Auger report to the LIP advisory

Ruben Conceição

on behalf of the Auger-LIP group

LIP

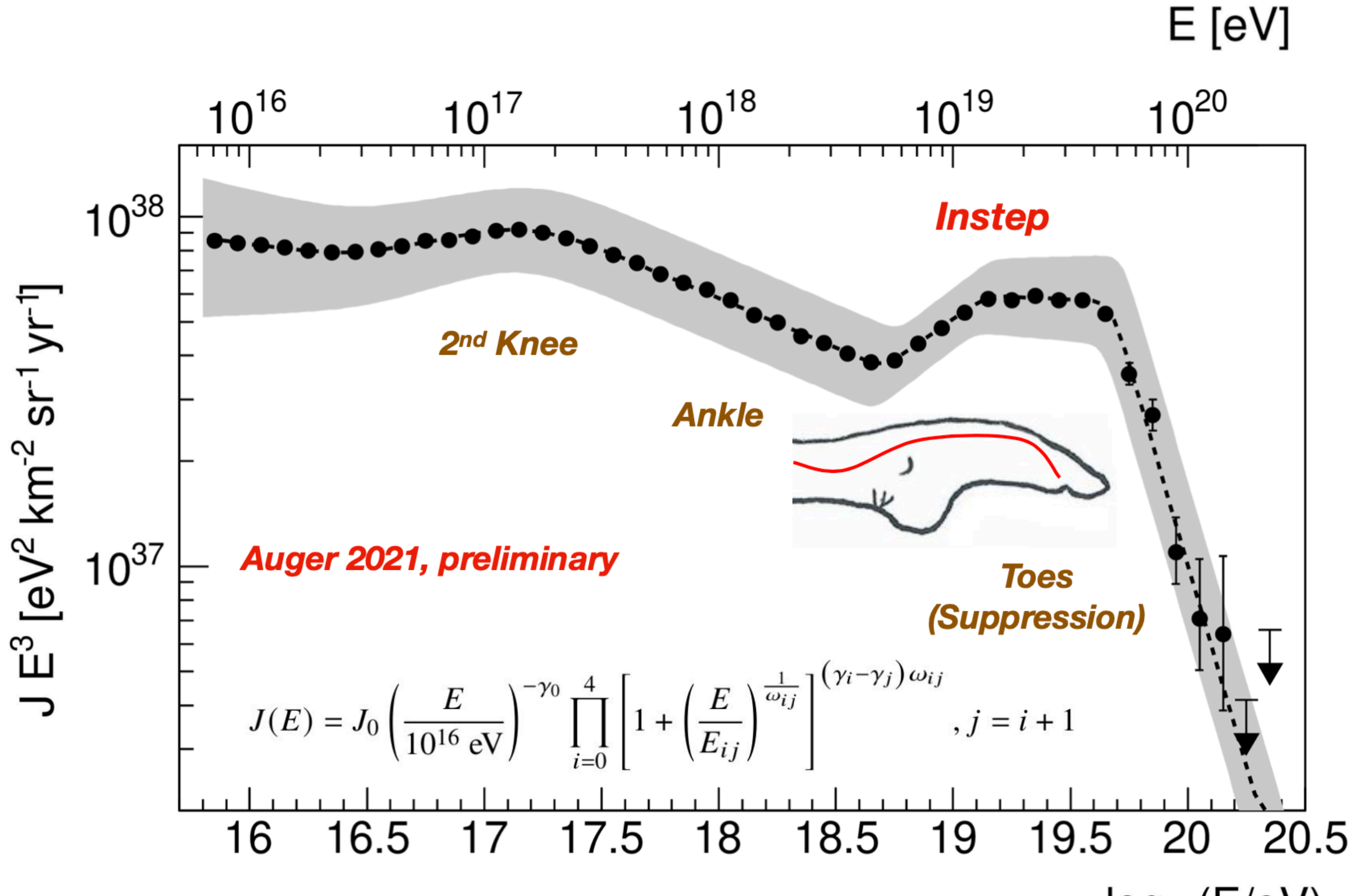
PIERRE AUGER OBSERVATORY

TÉCNICO LISBOA

LIP advisory, Lisbon, April 23rd 2025

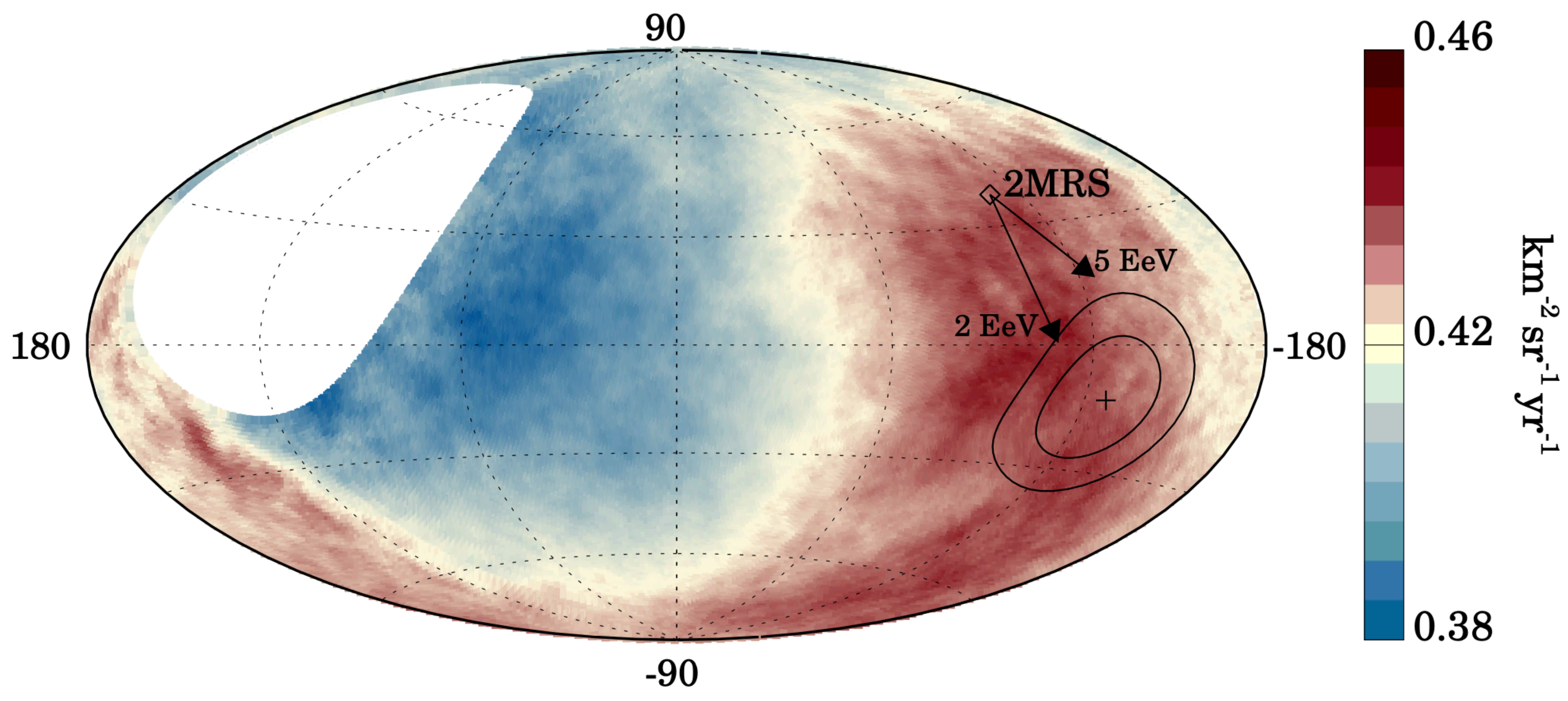
Pierre Auger collaboration results in a nutshell

