Modified Characteristics of Hadronic Interactions

Jiri Blazek[a], J. Vicha[a], J. Ebr[a], R. Ulrich[b], T. Pierog[b] and P. Travnicek[a]

[a]Institute of Physics of the Czech Academy of Sciences, Prague
[b]Karlsruhe Institute of Technology, Karlsruhe, Germany

blazekj@fzu.cz

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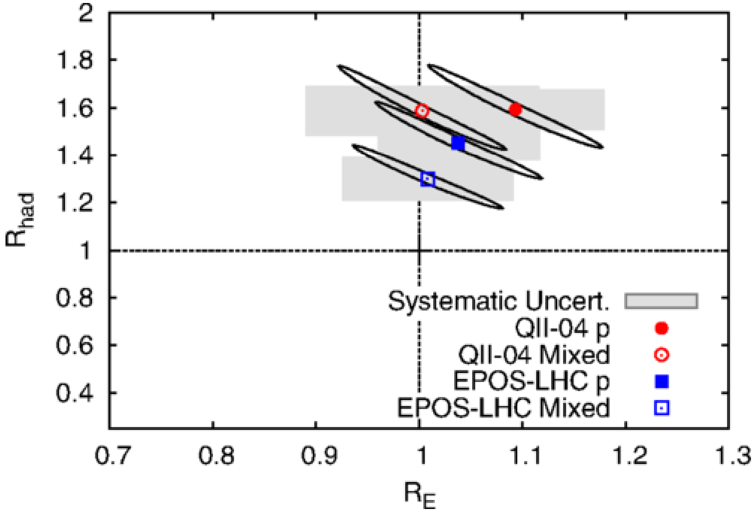
Motivation

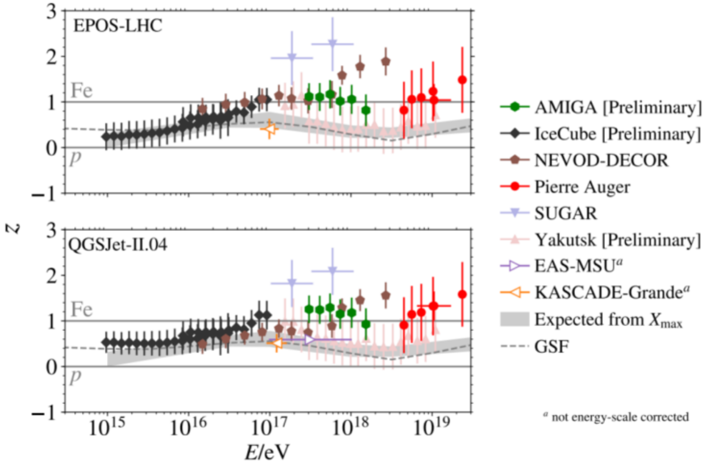
- The "**muon puzzle**" - observed excess of the hadronic signal in measured data when compared to predictions of various hadronic interaction models
- Observed at the Pierre Auger Observatory, Telescope Array and various other experiments

Phys. Rev. Lett. **117** (2016) no.19, 192001

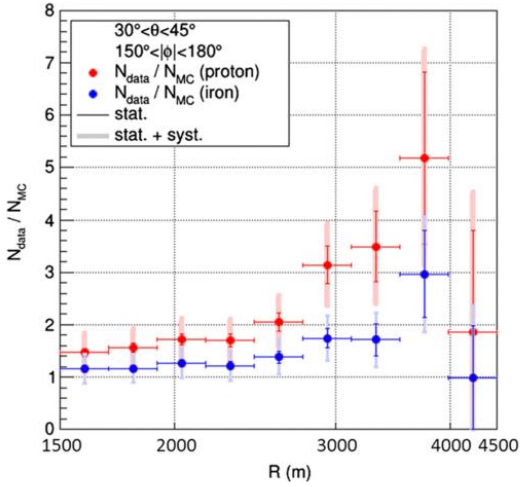


"Above 10 PeV, we find a muon deficit in simulated air showers for each of the six considered hadronic interaction models. The deficit is increasing with shower energy. For the models EPOS-LHC and QGSJet-II.04, the slope is found significant at 8 sigma."

