Measuring $\sigma_{p\text{-}air}$ and σ_{pp} with the Pierre Auger Observatory

Carola Dobrigkeit for the Pierre Auger Collaboration
RETINHA 2014

How we detect these UHE cosmic rays?

- Primary cosmic rays are detected via the extensive air showers they induce by interacting in the atmosphere.
- The Pierre Auger Observatory combines two complementary techniques for detection (hybrid detection).

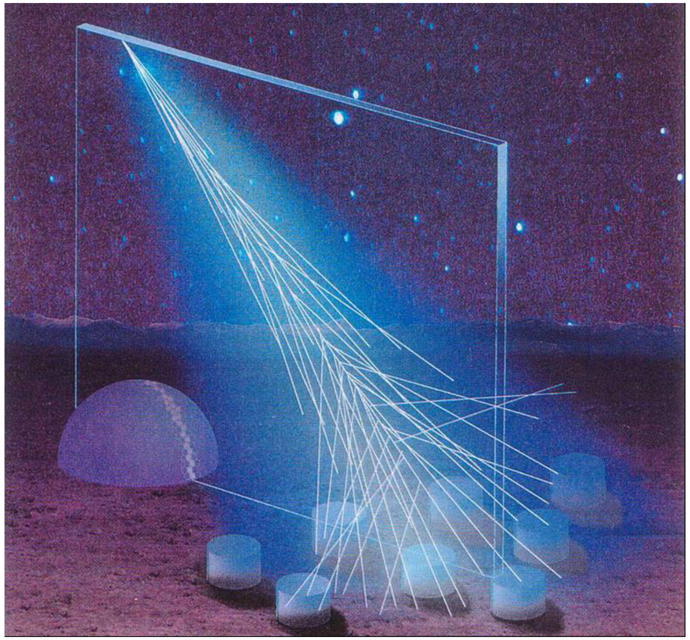
Hybrid detection:

Fluorescence Detector:

- **Almost calorimetric energy measurement**
- **Longitudinal development**
- **10-15% duty cycle**
- **Complex acceptance calculation**

Surface Detector Array:

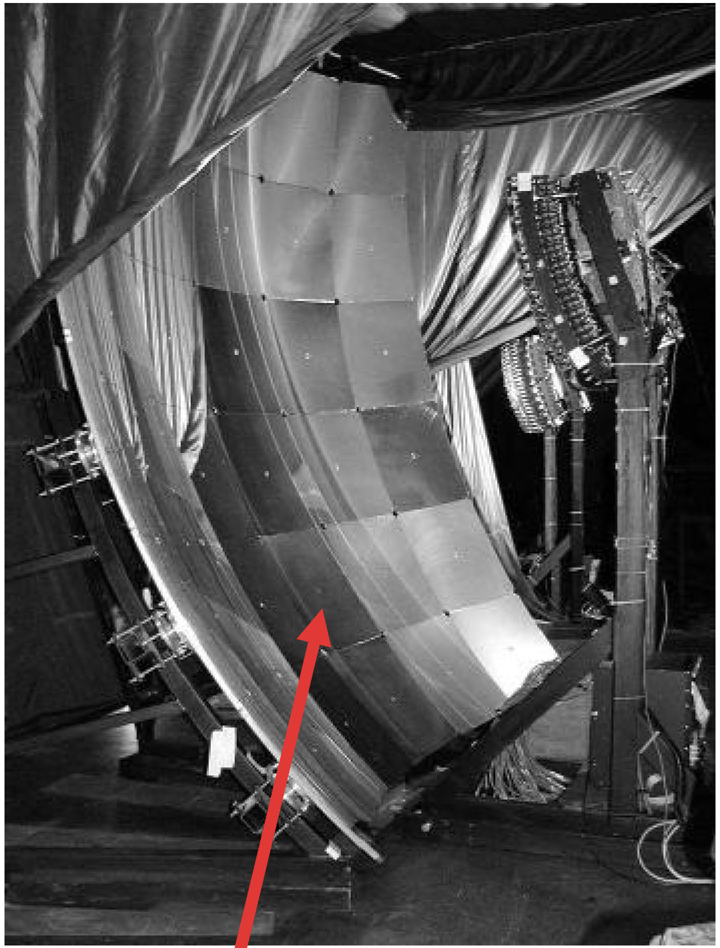
- **100% duty cycle**
- **Simple geometrical acceptance**
- **Extracting primary energy and mass is model dependent**



Combining both techniques allows:

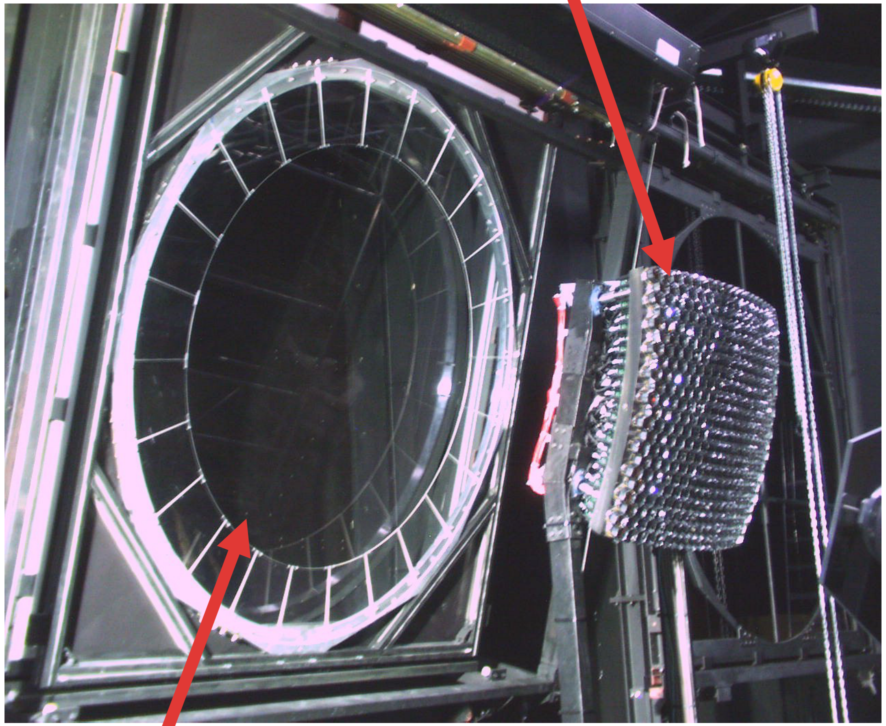
- **cross calibration in energy**
- **better angular resolution**

A fluorescence telescope (FD)



