High-energy Hadronic Interaction Models: Insights from the Pierre Auger Observatory

Ruben Conceição

on behalf of the Pierre Auger Observatory

LIP

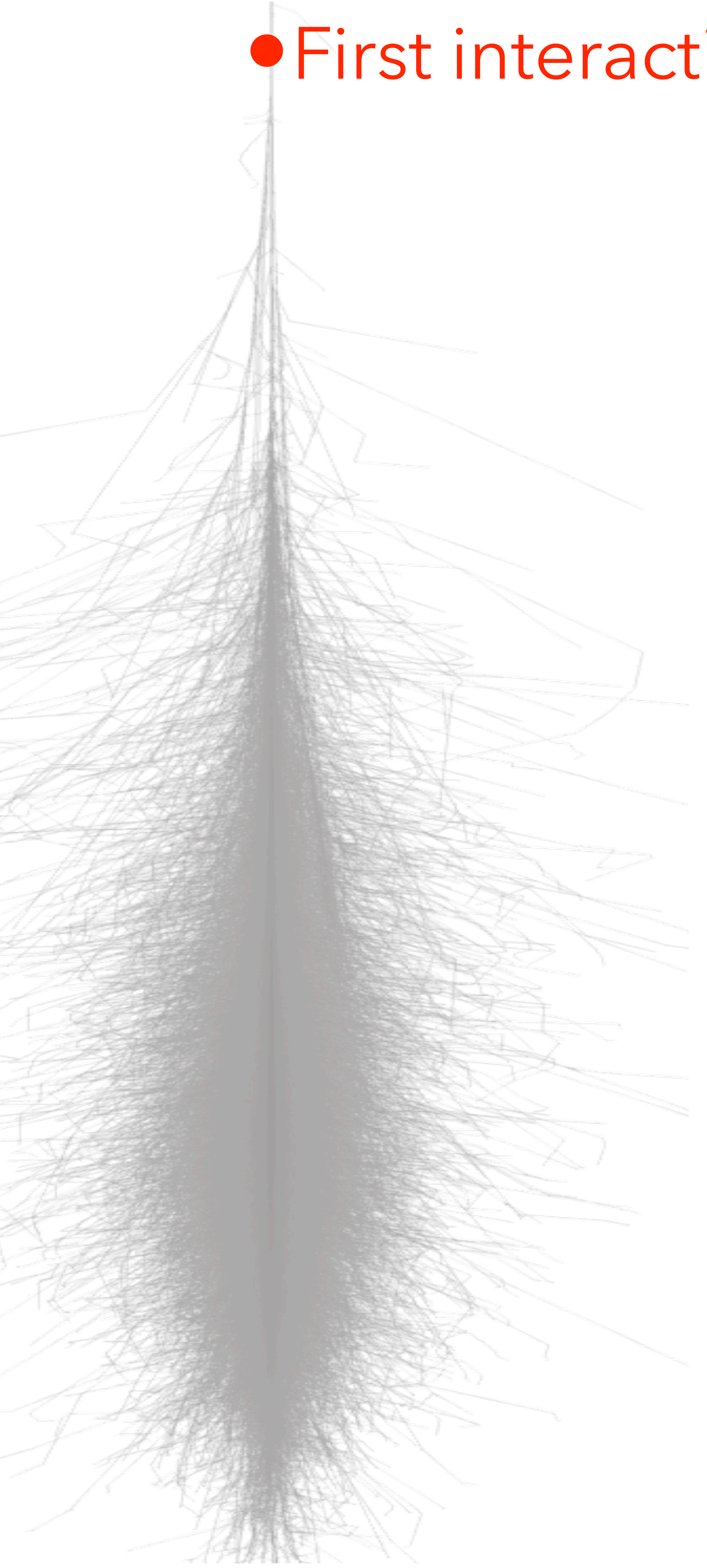
PIERRE AUGER OBSERVATORY

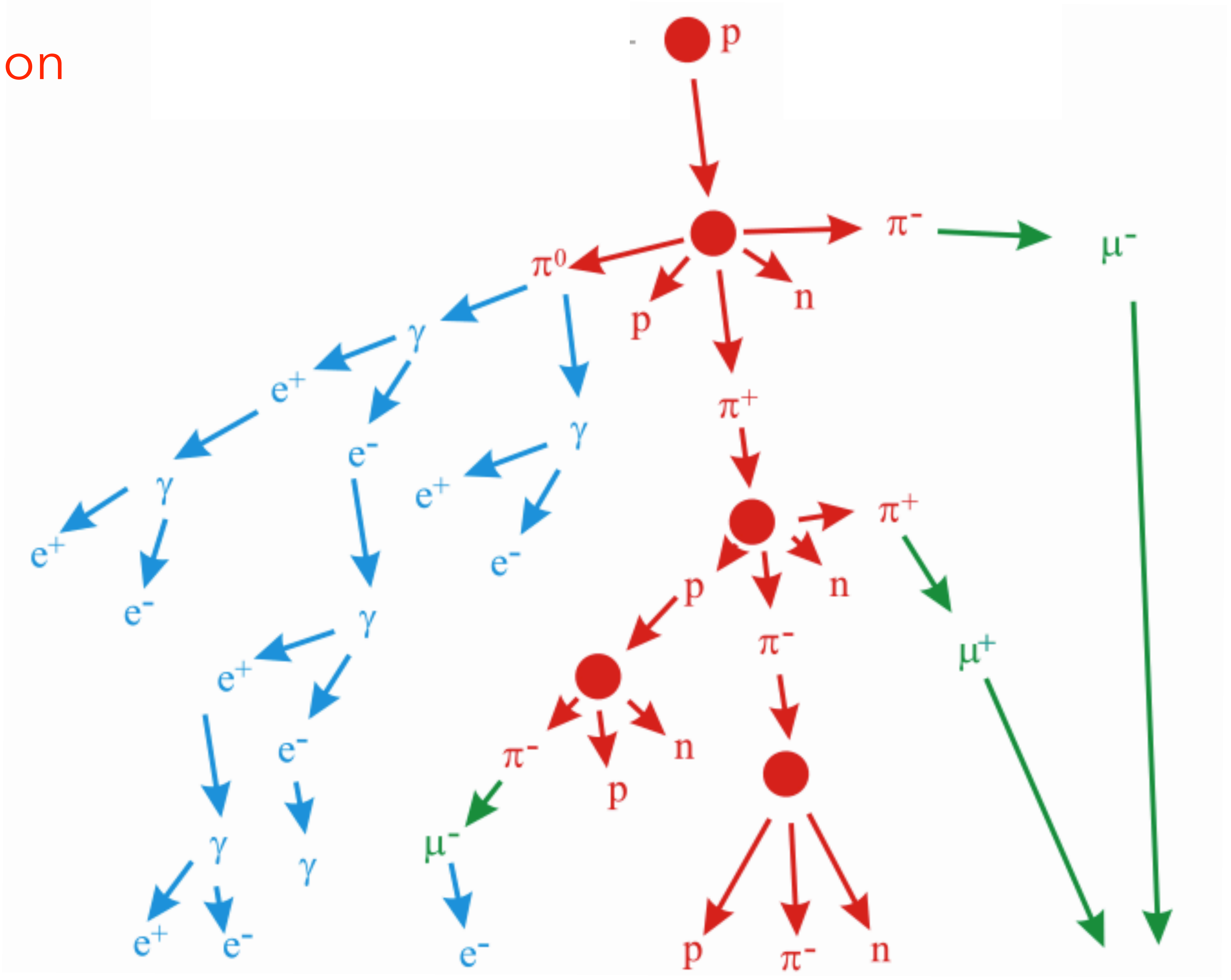
TÉCNICO LISBOA

ISVHECRI 2024, Puerto Vallarta, Mexico, July 9th 2024

UHECR & Air Shower Physics

Monte Carlo EAS simulation [CORSIKA]

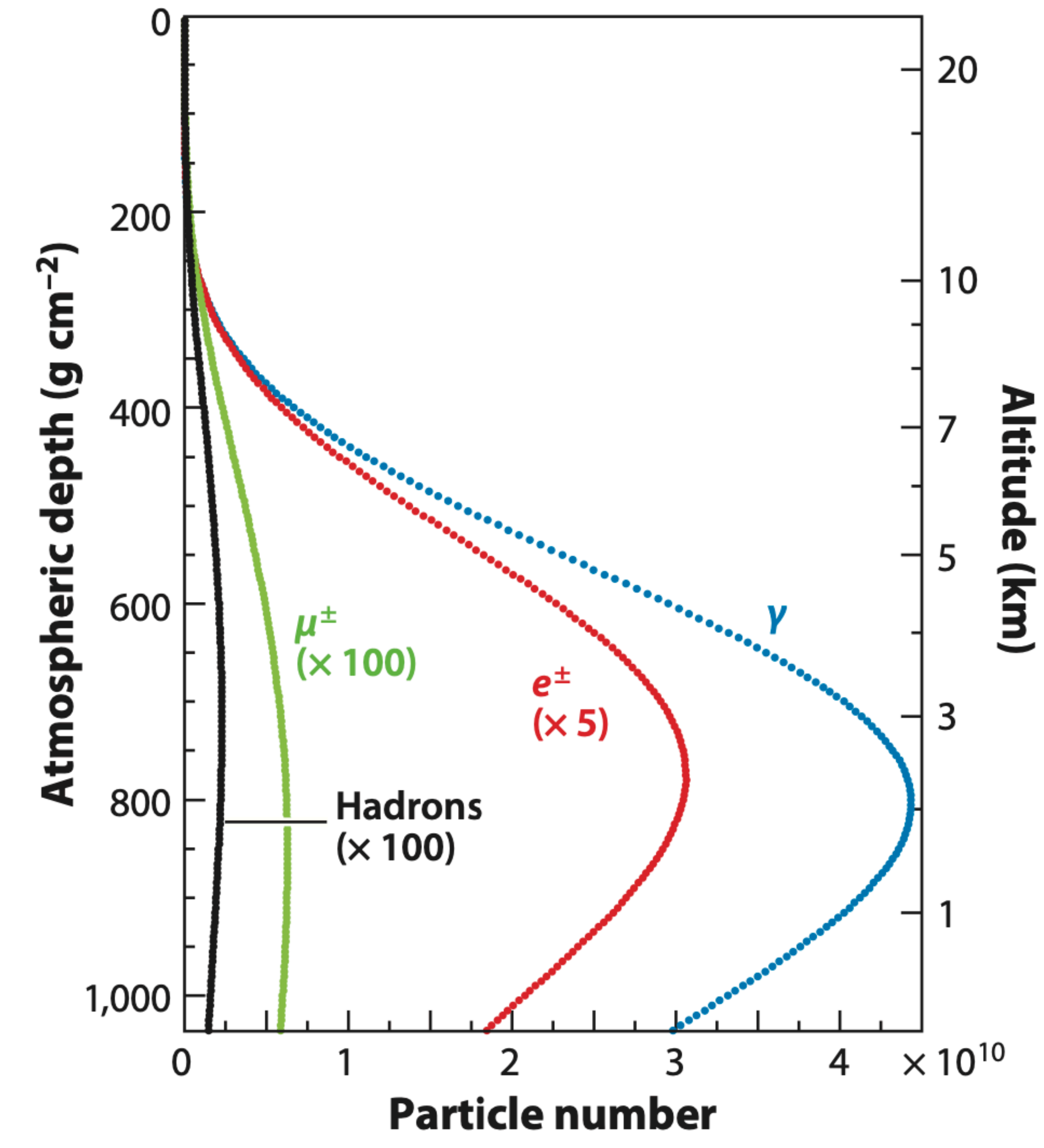


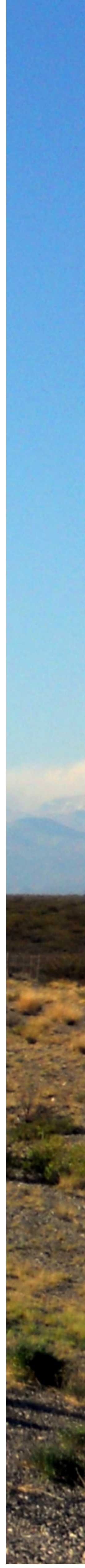


Electromagnetic component

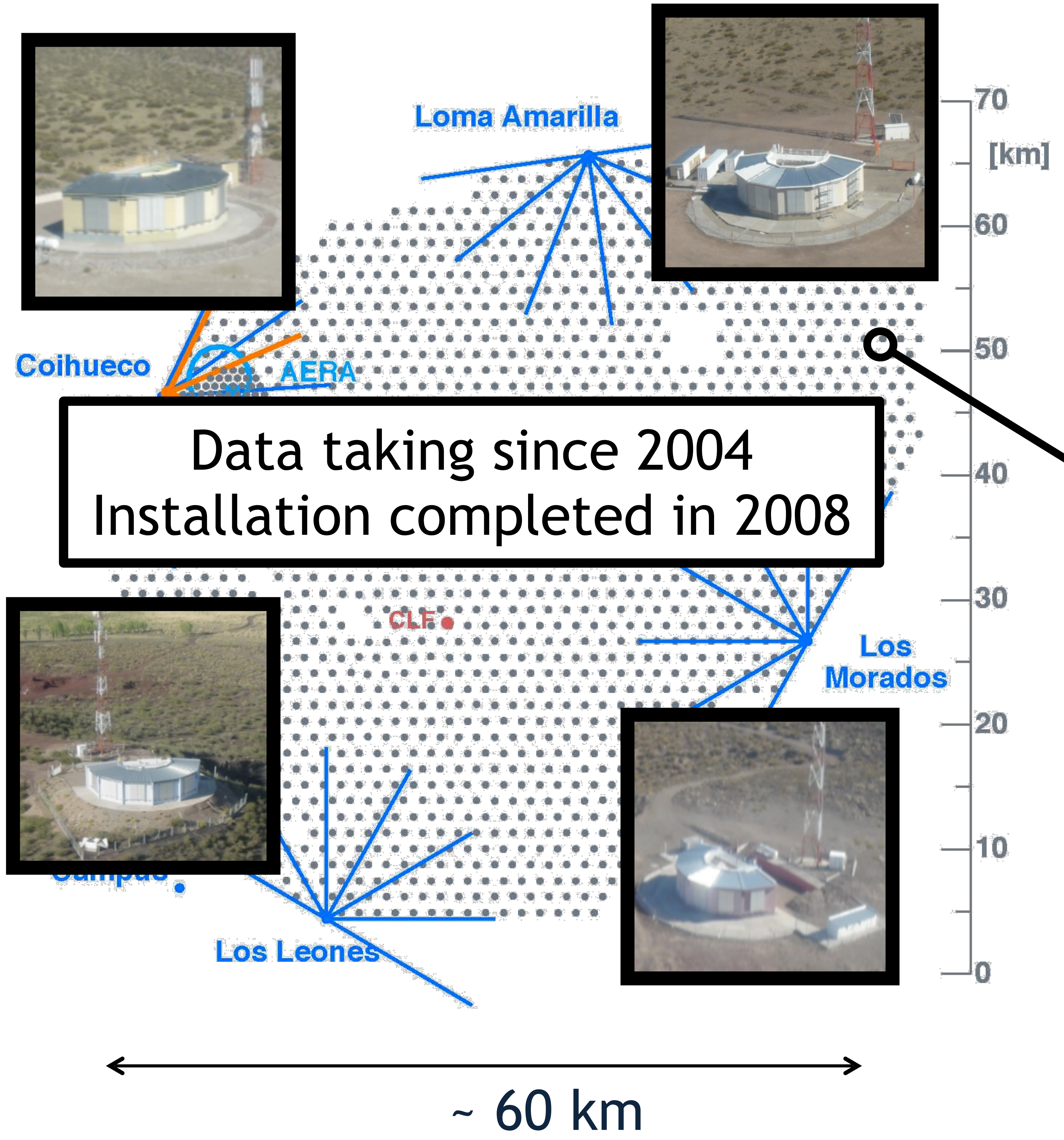
Hadronic component

Muonic component





Pierre Auger Observatory



Data taking since 2004
Installation completed in 2008

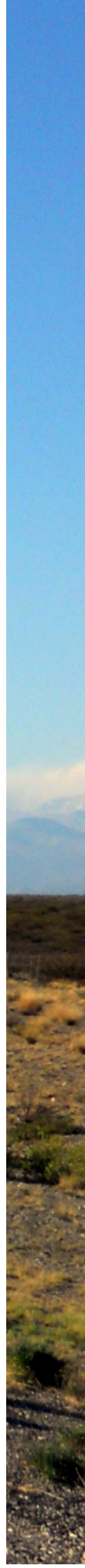
- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

Area: 3000 km^2

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

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



WCD + Fluorescence Detector

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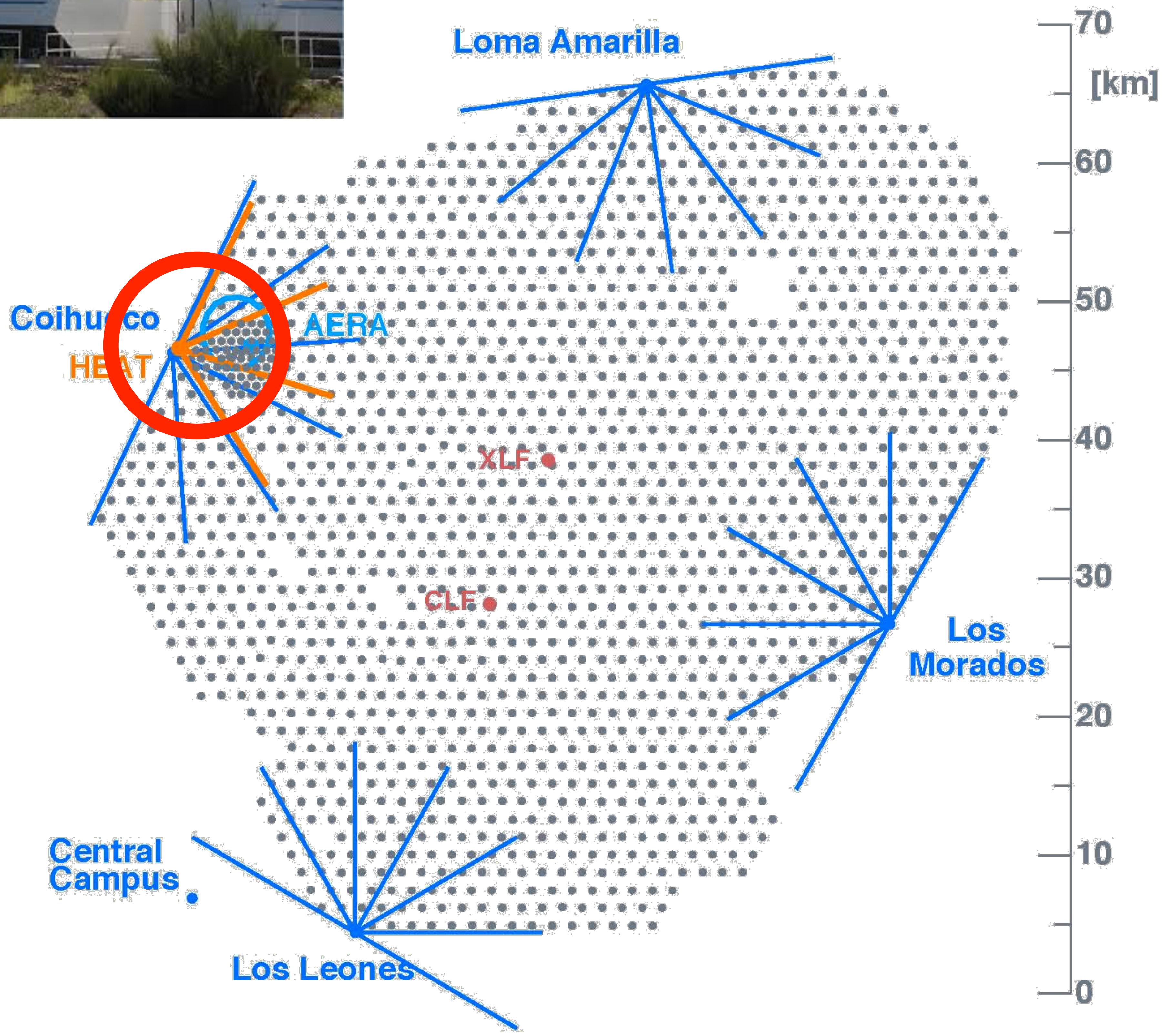
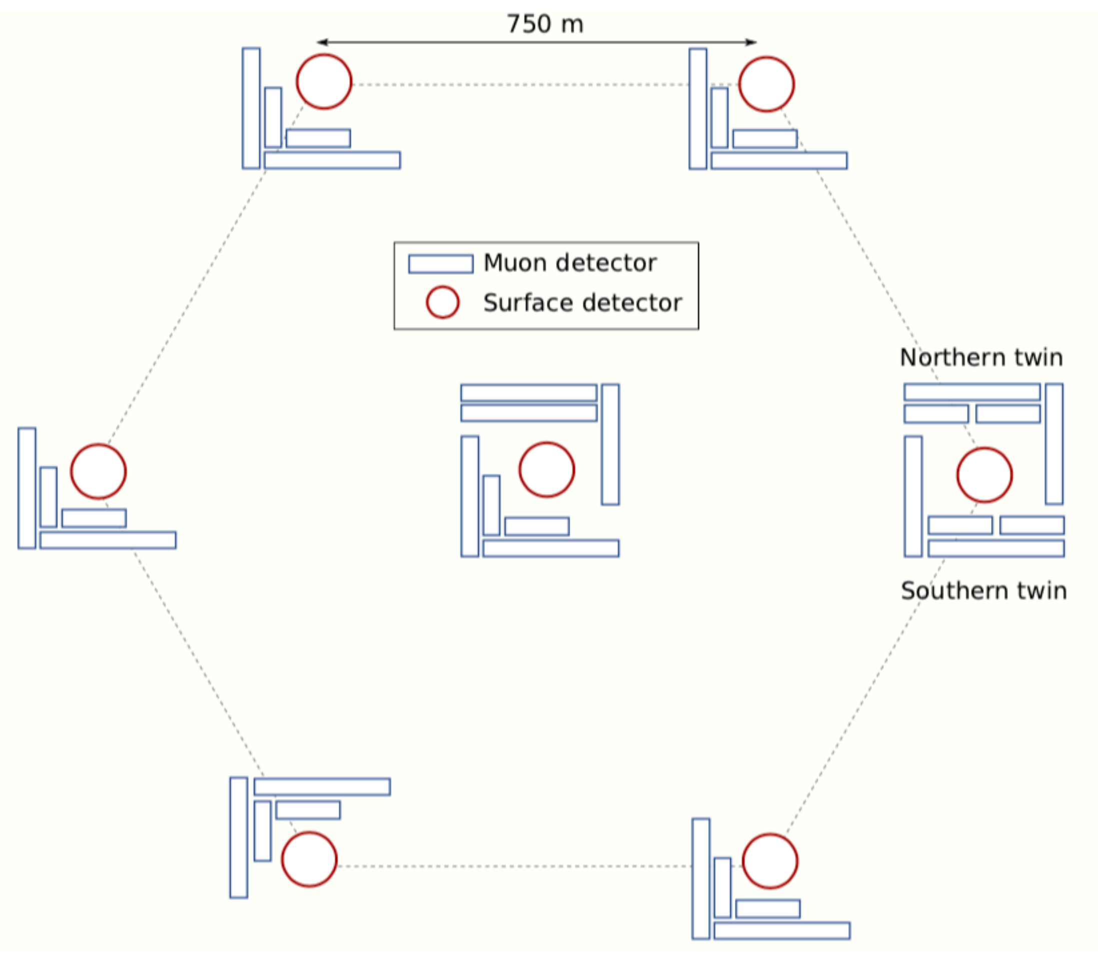
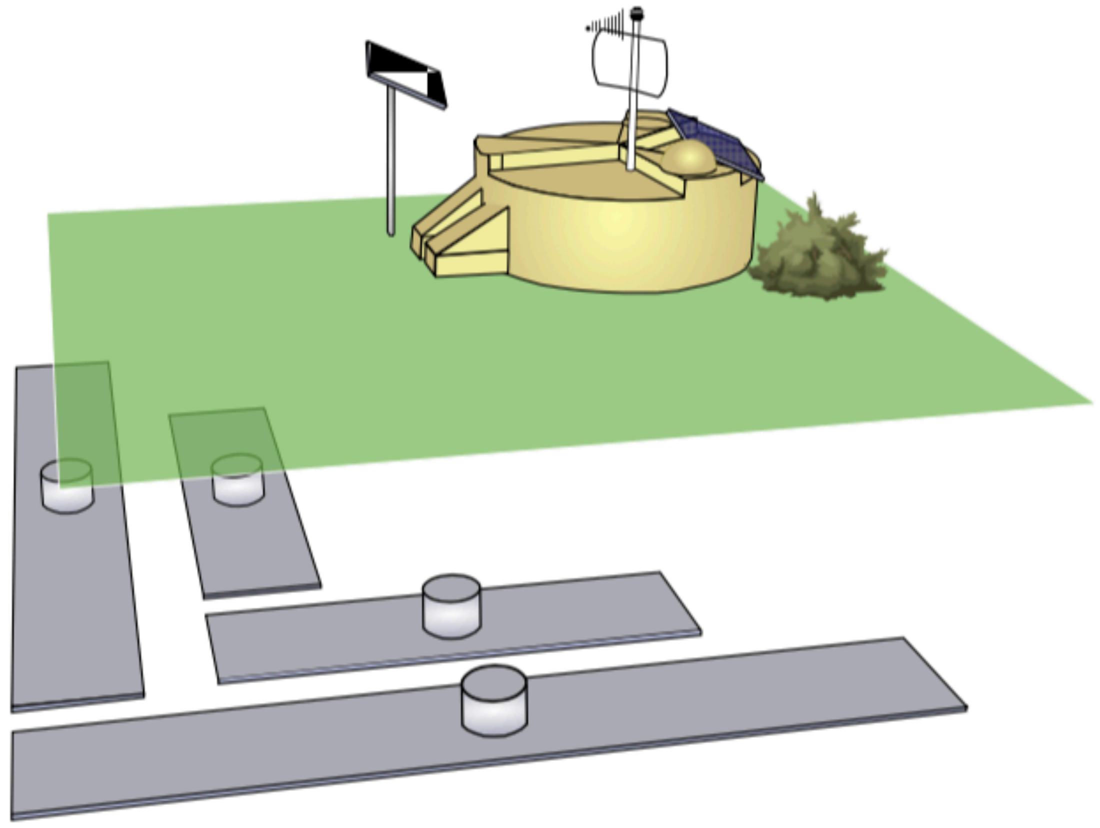
(Low energy extensions)



