MOdifed Characteristics of Hadronic Interactions

in ultra-high-energy cosmic-ray showers:

implications for current and future observations

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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

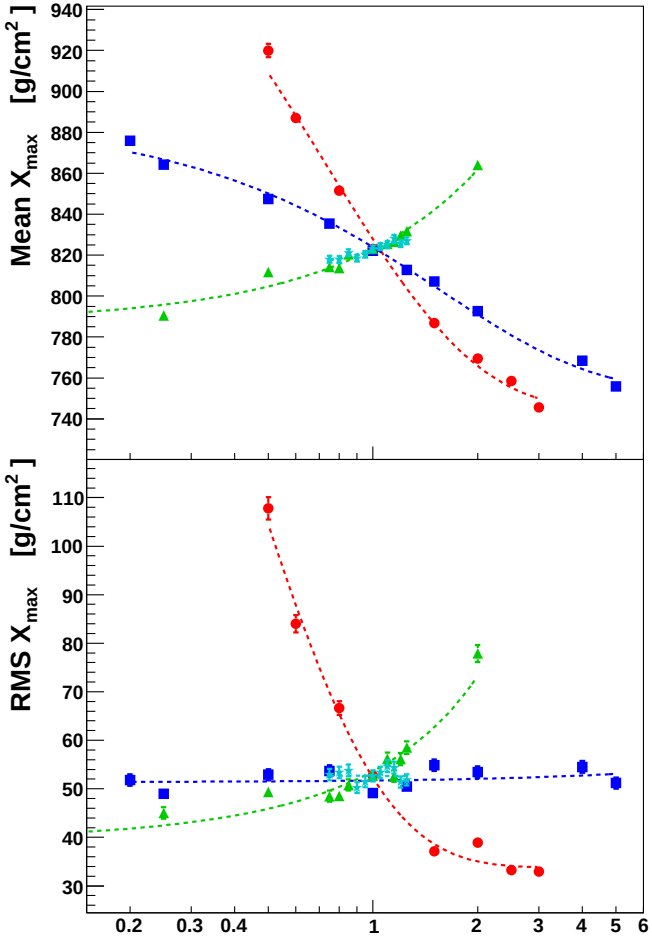
$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot \frac{\log_{10}(E/E_{\mathrm{thr}})}{\log_{10}(10\ \mathrm{EeV}/E_{\mathrm{thr}})}$$

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
- astro-ph/2410.15699

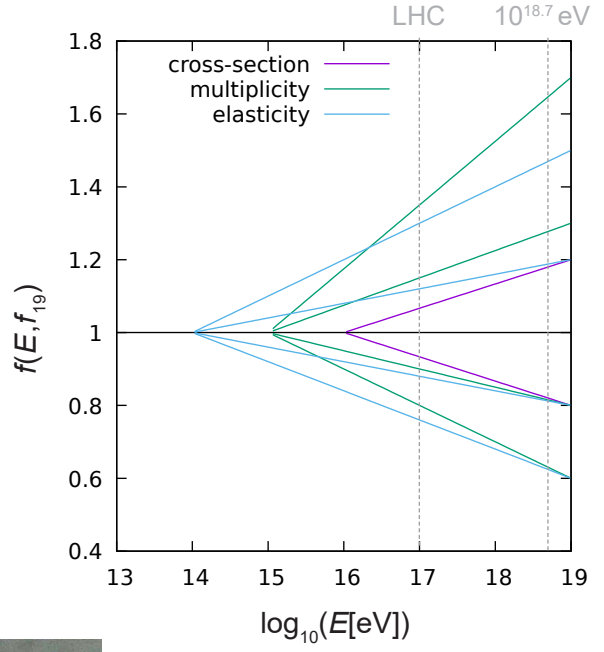


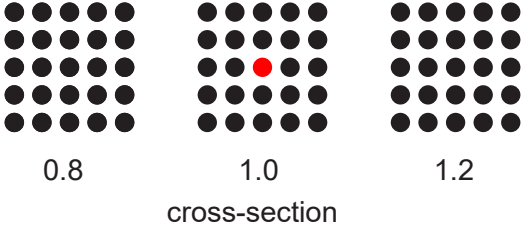
“Allowed” modifications and thresholds

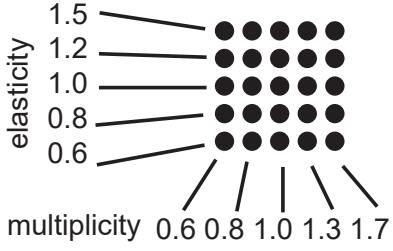
Cross-section (E_{thr} = 10^{16} eV)
- well constrained for p-p at LHC to a few %
- unc. in conversion to p-A limited by CMS p-Pb measurement

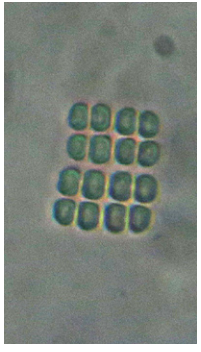
Multiplicity (E_{thr} = 10^{15} eV)
- no p-A data, limited rapidity coverage

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





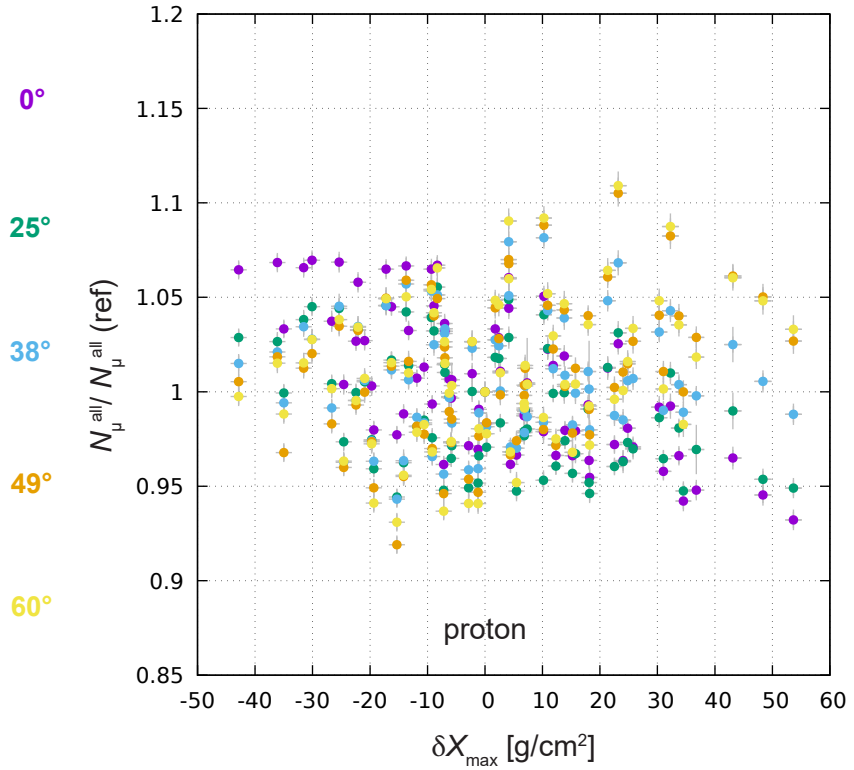




- energy $10^{18.7}$ eV
- proton and iron
- 5 zenith angles
- 1000 showers per „bin“
- 750 000 showers

