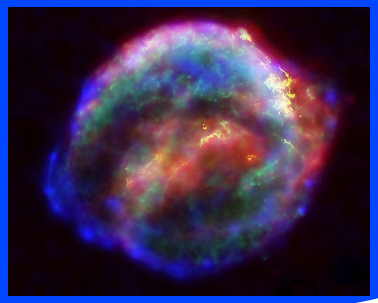
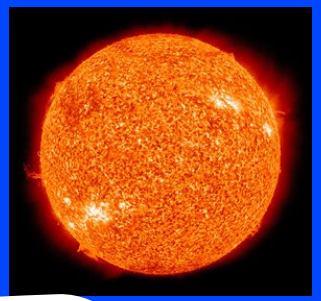
Measurements of High Energy Particle Interaction Properties with the Pierre Auger Cosmic Ray Observatory

(p-p cross section at 57 TeV)

SNR



Sun



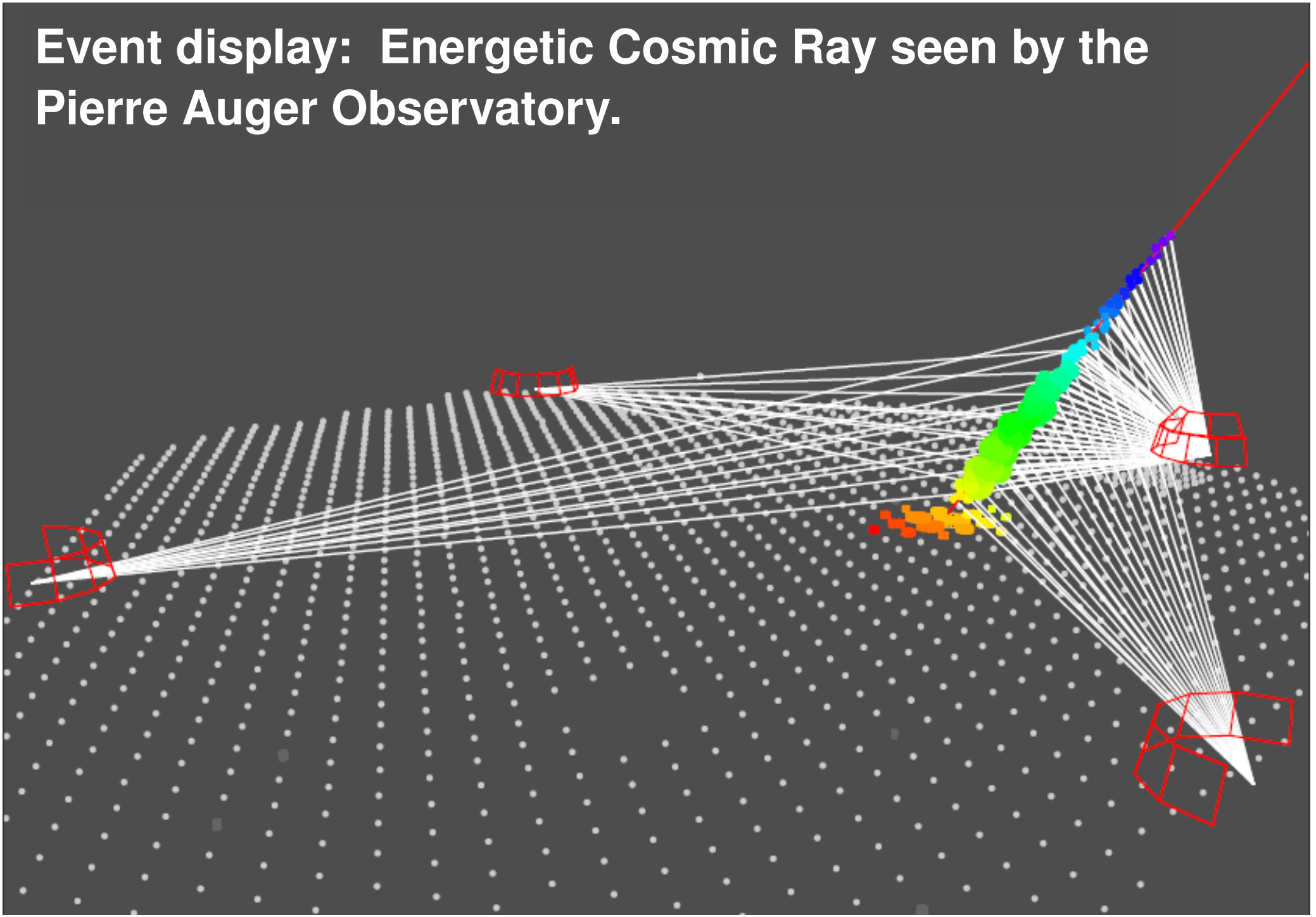
Galactic centre

Jose Bellido on behalf of the Pierre Auger Collaboration

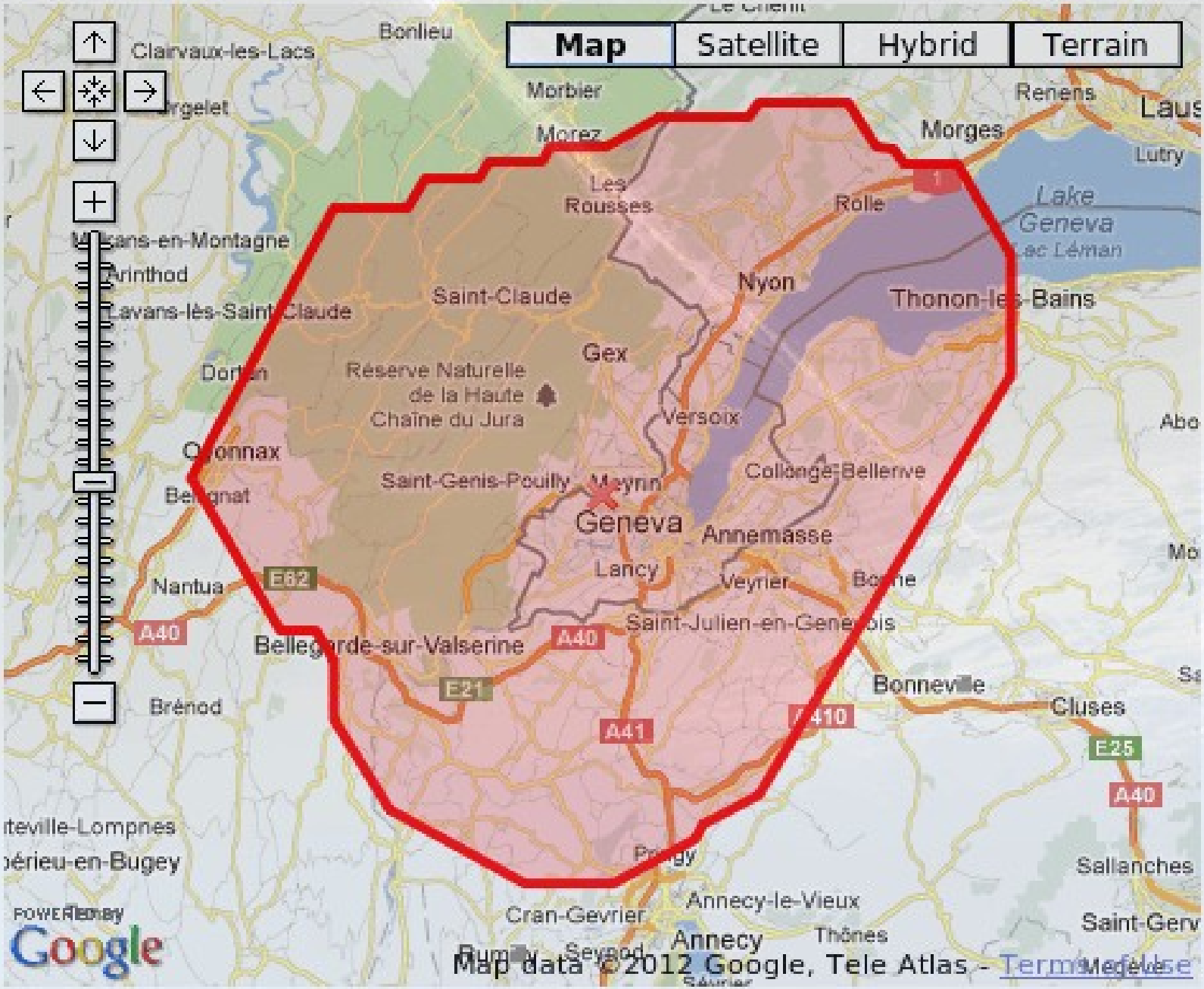
THE UNIVERSITY of ADELAIDE

ICHEP 2012
Melbourne, July 2012

Event display: Energetic Cosmic Ray seen by the Pierre Auger Observatory.



Size of the Pierre Auger Observatory

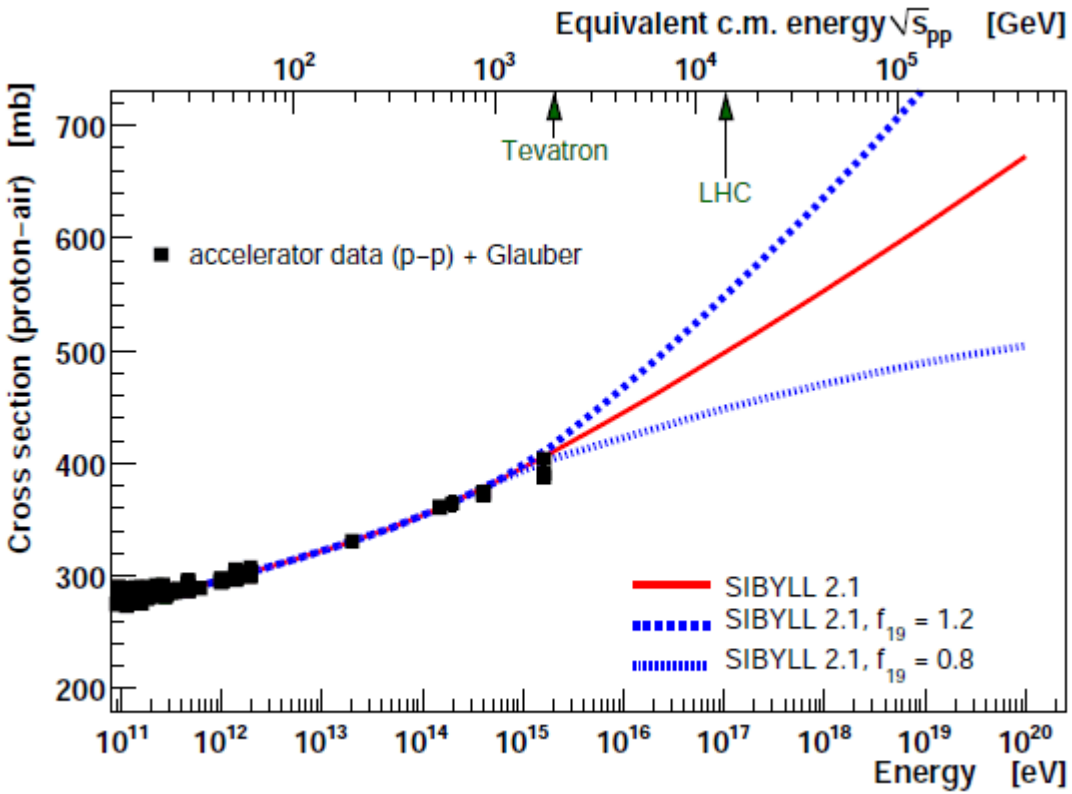


See Auger superimposed over Cern, geneve GO

The Pierre Auger Observatory has been designed to detect the highest energy cosmic rays and determine their:

- Arrival directions
- Energy
- Mass composition

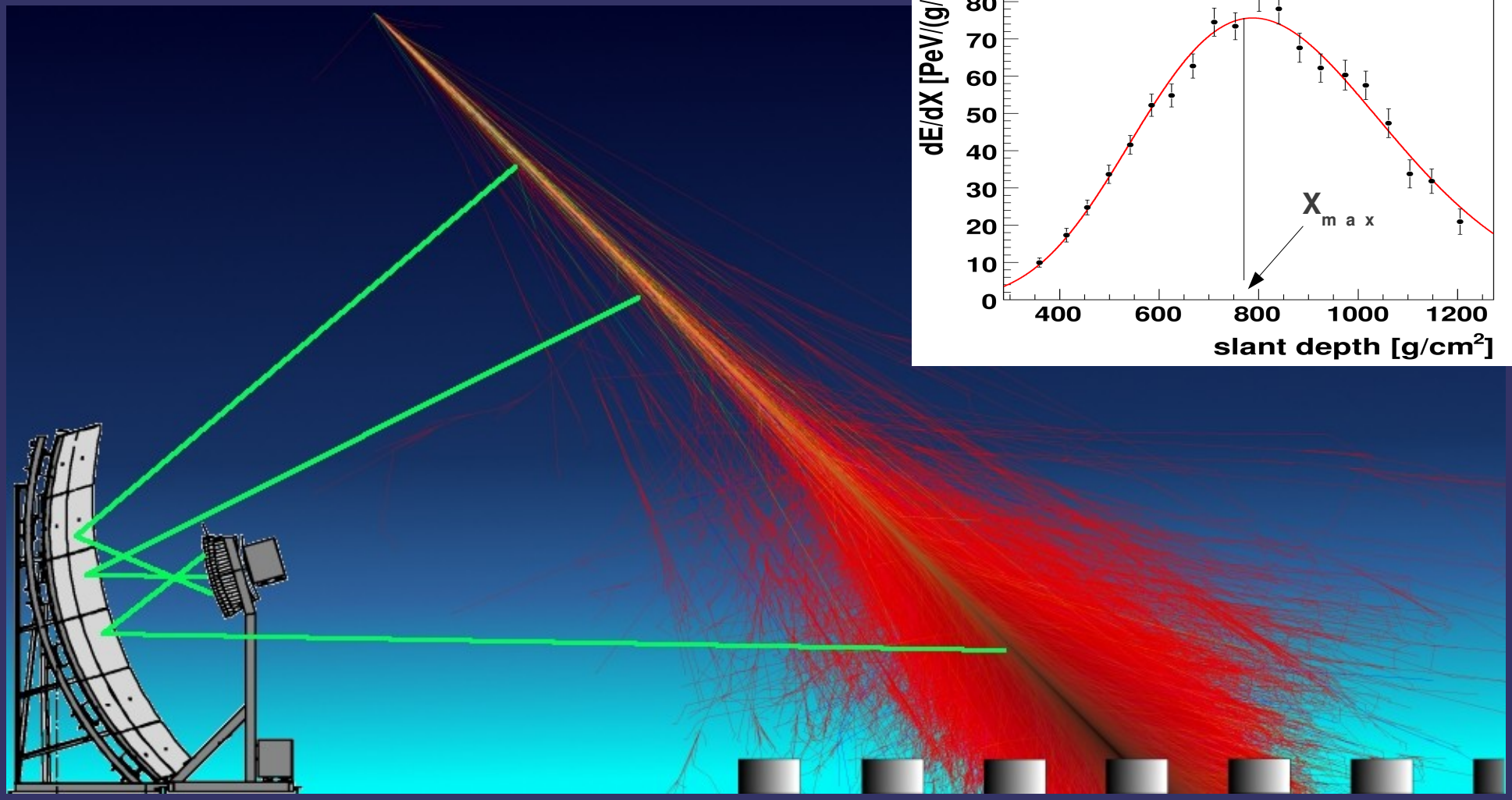
However, there is a problem to determine their mass composition. We need to extrapolate the particle interaction properties from particle accelerators energies to nearly three orders of magnitude higher energies and these extrapolations have unknown associated uncertainties. Fortunately the LHC is closing this gap soon!.

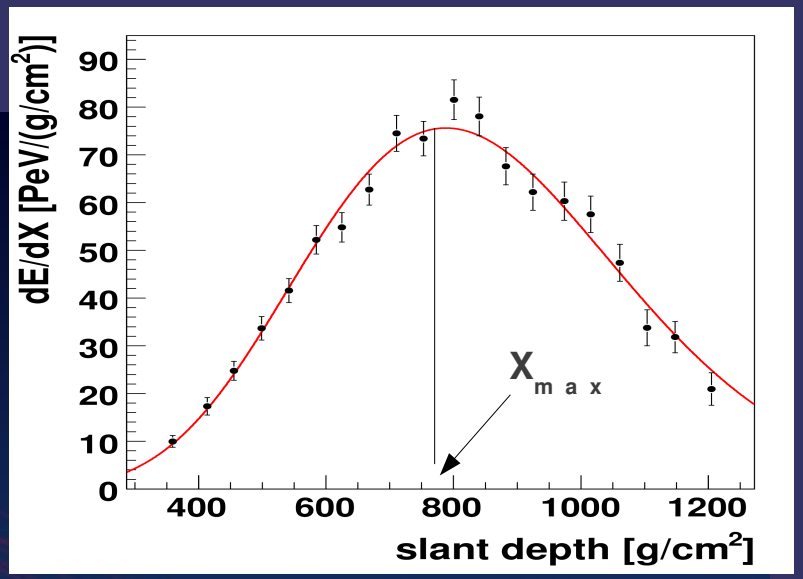


Mass Composition Measurements

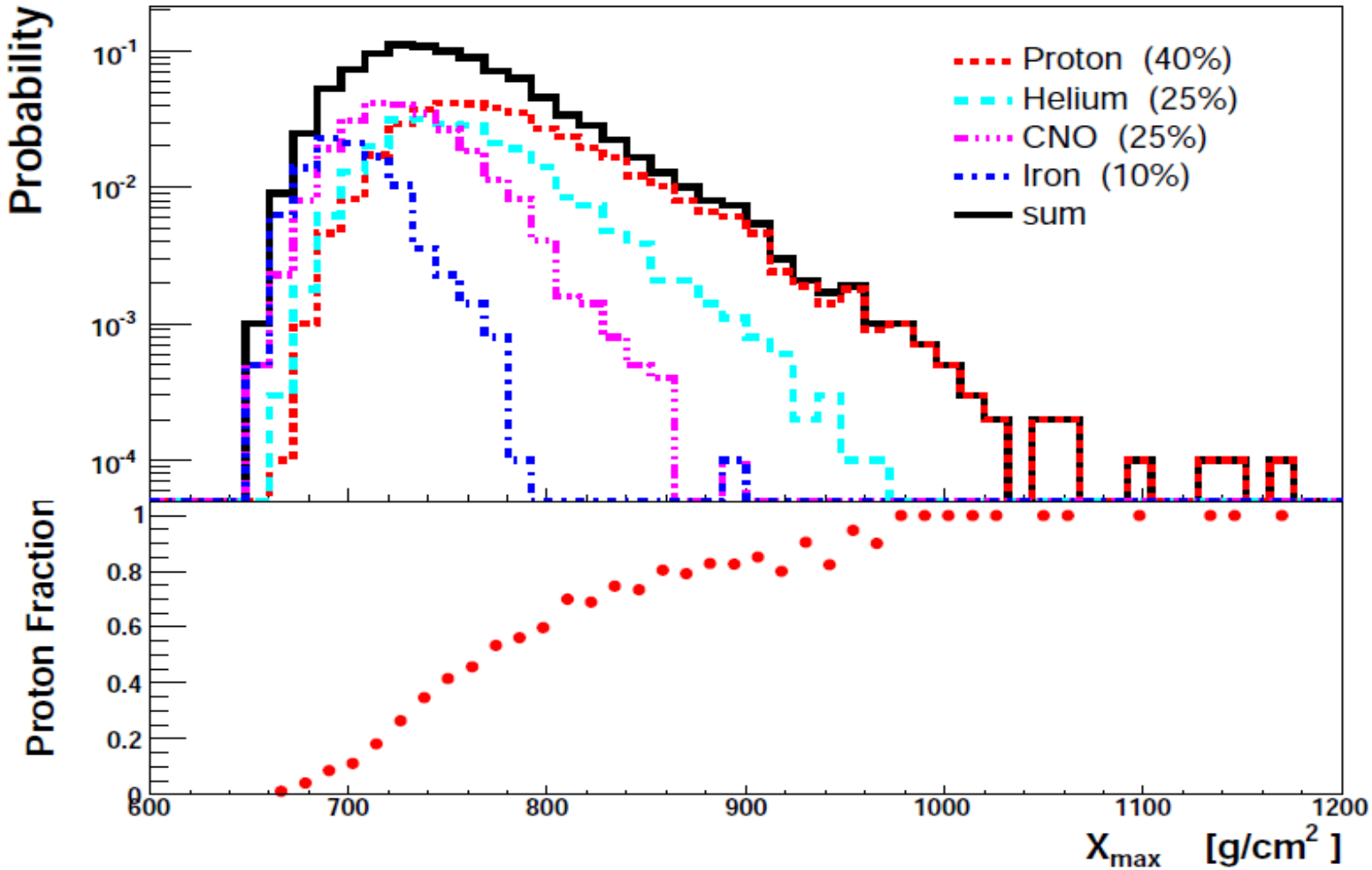
The Fluorescence detector measures the longitudinal shower profiles

