A Study of Modified Characteristics of Hadronic Interactions (MOCHI)

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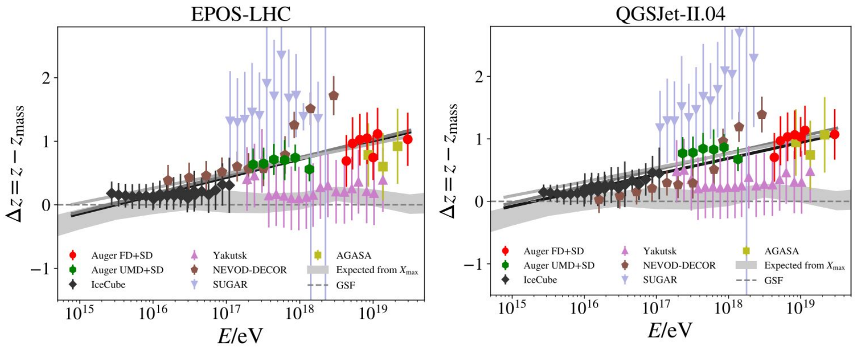
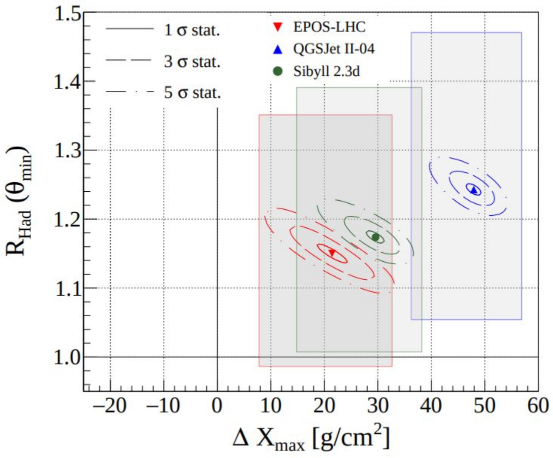
Motivation

- **Muon puzzle** - a well established tension between predictions of UHE hadronic interaction models and the data.
- Observed by the Pierre Auger Collaboration, Telescope Array and other experiments
- WISP group reports a **8 sigma** significance



PoS(ICRC2021)349, also this conference



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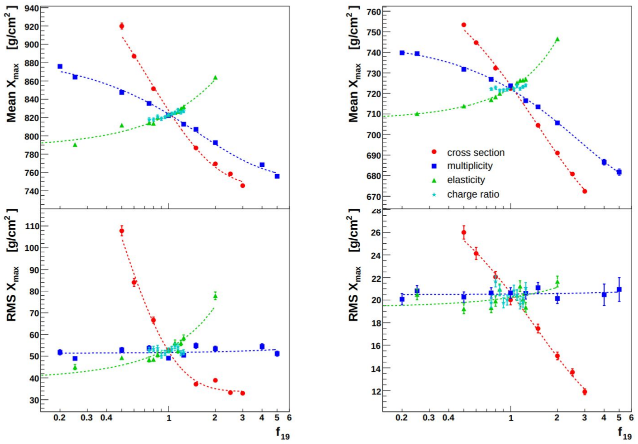
Motivation - modifying hadronic interactions

- Current models insufficient - can we guide their modifications to better match the data?
- There are several approaches with with well-motivated underlying physical scenarios - core corona, fireball model…
- Which features are actually important? We can try introducing ad-hoc modifications and observe the effect

Previously done by Ulrich et al., by introducing changes to **Cross-section**, **Multiplicity, Elasticity** and neutral/charged **pion ratio** using 1D (CONEX) Monte-Carlo code



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

Motivation - modifying hadronic interactions

- We want to use the full 3D information - the whole CONEX resampling code has been ported to CORSIKA
- 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

The LDFs from the CONEX in CORSIKA and standalone CORSIKA match within stat. uncertainties.

