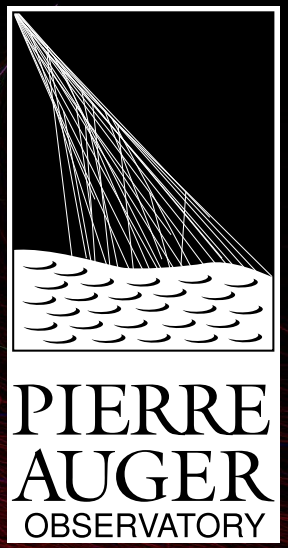
Ultra-high-energy hadronic physics at the Pierre Auger Observatory



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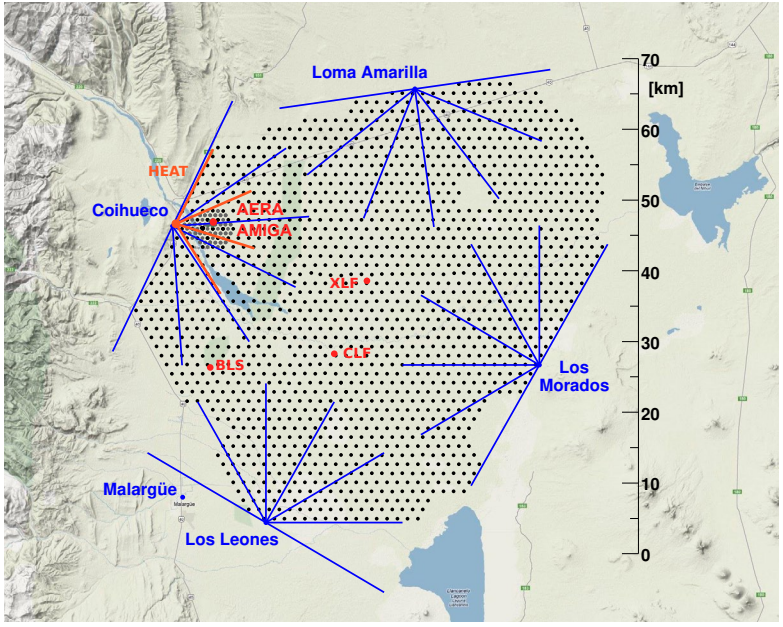
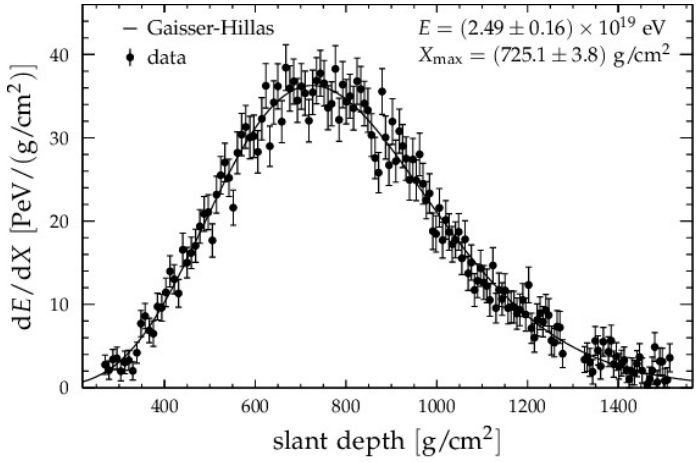
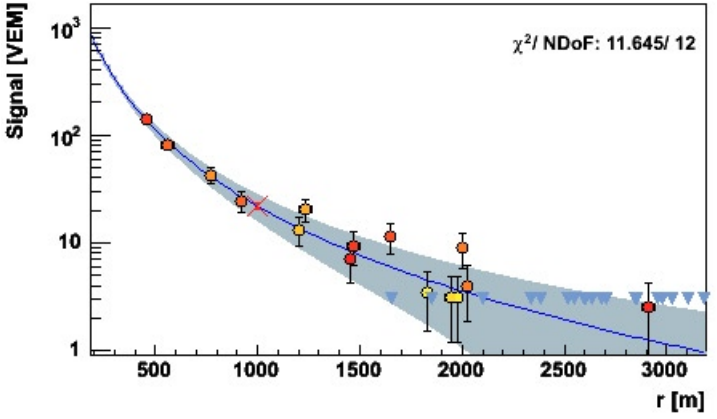
Pierre Auger Observatory

