Hadronic interaction studies at the Pierre Auger Observatory

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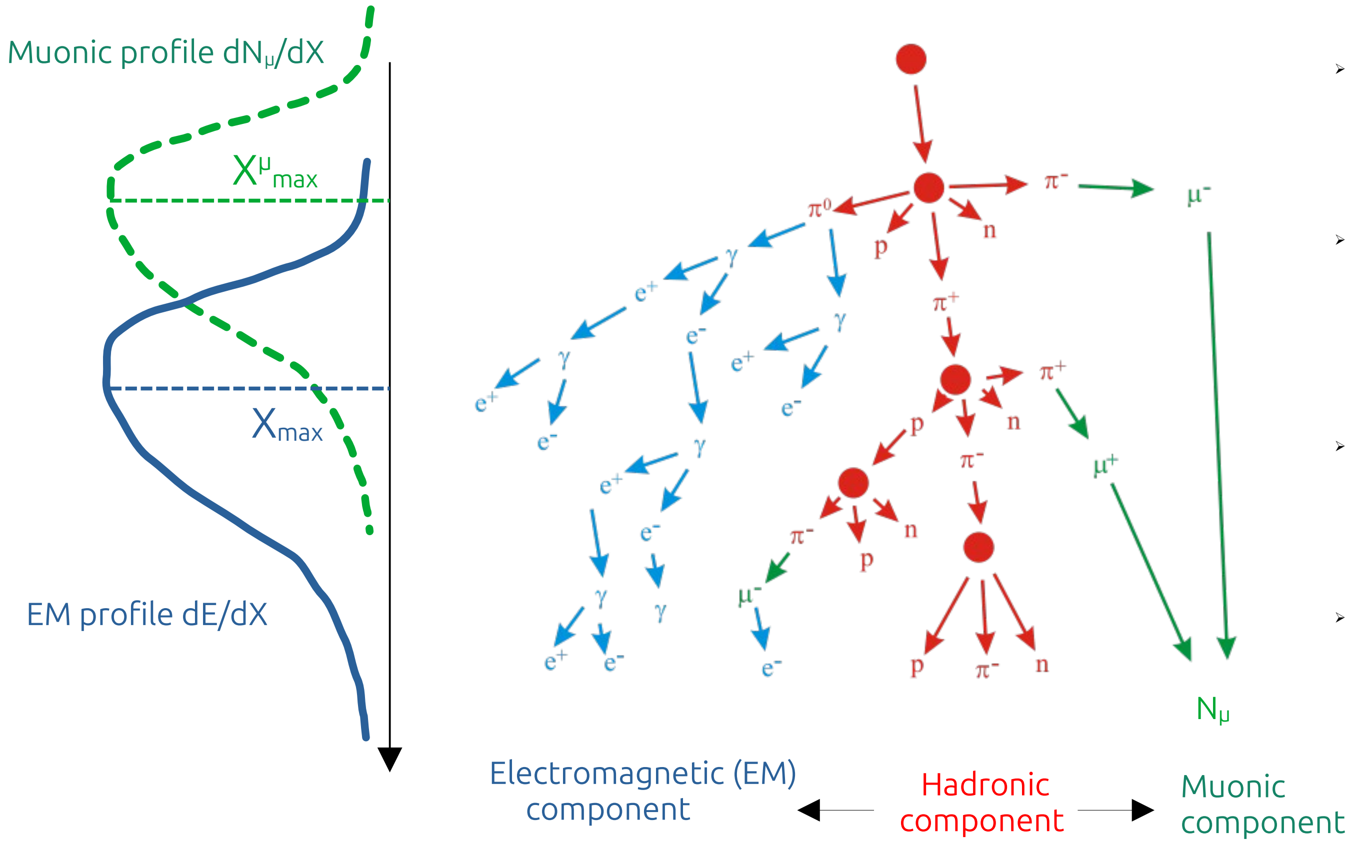
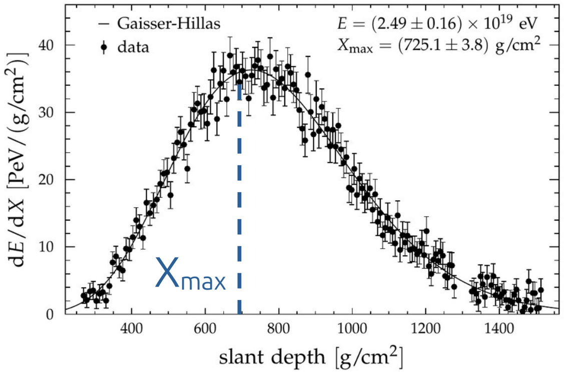
Probing high-energy interactions with Extensive Air Showers (EAS)

$E_{CR} \sim 10^{19}$ eV → $\sqrt{s} \sim 140$ TeV >> 14 TeV (LHC)



- EAS are unique laboratories for **hadronic interactions beyond accelerator energies**
- Hadronic models are essential for interpreting cosmic-ray measurements → **testing and improving them is crucial.**
- X_{max}, X^μ_{max}, and N_μ probe complementary aspects of shower development.
- Their combined interpretation provides stringent **tests of hadronic models**

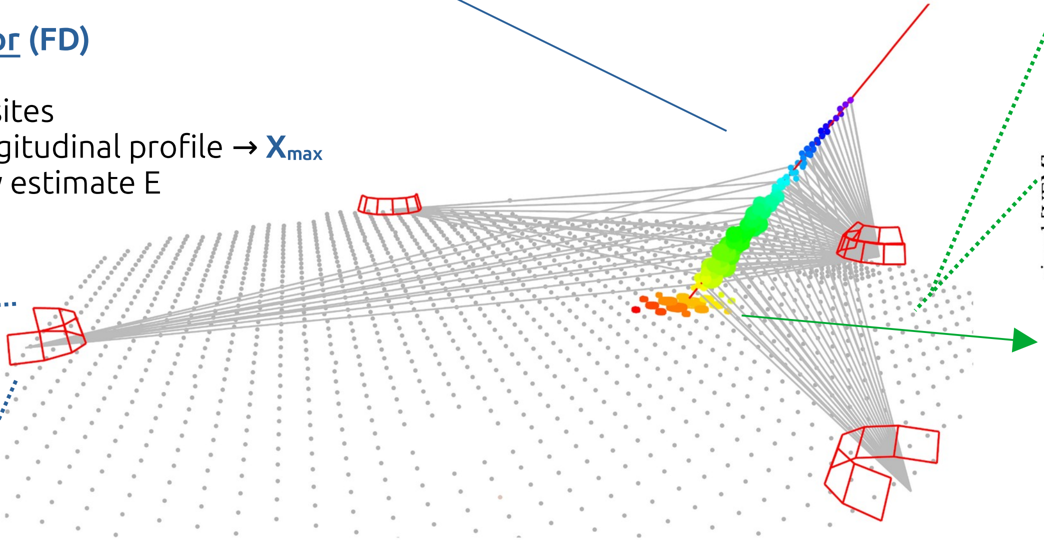
Measuring EAS at the Pierre Auger Observatory

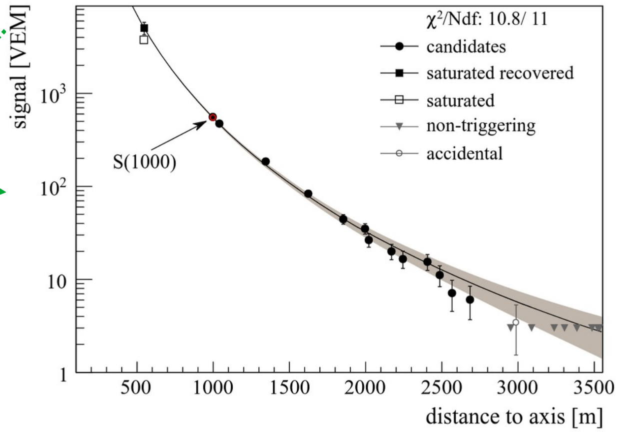


$$E_{CR} \propto \int_0^\infty \frac{dE}{dX}\, dX$$

- **Surface Detector (SD)**
  - 100 % duty cycle
  - 1660 water-Cherenkov detectors over 3000 km^2
  - sensitive to shower footprint on ground → N_μ and X^μ_{max}

- **Fluorescence Detector (FD)**
  - 15% duty cycle
  - 27 telescopes in 4 sites
  - sensitive to EM longitudinal profile → X_{max}
  - calorimetric energy estimate E