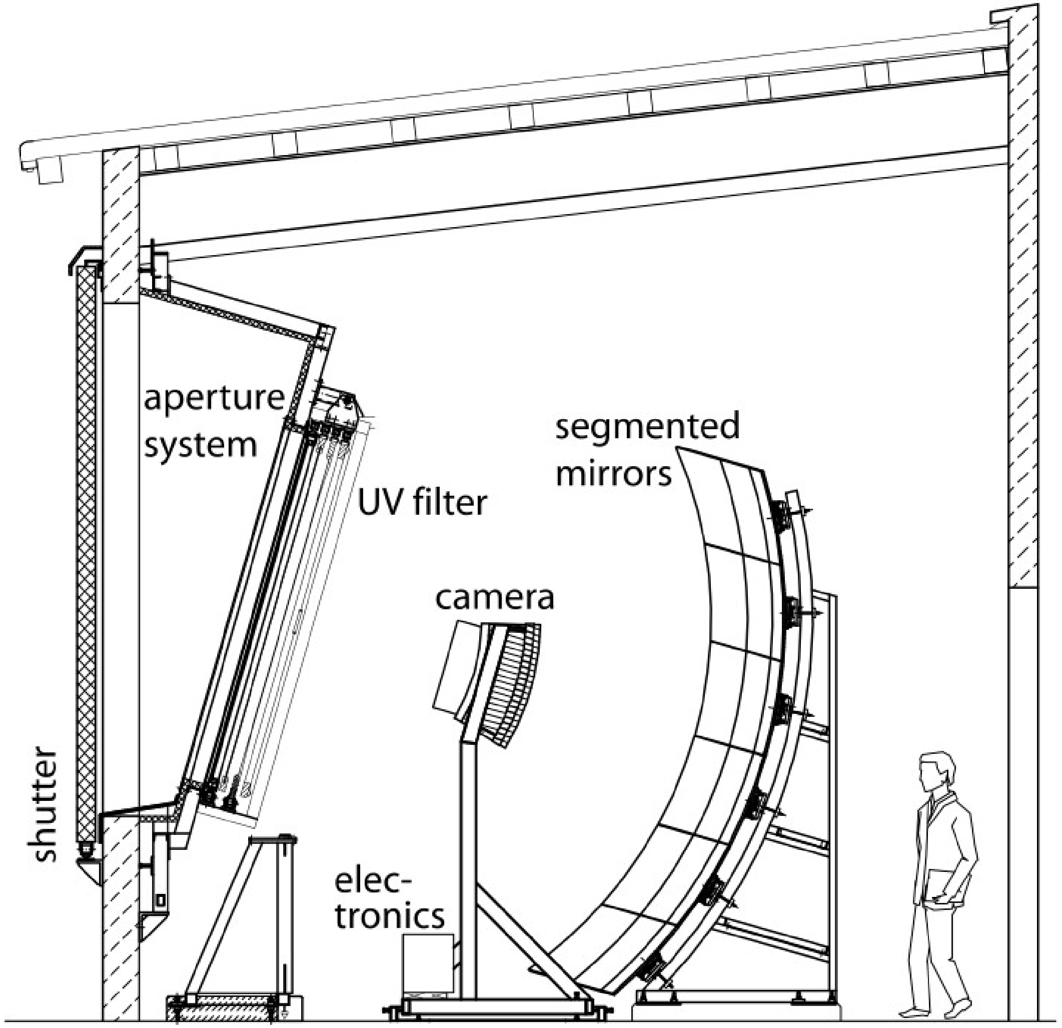
mirror 3 m^2

440 pixel camera
10 MHz sampling

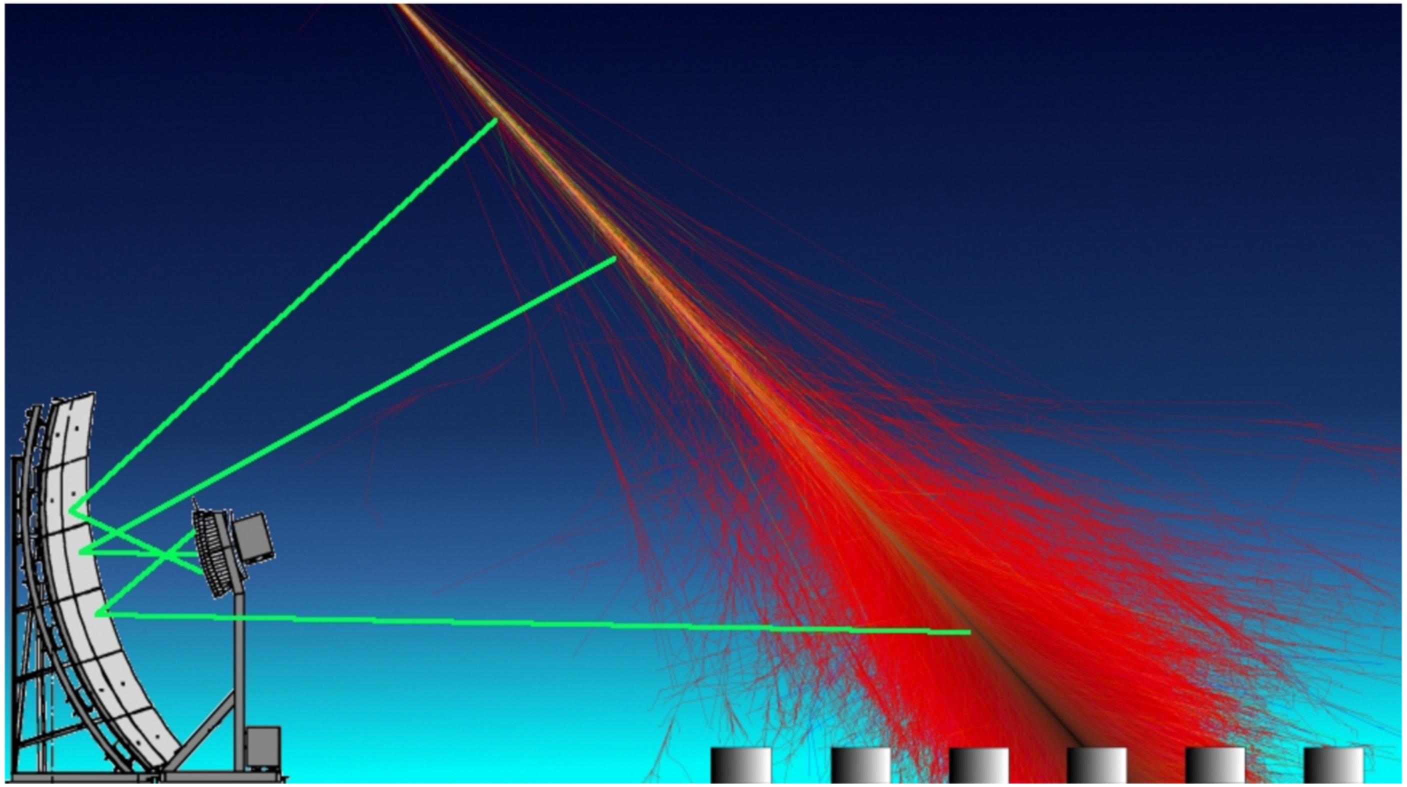


aperture, corrector ring and filter

A fluorescence telescope (FD)

