MOdifed Characteristics of Hadronic Interactions

in ultra-high-energy cosmic-ray showers

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Modified hadronic interactions

Phys. Rev. D, 83:054026, 2011

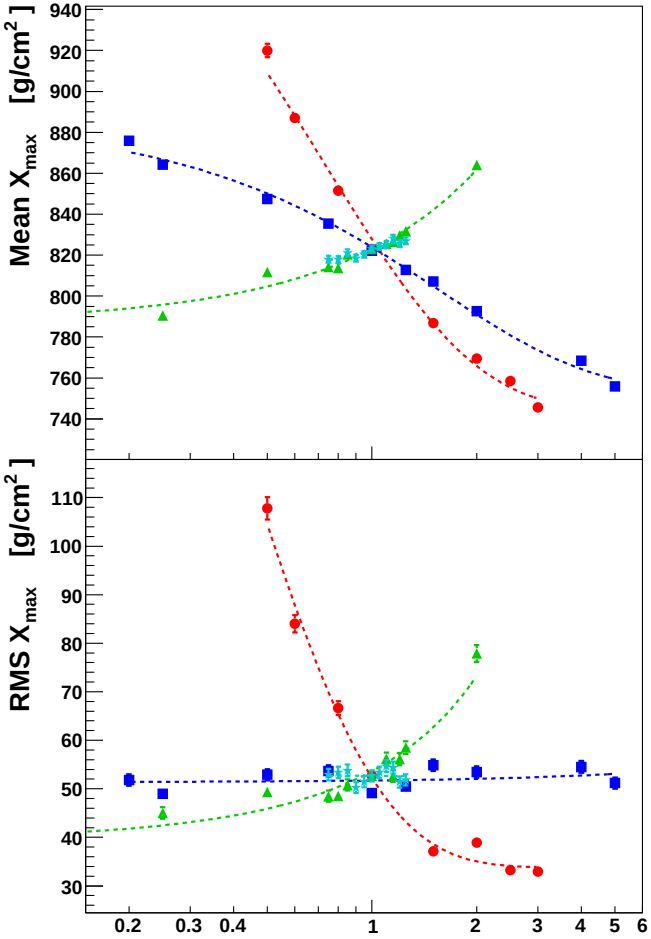
- individual changes of multiplicity, elasticity and cross-section in CONEX - 1D simulations
- 215 citations

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

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

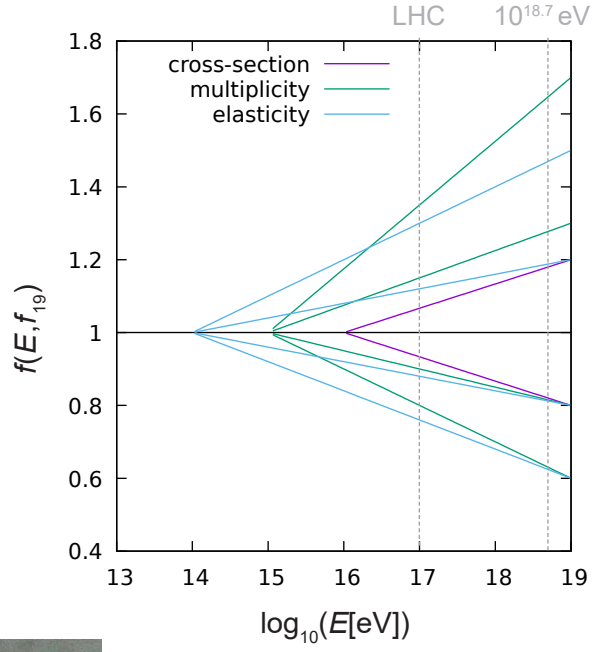


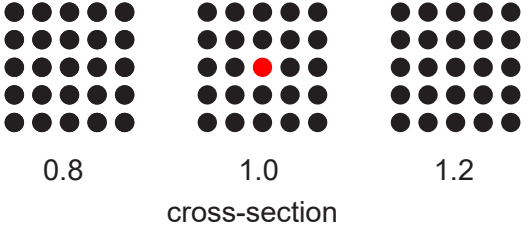
“Allowed” modifications and thresholds

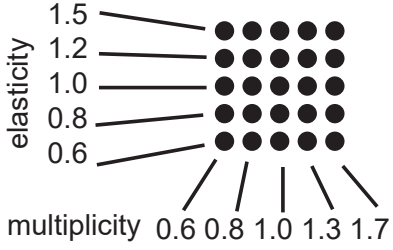
Cross-section (E_{thr} = 10^{16} eV)
- well constrained for p-p at LHC to a few %
- unc. in conversion to p-A limited by CMS p-Pb measurement

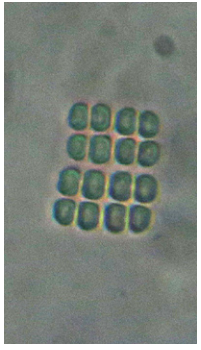
Multiplicity (E_{thr} = 10^{15} eV)
- no p-A data, limited rapidity coverage

