MOdifed Characteristics of Hadronic Interactions

in ultra-high-energy cosmic-ray showers

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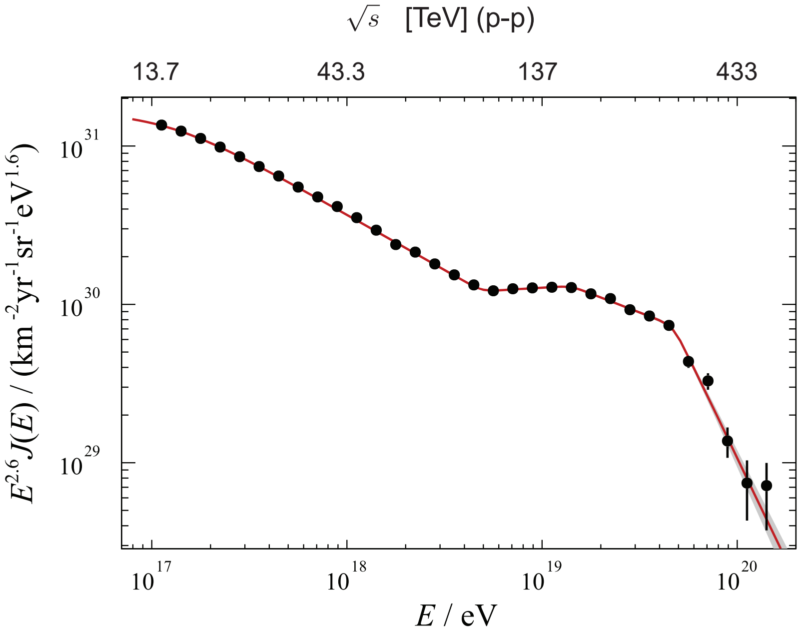
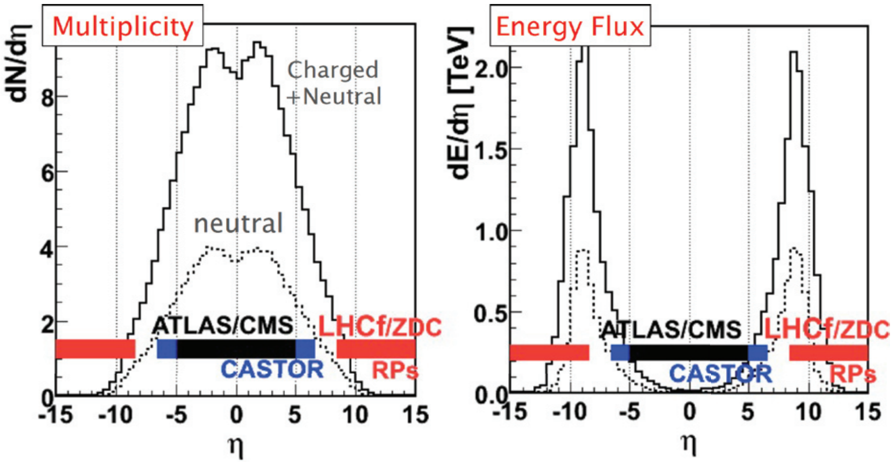
Hadronic interactions and UHECR (ultra-high-energy cosmic rays)

Primary interactions of CR observed at Auger mostly above 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.



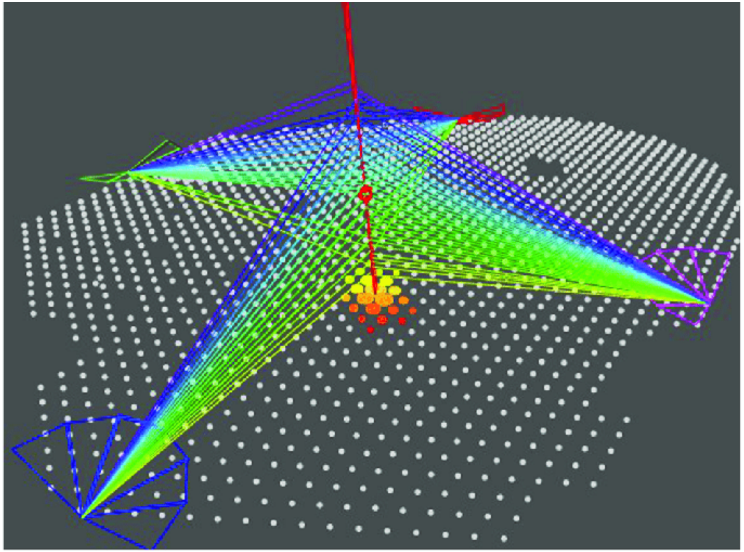


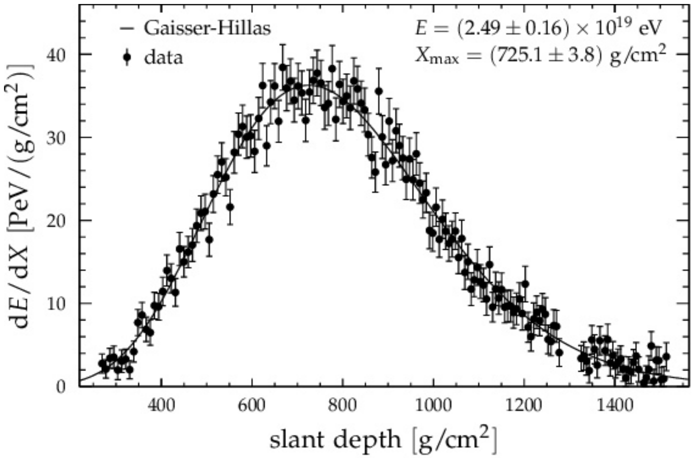
Eur. Phys. J. C (2021) 81:966

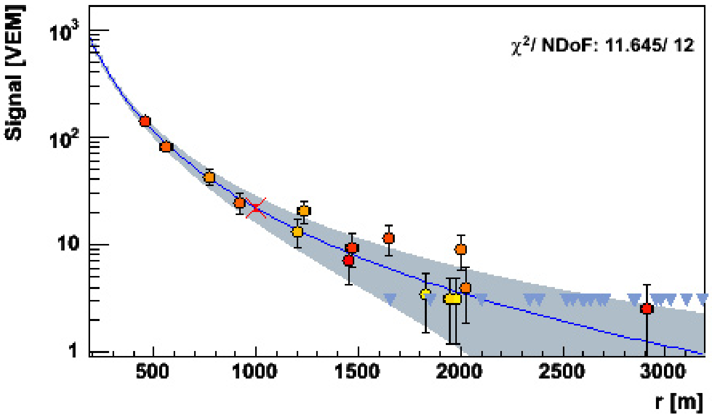
UHECR detection through air showers

- Pierre Auger Observatory (Argentina)
- Telescope Array (Utah)

- longitudinal shower profile (air fluorescence)
- particles arriving at ground (small sample)