It is possible to set **separate threshold energies** for every modification and **modify all features** at once in every interaction.

Modifications

The question we are trying to answer: Given **conservative assumptions** about the magnitude of changes to the had. interactions, is there a combination of parameters that describes the data?

Parameters we try to modify:

- Cross section (interaction length)
- Elasticity $\kappa_{\mathrm{el}} = E_{\mathrm{leading}}/E_{\mathrm{tot}}$
- Multiplicity, the total number of particles escaping the interaction

Ansatz for modification:

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

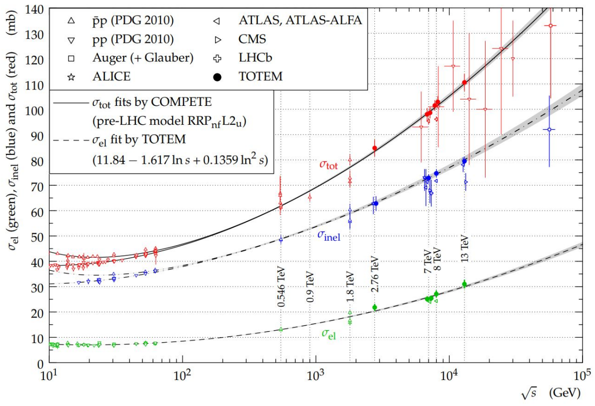
$$F(E) = \frac{\log_{10}(E/E_{\mathrm{thr}})}{\log_{10}(10\,\mathrm{EeV}/E_{\mathrm{thr}})}$$

How to set E_{thr}? Ideally, we would like to be at most **3 sigma** away from a measurement.

Cross section

The most straightforward, **strongly constrained** by the Glauber and available measurements of the p-p (TOTEM) and p-Pb (CMS) inealistic/total cross section.

Note: we are interested in **p-Air** cross section.
We set $E_{thr} = 10^{16}$ eV $f_{19} \subset (0.8, 1.2)$



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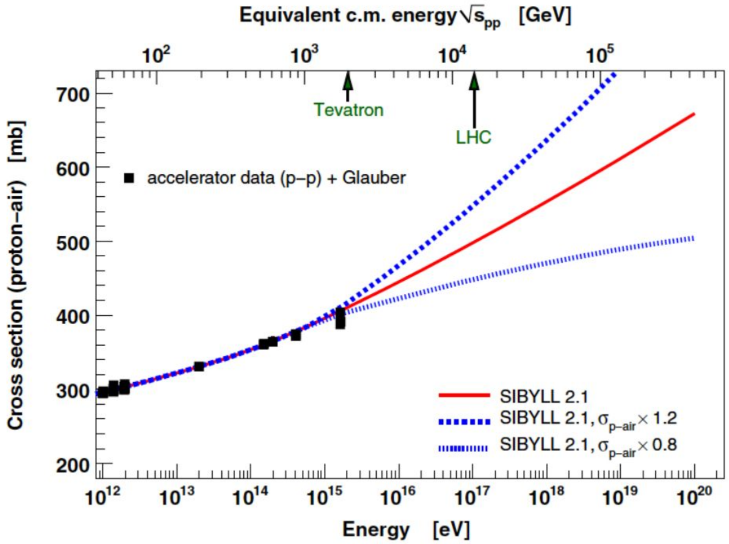


Multiplicity + Elasticity

More freedom for **multiplicity**.

