ICHEP 2022 INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

Saturday 9th July 2022

Probing hadronic interactions using the latest data measured by the Pierre Auger Observatory

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ICHEP 2022

Pierre Auger Observatory 20th Anniversary

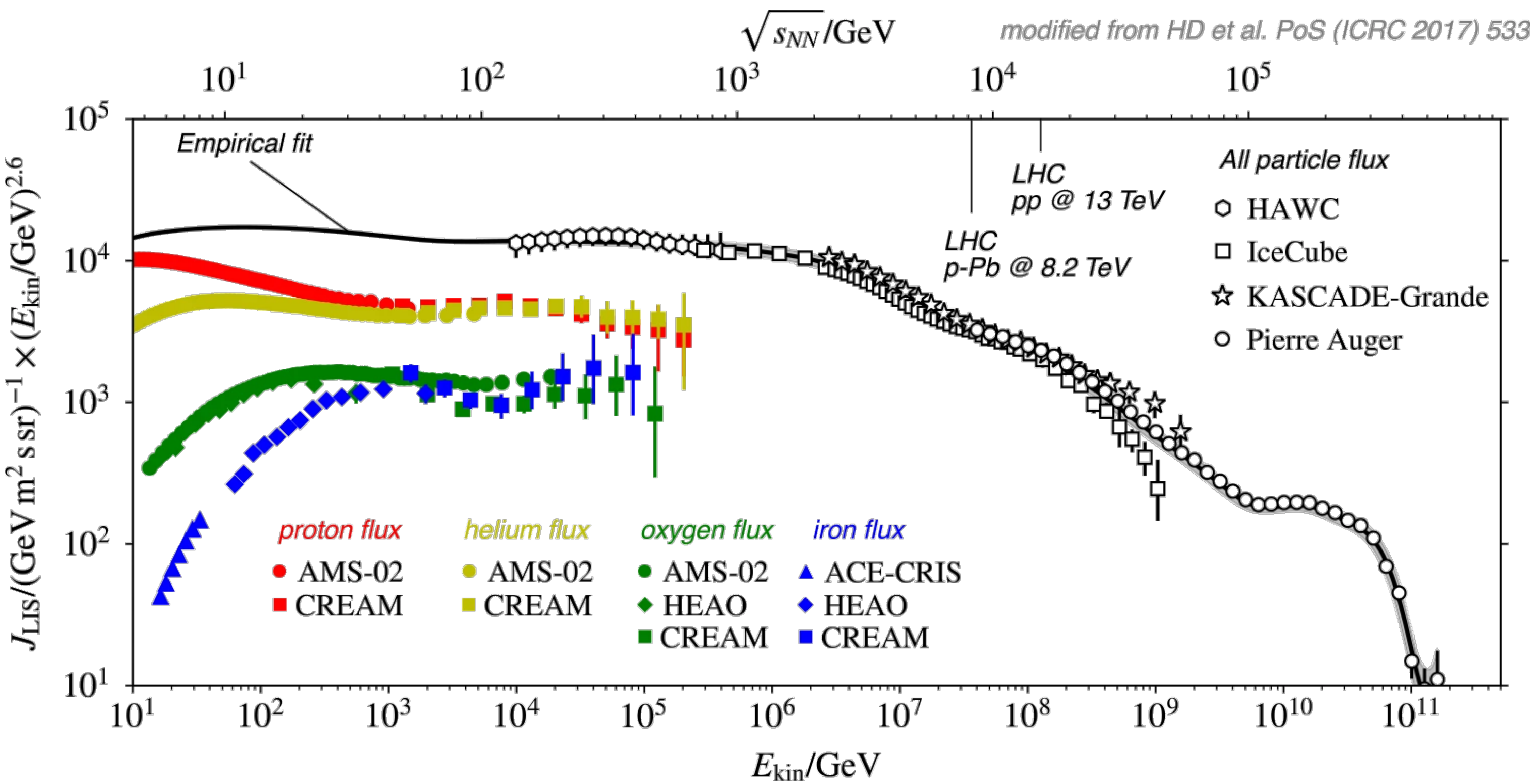
More than 400 members,
98 institutes, 17 countries

November 2019

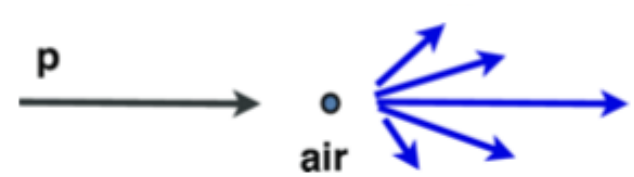
Pierre Auger Observatory
Malargue, Mendoza, Argentina

Ultra-high energy cosmic rays

Even the most powerful accelerator reaches only to equivalent energies of 10^{17} eV



Cosmic rays allow to study hadronic interactions at ultra-high energies



Astrophys.Space Sci. 367 (2022) 3, 27

UHECRs from Air Showers

- EAS simulations and hadronic interaction models are the key ingredients to study UHECRs

  Mass composition identification from the secondary particles

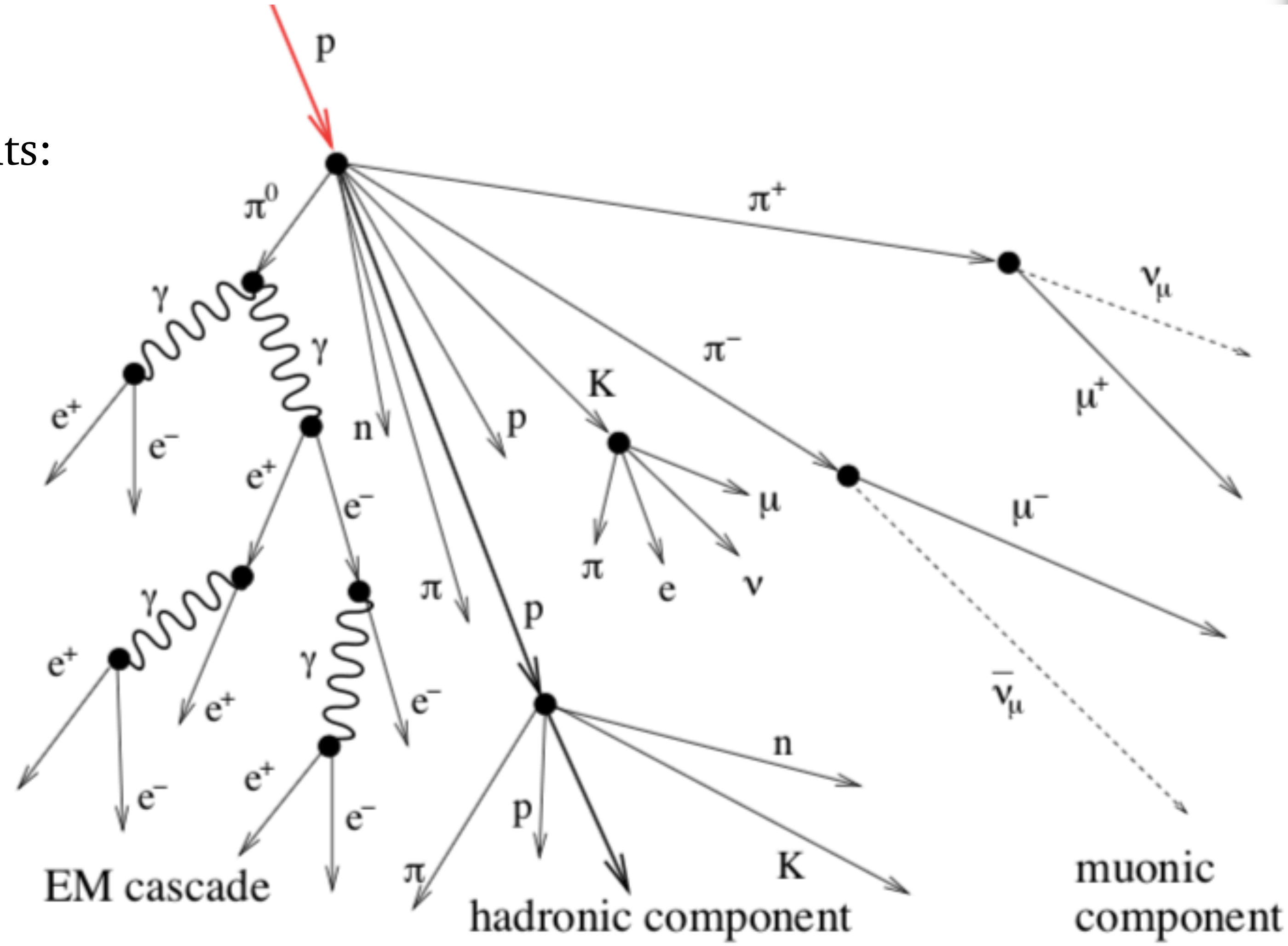
- Considered hadronic interaction models:
  EPOS-LHC
  QGSJET II-04
  Sibyll (2.3c/d)

Extensive Air shower

An air shower is an extensive cascade, with a length of many km, of ionized particles and electromagnetic radiation that initiates when a **primary cosmic ray** ($E > 10^{18}$ **eV)** enters the atmosphere.

The shower is composed of three components:

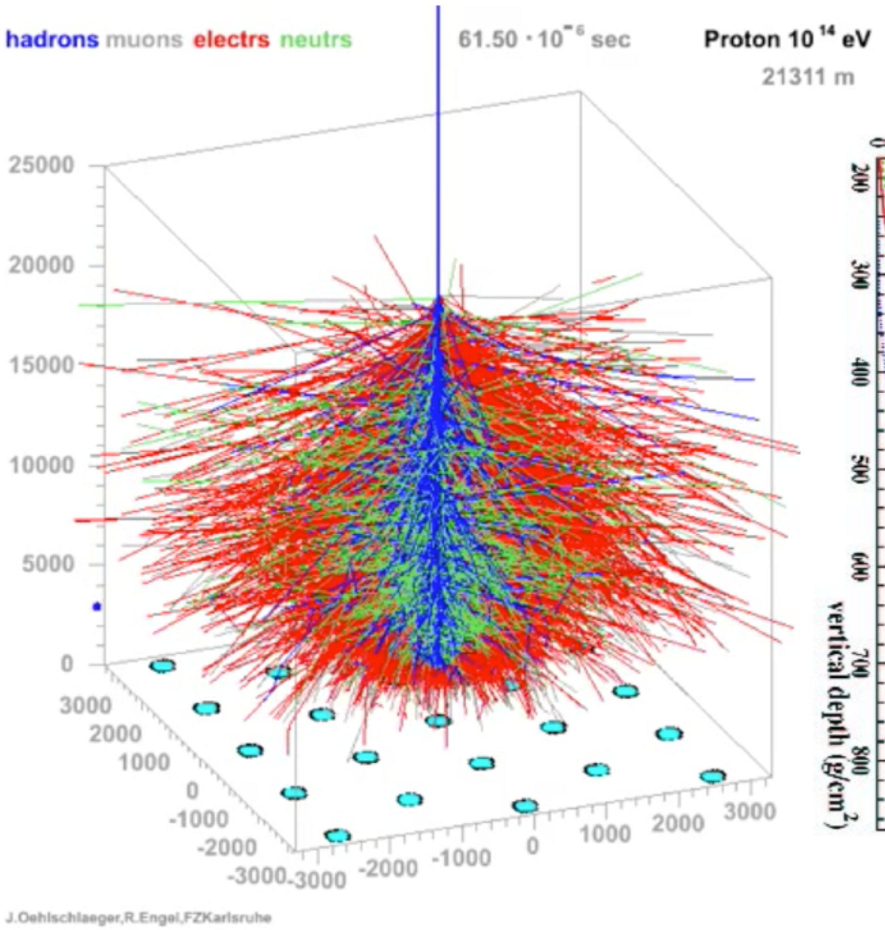
- The em component characterized by the **pair production**, the **bremsstrahlung** and the **ionization energy loss**;
- The hadronic component produced by **charged hadronic** particles involved in the **strong interactions** with the atmosphere;
- The muonic component weakly interacts and it can be detected at ground using SD.

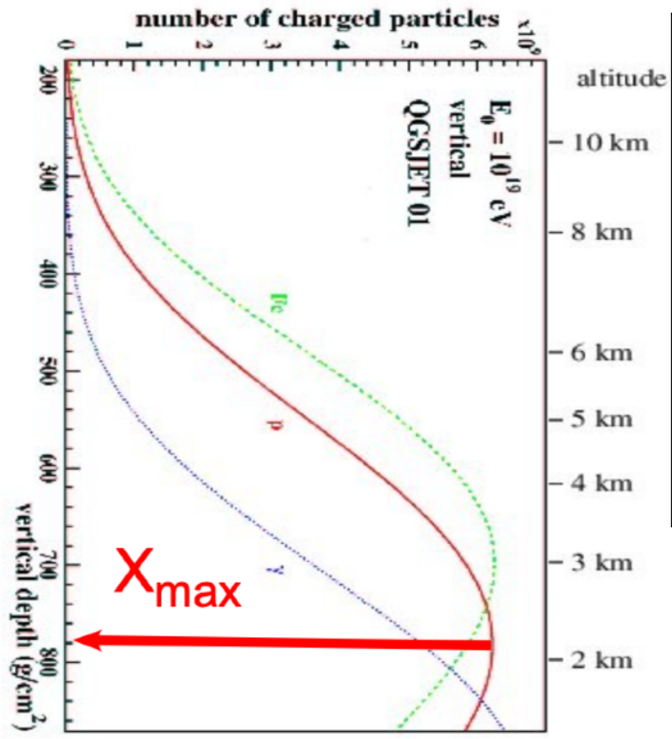


Heavier mass primaries induce showers with larger hadronic component and therefore more muons

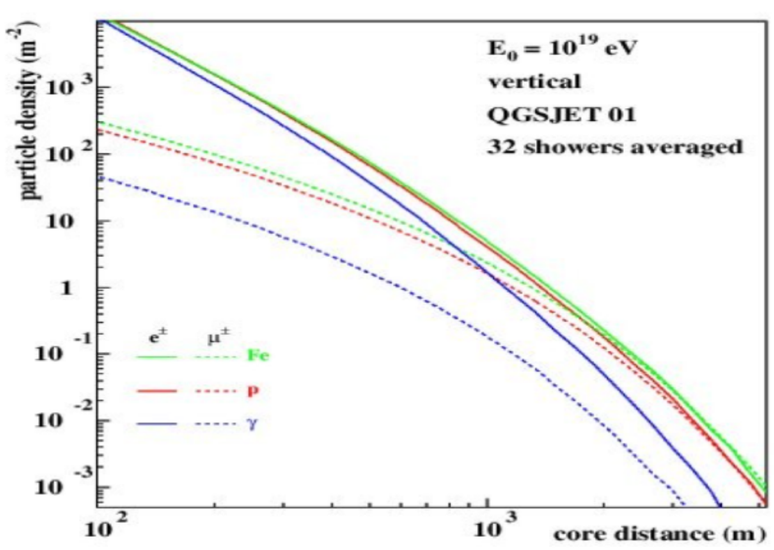
Electromagnetic component remains ~ the same

Extensive Air shower





- Longitudinal development
  > Number of particles as a function of the depth X
  > Larger number of particles at X_{max}
- The **lateral distribution function**;
  > Particle density at ground wrt distance to shower axis
  > Muons, electrons or mixture



- At a depth X the number of particles in the shower is $N(X) = 2^n = 2^{\frac{X}{\lambda_{em}}}$.

At the shower maximum we define:

- $N_{max} = E_0/E_c$;
- $X_{max} = X_0 + \lambda_{em} log_2(E_0/E_c)$

99,88% of electromagnetic (e/m) particles
0.1% of muons
0.02% hadrons

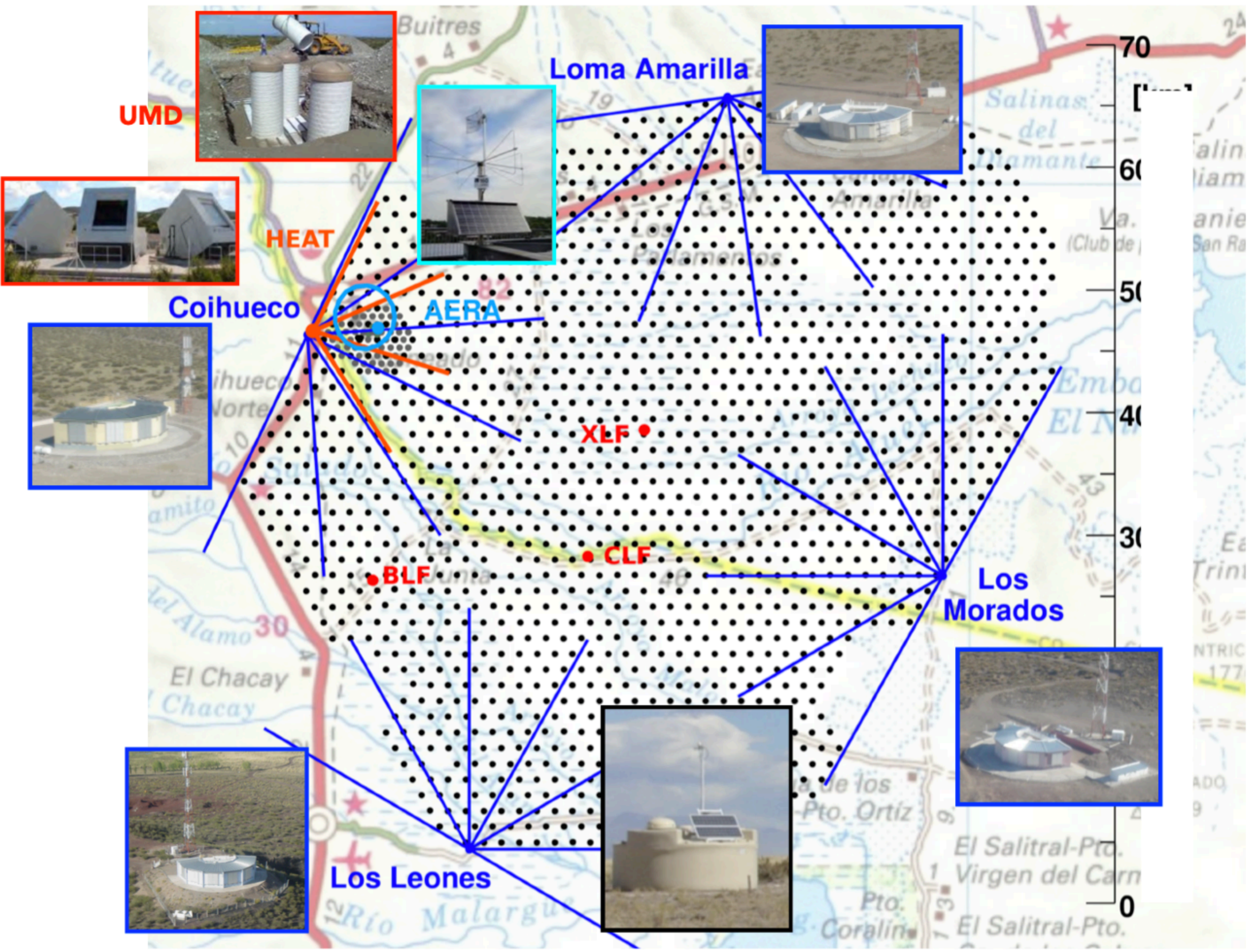
A nucleus with mass A and energy E_0 is considered as A independent nucleons with energy E_0/A each.