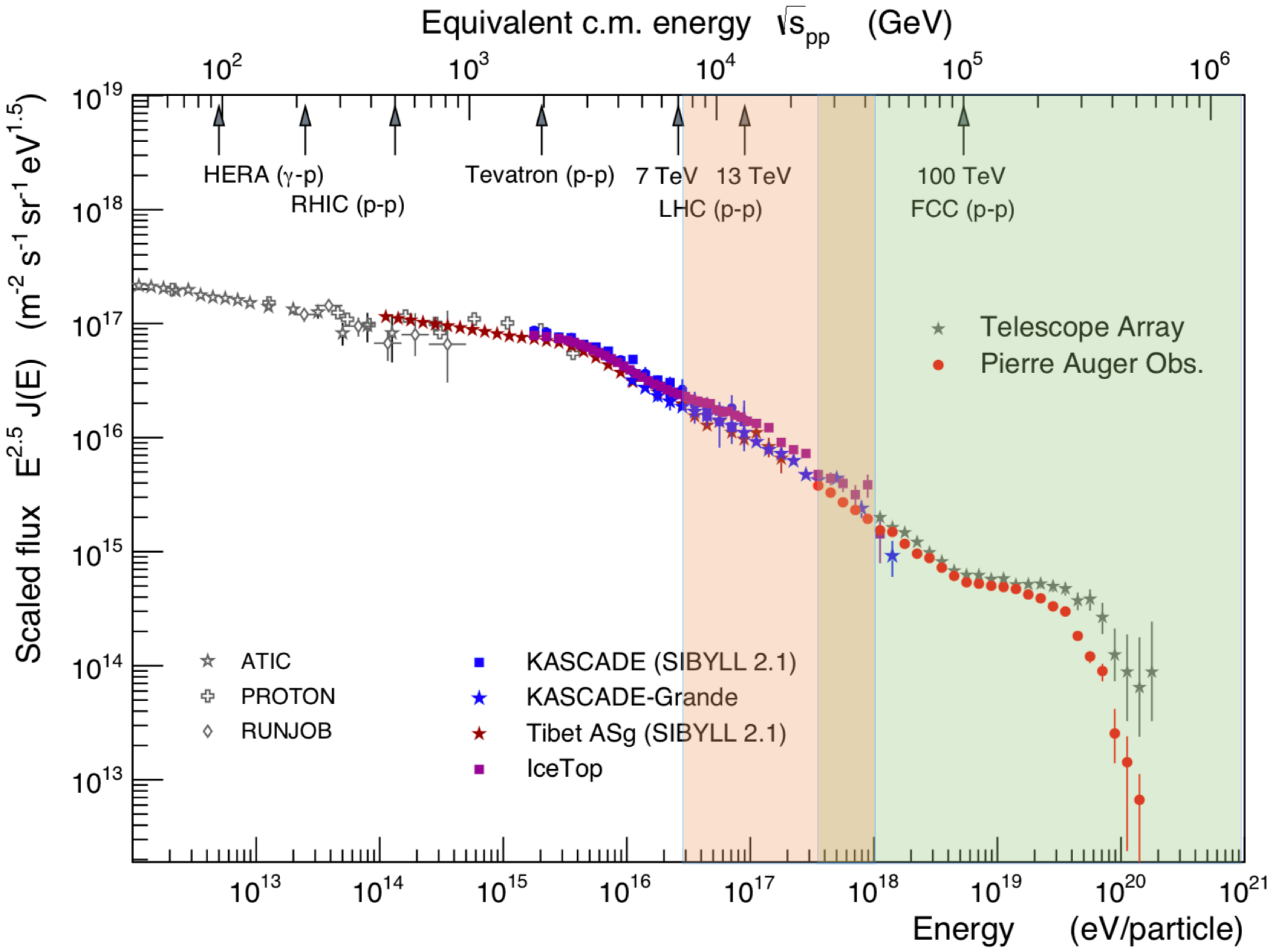
- **Infill** - Denser array
  - 433 m grid with 19 stations
  - 750 m grid with 61 stations
- **AMIGA** - Buried scintillators (muon detectors)
  - 19 (61) stations in 433 (750) m array, $10^{16.5} < E/\mathrm{eV} < 10^{19}$
  - 30 (60) m^2 scintillator modules
  - 2.3 m below ground
- **Auger Engineering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





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

Ultra High Energy Cosmic Rays



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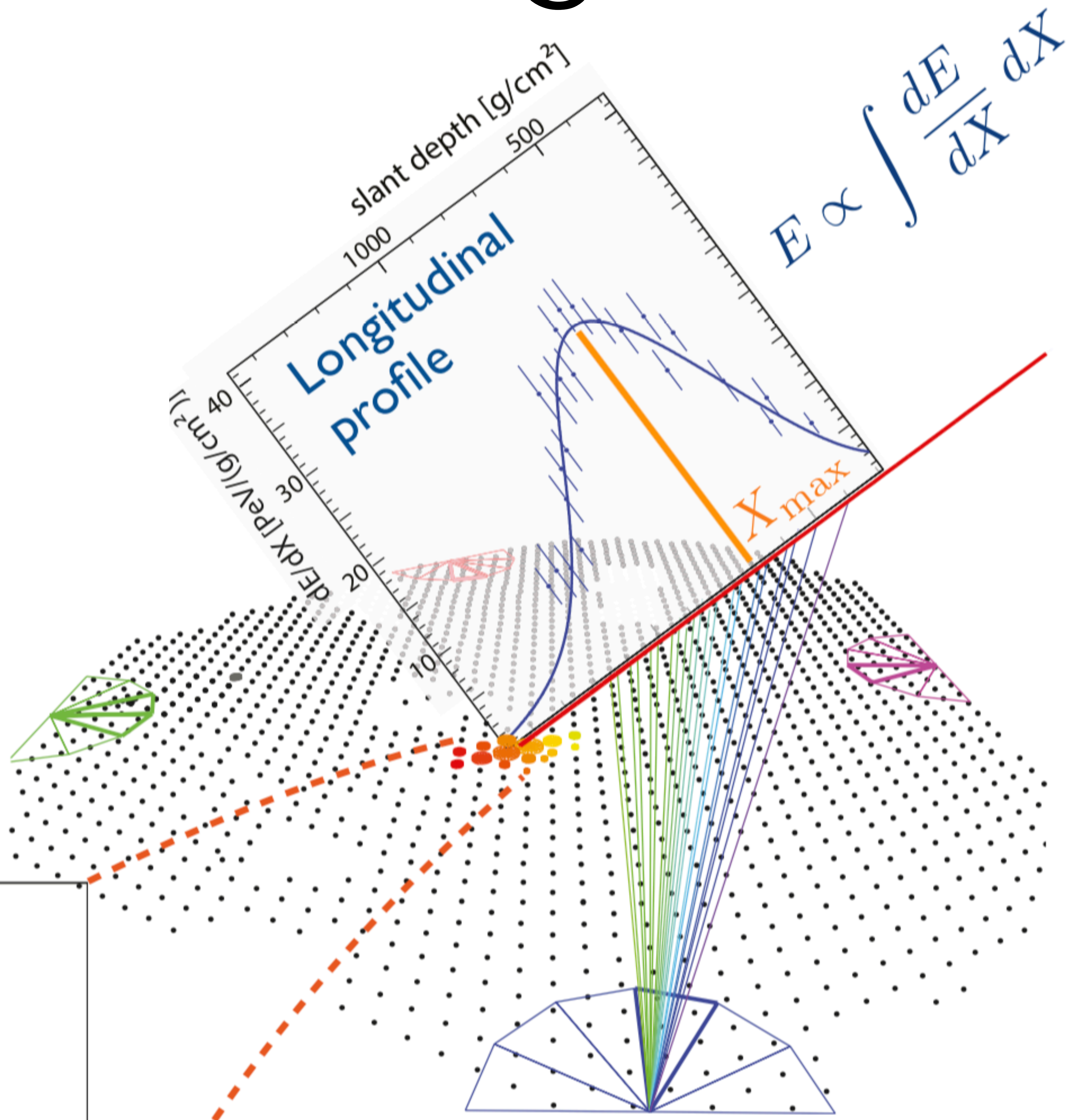
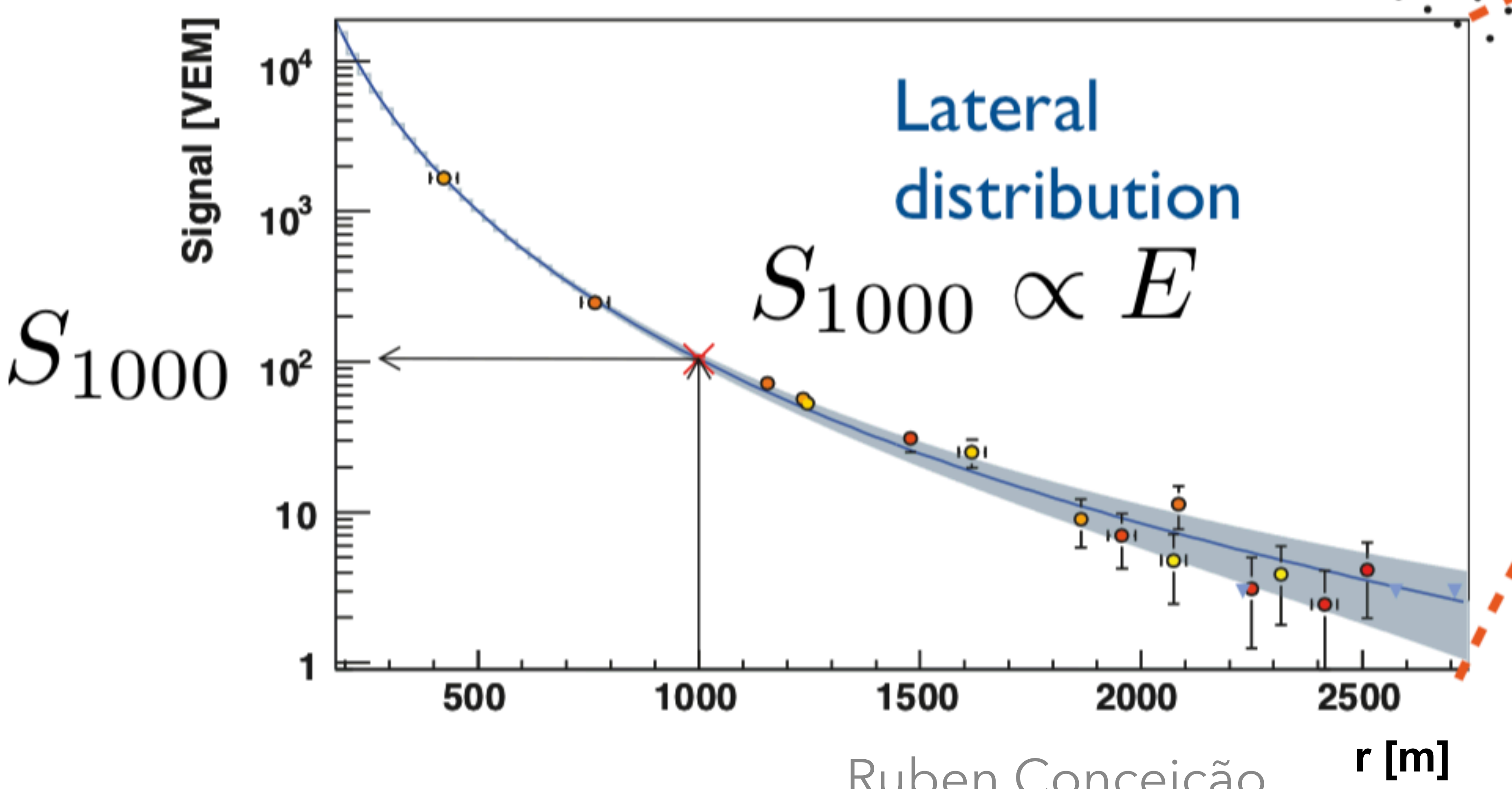
Low energy Extension

Measurement of EAS at Auger

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





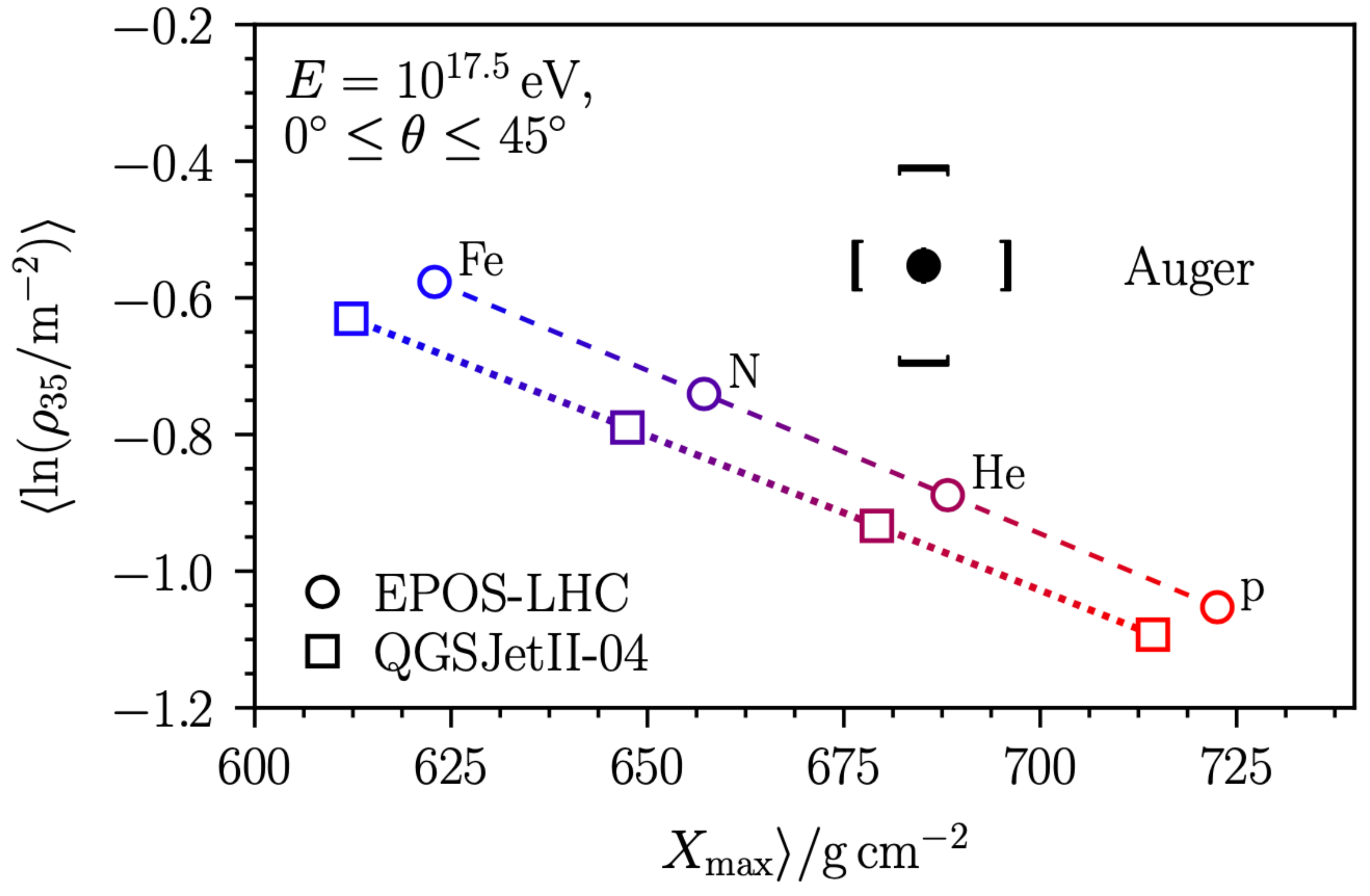
Hadronic Interaction Models

What is our current understanding of air showers?