EPJ Web Conf. **210** (2019), 02004



Phys. Rev. **98** (2018) no.2, 022002



Motivation

- Can we modify the models to better match the data?
- Various approaches modifying the fundamental physics: core-corona, fireball model, …
- Another option: modify the basic features of hadronic interactions (cross-section, multiplicity, elasticity, ...) **ad-hoc** and see if we can better describe the data
  - Previously done using a hybrid 1-D **CONEX** code

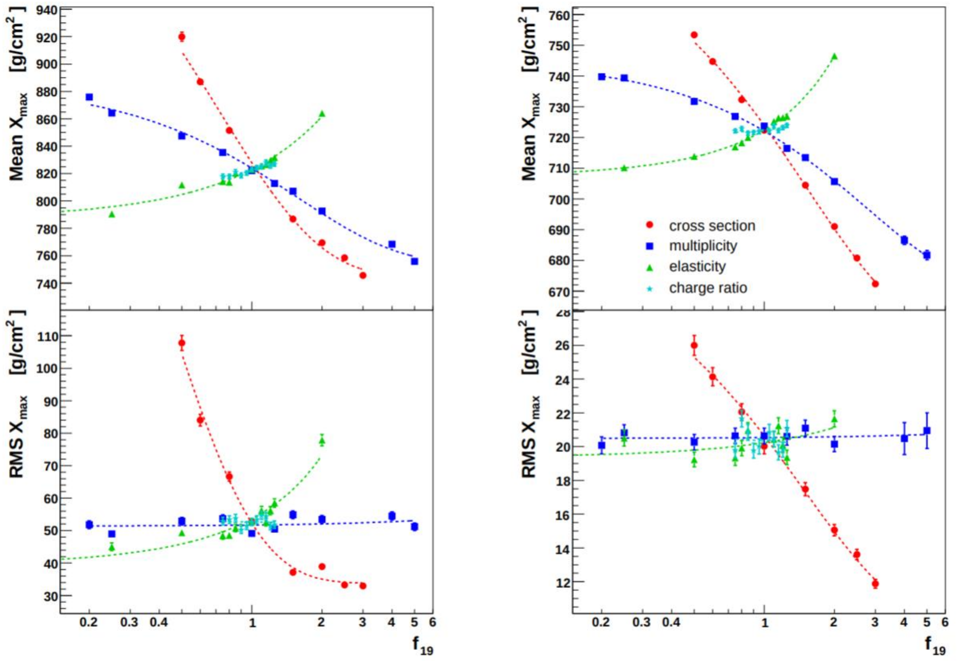
$$f(E, f_{19}) = 1 + (f_{19} - 1) \cdot F(E)$$

where $F(E) = 0$ below some threshold energy E_{thr} and otherwise

$$\frac{\log_{10}(E/E_{\mathrm{thr}})}{\log_{10}(10\ \mathrm{EeV}/E_{\mathrm{thr}})}.$$

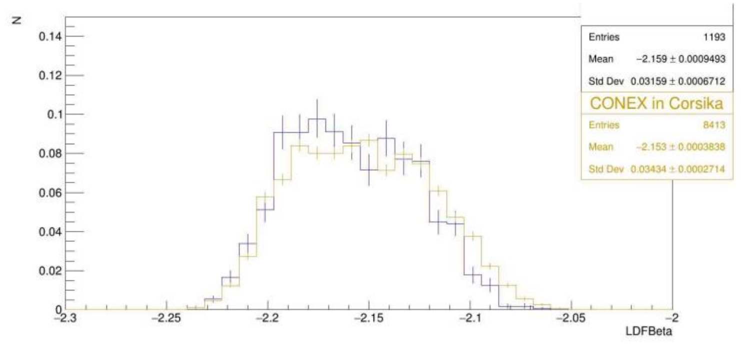
Can we extend this approach into a full 3-D treatment in order to get information about particles further from the shower core?

