Probing hadronic interactions with the Pierre Auger Observatory

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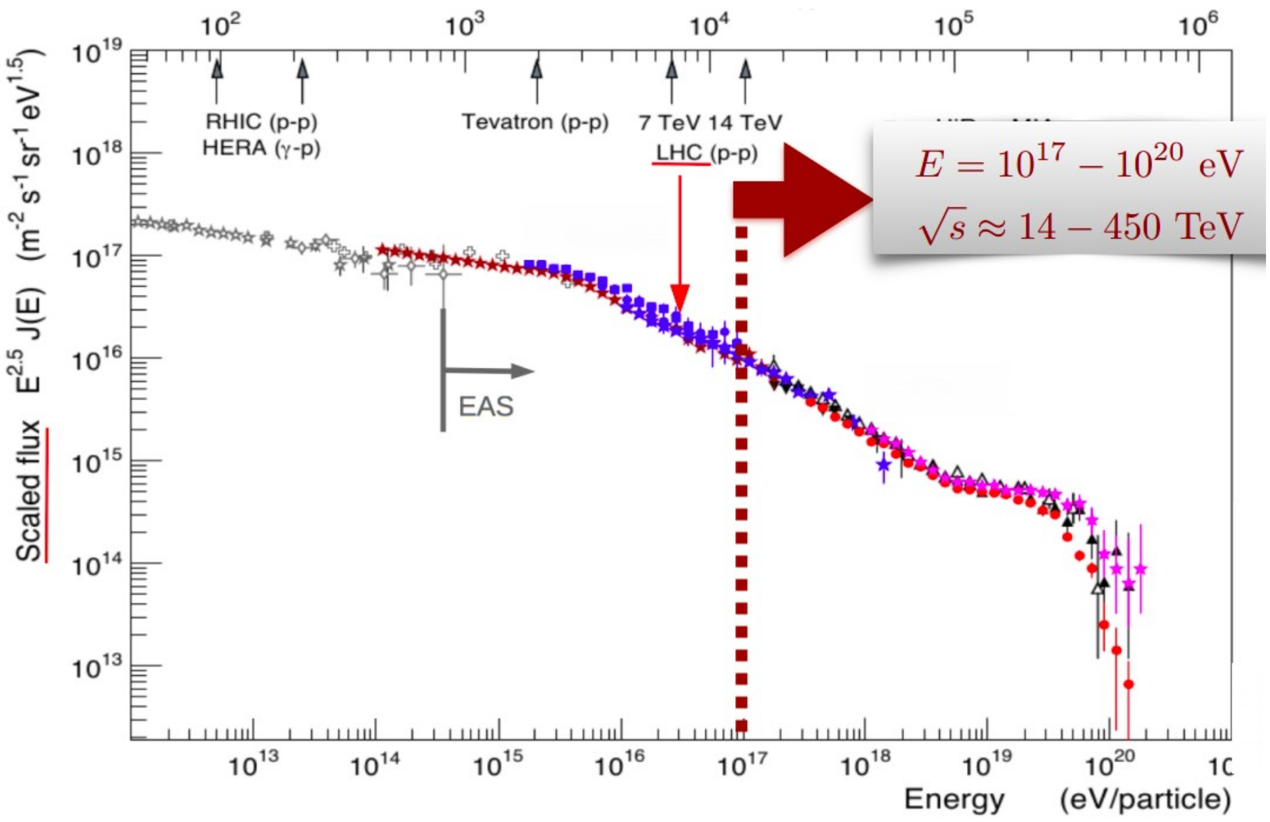
Photo: Steven Saffi,
University of Adelaide

Ultra high energy Cosmic Rays



High energy particles up to $E>10^{20}$ eV (> 400 TeV c.m.s. energy for protons)

Energy of UHECRs far above the ones achievable by present accelerators

- Possibility to study hadronic interactions at the most extreme energies

Limits of interaction models in UHECR field:

- Uncertainty on primary parameters (energy, direction, mass...)
- Extrapolation from LHC energy
- Extreme forward regions critical
- Hadron-air interactions are critical in CR science

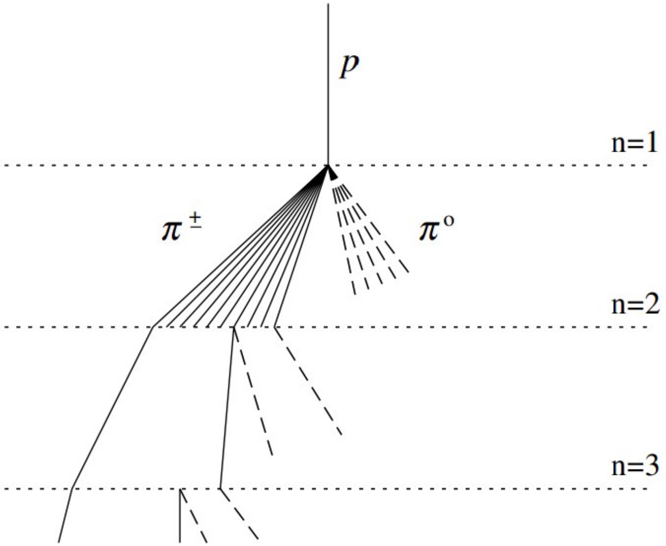
Extensive air showers

Longitudinal development:

- ➔ Fluorescence and Cherenkov telescopes

Lateral distribution:

- ➔ Ground arrays of particle detectors



X_{max}: slant depth of the shower maximum

N_μ: number of muons on ground

Electromagnetic fraction

$$<X^A_{max}> = <X^p_{max}> + f_E <lnA>$$

$$\sigma^2_A(X_{max}) = <\sigma^2_{sh}> + f^2_e \sigma^2(lnA)$$

Hadronic fraction

$$N_\mu = A^{1-\beta}\left(\frac{E_0}{\xi}\right)^\beta$$

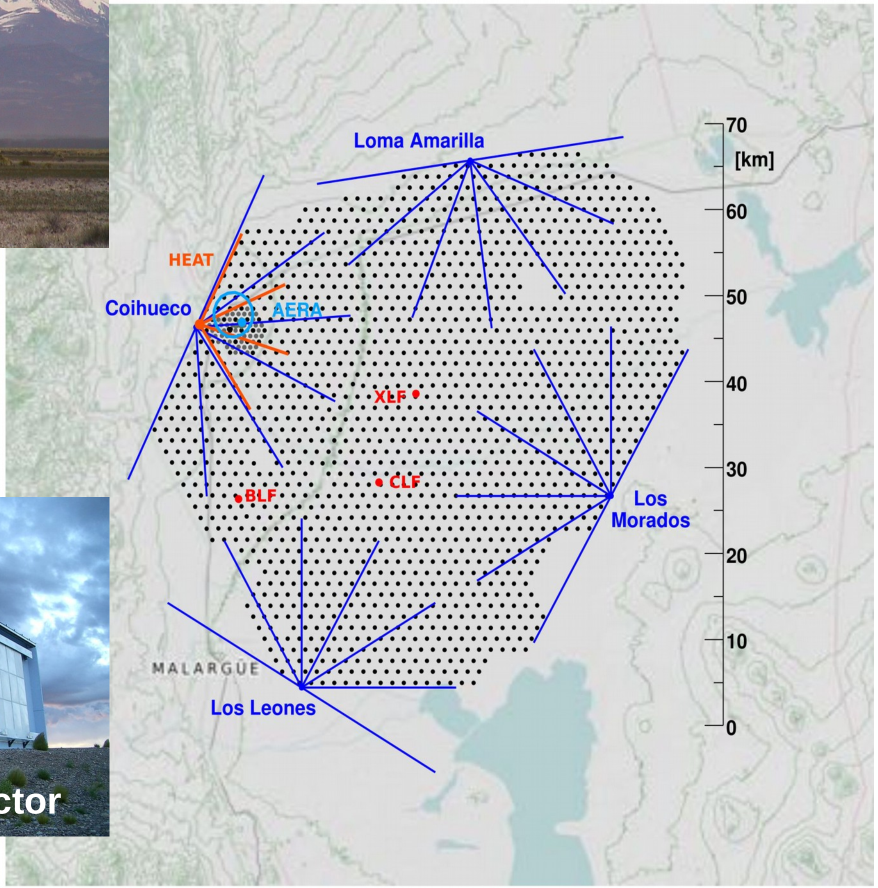
$$\beta = \frac{\ln(N_{mult}\,\alpha)}{\ln(N_{mult})}$$

