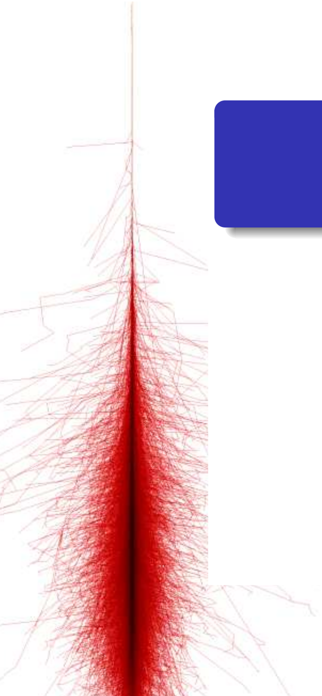


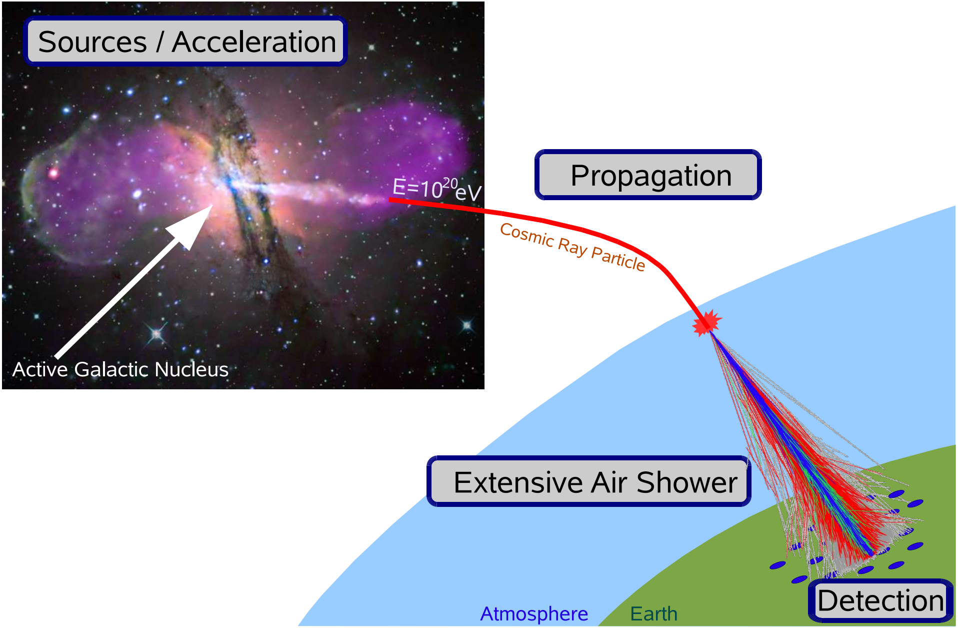
Cross Section Measurement Using Cosmic Ray Data

Ralf Ulrich

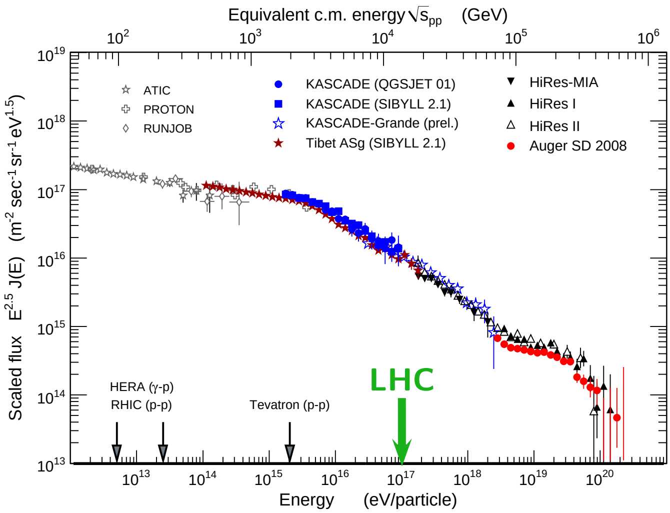
Pennsylvania State University

ECT* Trento, Nov 2010

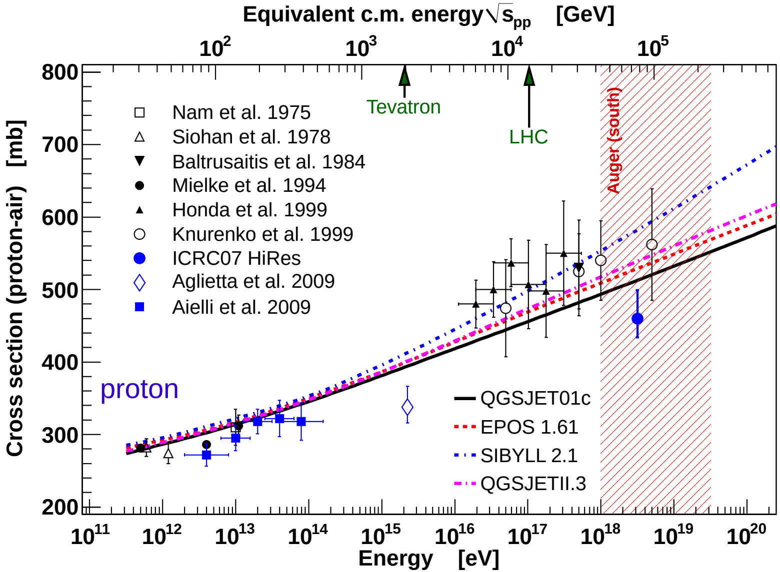
Connecting High Energy Particle Physics with Cosmic Rays



Cosmic Ray Energy Scale

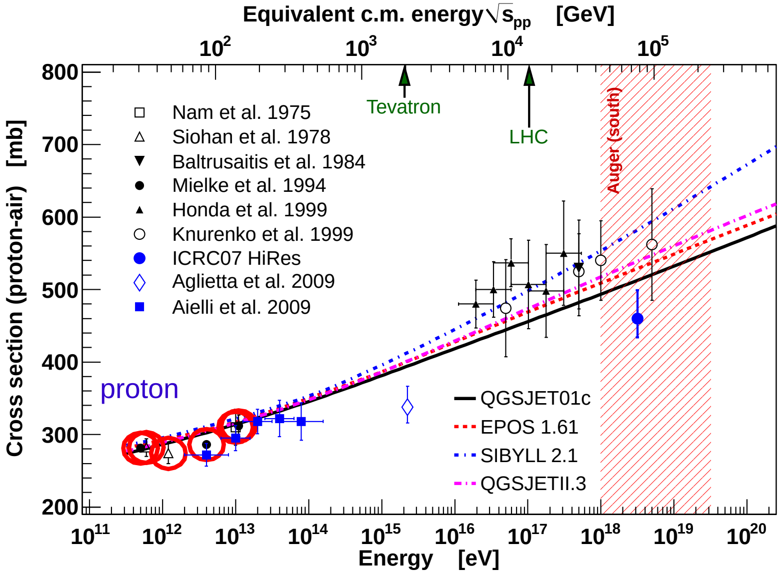


Overview



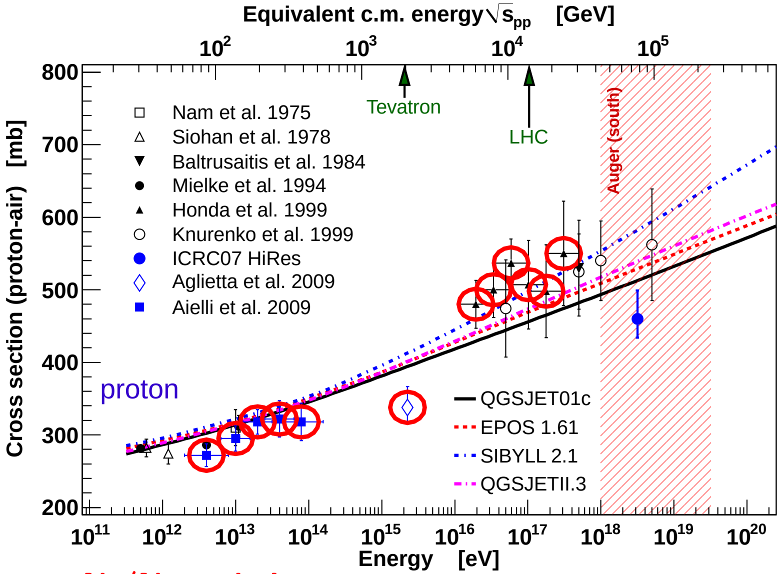
Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
800
700
600
500
400
300
200
Cross section (proton-air) [mb]
Tevatron
LHC
Auger (south)
Nam et al. 1975
Siohan et al. 1978
Baltrusaitis et al. 1984
Mielke et al. 1994
Honda et al. 1999
Knurenko et al. 1999
ICRC07 HiRes
Aglietta et al. 2009
Aielli et al. 2009
proton
QGSJET01c
EPOS 1.61
SIBYLL 2.1
QGSJETII.3
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV]

