The Pierre Auger Observatory

Leading the Astroparticle Physics field into a Golden Era

Ruben Conceição

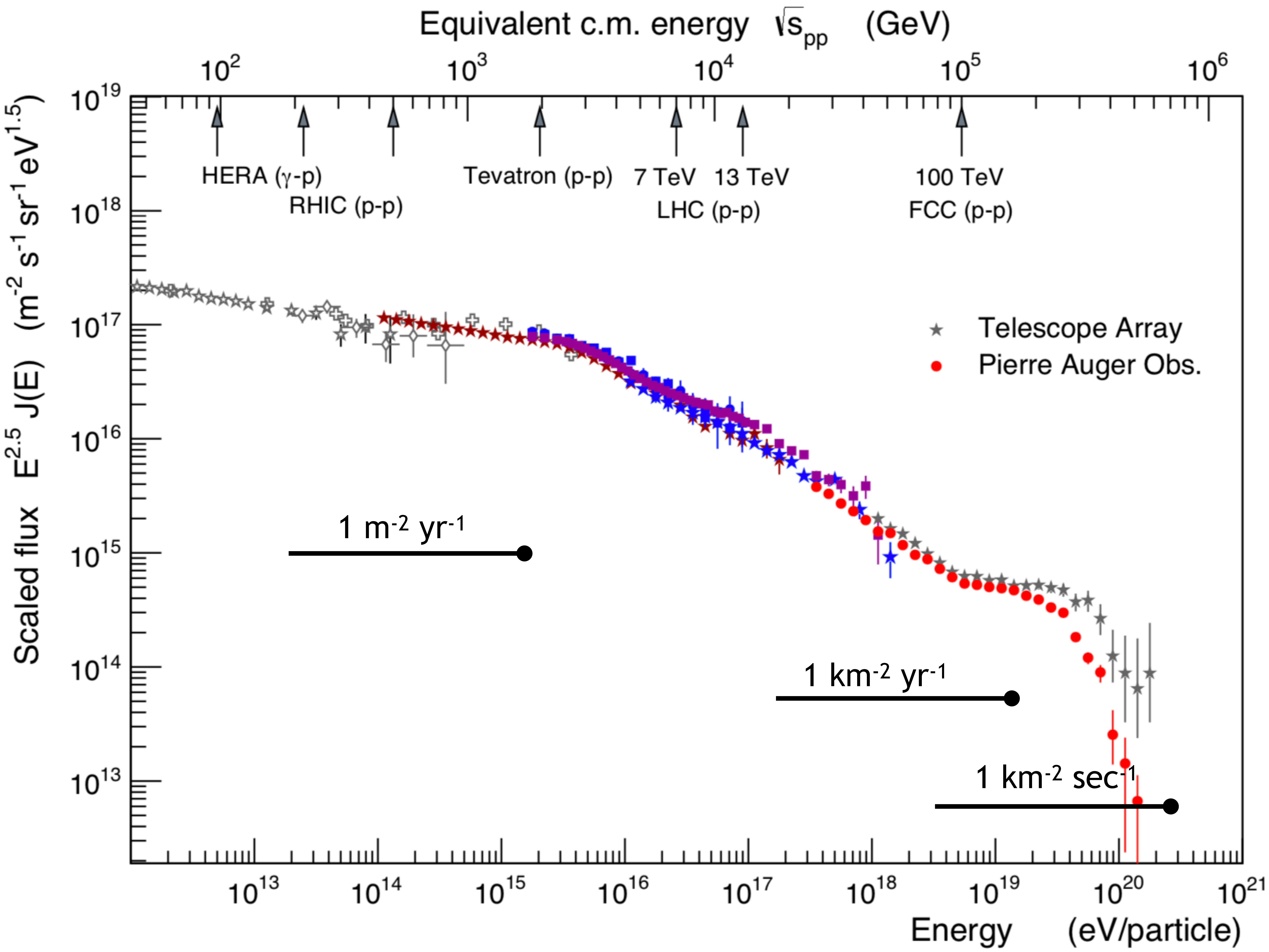
PIERRE AUGER OBSERVATORY

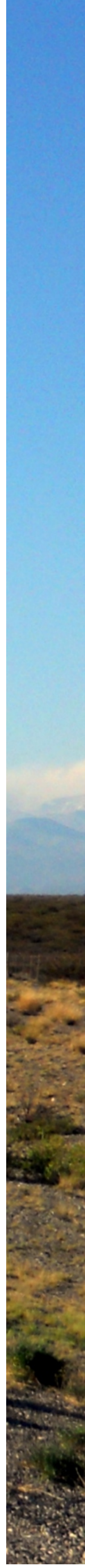
LIP

TÉCNICO LISBOA

LIP seminar, Lisbon, October 19th 2023

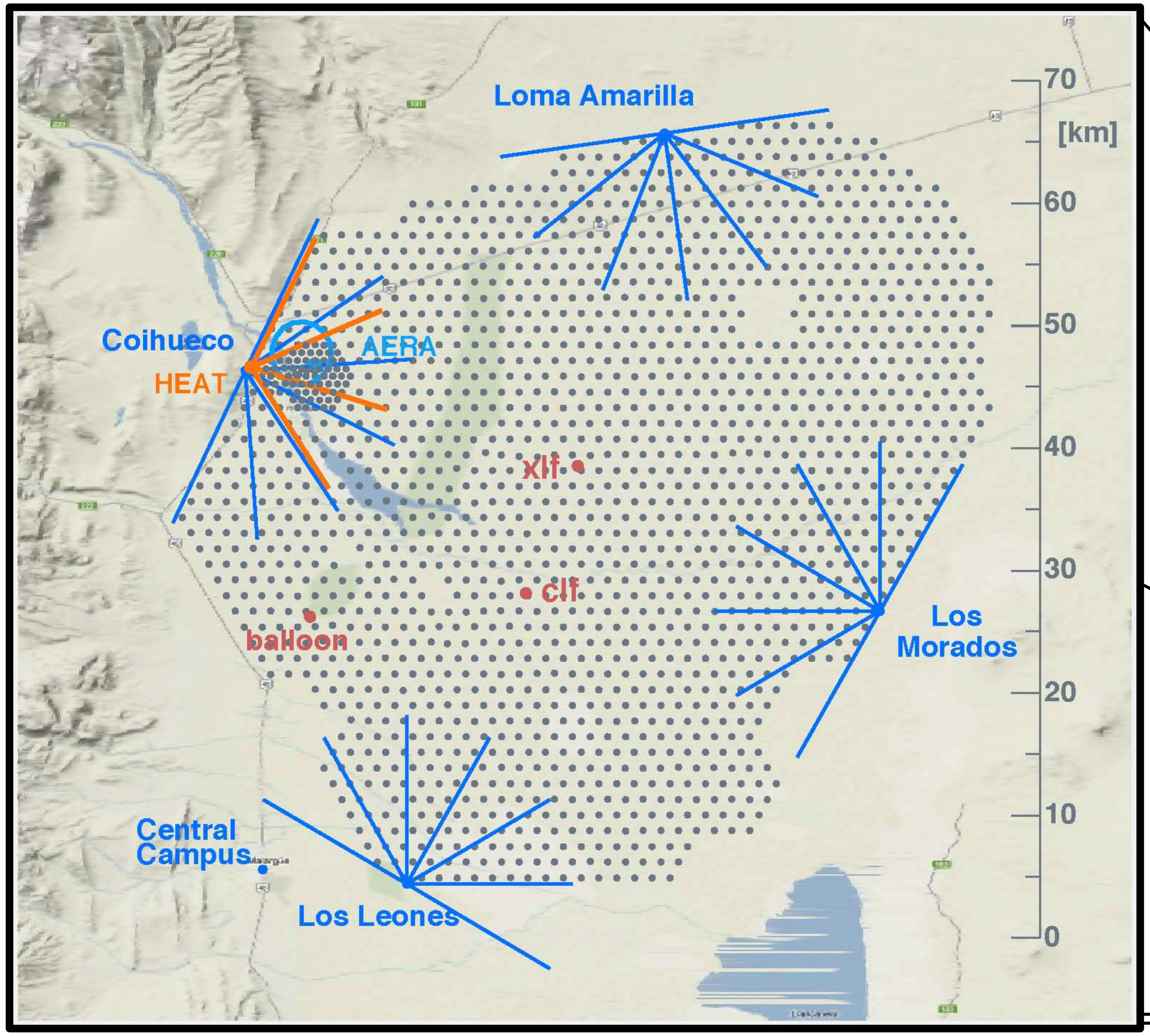
Ultra High Energy Cosmic Rays





Ruben Conceição

Pierre Auger Observatory



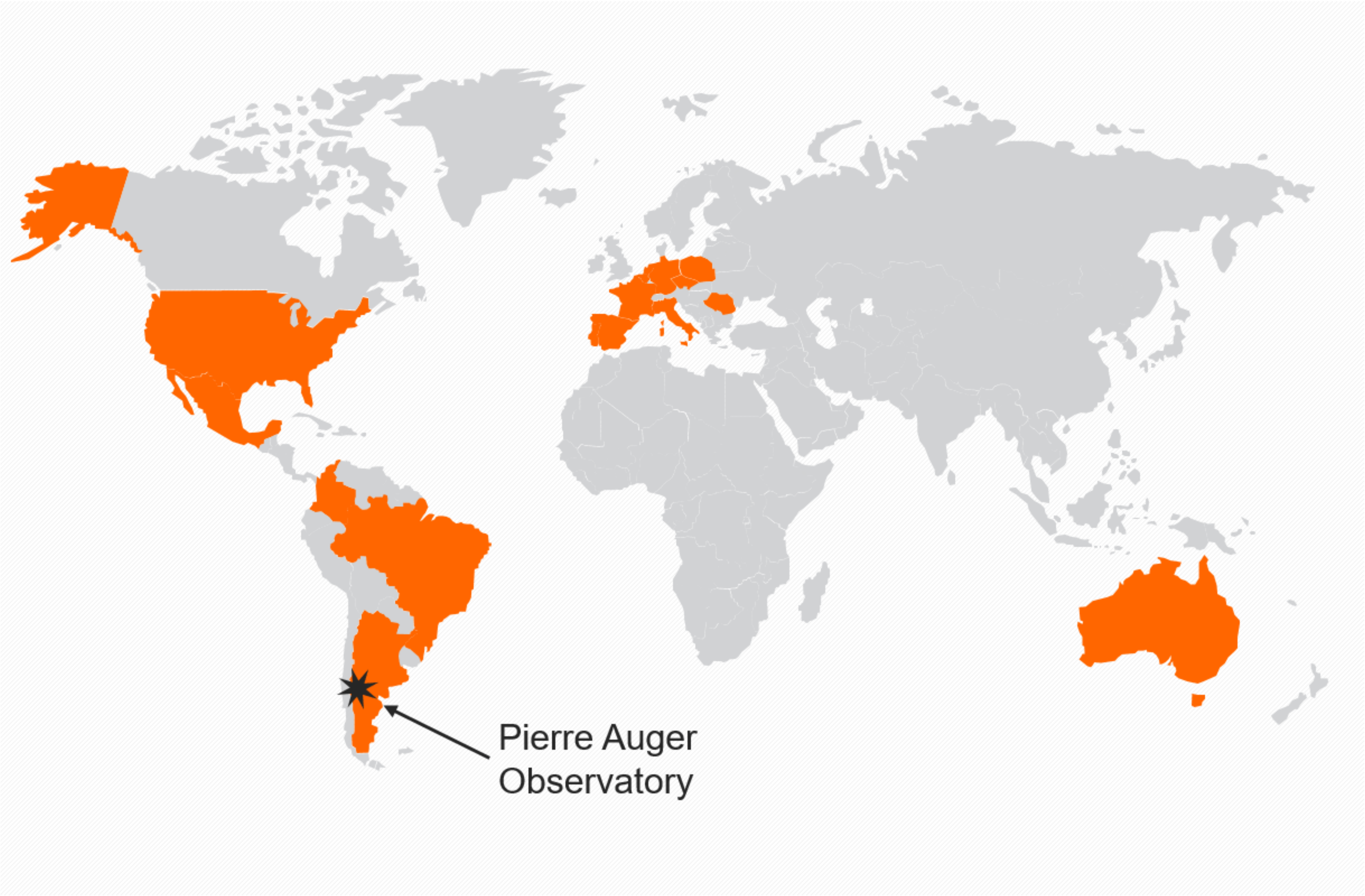
Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

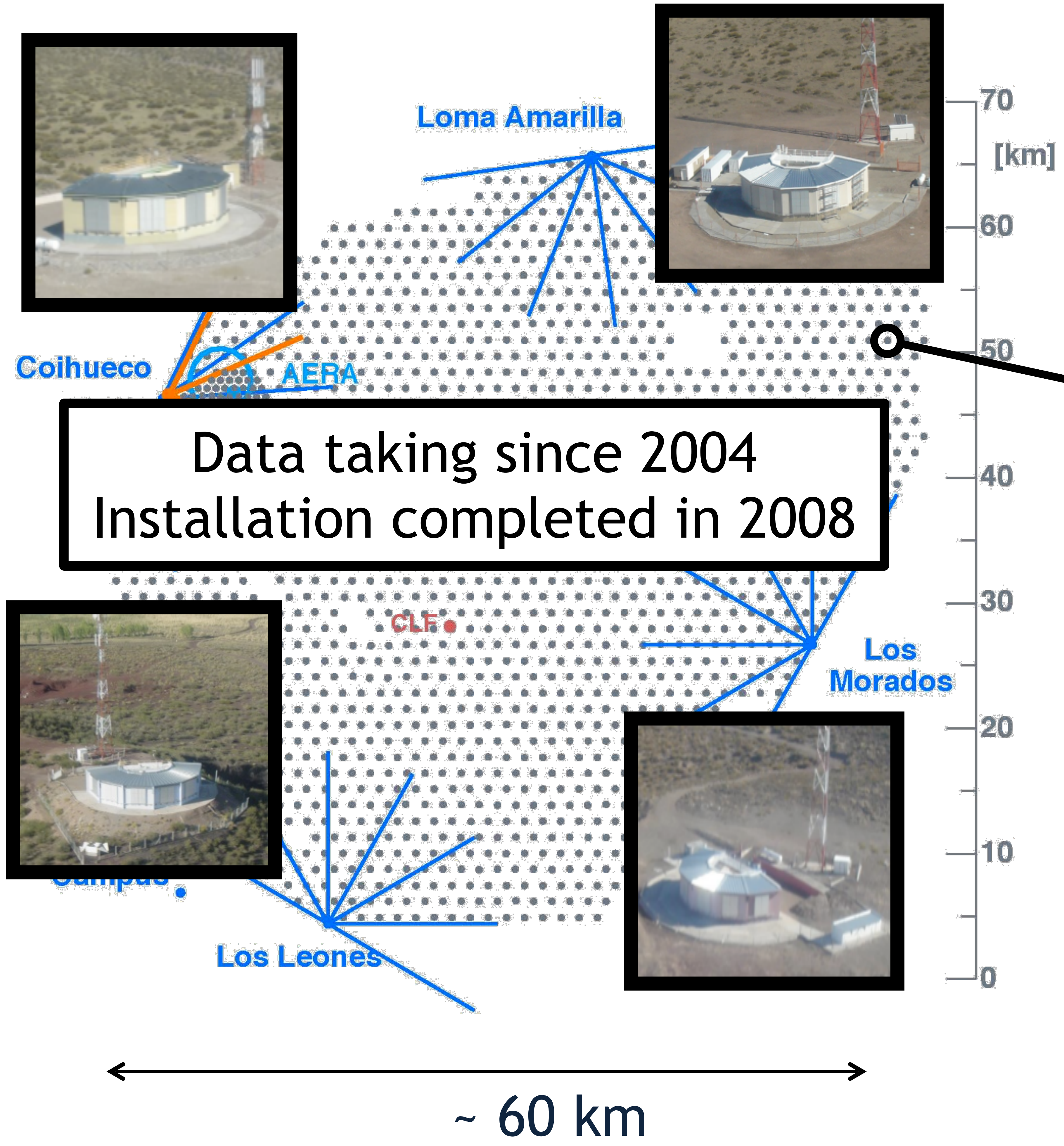
Pierre Auger Collaboration

Argentina
Australia
Belgium
Brazil
Colombia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA



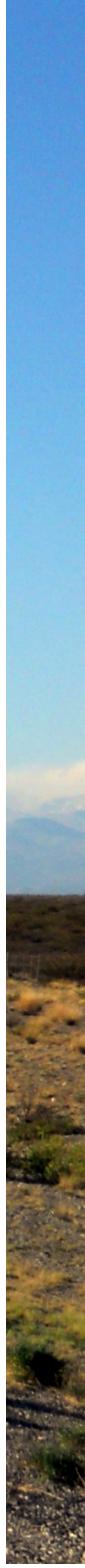
International collaboration of 17 Countries and ~ 400 scientists

Pierre Auger Observatory



- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

- 1600 Surface Detectors (SD) Stations
- SD stations spaced by 1.5 km
- Covering an area of 3000 km^2

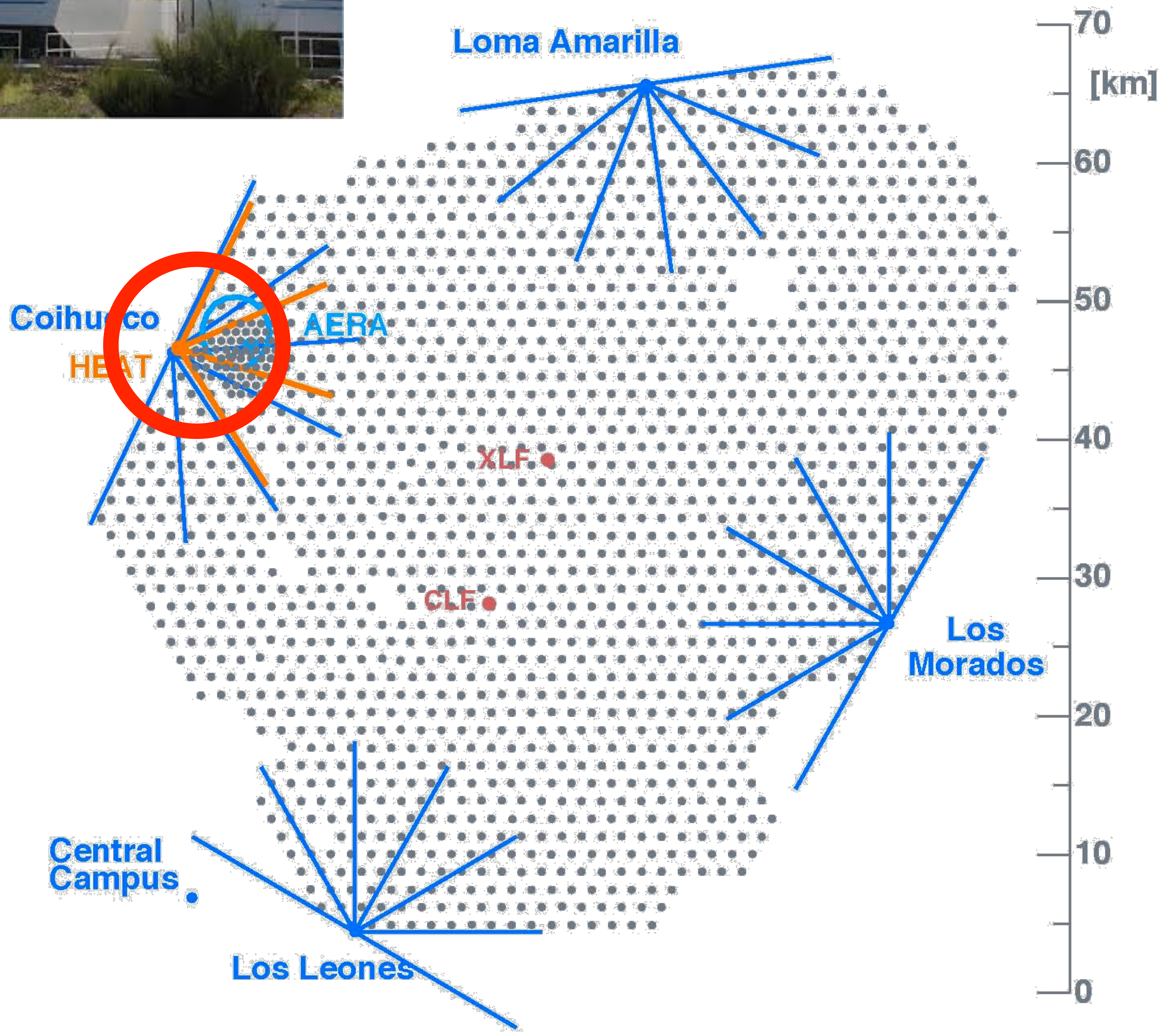


Surface detector

WCD + Fluorescence Detector

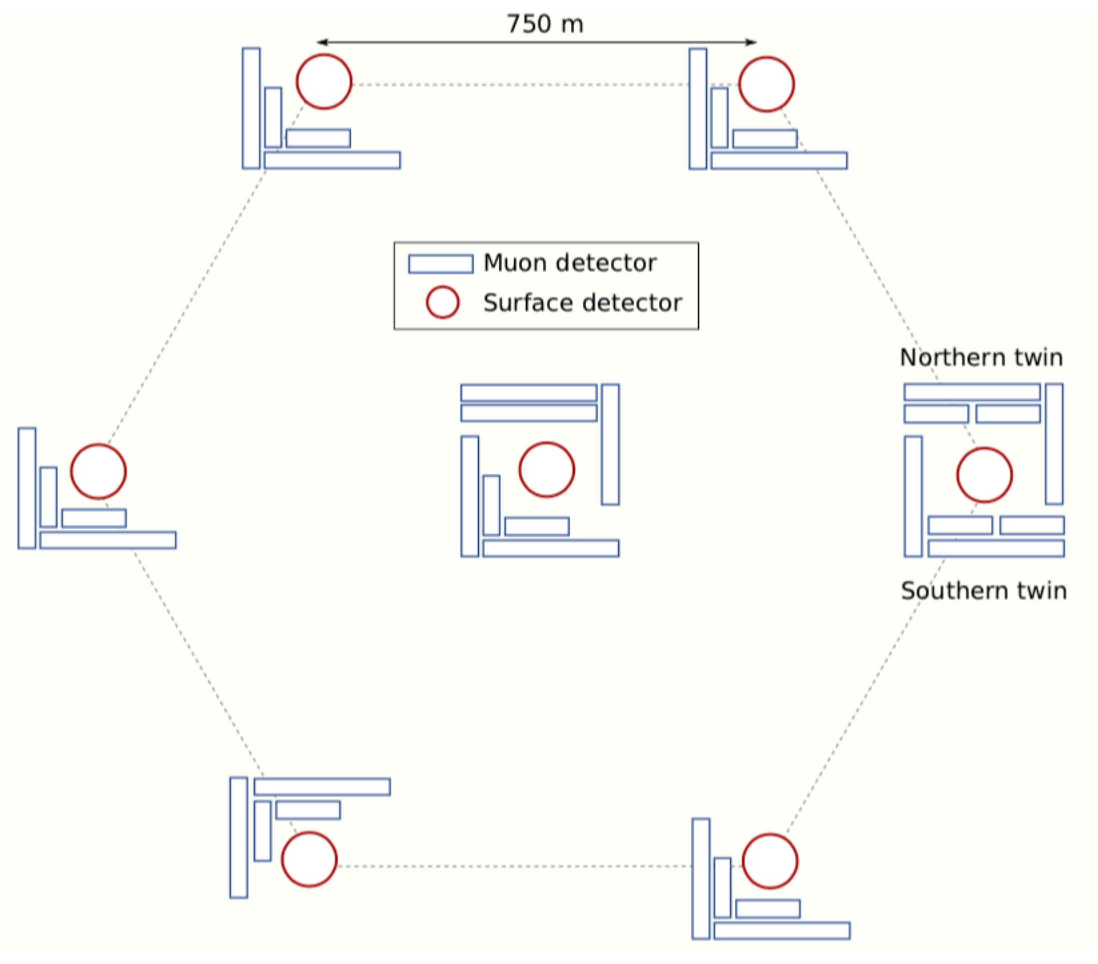
Pierre Auger Observatory

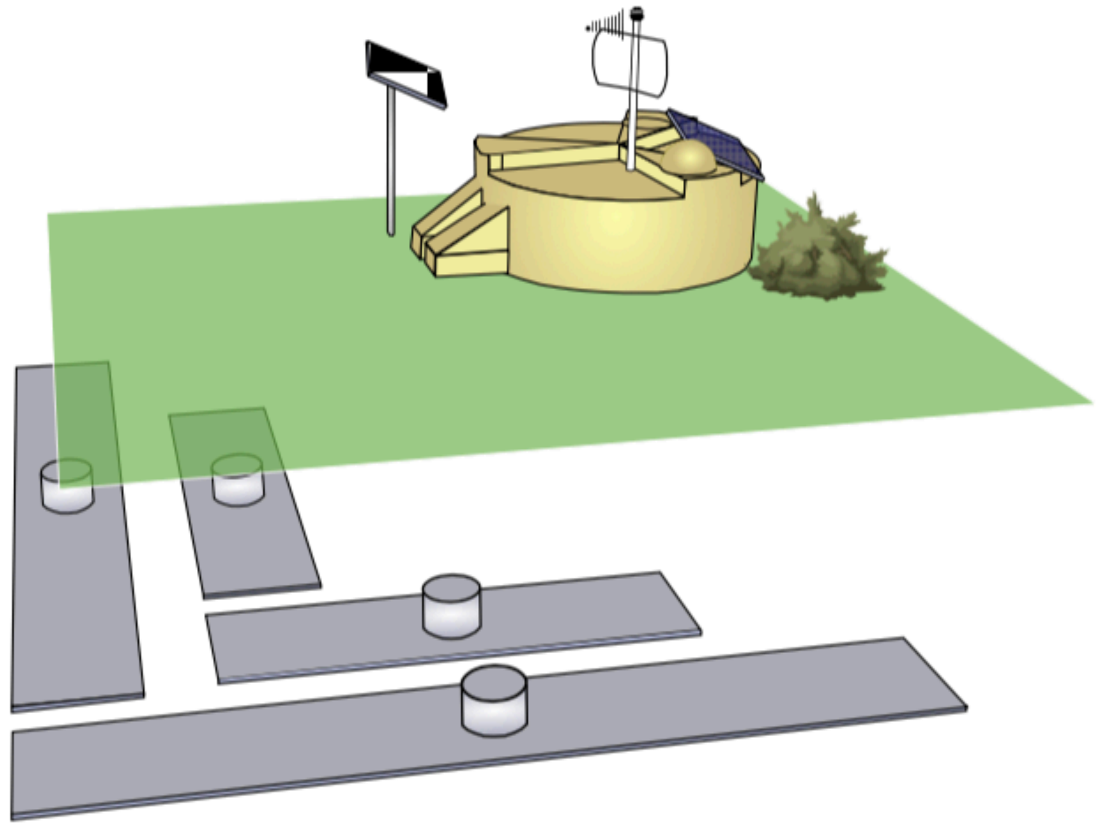
(Low energy extensions)

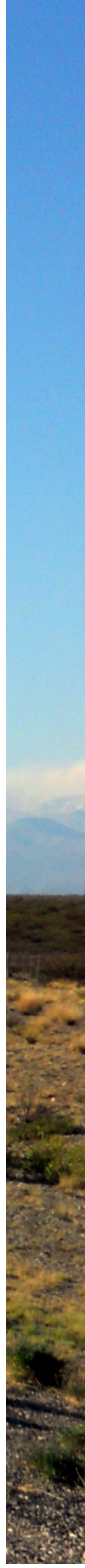


- **HEAT**
  - 3 additional FD telescopes with a high elevation FoV 30° - 60°, $E > 10^{17}$ eV

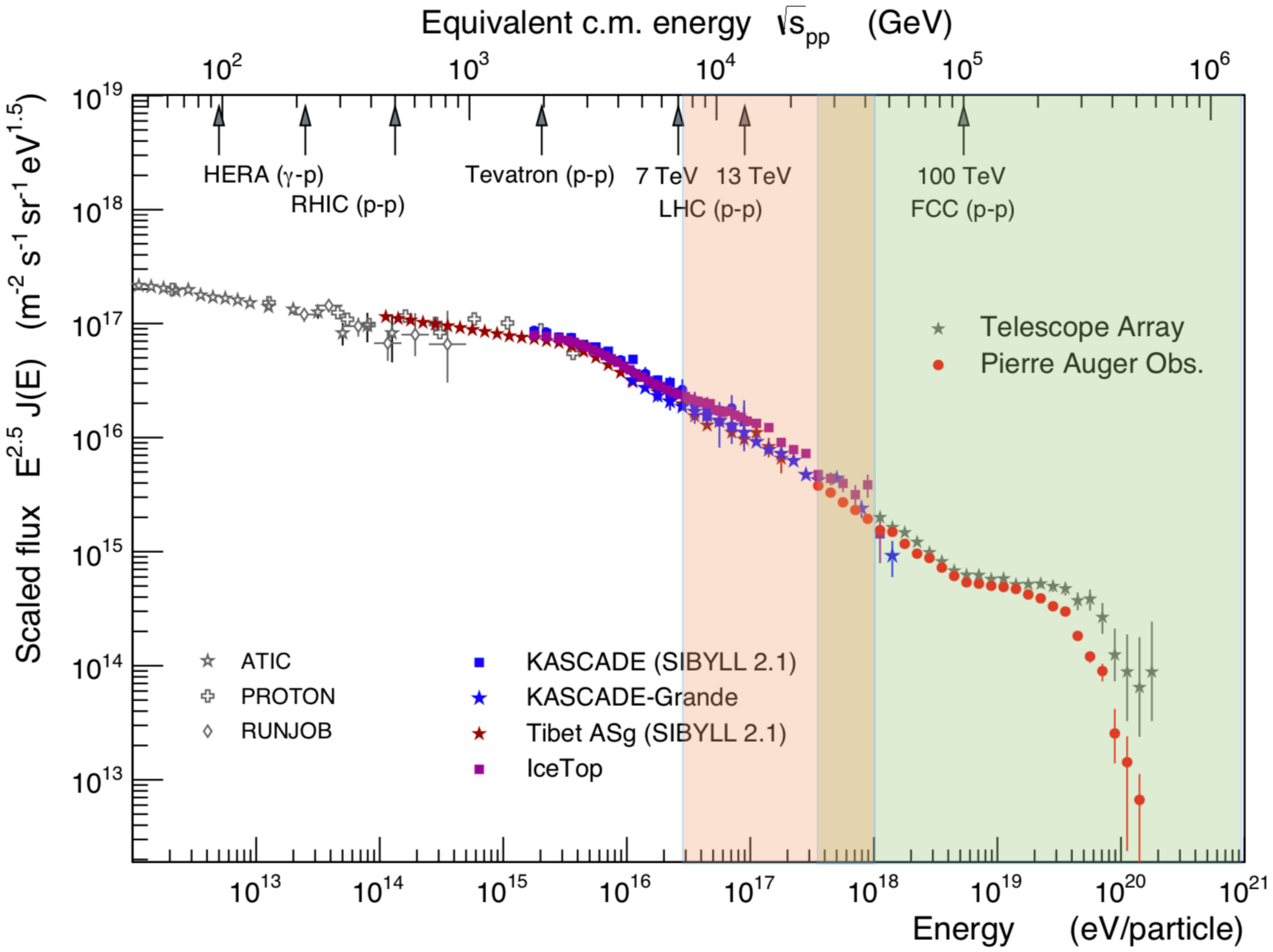
- **Infill** - Denser array
  - 433 m grid with 19 stations
  - 750 m grid with 61 stations
- **AMIGA** - Buried scintillators (muon detectors)
  - 19 (61) stations in 433 (750) m array, $10^{16.5} < E/\mathrm{eV} < 10^{19}$
  - 30 (60) m^2 scintillator modules
  - 2.3 m below ground
- **Auger Engineering Radio Array (AREA)**
  - 153 antennas in 17 km^2, $E > 4 \times 10^{18}$ eV







Ultra High Energy Cosmic Rays

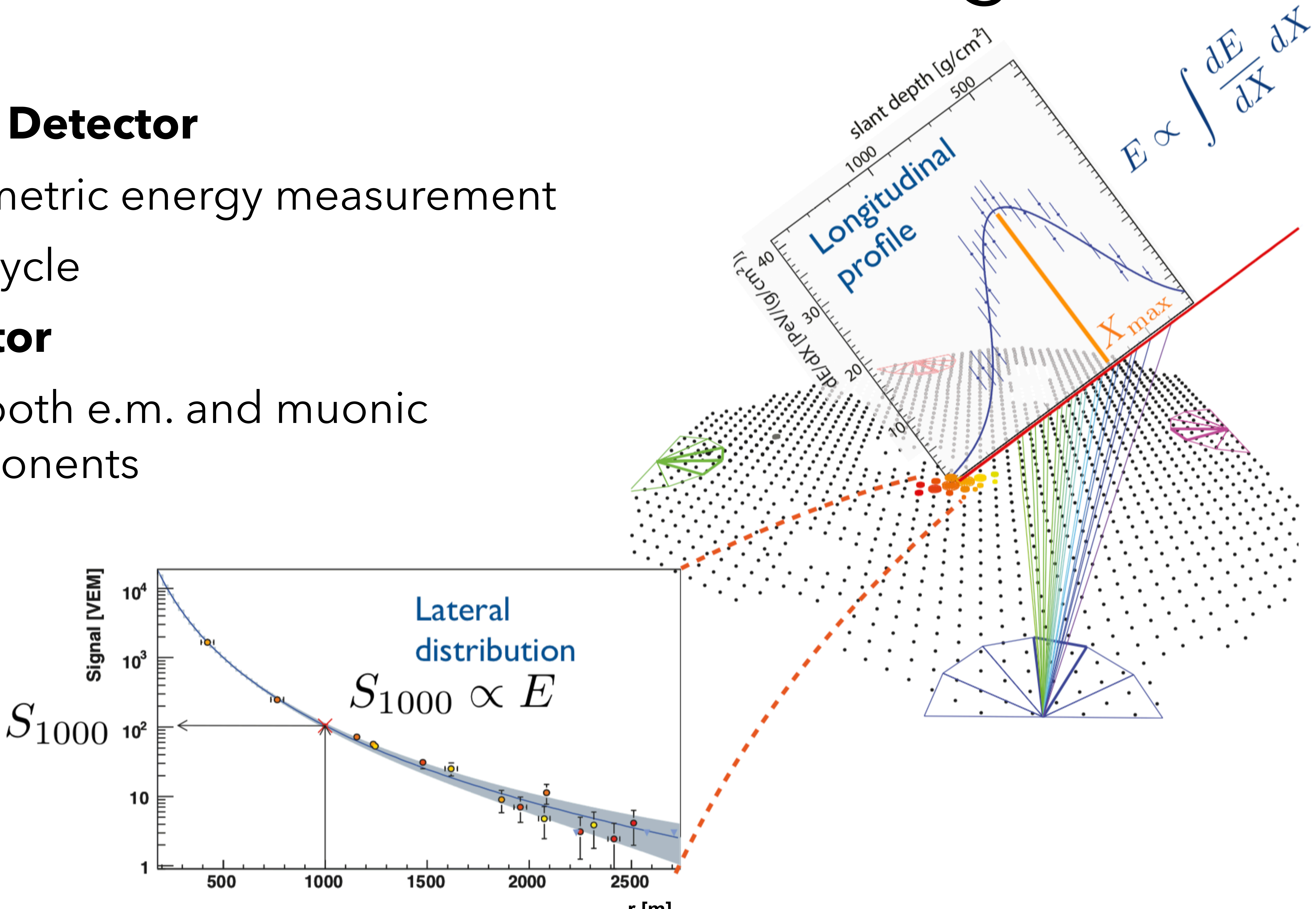


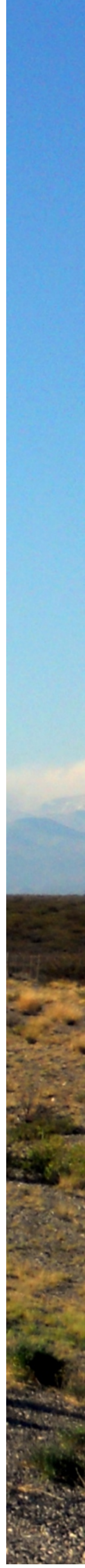
Pierre Auger Observatory

Low energy Extension

Measurement of EAS at Auger

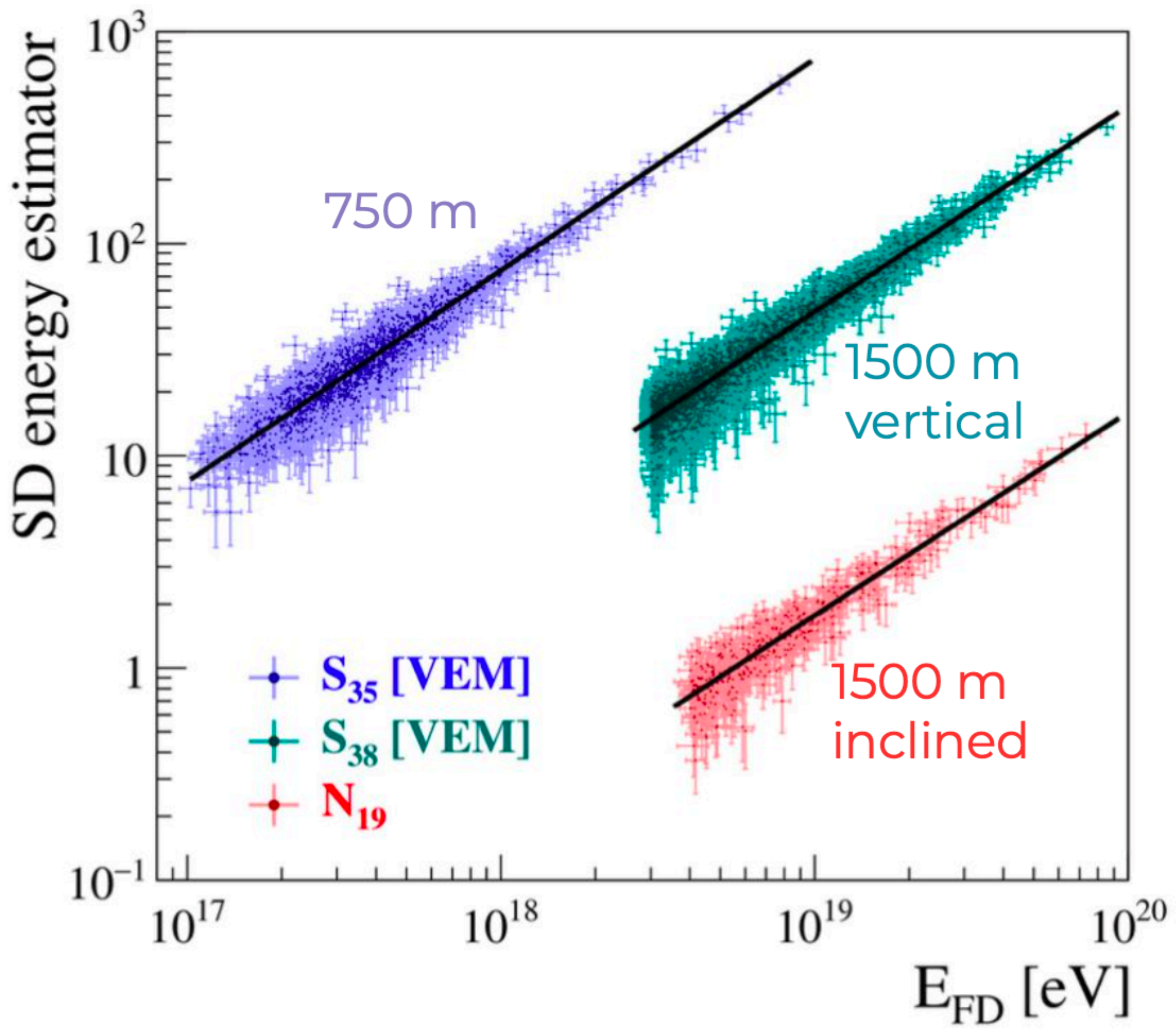
- **Fluorescence Detector**
  - Quasi-calorimetric energy measurement
  - ~ 15% duty cycle
- **Surface Detector**
  - Sensitive to both e.m. and muonic shower components

