Hadronic Cross-Sections in UHECR Air Showers and Accelerator Measurements

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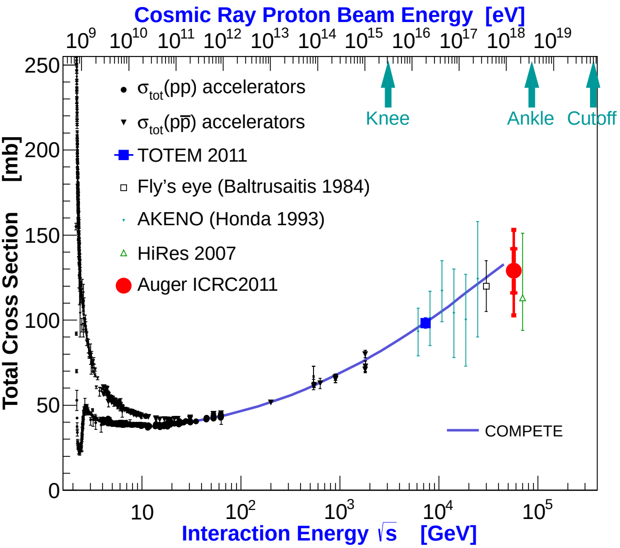
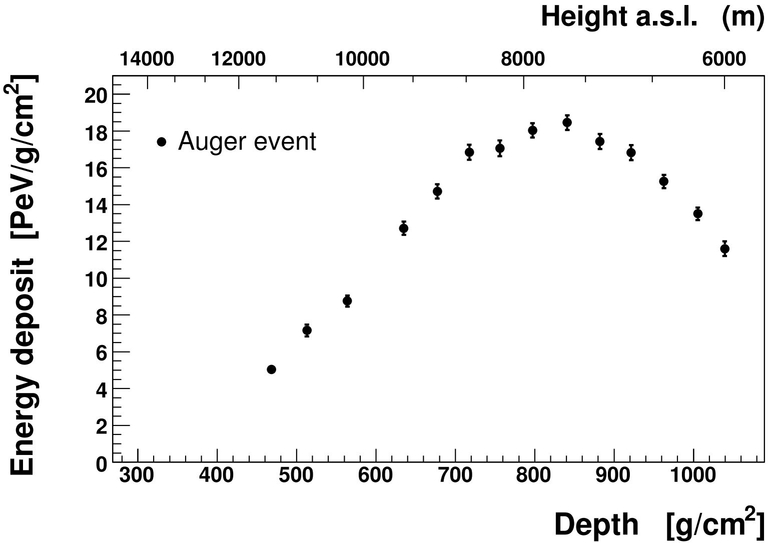
Vulcano Worshop 2014

Hadronic Cross-Sections, Overview



- Cross-Sections from UHECR Data
- Relation to accelerator measurements
- Glauber model plus extensions
- Accelerator input for model improvements
- Extrapolations and Uncertainties

Individual Event, Auger Observatory (10^{19} eV)



Longitudinal shower development, $E_0 \approx 10^{19}$ eV

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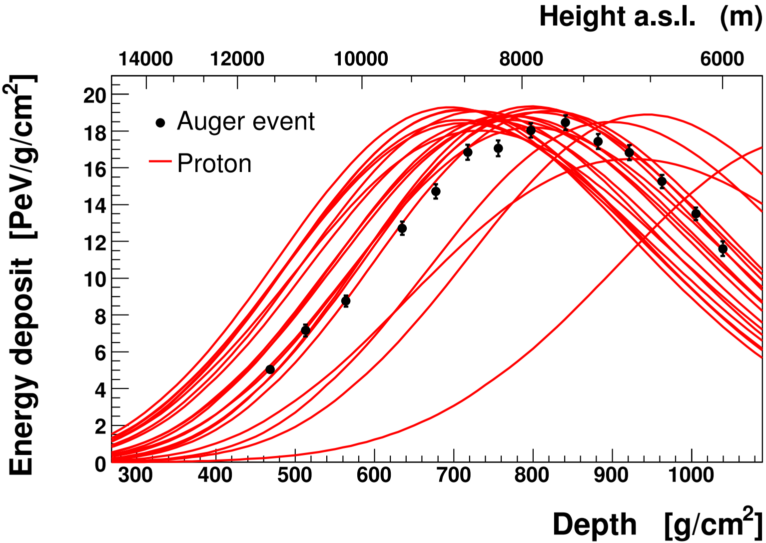