The X_{max} resolution is in average 20 g/cm²





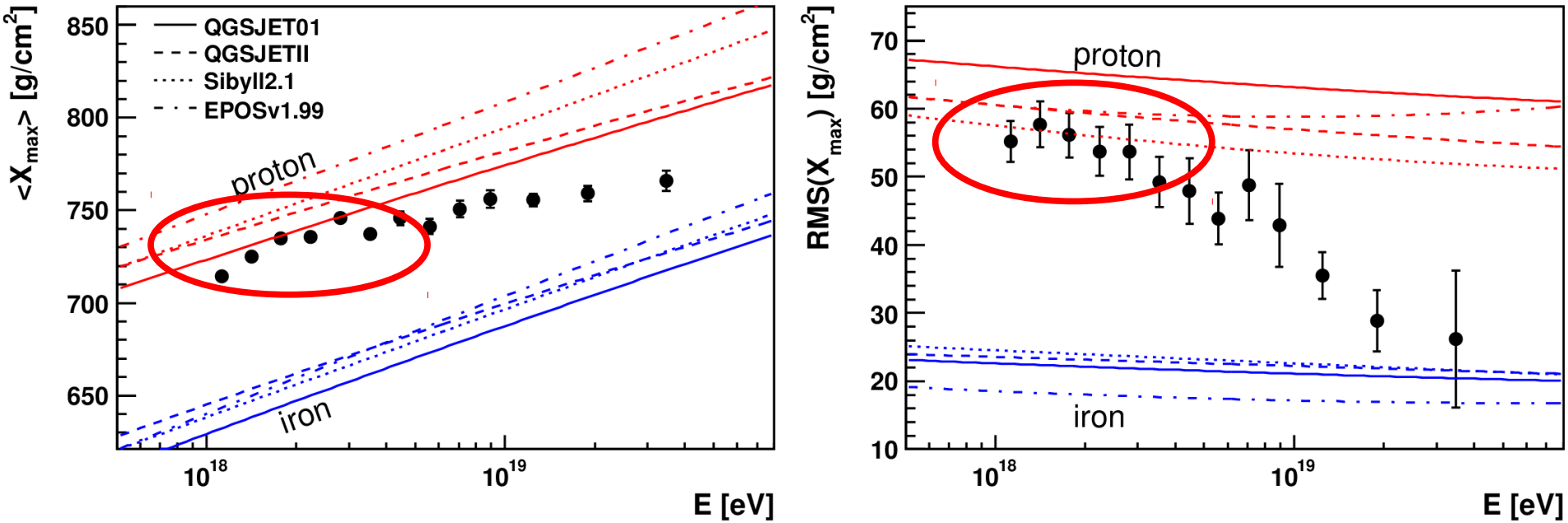
Fluctuations of Depth of Shower Maximum (Xmax)



The Xmax distribution for protons has a larger tail. Then, as long as there are some protons in the cosmic ray composition, the tail of the Xmax distribution will be populated by proton cosmic rays. This is important because <u>we will measure the tail of the Xmax distribution to estimate the p-p cross section</u>.

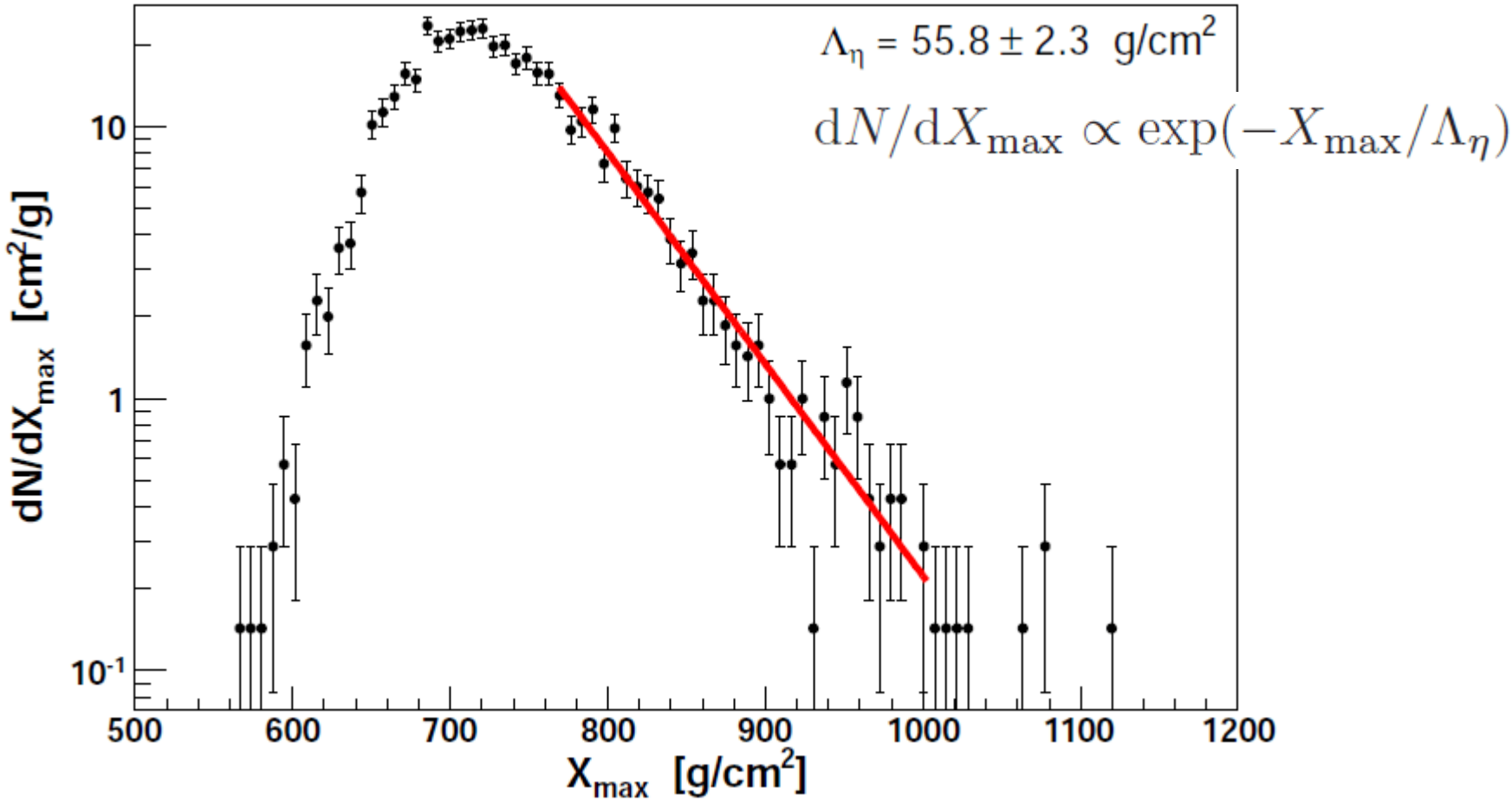
Ellworth et al. PRD 1982, Baltrusaitis et al. PRL 1984, etc...

Xmax observations indicate that at energies between 10^{18}-$10^{18.5}$ the composition is proton dominated



Physics Review Letters 104, 091101 (2010)

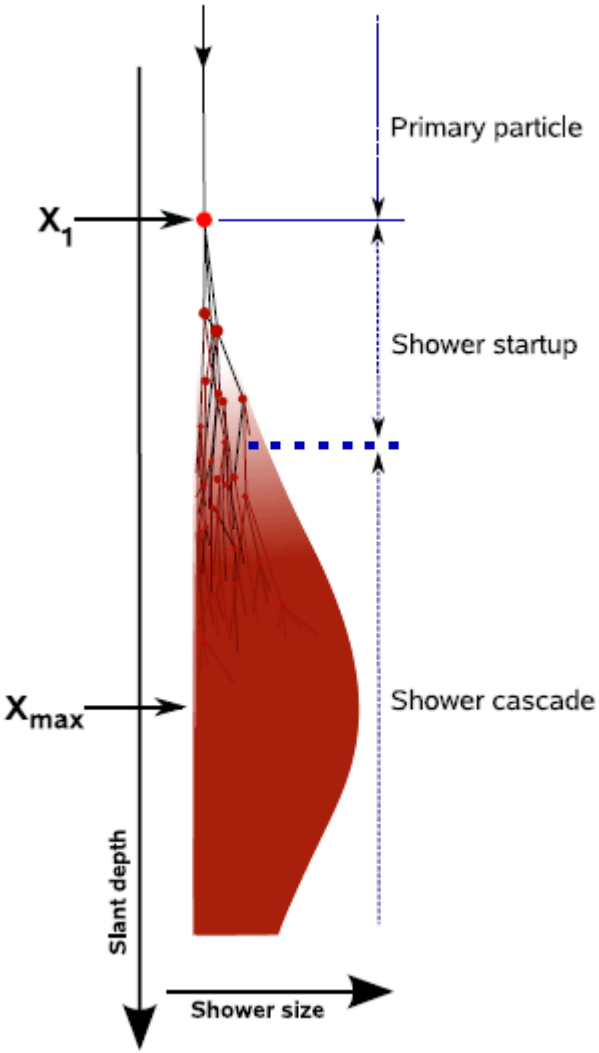
Observed Xmax distribution at energies between 10^{18}-$10^{18.5}$eV



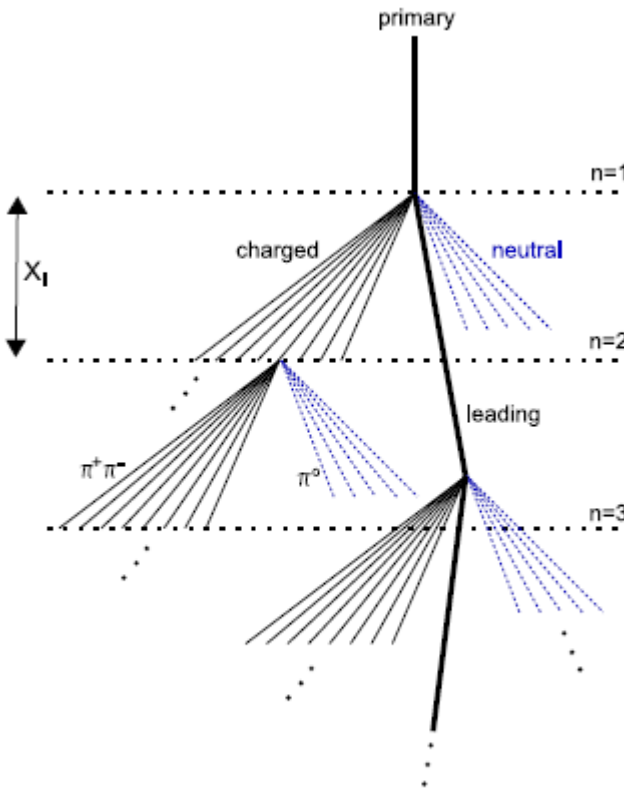
$$\Lambda_\eta = [55.8 \ \pm 2.3(\mathrm{stat}) \ \pm 1.6(\mathrm{sys})] \ \mathrm{g/cm}^2$$

Next step is to convert Λ_η to p-p cross section ...