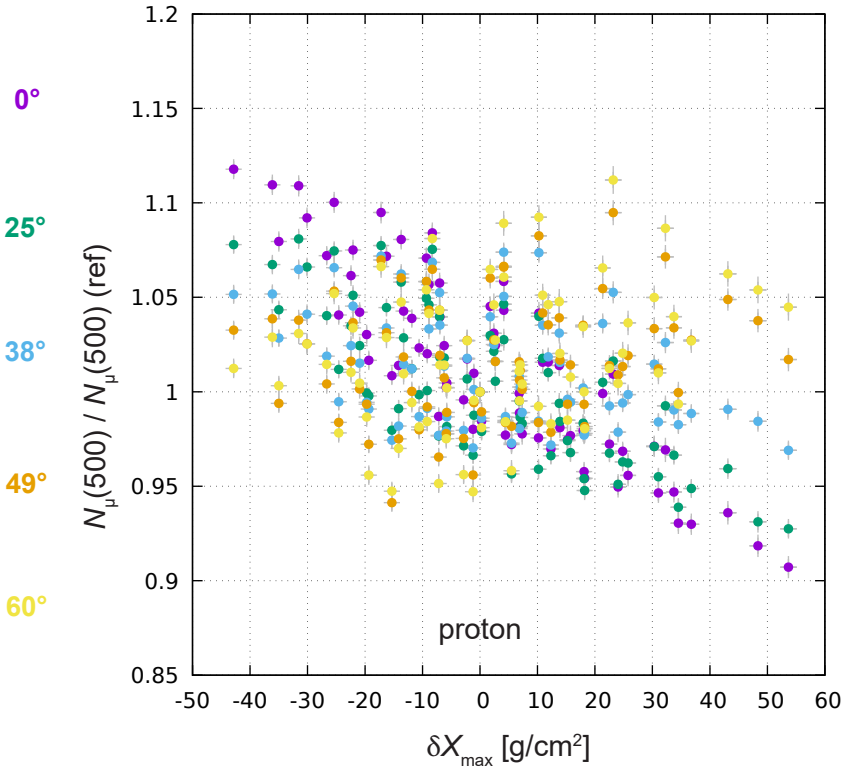
Number of muons vs. X_{max} for all muons

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



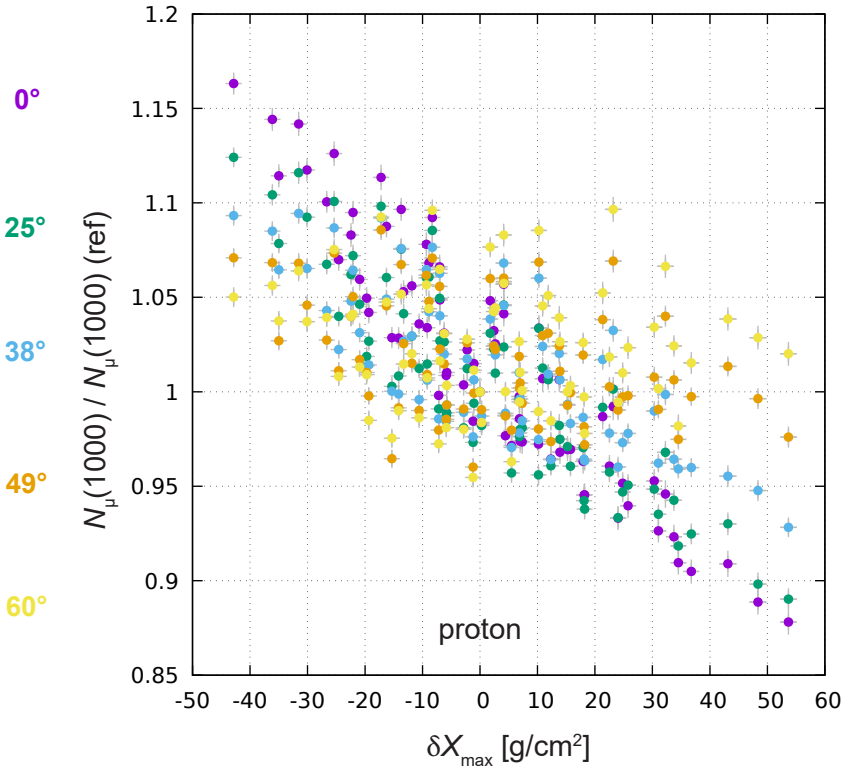
Number of muons vs. X_{max} @ 500 meters

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



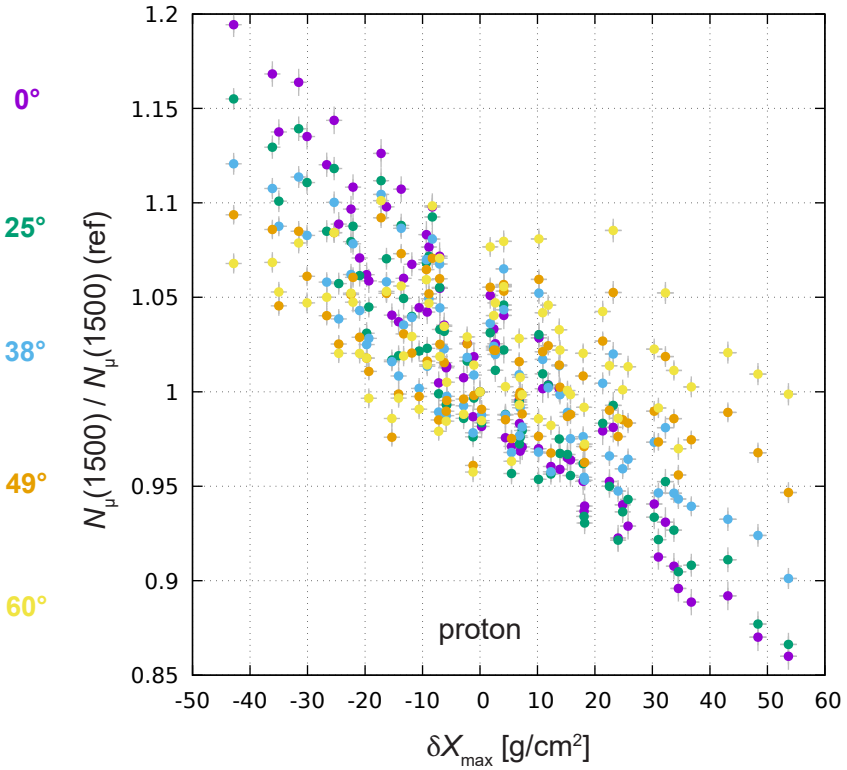
Number of muons vs. X_{max} @ 1000 meters