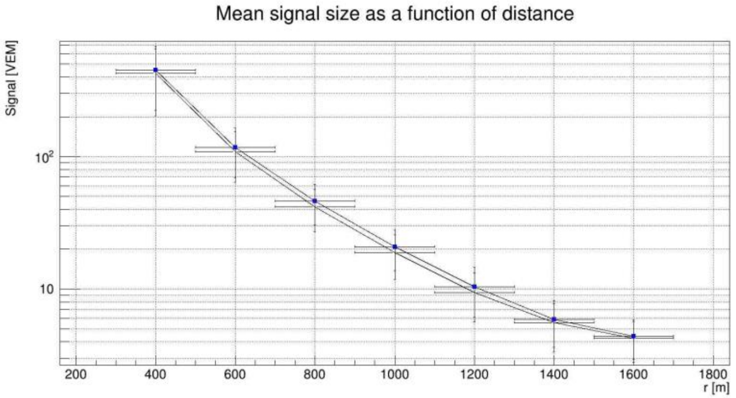
Ulrich et al., Phys. Rev. D **83** (2011), 054026



Modifying the hadronic interactions

- The CONEX resampling code ported into the **CORSIKA** shower generator (tracking of 3D information made possible)
- Simulation sequence:
    - First, full MC treatment by CONEX, resampling active if above E_{thr}
    - Below 10^{13} eV particles binned into cascade equations, solved analytically
    - At 100 GeV are the hadronic particles handed over to CORSIKA
    - Muons tracked by CORSIKA at all energies
- We made extensive checks that the LDFs from the CONEX in CORSIKA treatment and full CORSIKA treatment match within stat. uncertainties
- Furthermore, we can have **separate energy threholds** E_{thr} for each type of the modification
- We can also **perform all three types of modifications** in every interaction

