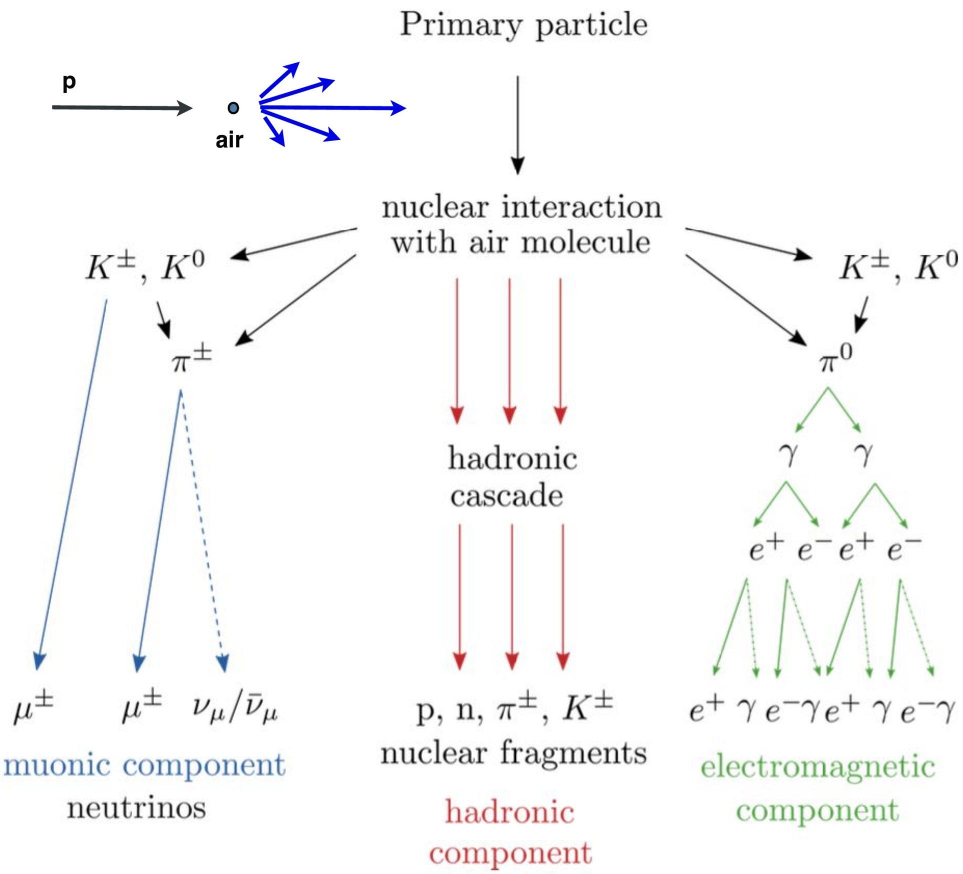
Extensive air showers

EM:

- mainly from the decay of neutral pions
  + photoproduction
- well understood
- ~90% of total energy

Muonic:

- mainly from the decay of charged pions
  + muon decay + low energy pion decay
- large model uncertainties
- ~10% of total energy

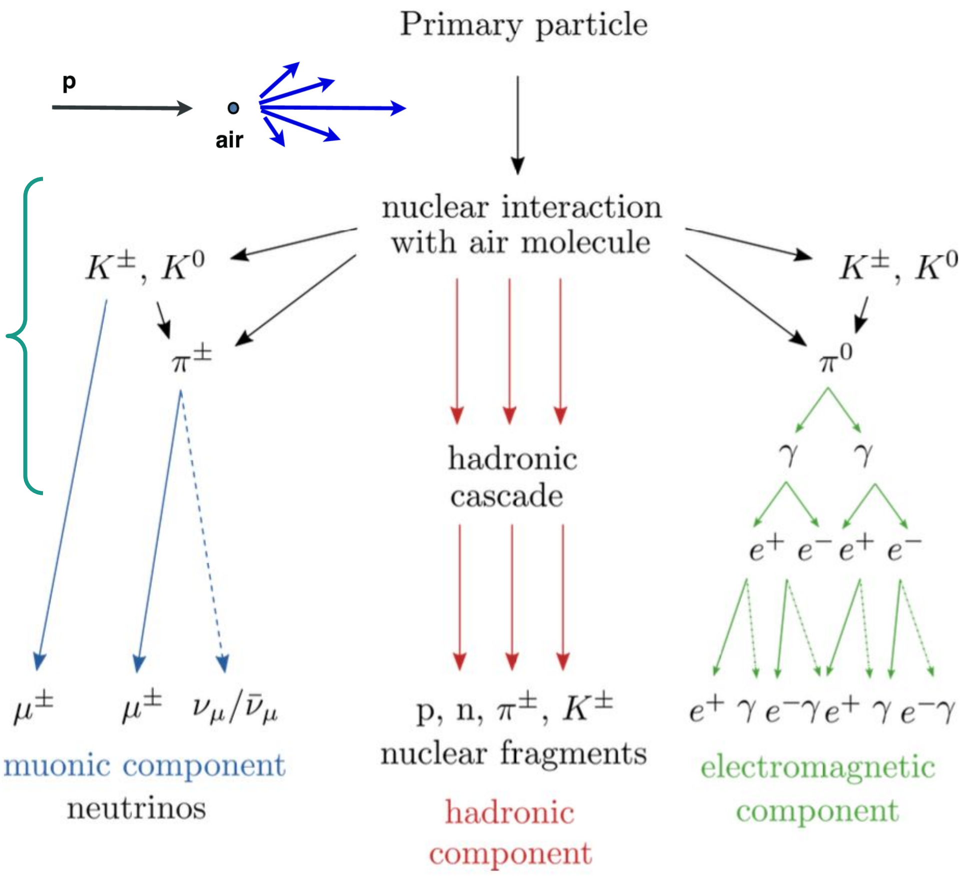


Extensive air showers

There are different models that describe high energy interactions tuned to LHC data:

- EPOS-LHC
- QGSJet-II-04
- SIBYLL-2.3d
- ...

High energy hadronic interactions



Highlights of The Pierre Auger Observatory
Eva Santos
Monday, 9.45 am.