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

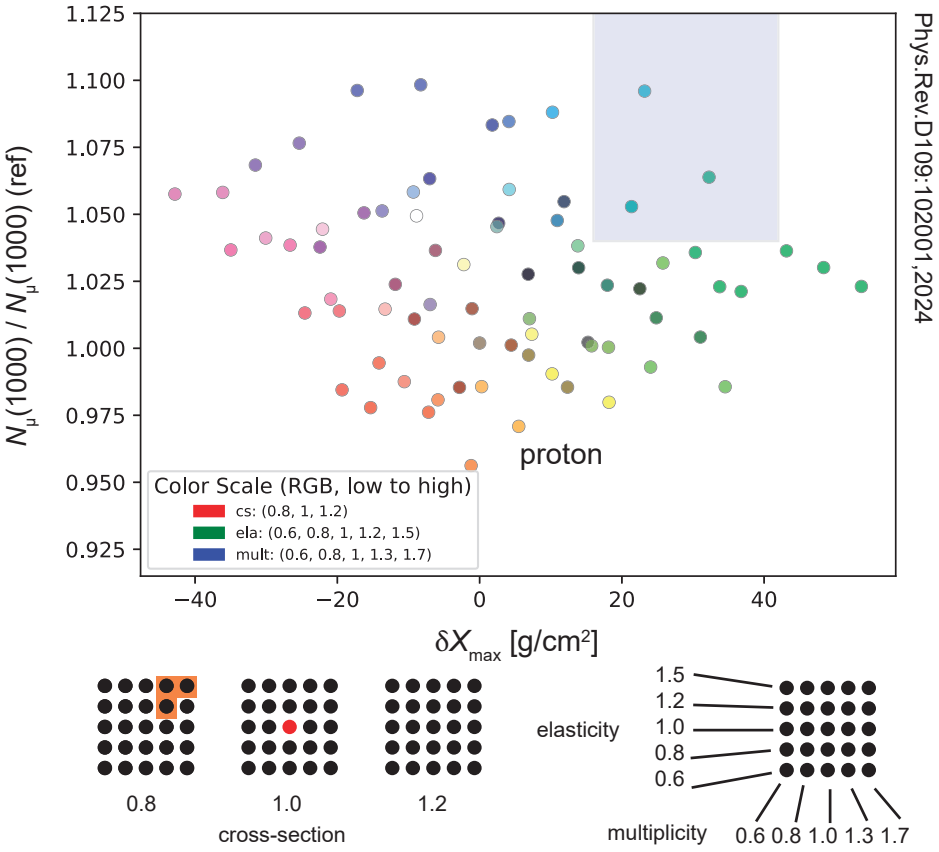


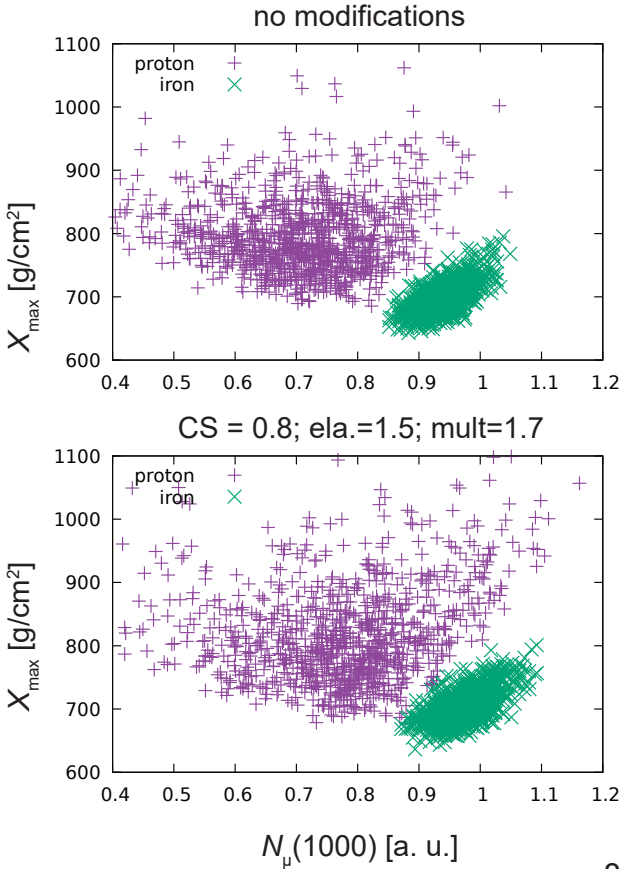
Number of muons vs. X_{max} @ 1500 meters

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



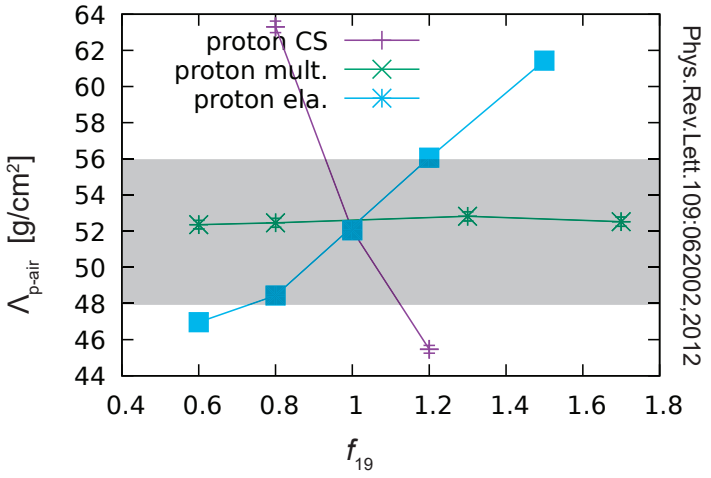
Muons at 1000 m (corrected for the effect of X_{max} shift) vs. Auger

