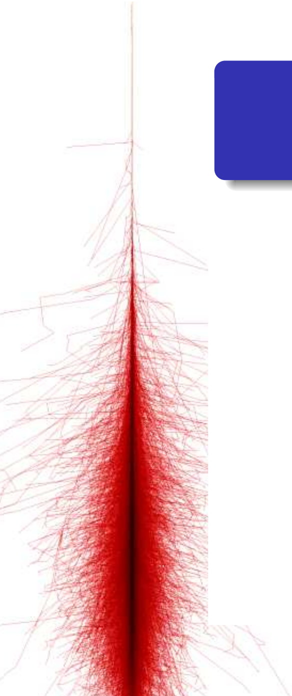


Hadronic Interactions in Extensive Air Showers

Ralf Ulrich

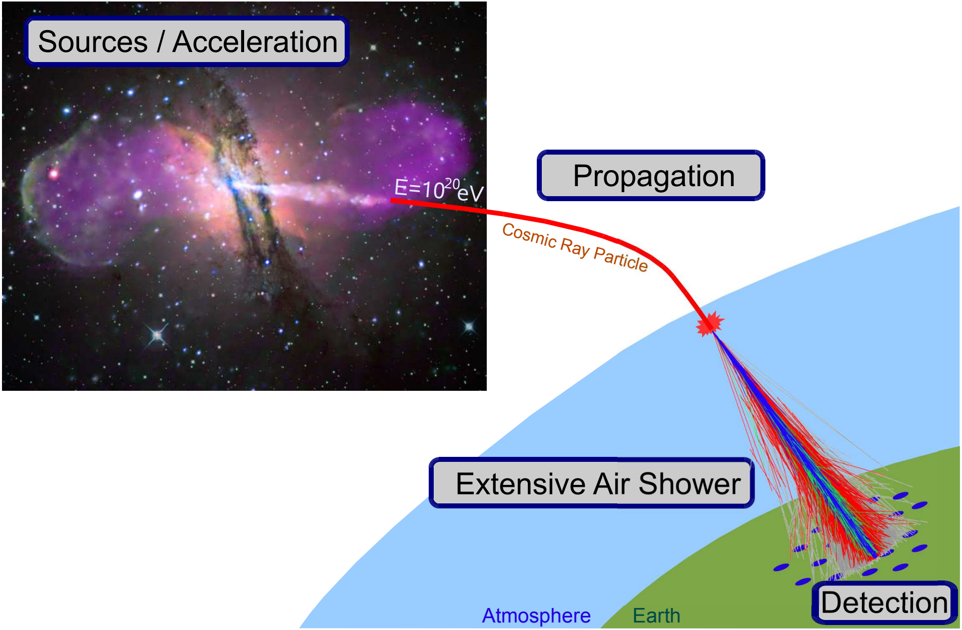
Pennsylvania State University

R. Engel, M. Unger

Karlsruhe Institute of Technology

WAPP 2010, Ooty, India

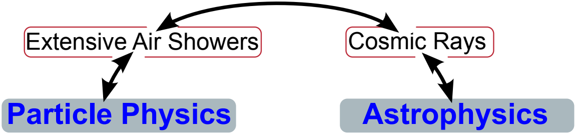
Cosmic Rays and Extensive Air Showers



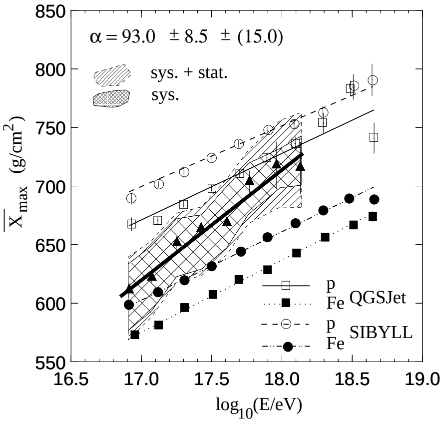
Overview

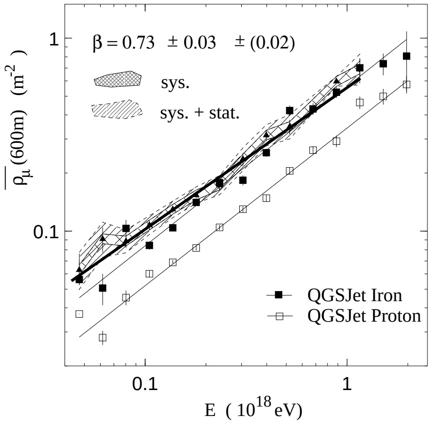