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

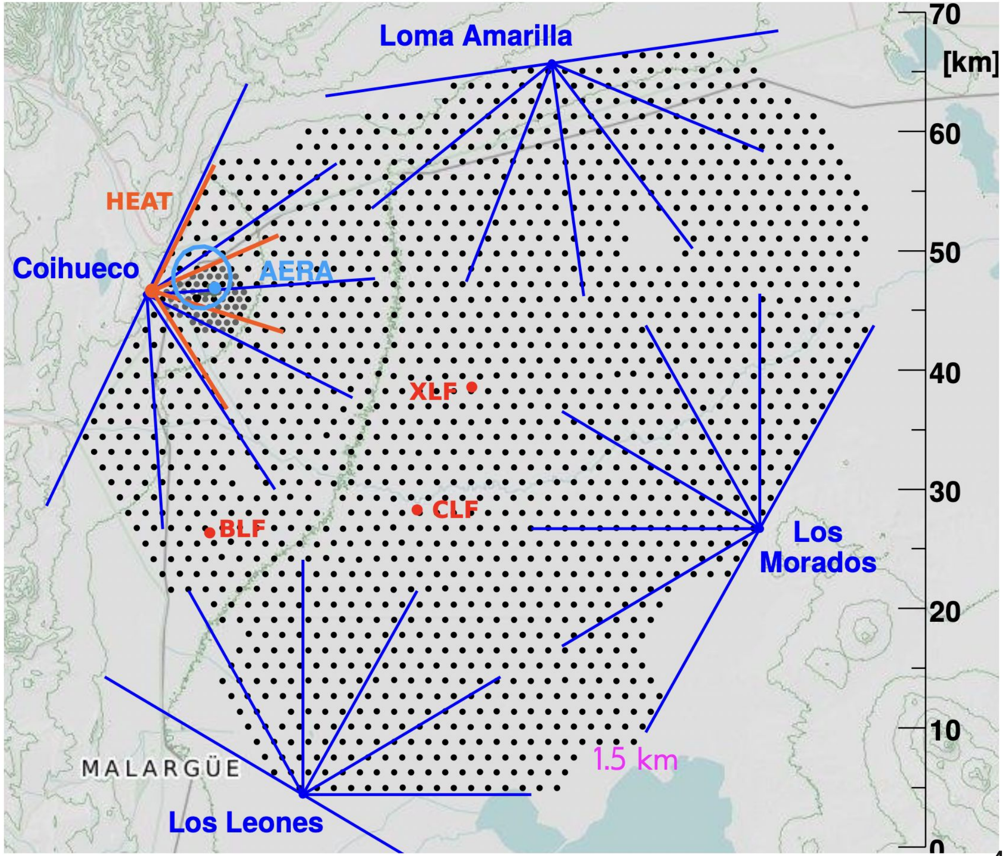
Fluorescence Detector (FD):

4 sites, 27 telescopes

E > 10^{17} eV

15% duty cycle

Location: Malargüe, Mendoza, Argentina.



Observables of interest @ Auger

Depth of maximum development X_{max}

FD

Direct measurement

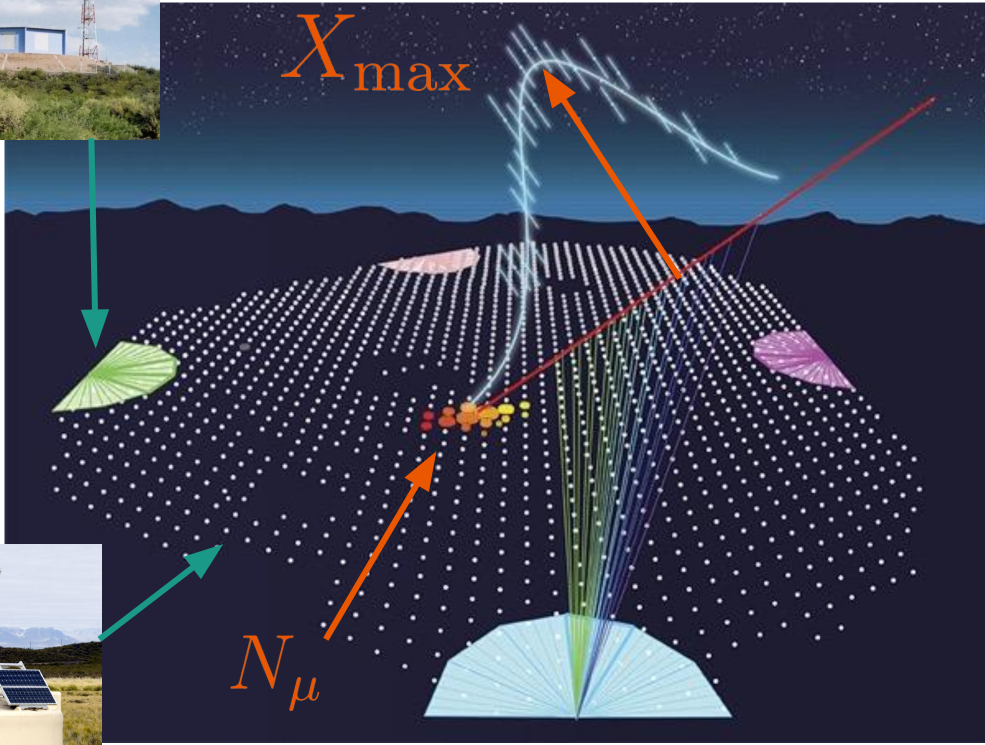
Currently the most precise mass estimator

Number of muons at ground N_{μ}

SD

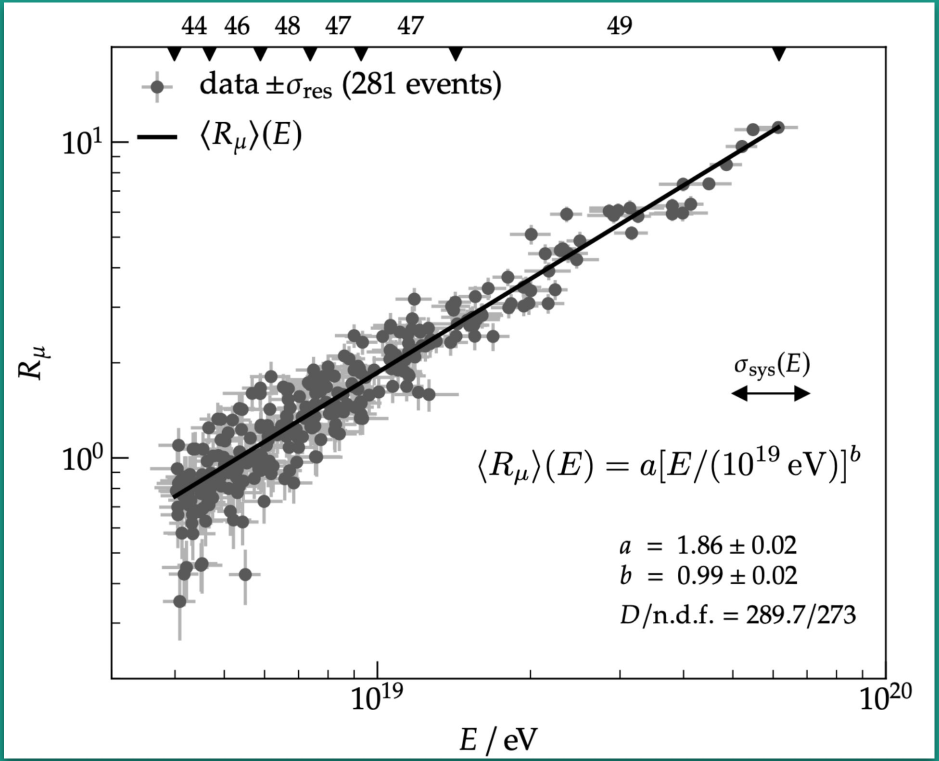
Arrival time of secondary particles at ground