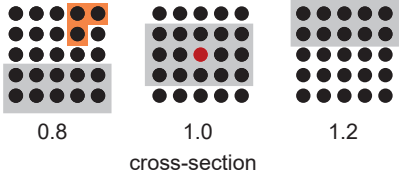


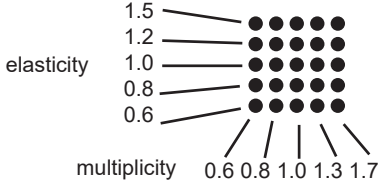


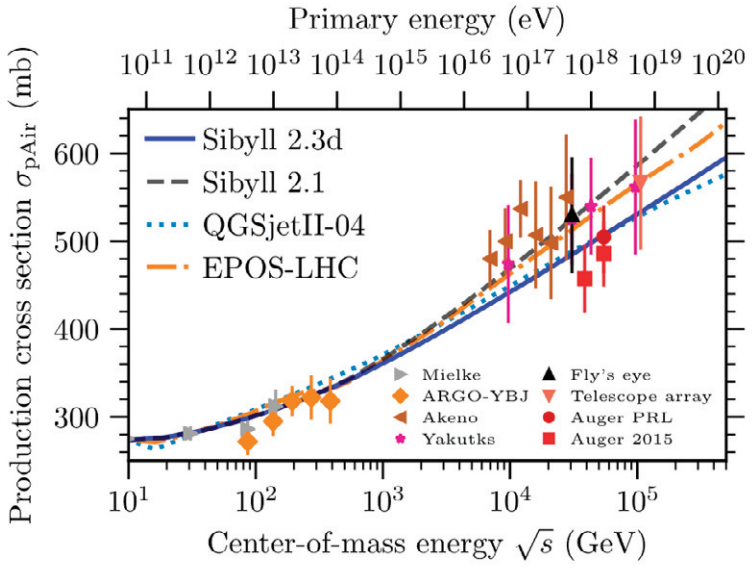
Auger cross-section measurement

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





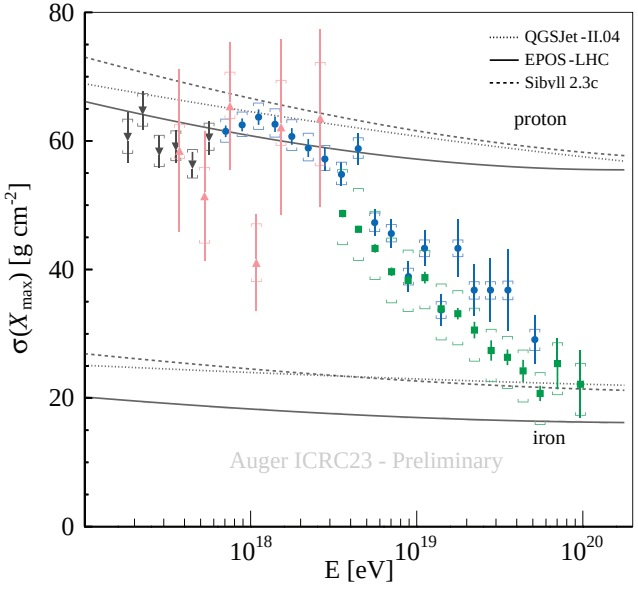


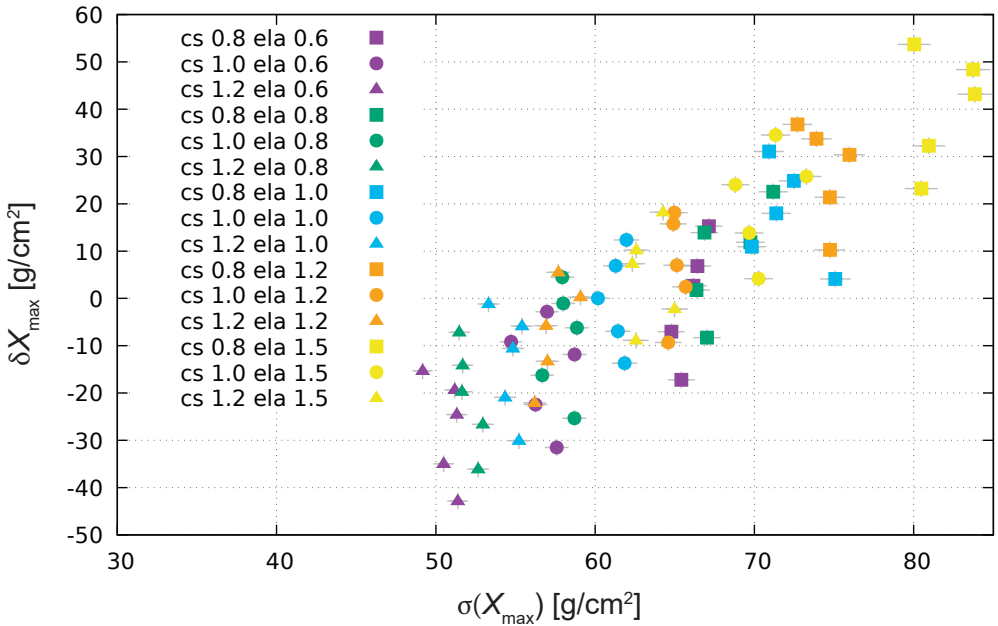


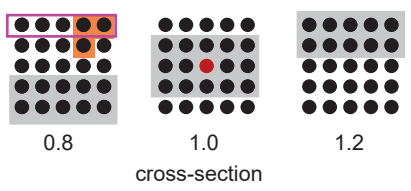
Phys.Rev.D102:063002,2020

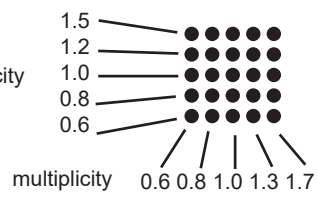
X_{max} fluctuations and Auger

PoS(ICRC2023)365









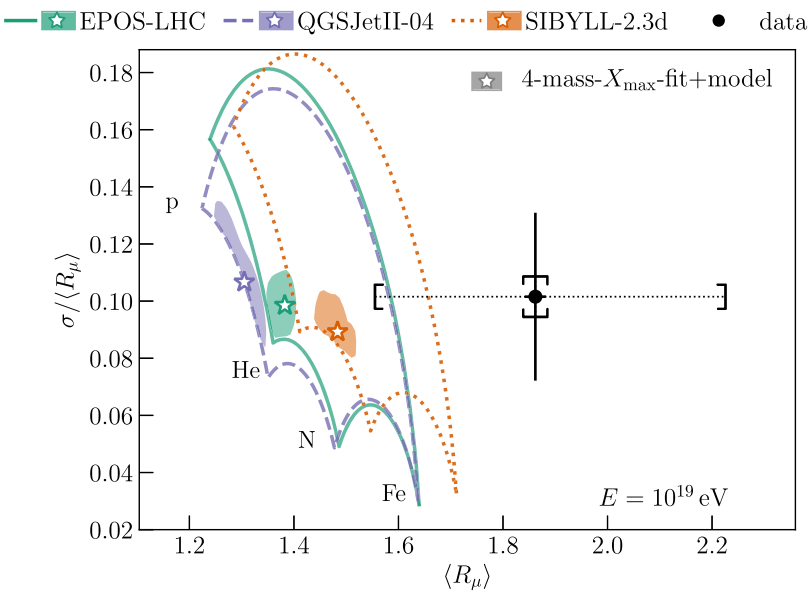
Low CS and high elasticity lead to very high X_{max} fluctuations that may be difficult to reconcile with Auger data

Note: fluctuations for Fe within ± +1.5 g/cm^2
- implications for “heavy metal scenarios”
- see Jakub Vícha’s poster for an example

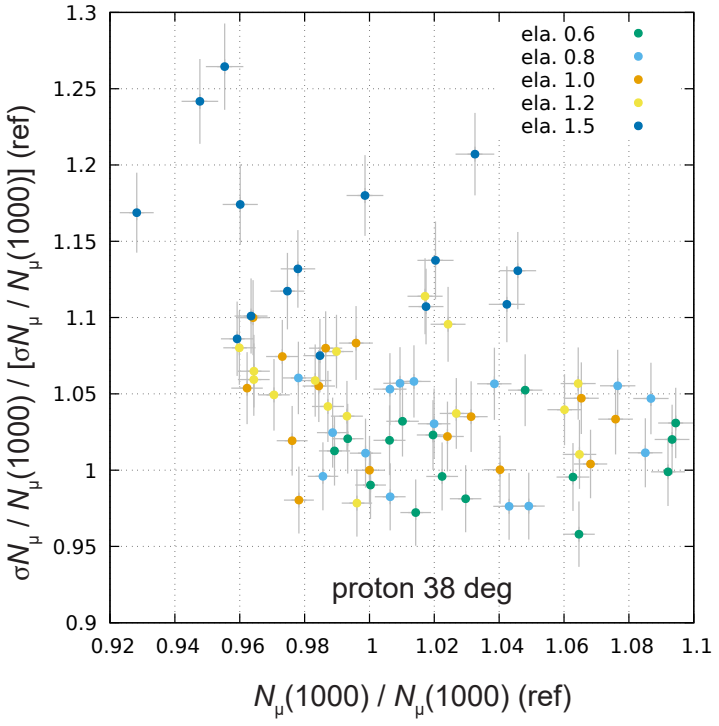
Ground particles: relative muon number fluctuations at 1000 meters