Observed shower profile



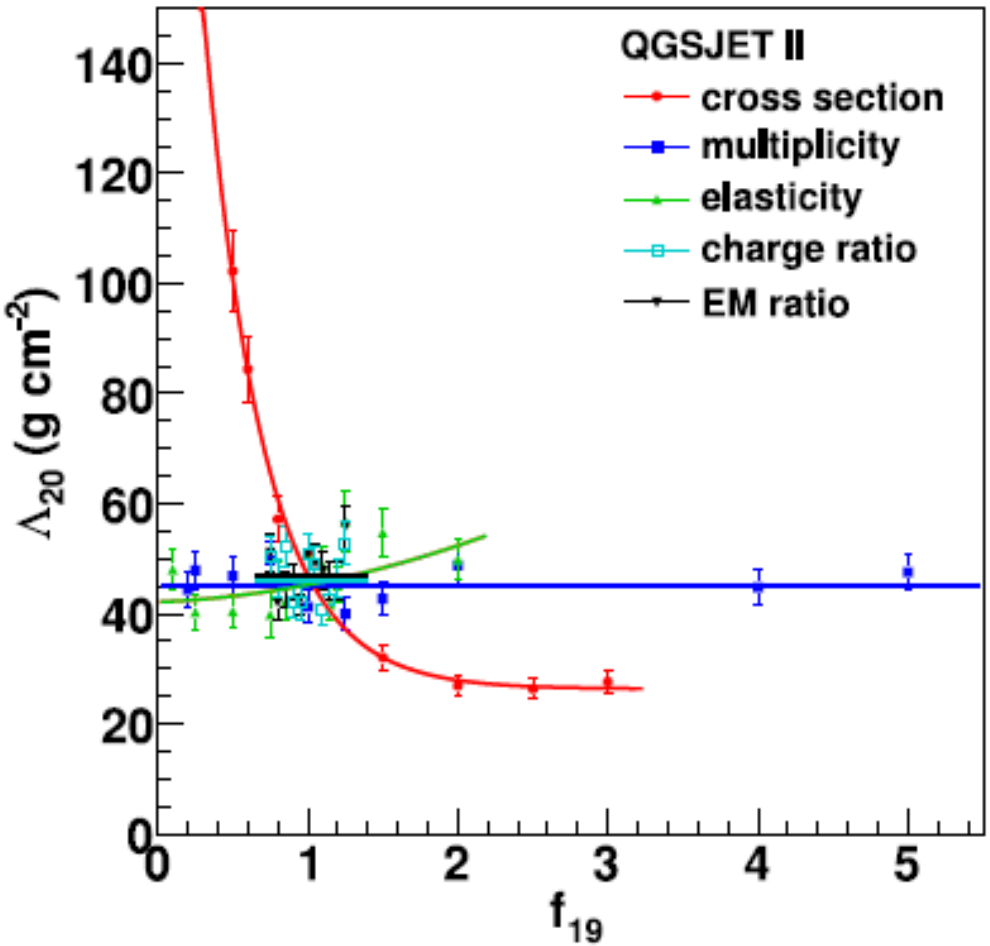
Physics behind the shower profile

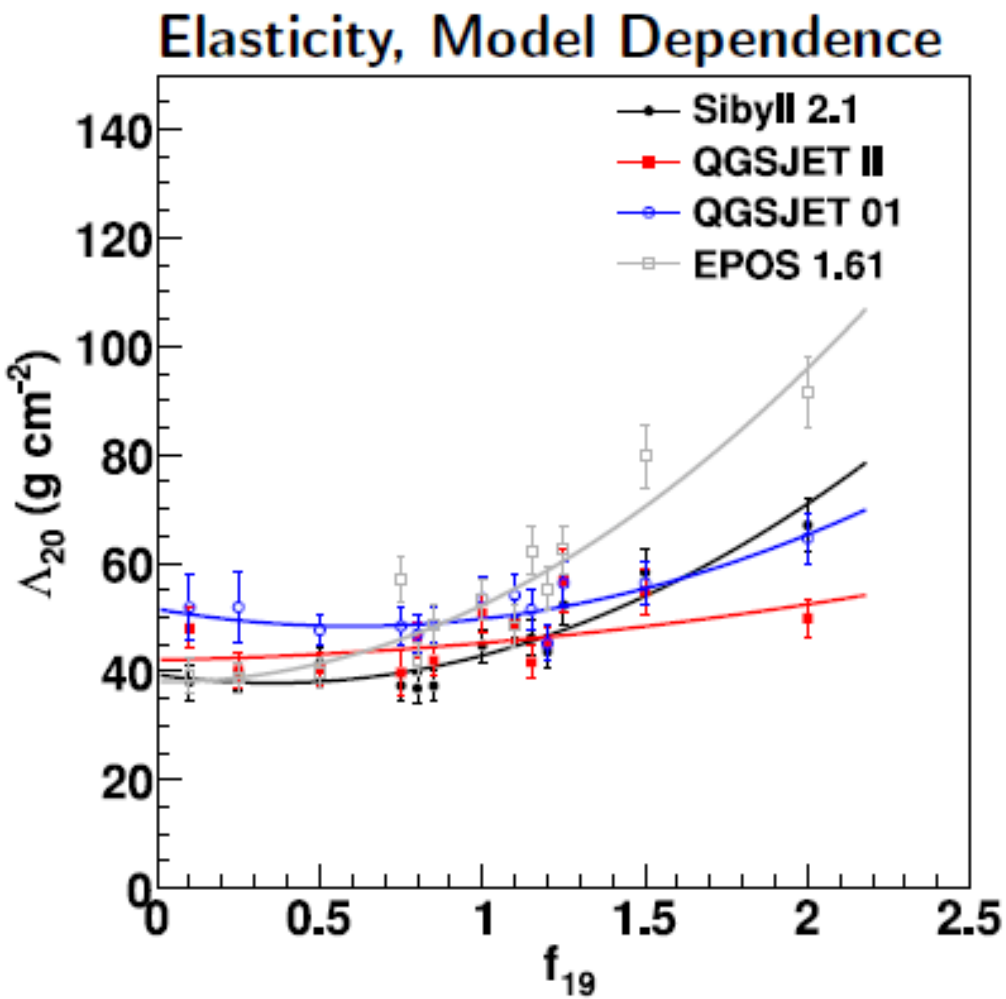


- Cross Section: λ
- Multiplicity: n_{mult}
- Ratio of energy going into e.m. particles: $r_{\mathrm{e.m.}} = E_{\mathrm{e.m.}}/E_{\mathrm{tot}}$
- Charge ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$
- Elasticity: $k_{\mathrm{ela}} = E_{\mathrm{max}}/E_{\mathrm{tot}}$
- Particle Spectra
- Nuclear primaries: A

Impact of particle interaction properties on the tail of the Xmax distribution

The cross section is the parameter that has by far the greatest impact on the tail of the Xmax distribution (Λ_η). However, the elasticity has a non negligible impact. So, its uncertainty is considered when estimating the systematic uncertainties of the estimated p-p cross section.





Summary of systematic uncertainties

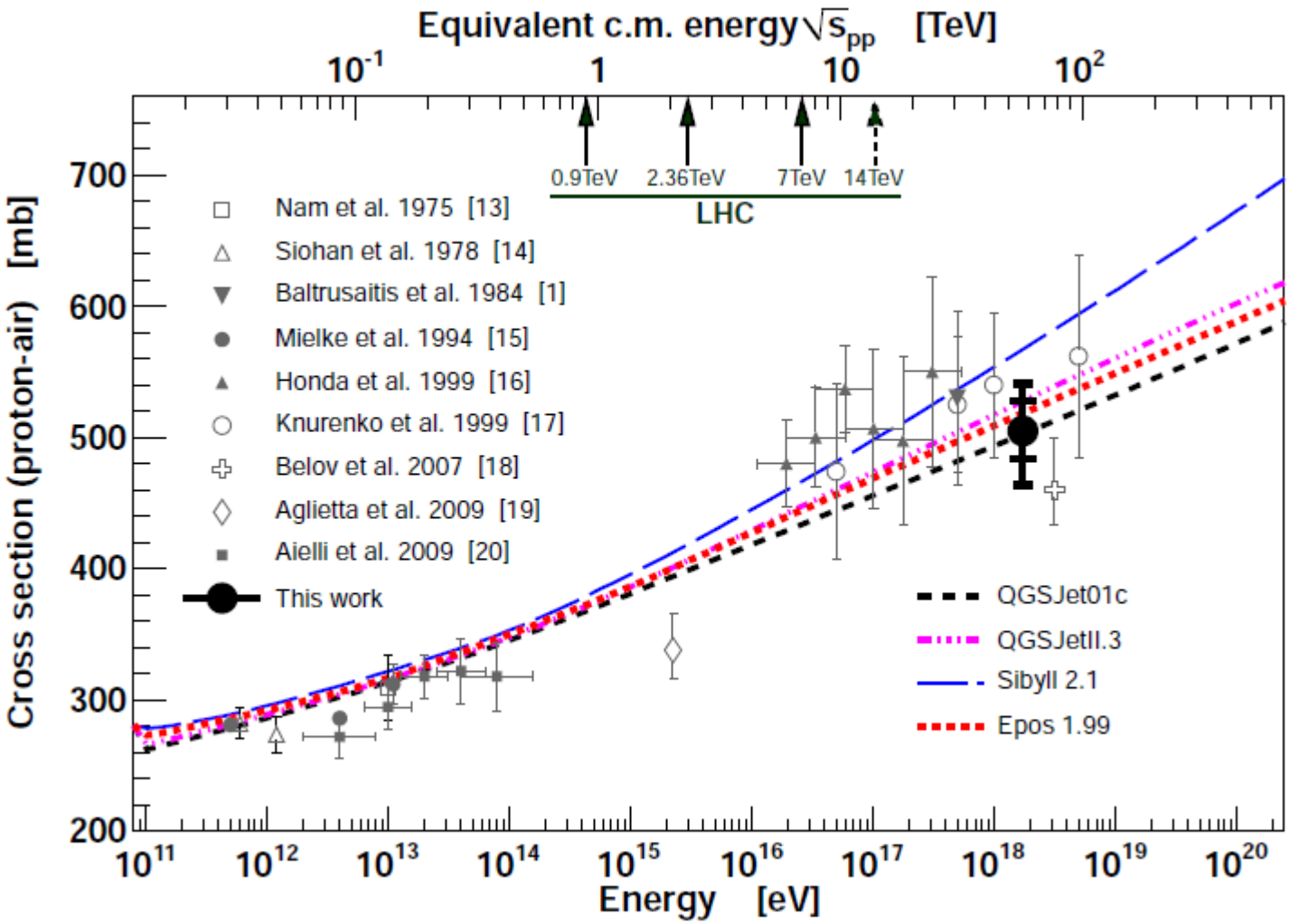
Description	Impact on $\sigma^{\text{prod}}_{p\text{-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, <0.5 %	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb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