FD: calorimetric measurement of E



SD: E estimator via $S(r_{opt})$

Muon measurements @ Auger

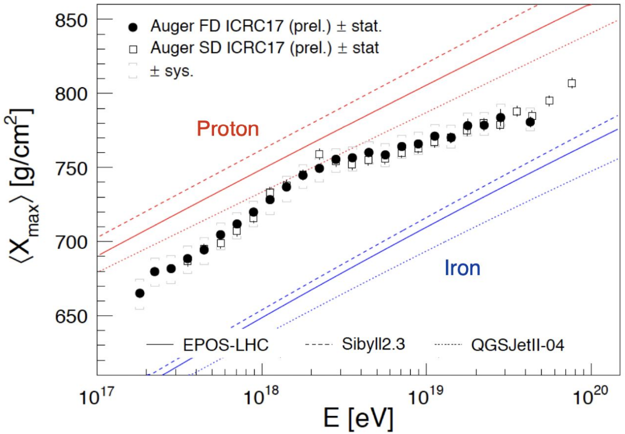


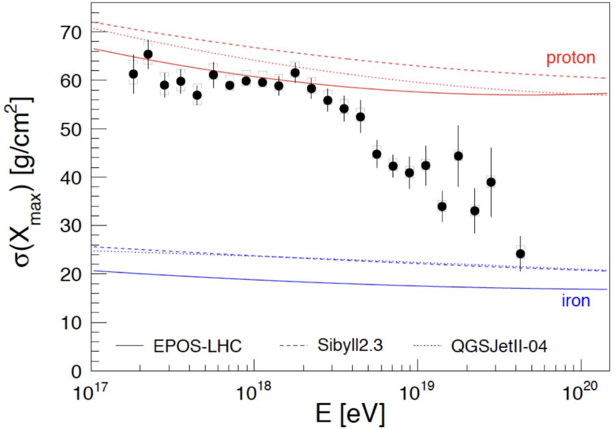
X_{max} distributions

Evolution towards lighter nuclei up to $10^{18.27}$ eV, then the trend reverses.

Measurements of $<X_{max}>$ and $\sigma(X_{max})$ are consistent with all hadronic interaction models.

Composition fits can be performed to obtain primary fractions for any given energy.

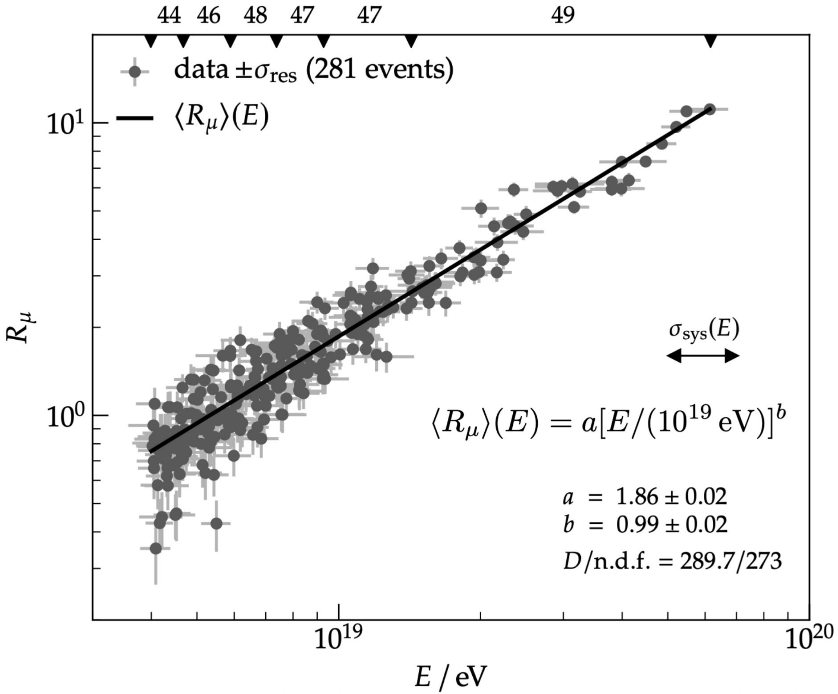




Number of muons from inclined showers

R_μ: integrated number of muons at ground divided by a reference value given by N_μ in simulated showers at 10^{19} eV

Fitted function: considering detector response, physical fluctuations (**σ**) and the probability distribution of hybrid events



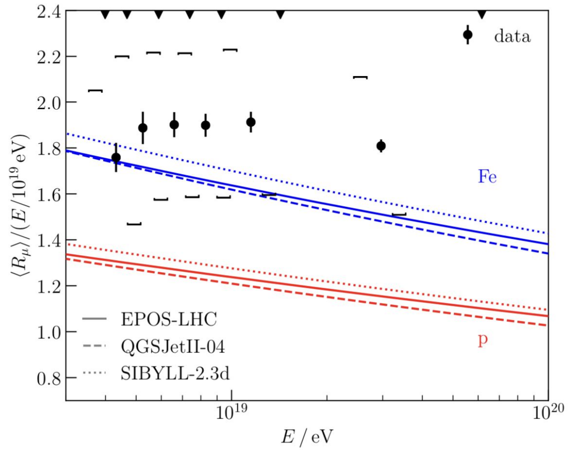
Number of muons from inclined showers

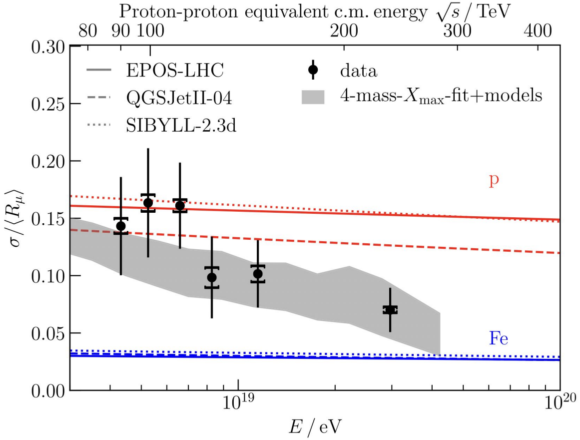
Average number of muons: the measurement **does not** fall within the expected range from the models

Relative fluctuations of the number of muons: the measurement **does** fall within the expected range from the models (grey area is expected region using mass composition information from X_{max} studies).