Overview



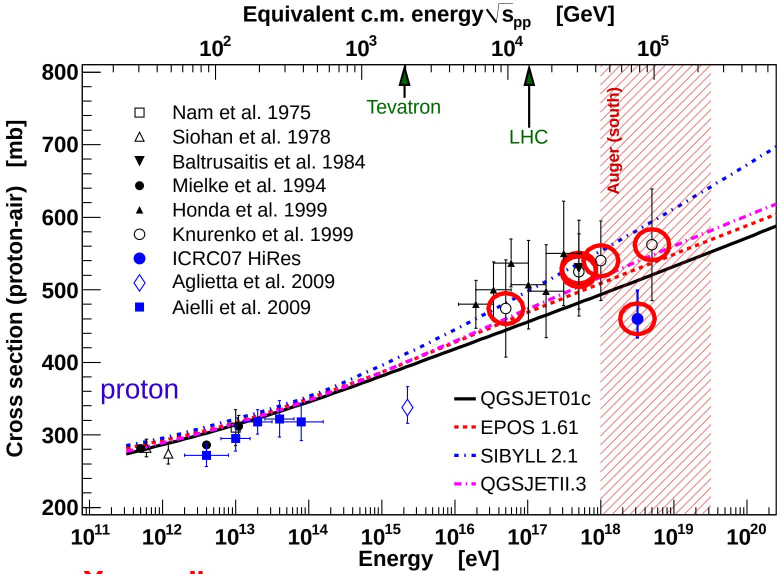
Unaccompanied hadrons

Overview

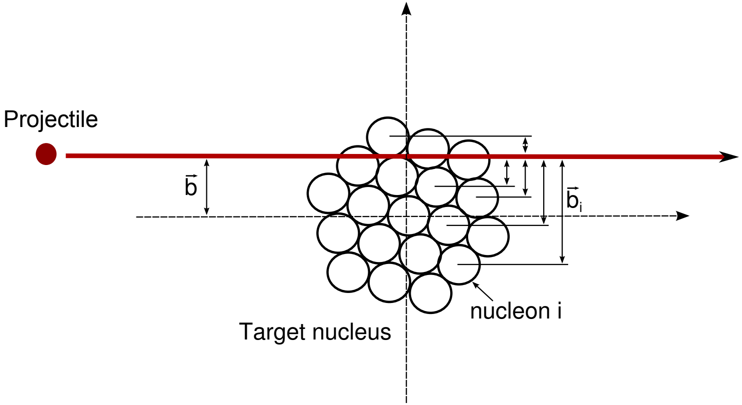


N_e/N_μ technique

Overview



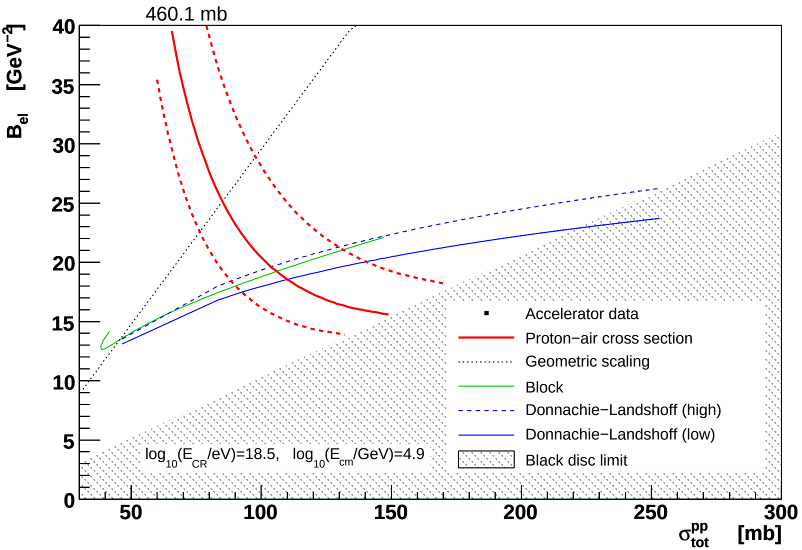
X_{max}-tail



$$\sigma_{\rm tot}^{\rm pA} = \int \left[\prod_i \mathrm{d}^3\vec{r}_i\right] \int \mathrm{d}^2\vec{b} \left[\prod_i \Psi_i^*(\vec{r}_i)\right] \left[1 - \prod_i \left(1 - a_i(s,\, \vec{b}_i)\right)\right] \left[\prod_i \Psi_i(\vec{r}_i)\right]$$

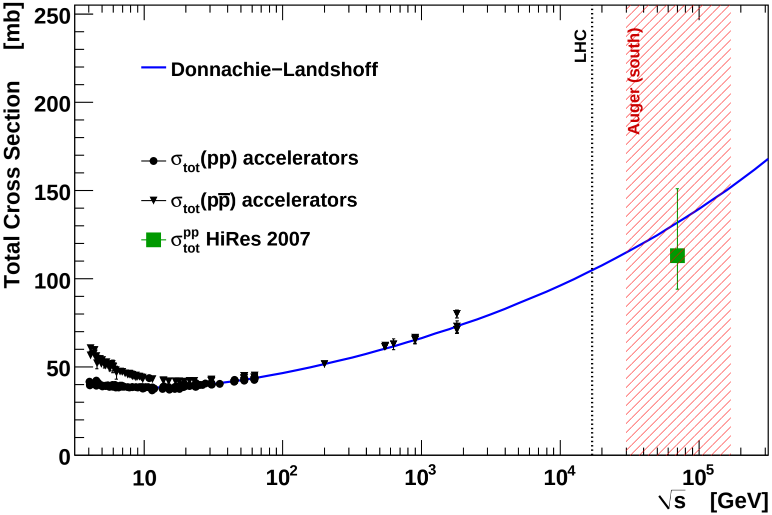
$$a_i(s,\, b_i) = \left(1 + \rho(s)\right) \frac{\sigma_{\rm tot}^{\rm pp}(s)}{4\pi B_{\rm el}(s)}\, e^{-\frac{1}{2}\,\vec{b}_i^{\,2}/B_{\rm el}(s)}$$

The Slope/Proton-Proton Cross Section Plane

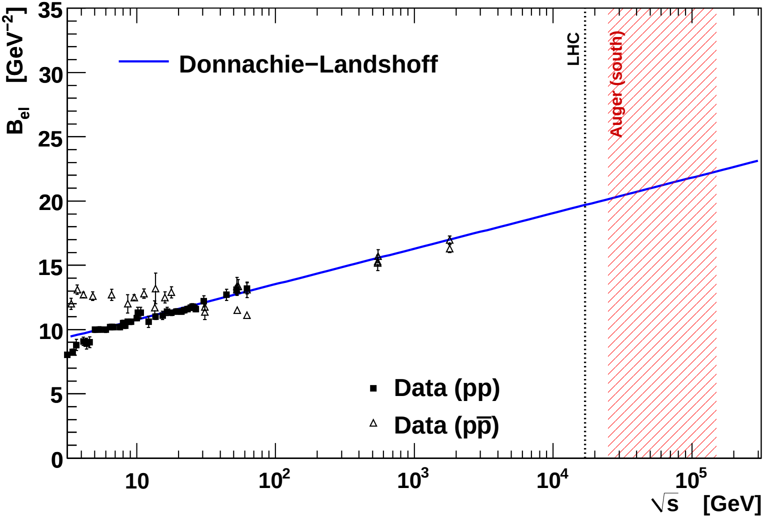


→ Additional uncertainties due to conversion

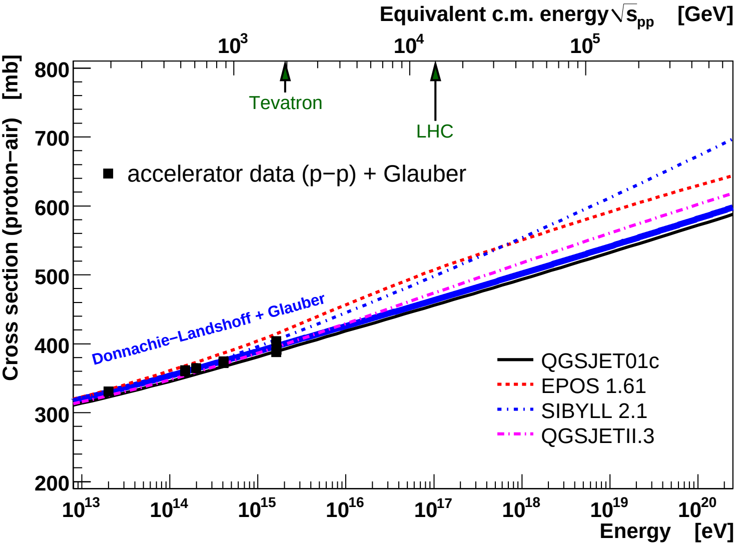
Proton-Proton Cross Section from Cosmic Ray Data