Hadronic interactions in cosmic ray showers

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

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

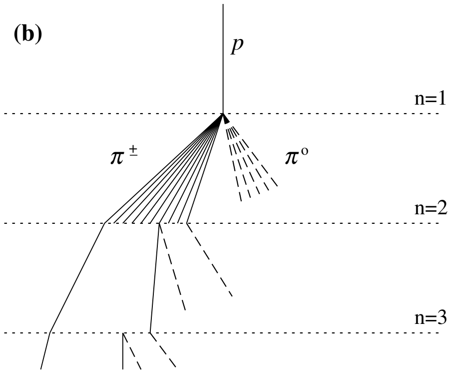
$$N_\mu \approx \left(\frac{E_0}{\xi_{\rm c}^{\pi}}\right)^{\beta} A^{(1-\beta)} \qquad \beta \approx 1 - \frac{\kappa}{3\ln[N_{\rm ch}]} > 0.9$$

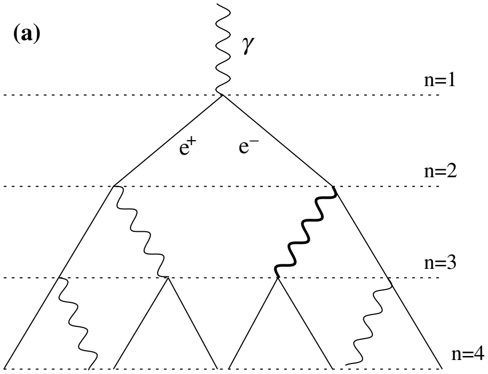
X_{max} and N_μ sensitive to both interaction properties
- multiplicity N_{ch} and elasticity κ

and primary mass A

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

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

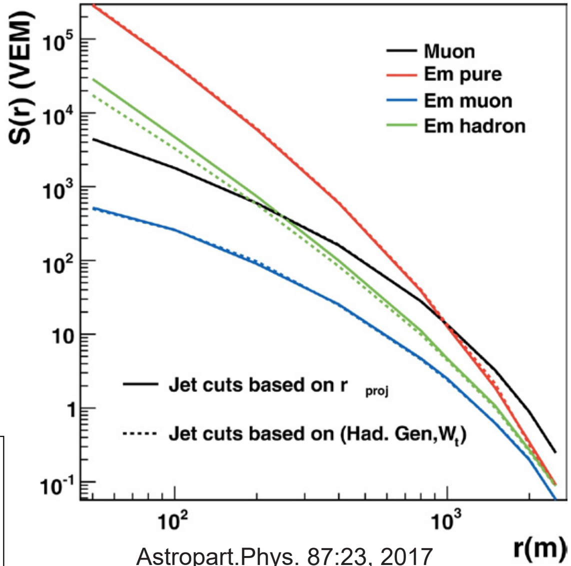




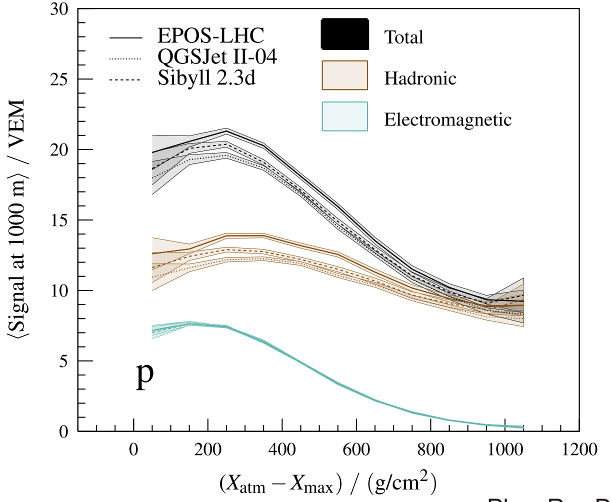
The importance of muons

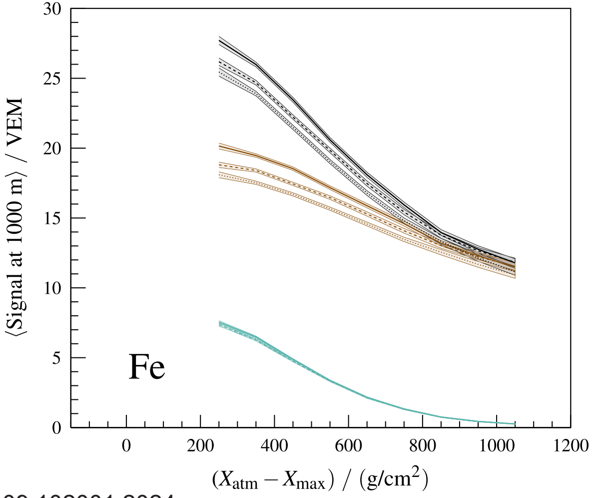
- 4-component shower model:
    - pure EM component
    - muons, EM from decay, EM from "jets" = hadronic component

- 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!

Modified hadronic interactions

Phys. Rev. D, 83:054026, 2011

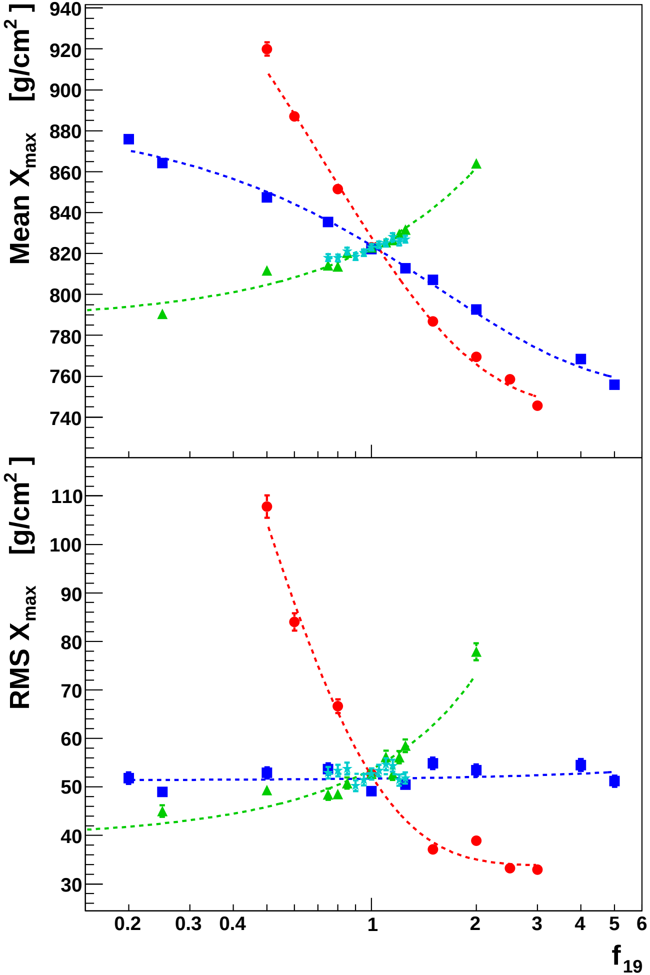
- individual changes of multiplicity, elasticity and cross-section in CONEX - 1D simulations
- 215 citations