α: Fraction of charged pions

N_{mult}: Multiplicity

J. Matthews, Astrop. Phys. 22, 387 (2005); P. Abreu et al., JCAP 02 026 (2013)

The Pierre Auger Observatory



Surface detector (SD)

- **1500 m array**

1600 detectors
3000 km^2, 1500 m grid
E>2.5EeV

- **750 m array**

61 detectors
24 km^2, 750 m grid
E>0.1EeV

Fluorescence detector (FD)

- **24 telescopes**

4 buildings
Elevation 0-30°
E> 1 EeV

- **3 additional telescopes**

Elevation 30-60°
E> 0.1 EeV

AERA

- **153 radio antennas**

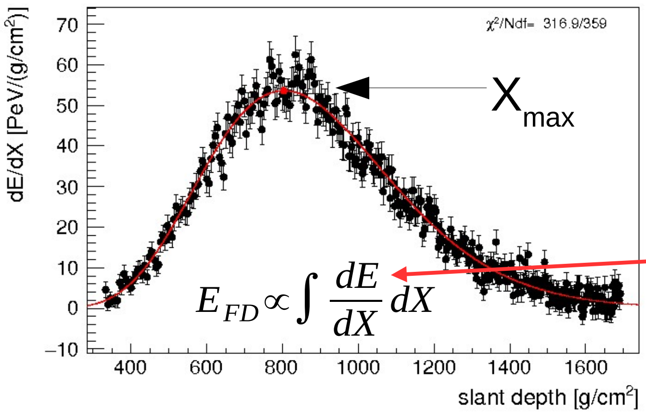
17 km^2
30-80 MHz
E>0.1EeV

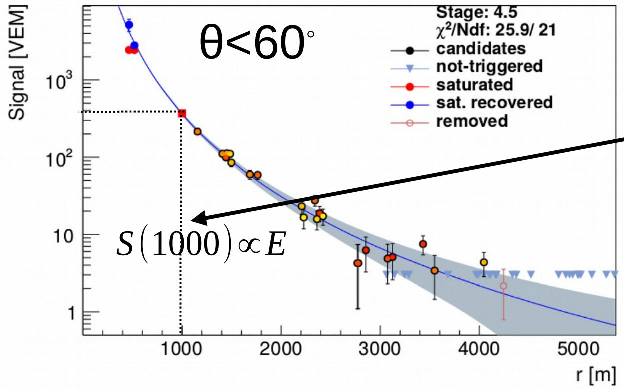
Atmospheric monitoring

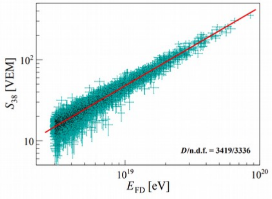
- **XLF, CLF**
- **Lidars, cloud camera**

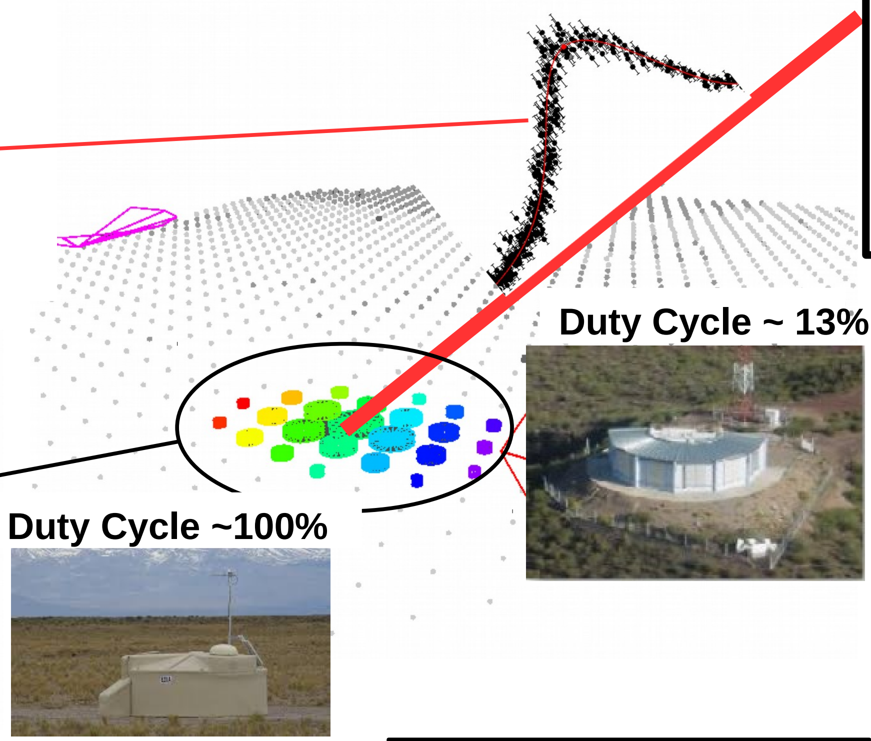
A. Aab et al., NIM A 798 (2015) 172-213

The hybrid detection









Energy scale
systematic uncertainty
14%

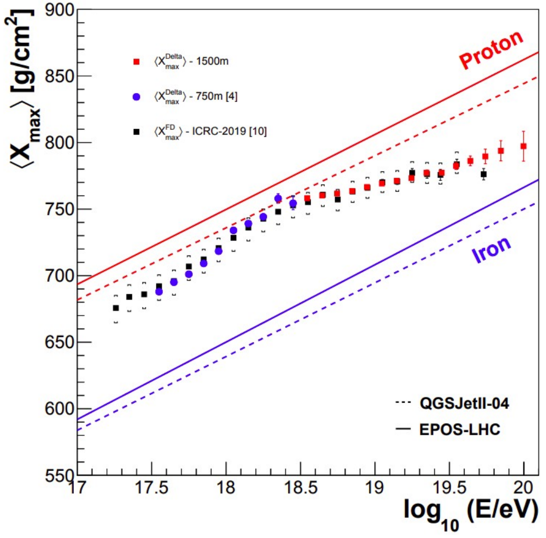
X_{max}
systematic uncertainty
~10 g/cm^2

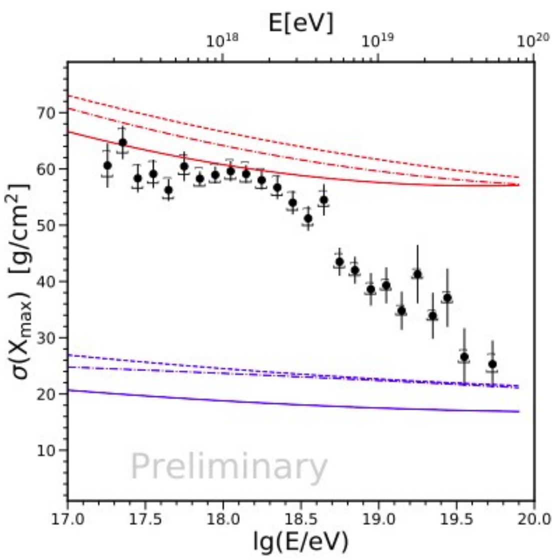
- Energy resolution:
  - 20% @ $3 \cdot 10^{18}$ eV
  - 7% E>$2 \cdot 10^{19}$ eV