Fluorescence detector: longitudinal shower profile

Surface detector: particles arriving at ground







Hadronic interactions in cosmic ray showers

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

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

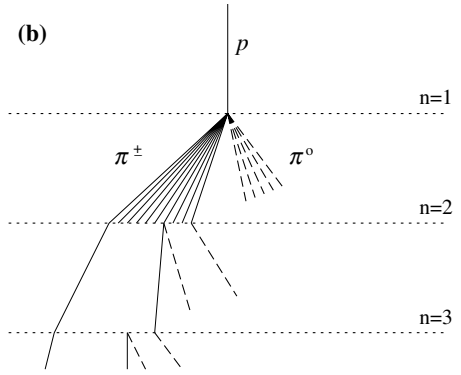
$$N_\mu \approx \left(\frac{E_0}{\xi_{\mathrm{c}}^{\pi}}\right)^{\beta} A^{(1-\beta)} \qquad \beta \approx 1 - \frac{\kappa}{3\ln[N_{\mathrm{ch}}]} > 0.9$$

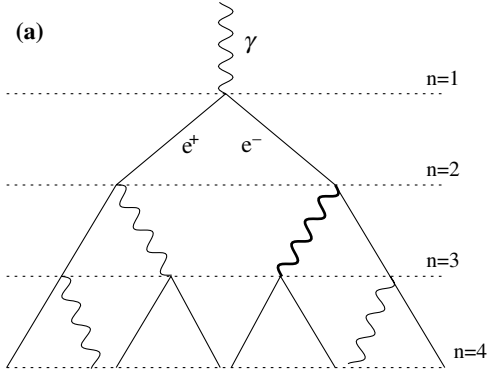
X_{max} and N_μ sensitive to both interaction properties and primary mass

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

$$\sqrt{s}$$

EM component dominant at UHE, less affected by interactions/mass
- ground signal changes mainly with X_{max} due to attenuation

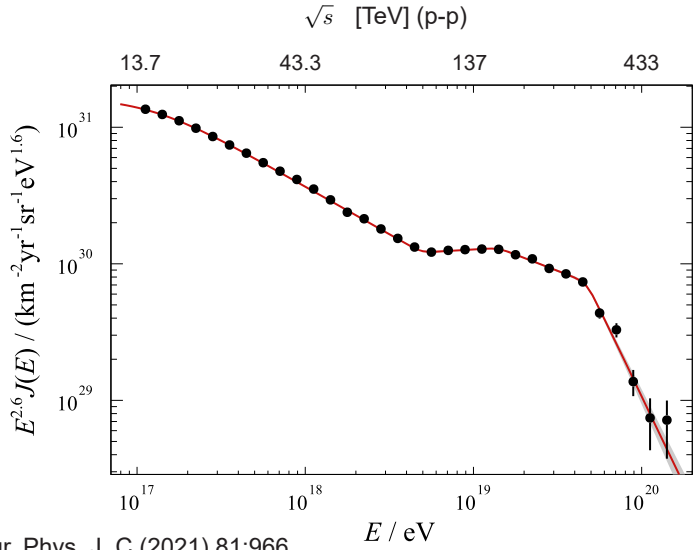




Hadronic interactions and UHECR

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

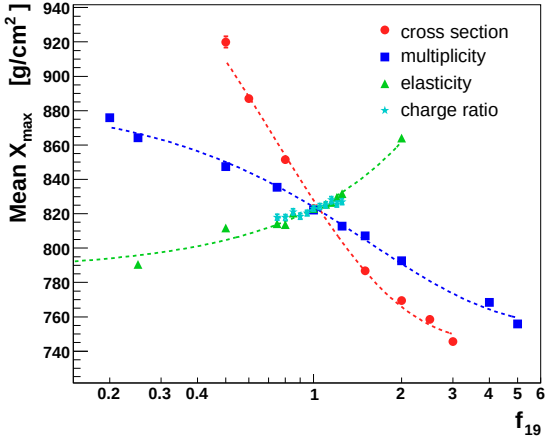
- even at LHC energy, models uncertain due to lack of forward measurements
- below LHC energy: uncertainties in nuclear and pion interactions etc.

