MOdifed CHaracteristics of Hadronic Interactions:

how changes of general features of interactions impact air shower simulations in CORSIKA 7

From octopuses
to cyanobacteria?

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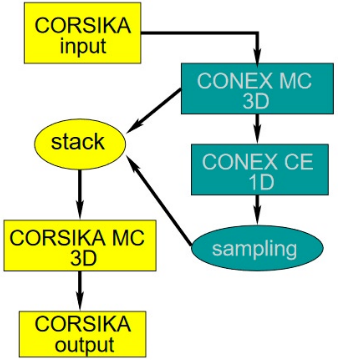
Modified hadronic interactions

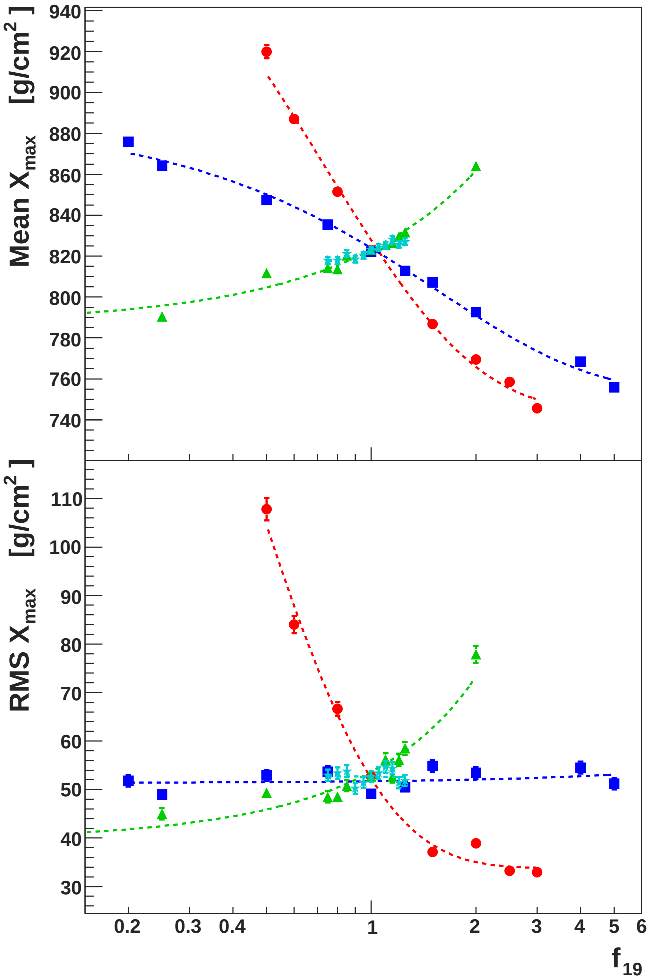
Phys. Rev. D, 83:054026, 2011

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

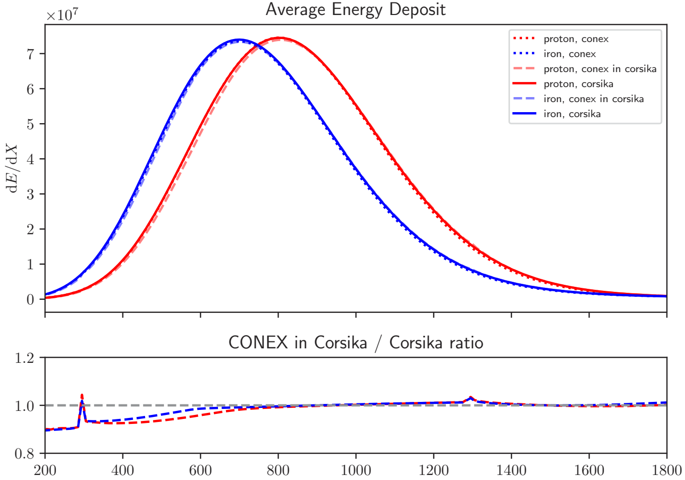


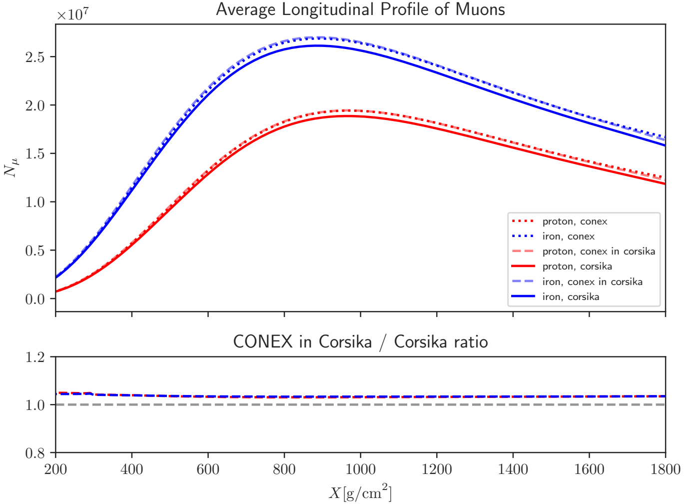
CONEX in Corsika (since 2009)

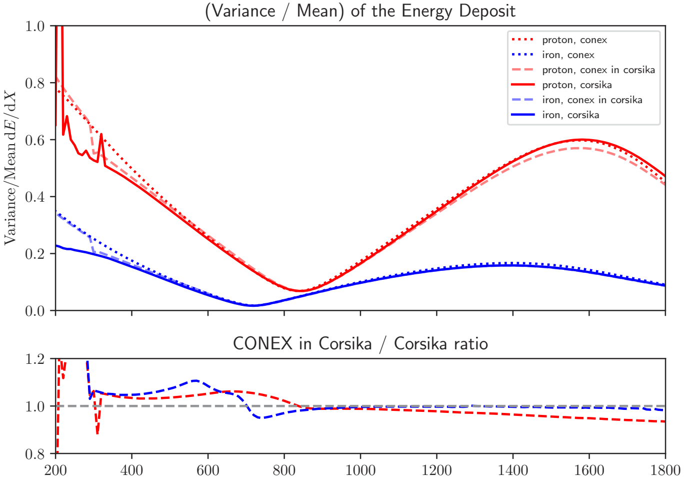
- allows to use the same code and get 3D information
- technical issues, validation

