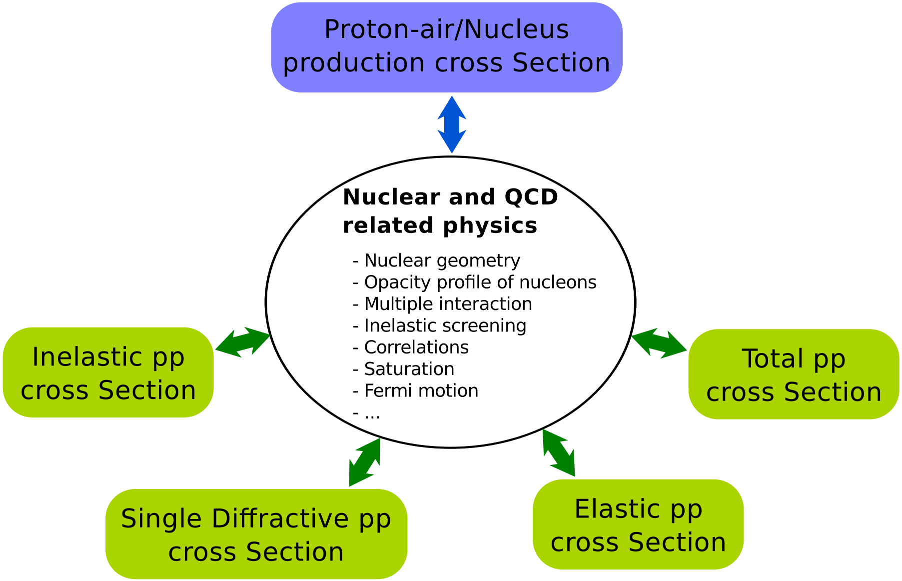
Karlsruhe Institute of Technology

Glauber Model Tests and Extrapolations in the Context of Cosmic-Rays

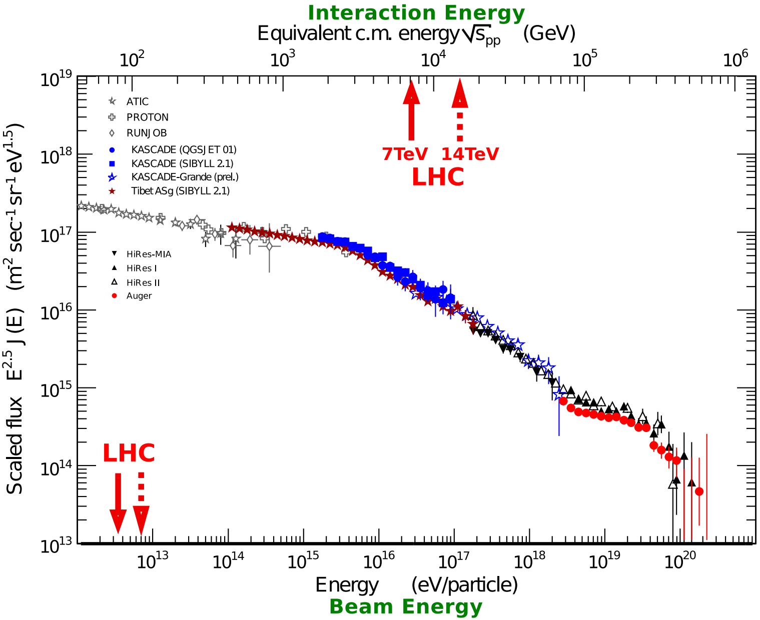
R. Ulrich and R. Engel

Karlsruhe Institute of Technology, Germany

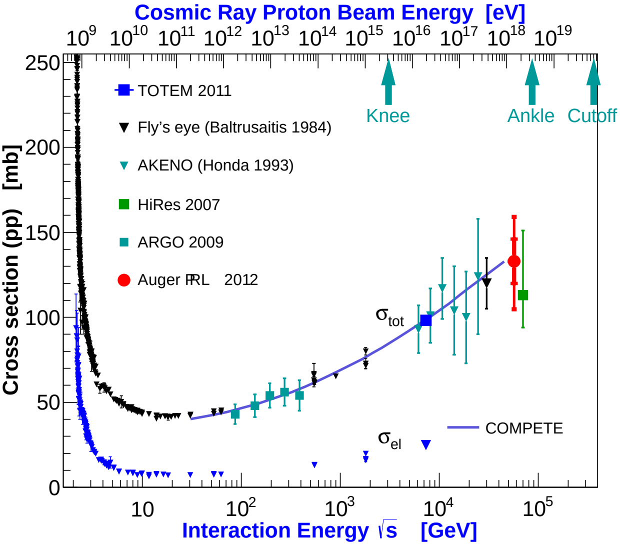
Workshop CERN, February 2013


Proton-air/Nucleus production cross Section
Nuclear and QCD related physics
- Nuclear geometry
- Opacity profile of nucleons
- Multiple interaction
- Inelastic screening
- Correlations
- Saturation
- Fermi motion
- ...
Inelastic pp cross Section
Total pp cross Section
Single Diffractive pp cross Section