Suggests a small effect at every stage of the shower (rather than a discrepancy in the first interaction).

What happens if we look at both observables simultaneously?



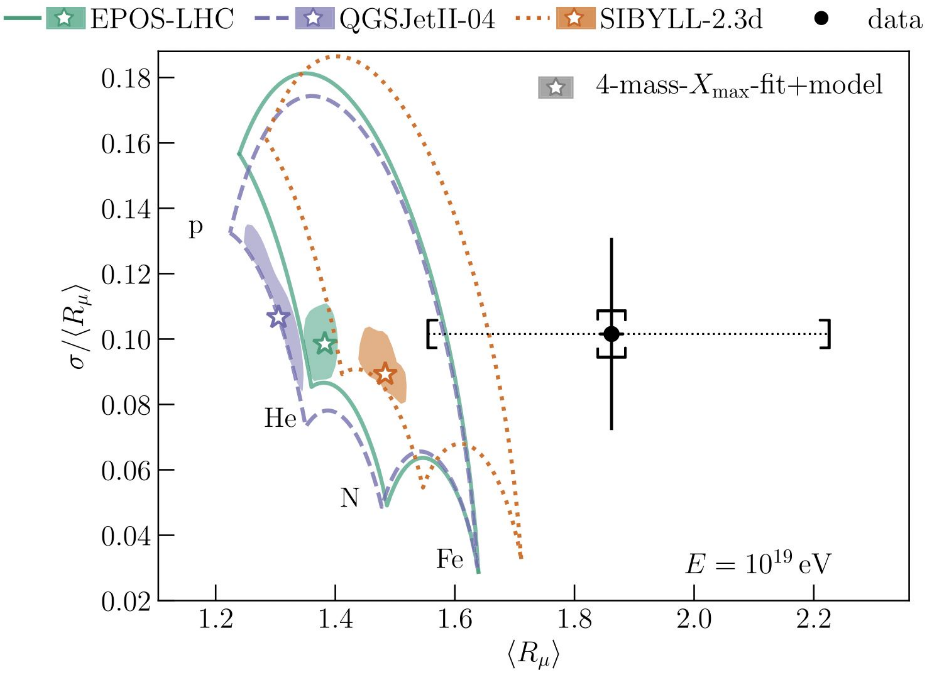


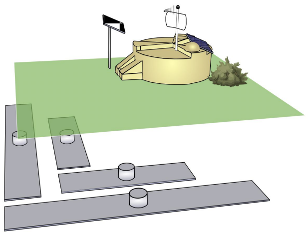
Number of muons from inclined showers

Stars and shaded regions: allowed regions considering statistical and systematic uncertainties from X_{max} measurements.

Data point: at 10^{19} eV, with statistical (error bars) and systematic (square brackets) uncertainties.

None of the predictions is consistent with the measurement.





Number of muons with UMD

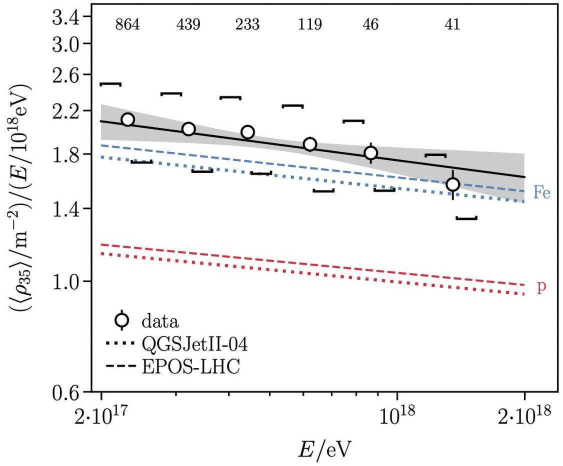
Underground Muon Detector: 30 m^2 scintillators buried at 2.3 m underground next to SD stations in the low energy region. Part of Auger Prime, still in deployment.

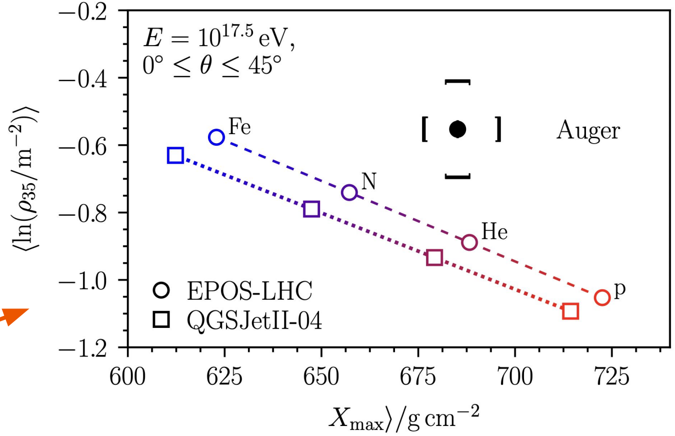
Lower energy measurements (closer to LHC data).

First direct measurement of muon content.

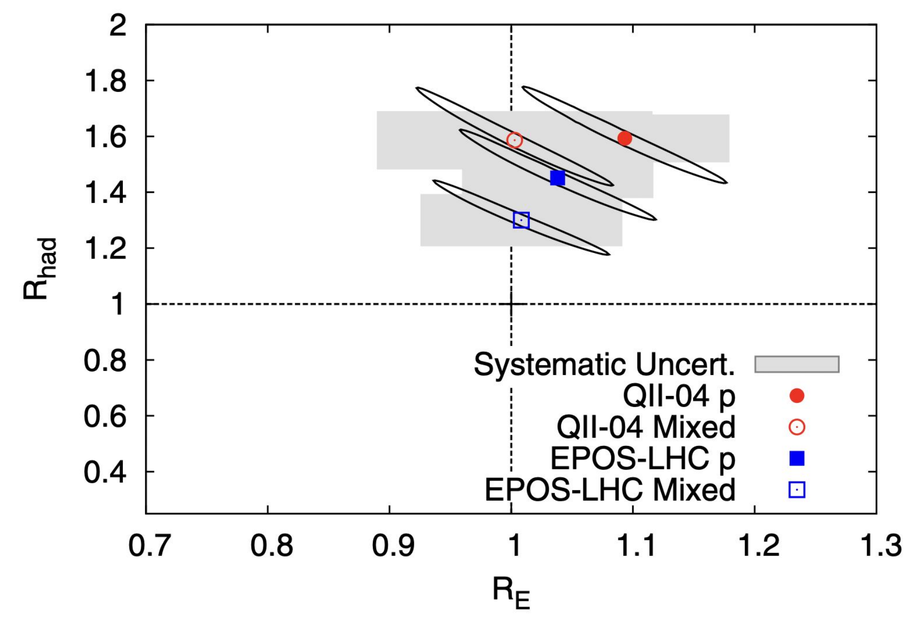
Larger muon content in data than in predictions, but compatible with iron primaries.