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





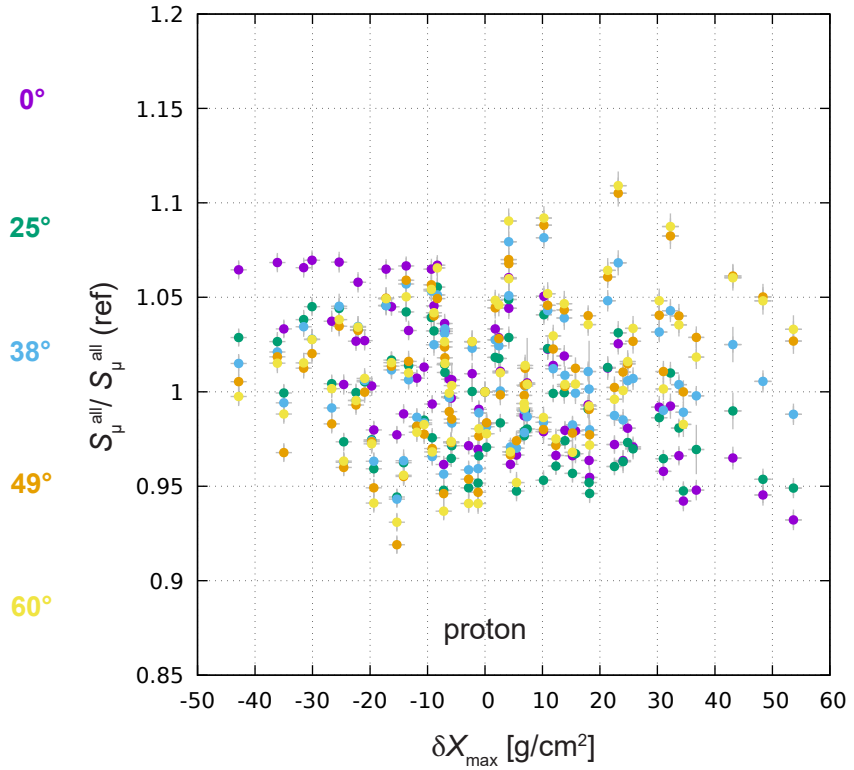




- energy $10^{18.7}$ eV
- proton and iron
- 5 zenith angles
- 1000 showers per „bin“
- 750 000 showers

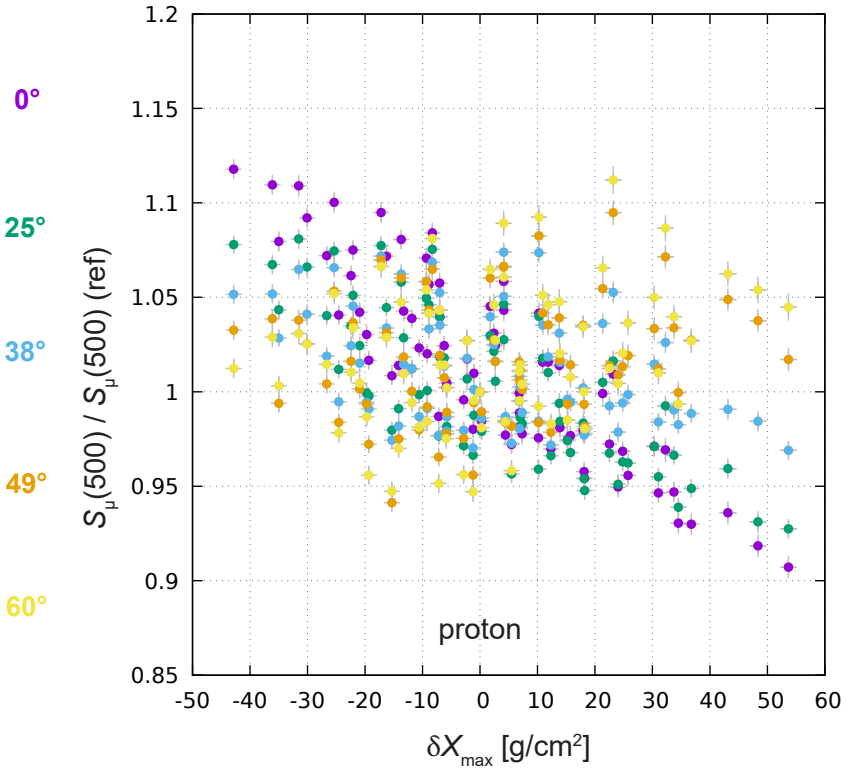
Number of muons vs. X_{max} for all muons

