Ultra-high-energy hadronic physics at the Pierre Auger Observatory: muon measurements

PIERRE AUGER OBSERVATORY

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

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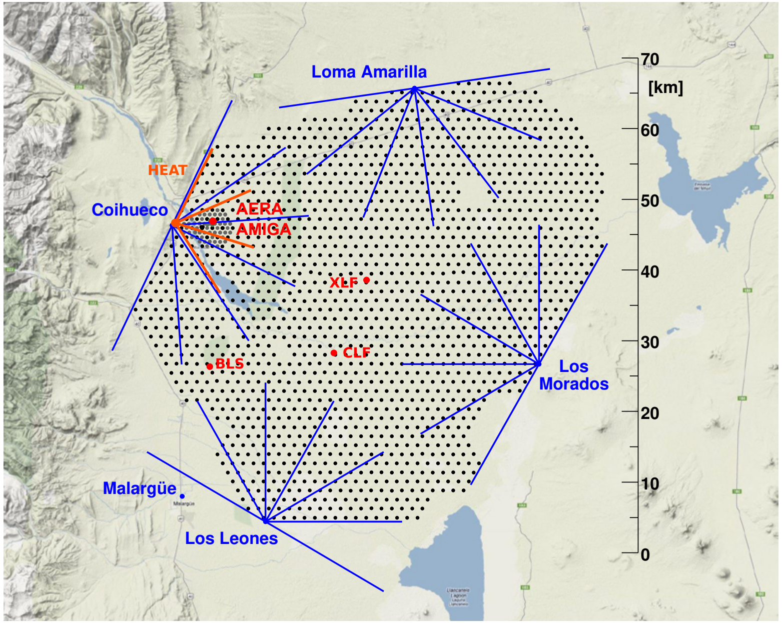
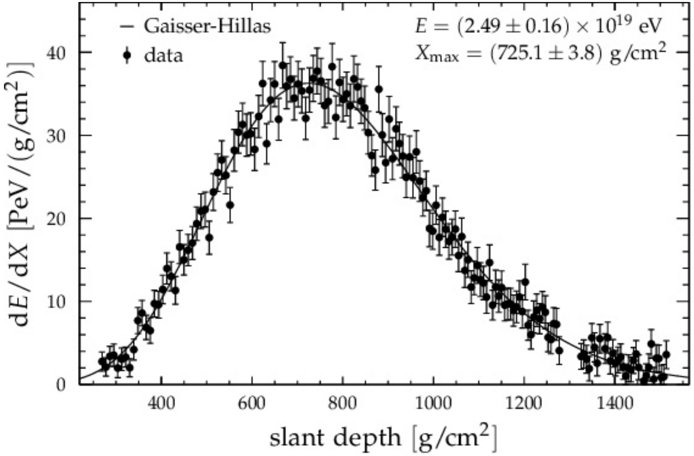
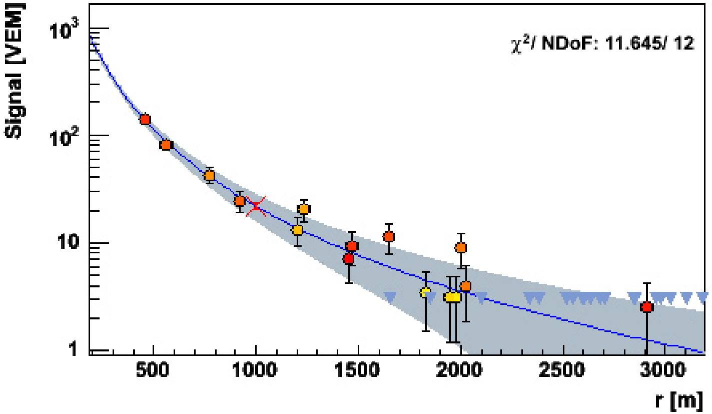
Pierre Auger Observatory

Fluorescence detector (FD): longitudinal shower profile

Surface detector (SD): particles arriving at ground







Hadronic interactions in cosmic ray showers

Heitler-Matthews model (Astropart. Phys. 22 (2005) 387)

$$X_{\max} \approx \lambda_{\mathrm{r}} \ln[E_0/\xi_{\mathrm{c}}^{\mathrm{e}}] + X_0 - \lambda_{\mathrm{r}}\{\ln[3N_{\mathrm{ch}}] + \ln[A]\}$$

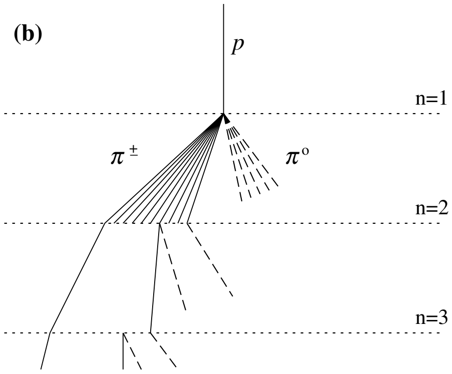
$$N_\mu \approx \left(\frac{E_0}{\xi_{\mathrm{c}}^{\pi}}\right)^{\beta} A^{(1-\beta)} \qquad \beta \approx 1 - \frac{\kappa}{3\ln[N_{\mathrm{ch}}]} > 0.9$$