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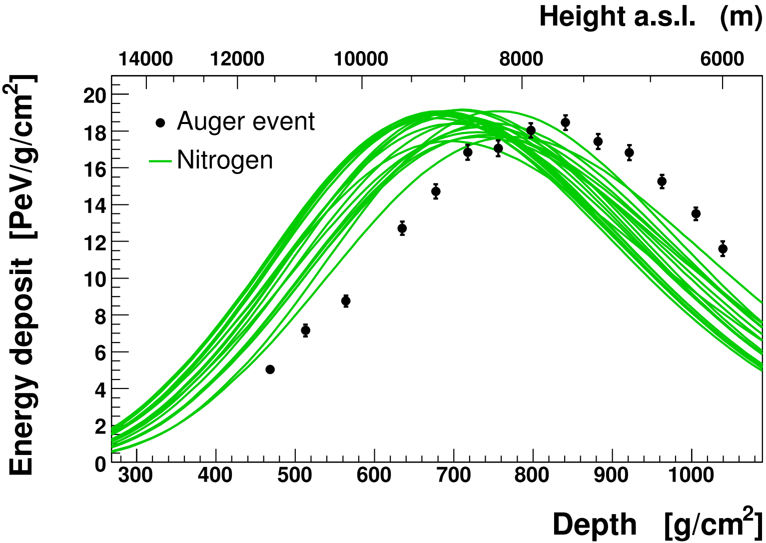

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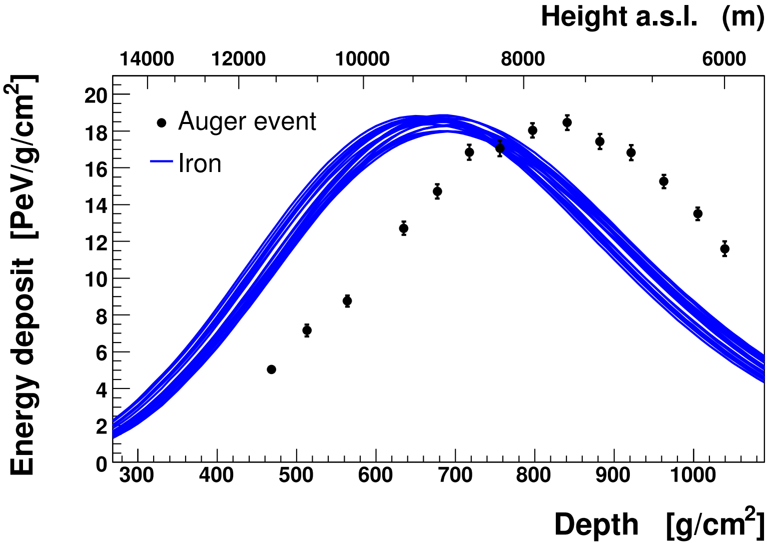

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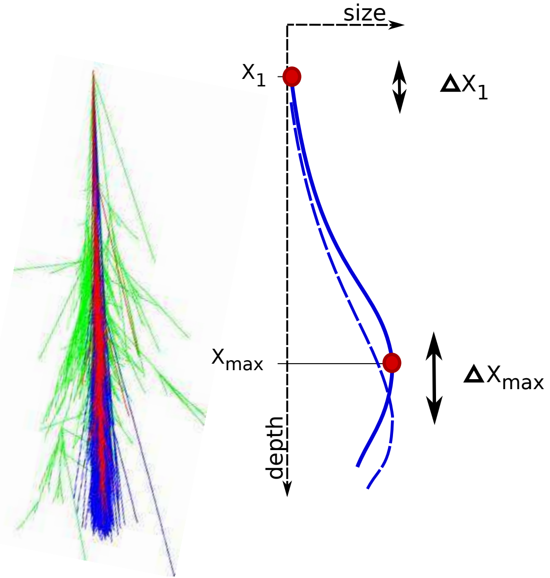