When X$_{max}$ information is considered, data is in tension with models.





Other muon studies @ Auger

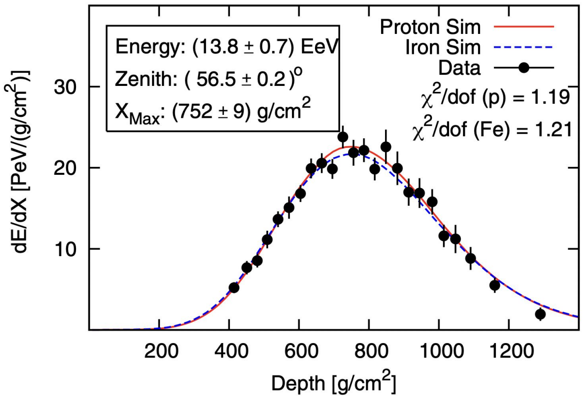


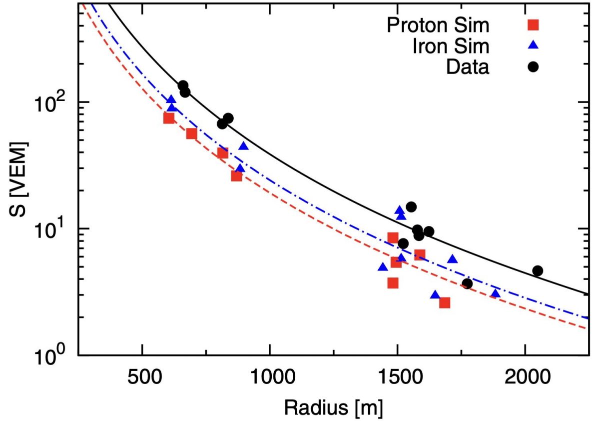
Muon rescaling with hybrid, vertical showers

Find simulations which match FD profile, **for each event.**

Compare SD signals for simulations and data.

Rescale muon content until simulated SD signals best matches data.





Muon rescaling with hybrid, vertical showers

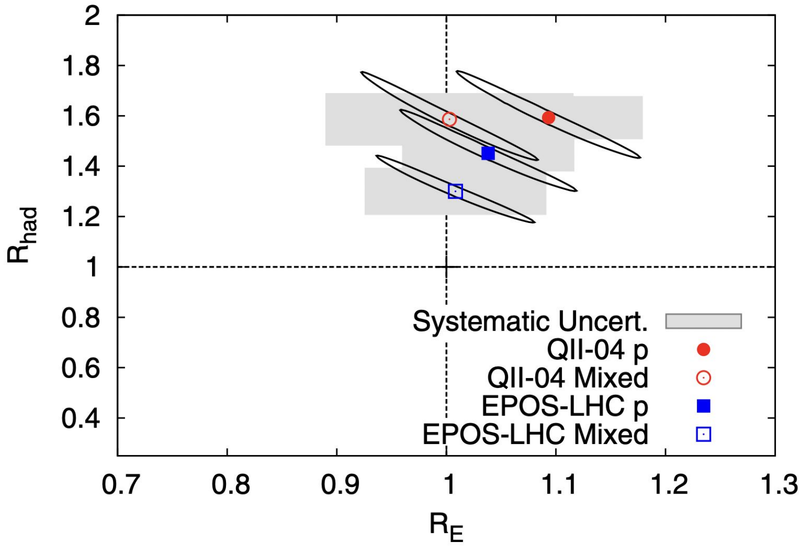
Find simulations which match FD profile, **for each event.**

Compare SD signals for simulations and data.

Rescale muon content until simulated SD signals best matches data.

No energy rescaling is needed.

The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models.



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	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

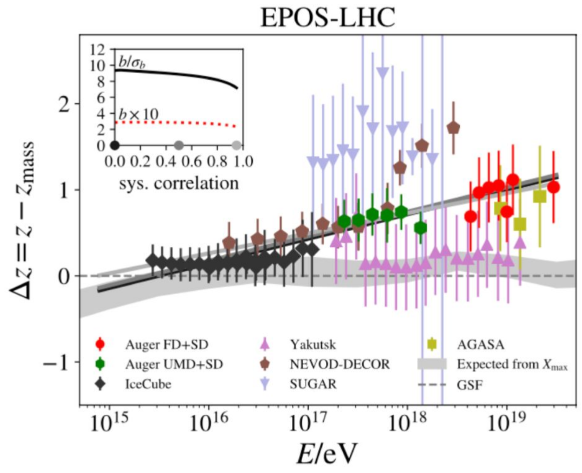
$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p}$$

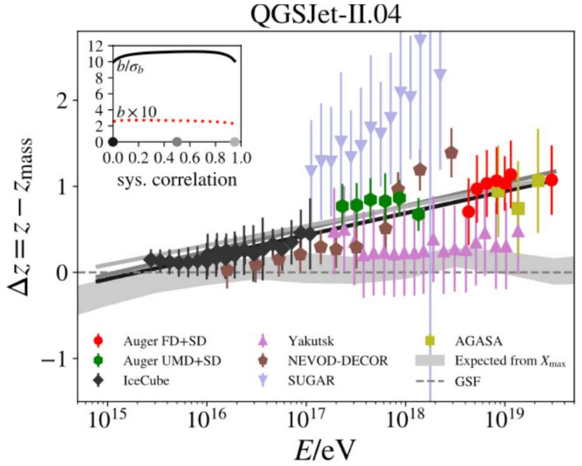
Working group on Hadronic Interactions and Shower Physics

Combined analysis of muon density measurements from air shower experiments with different

- measurement techniques
- zenith angle ranges
- energy thresholds for muon detection

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





X_{max} - S(1000) correlation

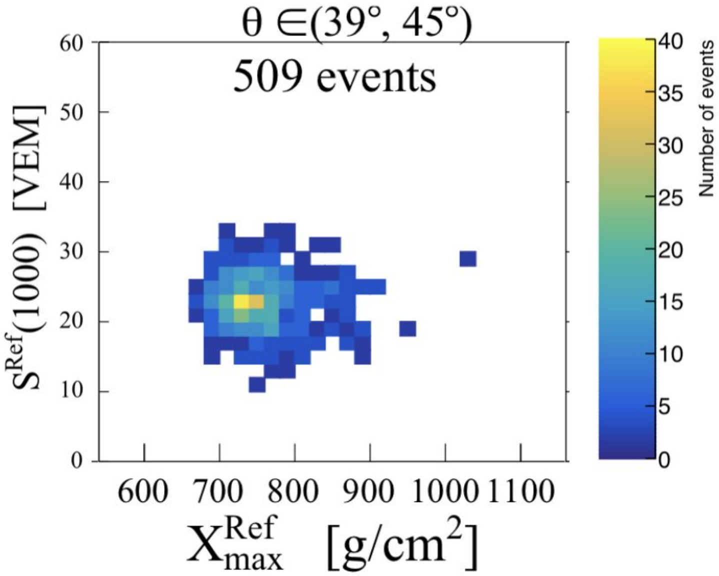
Hybrid measurements allow to test model consistency in more detail.