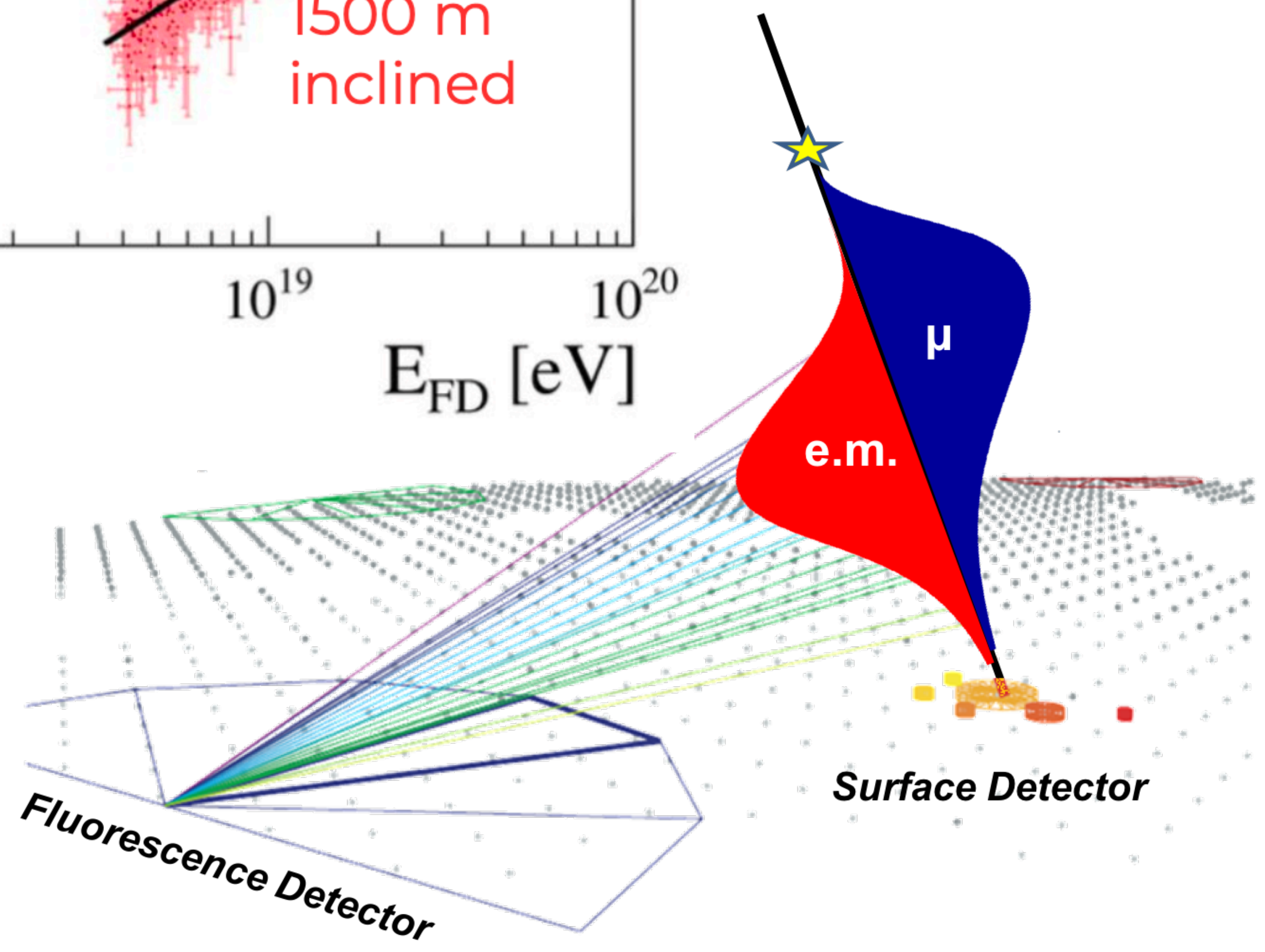


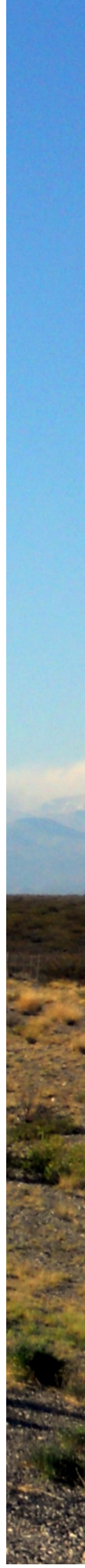


Hybrid technique

- Calibration of SD with FD
  - FD provides a quasi-calorimetric energy m
- Improve geometry reconstruction
  - For hybrid events
- Better assess/control systematic uncer
- Different insights of the shower
  - Access different shower components
  - Test shower consistency



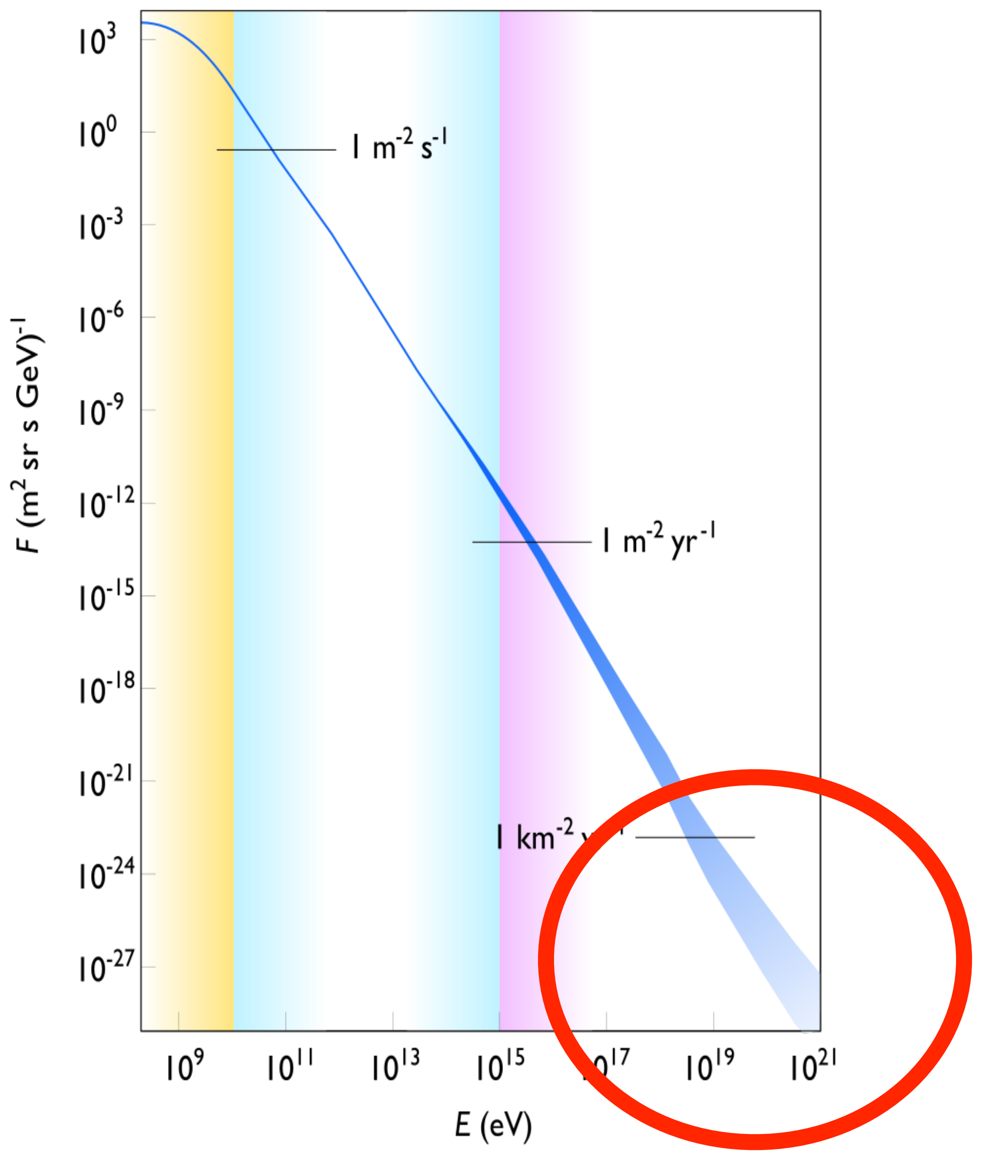




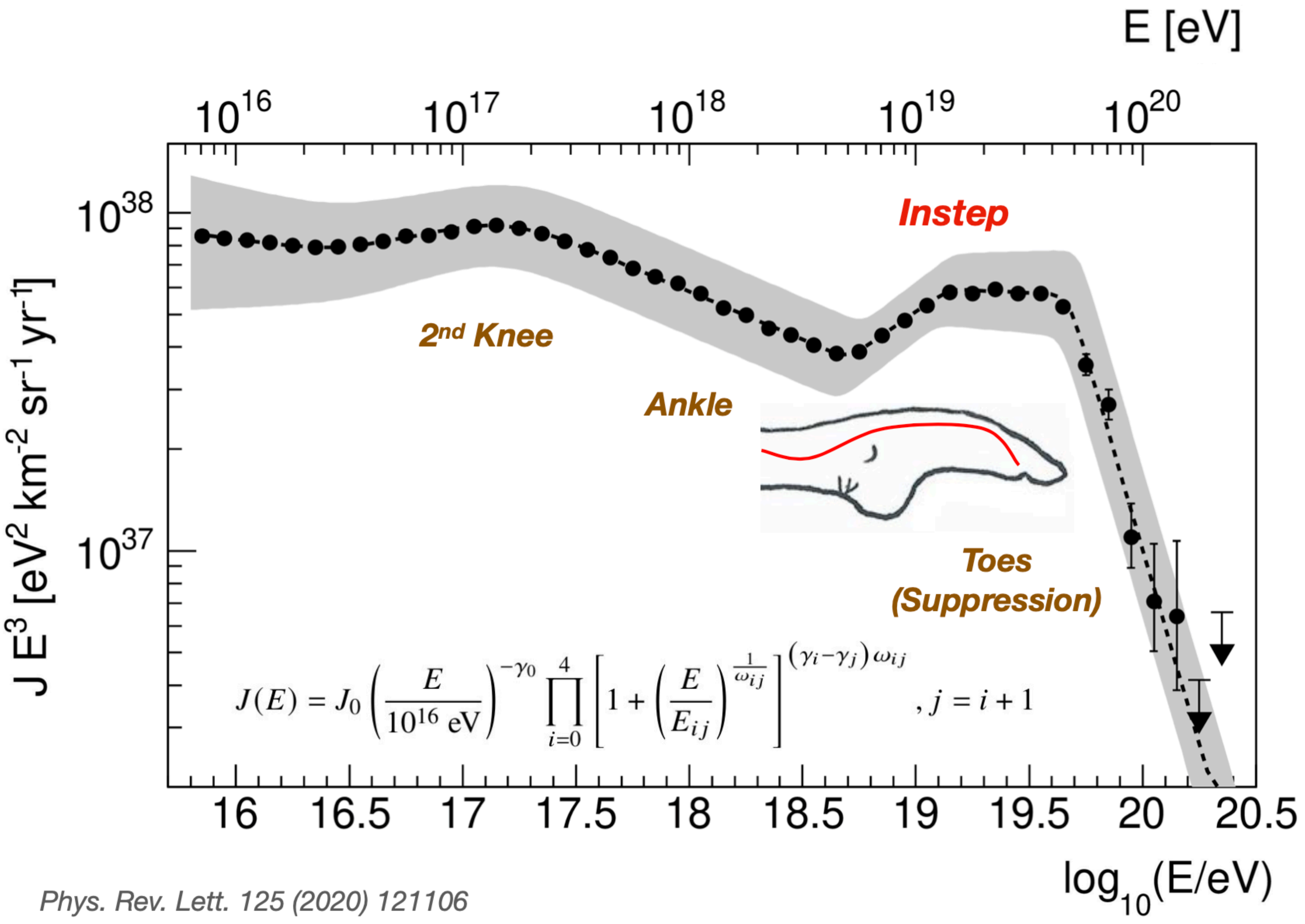
Ultra High Energy Cosmic Rays

What have we learned so far?

UHECR energy spectrum



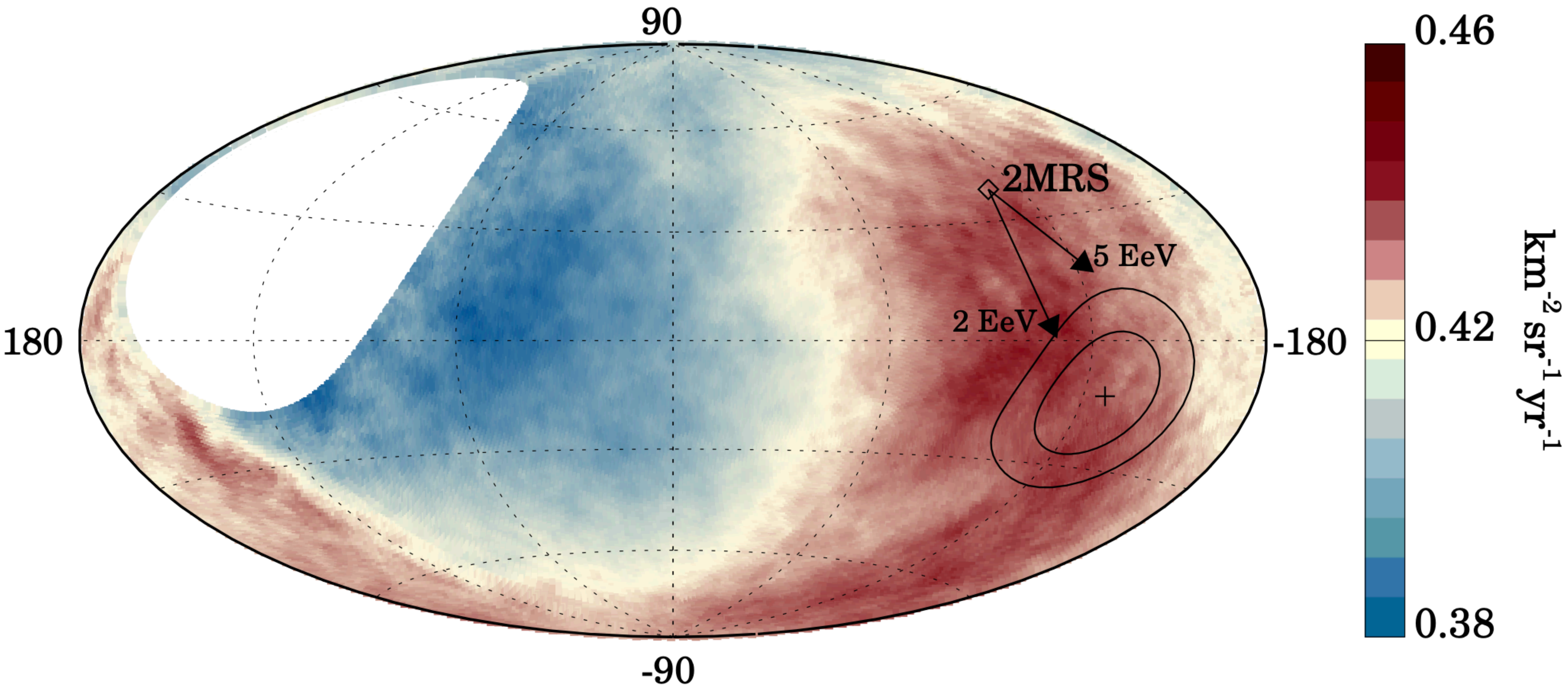
*The suppression effect can either be explained by a **propagation effect (e.g. GZK)** or by the **source exhaustion***



Phys. Rev. Lett. 125 (2020) 121106

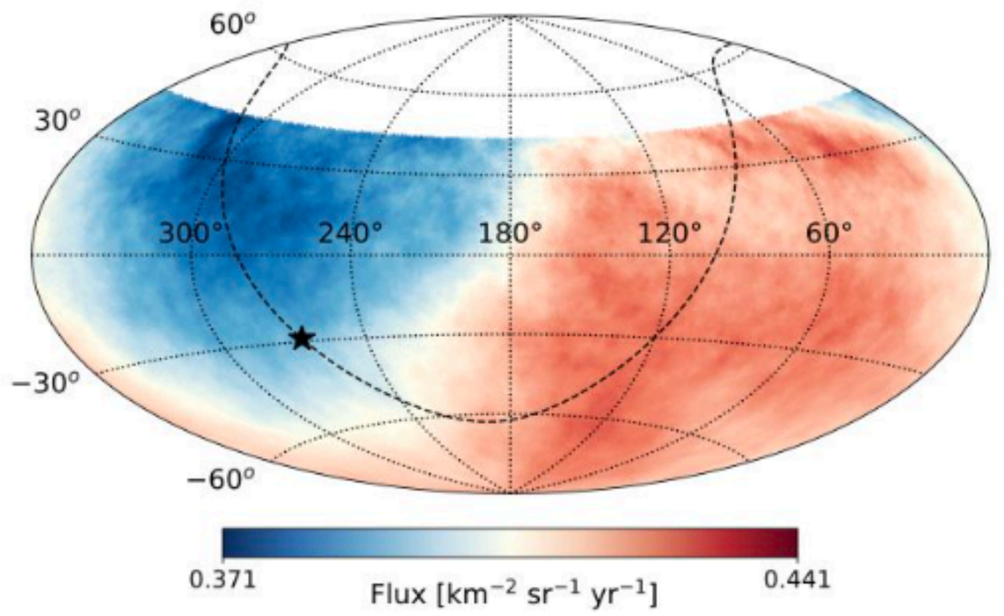
Arrival directions: large scale

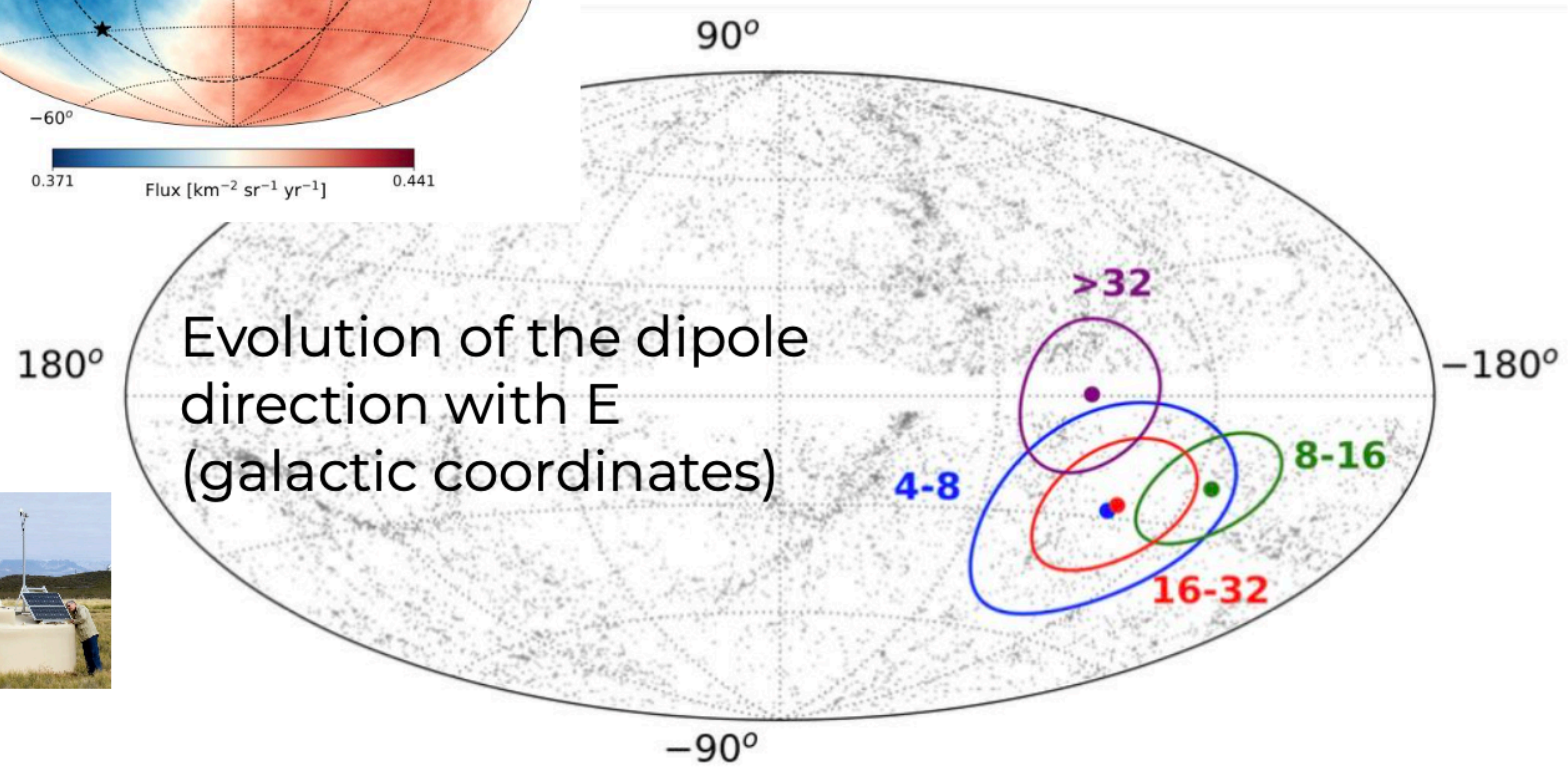
Science 357 (2017) no.6537, 1266-1270



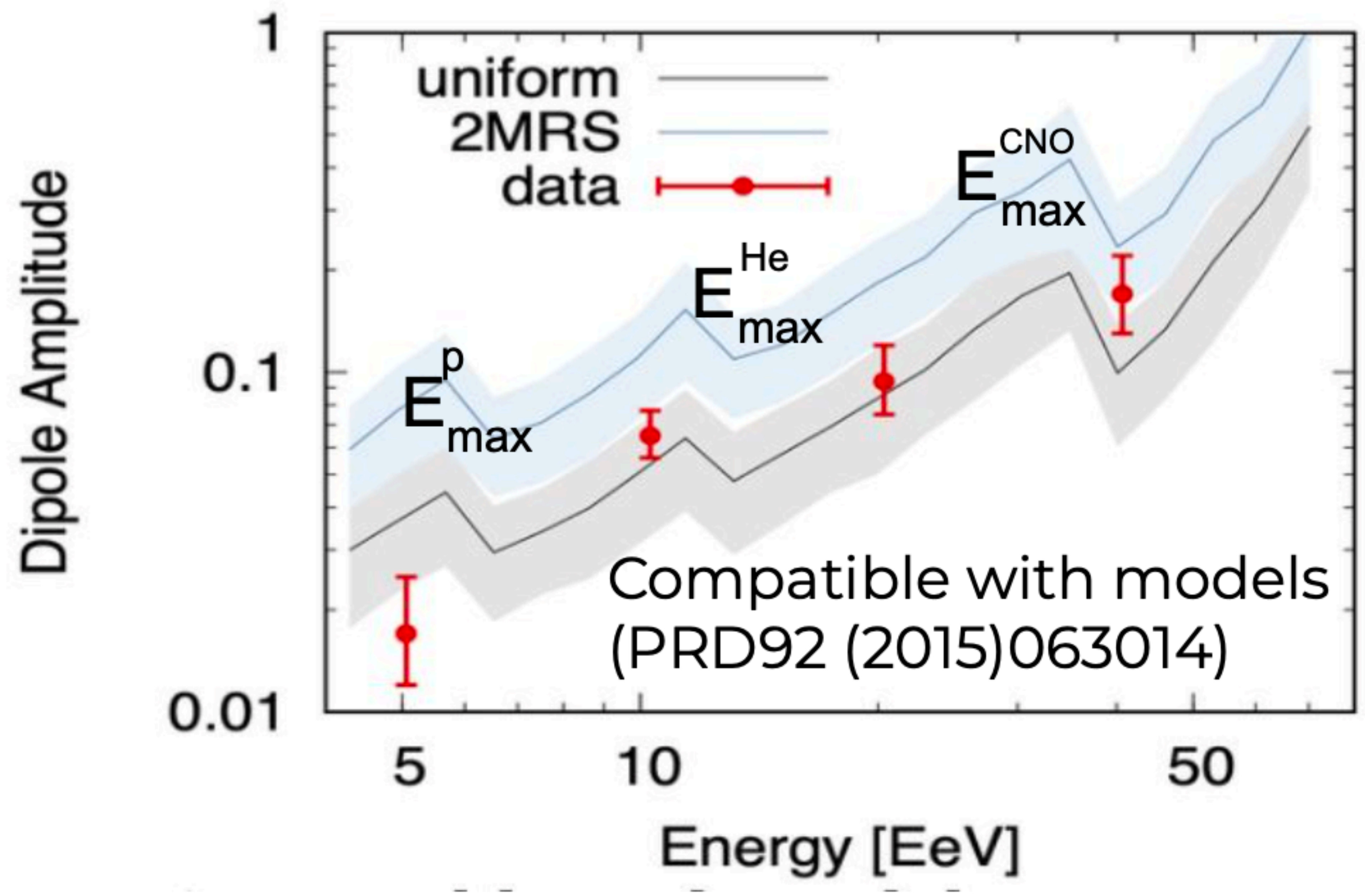
Dipole pointing $\sim 113^{\circ}$ away from the GC established at 6.9σ for energies $> 8 \times 10^{18}$ eV

Arrival directions: large scale

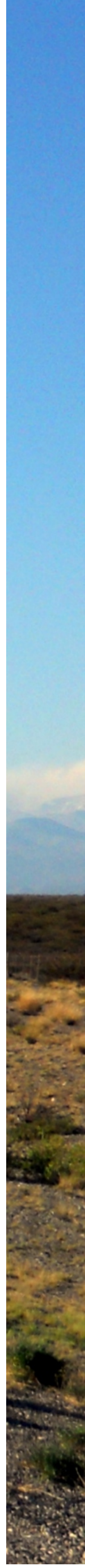




Evolution of the dipole direction with E (galactic coordinates)



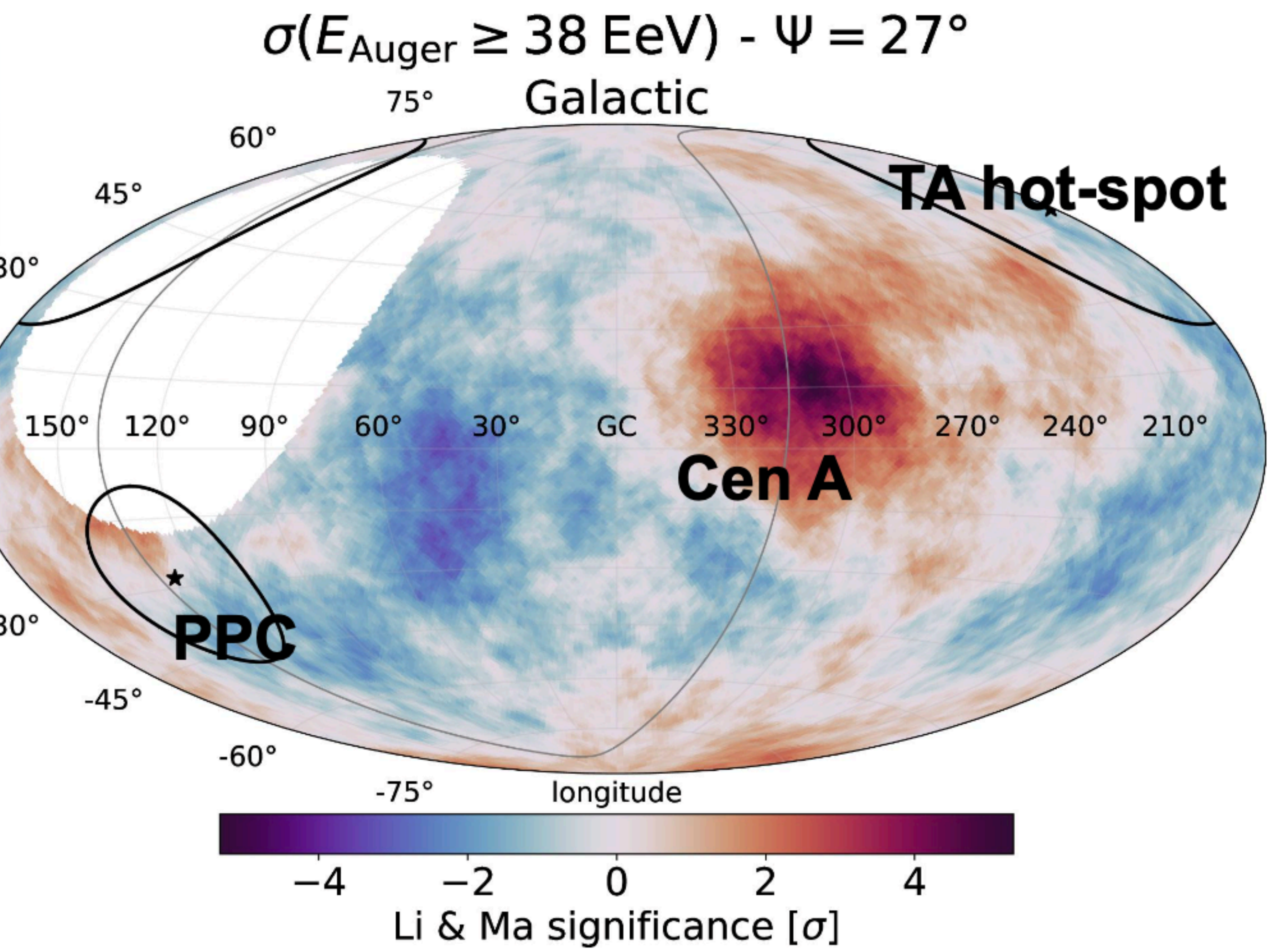
Compatible with models (PRD92 (2015)063014)

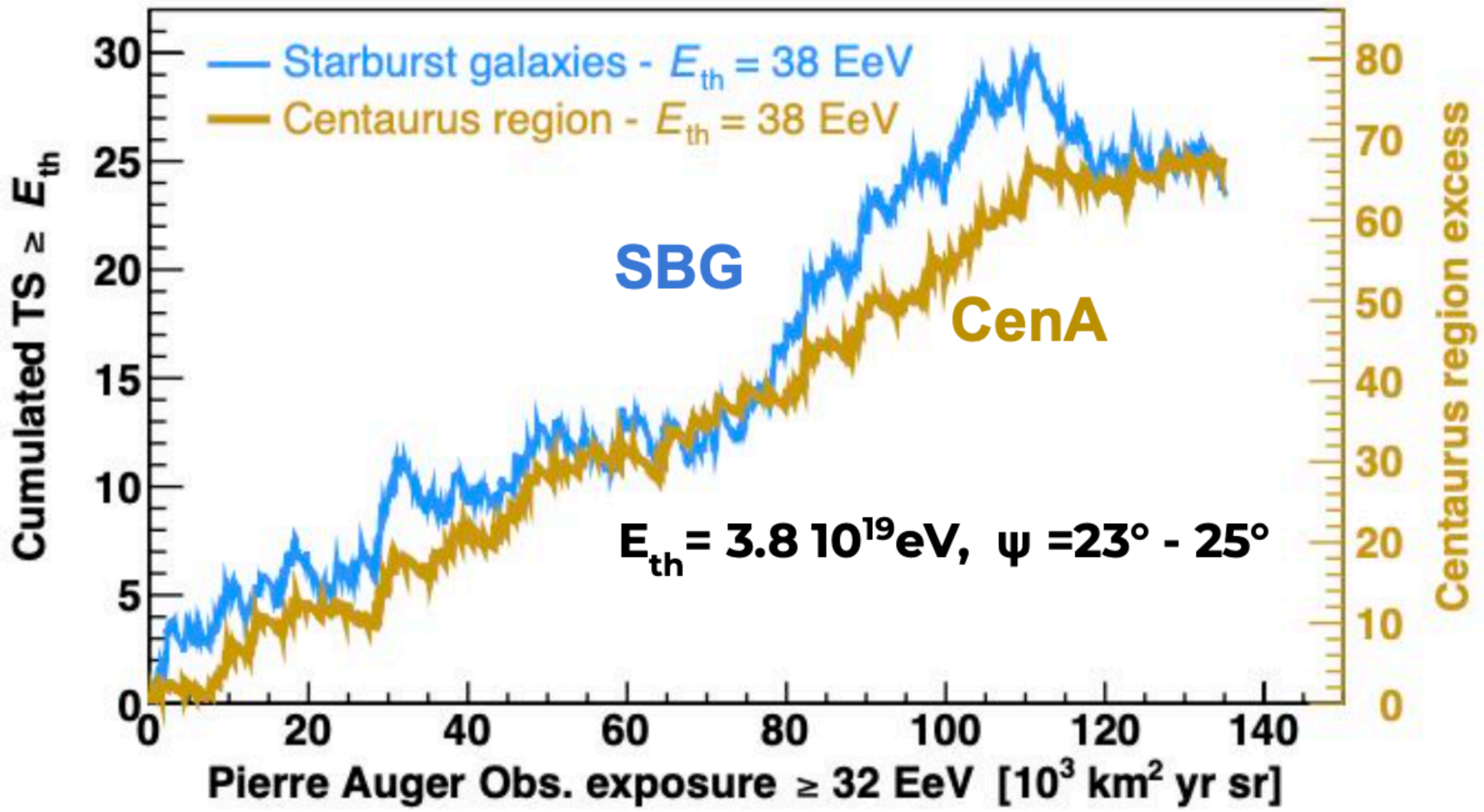


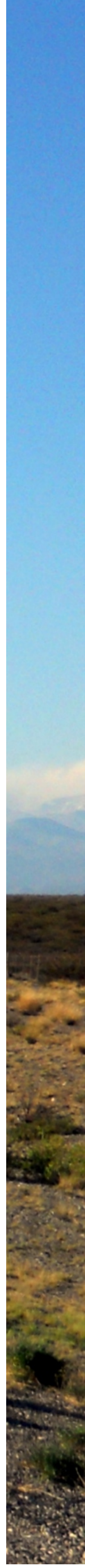
Rayleigh analysis: update of Science 315 (2017) 1266