$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot \frac{\log_{10}(E/E_{\mathrm{thr}})}{\log_{10}(10\ \mathrm{EeV}/E_{\mathrm{thr}})}$$

CONEX in Corsika: 3D information

MOCHI: CORSIKA 7.741 with CONEX option, Sibyll 2.3d

- nuclear projectiles treated as a set of p-Air interactions
- POS(ICRC2023)245
- POS(ICRC2021)441
- EPJ WoC 283:05005

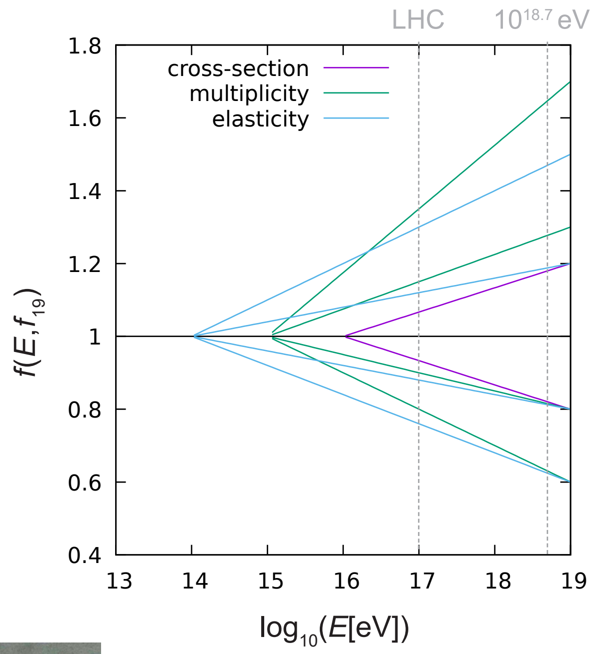


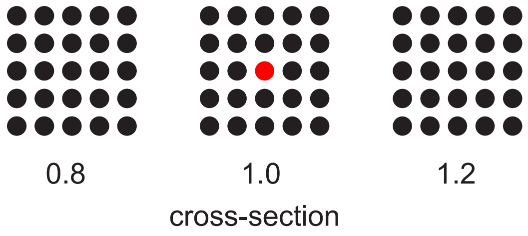
"Allowed" modifications and thresholds

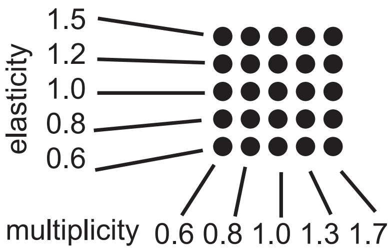
Cross-section (E_{thr} = 10^{16} eV)
- well constrained for p-p at LHC to a few %
- unc. in conversion to p-A limited by CMS p-Pb measurement

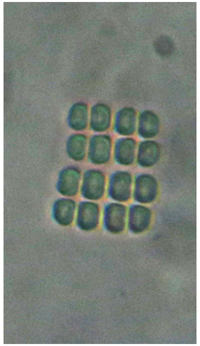
Multiplicity (E_{thr} = 10^{15} eV)
- no p-A data, limited rapidity coverage

Elasticity (E_{thr} = 10^{14} eV)
- difficult at accelerators, limits from nuclear emulsion chambers
- recent LHCf neutron elasticity measurement?
- range of modifications limited by internal consistency





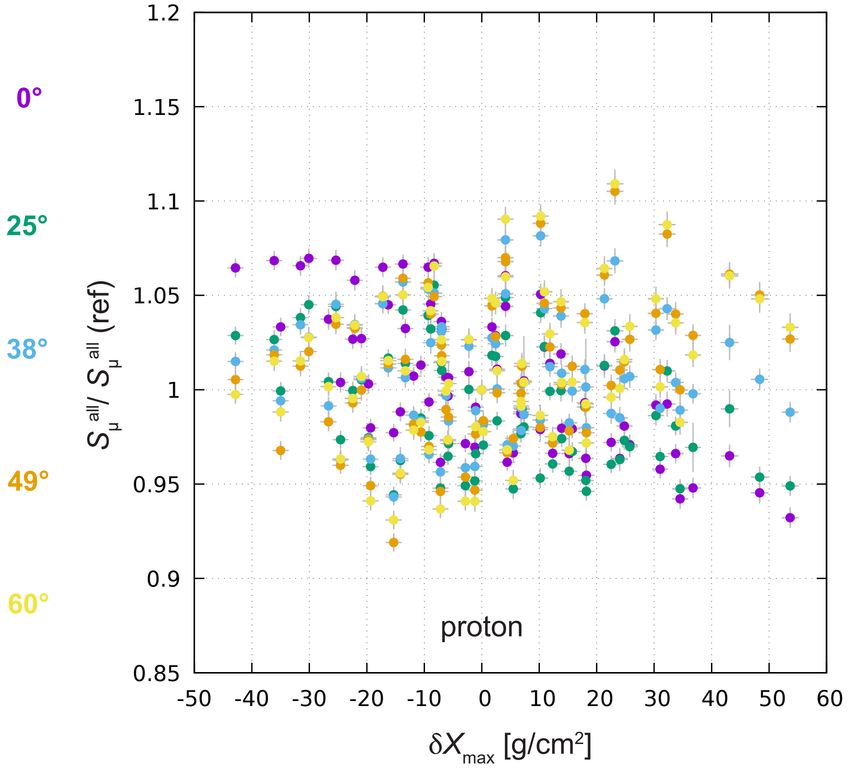




- energy $10^{18.7}$ eV
- proton and iron
- 5 zenith angles
- 1000 showers per „bin“
- 750 000 showers

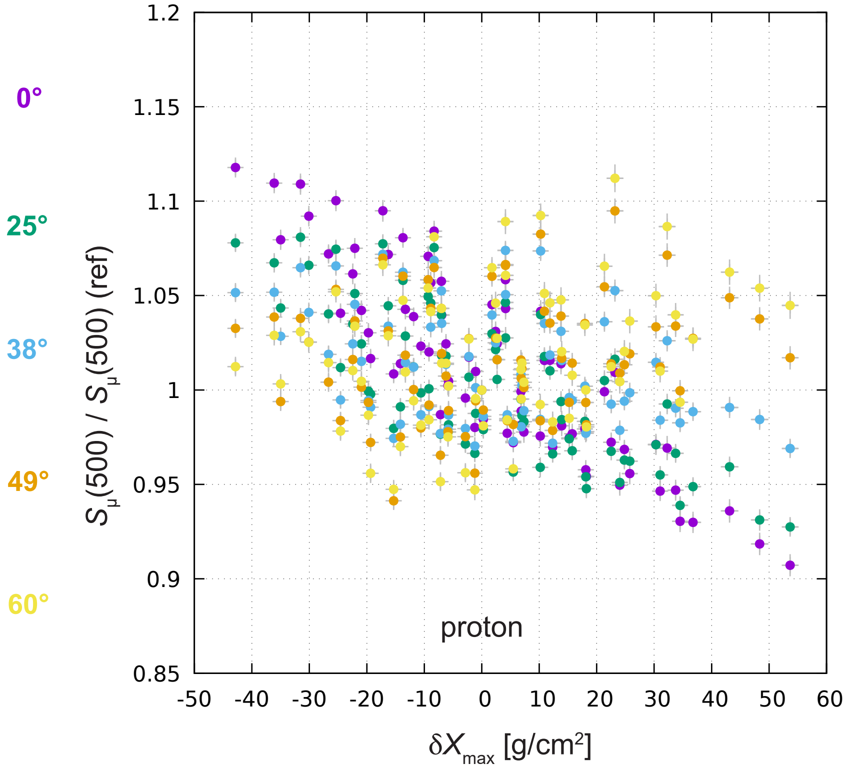
Number of muons vs. X_{max} for all muons