Aim to find which adjustments of simulated X_{max} and S(1000) are required for a consistent description of the measured two-dimensional distributions.

$$X^{\rm Ref}_{\rm max} \equiv \widehat{X^{\rm Ref}_{\rm max}} + \boxed{\Delta X_{\rm max}}$$

$$S^{\rm Ref}(1000) \equiv \widehat{S^{\rm Ref}(1000)} \cdot \underbrace{f_{\rm SD}(\theta)}_{R_{had}}$$

Final MC templates are a sum of templates of the form ϕ of individual primary species weighted by their relative fractions.



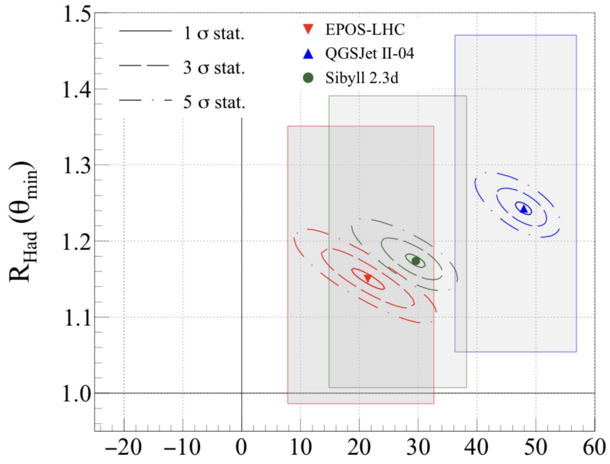
$$\phi = c \cdot f_{Gumbel}\left(X^{Ref}_{max}\right) \cdot f_{Gauss}\left(X^{Ref}_{max}, S^{Ref}(1000)\right)$$

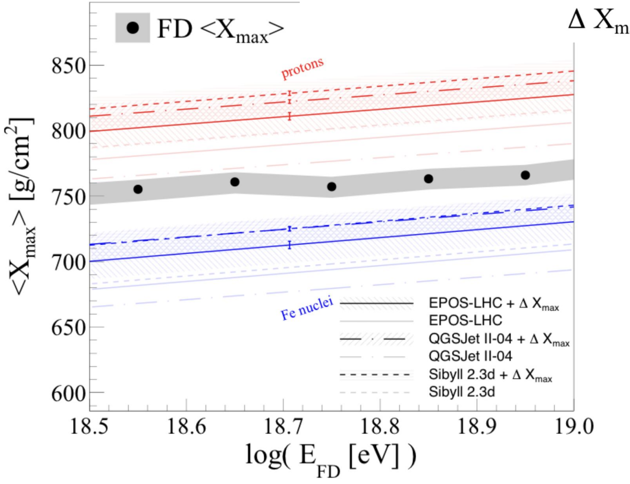
X_{max} - S(1000) correlation

Best fit of data requires multiple changes in hadronic interaction models:

- rescaling (increase) of muons (had. comp.)
- **shift in X_{max} toward higher mass (EM comp.)**

Deeper values of X_{max} are obtained which might indicate a decrease in the muon deficit in the simulations.





Take-home message

- The hybrid design of the Pierre Auger Observatory enables direct tests of hadronic interaction models at energies beyond human-made accelerators.
- Post-LHC hadronic interaction models are unable to provide a consistent description of air showers measured at the Pierre Auger Observatory
  - muon deficit established at 8σ
  - X_{max} also in tension with the data
- Auger Prime: upgrade of the Auger Observatory to disentangle EM and muon components → increasing sensitivity to hadronic interactions and mass composition

References

X_{max} distributions	Petrera, S. (2019). EPJ Web of Conferences, Vol. 208, p.08001
Number of muons with inclined showers	Phys. Rev. Lett. 126, 152002 (2021).
Number of muons with UMD	Eur. Phys. J. C (2020), 80:751.
Muon rescaling with hybrid events	Phys. Rev. Lett. 177, 192001 (2016).
WHISP	D. Soldin (WG), PoS (ICRC2021) 349.
X_{max} - S(1000) correlations	J. Vicha (Auger Coll.), PoS (ICRC2021) 310.

Thanks for your attention!

Any questions?

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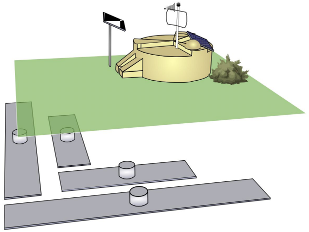
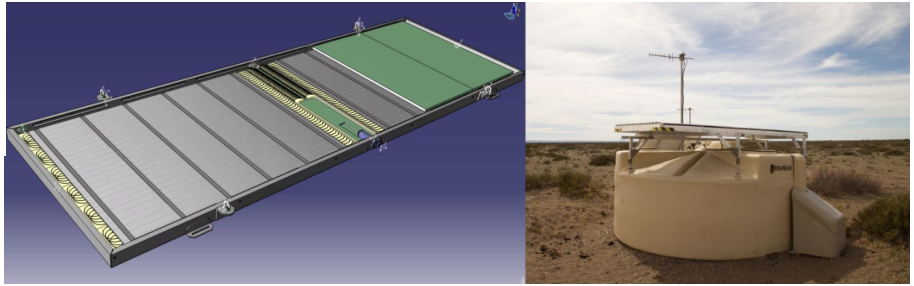
Backup

Auger Prime
Composition fits to X_{max}
Motivations for adjustments of MC prediction in X_{max}-S(1000) correlations
Primary fractions from X_{max}-S(1000) correlations
Muon production depth
Risetime measurement
Theoretical work to explain muon deficit