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



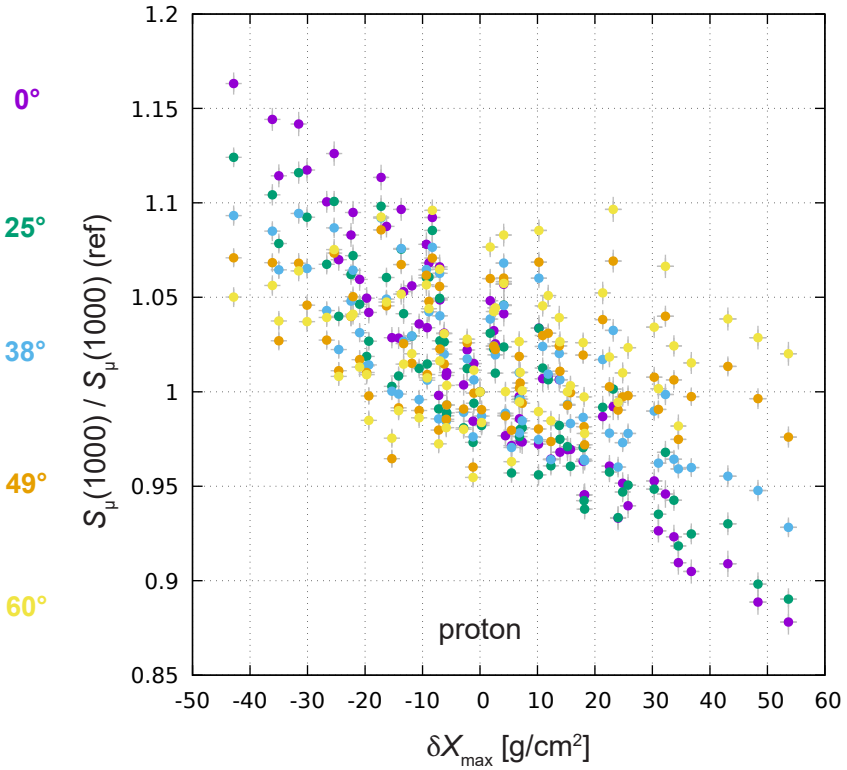
Number of muons vs. X_{max} @ 500 meters

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



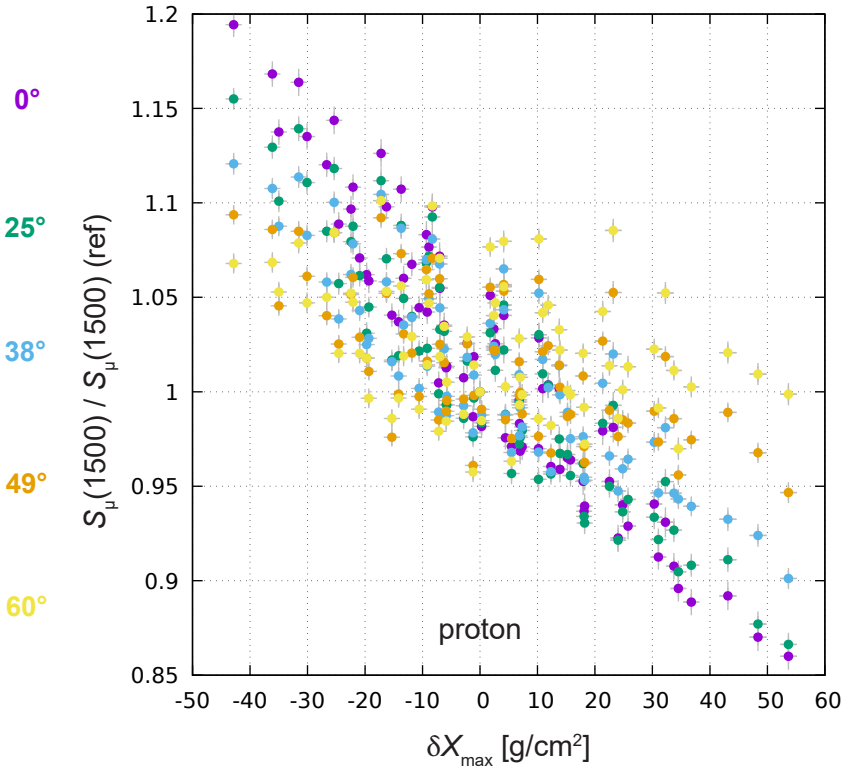
Number of muons vs. X_{max} @ 1000 meters

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



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

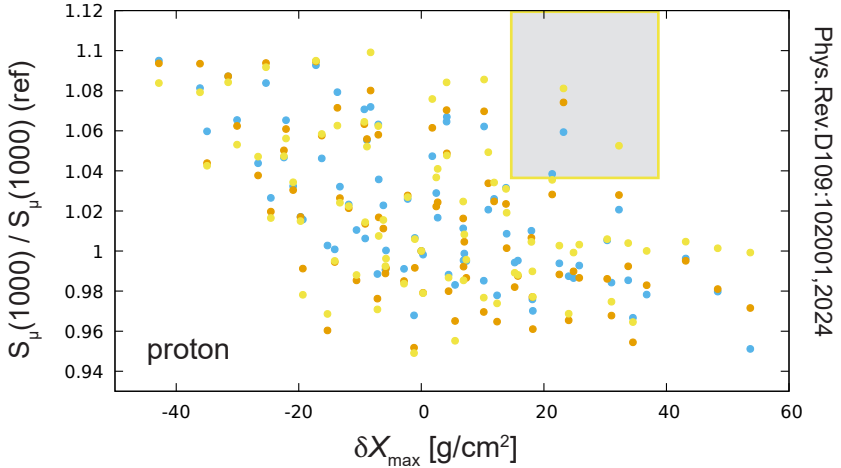
More dependent on *r* for vertical showers, less for inclined