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

At [57 ± 0.3(stat) ± 6(sys)] TeV

- Overall Monte Carlo model systematics not dominating
- Helium bias potentially most dangerous
- Total systematics on same level as statistical resolution

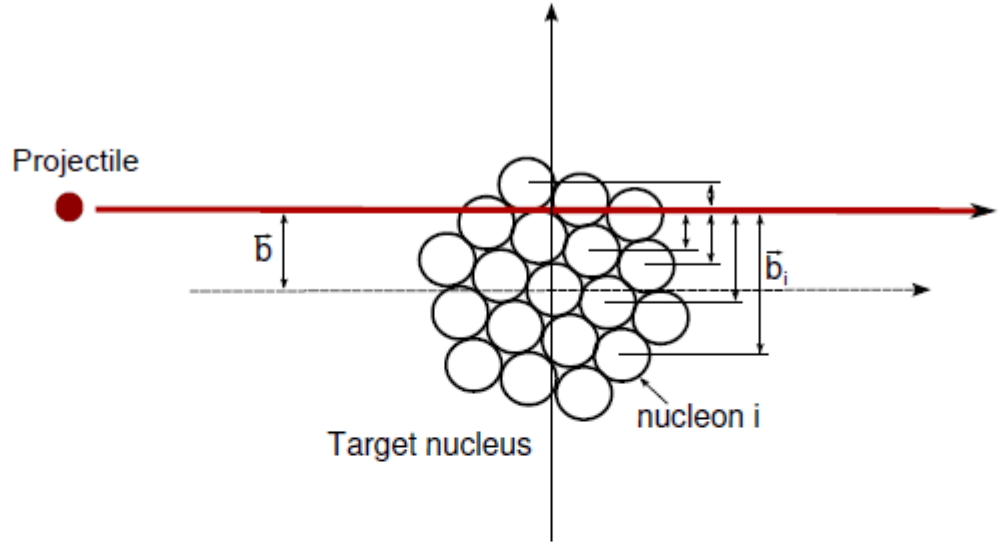
Lines come from measurements in particle accelerators (below 1TeV c.m. energy) and from extrapolations. Data points correspond to measurements using cosmic ray data. The solid circle correspond to Auger measurements.



Conversion of p-air cross section to p-p cross section (Glauber formalism)

R. Ulrich et. al.

Nucl.Phys.Proc.Suppl. 196 (2009) 335-340



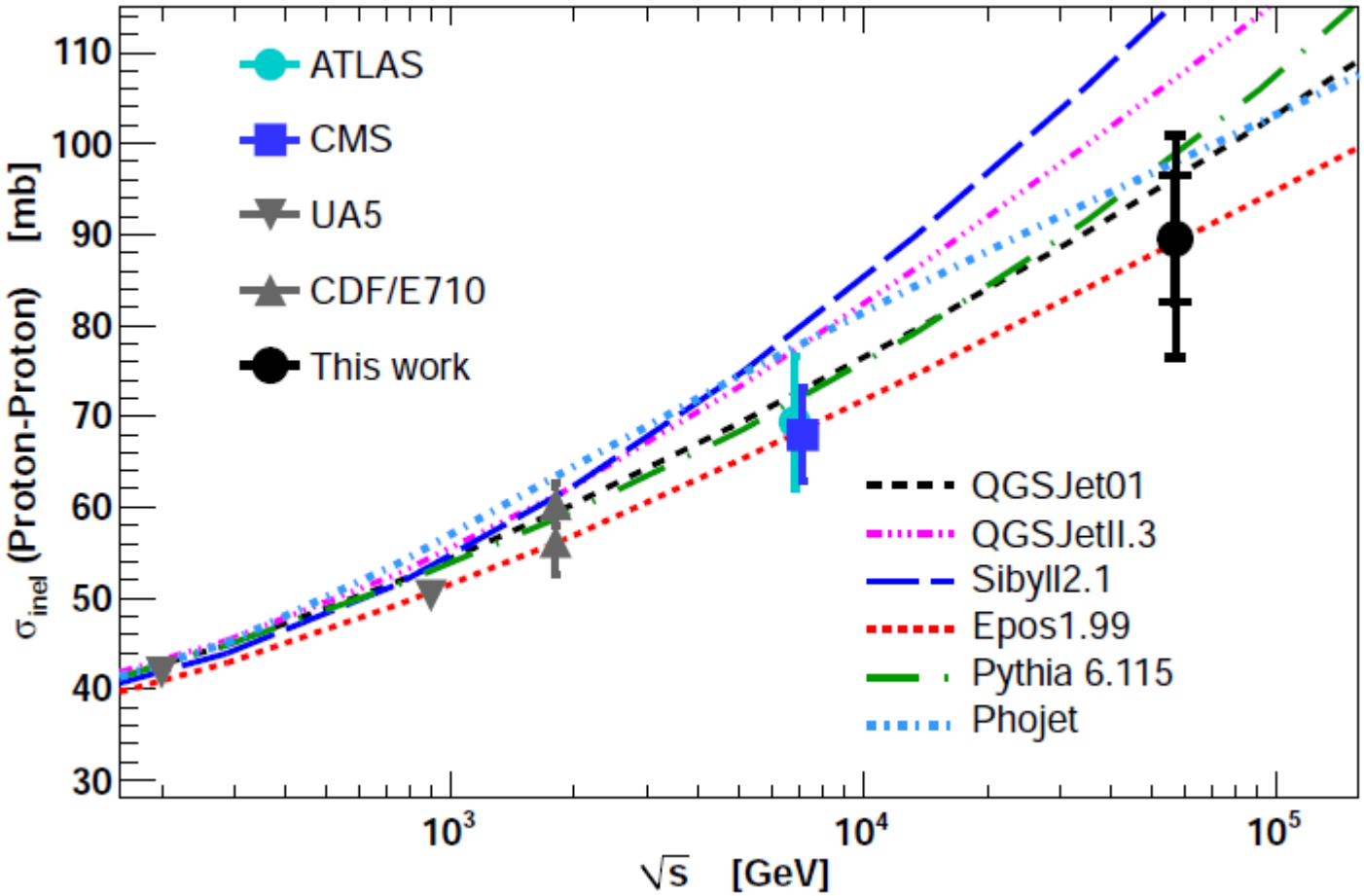
$$\sigma_{\mathrm{p-air}} = \int \left[\prod_i \mathrm{d}^3\vec{r}_i\right] \int \mathrm{d}^2\vec{b} \left[\prod_i \Psi_i^*(\vec{r}_i)\right] \left[1 - \prod_i (1 - a(s, \vec{b}_i))\right] \left[\prod_i \Psi_i(\vec{r}_i)\right]$$

$$a_j(s, b_j) = \frac{(1+\rho(s))\,\sigma_{\mathrm{tot}}^{\mathrm{PP}}(s)}{4\pi B_{\mathrm{ela}}(s)}\, \mathrm{e}^{-\vec{b}_j^{\,2}/(2\,B_{\mathrm{ela}}(s))}$$

$$\sigma_{pp}^{\mathrm{tot}} = \left[129 \ \pm 13(\mathrm{stat})\ {}^{+17}_{-20}(\mathrm{sys}) \ \pm 11(\mathrm{Glauber})\right]\ \mathrm{mb}.$$

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

Measurements of the p-p inelastic cross section in particle accelerators and in cosmic rays

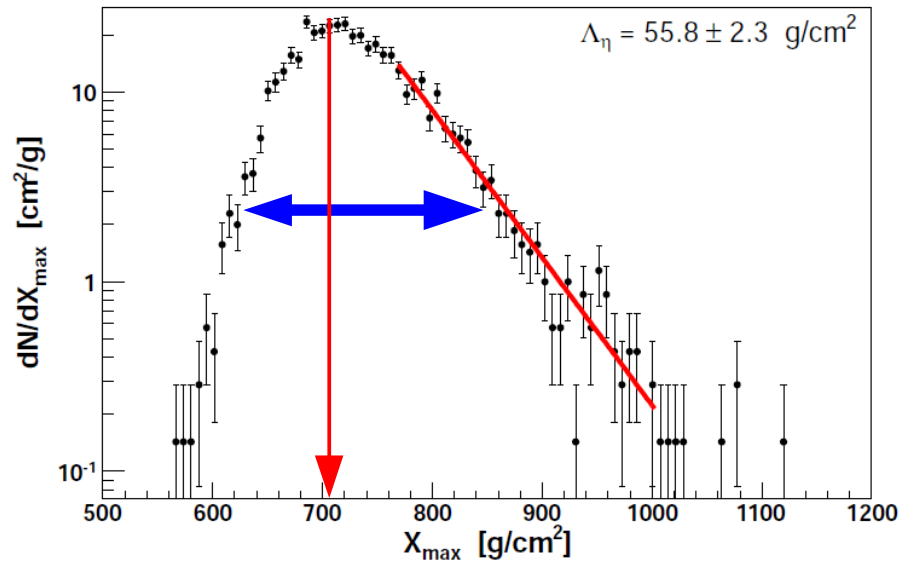


This work has just been accepted for publication in Phys. Rev. Lett.