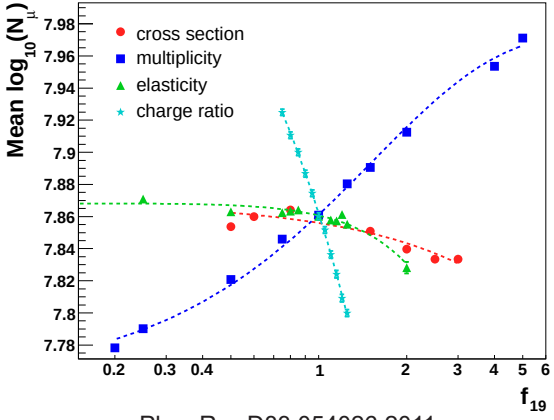


Eur. Phys. J. C (2021) 81:966

Models predict interaction properties above experimentally accessible data

- modifications of predictions have strong impact on air-shower observables





Phys.Rev.D83:054026,2011

The simplest test: are data between proton and iron?

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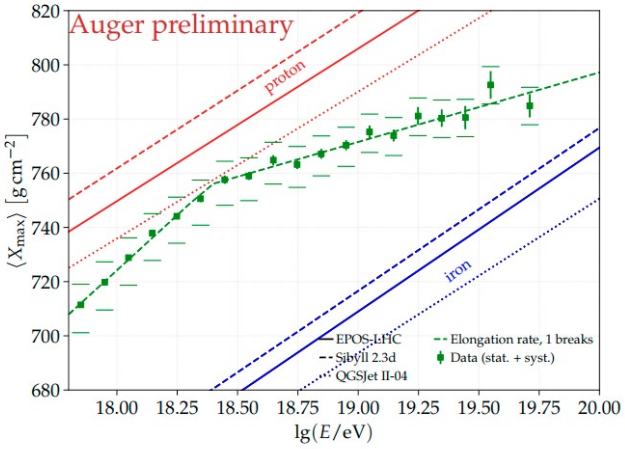

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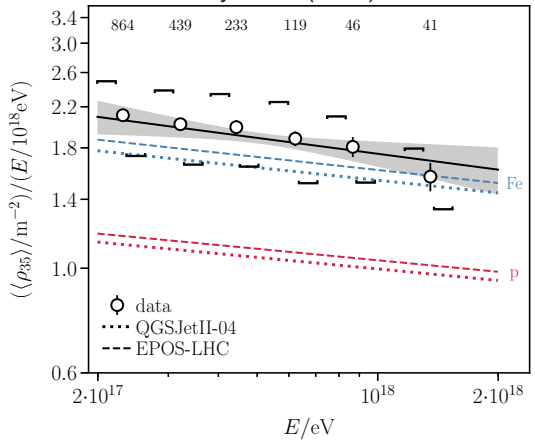
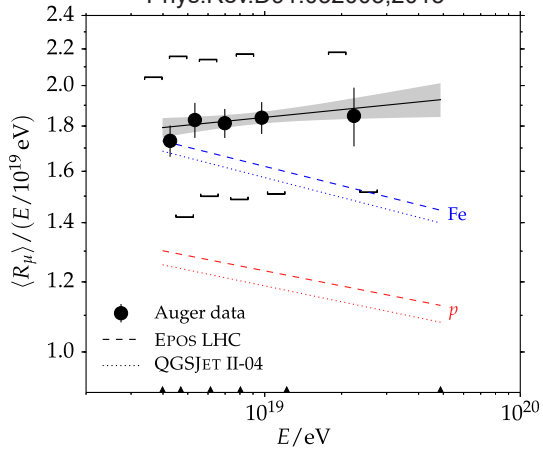