Our understanding of hadronic interactions at cosmic ray energies is incomplete

- The interpretation of air shower data is very model dependent
- Hadronic interaction features are not well constraint at cosmic ray energies
- Determine properties of hadronic interactions at ultra-high energies with cosmic ray data



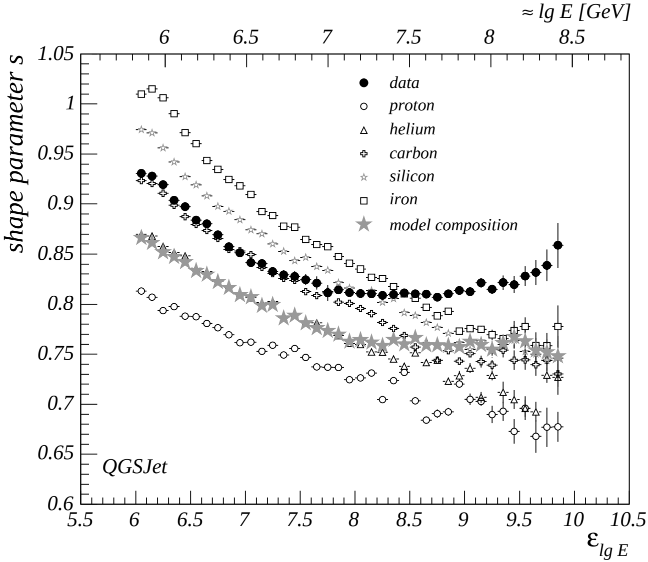
HiRes/MIA: Muons vs. X_{max}



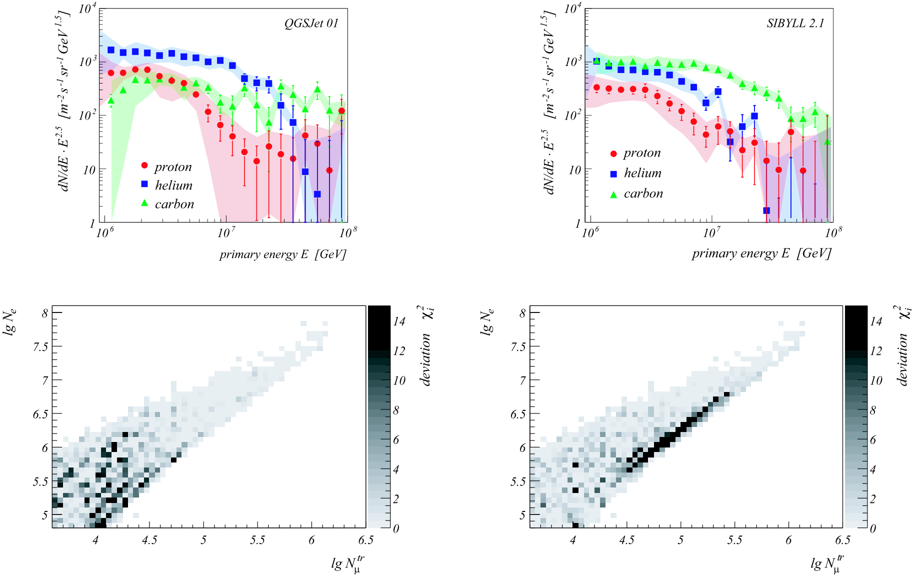


(HiRes/MIA, PRL:84 4276 (2000), astro-ph/9911144)