Arrival directions: intermediate scale

overdensity map in Galactic coordinates



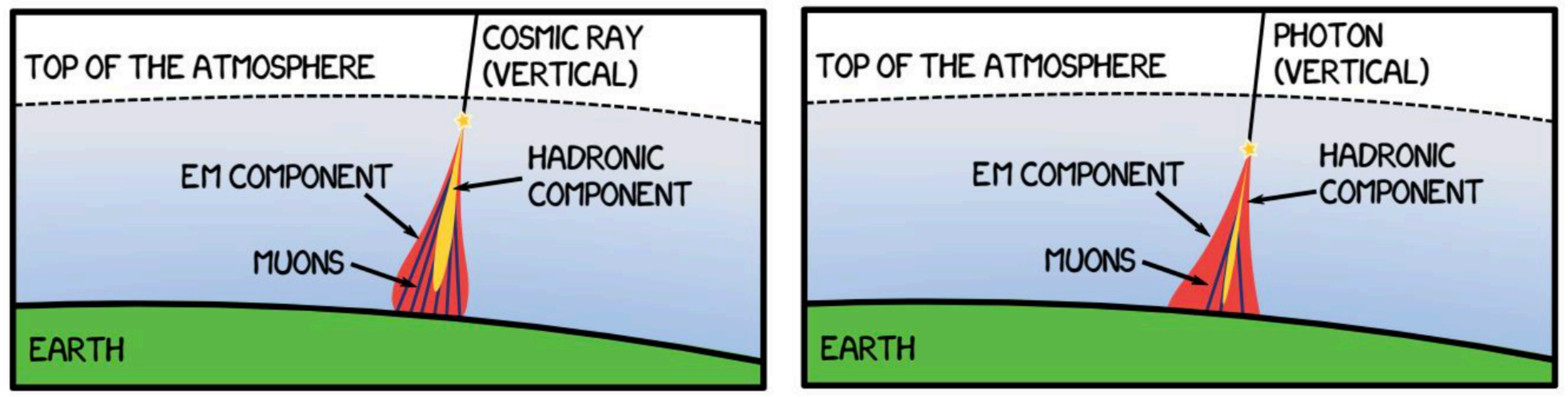


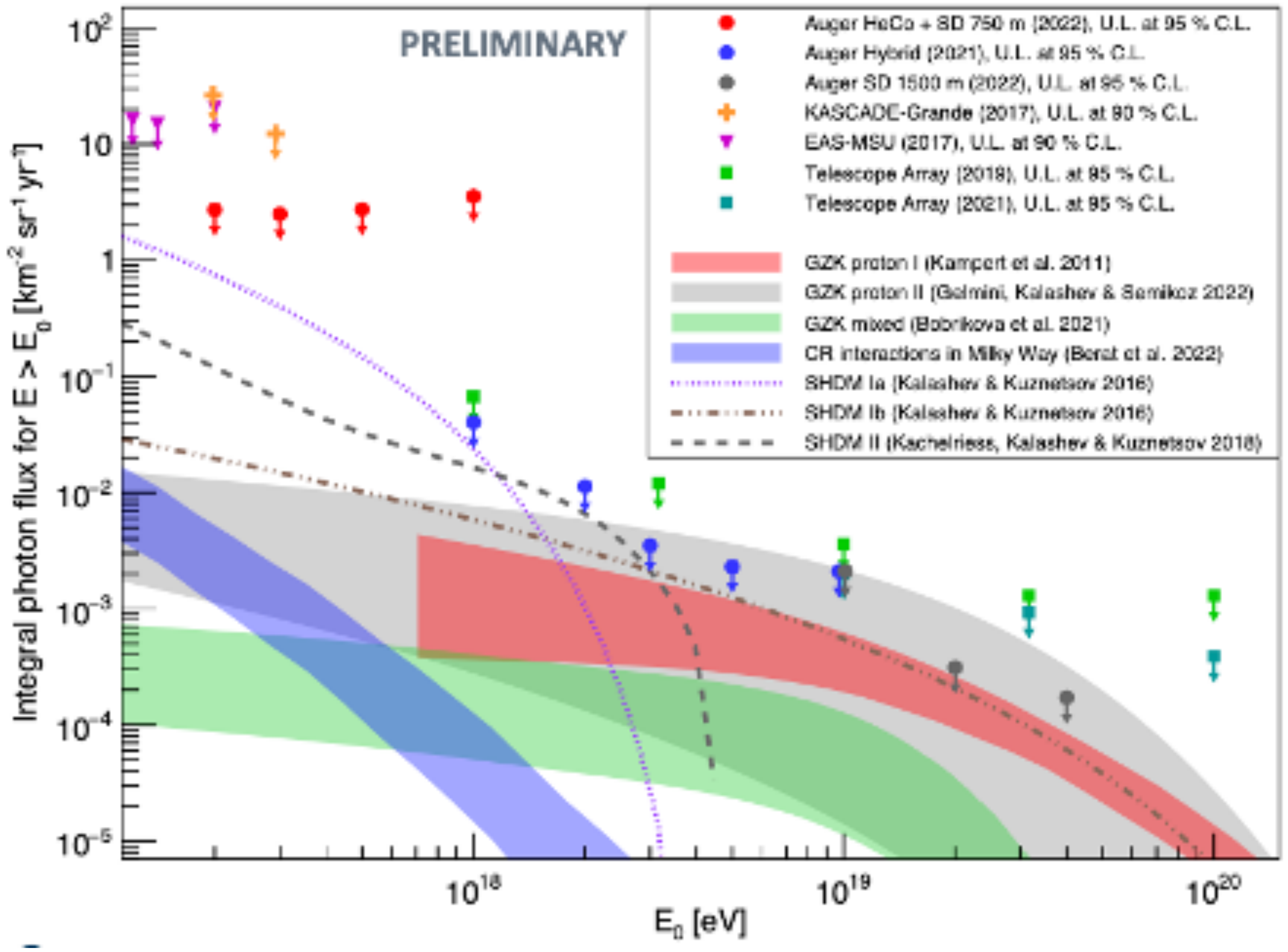


- The most significant excess at Cen A 4σ
- Several likelihood tests for correction of arrival direction with astrophysical catalogs
- Most significant signal at 3.8σ for Star Burst Galaxies catalog

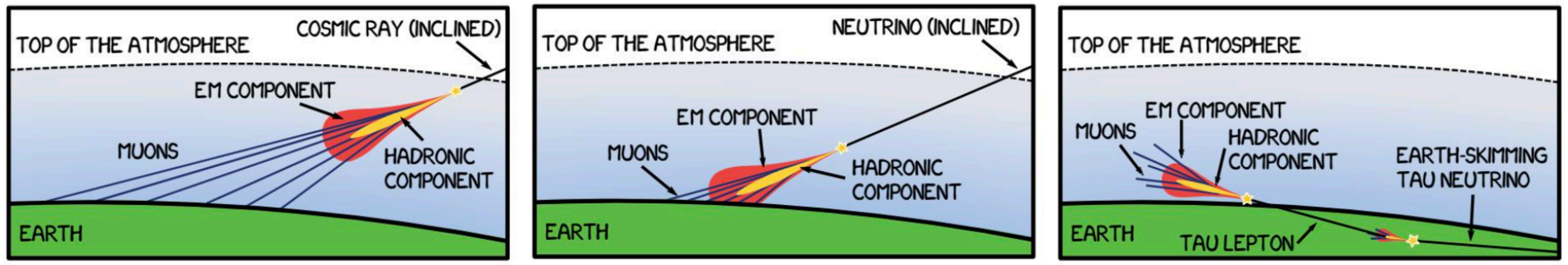
Neutral particles searches

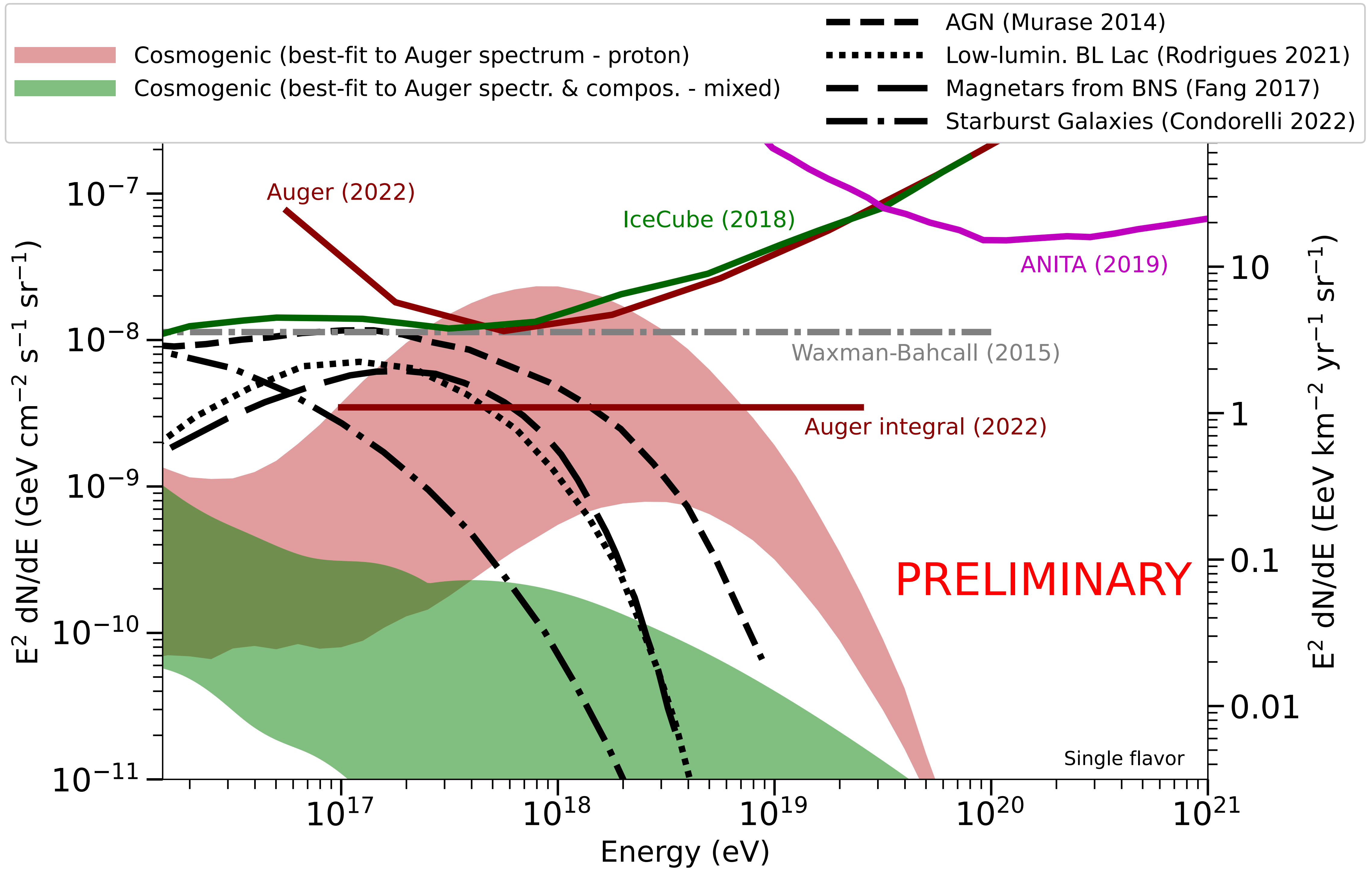
Photons





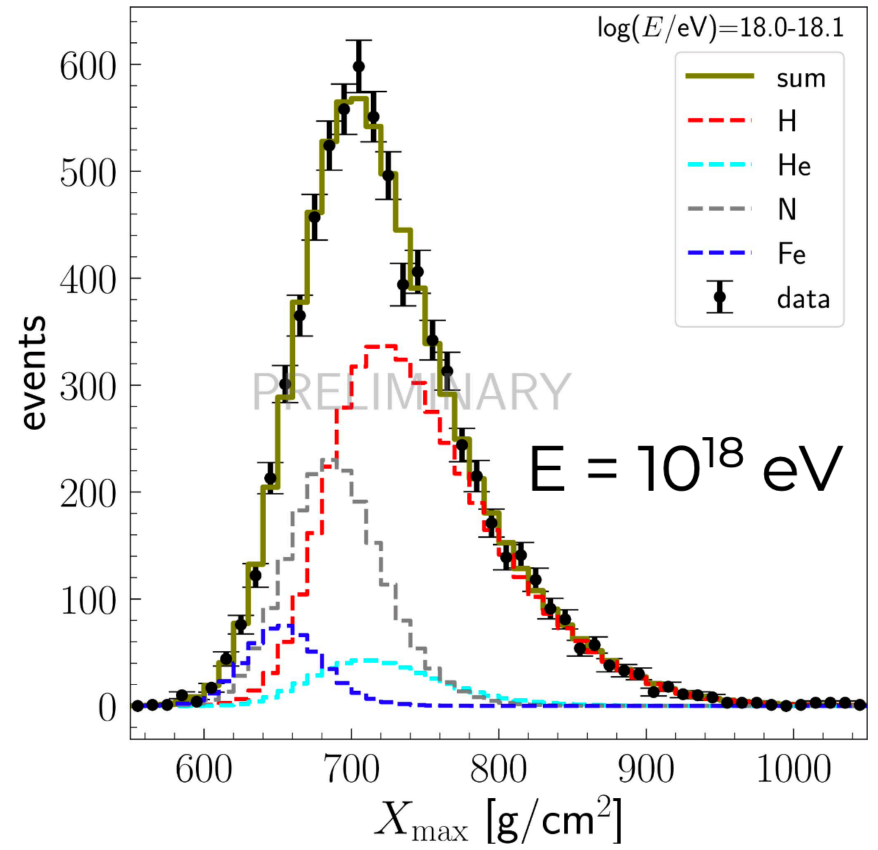
NeutrInos

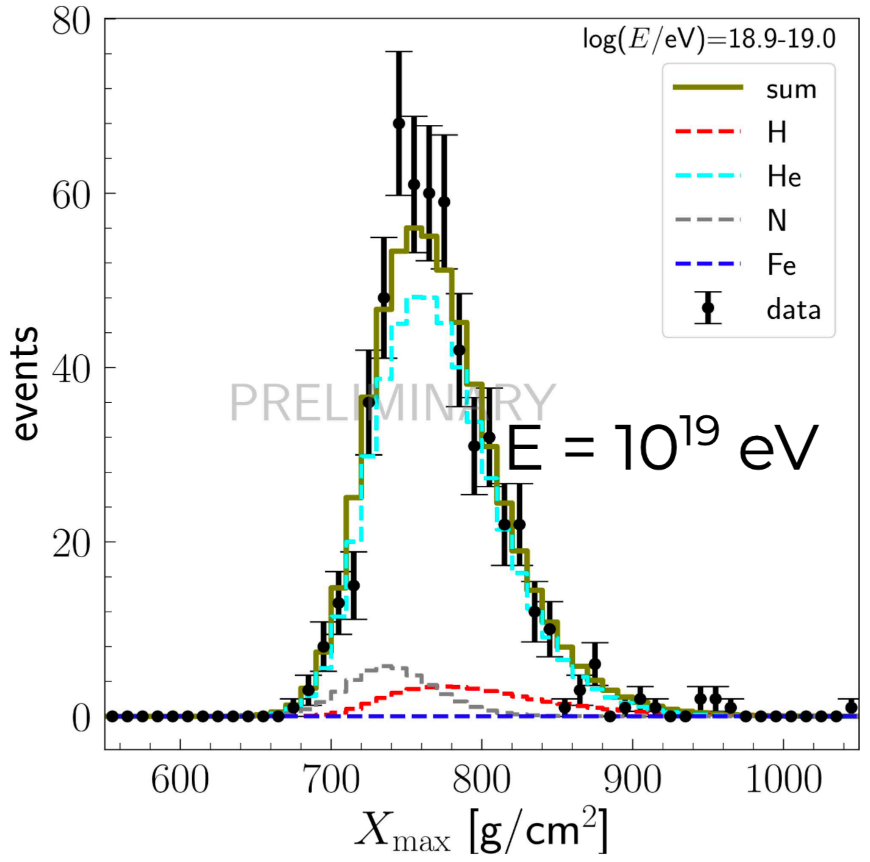


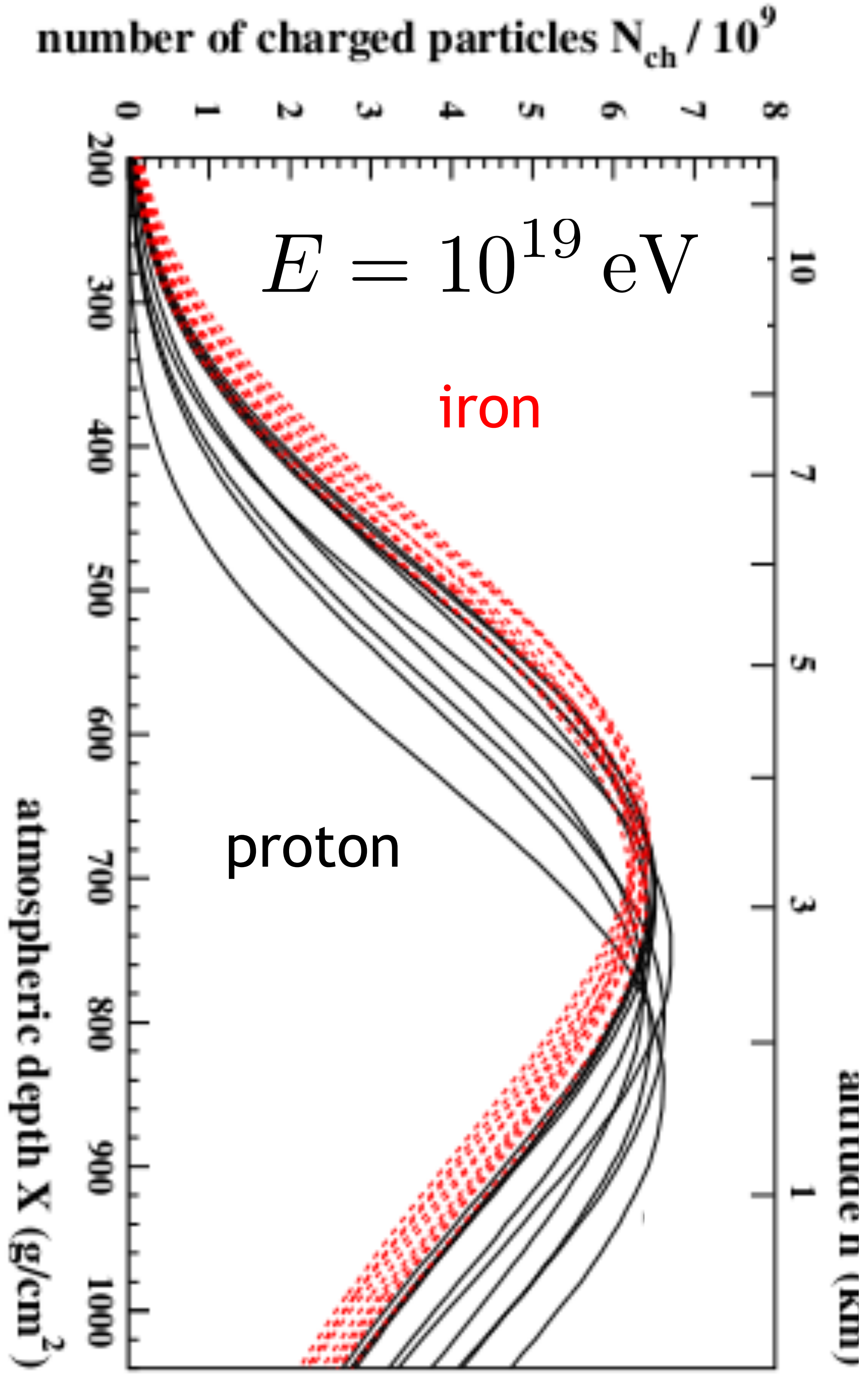


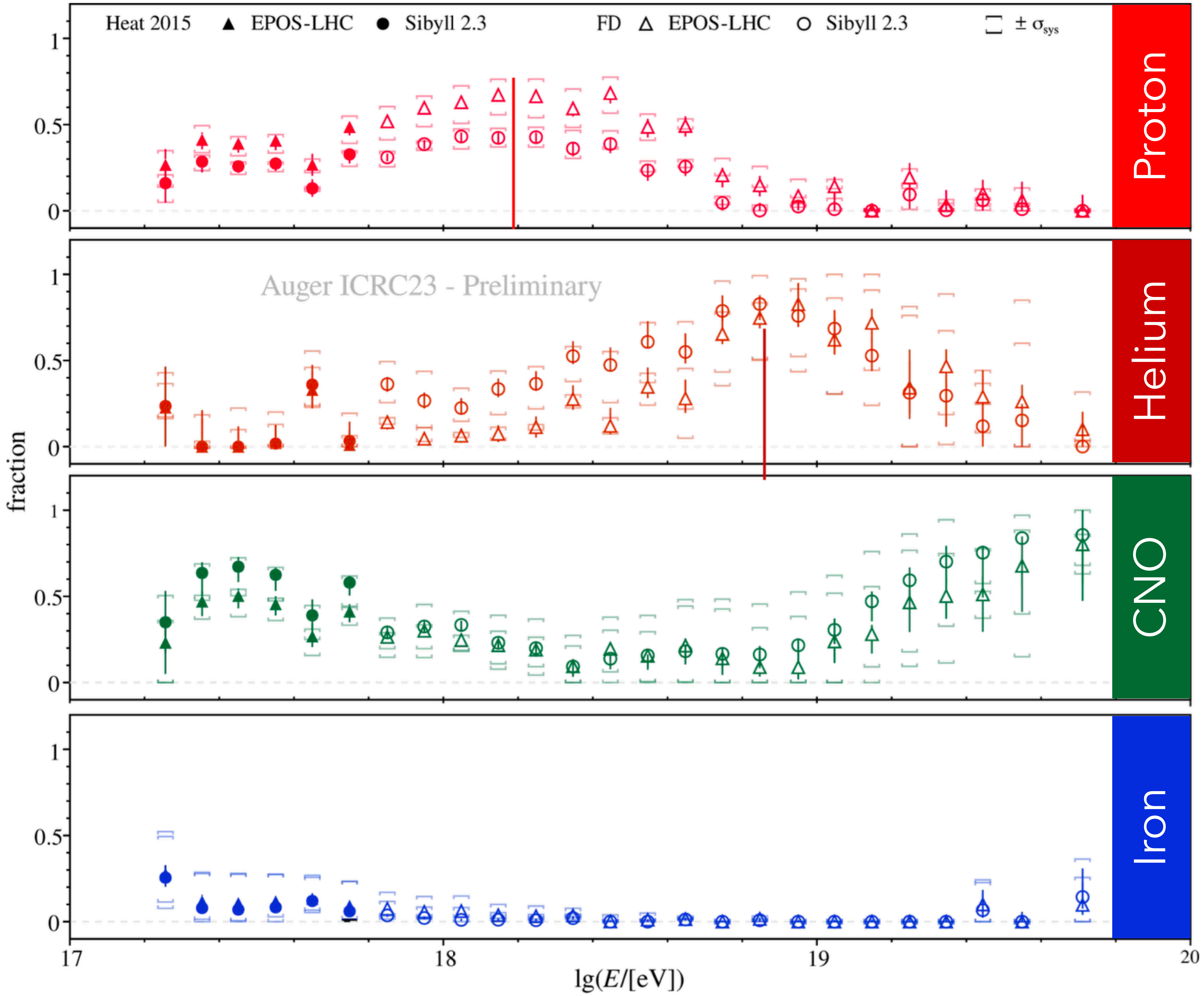
No UHE photons or neutrino have been observed yet

Composition fits to X_{max}



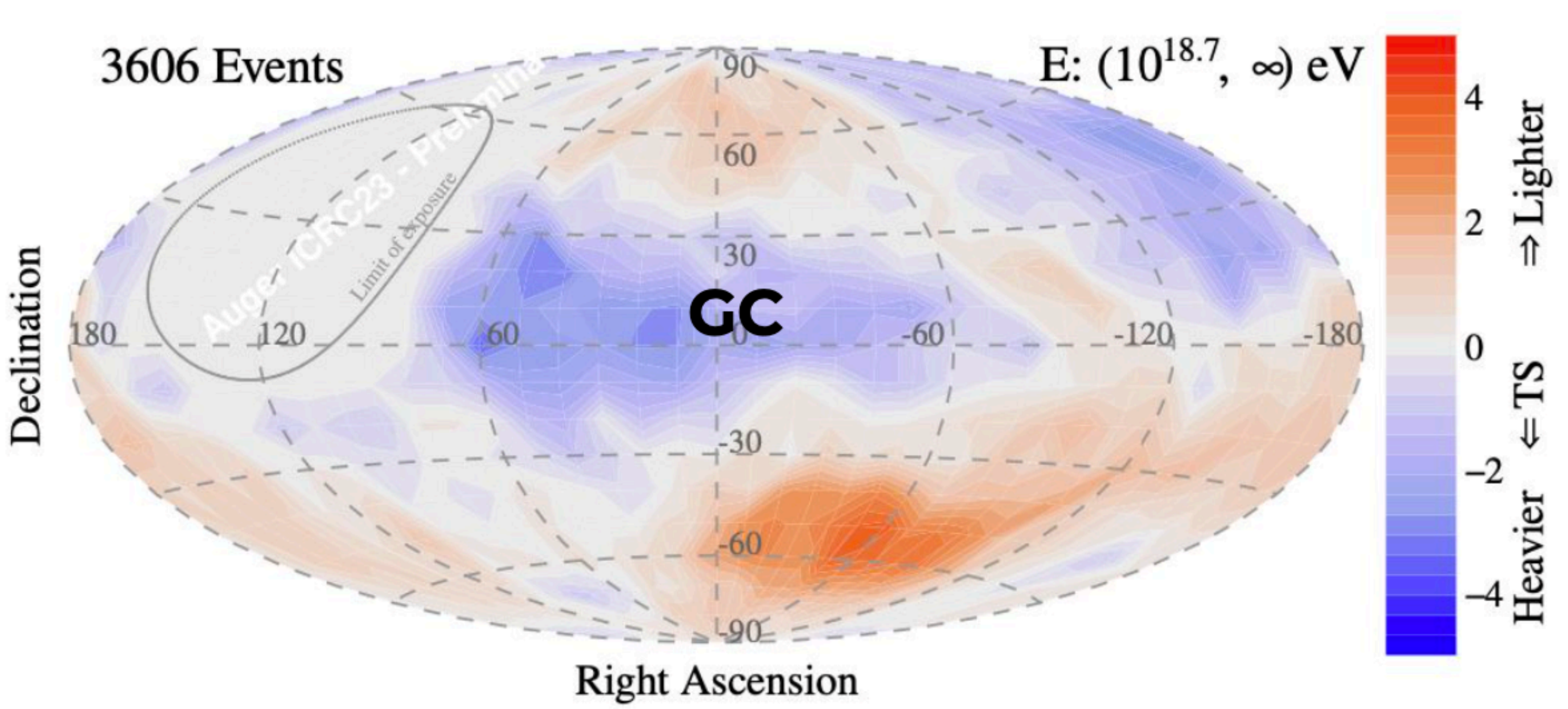


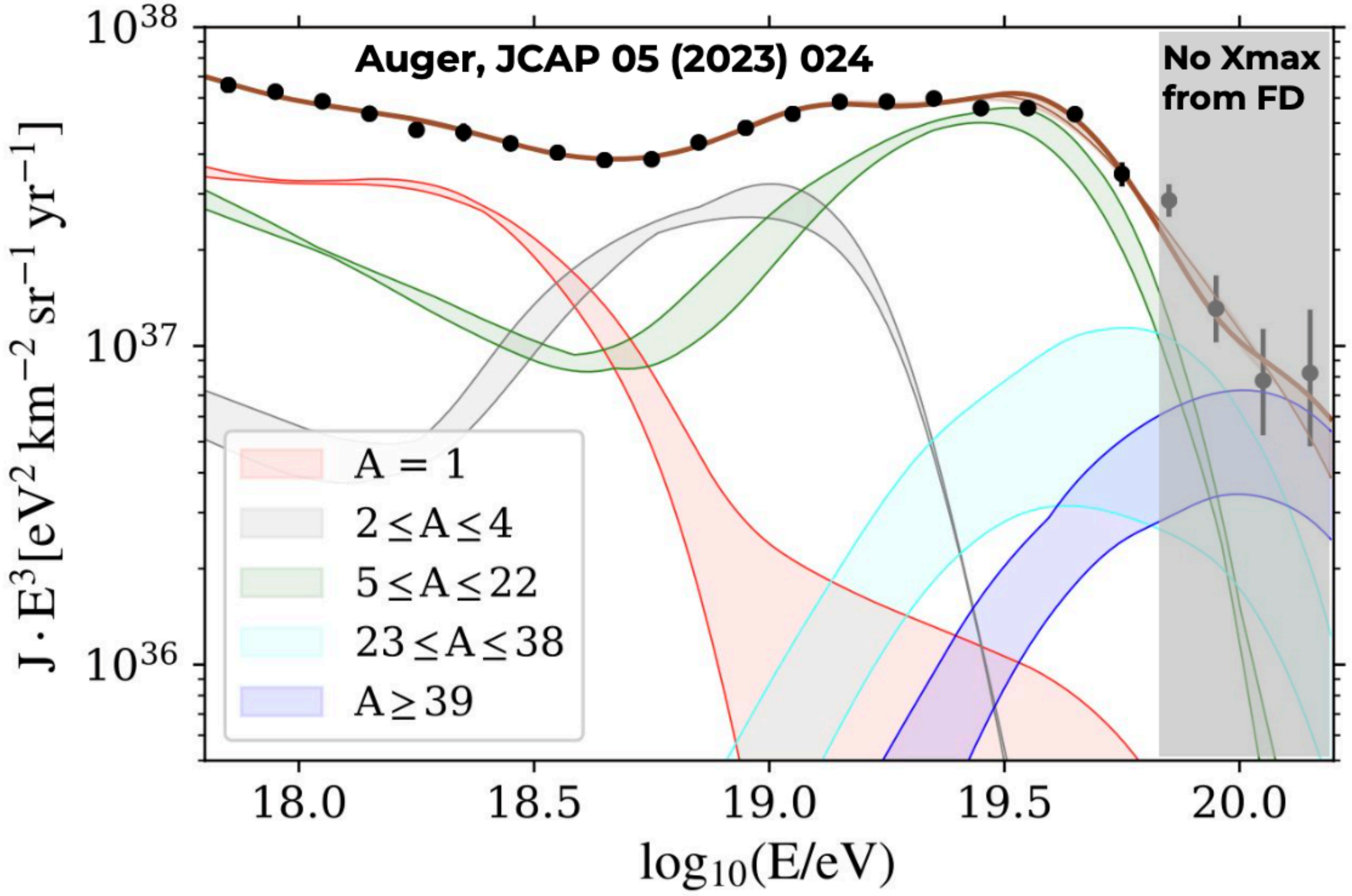


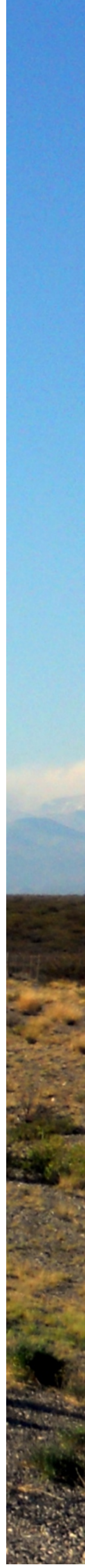


*The primary **composition** goes from **light to heavier** as its energy increases*

Mass composition enhanced anisotropy



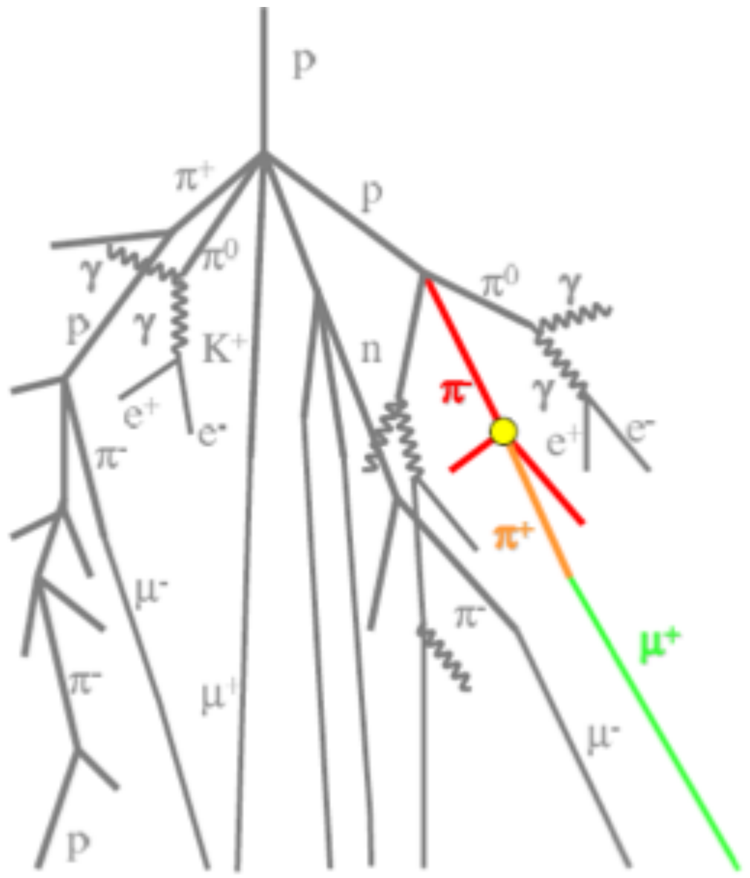




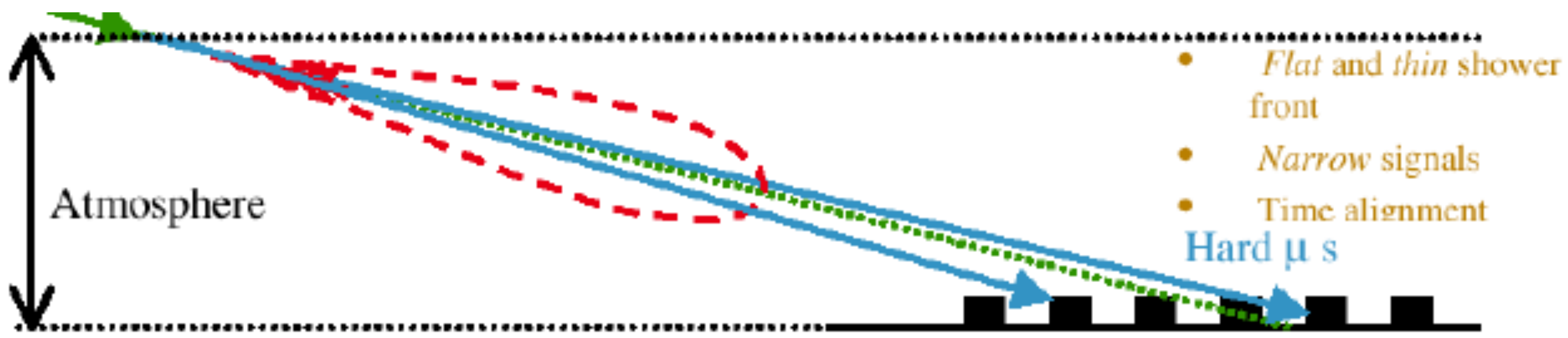
- ✧ Heavier composition from the galactic plane ($< 4\,\sigma$)
- ✧ Combined spectrum + composition fit suggest an acceleration mechanism $\propto A$

