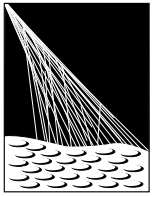


Extension of the measurement of the proton-air cross section with the Pierre Auger Observatory

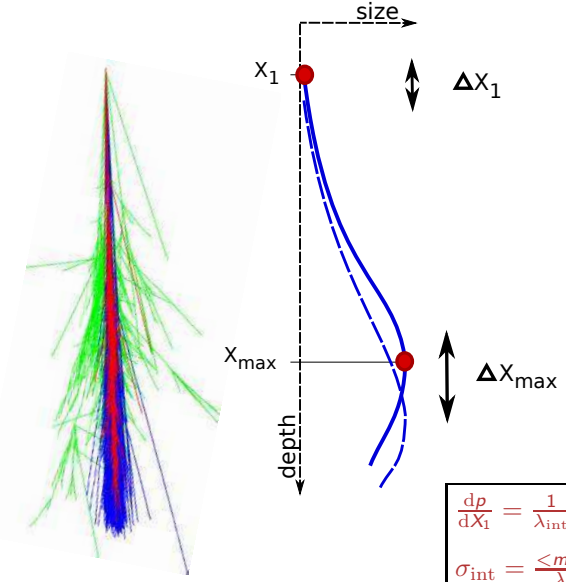
Ralf Ulrich[1] for the Pierre Auger Collaboration[2]

[1]KIT, Germany

[2]Observatorio Pierre Auger, Malargüe, Argentina
http://www.auger.org/archive/authors_2011_05.html

34$^{\text{th}}$ ICRC, The Hague 2015

Overview



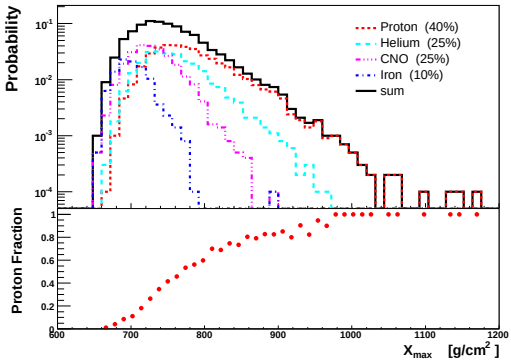
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

With respect to
The Pierre Auger Collaboration
PRL 109, 062002 (2012)

- About four times more data:
  44218 events
- Two bins in energy:
  $10^{17.8} - 10^{18.0} - 10^{18.5}$ eV
- Updated systematic uncertainties
- New hadronic interaction models:
  EPOS-LHC, QGSJetII.4
  tuned to LHC data

Analysis approach



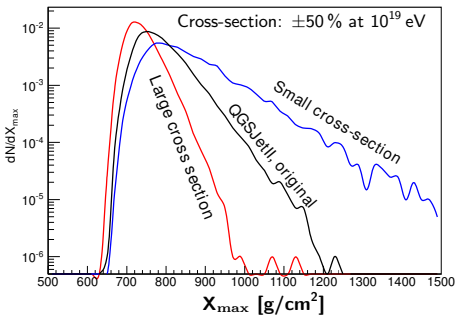
Select deeply penetrating showers to enhance proton fraction