Probing hadronic interactions at the Pierre Auger Observatory

1) Measurement of mean muon content N_μ Phys. Rev. D 91 (2015) 032003

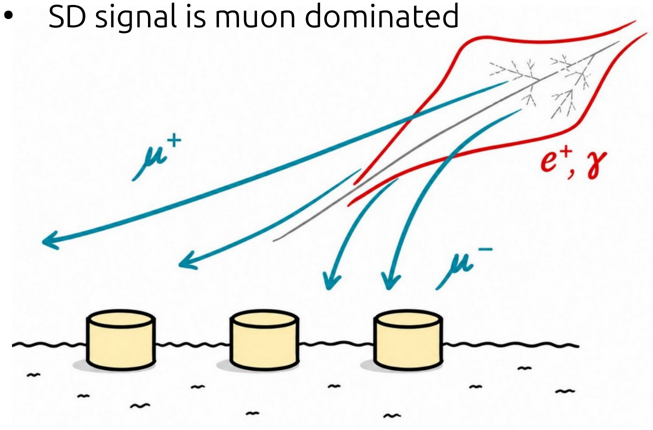
2) Measurement of fluctuations of the muon content N_μ Phys. Rev. Lett. 126 (2021) 152002

3) Measurement of X^μ_{max} Phys. Rev. D 90 (2014) 012012

4) (X_{max}, S_{1000}) rescaling Phys. Rev. D 109 (2024) 102001

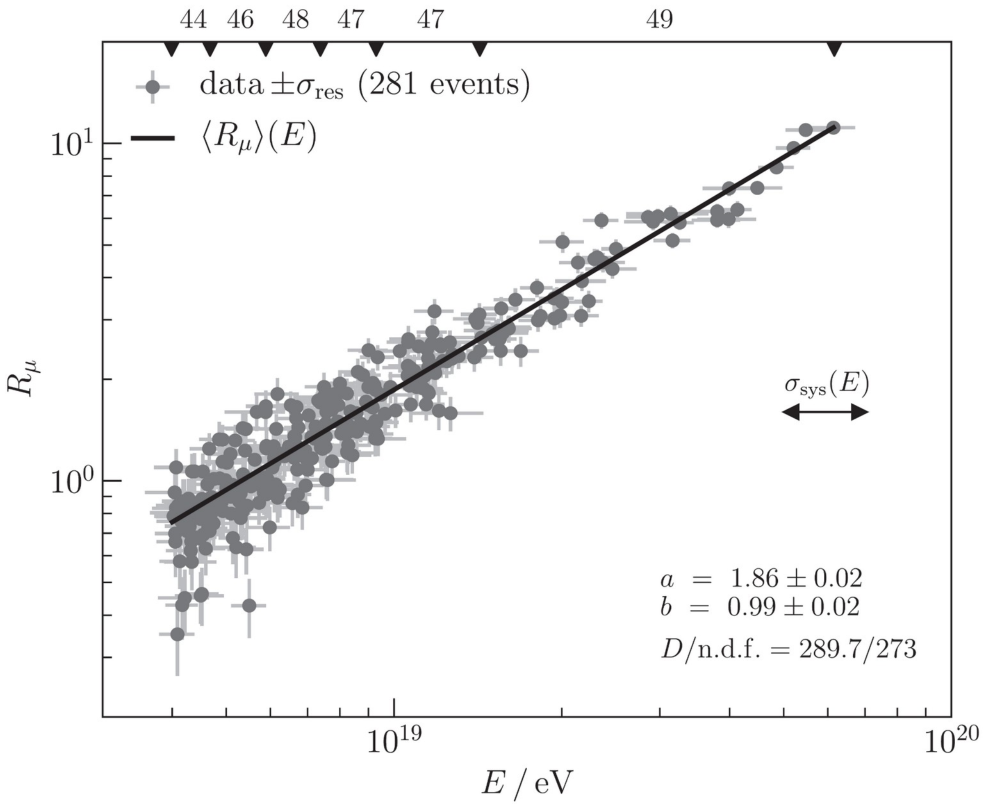
Mean muon content in Inclined Air Showers

- Showers with E > 4×10^{18} eV and $62° < \theta < 80°$
  - EM component largely absorbed in the atmosphere
  - SD signal is muon dominated



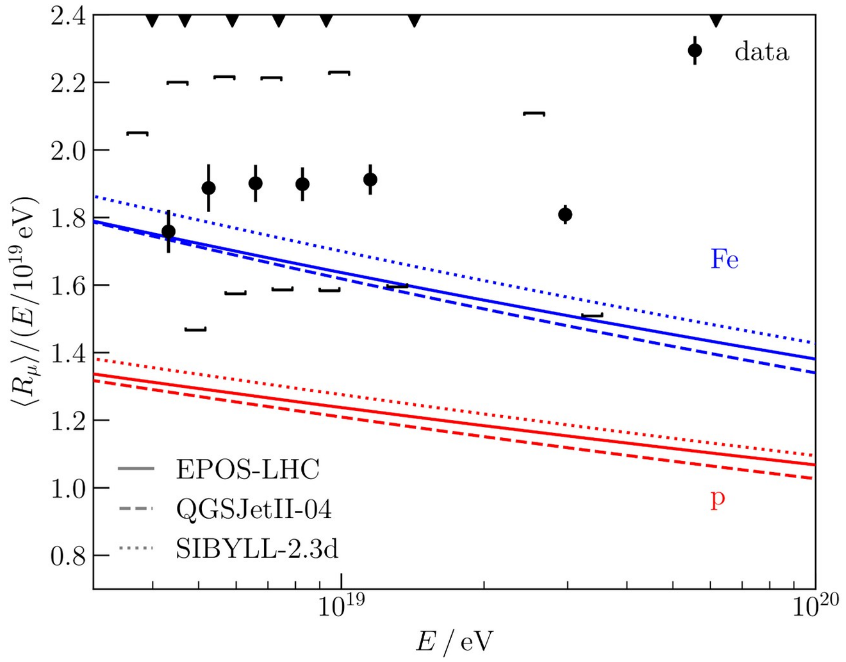
- Hybrid events: simultaneously observed by the FD and SD
  - **FD** → measures energy E
  - **SD** → measures muon content R_μ (integrated N_μ at ground normalized by a reference value)

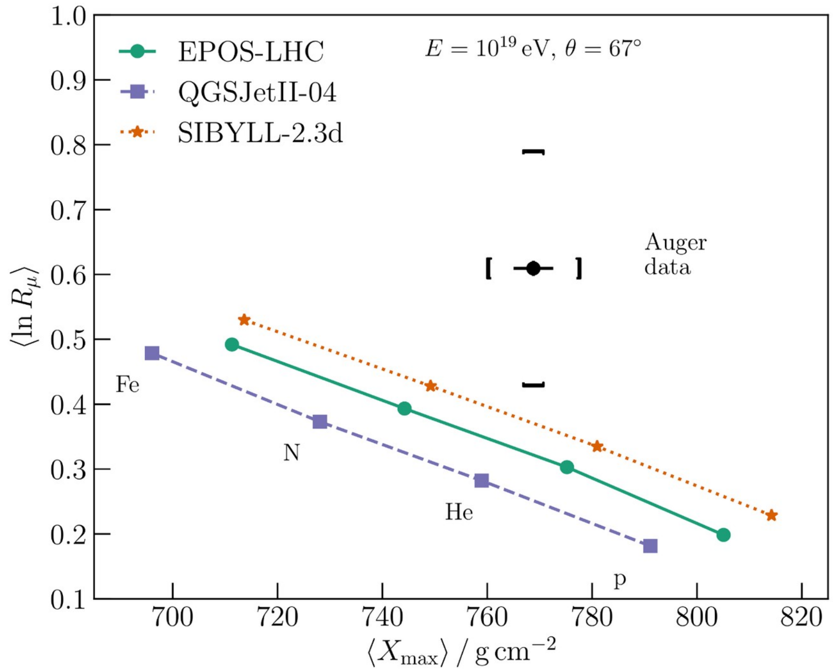
- R_μ is obtained by fitting the SD footprint to a reference 2D muon distribution



Phys. Rev. D 91 (2015) 032003
Phys. Rev. Lett. 126 (2021) 152002

Mean muon content in Inclined Air Showers





- **Models cannot simultaneously describe X_{max} and the mean muon content**.
- Assuming the composition inferred from X_{max}, **simulations underpredict the mean muon content**:
  - QGSJetII-04: +43% required
  - EPOS-LHC: +35%
  - Sibyll 2.3d: +26%