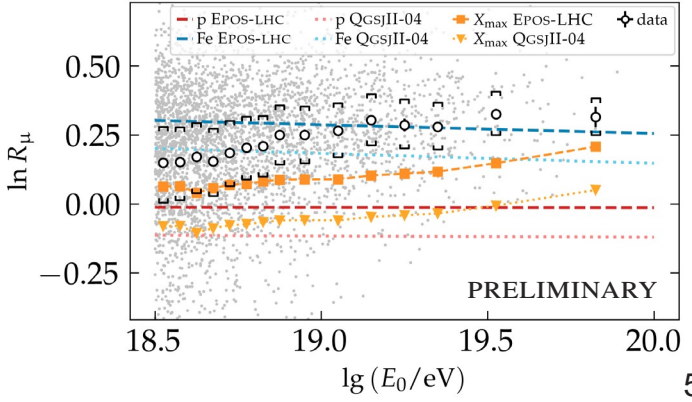
Phys.Rev.D91:032003,2015



X_{max}: measured directly by fluorescence telescopes → yes.

N_μ (or R_μ, relative to a reference model): measured using
- underground muon detectors
- highly inclined showers (EM component attenuated)
- hybrid showers (using signal model and FD data)

→ pure iron would be needed, or even slightly heavier



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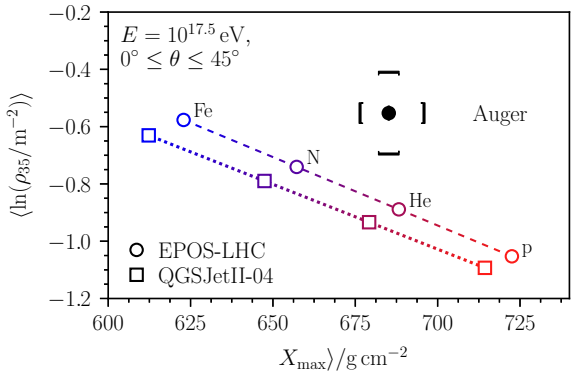
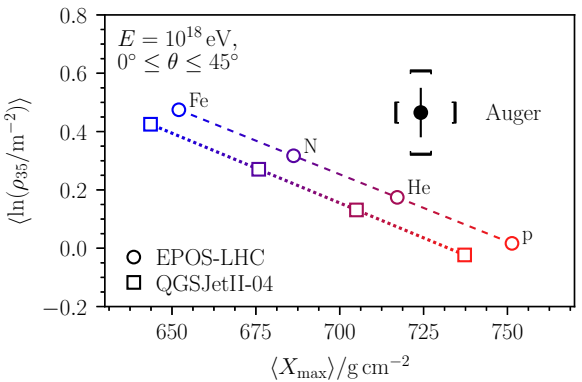
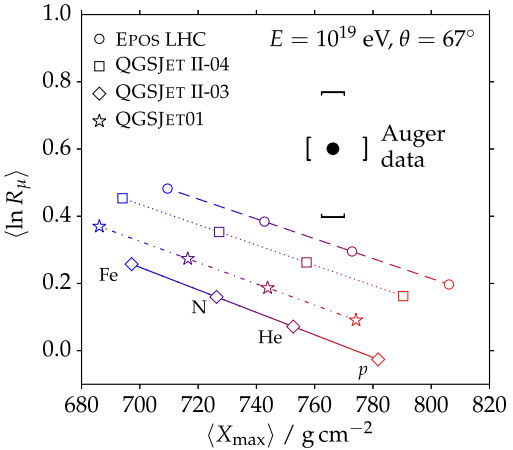
Are muon measurements consistent with X_{max} data?