Auger Prime





3.8 m^2 scintillators (SSD) on each SD station

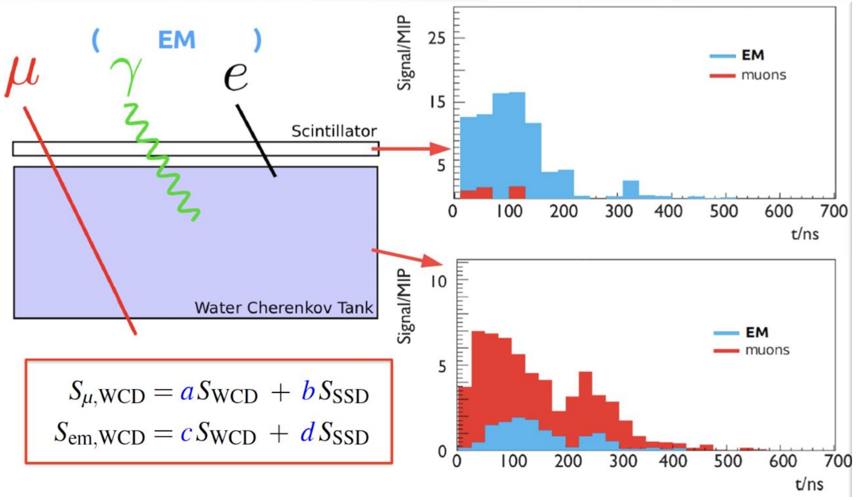
Upgrade SD electronics

Additional small PMT to increase dynamic range

Buried muon counters (UMD) in SD-750 stations

Increase FD uptime

Will increase accuracy of muon measurements also for individual events.



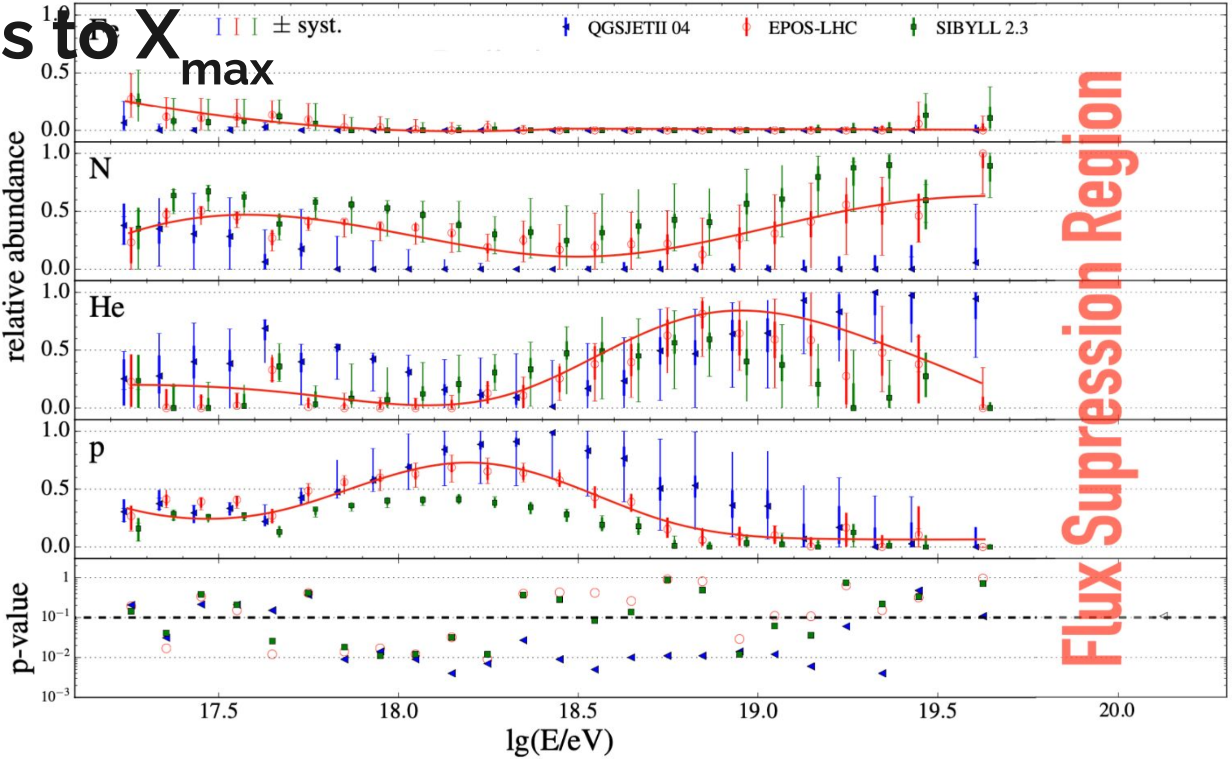
$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

$$S_{\mathrm{em,WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

Composition fits to X_{max}

Four composition (p, He, N, Fe) fit to X_{max}.

Reasonable ability to describe X_{max} distribution data.



35th ICRC, PoS (2017) 506

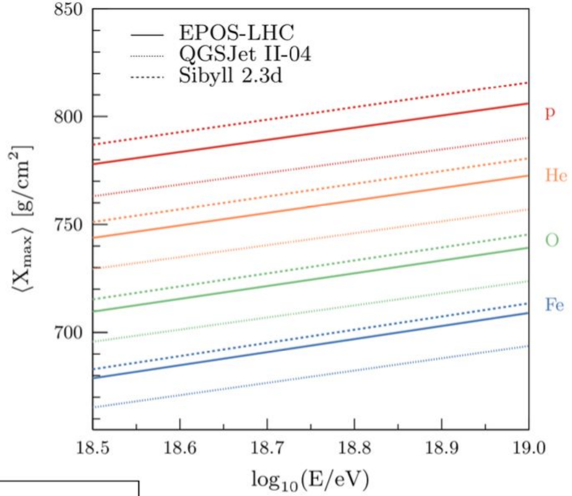
Motivation for adjustments of MC predictions

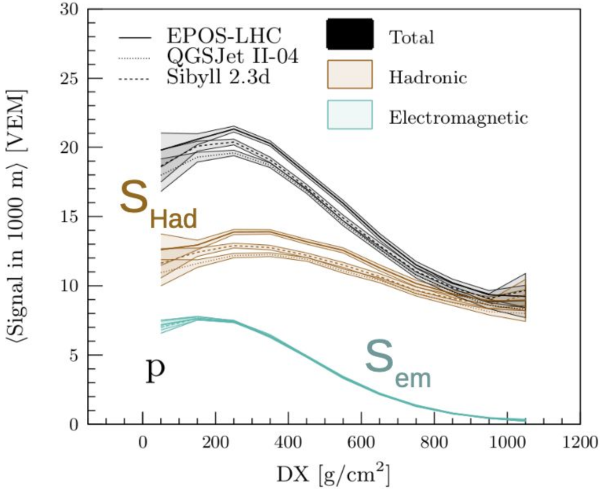
Properties of shower universality:

- $S(1000) = S_{had} + S_{EM}$
- S_{EM} very universal

Main differences between model predictions:

- Scale of $<X_{max}>$ and $<S_{had}>$ are approx. primary and energy independent.