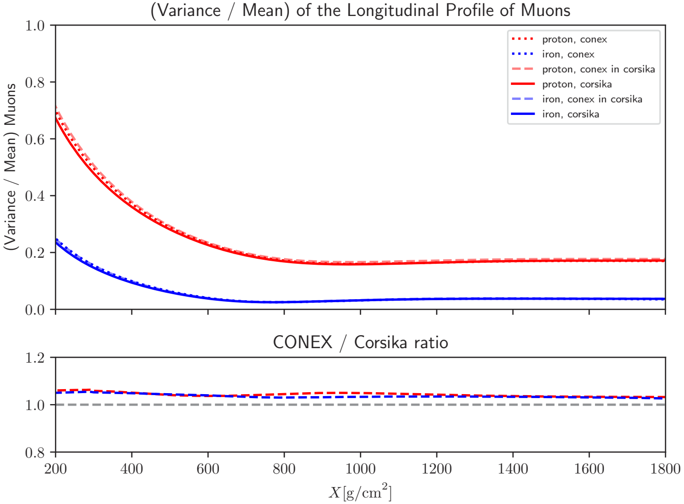


CORSIKA-CONEX vs. CORSIKA vs. CONEX for longitudinal profiles

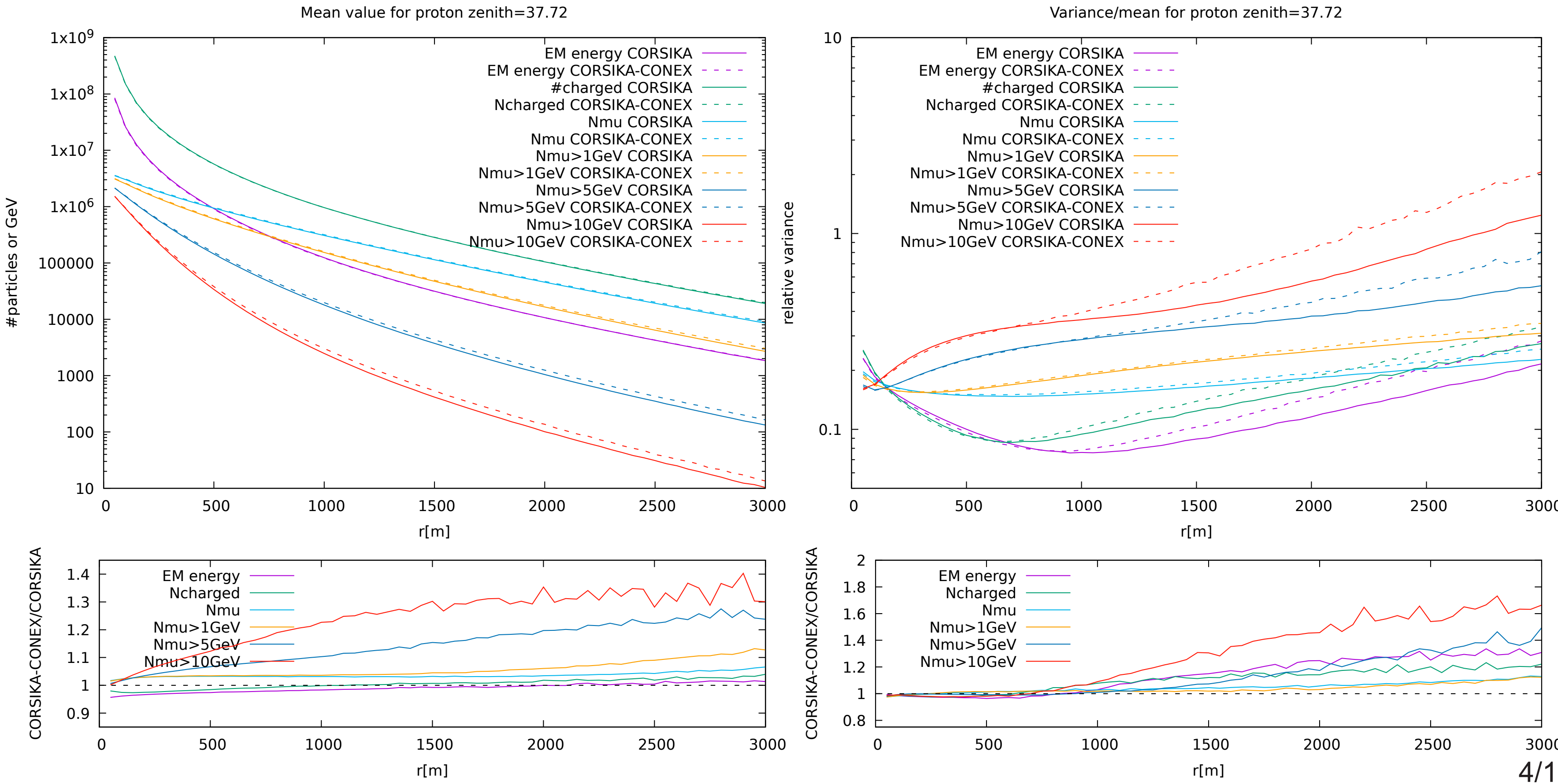






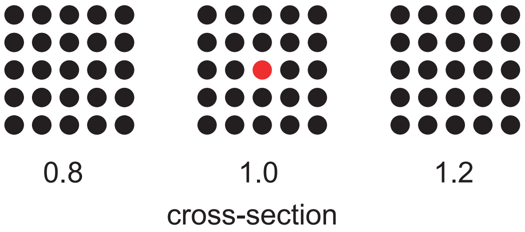


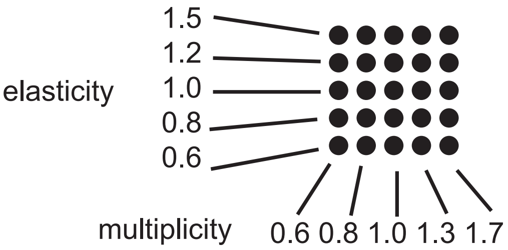
CORSIKA-CONEX vs. CORSIKA for particles at ground

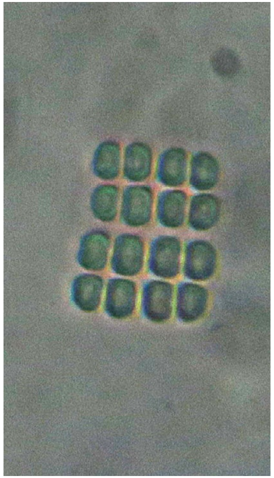


What's new in the CORSIKA-CONEX implementation?

- all three types of modifications possible in parallel
  - 3D cube of of parameters

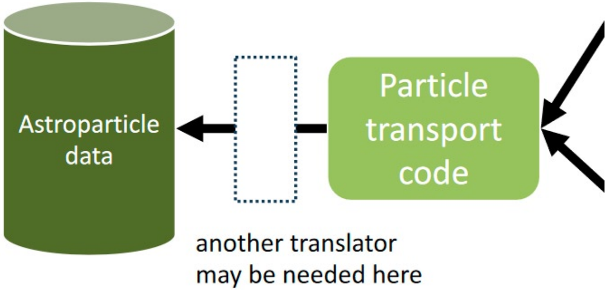






- independent thresholds for each modification
- fully configurable from CORSIKA steering files

- large spectrum of possible "observables"

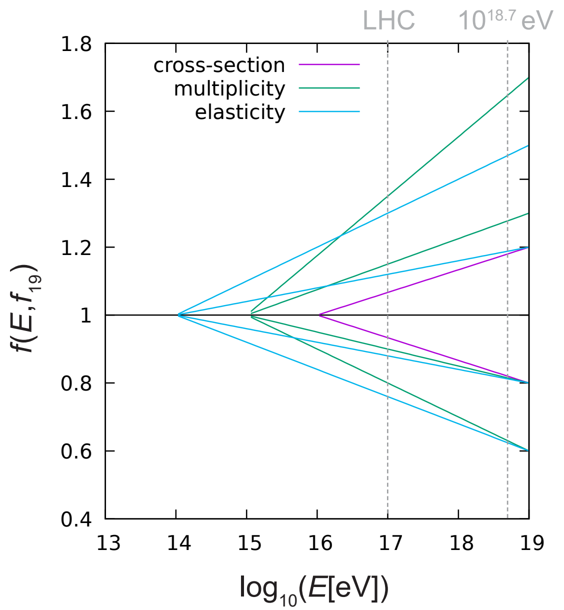


The MOCHI library

CORSIKA 7.741 with CONEX option, Sibyll 2.3d

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

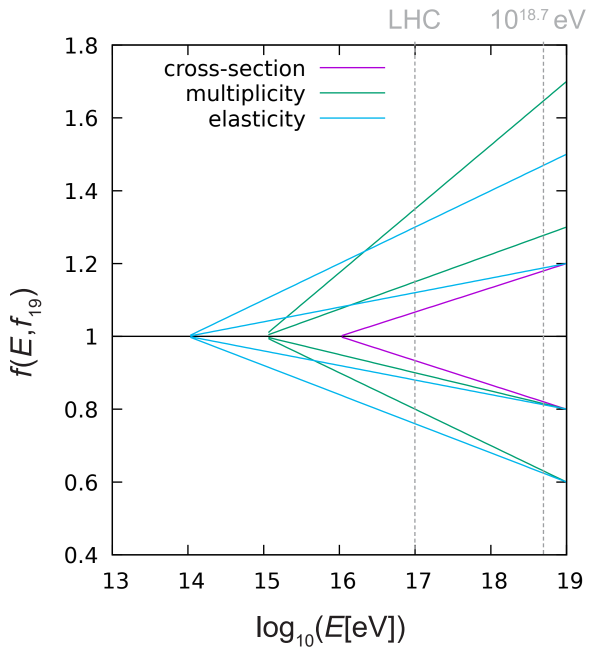
- nuclear projectiles treated as a set of p-Air interactions
    - only straightforward in Sibyll
- see POS(ICRC2023)245, POS(ICRC2021)441 and EPJ WoC 283:05005