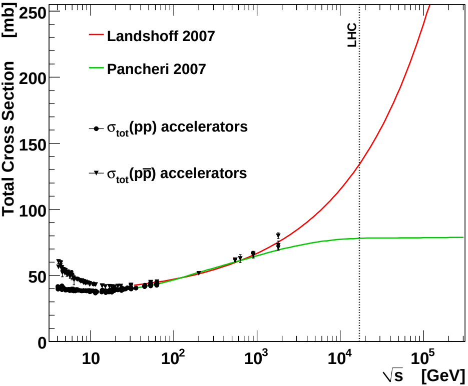
Elastic Slope Parameter (B_{el})

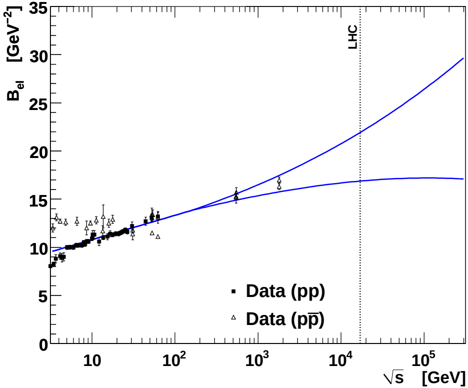


Resulting Proton-Air Cross Section

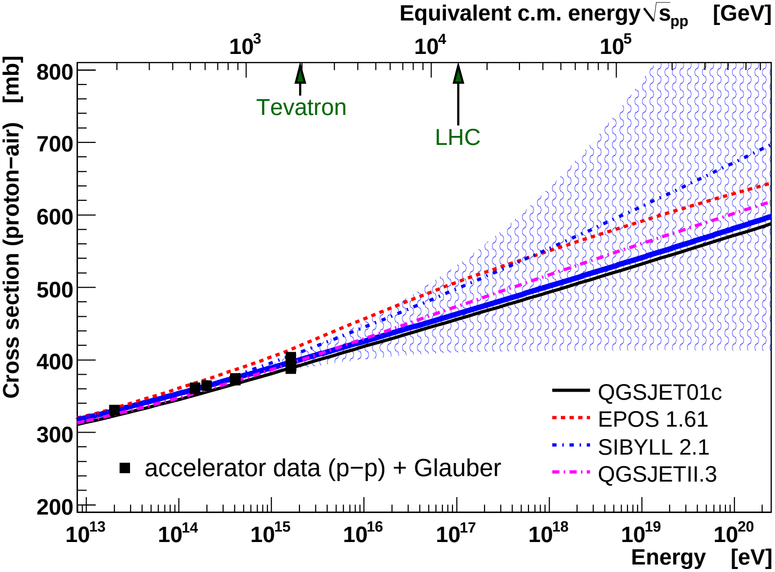


The Extrapolation to Cosmic Ray Energies

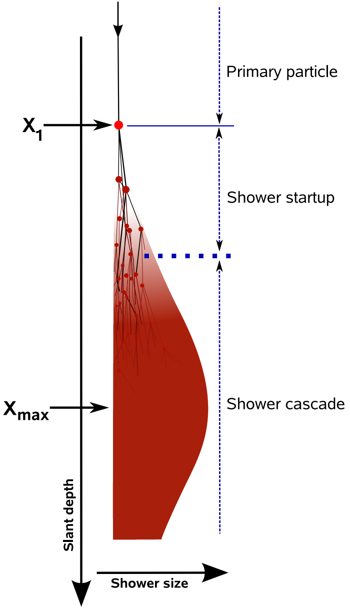


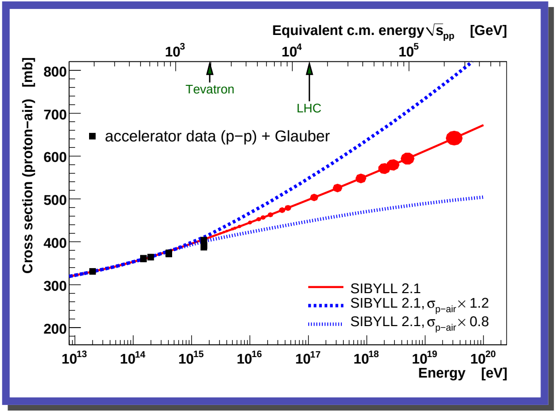


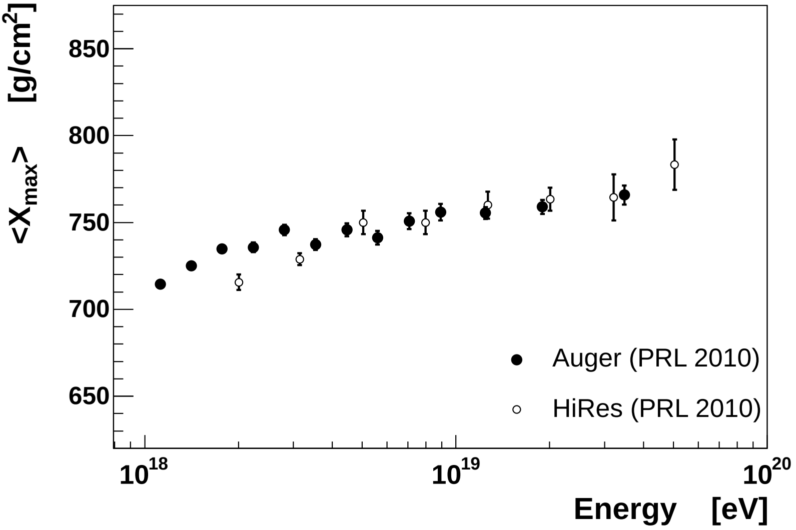
The Extrapolation to Cosmic Ray Energies



