Measurement of the Proton-Air Cross-Section with the Pierre Auger Observatory

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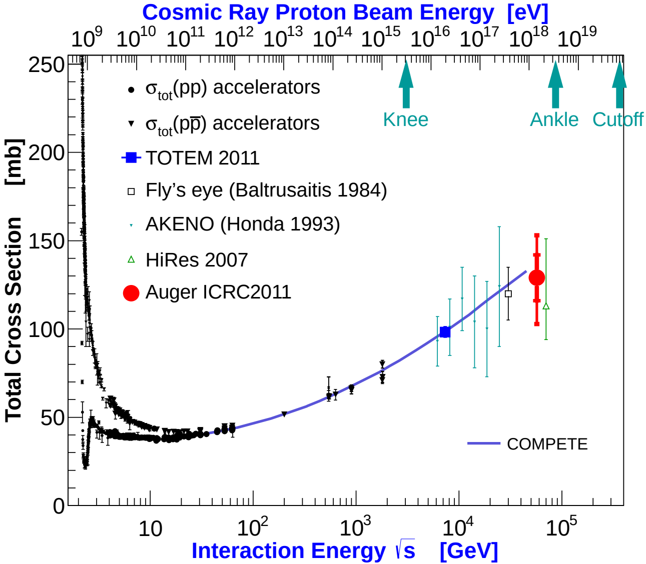
http://www.auger.org/archive/authors_2011_05.html