Phys. Rev. D 91 (2015) 032003
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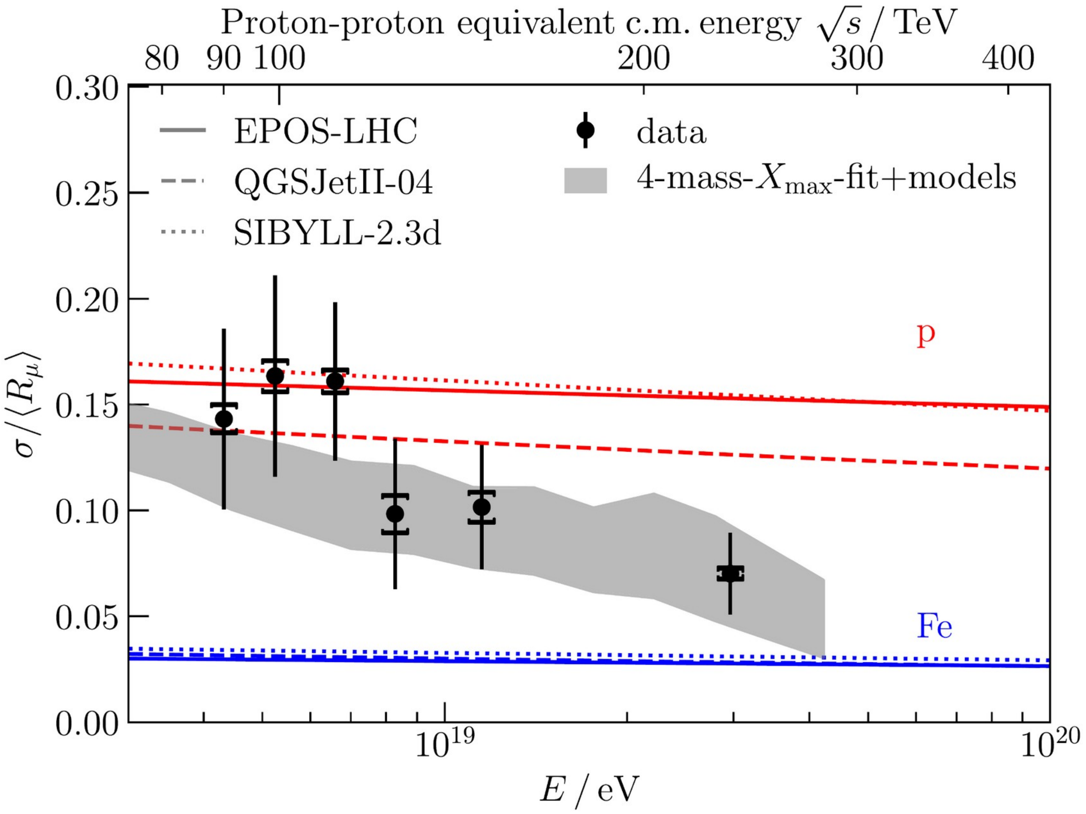
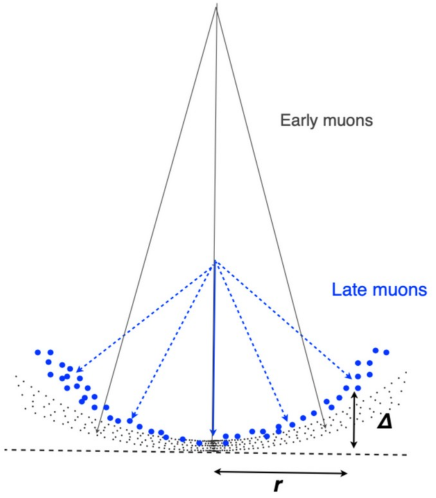
Fluctuations in the muon content in Inclined Air Showers

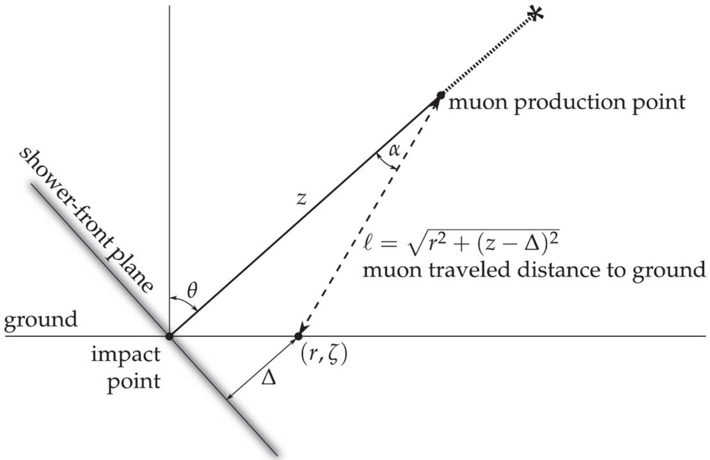


- Relative muon fluctuation are **consistent** with model expectations for X_{max} mass composition
- Fluctuations are dominated by the first interaction, while <N_μ> accumulates effects over the full cascade.
- The muon deficit observed in <N_μ> is unlikely to arise from a large mismatch of the first interaction → **small mismatches accumulating throughout the cascade are favored**.

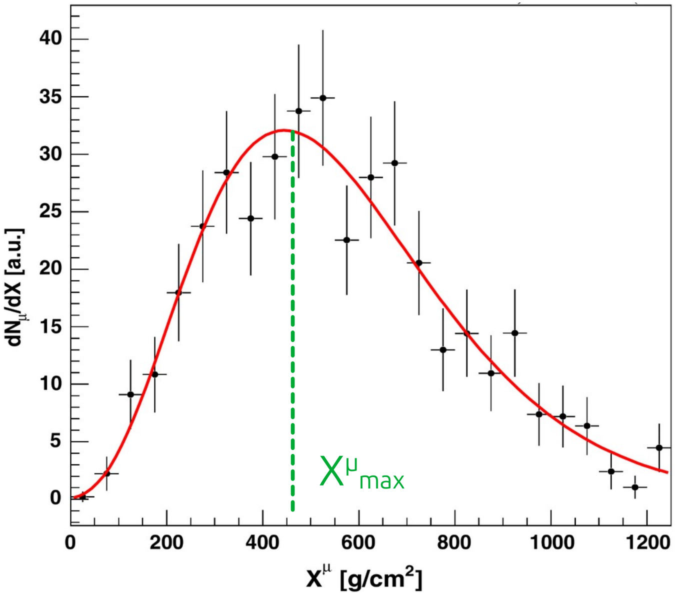
Phys. Rev. Lett. 126 (2021) 152002

Measurement of Muon Production Depth (MPD)





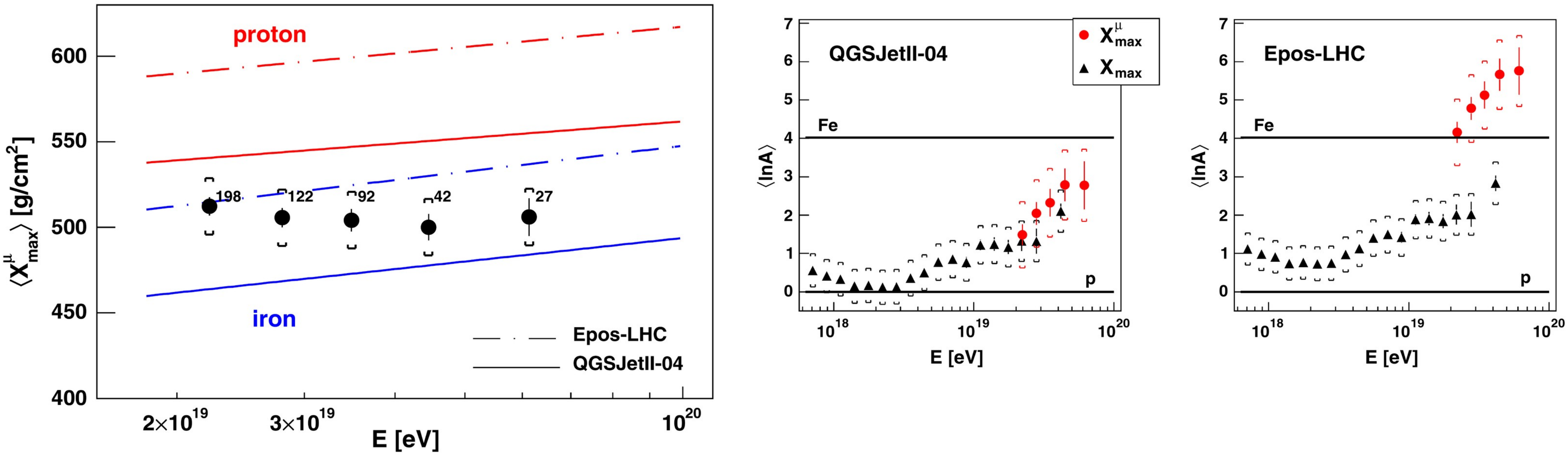
- Arrival time of muons encodes their production depth
- Modeling the muon delay allows to map the arrival time into production depth



- Cuts to minimize EM contamination and dependence of MPD with r
- Showers with E > $10^{19.3}$ eV and 55º < θ < 65º
- Detectors with r > 1700 m
- Signal bins >15% of trace maximum
- Gaisser–Hillas fit to MPD → X^μ_{max}