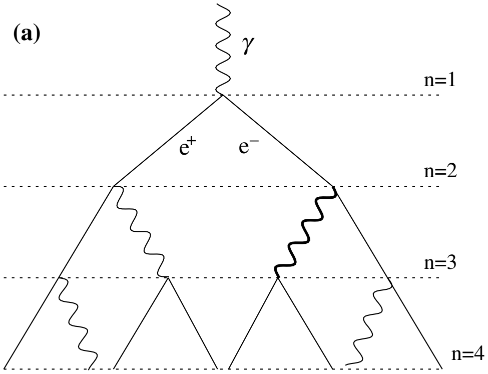
X_{max} and N_μ sensitive to both interaction properties
- multiplicity N_{ch} and elasticity κ

and primary mass A

$$\frac{E_{\mathrm{em}}}{E_0} = 1 - \left(\frac{E_0}{\xi_{\mathrm{c}}^{\pi} A}\right)^{\beta-1} \qquad \xi_{\mathrm{c}}^{\pi} \approx 20\,\mathrm{GeV}$$

~ 90 % for 10^{19} eV protons – showers dominated by EM particles!

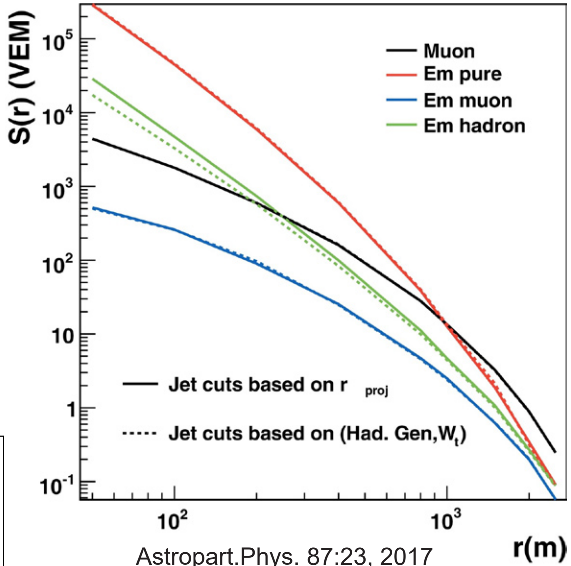




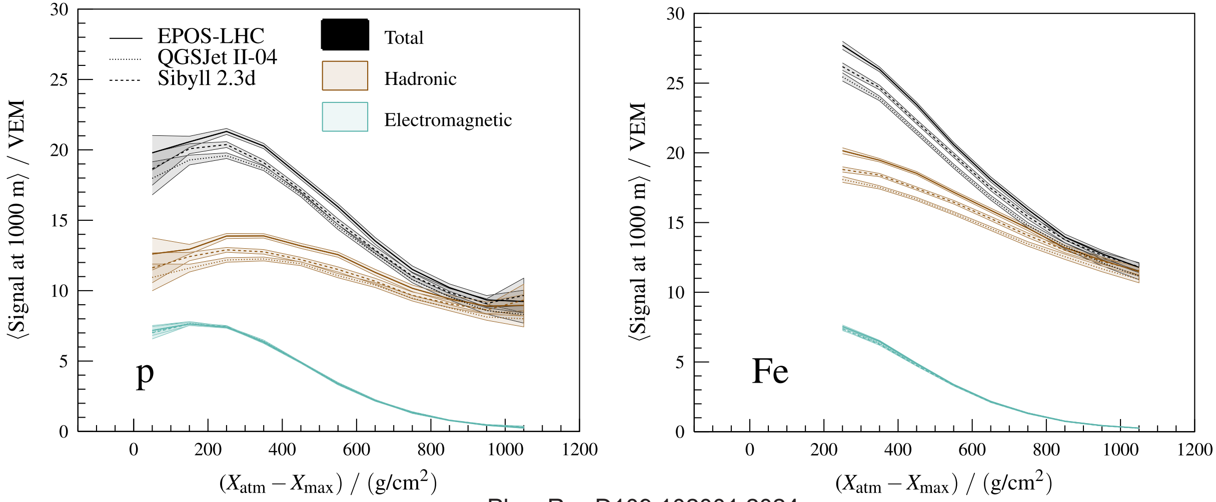
The importance of muons

- 4-component shower model:
  - pure EM component
  - muons, EM from decay, EM from "jets" = hadronic component

- pure EM component universal, changes mainly with distance to X_{max}



Astropart.Phys. 87:23, 2017



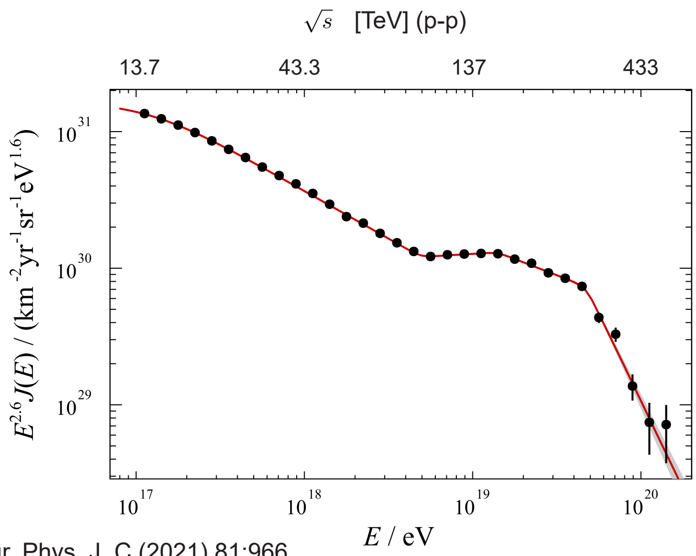
Phys.Rev.D109:102001,2024

- muons: small fraction of energy, large fraction of information on hadronic interactions!