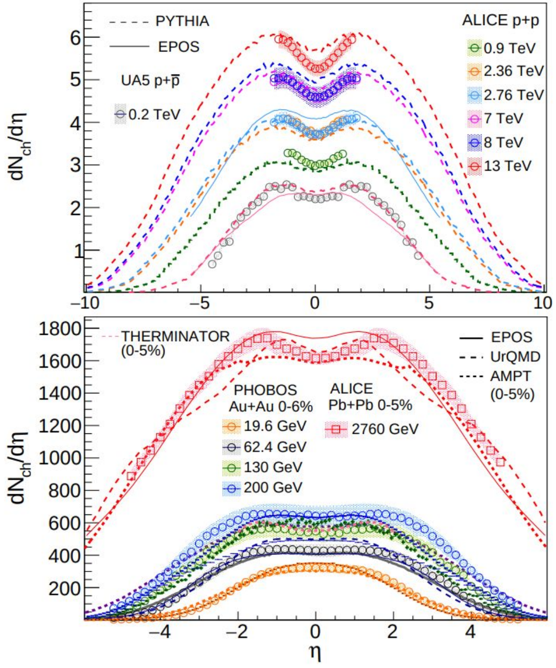
- Not full coverage in pseudorapidity even in p-p collisions
- No relevant **p-Air** measurements
- models differ by around 20% in the area where we have coverage

We set $E_{thr} = 10^{15}$ eV $\quad f_{19} \subset (0.6, 1.7)$

Most freedom for elasticity.

- no relevant accelerator data
- most strigent limits probably from cosmic ray experiments using nuclear emulsion chambers

We set $E_{thr} = 10^{14}$ eV $\quad f_{19} \subset (0.6, 1.5)$



J. Phys. G 48 (2020) 025103

Resampling of (non-proton) nuclei

- A word of slight caution: resampling of nuclei is not treated consistently in CONEX
- All the effect comes from resampled secondaries
- However, several effects help minimize this inconsistency:
  - the heavier the nucleus, the lesser the mean free path and the lesser the effect
  - the modification is applied at energy *E* / *A*, which further lessens the effect
  - The modification to f_{19} (nucleus - air) can be parametrized from the dependence of nucleus - air cross section on proton - air cross section reported by the models
  - The effect is of the order of ~ 1 g / cm^2 for iron nuclei, we will neglect it

Simulation setup

- **Proton**, **iron** primary
- Energy of the primary particle 7 EeV
- Five zenith values simulated for proton, distributed uniformly in cos2(theta) for theta in (0, 60) degrees, 2 for iron (0 and 60 degrees)
- Range of f19 (cross-section) = (0.8, 1., 1.2)
- Range of f19 (elasticity) = (0.6, 0.8, 1., 1.2, 1.5)
- Range of f19 (multiplicity) = (0.6, 0.8, 1., 1.3, 1.7)
- **525 combinations in total**
- ~500 showers simulated for each combination
- Sibyll2.3d (because the **superposition model** is easiest to work with)

Results

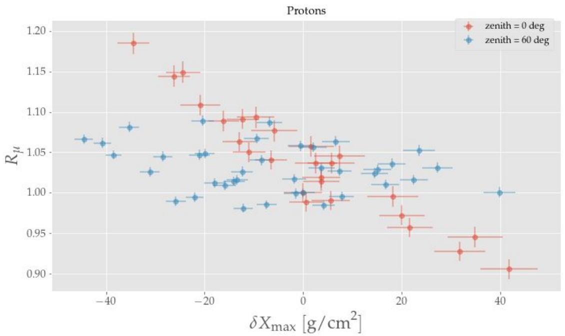
Our observables: X_{max} and number of muons read out in concentric thin circles.

We define the shift in X_{max} as $X_{\max}\colon\ \delta X_{\max} = X_{\max} - X_{\max}^{\mathrm{ref}}$

The muon number enhanced as $R_\mu = S_\mu^*(1000) \,/\, S_\mu^{*(\mathrm{ref})}(1000)$