1) $X_{max} \propto \lambda \dfrac{E_0}{AE_c}$

2) $N_\mu^A(X_{\text{max}}) = A\left(\dfrac{E_0/A}{E_{dec}}\right)^\alpha = A^{1-\alpha} N_\mu^p(X_{\text{max}})$

The Observatory

Located in the southern hemisphere is the largest air shower detector built so far



- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km²
  - ➡SD750 : 61, 0.75 km grid, 25 km²
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30⁰ FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60⁰ FoV
  - For reconstructing showers more reliably at ~10^{17}eV
- AERA radio antennas
  - ➡153 graded 17 km²

+Atmospheric monitoring devices
CLF, XLF, Lidars, …

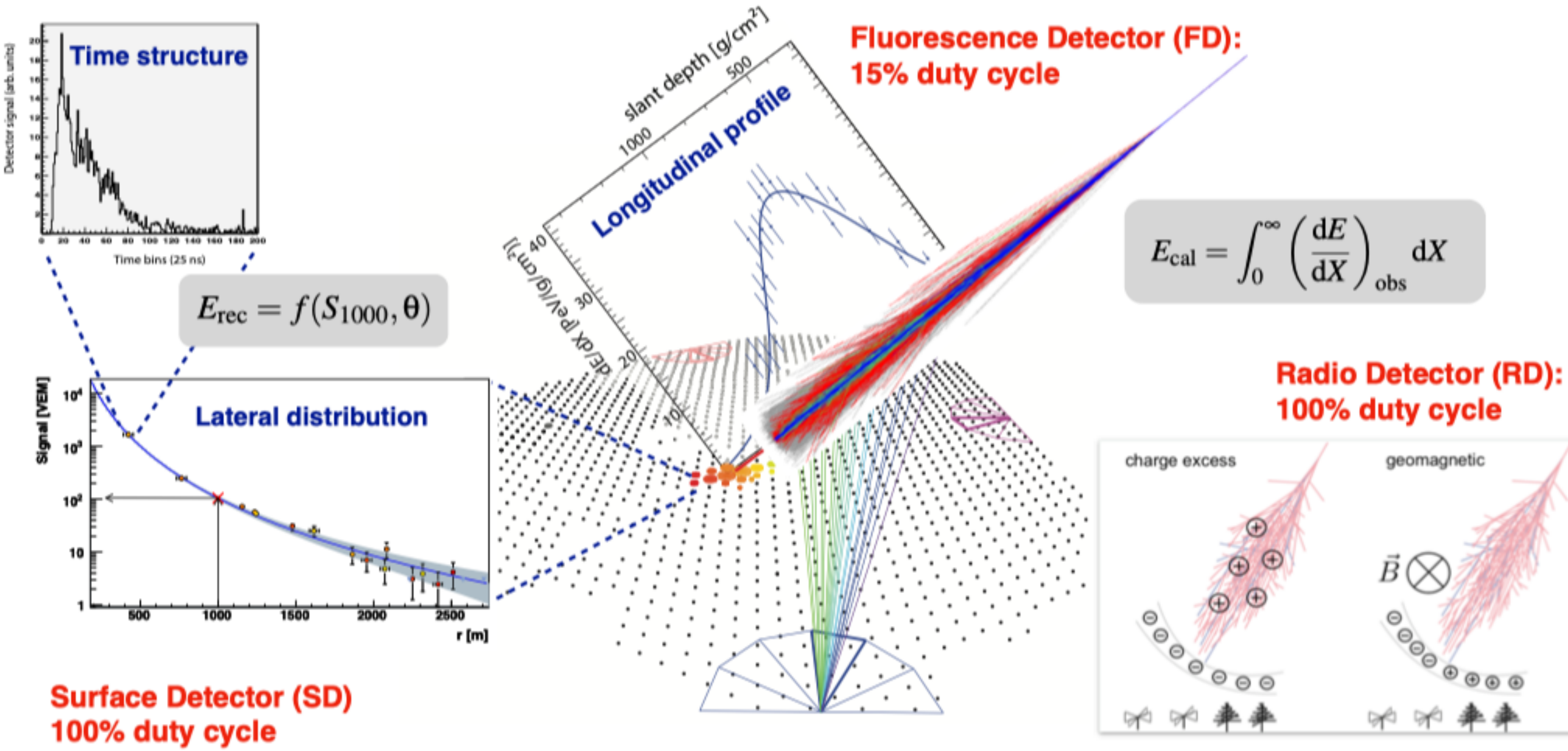
Hybrid Detection

The SDs measure photons and charged particles at ground level

The FDs observe longitudinal development of air showers in the atmosphere

The RDs complement this setup studying radio emission from air showers

AugerObservatory Phase I



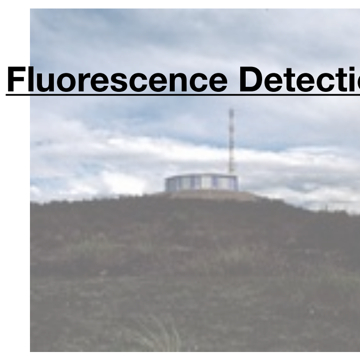
Calibration of the SD risetime with $X_{\rm max}$ distributions measured with the FD

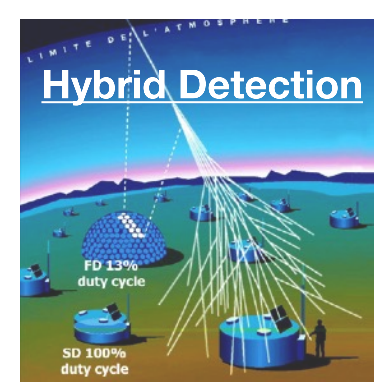
The Pierre Auger Observatory has been designed to investigate the highest energy cosmic rays with energy exceeding 10^{19}eV, combining a surface array of particle detectors with fluorescence telescopes for hybrid detection

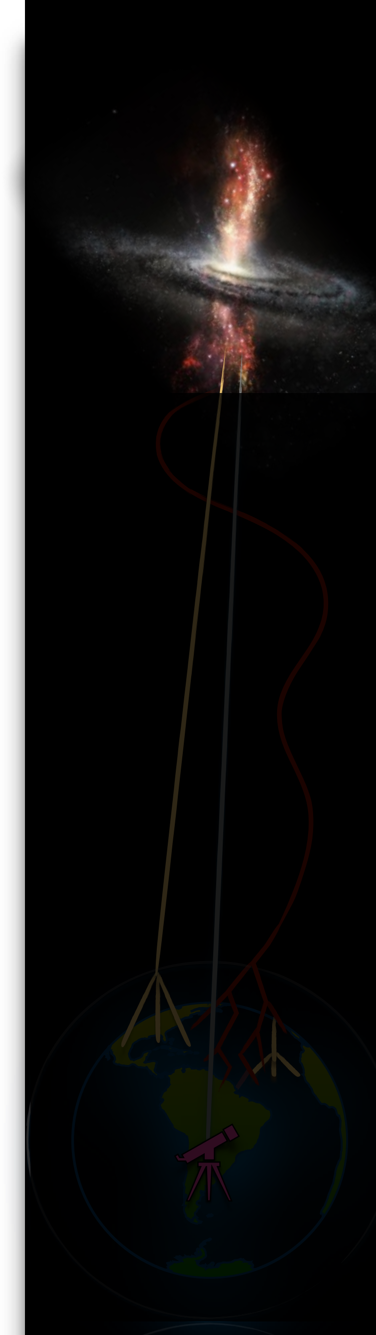
Probing hadronic interactions…

Self-consistency tests of the post-LHC hadronic models using measurements of the depth of the shower maximum and the main features of the muon component at the ground.

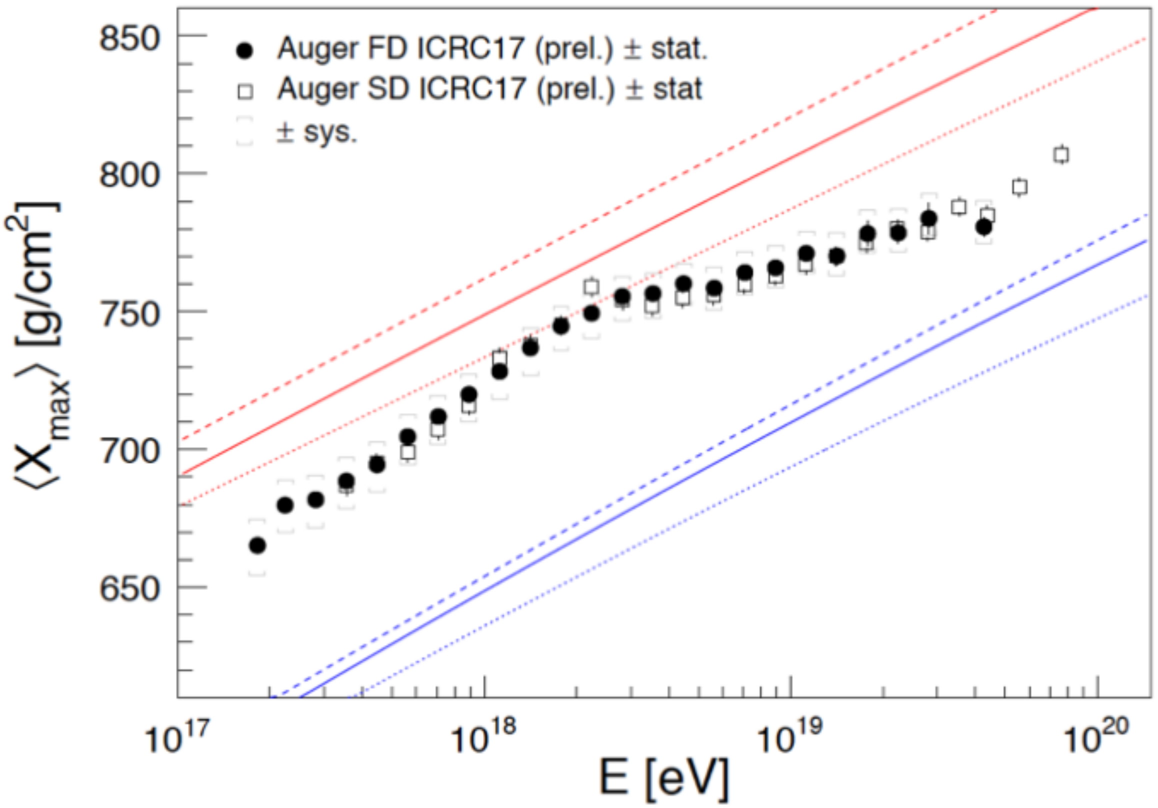
- Depth of the shower maximum;
- Cross section measurement ;
- Muon measurement with highly inclined showers;
- Direct measurement with buried muon counters;
- Fluctuations in the number of muons;

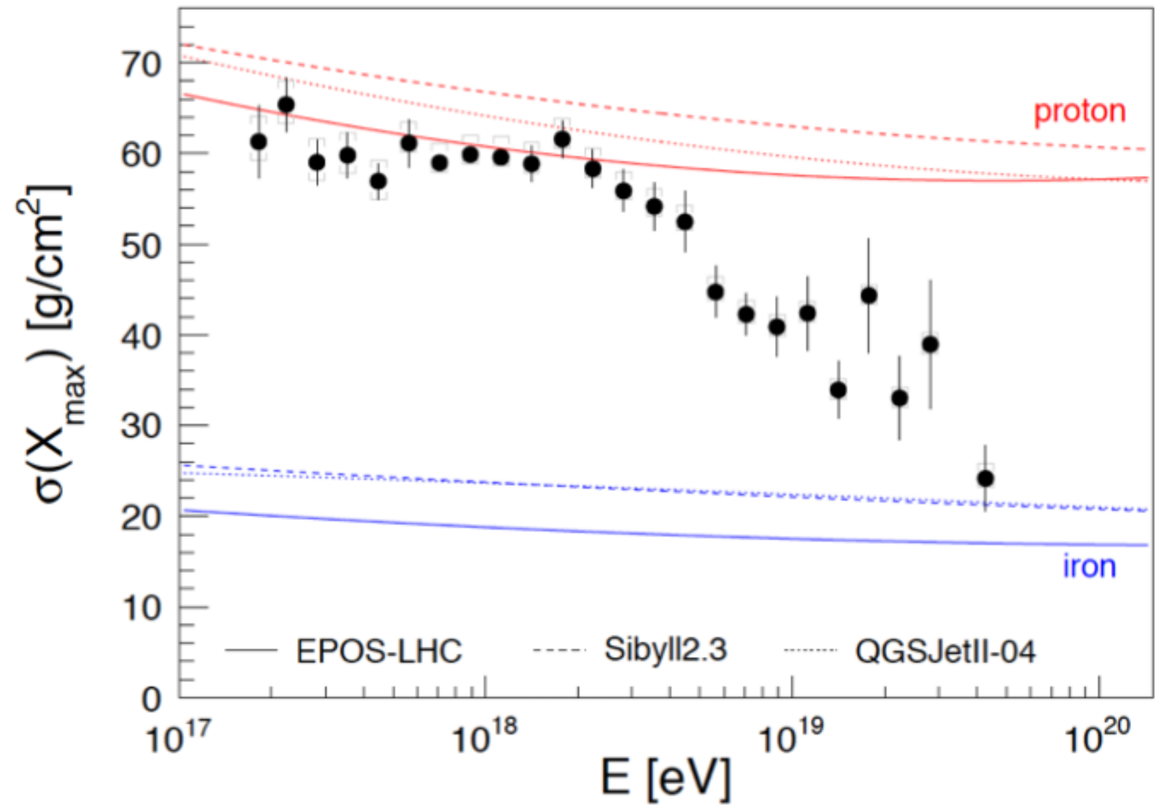


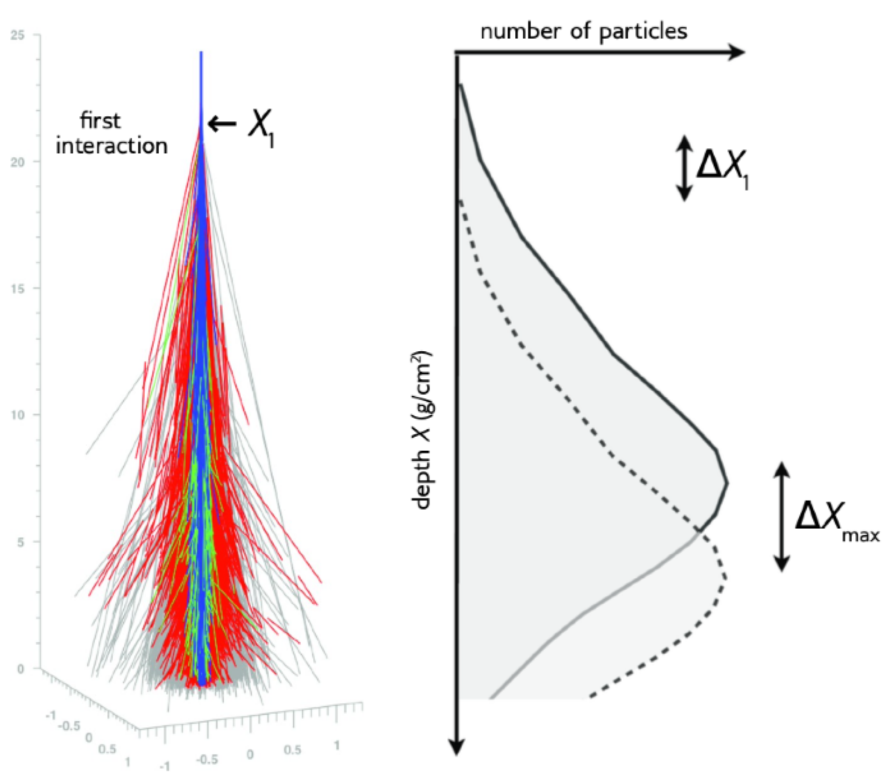




Depth of shower maximum

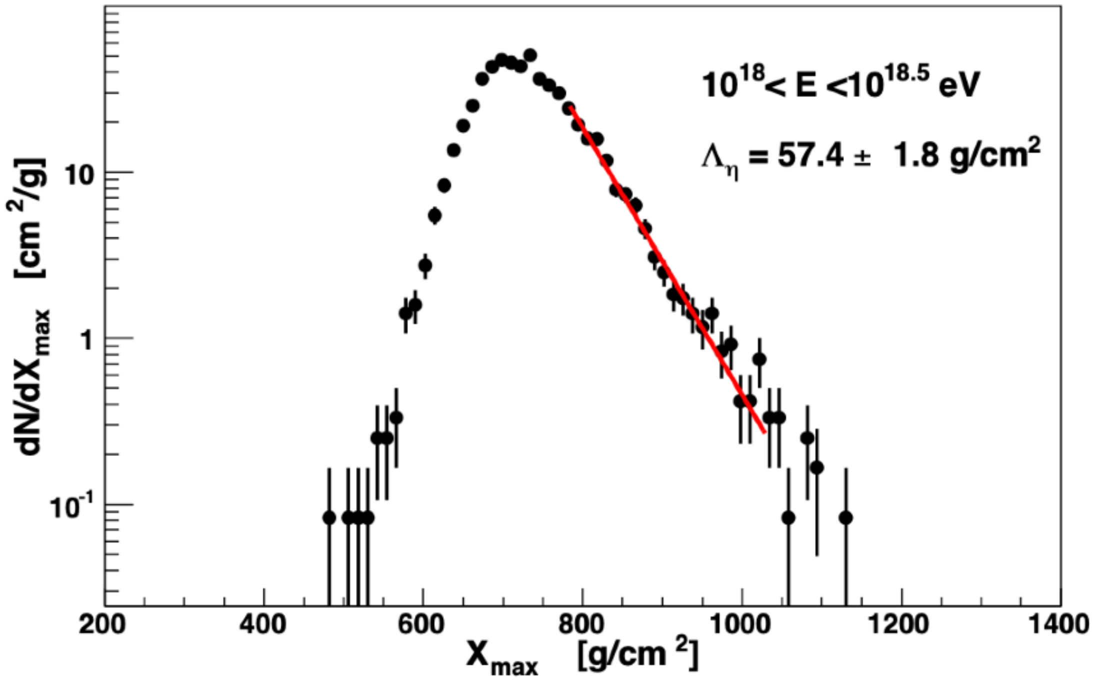






The Pierre Auger Collaboration, Phys.Rev,D90(2014) 122005
J. Bellido (Auger Coll.) PoS (ICRC2017) 506
The Pierre Auger Collaboration, EPJ Web of Conferences 208, 08001 (2019).