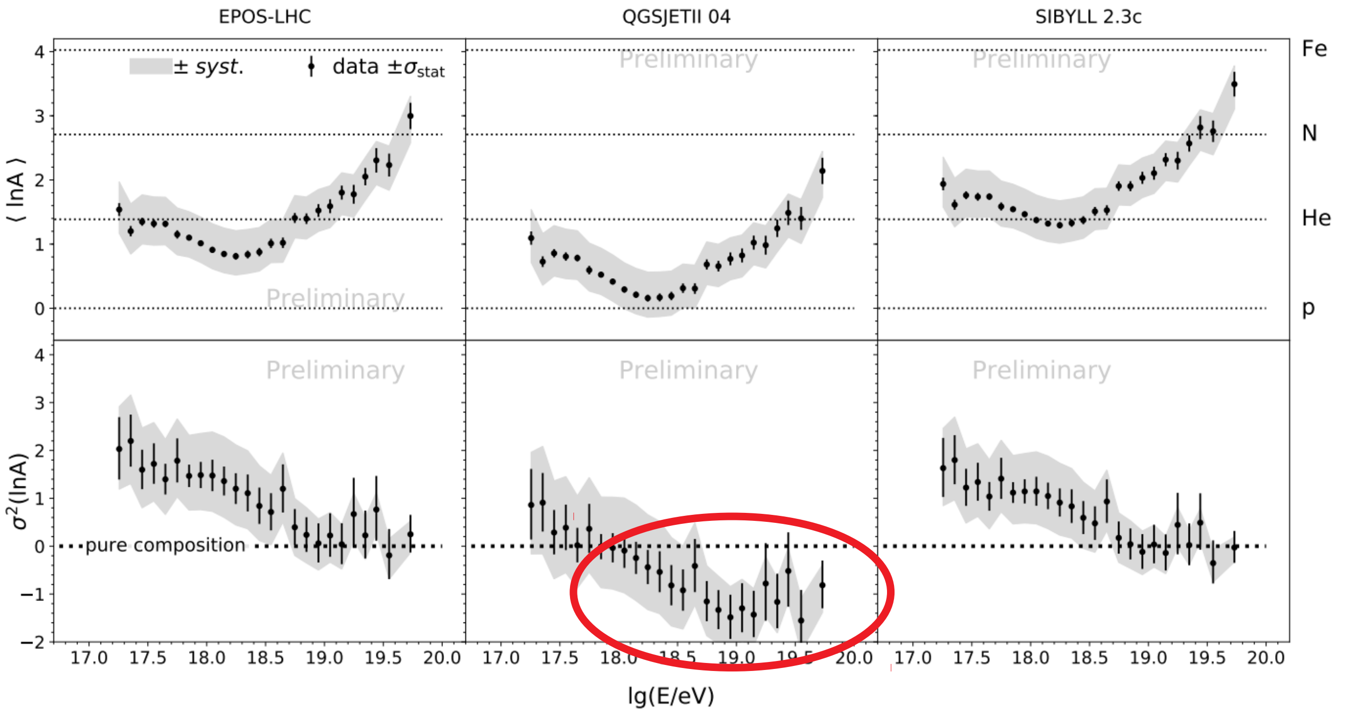
- X_{max} resolution
  - 40 g/cm^2 @ 10^{17} eV
  - 25 g/cm^2 @ 10^{18} eV
  - 15 g/cm^2 E>10^{19} eV

Pierre Auger energy scale based on hybrid events

Composition from X_{max}



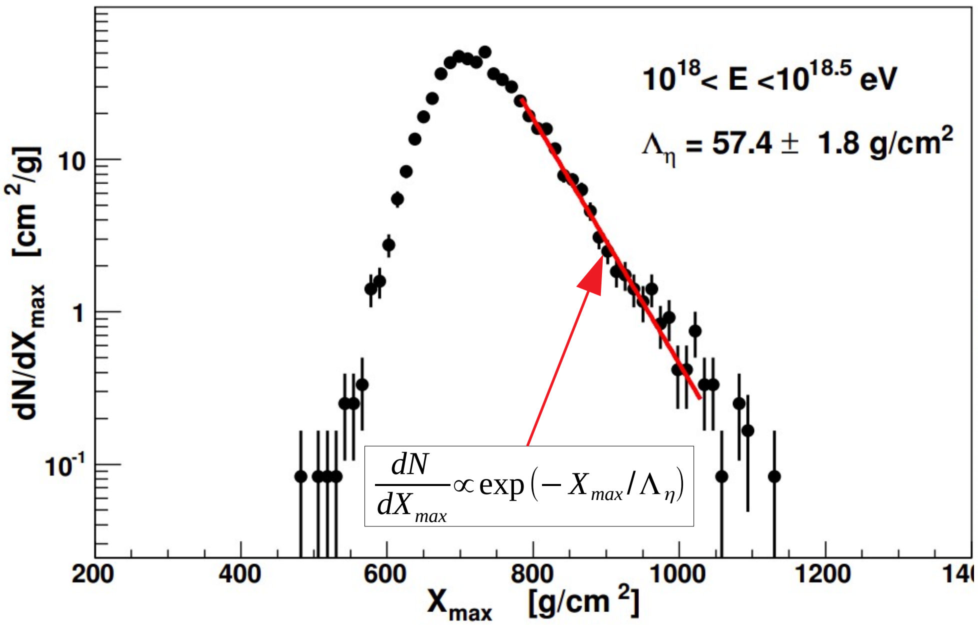


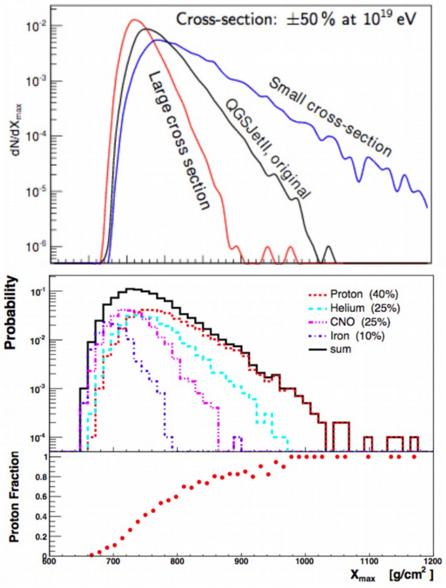


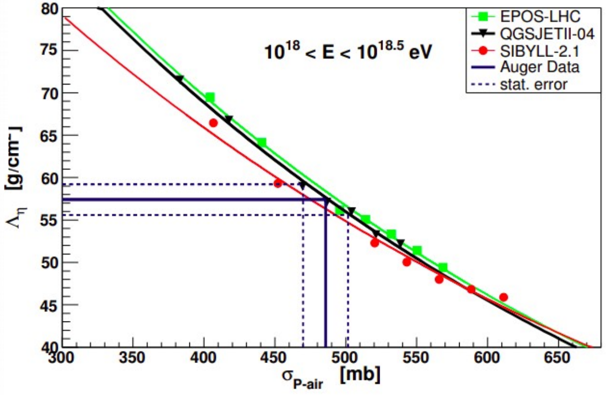
- Mixed composition
  - Getting lighter toward $10^{18.3}$ eV, intermediate-heavier above
- Largest systematic uncertainty from hadronic interaction models
- With QGSJetII-04: variance of lnA not physical

A. Yushkov, PoS(ICRC2019)482; C. G. Todero Peixoto PoS(ICRC2019)440

Measurement of the p-air cross section







Step 1: identification of a cross section dependent observable (Λ_η)

Tail of distribution dominated by protons

Most important systematic: He contamination (~6% uncertainty for a 25% He fraction)