International Symposium on Future Directions in UHECR Physics

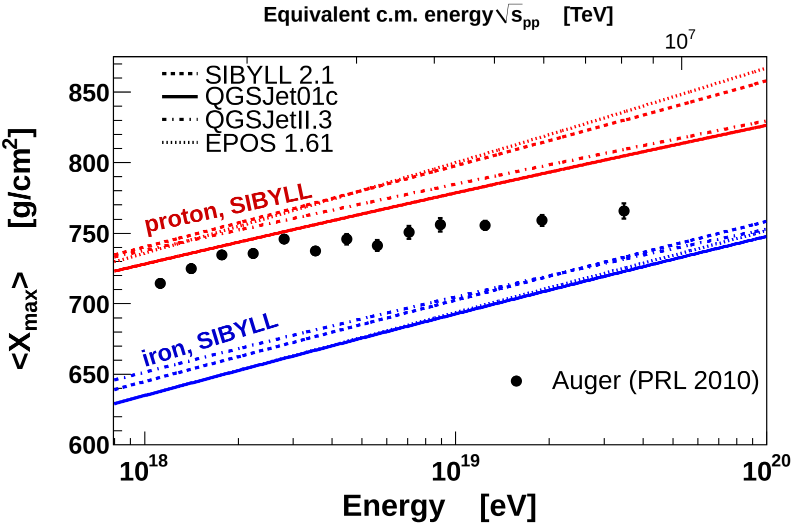
CERN 2012

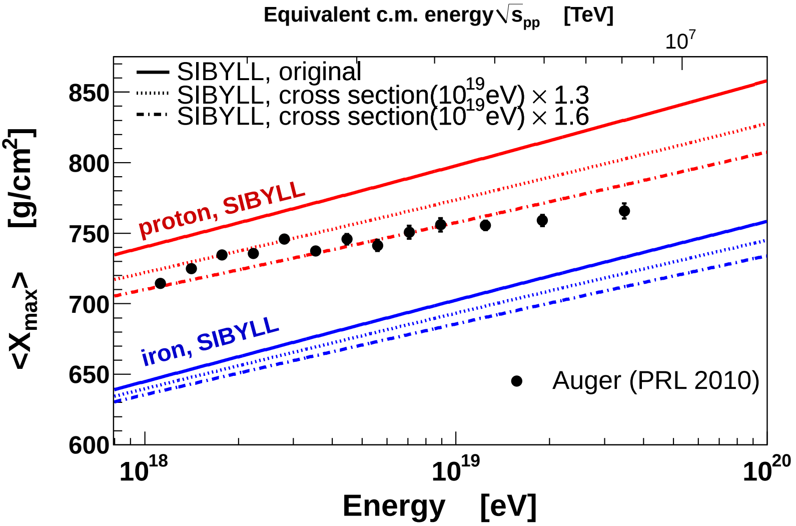
Hadronic Cross-Sections, Overview



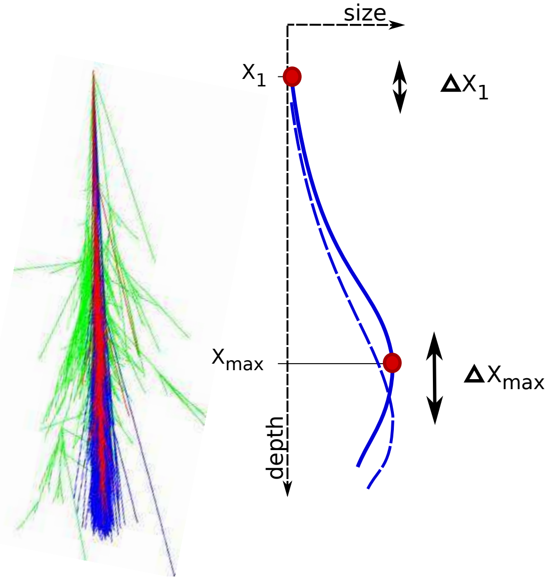
- Fundamental parameter of physics
- Important impact on extensive air showers

Interpretation of $\langle X_{max} \rangle$-data




Equivalent c.m. energy $\sqrt{s_{pp}}$ [TeV]
10^7
SIBYLL, original
SIBYLL, cross section(10^{19}eV) × 1.3
SIBYLL, cross section(10^{19}eV) × 1.6
proton, SIBYLL
iron, SIBYLL
Auger (PRL 2010)
850
800
750
700
650
600
$<X_{max}>$ [g/cm^2]
10^{18}
10^{19}
10^{20}
Energy [eV]

Relating Longitudinal Development to X_1



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

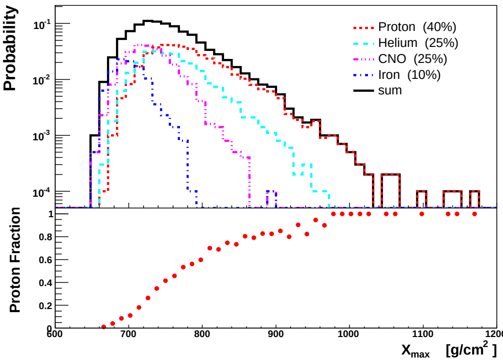
$$\mathrm{RMS}(X_1) = \lambda_{\mathrm{int}}$$

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

Difficulties:

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

Analysis Approach of the Pierre Auger Collaboration



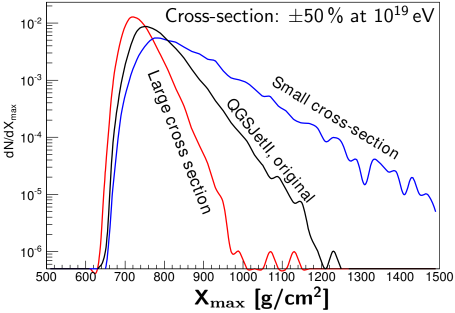
Select deeply penetrating showers to enhance proton fraction

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

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

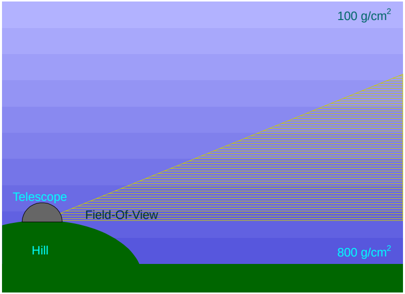
$$\mathbf{dN/dX_{max} \propto exp(-X_{max}/\Lambda_\eta)}$$