(a) $E = 10^{17.5}$ eV



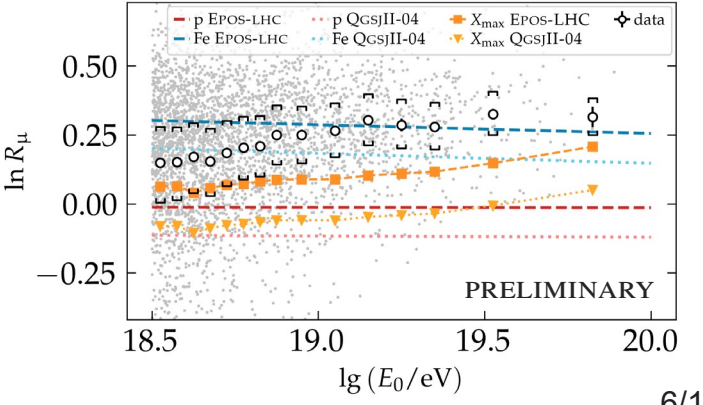
(b) $E = 10^{18}$ eV



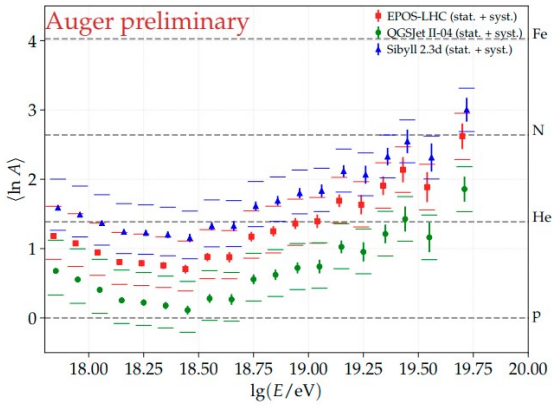
„Muon puzzle“: muon data indicate much heavier primary composition than depths of maxima

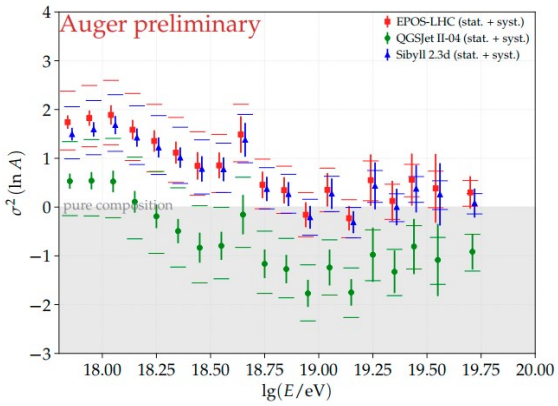
- indicates insufficient understanding of hadronic interactions at UHE energies

- note the still large uncertainties



Beyond mean values: fluctuations

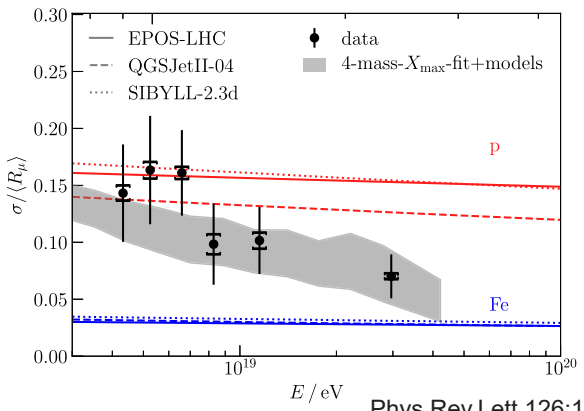


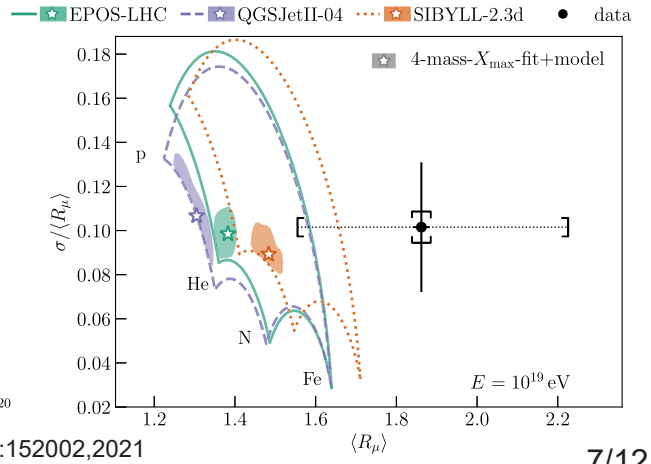


X_{max} fluctuations: no consistent combination of mean ln *A* and its variation describes data when interpreted using QGSJET-II-04

- OK for other models

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!