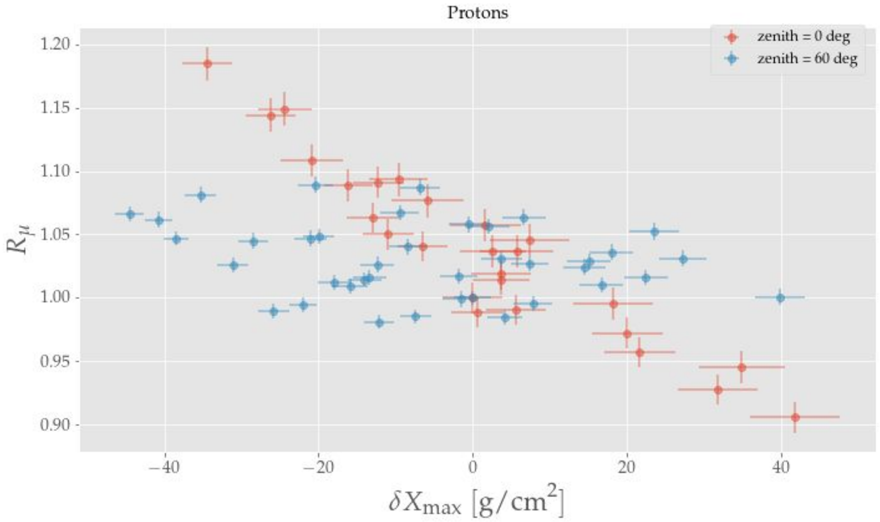
The reference values are chosen as $f_{19}^{\sigma} = f_{19}^{\mathrm{el}} = f_{19}^{\mathrm{mult}} = 1$

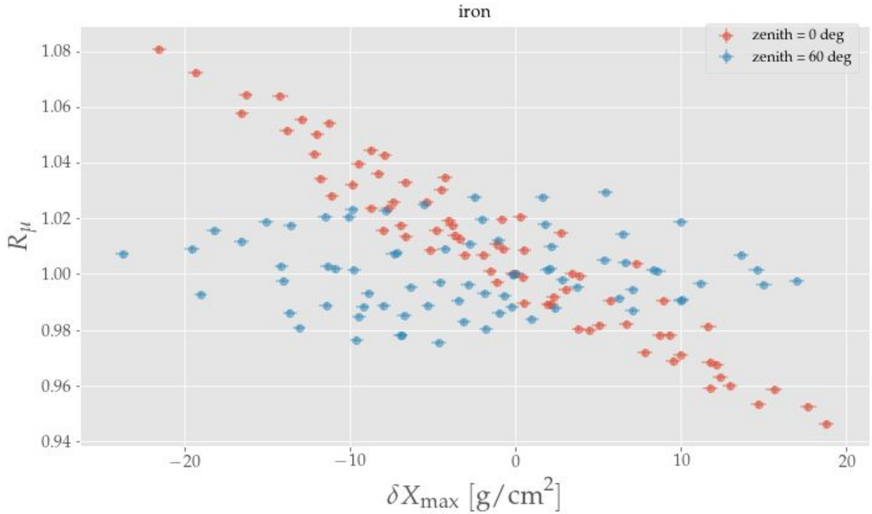
We have also taken look at the LDF parameter β and the correlation coefficient r_G



Results

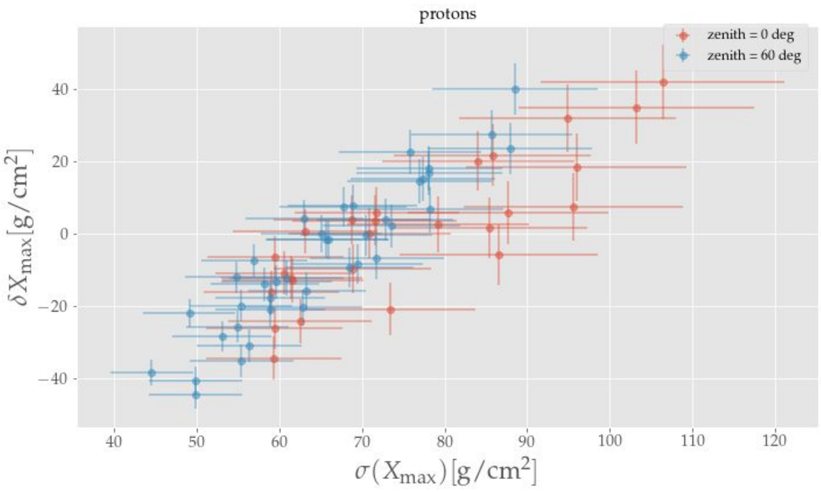
- We will show just the two extremal zenith bins for clarity
- Clear zenith dependence of the muon fraction visible
- Shift in X_{max} largely zenith independent, as expected