Hadronic interactions and UHECR

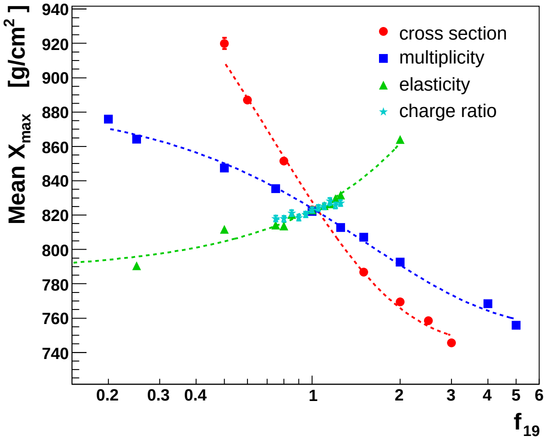
Primary interactions of CR observed at Auger mostly above the c.m.s energy of LHC (for p-p collisions)

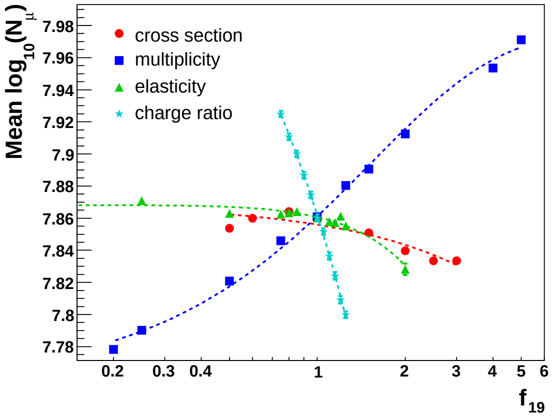
- even at LHC energy, models uncertain due to lack of forward measurements
- below LHC energy: uncertainties in nuclear and pion interactions etc.



Eur. Phys. J. C (2021) 81:966

Models predict interaction properties above experimentally accessible data
- modifications of predictions have strong impact on air-shower observables



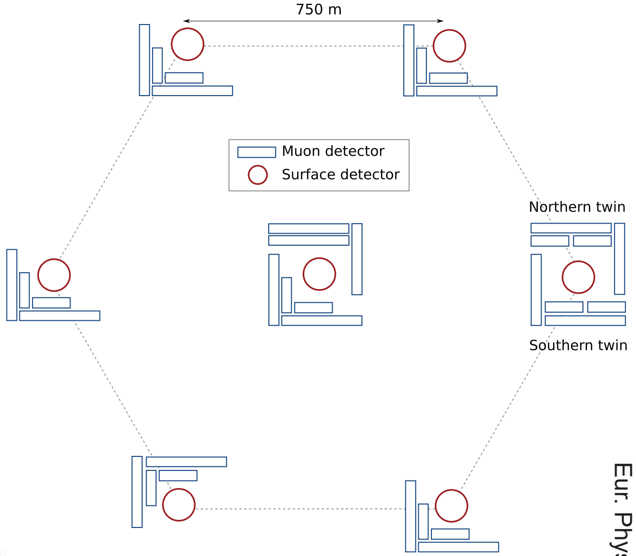


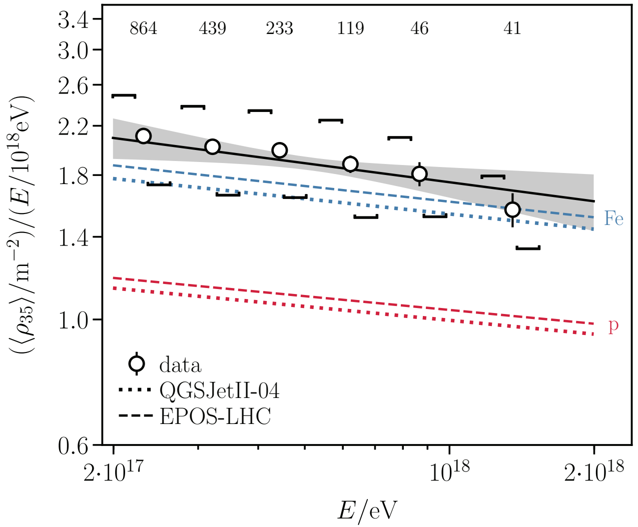
Phys.Rev.D83:054026,2011

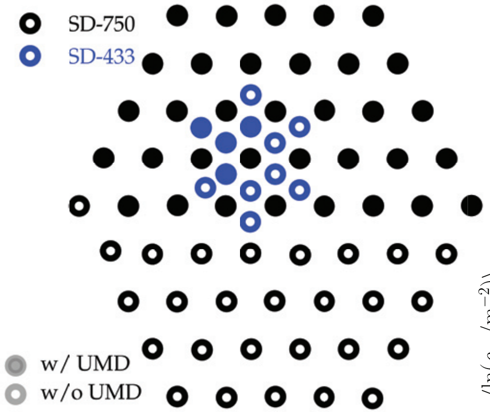
Underground muon detectors

- 30 m² of plastic scintillators per station, 1 GeV vertical cutoff
- engineering array data processed, larger array underway

- compatible with pure iron, in conflict with X_{max} data
- disagreement with models even at LHC primary energies!