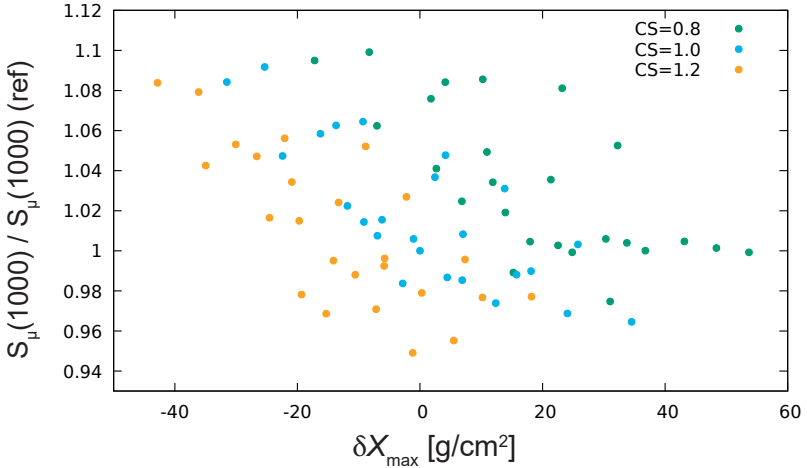


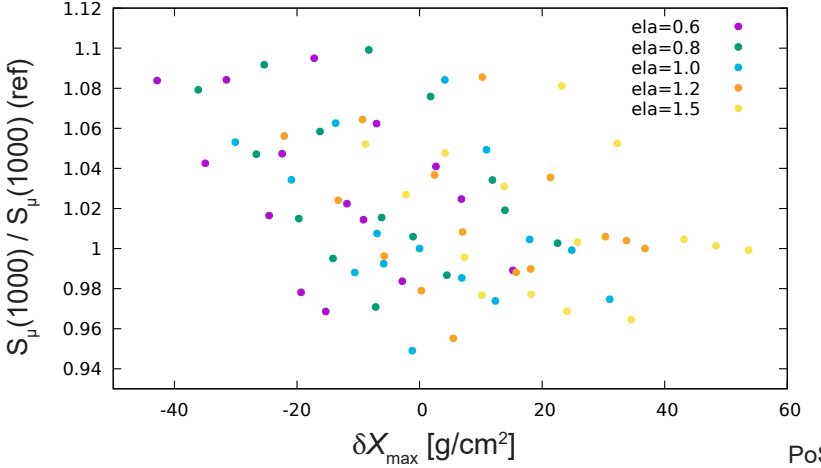
Phys.Rev.Lett.126:152002,2021

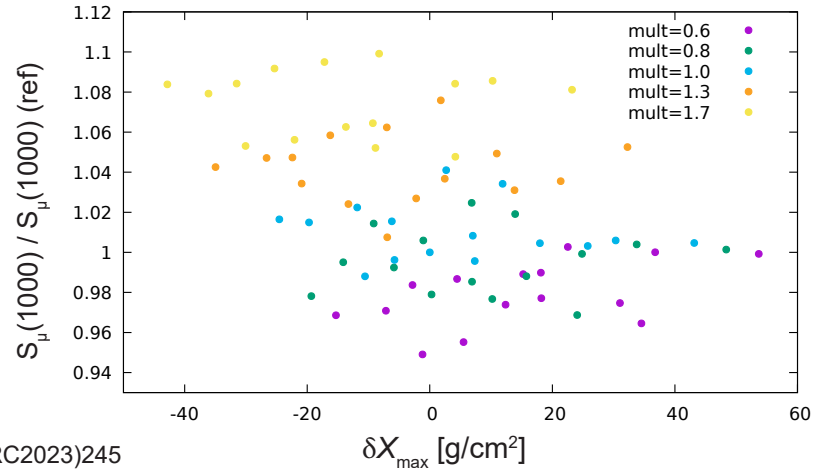
Is the „muon problem“ really just a muon problem?