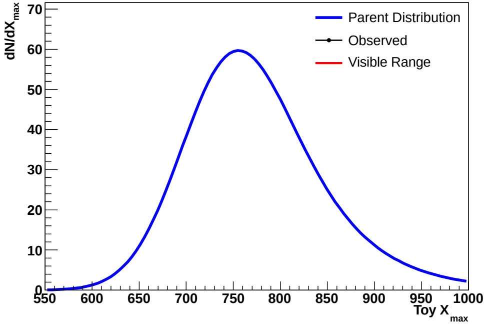
Simulation for proton showers with different cross sections: very good sensitivity of tail of distribution



Pierre Auger Collaboration, CERN February 2012

Demonstration with Toy-Simulation:





- Only geometry
- Exponential atmosphere: $\rho(h) = \rho_o \exp(-h/\lambda)$
- Random events

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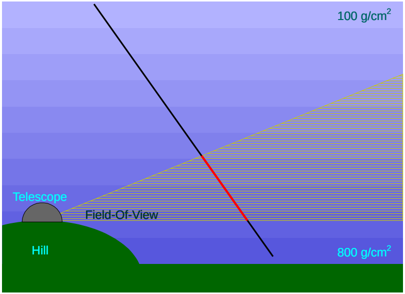

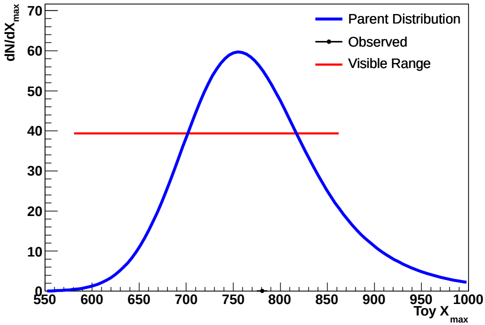

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Fiducial Geometry Selection

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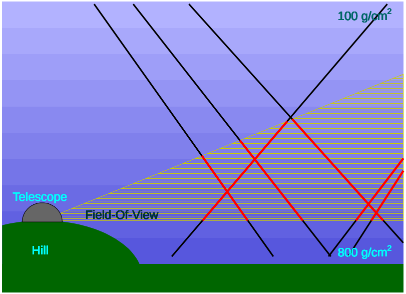

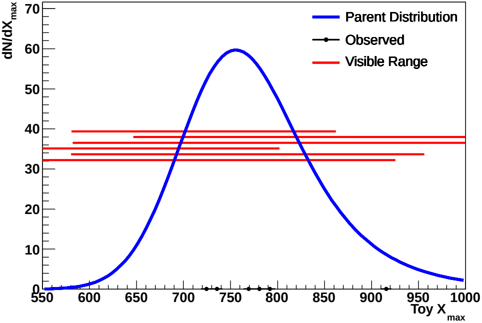

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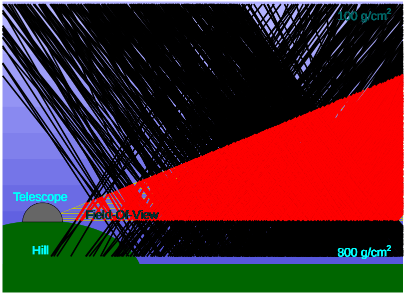

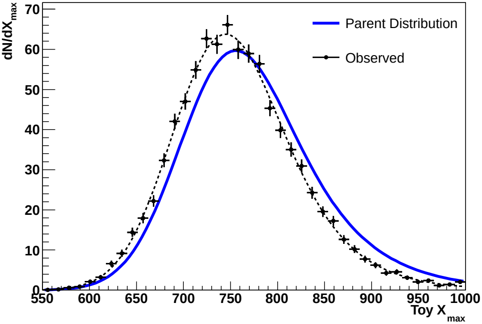

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$\Rightarrow$ **Observation bias !**

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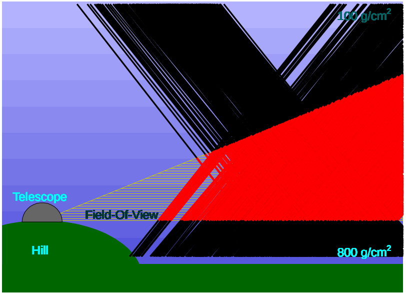