Extensive Air Showers

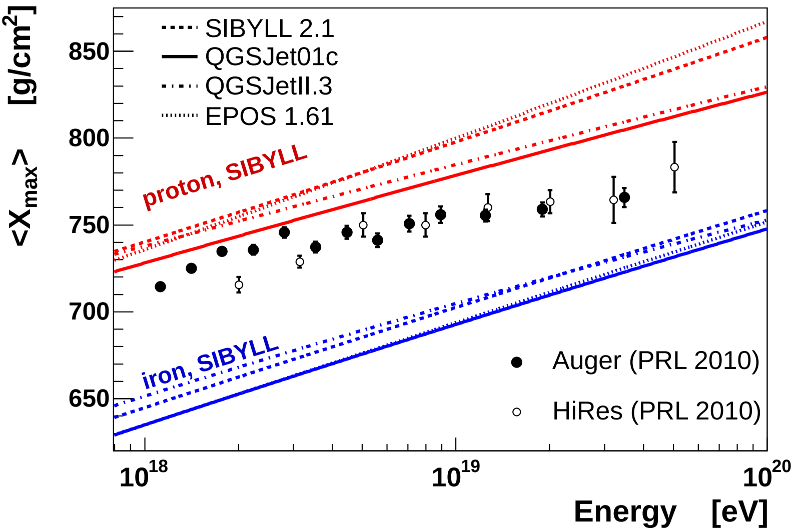




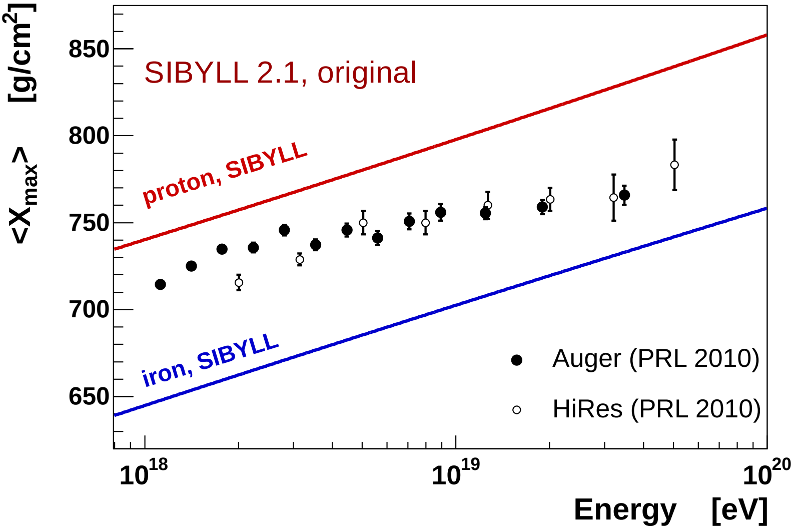


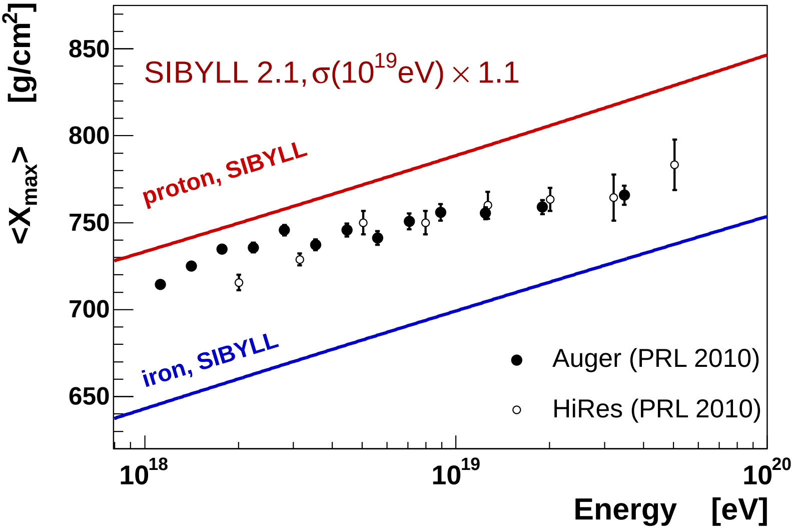
850
800
750
700
650
<Xmax> [g/cm2]
10^18
10^19
10^20
Energy [eV]
Auger (PRL 2010)
HiRes (PRL 2010)

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



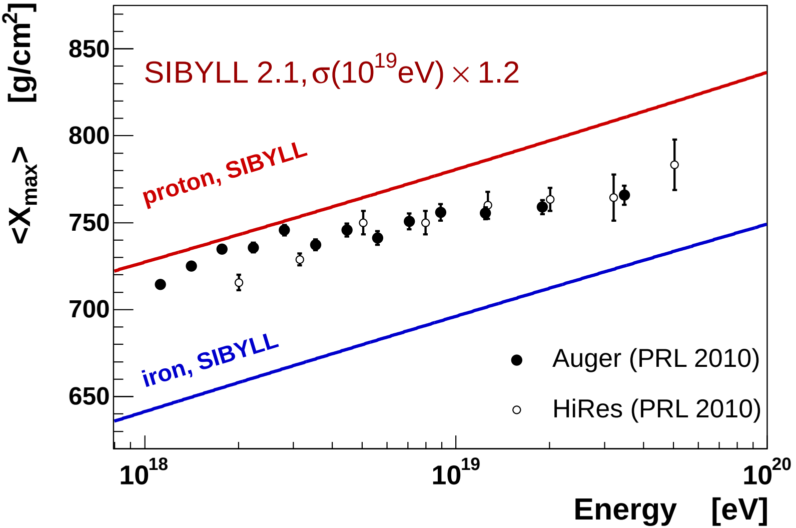
Interpretation of $\langle X_{max} \rangle$-data



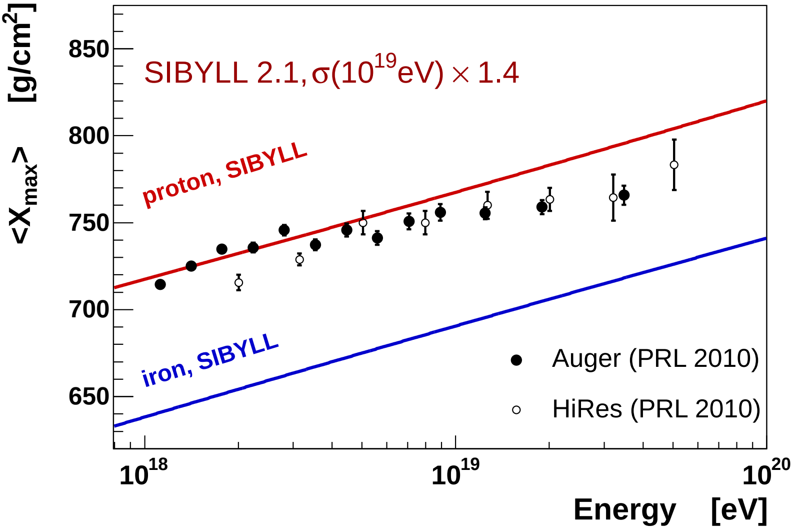


$\langle X_{max} \rangle$ [g/cm²]
850
800
750
700
650
SIBYLL 2.1, σ(10¹⁹eV) × 1.1
proton, SIBYLL
iron, SIBYLL
Auger (PRL 2010)
HiRes (PRL 2010)
10¹⁸
10¹⁹
10²⁰
Energy [eV]

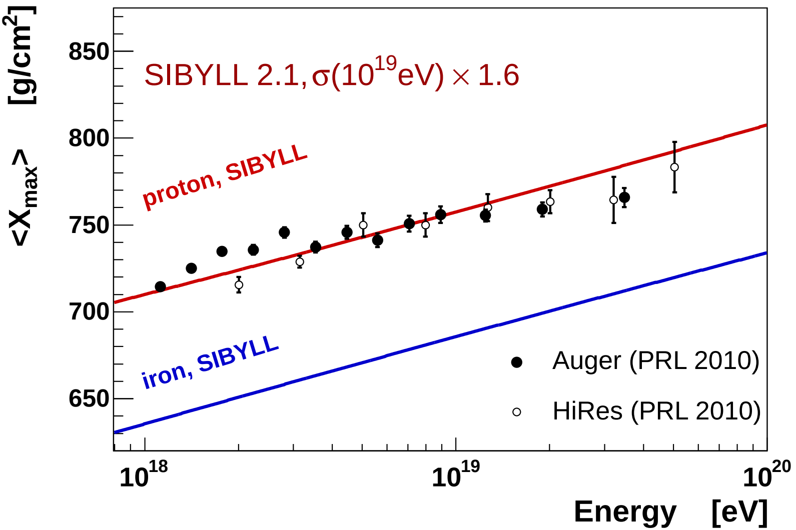
Interpretation of $\langle X_{\max} \rangle$-data



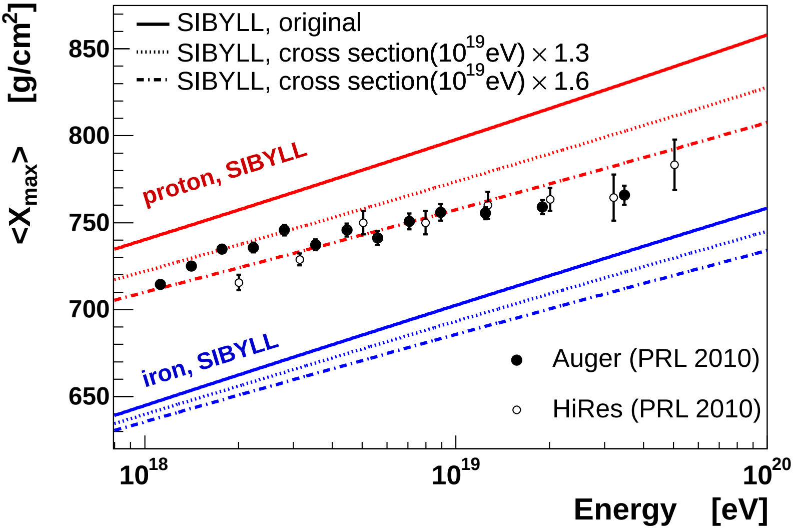
Interpretation of $\langle X_{\max} \rangle$-data