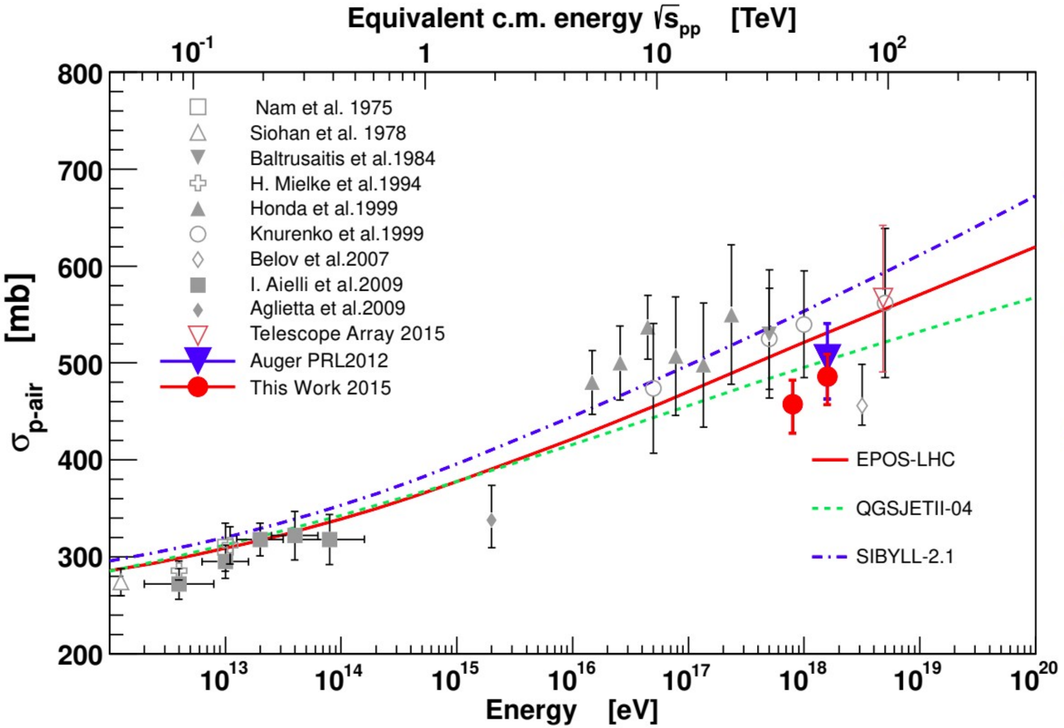
Step 2: tuning the cross section to reproduce Λ_η.

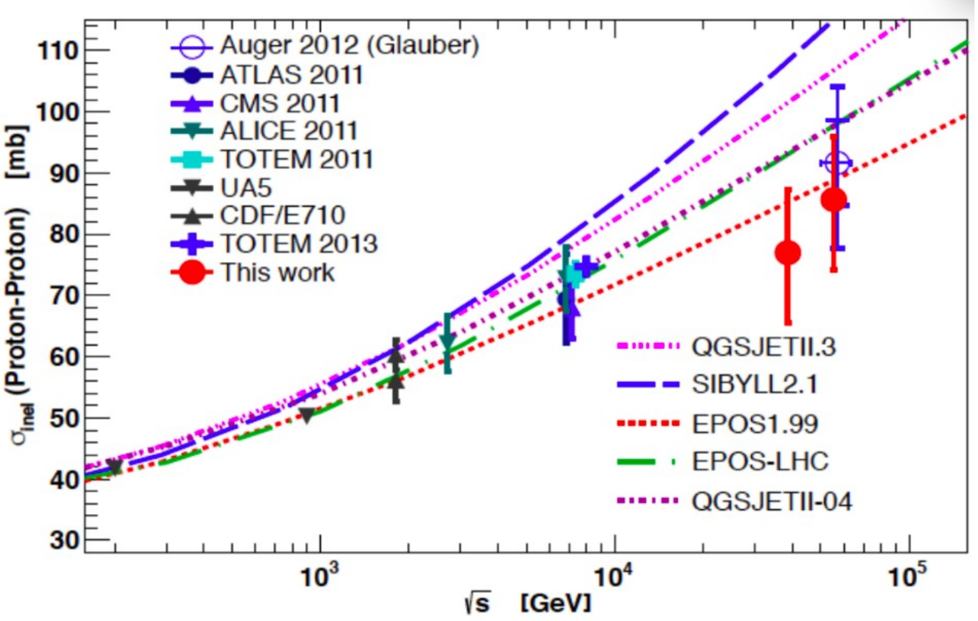
Energy dependent rescaling of the cross section. (F=1 at accelerator energies)

$$F(E, f_{19}) = 1 + (f_{19} - 1)\ \frac{\log(E/E_{\text{thr}})}{\log(10^{19}\,\text{eV}/E_{\text{thr}})}$$

R. Ulrich, PoS(ICRC2015)401

Measurement of the p-air cross section





From p-air to p-p cross section using Glauber formalism

$\sigma_{p\text{-}air}$ = 457.5 mb ($10^{17.8}$ eV < E < 10^{18} eV)

$\sigma_{p\text{-}air}$ = 485.8 mb (10^{18} eV < E < $10^{18.5}$ eV)

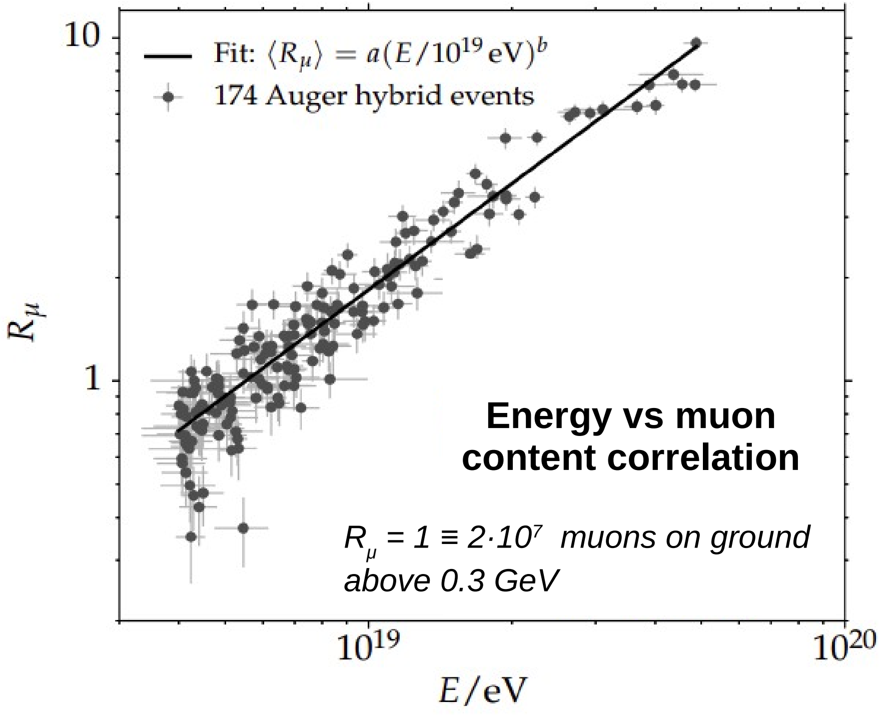
Direct comparison with accelerators $\sigma_{p\text{-}p}$ measurement

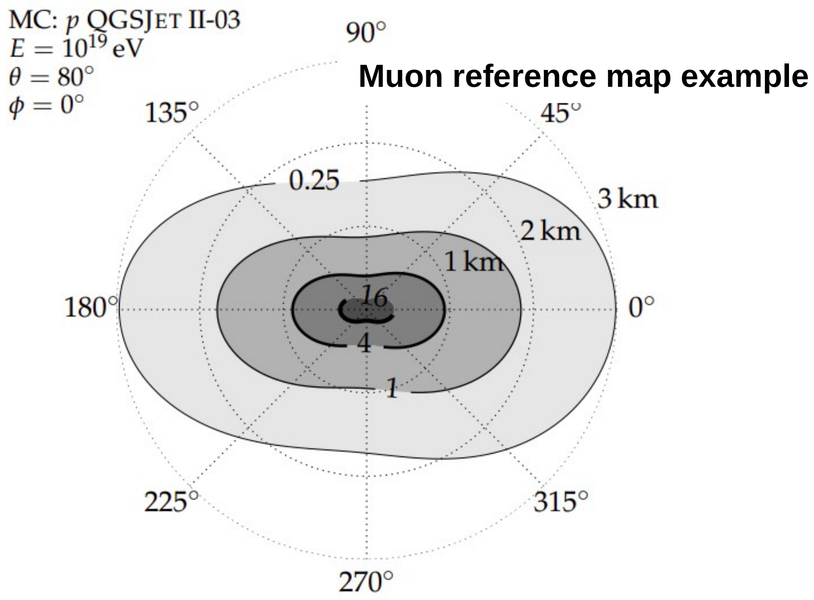
$\sigma^{inel}_{p\text{-}p}$ = 85.62 mb @ 55.5 TeV