Phys. Rev. D 90 (2014) 012012

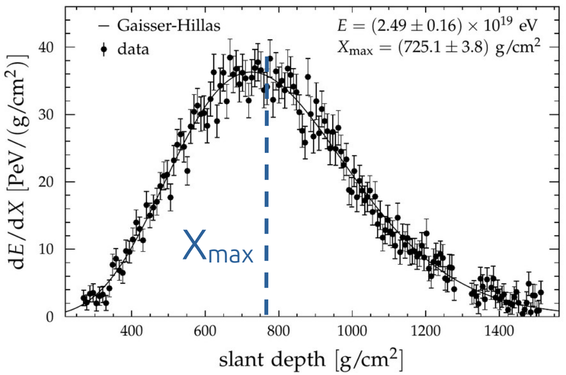
Measurement of X_μ^{max}



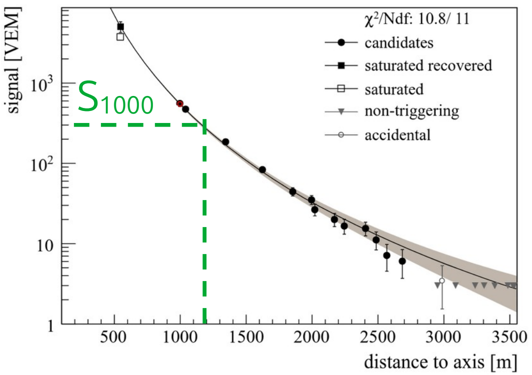
- X^μ_{max} favors an evolution towards increasing mass with energy
- EPOS-LHC in tension with X_{max} mass composition (>2.5σ)
- QGSJetII-04 in agreement, but this model does not reproduce $\sigma(X_{max})$
- **None of the tested models reproduces X_{max} and X^μ_{max} consistently**

(X_{max}, S_{1000}) rescaling

Measured with Fluorescence Detector

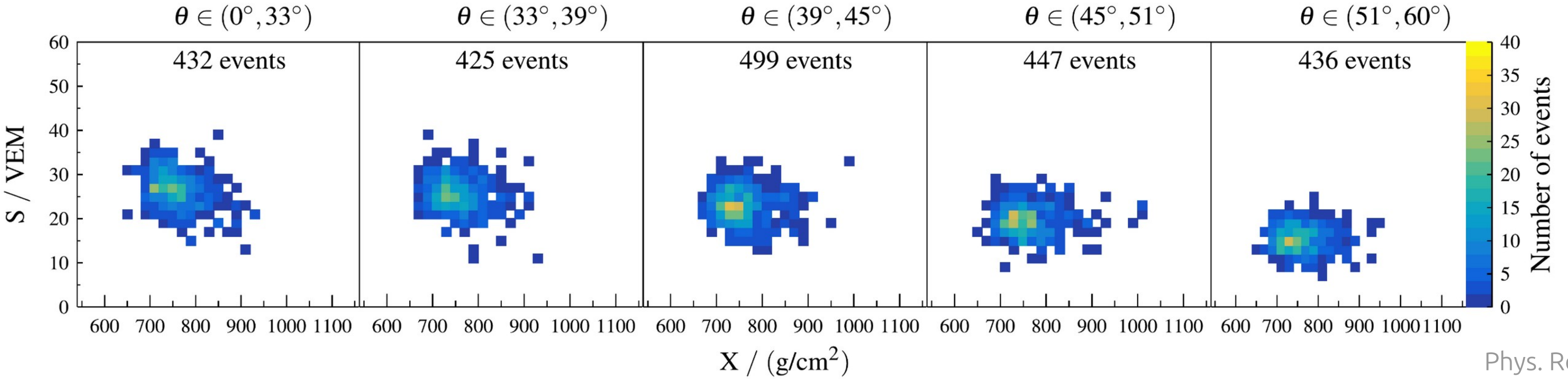


Measured with Surface Detector



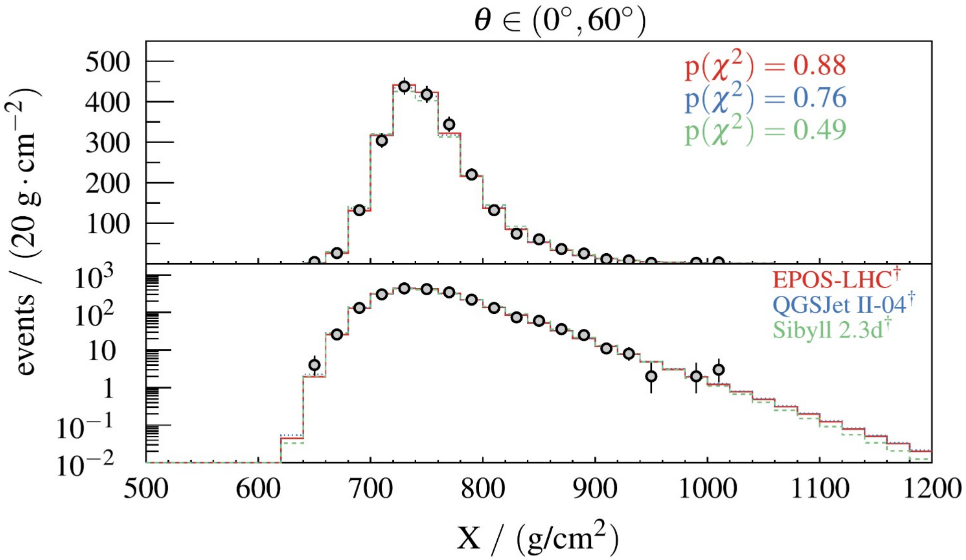
- Previous muon comparison relied on composition from X_{max} → **what if X_{max} scale itself is wrong?**
- 2239 high-quality hybrid events ($10^{18.5}$ eV < E < 10^{19} eV and θ < 60°)
  - **FD** measures E and **X_{max}**
  - **SD** measures **S_{1000}** (signal at 1000 m from the core)
- Can models reproduce the joint (X_{max}, S_{1000}) distribution?
  - Produce MC template of joint (X_{max}, S_{1000}) dist. for each (primary, model, θ), with 5 θ bins
  - Global fit of data to MC templates allowing for a **shift in MC X_{max} scale (ΔX_{max}) and rescaling of the hadronic ground signal (R_{had})**