The EAS muon puzzle @ Auger

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

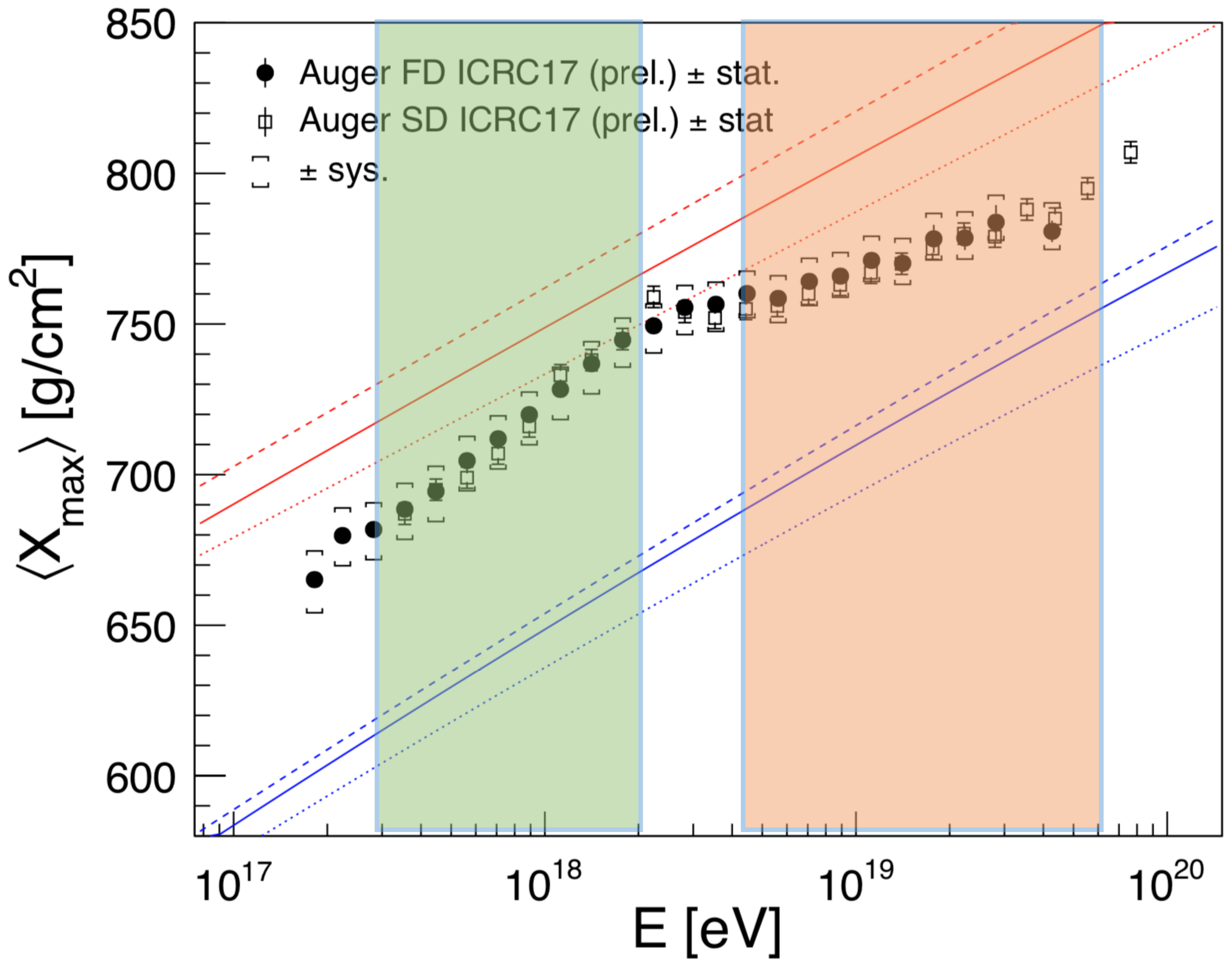
Phys.Rev.Lett. 126 (2021) 15, 152002

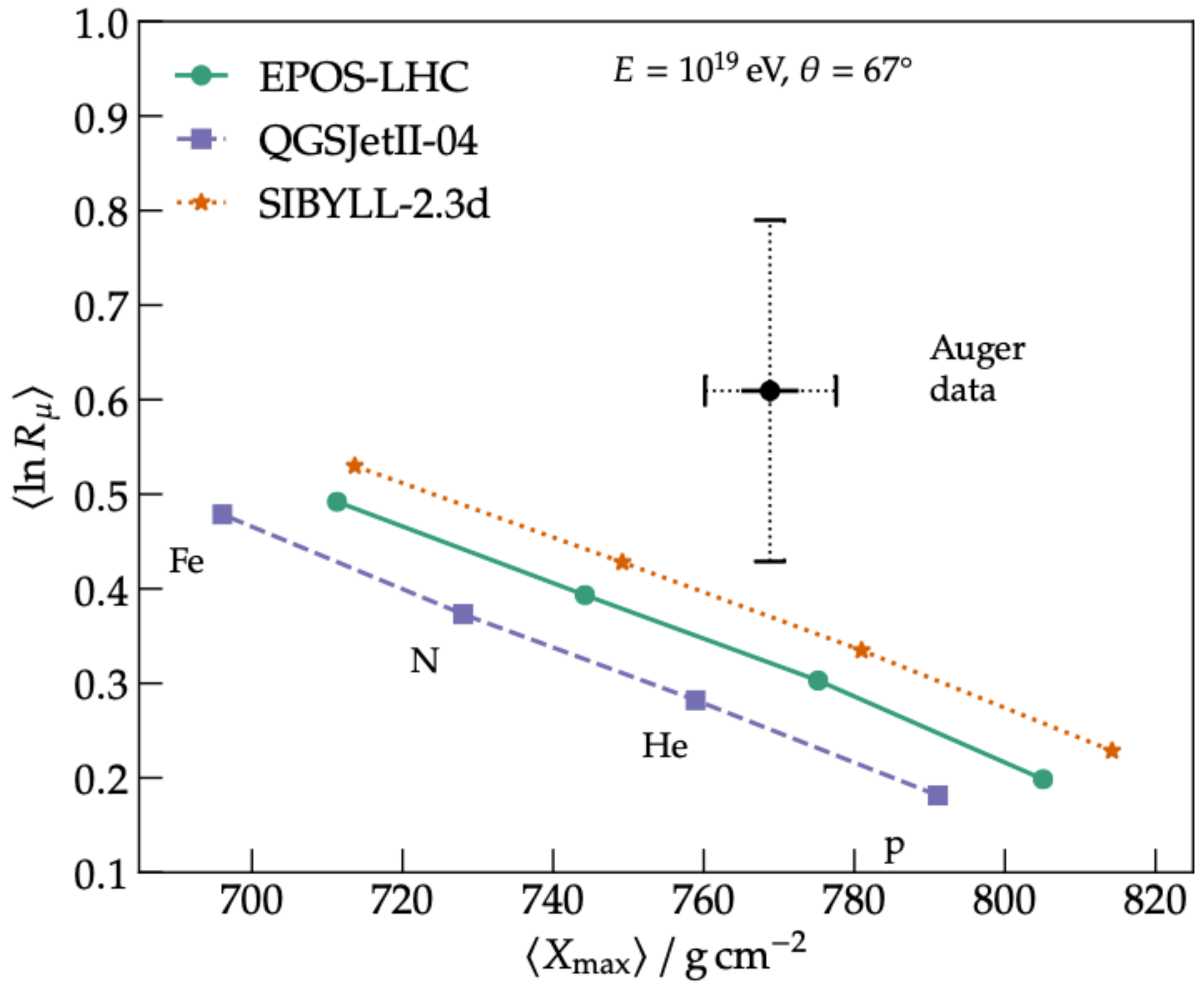


Buried Scintillators + FD

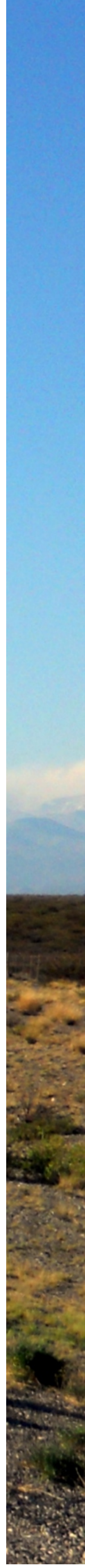
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

FD data



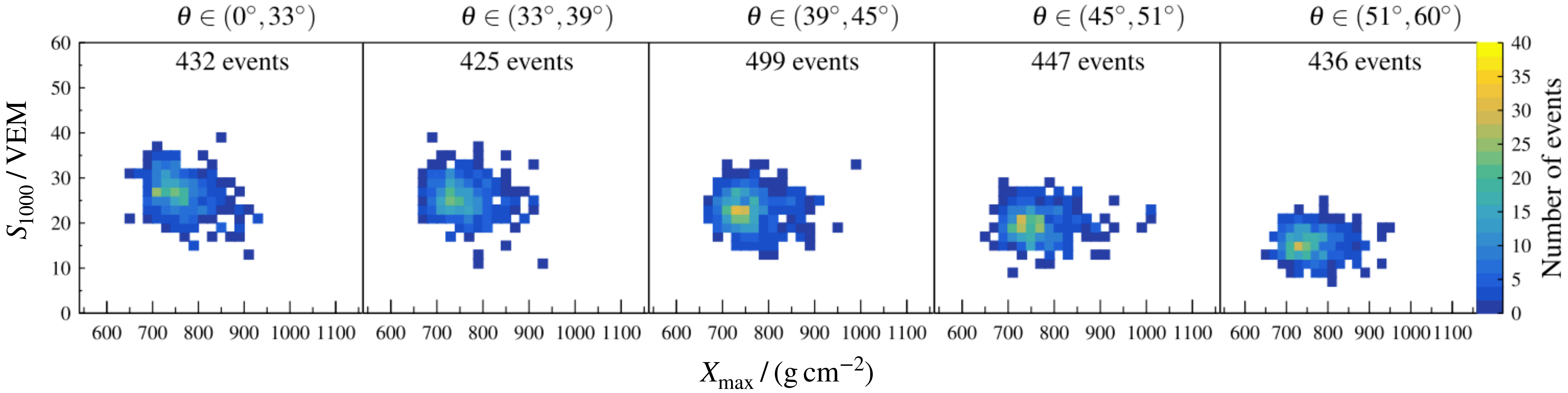


SD inclined + FD



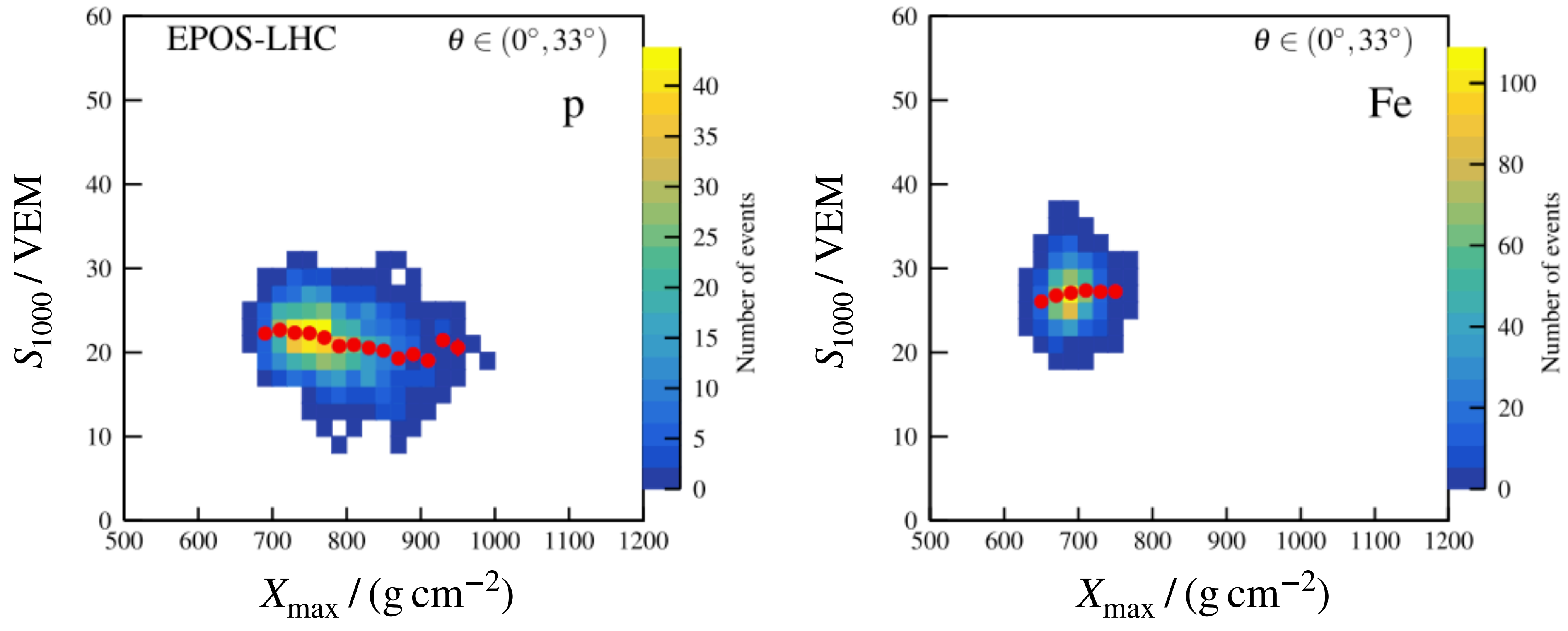
Analysis of the (X_{max}, S_{1000}) distribution

Phys.Rev.D 109 (2024) 10, 102001

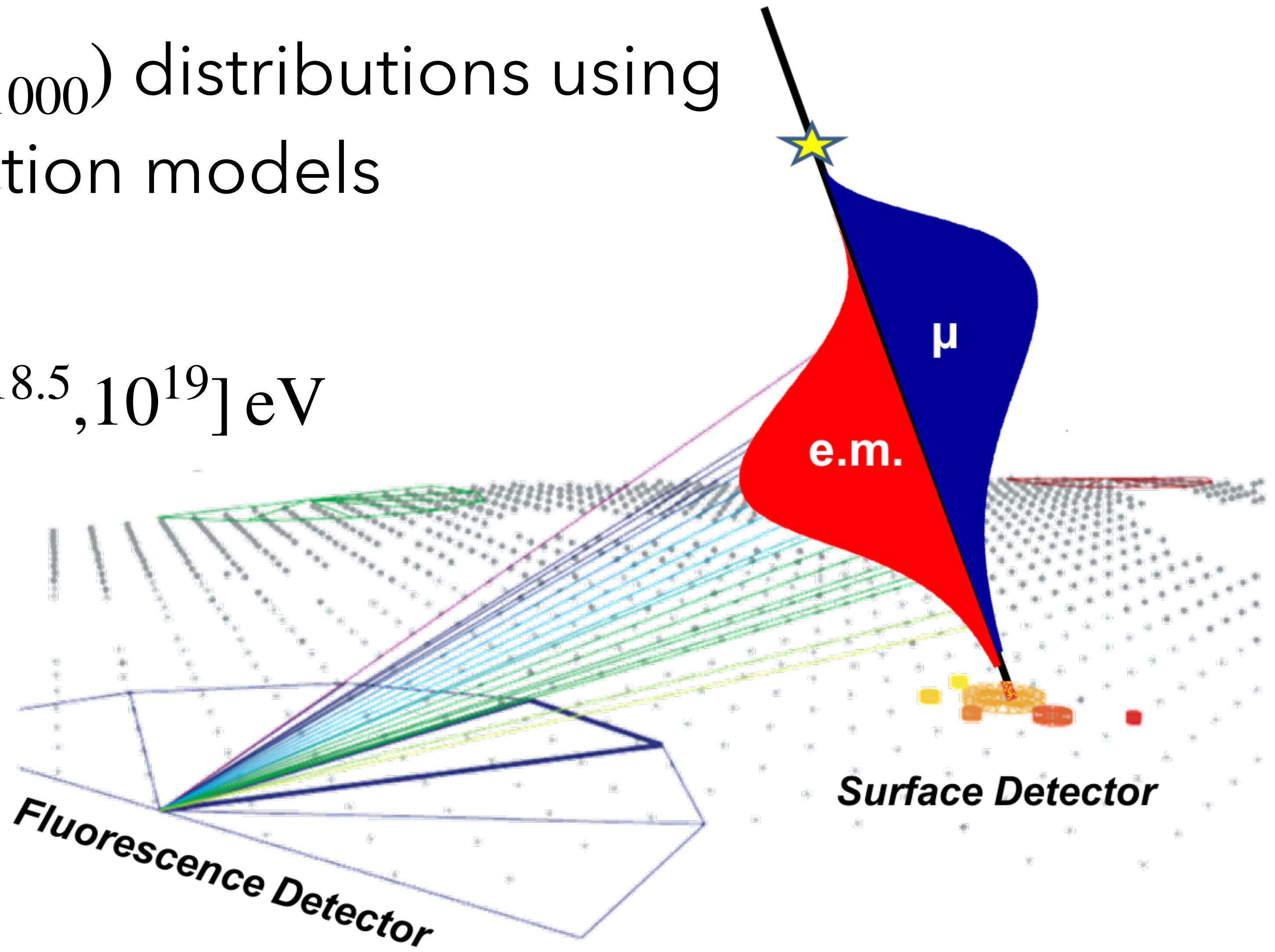


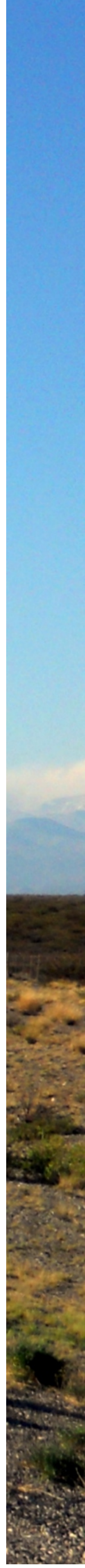
Explore hybrid FD-SD events and **fit the measured two-dimensional** (X_{max}, S_{1000}) distributions using templates for simulated air showers produced with hadronic interaction models

Example of MC templates



$E \in [10^{18.5}, 10^{19}]$ eV





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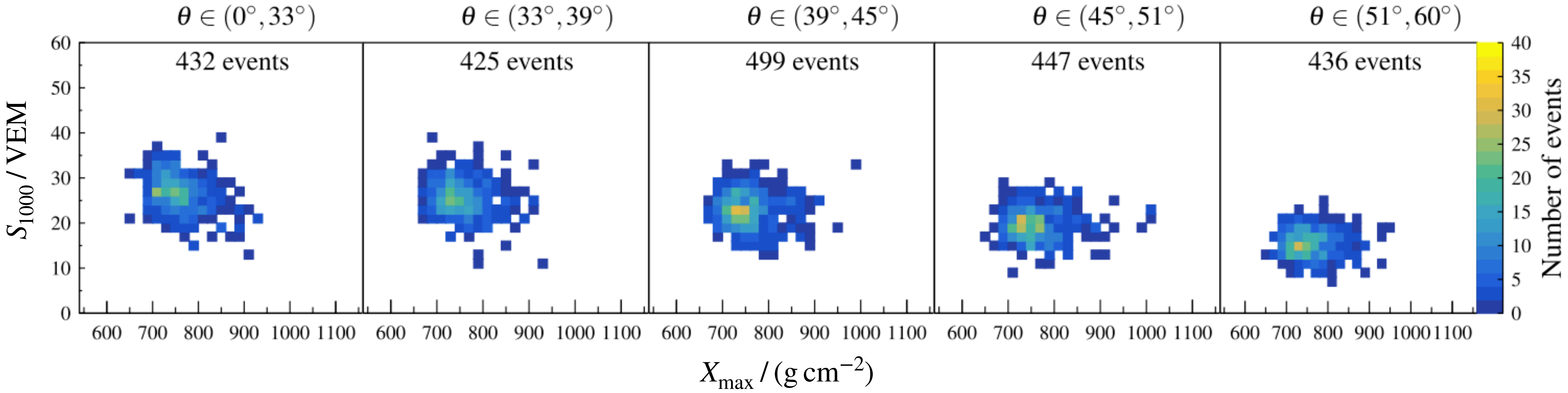


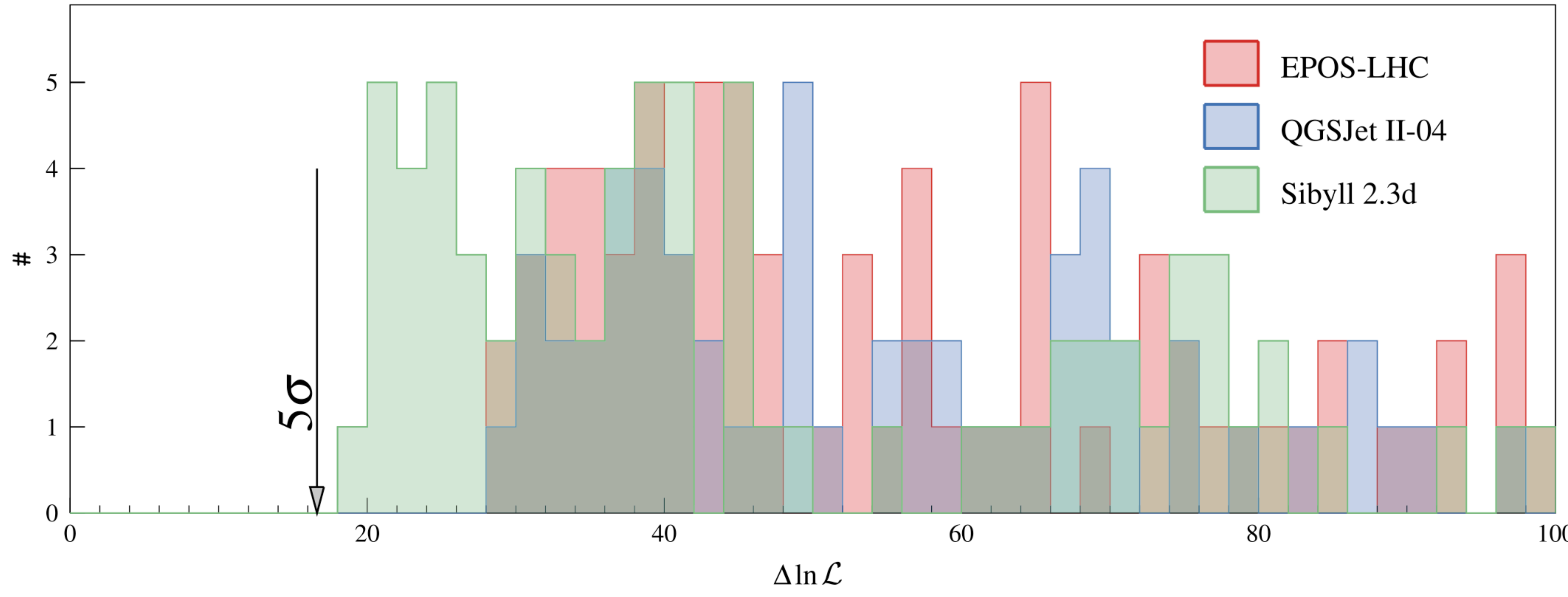
Systematic uncertainties

$E - 14\%$

$E + 14\%$

$X_{\max} - 9\mathrm{g/cm}^2$

$X_{\max} + 8\mathrm{g/cm}^2$

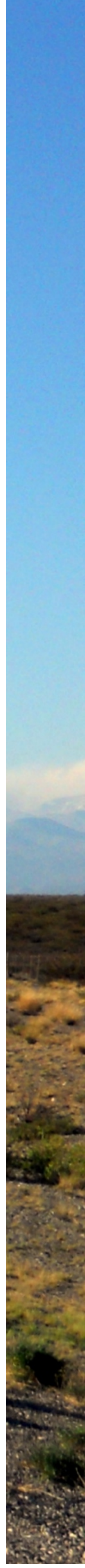


Systematic uncertainties

$S(1000) - 5\%$

$S(1000) + 5\%$

Method



None of the post-LHC hadronic interaction models can describe the Auger $(X_{\max}, S_{1000})$ data, even considering the systematic uncertainties