$\sigma^{inel}_{p\text{-}p}$ = 76.95 mb @ 38.7 TeV

R. Ulrich, PoS(ICRC2015)401; P. Abreu et al., PRL 109, 062002 (2012)

Muon signal on ground





Muons detected with the SD array

Analysis based on inclined hybrid events (zenith angle > 62°, calorimetric energy and muon distribution on ground are measured)

Fit with a reference muon map from MC ($\rho_{\mu,19}$)

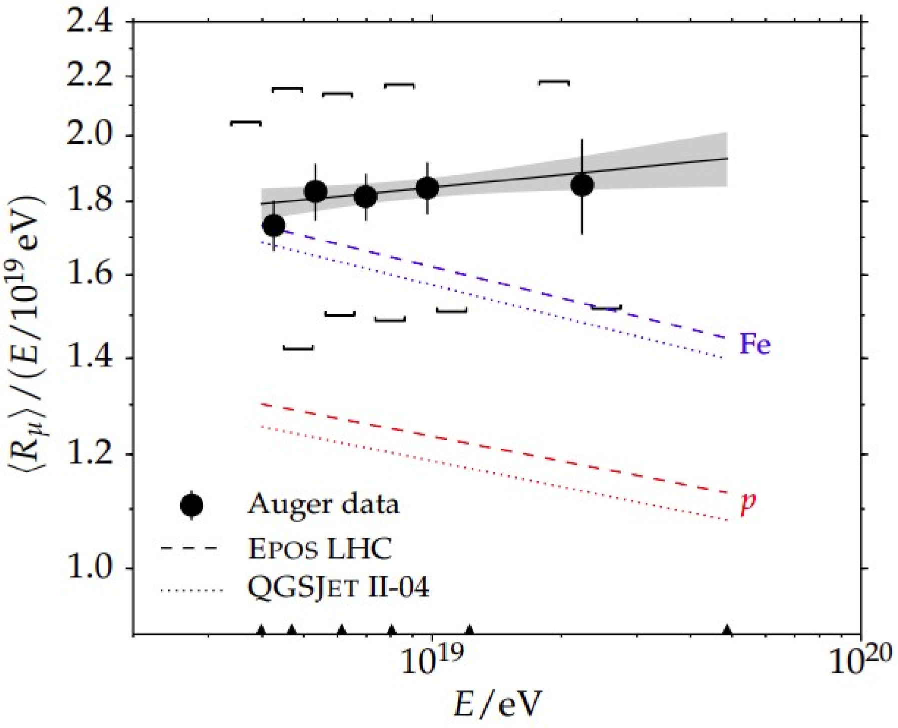
$$\rho_\mu(\vec{r}) = N_{19}\,\rho_{\mu,19}(\vec{r};\theta,\Phi)$$

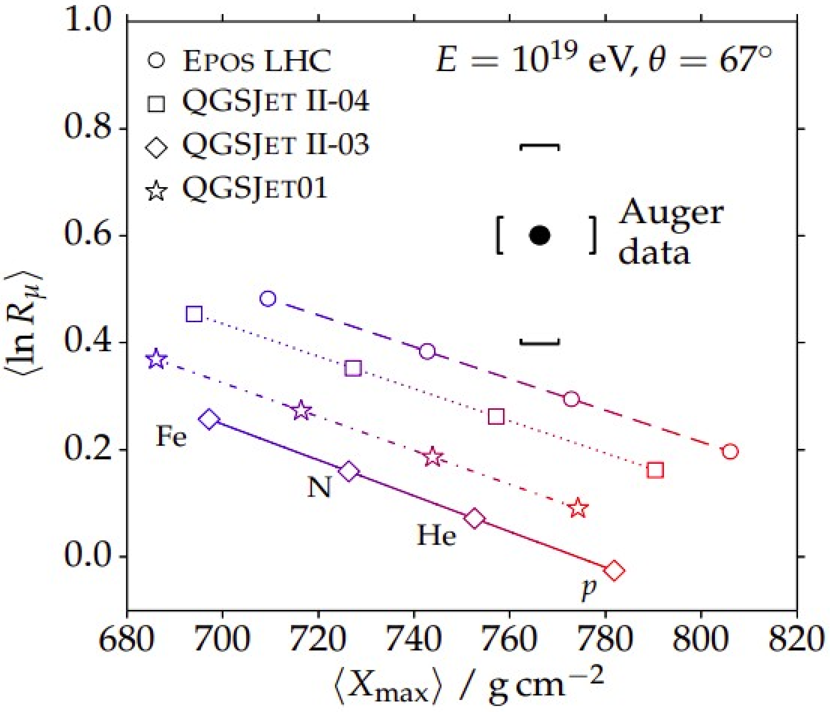
Normalization factor muon density N_{19}

Total number of muons on ground relative to a 10^{19} eV shower → $R_\mu \propto N_{19}$

A. Aab et al., PRD 91, 032003 (2015)

Muon density on ground – high energy



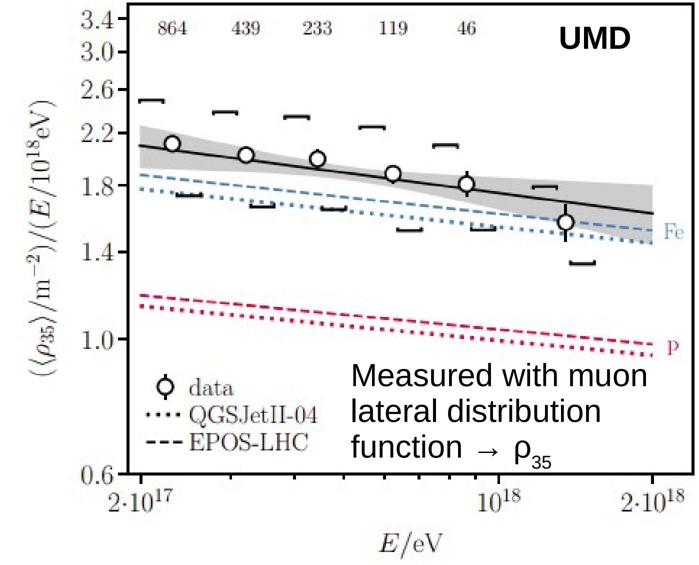


Clear deficit in the muon density predictions

From 30-80% deficit at 10^{19} eV depending on the model

Aab et al., PRD 91, 032003 (2015)