- 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



Conclusions I

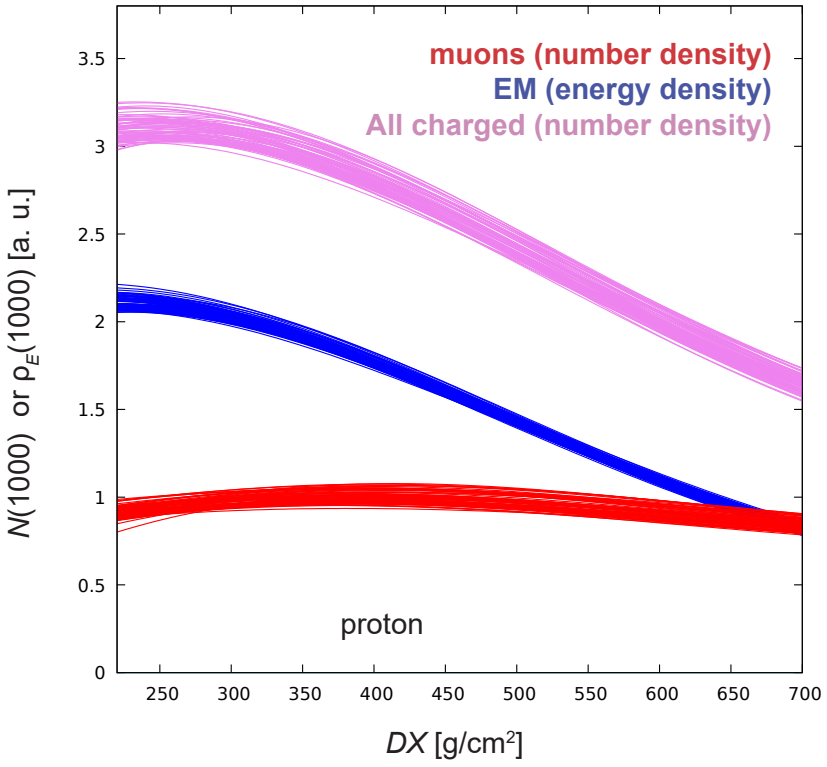
- changing cross-section, elasticity and multiplicity within reasonable limits can have major impact on air-shower properties

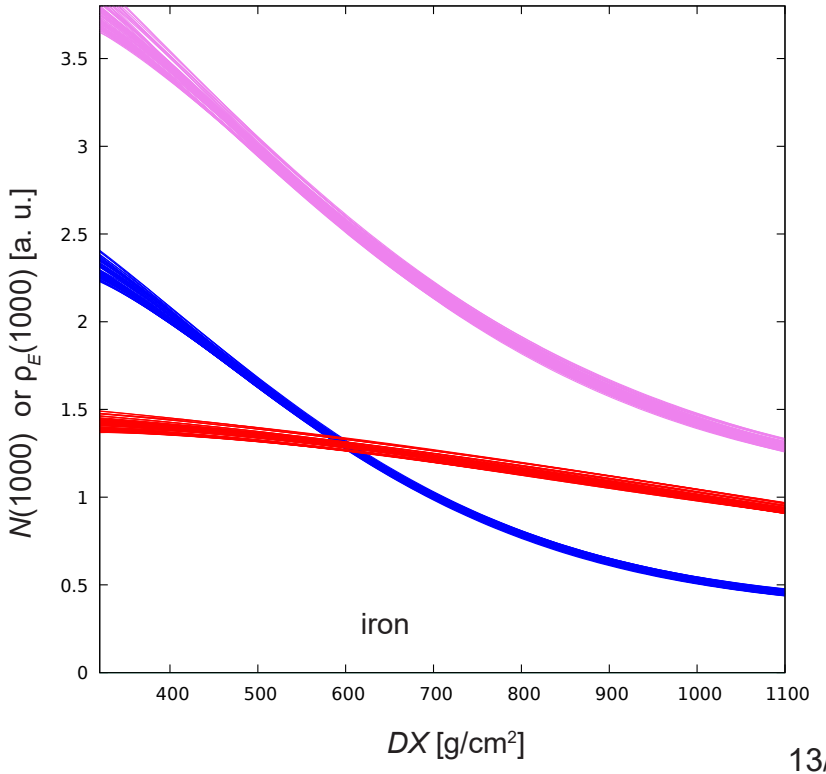
- the impact can be quite different for quantities depending on 3D geometry as opposed to 1D sums

- 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

Modified simulations as an estimate of modelling uncertainty

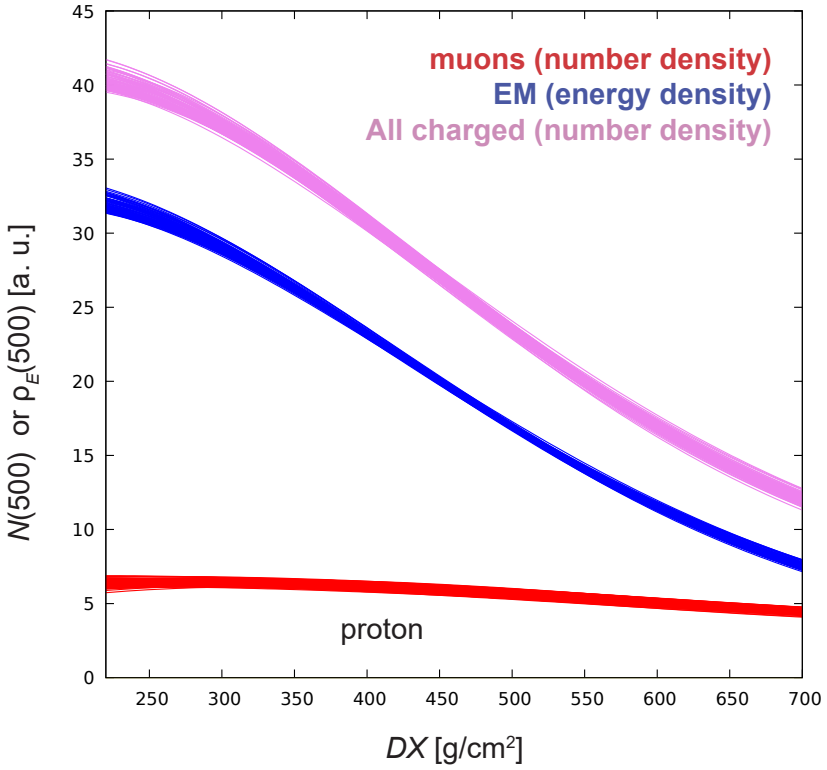
Shape of longitudinal profiles conserved, normalization less affected for EM energy