Muon puzzle

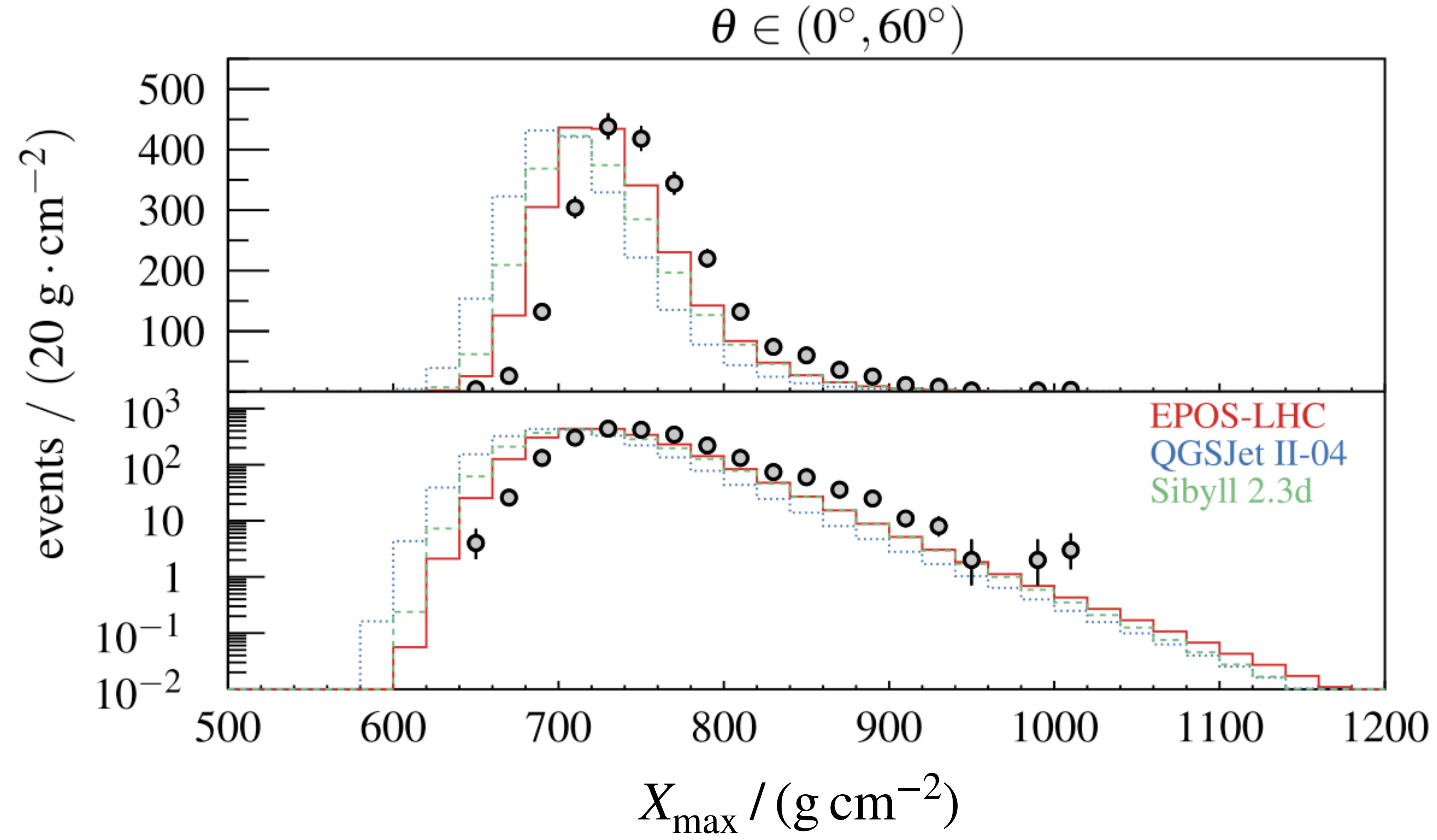
Phys.Rev.D 109 (2024) 10, 102001

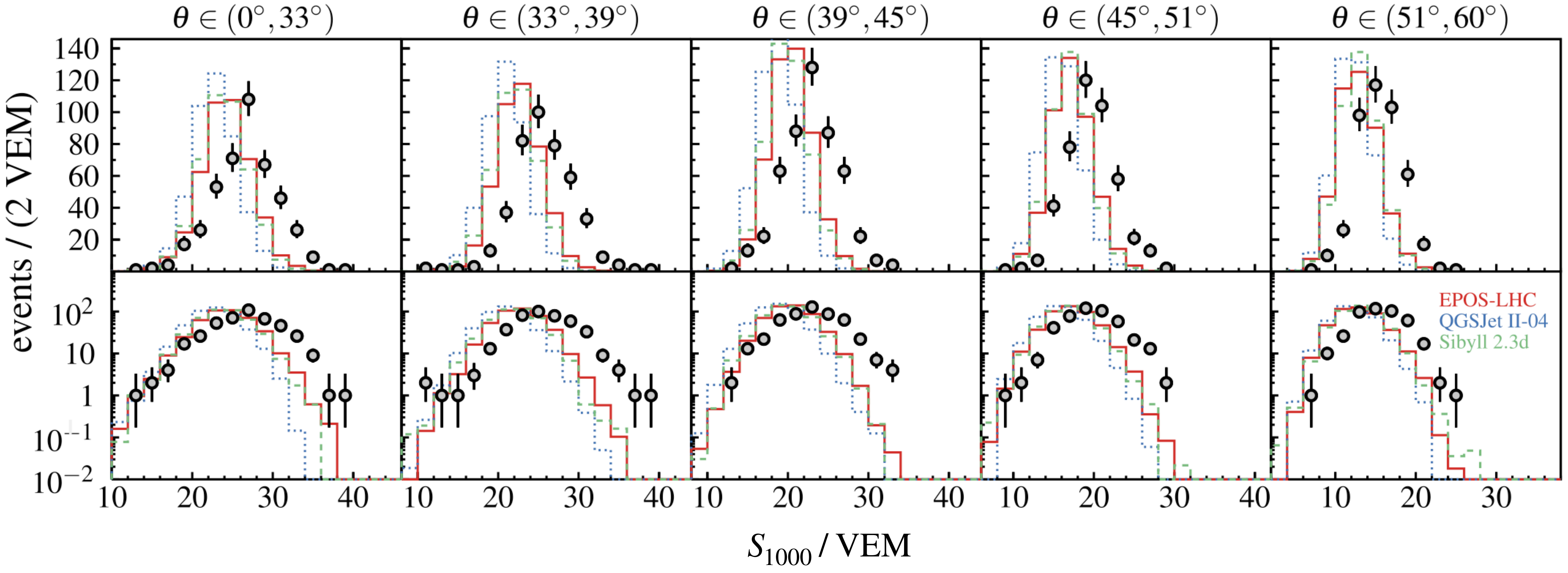
Allow for a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}

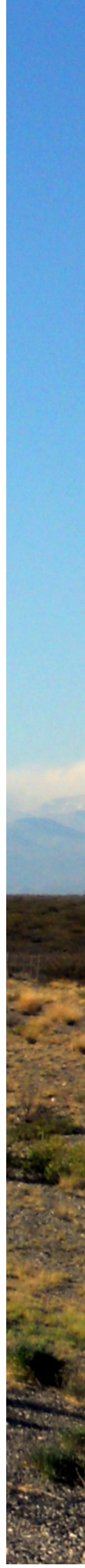
$R_{\mathrm{had}} > 1$ for all tested hadronic interaction models - EAS muon puzzle

In accordance with previous Auger results *Phys.Rev.Lett. 117 (2016) 19, 192001*

Poor agreement between data and simulations



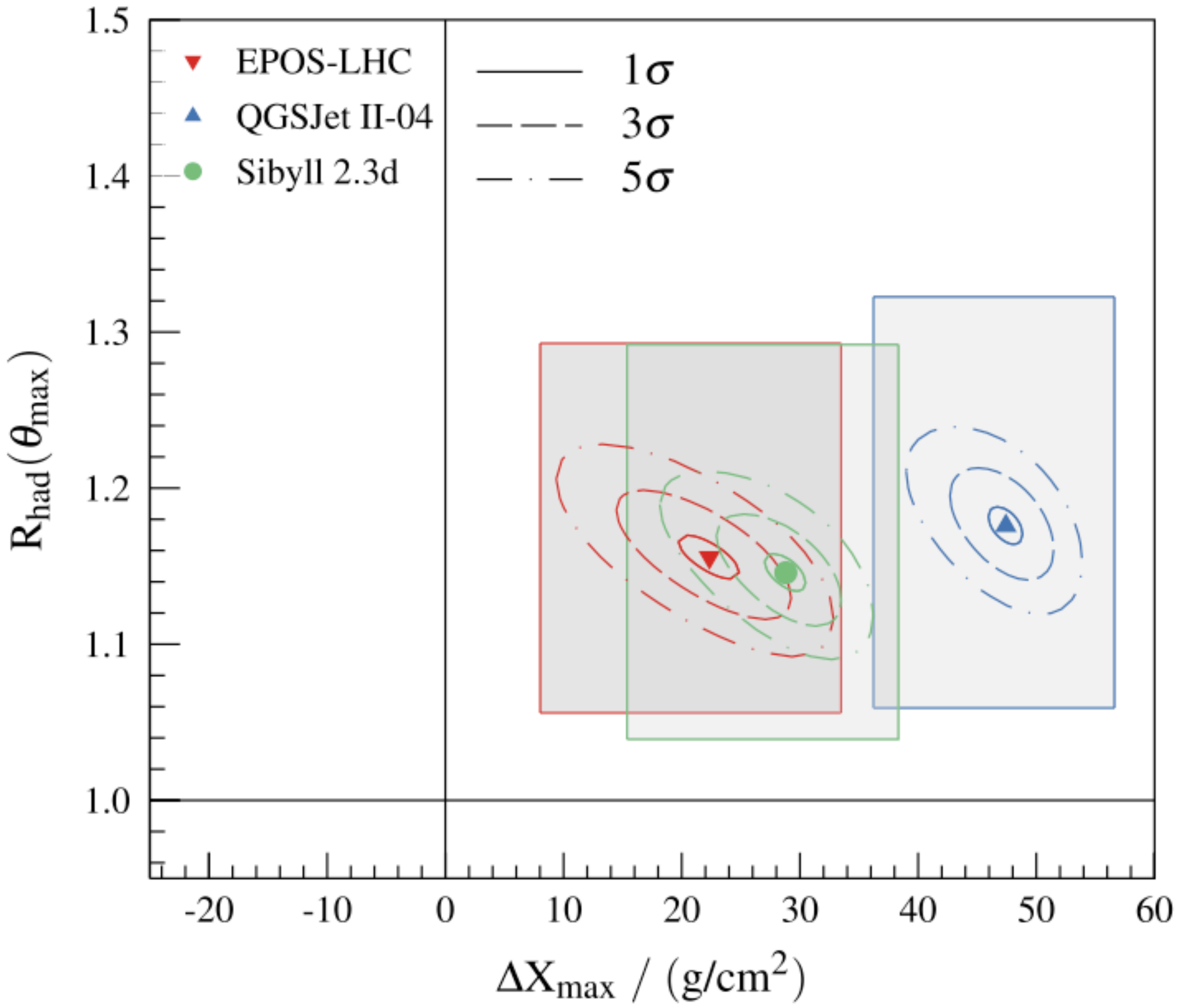


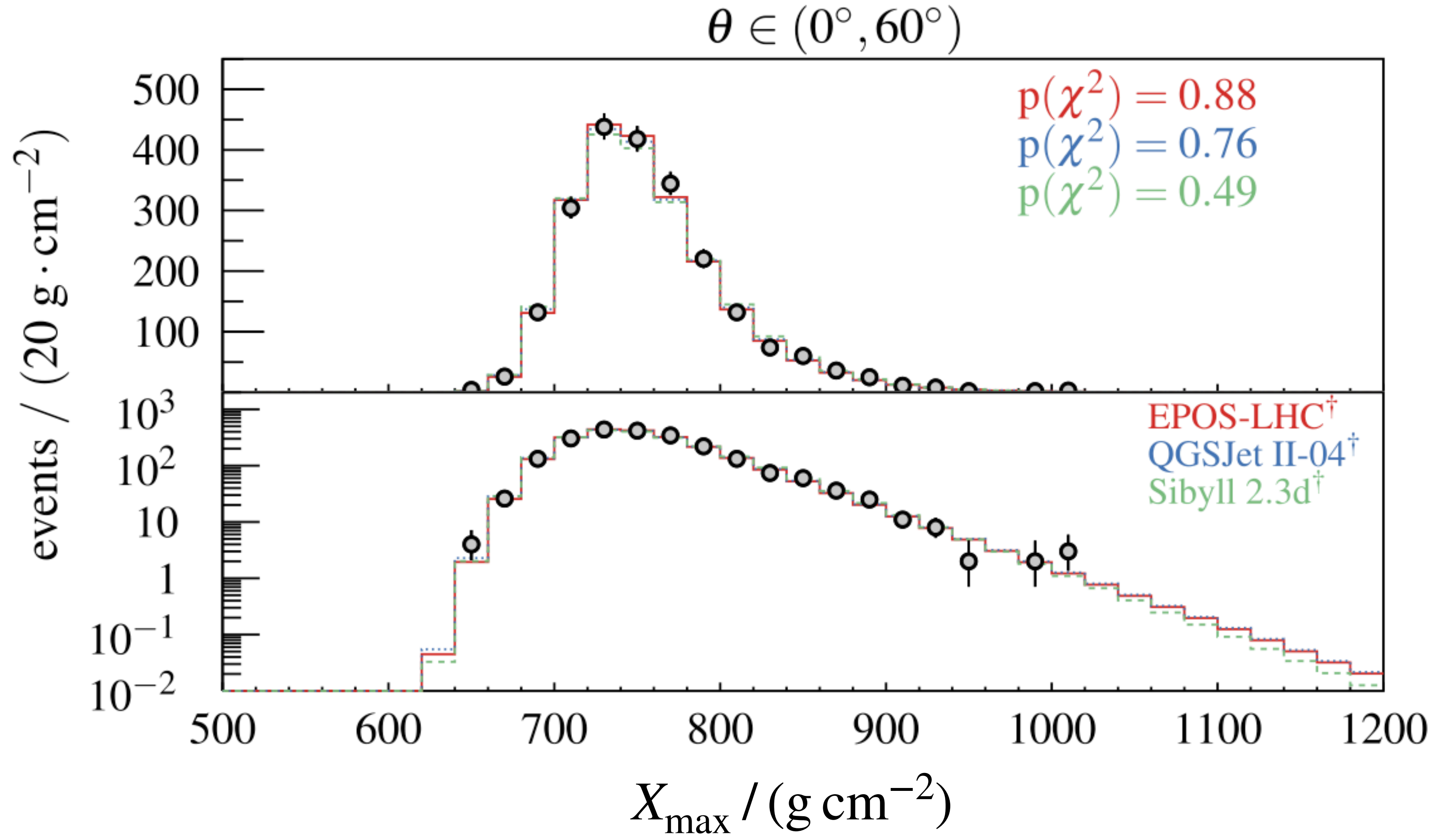


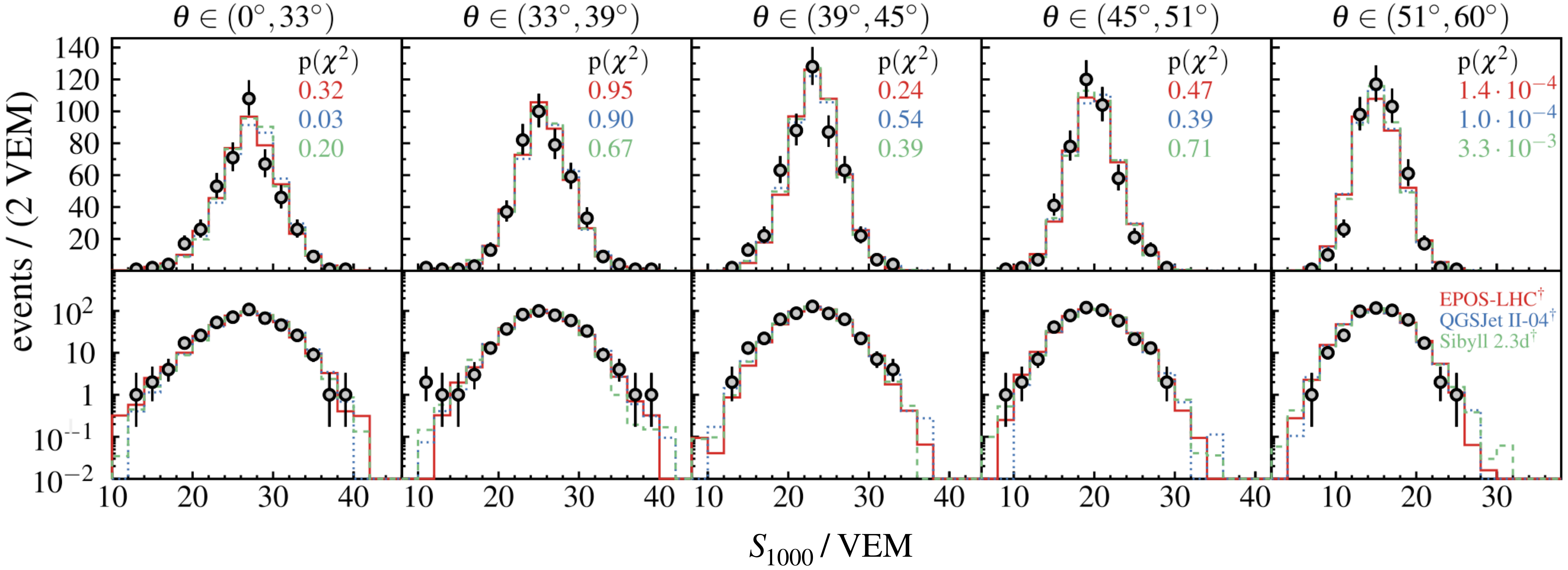
Muon puzzle + Shift in X_{max} scale

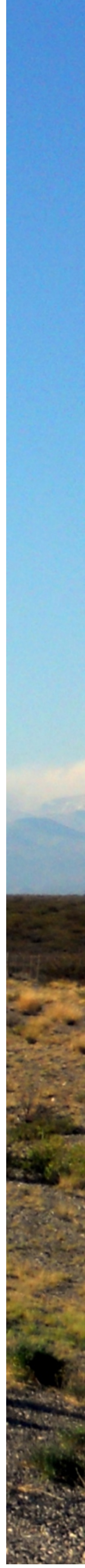
Phys.Rev.D 109 (2024) 10, 102001

Allow simultaneously for an ad-hoc **shift on the** X_{max} scale and a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}



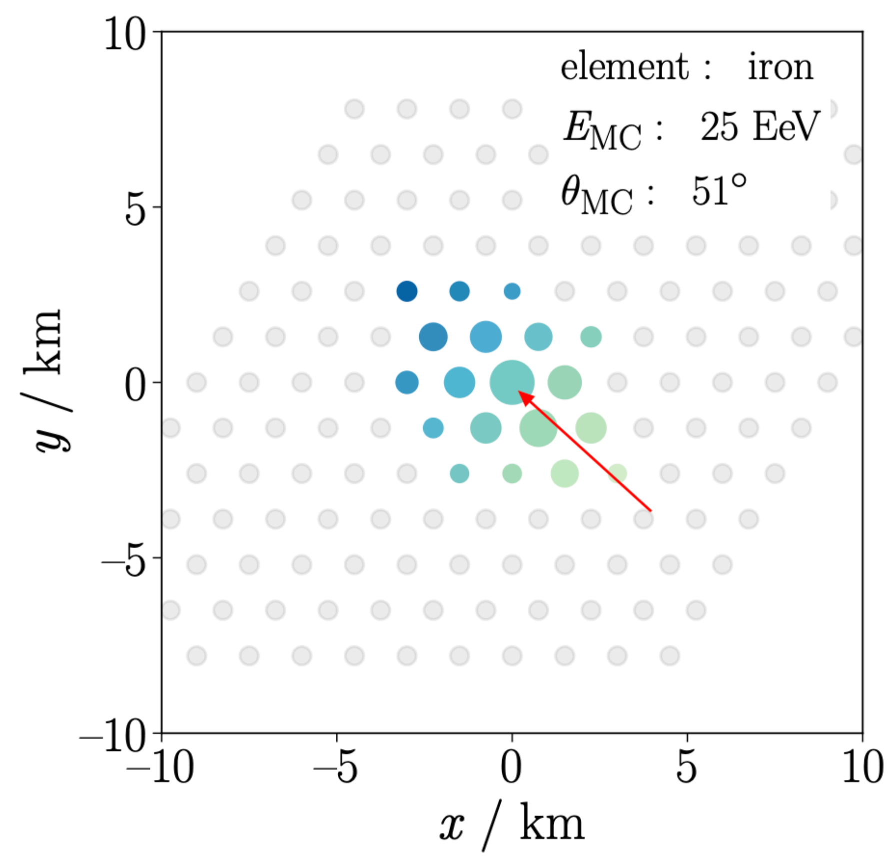


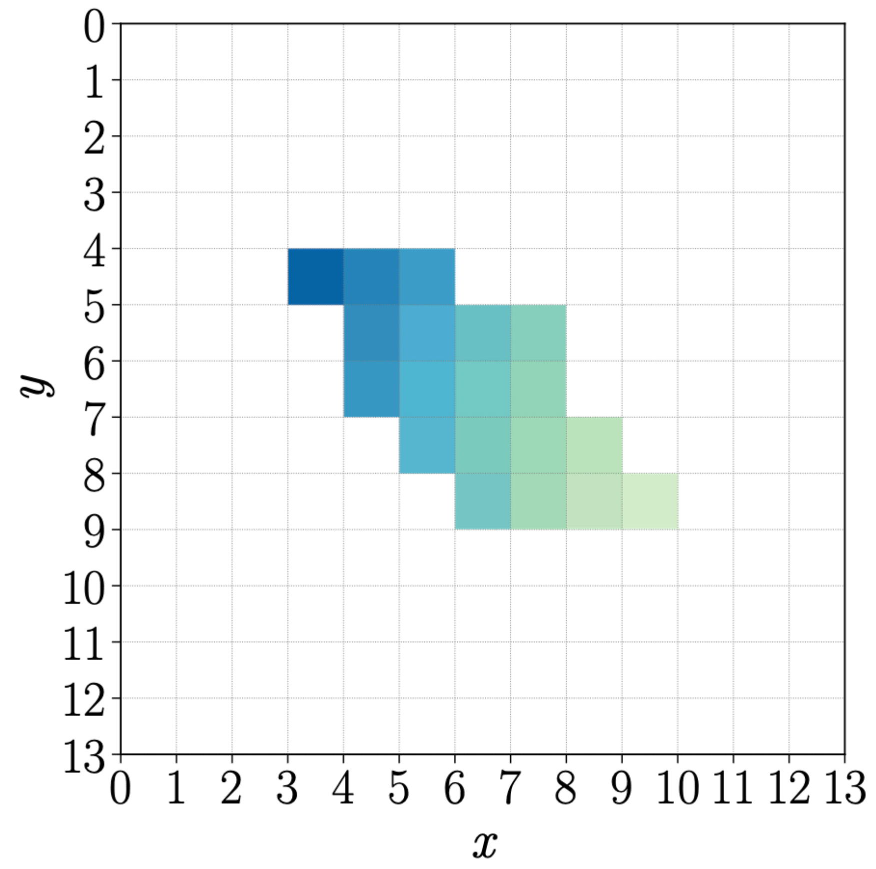




$X_{\max}$ from SD trace using a DNN

Accepted in PRL + PRD (2024)