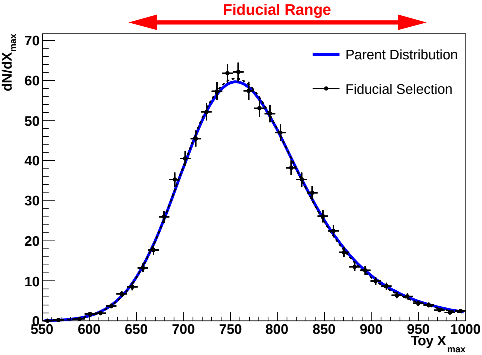

- Only geometry
- Exponential atmosphere: $\rho(h) = \rho_o \exp(-h/\lambda)$
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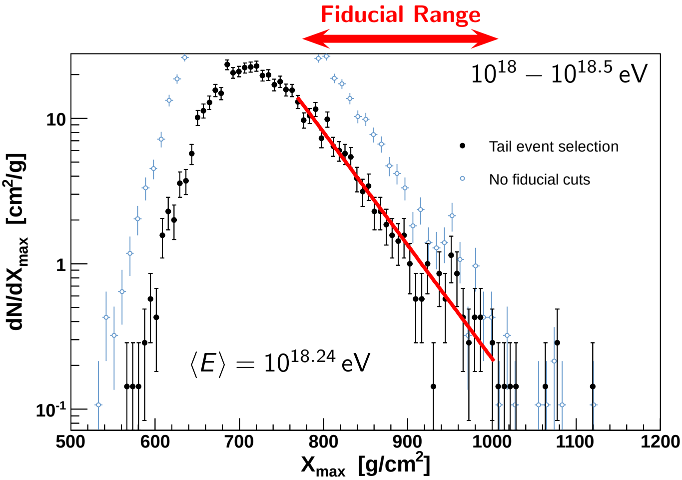
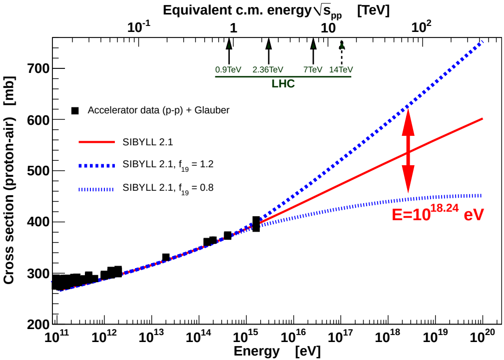
$\Rightarrow$ **Observation bias !**

$\Rightarrow$ **Can be corrected with fiducial geometry selection !**
Efficiency in Toy-Example: $\epsilon = 0.37$



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

Unbinned likelihood analysis, 3082 events

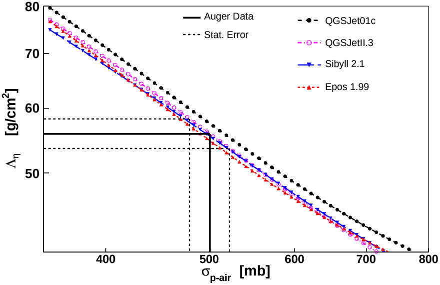


$$f(E,\, f_{19}) = 1 + (f_{19} - 1)\, F(E)$$

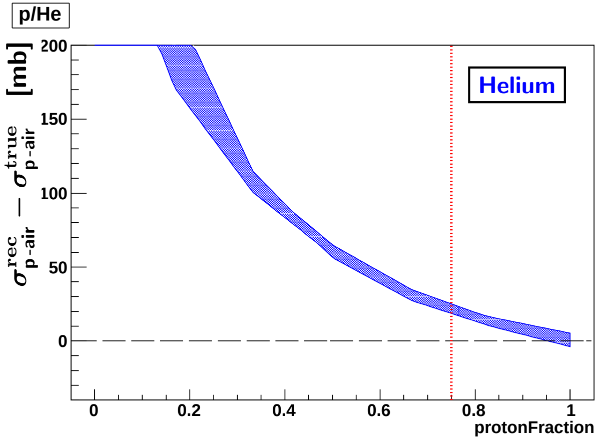
$$F(E) = \frac{\lg\left(E/10^{15}\,\mathrm{eV}\right)}{\lg\left(10^{19}\,\mathrm{eV}/10^{15}\,\mathrm{eV}\right)}$$