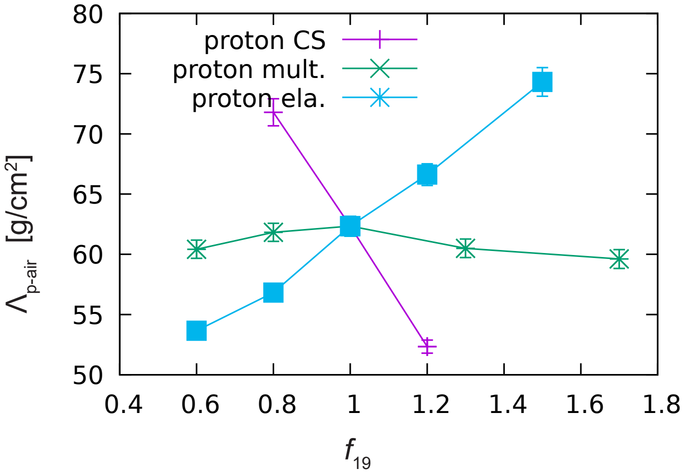
75 combinations

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

"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
- air-shower measurement exists, but is affected by models!
    - $\Lambda_{\text{p-air}}$ fitted from tails of X_{max} distributions
    - depends strongly on elasticity changes
    - composition-related systematics



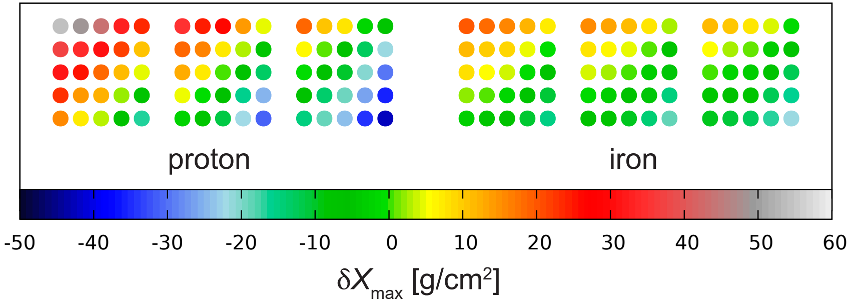
Multiplicity (E_{thr} = 10^{15} eV)
- no p-A data
- limited rapidity coverage

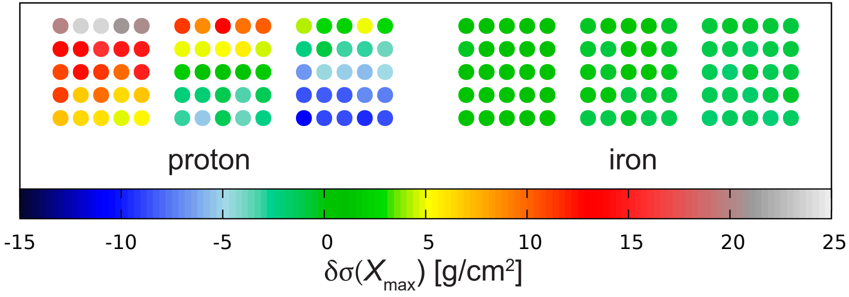
Elasticity (E_{thr} = 10^{14} eV)
- difficult to measure at accelerators, limits from nuclear emulsion chambers
- recent LHCf neutron elasticity measurement?
- range of modifications limited by internal consistency

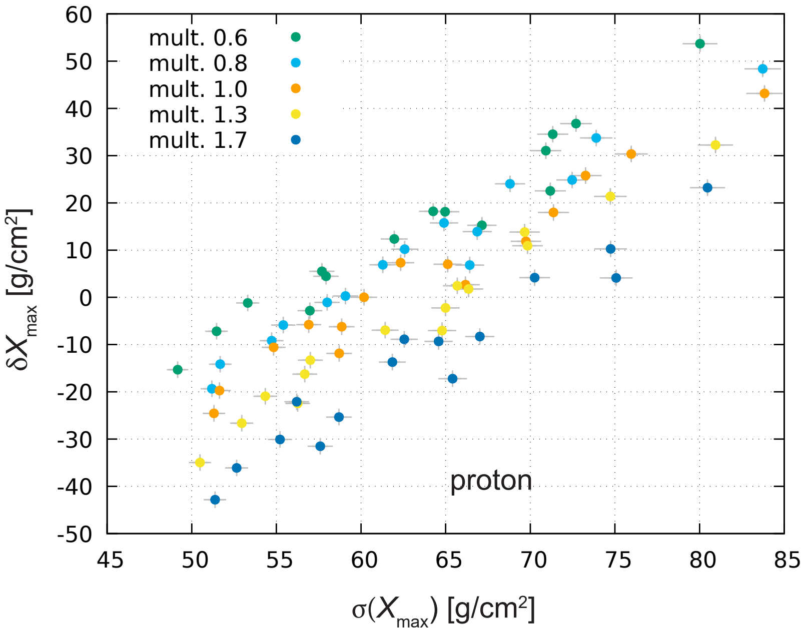
Longitudinal profile: depth of maximum X_{max}

- for proton, fluctuations correlated with mean value, particularly for constant change of multiplicity

- for iron, mean X_{max} changes ~ 40 % w.r.t proton, fluctuations virtually unchanged