Data

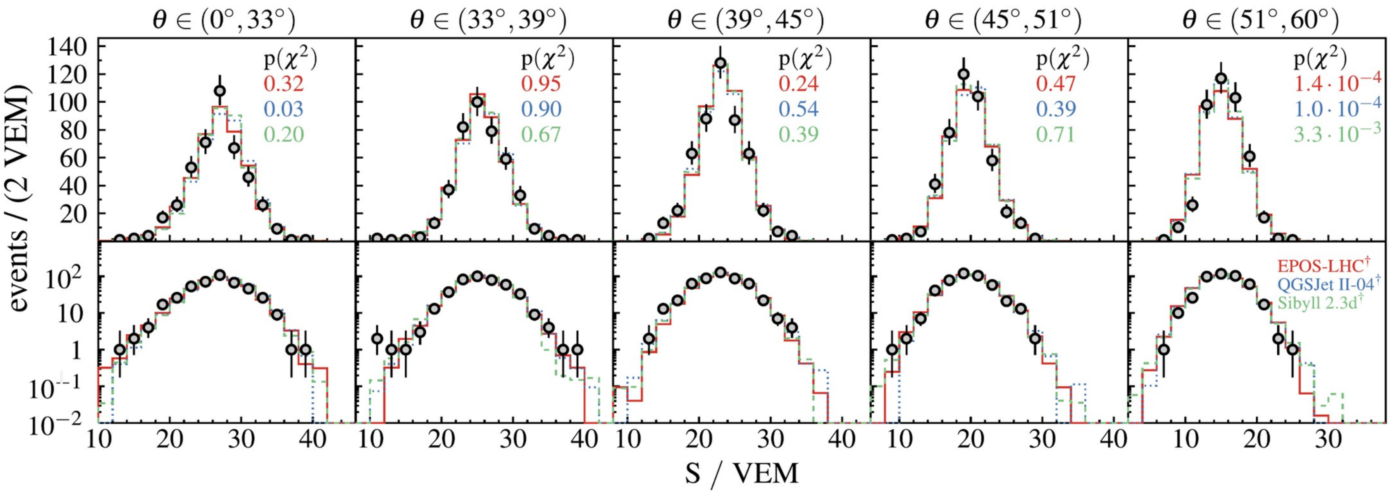


Phys. Rev. D 109 (2024) 102001

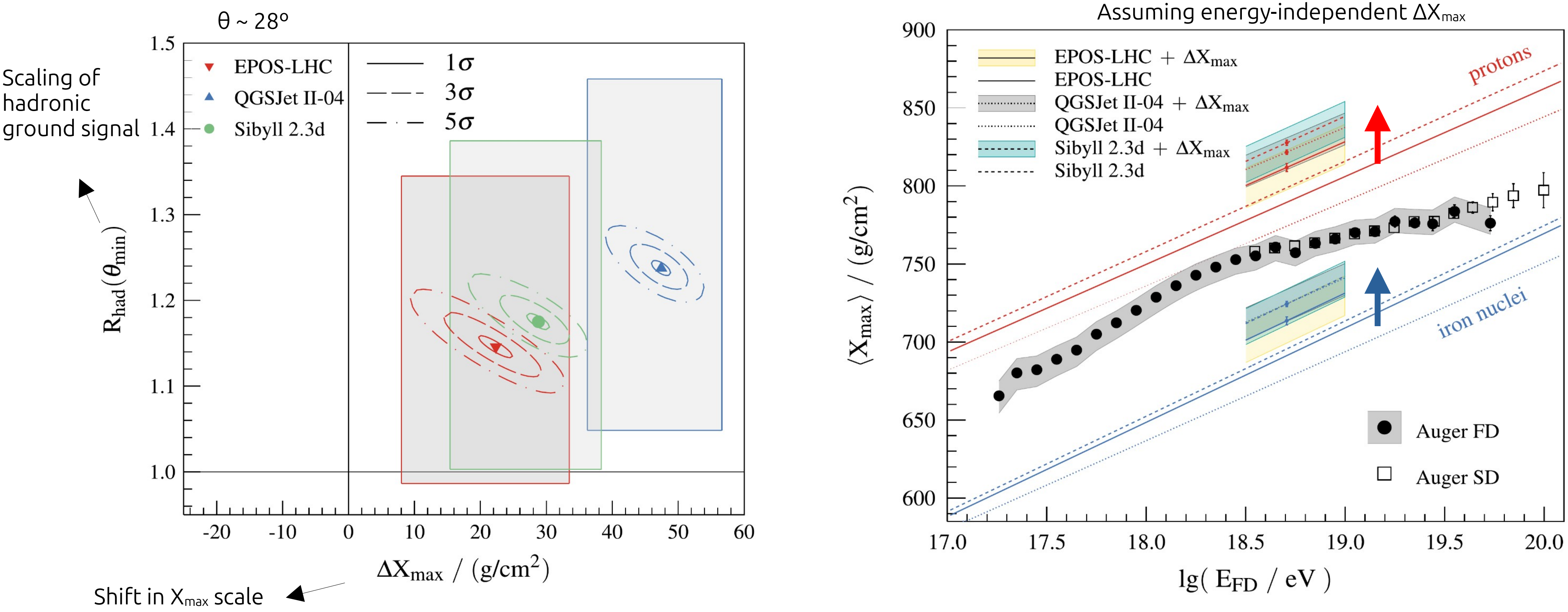
(X_{max}, S_{1000}) rescaling



- Simultaneously fit p, He, O, Fe fractions + ΔX_{max} + $R_{had}(\theta)$.
- Global 2D p-values fit: 10-30%
- After allowing ΔX_{max} and $R_{had}(\theta)$, all three models provide a successful **simultaneous description of the data** (fitting mass fractions alone does not describe well the data)



(X_{max}, S_{1000}) rescaling



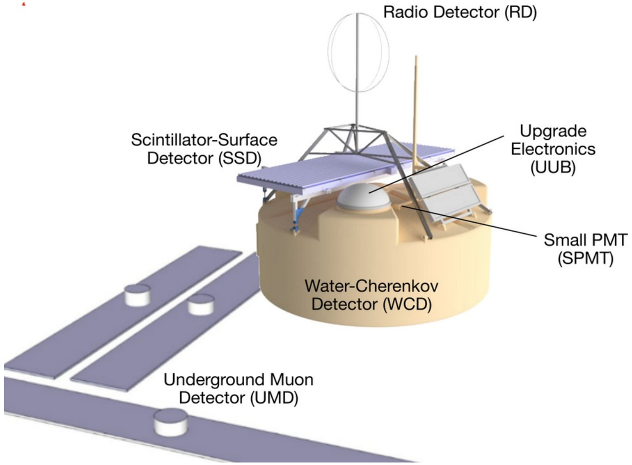
- X_{max} scale in models needs to be **shifted (20-50) g/cm² deeper**, and **hadronic ground signal needs to be scaled 15-25%** to better describe Auger Data (>5σ significance)
- The deeper X_{max} scale implies a **heavier inferred composition, partially reducing (but not removing) the muon deficit.**

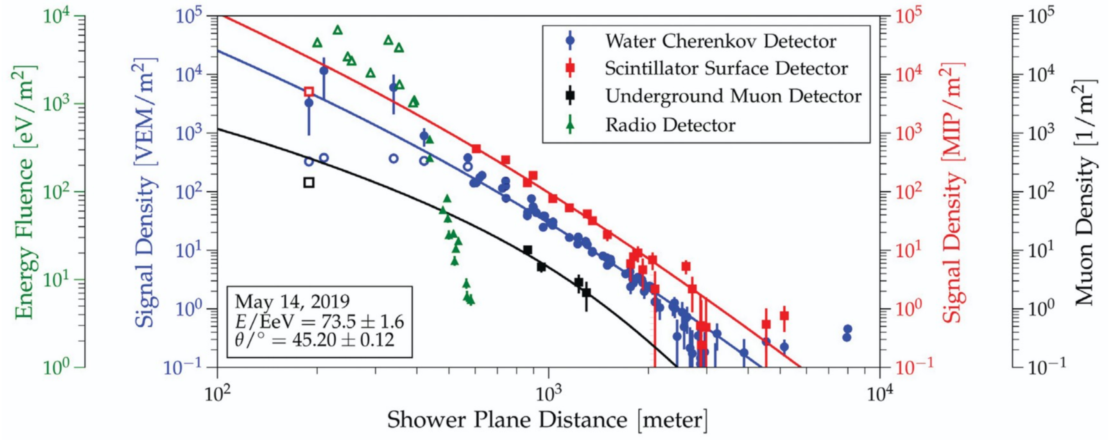
Summary & Outlook

- The hybrid design of the Pierre Auger Observatory **probes hadronic interactions at energies beyond the Large Hadron Collider scale (√s ~ 100 TeV)**

- Hadronic models fail to reproduce key air shower observables → modeling of ultra-high energy hadronic interactions remains incomplete

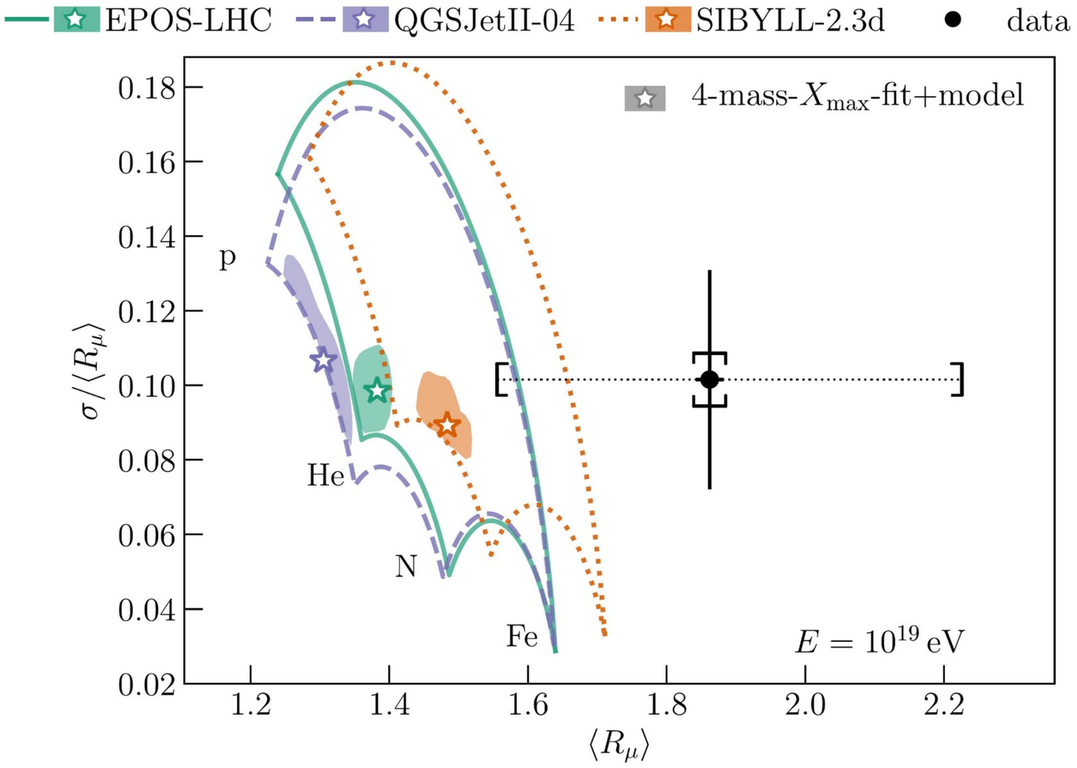
- The AugerPrime upgrade will enable new **multi-hybrid measurements**, allowing further testing and improvement of hadronic interactions → Stay tuned!