Cross Section Measurements



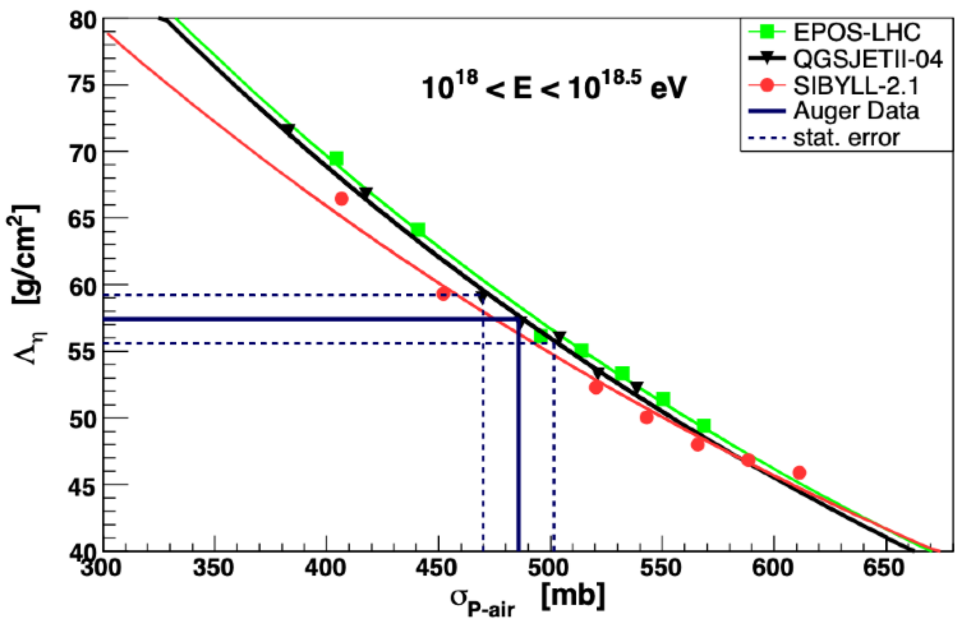
$$\mathrm{d}N/\mathrm{d}X_{\max} \propto \exp\left(-X_{\max}/\Lambda_\eta\right)$$

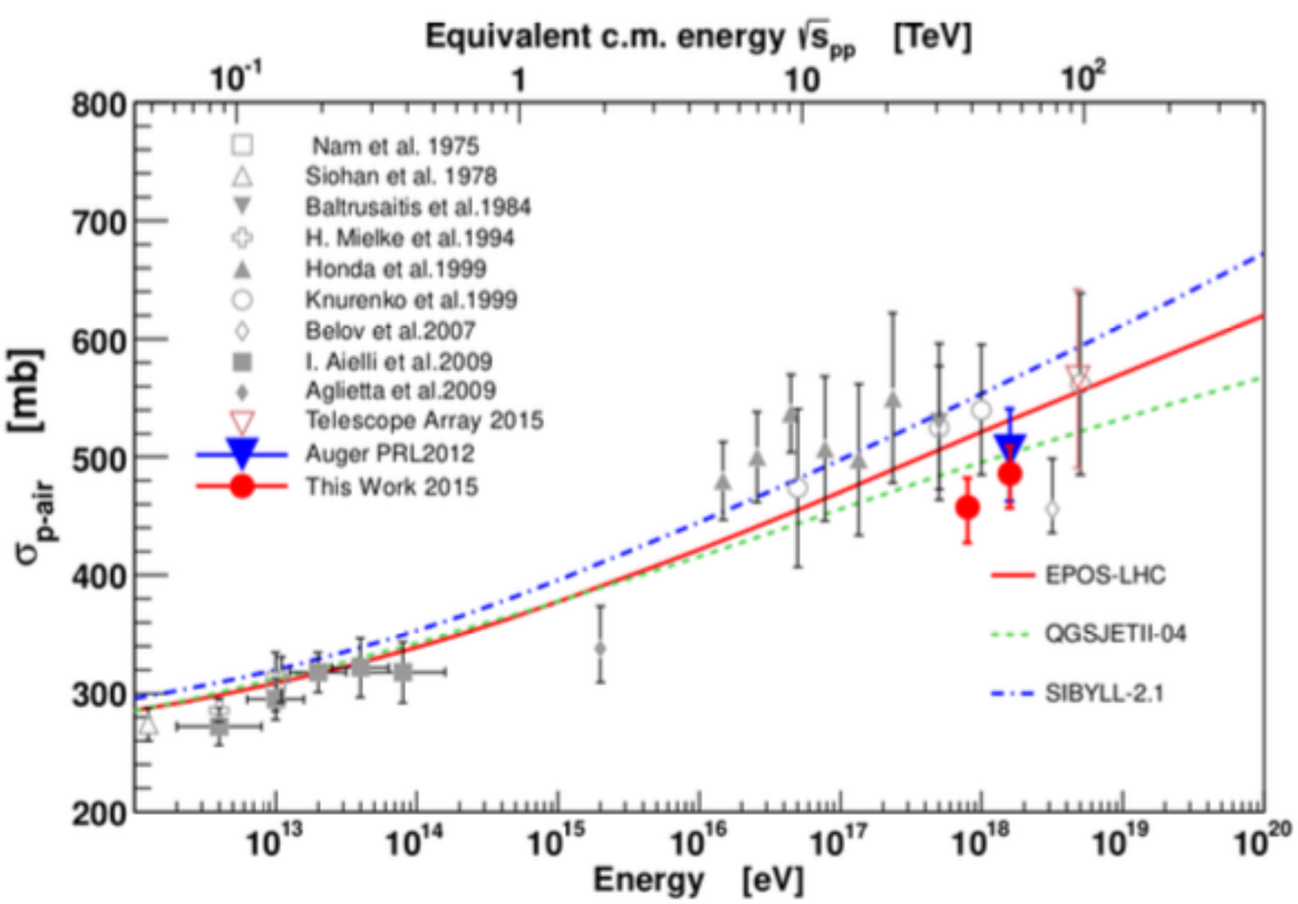
Measured Λ_η related to the cross section

20% most deeply penetrating showers (proton fraction the data set enhanced)

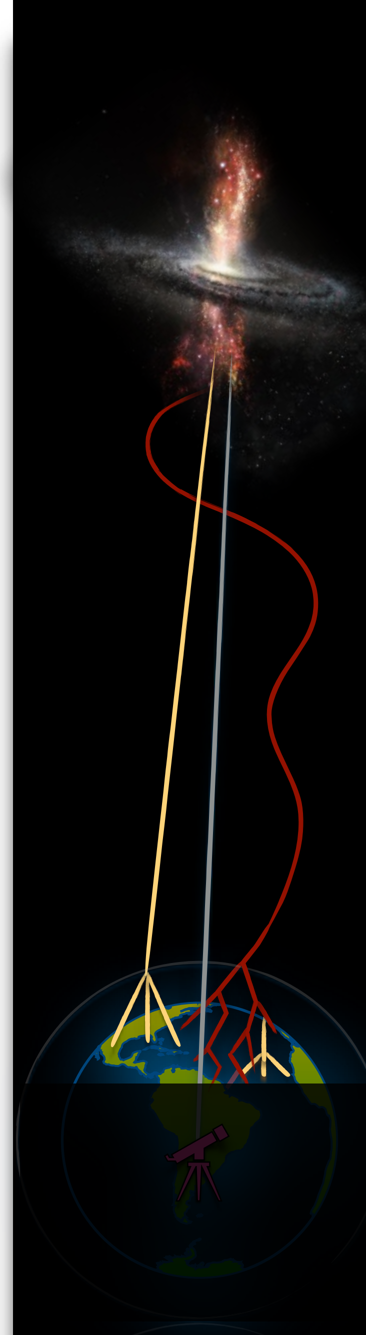
Energy Ranges

LAB	CMS pp
$\log(E/\mathrm{eV}) = 17.8 - 18$	38.7 TeV
$\log(E/\mathrm{eV}) = 18 - 18.5$	55.5 TeV



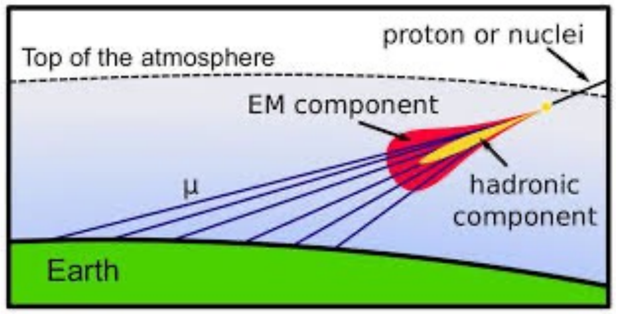


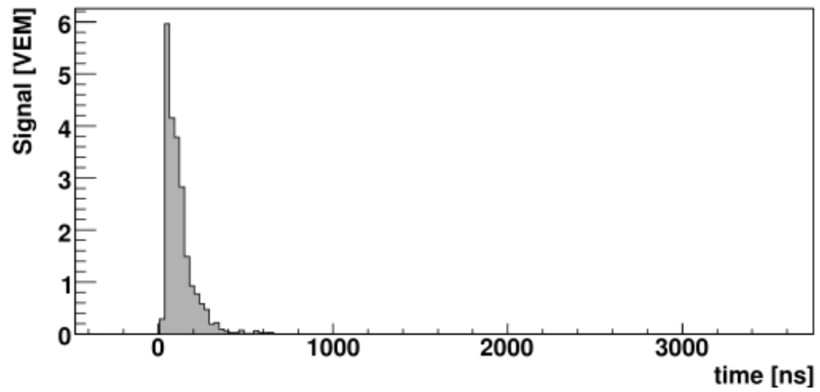
The Pierre Auger Collaboration, Phys.Rev,Lett. 109 (2012) 062002
R. Ulrich (Auger Coll.) PoS (ICRC2015) 401

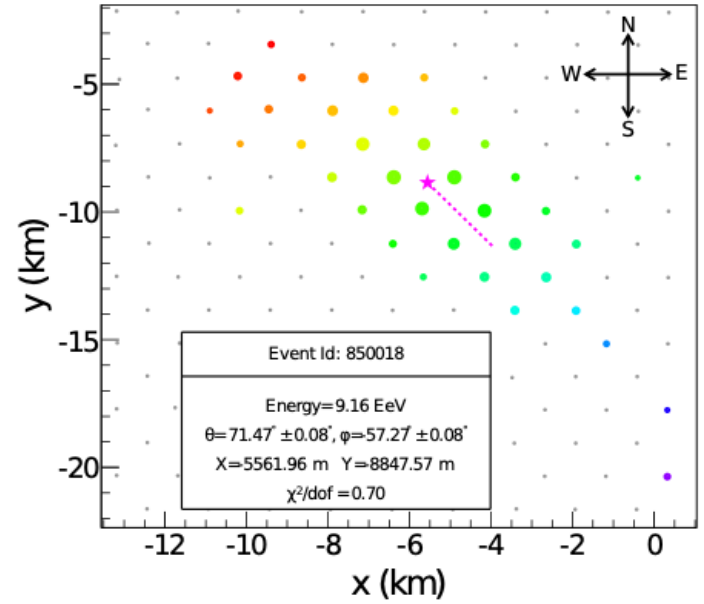


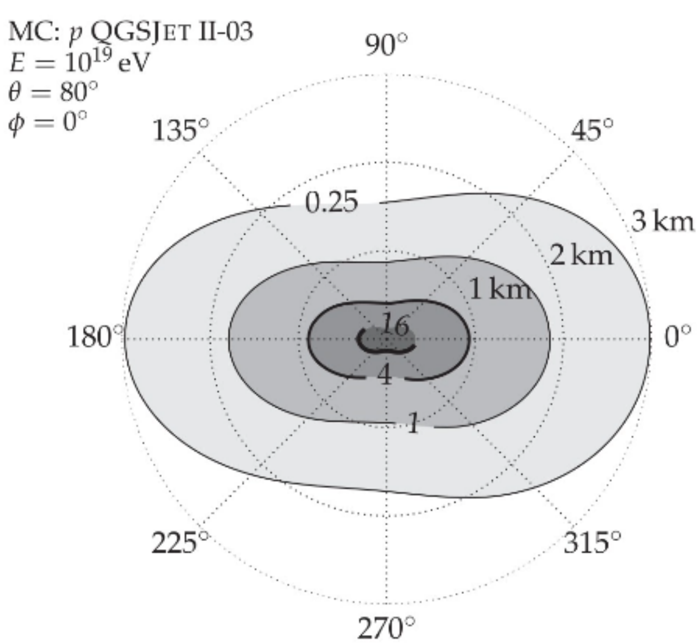
Muon measurement with highly inclined showers