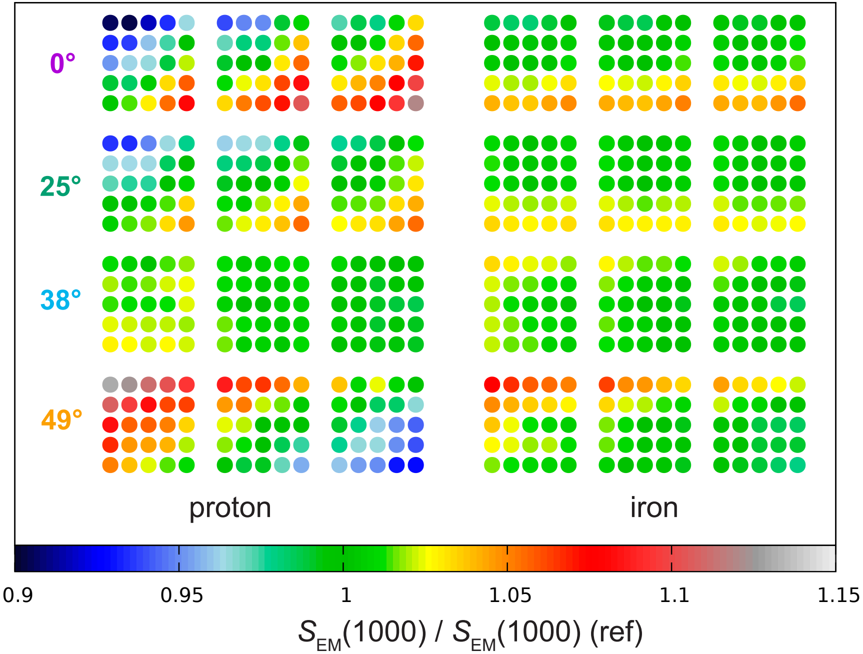


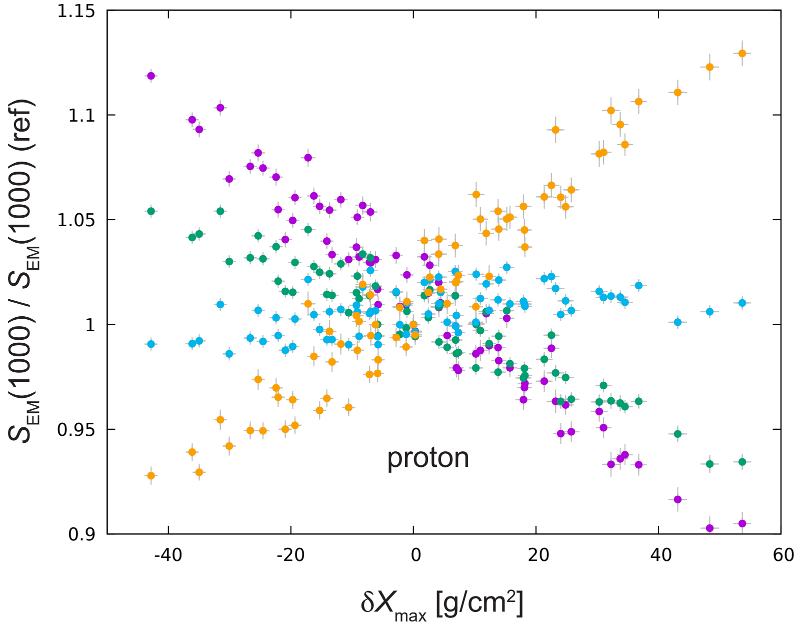




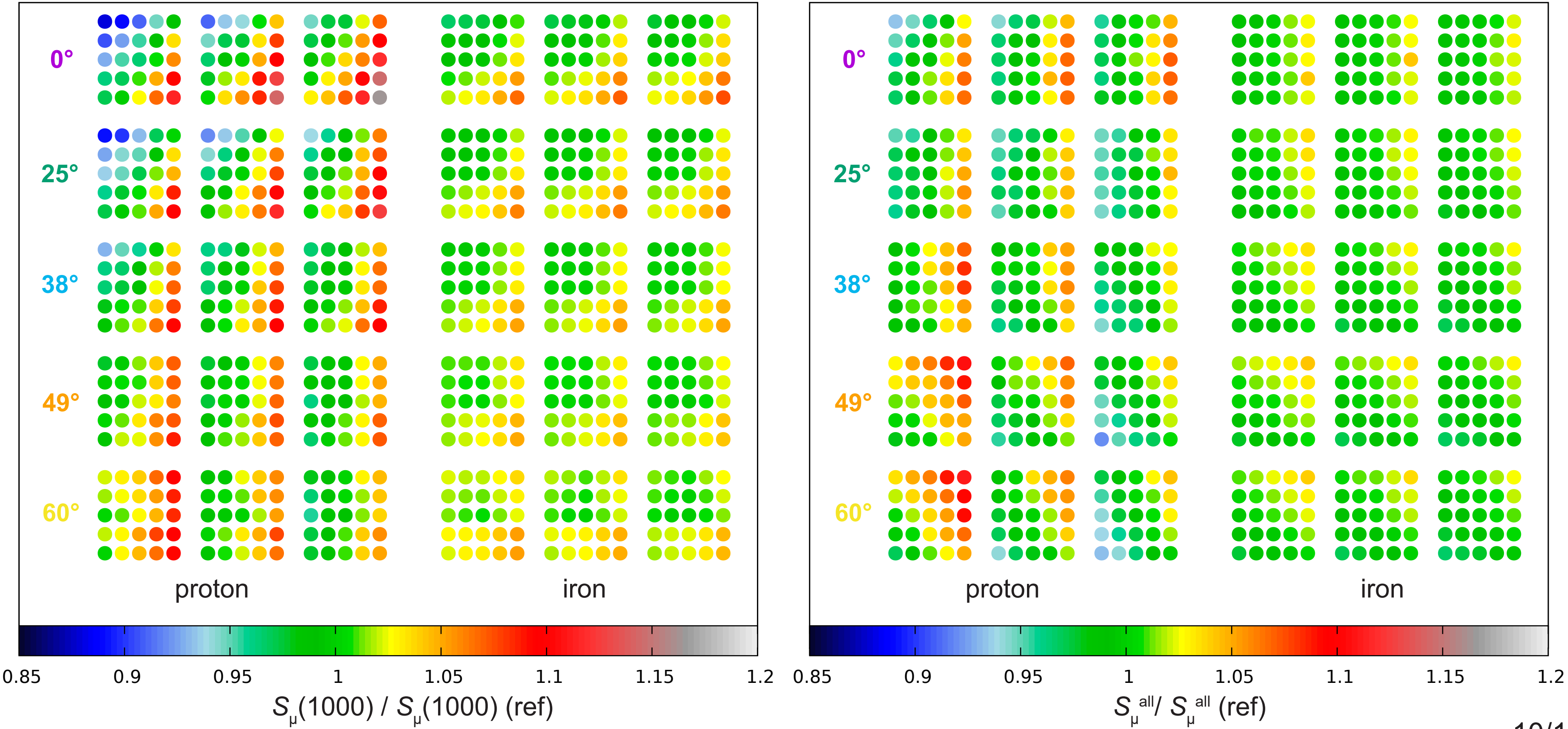
Ground particles: energy density of EM particles r = 1000 m

- e^+/e^- and photon energy density, r = 1000 m perpendicularly to shower axis, LDF fitting to smoothen
- changes w.r.t. reference values for given primary and zenith
- for given zenith angle strong correlation with δX_{max} (zenith 60 deg signal too weak)