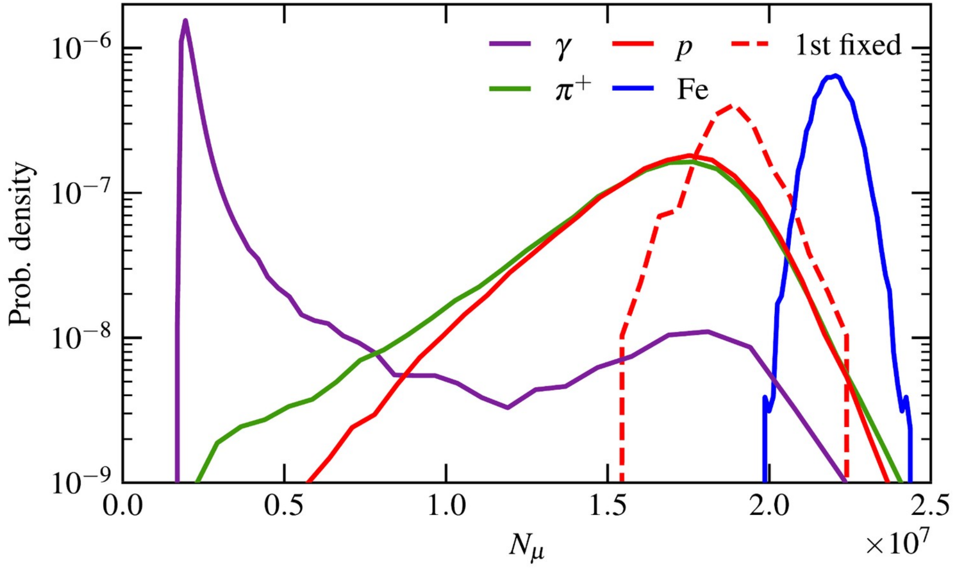
Backup slides

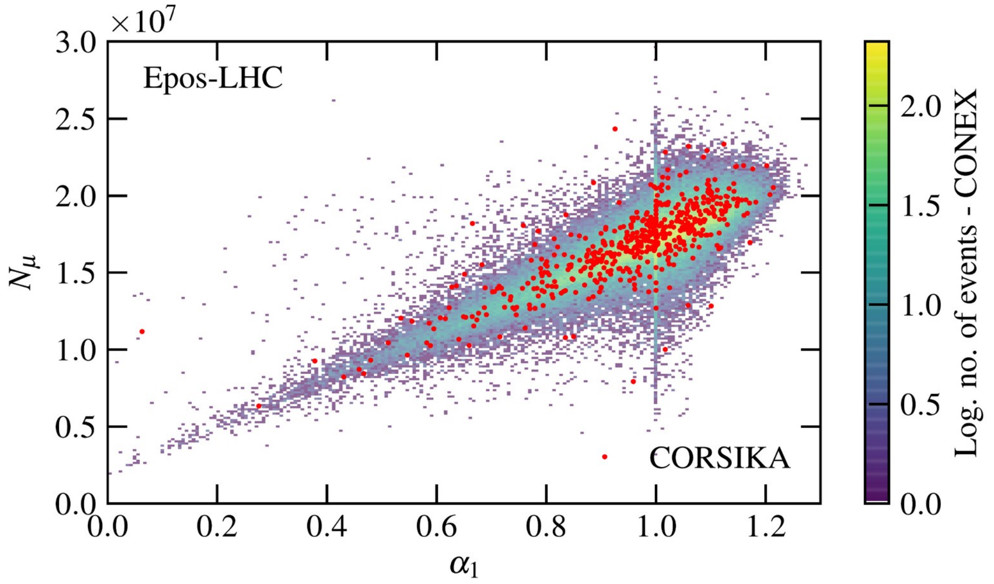
N_μ: mean and fluctuations provide complementary constraints



- Any p–He–N–Fe mixture lies within each contour (stars: X_{max}-inferred composition)
- Data require a larger <N_μ>, but not larger relative fluctuations

N_μ: Fluctuations and 1st interaction

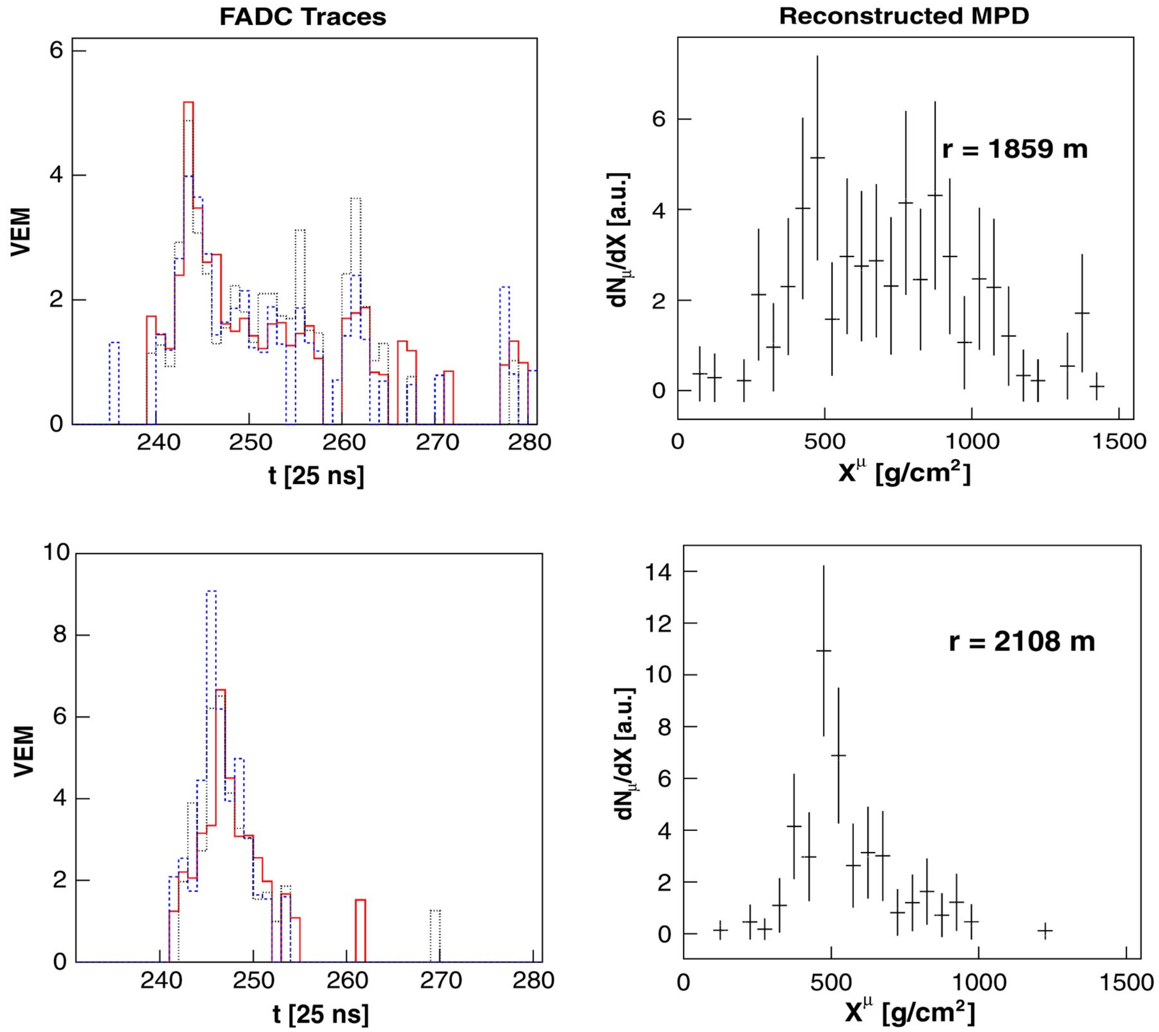




- Fixing 1st interaction reduces the fluctuations in N_μ (mean unchanged) → first-interaction fluctuations dominate the shower-to-shower fluctuations of N_μ
- 1rst interaction quantity: α_1 → modified fraction of the energy of 1st interaction that remains in the hadronic sector
- $\sigma(\alpha_1)$ explains ~70% of $\sigma(N_\mu)$

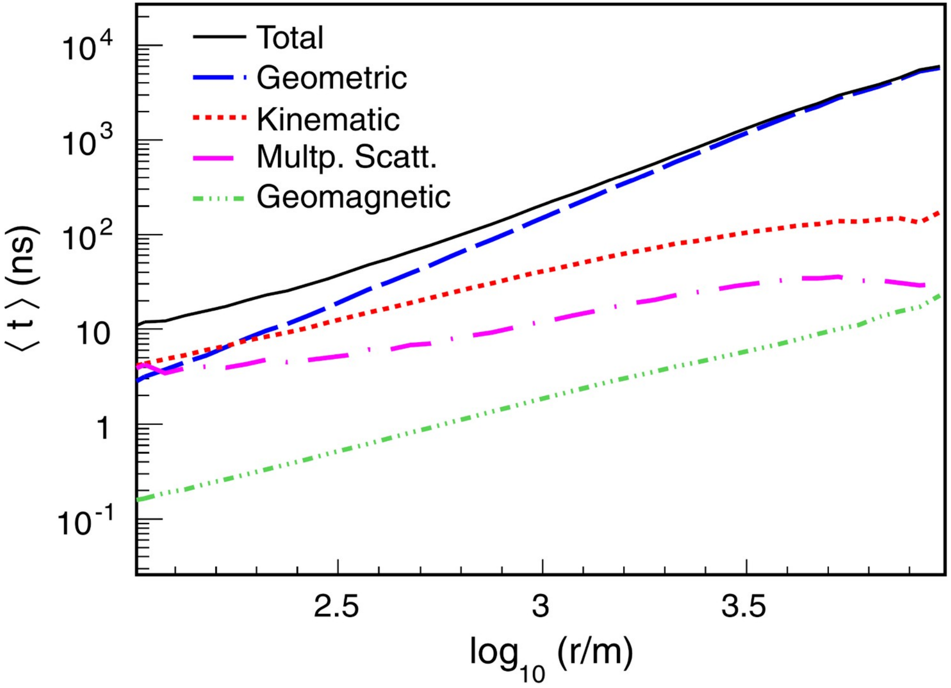
Riehn et al., Phys. Lett. B 784 (2018) 68-76