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

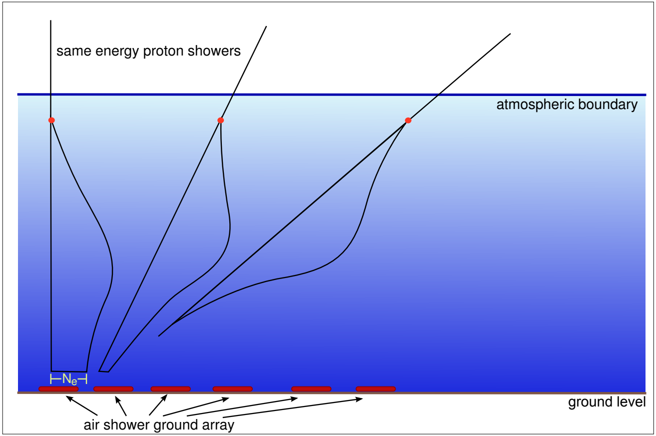


Interpretation of $\langle X_{\max} \rangle$-data



Principle of N_e–N_μ Technique

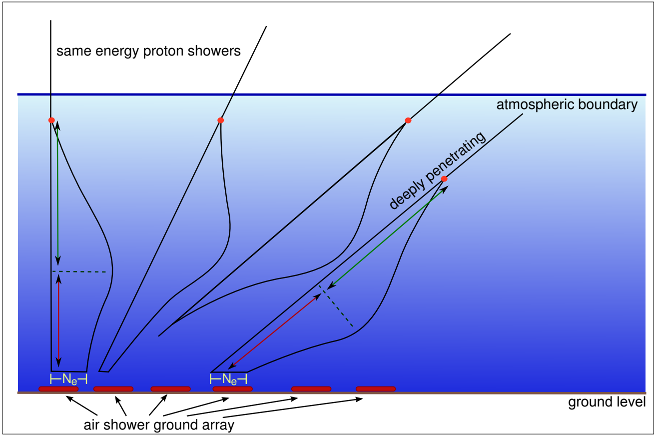
→ Attenuation of shower cascades in the atmosphere



experimental results from: Baltrusaitis et al. (Fly's eye, 1984), Knurenko et al. (Yakutsk, 1999), Belov et al. (HiRes, 2006), Honda et al. (1993), Hara et al. (1999), Aglietta et al. (1999), ...

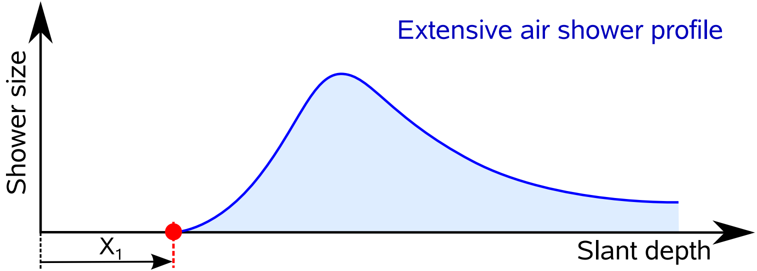
Principle of N_e–N_μ Technique

→ Attenuation of shower cascades in the atmosphere

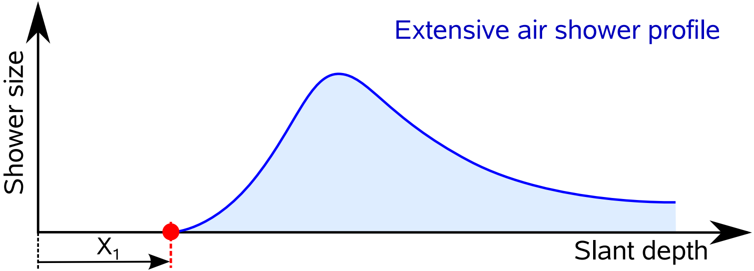


experimental results from: Baltrusaitis et al. (Fly's eye, 1984), Knurenko et al. (Yakutsk, 1999), Belov et al. (HiRes, 2006), Honda et al. (1993), Hara et al. (1999), Aglietta et al. (1999), ...

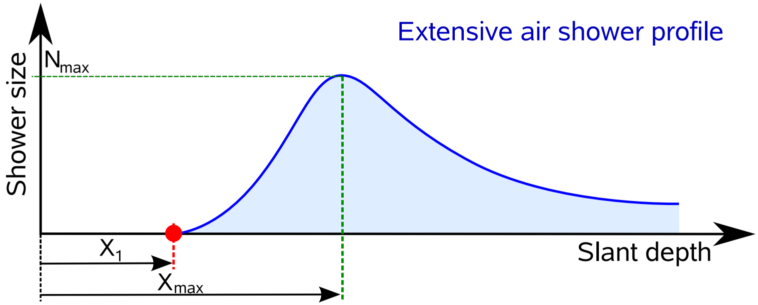
Air Shower Development



Air Shower Development

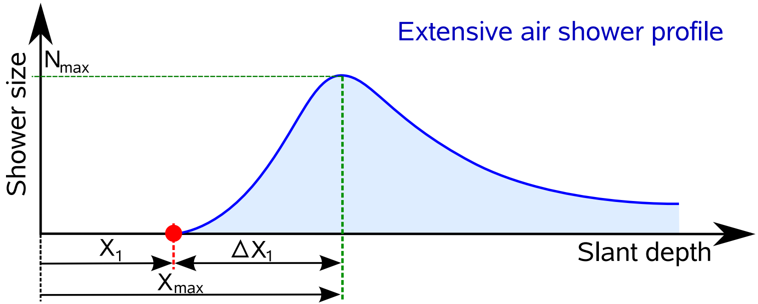


$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\max}^{\mathrm{rec}}} =$$



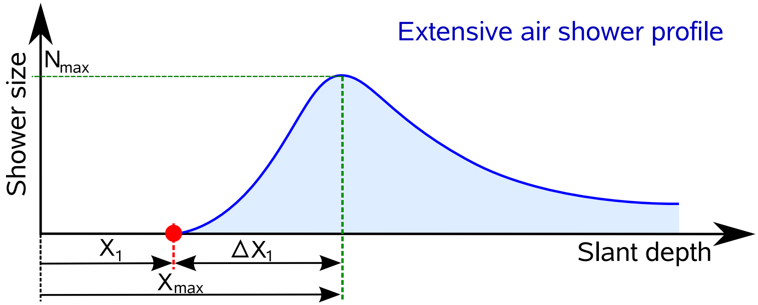
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\max}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \qquad \frac{\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}}$$

Air Shower Development



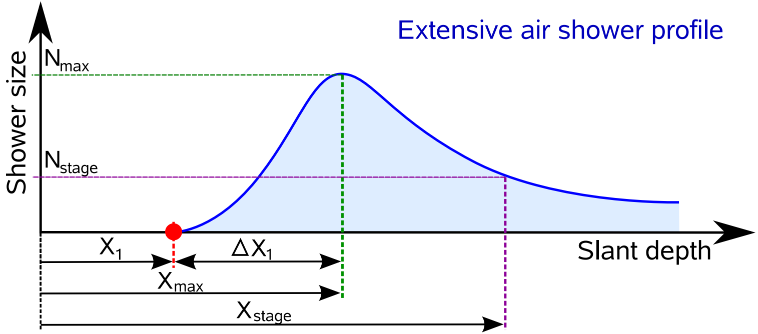
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{max}}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1)$$

Air Shower Development



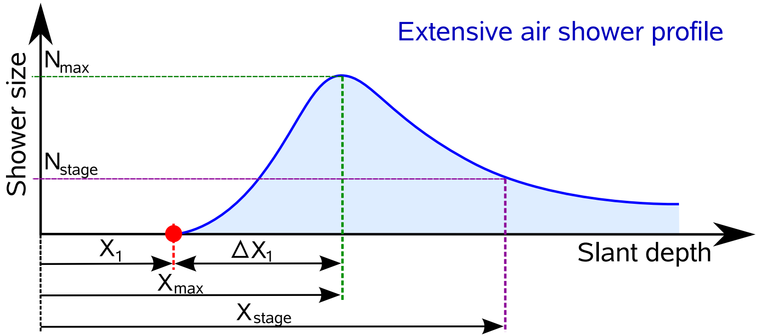
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\max}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \;\; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1)\; P_{\mathrm{res}}^{\mathrm{S}}(X_{\max}^{\mathrm{rec}} \,|\, X_{\max})$$