More dependent on *r* for vertical showers, less for inclined



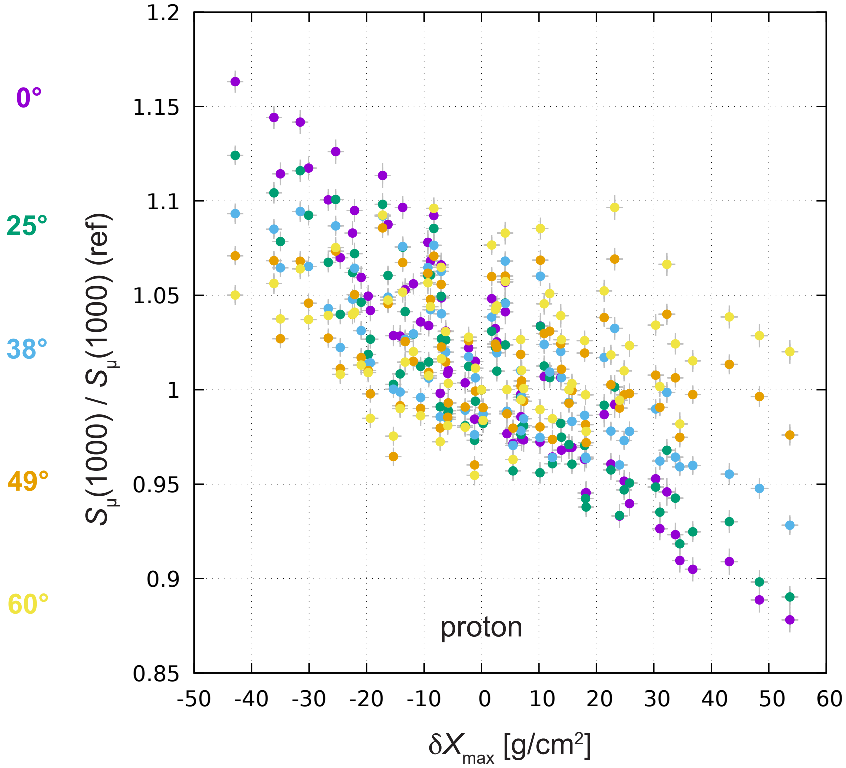
Number of muons vs. X_{max} @ 500 meters

More dependent on *r* for vertical showers, less for inclined



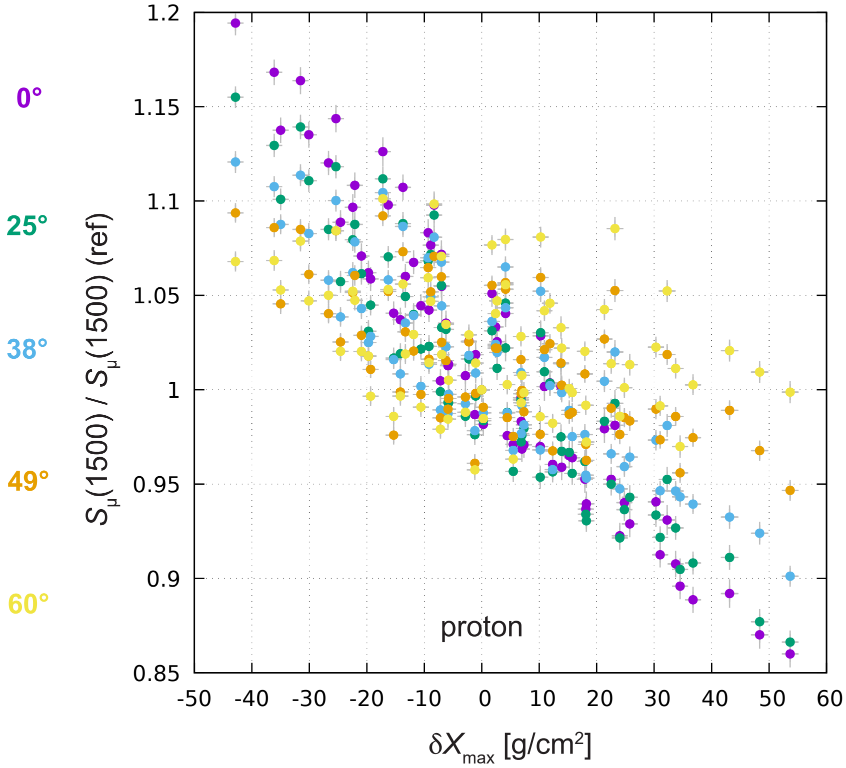
Number of muons vs. X_{max} @ 1000 meters