Reconstruction of Muon Production Depth (MPD)



- Contribution to the MPD of two detectors in the same event
- Only bins with signal > 15% of the maximum are used for MPD reconstruction (minimizes EM contamination and ensures 85% muon purity)
- MPDs from all selected stations are combined into the event MPD

Reconstruction of Muon Production Depth (MPD)



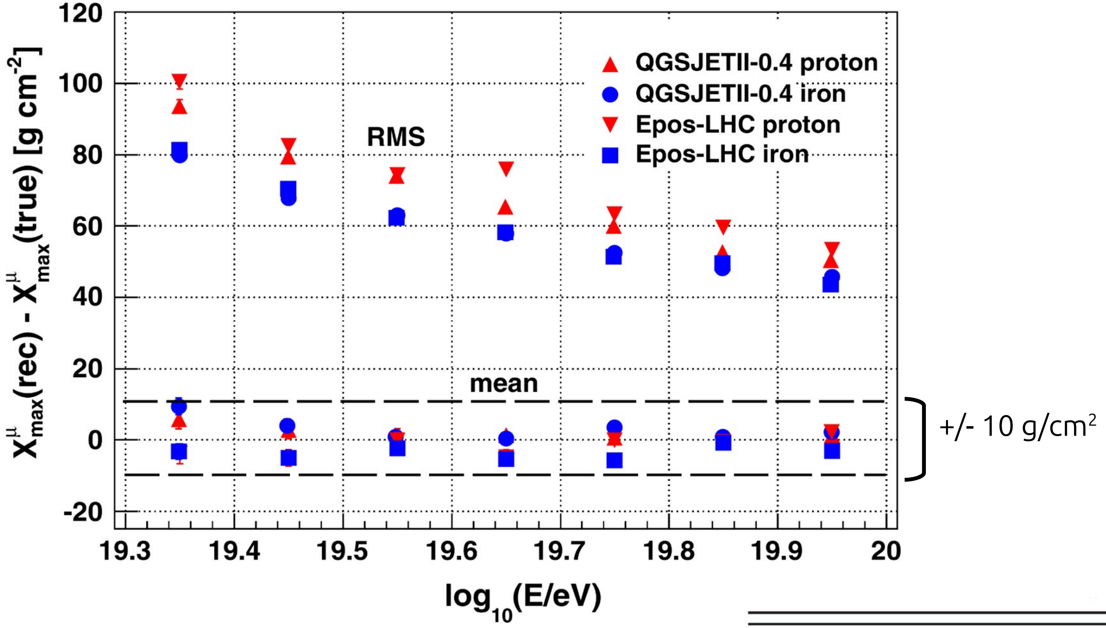
- Muon arrival time is determined by
  - Geometric delay → extra path length relative to a shower plane moving at c
  - Kinematic delay → Correction due to sub-luminal velocity
  - Multiple scattering → Coulumb scattering
  - Geomagnetic deflection

Sub-dominant

- For the selected geometry, t_{geom} dominates. After correcting the mean kinematic delay, $t_{geom} \rightarrow z \rightarrow X_{\mu}$.

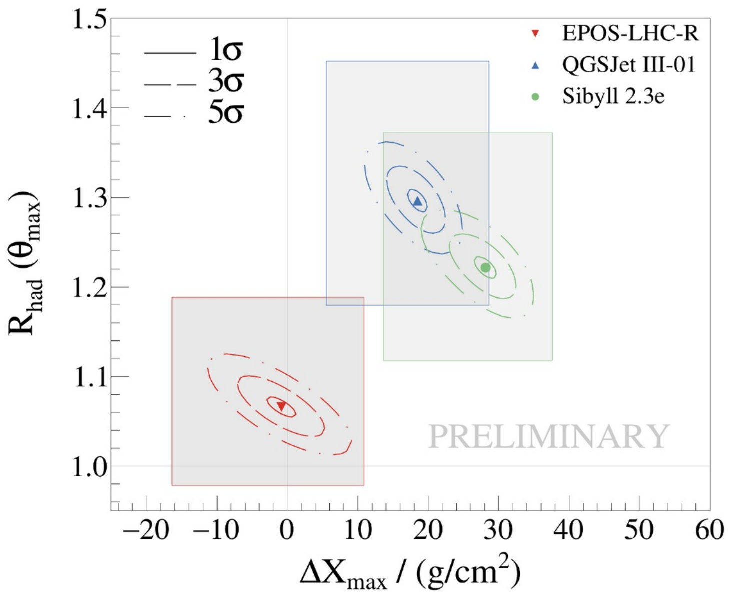
Cazon, et al. Astropart. Phys. 36, 211 (2012).

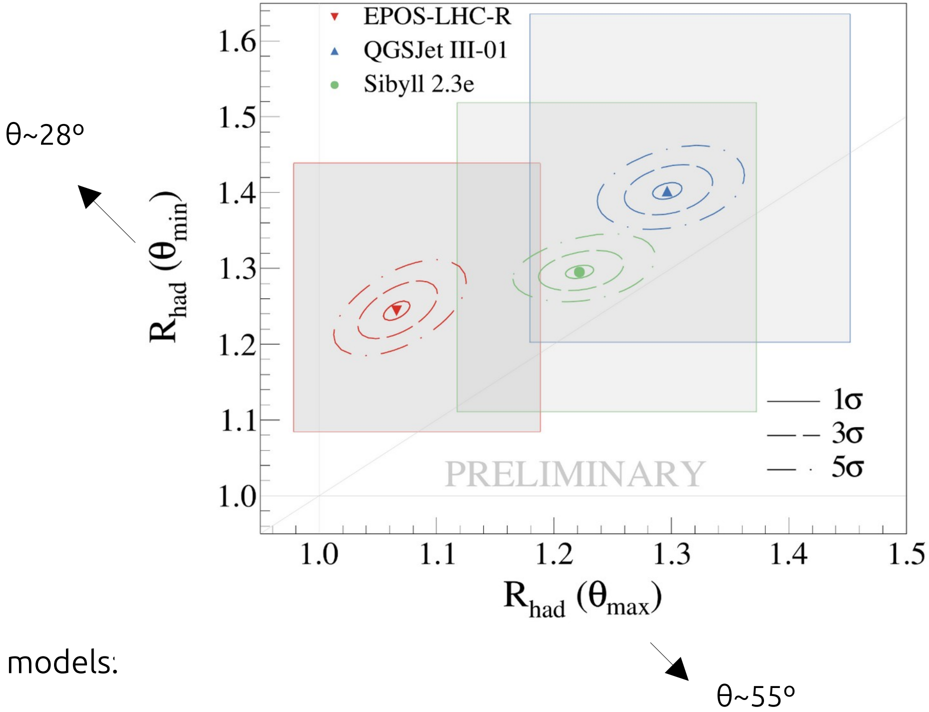
Reconstruction of Muon Production Depth (MPD): systematics



Source	Sys. uncertainty [g/cm^2]
Reconstruction, hadronic model and primary	10
Seasonal effect	12
Time variance model	5
Total	17

(X_{max}, S_{1000}) analysis with newest models (preliminary ICRC2025 update)