Air Shower Development



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{max}}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1) \; P_{\mathrm{res}}^{\mathrm{S}}(X_{\mathrm{max}}^{\mathrm{rec}} \,|\, X_{\mathrm{max}})$$

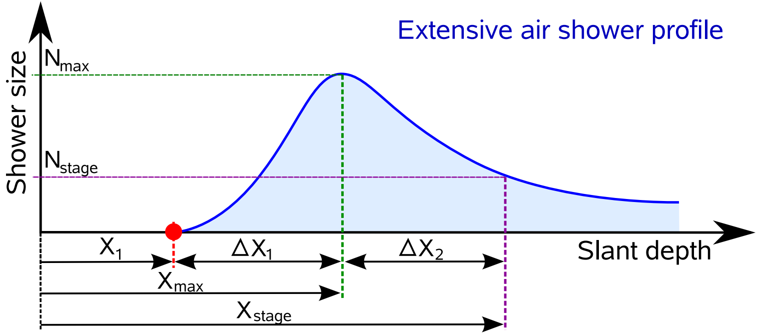
$$\frac{1}{N}\,\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{stage}}^{\mathrm{rec}}}\bigg|_{N_{\mathrm{e}}^{\mathrm{rec}},\,N_{\mu}^{\mathrm{rec}}} =$$



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{max}}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1) \; P_{\mathrm{res}}^{\mathrm{S}}(X_{\mathrm{max}}^{\mathrm{rec}} \,|\, X_{\mathrm{max}})$$

$$\frac{1}{N}\left.\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{stage}}^{\mathrm{rec}}}\right|_{N_e^{\mathrm{rec}},\, N_\mu^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1)$$

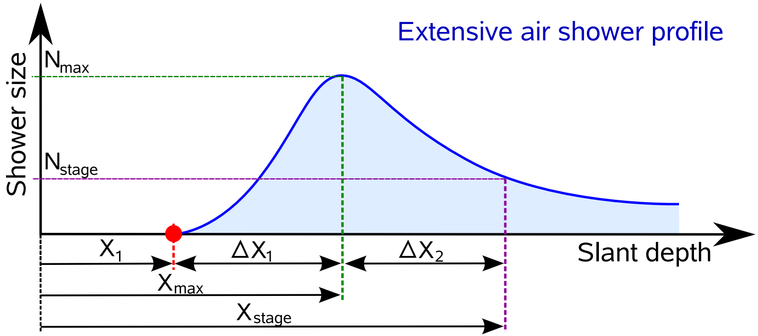
Air Shower Development



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\max}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1) \; P_{\mathrm{res}}^{\mathrm{S}}(X_{\max}^{\mathrm{rec}} \,|\, X_{\max})$$

$$\frac{1}{N}\left.\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{stage}}^{\mathrm{rec}}}\right|_{N_{\mathrm{e}}^{\mathrm{rec}},\,N_{\mu}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \int \mathrm{d}\Delta X_2 \; \frac{e^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \,|\, X_1)$$
$$P_2(N_{\mathrm{e}}(X_{\mathrm{stage}}),\, N_{\mu}(X_{\mathrm{stage}}) \,|\, X_{\max},\, X_{\mathrm{obs}})$$

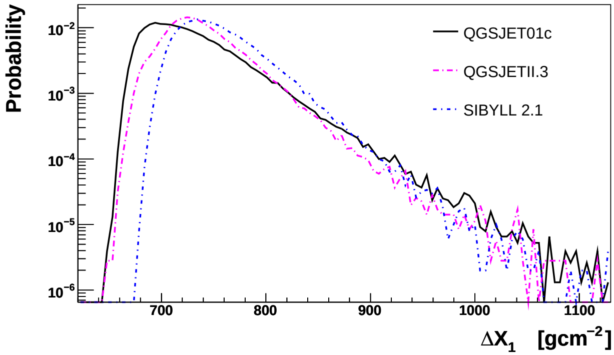
Air Shower Development



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{max}}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \; \frac{\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \mid X_1)\; P_{\mathrm{res}}^{\mathrm{S}}(X_{\mathrm{max}}^{\mathrm{rec}} \mid X_{\mathrm{max}})$$

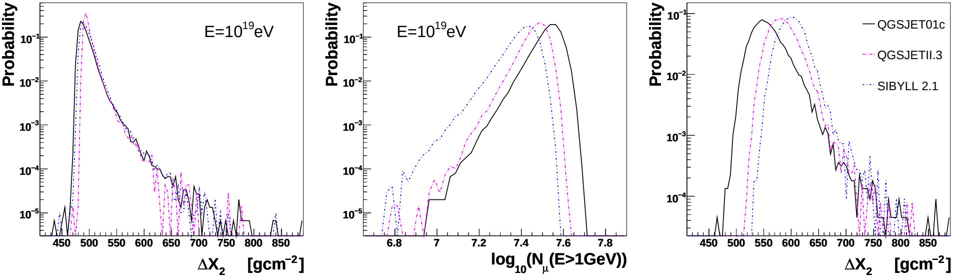
$$\frac{1}{N}\left.\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{stage}}^{\mathrm{rec}}}\right|_{N_{\mathrm{e}}^{\mathrm{rec}},\,N_{\mu}^{\mathrm{rec}}} = \int \mathrm{d}X_1 \int \mathrm{d}\Delta X_1 \int \mathrm{d}\Delta X_2 \; \frac{\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}}}{\lambda_{\mathrm{int}}} \; P_1(\Delta X_1 \mid X_1)$$
$$P_2(N_{\mathrm{e}}(X_{\mathrm{stage}}),\, N_{\mu}(X_{\mathrm{stage}}) \mid X_{\mathrm{max}},\, X_{\mathrm{obs}})\; P_{\mathrm{res}}^{\mathrm{S}}(N_{\mu}^{\mathrm{rec}},\, N_{\mathrm{e}}^{\mathrm{rec}} \mid N_{\mu},\, N_{\mathrm{e}})$$

Model Dependence of ΔX_1



$\Rightarrow$ Important to understand and quantify model dependence !

Model Dependence of ΔX_2 and Muon Numbers

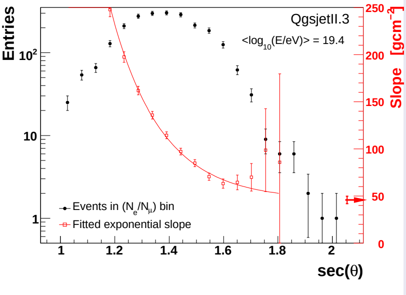


$\Rightarrow$ Model dependence more pronounced due to muon numbers

Limitation of the analysis to the tails at large grammages:

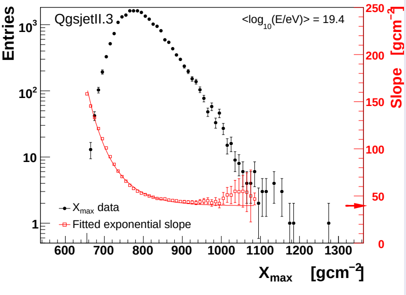
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}X_{\mathrm{obs}}} \propto \mathrm{e}^{-X_{\mathrm{obs}}/\Lambda_{\mathrm{obs}}} \qquad \textbf{and} \qquad \Lambda_{\mathrm{obs}} = k\,\lambda_{\mathrm{p-air}}$$

N_e/N_μ



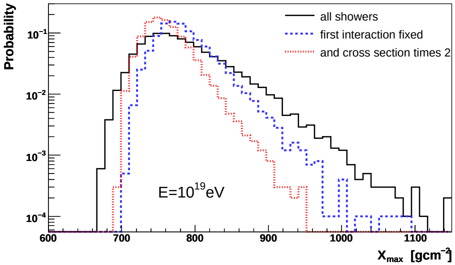
$$X^{\mathrm{rec}}_{\mathrm{stage}} \simeq X^{\mathrm{vert}}_{\mathrm{obs}}\ \sec\theta$$