Exploration of inclined showers

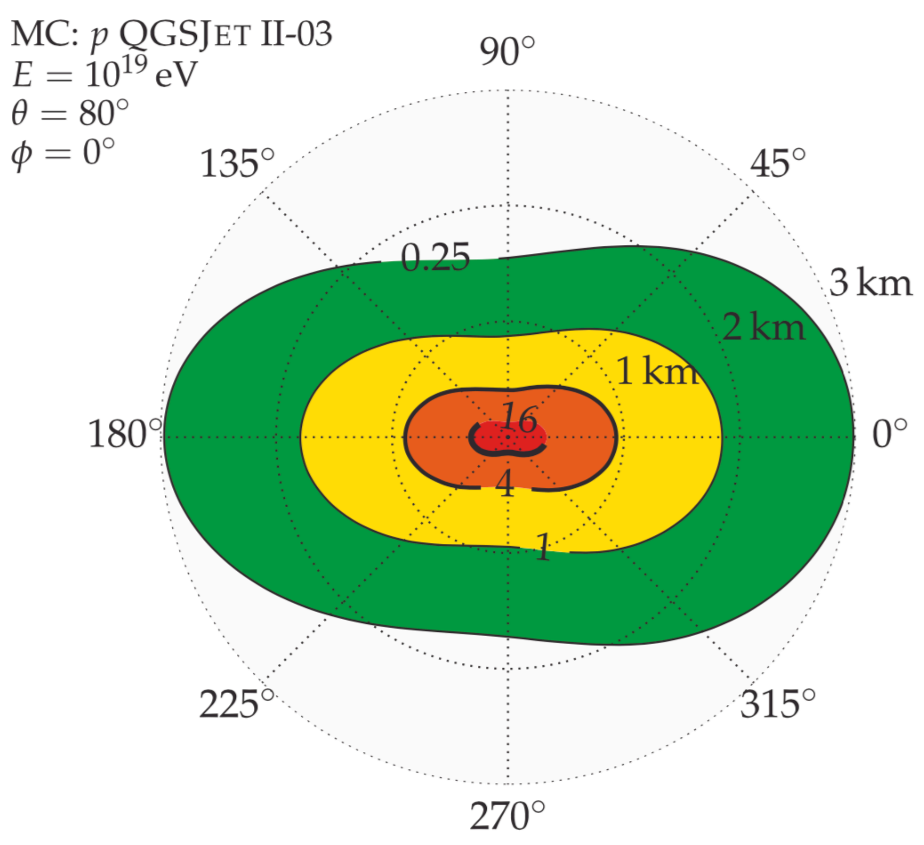
- Muons → Assess Hadronic interaction models
- Data selection
  - Zenith angles [62° ; 80°]
  - E > 4 x 10^{18} eV

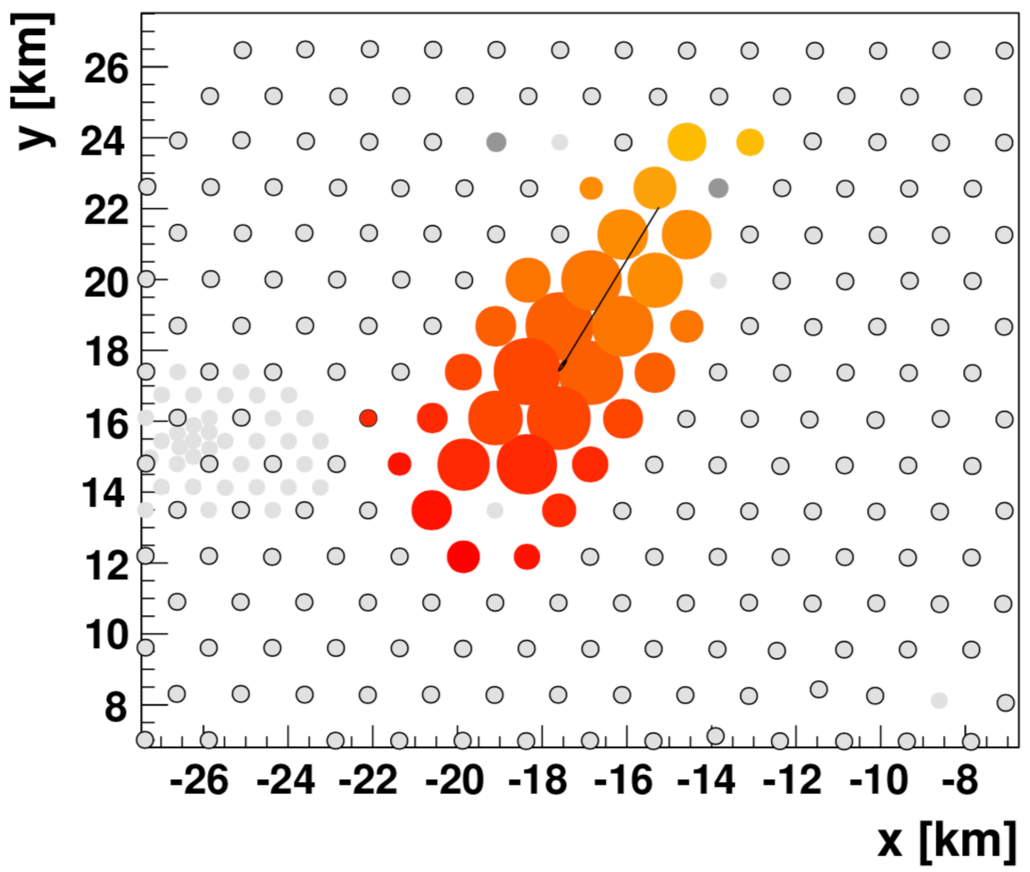


- Inclined shower → Muons



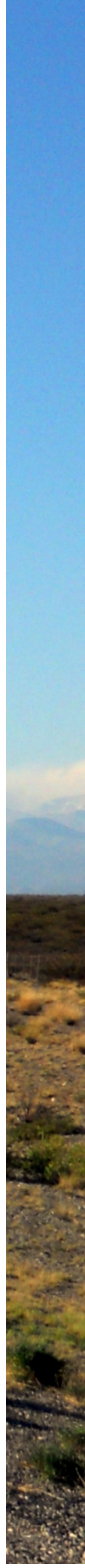
- Energy given by the Fluorescence Detector
- 281 hybrid events





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

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

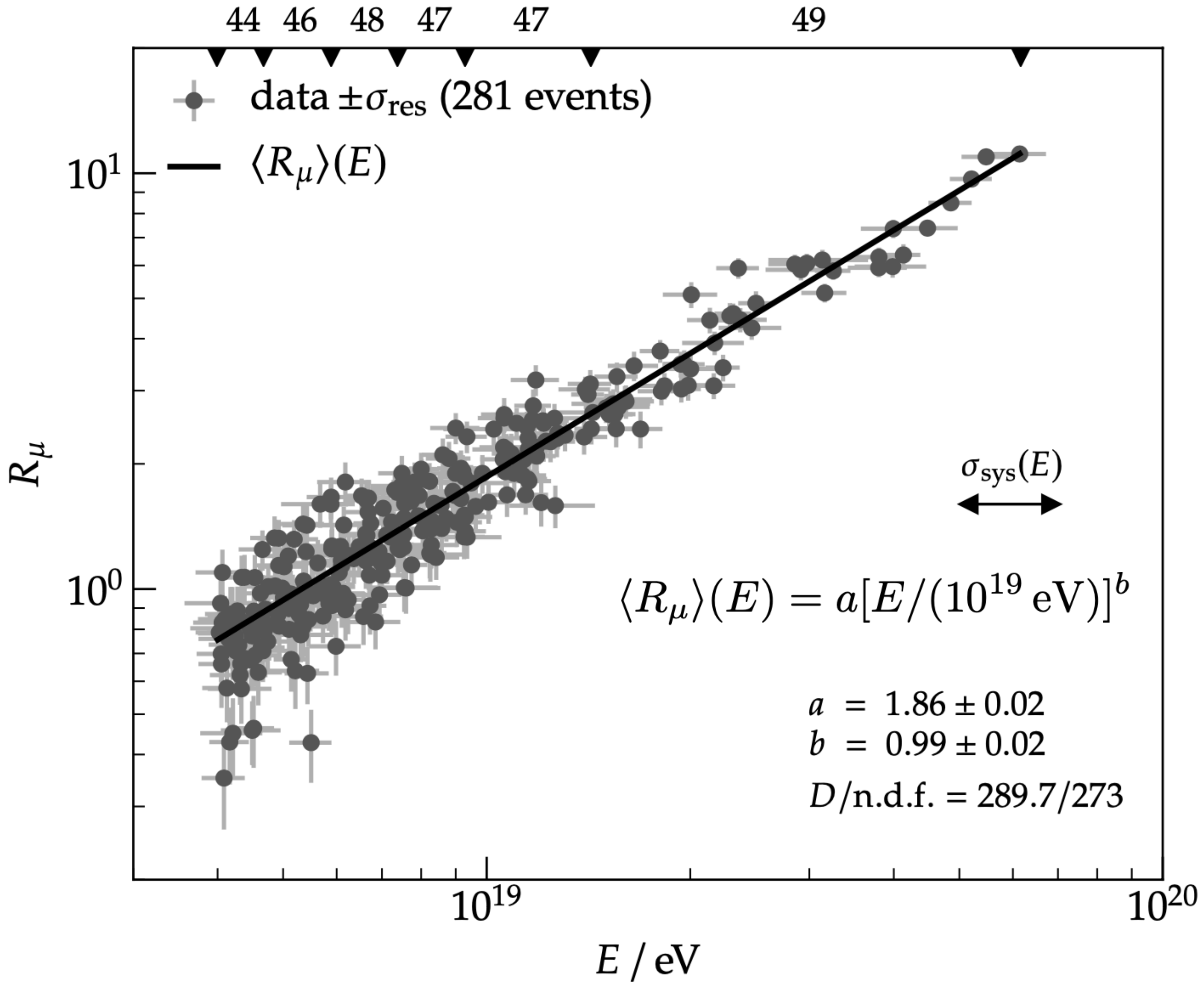


Measurement of the EAS muon content

- Done using hybrid inclined showers
- Perform a **likelihood fit** including all reconstruction uncertainties (detector, energy…)
- Extraction of the **two** first **momenta of the muon distribution** as a function of the primary energy

Phys.Rev.Lett. 126 (2021) 15, 152002

Sensitive to the EAS muon number - R_μ



Sensitive to the EAS calorimetric energy - E

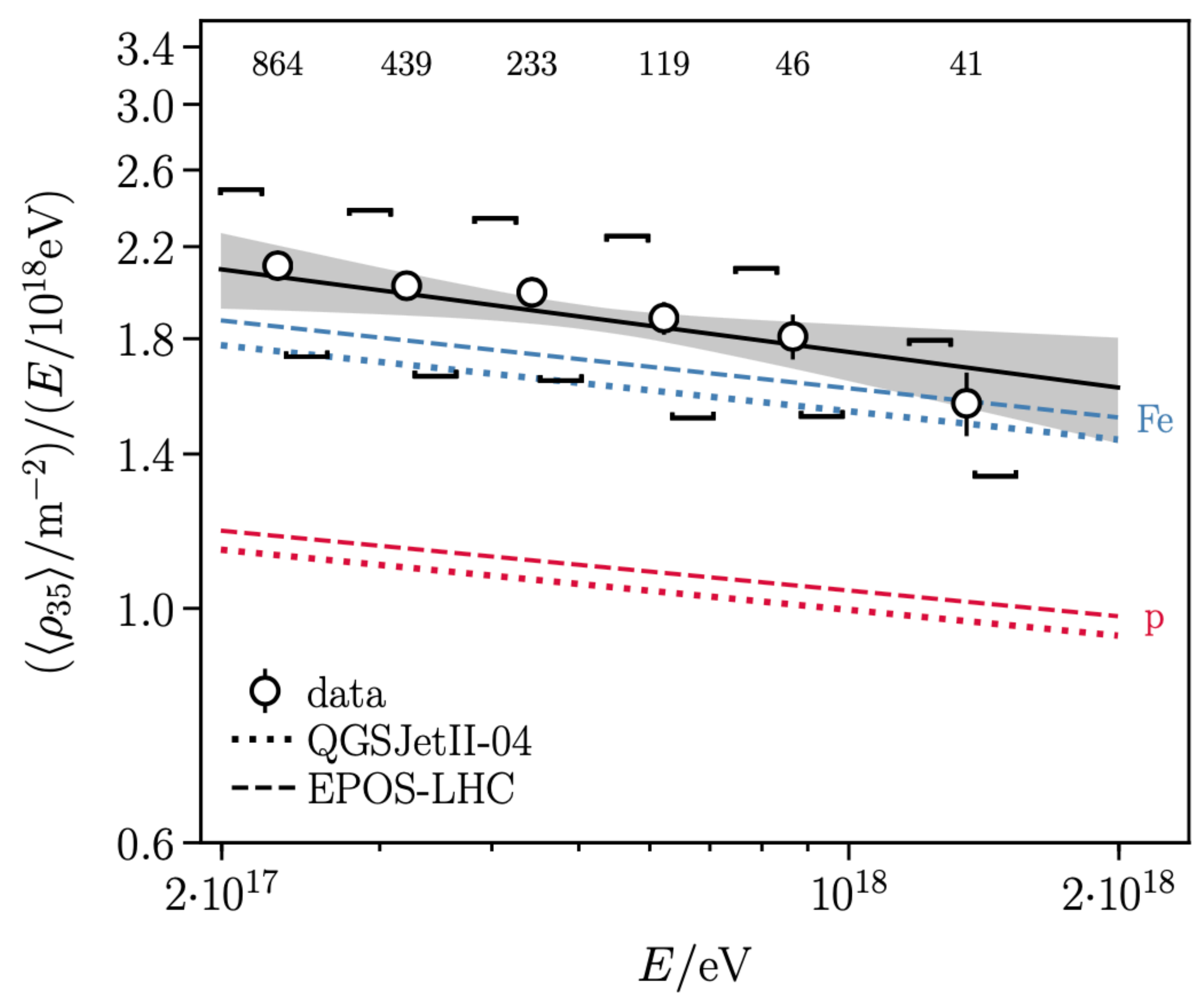
EAS muon content over an extended energy range

Eur.Phys.J.C 80 (2020) 8, 751

Phys.Rev.Lett. 126 (2021) 15, 152002

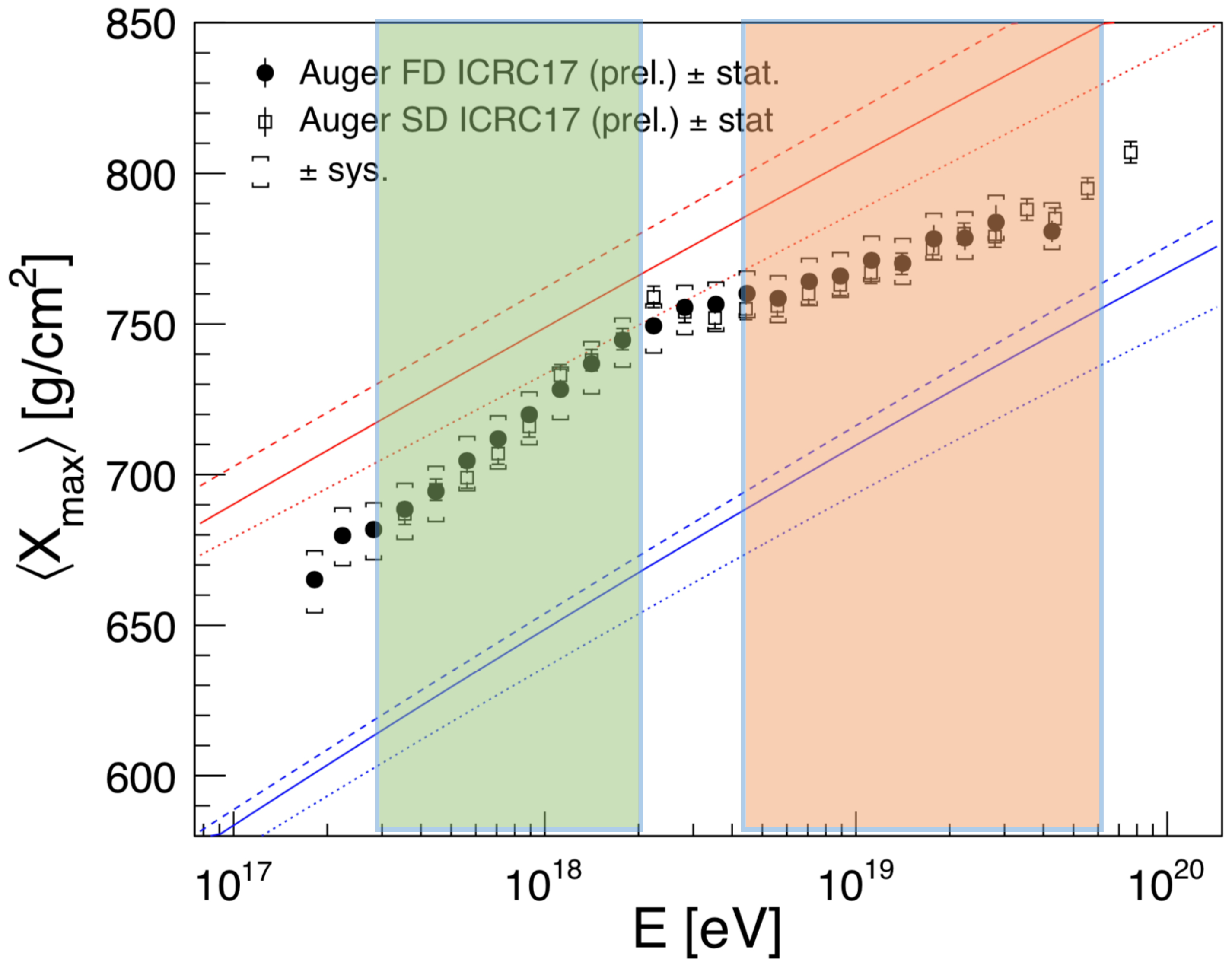
Data slightly above iron model predictions

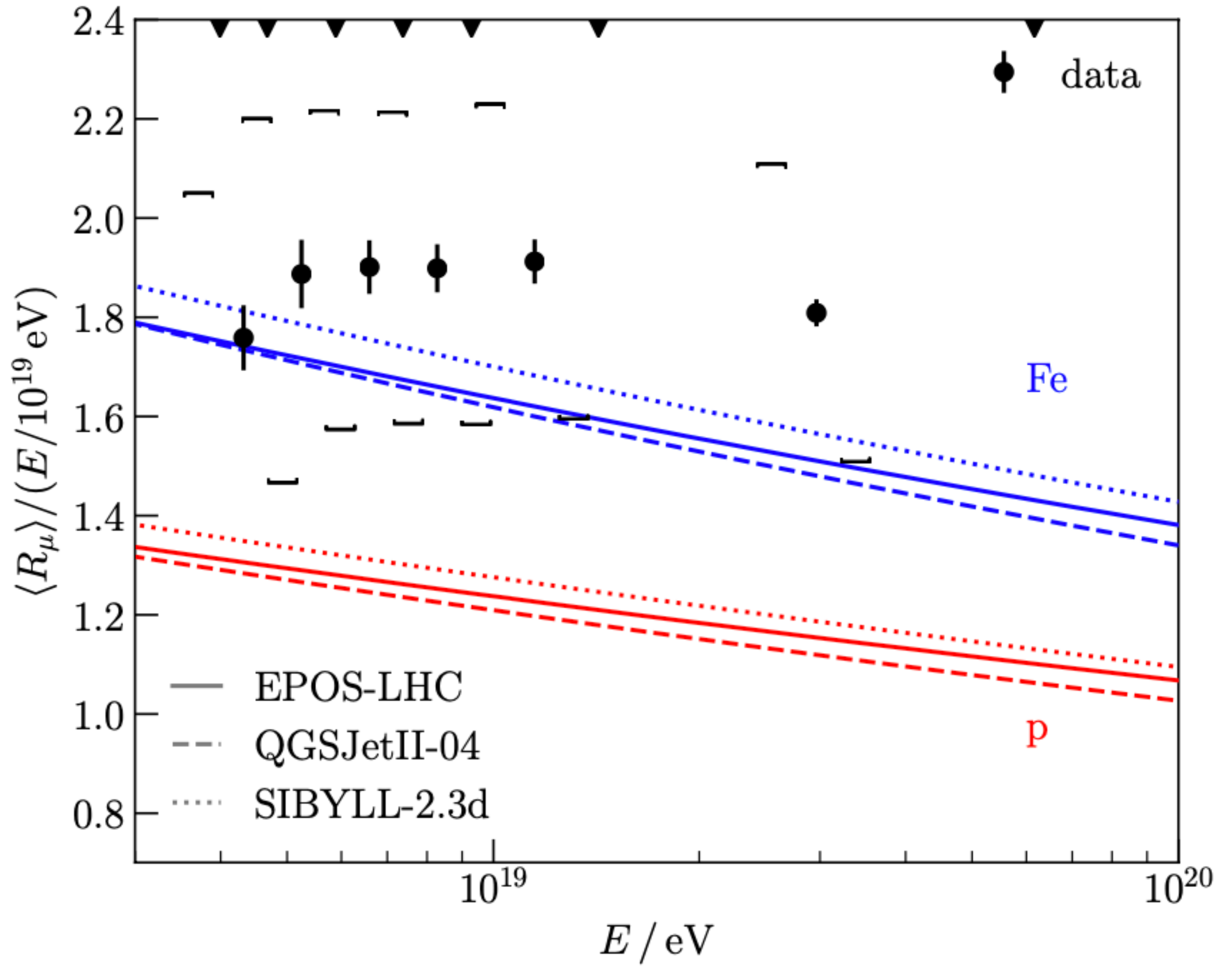
Large errors due to energy scale uncertainty



AMIGA

FD data





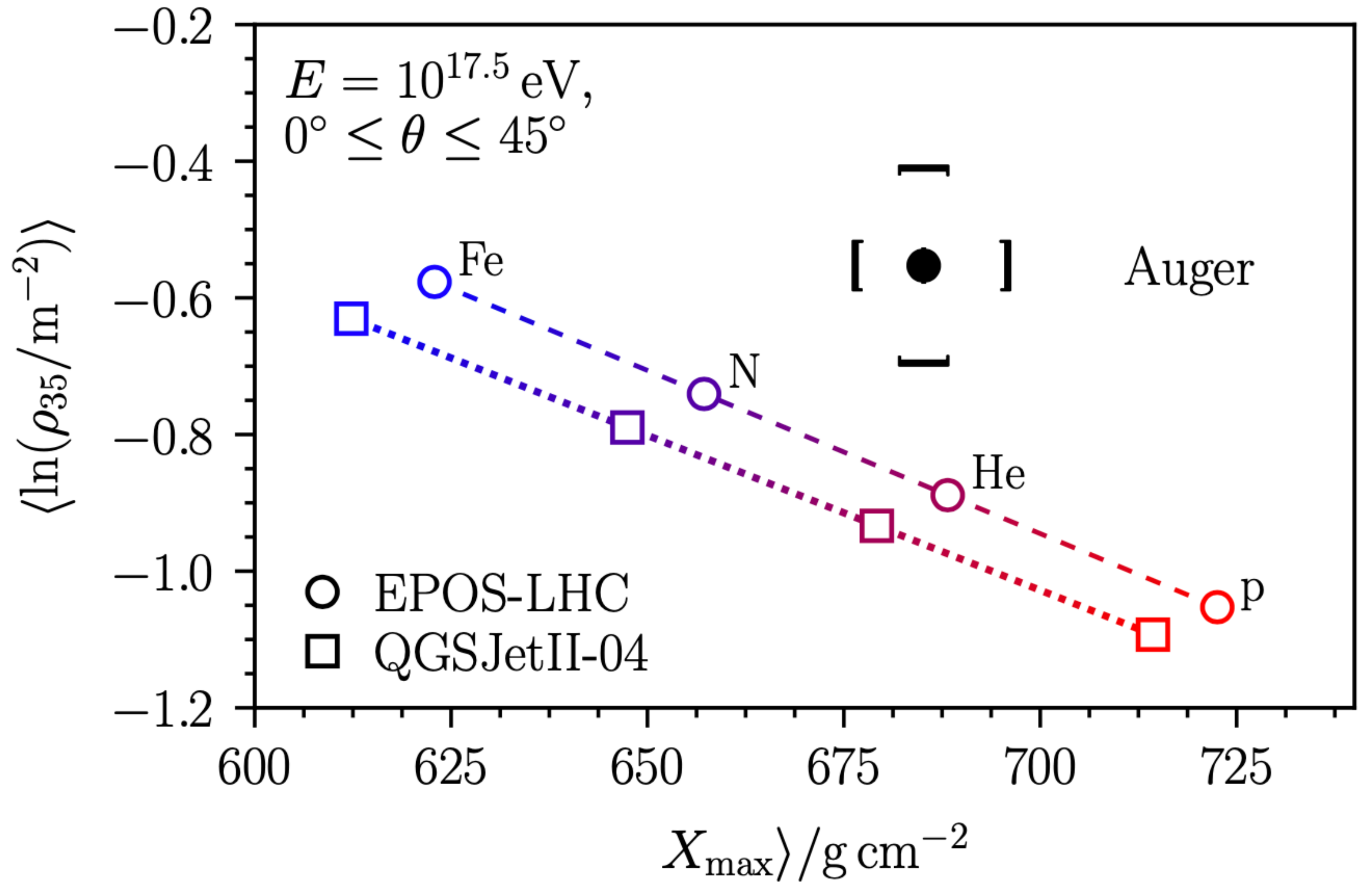
SD inclined

The EAS muon puzzle @ Auger

Eur.Phys.J.C 80 (2020) 8, 751

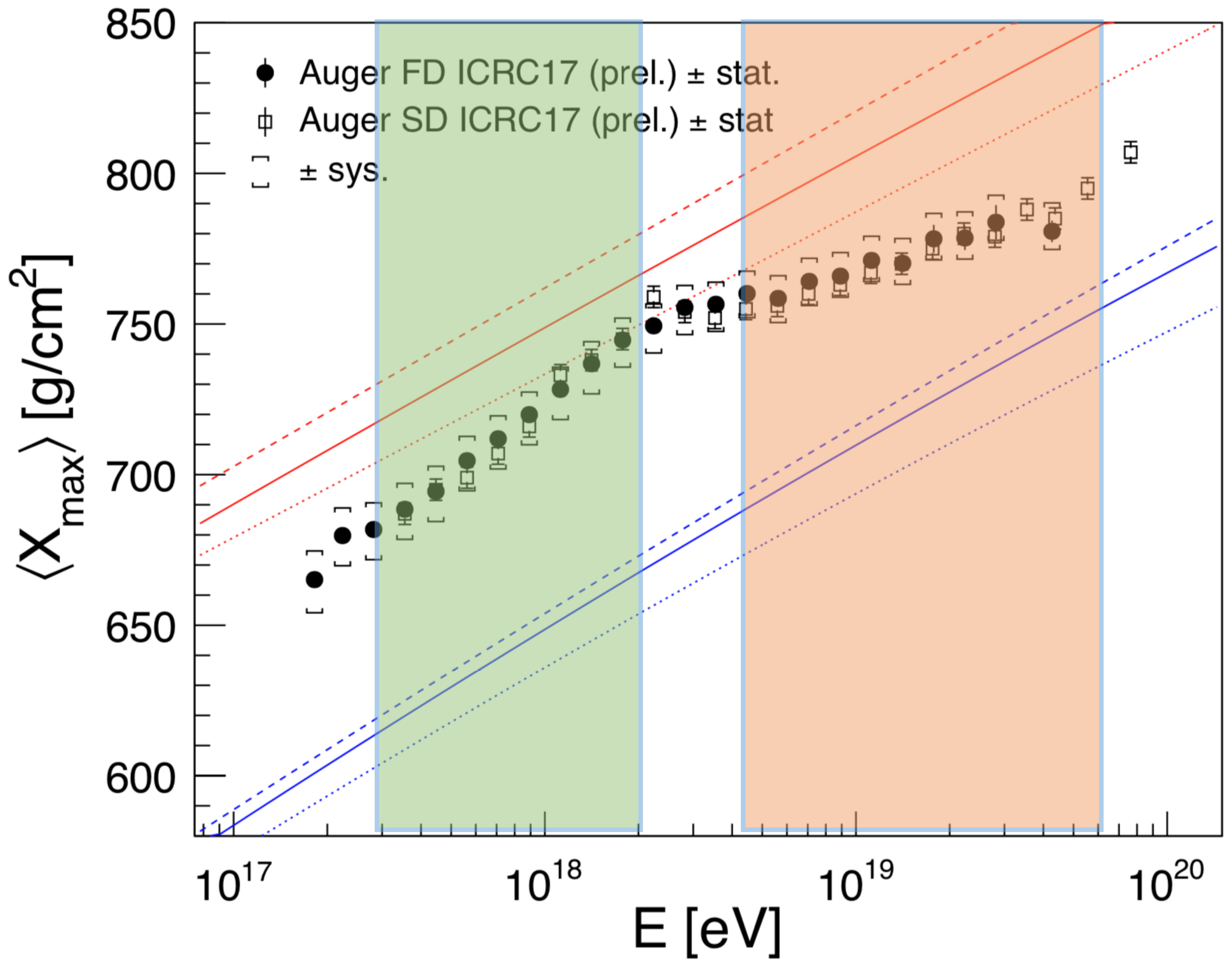
Phys.Rev.Lett. 126 (2021) 15, 152002

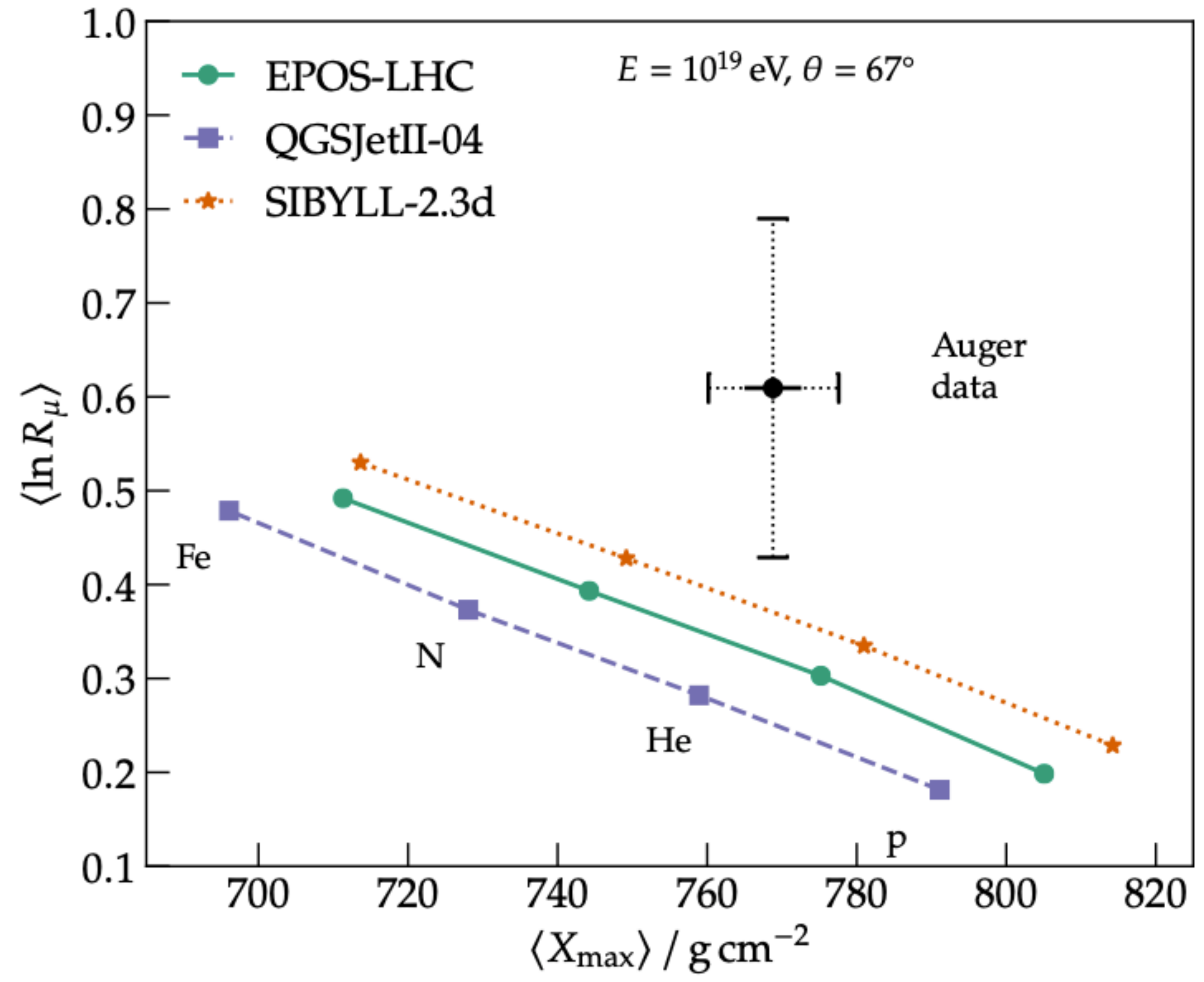
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition



AMIGA

FD data

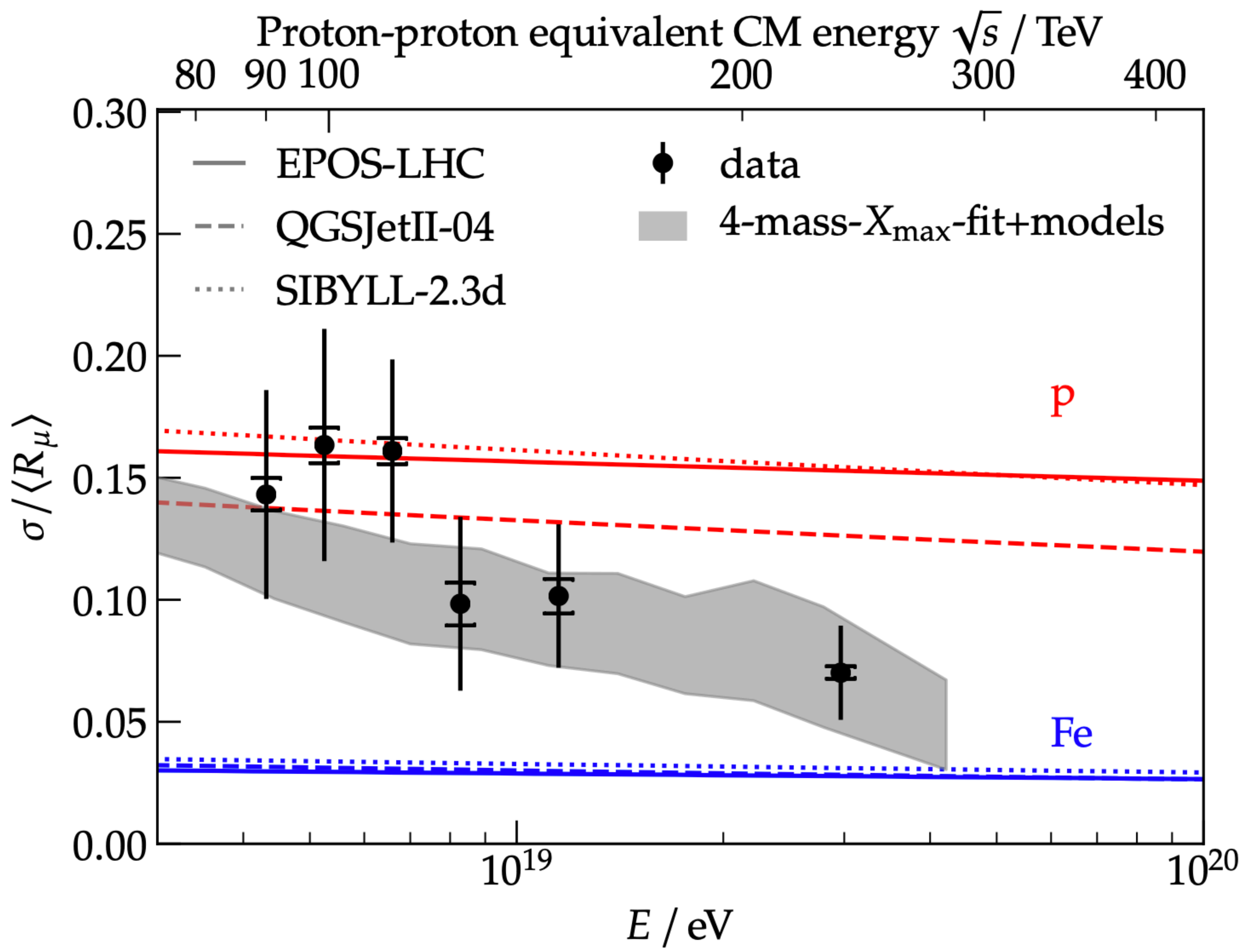




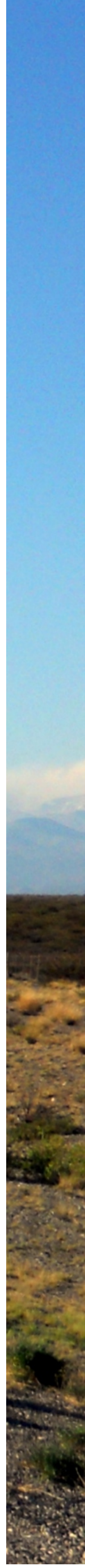
SD inclined

EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002

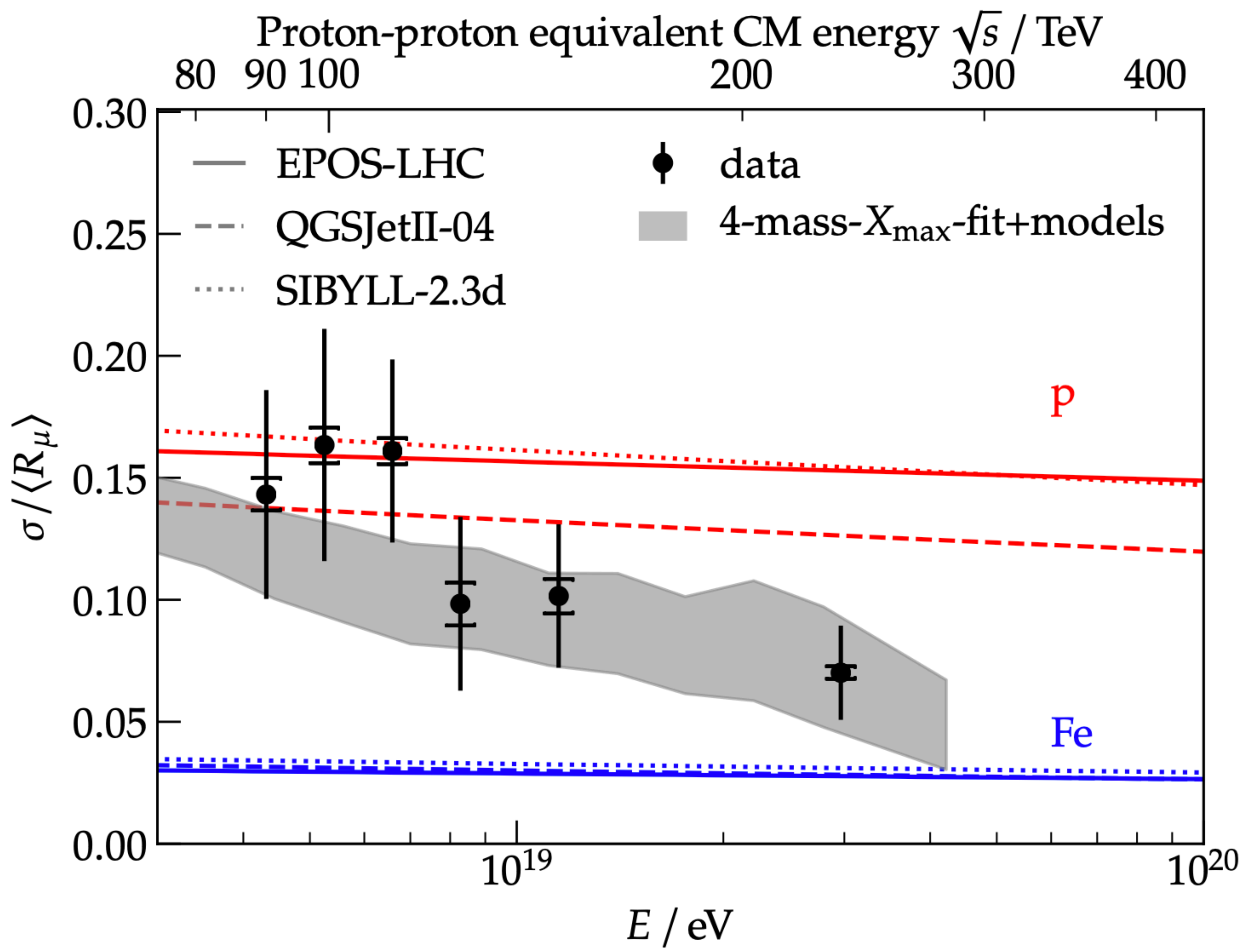


The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data



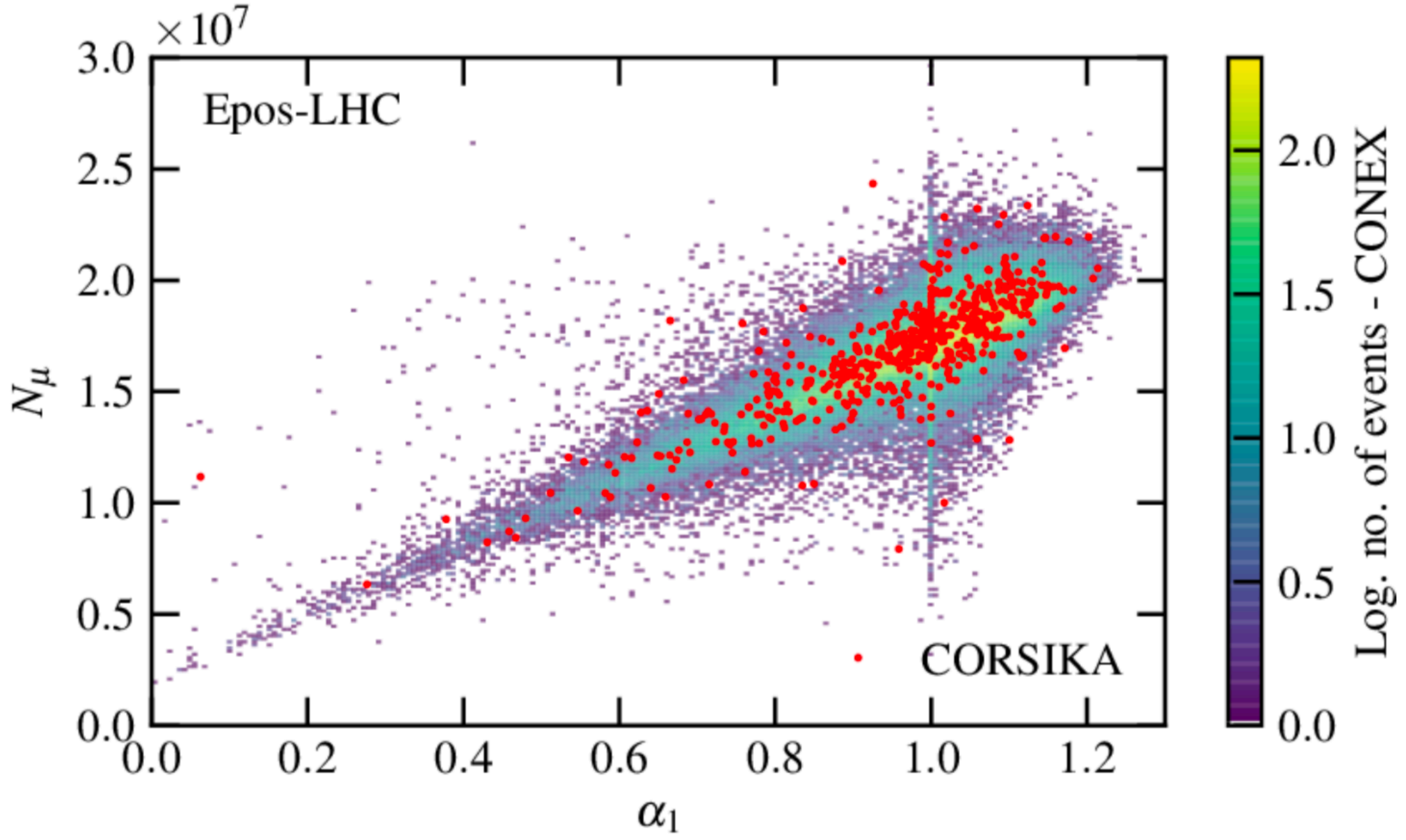
EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



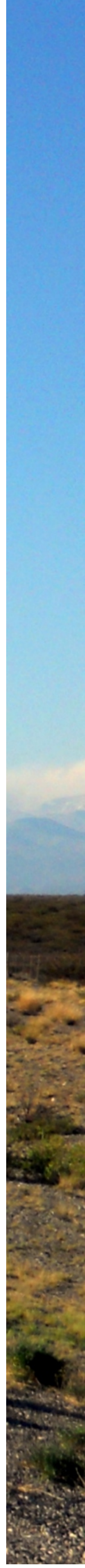
The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76



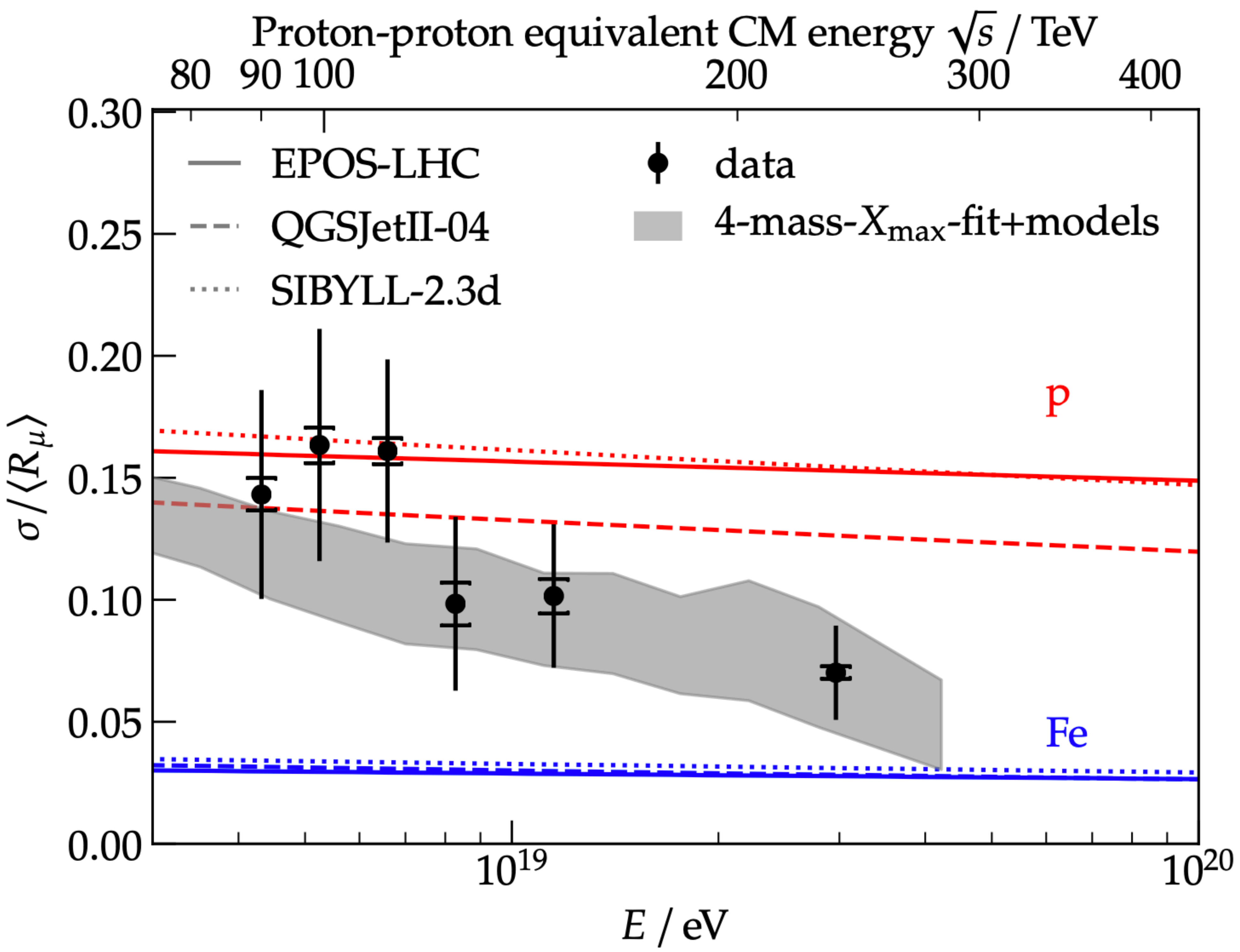
α_1 is the fraction of energy going into the hadronic sector in the first interaction

$$\sigma(\alpha_1) \rightarrow 70\,\%\,\sigma(N_\mu)$$



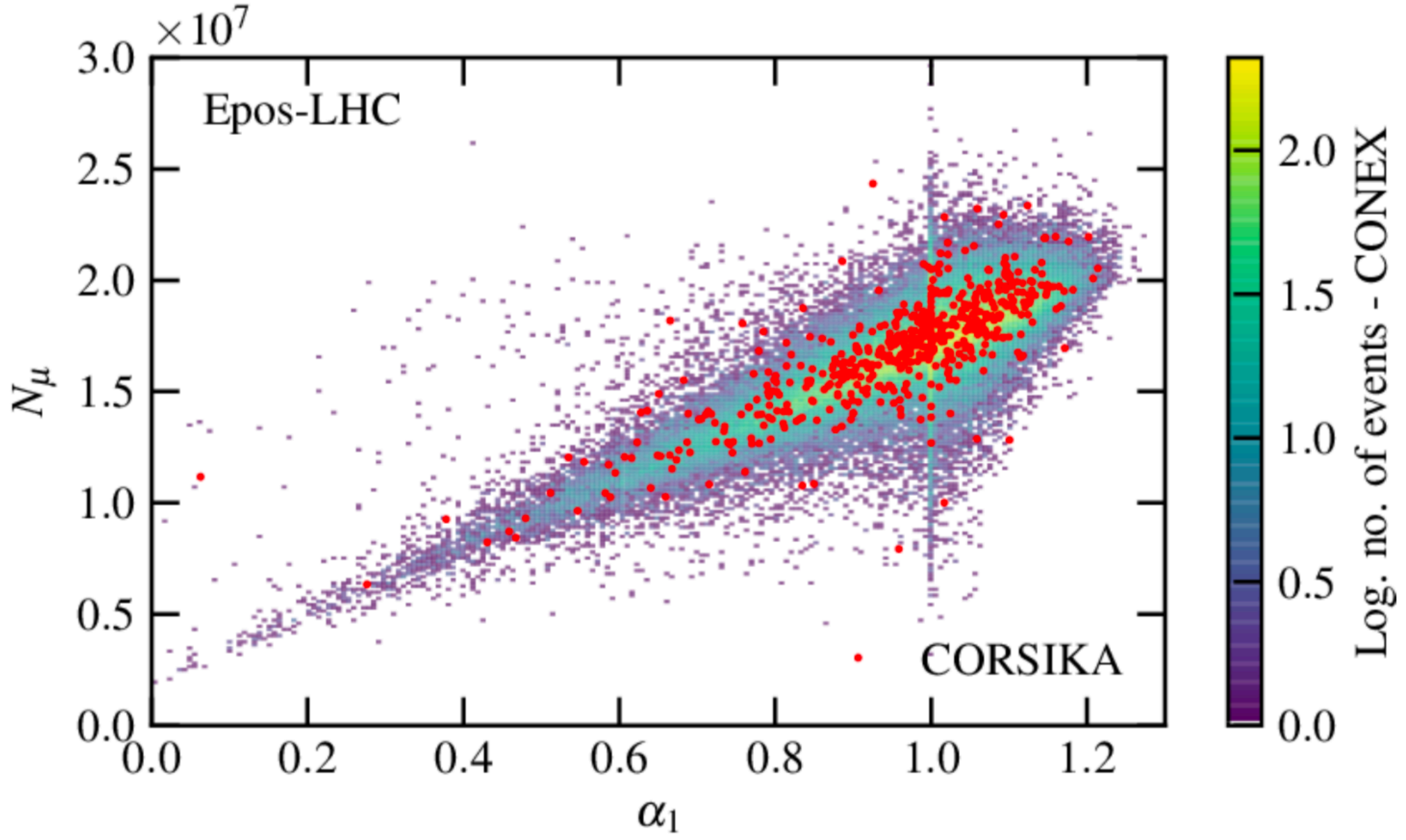
EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76

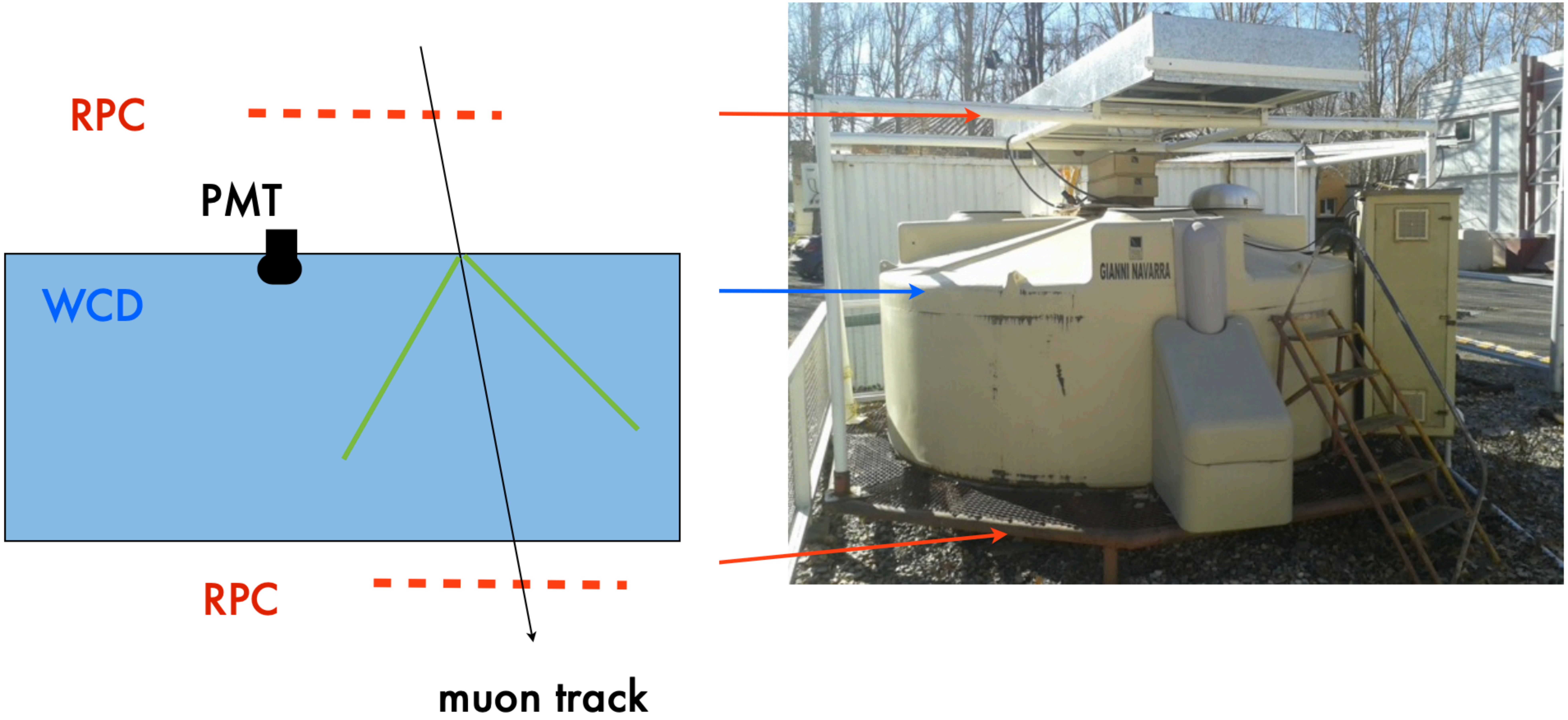


α_1 is the fraction of energy going into the hadronic sector in the first interaction

$$\sigma(\alpha_1) \rightarrow 70\,\%\,\sigma(N_\mu)$$

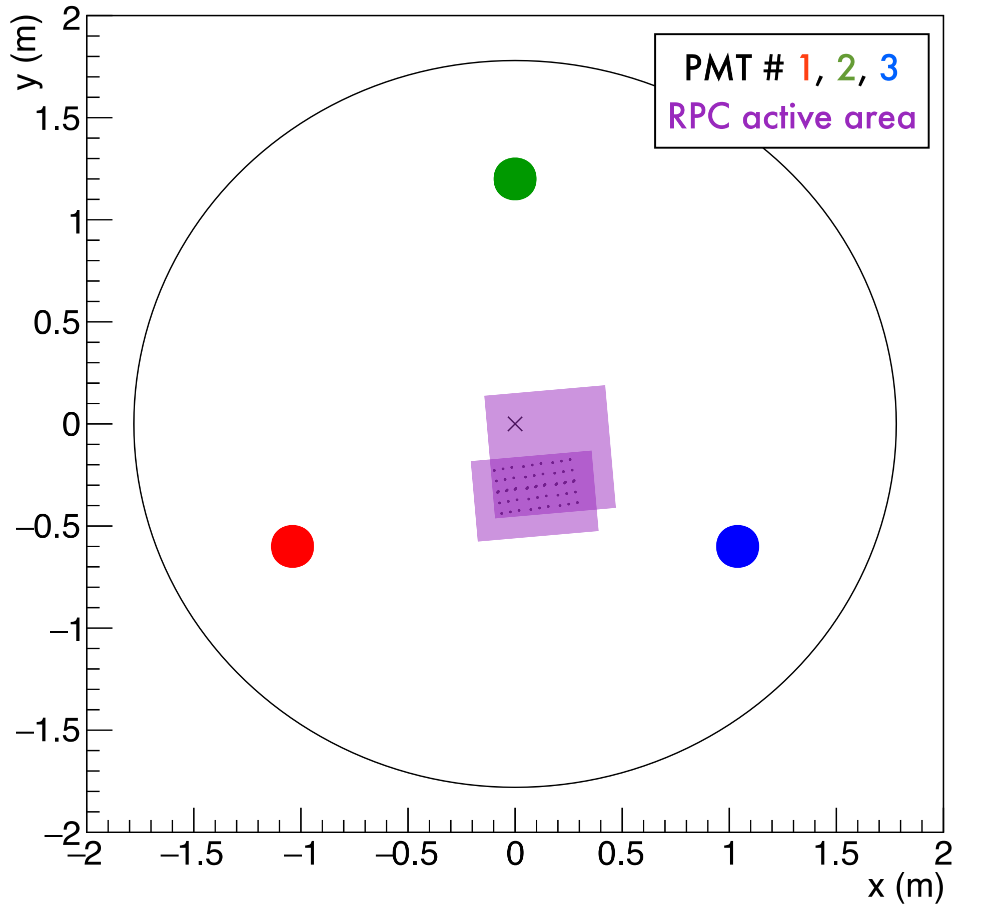
Suggestion that muon deficit might be related with description of low energy interactions

The RPC hodoscope at the Auger test WCD



- ✧ Resistive Plate Chambers (RPC) - LIP Coimbra: position-sensitive detectors
- ✧ Trigger on atmospheric muons and study the WCD response for selected trajectories

Results: VEM calibration

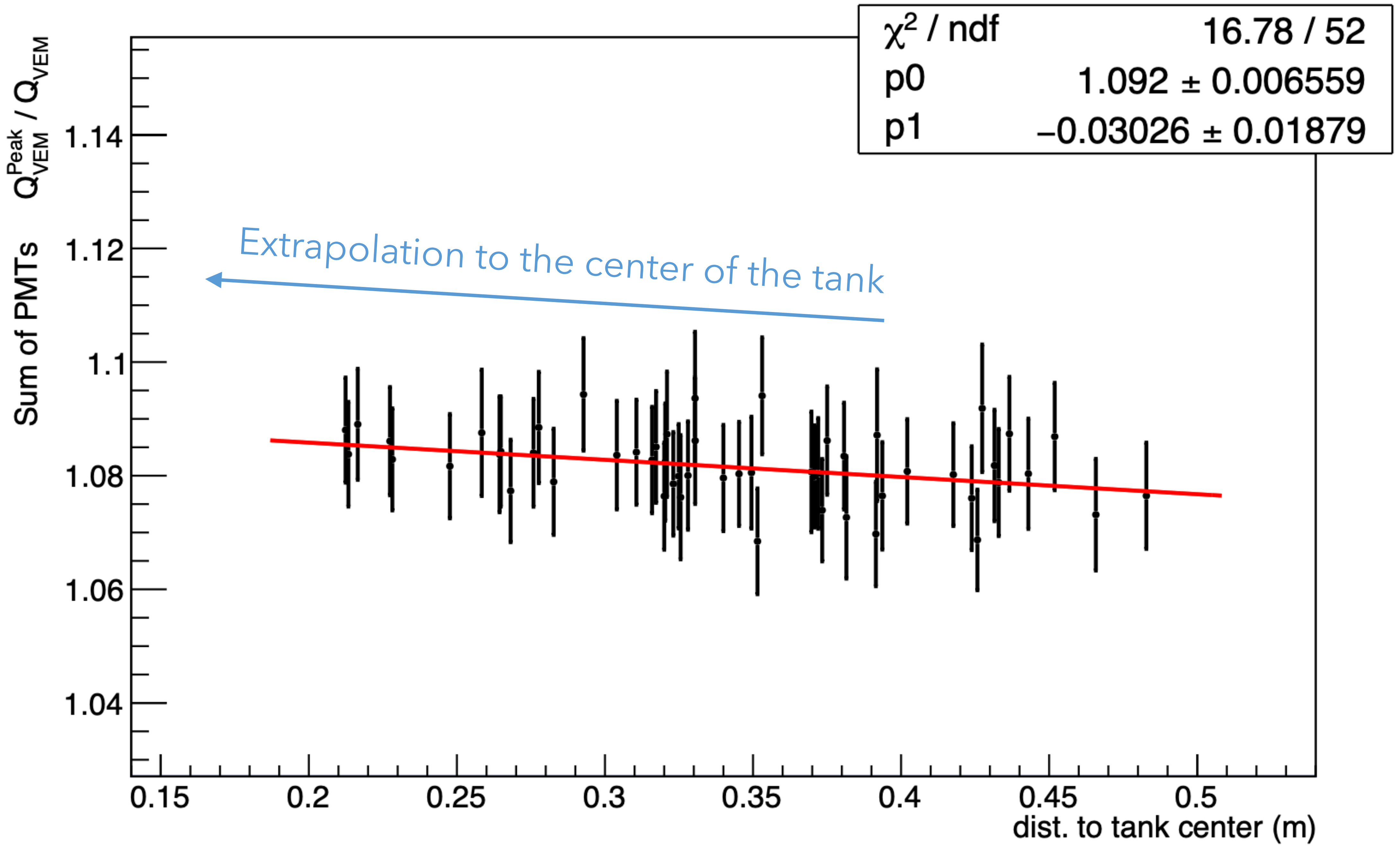


- Shower *size* in Auger is given in **VEM unit**

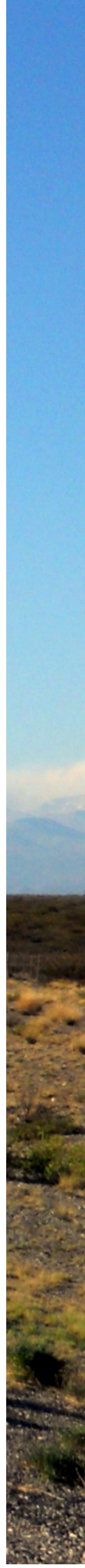
  - The reference is the light detected by the PMTs given the passage a vertical centred muon

  - The ratio omnidirectional/vertical remains the same for a station with more than **10 years** of operation, i.e., no ageing effects on the calibration

Pierre Auger coll., JINST 15 (2020) 09, P09002



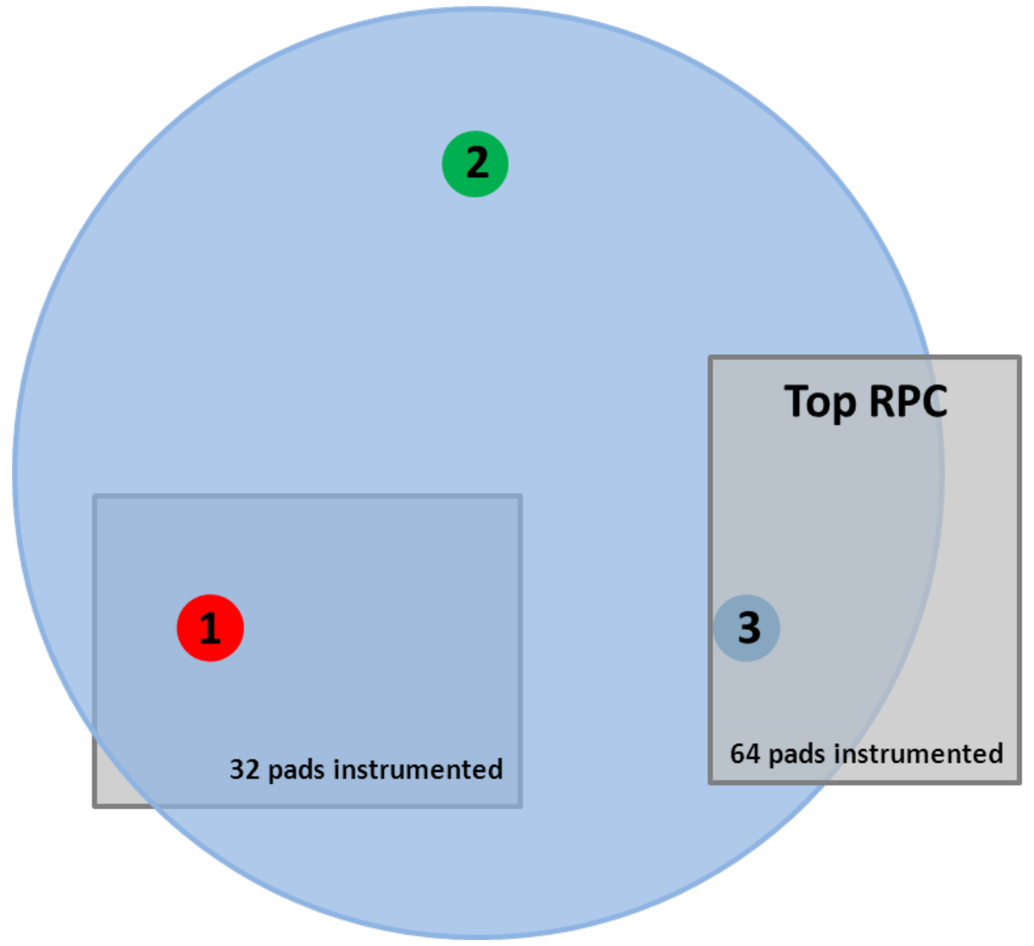
Conversion factor	PMT average	PMT sum
Q^{peak}_{VEM}/Q_{VEM}	1.00 ± 0.02	1.09 ± 0.01
I^{peak}_{VEM}/I_{VEM}	0.92 ± 0.03	

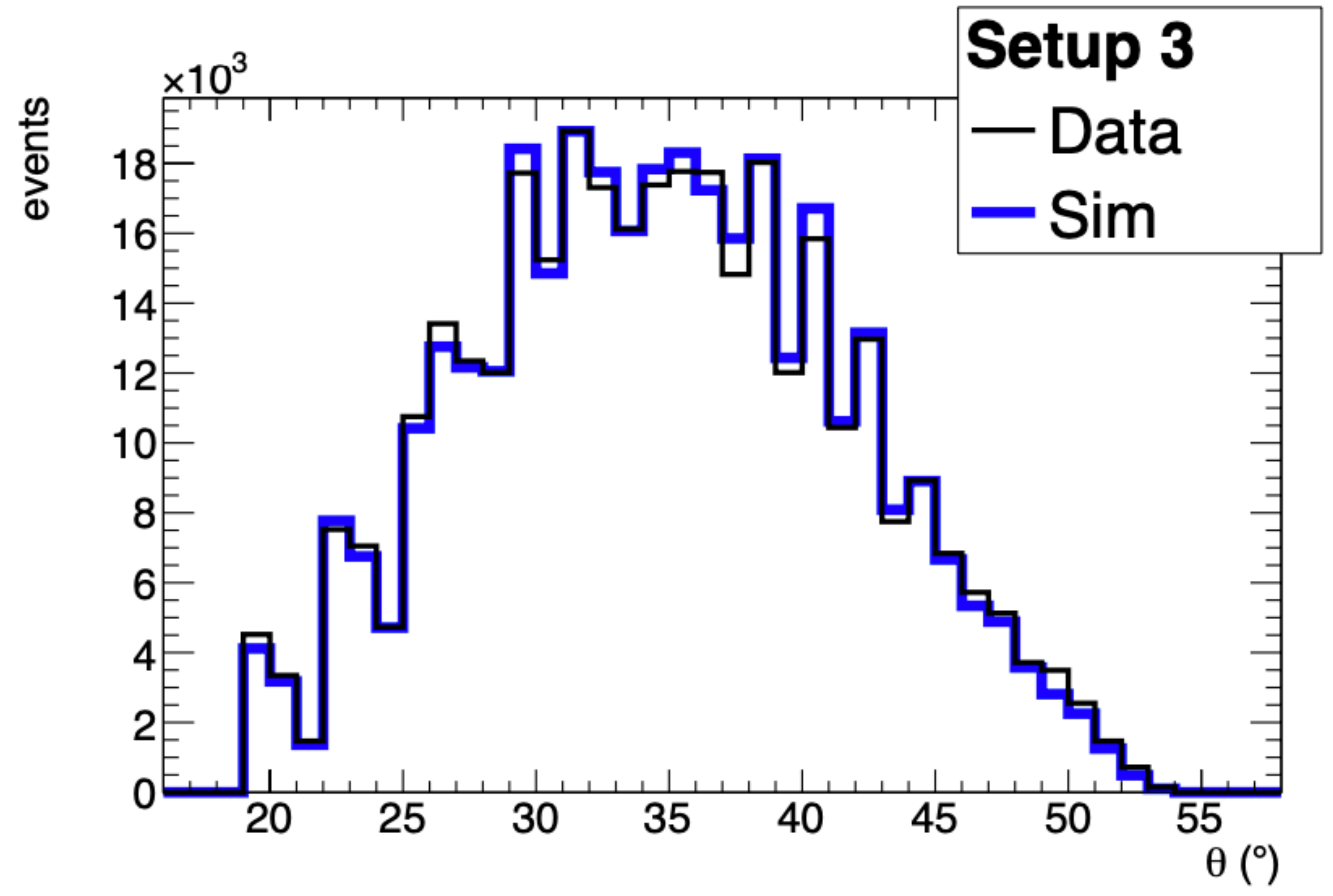


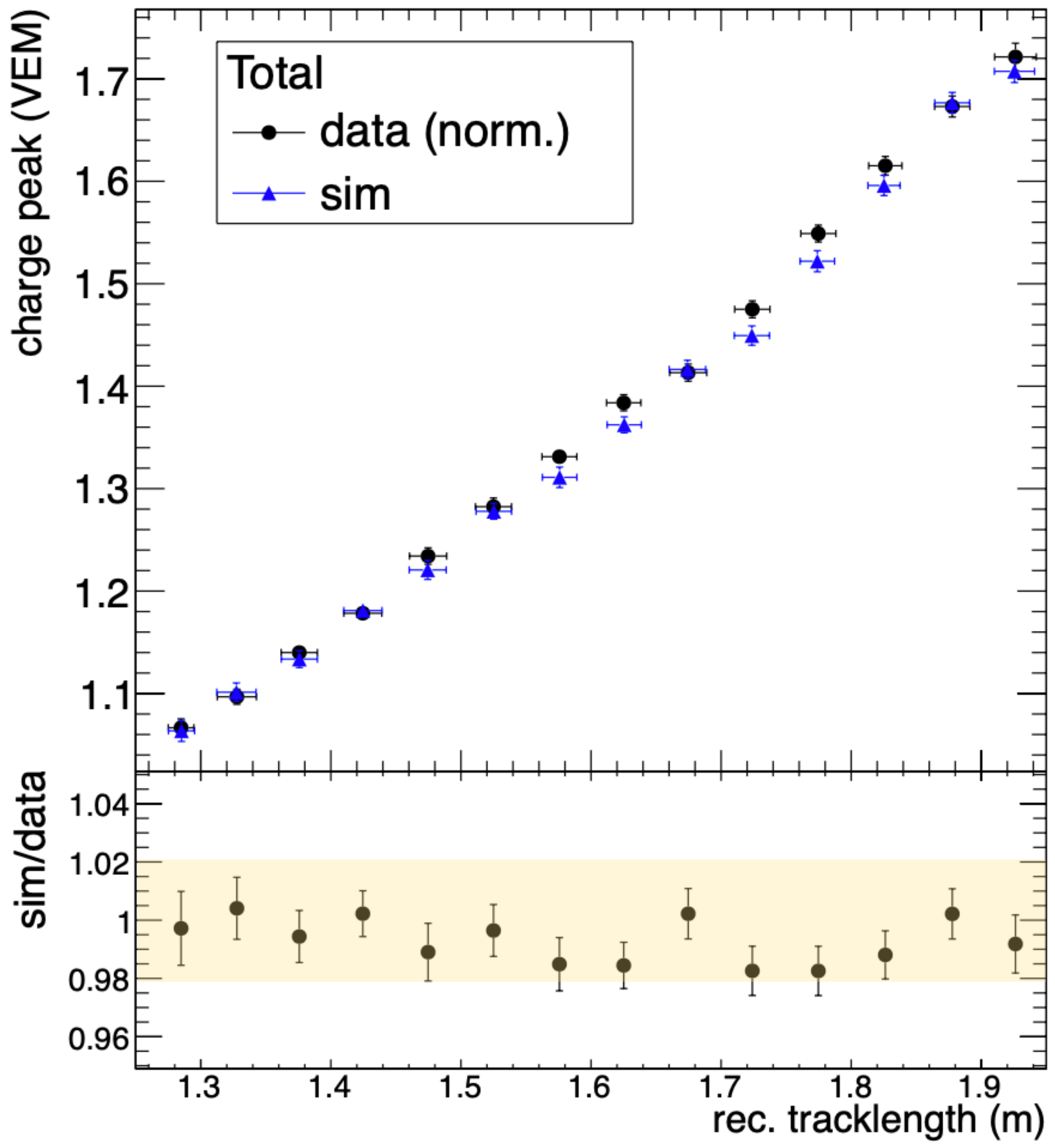
Results: inclined muons

Pierre Auger coll., JINST 15 (2020) 09, P09002

- WCD signal response for atmospheric muons with inclinations of $\theta \in [20°; 50°]$
- Simulation able to describe data at the percent level