Zenith angles 62°-80°

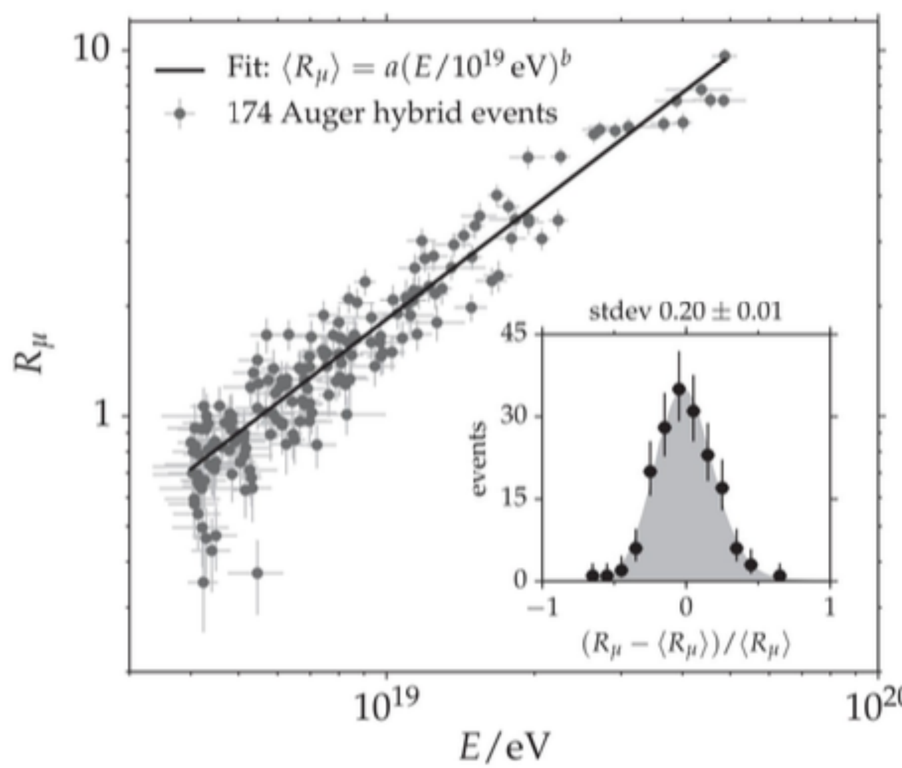








$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

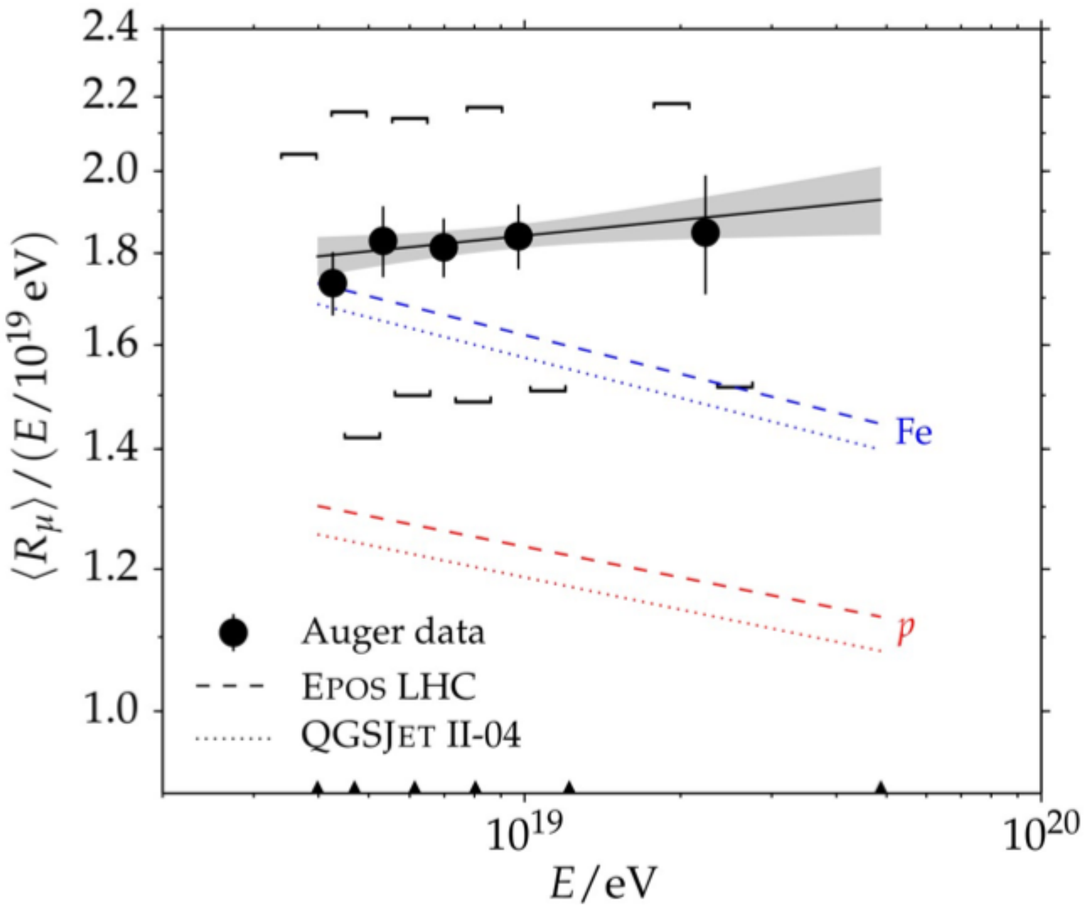


$$\rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

$$\langle R_\mu \rangle = a(E/10^{19}\ \text{eV})^b$$

The Pierre Auger Collaboration, Phys.Rev,D. 91 (2015) 032003

Muon measurement with highly inclined showers

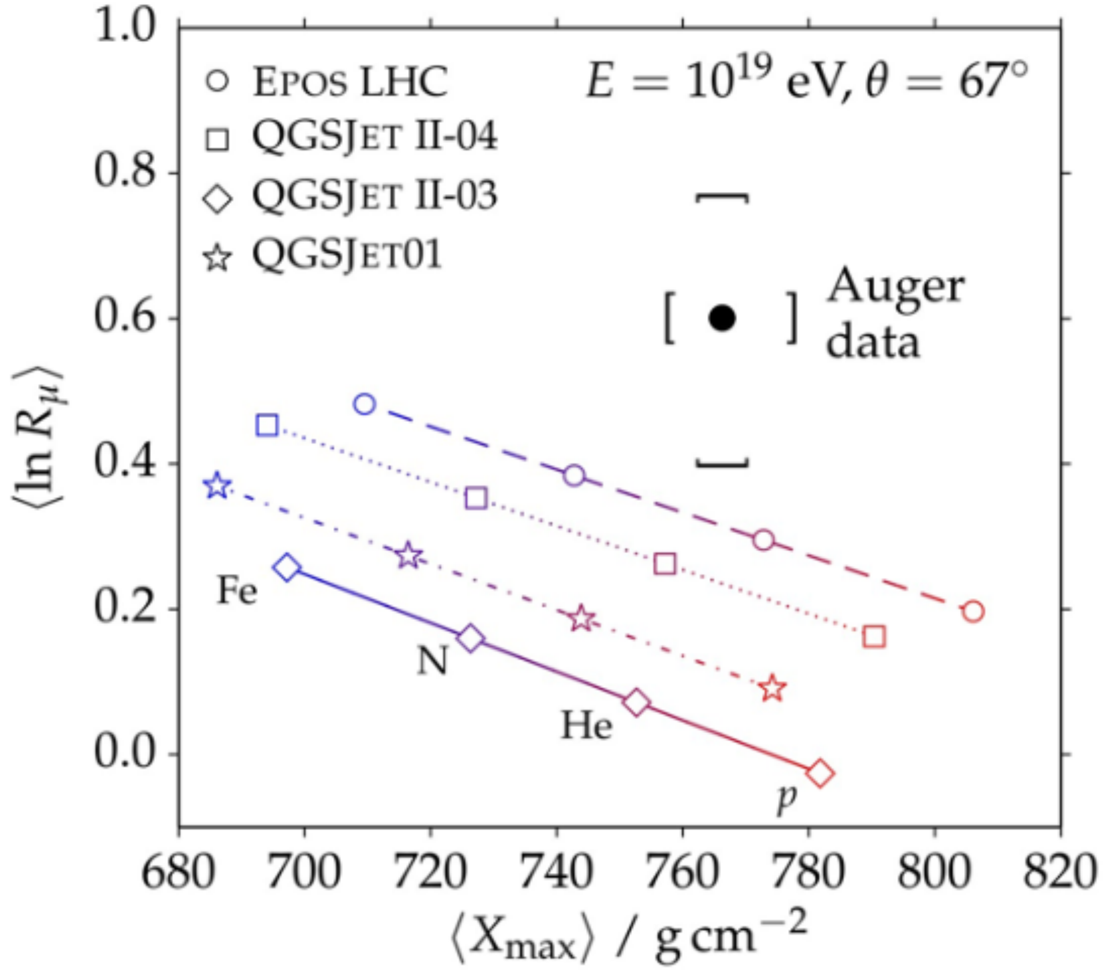


Disagreement quantified using the mass composition inferred from $X_{\max}$

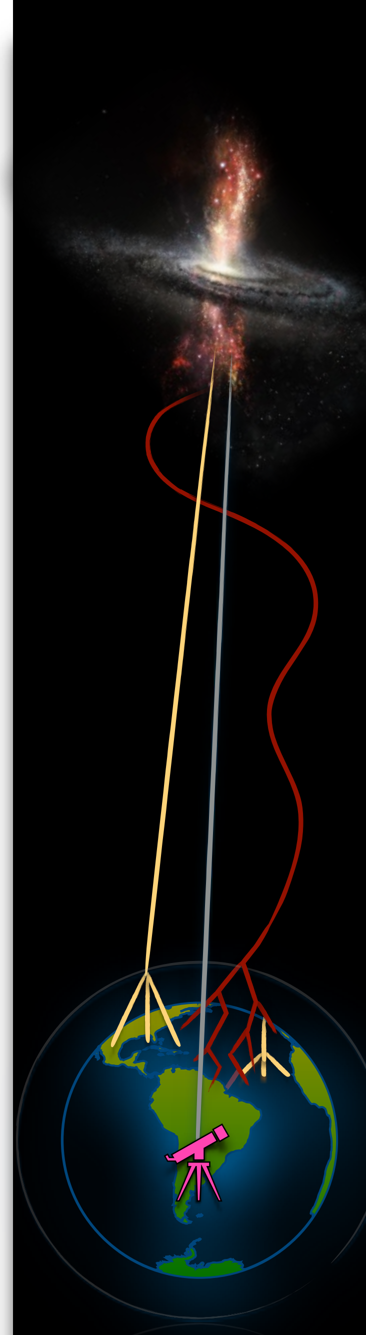
$$\langle X_{\max} \rangle = \langle X_{\max} \rangle_p + f_E \langle \ln A \rangle$$

P. Abreu *et al.* (Pierre Auger Collaboration), J. Cosmol. Astropart. Phys. 02 (2013) 026.

$$\langle \ln N_\mu \rangle = \langle \ln N_\mu \rangle_p + (1-\beta)\langle \ln A \rangle$$

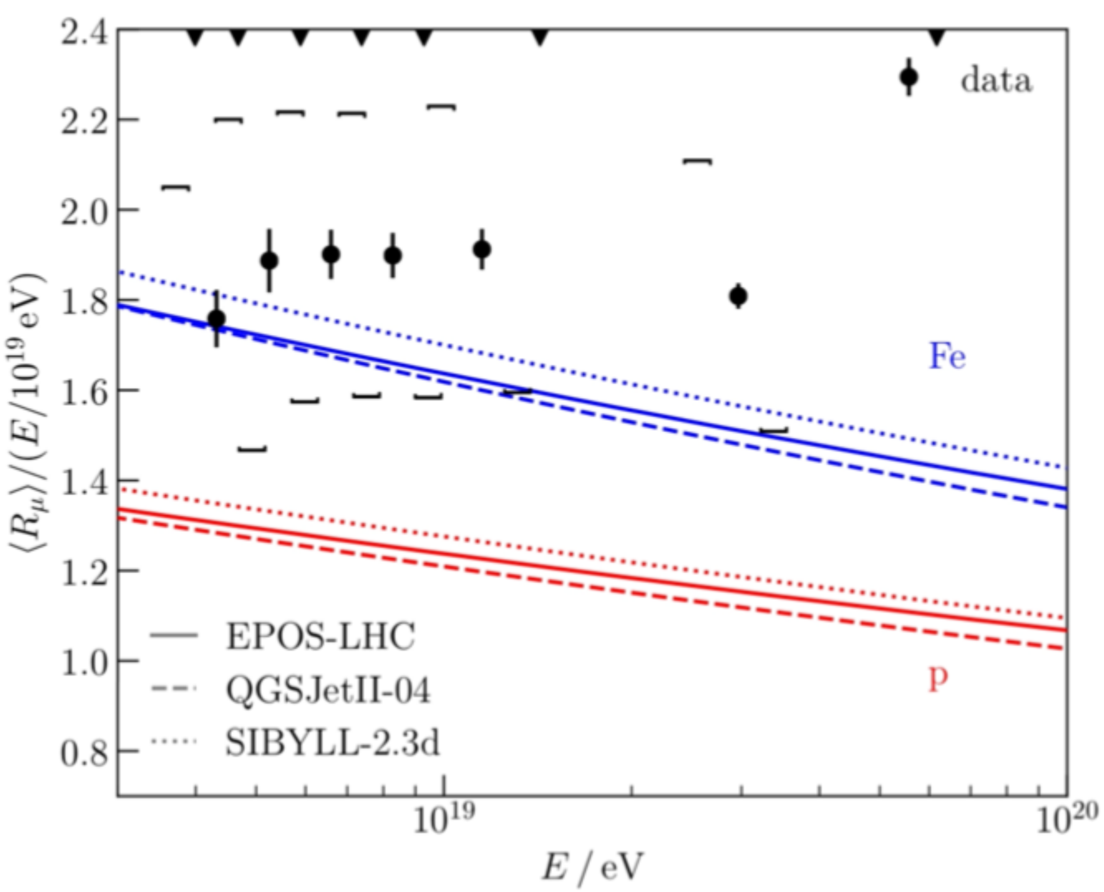


The Pierre Auger Collaboration, Phys.Rev,D. 91 (2015) 032003

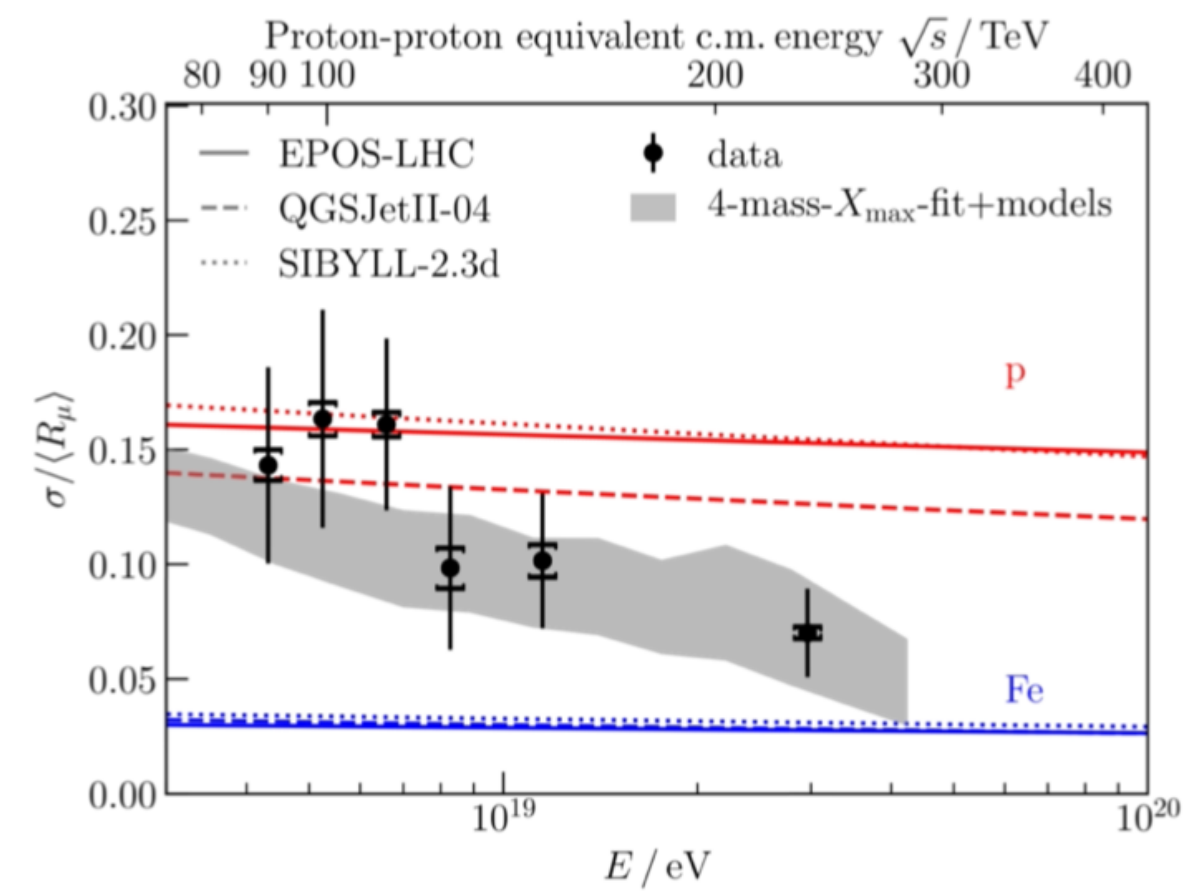


INTRODUCTION
The Observatory
Mass Composition
Cross Sections
Muon Measurement
CONCLUSIONS

Measurement of the fluctuation in the number of muons



Fluctuations in the number of muons between showers



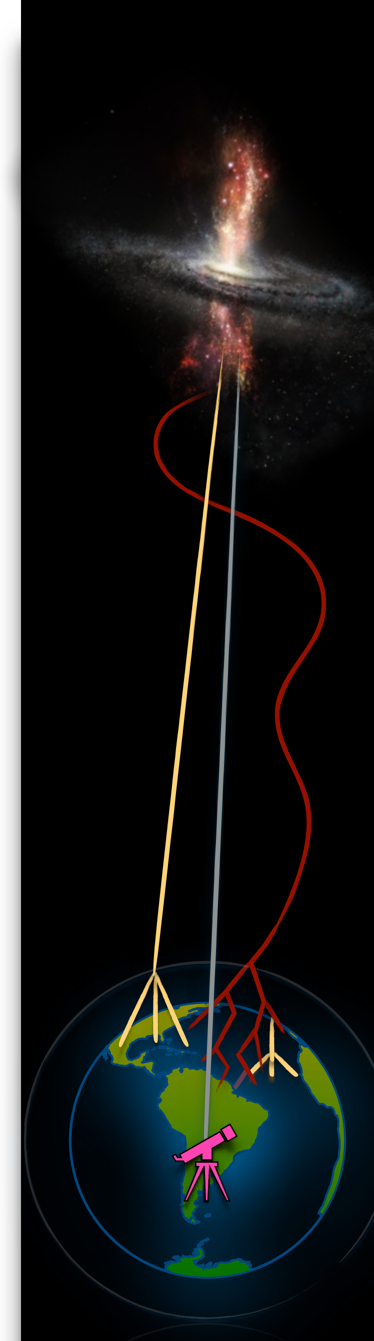
The necessary increases in the average number of muons to reconcile the simulated values with the measurement vary from 26% to 43%

$$\langle N_\mu(E) \rangle = m^g = CE^\beta \longrightarrow \sigma(m_i) = \frac{\sigma(m)}{\sqrt{N_{i-1}}}$$

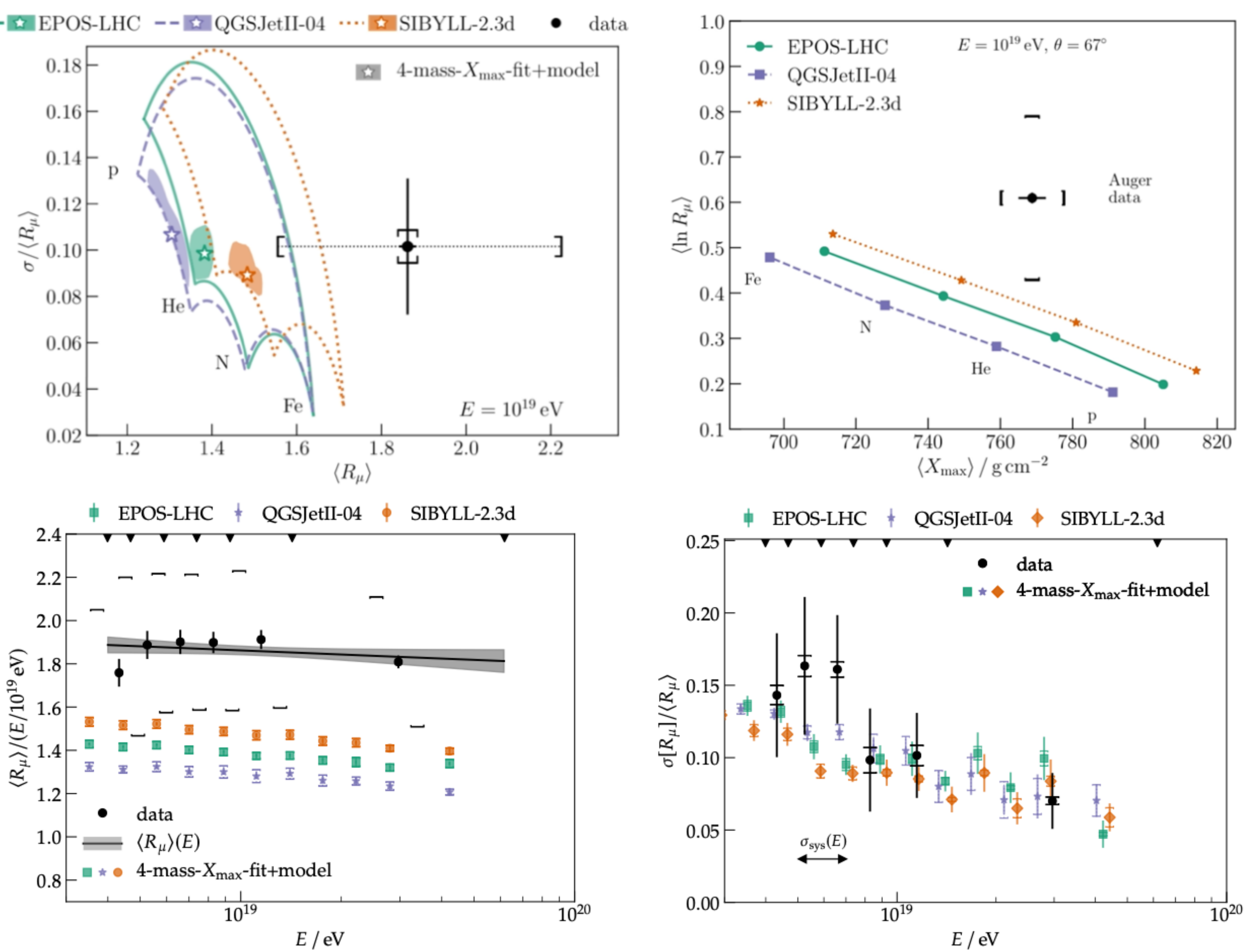
the fluctuations are mostly dominated by the first interaction!

An agreement between models and data for the fluctuations and a significant deficit in the total number of muons are observed!