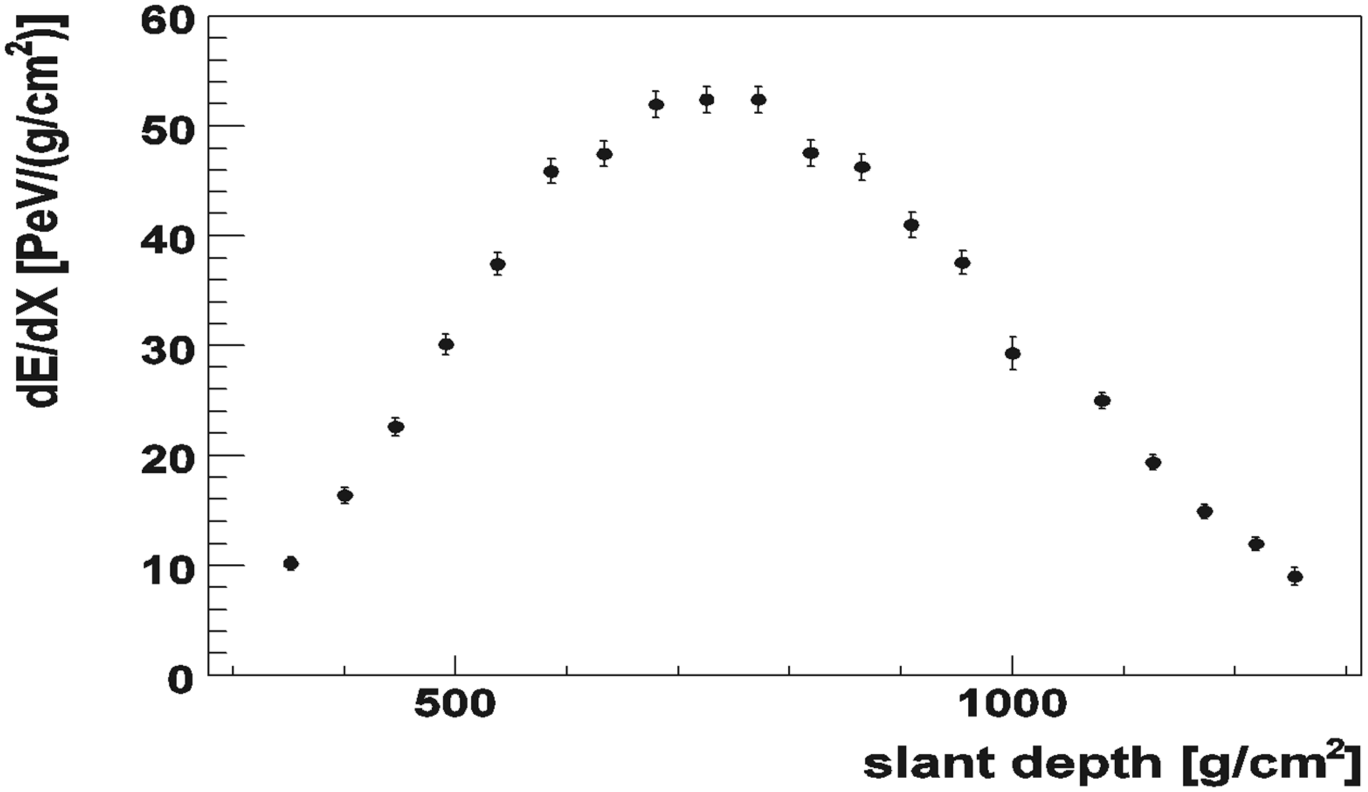


Telescope view



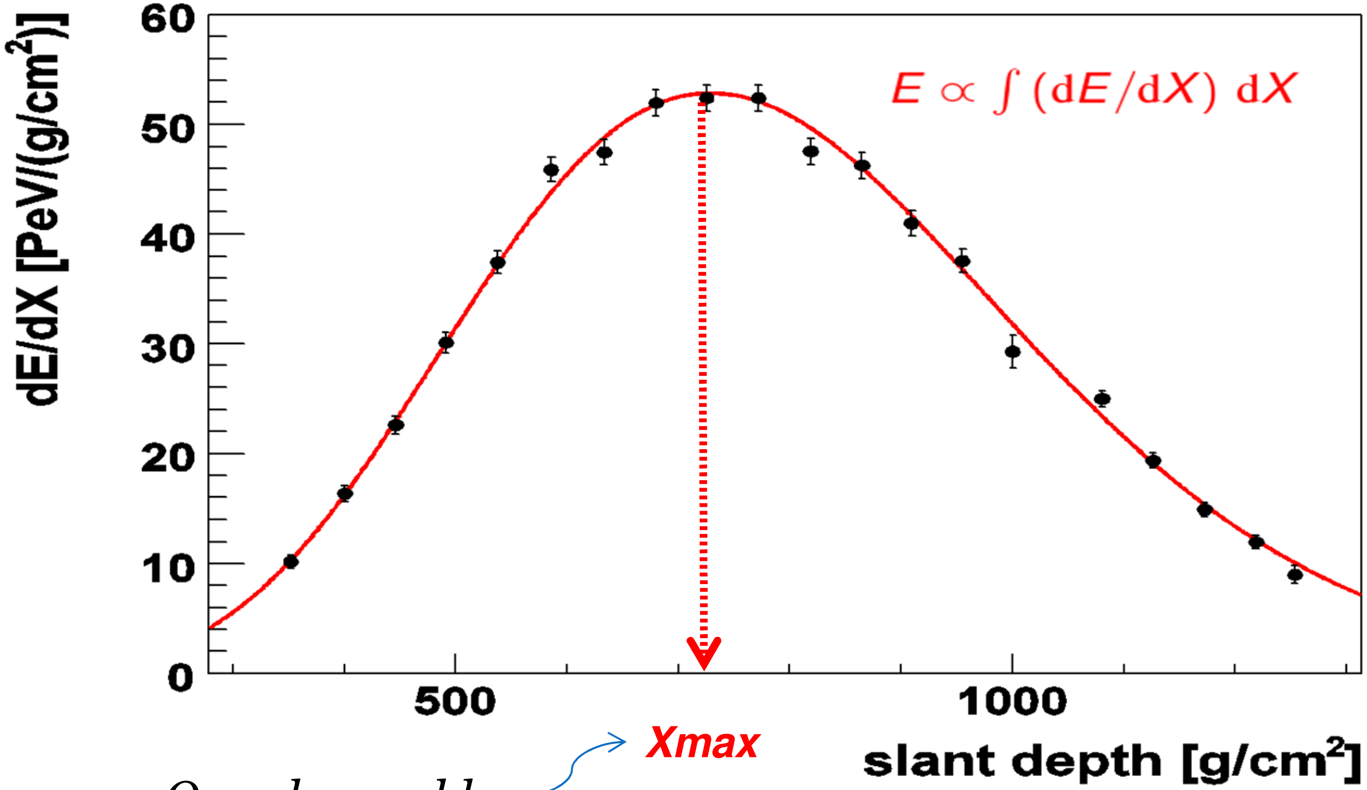
Telescopes measure the intensity and arrival time
of the fluorescence light

Longitudinal Profile



The intensity as a function of elevation can be transformed into the energy deposited in the atmosphere as a function of depth