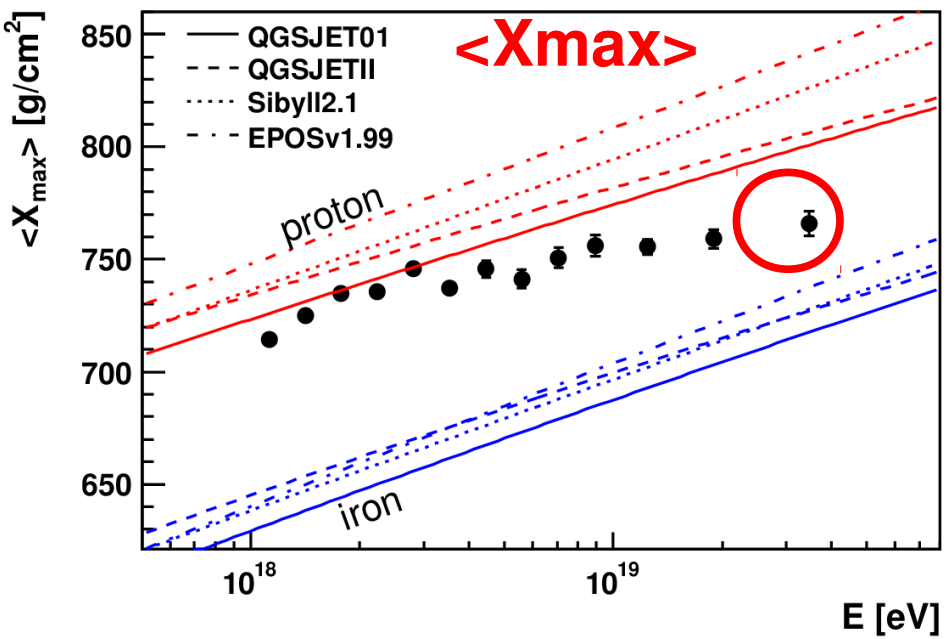
Speculating on the particle interaction properties at energies above $10^{19.4}$eV (c.m. 300 TeV)

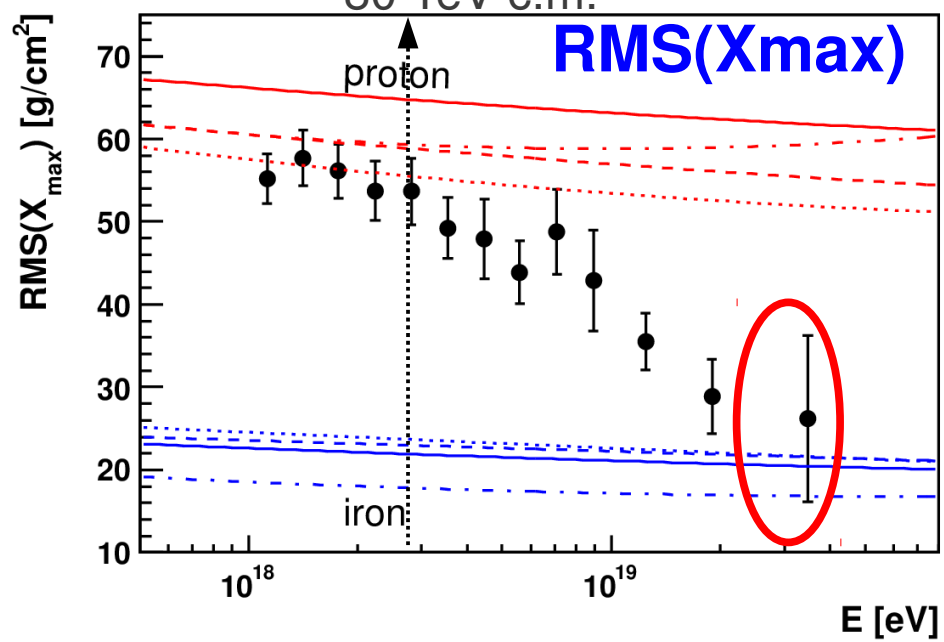
Following, we use the muon numbers detected at ground, and the <Xmax> and RMS(Xmax) of the observed depth of shower maximum (Xmax) distribution at energies above:

$10^{19.4}$eV (c.m. ~300 TeV)



80 TeV c.m.





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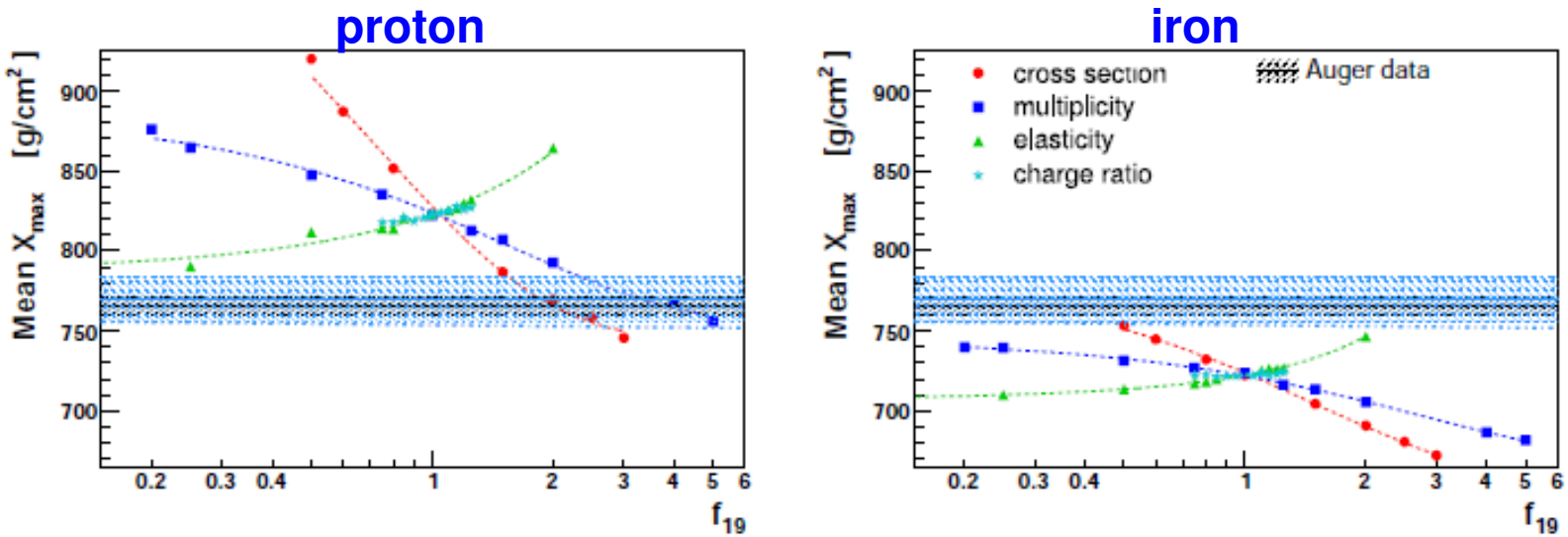
Speculating on the particle interaction properties at energies above $10^{19.4}$eV (c.m. 300 TeV)

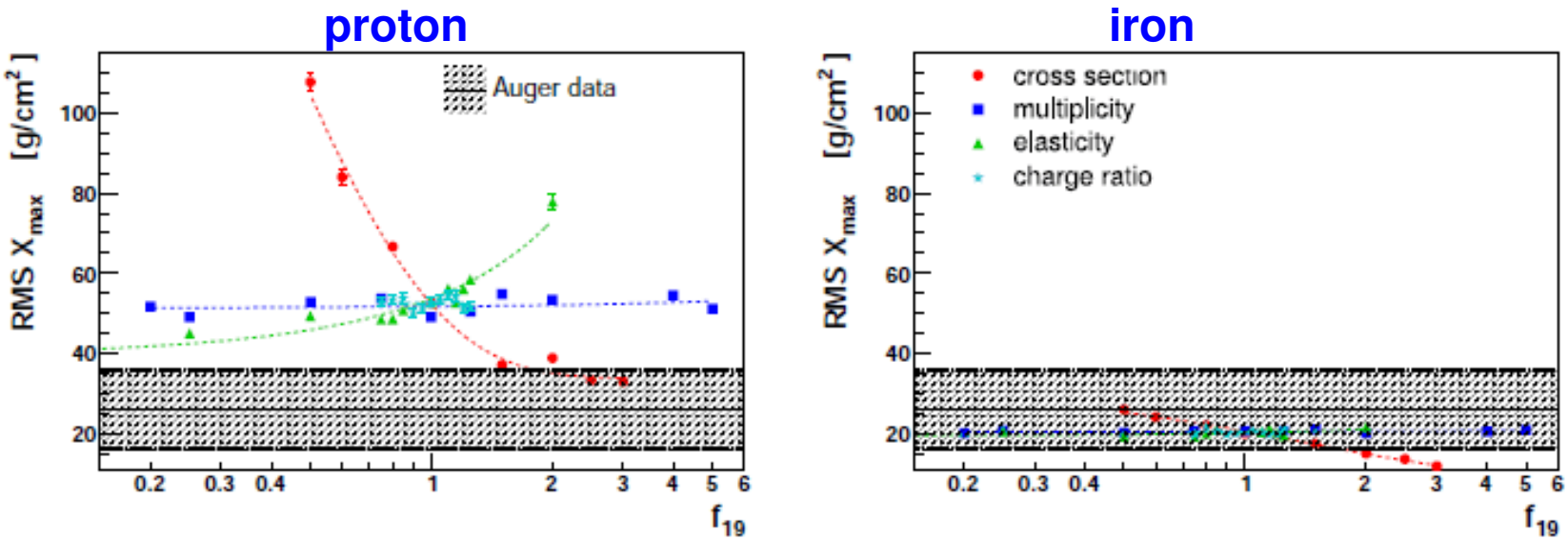
Using the observed mean of the Xmax distribution



- $\langle X_{\max} \rangle$ can be shifted significantly
- Auger data is suggesting:
  - Large cross section for a proton dominated composition
  - Small cross section for a iron dominated composition
  - or: intermediate mass, mixed composition

Speculating on the particle interaction properties at energies above $10^{19.4}$eV (c.m. 300 TeV)