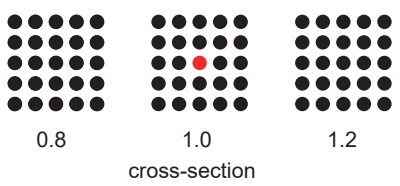


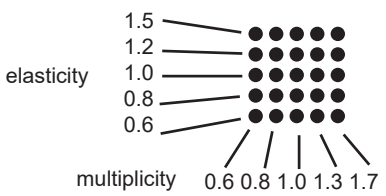
Muons at 1000 m at fixed *DX*

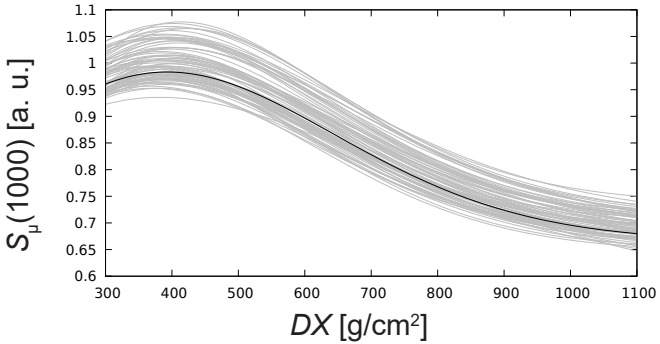
- remove effects of shifting X_{max} on S_μ by fitting a dependence on *DX* - allows comparison recent with Auger analysis

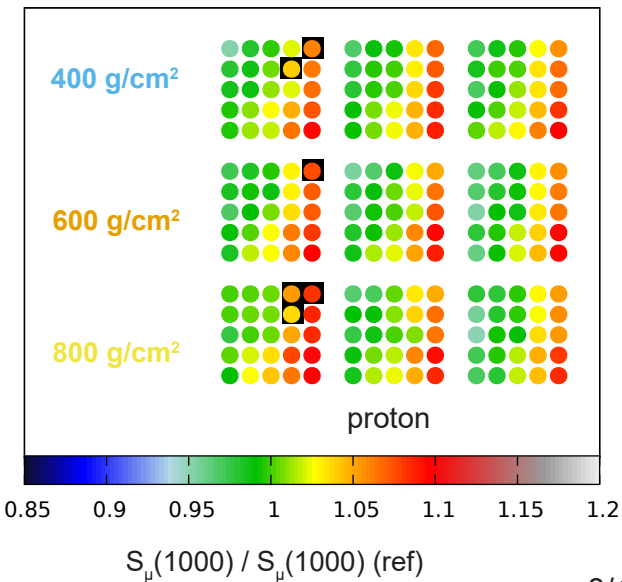
- note: Auger has universal correction to ground signal