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_μ plane?







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

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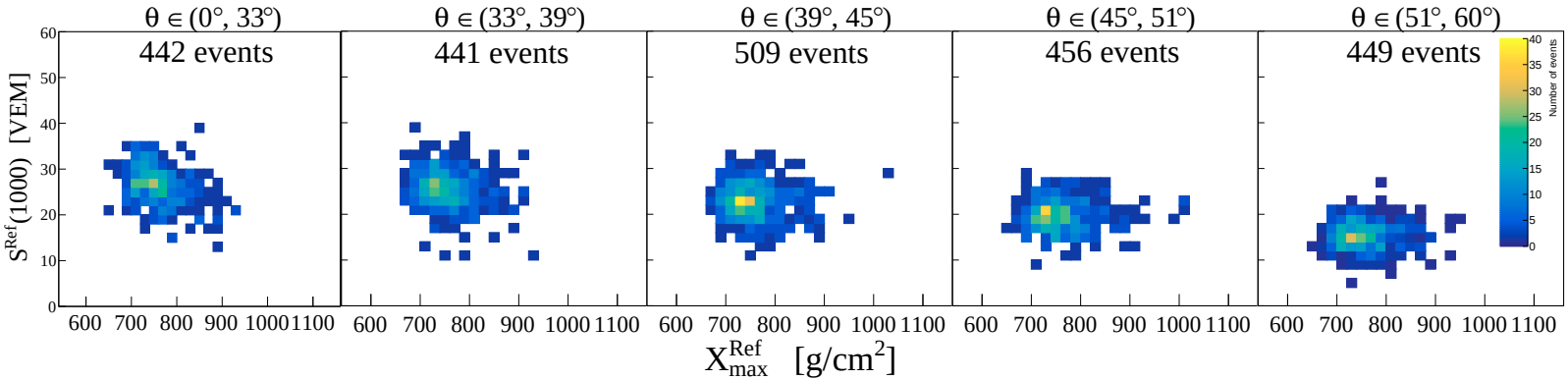


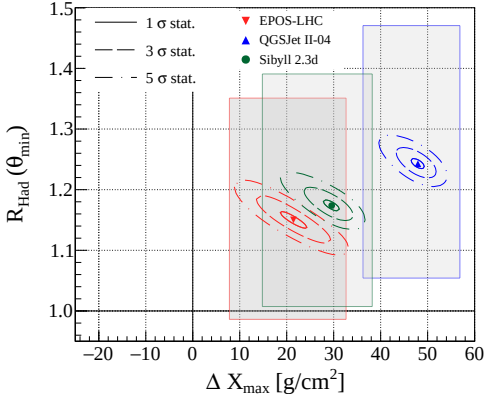
2D distributions of ground signal S(1000) and X_{max} for hybrid events with E between $10^{18.5}$–10^{19} eV are split into zenith angle bins, adjusted to a reference energy and fitted with simulated templates of sets of p, He, O and Fe showers, with free parameters being:

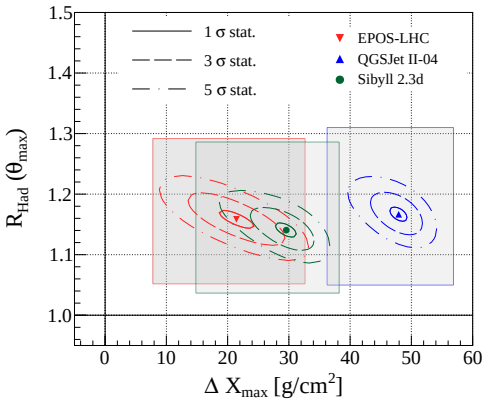
- the fractions of individual nuclei in the primary beam
- a uniform shift in depth of maximum ΔX_{max}
- a rescaling parameter R_{had} for the hadronic part of the ground signal, closely related to R_{μ}
  - the split of the signal into hadronic/EM parts follows the simulations
  - secondary change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