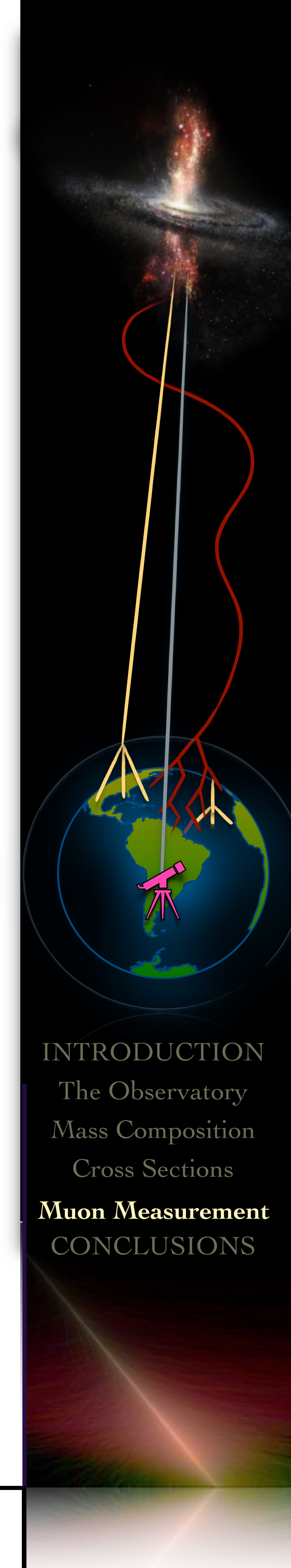
The Pierre Auger Collaboration, Phys.Rev,Lett. 126 (2021) 152002



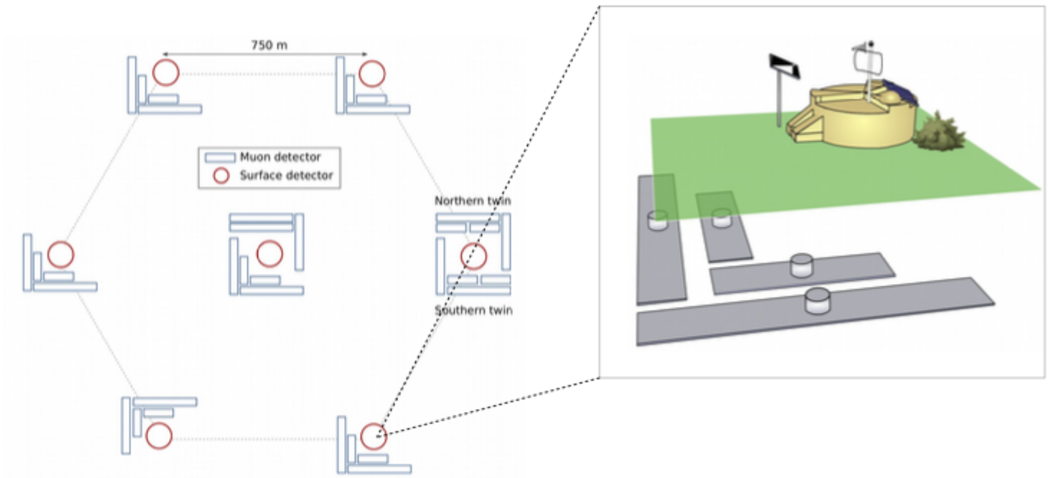
Measurement of the fluctuation in the number of muons



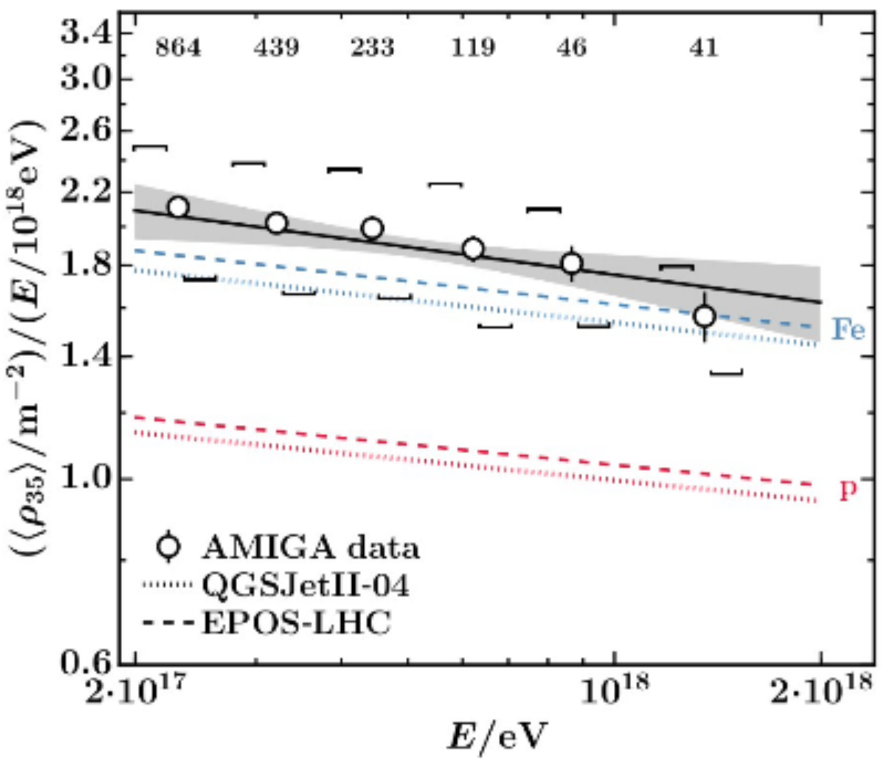
The Pierre Auger Collaboration, Phys.Rev,Lett. 126 (2021) 152002

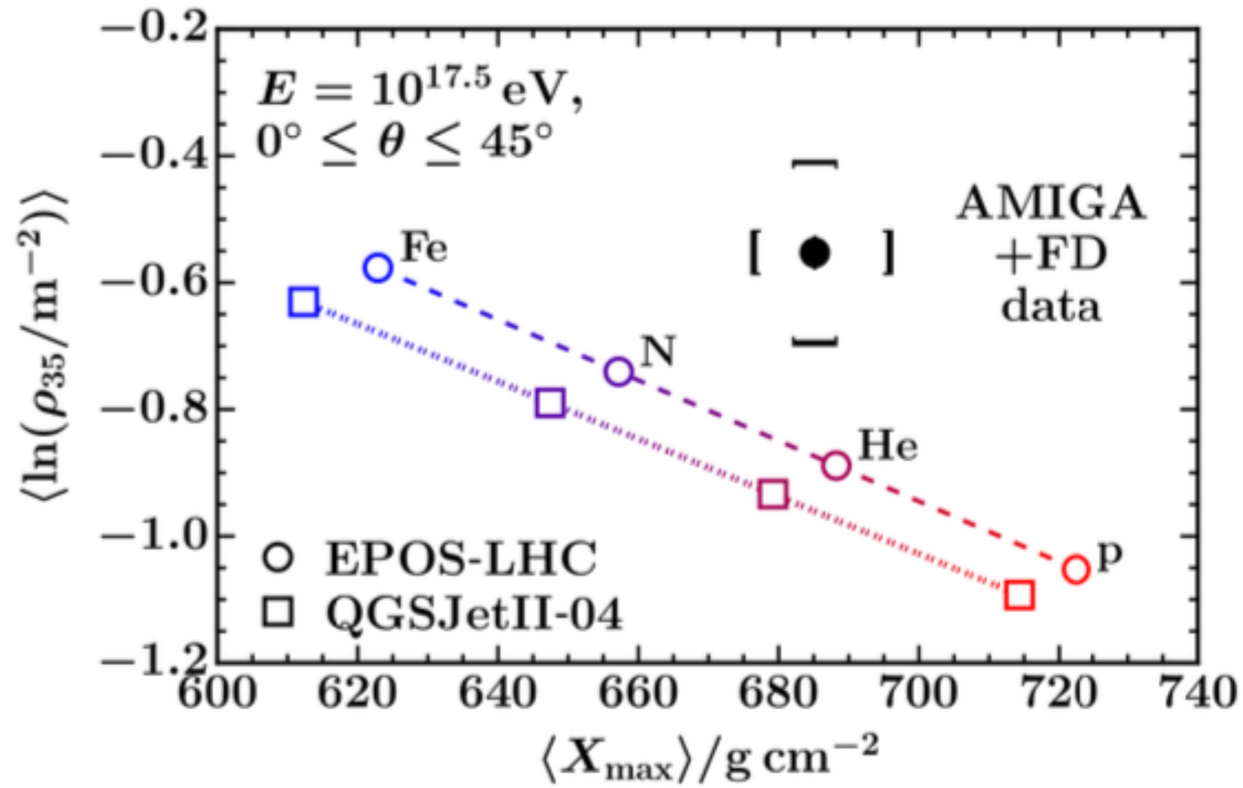


Direct measurement above $10^{17.5}$

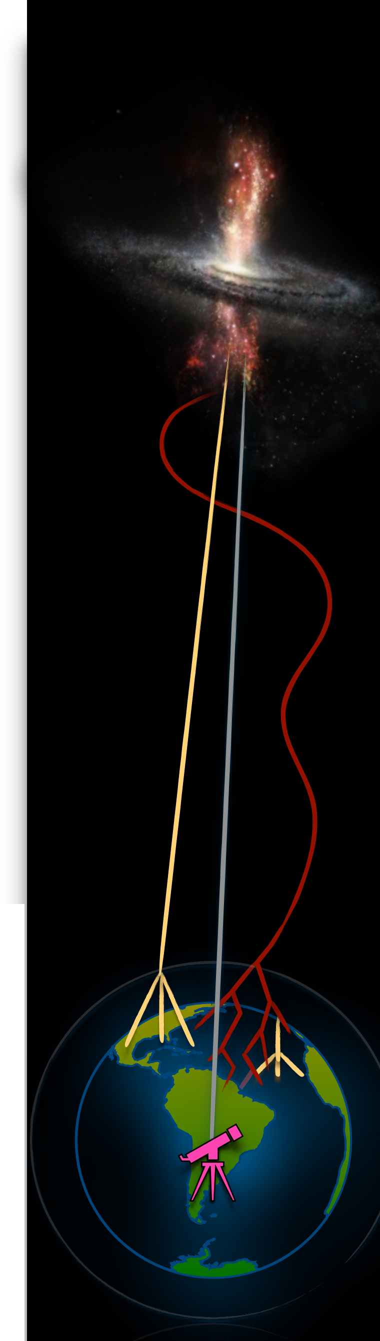


30 m² scintillators buried 2.3 m below surface at 7 WCD locations



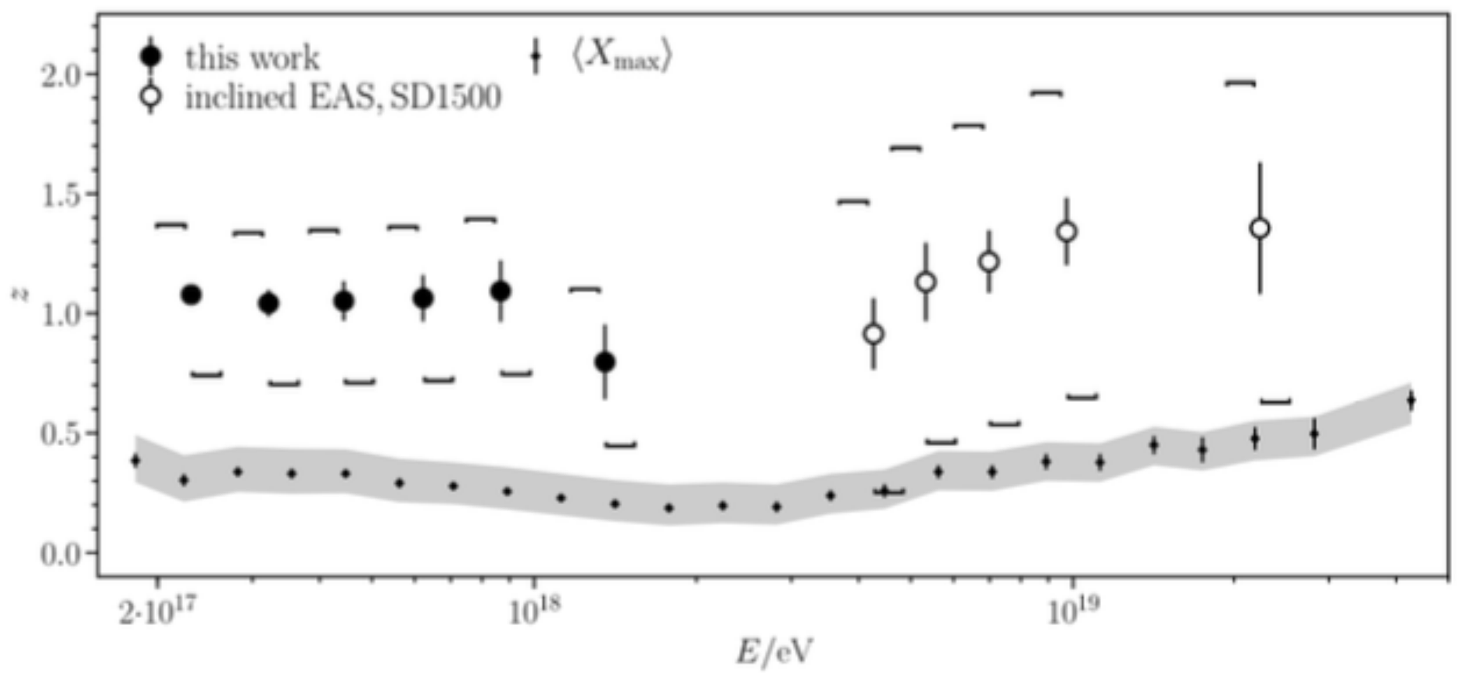


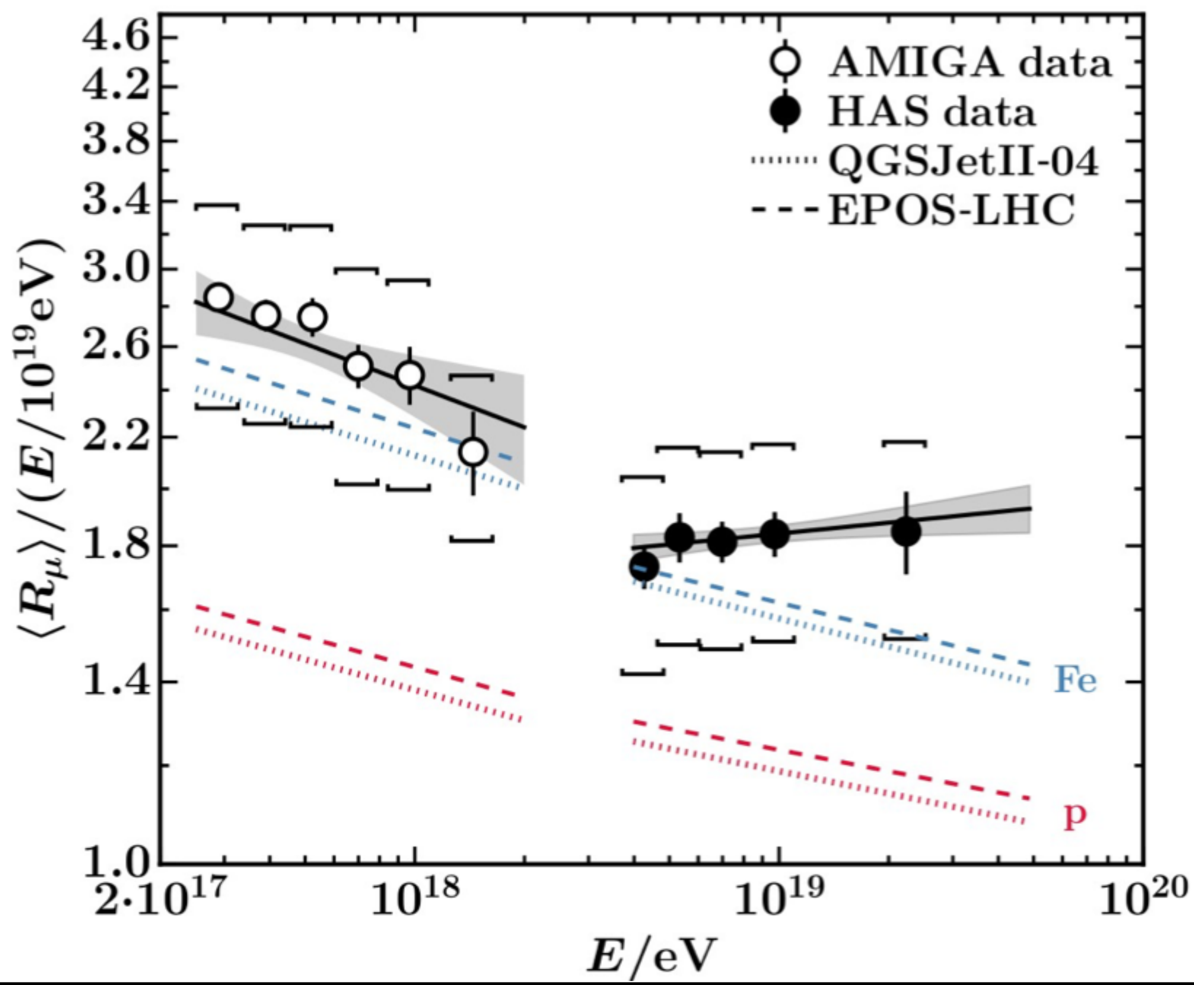
F. Sanchez (Auger Coll.) PoS (ICRC2019) 411
The Pierre Auger Collaboration, Eur.Phys.J. C80 (2020) 751



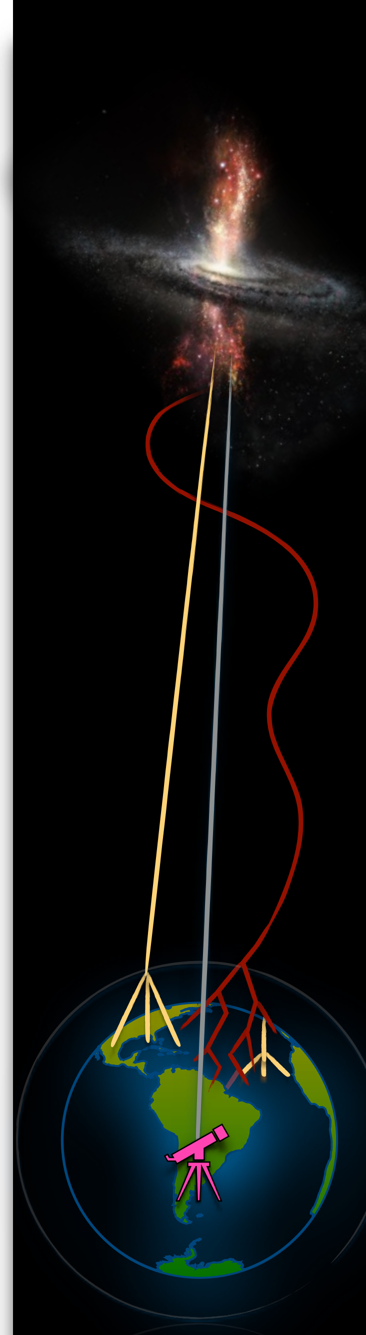
Measurement of the number of muons

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





F. Sanchez (Auger Coll.) PoS (ICRC2019) 411
The Pierre Auger Collaboration, Eur.Phys.J. C80 (2020) 751



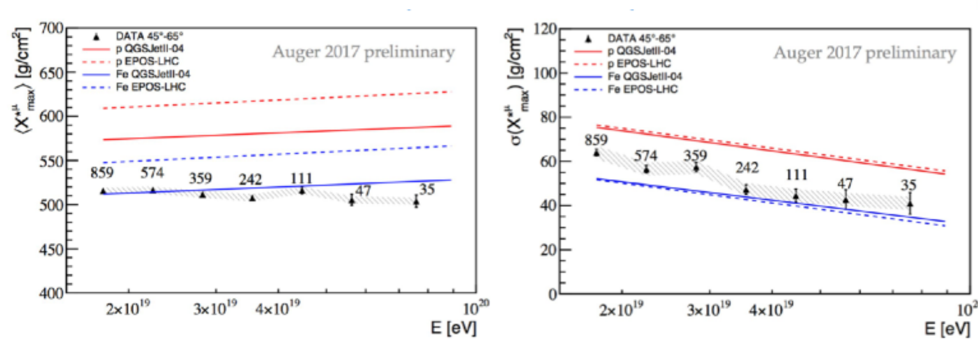
Further works

- Hybrid muon measurement

The Pierre Auger Collaboration, Phys.Rev.Lett. 117 (2016) 192001

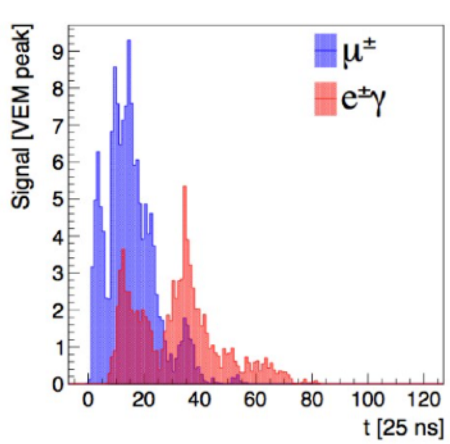
- Muon Production depth

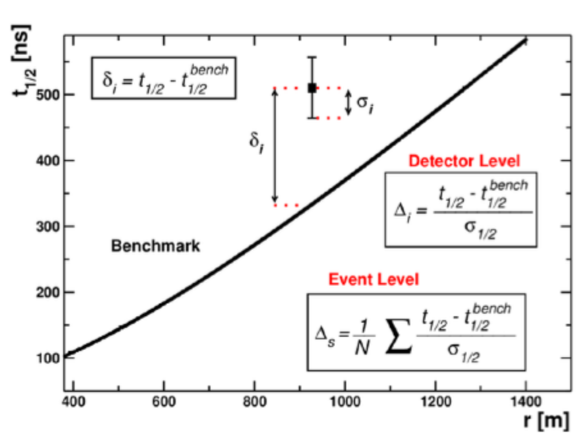
The Pierre Auger Collaboration, Phys.Rev.D. 90 (2014) 012012
M. Mallamaci (Auger Coll.) PoS (ICRC2017) 509