UHECR energy spectrum features



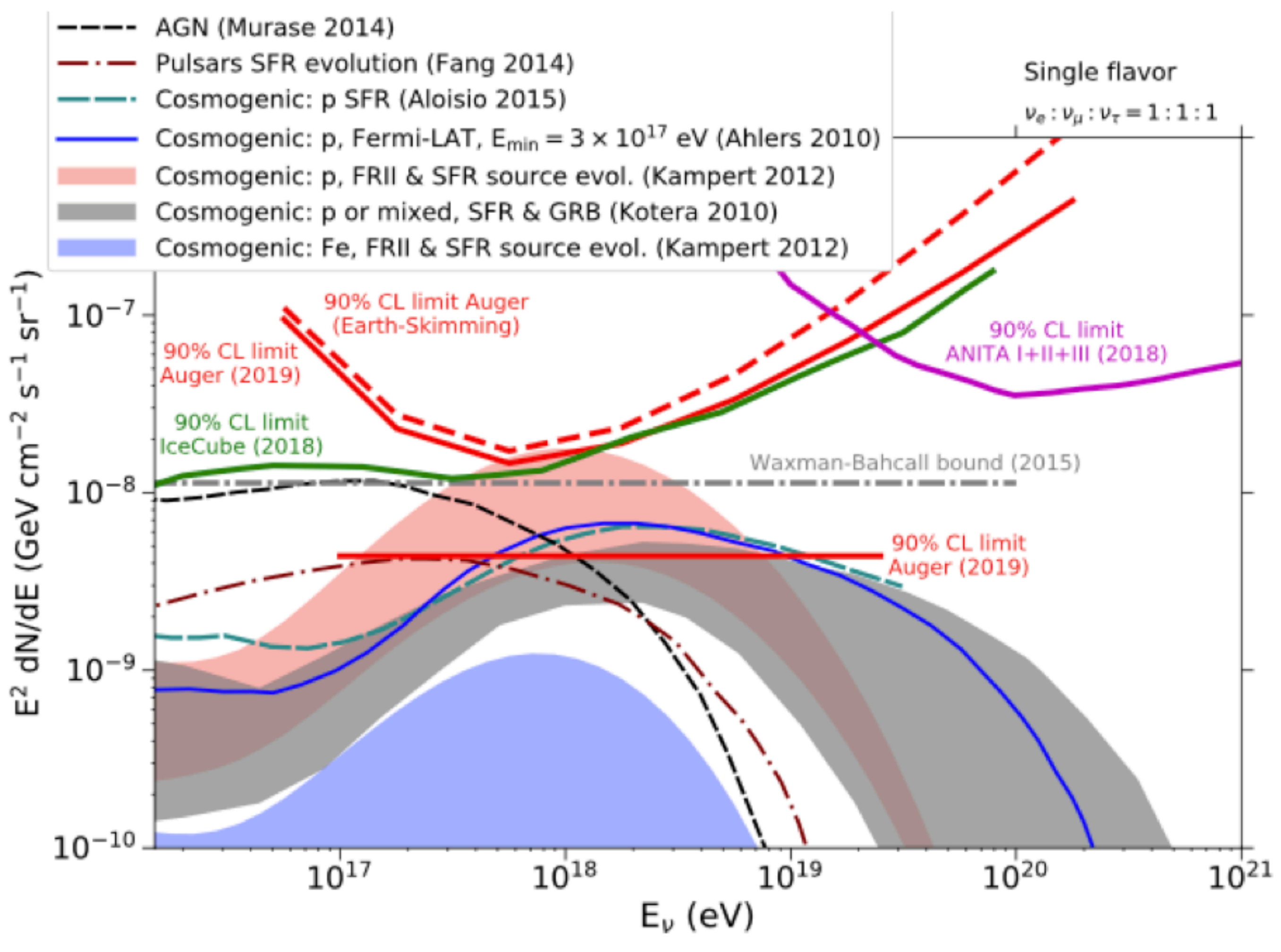
Phys. Rev. Lett. 125 (2020) 121106

UHECR have an extra-galactic origin



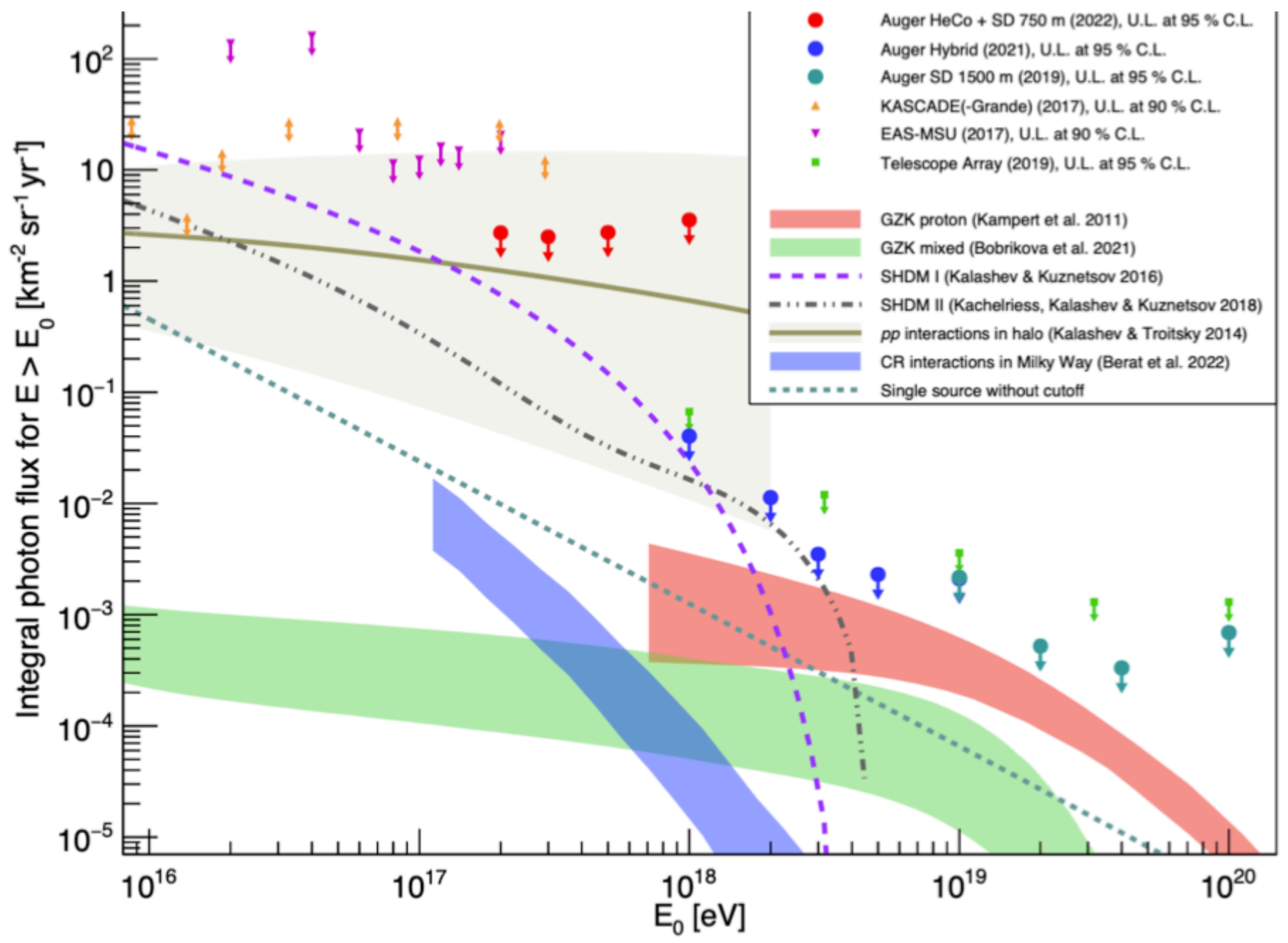
Science 357 (2017) 6537, 1266-1270

Stringent limits on UHE neutrinos



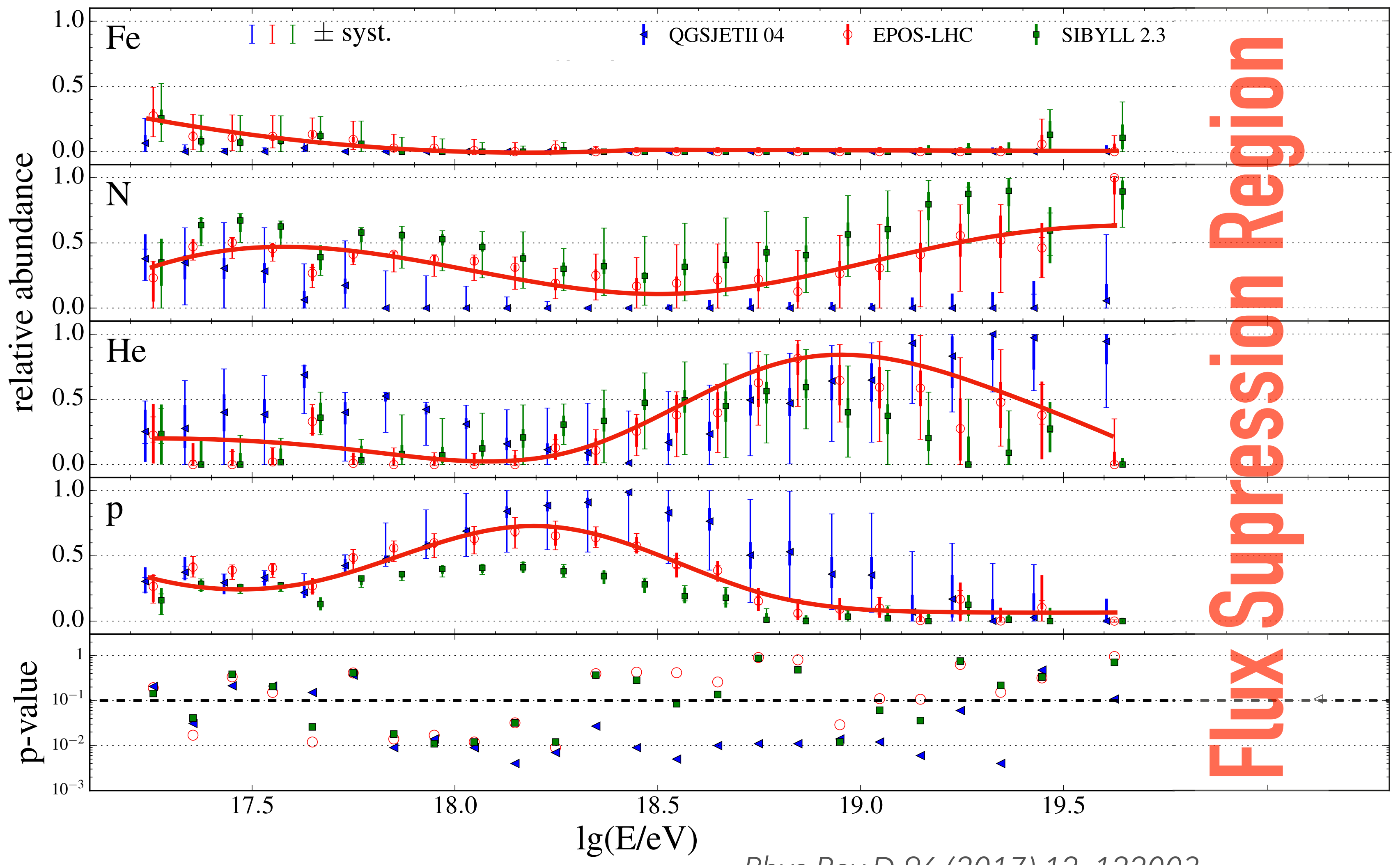