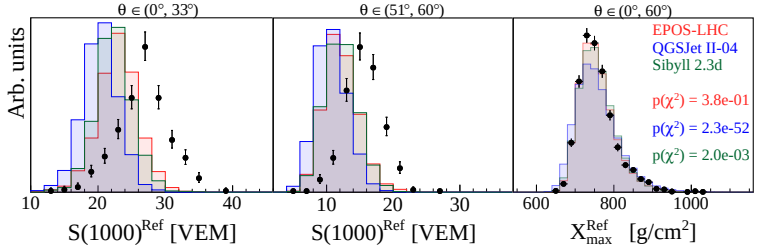
Fits of of X_{max} and ground signals

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

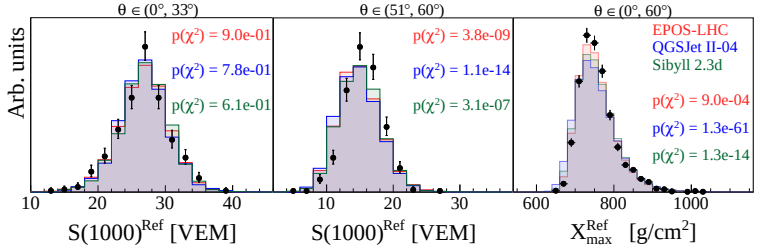
- dominant systematics is the energy scale
- note that the change of X_{max} scale changes the composition interpretation of the data



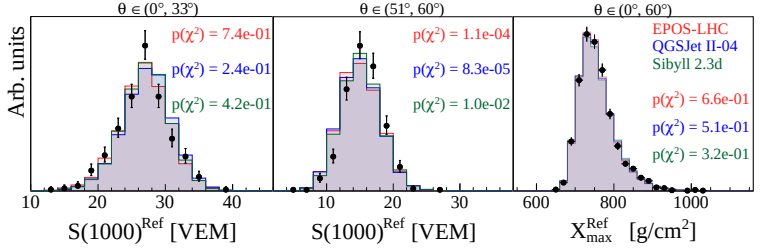




(a) No MC corrections



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



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

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, more channels)
- Small PMT (increased dynamic range)

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

Current status:
- 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

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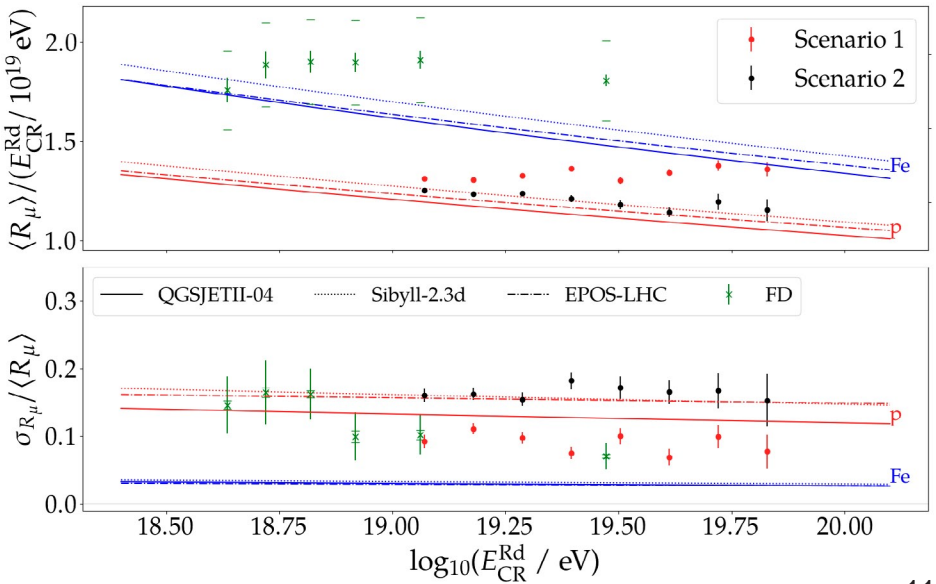

Summary

● 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.