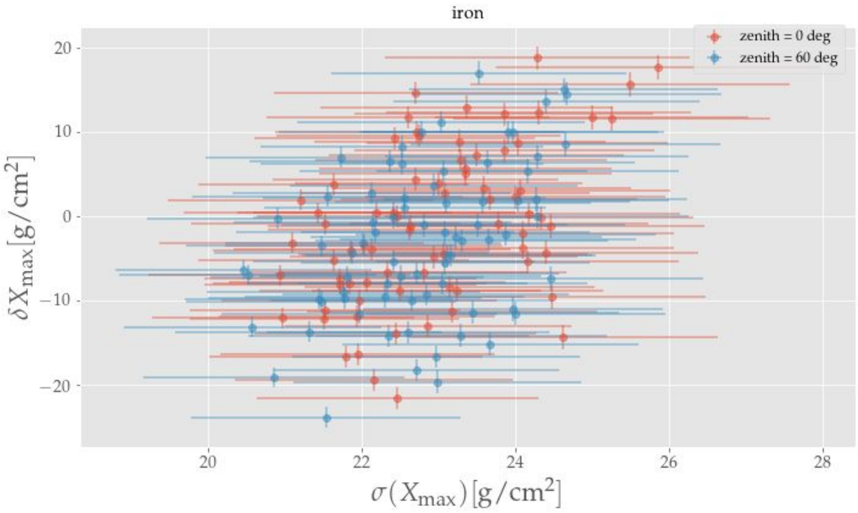




Results

- We will show just the two extremal zenith bins for clarity
- Clear correlation seen for the light nucleus, making it difficult to shift Xmax independently of its variance, which is constrained

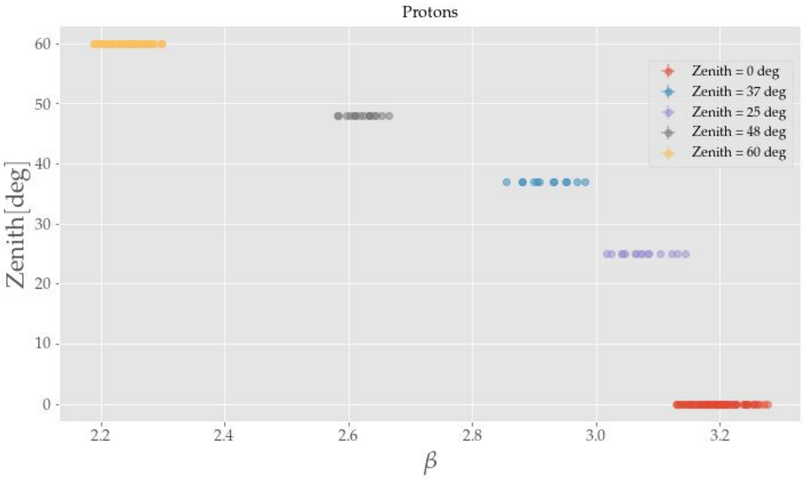




β coefficient

- Aim: investigate the changes in the lateral shape of muon profiles
- Strongly zenith dependent
- Preliminary stage of analysis

$$\rho(r) = k\left(\frac{r}{r_s}\right)^{-\beta}\left(1+\frac{r}{r_s}\right)^{-\beta}$$



Conclusions

- We have produced a large simulation dataset of large of 525 parameter combinations and showed the dependence of various observables on the modifications
- However, it still proves to be **very difficult to move in the direction** of adding muons **without** simultaneously **shifting the variance of X_{max}** too much
- But some of the combinations might be able to describe current data, see Jakub's talk in this session. Such a statement however requires careful folding in of the detector responses.