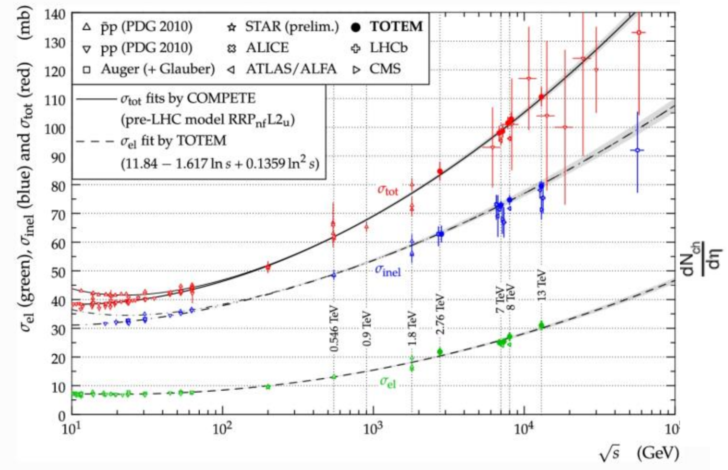




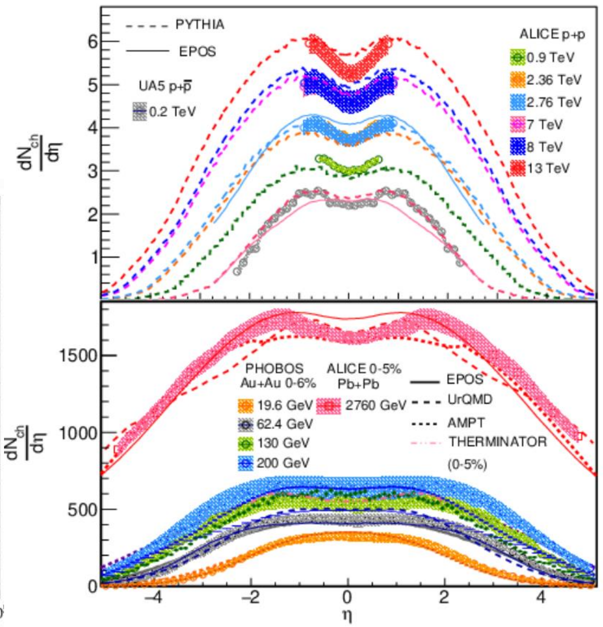
Modifying the hadronic interactions

- Three modifications:
  - Cross section (interaction length)
  - Elasticity $\kappa_{\mathrm{el}} = E_{\mathrm{leading}} / E_{\mathrm{tot}}$
  - Multiplicity, the total number of particles escaping the interaction
- We can set the the thresholds separately, but how?
- We aim to be **conservative**, start slightly below some measurement from accelerators and be at most **3-sigma** away
- Most easily done with cross-section
  - $E_{thr} = 10^{16}$ eV
- Multiplicity more complicated
  - $E_{thr} = 10^{15}$ eV
- Most freedom with elasticity
  - $E_{thr} = 10^{14}$ eV

Eur. Phys. J. C **79** (2019) no.2, 103



J. Phys. G **48** (2020) 025103



Simulation setup

- Proton primary
- Energy of the primary particle 7 EeV
- Five zenith values simulated, distributed uniformly in $\cos^2$(theta) for theta in (0, 60) degrees
- Range of f_{19} (cross-section) = (0.8, 1., 1.2)
- Range of f_{19} (elasticity) = (0.6, 0.8, 1., 1.2, 1.5)
- Range of f_{19} (multiplicity) = (0.6, 0.8, 1., 1.3, 1.7)
- 375 combinations in total
- 500 showers simulated for each combination
- Sibyll2.3d

Results

- We define our first observable as the shift in X_{max} wrt. to a reference value

$$\delta X_{\max} = X_{\max} - X_{\max}^{\mathrm{ref}}$$

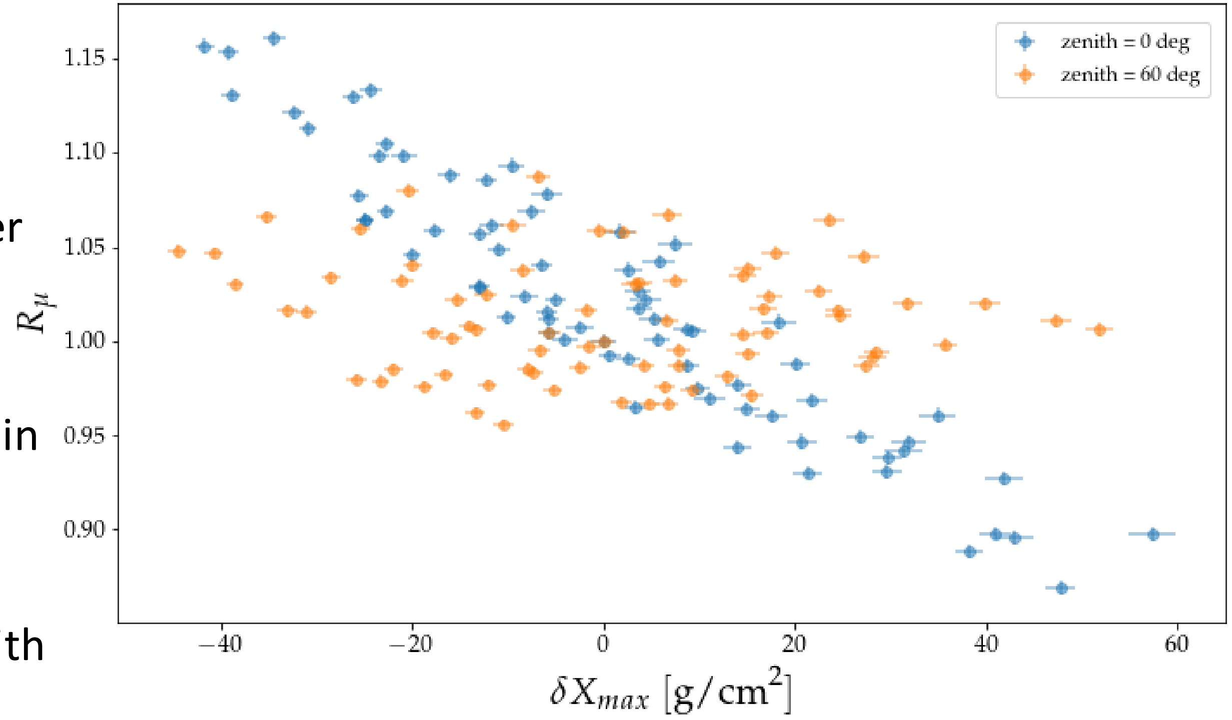
- The second observable we take as the total number of muons in a thin ring in a given distance from the shower axis, divided by a reference value.