KASCADE - Lateral Particle Distribution

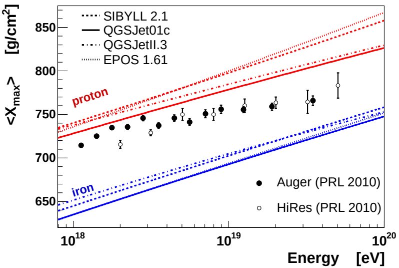


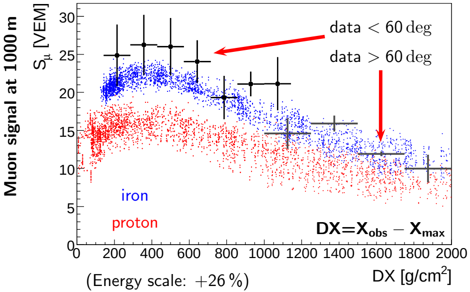
(KASCADE, APP:24 467 (2006), astro-ph/0510810)



(KASCADE, APP:24 1 (2005), astro-ph/0505413)

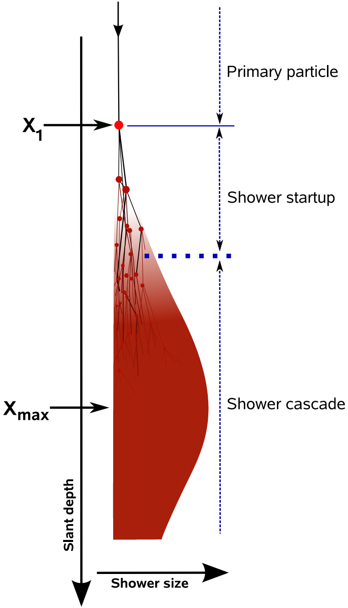
Pierre Auger Observatory: X_{max} vs. Muons





(Auger/HiRes X_{max}: PRL 2010, Muons: ICRC 2007, arXiv:0706.1921 [astro-ph])

Air Shower Development



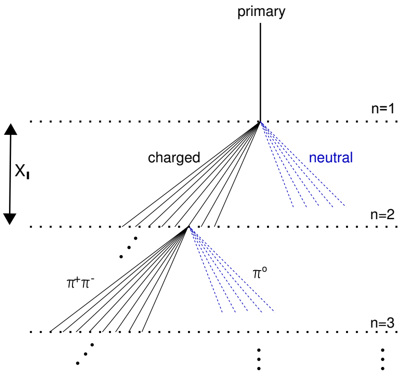
Typical observable EAS properties are:

X_{max}	Slant depth of shower maximum
N_e	Number of electrons at ground level
N_μ	Number of muons at ground level

For this work:

- N_e is the total number of electrons above 1 MeV at 1000 g/cm^2
- N_μ is the total number of muons above 1 GeV at 1000 g/cm^2

Extended Heitler Model



Shower maximum

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

Muon number at observation level

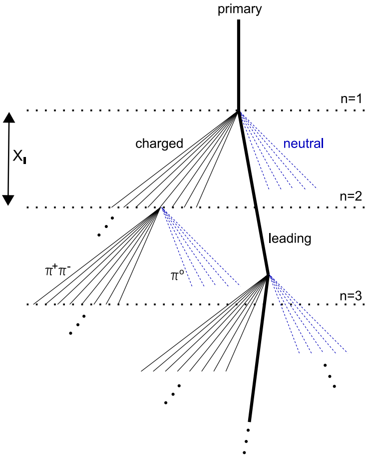
$$N_\mu = N_{\pi^\pm} = \left(\frac{E_0}{E_{\text{crit}}^{\text{I}}}\right)^\beta$$

where

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

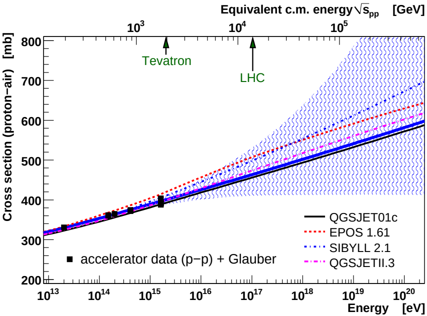
(J. Matthews, APP 22 (2005) 387)

Beyond the Heitler Model ...