Extract the $X_{\max}$ from SD-only events

X_{max} from SD trace using a DNN

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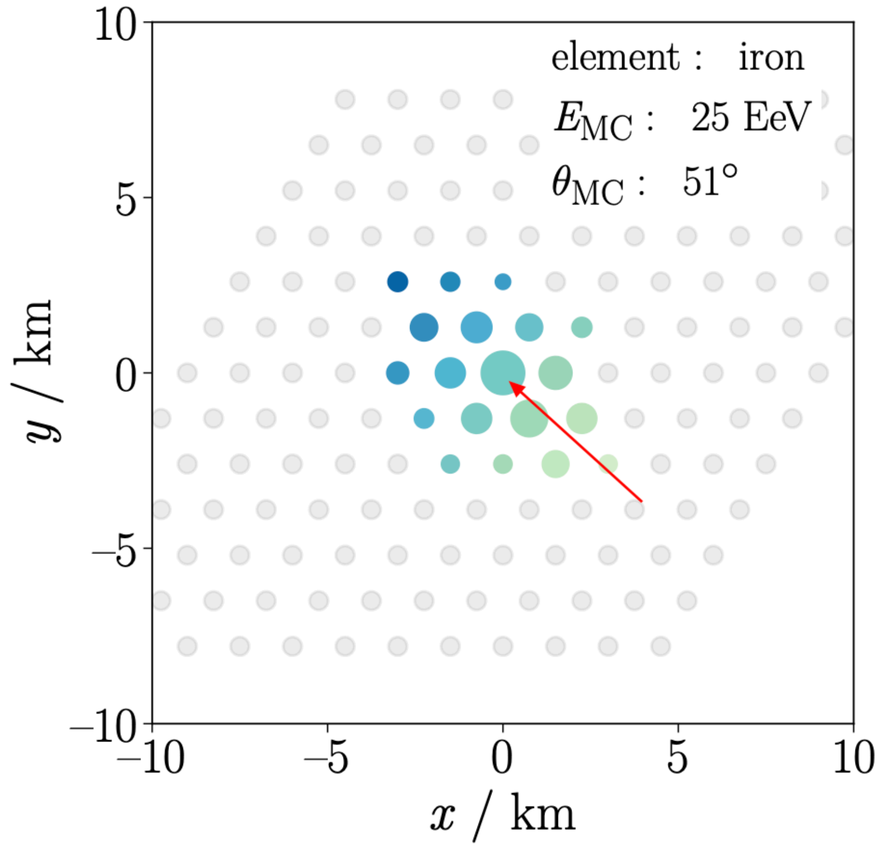

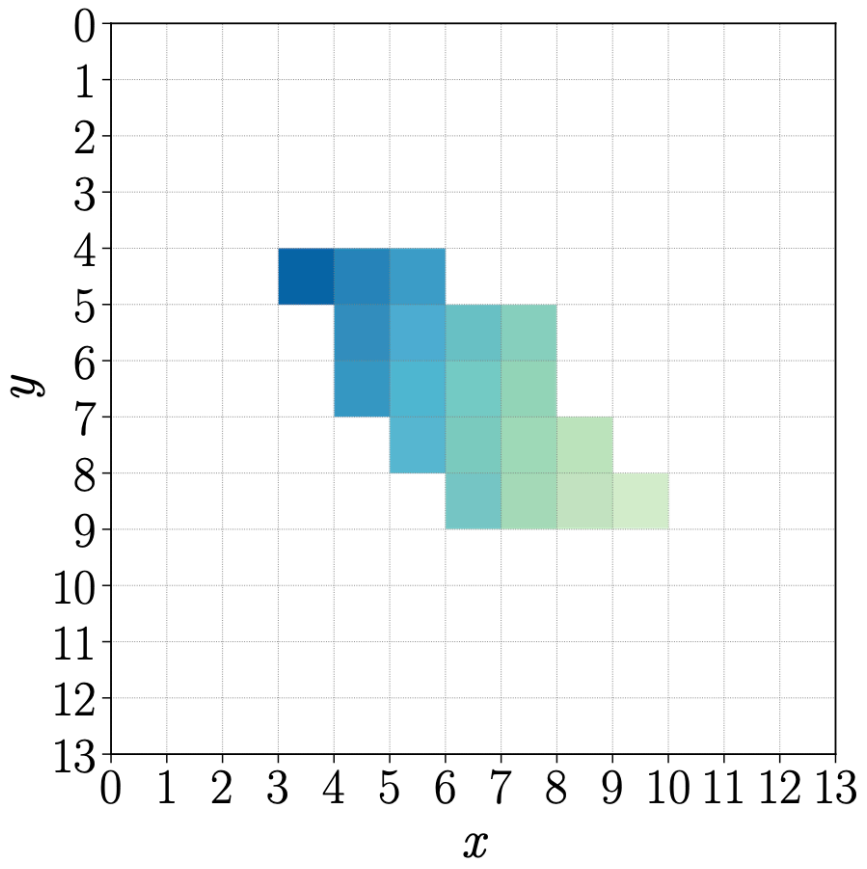

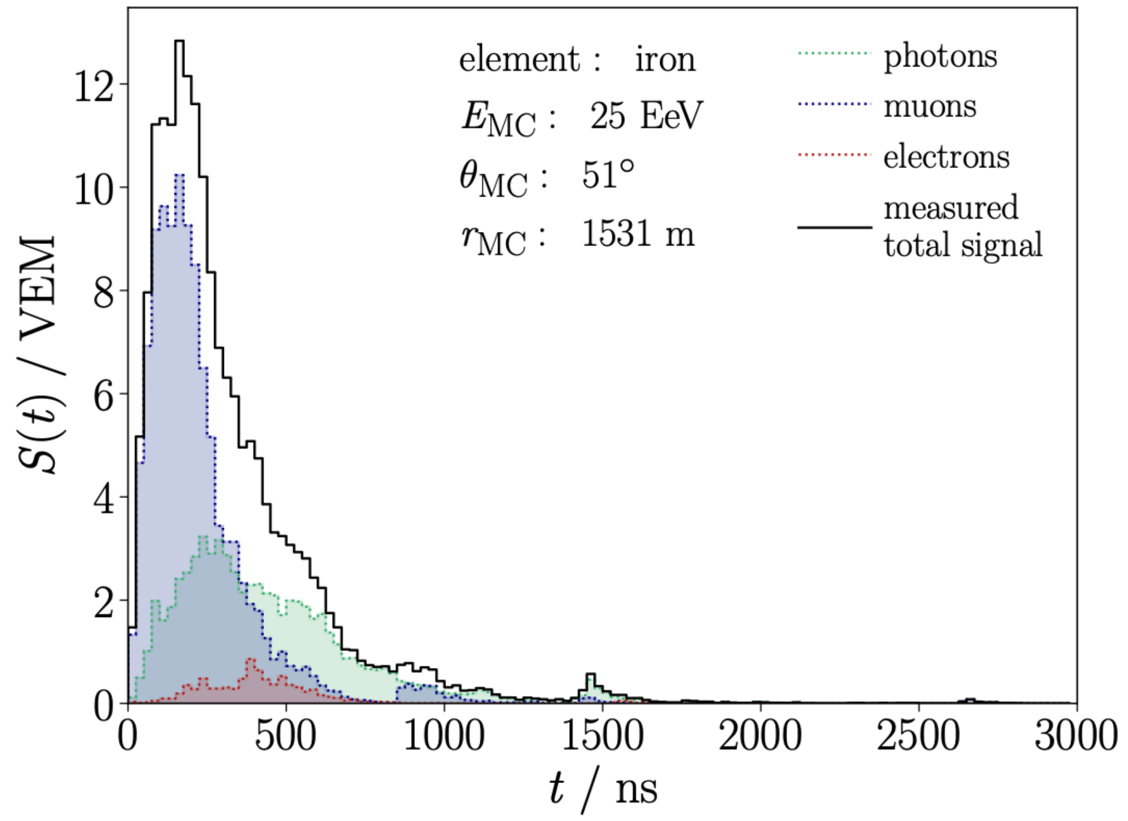

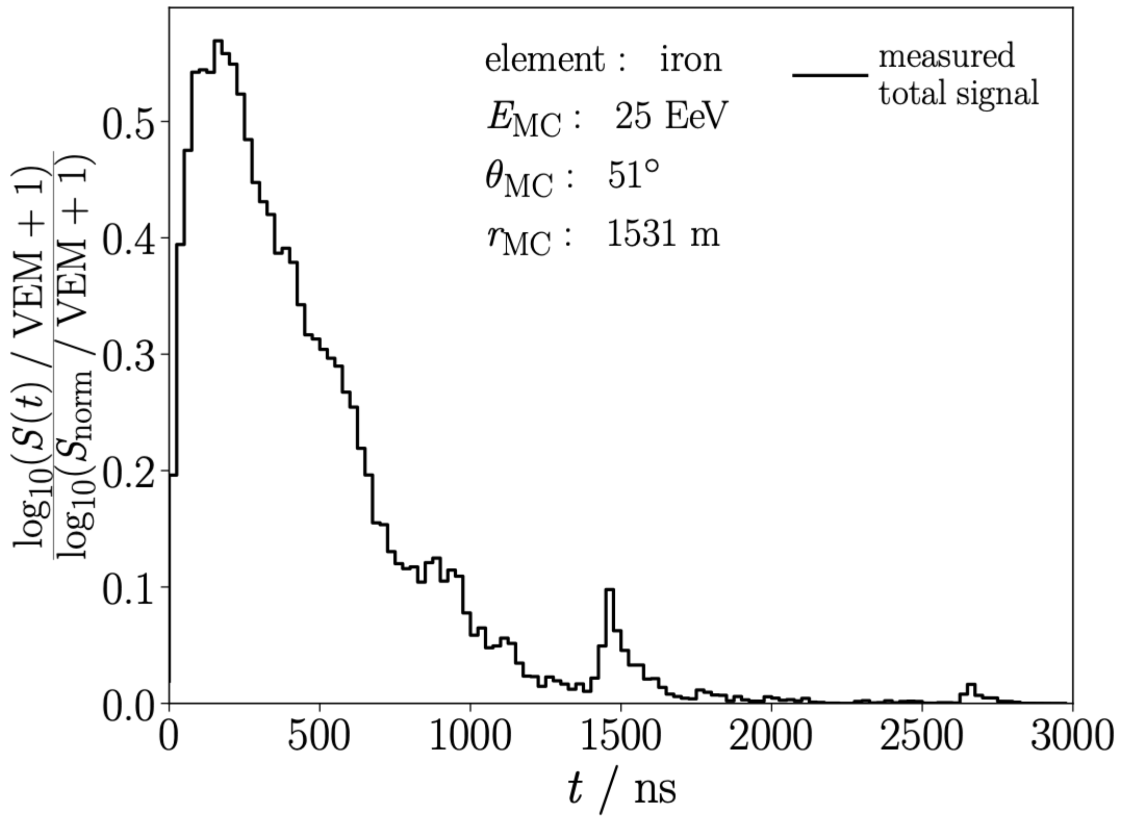

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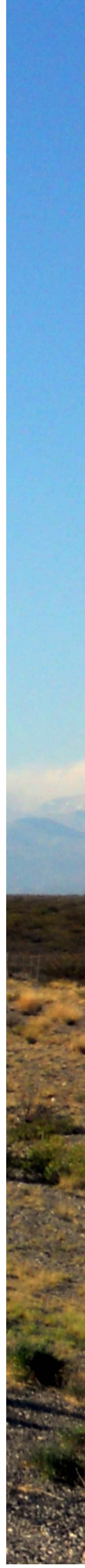

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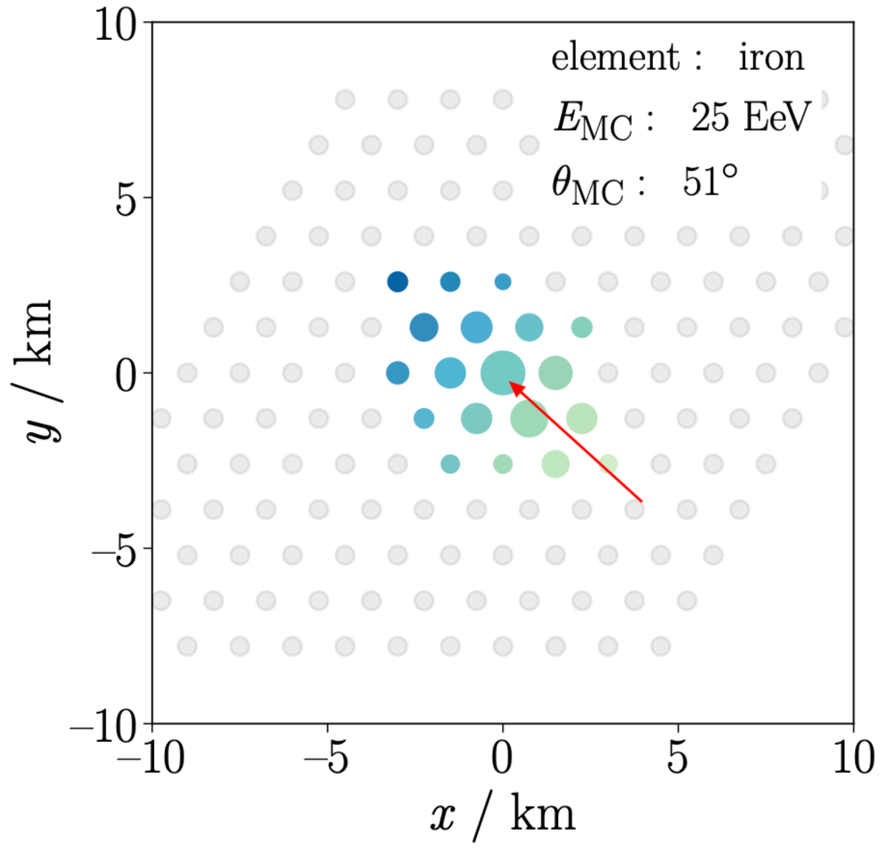

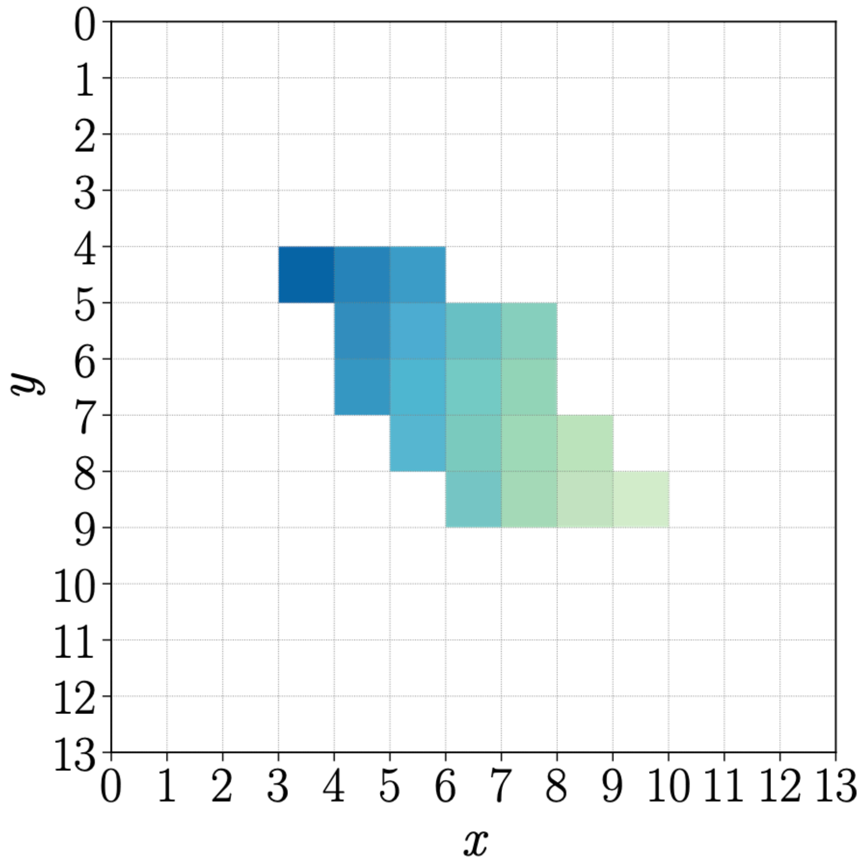

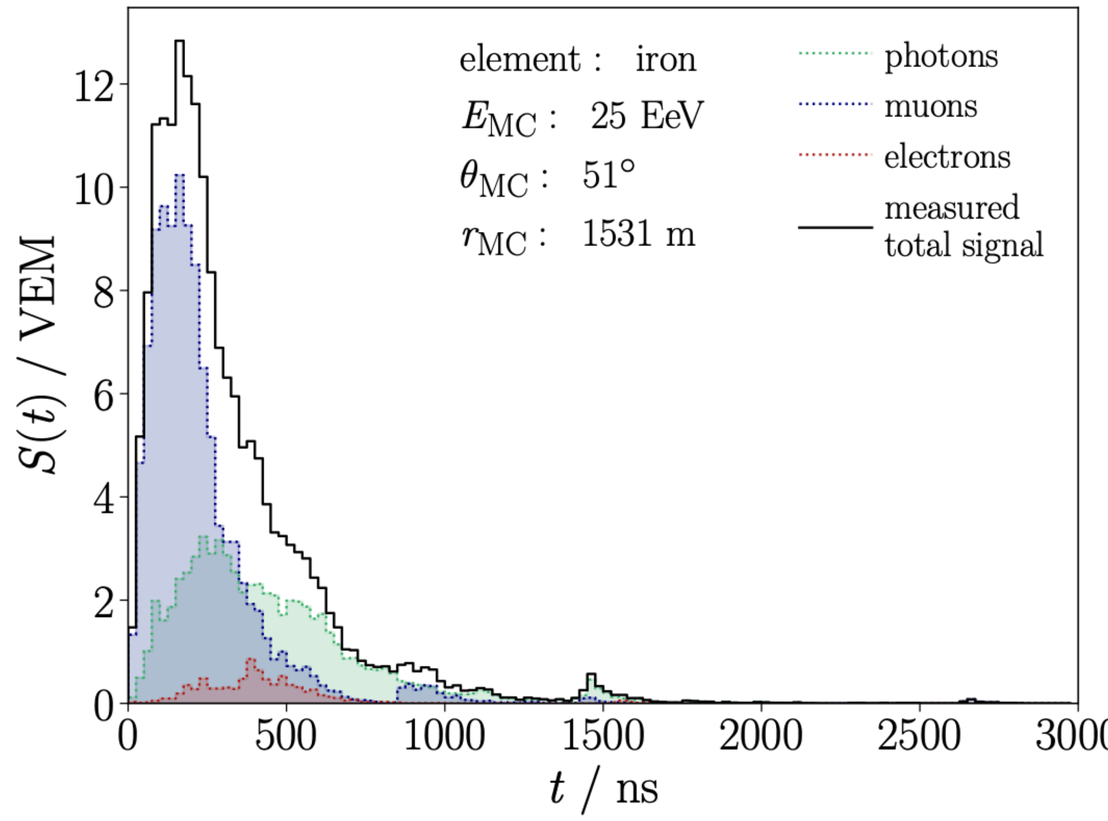

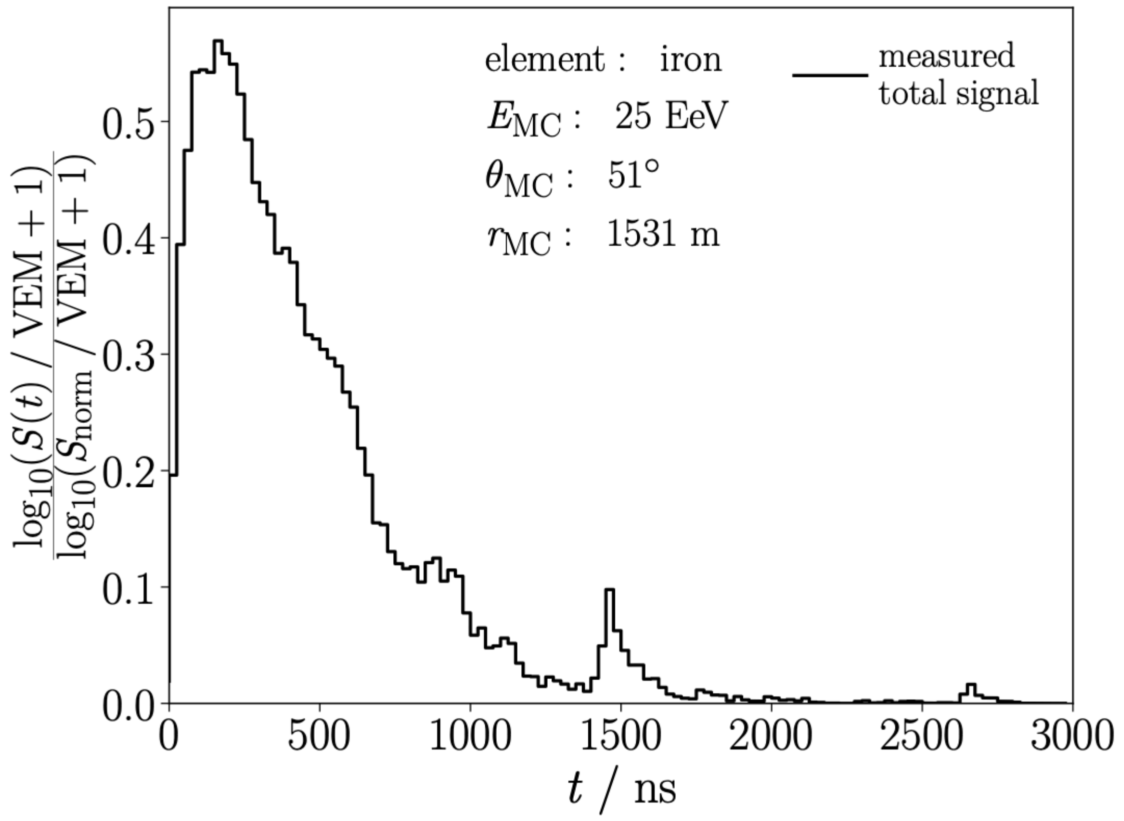

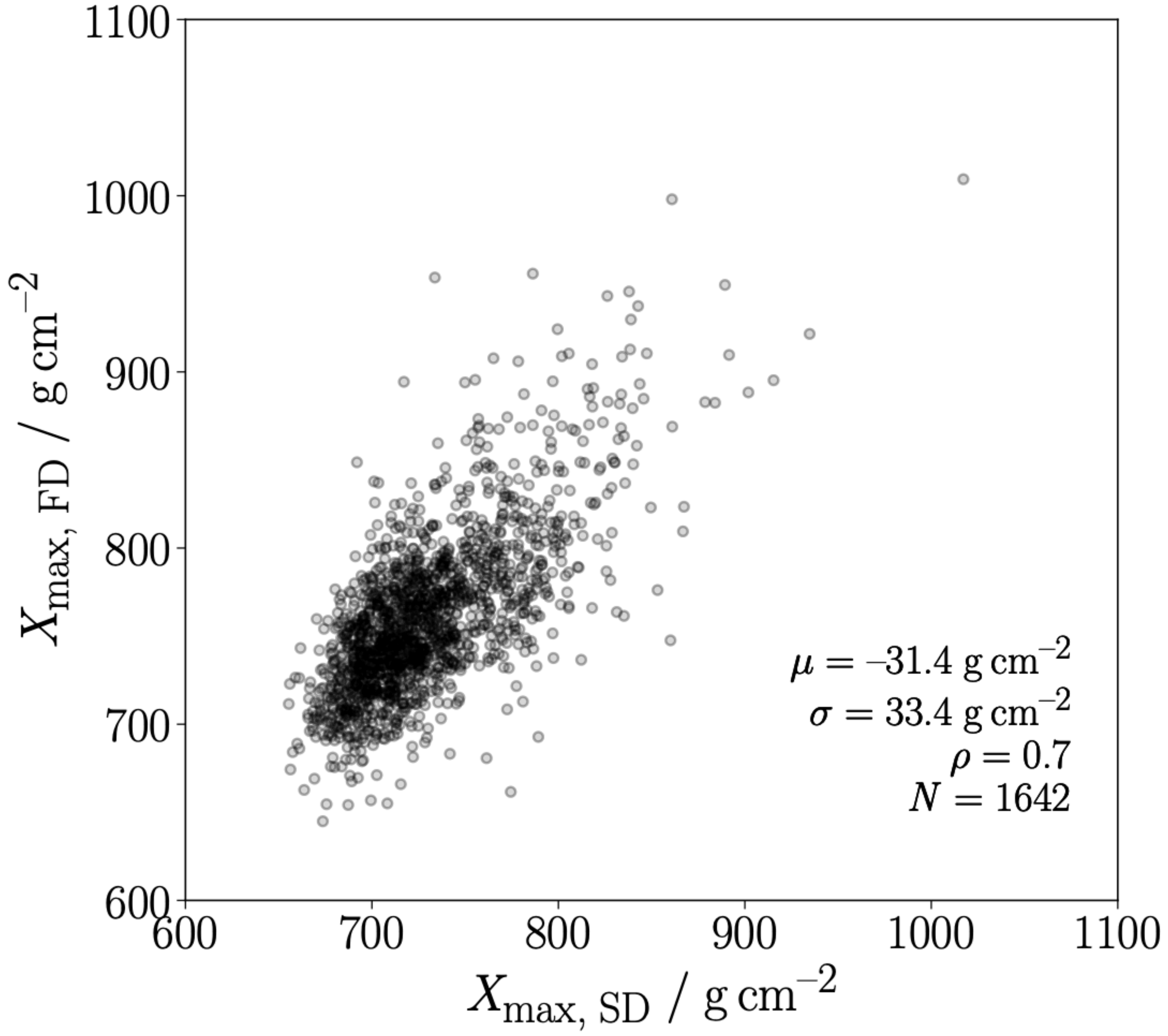

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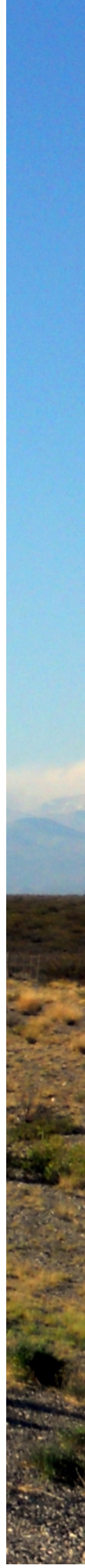
Exploit the SD traces using a Deep Neural Network