Simulations with f_{19}:

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



Mixed Composition



Simulations:
Realistic energy-distribution and $X_{\max}$ + energy resolution;
Spread: models

- Depending on helium fraction, single number not enough
- Up to 25 % Helium: induced bias < 30 mb
- CNO induces no bias up to 50 % of CNO
- Up to 0.5 % of Photons: induced bias < 10 mb

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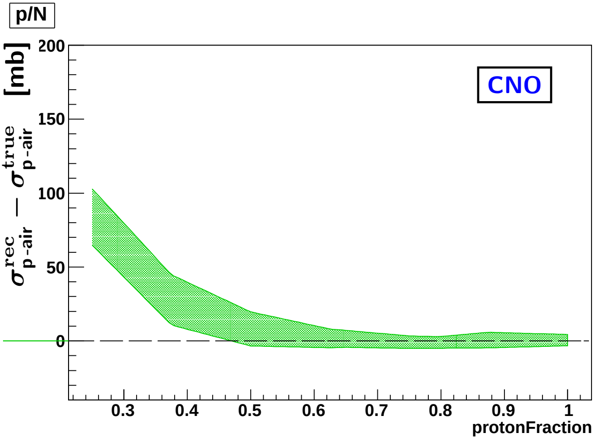

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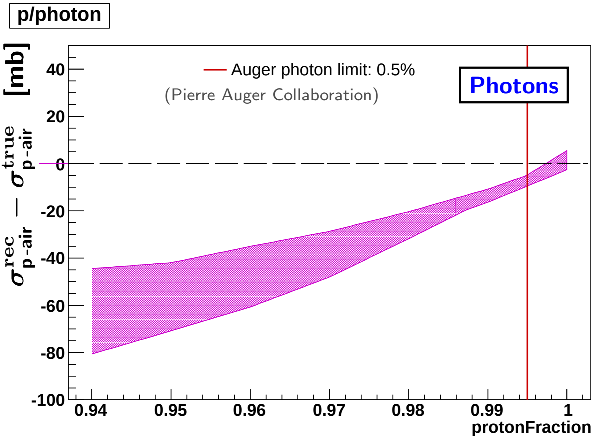

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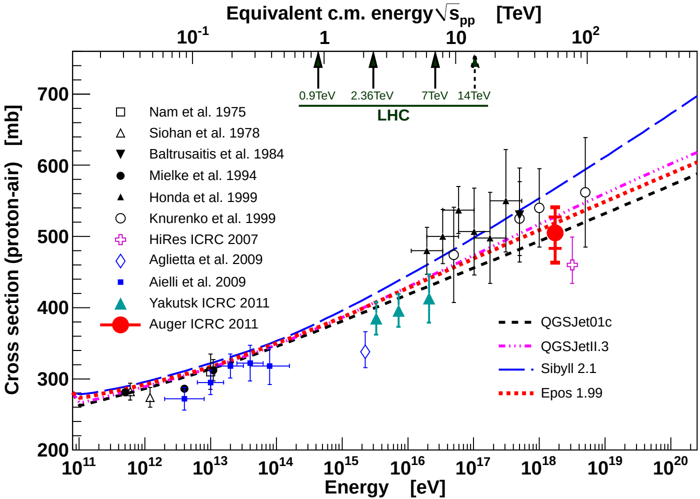
Overview of Systematic Studies at Auger

Description	**Impact on $\sigma_{\text{p-air}}$**
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma_{p\text{-air}}^{\text{prod}}$	± 7 mb
Photons, <0.5 %	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb

- Extensive cut-variation, sub-sample and parameter-scan analysis
- Helium bias potentially most important

Total systematics includes $+10$ mb for photon-contribution and -30 mb for helium contribution in the following.