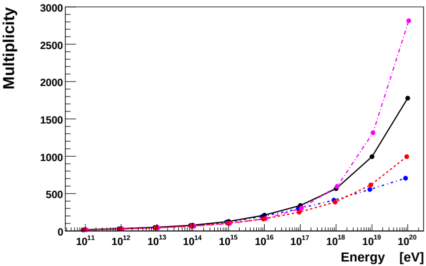


- Cross Section: λ
- Multiplicity: n_{mult}
- Elasticity: $k_{\mathrm{ela}} = E_{\mathrm{max}}/E_{\mathrm{tot}}$
- Charge ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$
- Nuclear primary: A

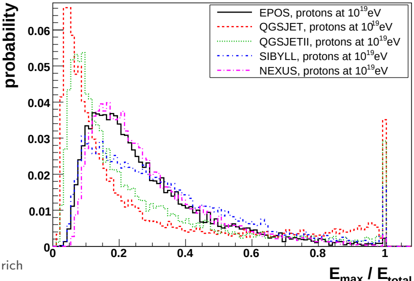
Cross Section



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

(R. Ulrich et al., submitted to PRD, arXiv 1010.4310 [hep-ph])

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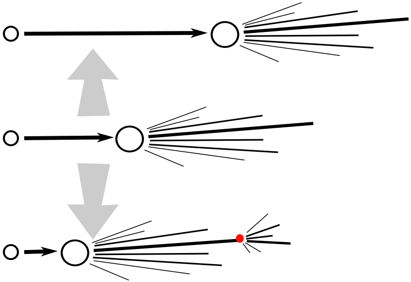
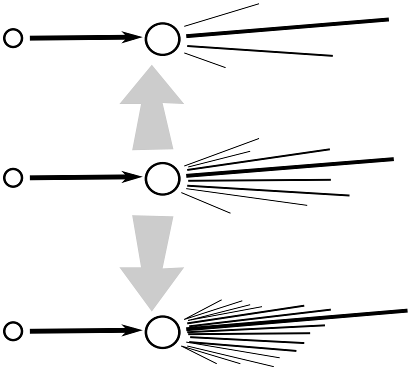
Modified Cross Section



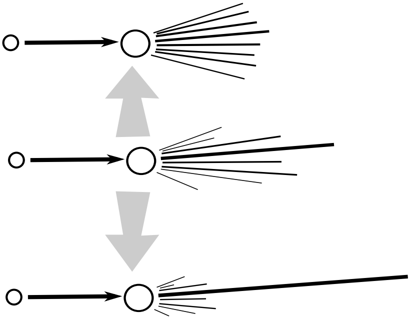
→ Equally scale all hadronic cross sections.