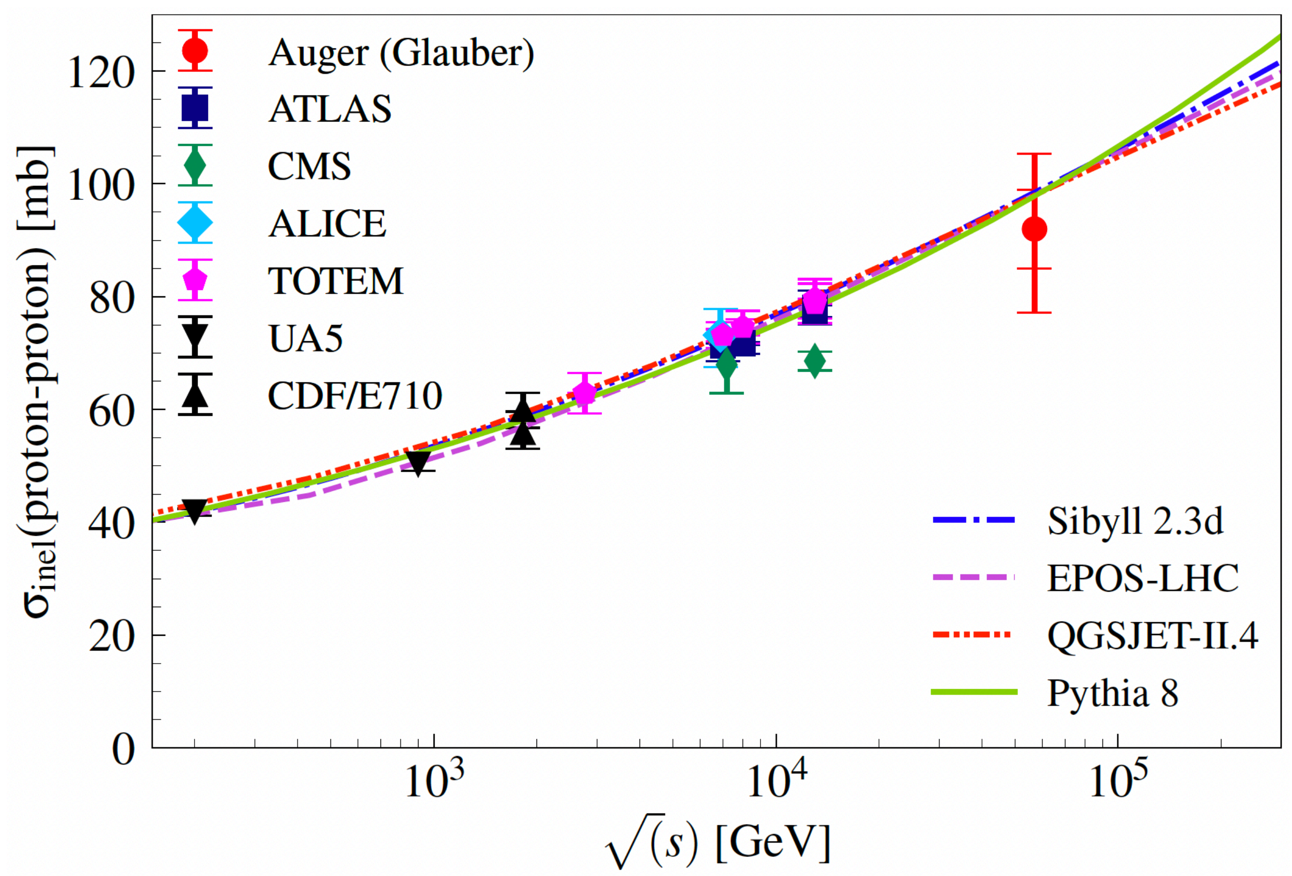






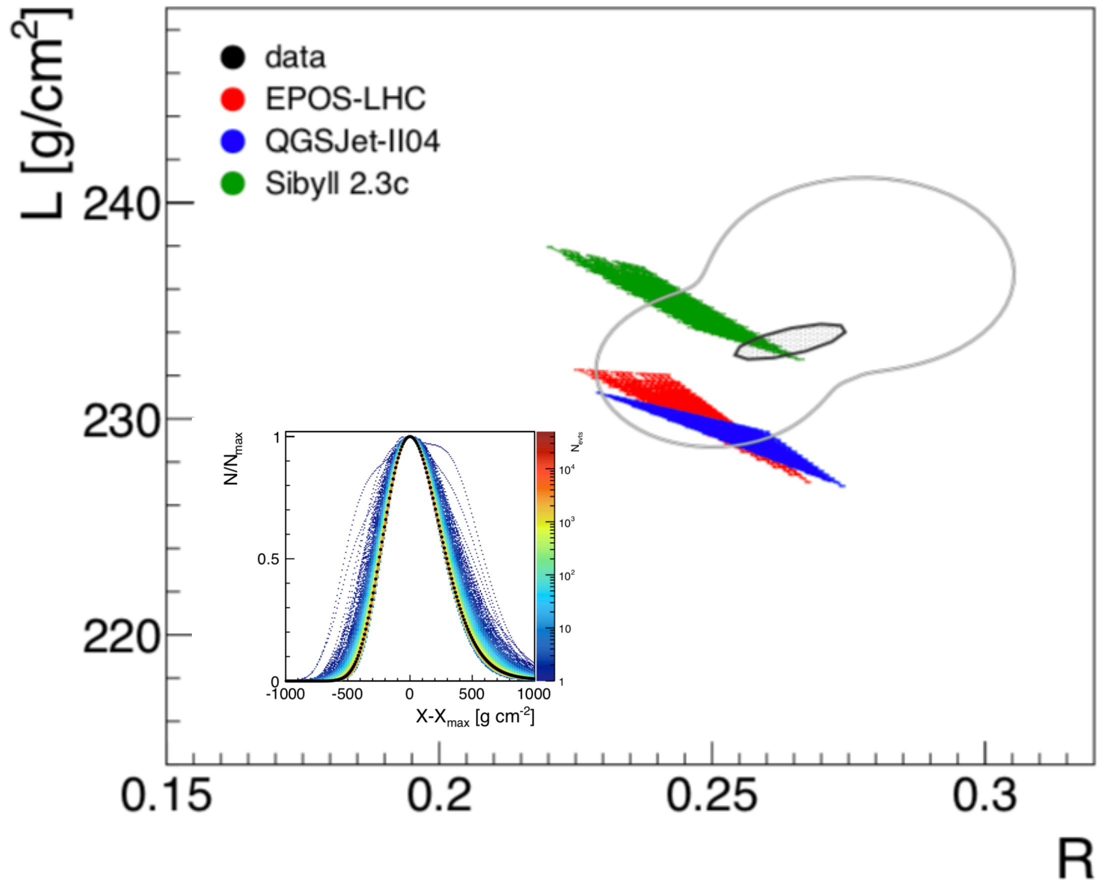
Many other EAS measurements…

Phys.Rev.Lett. 109 (2012) 062002



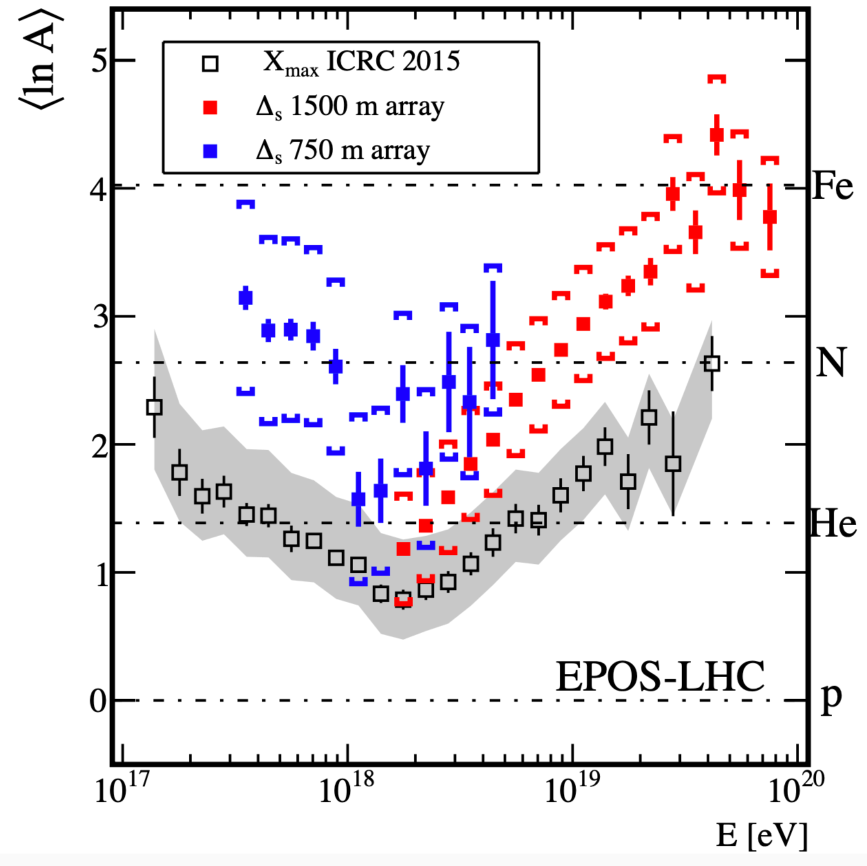
Measurement of the proton-air cross-section at E~10^{18} eV

JCAP 1903 (2019) no.03, 018



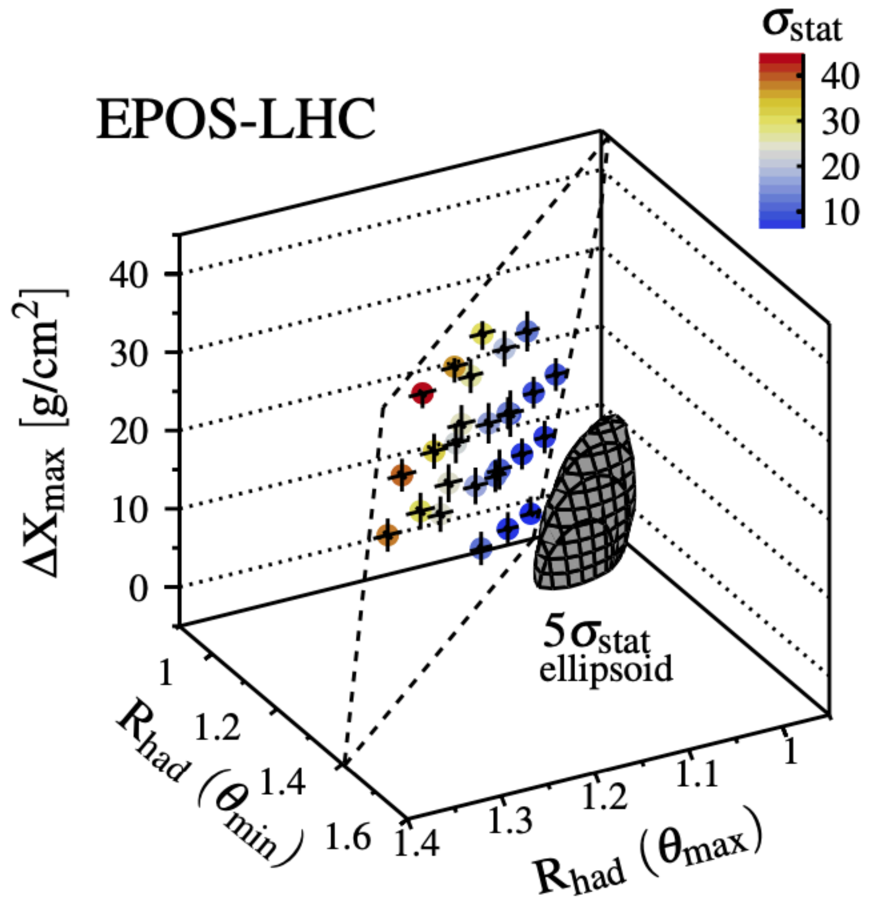
Measurement of average e.m. longitudinal profile shape

Phys.Rev.D 96 (2017) 12, 122003

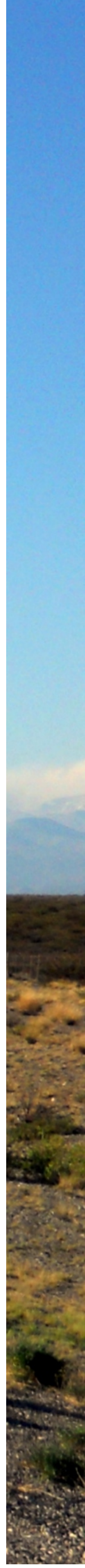


Measurement of time profiles of the signals recorded with the water-Cherenkov detectors

PoS ICRC (2021) 310



Simultaneous fits to the X_{max} (FD) and the ground signal (SD)

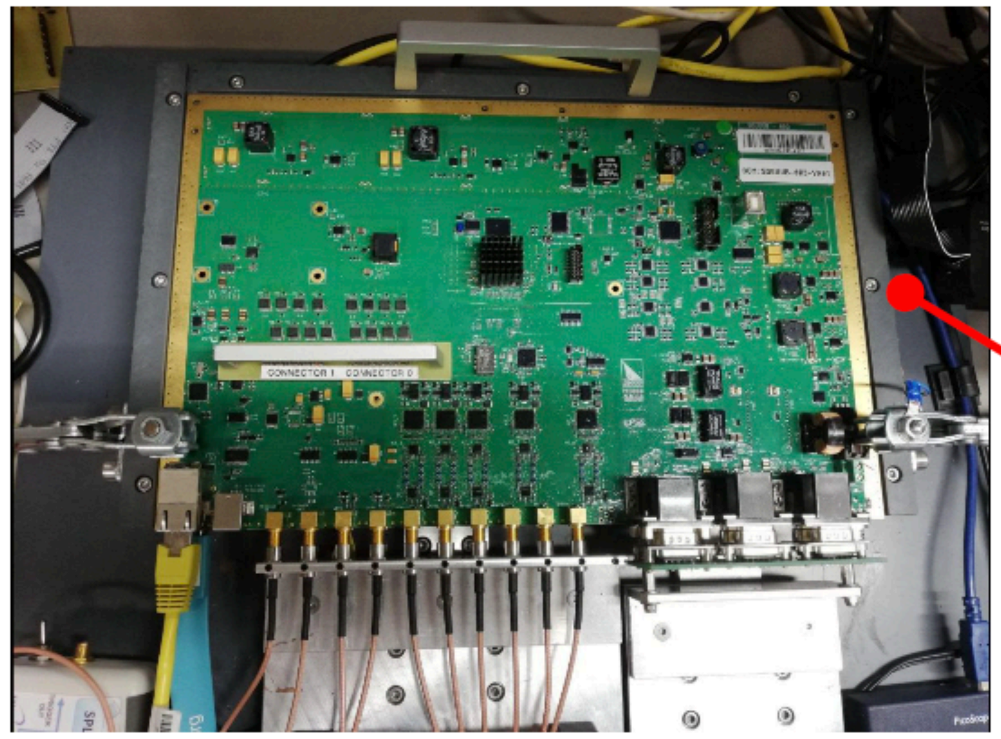


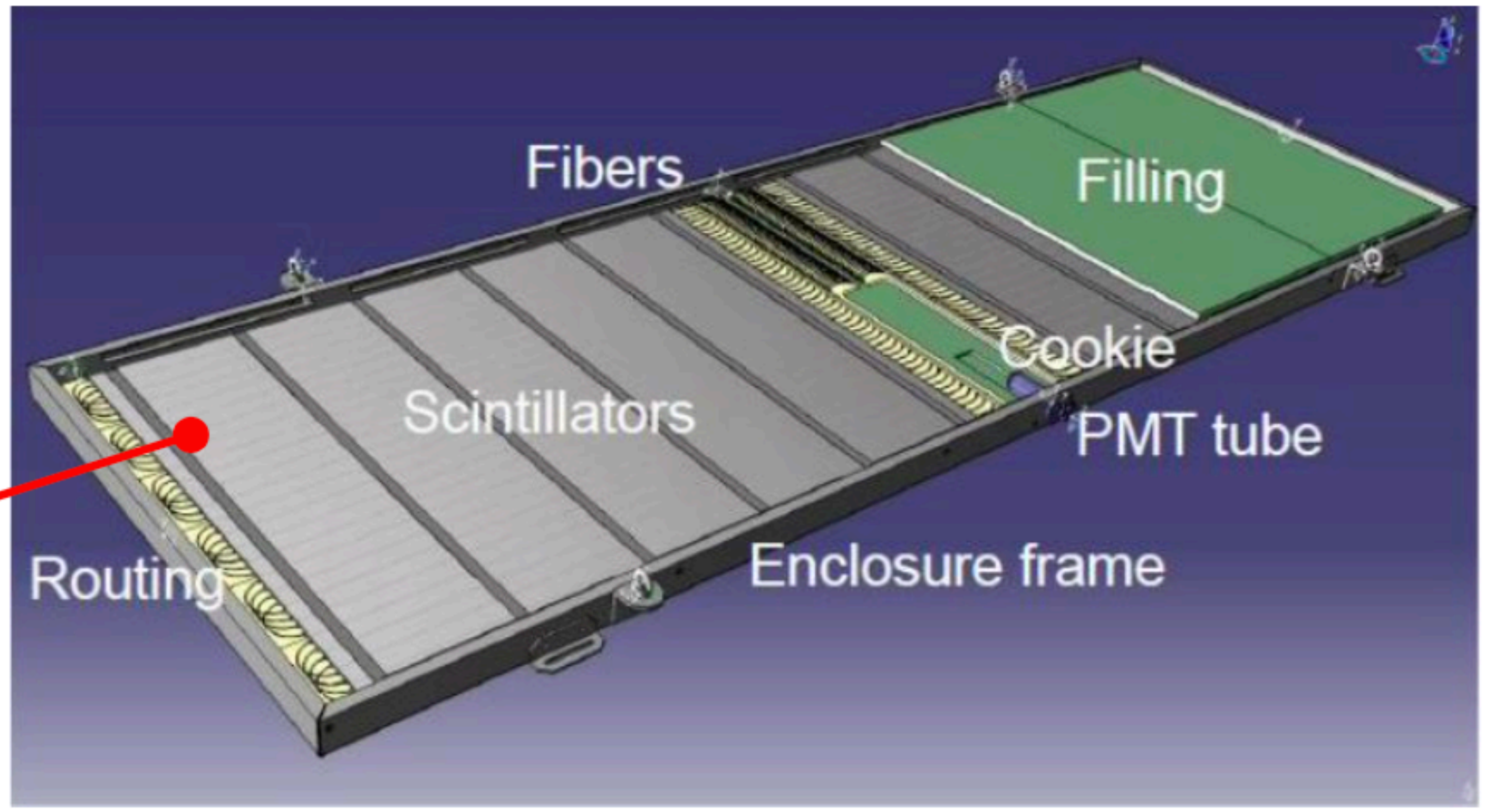
Pierre Auger Observatory

The future of the observatory

Auger Prime detectors

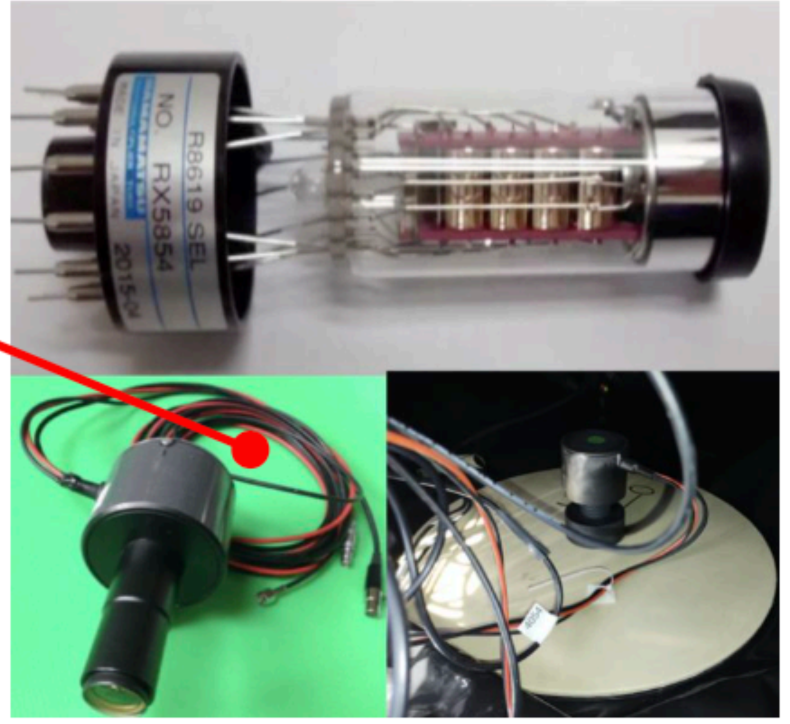
New electronics (UUB) and Scintillators(SSD)





Radio Upgrade

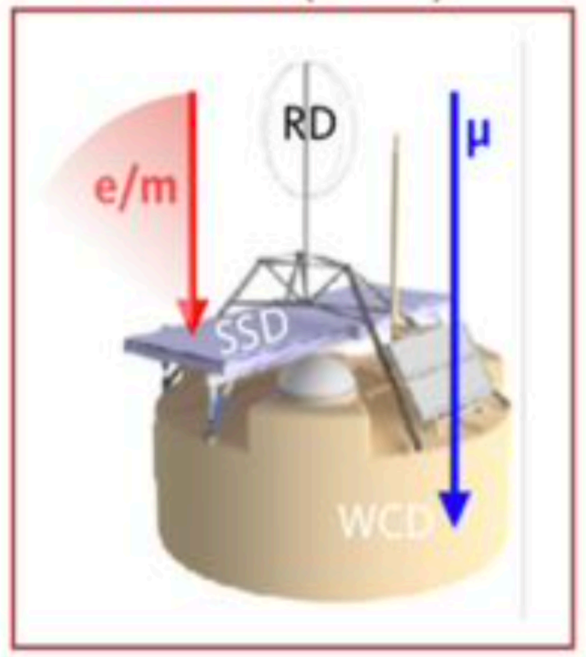
High dynamic range PMTs



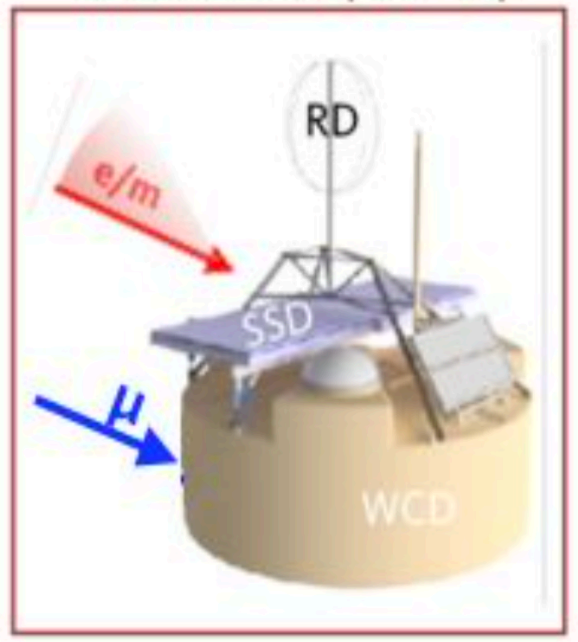
Underground Muon Detector (UMD)

The strategy

VERTICAL (0-60°)



HORIZONTAL (60-90°)



Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2021

Auger Phase II data taking from 2024 to 2035

AugerPrime timeline

Start of the Upgrade phase — 2019

end of PMTs fabrication — 2020

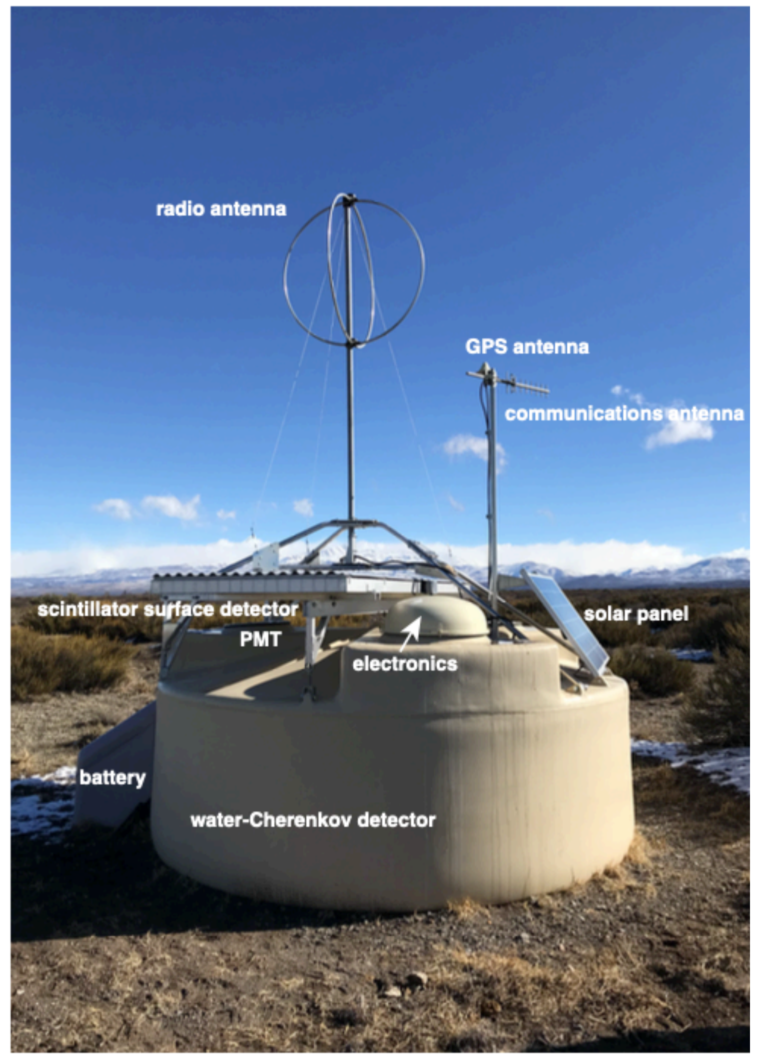
end of SSD shipment on site — 2021

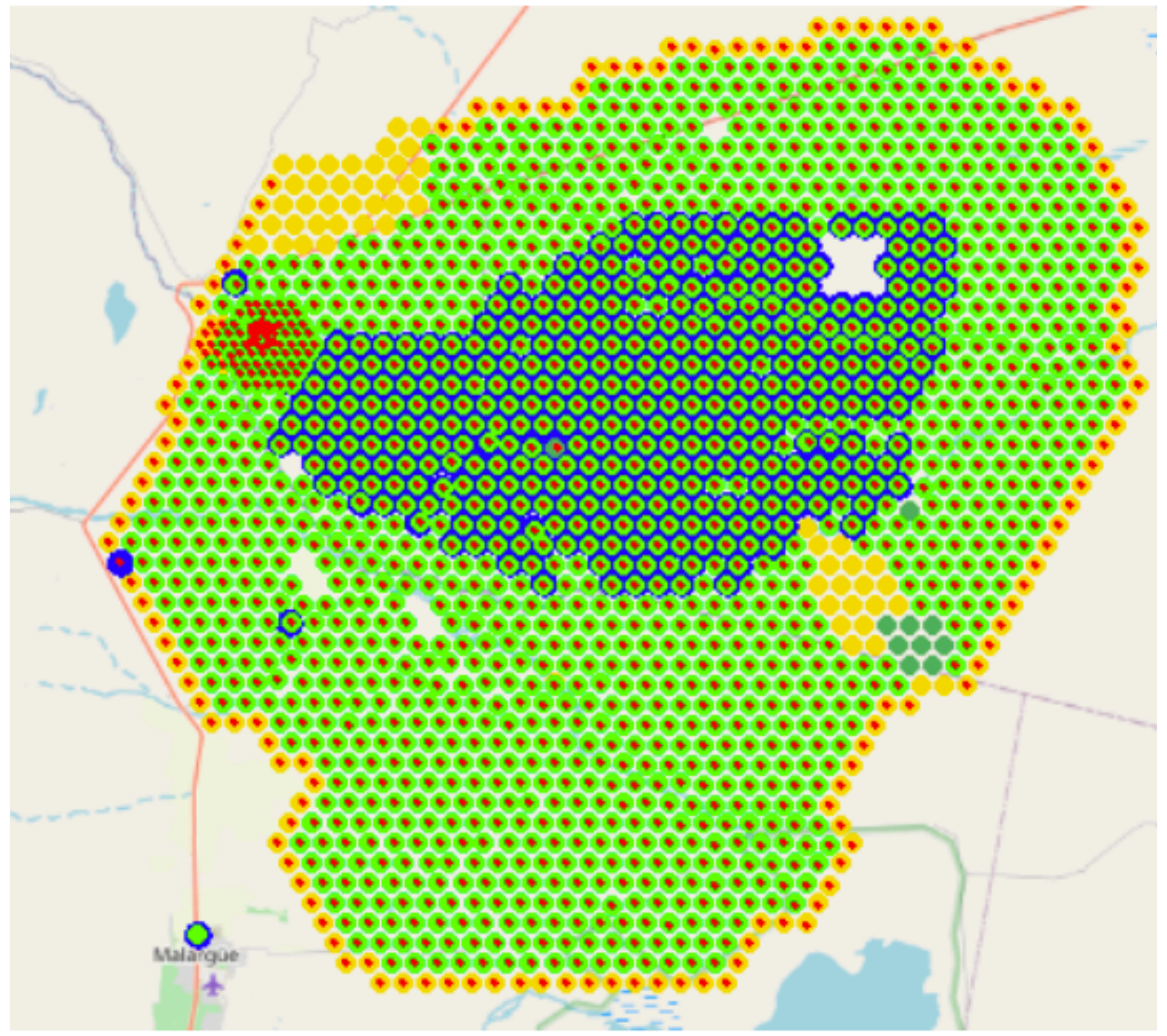
end of SSD deployment — 2022

end of UUB production and shipment — 2023

end of UUB + PMTs deployment

end of Radio+ UMD deployment — 2024





Status
21 September 2023

Stations w/ UUB

Stations w/ UUB + SSD

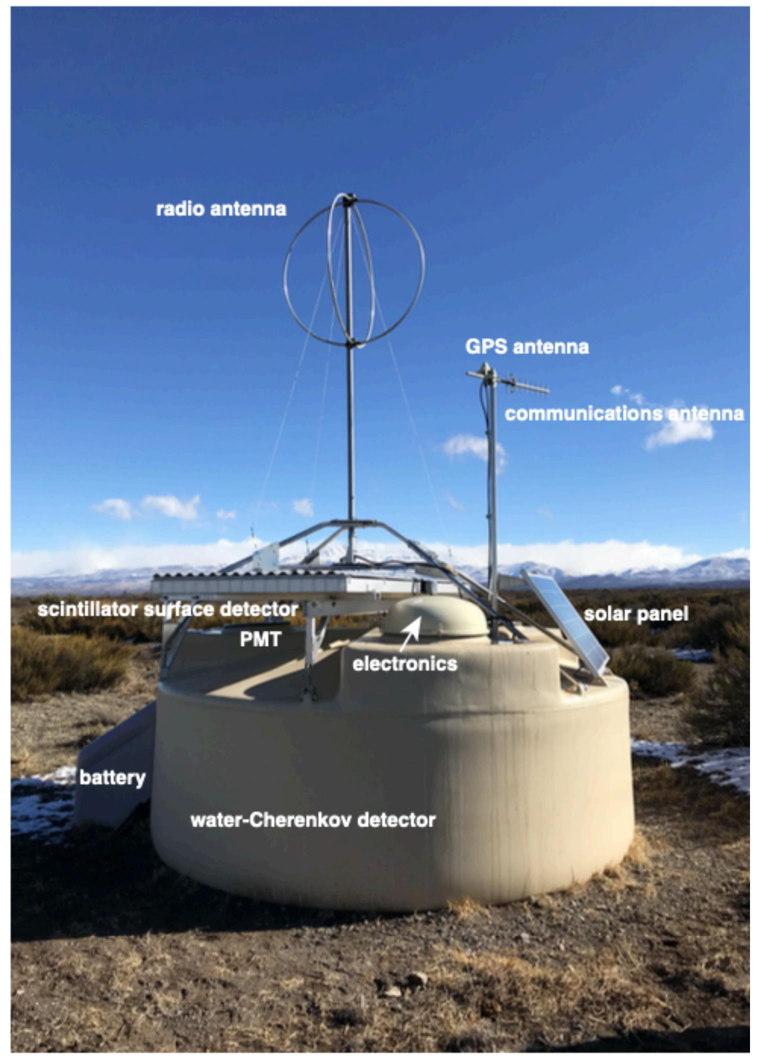
Stations w/ UUB + SSD without PMT

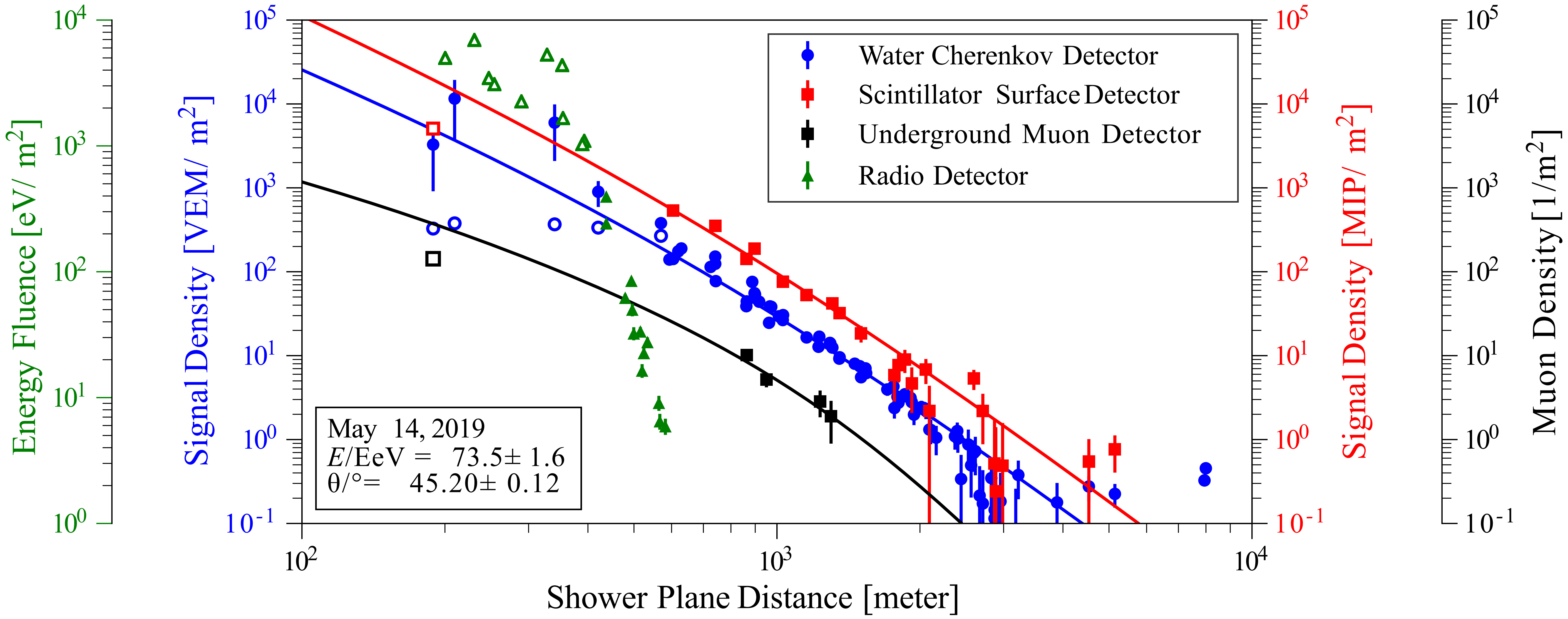
RD antenna

No access

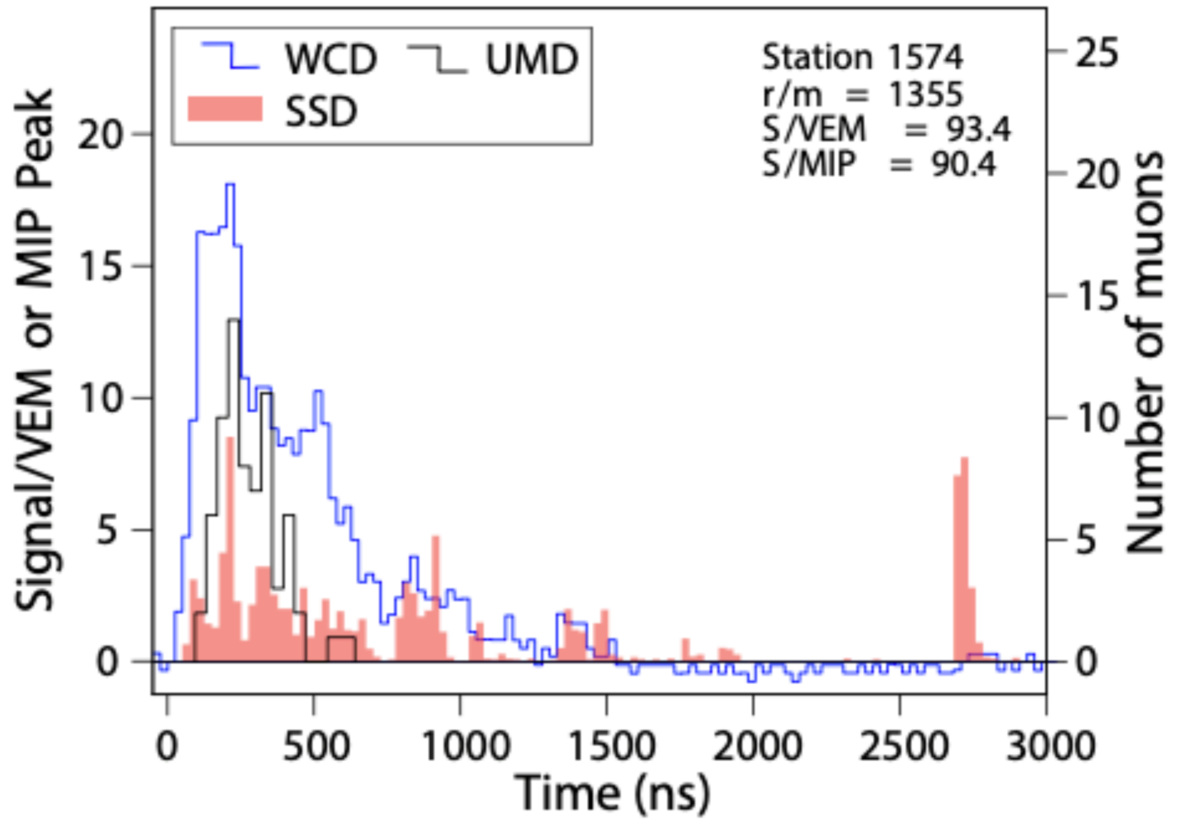
AugerPrime: A Wealth of Information

Auger multi-hybrid event

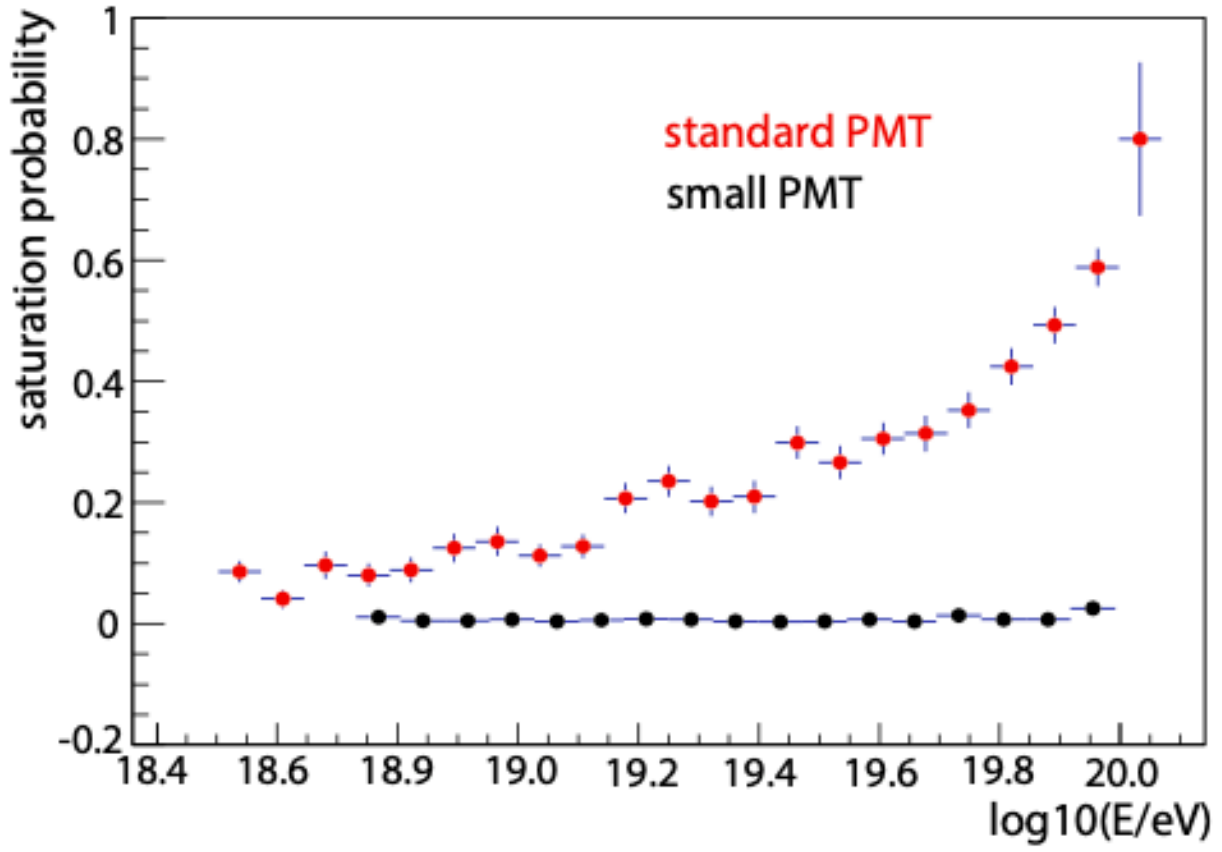


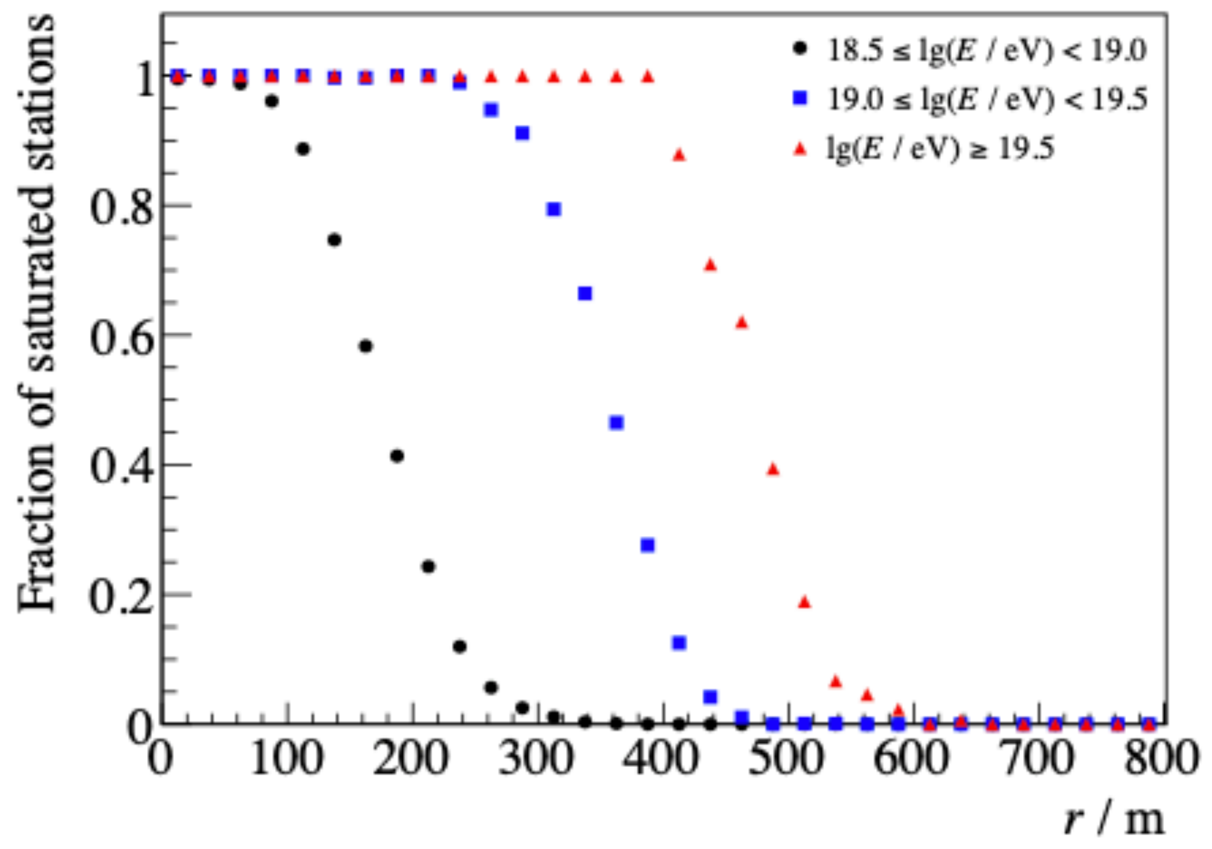


PMTs signal time trace



Small PMT in the WCD

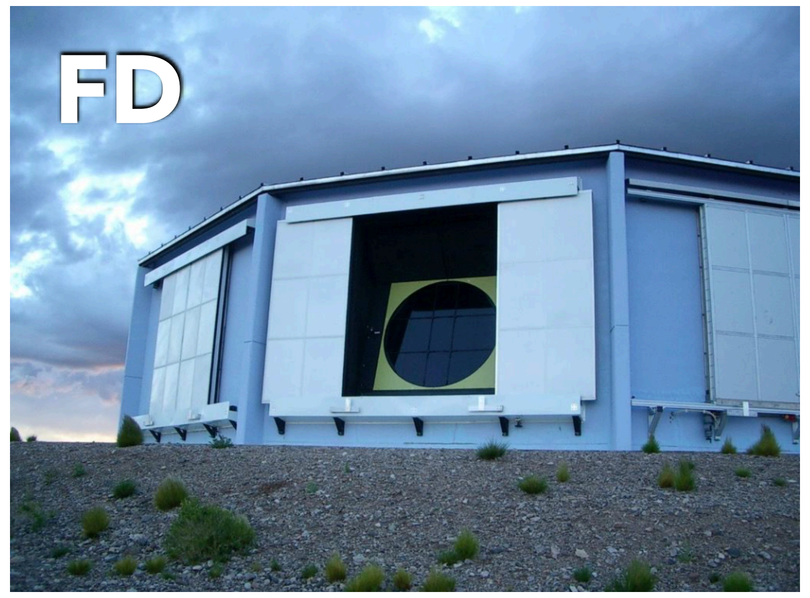


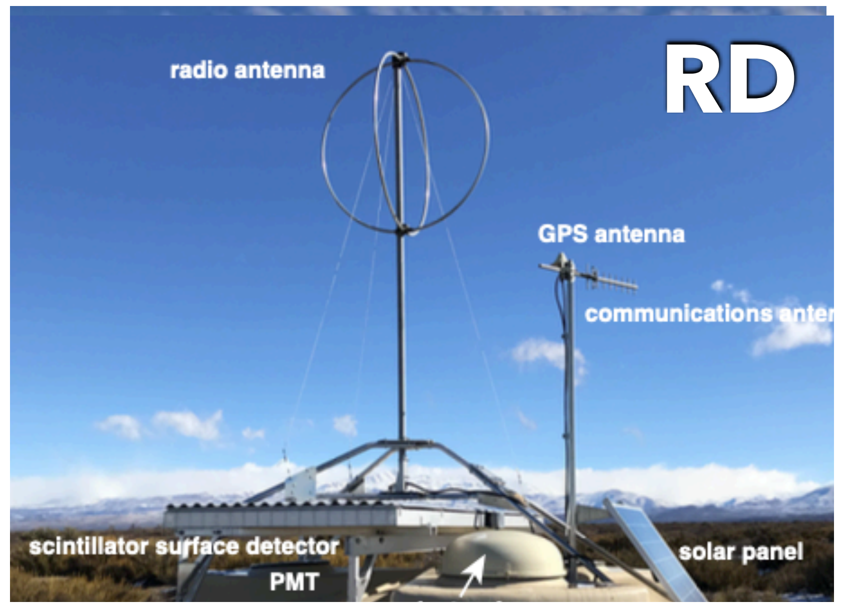


More events than ever…

Vertical Events

Horizontal Events



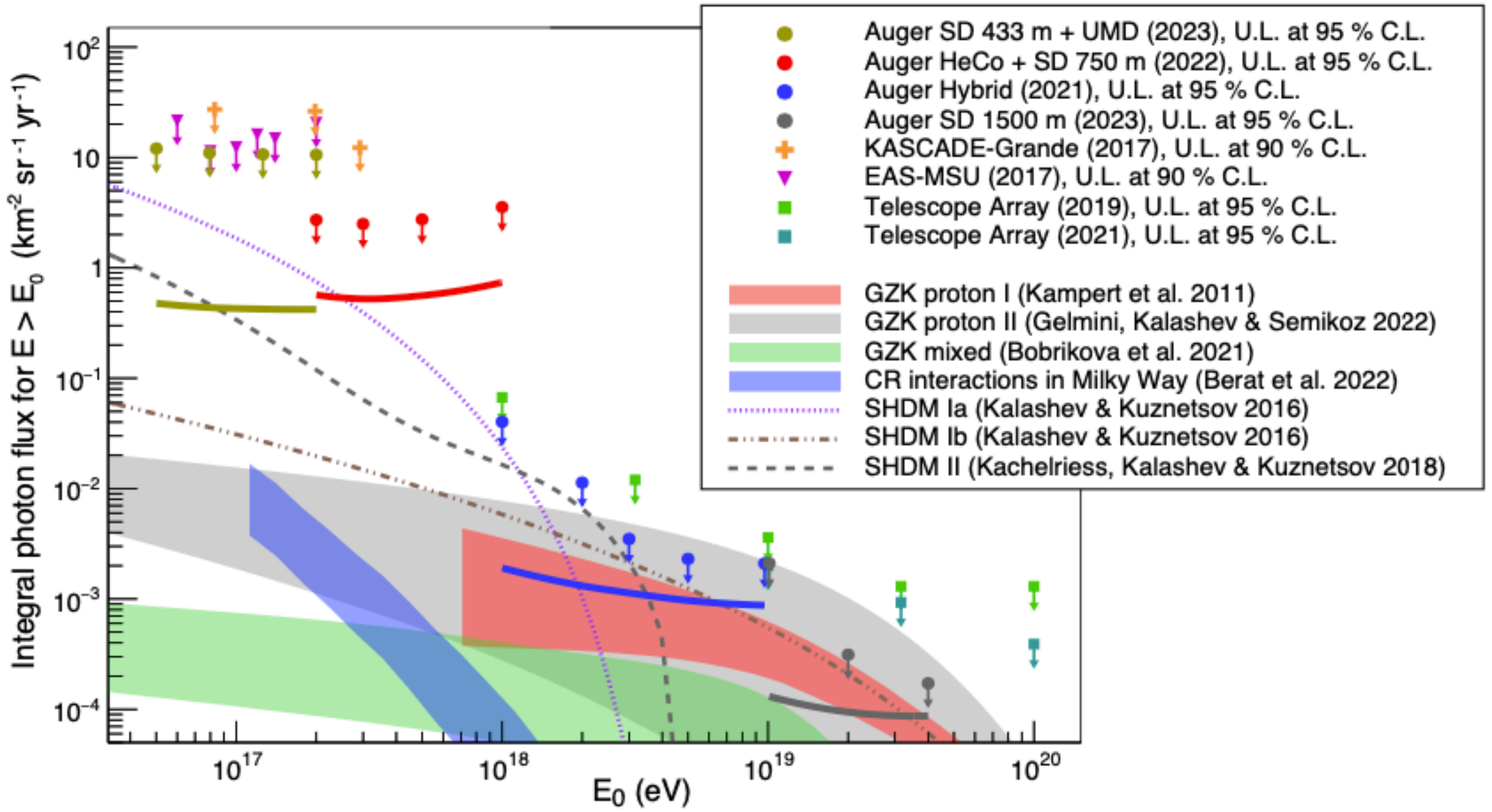


Energy scale

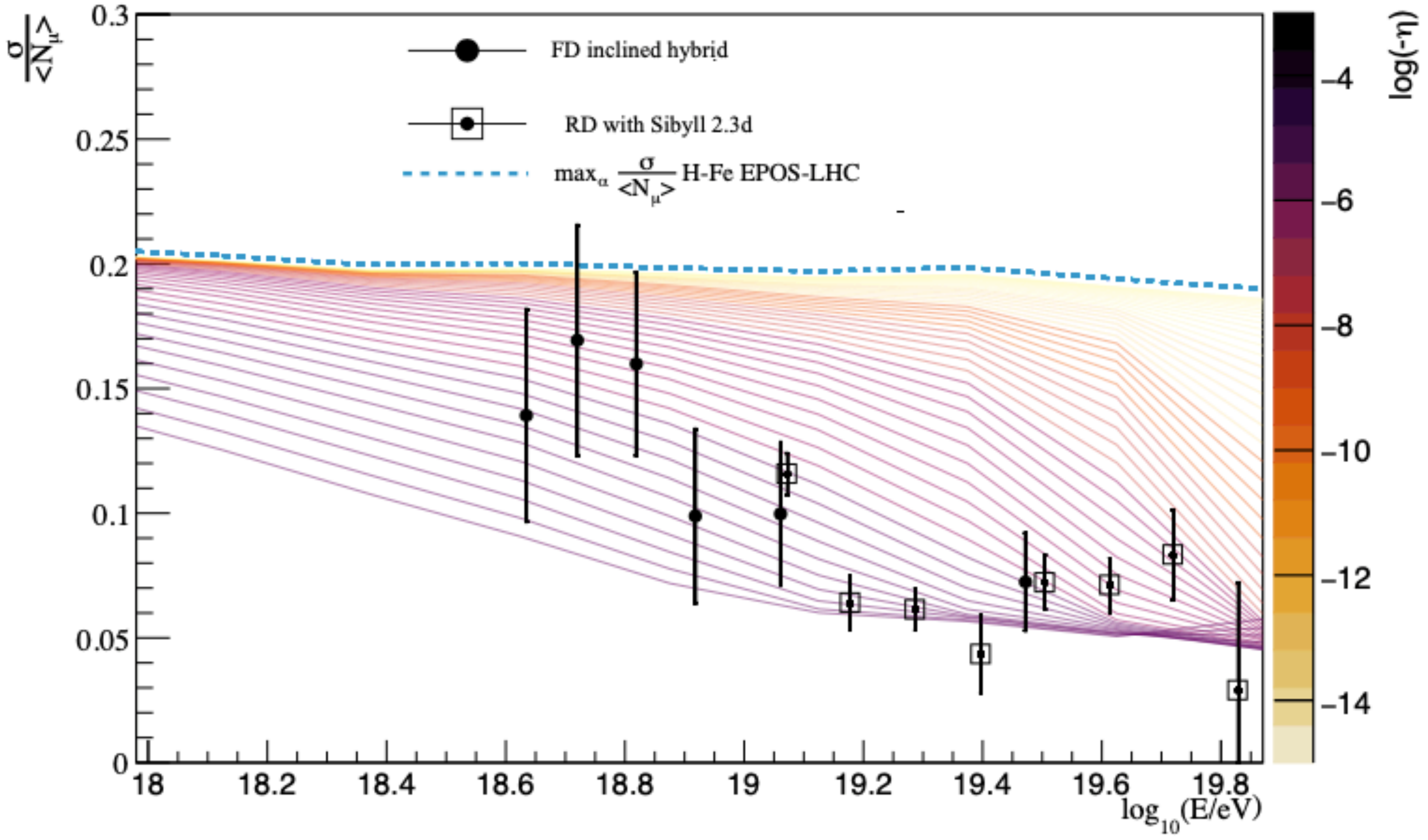
Particles at the ground

Energy scale

Photon Limits



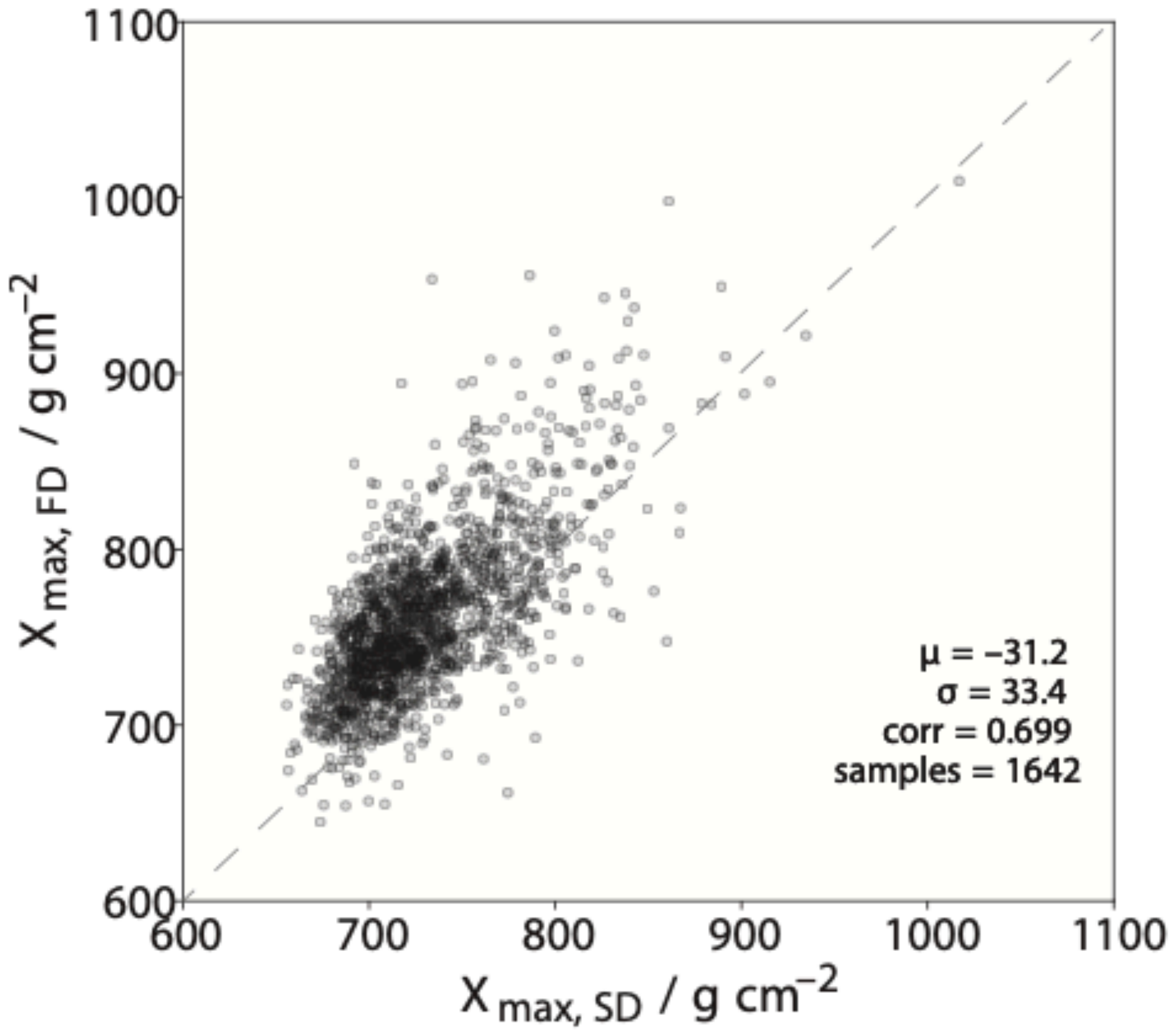
Lorenz Invariance Violation



The dawn of Machine Learning @ Auger

Extraction of Xmax from the SD ground signal

Pierre Auger coll., JINST 16 (2021) 07, P07019

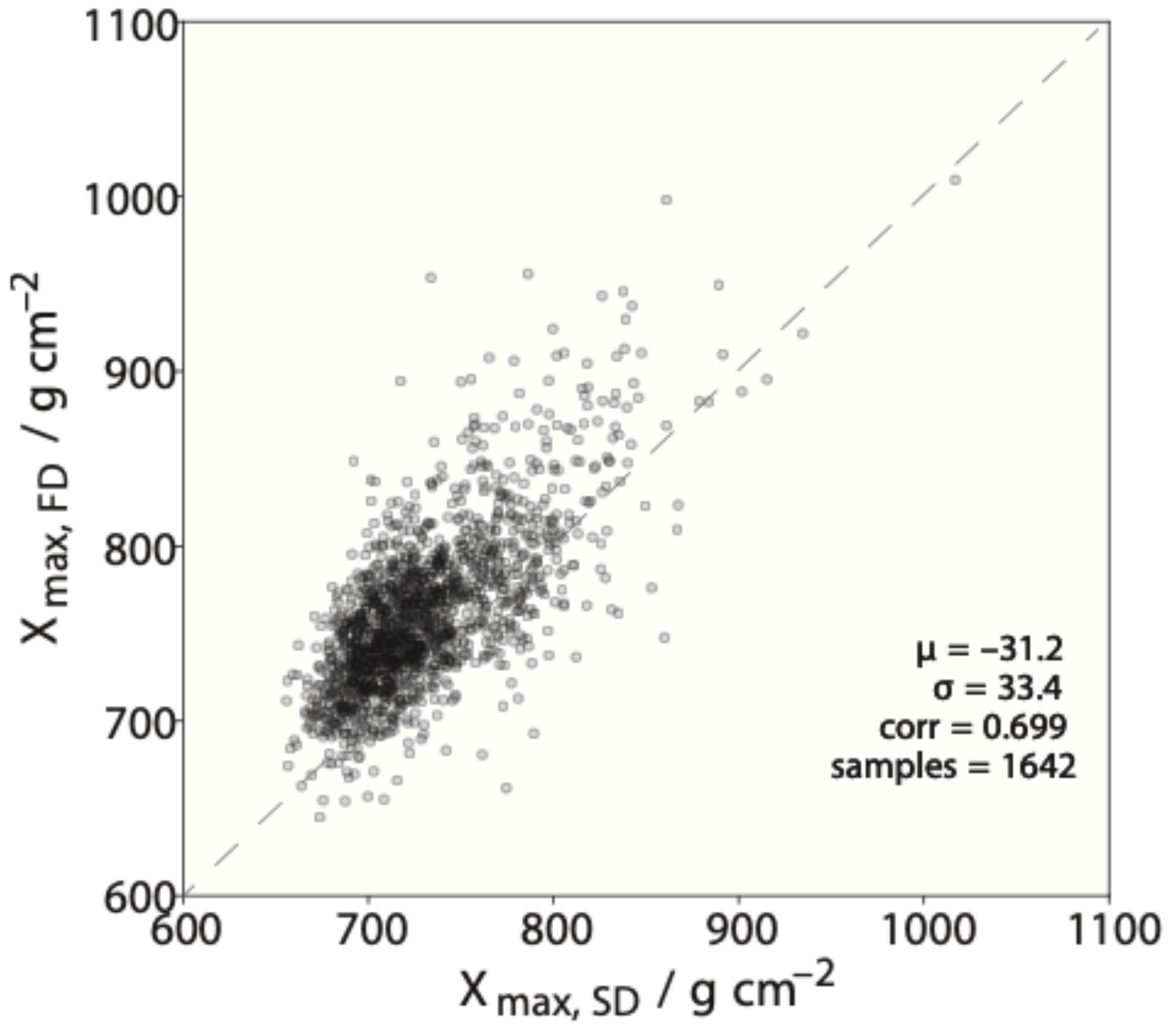


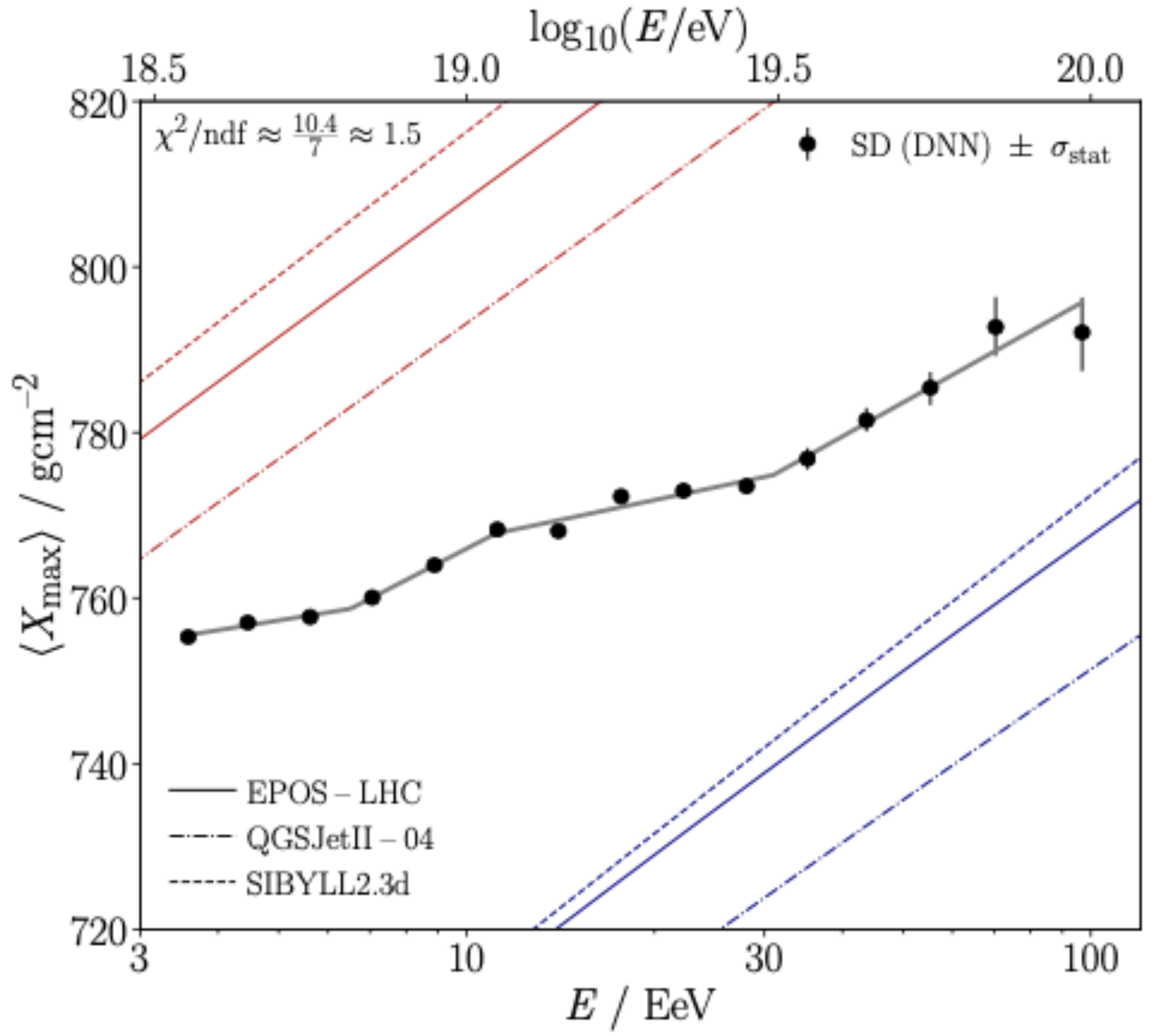
- **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- Algorithms highly **dependent of simulations** and might be picking up unknown less controlled shower characteristics

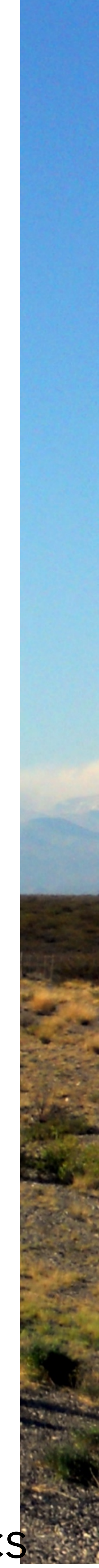
The dawn of Machine Learning @ Auger

Extraction of Xmax from the SD ground signal

Pierre Auger coll., JINST 16 (2021) 07, P07019

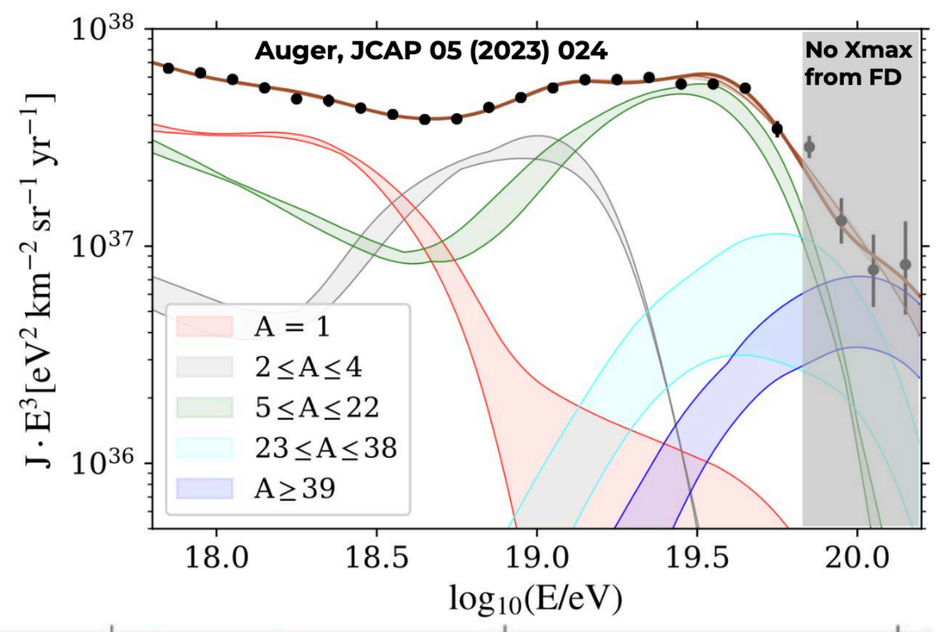






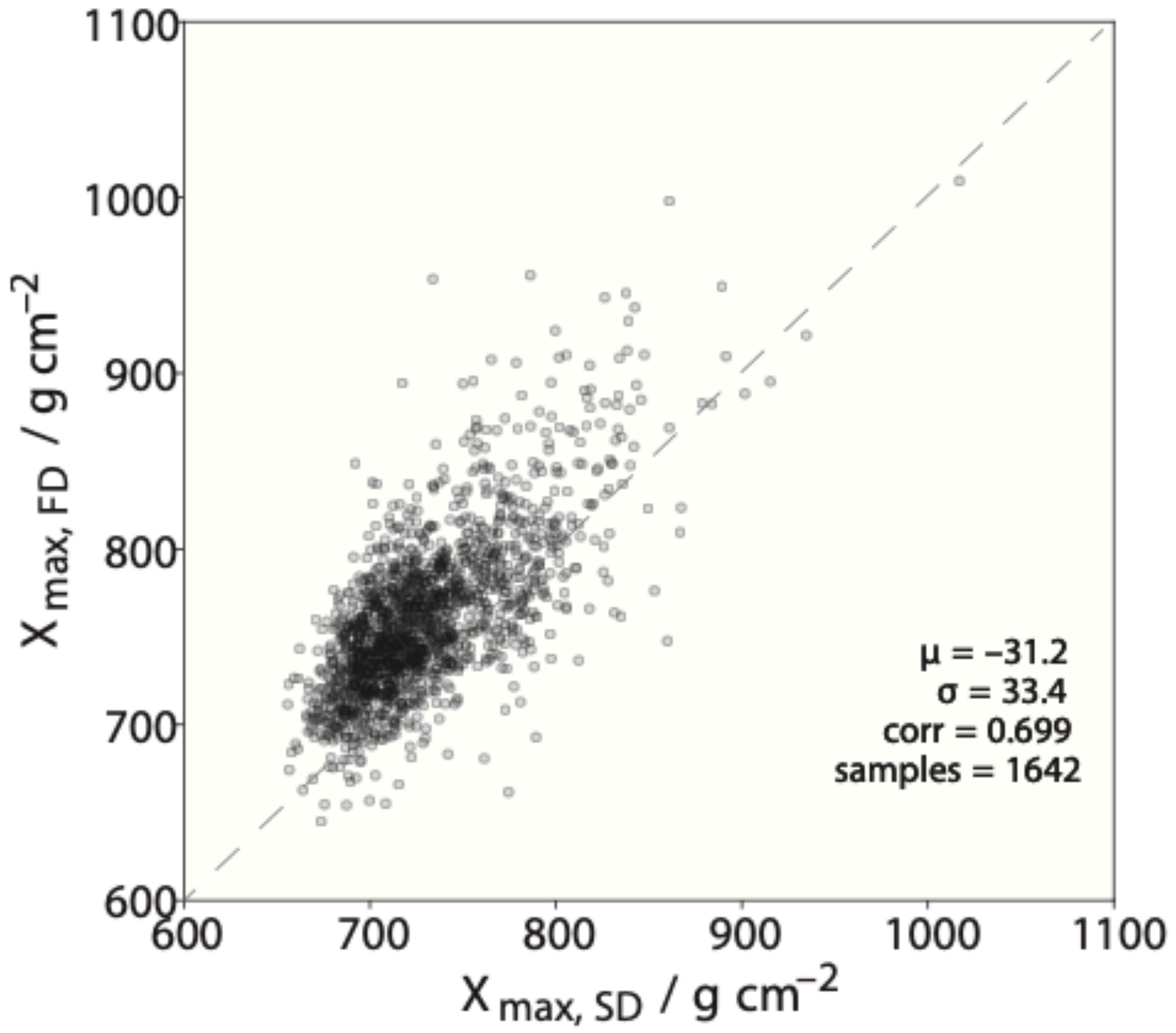
- ✧ **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- ✧ Algorithms highly **dependent of simulations** and might be picking up unknown less controlled shower characteristics