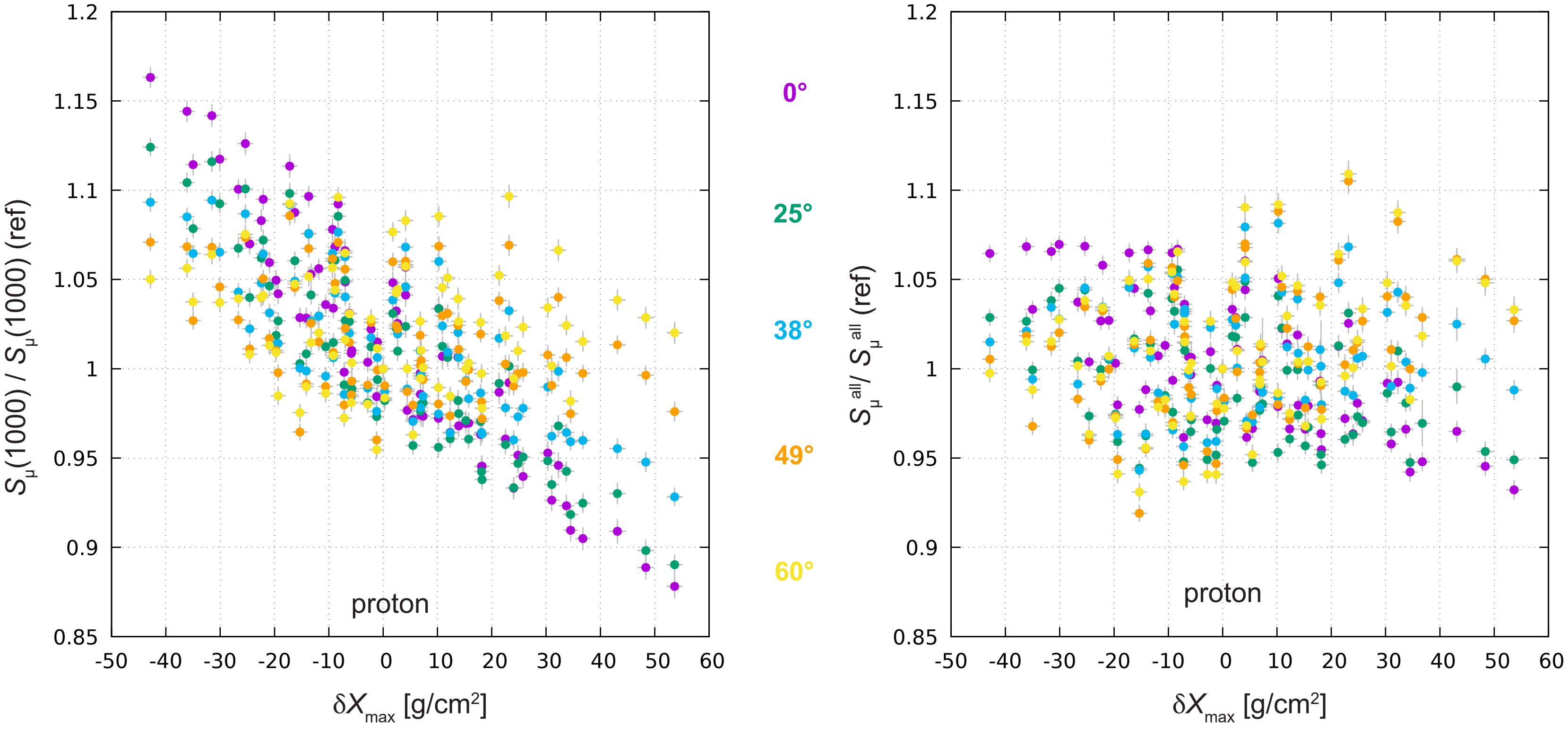


Ground particles: number of muons at 1000 m vs. all muons



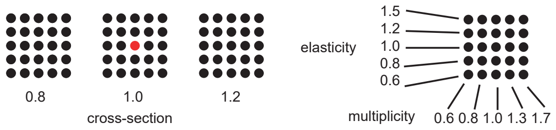
Number of muons at 1000 m vs. all muons: correlation with X_{max}

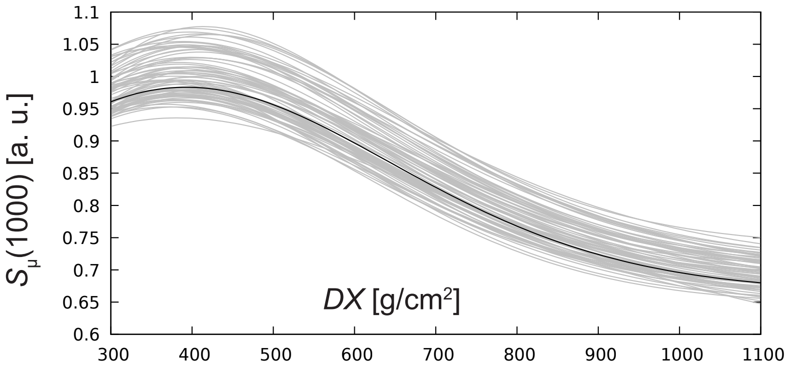
More different for vertical showers, less for inclined

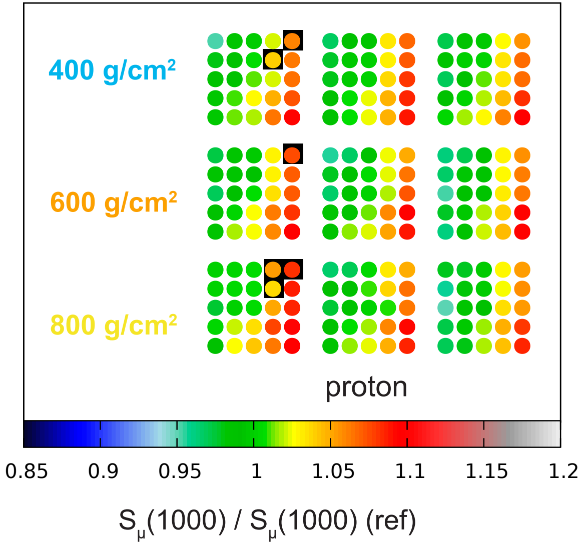


Muons at 1000 m at fixed *DX*

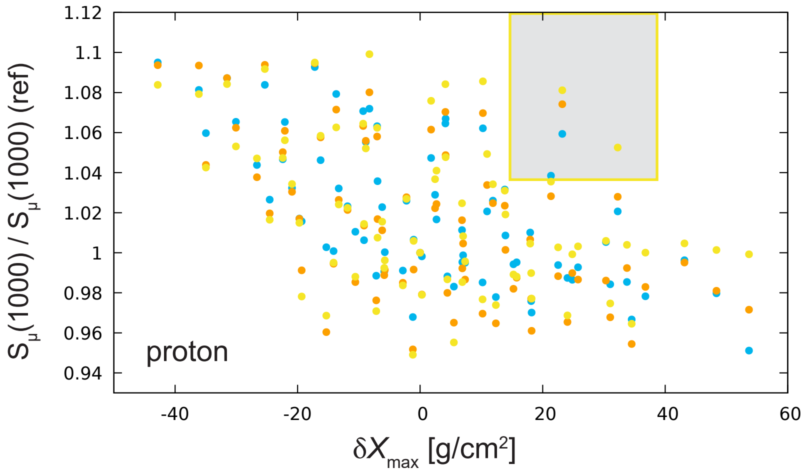
- remove effects of shifting X_{max} on S_{μ} by fitting a dependence on distance between X_{max} and ground







Pierre Auger Observatory analysis: arXiv:2401.10740

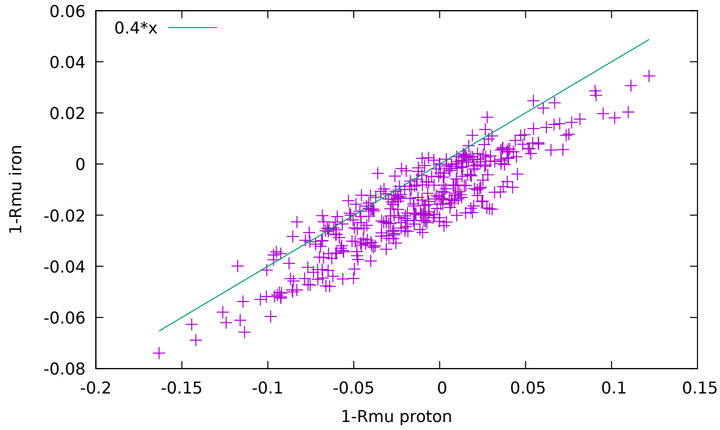


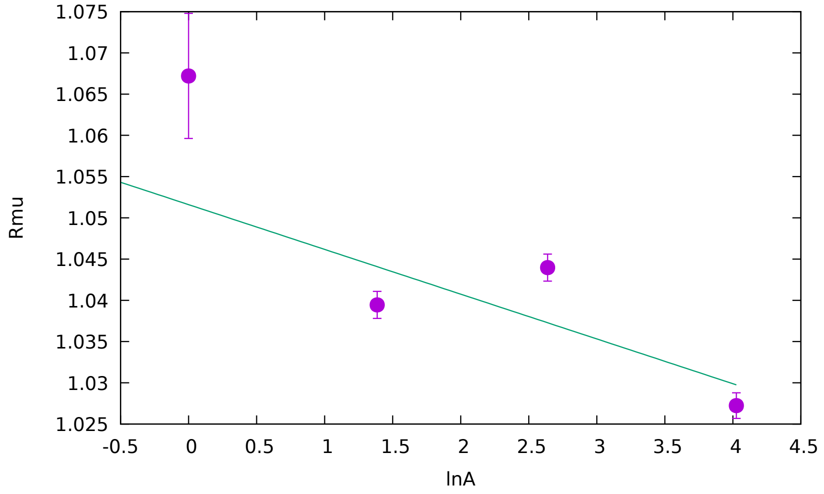
- δX_{max} and R_{had} from complex fit of data, simple scaling to S_{μ}