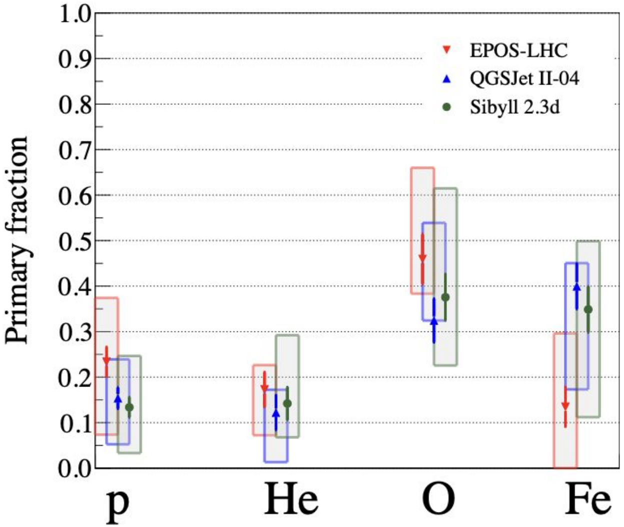
$DX = 880\, g/cm^2/\cos(\theta) - X_{max}$

J. Vicha (Auger Coll.) at UHECR 2022

Primary fractions from X_{max}-S(1000) correlations

Shifts from simulated Xmax values lead to a heavier mass composition compared to the inferences with the unaltered hadronic interaction models.

The inferences on the mass composition are much less model dependent.



J. Vicha (Auger Coll.) at UHECR 2022

$DX = 880\, g/cm^2/\cos(\theta) - X_{max}$

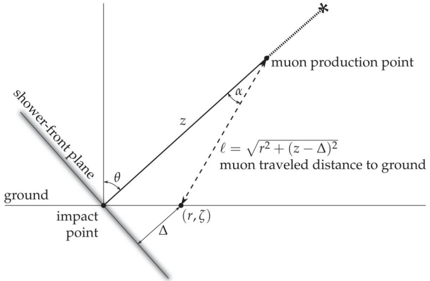
Muon Production Depth

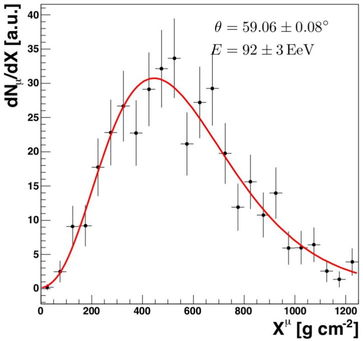
Assumptions:

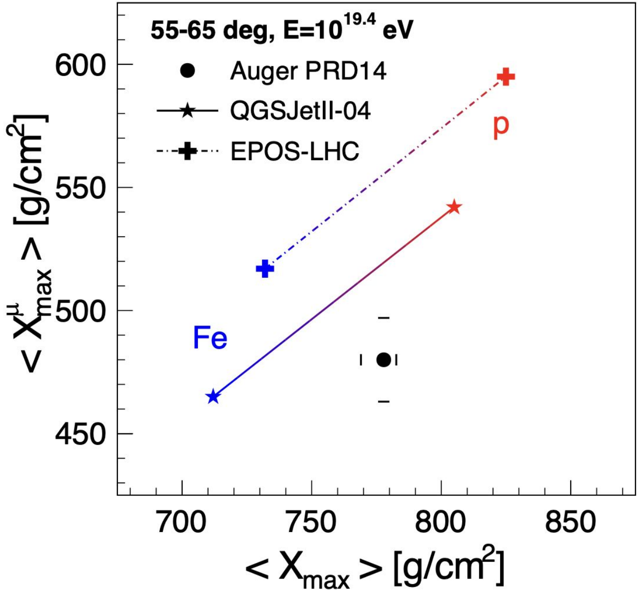
- muons are produced along the shower axis
- muons have straight trajectories

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

No model provides a consisten description of EM and MPD profiles







Phys. Rev. D 90, 012012 (2014)

Risetime measurements

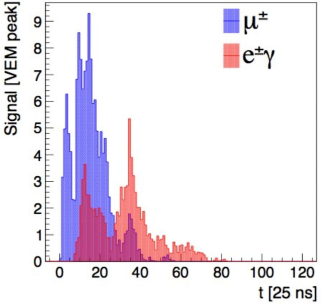
SD signals in vertical events.

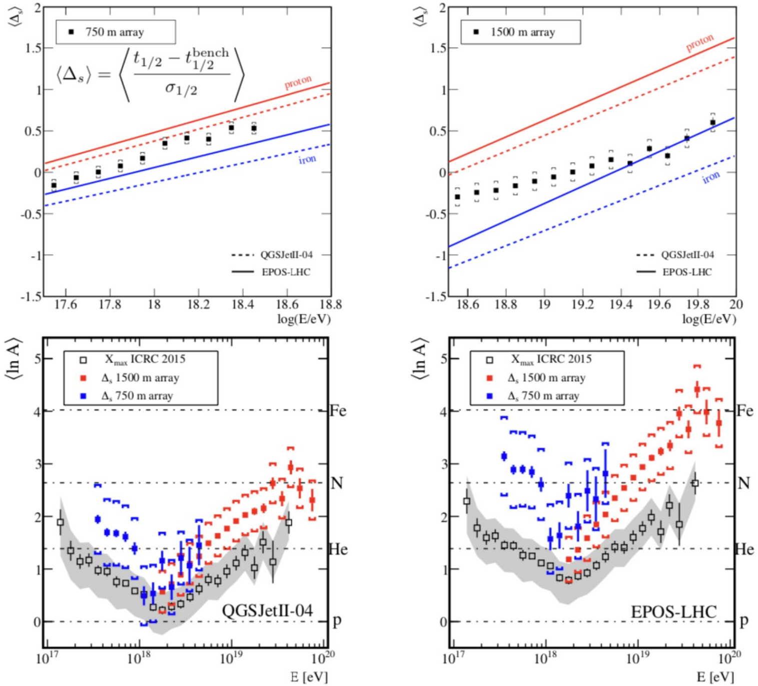
Risetime = time between signal reaching 10% and 50% of total signal used.

Sensitive both to EM and Muon components.

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)

Theoretical models to explain muon deficit

Core-Corona Model	arXiv:1902.09625 (2019)
Strange Fireball	Phys. Rev. D 95 no.6, 063005 (2017)
String Percolation	arXiv:1209.6474 (2012)
Chiral Symmetry Restoration	EPJ Web Conf. 53, 07007 (2013)
Increasing Inelastic Cross Section	arXiv:1902.11271 (2019)
Lorentz Invariance Violation	Frascati Phys. Ser. 58, 274 (2014)

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