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

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

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

chose $\eta = 0.2$ to achieve: $\sigma(stat) \approx \sigma(syst)$

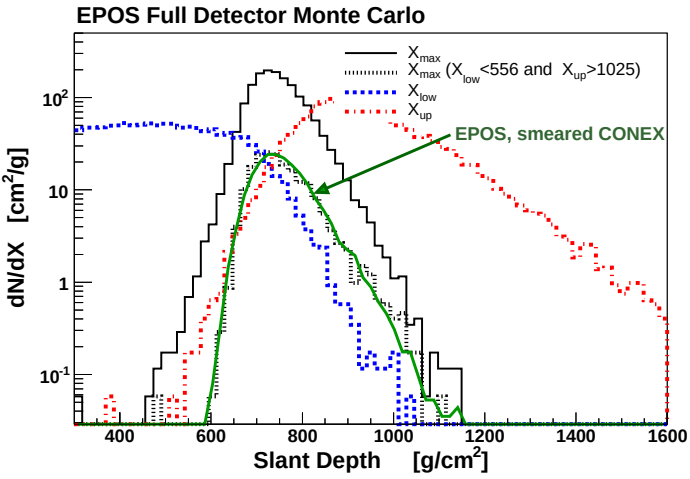


Simulation for proton showers with different cross sections: very good sensitivity of tail of distribution

Fiducial event selection

1. Use all high-quality events
2. Dismiss 0.1% of highest and lowest $X_{\max}$ events
3. Select only showers geometrically visible over the full central 99.8% $X_{\max}$-range
4. Determine range of 20% deepest $X_{\max}$ events ($\rightarrow$tail, $\eta = 0.2$)
5. Re-select showers geometrically visible over the full tail range ($\rightarrow$ factor 3 more events)

End-To-End Full Monte Carlo Check (w/ EPOS)



Composition and energy range of analysis

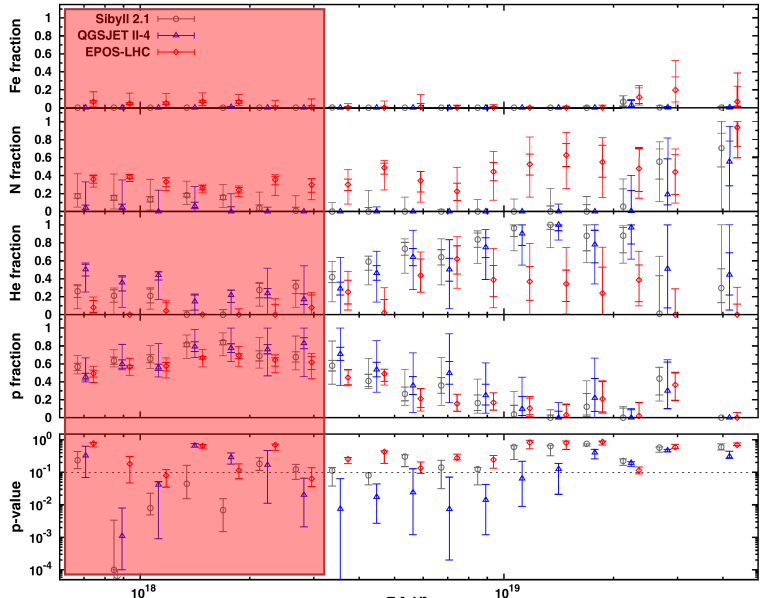


Figure from:
The Pierre Auger Collaboration
PRD 90, 122006 (2014)

Red area:
$10^{17.8} - 10^{18.0} - 10^{18.5}$ eV

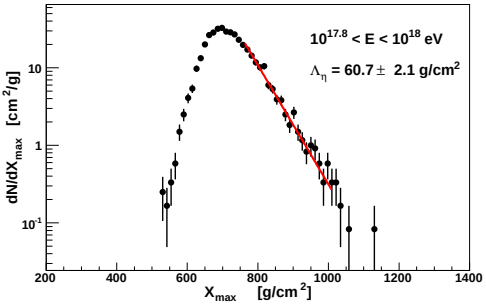
→ Most compatible with high proton fraction

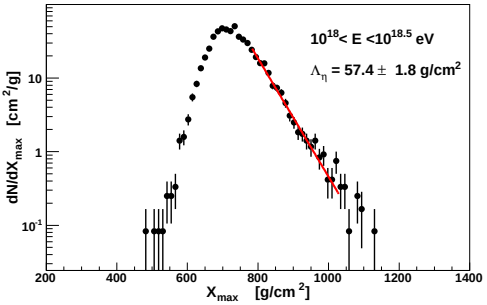
→ Helium fraction smallest

At higher energies:

→ proton ↓, helium ↑

Measurement of Λ_η





$\langle E \rangle = 10^{17.90}$ eV

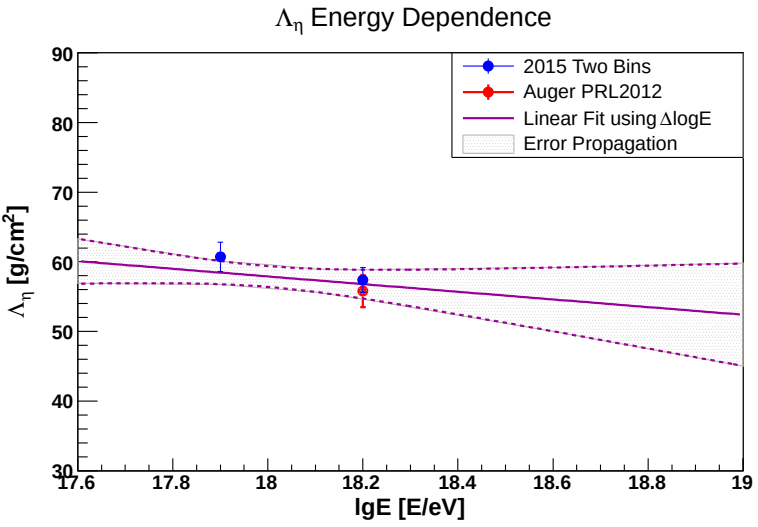
$\Lambda_\eta = 60.7 \pm 2.1(\text{stat}) \pm 1.6(\text{syst})$ g/cm^2

$\langle E \rangle = 10^{18.22}$ eV

$\Lambda_\eta = 57.4 \pm 1.8(\text{stat}) \pm 1.6(\text{syst})$ g/cm^2

- Unbinned likelihood analysis
- Data corrected for detector acceptance → Can be used directly by theorists

Unbinned fit of energy dependence

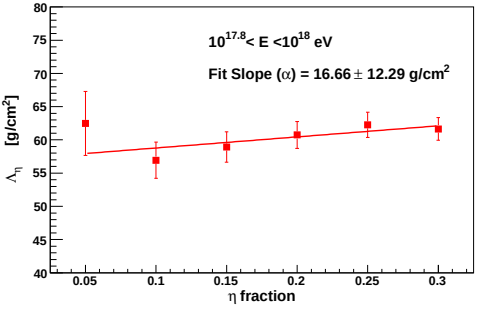


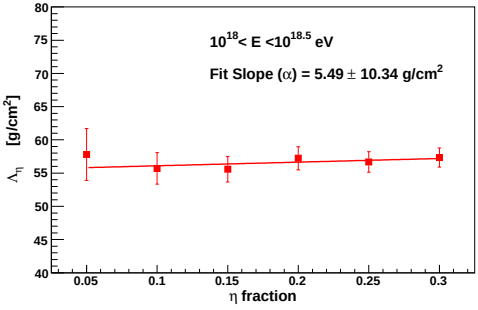
$$\Lambda_\eta(E) = \Lambda_\eta^0 + s_\eta(\lg E/\mathrm{eV} - 18)$$

Better sensitivity to slope, however, leverarm in energy and/or event statistics not yet high enough for strong conclusion

Stability of Λ_η as a function of η

Dependence of Λ_η on η in data: slope α

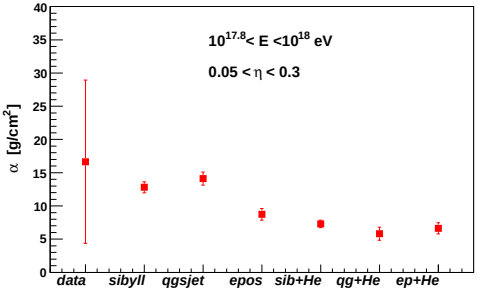


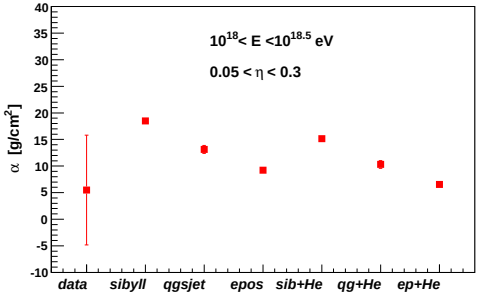


It is expected that $\alpha > 0$ also from simulations, depending on:

- Hadronic interactions
- Detector acceptance
- Mass composition

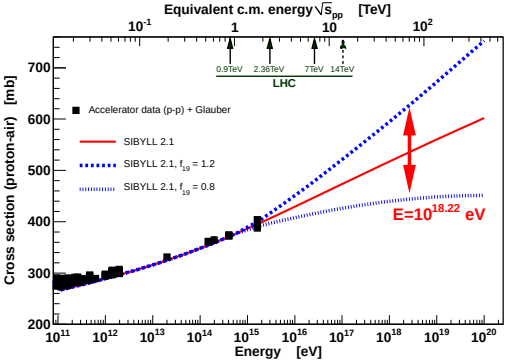
Comparison of α with model expectations





- Slope in data and different simulation scenarios do not indicate any discrepancy incompatible with the assumptions of the analysis
- This can change with the choice of air shower energies, e.g. because of a changing mass composition

Conversion of Λ_η to proton-air cross section

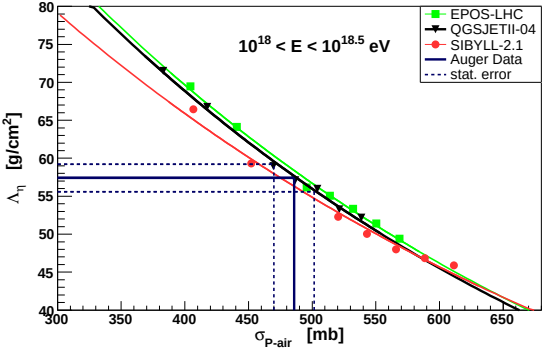


Simulations with f_{19}:

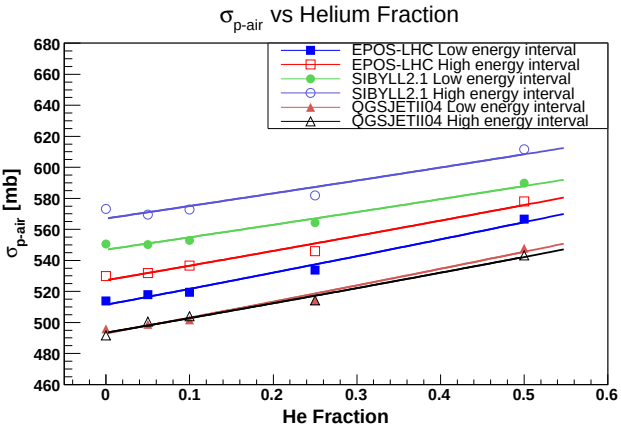
- Consistent description of cross-section
- No discontinuities in cross-section predictions

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

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



Mass composition



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

- Helium fraction does not exceed $\approx 25\%$ in mass composition fits published by Auger
- Up to 25 % Helium: induced bias < 20 mb
- CNO induces no bias up to 50 % of CNO.
- Up to 0.5 % of Photons: induced bias < 10 mb