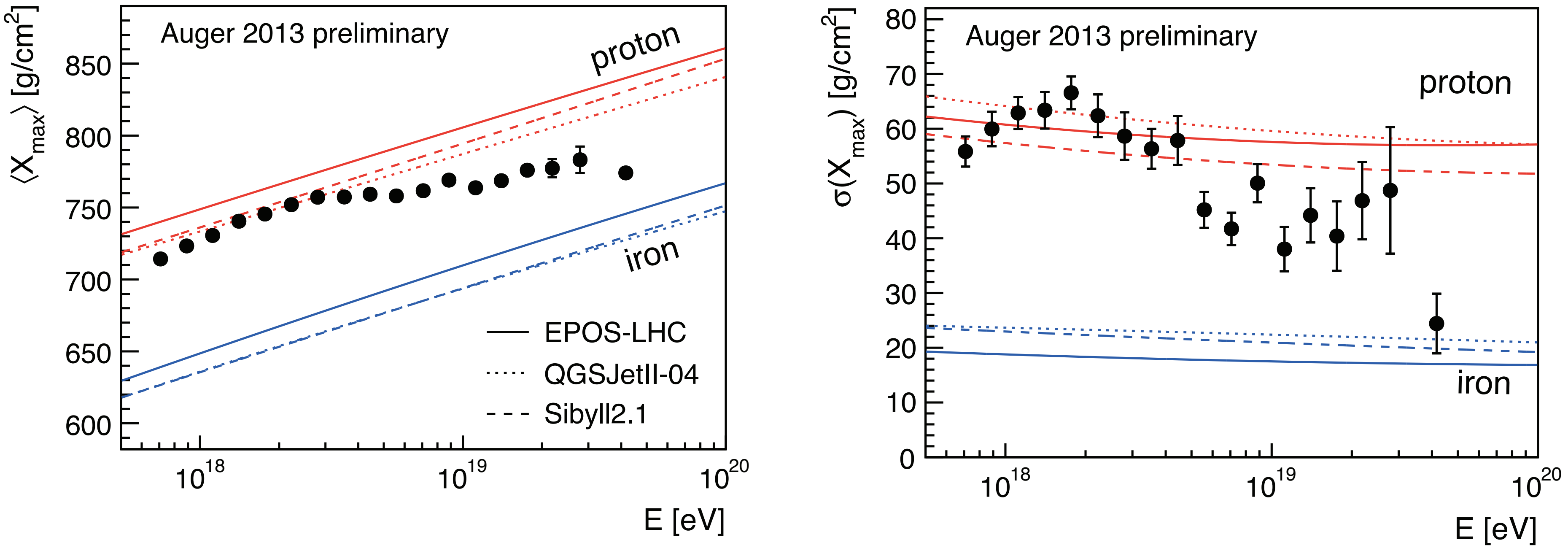
Fitting the Longitudinal Profile



Our observable

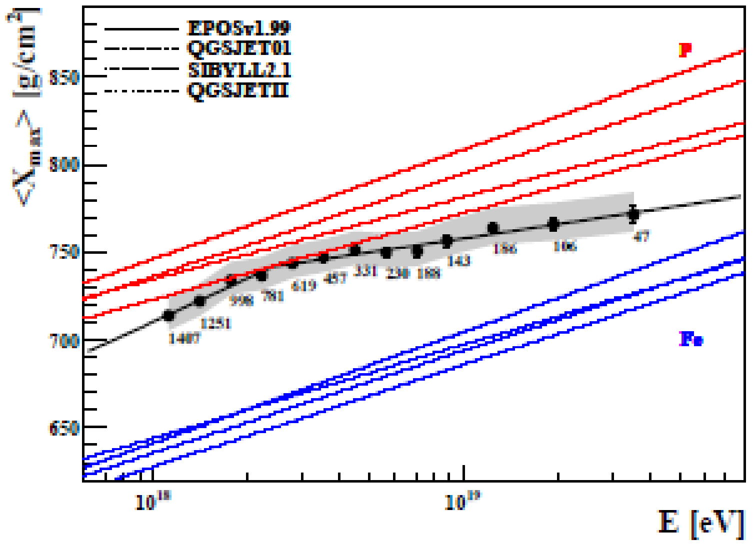
The total calorimetric energy of the shower is proportional to the integral of the energy deposited