ApJ 902 (2020)105

Stringent limits on UHE photons



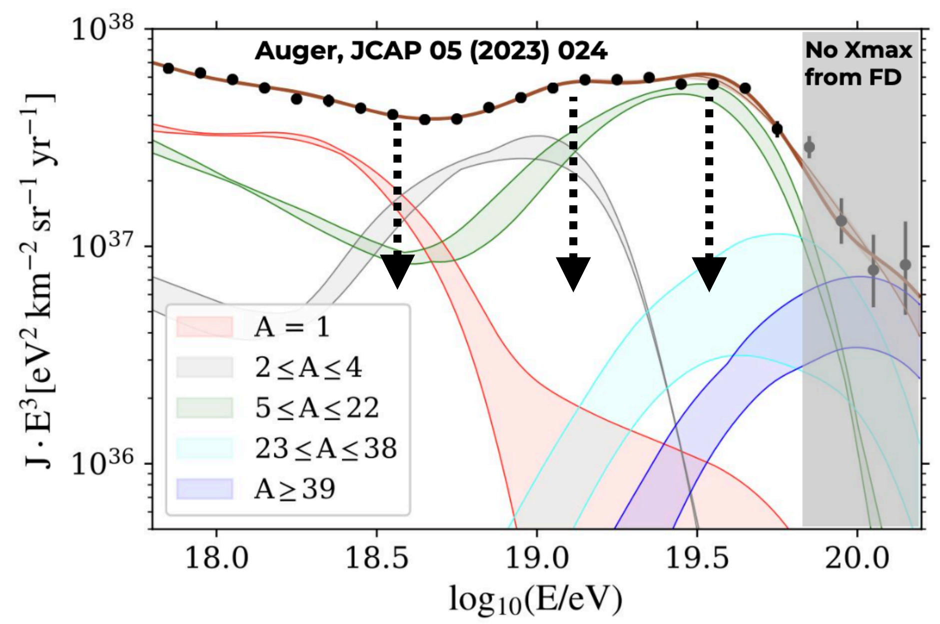
Astrophys.J. 933 (2022) 2, 125

Mass composition evolution towards heavier elements



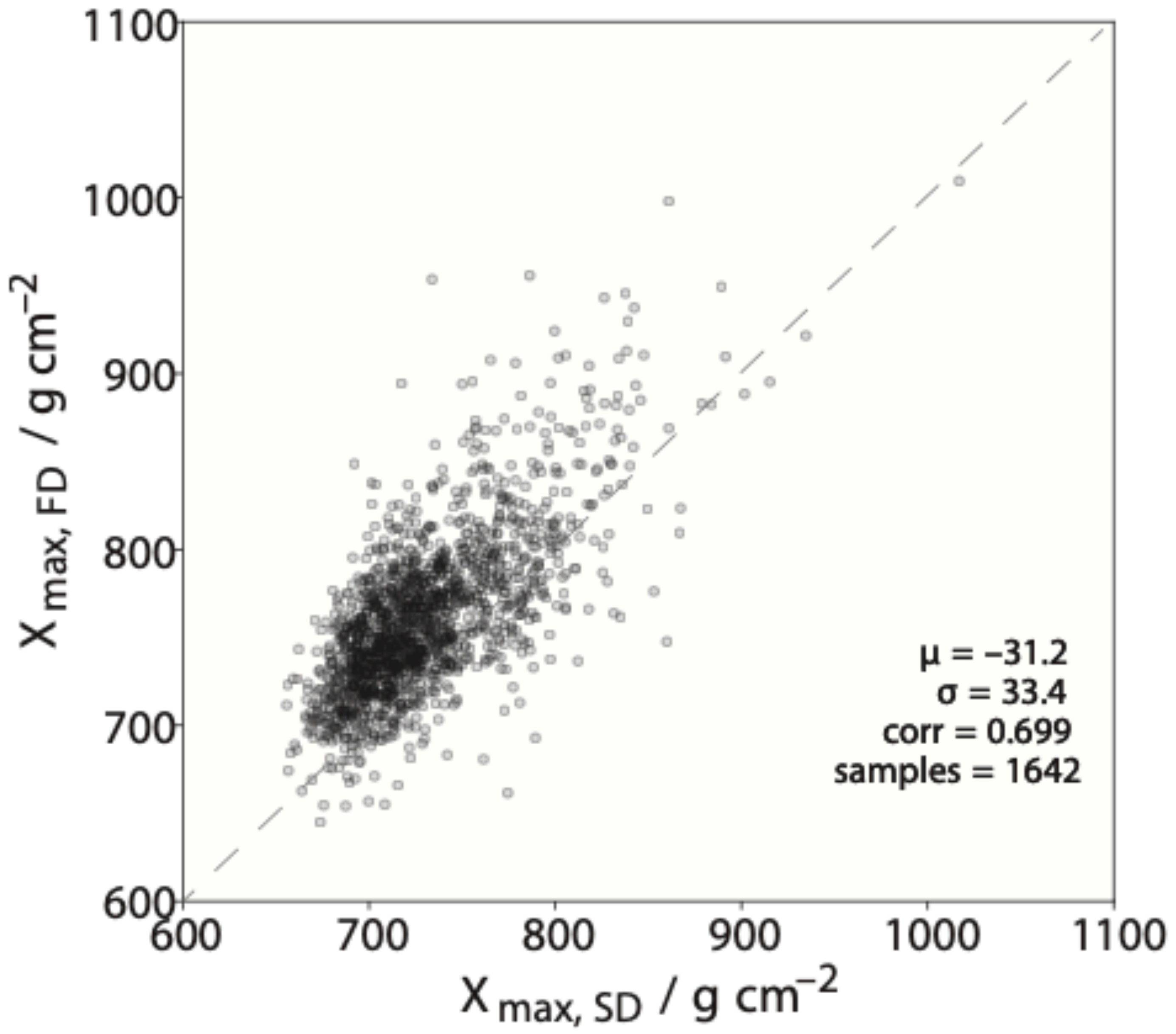
Phys.Rev.D 96 (2017) 12, 122003

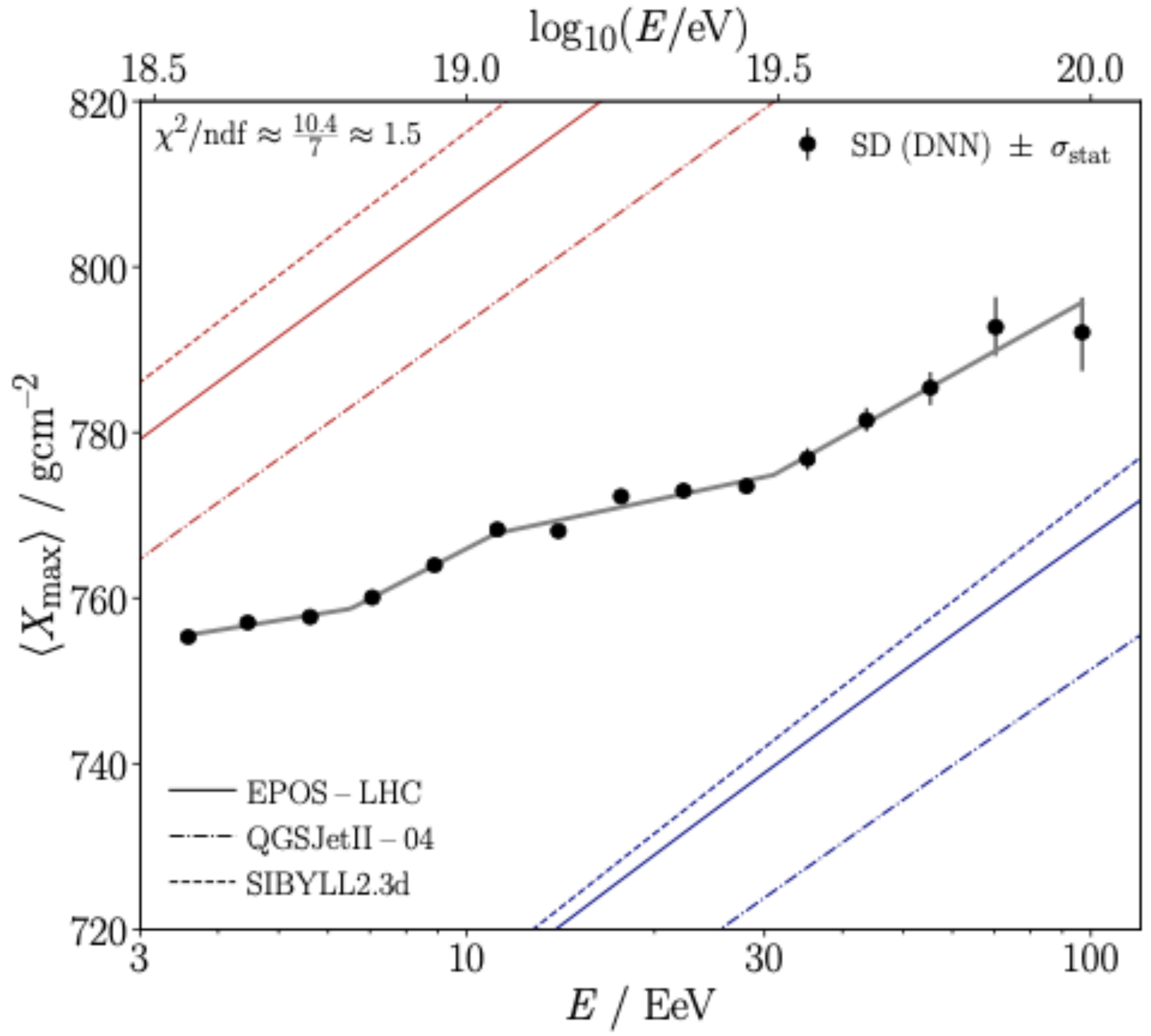