More dependent on *r* for vertical showers, less for inclined

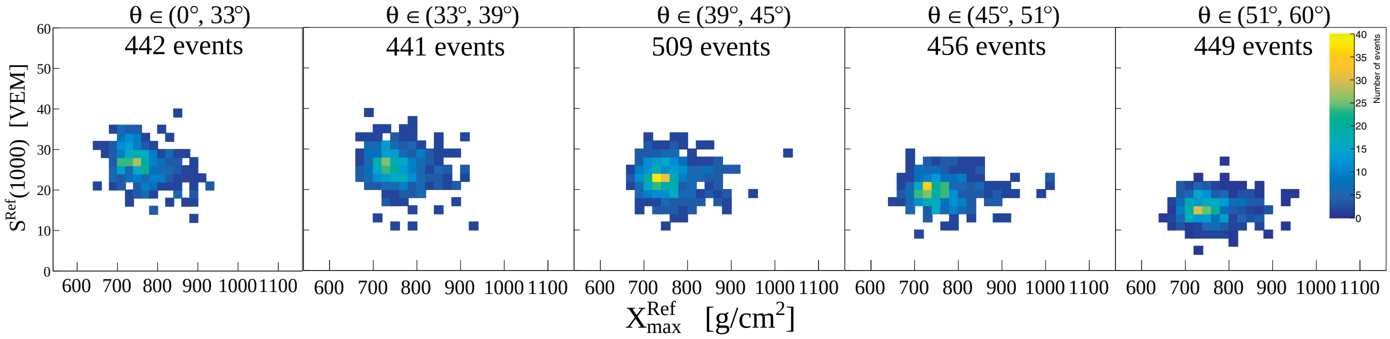


Number of muons vs. X_{max} @ 1500 meters

More dependent on *r* for vertical showers, less for inclined

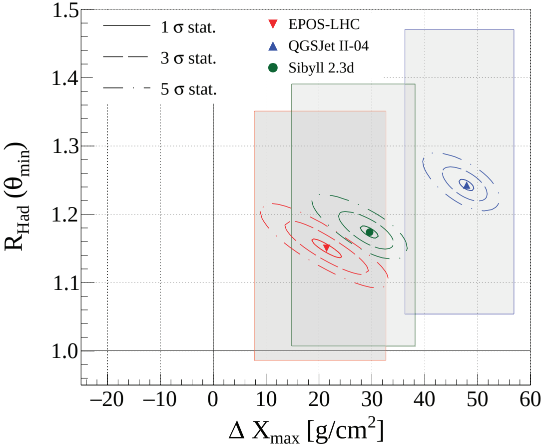


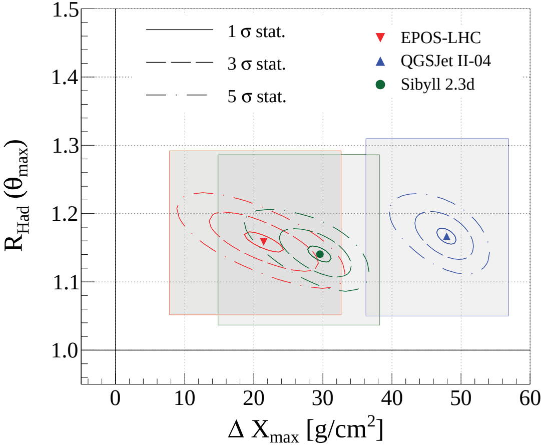
Auger: combined fits of full distributions of X_{max} and ground signals



2D distributions of ground signal S(1000) and X_{max} for hybrid events with E between $10^{18.5}$–10^{19} eV are fit with freedom in mass composition and changes in muon signal and depth of shower maximum.

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

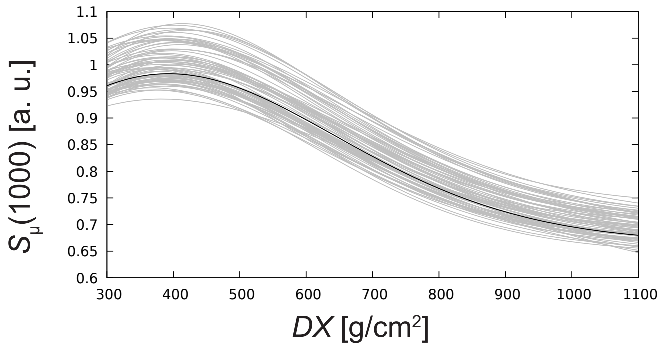


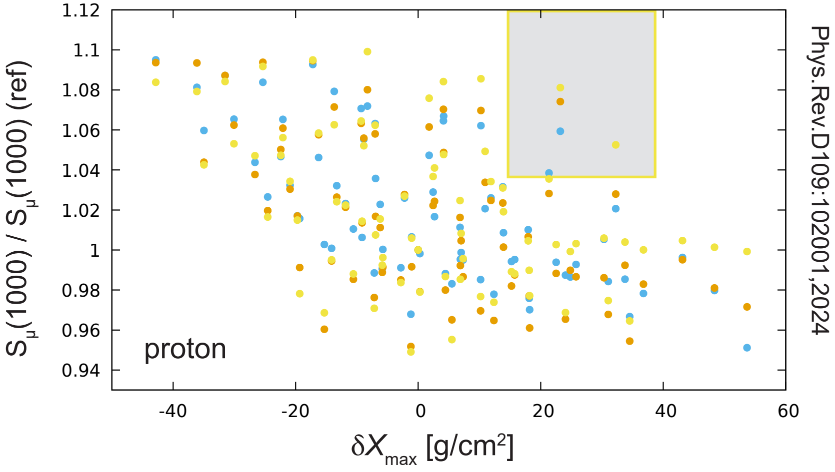


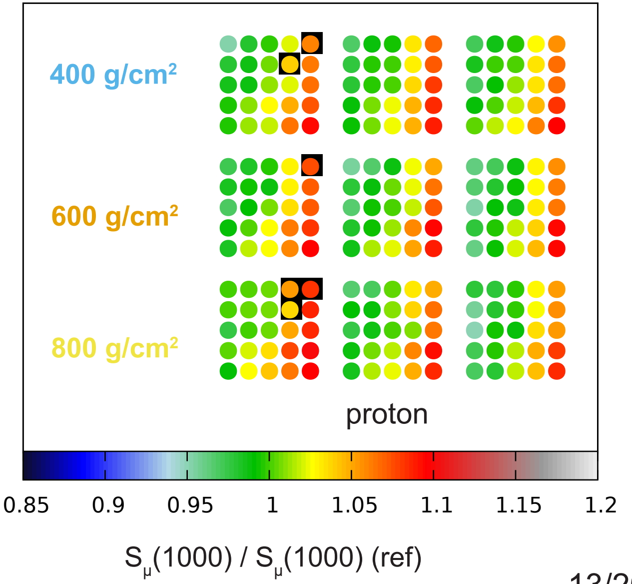
Phys.Rev.D109:102001,2024

Muons at 1000 m at fixed *DX*

- remove effects of shifting X_{max} on S_μ by fitting a dependence on *DX*
- only a combination of extreme modifications works