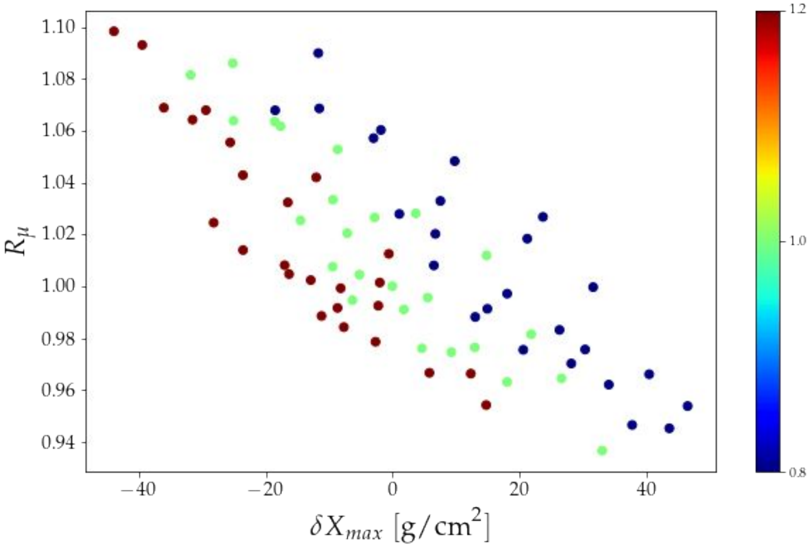
Outlook

- We plan to explore further variables, such as the Muon Production Depth (MPD) and the correlation coefficient between the N_{mu} and X_{max}
- We plan to enhance the simulation library with intermediate masses
- Possibility of modifying more fundamental features of hadronic interactions, such as production spectra
- Possibility of folding in the detector response and compare the result with data

Backup

Backup

Cross section



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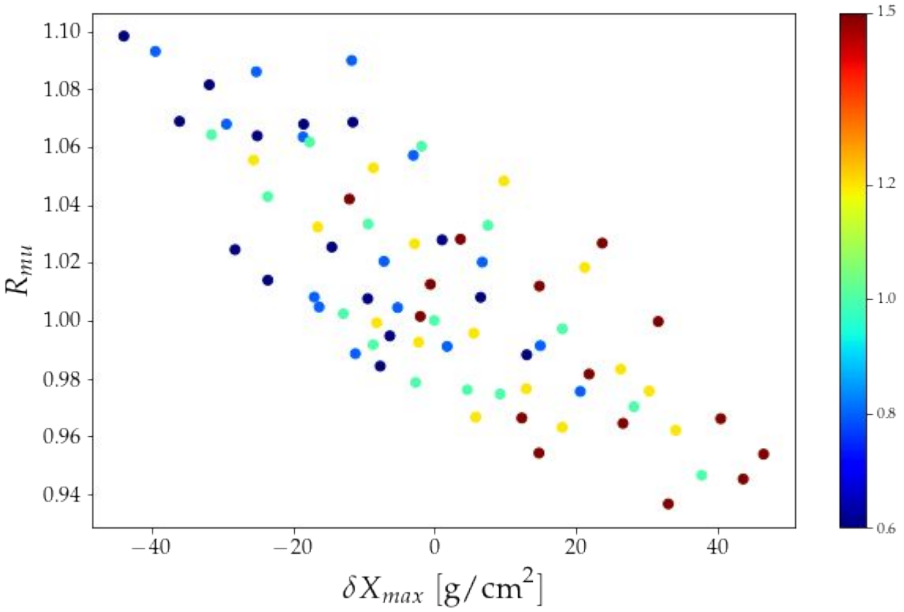
Elasticity



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Multiplicity