X_{max}

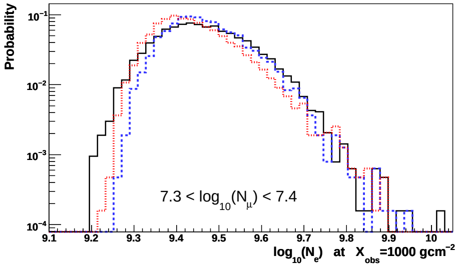


Sensitivity

X_{max}

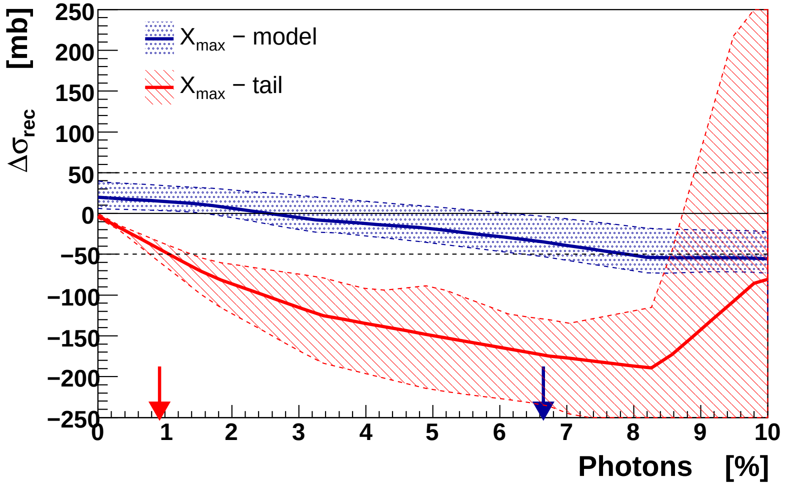


N_{e}–N_{μ}



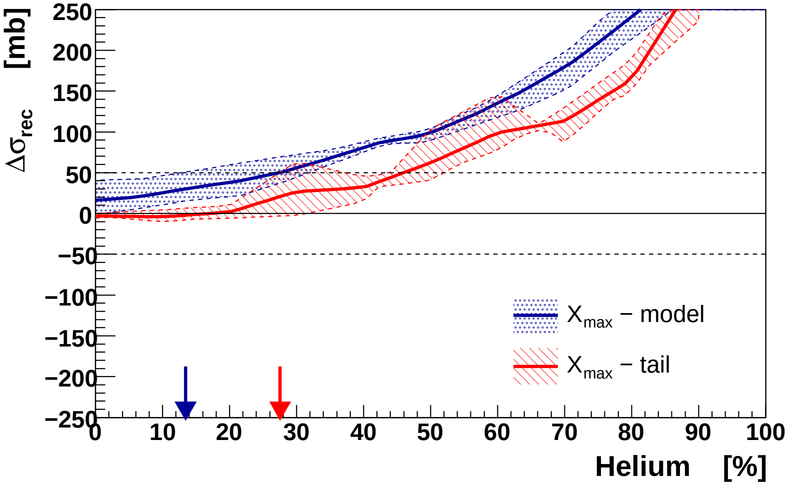
Primary Cosmic Ray Mass composition

Primary Cosmic Ray Photons

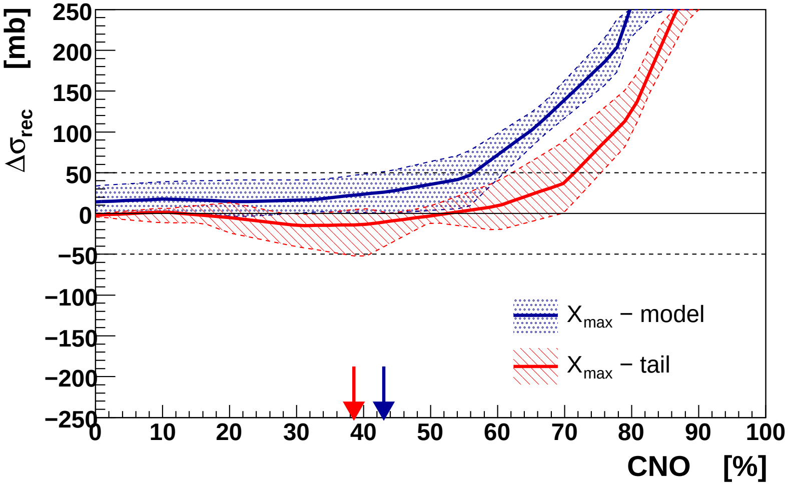


(at 10^{19} eV)

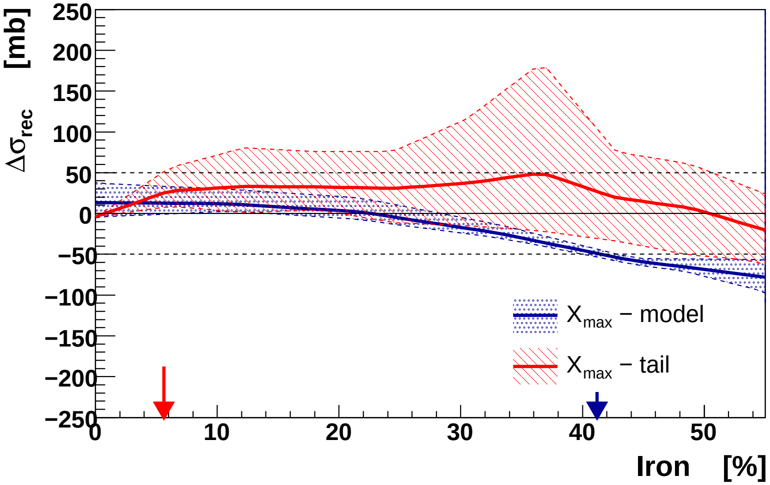
Fortunately: Photon limits down to $< 1\,\%$


$\Delta\sigma_{rec}$ [mb]
250
200
150
100
50
0
−50
−100
−150
−200
−250
0
10
20
30
40
50
60
70
80
90
100
Helium [%]
X_{max} − model
X_{max} − tail

(at 10^{19} eV)

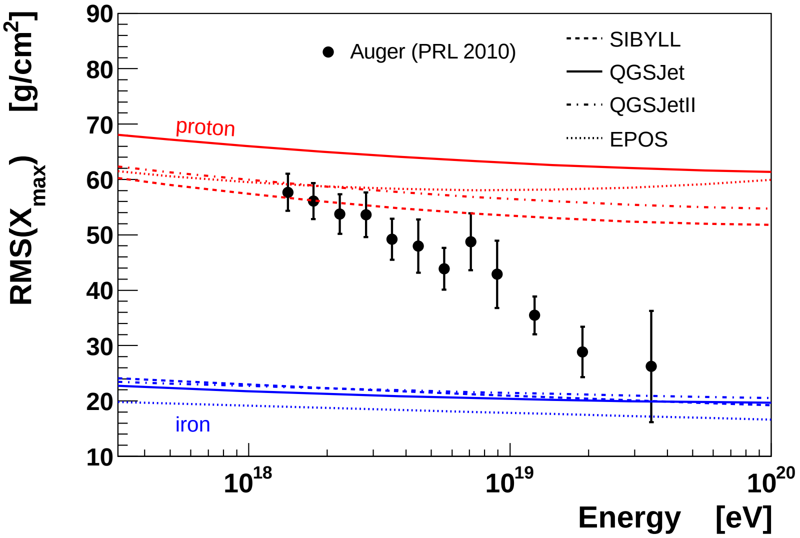

Δσrec [mb]
250
200
150
100
50
0
−50
−100
−150
−200
−250
0
10
20
30
40
50
60
70
80
90
100
CNO [%]
Xmax − model
Xmax − tail

(at 10^{19} eV)


250
200
150
100
50
0
−50
−100
−150
−200
−250
0
10
20
30
40
50
$\Delta\sigma_{rec}$ [mb]
Iron [%]
X_{max} − model
X_{max} − tail

(at 10^{19} eV)

Auger Shower Fluctuations RMS(X_{max})