Test DNN performance using FD-SD **hybrid events**



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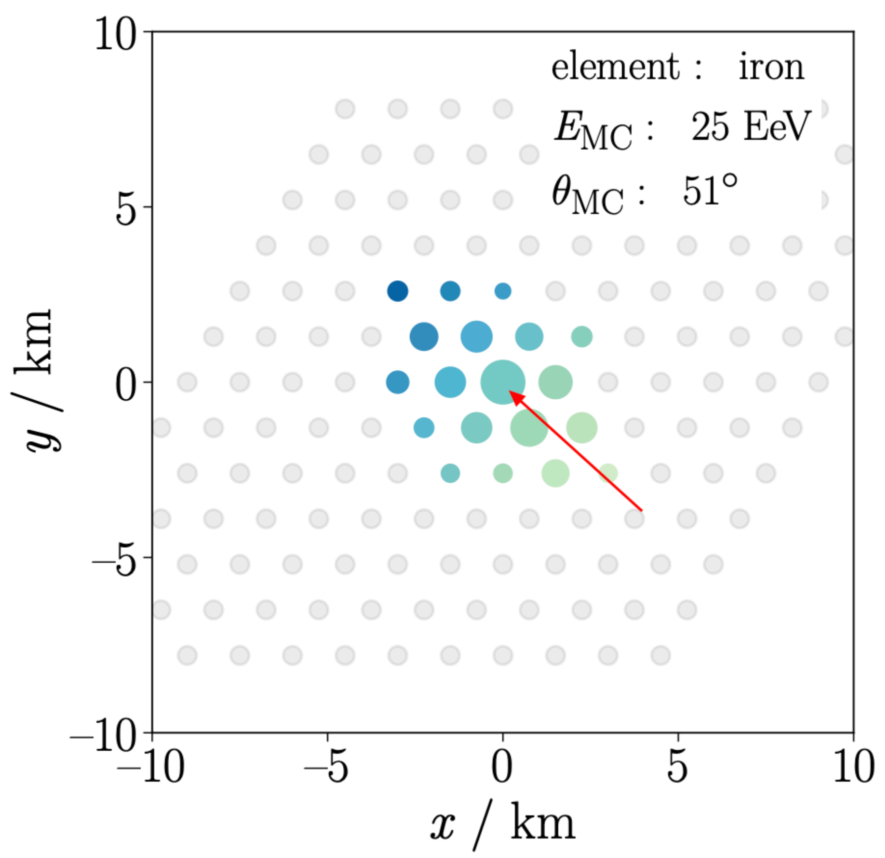

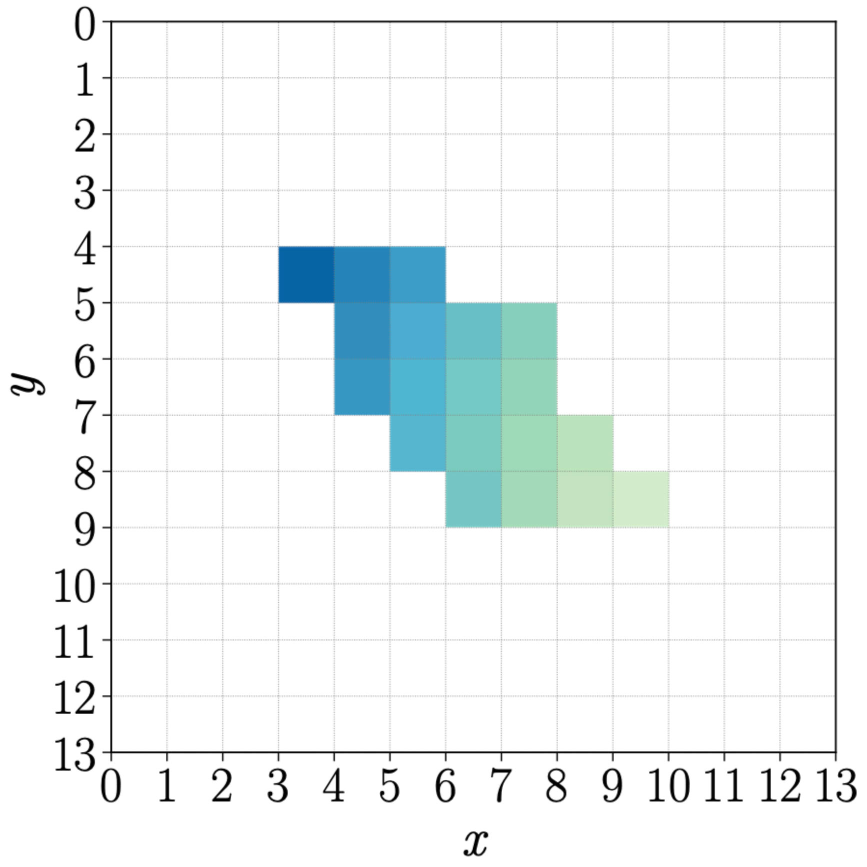

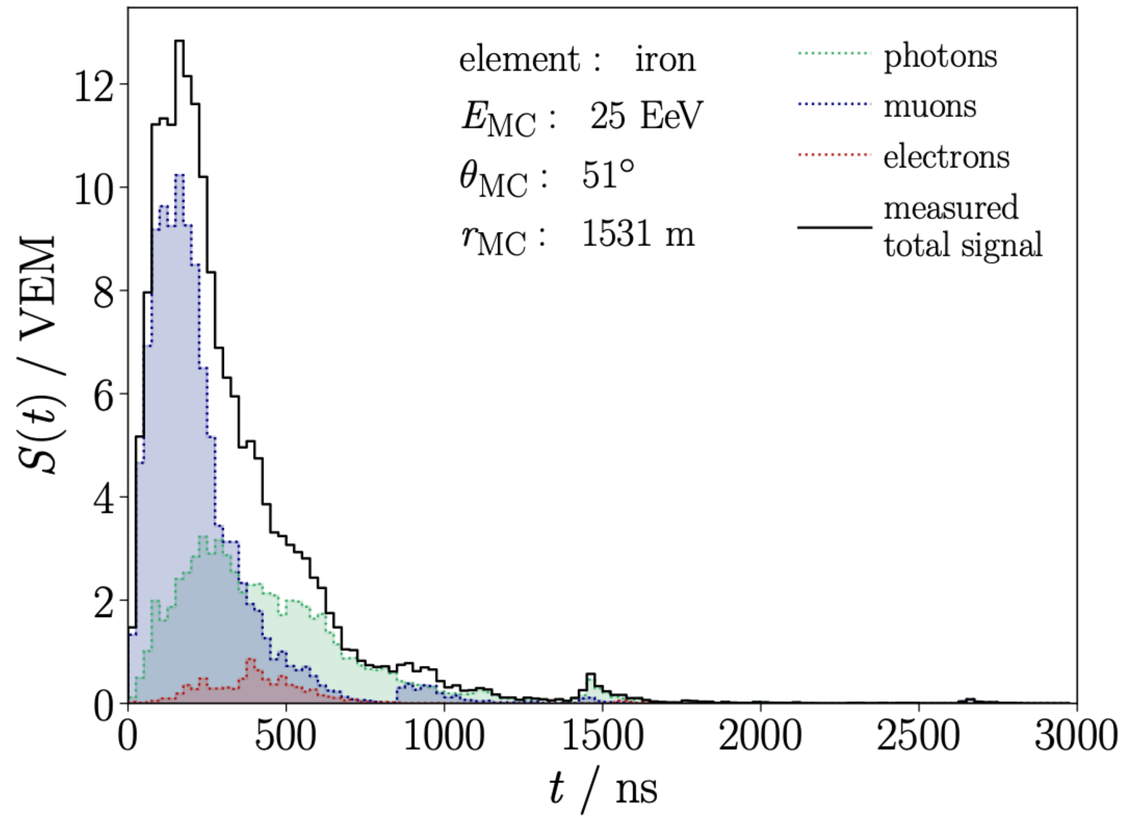

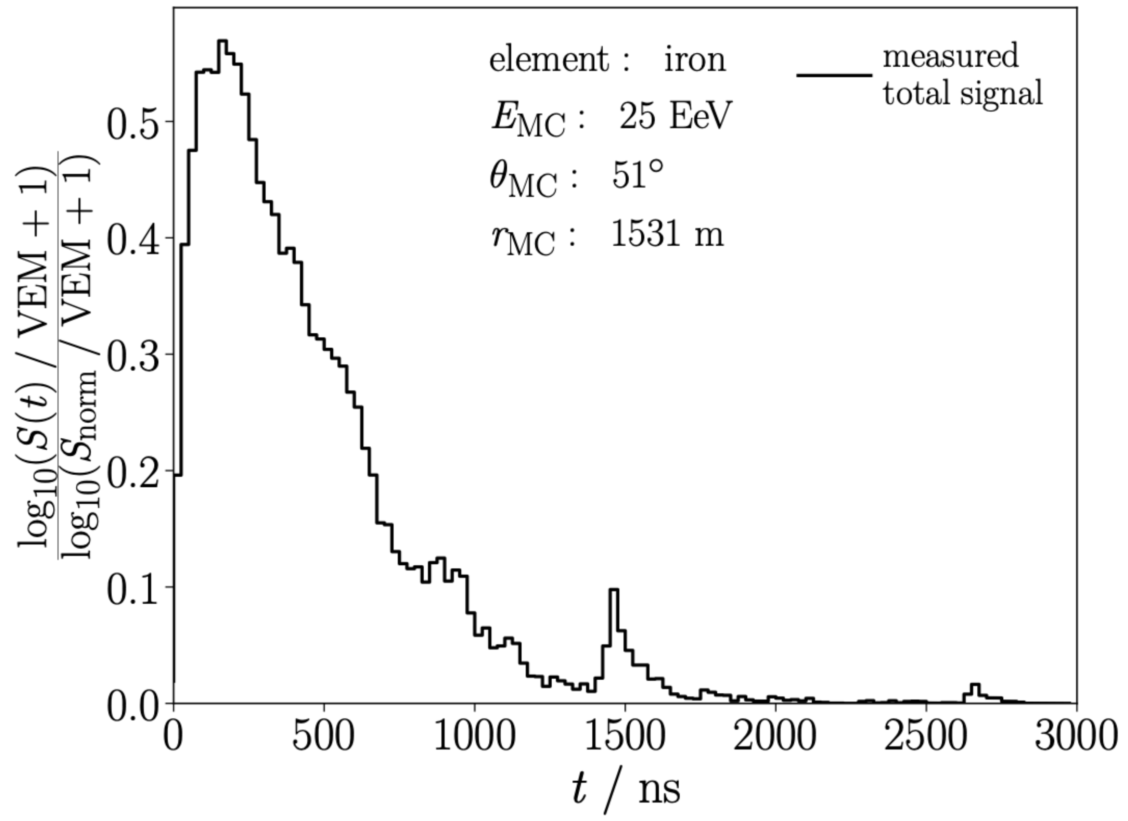

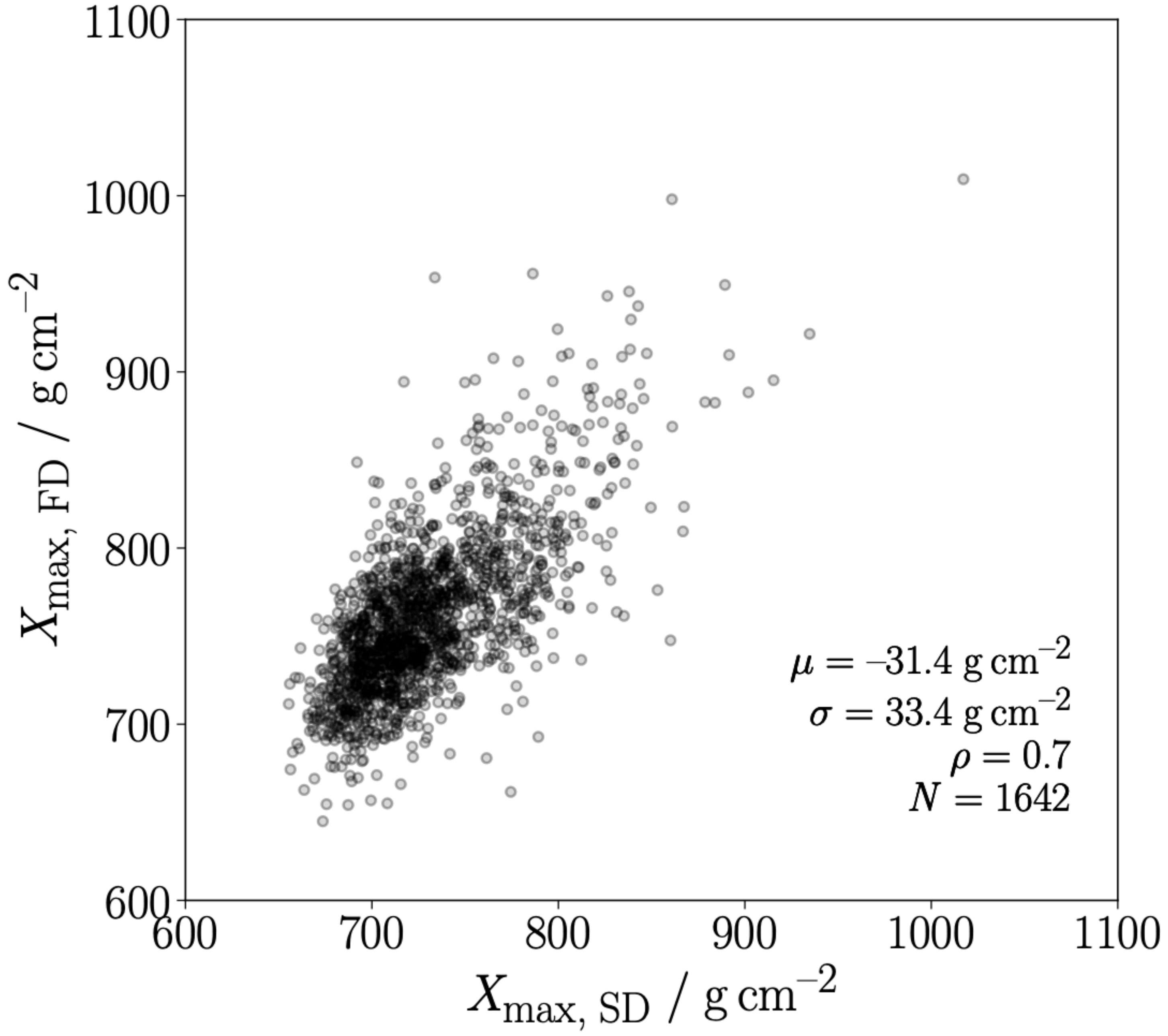

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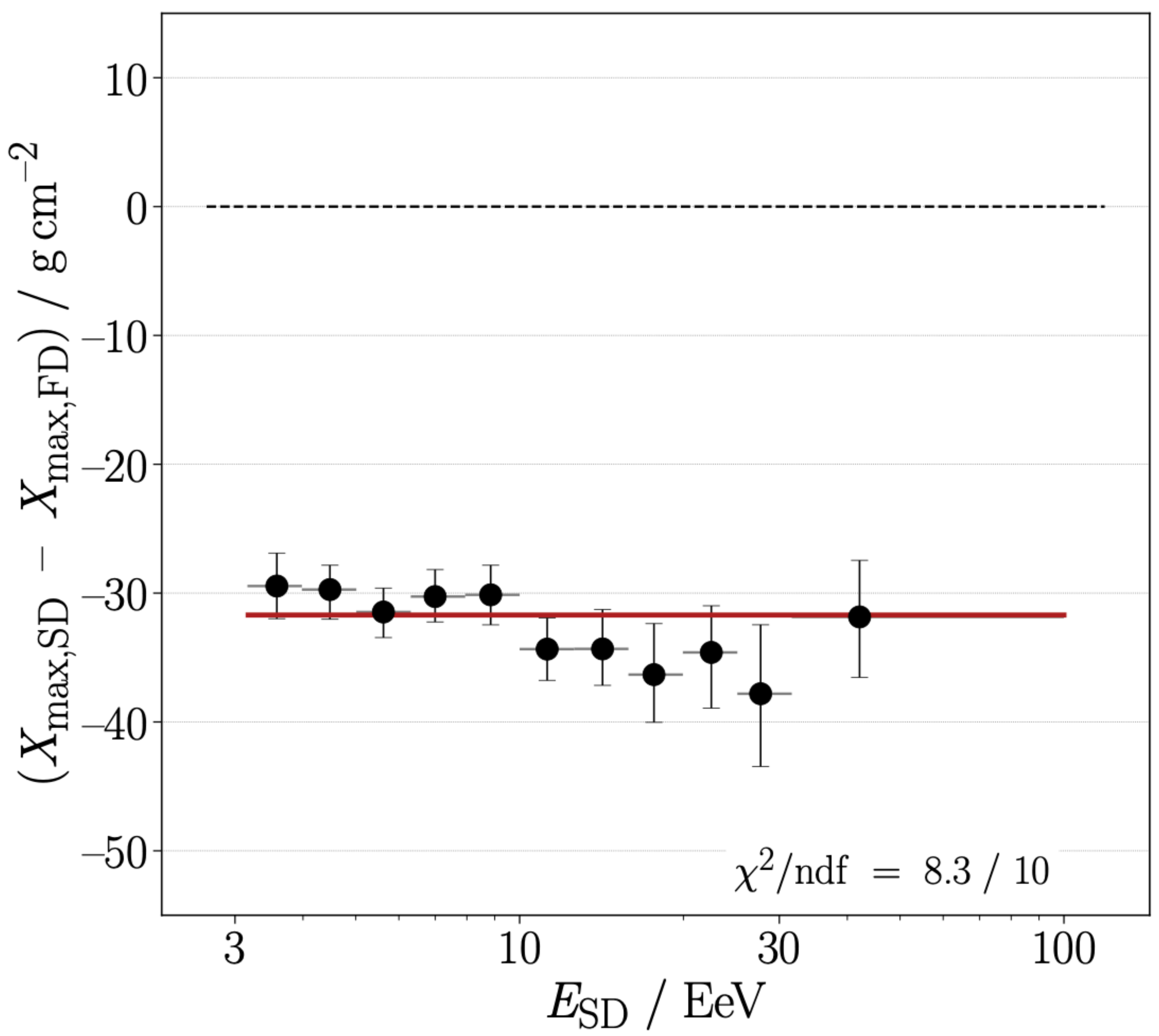
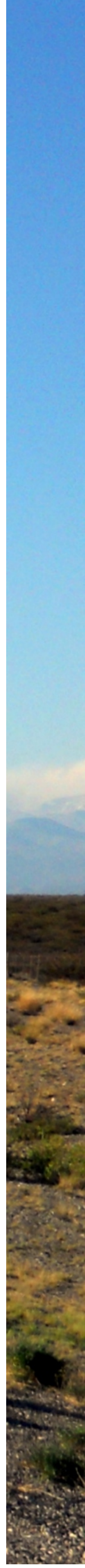
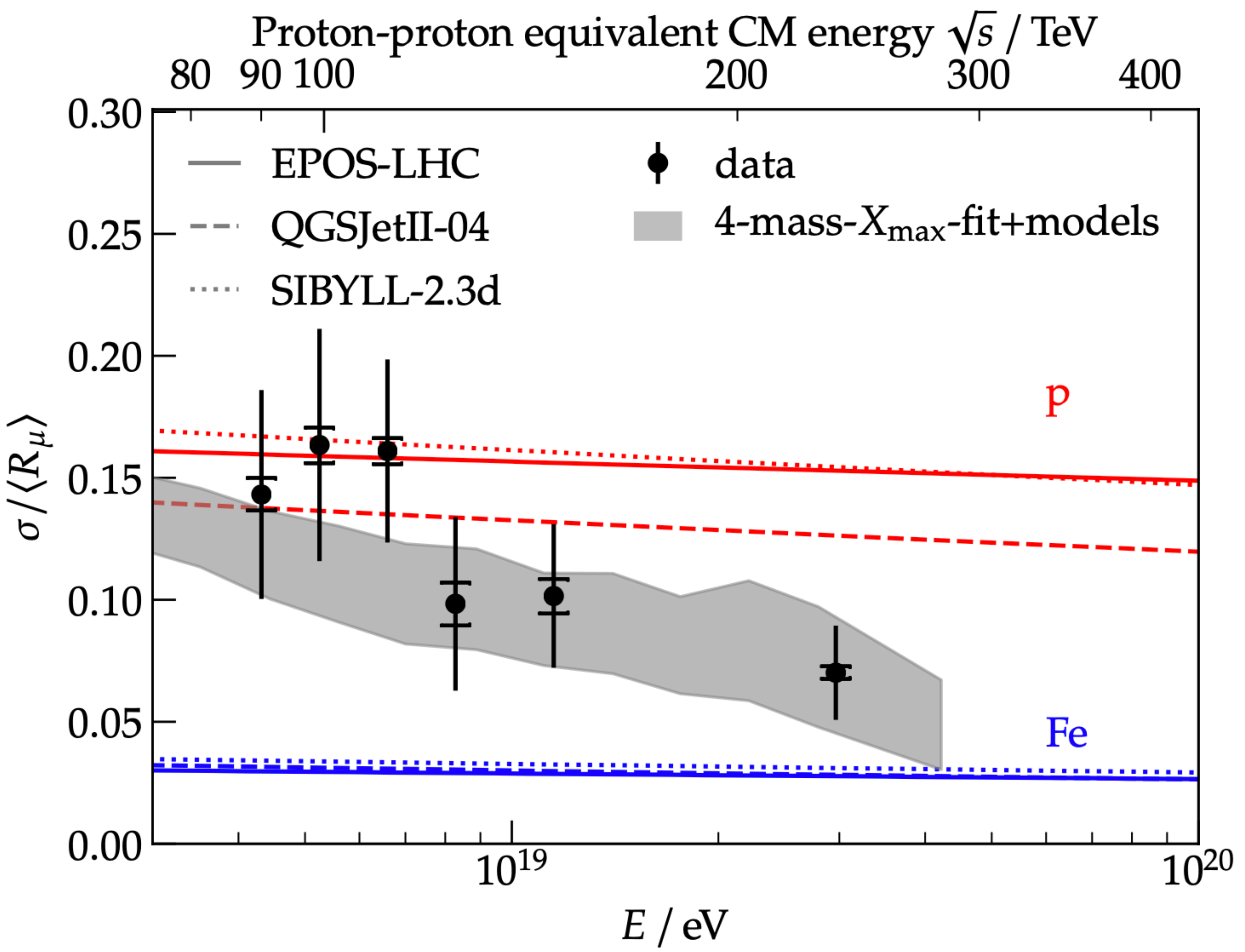