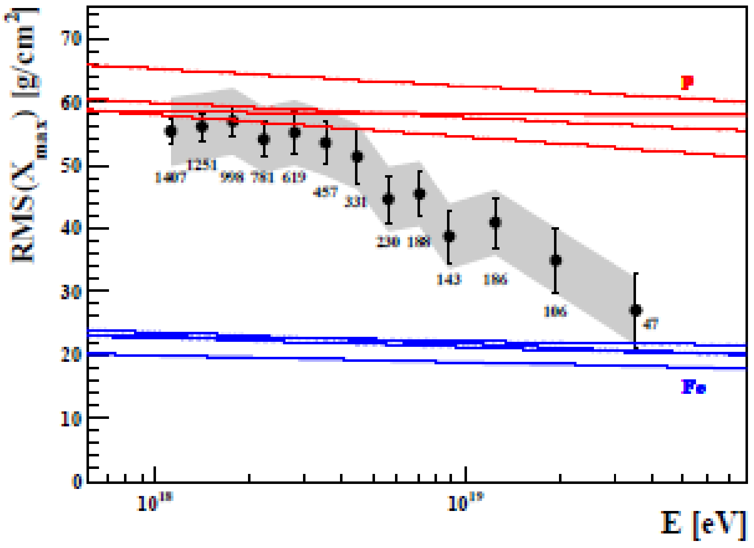
Studying the primary mass composition

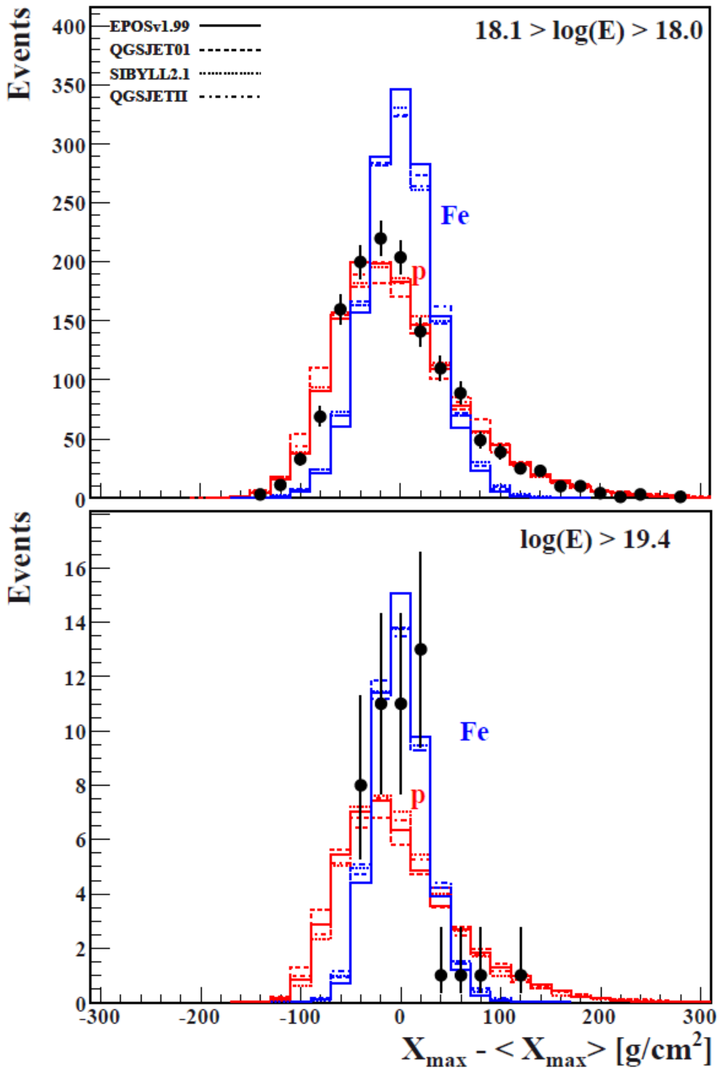


Letessier-Selvon for The Pierre Auger Collaboration, ICRC 2013

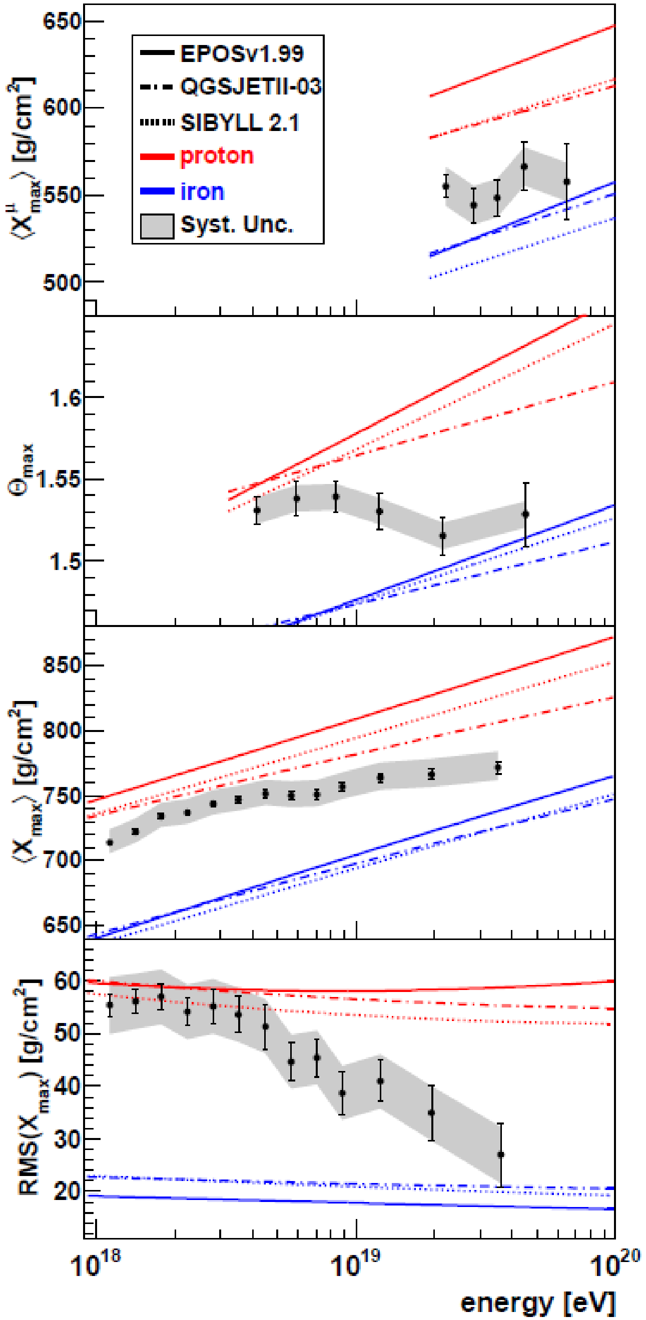
X_{max} and RMS (X_{max})







The Pierre Auger Collaboration, ICRC 2011

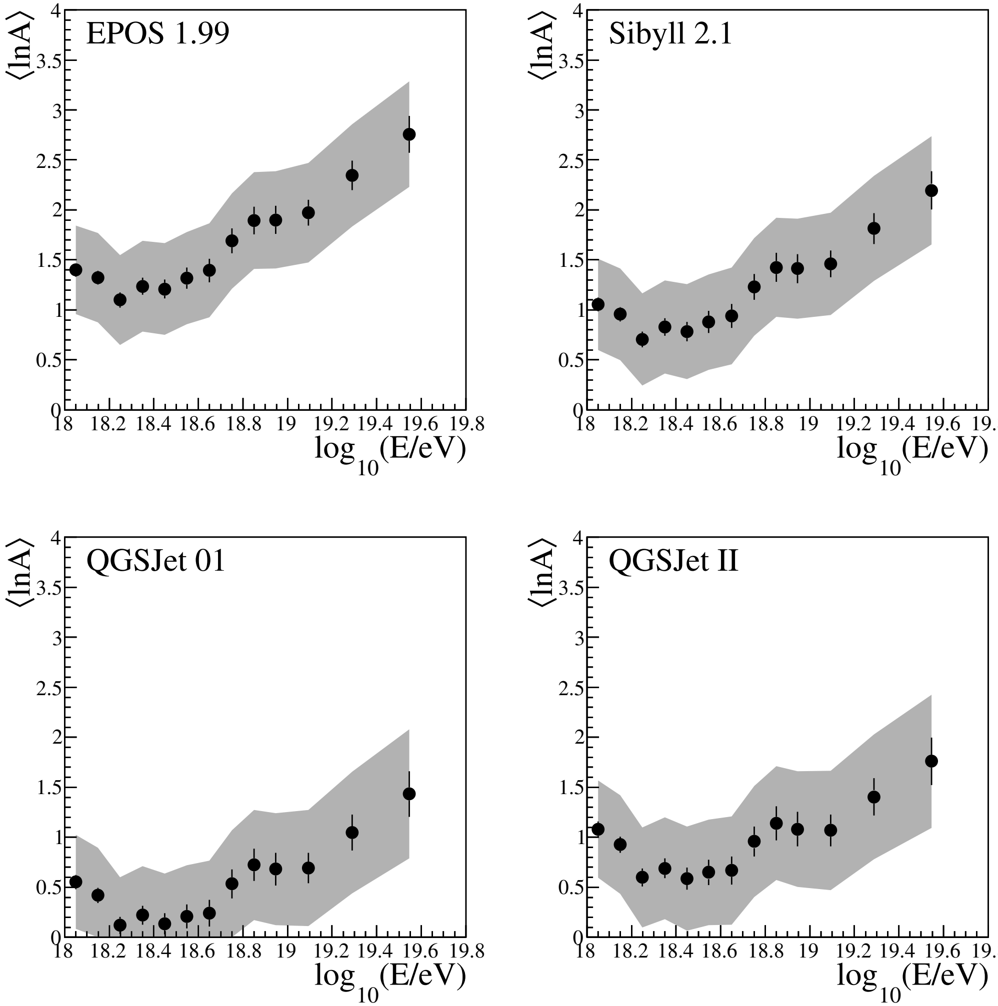


Results of the evolution of shower observables that are sensitive to X_{max} and comparison with predictions from various hadronic interaction models.

The Pierre Auger Collaboration, ICRC 2011

<*lnA*> as function of *logE* from Auger data

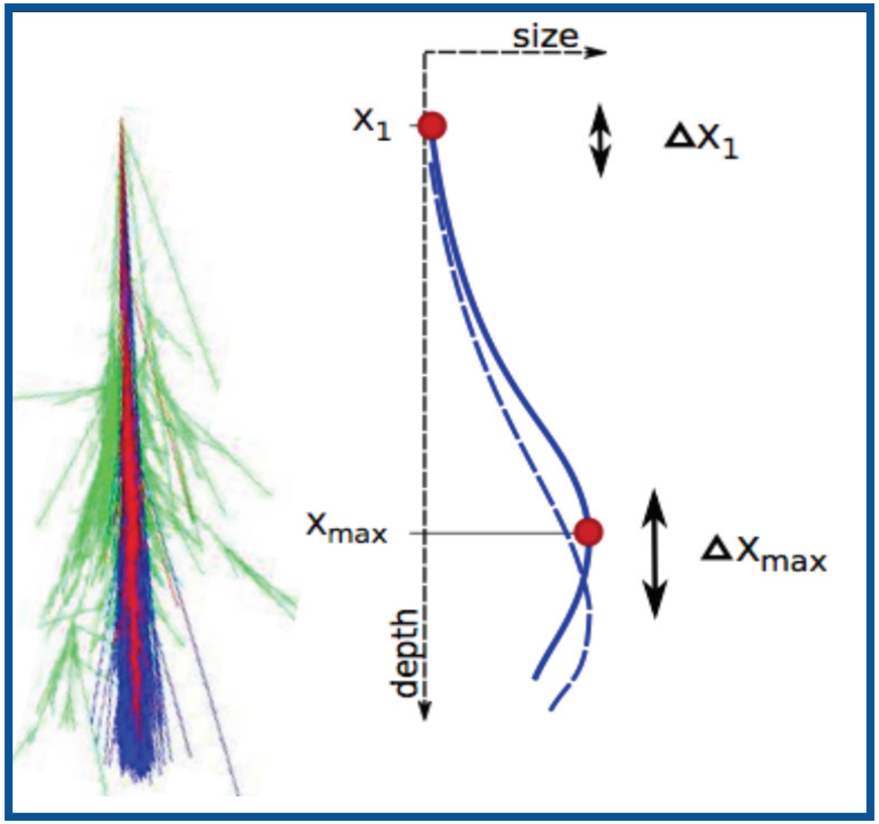
using different hadronic interaction models