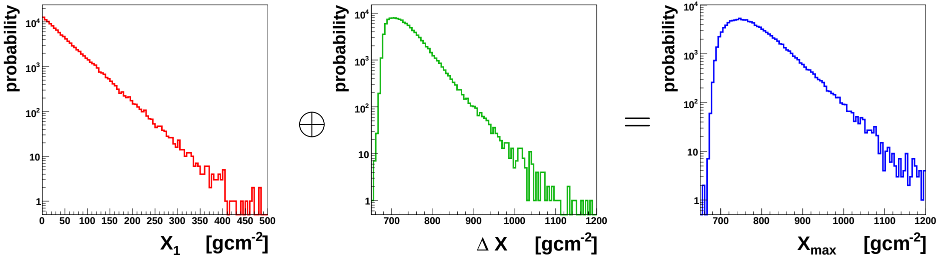


Limit on the Cosmic Ray-Proton Cross Section

Assume that all fluctuations in X_{max} are directly coming from X_1

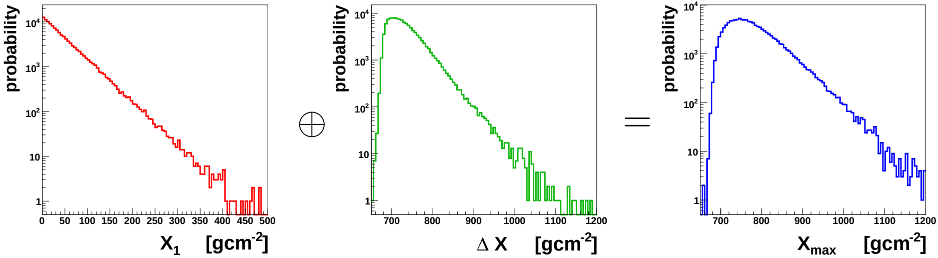
Limit on the Cosmic Ray-Proton Cross Section

Assume that all fluctuations in X_{max} are directly coming from X_1



Limit on the Cosmic Ray-Proton Cross Section

Assume that all fluctuations in $X_{\max}$ are directly coming from X_1



$$\frac{\mathrm{d}N}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}}\,\mathrm{e}^{-X_1/\lambda_{\mathrm{int}}} \quad \rightarrow \quad \sigma(X_1) = \lambda_{\mathrm{int}} \quad \text{and} \quad \sigma_{\mathrm{prod}} = \langle m_{\mathrm{air}} \rangle / \lambda_{\mathrm{int}}$$

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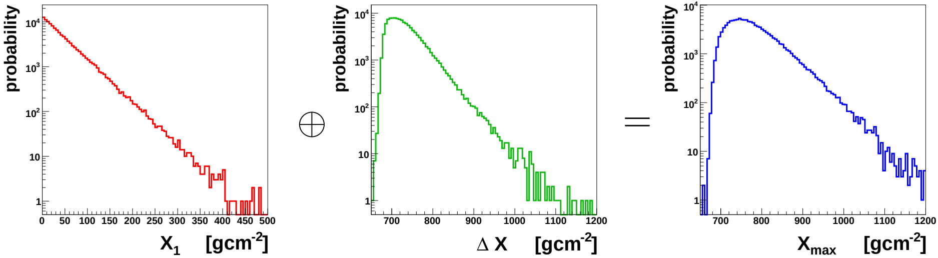

$$\frac{\mathrm{d}N}{\mathrm{d}X_1} = \frac{1}{\lambda_{\rm int}}\,\mathrm{e}^{-X_1/\lambda_{\rm int}} \quad \rightarrow \quad \sigma(X_1) = \lambda_{\rm int} \quad \text{and} \quad \sigma_{\rm prod} = \langle m_{\rm air}\rangle/\lambda_{\rm int}$$

$$\lambda_{\rm int} = \sigma(X_1) = \sqrt{\sigma(X_{\rm max})^2 - \sigma(EAS)^2}$$

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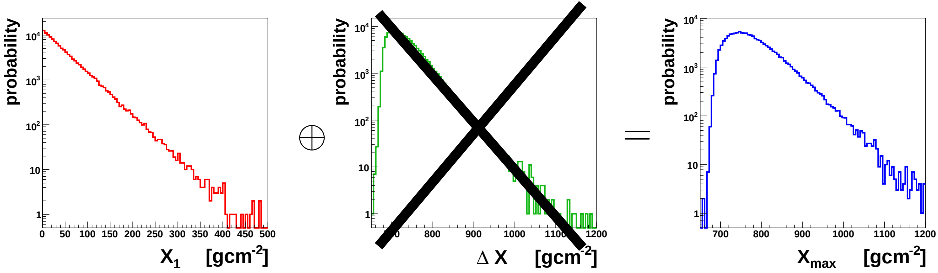

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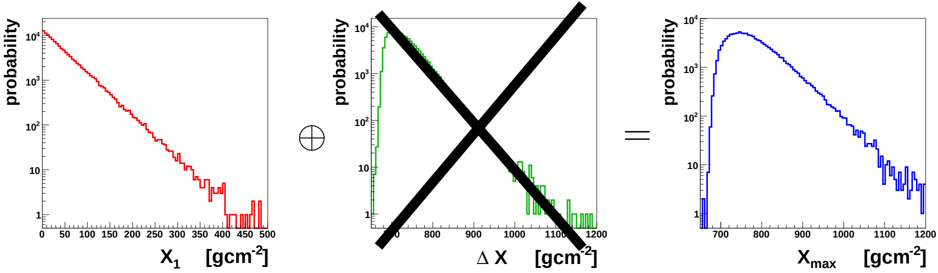

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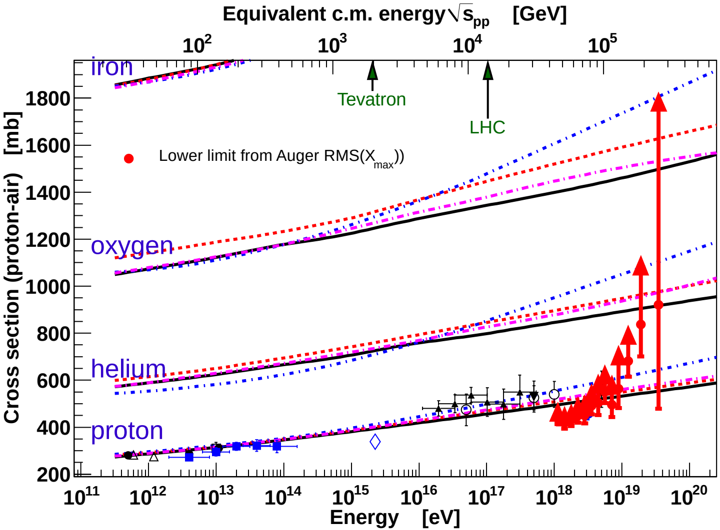
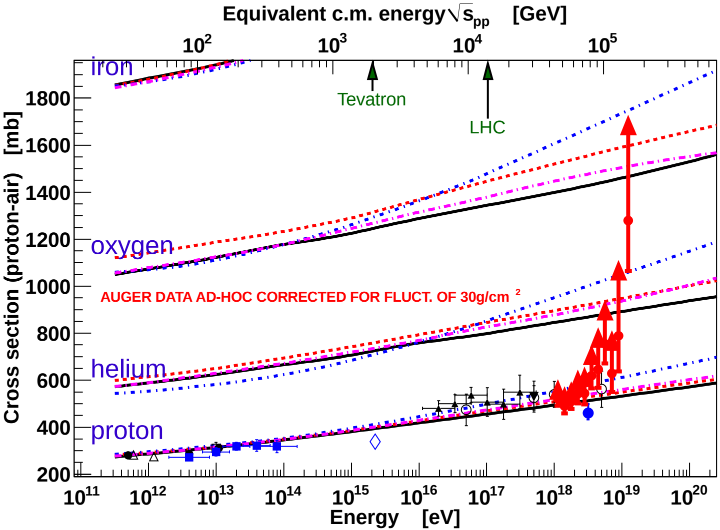
$$\sigma_{\mathrm{int}} > \frac{\langle m_{\mathrm{air}}\rangle}{\sigma(X_{\max})}$$

Cross Section Limit from Auger RMS Data



(Auger $X_{\max}$-data from PRD2010, 90 % C.L.)

Cross Section Limit from Auger RMS Data



(Auger X_{max}-data from PRD2010, 90 % C.L.)

Summary

Air shower fluctuations are sensitive
to cross sections

Precise measurements extremely challenging

Most critical at the highest energies:

- Primary composition
- Model dependence

LHC has potential to drastically reduce existing uncertainties in air shower interpretation

The big potential of cosmic rays is the energy region beyond the LHC:
QCD and/or new physics.