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

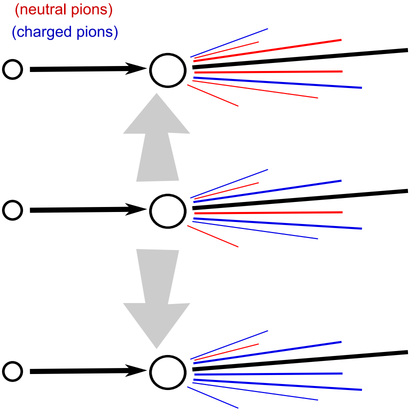
Modify Elasticity



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

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

Modified Charge-Ratio

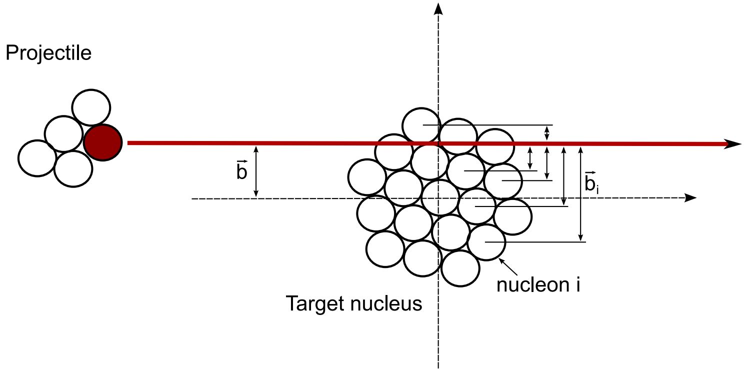


$$c = n_{\pi^0} / (n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$$

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

Primary Nuclei

⇒ Glauber Formalism

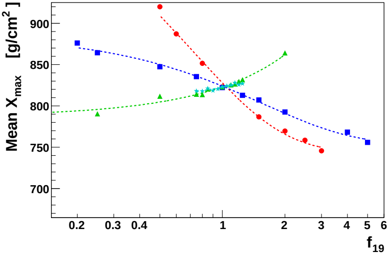


- Scale the fundamental nucleon-nucleon cross section
- Compute the nucleus-nucleus cross section with Glauber

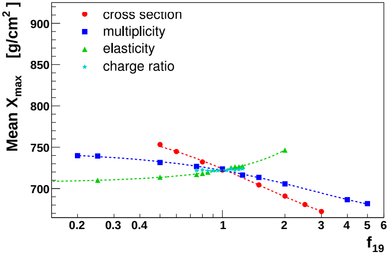
→ **SIBYLL**

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

Proton



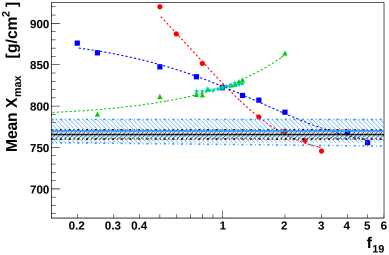
Iron



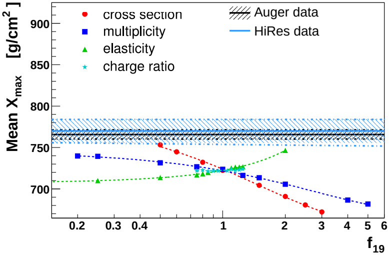
- $\langle X_{\max} \rangle$ can be shifted significantly
- Data are suggesting
  - Intermediate mass, mixed composition, or:
  - Large cross section for a proton dominated composition
  - Small cross section for a iron dominated composition

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

Proton



Iron



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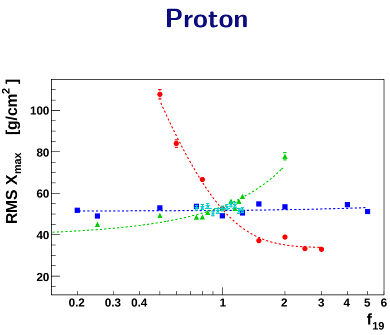
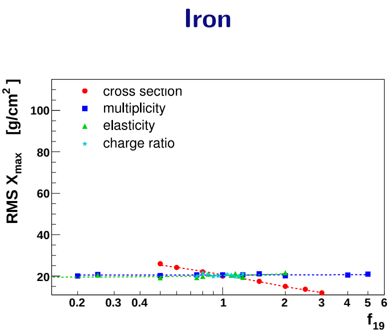
Results for RMS(X_{max})