The Pierre Auger Collaboration, JCAP 02 (2013) 026

Measuring cross section @ $\sqrt{s}$ = 57 TeV

- The path before the interaction, X_{1}, is a function of the p-air cross section.
- The fluorescence telescopes measure the position of the maximum of the shower, X_{max}.
- Use MC models to related X_{max} to X_{1}, and then $\sigma_{p\text{-}air}$.
- Using models, the value of σ_{inel} $(p\text{-}air)$ is inferred, and then using a technique based on the Glauber method, $\sigma_{\mathrm{inel}}\,(pp)$ is evaluated.



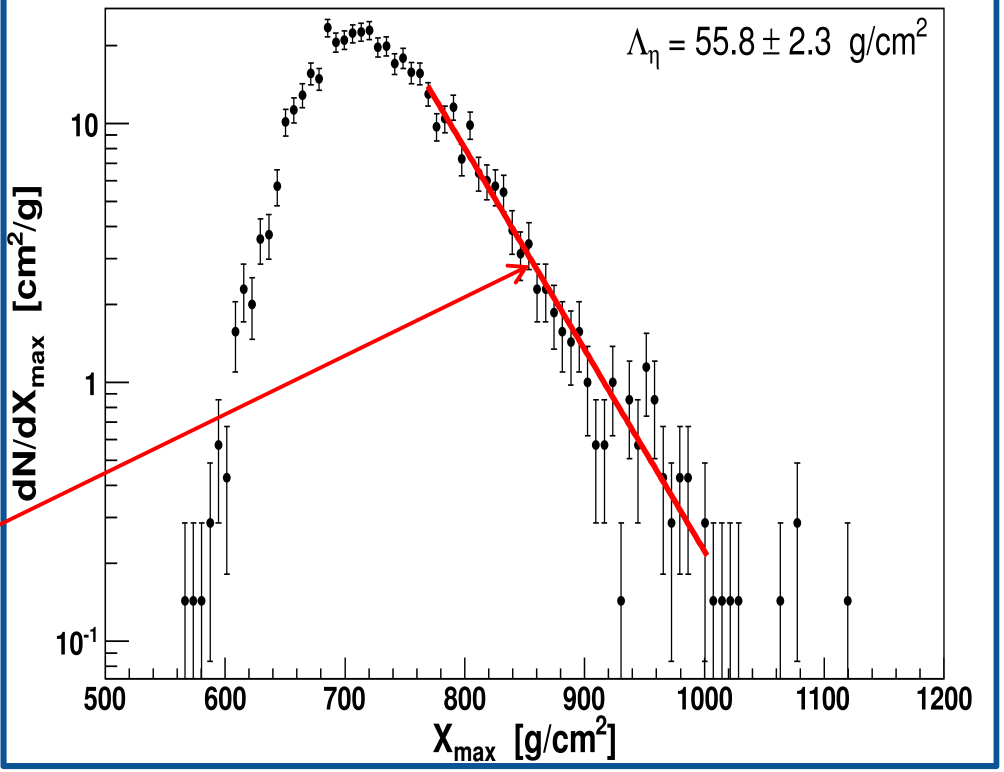
Selecting deep showers....

The position of the air shower maximum, at fixed energy, X_{max}, is sensitive to the cross section

$18<\log_{10}(E/eV)<18.5$
=> protons give a significant contribution to the overall flux