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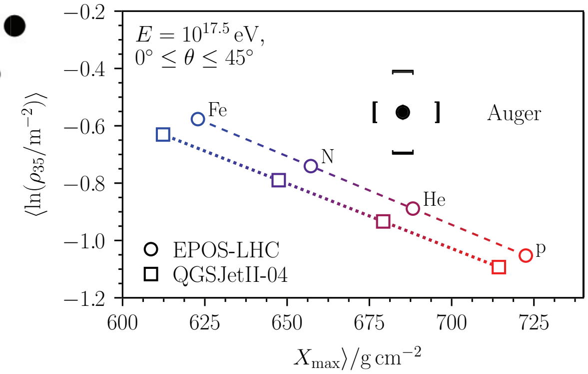
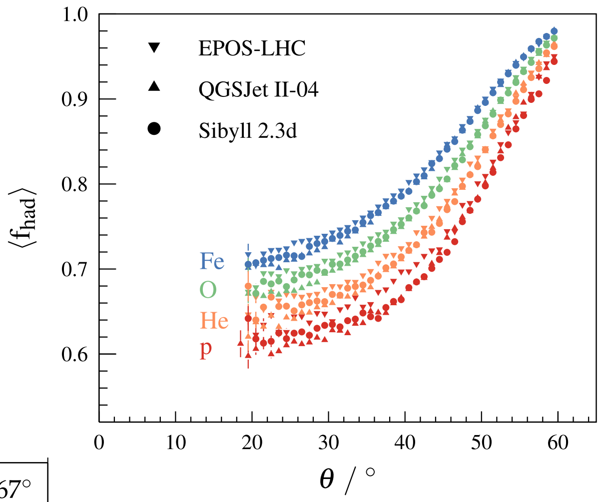


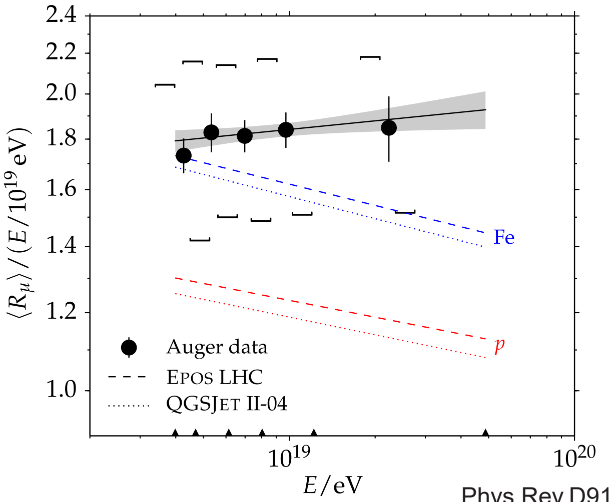
Eur. Phys. J. C (2020) 80:751

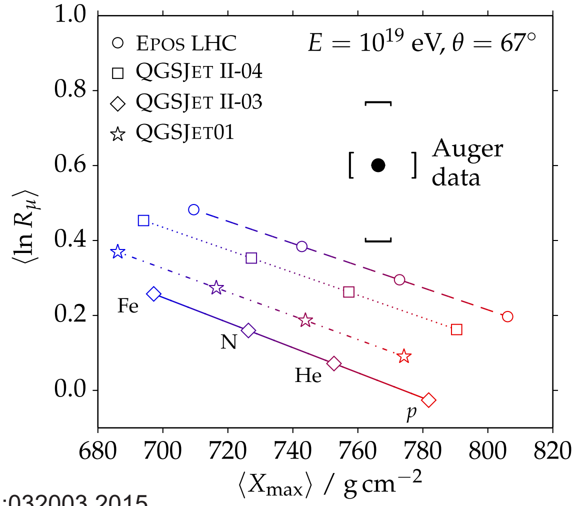
Inclined hybrid showers

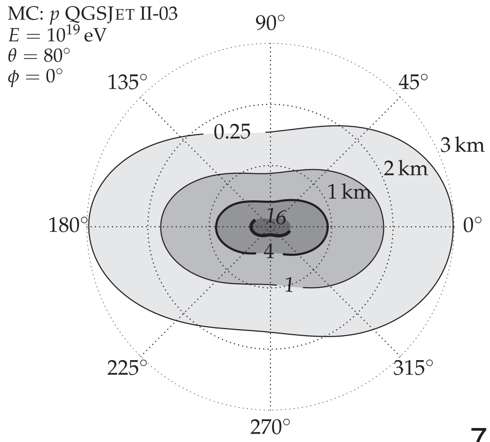
At high zenith angle ground signal dominated by muons
- 174 hybrid showers between 62°–80° zenith angle
- primary energy measured by FD (number of muons ~ $E^{0.9}$)
- ground signal scaled to match muon maps from models