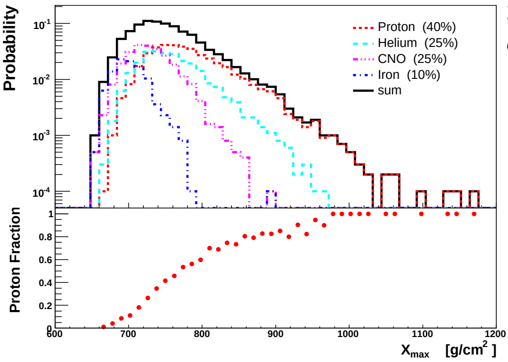
$$\frac{\mathrm{d}p}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}}\,\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}$$

$$\mathrm{RMS}(X_1) = \lambda_{\mathrm{int}}$$

$$\sigma_{\mathrm{int}} = \frac{<m_{\mathrm{air}}>}{\lambda_{\mathrm{int}}}$$

Difficulties:

- mass composition
- fluctuations in shower development $\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{\mathrm{max}} - X_1)$
  $\Rightarrow$ model needed for correction

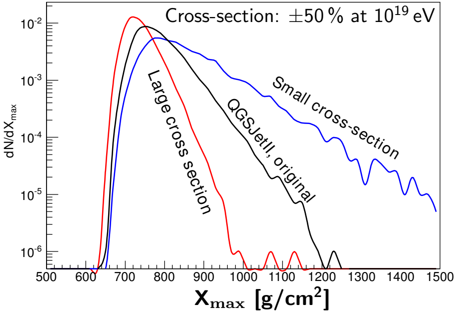


Select deeply penetrating showers to enhance proton fraction

$\Rightarrow$ Tail of X_{max}–Distribution

Ellsworth et al. PRD 1982
Baltrusaitis et al. PRL 1984

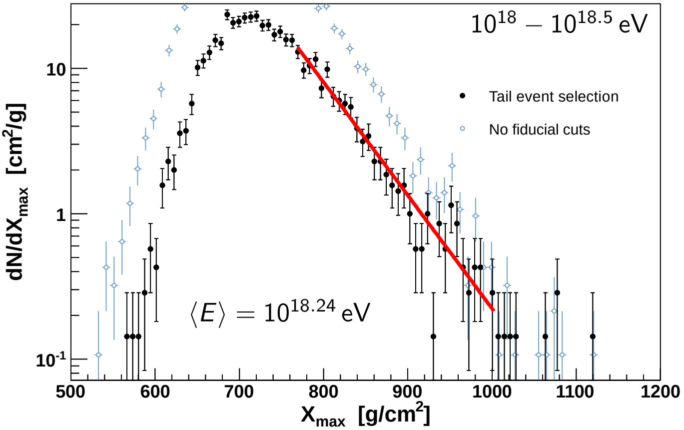
$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$



Simulation for proton showers with different cross sections: very good sensitivity of tail of distribution

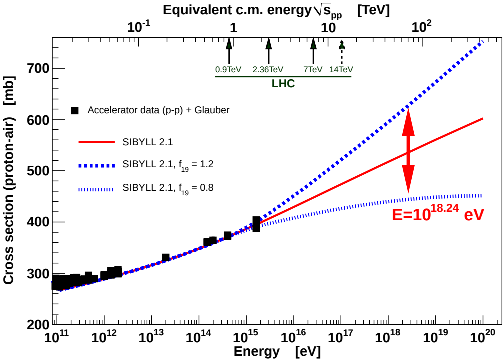
Pierre Auger Collaboration, CERN February 2012

