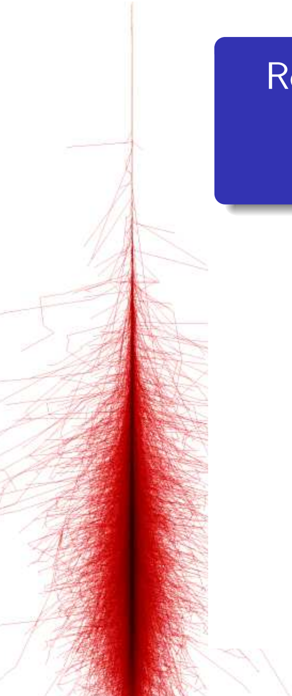

Relation of Interaction Characteristics at Ultra-High Energies to Extensive Air Shower Observables

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Pennsylvania State University

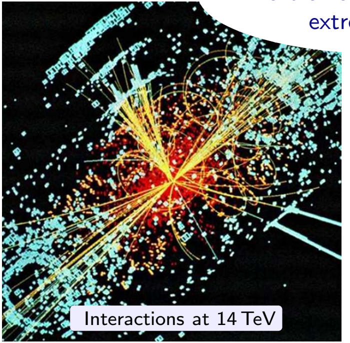
R. Engel, M. Unger

Karlsruhe Institute of Technology

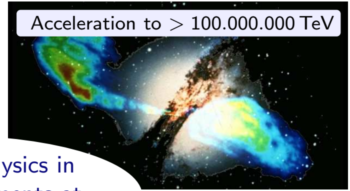
ECT* Trento, Nov 2010

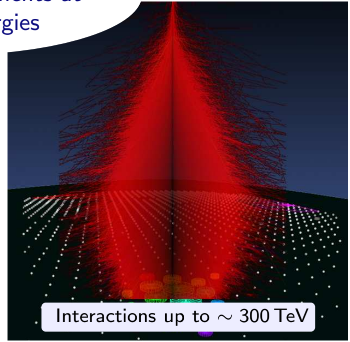
Particle Accelerators: Man-Made versus Cosmic Rays

Large Hadron Collider (LHC)



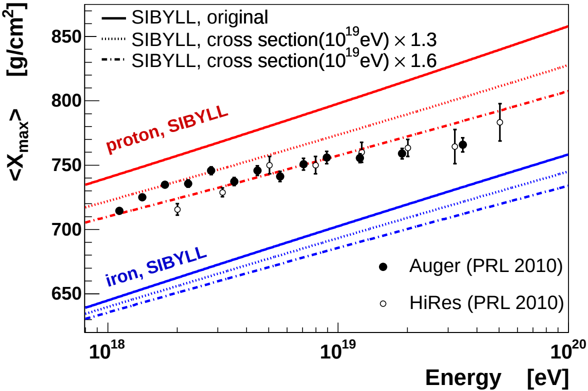
Ultra-High Energy Cosmic Rays





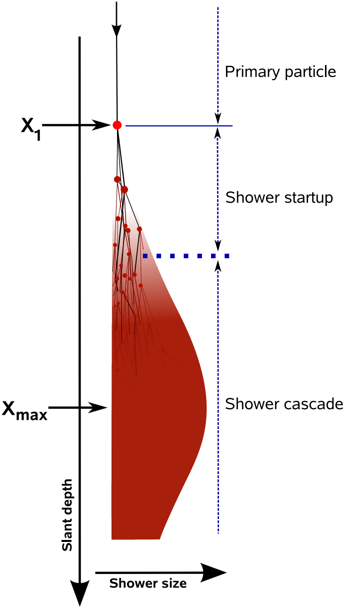
Fundamental physics in extreme environments at extreme energies

Overview



- The interpretation of air shower data is very model dependent
- Hadronic interaction features are not well constraint at cosmic ray energies
- From high statistics and high quality air shower data we can determine something about properties of hadronic interactions at ultra-high energies

Air Shower Development



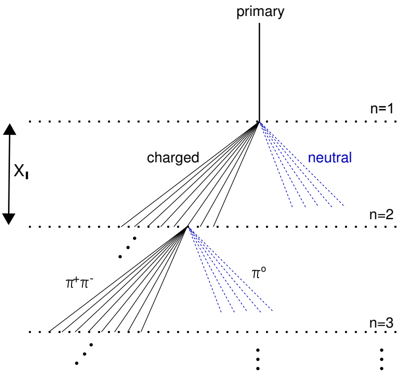
Typical observable EAS properties are:

- $\mathbf{X_{max}}$ Slant depth of shower maximum
- $\mathbf{N_e}$ Number of electrons at ground level
- $\mathbf{N_\mu}$ Number of muons at ground level

For this work:

- N_e is the total number of electrons above 1 MeV at 1000 $\mathrm{g/cm^2}$
- N_μ is the total number of muons above 1 GeV at 1000 $\mathrm{g/cm^2}$
- $\Delta X = X_{\max} - X_1$

Extended Heitler Model



Shower maximum

$$X_{\max} \approx \lambda_{\mathrm{I}} + X_0 \ln \frac{E_0}{N_{\mathrm{mult}}\, E_{\mathrm{crit}}^{\mathrm{e.m.}}}$$

Muon number at observation level

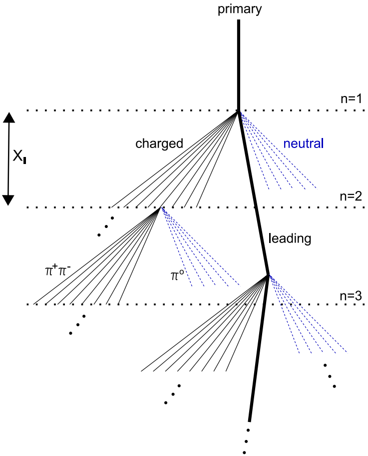
$$N_\mu = N_{\pi^\pm} = \left(\frac{E_0}{E_{\mathrm{crit}}^{\mathrm{I}}} \right)^{\beta}$$

where

$$\beta = \ln\left(\tfrac{2}{3}\, N_{\mathrm{mult}}\right) / \ln\left(N_{\mathrm{mult}}\right) \approx 0.9$$

(J. Matthews, APP 22 (2005) 387)

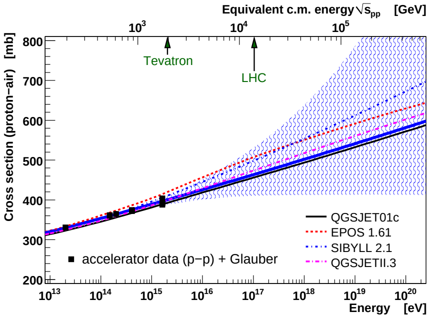
Beyond the Heitler Model ...



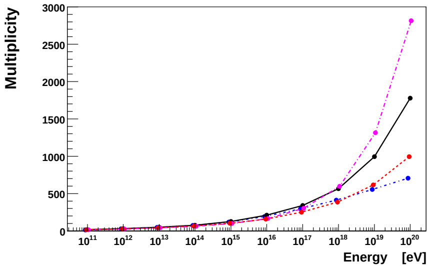
- Cross Section: λ
- Multiplicity: n_{mult}
- Elasticity: $k_{\text{ela}} = E_{\text{max}}/E_{\text{tot}}$
- Charge ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$
- Nuclear primary: A

Modeling Uncertainties

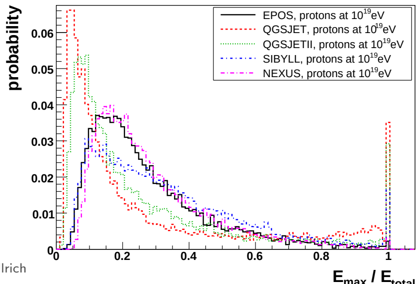
Cross Section



Multiplicity



Elasticity



Customized CONEX Version

Modify specific features of hadronic interactions during air shower Monte-Carlo simulation:

- Assume logarithmically growing deviation from original model prediction above 10^{15} eV.
- Below 10^{15} eV the original model is used.
- The parameter f_{19} denotes the nominal deviation at 10^{19} eV.

$$\alpha^{\mathrm{modified}}(\mathrm{E}) = \alpha^{\mathrm{HE-model}}(\mathrm{E}) \cdot \left(1 + (\mathrm{f}_{19} - 1) \cdot \frac{\log_{10}(\mathrm{E}/1\,\mathrm{PeV})}{\log_{10}(10\,\mathrm{EeV}/1\,\mathrm{PeV})}\right)$$

Where α can be:

- Cross Section: $\sigma_{\mathrm{had}}^{\mathrm{prod}}$
- Multiplicity: n_{mult}
- Elasticity: $k_{\mathrm{ela}} = E_{\mathrm{leading}}/E_{\mathrm{max}}$
- Pion-Charge Ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^+} + n_{\pi^-})$

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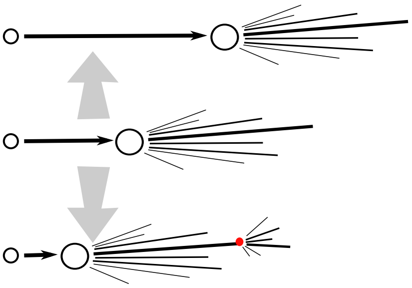
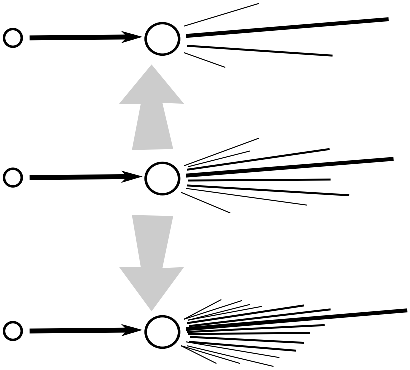
Modified Cross Section



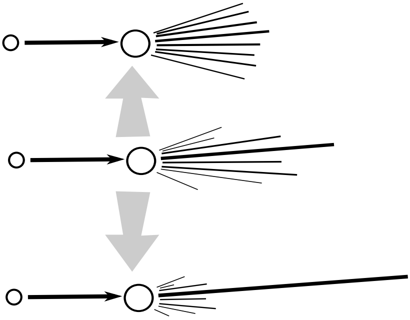
→ Equally scale all hadronic cross sections.

Modify Secondary Multiplicity



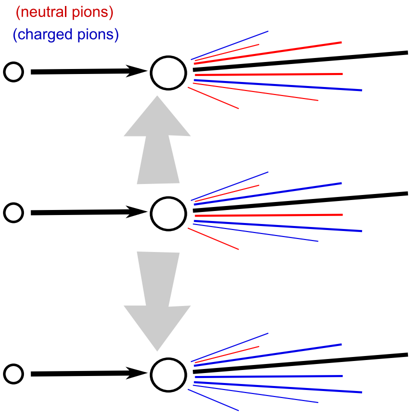
- **Resampling** of secondaries after each hadronic interaction.
- Duplication or deletion of secondary particles.
- Algorithm changes the particle multiplicity while conserving:
  - Energy
  - Charge
  - Relative energy in particle type groups

Modify Elasticity



$$k_{\text{inel}} = 1 - {}^{E_{\max}}/{}_{E_{\text{tot}}}$$

- **Redistributing** of energy among the leading particle and the other secondaries.
- Algorithm changes the interaction elasticity while conserving the total energy

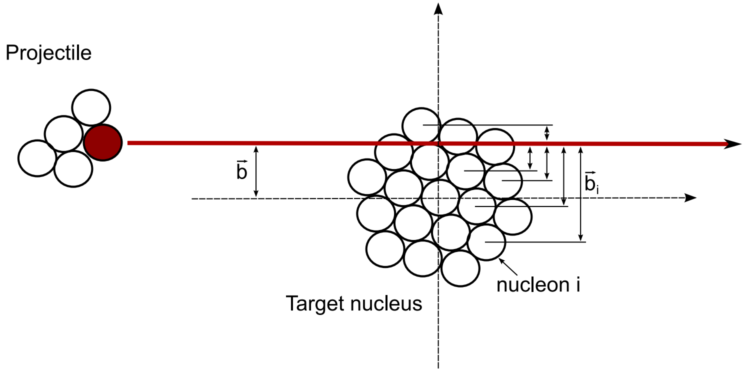


$$c = n_{\pi^0} / (n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$$

- **Switch** between pion types: $\pi^0 \leftrightarrow \pi^{\pm}$

Primary Nuclei

⇒ Glauber Formalism

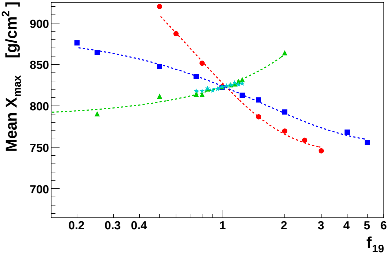


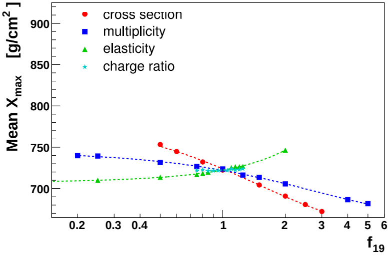
- Scale the fundamental nucleon-nucleon cross section
- Compute the nucleus-nucleus cross section with Glauber