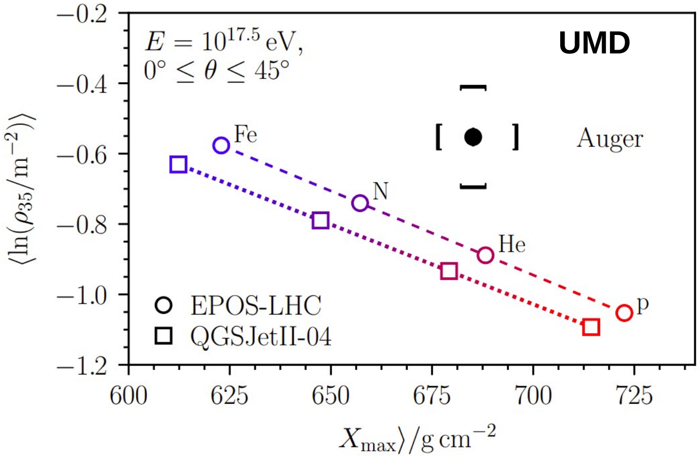
Direct muons with AMIGA



QGSJetII-04

50% deficit @$10^{17.5}$ eV

53% deficit @ 10^{18} eV



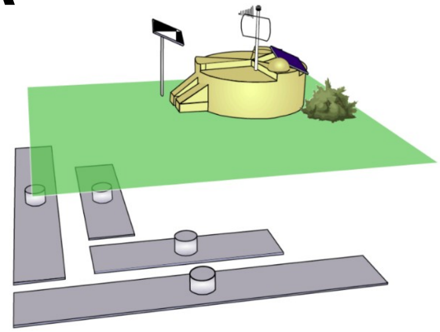
EPOS-LHC

38% deficit @$10^{17.5}$ eV

38% deficit @10^{18} eV

7 scintillator detectors

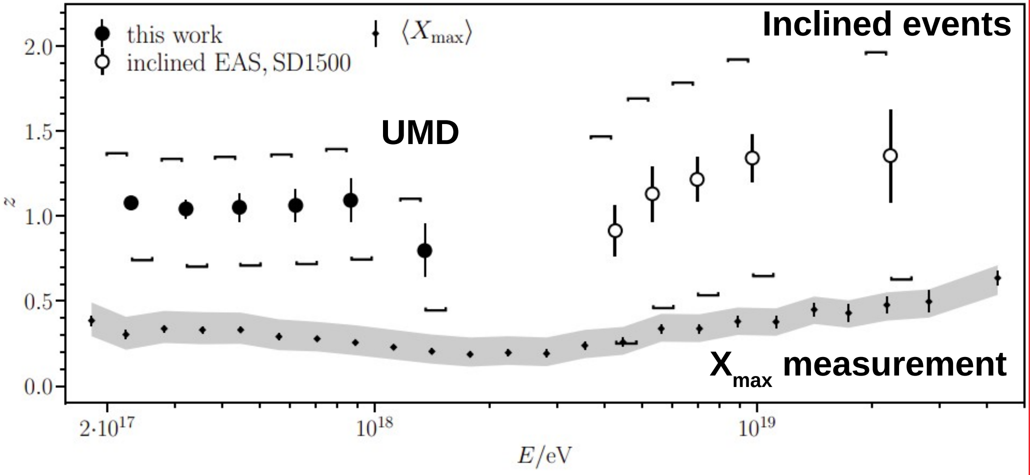
- 30 m^2 each
- 2.3 m underground
- Muon threshold: 1GeV/cos(θ)



Test of the models at all the energies

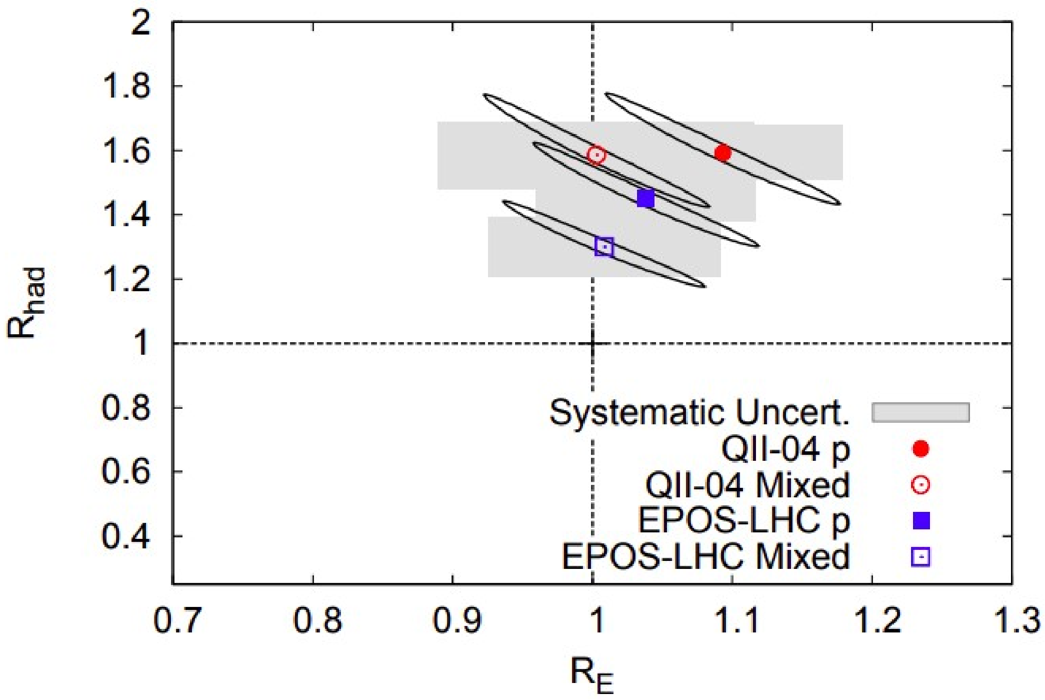
$$z = \frac{\langle \ln x \rangle - \langle \ln x \rangle_p}{\langle \ln x \rangle_{Fe} - \langle \ln x \rangle_p}$$

x: muon number estimator (ρ_{35} or R_μ)



A. Aab et al., Eur. Phys. J. C (2020) 80:751

Muons from hybrid events



$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\mathrm{had}}\, R_E^{\alpha}\, S_{\mathrm{had},i,j}$$

Muon excess or energy scale shift?

Analysis:

- Simulate showers matching the measured event longitudinal profile (with the same θ and E)
- Compare expected LDF with measured one
- Rescale FD energy and hadronic signal to obtain best fit to the LDF

Only a rescaling of the muon fraction needed

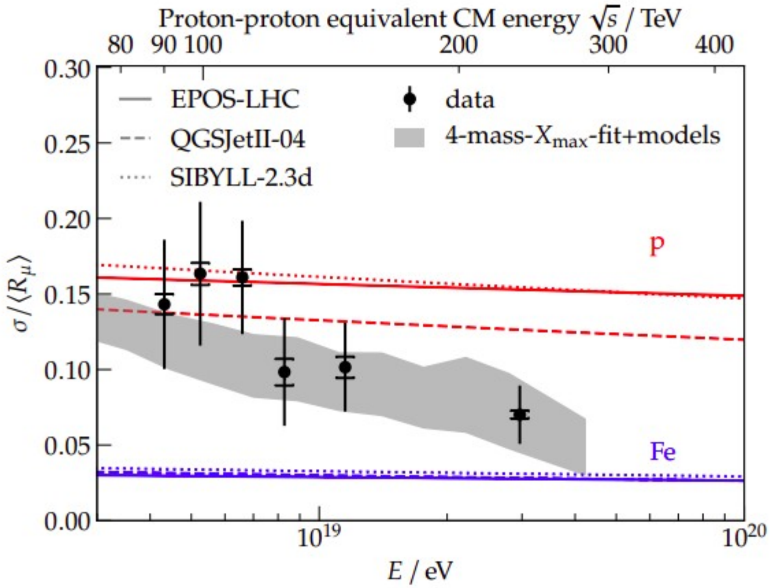
30-60% muon deficit in models

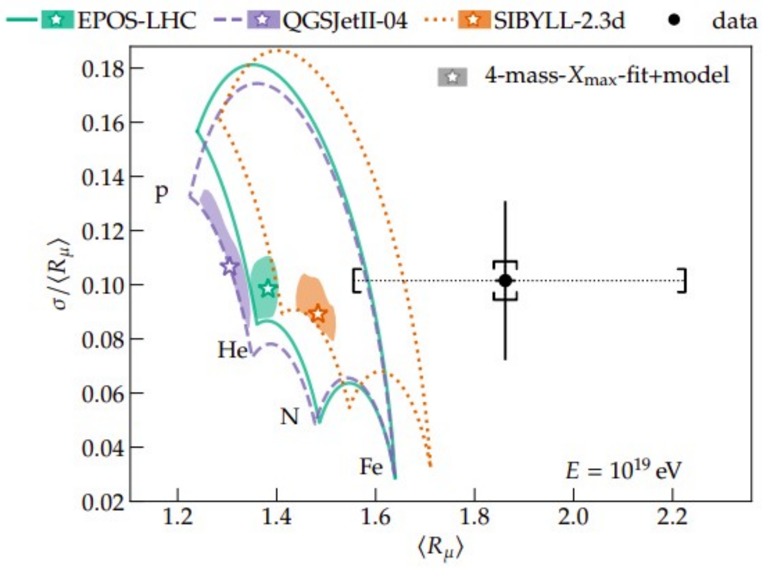
No energy rescaling needed

Smallest discrepancy with EPOS-LHC (1.9 σ)