$$R_\mu = S^*_\mu(1000) \;/\; S^{*(\mathrm{ref})}_\mu(1000)$$

- The reference value is defined as the unmodified point in the phase space for a given zenith

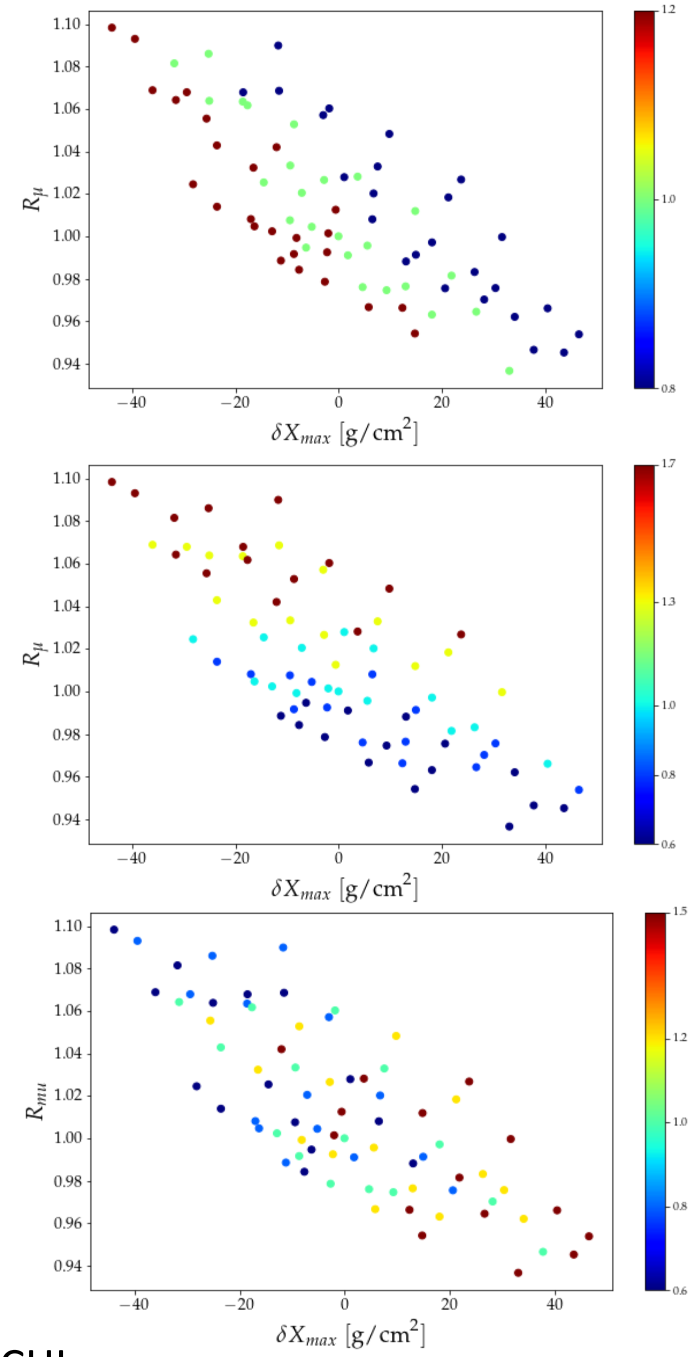
$$f_{19}^{\sigma} = f_{19}^{\mathrm{el}} = f_{19}^{\mathrm{mult}} = 1$$