Measurement of Λ_η



$$\Lambda_\eta = [55.8 \pm 2.3_{\text{stat}} \pm 1.6_{\text{sys}}]\, \text{g/cm}^2$$

Unbinned likelihood analysis, 3082 events

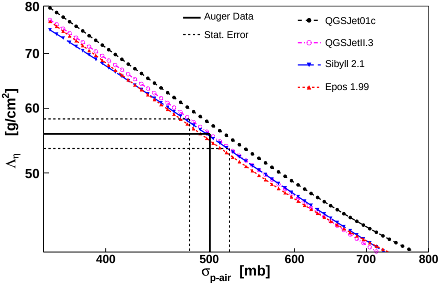


$$f(E,\ f_{19}) = 1 + (f_{19} - 1)\ F(E)$$

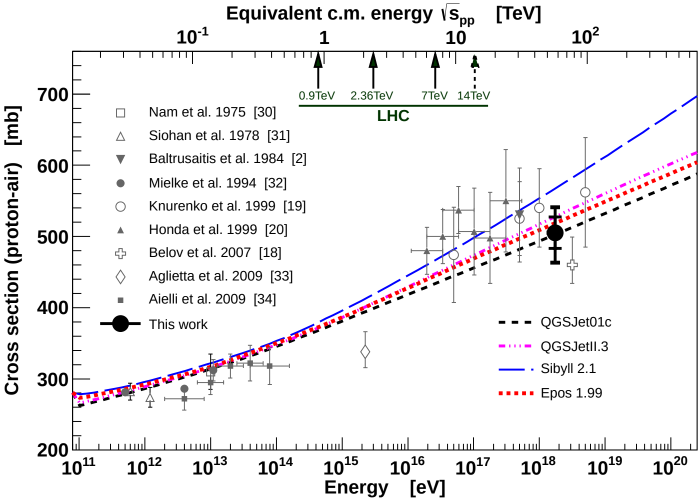
$$F(E) = \frac{\lg\left(E/10^{15}\,\mathrm{eV}\right)}{\lg\left(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV}\right)}$$

Simulations with f_{19}:

- Consistent description of cross-section
- No discontinuities in cross-section predictions

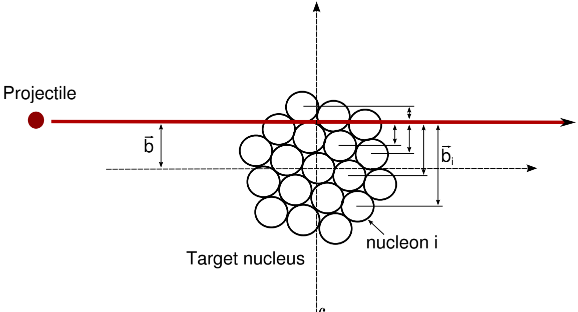


Proton-Air Cross-Section Summary



$$\sigma_{\text{p-air}} = \left[505 \pm 22_{\text{stat}} \; (^{+28}_{-36})_{\text{sys}} \right] \text{ mb}$$

Glauber Calculation



$$\sigma_{hA}^{\mathrm{tot}} = 2\Re e \int \Gamma_{hA}(\vec{b}) d^2 b$$

$$\sigma_{hA}^{\mathrm{ela}} = \int \left| \Gamma_{hA}(\vec{b}) \right|^2 d^2 b$$

where $\Gamma_{hA}(\vec{b})$ is the impact parameter profile folded with the nucleus wave function. Correlations typically not taken into account. Only shells.