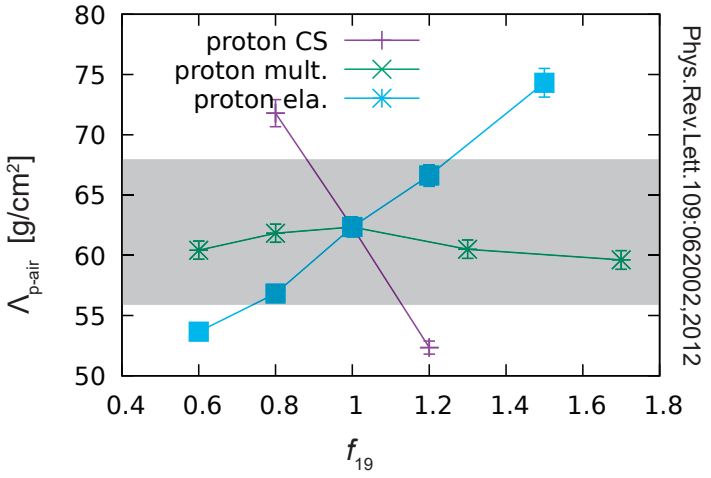


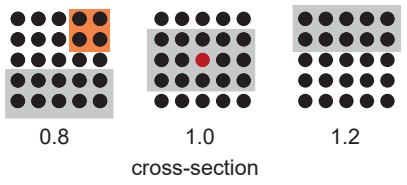


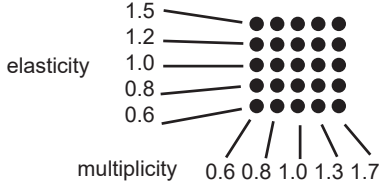


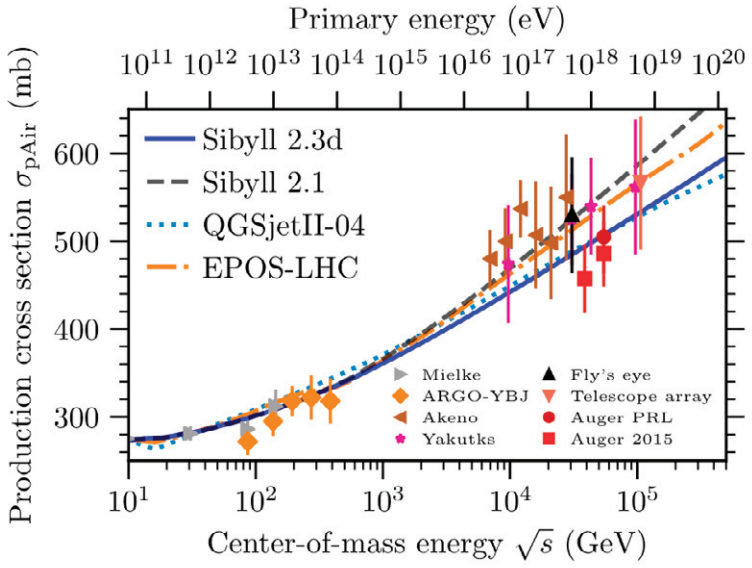
Auger cross-section measurement

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



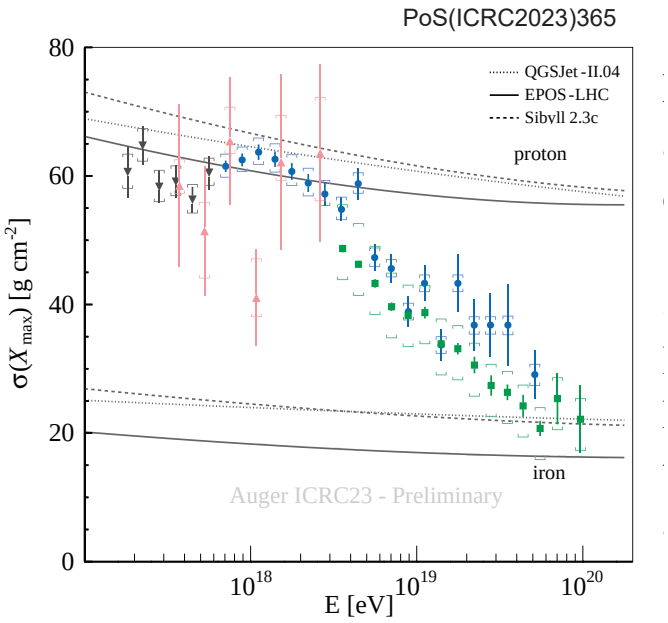