- On the left figure are shown only two values of the zenith angle, for visual clarity
- Clear zenith dependence of R_{mu}



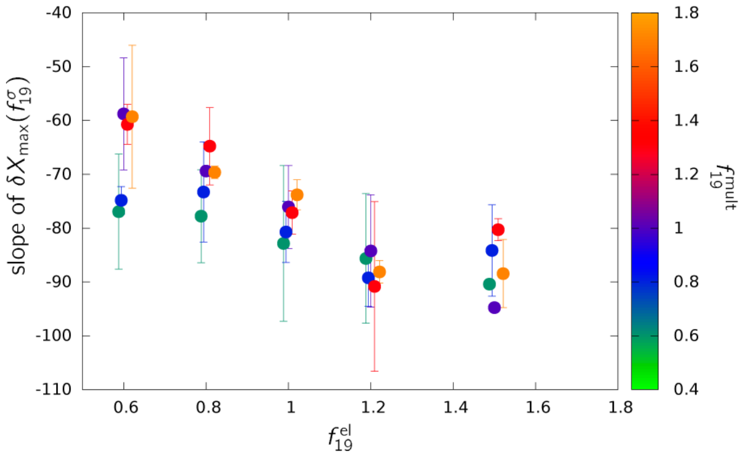
Results

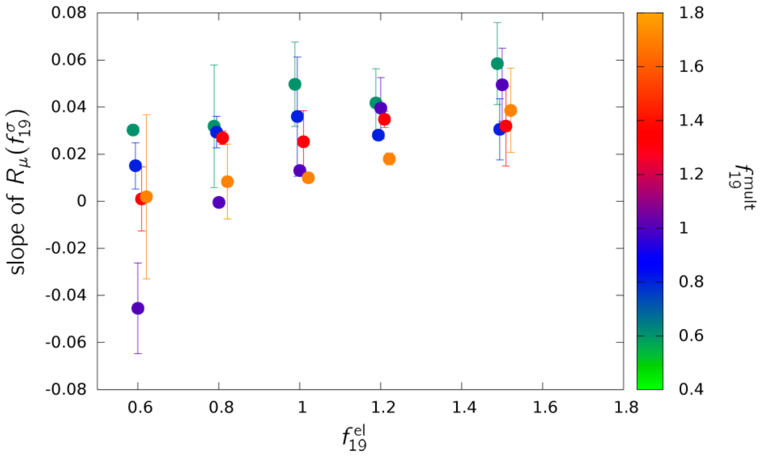
- Next we want to know if the behavior of the particular modifications is universal across the whole phase space
- For each combination of the f_{19} factors we average over all the zenith bins, in order to retain as much information as possible
- For cross section, the shifts the distributions along the x-axis
- For multiplicity, the shifts the distributions along the y-axis
- For elasticity, the distributions are shifted along the anti-diagonal



Results

- Unlike in Ulrich et al., we simulated a full phase space of modifications
- A question: are the results a trivial combination of the changes or not?
- For every zenith angle, we fit a line through simulations that differ only in one of the modification factors, then we look at the dependence of the slope of the line on other factors -> interplay of different modifications
- Most of the time the the effect is modest
- Most pronounced for f_{19}(cross section) -> the effect of the modification of cross section depends on the magnitude of the modification of elasticity





Discussion & Outlook

- The modifications of hadronic interactions applied in the 3D CORSIKA simulation package affect not only the total number of muons, but also the number of muons at distances from the shower axis relevant for the ground based measurements
- The modifications are **not quite sufficient** enough to describe the muon problem discrepancy as reported by the Pierre Auger Collaboration
- But still interesting in light of recent developments, see the talk of Jakub Vicha for the Pierre Auger Collaboration on this conference (CRI-528, PoS(ICRC2021)310)!
- Modifications of different parameters in parallel make sense, because the result is not a simple addition of individual effects

Outlook

- We plan to further enlarge the phase space: more primaries than proton, more hadronic interaction models
- We plan to extract more variables than just X_{max} and R_{mu} and determine which combinations of baseline models and interaction modification provide the **best description of the data**