At these depths, protons showers dominate

$$\frac{dN}{dX_{max}} = exp\left(-\frac{X_{max}}{\Lambda_\eta}\right)$$

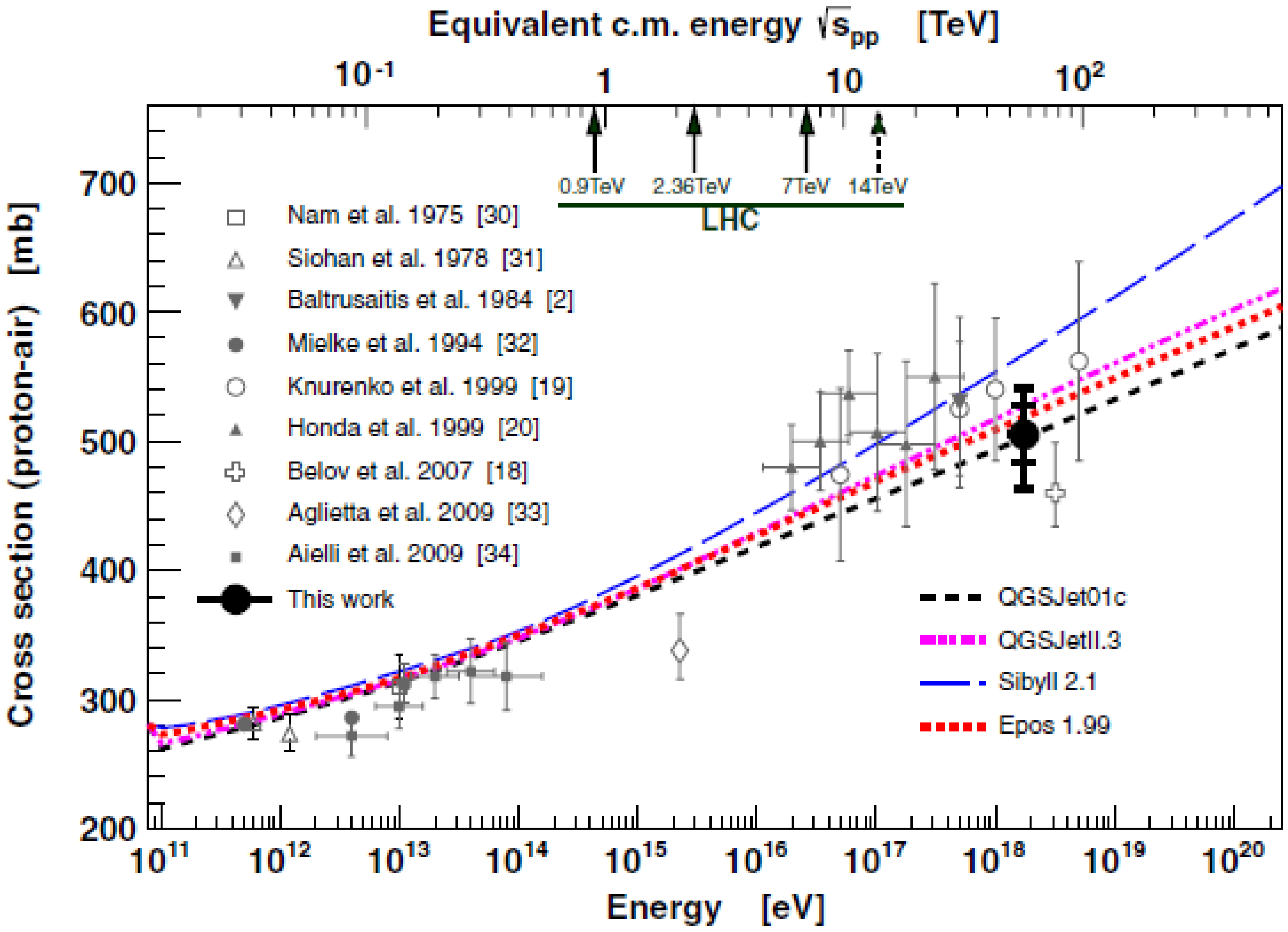


The PA Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

proton-air cross section for particle production

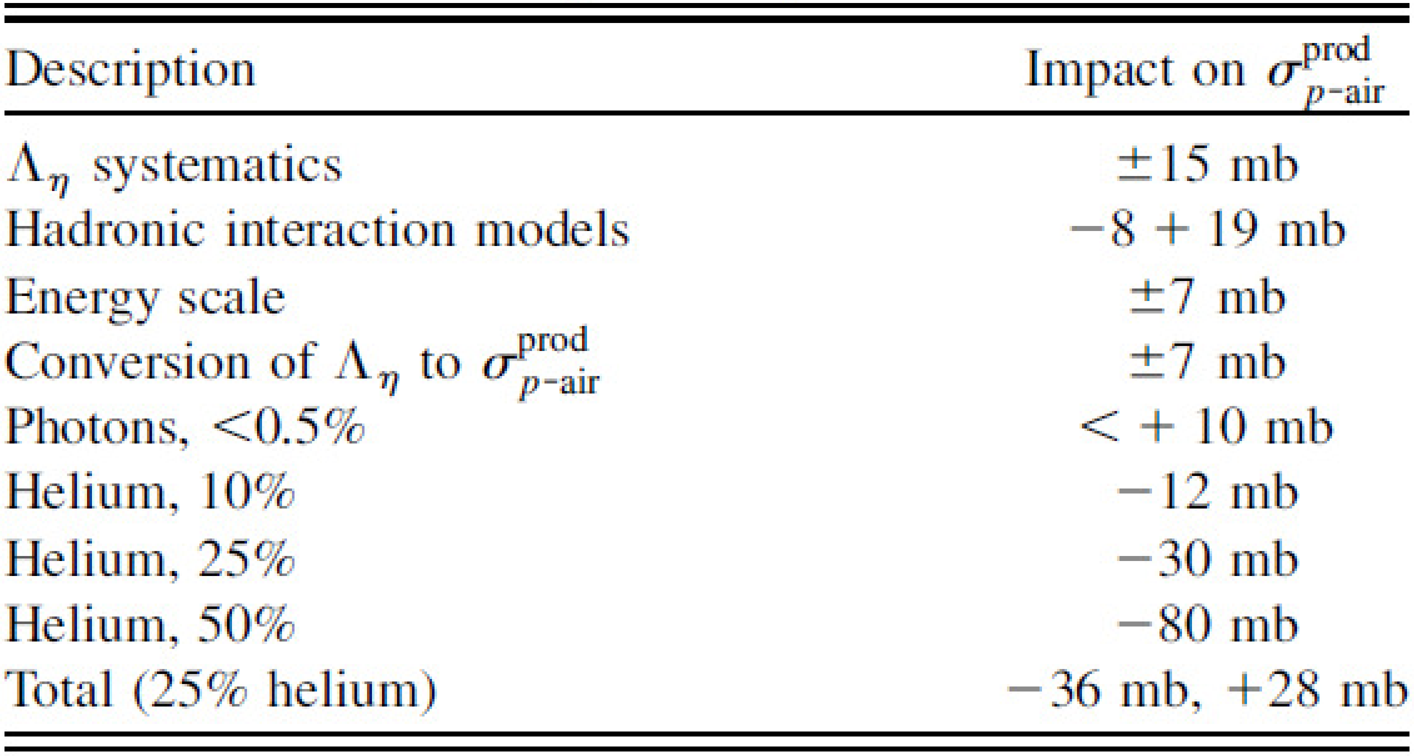
First:

$$\sigma_{p-air}^{prod} = \left(505 \pm 22\Big|_{stat} {}^{+28}_{-36}\Big|_{syst}\right) mb$$



The PA Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

TABLE I. Summary of the systematic uncertainties.



Description	Impact on $\sigma_{p\text{-air}}^{\text{prod}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$-8 + 19$ 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

The PA Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

The basic concepts…

$$\Gamma_{hA}\left(\vec{b}\right)=1-\prod_{j=1}^{A}\left[1-\int \Gamma_{hN}\left(\vec{b}-\vec{s}_{j}\right)\rho_{j}\left(\vec{r}_{j}\right)d^{3}r_{j}\right]$$

$$\sigma_{hA}^{tot}=\frac{4\pi}{\left|\vec{k}\right|}\Im m\left\{f_{ii}^{hA}(S,\vec{q}_{2}\to 0)\right\}=2\Re e\int \Gamma_{hA}\left(\vec{b}\right)d^{2}b$$

$$\sigma_{hA}^{ela}=\int \frac{1}{\left|\vec{k}\right|^{2}}\left|f_{ii}^{hA}(S,\vec{q}_{2})\right|^{2}d^{2}q=\int \left|\Gamma_{hA}\left(\vec{b}\right)\right|^{2}d^{2}b$$