- barely compatible with pure Iron, again in conflict with X_{max} data





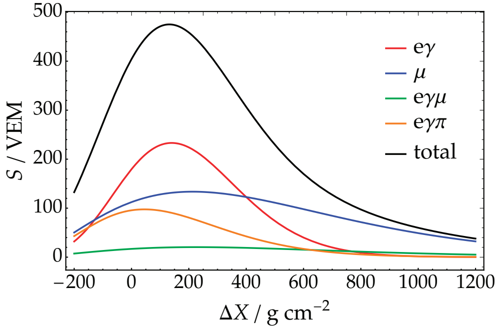


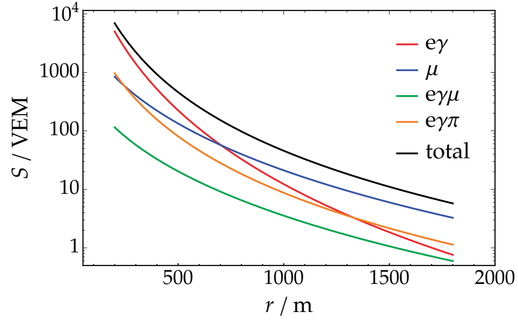


Phys.Rev.D91:032003,2015

“Vertical” hybrid showers

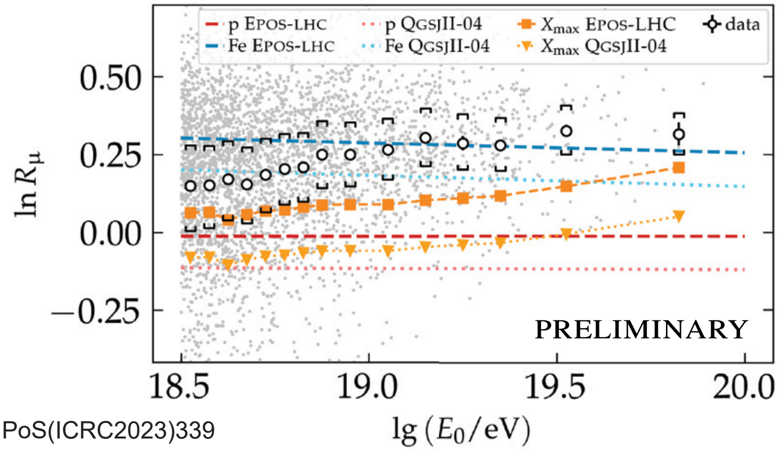
4-component universality used to construct a signal model for each energy and geometry
- high-quality hybrids 0°–60° zenith





E and X_{max} from FD = R_μ only free parameter

- again inconsitent with composition from X_{max}



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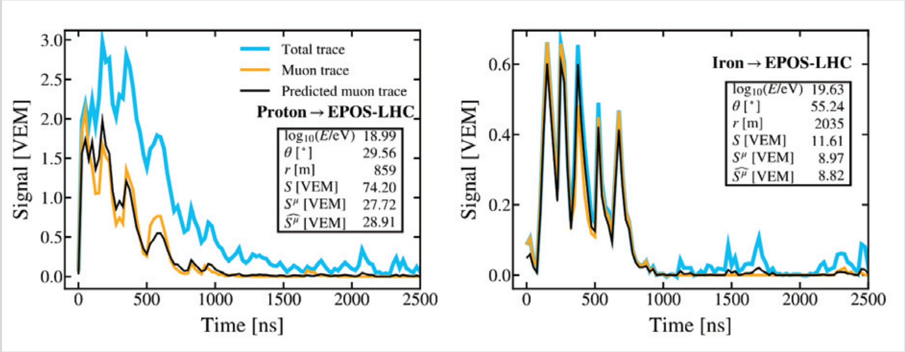
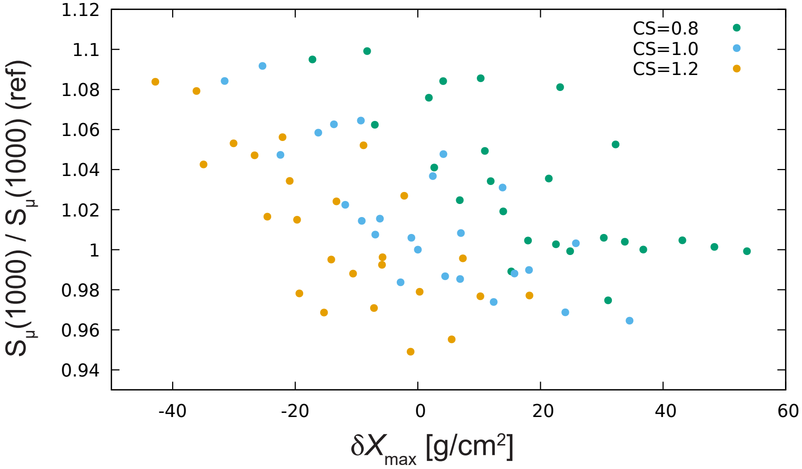