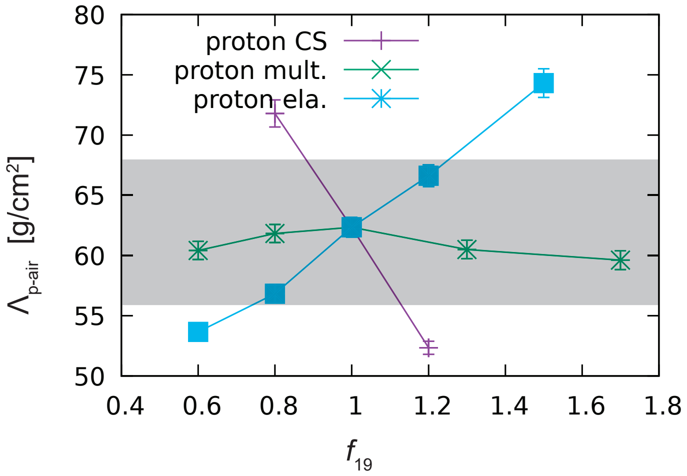


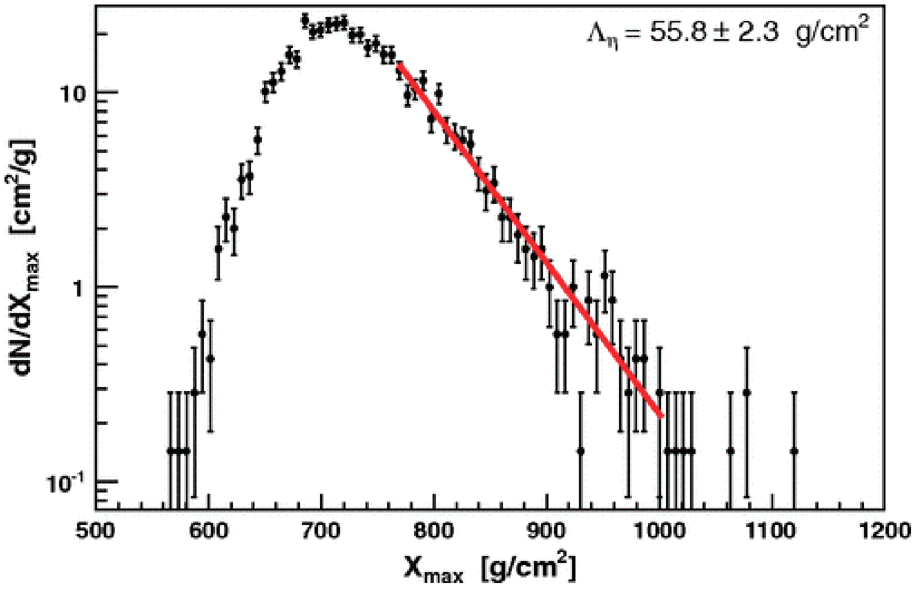




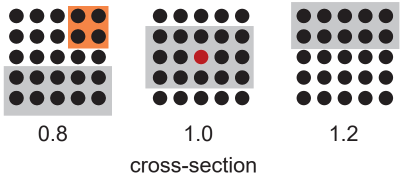
Auger cross-section measurement

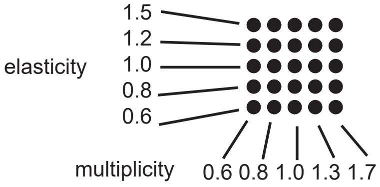
- modifications of elasticity change Λ→σ conversion: Auger CS = constraint in σ–elasticity space
- unmodified Sibyll 2.3d smack on data; uncertainty extrapolation with $f(E,f_{19})$



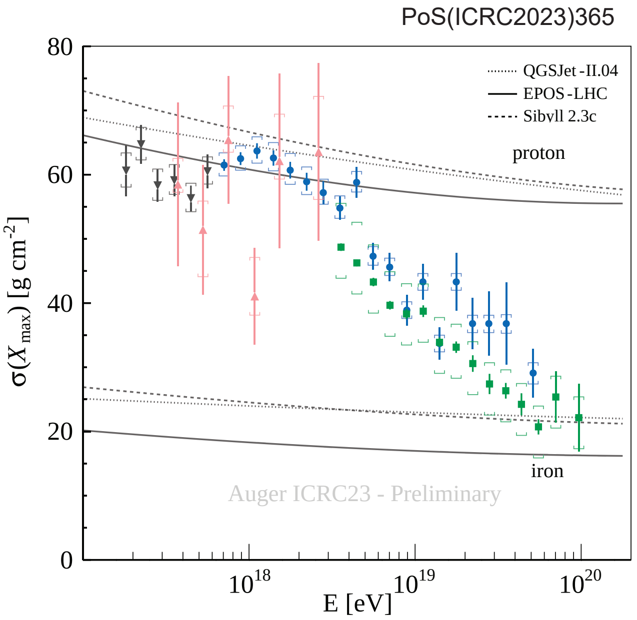


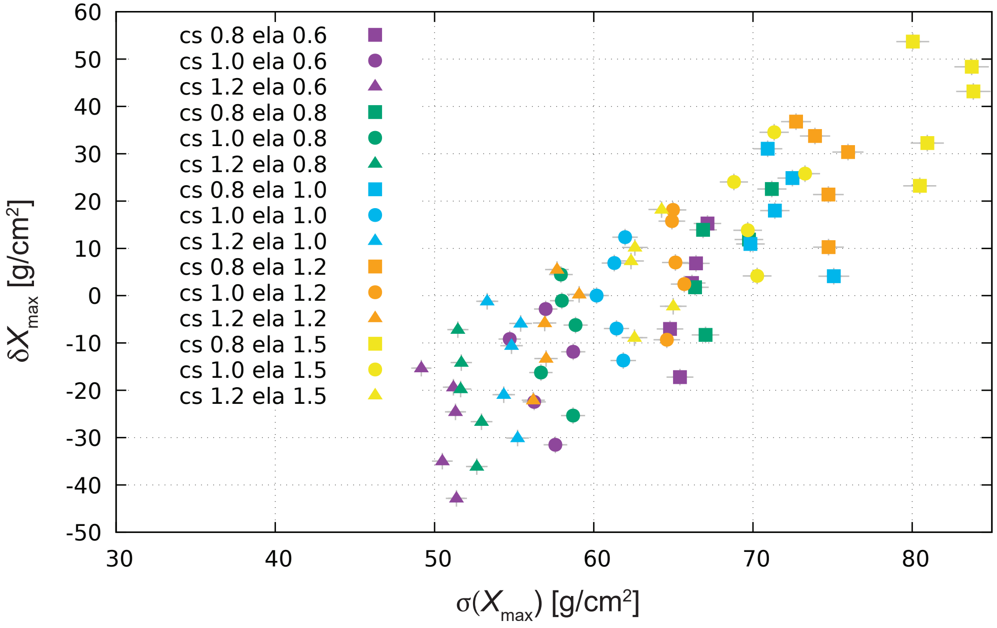
Phys.Rev.Lett.109:062002,2012

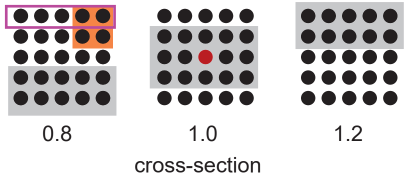


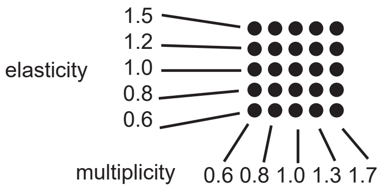


X_{max} fluctuations









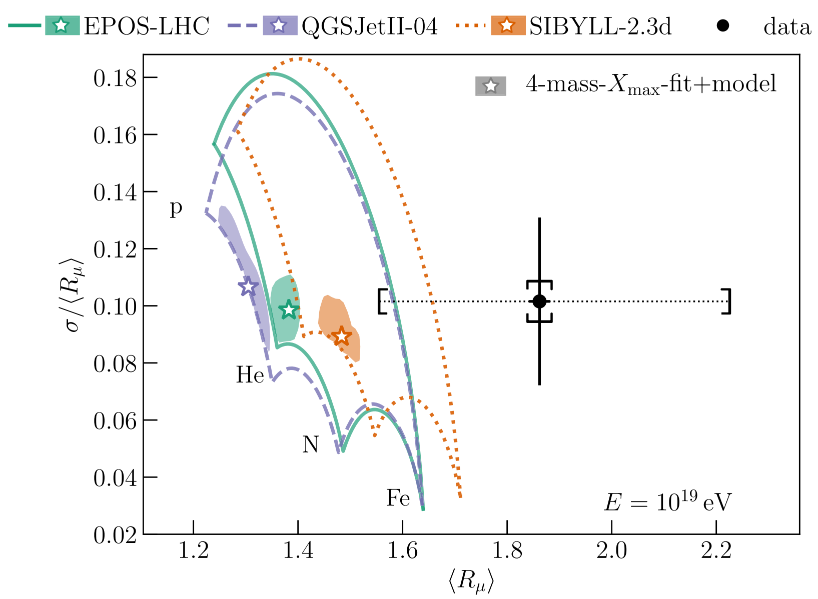
Low CS and high elasticity leads to very high X_{max} fluctuations that may be difficult to reconcile with Auger data