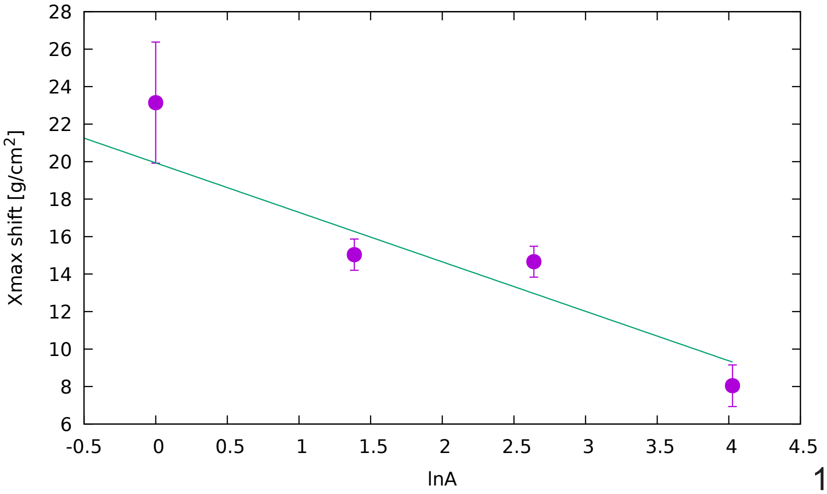
Dependence on A

- Auger method assumes single modification factors for all primaries

- Auger method also fits mass composition, which would change while using a modified model

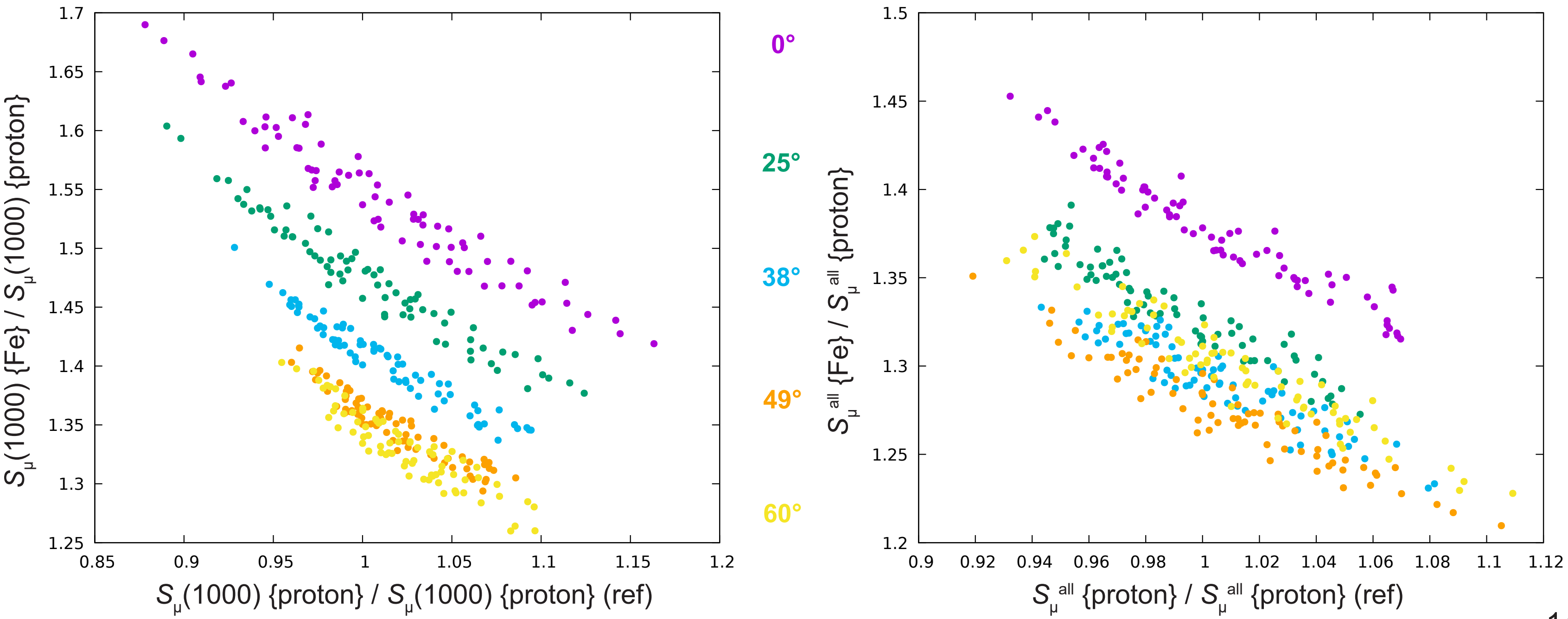






Adding muons and proton/iron separation

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



Conclusions

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

- some effects are a direct consequence of changing the depth of maximum, but some are not

- the changes of hadronic interactions indicated by the Pierre Auger Observatory are just reachable
    - but only with a *combination* of modifications!

- 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

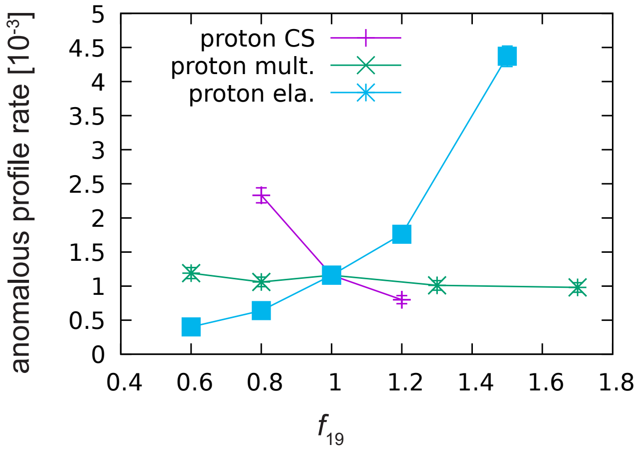
BACKUP

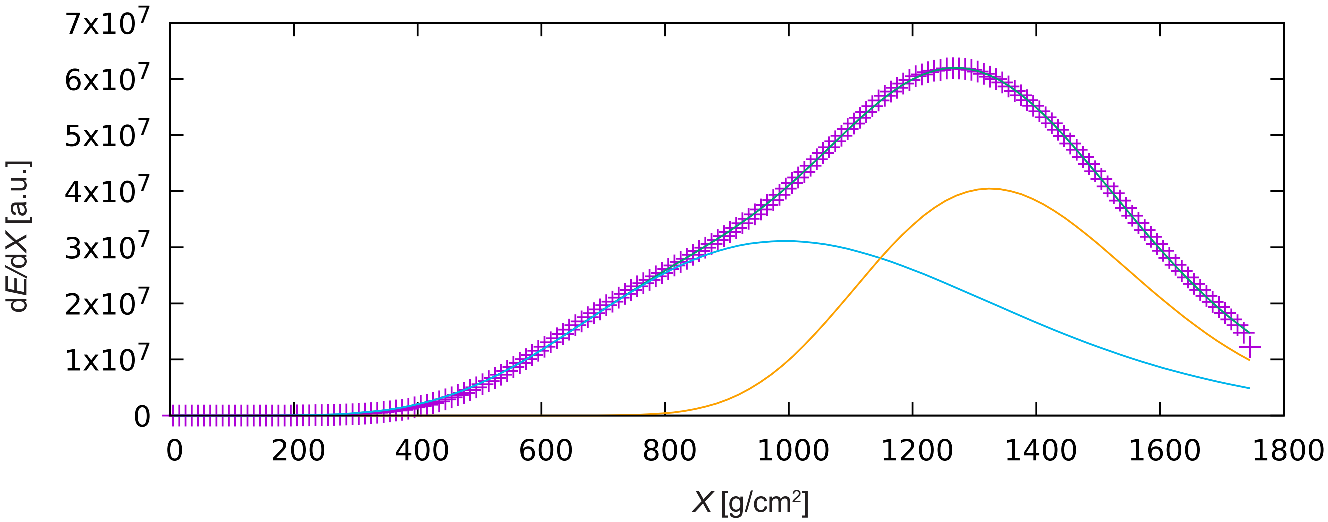
Anomalous profiles

Side test: high-statistics (200 000 showers per bin)

- single-modification only in CONEX

- anomalous profiles by abs. values of residuals w.r.t . GH fit
  - well correlated with „double-bumpiness“
    - (ratio of χ^2 w.r.t. double-GH fit)
  - fraction rises with elasticity