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

Elastic scattering and inelastic diffraction

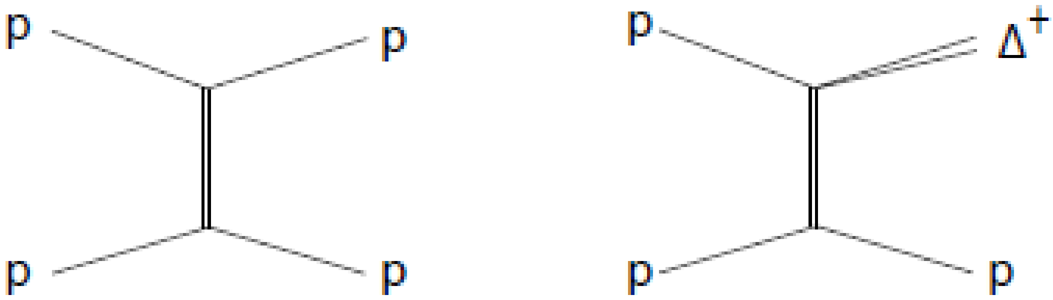
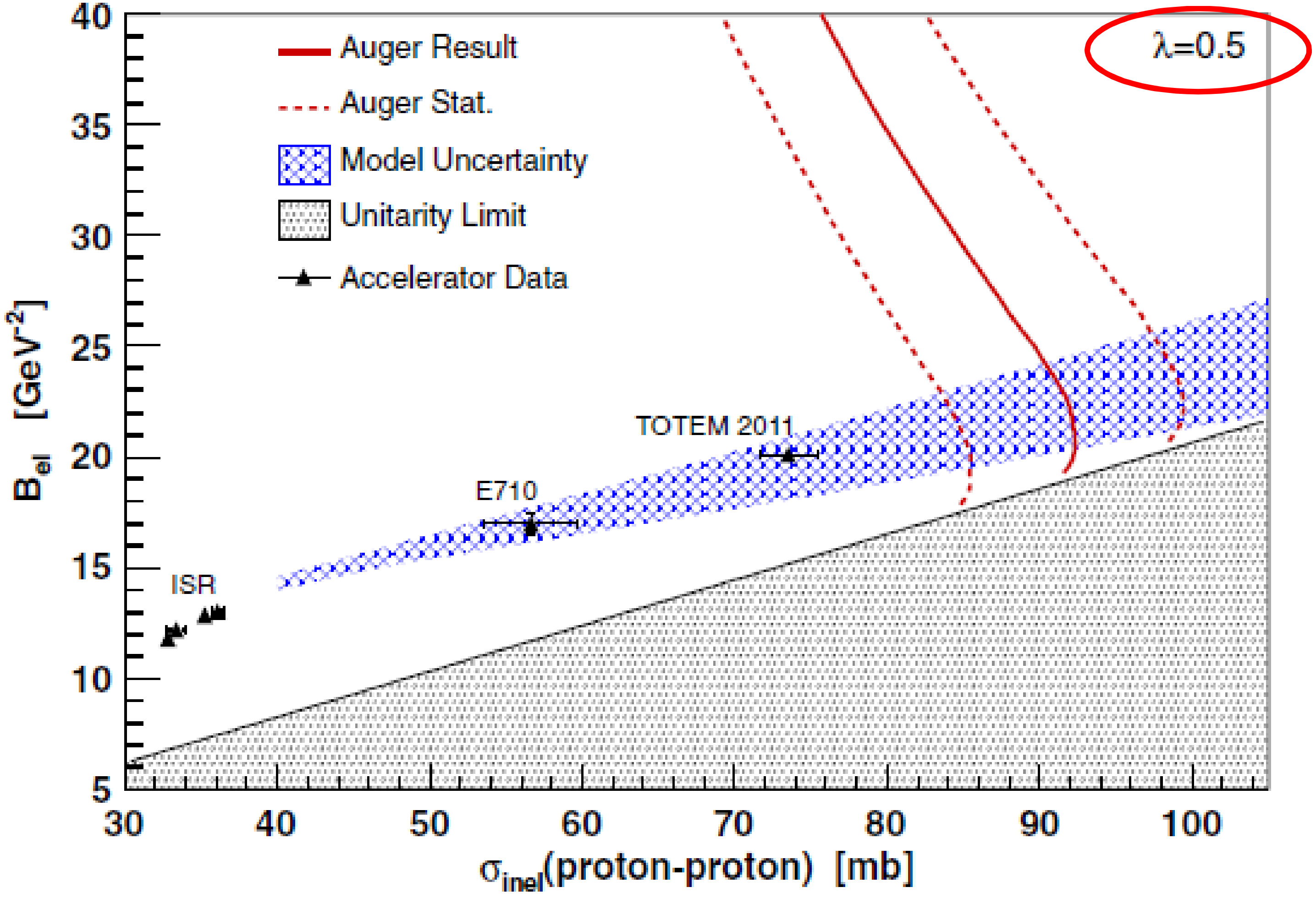


Figure 1: Left panel: Elastic scattering, Right panel: inelastic diffraction.

Step by step….

- Parametrization of the p-p and p-n cross sections and of the ratio real/imaginary part of the scattering amplitude
- Parametrization of the energy dependence of the data on single diffraction dissociation
- Determination of the ratio of the cross sections for diffraction dissociation and elastic scattering in depedence on the maxima mass of the diffractive system as parameter $M_{D,max}$
- Calibration of the parameter $M_{D,max}$ with proton-carbon data
- Application of this value for the mass limit in the Glauber calculation to convert the measured proton-air cross section to the *pp* inelastic cross section

Correlation of B_{el} and $\sigma^{inel}(pp)$ in Glauber

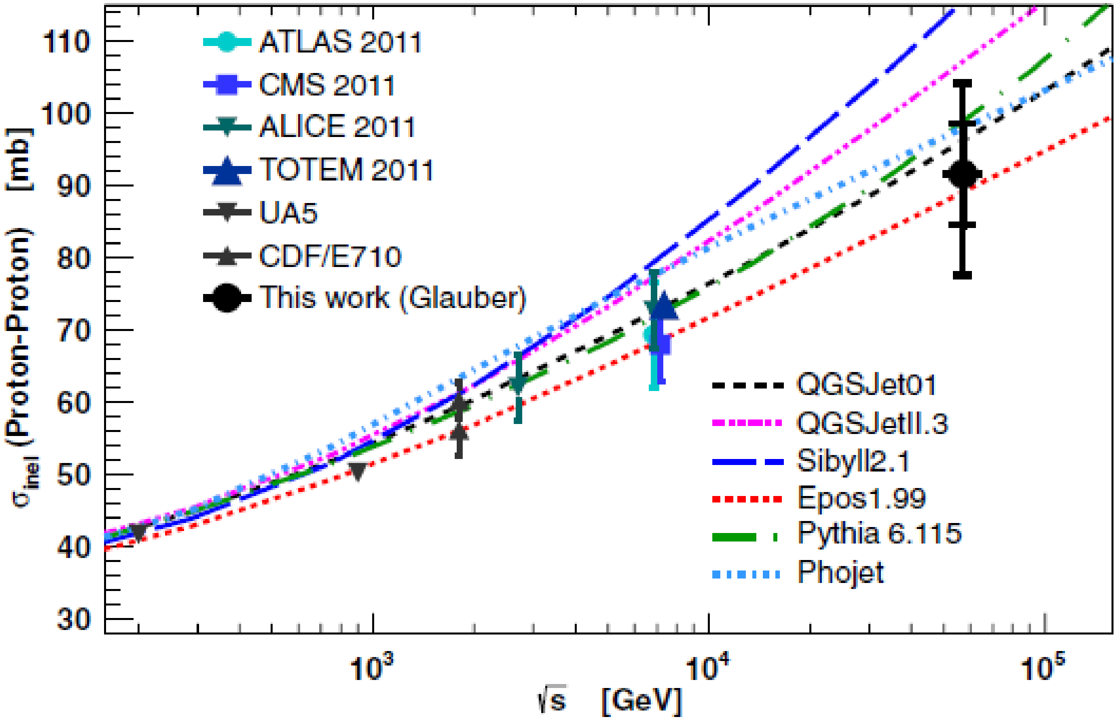


The PA Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

proton-proton cross section

$$\sigma_{pp}^{inel} = \left(92 \pm 7\big|_{stat}\ {}^{+9}_{-11}\big|_{syst}\ \pm 7\big|_{Glauber}\right) mb$$

$$\boldsymbol{\sigma_{pp}^{tot}} = \left(133 \pm 13\big|_{\boldsymbol{stat}}\ {}^{+17}_{-20}\big|_{\boldsymbol{syst}}\ \pm 16\big|_{\boldsymbol{Glauber}}\right) \boldsymbol{mb}$$



σ_{pp} is inferred using an extended Glauber approach: calculation with parameters from accelerator measurements @ lower energies that are extrapolated to CR energies

The PA Collaboration, Phys. Rev. Lett. 109, 062002 (2012)

Final results:

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

$$\sigma_{pp}^{tot} = \left[133 \pm 13\,(stat) + 17/-20\,(syst) \pm 16\,(Glauber)\right]\ mb$$

ACKNOWLEDGEMENTS

FAPESP