n.b. no change of fluctuations for Fe

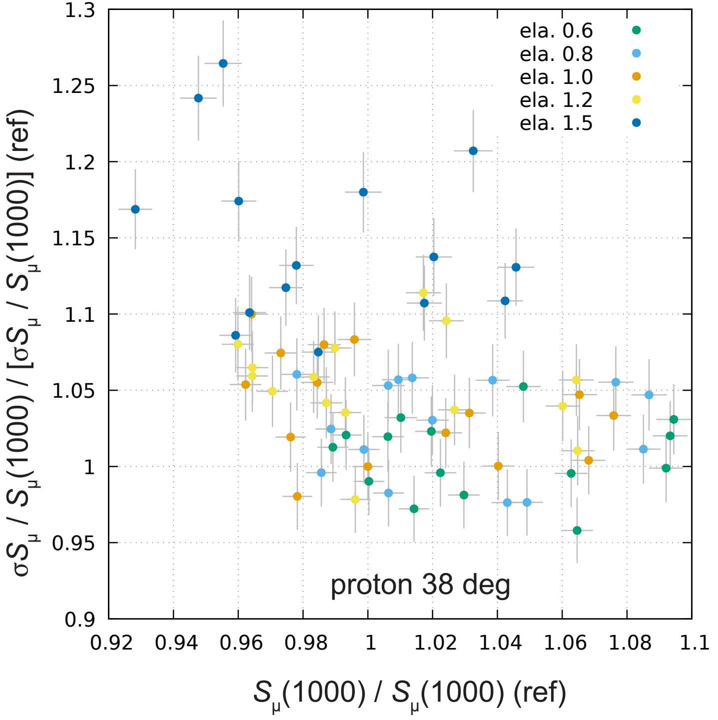
Ground particles: relative muon number fluctuations at 1000 meters

- not correlated with absolute changes in muon number, sensitive to high elasticity changes