Elastic pp cross Section

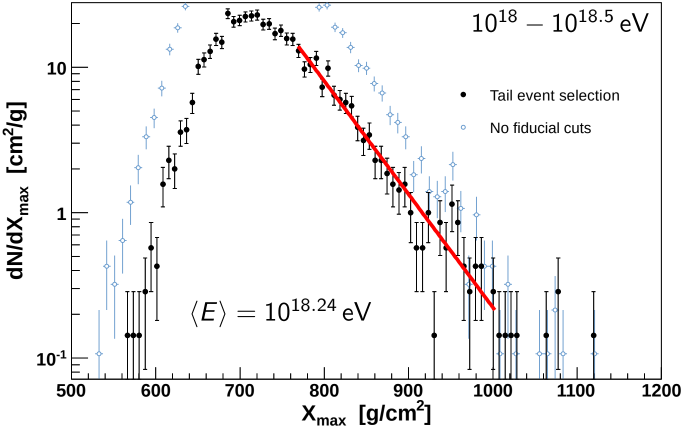
Energy Scales: Acceleration and Interactions



Hadronic Cross-Sections, Overview



Air Shower Fluctuations at the Pierre Auger Observatory



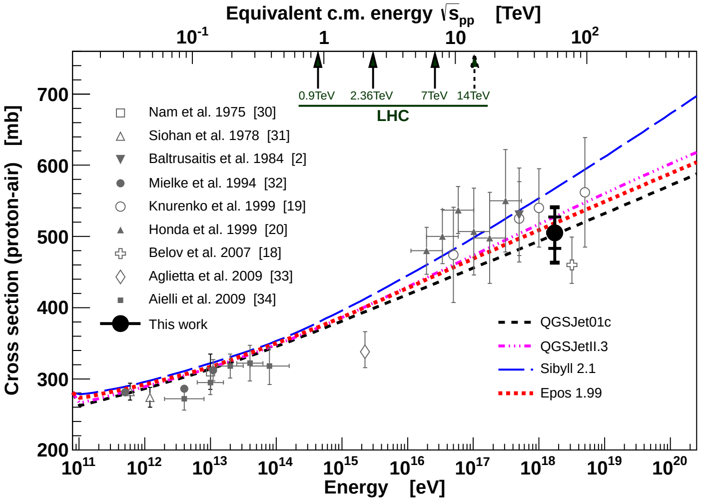
Phys.Rev.Lett. 109 (2012) 062002

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

$\sqrt{s} = 57$ TeV

Unbinned likelihood analysis, 3082 events

Proton-Air Cross-Section from Cosmic-Rays



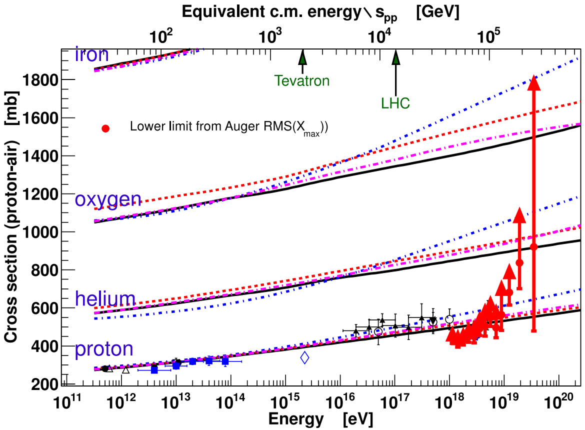
Phys.Rev.Lett. 109 (2012) 062002

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

Proton-Air Cross-Section Limits from RMS($X_{\max}$)