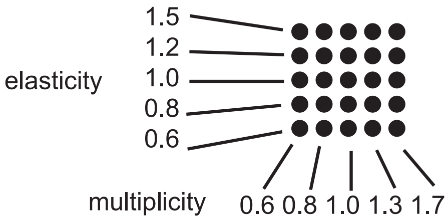


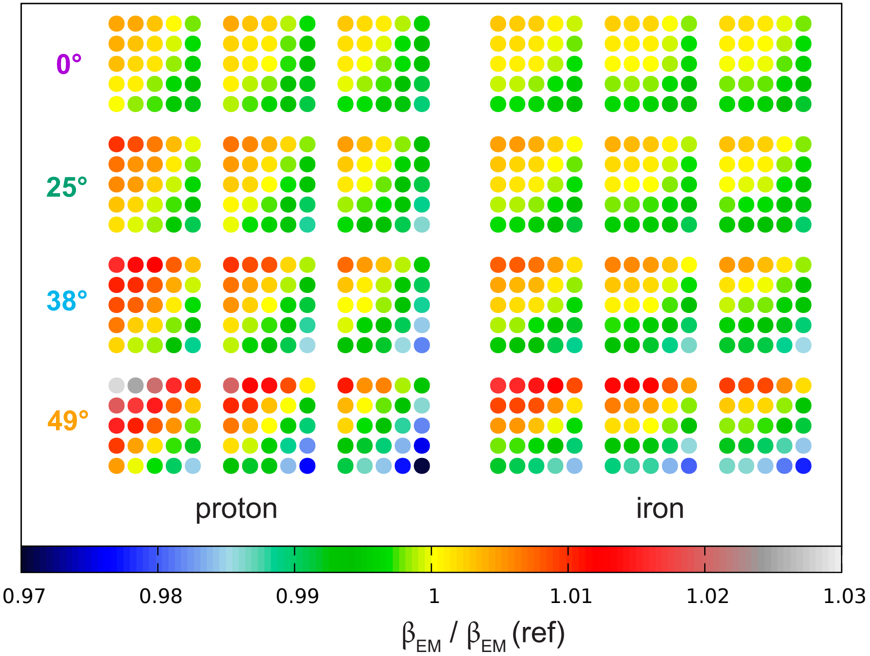


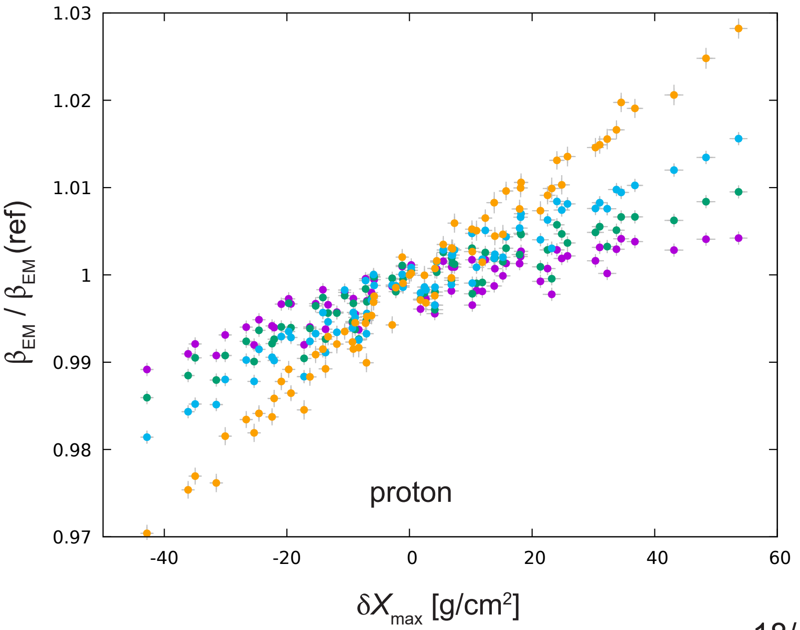
Ground particles: EM lateral distribution slope β