- Auger sees muon fluctuations consistent with models

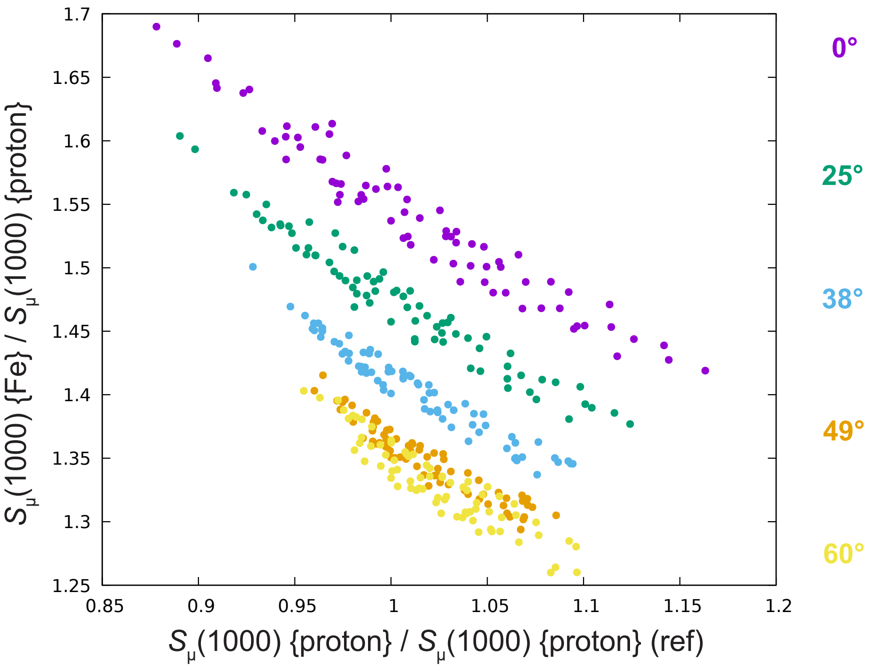


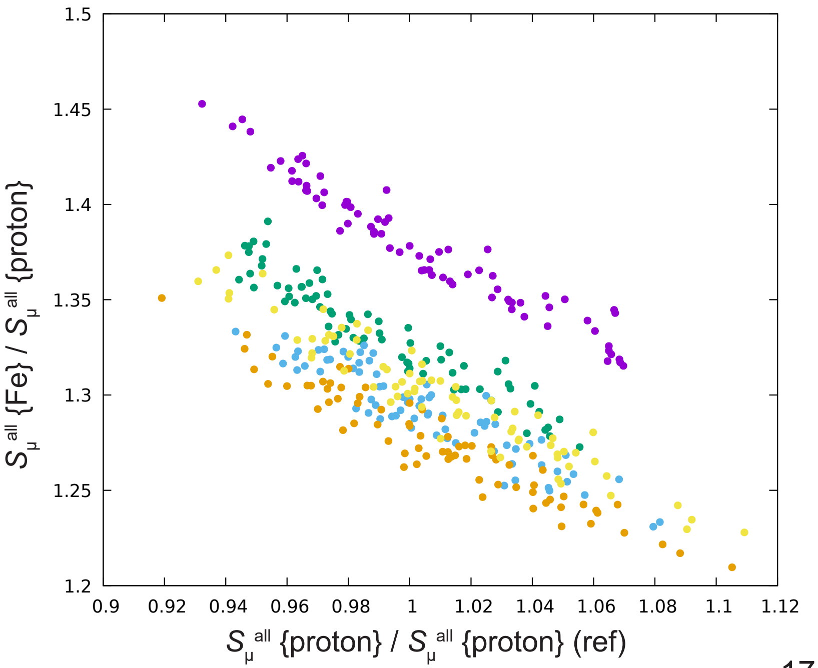
Phys.Rev.Lett.126:152002,2021



Adding muons and proton/iron separation

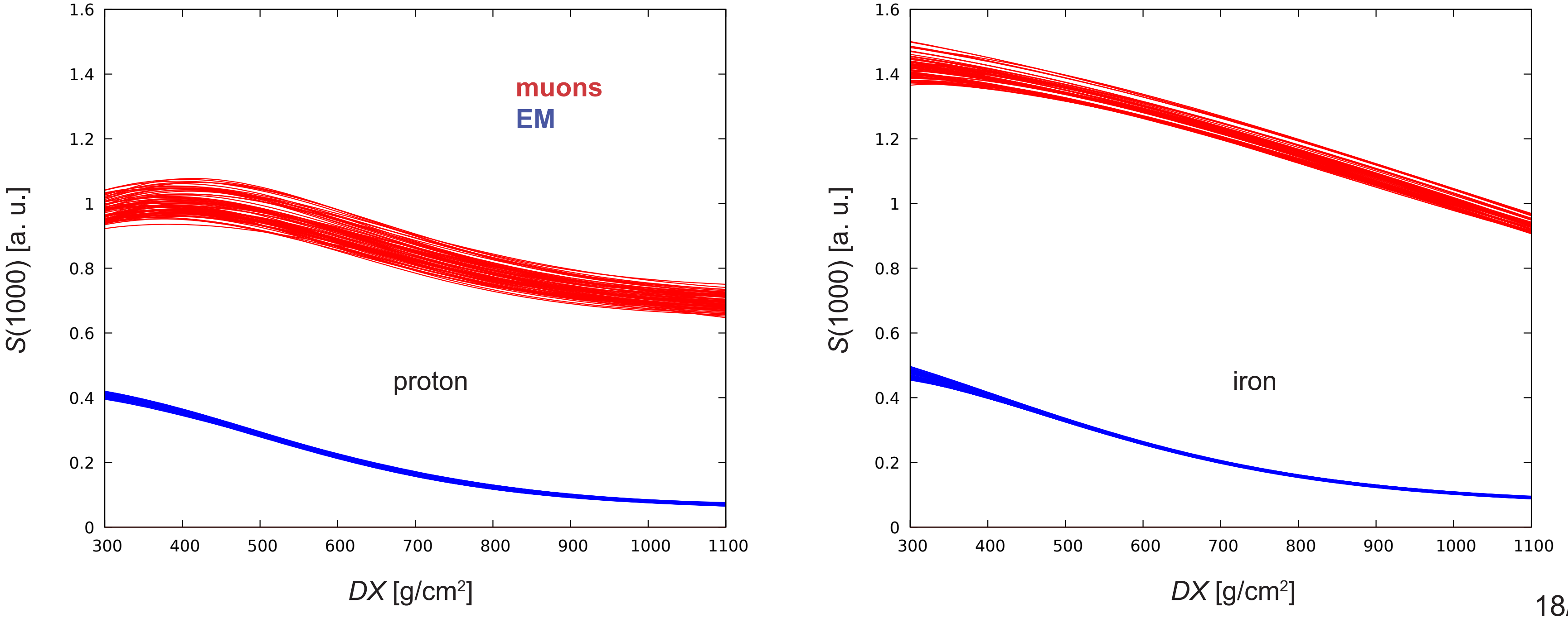
Ratio between number of muons for iron and proton tends down when muons are added
- whatever the answer to the muon problem is, it may make primary separation more difficult





Universality

Muon signal far more affected than EM (also lateral shape of EM well preserved)
(notes: no complete 4-component model, arbitrary normalization between muon/EM)

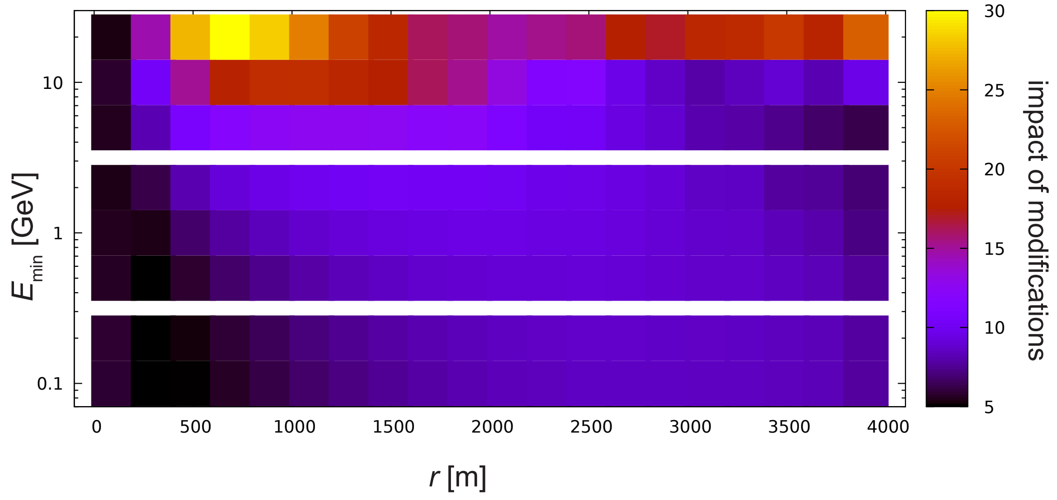


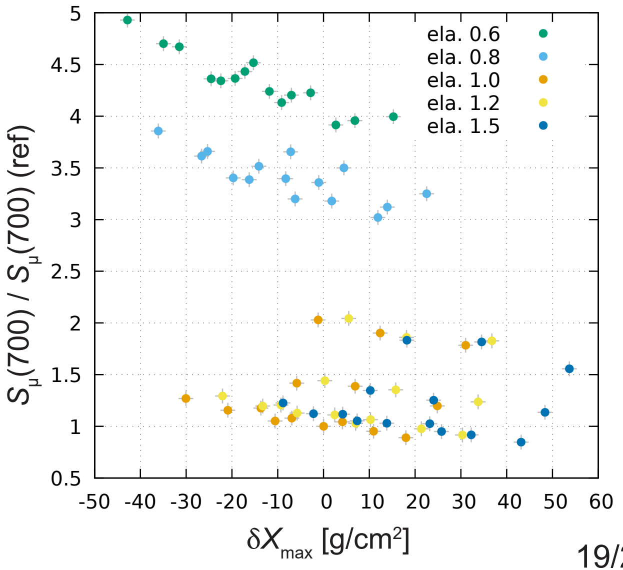
Sensitivity of muon number to modification as a function of E_{min}, r

- sum of absolute values of changes of muon density divided by statistical uncertainty (1000 showers)

- example: proton @ 38 degrees

- large deviations in the most significant point in (E_{min},r) space overwhelmingly due to low elasticity bins
    - deep underground measurements highly interesting for particle physics!





Conclusions

- changing cross-section, elasticity and multiplicity within reasonable limits can have major impact on air-shower properties

- the impact can be quite different for quantities depending on 3D geometry as opposed to 1D sums

- the changes of hadronic interactions indicated by the Pierre Auger Observatory are just reachable
    - but only with a *combination* of modifications!
    - and already in a tension with other measurements

- a wealth of other features can be studied - see POS(ICRC2023)245 (full papers soon)

- even if some modifications are not realistic, we can learn interesting insights