R. Glauber, Phys. Rev. **100**, 242 (1955).

R. Glauber and G. Matthiae, Nucl. Phys. B **21**, 135 (1970).

Multiple Scattering:

$$\Gamma_{hA}(\vec{b}, \vec{s}_1 \dots \vec{s}_A) = 1 - \exp\left\{ i \sum_{j=1}^{A} \chi_j(\vec{b} - \vec{s}_j) \right\} = 1 - \prod_{j=1}^{A} \left[1 - \Gamma_{hN}(\vec{b} - \vec{s}_j) \right]$$

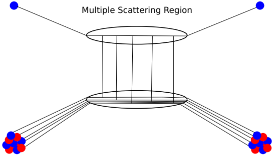
with the projectile-nucleon amplitude:

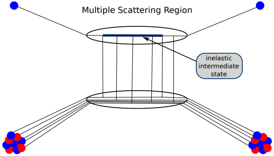
$$\Gamma_{hN}(\vec{b}) = (1 - i\rho_{hN}) \frac{\sigma_{hN}^{\mathrm{tot}}}{4\pi B_{hN}^{\mathrm{el}}} \exp\left\{ -\frac{\vec{b}^2}{2 B_{hN}^{\mathrm{el}}} \right\}$$

Integrating over all all possible nucleus configurations:

$$\Gamma_{hA}(\vec{b}) = \int \Psi_i^*(r_1, \dots, r_A) \Gamma_{hA}(\vec{b}, \vec{s}_1 \dots \vec{s}_A) \Psi_i(r_1, \dots, r_A) \prod_{j=1}^{A} \mathrm{d}^3 \vec{r}_j$$

- **Inelastic Screening, Diffraction**





$$\Gamma_{pp\to pX}(s,\vec{b}) = \lambda(s)\Gamma_{pp\to pp}(s,\vec{b})$$

$$\lambda^2(s) = \frac{\sigma_{pp}^{\mathrm{SD}}(s, M^2_{\mathrm{D,max}})}{2\sigma_{pp}^{\mathrm{ela}}(s)}$$

Implementation (Good-Walker)

Two-Channel Model:

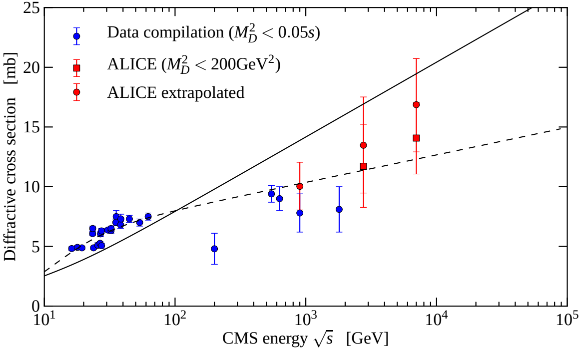
$$|p\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |p^\star\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \hat{\Gamma}_{pp} = \begin{pmatrix} 1 & \lambda \\ \lambda & 1 \end{pmatrix} \Gamma_{pp}$$

Elastic Cross-Section:

$$\begin{aligned} \Gamma_{hA}(\vec{b}, \vec{s}_1 \ldots \vec{s}_A) =& \langle p|\hat{\Gamma}_{hA}(\vec{b}, \vec{s}_1 \ldots \vec{s}_A)|p\rangle = 1 - \langle p| \prod_{j=1}^{A} \left[1 - \hat{\Gamma}_{hN}(\vec{b} - \vec{s}_j)\right] |p\rangle \\ =& 1 - \frac{1}{2} \prod_{j=1}^{A} \left[1 - (1+\lambda)\Gamma_{hN}(\vec{b} - \vec{s}_j)\right] \\ & - \frac{1}{2} \prod_{j=1}^{A} \left[1 - (1-\lambda)\Gamma_{hN}(\vec{b} - \vec{s}_j)\right] \end{aligned}$$

(Inelastic, quasi-elastic (and diffractive) cross-sections calculated individually)

Measurements of Diffraction



solid line:

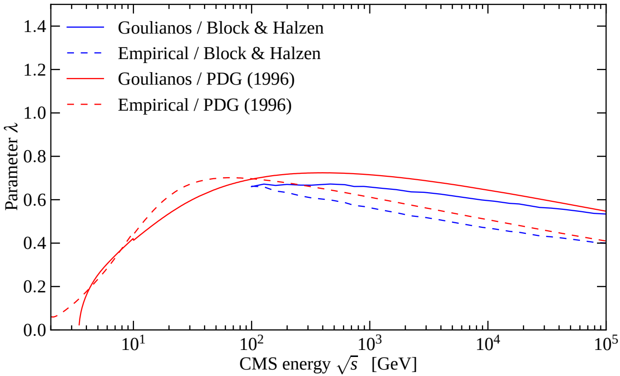
$$\sigma_{\rm SD}(s, M^2_{\rm D,max}) = 0.68(1 + 36\,{\rm GeV}^2/s)\log\left[(0.6 + M^2_{\rm D,max}/(1.5\,{\rm GeV}^2))\right]\ {\rm mb}$$

Goulianos, 1995

dashed line:

empirical fit

Problem: $\sigma_{\rm SD}$ depends on $M^2_{\rm D,max}$-cut (can be re-normalized)



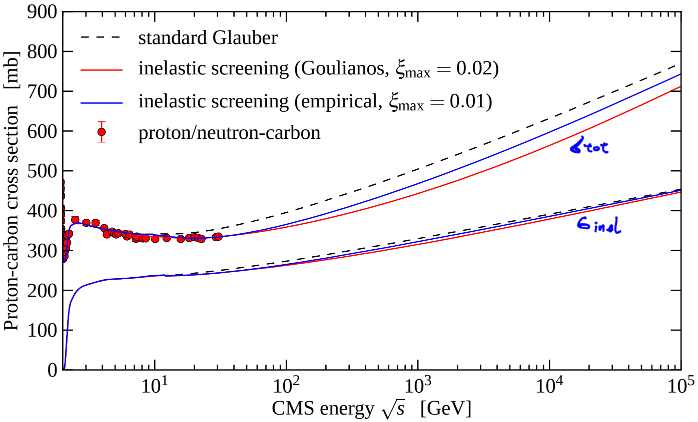
At 57 TeV (Pierre Auger Analysis):

$\lambda = 0.5 \pm 0.15$

and

$\xi_{\max} = \frac{M_{\mathrm{D}}^2}{s} = 0.01 - 0.02$

Impact and Test on pC Data

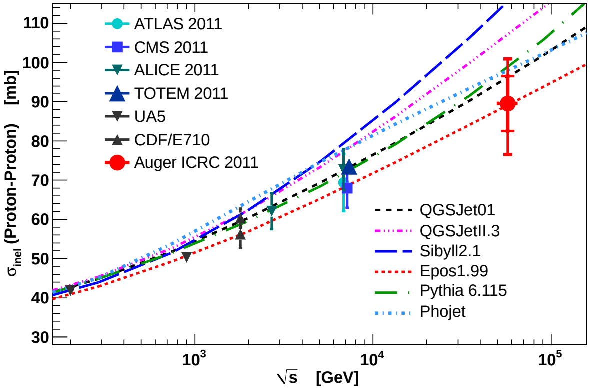


Total and production cross sections of proton-carbon interactions

Production cross-section hardly affected

Inelastic Proton-Proton Cross-Section

Extended Glauber conversion + propagation of parameter uncertainties



$$\sigma_{pp}^{inel} = \left[92 \pm 7(\text{stat}) \,^{+9}_{-11}(\text{sys}) \pm 7(\text{Glauber}) \right] \text{mb}$$

$$(\sigma_{pp}^{inel} = 90\,\text{mb for } \lambda = 0)$$

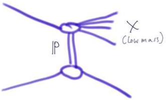
$$\sqrt{s_{pp}} = [57 \pm 0.3_{\text{stat}} \pm 6_{\text{sys}}] \text{ TeV}$$