→ **SIBYLL**

Results for $\langle X_{\max} \rangle$

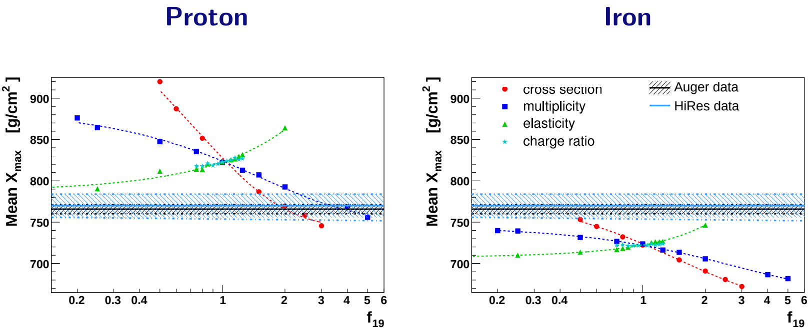
Proton **Iron**





- $\langle X_{\max} \rangle$ can be shifted significantly
- Auger and HiRes data are suggesting
  - Large cross section for a proton dominated composition
  - Small cross section for a iron dominated composition
  - or: intermediate mass, mixed composition

Results for $\langle X_{\max} \rangle$



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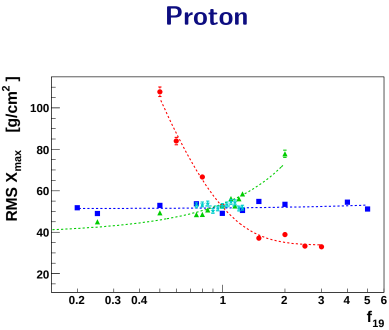
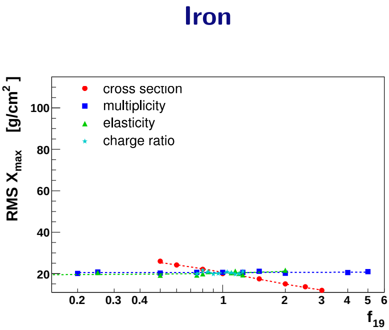
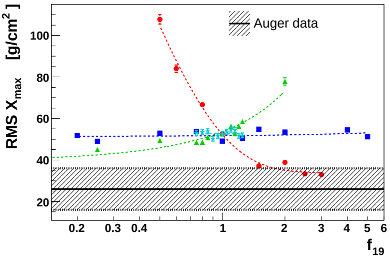
Results for RMS(X_{max})



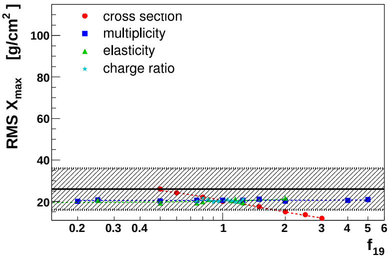


- RMS(X_{max}) mostly impacted by cross section, and elasticity
- Iron induced showers very robust
- Auger data only marginally compatible with protons in a high cross section scenario

Proton



Iron



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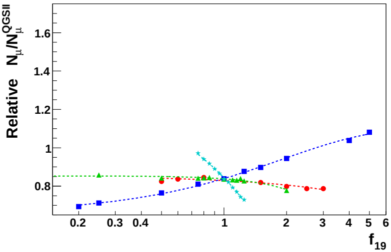
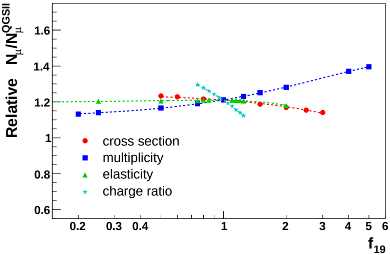
Results for Muon Numbers