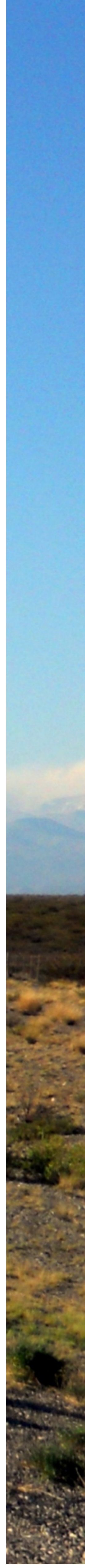


EAS muon fluctuations

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

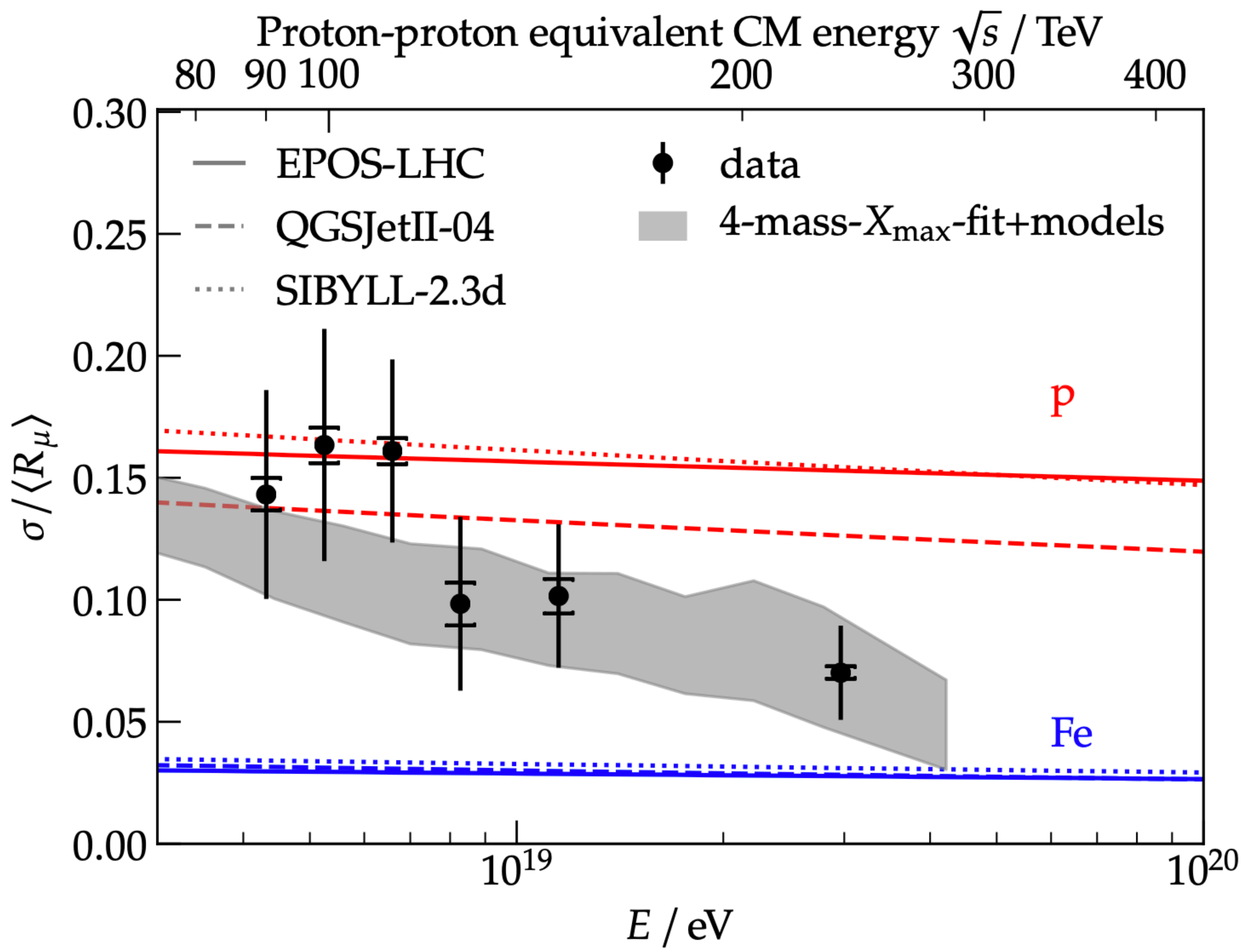


The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data



EAS muon fluctuations

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



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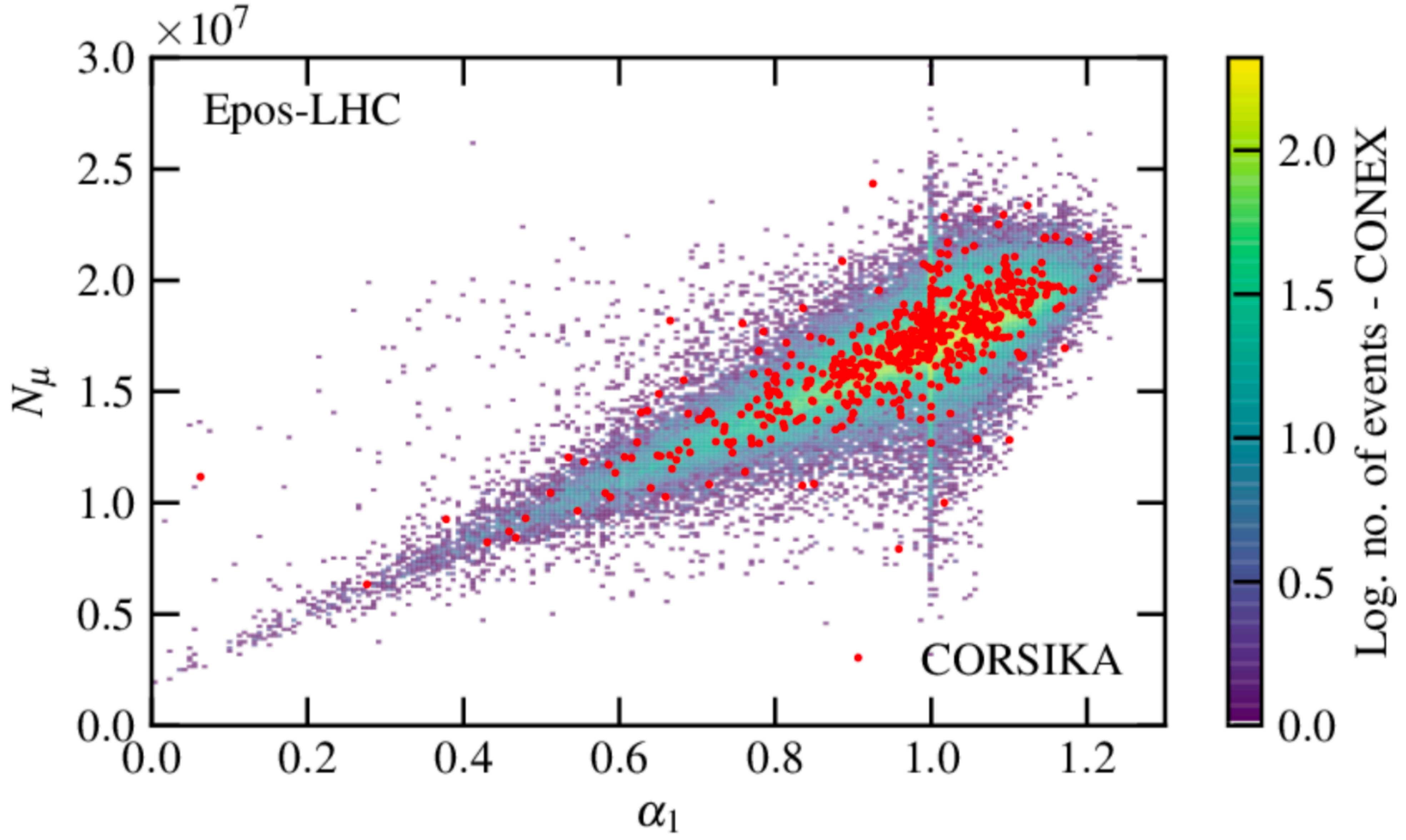
L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76

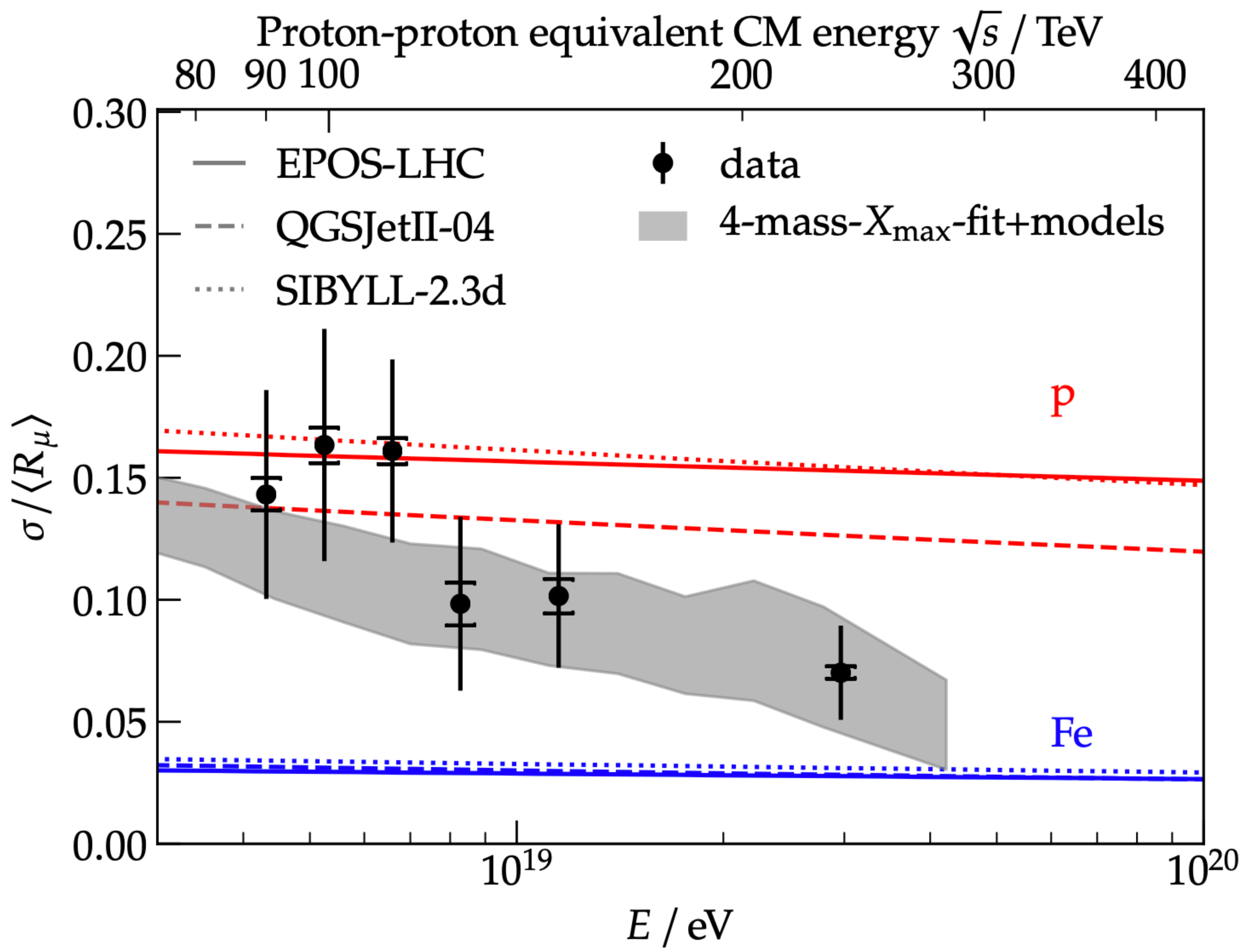


α_1 is the fraction of energy going into the hadronic sector in the first interaction

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

EAS muon fluctuations

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



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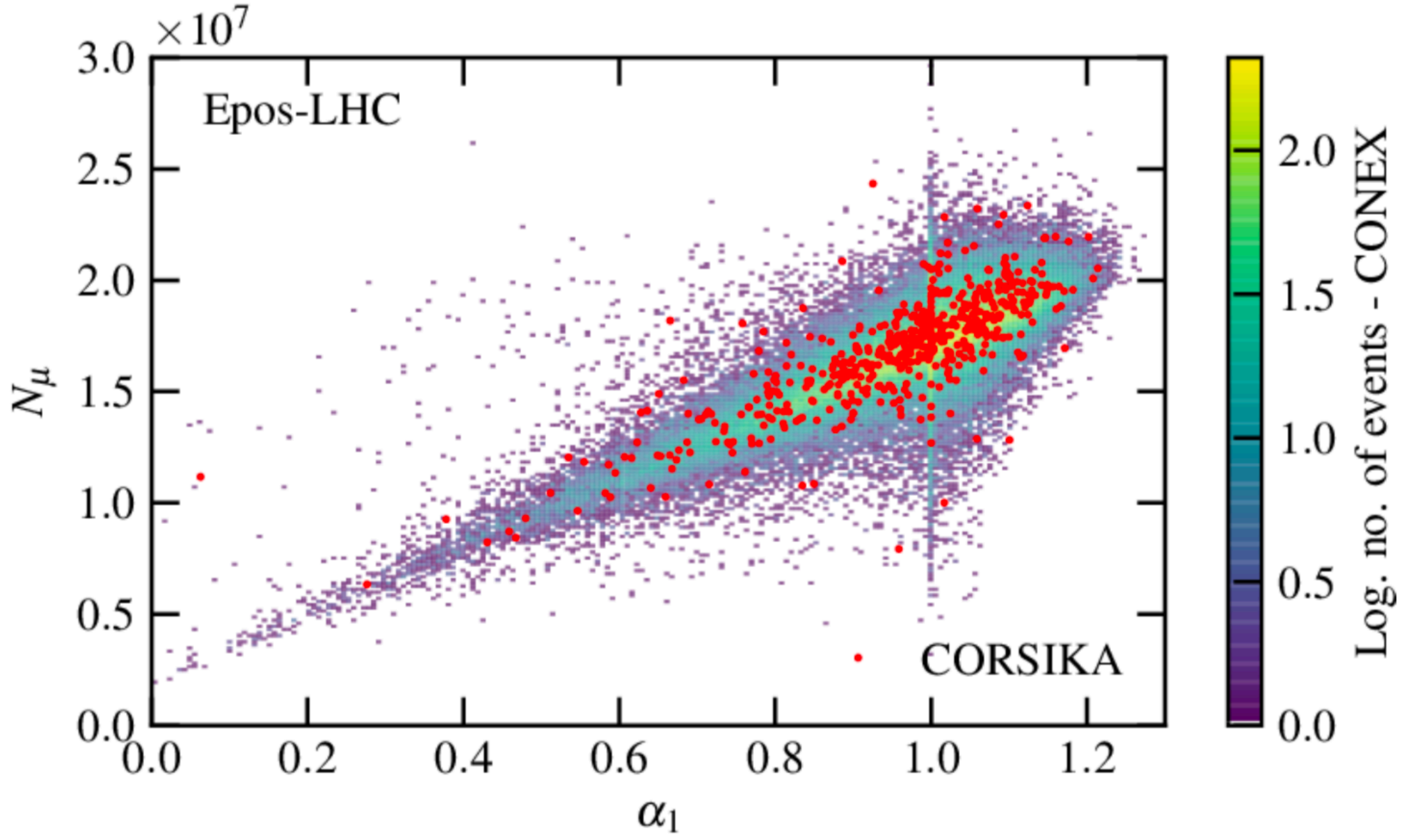
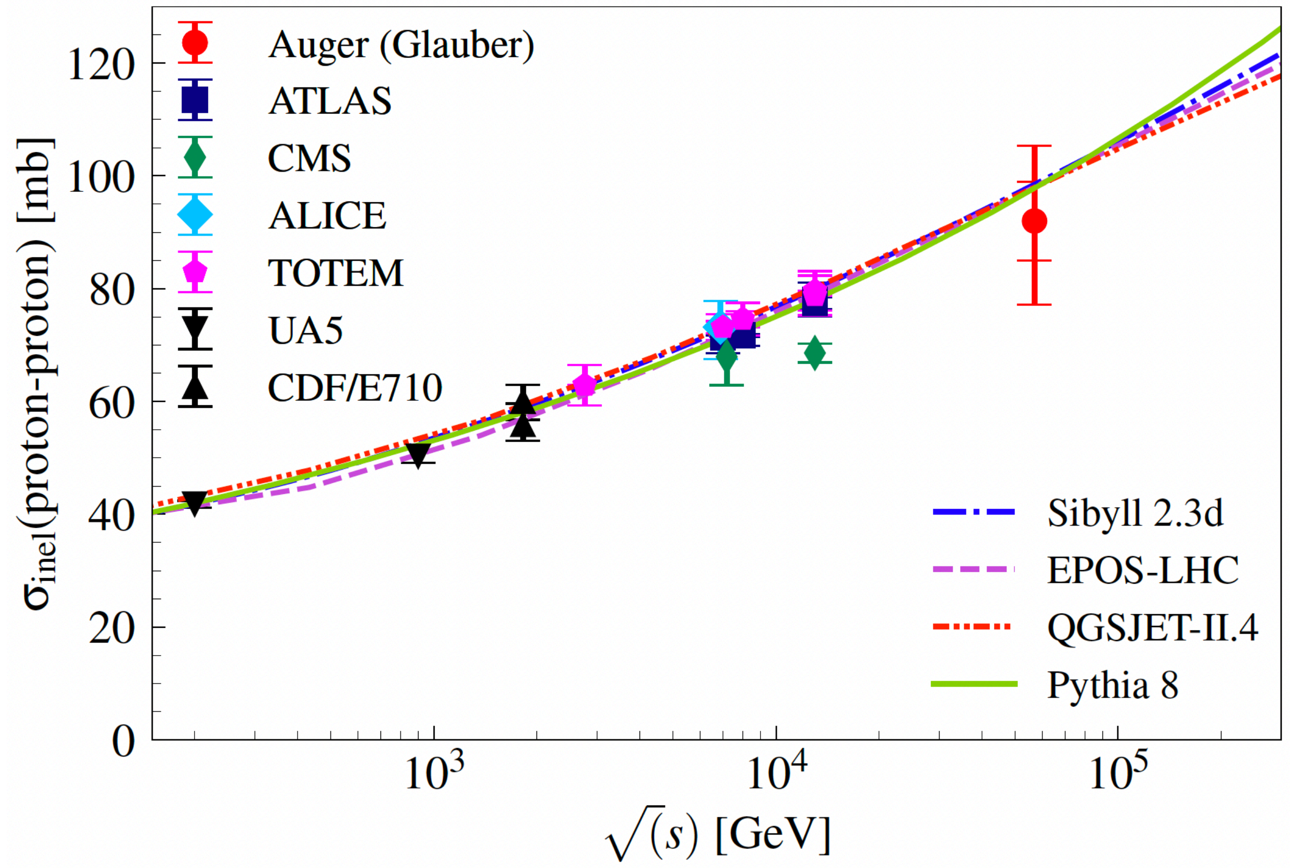


α_1 is the fraction of energy going into the hadronic sector in the first interaction