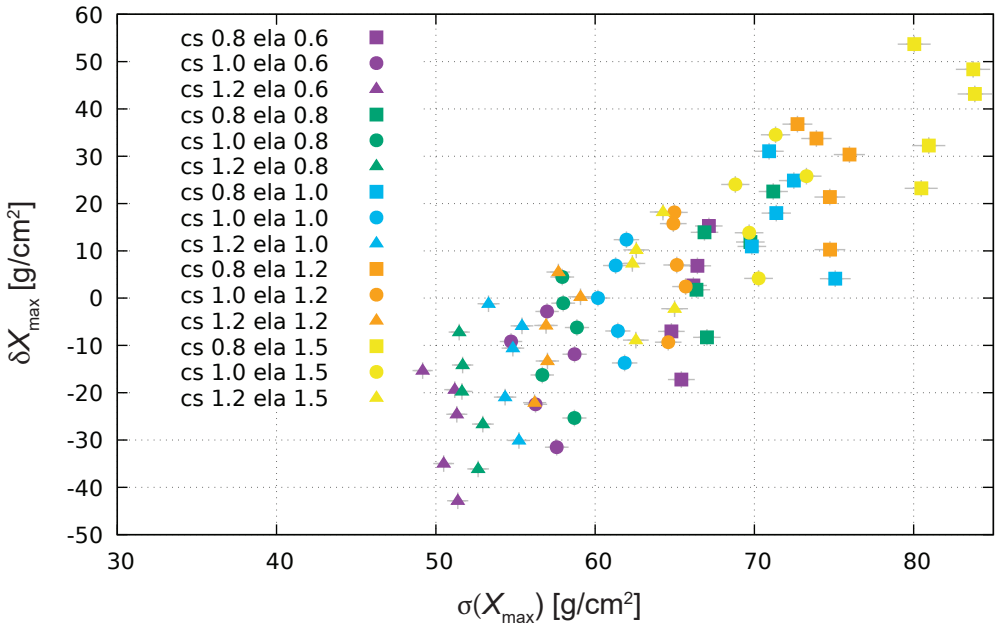


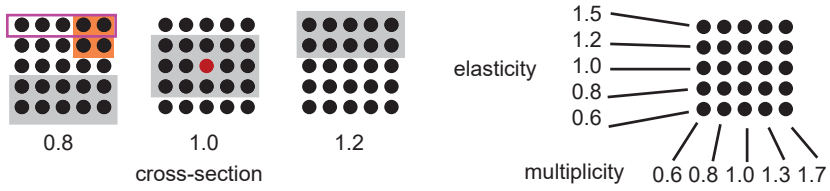


Phys.Rev.D102:063002,2020

X_{max} fluctuations





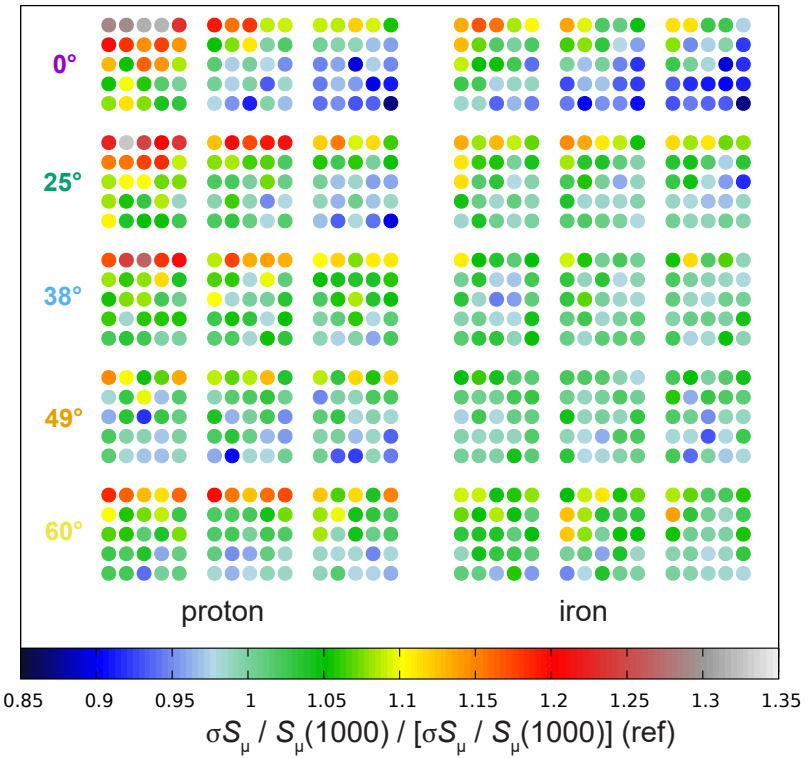


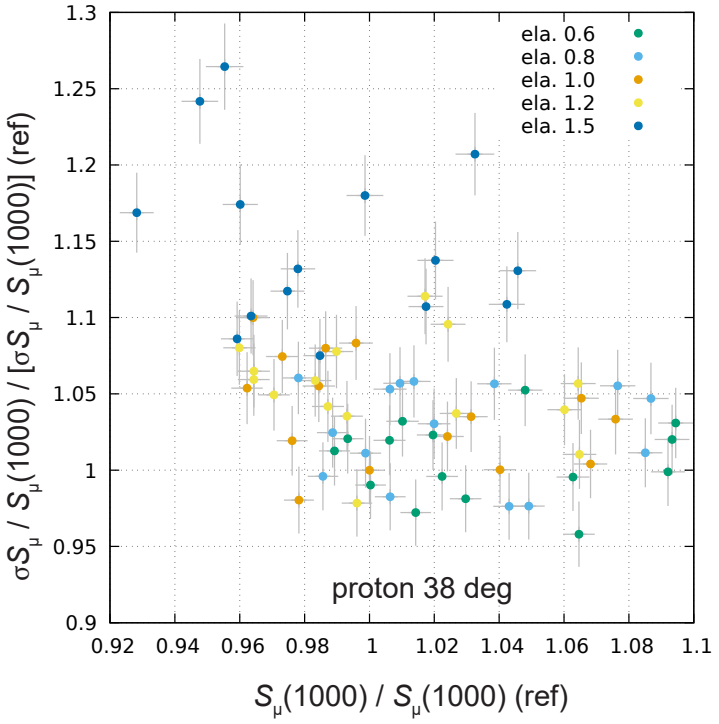
Low CS and high elasticity leads to very high X_{max} fluctuations that may be difficult to reconcile with Auger data