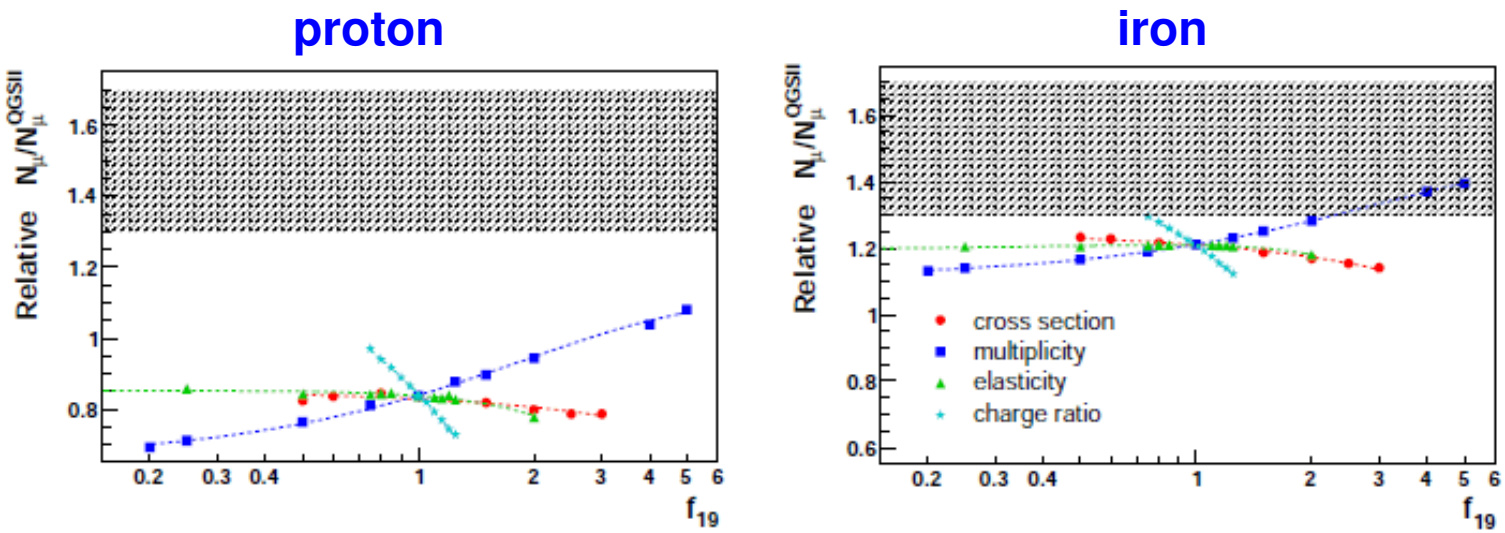
Using the observed RMS of the Xmax distribution



- RMS($X_{\max}$) mostly impacted by cross section, and elasticity
- Iron induced showers very robust
- Auger data only marginally compatible with protons in a high cross section scenario

Speculating on the particle interaction properties at energies above $10^{19.4}$eV (c.m. 300 TeV)

Using the observed muon number at ground detectors

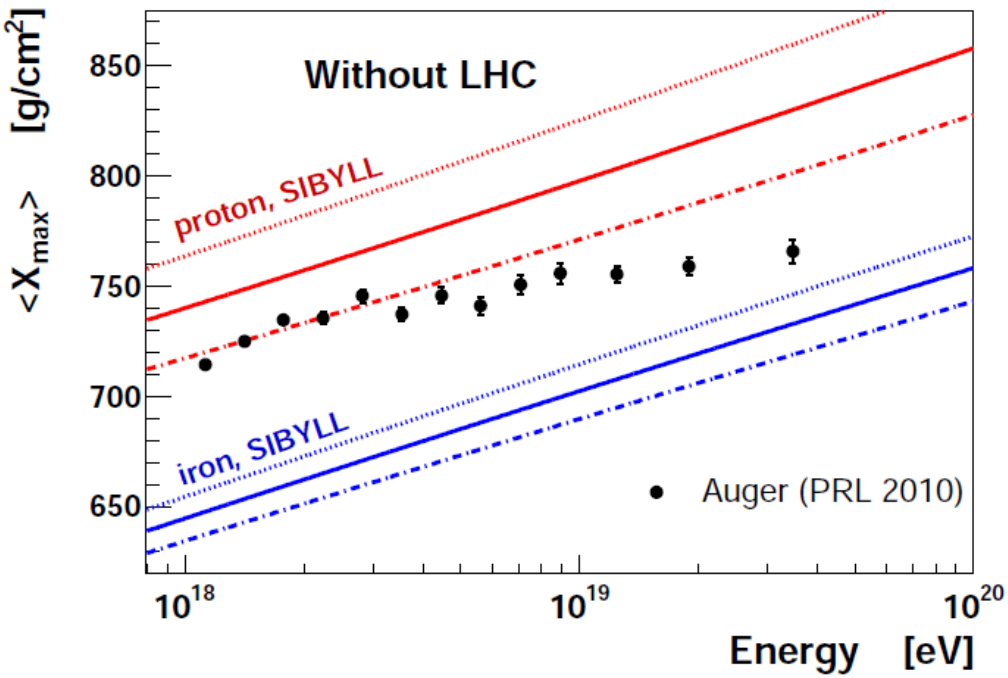


- Multiplicity and Pion charge ratio are shifting model predictions
- Auger muon data incompatible with proton scenario
- Even for iron primaries: multiplicity must be high and pion-charge-ratio small

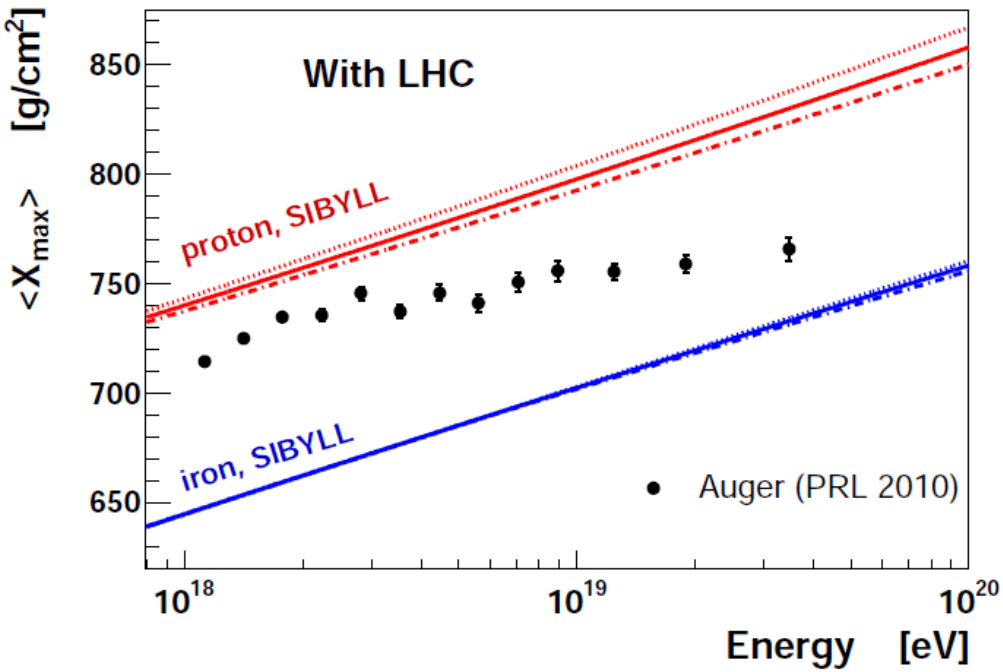
Caution: Definition of Muon number is not identical, e.g.:
Auger measures at 1000 m, Simulations give total muon number

Potential Impact of LHC on Interpretation of EAS Data

At the example of a precise measurement of the elasticity



- Precise measurement of elasticity at 300 GeV
- Extrapolation uncertainty grows by 10 % per decade in energy



- Precise measurement of elasticity at 14 TeV
- Extrapolation uncertainty grows by 10 % per decade in energy

Summary

- Cosmic ray observations have been used to estimate the p-p cross section at 57 TeV c.m. energy:

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

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

$$\sigma^{\text{tot}}_{pp} = \left[129 \ \pm 13(\text{stat}) \ ^{+17}_{-20}(\text{sys}) \ \pm 11(\text{Glauber})\right] \ \text{mb}.$$

- Models need tuning to data as close as possible to the phase space relevant in air showers

- Interaction characteristics has impact on air shower observables on the same order of magnitude as primary mass composition

  ⇒ Almost impossible to “measure” mass composition from air shower observables at this moment