This assessment will be different at higher energies

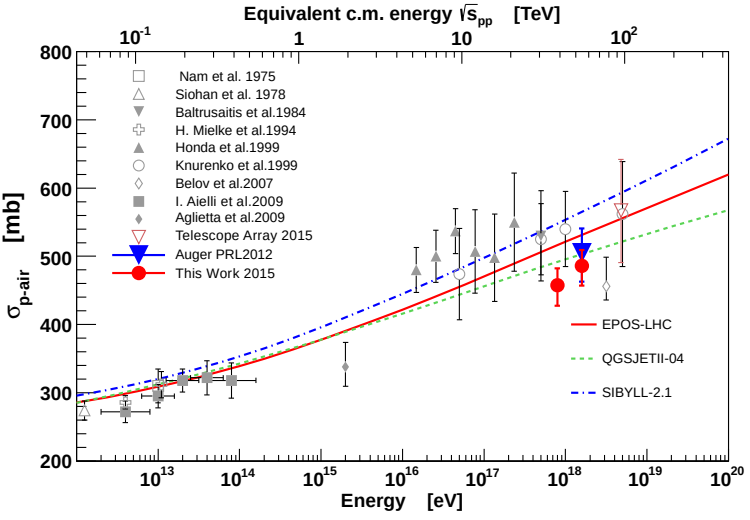
Overview of systematic studies

	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\mathrm{p-air}}$ (mb)	7	7
Photons (mb)	+4.7	+4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\mathrm{p-air}}$ (mb)	+19/-25	+19/-25

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

Analysis design: Systematic uncertainties ($\rightarrow$helium) on same level as statistical precision

Proton-air cross section

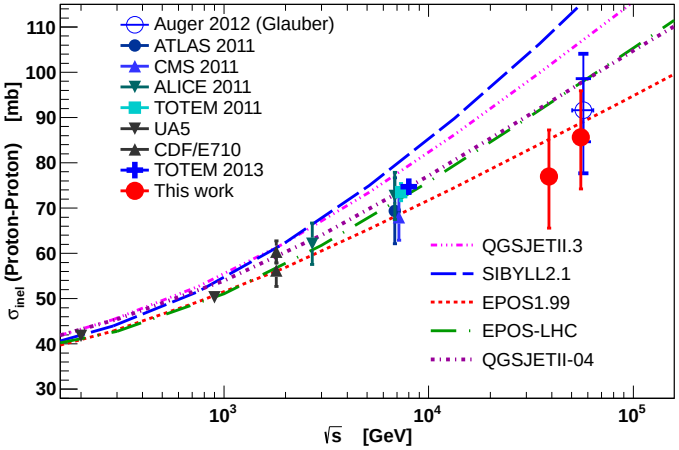


Results, $\sigma_{\mathrm{p-air}}$ in mb

- Lower energy point
  457.5±17.8(stat)+19/-25(syst)
- Higher energy point
  485.8±15.8(stat)+19/-25(syst)

Inelastic proton-proton cross section

Extended Glauber conversion with inelastic screening + propagation of modeling uncertainties

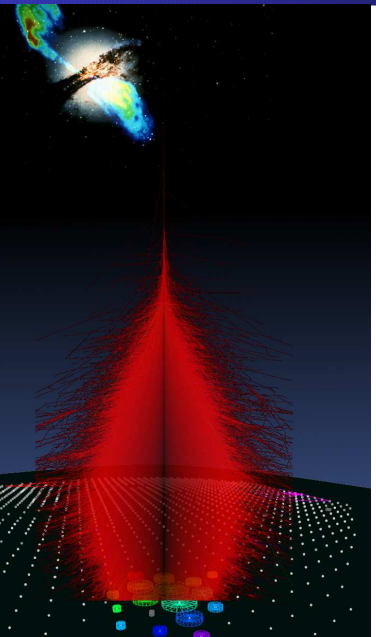


Results, σ_{pp}^{inel} in mb

- Lower energy point
  76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)
  at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV
- Higher energy point
  85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)
  at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV

(Model uncertainties may be underestimated, since there are other theoretical models available for the conversion)

Summary



- Well beyond LHC energies
- Further improved analysis approach and reduced uncertainties

- 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 becoming smaller (QGSJetII.4, EPOS-LHC) after tuning to LHC data

Many thanks to the whole Collaboration, in particular to Alaa Kuotb