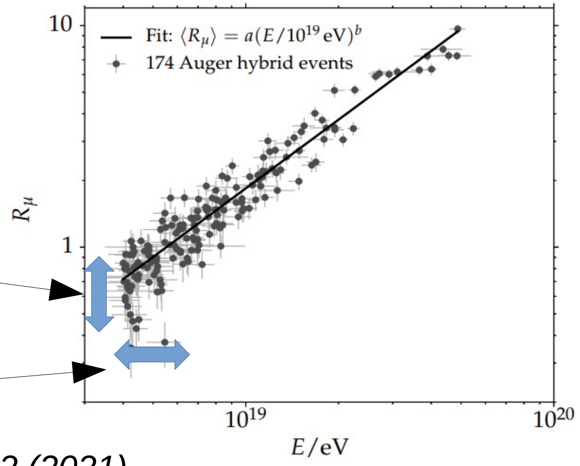
A. Aab et al., PRL 117, 192001 (2016)

Muon number fluctuations





Fluctuations on R_μ from detector resolution and **intrinsic fluctuations**



Energy resolution

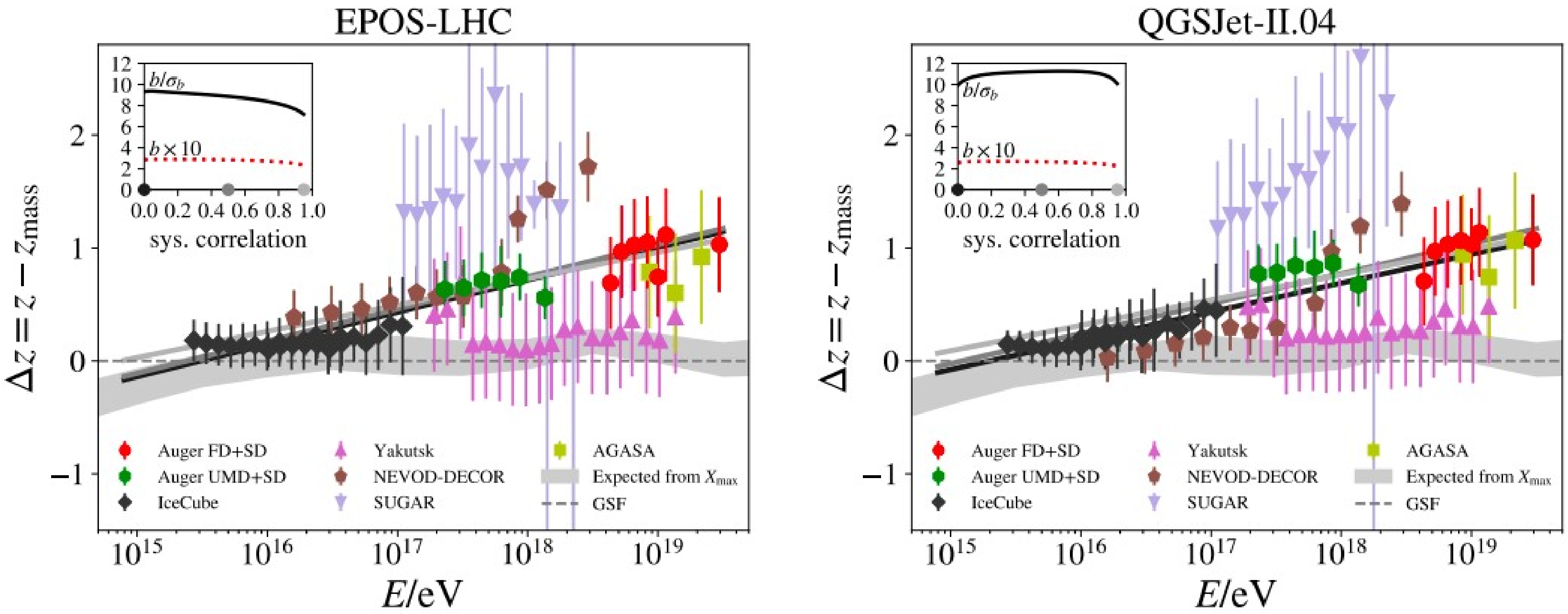
Muon density fluctuations consistent with expectations

Small effect accumulating over several interactions

- Large muon content
- Fluctuations consistent with the expectations

A. Aab at al., PRL 126, 152002 (2021)

An overview from different experiments



$$z = \frac{\ln\langle N_{\mu}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

$$\Delta z = z - z_{mass}$$

Consistency with hadronic models to E~10^{16} eV

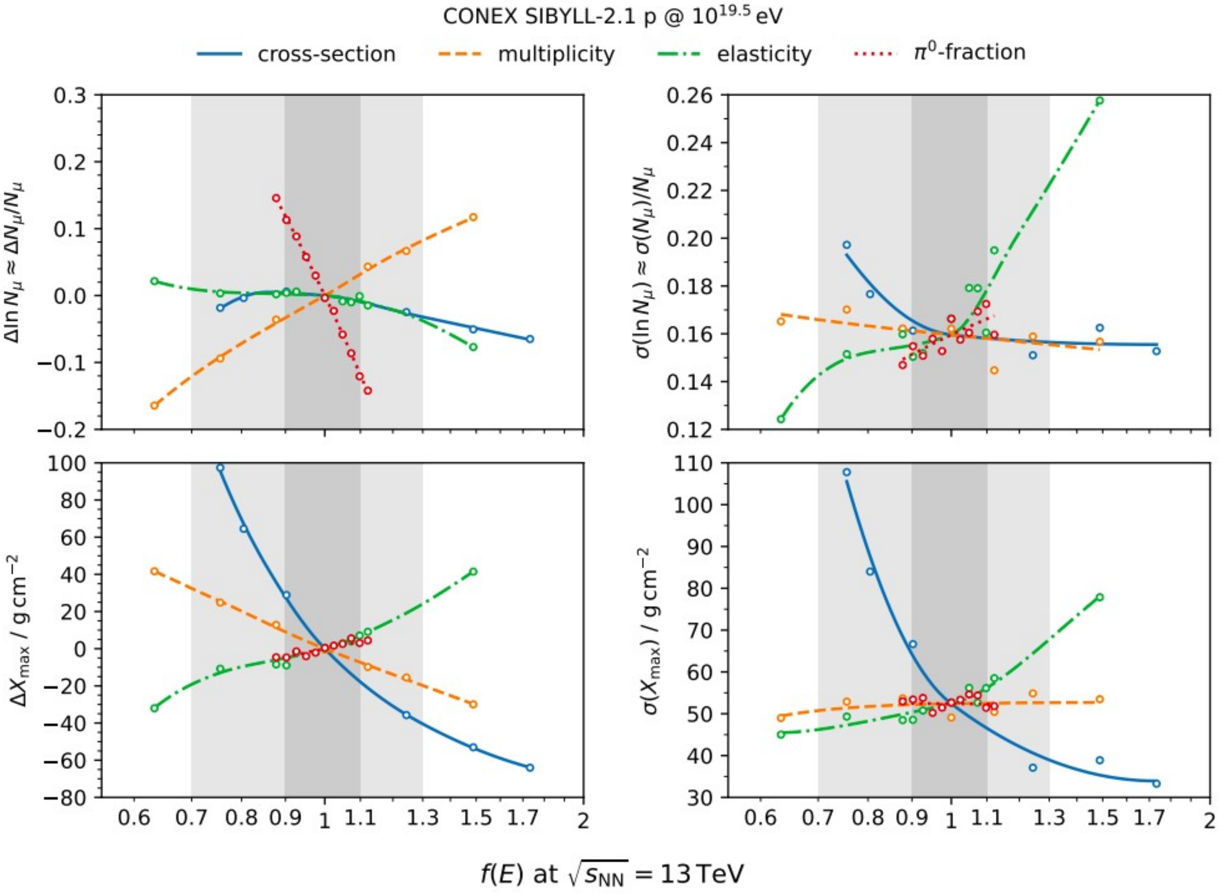
Above E~10^{16} eV: hint of linearly increasing inconsistency (8 σ significance)