Proton



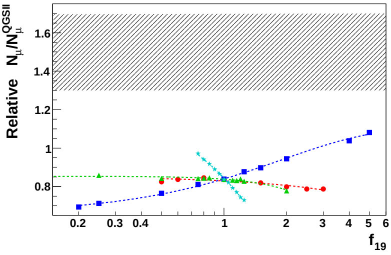
Iron



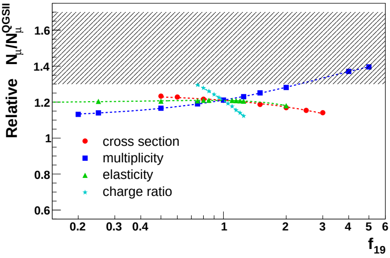
- Multiplicity and Pion charge ratio are shifting model predictions
- Auger muon data incompatible with proton scenario
- Even for iron primaries: multiplicity must be high and pion-charge-ratio small

Results for Muon Numbers

Proton



Iron



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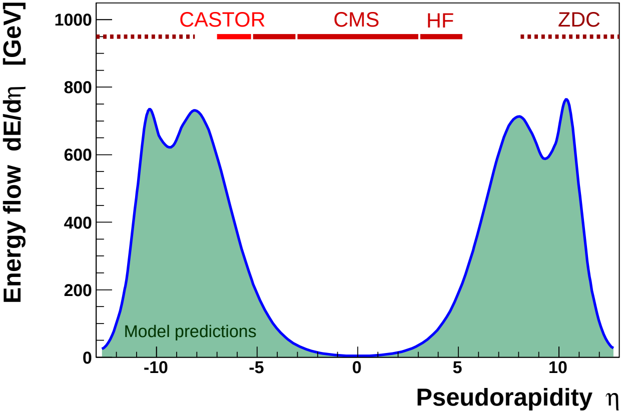
Caution: Definition of Muon number is not identical, e.g.:

Auger measures at 1000 m, Simulations give total muon number

Potential Impact of LHC on Interpretation of EAS Data

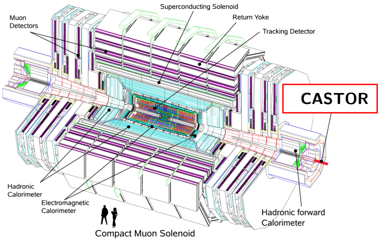
At the example of a precise measurement of the elasticity

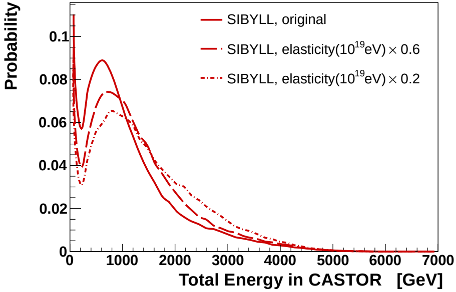
Forward Detectors

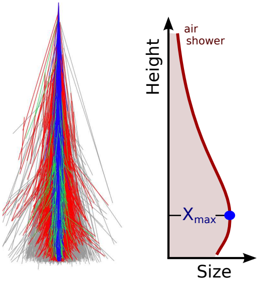


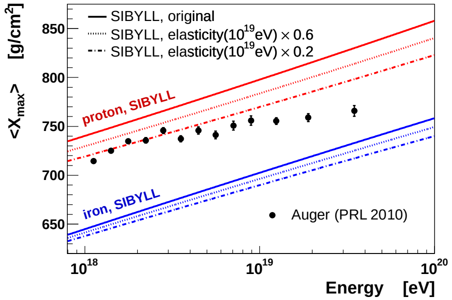
⇒ Crucial for air showers is particle production in **forward direction**!