$$RMS(X_1) = \lambda_{\rm int} = \sqrt{RMS(X_{\max})^2 - RMS(\Delta X)^2} < RMS(X_{\max})$$

$$\sigma_{\rm int} > \langle m_{\rm air}\rangle / RMS(X_{\max})$$



Relation between Proton-Air and Proton-Proton Cross-Section

Challenges

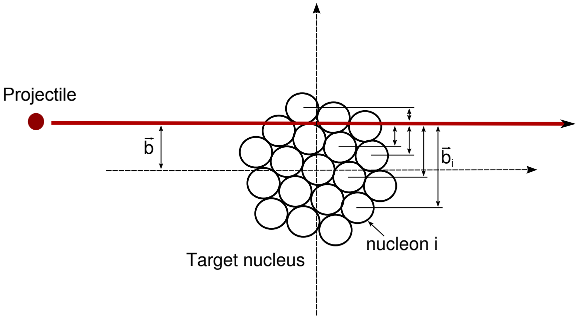
Nuclear and QCD related physics:

- **Nuclear geometry** (transverse size of nuclei)
- **Opacity profile of nucleons**
- **Multiple interactions**
- Inelastic screening
- Correlations
- Saturation
- Fermi motion
- ...

(roughly ordered by importance)

$\Rightarrow$ handled by extended Glauber model

Glauber Calculation



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

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

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

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

Glauber Approximation

Multiple Scattering in Nuclei:

$$\Gamma_{hA}(\vec{b}) = \int \psi_i^\star(\vec{r}_1 \ldots \vec{r}_A) \left\{ 1 - \prod_{j=1}^{A} \left[1 - \Gamma_{hN}(\vec{b} - \vec{s}_j) \right] \right\} \psi_i(\vec{r}_1 \ldots \vec{r}_A) \prod_{j=1}^{A} d^3 r_j$$

Neglecting correlations between the nucleons

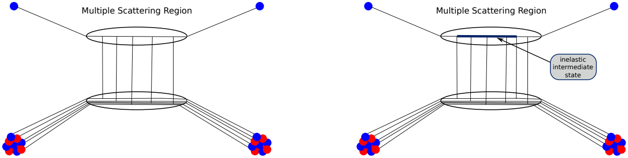
$$\psi_i^\star(\vec{r}_1 \ldots \vec{r}_A)\psi_i(\vec{r}_1 \ldots \vec{r}_A) = \prod_{j=1}^{A} \rho_j(\vec{r}_j)$$

Impact Parameter Space Amplitude:

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

Extension of Glauber

- **Inelastic Screening, Low-Mass Diffraction**



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

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

Good and Walker, Phys. Rev. 120 (1960) 1857
Kalmykov and Ostapchenko (QGSJet01), Phys. Atom. Nucl. 56 (1993) 346

This technique does not easily account for high mass diffraction.
See e.g. QGSJetII for the theoretical extension.

Implementation (Good-Walker)

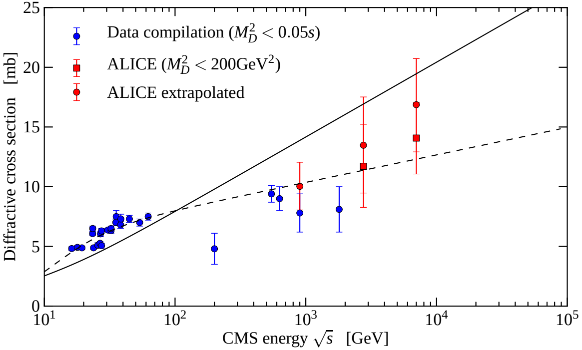
Two-Channel Model:

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

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)



solid line:

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

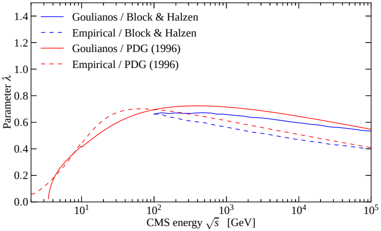
Goulianos, 1995

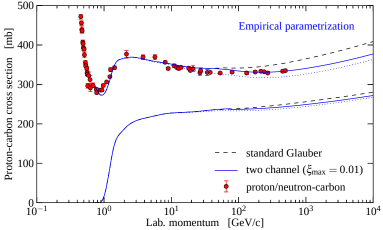
dashed line:

empirical fit

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

Inelastic Screening Parameter





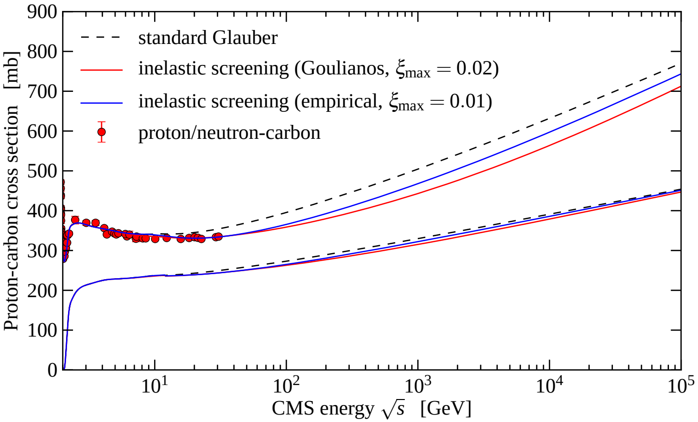
At 57 TeV (Pierre Auger Analysis):

$\lambda = 0.5 \pm 0.15$

and

$\xi_{\max} = \frac{M_D^2}{s} = 0.01 - 0.02$

Impact and Test on pC Data

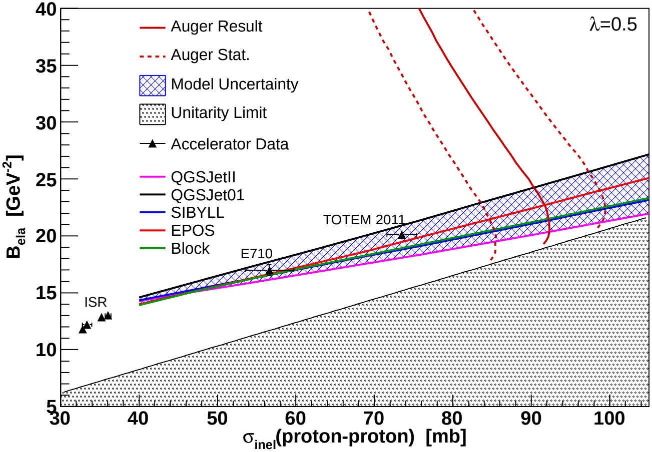


Total and production cross sections of proton-carbon interactions

Production cross-section hardly affected

Correlation of Cross Section and Elastic Slope Parameter

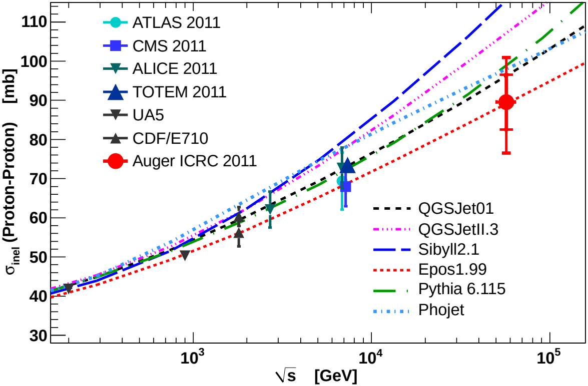
Glauber($\sigma_{pp}^{\mathrm{tot}}$, B_{el}, λ, ...) $\rightarrow$ $\sigma_{\mathrm{p-air}}$



Correlation very "steep" $\rightarrow$ small impact on resulting $\sigma_{\mathrm{pp}}^{\mathrm{inel}}$