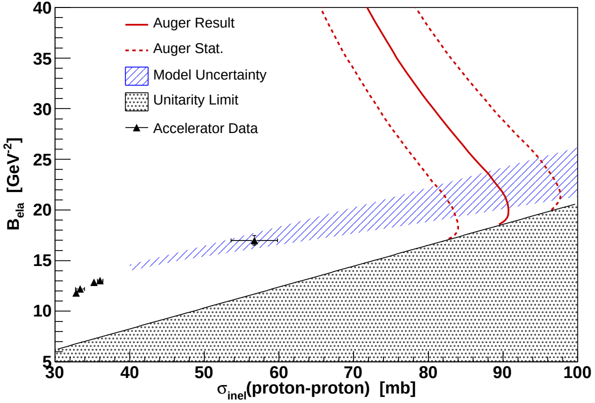
Proton-Air Cross-Section Summary



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

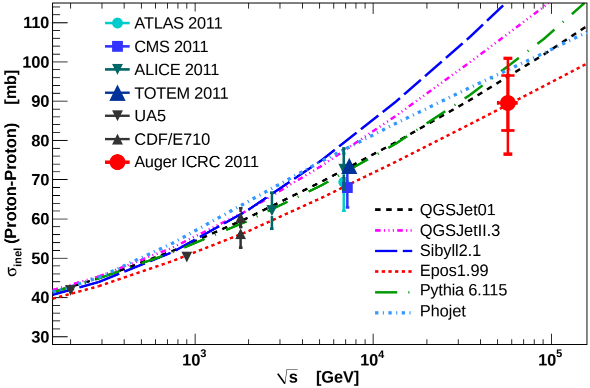
Conversion to inelastic proton-proton cross-section

⇒ Model dependent: Correlation between B_{ela} and cross-sections (Standard Glauber approach)



⇒ **Soon:** Consider impact of diffraction: $\sigma_{pp}^{\mathrm{inel}}$ increases by $5 - 10\,\%$ (private comm.: P. Lipari, S. Ostapchenko)

Standard Glauber conversion + propagation of modeling uncertainties

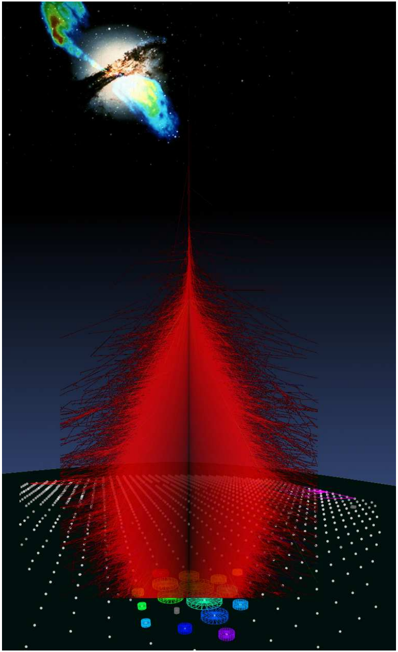


$$\sigma_{\mathrm{pp}}^{\mathrm{inel}} = \left[\mathbf{90}\ \pm \mathbf{7}_{\mathrm{stat}}\ \left({}^{+9}_{-11}\right)_{\mathrm{sys}}\ \pm \mathbf{1.5}_{\mathrm{Glauber}}\right]\ \mathrm{mb}$$

$$\sqrt{s_{\mathrm{pp}}} = [\mathbf{57}\ \pm 6]\ \mathrm{TeV}$$

The 1.5 mb do not reflect the total theoretical uncertainty, since there are other models available for the conversion.

Summary



- Well beyond LHC energies: $E_{\mathrm{cr}} = 10^{18.24}\,\mathrm{eV}$, $\sqrt{s_{pp}} = 57\,\mathrm{TeV}$
- Significantly improved analysis approach at these energies

- Dedicated fiducial event selection for deeply penetrating events
- Consistent description of cross-section in air showers
- Composition systematics studied in detail, Helium dominated
- Monte-Carlo model systematics not large (QGSJet, QGSJetII, EPOS, SIBYLL)

$\Rightarrow$ Systematic uncertainties reliably estimated