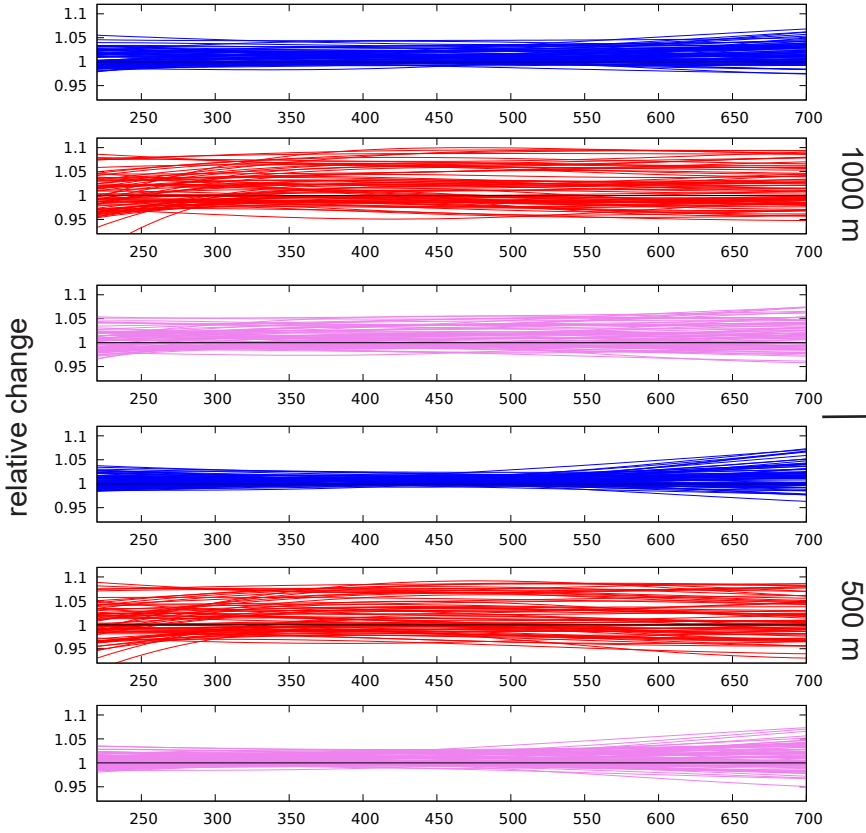




Modelling uncertainty vs. core distance

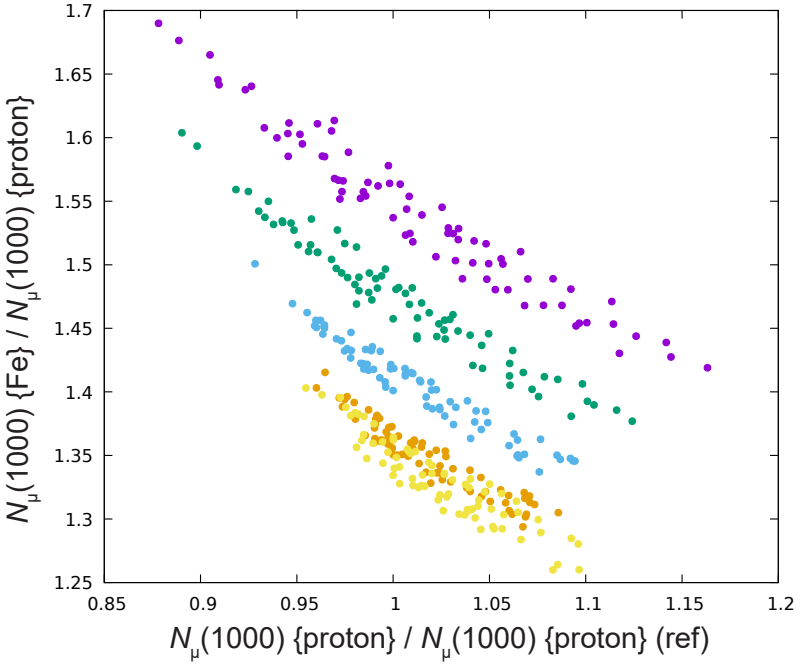
Density of charged particles most sensitive





Muons at 1000 meters and proton/iron separation

Ratio between number of muons for iron and proton tends down when muons are added
- consequence of using the superposition model for modifications in nuclear interactions



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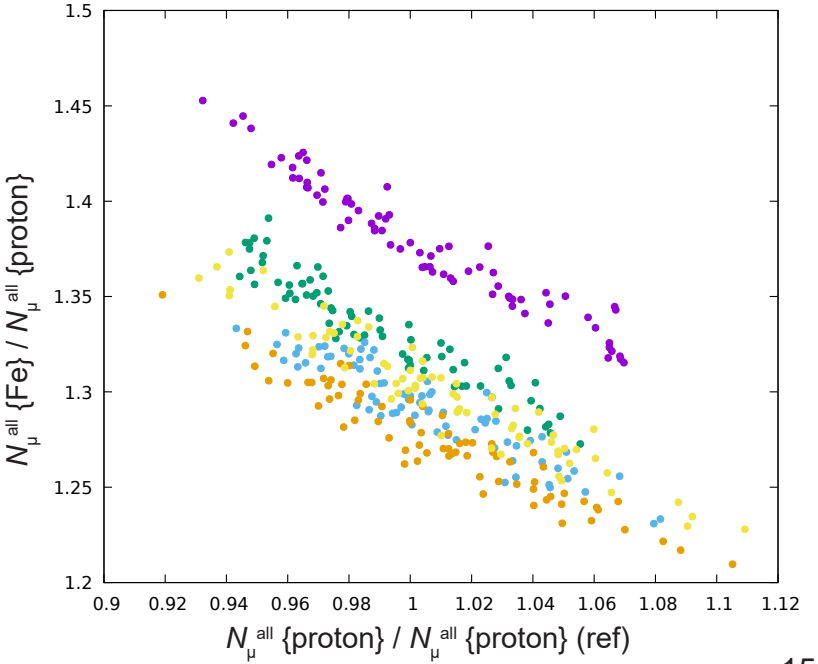
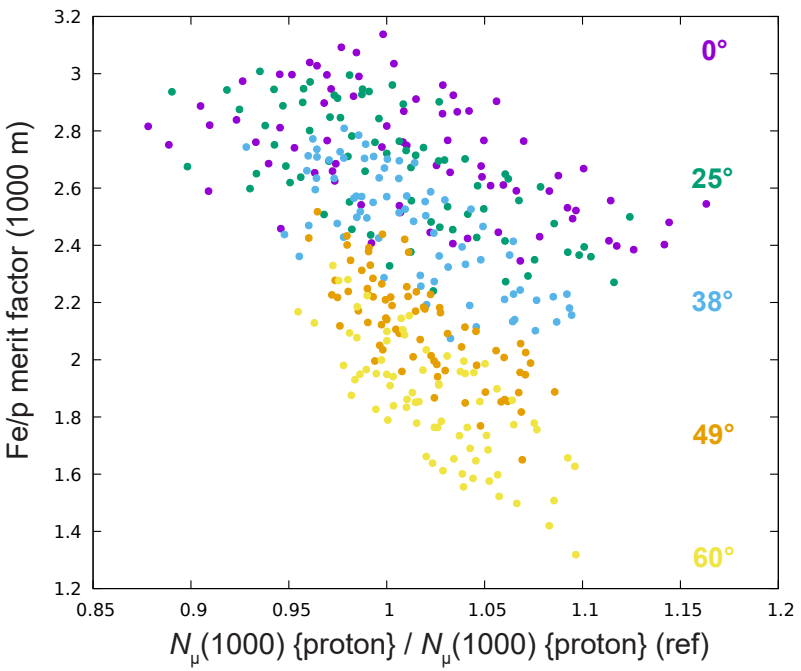
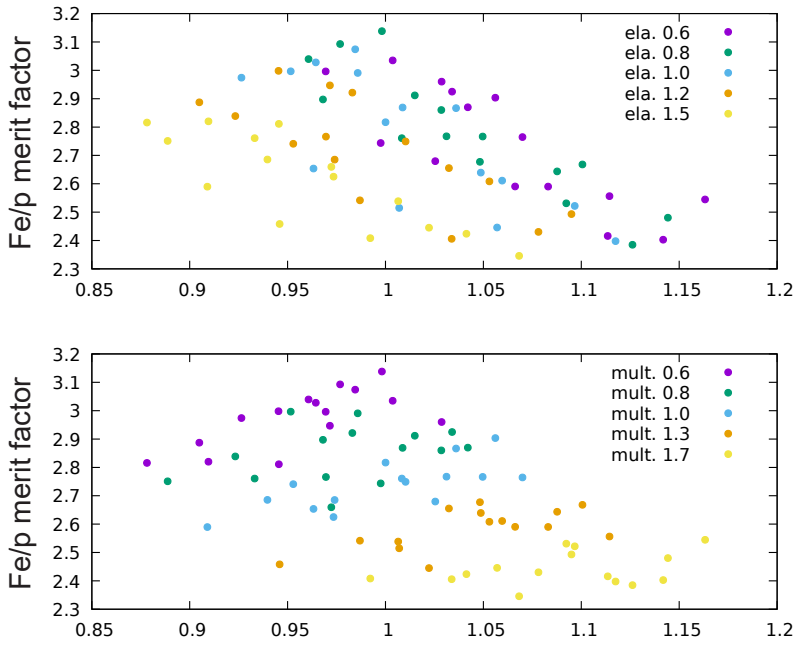