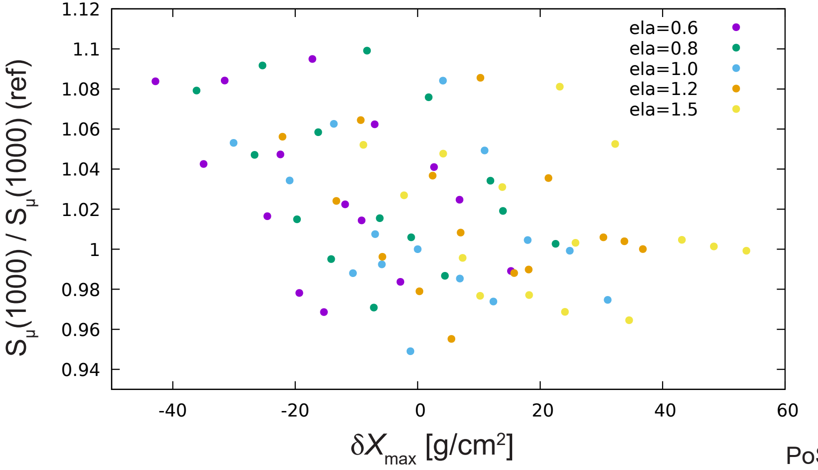
Muon information also in time structure of SD traces
- has been notoriously difficult to use
- neural networks show promising results

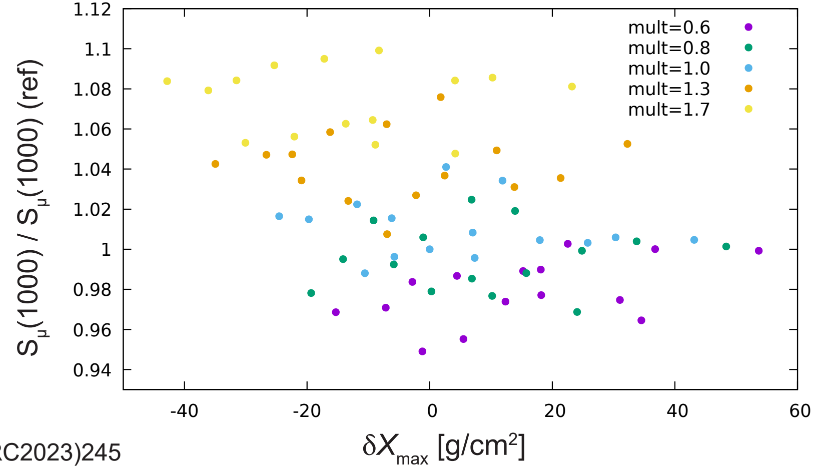
Is the „muon problem“ really just a muon problem?

Simulations with general modified characteristics of hadronic interactions above experimental limits show that modifications change predictions for both X_{max} and N_μ.

- what do data say in the $X_{max} - N_\mu$ plane?







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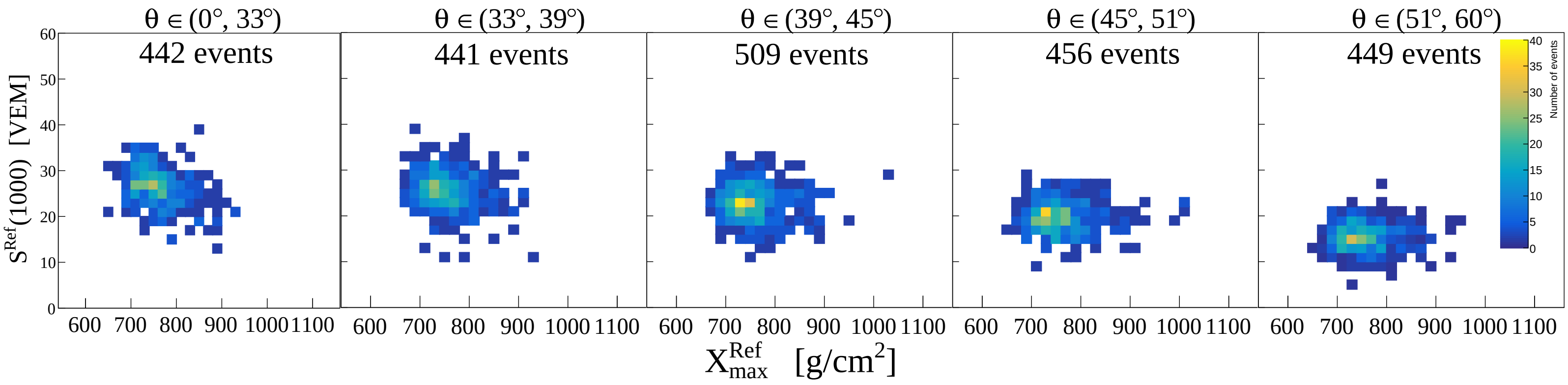
Combined fits of full distributions of X_{max} and ground signals



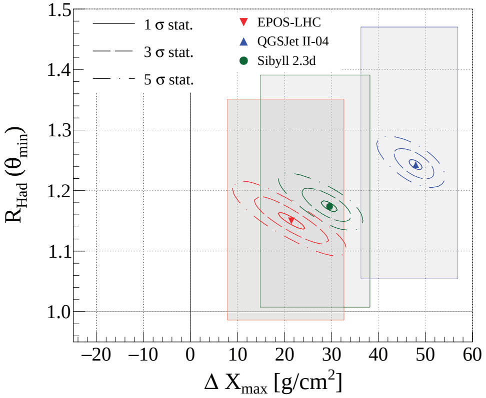
2D distributions of ground signal S(1000) and X_{max} for hybrid events with E between $10^{18.5}$–10^{19} eV are split into zenith angle bins, adjusted to a reference energy and fitted with simulated templates of sets of p, He, O and Fe showers, with free parameters being:

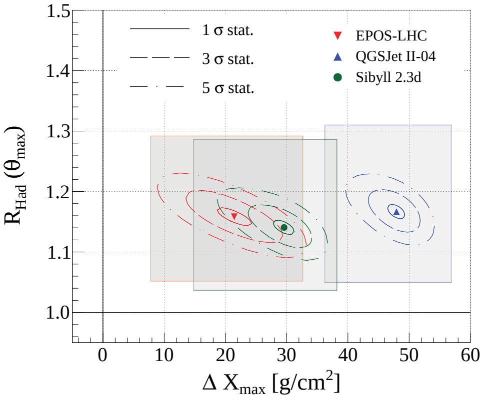
- the fractions of individual nuclei in the primary beam
- a uniform shift in depth of maximum ΔX_{max}
- a rescaling parameter R_{had} for the hadronic part of the ground signal, closely related to R_{μ}
    - the split of the signal into hadronic/EM parts follows the simulations
    - secondary change of ground signal due to ΔX_{max} is accounted for separately

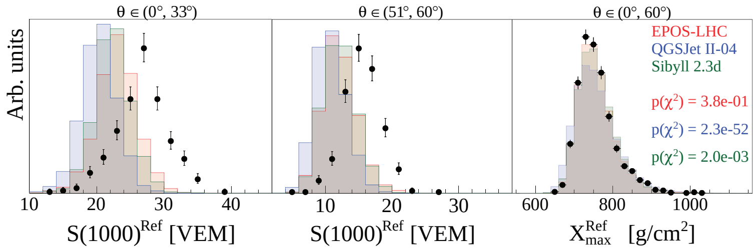
Fits of of X_{max} and ground signals

Both R_{had} and ΔX_{max} needed to account for data

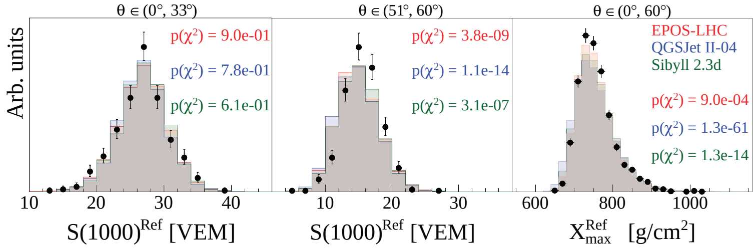
- dominant systematics is the energy scale
- note that the change of X_{max} scale changes the composition interpretation of the data



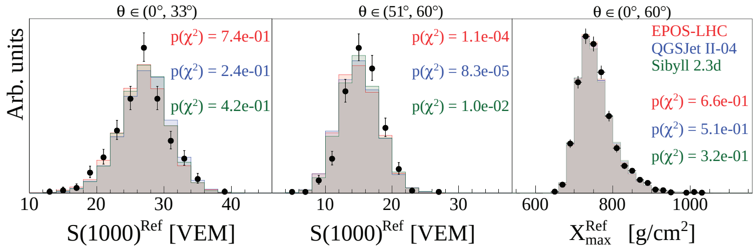




(a) No MC corrections



(b) MC corrections: $R_{Had}(\theta)$



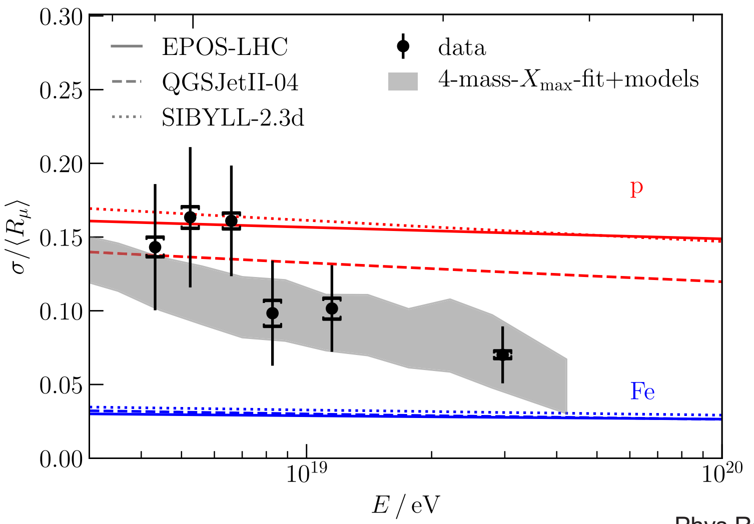
(c) MC corrections: ΔX_{max} and $R_{Had}(\theta)$