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

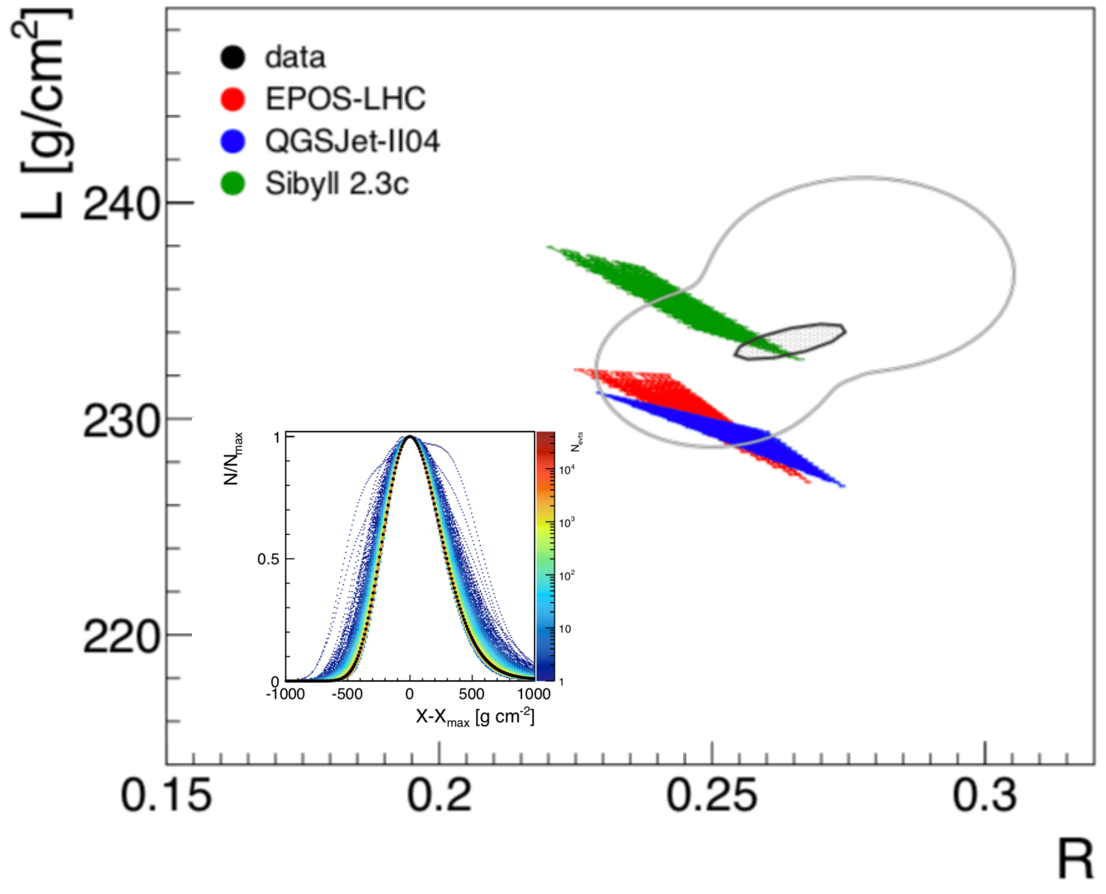
Suggestion that muon deficit might be related with description of low energy interactions

Many other EAS measurements…



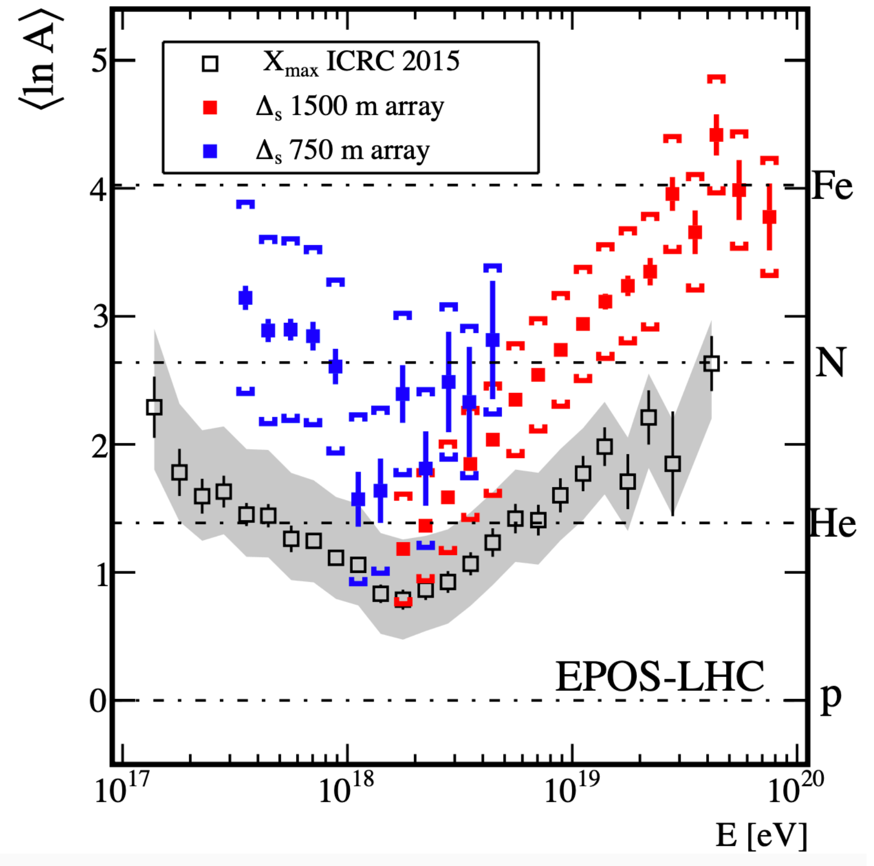
Phys.Rev.Lett. 109 (2012) 062002

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



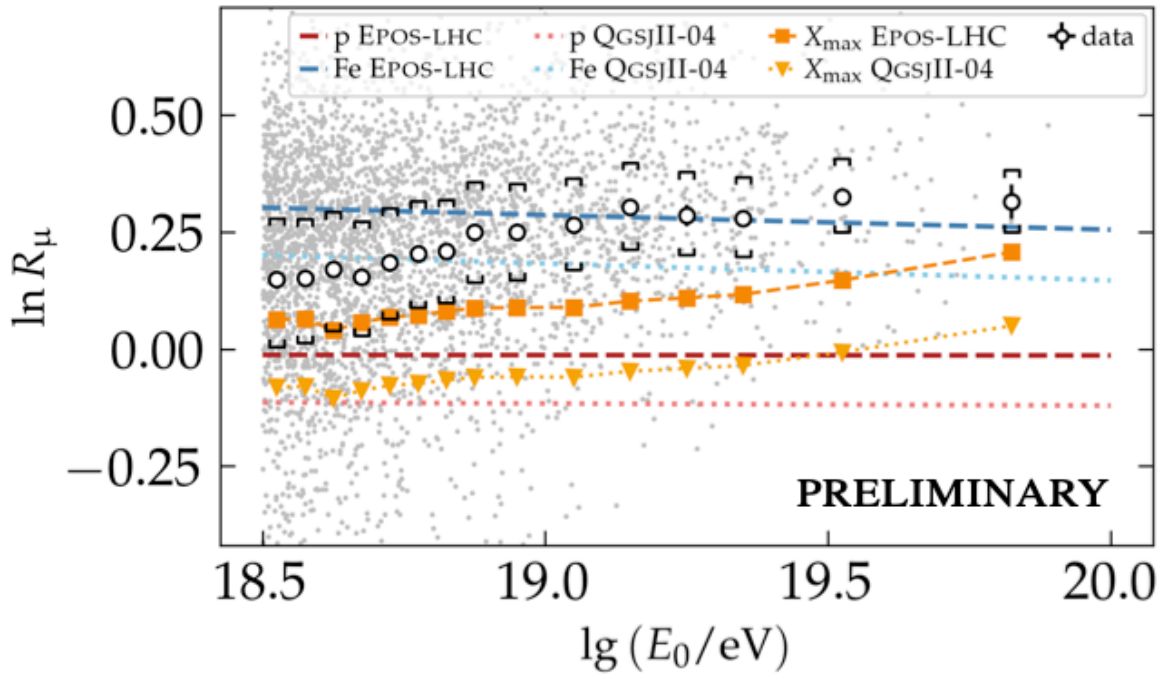
JCAP 1903 (2019) no.03, 018

Measurement of average e.m. longitudinal profile shape



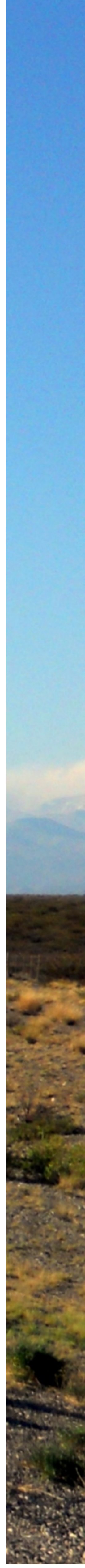
Phys.Rev.D 96 (2017) 12, 122003

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



PoS (ICRC2023) 339

The number of muons measured in hybrid events



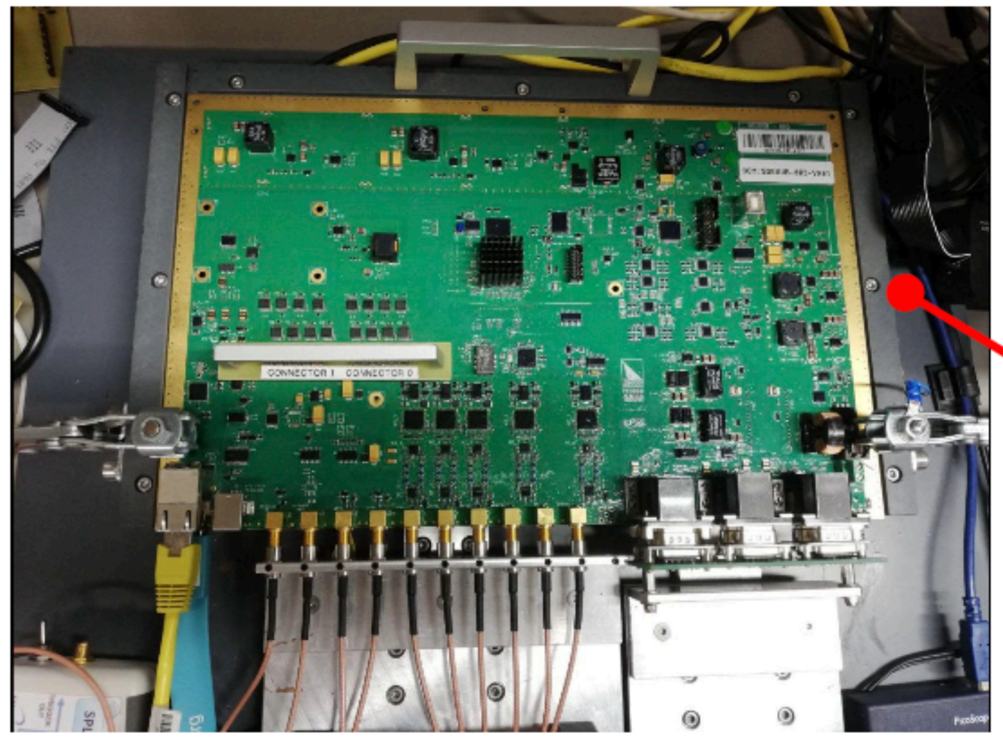
Pierre Auger Observatory

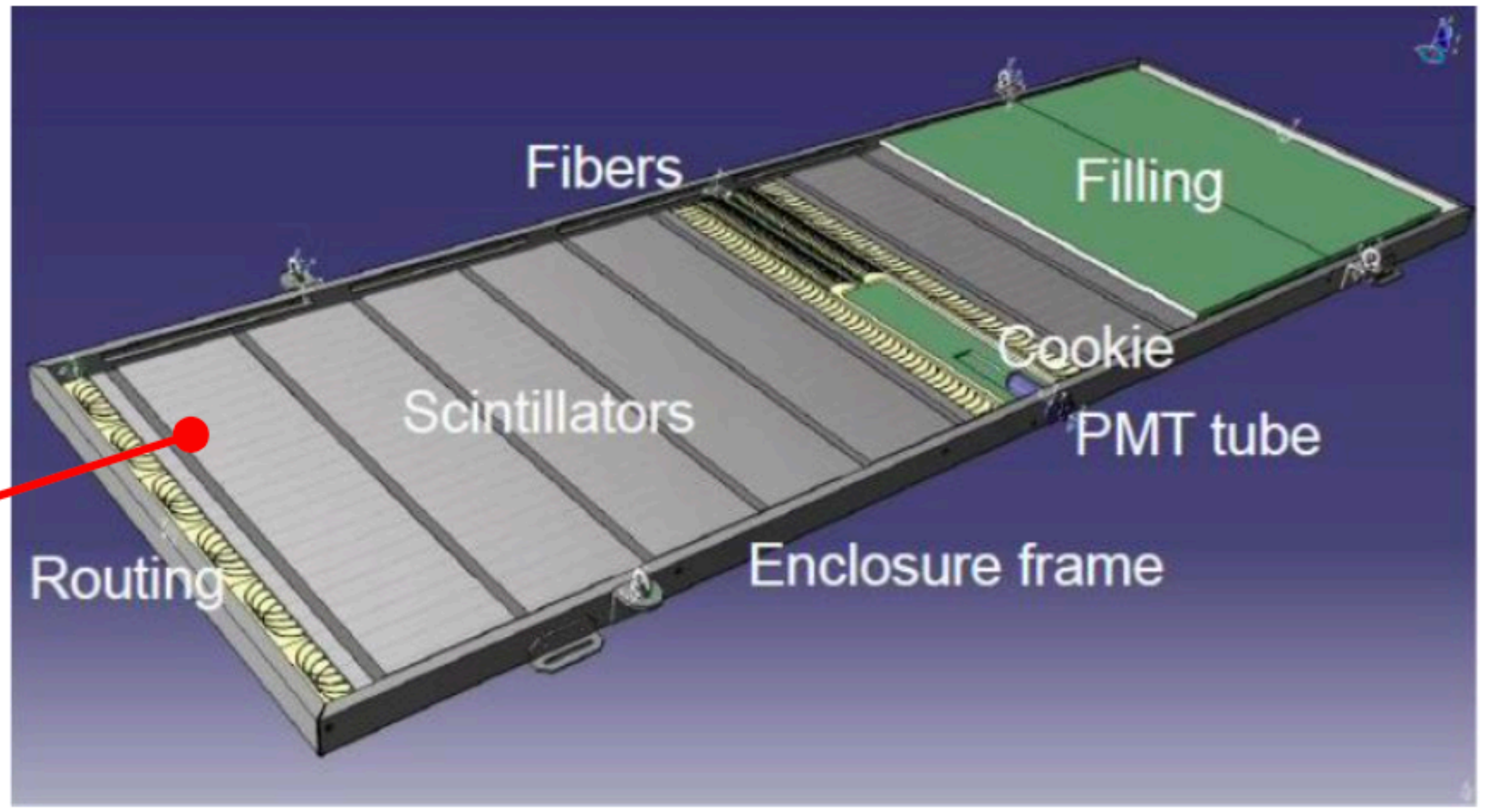
The future of the observatory

Auger Prime

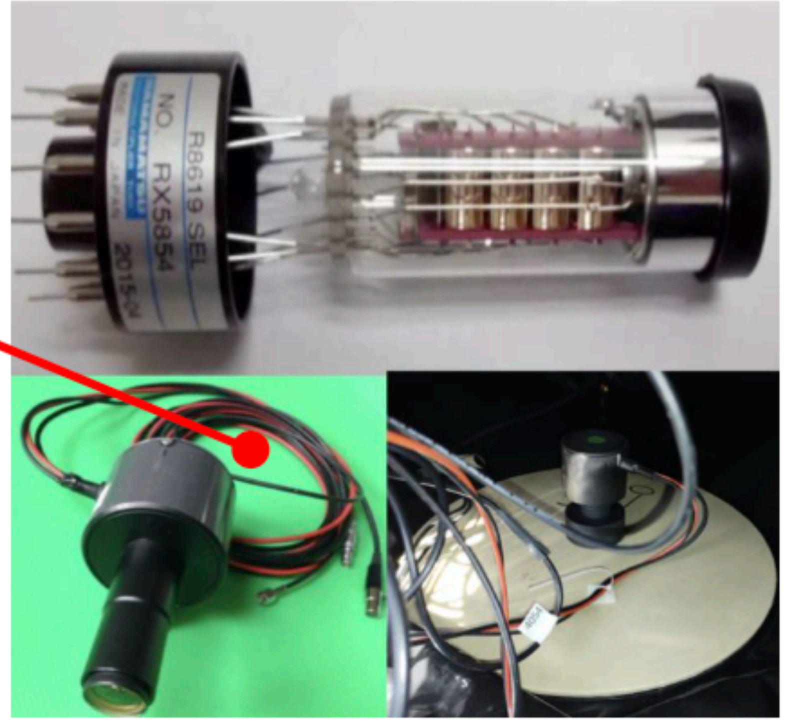
(see A. Castellina presentation, tomorrow!)

New electronics (UUB) and Scintillators(SSD)





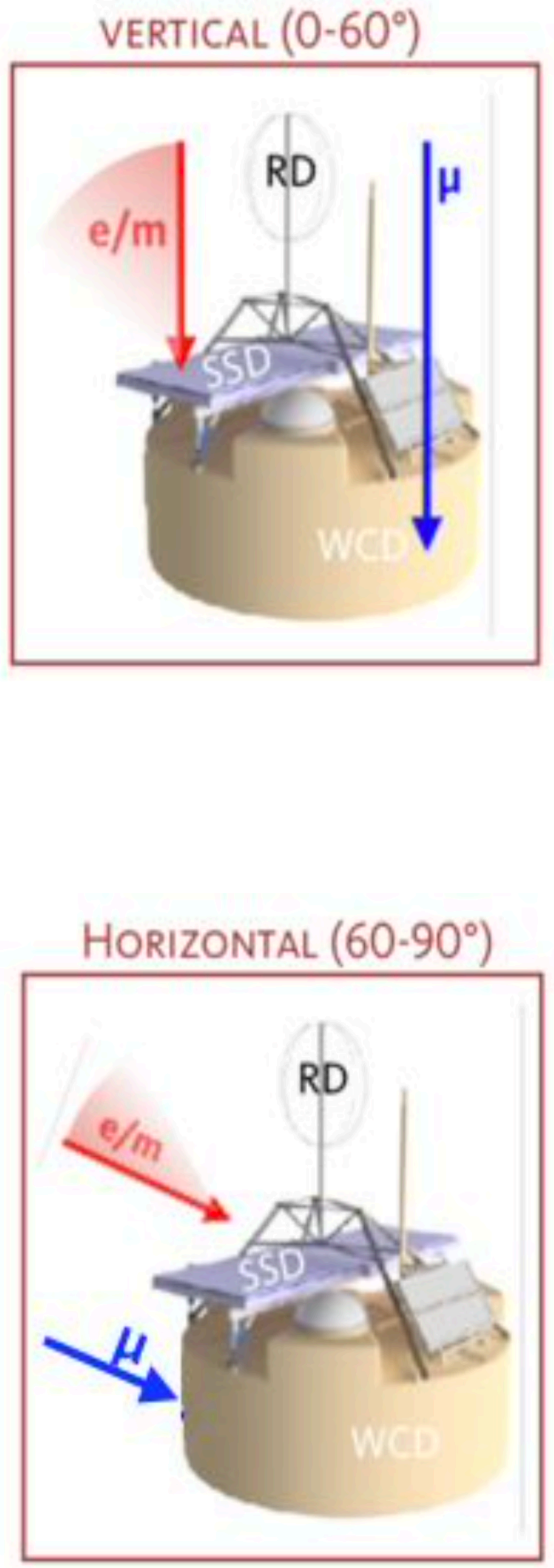
High dynamic range PMTs



Radio Upgrade

Underground Muon Detector (UMD)

The strategy

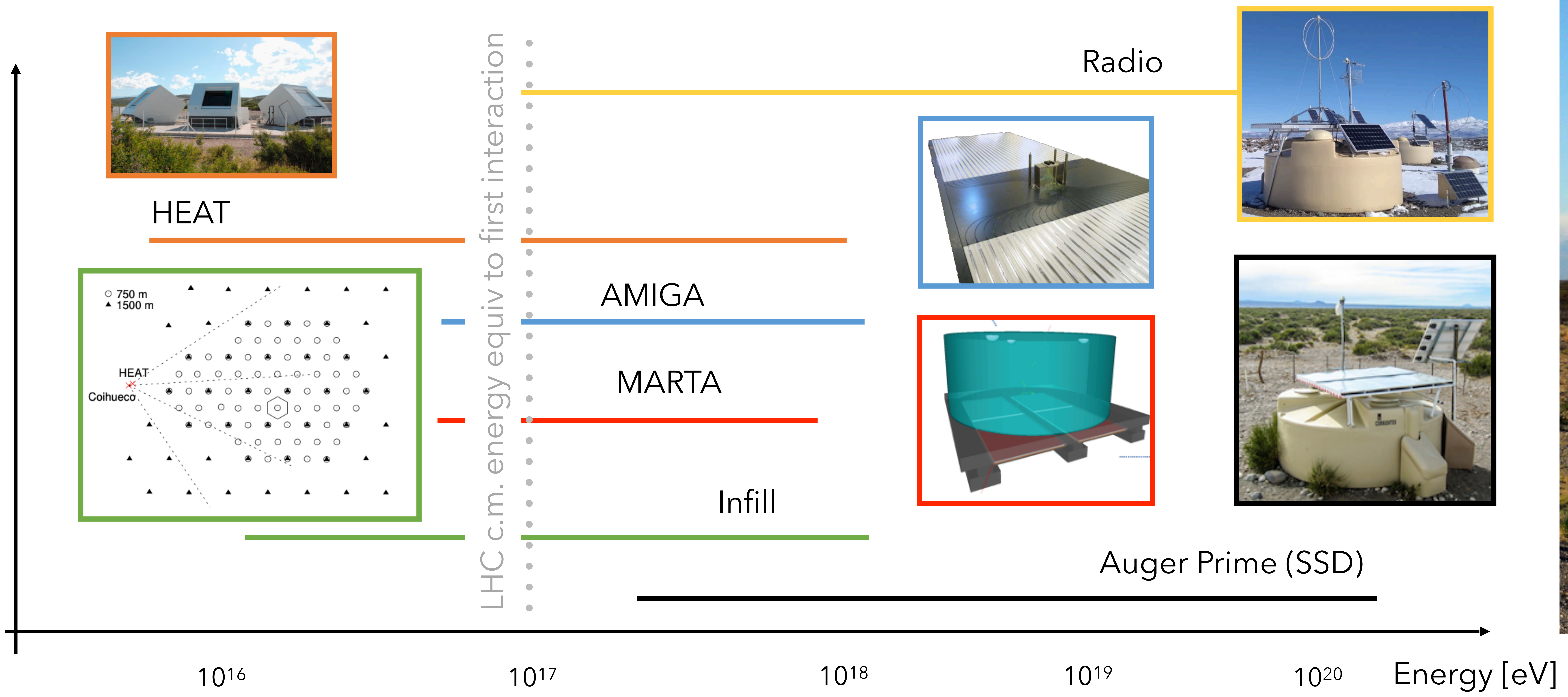


Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2021

Auger Phase II data taking from 2022 to 2035

Multi-hybrid shower events

(A plethora of measurements to fully understand the shower)



Acknowledgements

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