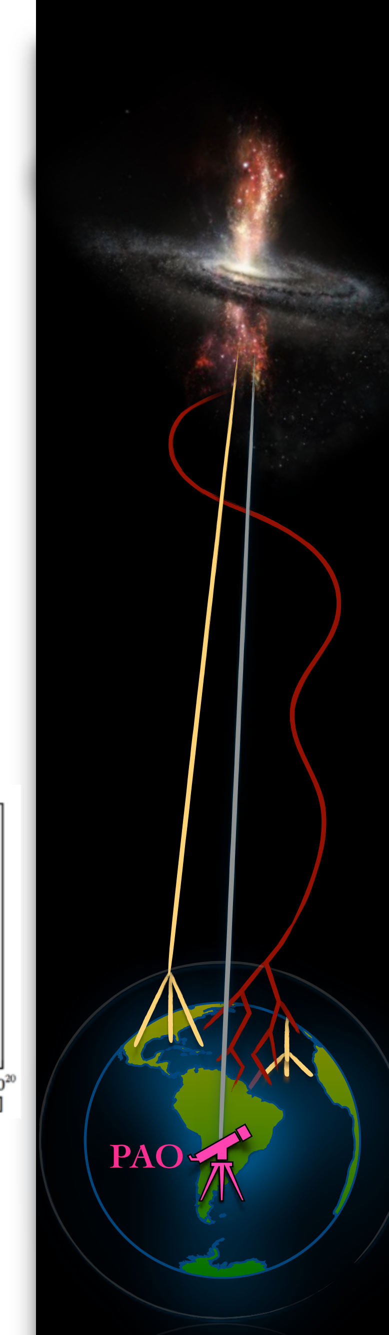


- Measurement with risetime

The Pierre Auger Collaboration, Phys.Rev.D. 96 (2017) 122003







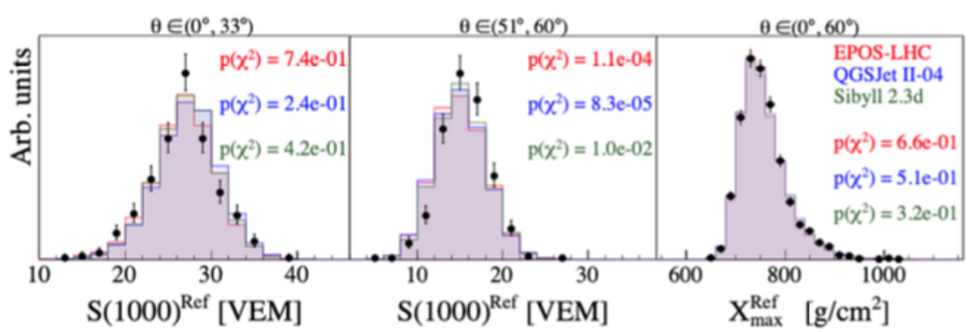
Conclusions and Future Prospects

The Pierre Auger observatory hybrid detection allow to measure the electromagnetic and hadronic components of air showers

- The number of muons is not well reproduced ;
- Fluctuations in the number of muons within the range predicted by the current hadronic interaction models;
- Proton-air cross section measurement using X_{max} distributions;

Improvements given by the upgrade of the Observatory detection system AugerPrime **(See F. Sanchez talk)**

- Adjustments to the predictions of X_{max} and the hadronic signal at the ground

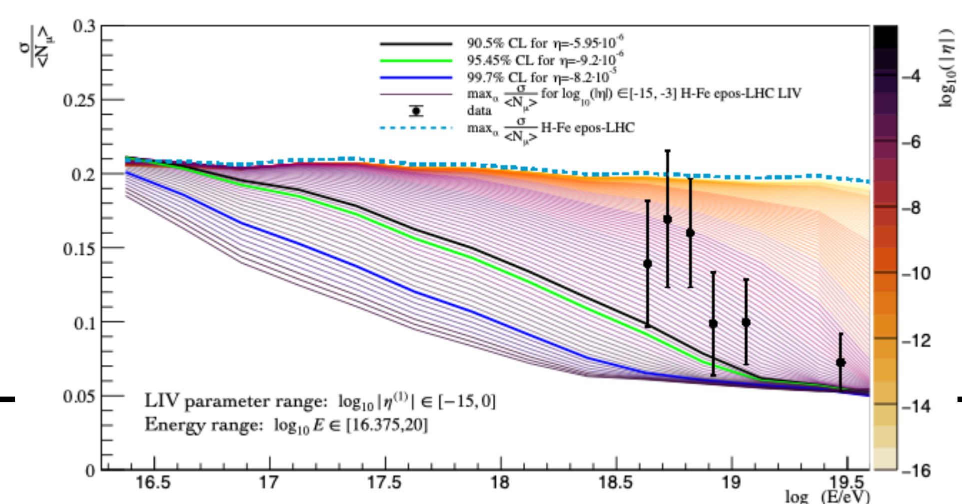


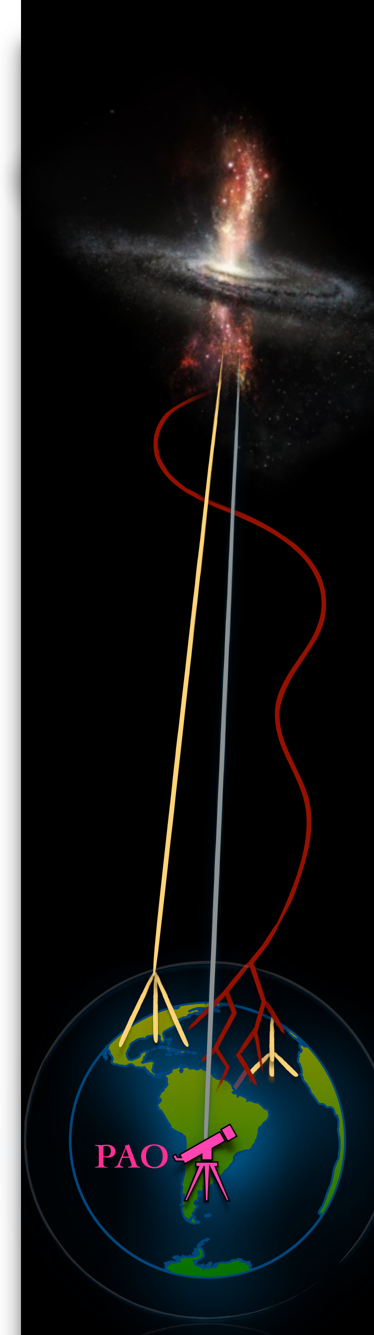
J. Vicha (Auger Coll.) PoS (ICRC2021) 310

allowing a shift in hadronic signal AND X_{max}

- Lorentz Invariance Violation model?

C. Trimarelli (Auger Coll.) PoS (ICRC2021) 340





Thanks for your attention!

Backup

Upgrade of the Pierre Auger Observatory

AugerPrime

Physics motivation

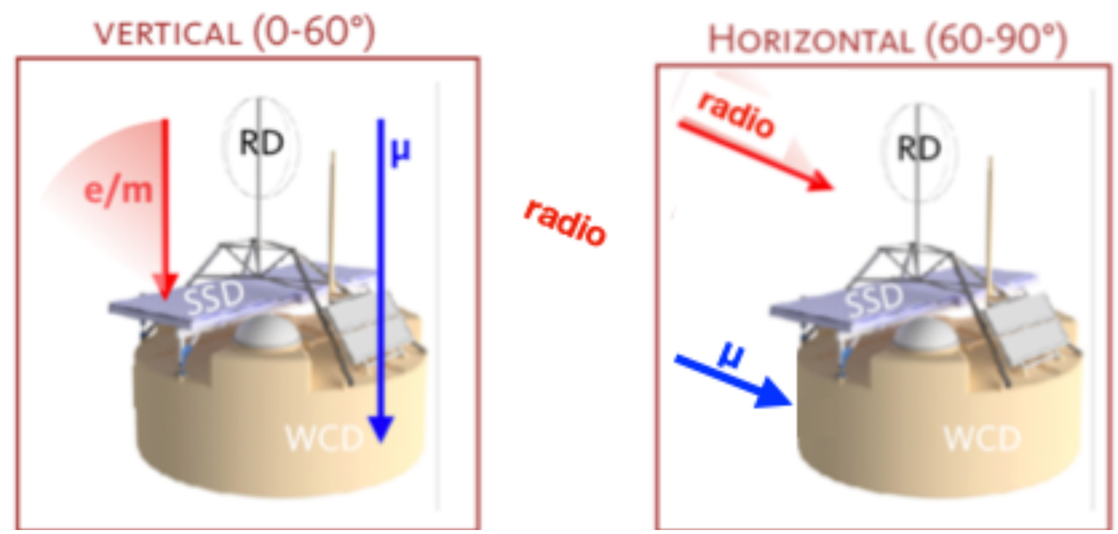
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle Physics with air showers (muon estimate)
- Much better understanding of new and old data

Auger Observatory Phase II

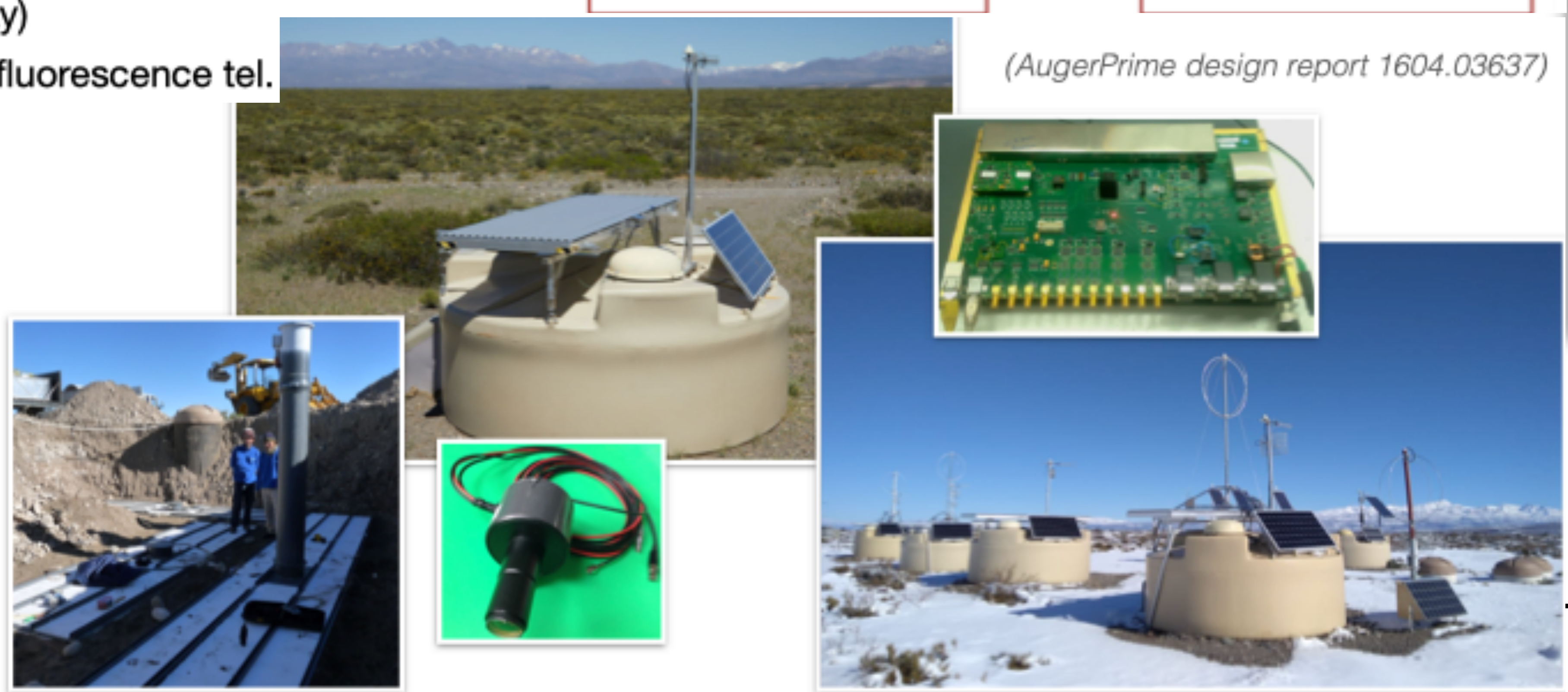
- Data taking 2022/23 – 2030
- AugerPrime (8 years, θ < 60°): 40,000 km² sr yr (Phase II), 80,000 km² sr yr (Phase I)
- Re-analysis of old data set (deep learning)

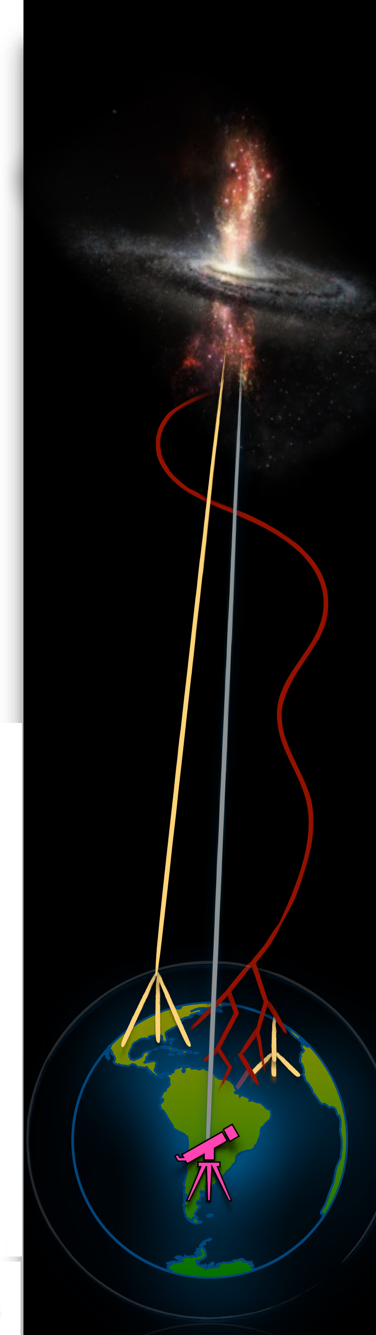
Components of AugerPrime

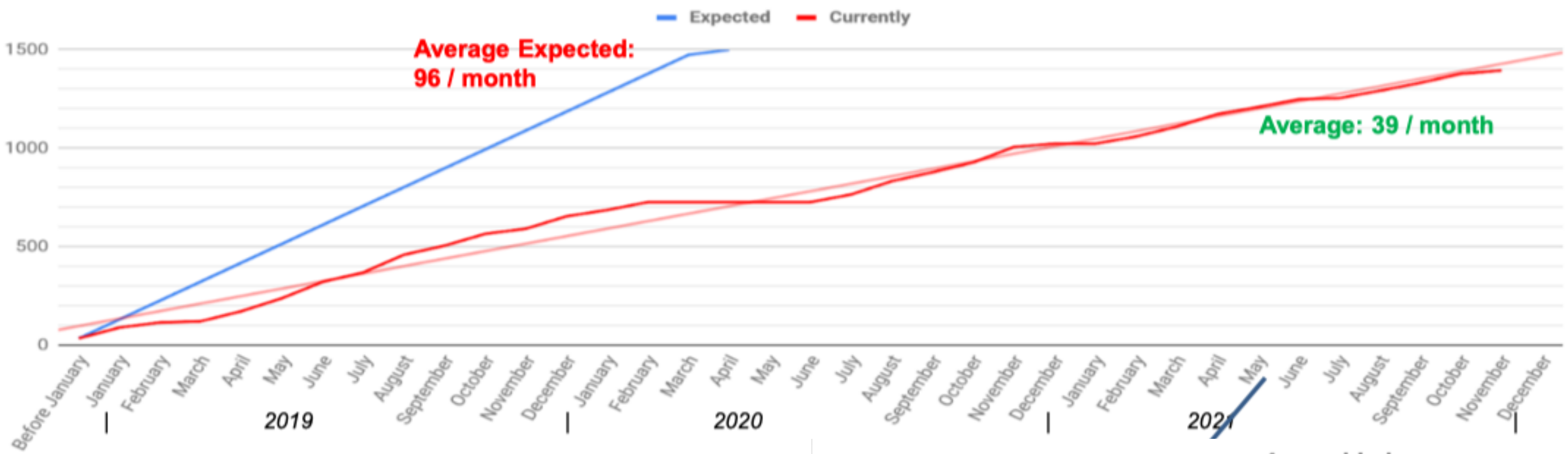
- 3.8 m² scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