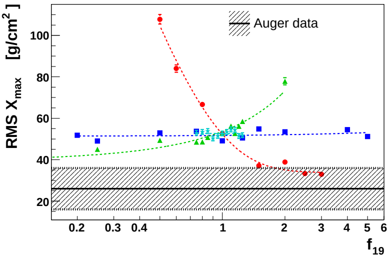




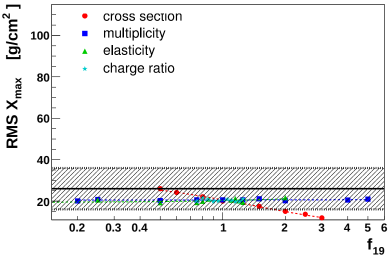
- RMS(X_{max}) mostly impacted by cross section, and elasticity
- Iron induced showers very robust
- Auger data only marginally compatible with protons in a high cross section scenario

Results for RMS($X_{\max}$)

Proton



Iron



- RMS($X_{\max}$) mostly impacted by cross section, and elasticity
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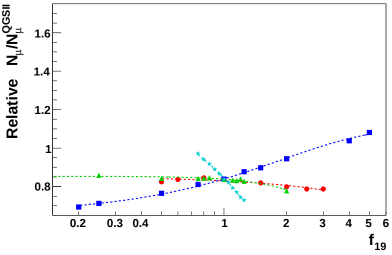
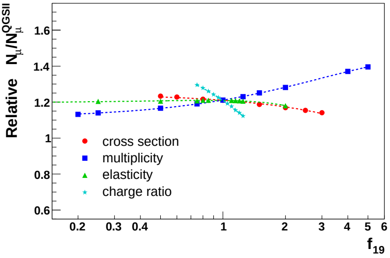
Results for Muon Numbers

Proton

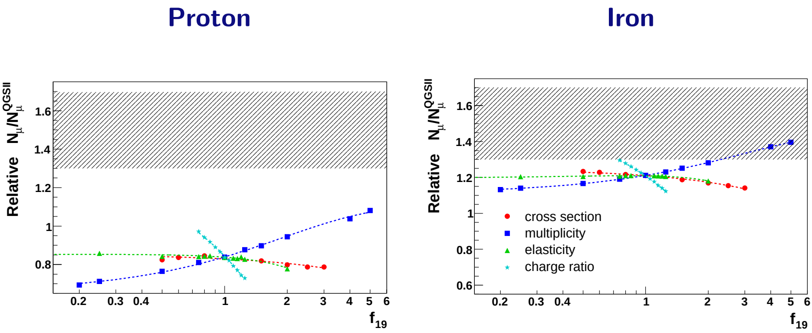


Iron



- 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



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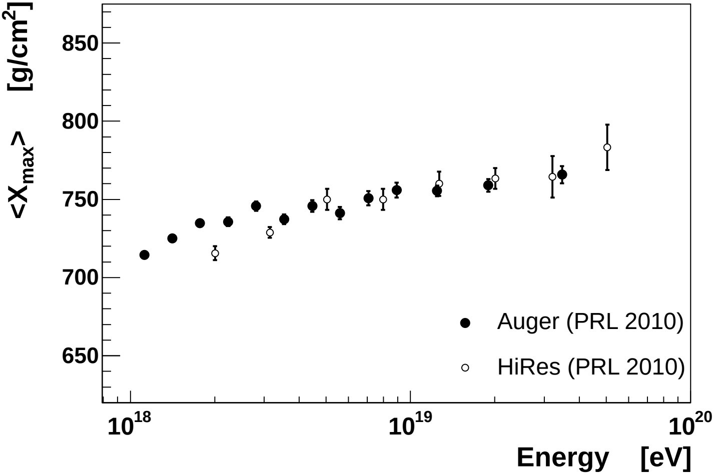
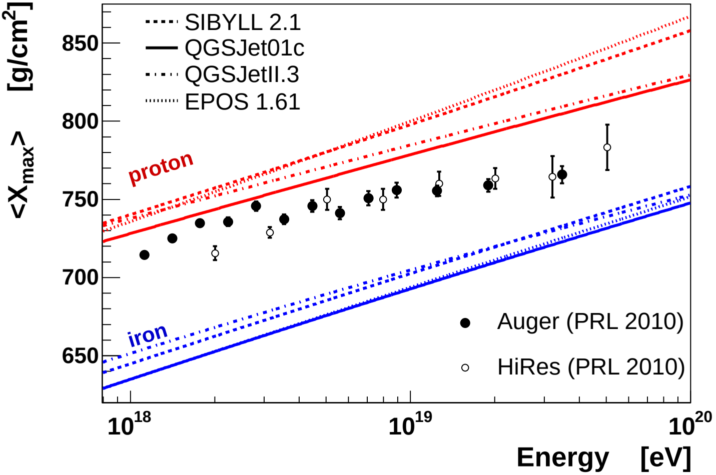
Caution: Definition of Muon number is not identical, e.g.:

Auger measures at 1000 m, Simulations give total muon number

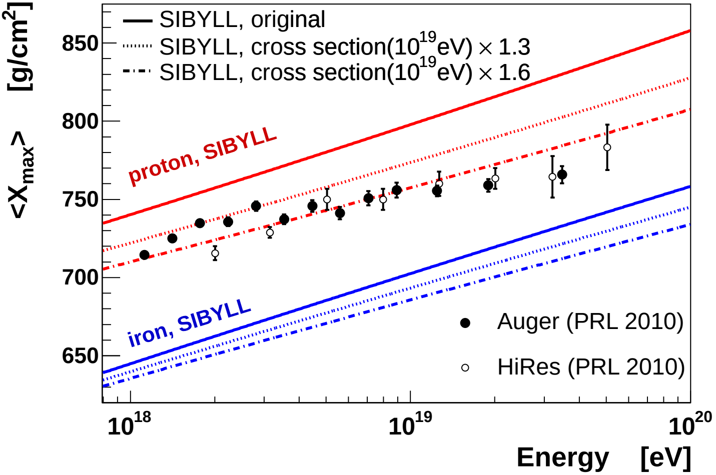


<Xmax>   [g/cm2]
850
800
750
700
650
10^18
10^19
10^20
Energy   [eV]
Auger (PRL 2010)
HiRes (PRL 2010)



SIBYLL 2.1
QGSJet01c
QGSJetII.3
EPOS 1.61
proton
iron
Auger (PRL 2010)
HiRes (PRL 2010)
<Xmax> [g/cm2]
850
800
750
700
650
10^18
10^19
10^20
Energy [eV]

Interpretation of Cosmic Ray Data

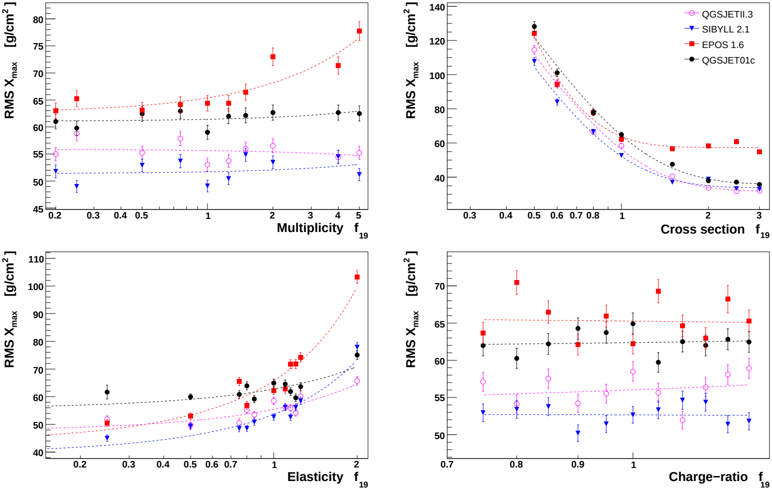


Summary

- 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
- If cosmic ray mass composition is constrained
  $\Rightarrow$ Air shower data sensitive to interaction physics up to $\sim 300\,\text{TeV}$

Additional Slides

Model Dependence – RMS(X_{max})



Model Dependence – Muon Numbers