The rise of Machine Learning @ Auger

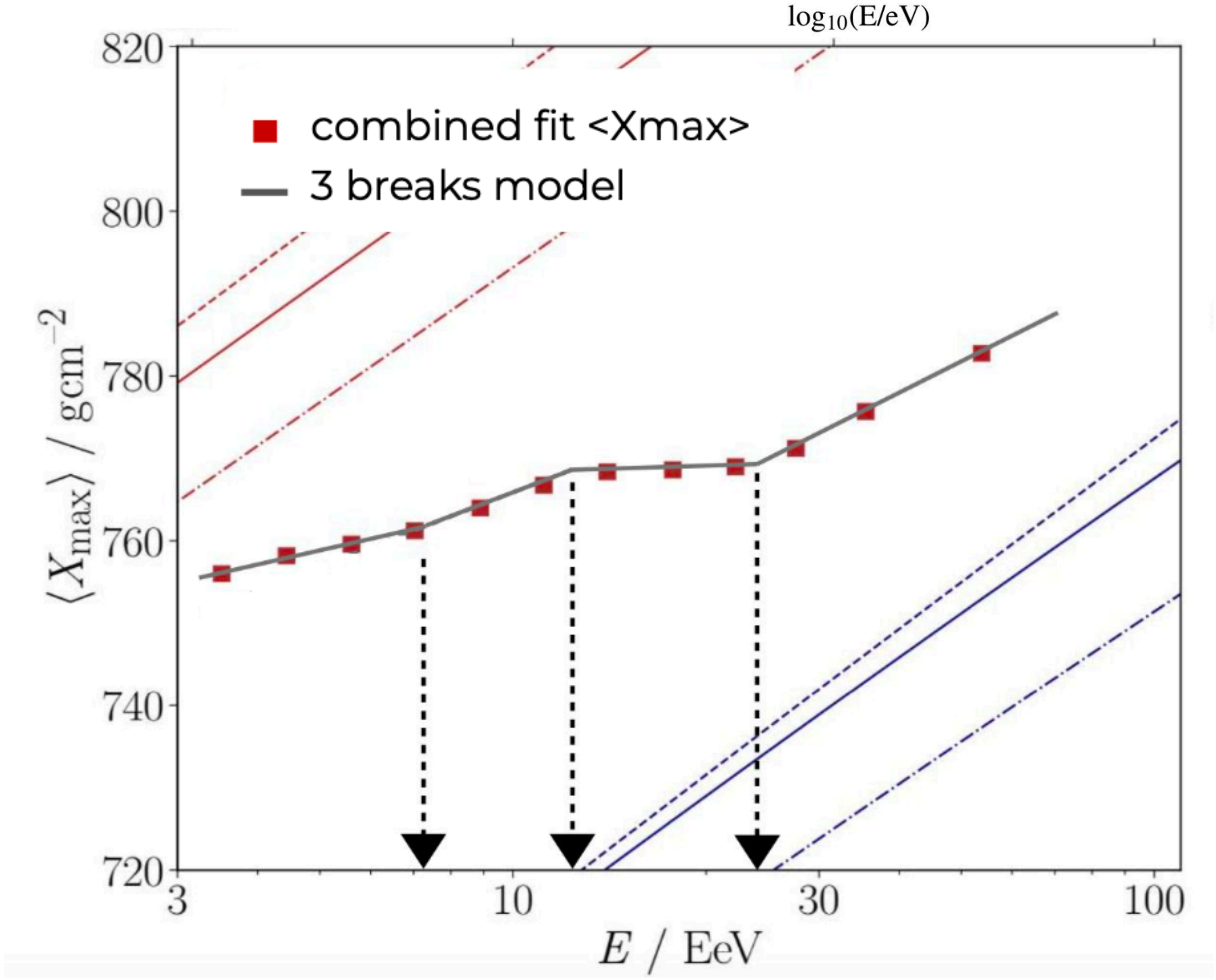


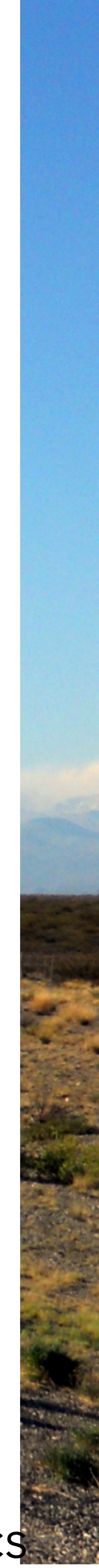
Extraction of Xmax from the SD ground signal

Pierre Auger coll., Phys.Rev.Lett. 134 (2025) 2, 021001 & Phys.Rev.D 111 (2025) 2, 022003





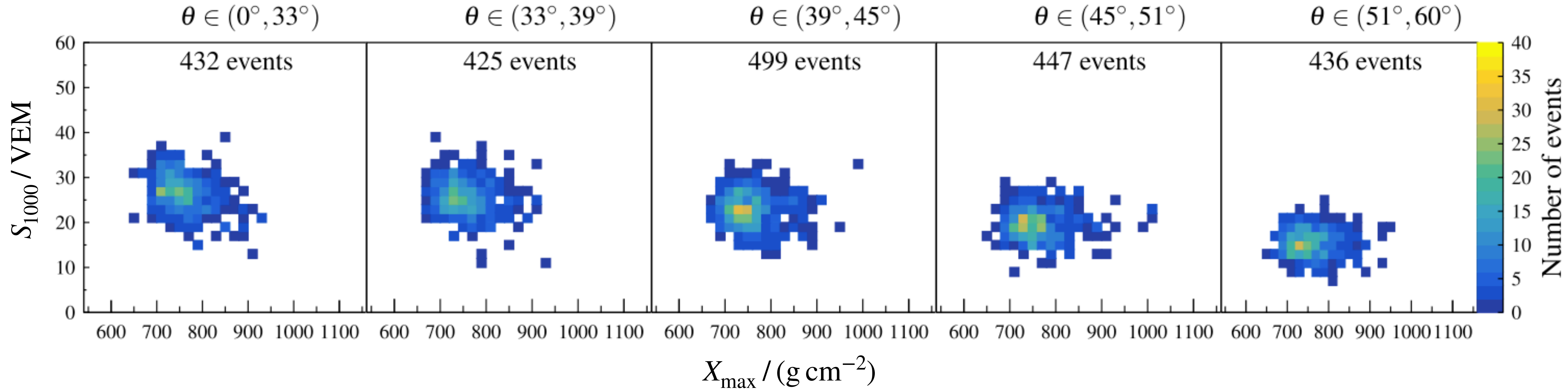




- ✧ **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- ✧ Algorithms highly **dependent of simulations** and might be picking up unknown less controlled shower characteristics
- ✧ **It is vital to control the Extensive Air Showers and detector systematic uncertainties!!**