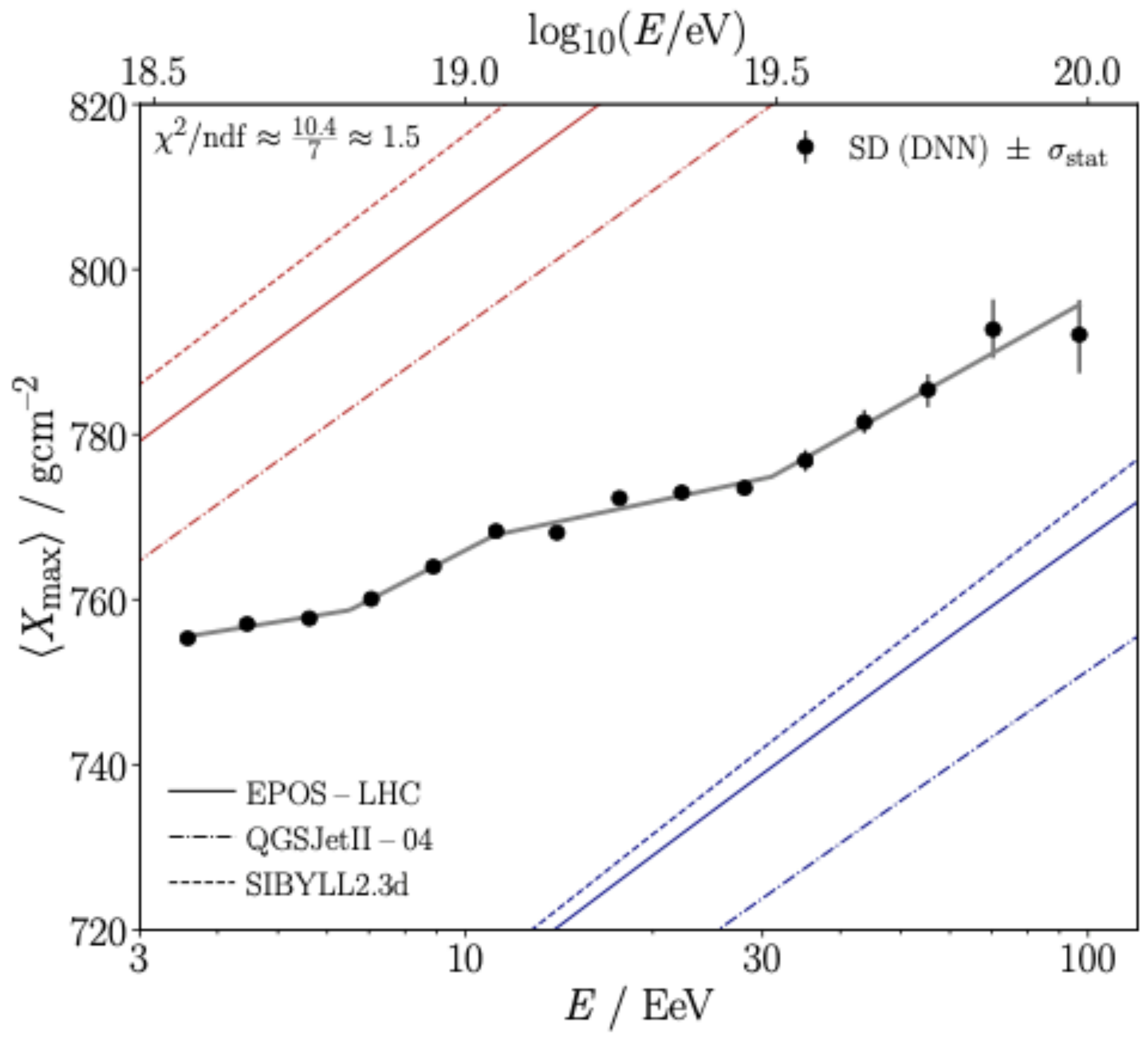
The dawn of Machine Learning @ Auger

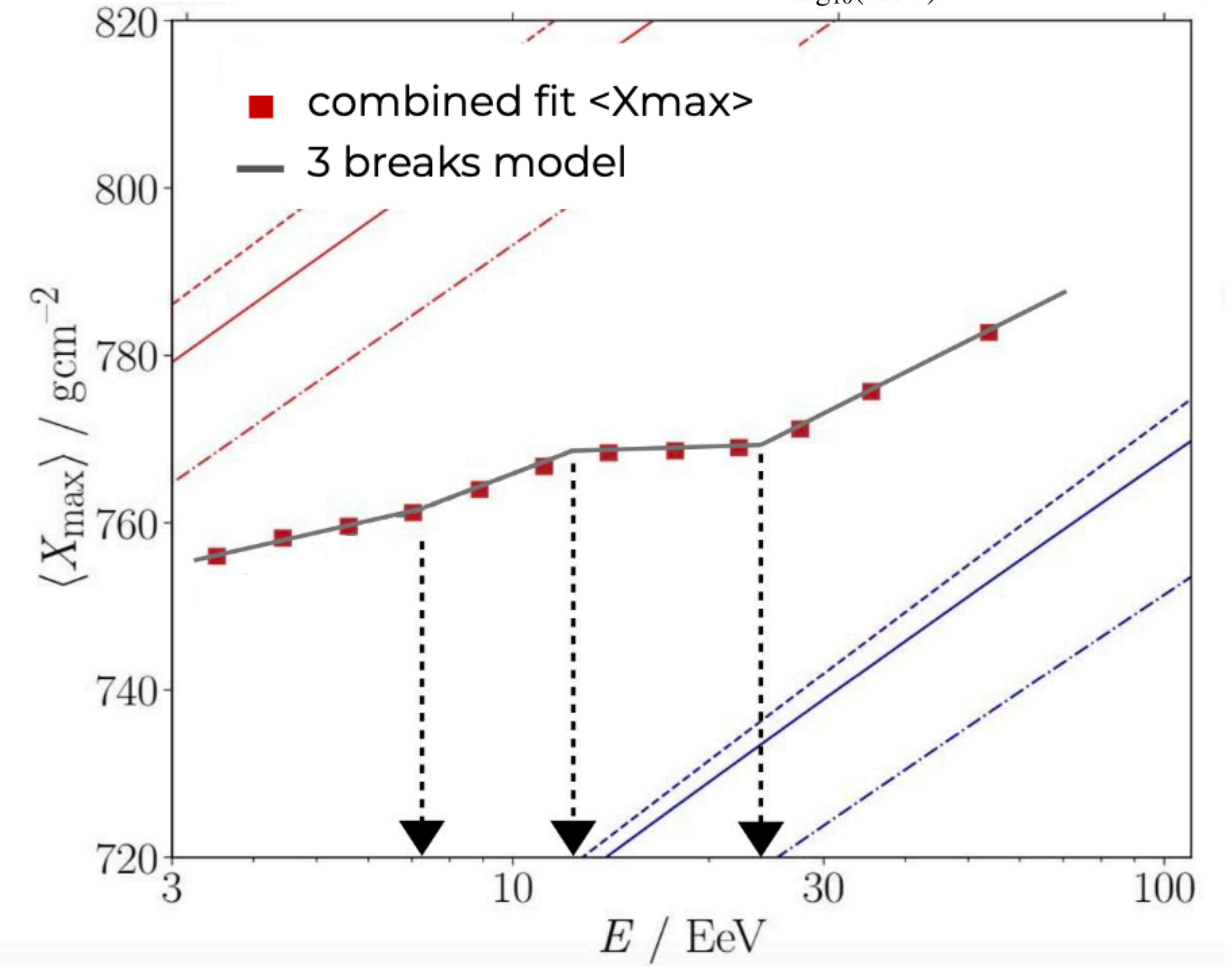


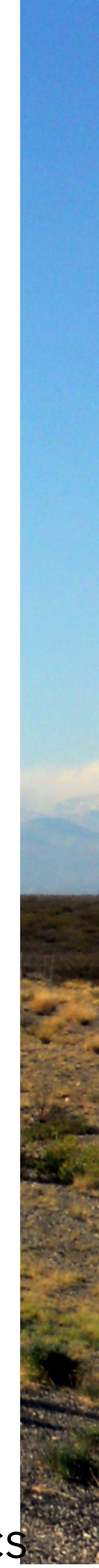
Extraction of Xmax from the SD ground signal

Pierre Auger coll., JINST 16 (2021) 07, P07019





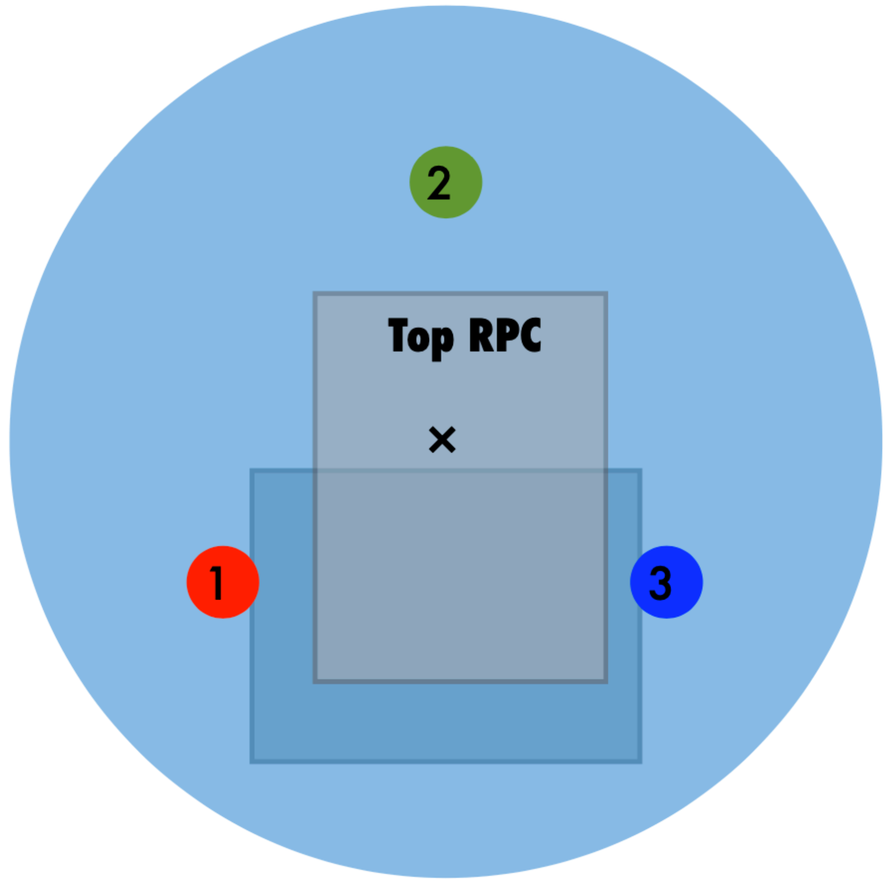


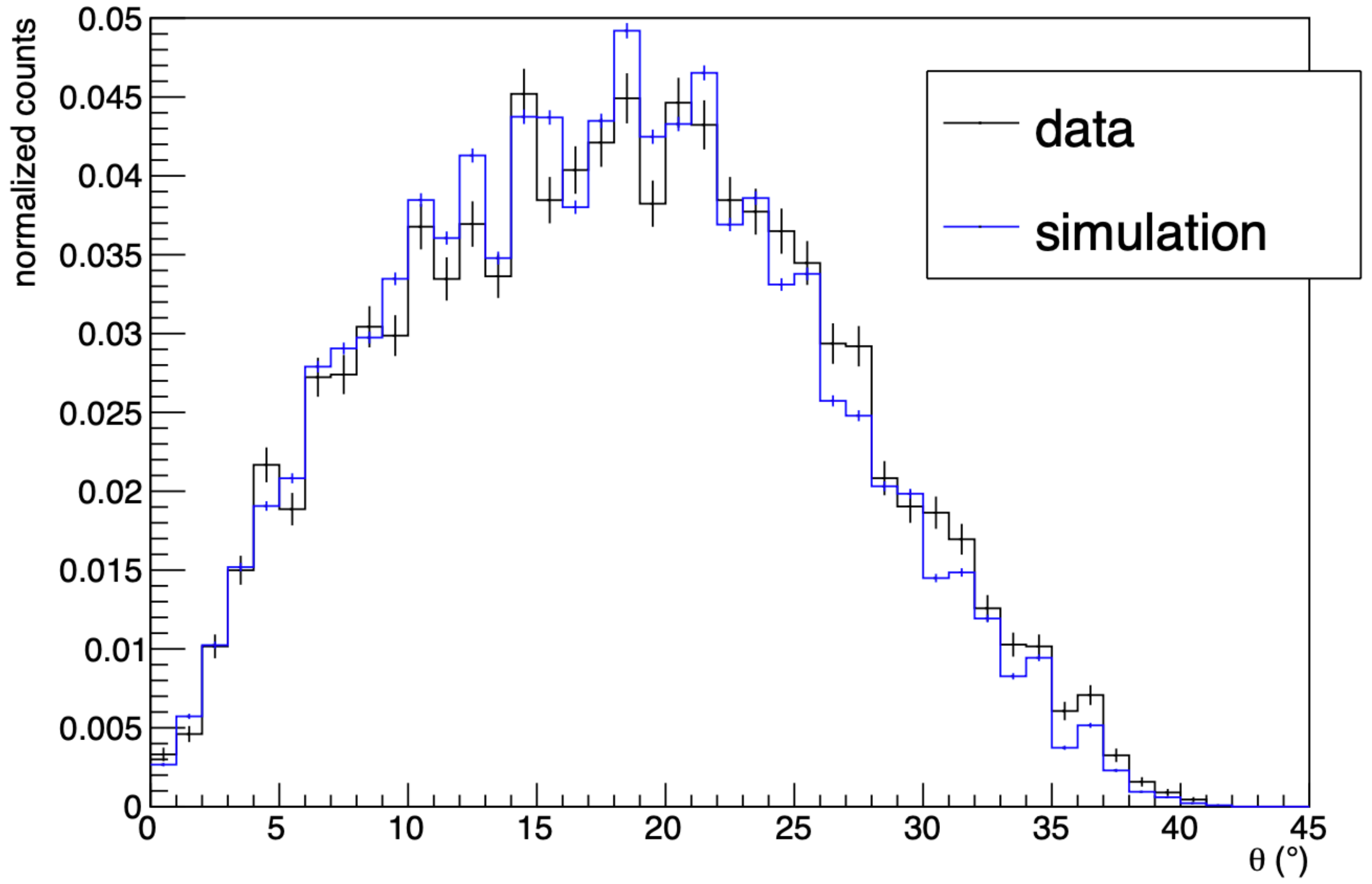


- ✧ **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- ✧ Algorithms highly **dependent of simulations** and might be picking up unknown less controlled shower characteristics
- ✧ It is vital to create strategies to achieve self consistent solutions ⇒ **RPC hodoscope**

Back to the calibration with the RPC hodoscope

- RPC hodoscope installed in the Gianni Navarra tank was reconfigured to include one of the Auger Prime detectors

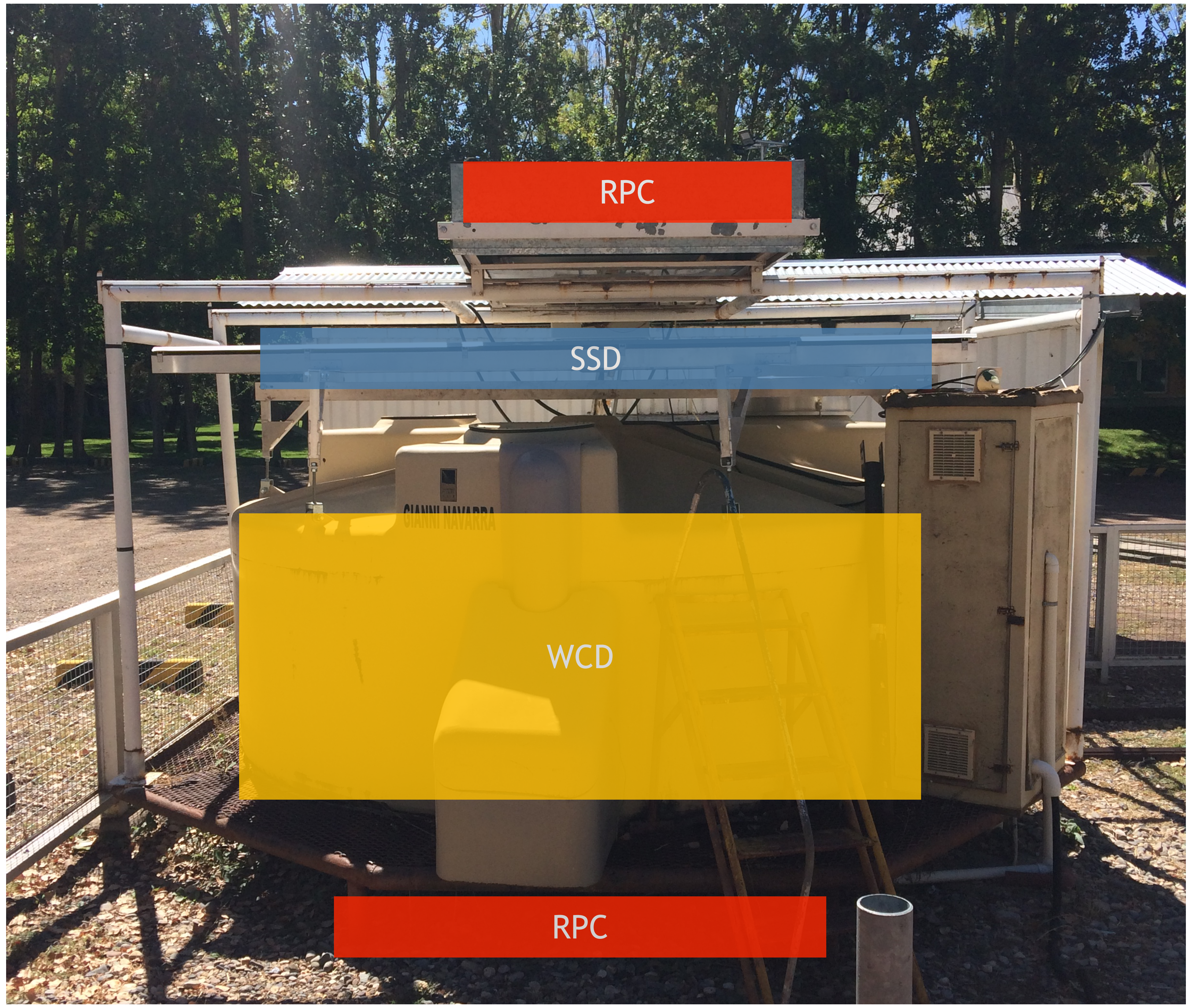


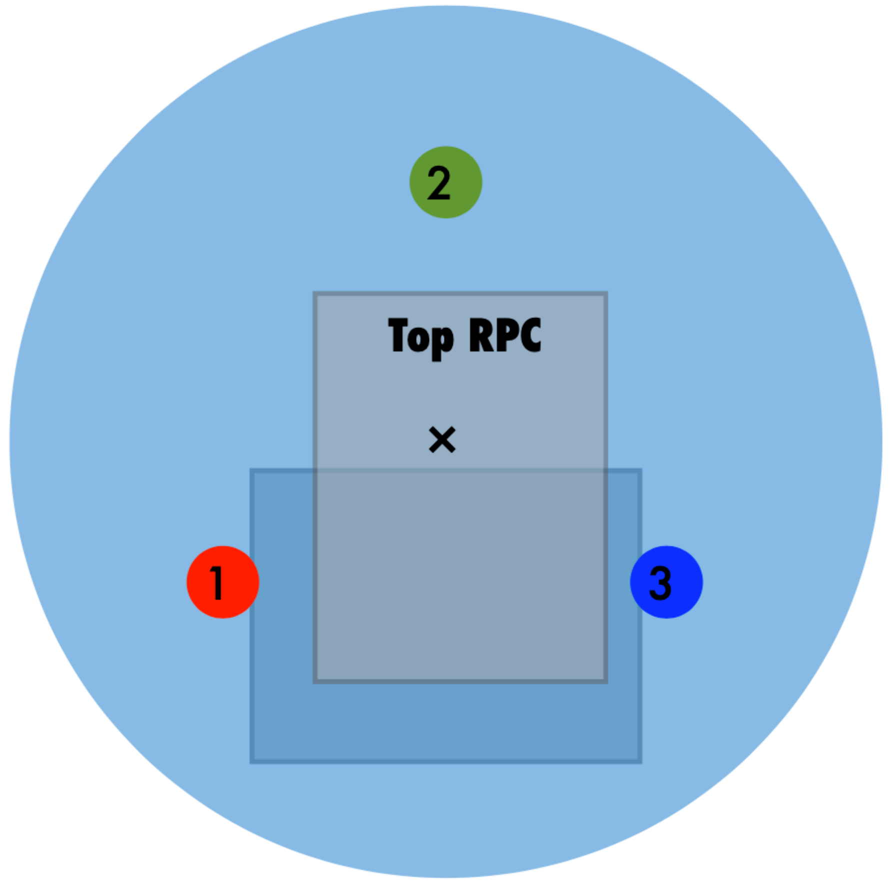


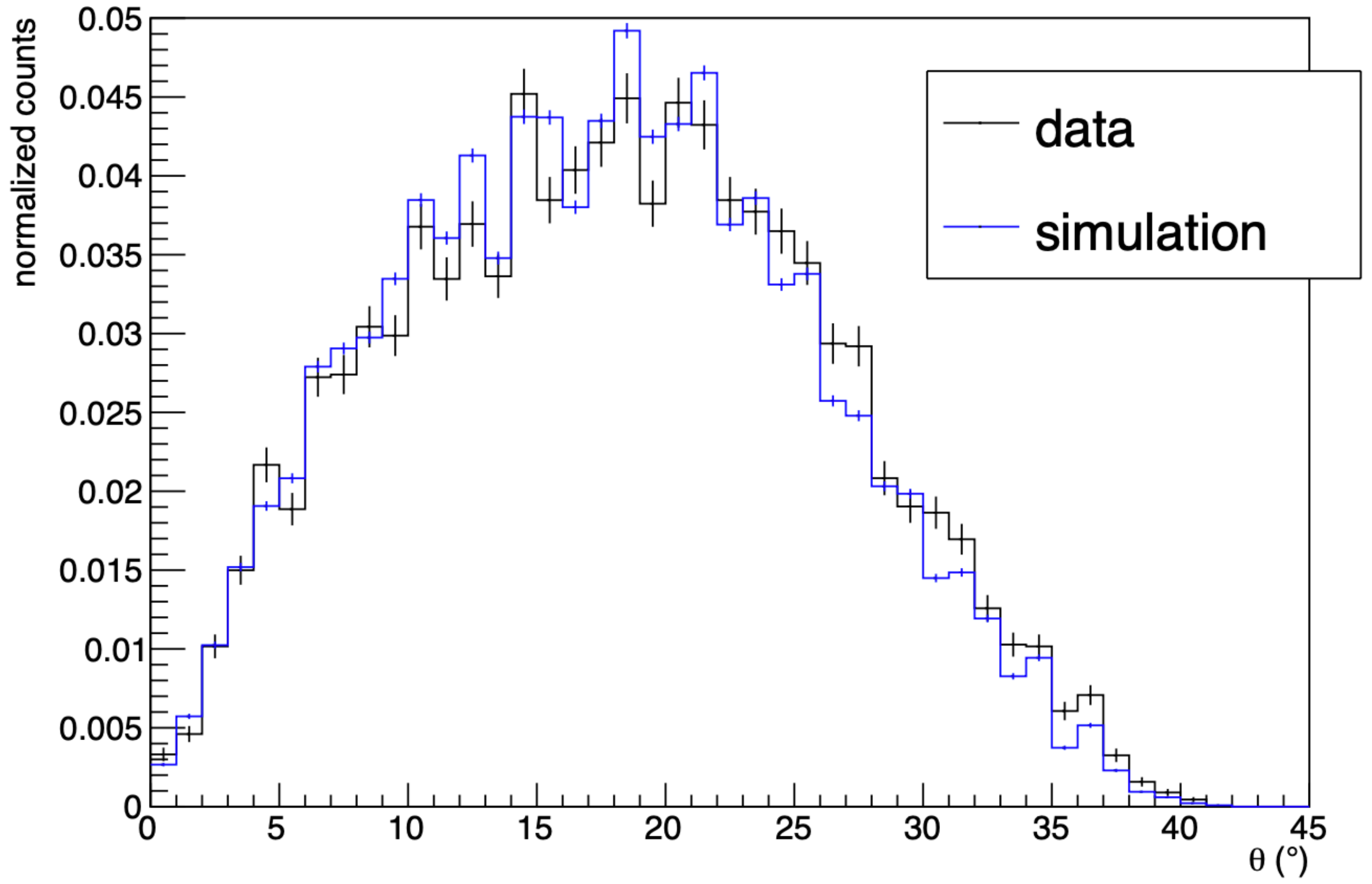
- The data acquisition system was also upgraded to cope with the new electronics board of the WCD and have a more robust/faster acquisition system

Back to the calibration with the RPC hodoscope

- RPC hodoscope installed in the Gianni Navarra tank was reconfigured to include one of the Auger Prime detectors



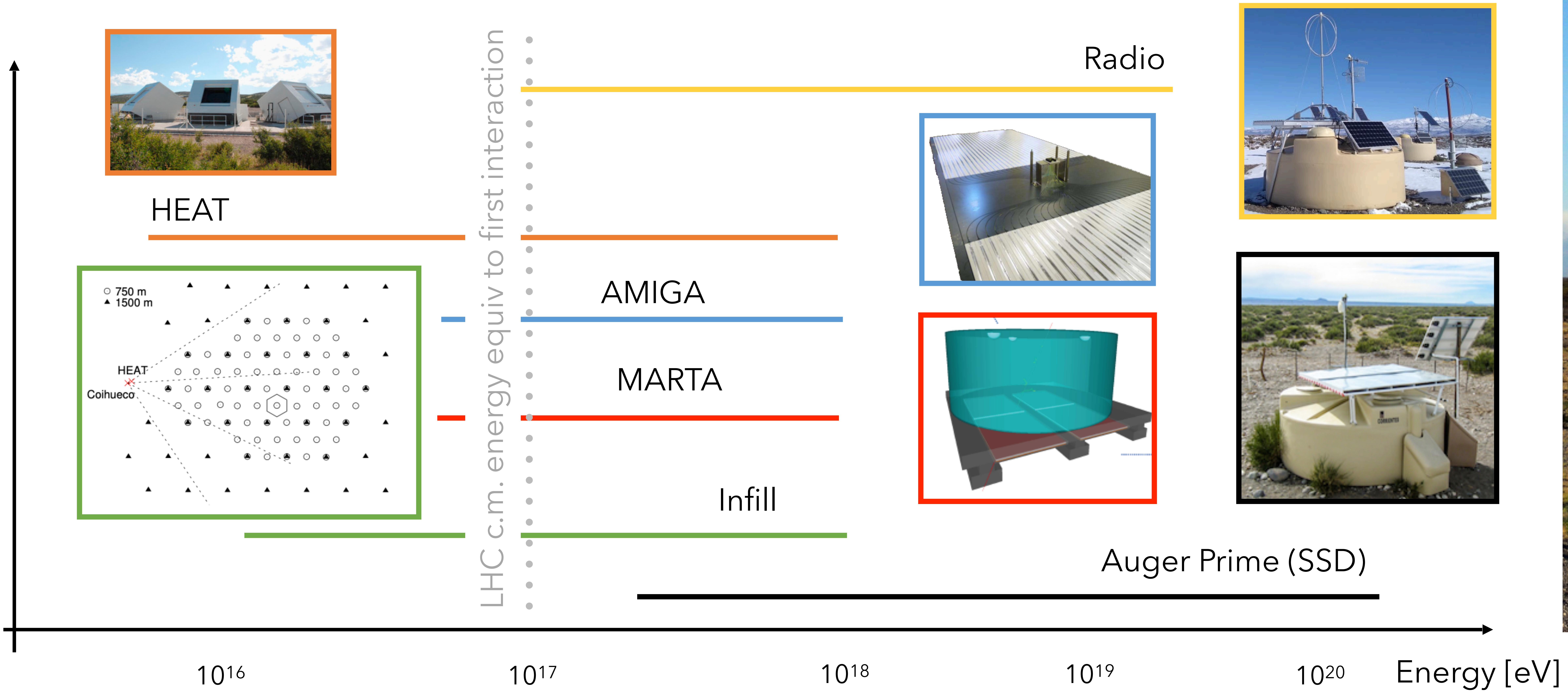




- The data acquisition system was also upgraded to cope with the new electronics board of the WCD and have a more robust/faster acquisition system

Multi-hybrid shower events

(A plethora of measurements to fully understand the shower)



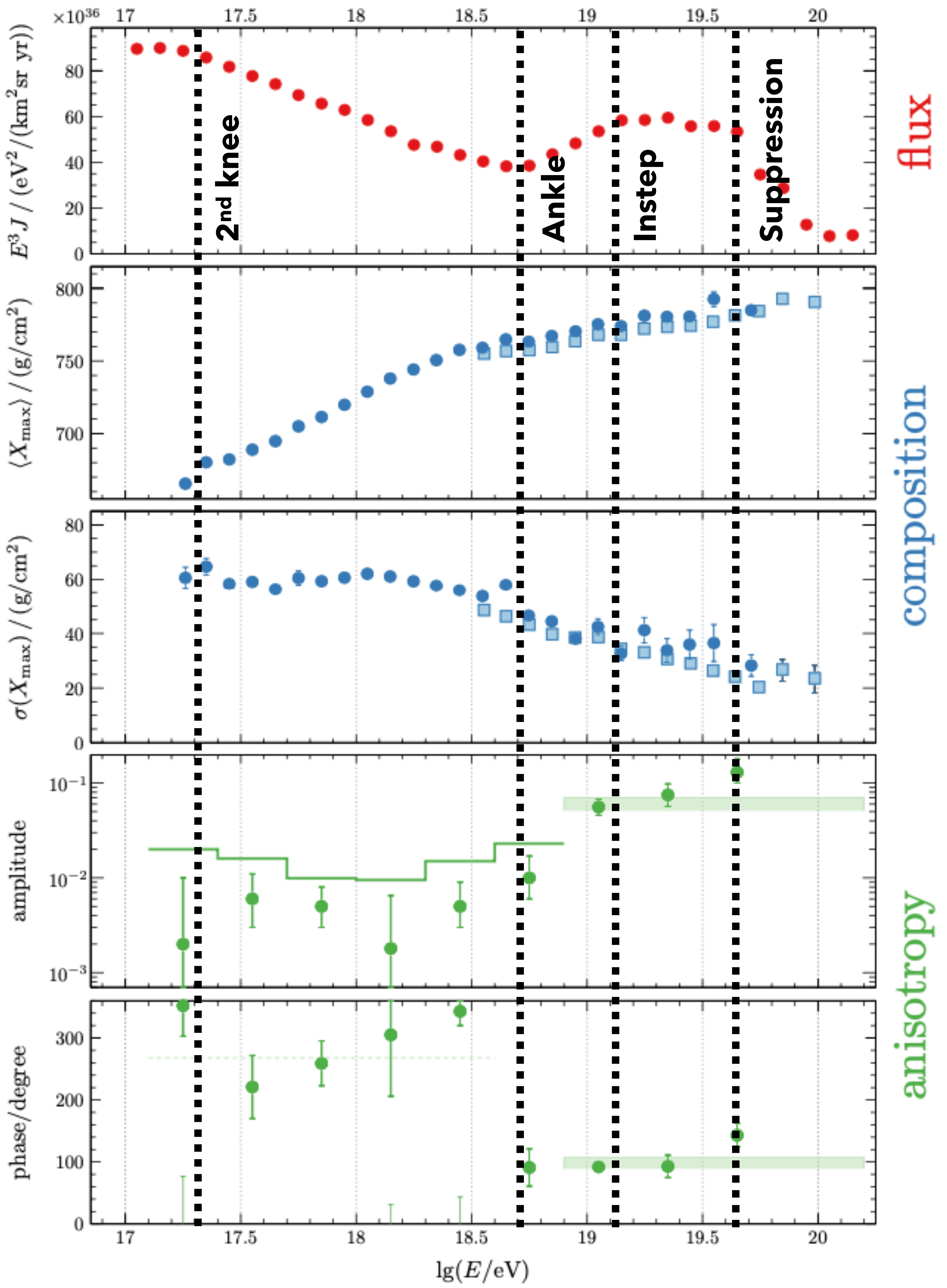
Summary

✧ Increasingly coherent picture emerging from Auger Phase I data (many more results not shown, e.g. BSM searches, geo-cosmo physics…)

✧ The mass composition determination is essential to rule out scenarios

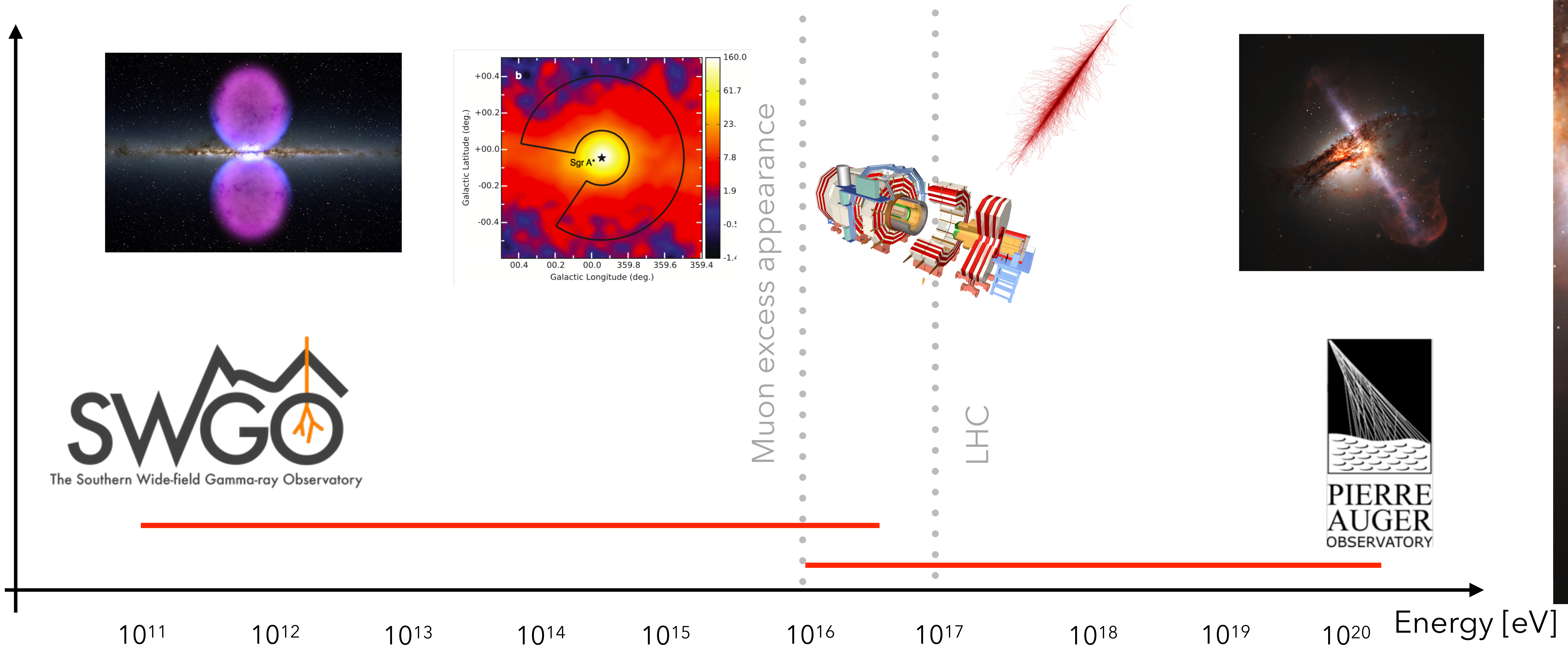
✧ The post-LHC hadronic interaction models are unable to provide a consistent description of the measured showers

✧ In the next years, a new set of multi-hybrid shower measurements (Auger Phase II) will be available to further constrain hadronic interactions properties in EAS



Astroparticle Physics

A unique opportunity to explore the extreme energy Universe



Acknowledgements

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

REPÚBLICA PORTUGUESA

LIP

TÉCNICO LISBOA