n.b. no change of fluctuations for Fe

Ground particles: relative muon number fluctuations at 1000 meters

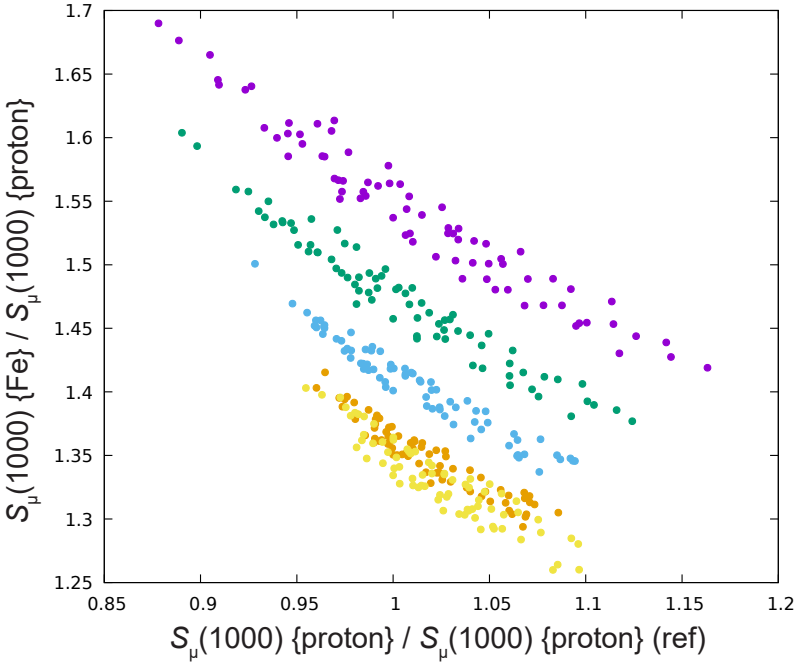
- not correlated with absolute changes in muon number, sensitive to high elasticity changes