- LDF fitted $S_{\mathrm{EM}}(r) = N[(r/700)(1 + r/700)]^{-\beta_{\mathrm{EM}}}$

- δX_{max} correlation even stronger - almost purely effect of geometry

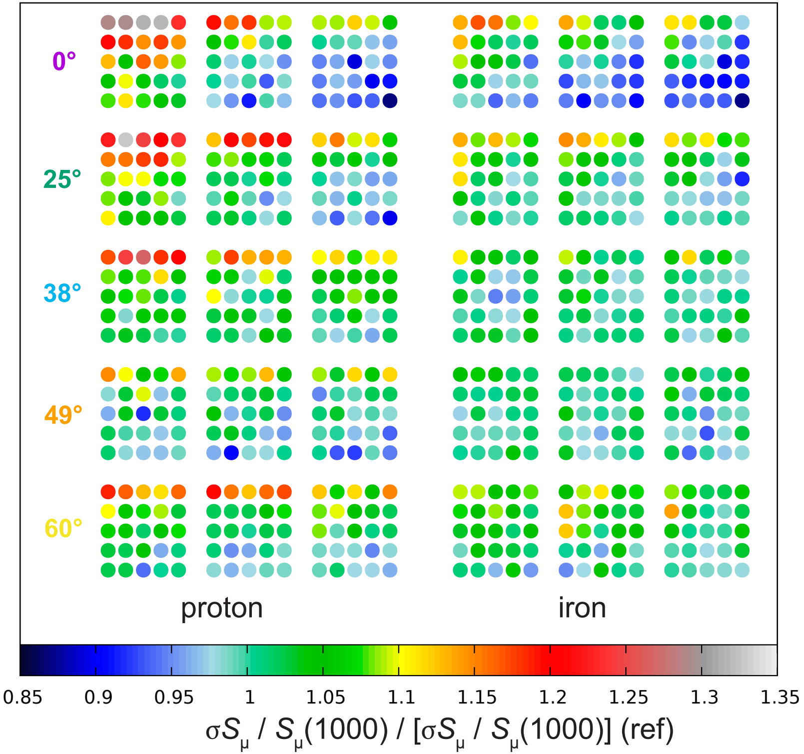


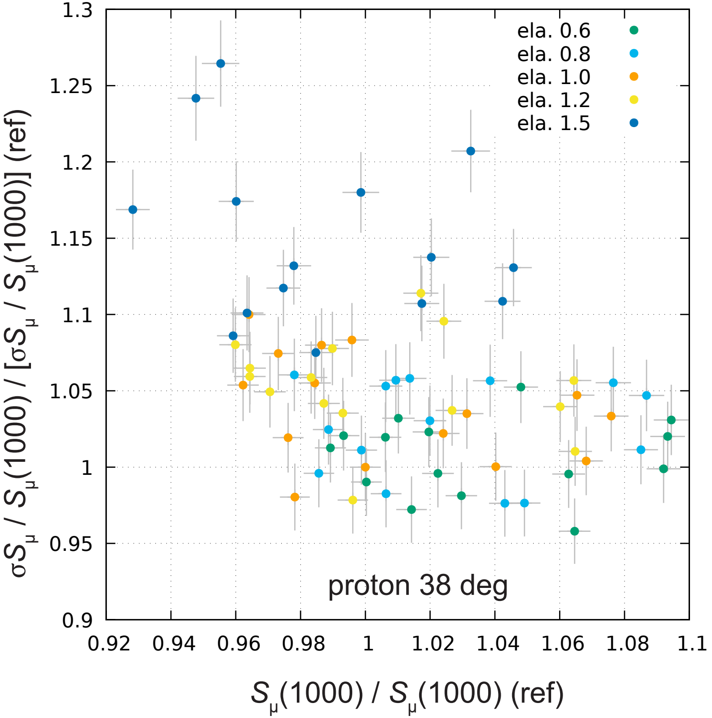




Ground particles: relative muon number fluctuations at 1000 meters

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



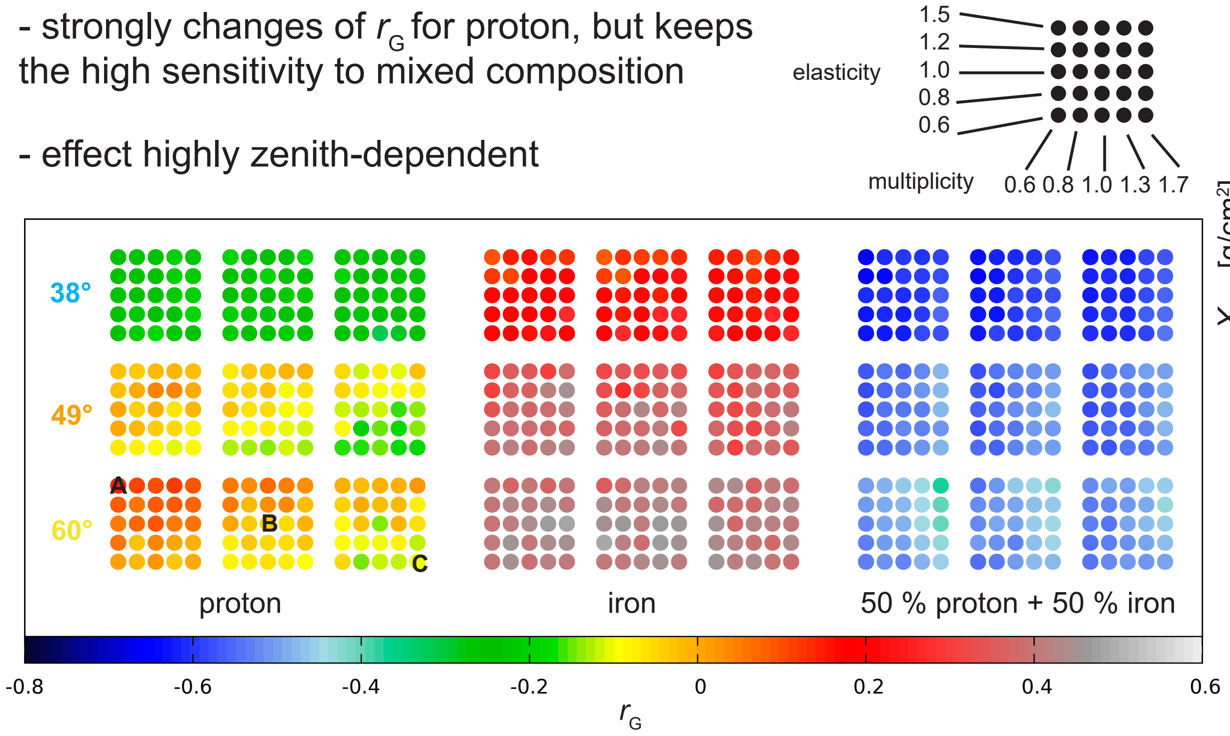


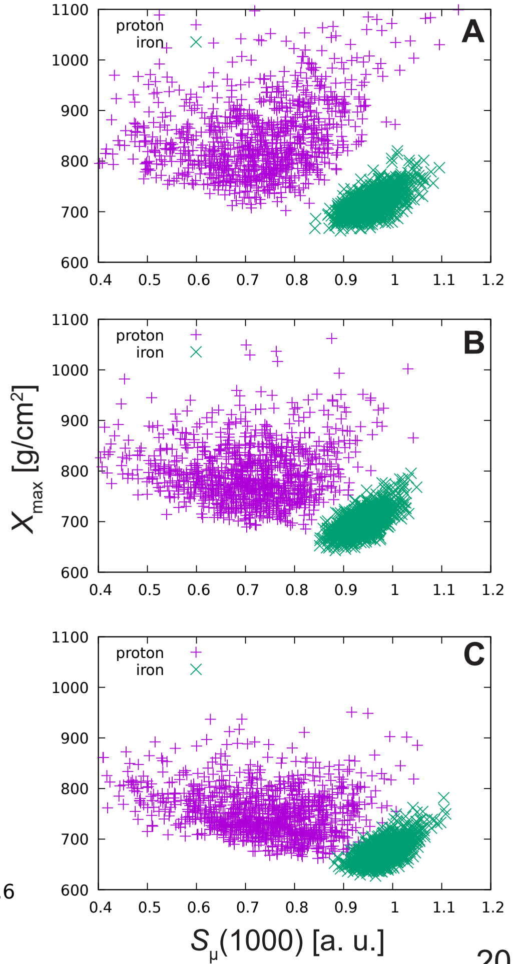
Correlation of muon signal and depth of maximum

Gideon-Hollister ranking correlation coefficient r_G for $S_\mu(1000)$ and X_{max}

- strongly changes of r_G for proton, but keeps the high sensitivity to mixed composition

- effect highly zenith-dependent



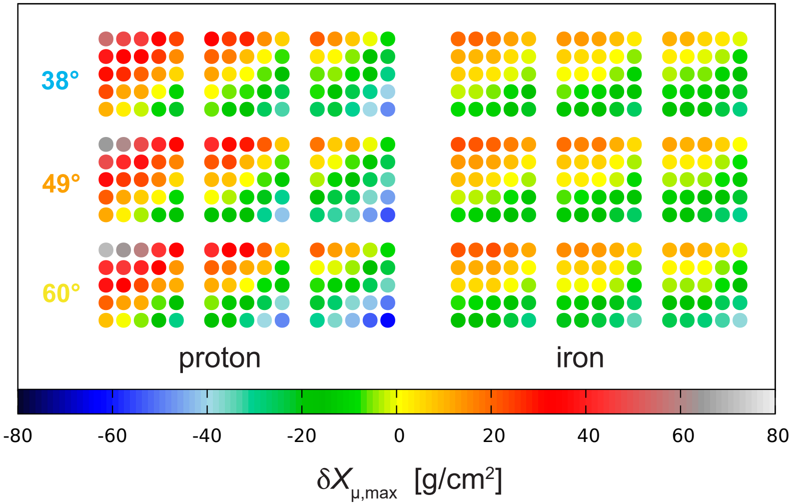


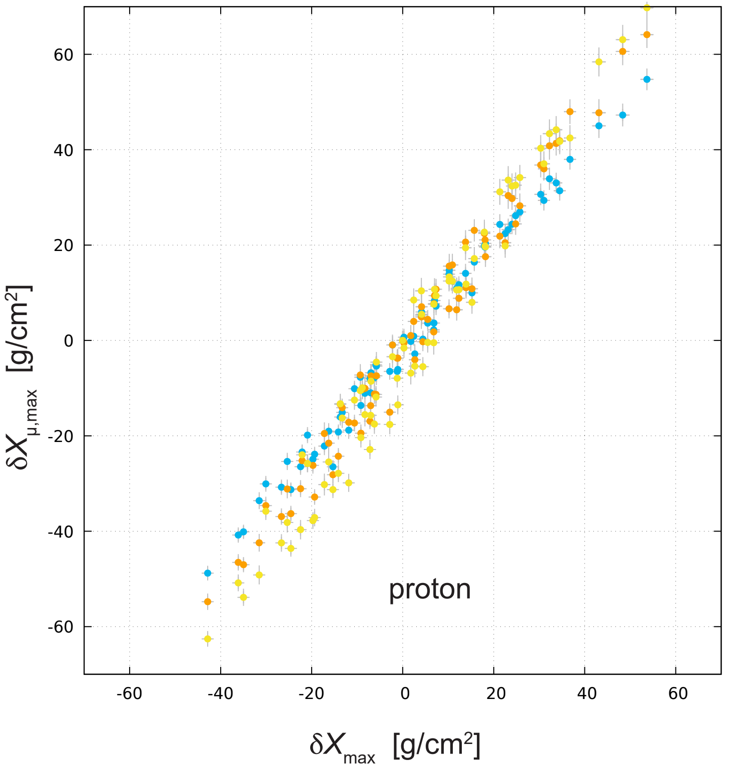
Maximum of apparent muon production depth $X_{\mu,max}$

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





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!