Cross-section Decomposition

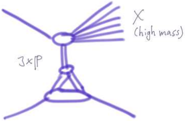
- Very distinct event final states exists in QCD collisions
- The most relevant in the context of air showers are:

Inelastic

Low Mass Diffraction

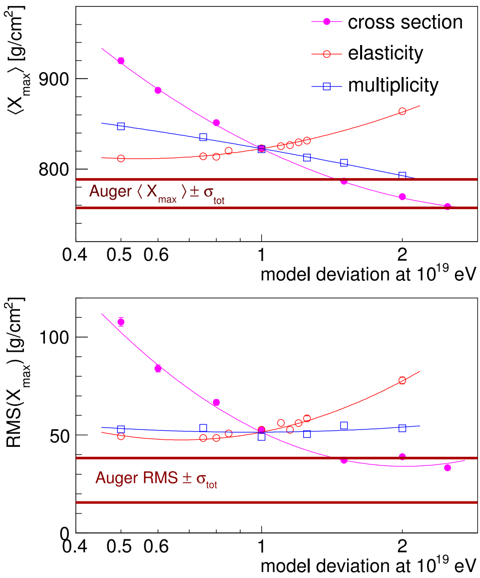


High Mass Diffraction



- These are crucial to understand air-shower physics:
  - They all contribute to particle production, thus, energy dissipation
  - Diffraction can be up to 30 % of inelastic
  - Diffraction is characterized by high elasticity and low multiplicity final states
  - Diffraction contributes to inelastic screening

Impact of Elasticity and Multiplicity

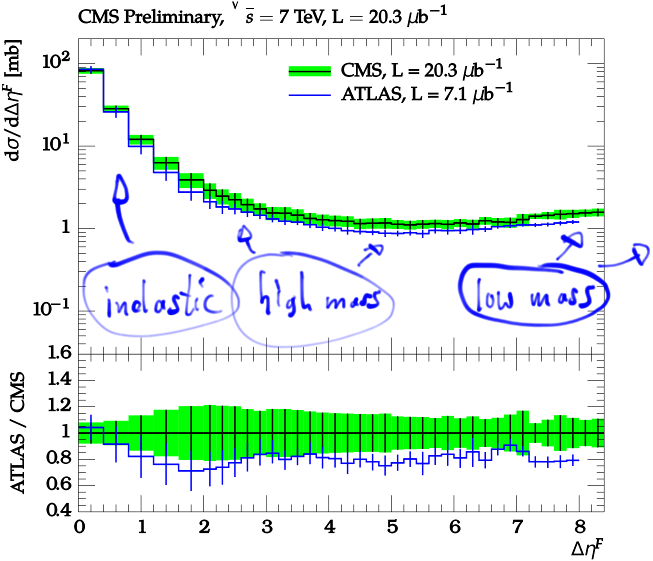


⇒ Model features are modified by the scale factor f_{19} at 10^{19}eV.

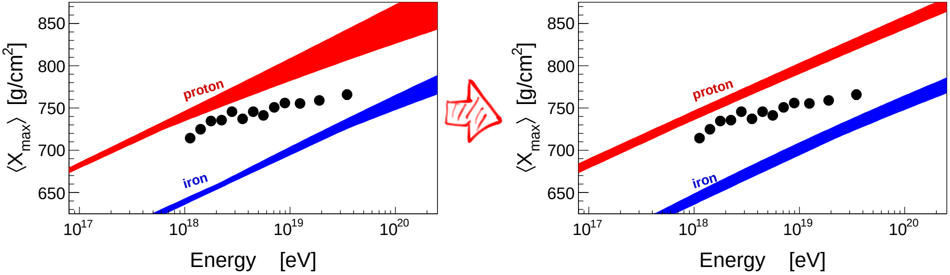
⇒ Here: proton primaries at $10^{19.5}$eV compared to Auger data.