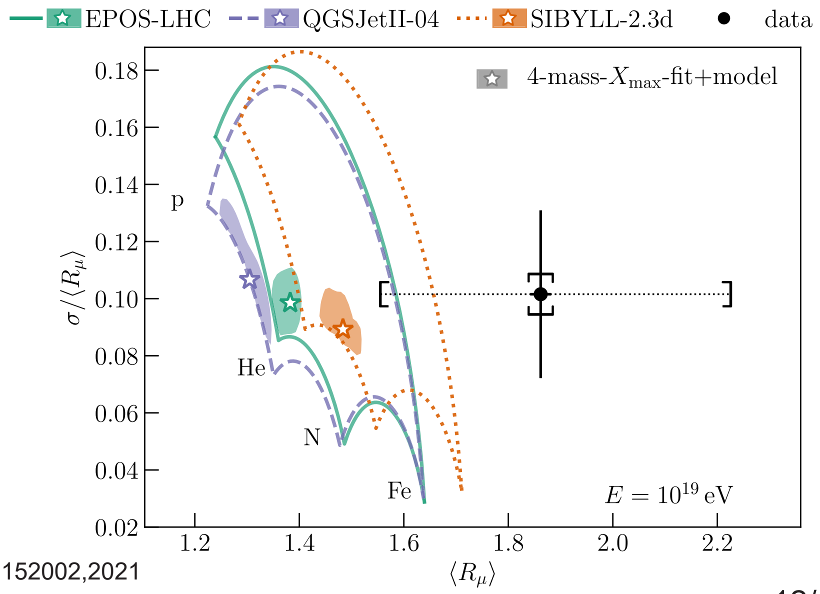
Phys.Rev.D109:102001,2024

Where do the extra muons come from?

N_μ fluctuations (from inclined showers): fluctuations consistent with models!

- fluctuations dominated by first interaction
- muon puzzle likely due to small changes in multiple generations, not a big change in first interacion





Phys.Rev.Lett.126:152002,2021

Future prospects: AugerPrime upgrade

Surface detector upgrades for the entire array:

- Scintillator-based surface detector (SSD, muon/EM separation for lower zenith angles)

- Radio detector (RD, muon/EM separation for larger zenith angles)

- Upgraded Unified Board (faster electronics for better time structure of traces, more channels)

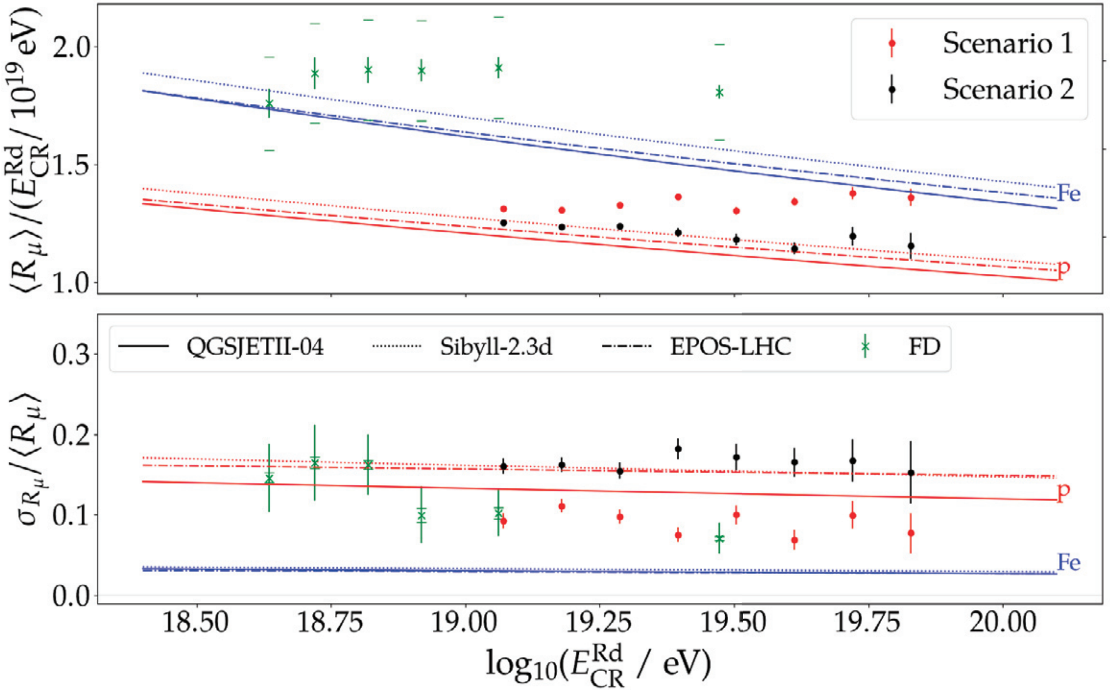
- Small PMT (increased dynamic range)

Underground Muon Detectors:
- smaller part of the array
- direct muon counting

Future prospects: AugerPrime upgrade

- UUB, SSD and Small PMT
  - deployed in all accessible areas
- RD and UMD deployment underway

Relevant expectations for hadronic physics:
- improved muon measurements
- improved X_{max} from ground-only data



Summary

● UHE Cosmic Rays detected by the Pierre Auger Observatory offer a unique look into the hadronic interactions at energies far beyond the capabilities of human-made accelerators.

● Multiple methods of measurement of the muon number point towards a discrepancy between models and data, which is most likely due to cumulative effects of small changes in several generations of hadronic interactions.

● The observed combined distributions of muon numbers and depth of maxima for well-observed showers indicate that the model predictions should be adjusted not only for the muon number, but also for the depth of maximum.

● The AugerPrime upgrade of the observatory has already started taking data and will bring significantly more precise measurements of the muon component of CR showers.