Trend observed by *almost* all the experiments

Deviation emerging at ~LHC energies (~8 TeV c.m.s.)

D. Soldin, PoS(ICRC2021)349

Possible solutions to the muon deficit problem



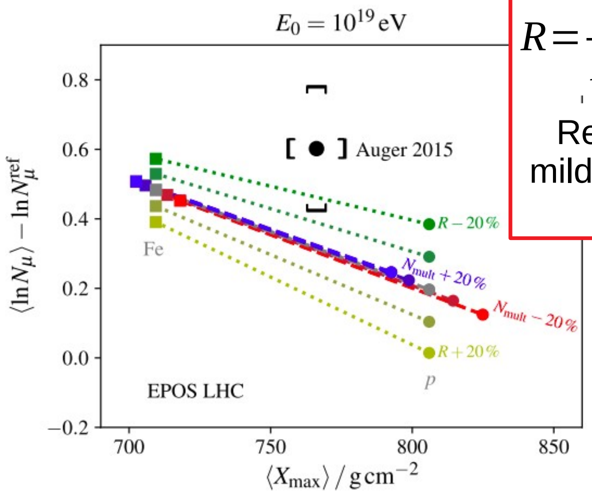
$$f(E) = 1 + (f_{19} - 1) \cdot \begin{cases} 0 & E < 1\,\mathrm{PeV} \\ \dfrac{\log_{10}\left(\frac{E}{1\,\mathrm{PeV}}\right)}{\log_{10}\left(\frac{10\,\mathrm{EeV}}{1\,\mathrm{PeV}}\right)} & E \geq 1\,\mathrm{PeV} \end{cases}$$

N_μ very sensitive to **π^0 fraction**
(low π^0 fraction → more muons)

Some sensitivity also to multiplicity

Elasticity constrained by μ fluctuations measurements

Cross section constrained by X_{max}

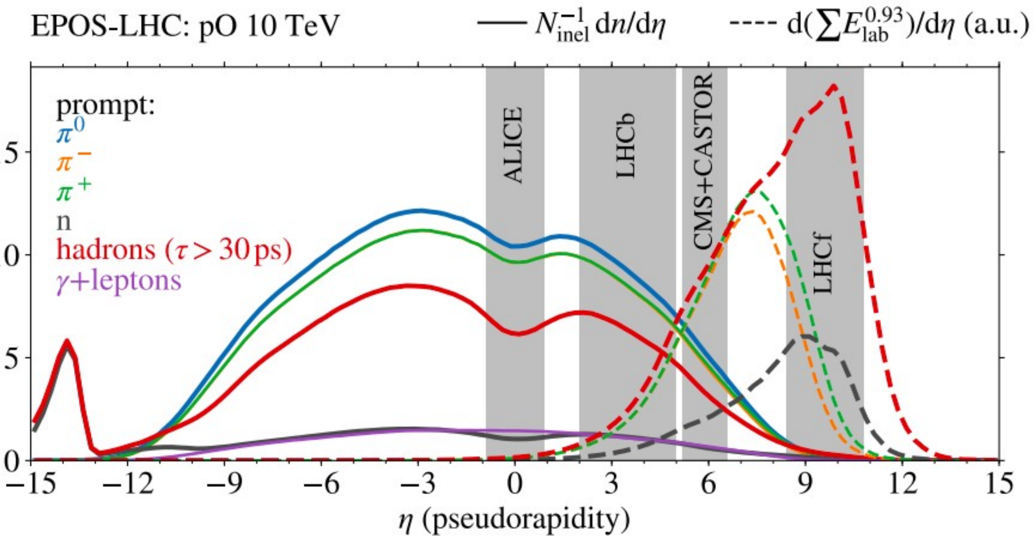


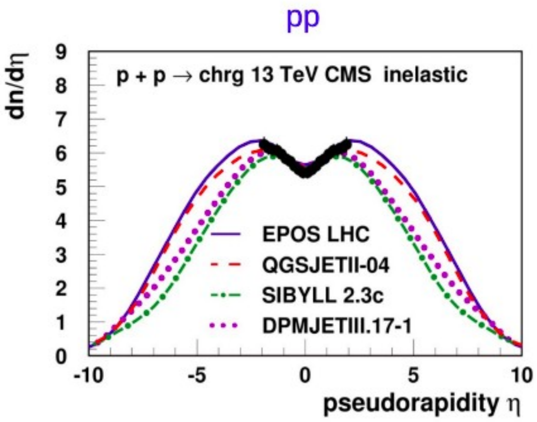
$$R = \frac{E_{\pi^0}}{E_{Other\ hadrons}}$$

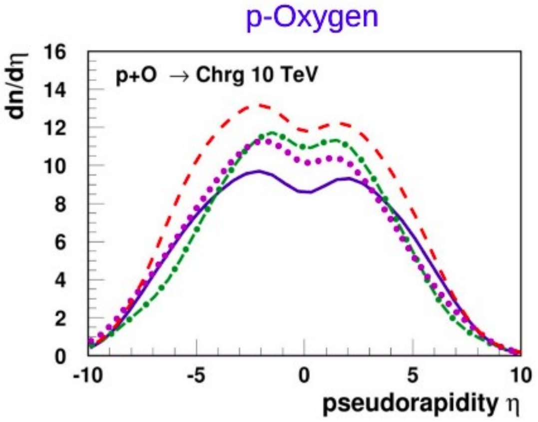
Reduction of R mildens the muon deficit

R. Ulrich, Phys. Rev. D83, 054026 (2011); S. Baur et al., arXiv.1902.09265

Future prospects







Most of muons produced by hadrons emitted in the forward direction

Models do not agree in forward regions and for p-O interactions

Tests to solve the muon puzzle:

At the accelerators:

- Test interactions at the LHC in the forward regions
- p-O and O-O collisions (approved for LHC run 3 – 2023/2024)

At Auger: upgrade of the observatory

- Auger Prime

J. Albrecht et al., arXiv:2105.06148; T. Pierog, ISVHECRI 2018

Conclusions

Auger data offer complementary information on hadronic interactions

- Cross sections p-air above the LHC range (34–77 TeV)
- Muon content in showers measured
- Information on first interaction from muon fluctuation measurement
- Beyond standard model searches LIV, monopoles, top-down models...

Origin of muon discrepancy

- Possibly an issue in forward soft-QCD reducing the π^0 energy ratio
- Lack of nucleon-air measurements
- Small modification in the hadronic models cumulated over several interactions
  (allows for: muon excess + consistent muon fluctuations + consistent X_{max} moments)

Future steps:

- Measurements at high η and p-O collisions at LHC
- Auger Prime to improve the sensitivity to the muonic component