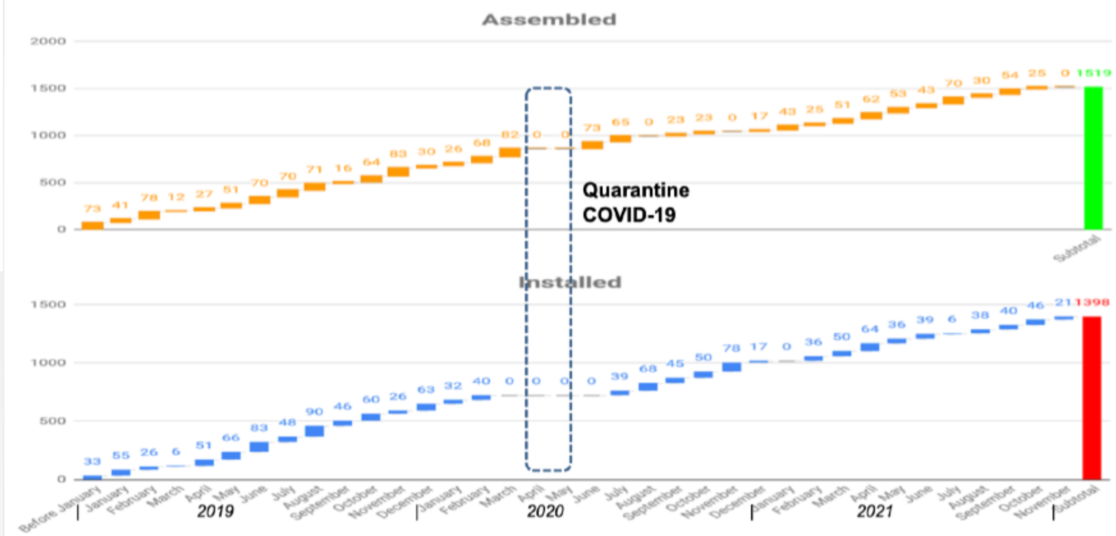


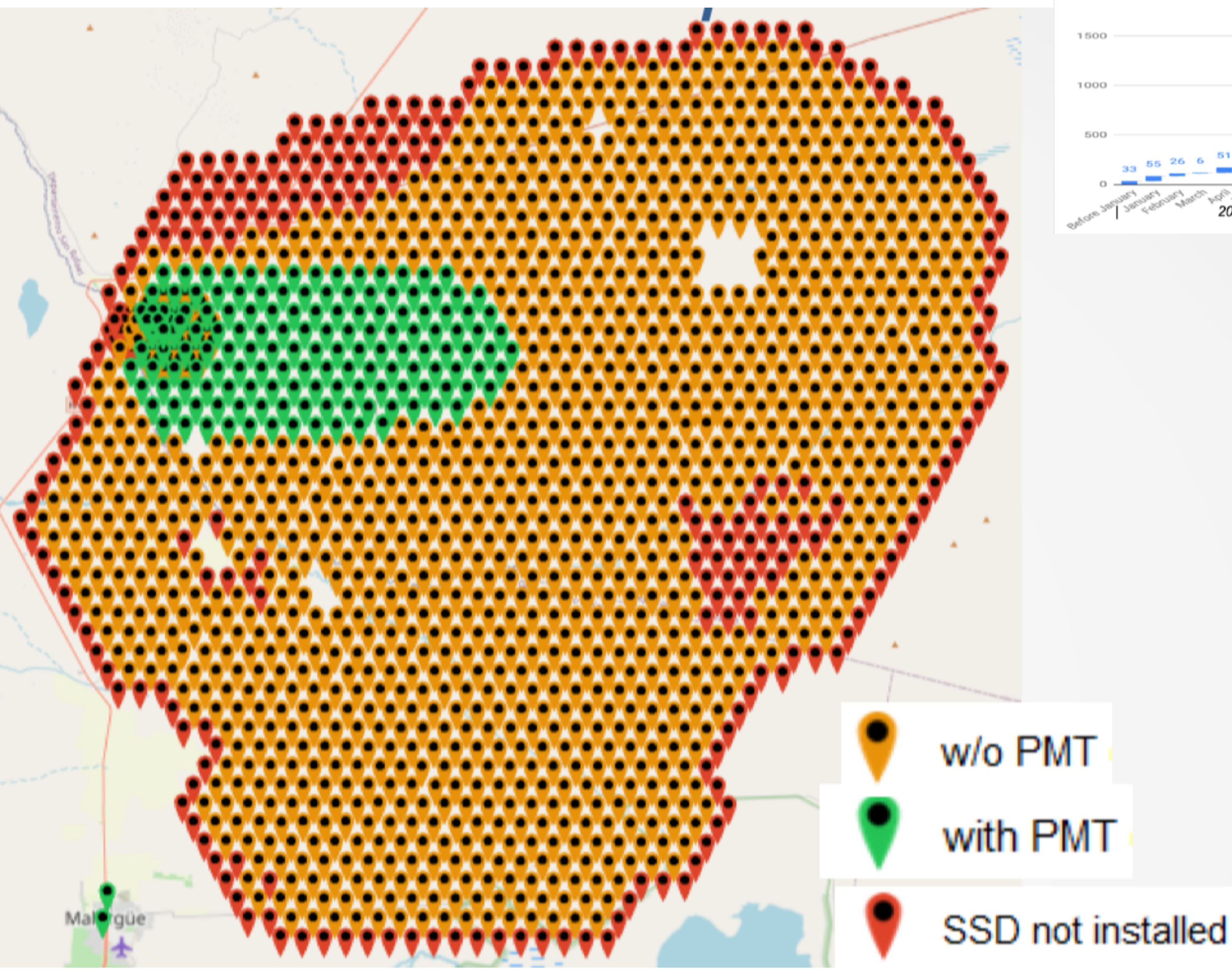
(AugerPrime design report 1604.03637)







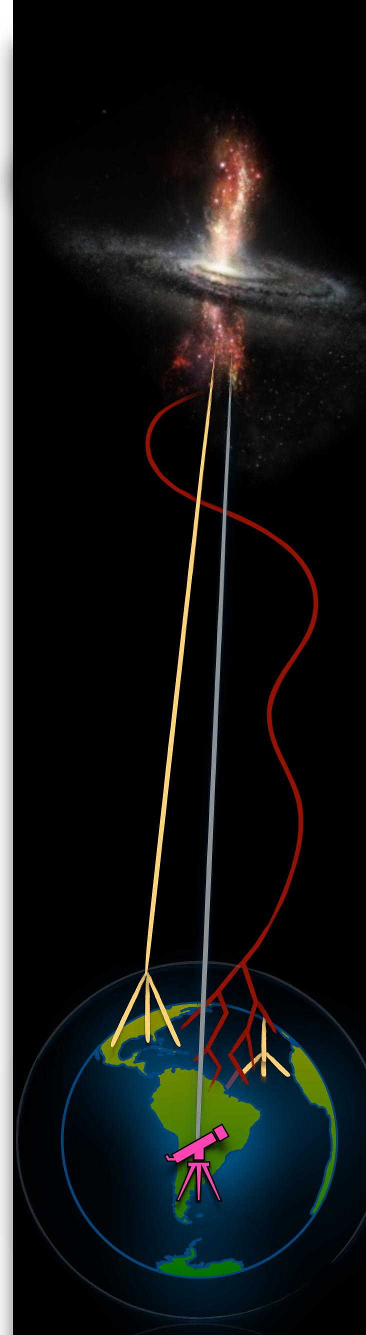




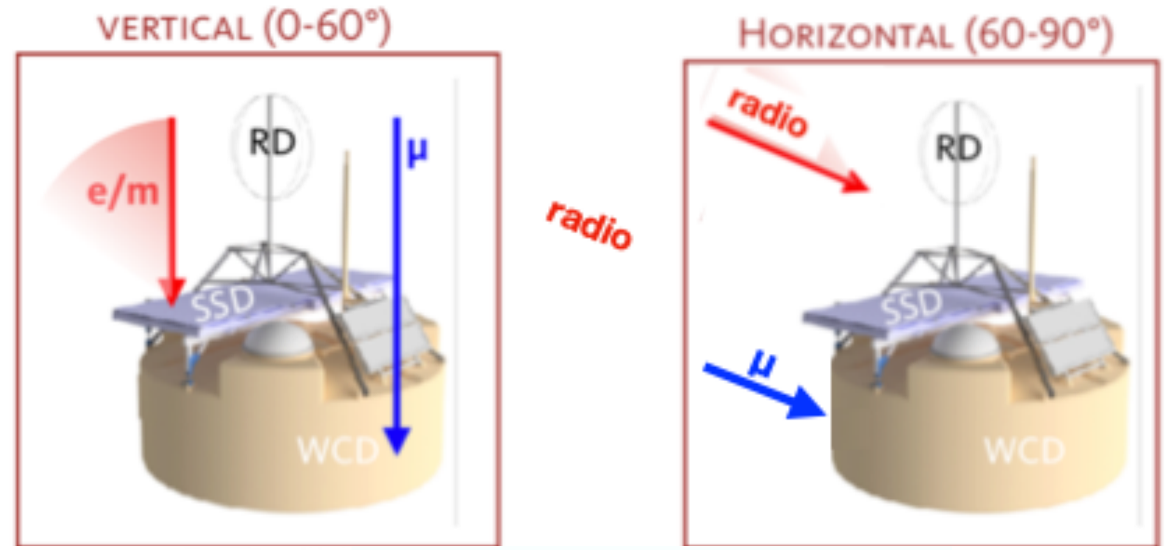
Total SSD to install: 1493
Installed: 1398 (93%)
To install: 99 (7%)

Total SSD with PMT :1493
Installed: 153 (10%)
To install: 1340 (90%)

Total SSD to assemble: 1519
Assembled: 1519 (100 %)
To assemble: 0 (0%)



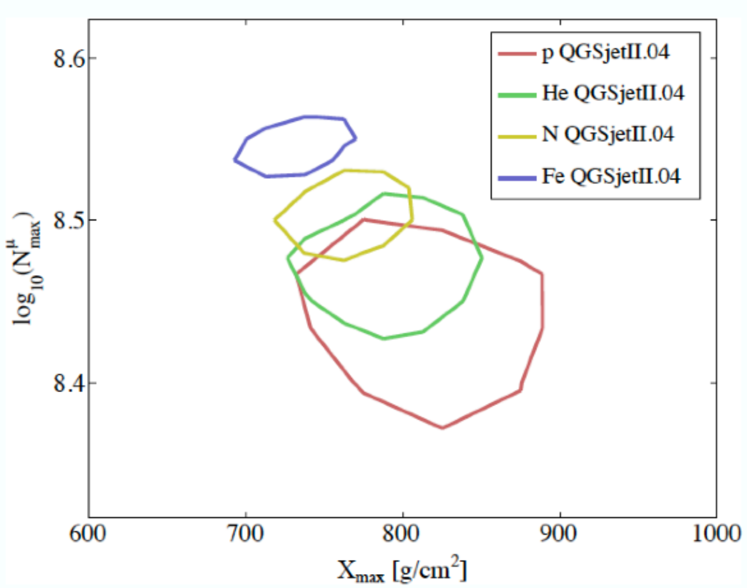
Upgrade of the Pierre Auger Observatory: *AugerPrime*



Composition sensitivity with 100% duty cycle

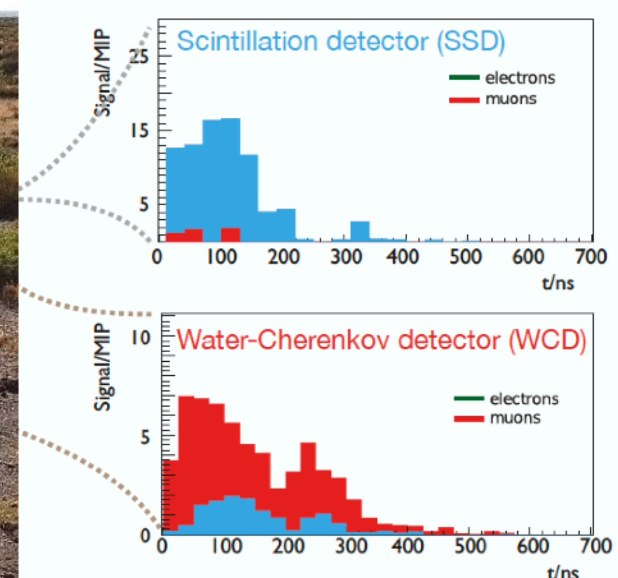
To increase exposure with composition sensitive data Surface array needed!

Duty cycle: 100% (SD) vs 15% (FD)

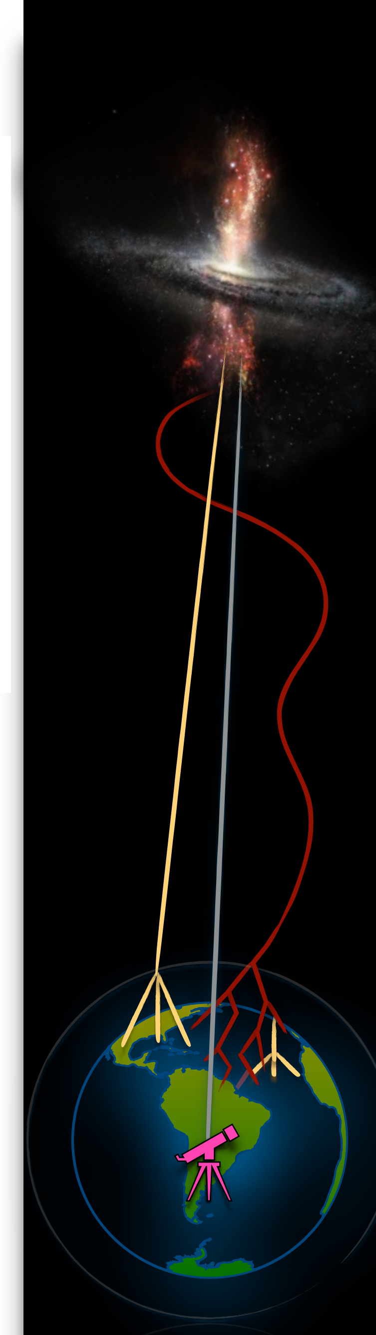


(AugerPrime design report 1604.03637)

complementarity of light responses used to discriminate e.m. and muonic component

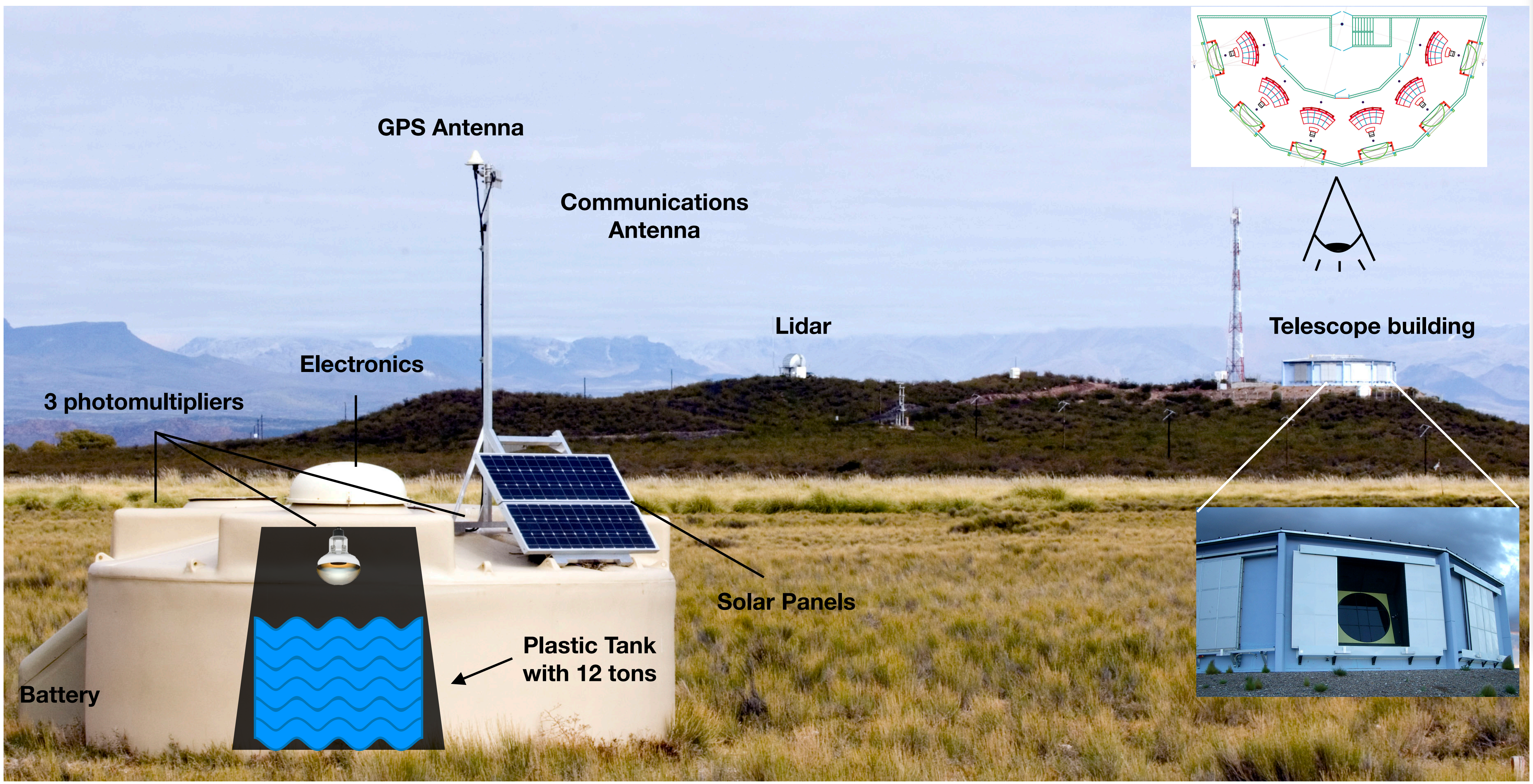


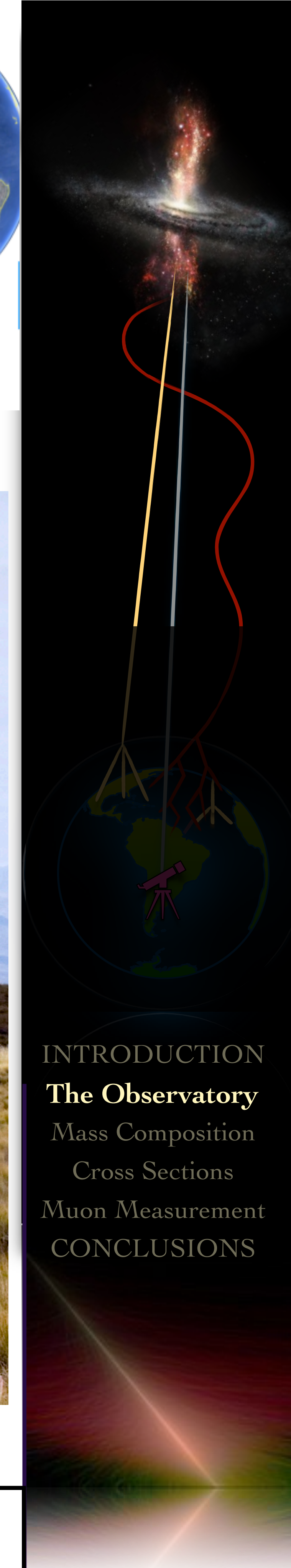
Moreover
- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