Muons at 1000 meteres and proton/iron separation: merit factor

Modifications affect both muon number and fluctuations
- significant effect for maximal theoretical performance in proton/iron separation

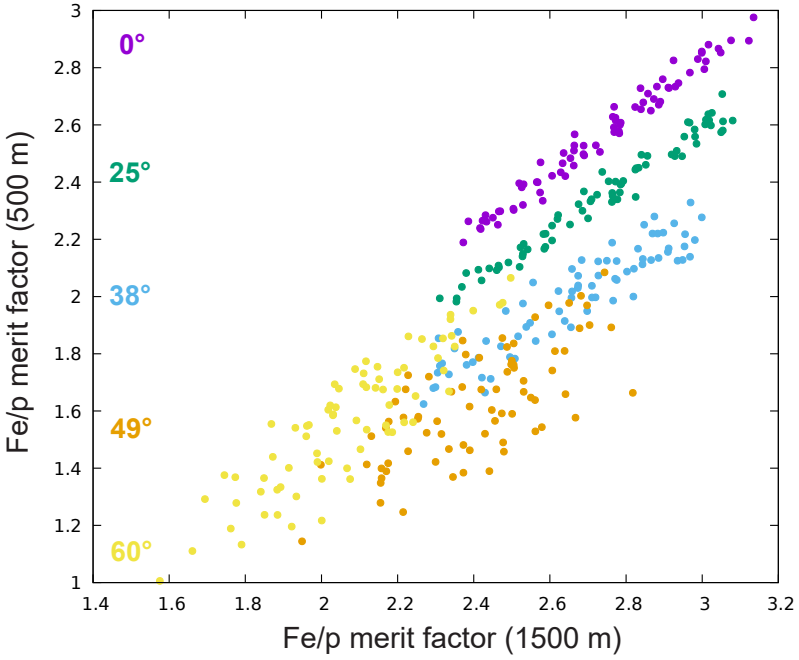
$$MF = \frac{\langle A \rangle - \langle B \rangle}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

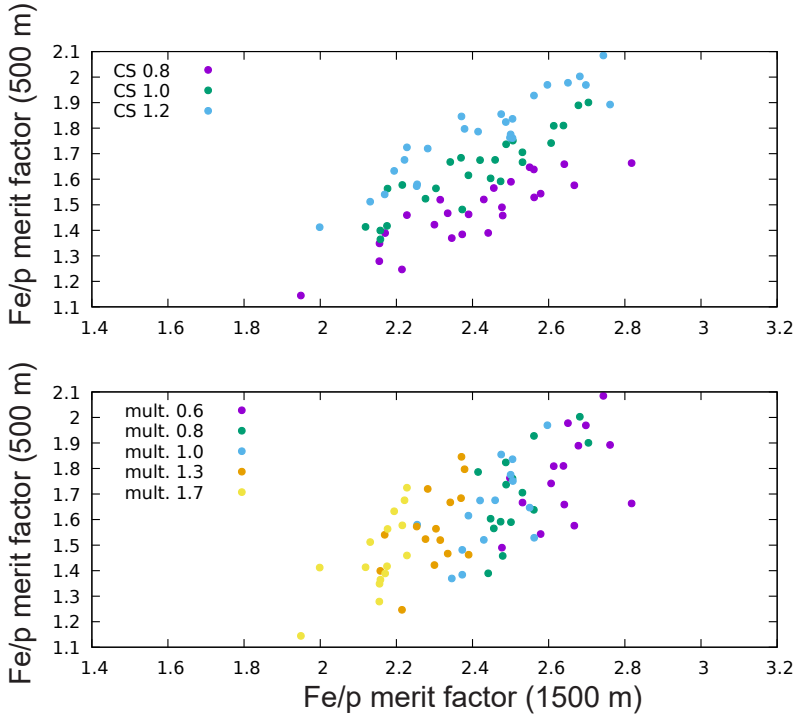




Proton/iron separation and distance to shower axis

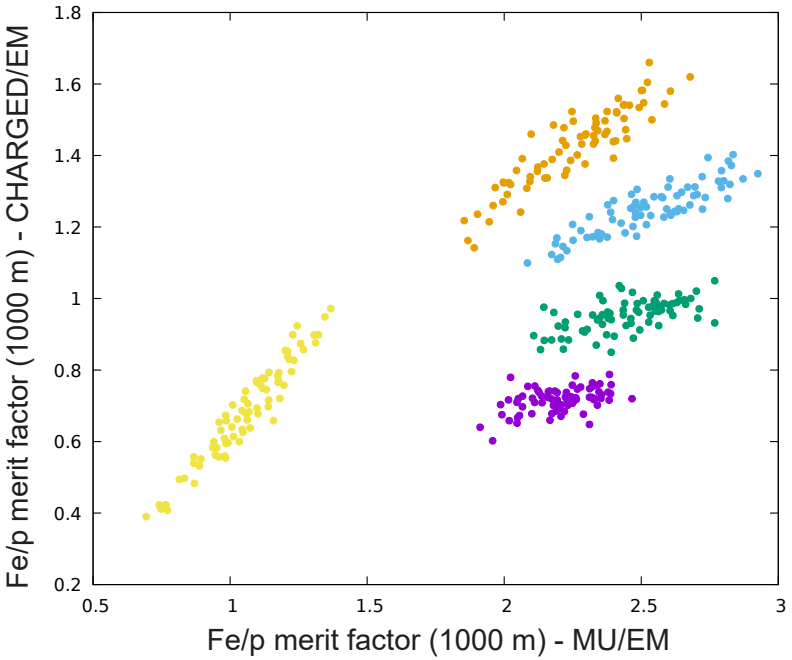
Full 3D simulations allow study of effects in ... 3D
- modified interactions may change the optimal geometry for a detector and/or data analysis