Inelastic Proton-Proton Cross-Section

Extended Glauber conversion + propagation of parameter uncertainties



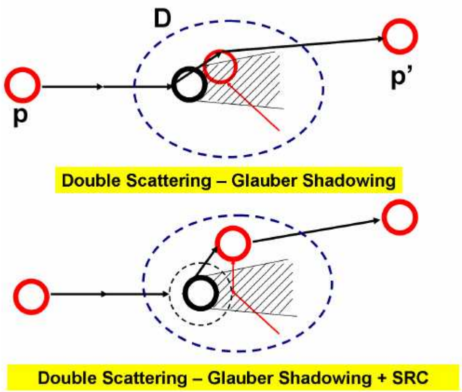
$$\boldsymbol{\sigma_{pp}^{inel}} = \left[\mathbf{92} \ \pm \mathbf{7}(\text{stat}) \ ^{+9}_{-11}(\text{sys}) \ \pm \mathbf{7}(\text{Glauber})\right] \ \mathbf{mb}$$

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

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

Nucleon Correlations and Short Range Correlations

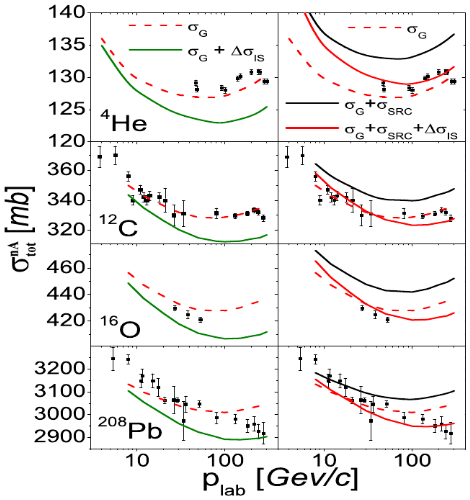
$$\sigma^{\mathrm{pD}}_{\mathrm{tot}} = \sigma^{\mathrm{pp}}_{\mathrm{tot}} + \sigma^{\mathrm{pn}}_{\mathrm{tot}} - \Delta\sigma_{\mathrm{shad}}$$



C. Ciofi

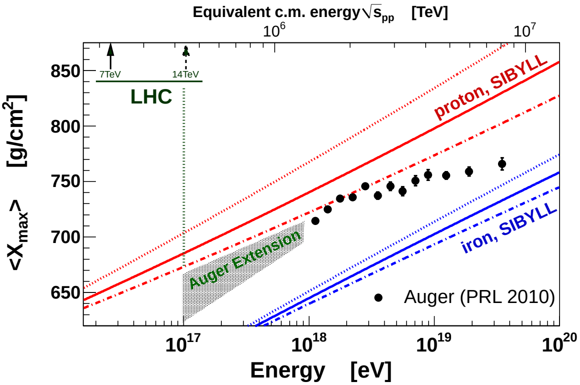
⇒ **Opposite effect with respect to inelastic screening**

Neutron-A scattering data:



M. Alvioli et al., Phys. Rev. C 78, 031601 (2008)

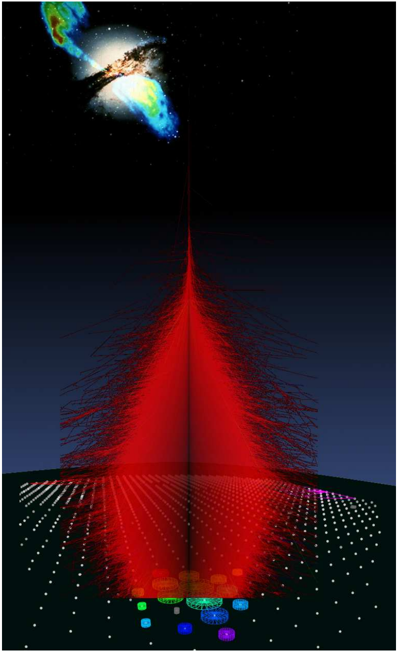
Outlook



Current Situation

- Auger: proton-air at $\sqrt{s_{NN}} = 57$ TeV
- LHC:
  - proton-proton at $\sqrt{s} = 7$ and 8 TeV
  - lead-lead at $\sqrt{s_{NN}} = 2.76$ TeV
  - proton-lead at $\sqrt{s_{NN}} = 5$ TeV

Summary



- Cosmic-ray interactions are at the highest accessible energies
- Primary cosmic-ray mass composition still not clear. But protons can be enriched for specific analyses.
- Nuclear effects are relevant
- Measurements at overlapping energies with LHC and cosmic-ray experiments are testing Glauber model
- So far no significant disagreement apparent
- New data will significantly increase sensitivity