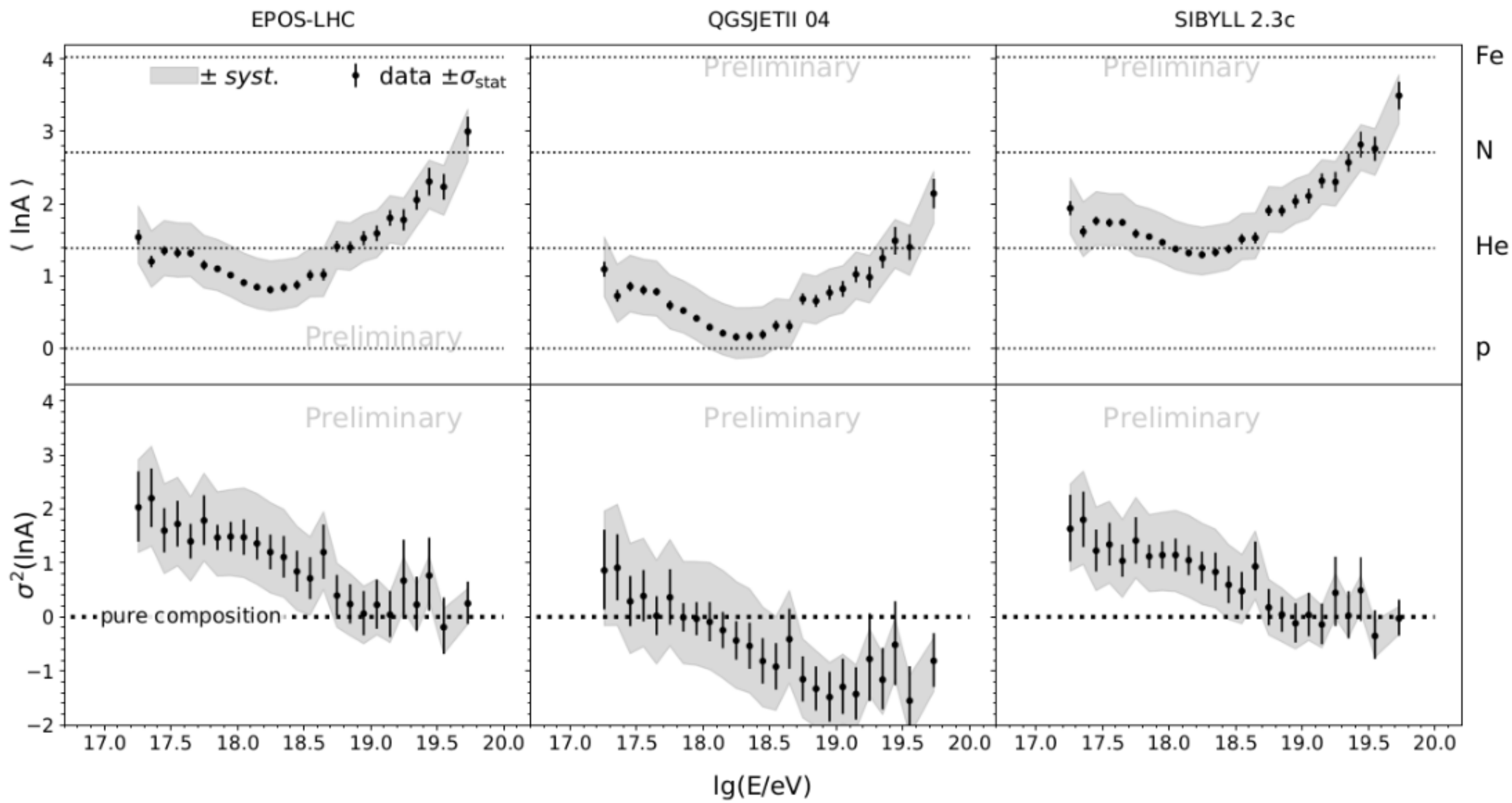


The Observatory

Located in the southern hemisphere is the largest air shower detector built so far

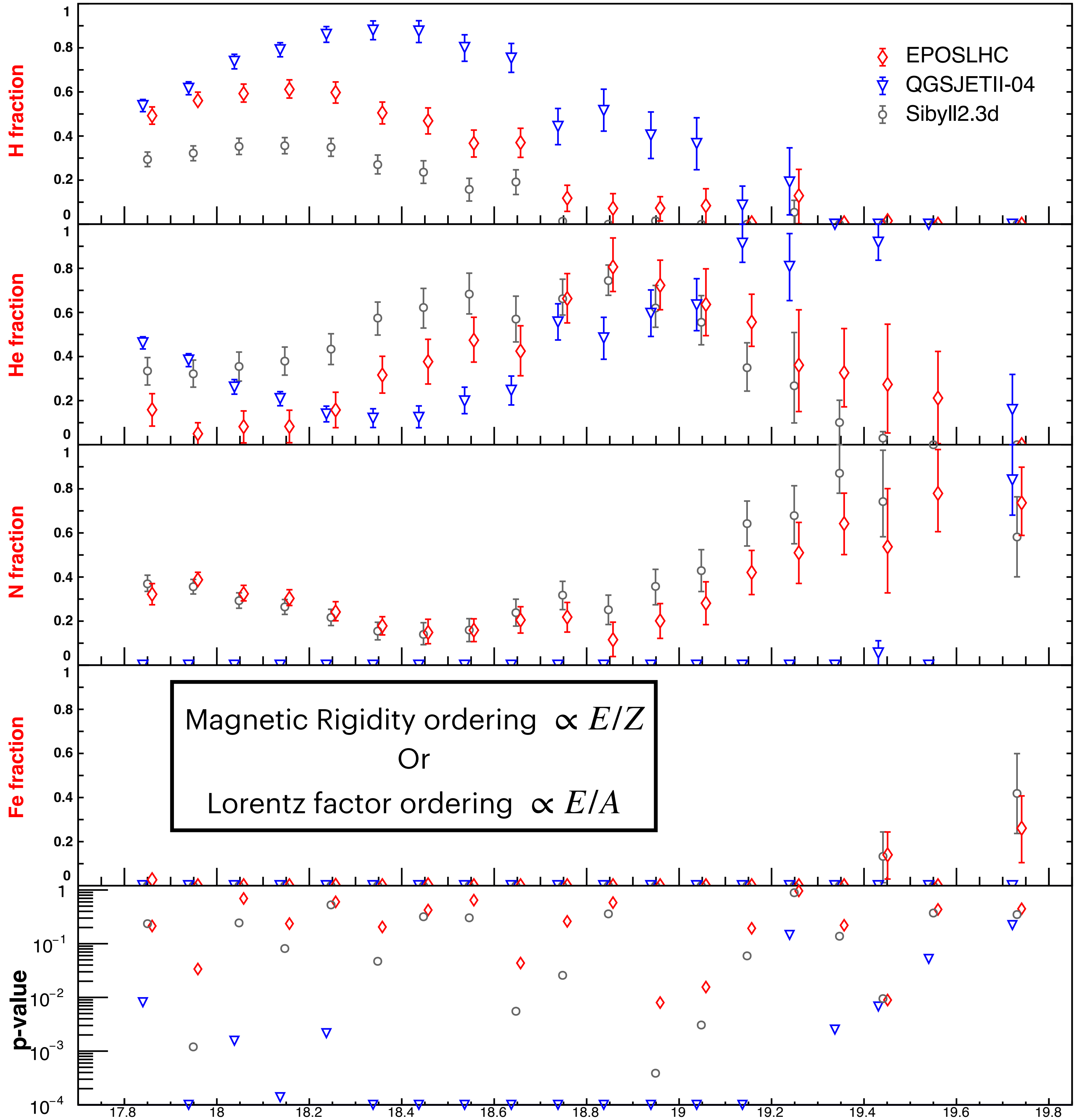




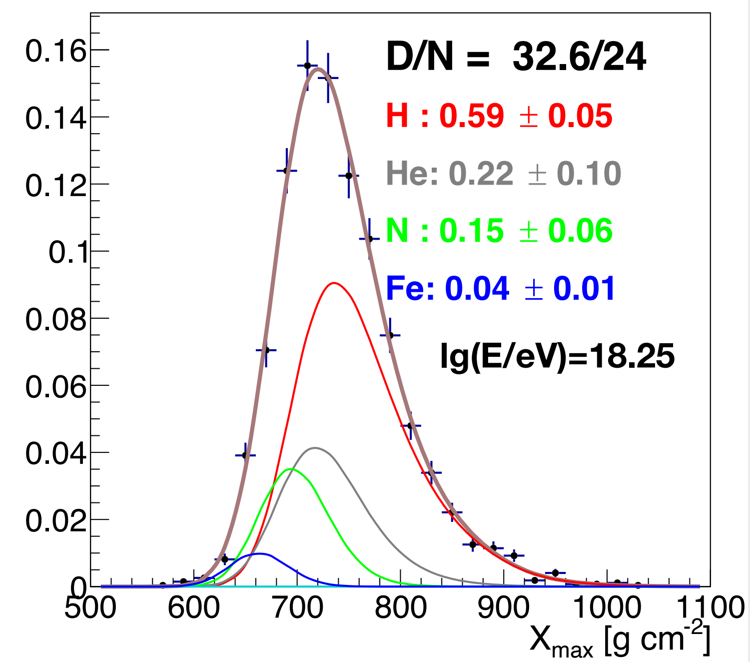

EPOS-LHC
QGSJETII 04
SIBYLL 2.3c
± syst.
data $\pm\sigma_{stat}$
Preliminary
Fe
N
He
p
⟨ lnA ⟩
σ^2(lnA)
pure composition
lg(E/eV)

Mass Composition @ Earth

Measured considering the atmospheric depth at which the number of particles in an air shower reaches its maximum



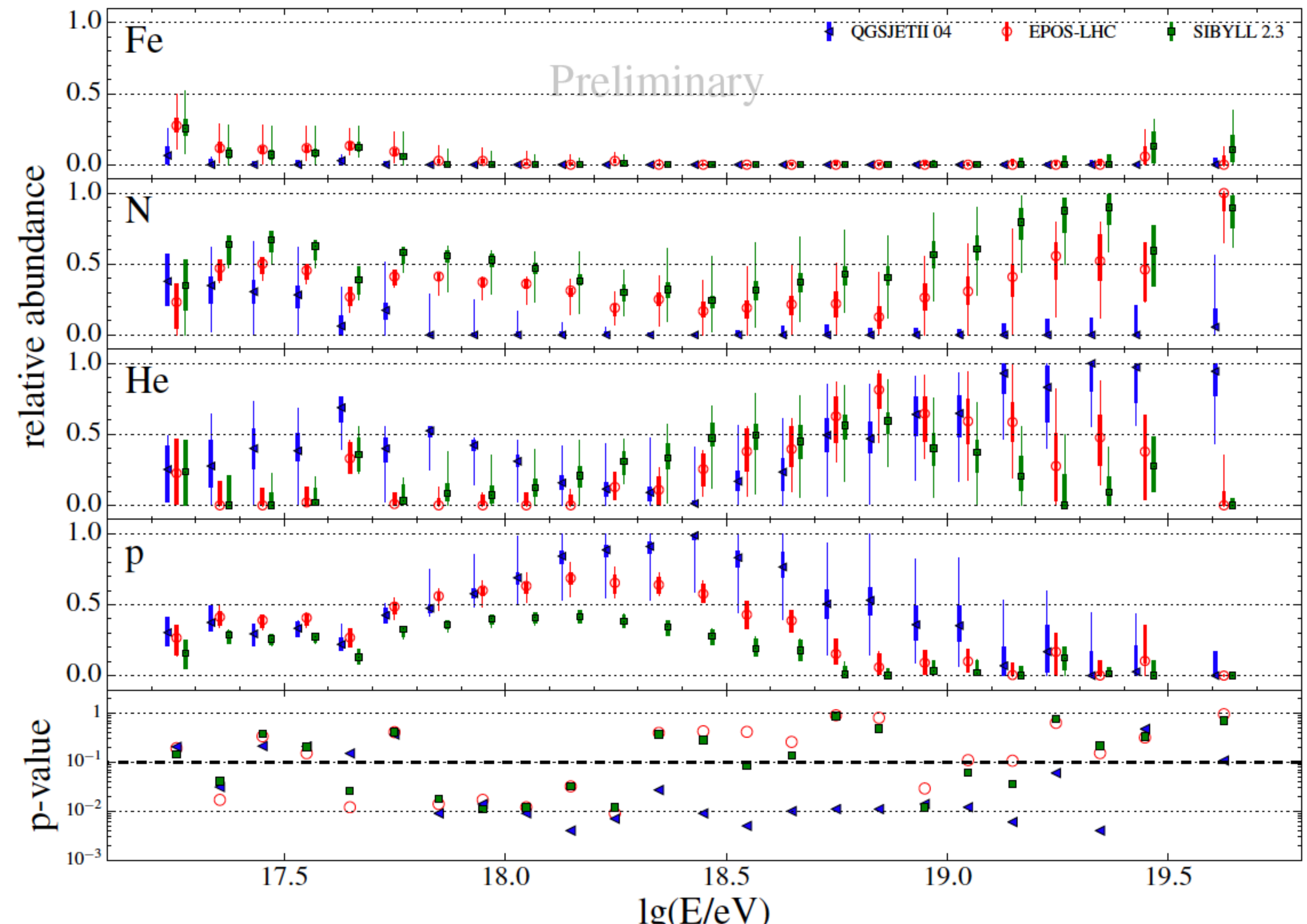
$$< X_{\mathrm{max}} > \propto \lg(E/A)$$



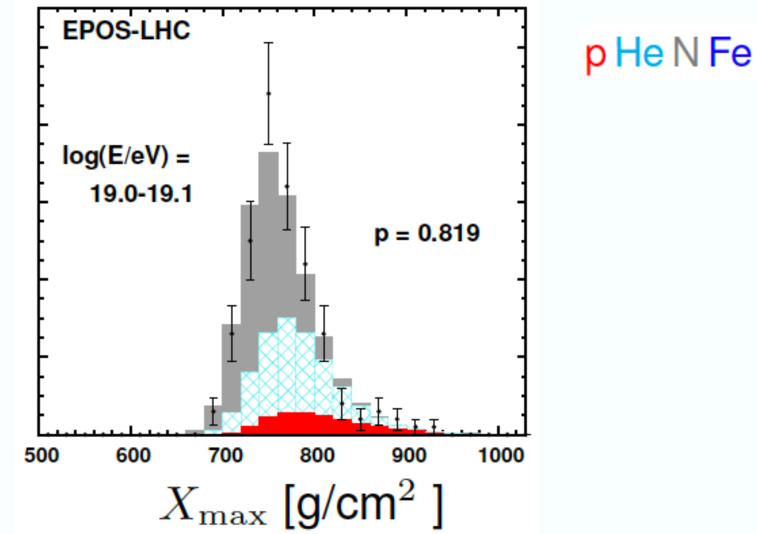
- X_{max} **distributions fitted with four-mass Gumbel function from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

Mass Composition @ Earth

Mass composition @ Earth (top of the atmosphere)

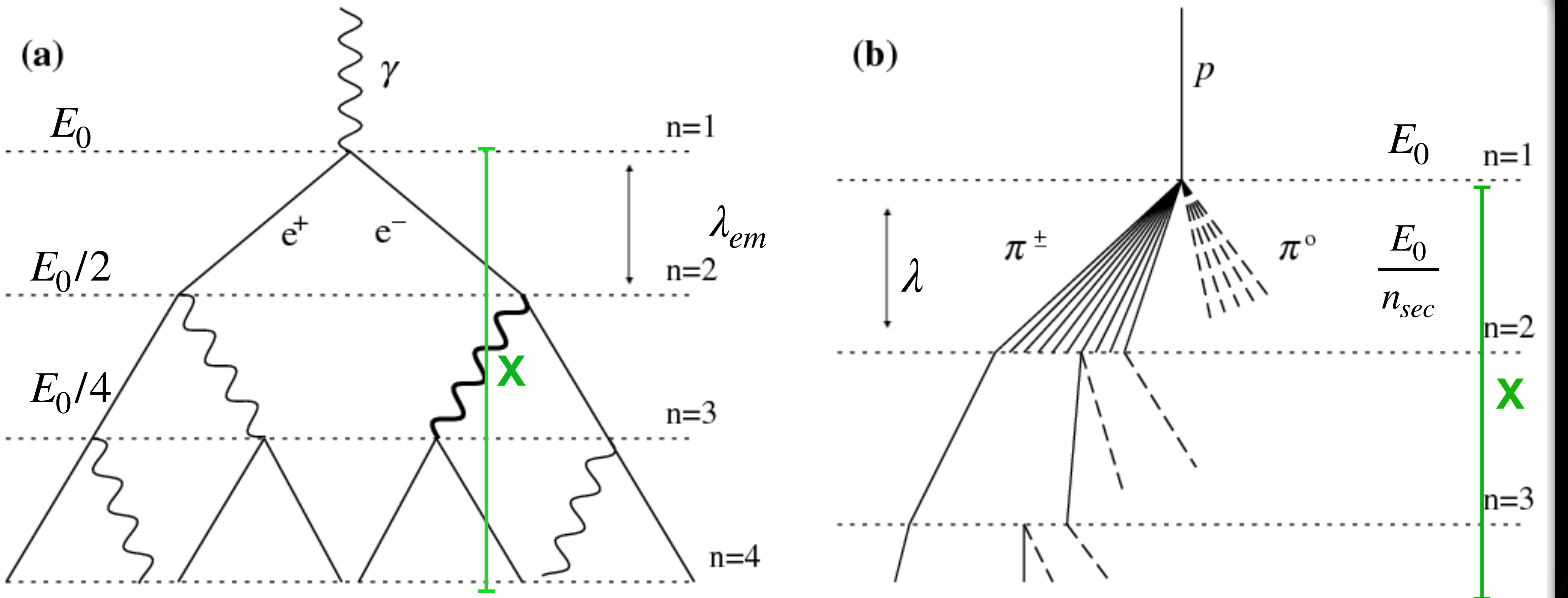


(Bellido ICRC 2017)



- **Xmax distributions fitted with four-mass CONEX showers from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

Heitler Model



At the shower maximum we define:

- $N_{max} = E_0/E_c$;
- $X_{max} = X_0 + \lambda_{em} log_2(E_0/E_c)$

A nucleus with mass A and energy E_0 is considered as A independent nucleons with energy E_0/A each.

The superposition of the individual nucleon showers yields:

1) $X_{max} \propto \lambda \dfrac{E_0}{AE_c}$

2) $N_\mu^A(X_{\max}) = A\left(\dfrac{E_0/A}{E_{dec}}\right)^\alpha = A^{1-\alpha} N_\mu^p(X_{\max})$