Proton/iron separation with different detectors

What we measure is not really “number of muons”, but “N_μ at an energy established by other means”.
- simplification: signal ratios
- at 1000 meters: strong correlations, but note non-zero intercepts



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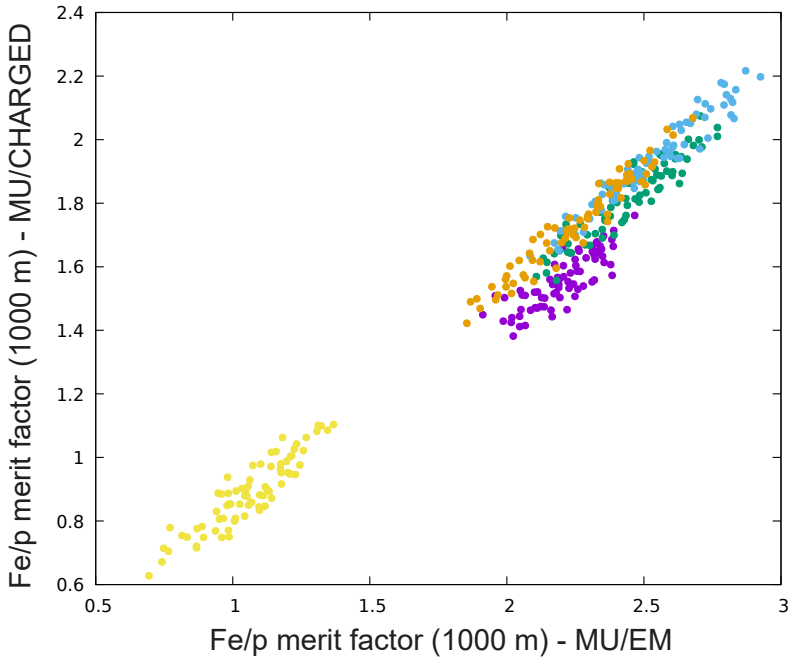
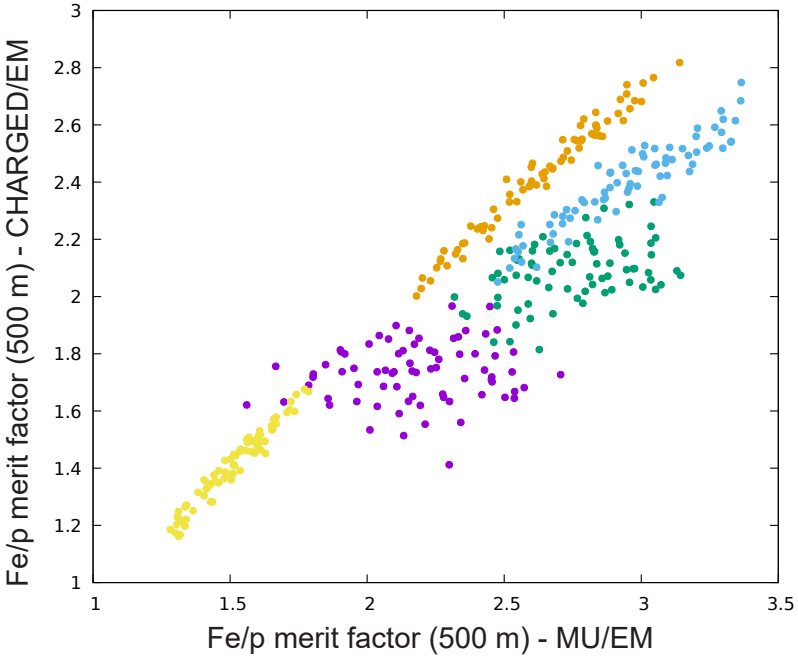


Proton/iron separation with different detectors

- at 500 meters more complicated: spread for CHARGED/EM due to elasiticity changes
- note once again the consequence of the energy threshold/superposition model combination
- other libraries can be made with different assumptions!



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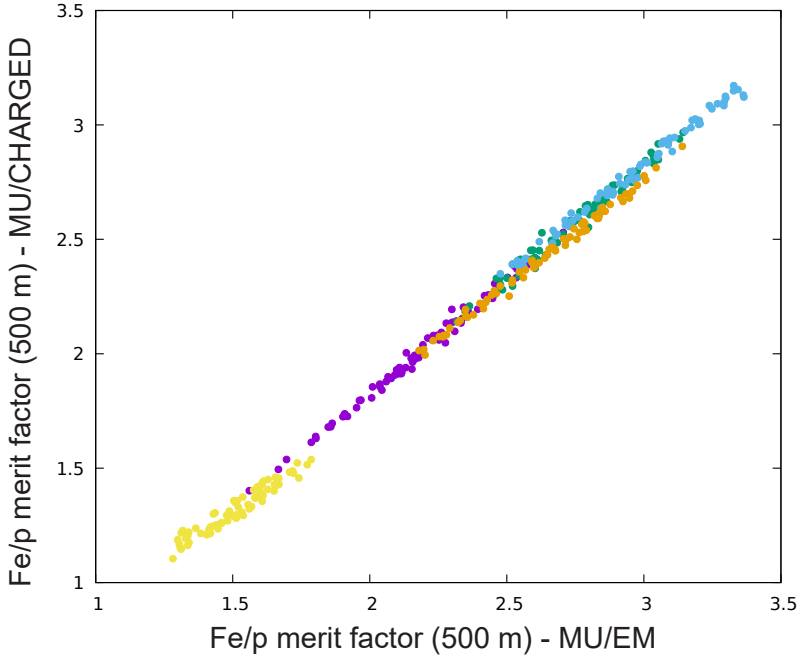

Conclusions II

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- 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

- even if some modifications are not realistic (after all, there is only one Universe), we can learn interesting insights
    - effects of 3D modifications are highly dependent on distance to shower axis
    - number of muons is more affected than EM energy density
    - proton/iron separation power can vary significantly
        - but note the implicit assumption on A-dependence of modifications

Do I use the three major models for my systematic uncertainty? What about using (up to) 75 instead!

BACKUP

Maximum of apparent muon production depth $X_{\mu,max}$

Apparent MPD distribution from muons reaching ground at $r > 1000$ m

- noisy, complex fitting procedure
- reliable only for larger zenith angle
- results preliminary!

Highly correlated with δX_{max}, but slightly steeper