- Model predictions can be modified slightly
- Possibility for significant composition changes is limited

Rapidity gap Cross-Section at LHC



EPOS 1.99	→	**EPOS LHC**
QGSJetII.3	→	**QGSJetII.4**

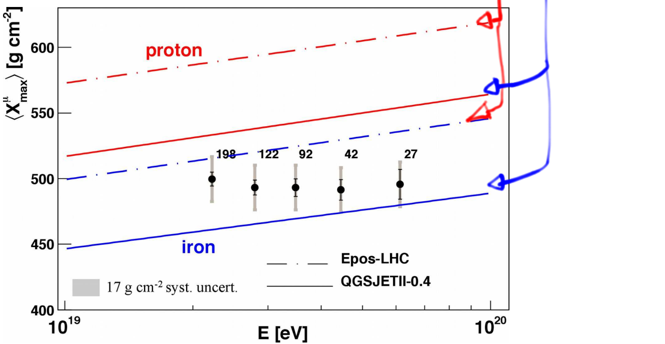


Caveats / Potential:

- Only central rapidities $|\eta| < 2$
- Not highest possible center-of-mass energies
- Mainly proton-proton data

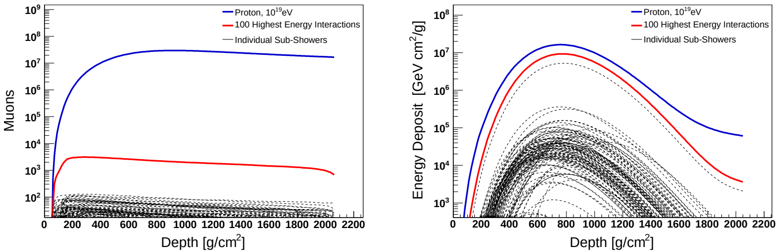
EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**



- General model performance after first LHC tuning better, but not yet sufficient
- More aspects and more data needs to be taken into account
- Partly description of UHECR became worse!

Sensitivity of Air Showers to Interactions



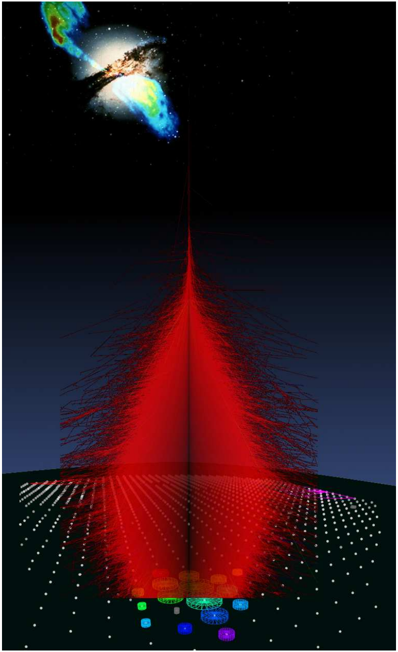
- Global shower properties and the **shower maximum** are sensitive to the highest energy interactions
- Muons in air showers are sensitive to the hadronic cascade over all energies
  - $\rightarrow$ Large problem in predicting the overall muon number is small problem on the level of individual interactions

Acceptance and Extrapolations of Accelerator Experiments

⇒ **Reduce extrapolation uncertainties in interaction models**

- **Center-of-mass-energy**
  LHC, Central measurements plus **forward region**
- **Phase-space**
  - **Nuclear Effects**
    LHC: compare p-p, Pb-p and e.g. **p-O**
  - **high-x_F**
    Fixed Target Experiments at SPS, but also with **LHC beam**

Summary



UHECR data contains information on hadronic cross sections !

- Well beyond LHC energies: $E_{\mathrm{cr}} = 10^{18.24}$ eV, $\sqrt{s_{pp}} = 57$ TeV
- Very high quality data + advanced analysis techniques

- Nuclear Effects and Diffraction are needed to compare proton-air to proton-proton data
- Good-Walker and extended Glauber Model

- Recent LHC data as input
- Impact on Air-Shower predictions
- Need: high-energy, forward and light nuclei