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

Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001



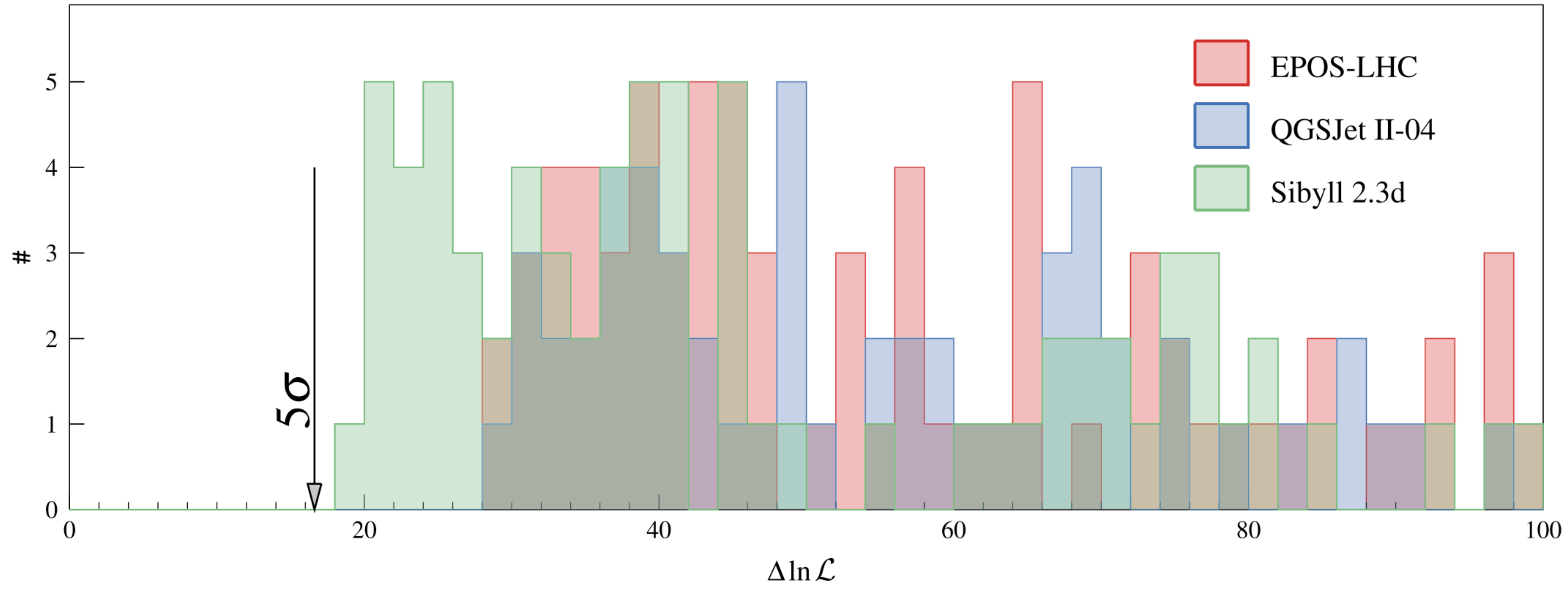
Systematic uncertainties

$E - 14\%$

$E + 14\%$

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

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



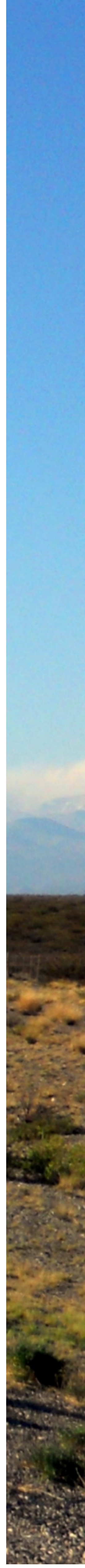
Systematic uncertainties

S(1000) − 5%

S(1000) + 5%

Method

None of the **post-LHC tuned hadronic interaction models** can describe the Auger (X_{max}, S_{1000}) data, even considering the systematic uncertainties - **Shift on muon and X_{max} scale needed?!**



Multi-hybrid shower events

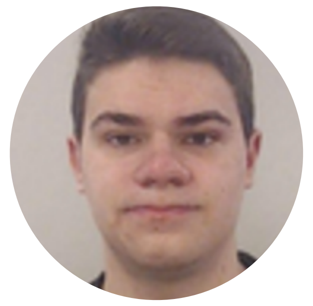
(A plethora of measurements to fully understand the shower)