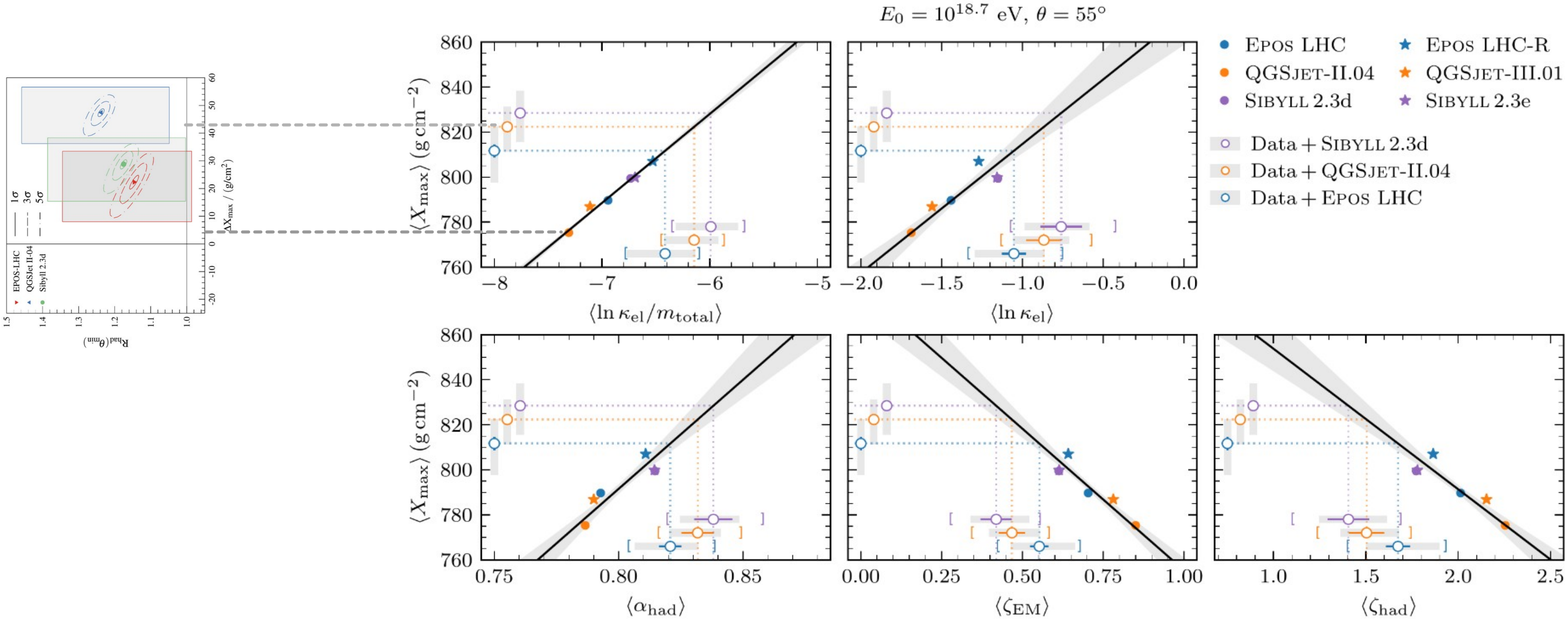




- Updated analysis: ~20% more hybrid events + newer hadronic models:
  - EPOS-LHC-R, QGSJet III-01, Sibyll 2.3e
- **New models improve the predicted X_{max} scale, but tensions remain**
  - EPOS-LHC-R: ΔX_{max}~0, but strong zenith dependence of R_{had} → muon spectrum too hard
  - No significant energy dependence of ΔX_{max} or R_{had}

J. Vicha, PoS(ICRC2025) 431

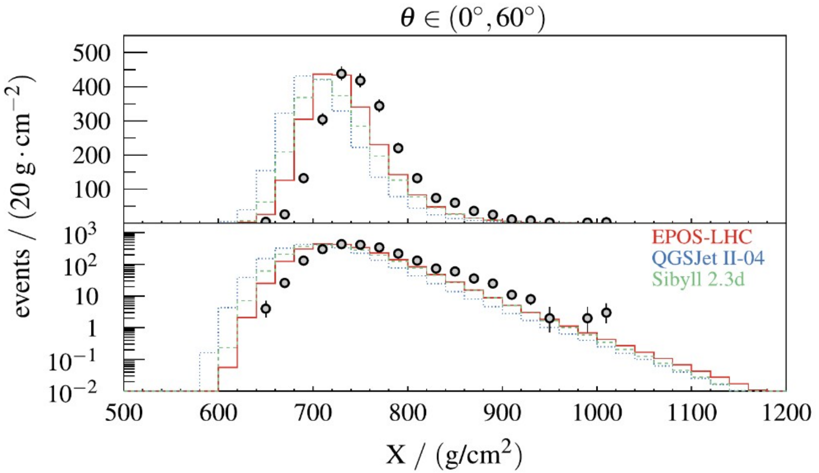
Xmax shift: implications for the first interaction



- There exists a universal relation between <Xmax> and variables related to the first interaction (α_{had}, K_{el}, ξ_{had}, ..) → use it to interpret the shift in X_{max} suggested by data
- Data suggests that models need **higher elasticity** and **fraction of hadronic energy** in 1st interaction

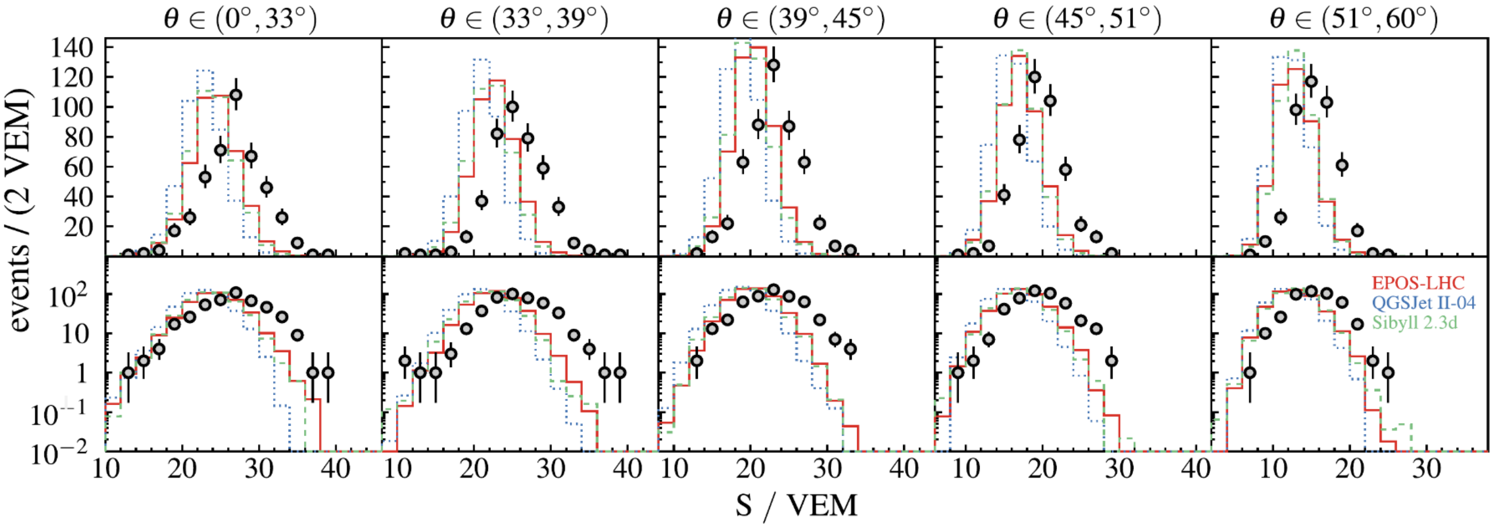
Martins et al, Phys.Rev.D 112 (2025) 4, 043016
Martins et al., arXiv.2602.22105
Pierre Auger Collaboration, arXiv:2607.22323

(X_{max}, S_{1000}) rescaling: fits without shifts



- Only fitting the mass fractions (f_p, f_{He}, f_O, f_{Fe}) without modifying X_{max} or S_{had} scale (with $f_p + f_{He} + f_O + f_{Fe} = 1$)

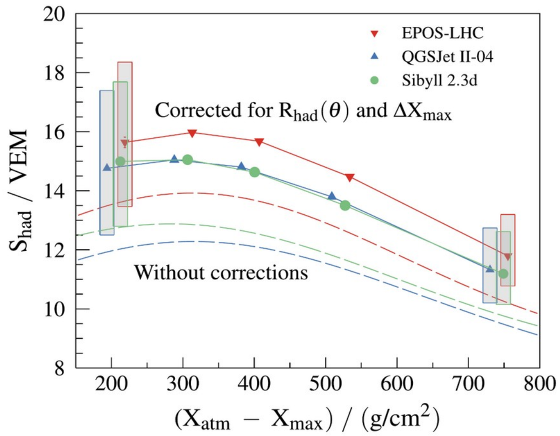
- Composition alone cannot describe the data → **model-scale shifts are required**



(X_{max}, S_{1000}) rescaling: fit details

- X_{max} and S_{1000} of each event is corrected for the energy evolution
  - $X = X_{max} + D\,\lg(10^{18.7}\,\text{eV} / E_{FD})$
  - $S = S_{1000}\,(10^{18.7}\,\text{eV} / E_{FD})^{1/B}$

- Six free fit parameters:
  - 3 mass fractions (f_p, f_{He}, f_O, $f_{Fe} = 1 - f_p - f_{He} - f_O$) → independent of E and θ
  - 2 hadronic scaling factors ($R_{had}(\theta_{min})$, $R_{had}(\theta_{max})$) → interpolated linearly in $X_{atm}–X_{max}$.
  - 1 X_{max} shift ΔX_{max} → independent of primary, E and θ



- Shifts in X_{max} also influence the signal at 1000 m
  - if X_{max} is deeper, shower maximum is closer to ground and more particles reach the ground, increasing S_{1000}
  - R_{had} rescales S_{had} only, ΔX_{max} also changes S_{had} and S_{em}

- Goodness of fit: p-values obtained from 500 MC pseudo-experiments (2239 events each) generated with the best-fit composition and modifications; the data $\ln L_{min}$ is compared with the MC distribution