Relevance of CASTOR for Cosmic Ray Interpretation

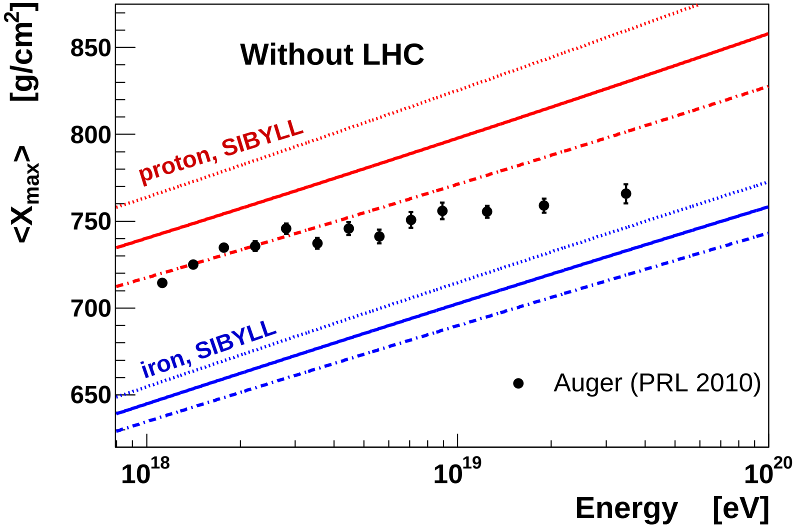








Impact of Elasticity / Leading Particles



- Precise measurement of elasticity at 300 GeV
- Extrapolation uncertainty grows by 10 % per decade in energy

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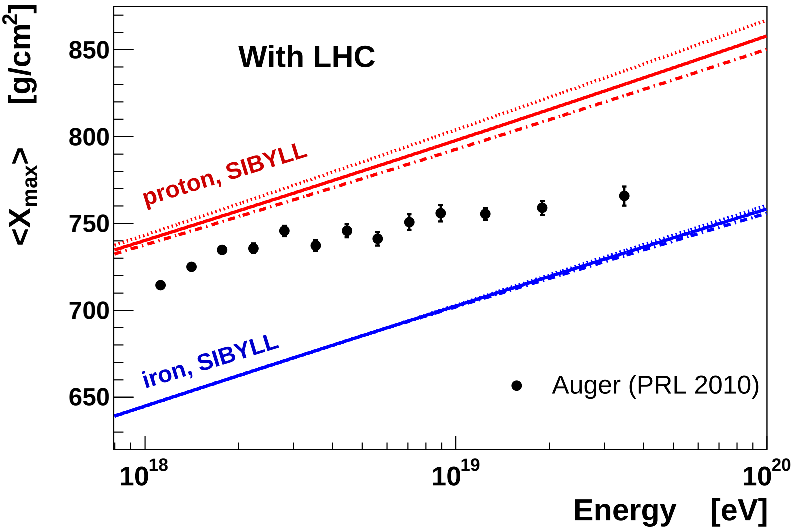


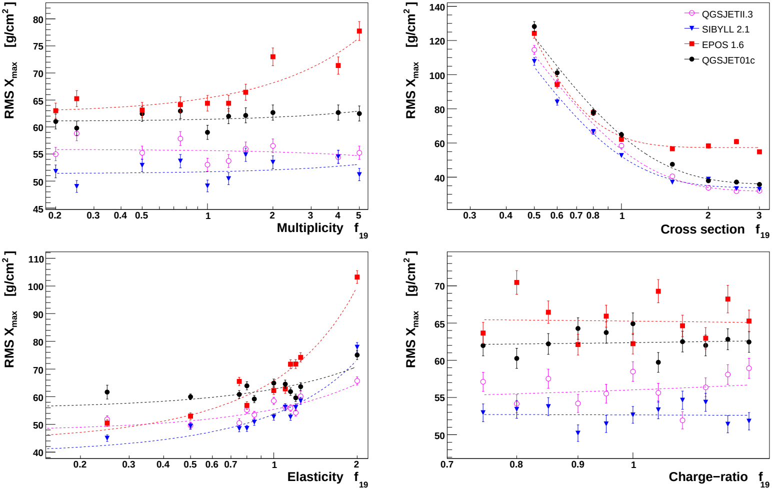
- Precise measurement of elasticity at 14 TeV
- Extrapolation uncertainty grows by 10 % per decade in energy

Summary

- High energy models are not sampling the full range of existing uncertainties
- Models need tuning to data as close to the phase space relevant in air showers as possible
- Interaction characteristics has impact on air shower observables on the same order of magnitude as as primary mass composition
  - $\Rightarrow$ Almost impossible to "measure" mass composition from air shower observables in the moment
- LHC has the potential to bring significant improvements in analysing air shower data
- If cosmic ray mass composition is constrained
  $\Rightarrow$ Air shower data sensitive to interaction physics up to $\sim$ 300 TeV

Additional Slides

Model Dependence – RMS(X_{max})



Model Dependence – Muon Numbers