Cosmic Ray

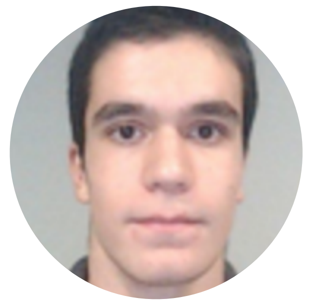
LIP-Auger group


Alexandra Fernandes


Bernardo Tomé


David Dias


José Carlos Nogueira


Guilherme Neves


Luís Lopes


Mário Pimenta

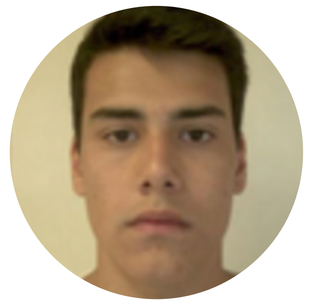

Miguel Ferreira


Milton Freitas


Pedro Abreu

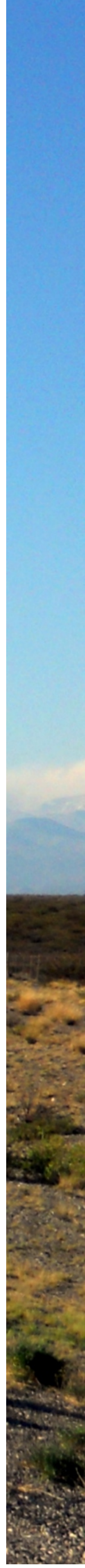

Pedro Assis


Pedro Costa


Pedro Tomé


Raul Sarmento

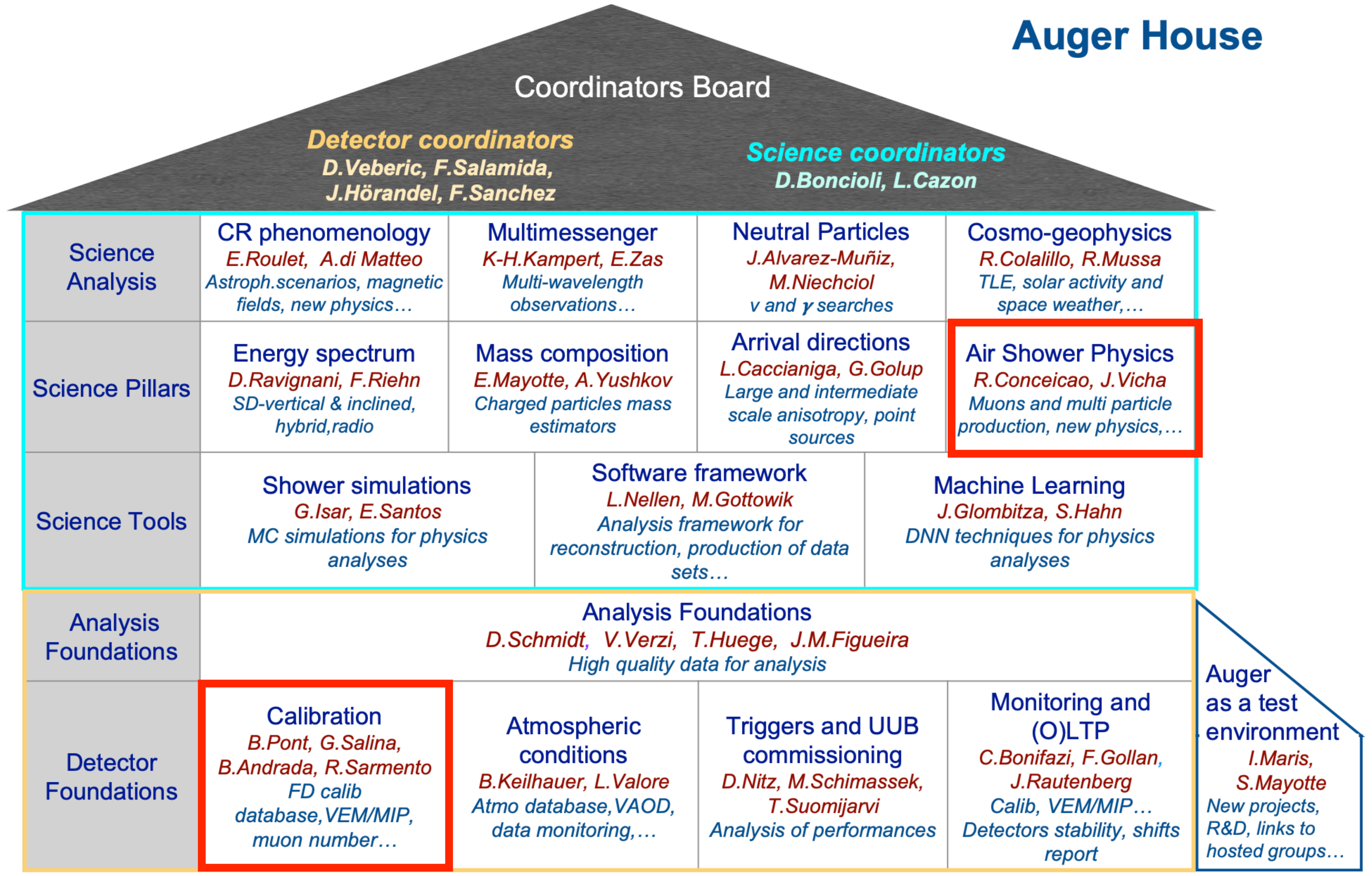

Ruben Conceição



Close collaborators: Alberto Blanco, Felix Riehn, Liliana Apolinário, Lorenzo Cazon, Luís Afonso, Luís Mendes, Miguel Martins, Patrícia Gonçalves, Sofia Andringa, Ulisses Barres de Almeida

Responsibilities @ Auger

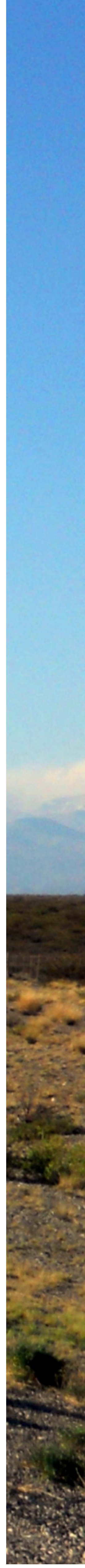
The Auger-LIP group has been actively shaping the collaboration's activities and decisions since its entry in 2005



- **Current responsibilities**
  - Air Shower Physics task coordinator - *R. Conceição*