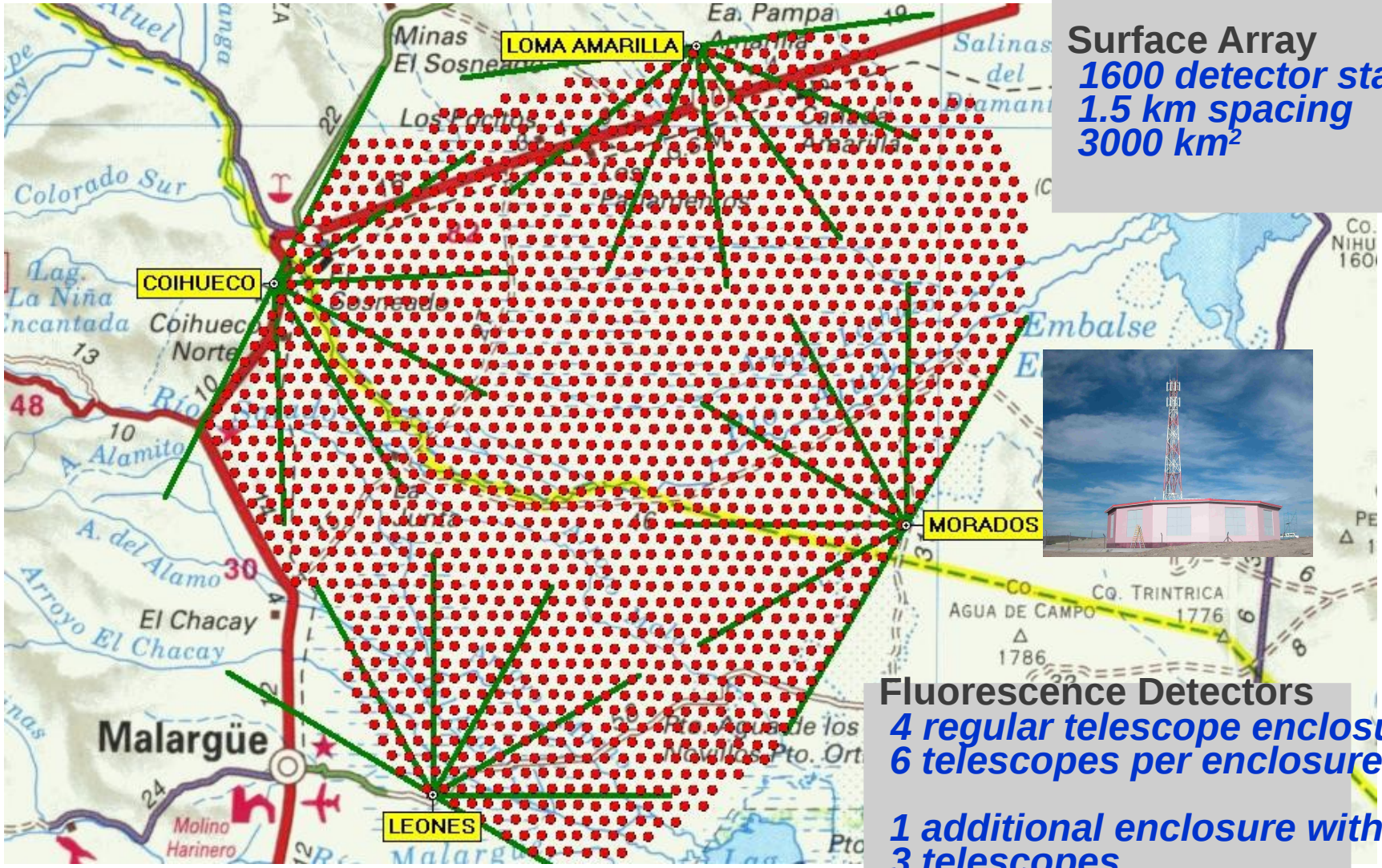
- LHC has the potential to bring significant improvements in analyzing air shower data

- If cosmic ray mass composition is constrained (using the information from their arriving directions):

  ⇒ Air shower data sensitive to interaction physics up to ~ 300 TeV

Back up slides

The Pierre Auger Observatory



Surface Array

1600 detector stations
1.5 km spacing
3000 km²

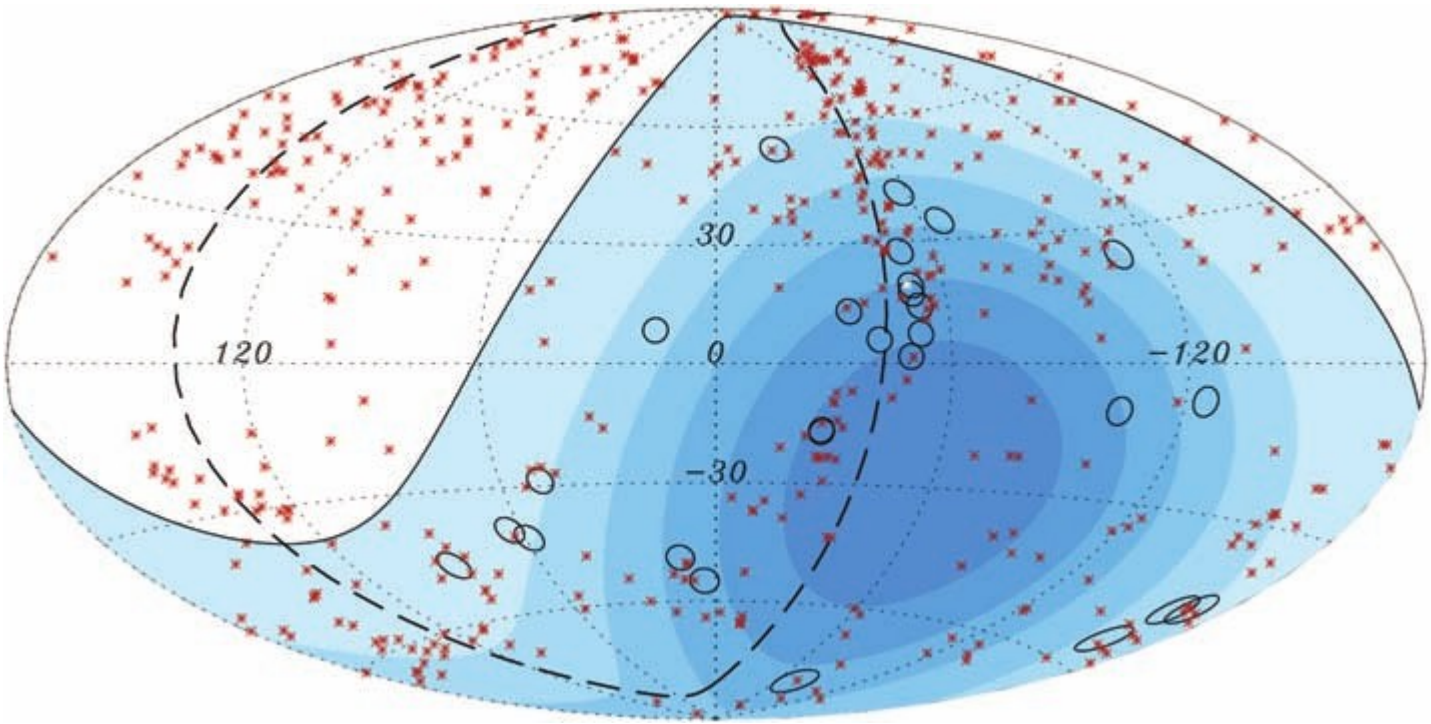
Fluorescence Detectors

4 regular telescope enclosures
6 telescopes per enclosure

1 additional enclosure with 3 telescopes

27 Telescopes total

Correlation of Energetic Cosmic Rays with nearby AGNs



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Ψ=3.1° **z_{max}=0.018 (D<75 Mpc)** **E_{th}=56 EeV**

Evaluating the effect of different extrapolations (of the particle interaction properties) on the observed tail of the Xmax distribution (Λ_η)

Modify specific features of hadronic interactions during air shower Monte-Carlo simulation:

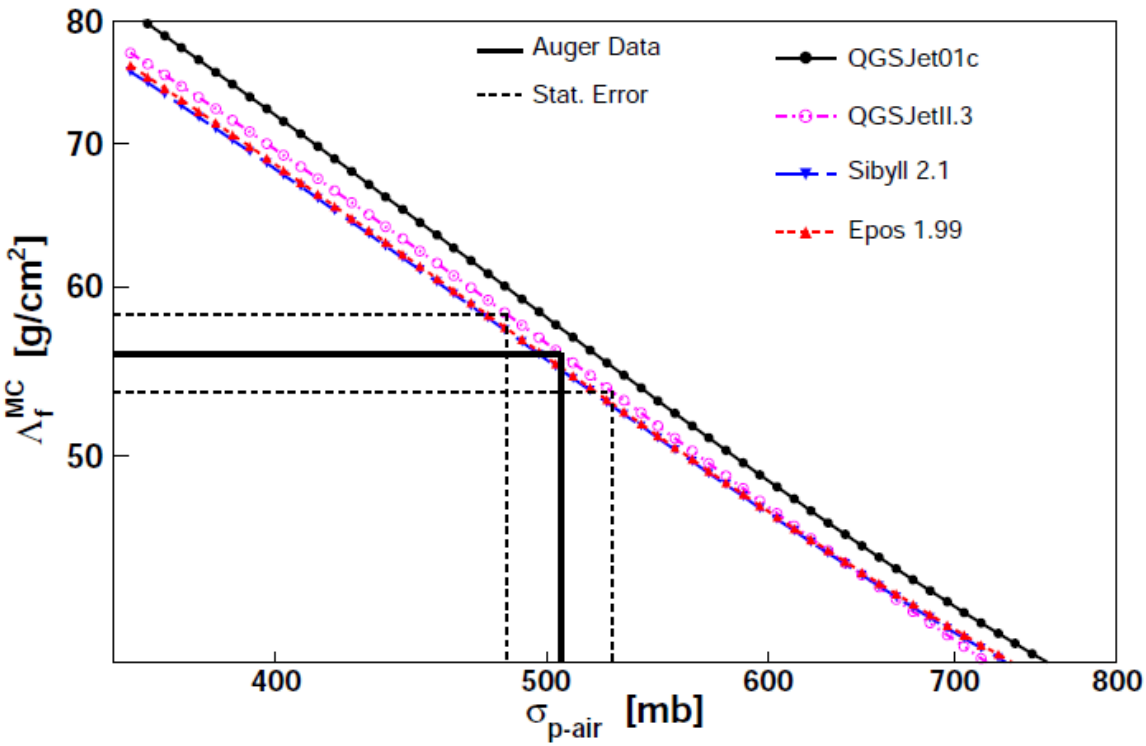
- Assume logarithmically growing deviation from original model prediction above 10^{15} eV.
- Below 10^{15} eV the original model is used.
- The parameter f_{19} denotes the nominal deviation at 10^{19} eV.

$$\alpha^{\mathrm{modified}}(\mathrm{E}) = \alpha^{\mathrm{HE-model}}(\mathrm{E}) \cdot \left(1 + (\mathrm{f}_{19} - 1) \cdot \frac{\log_{10}(\mathrm{E}/1\ \mathrm{PeV})}{\log_{10}(10\ \mathrm{EeV}/1\ \mathrm{PeV})}\right)$$

Where α can be:

- Cross Section: λ
- Multiplicity: n_{mult}
- Ratio of energy going into e.m. particles: $r_{\mathrm{e.m.}} = E_{\mathrm{e.m.}}/E_{\mathrm{tot}}$
- Charge ratio: $c = n_{\pi^0}/(n_{\pi^0} + n_{\pi^-} + n_{\pi^+})$
- Elasticity: $k_{\mathrm{ela}} = E_{\mathrm{max}}/E_{\mathrm{tot}}$

Converting Λ_η to p-air cross section.



Model	Rescaling at $10^{18.24}$ eV	σ_{p-air}/mb
QGSJet01	1.04 ± 0.04	524 ± 23
QGSJetII.3	0.95 ± 0.04	503 ± 22
SIBYLL 2.1	0.88 ± 0.04	497 ± 23
EPOS 1.99	0.96 ± 0.04	498 ± 22

- Model dependence as sys. uncertainty