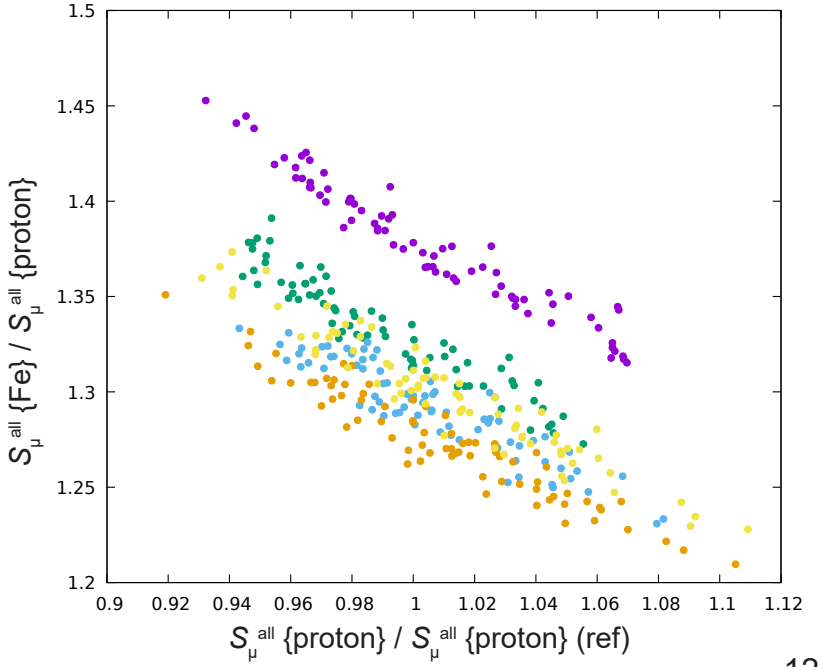


Adding muons and proton/iron separation

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

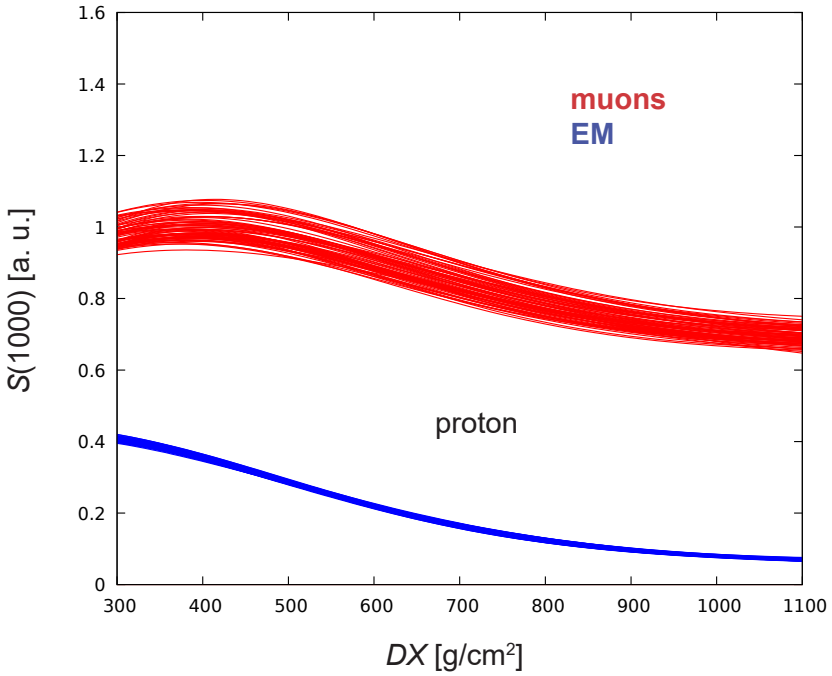


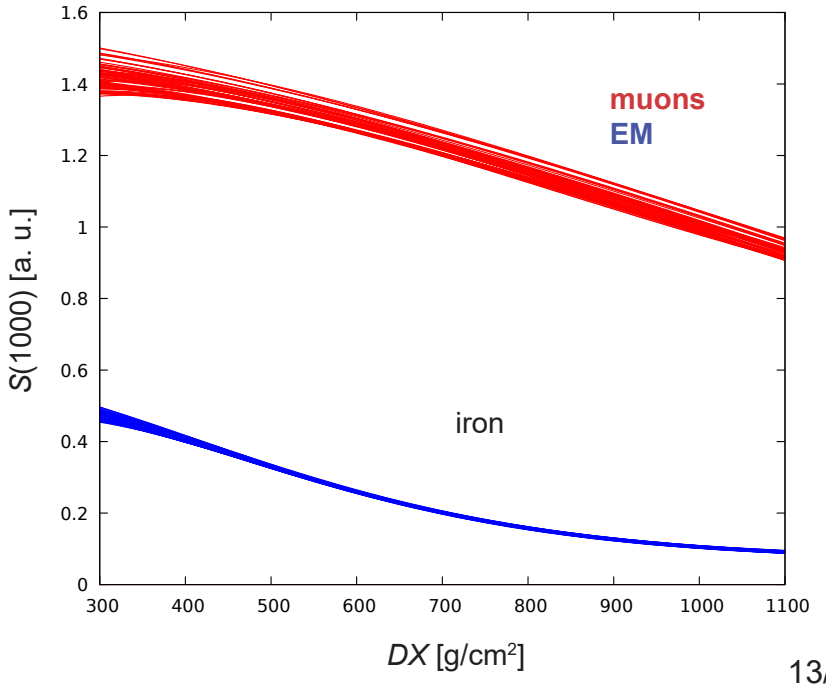
0°
25°
38°
49°
60°



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)



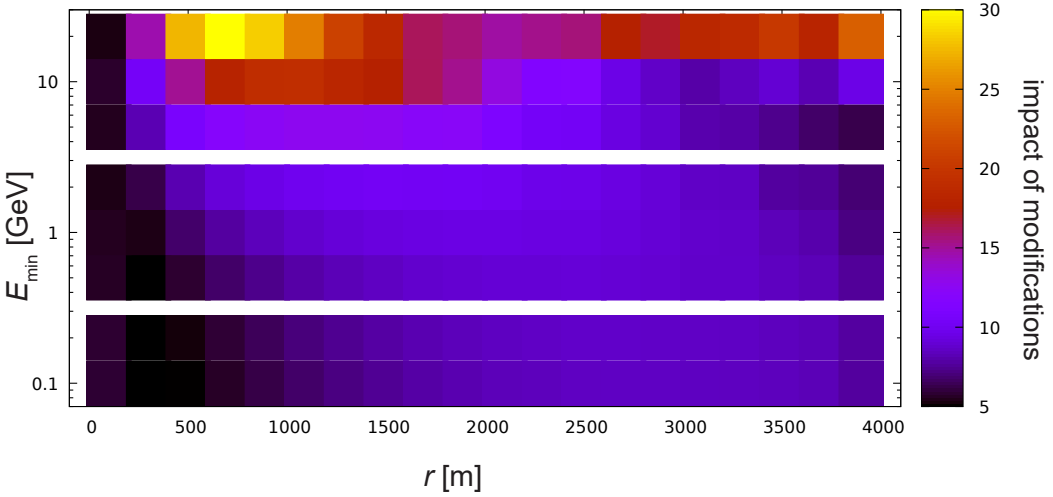


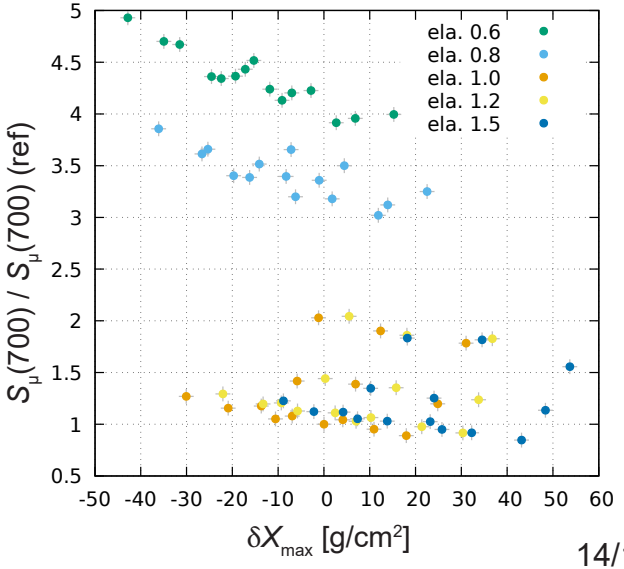
Sensitivity of muon number to modification as a function of E_{min}, r

- 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