  - Calibration SD/SSD task coordinator - *R. Sarmento*
  - Ombudsperson - *P. Assis*
  - Representative Auger member at IPPOG - *R. Sarmento*
  - Member search committee for CB (co-)chair election - *R. Conceição*
- Previous responsibilities
  - Science Coordinator, Air Shower Physics task coordinator, Calibration task coordinator, Long-term-performance coordinator, Member of the conference committee, Member of search committee for (co-)spokesperson election
- Invited plenary talks on EAS physics at ECRS24 and UHECR24
- **MoU for the Portuguese participation in Auger has been extended up to 2035** - MoU to be signed this November during the AugerPrime extension ceremony

Auger-LIP group main lines of activity

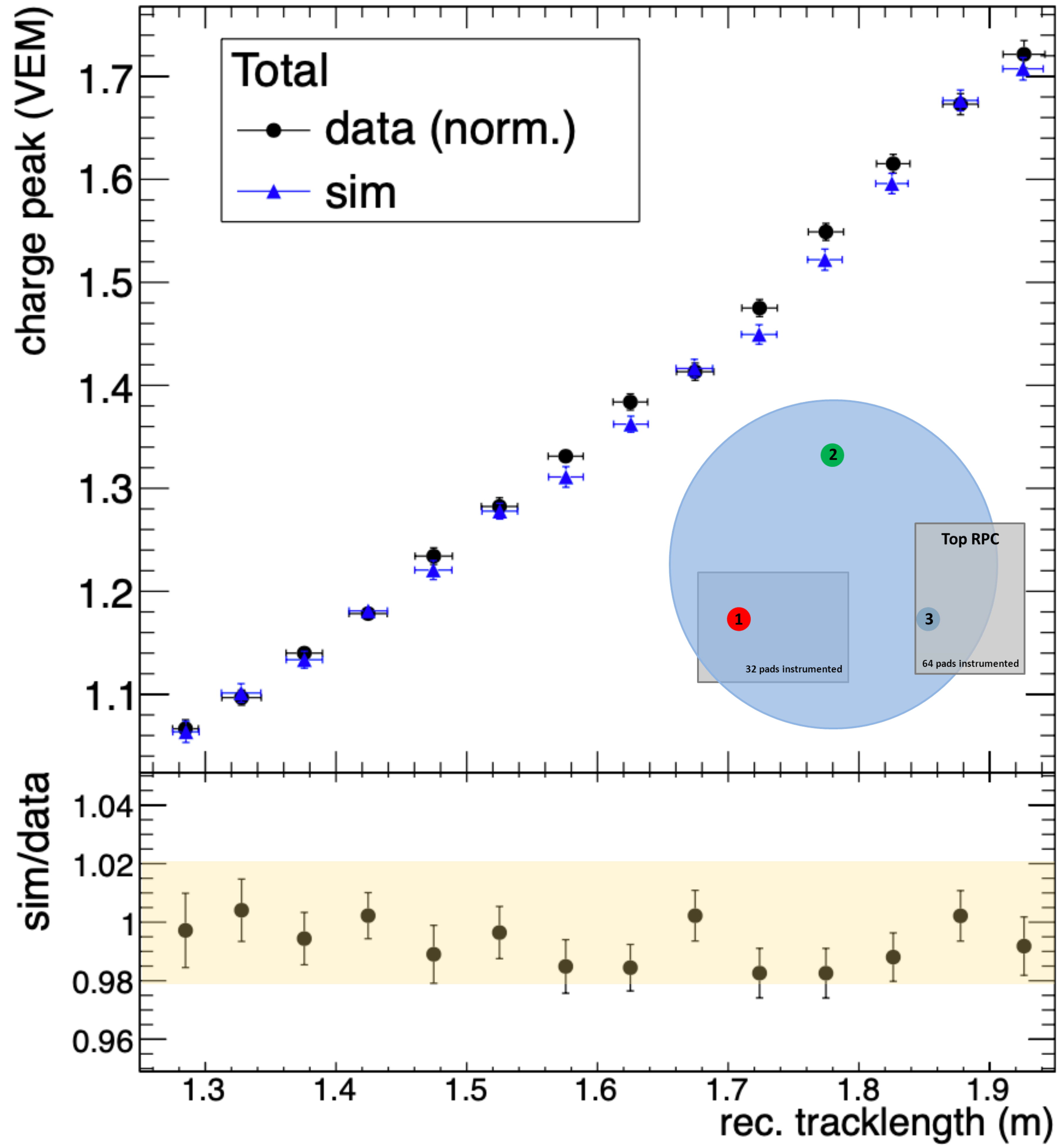
Calibration | **MARTA** | **EAS phenomenology** | **Neutral searches** | **Outreach**

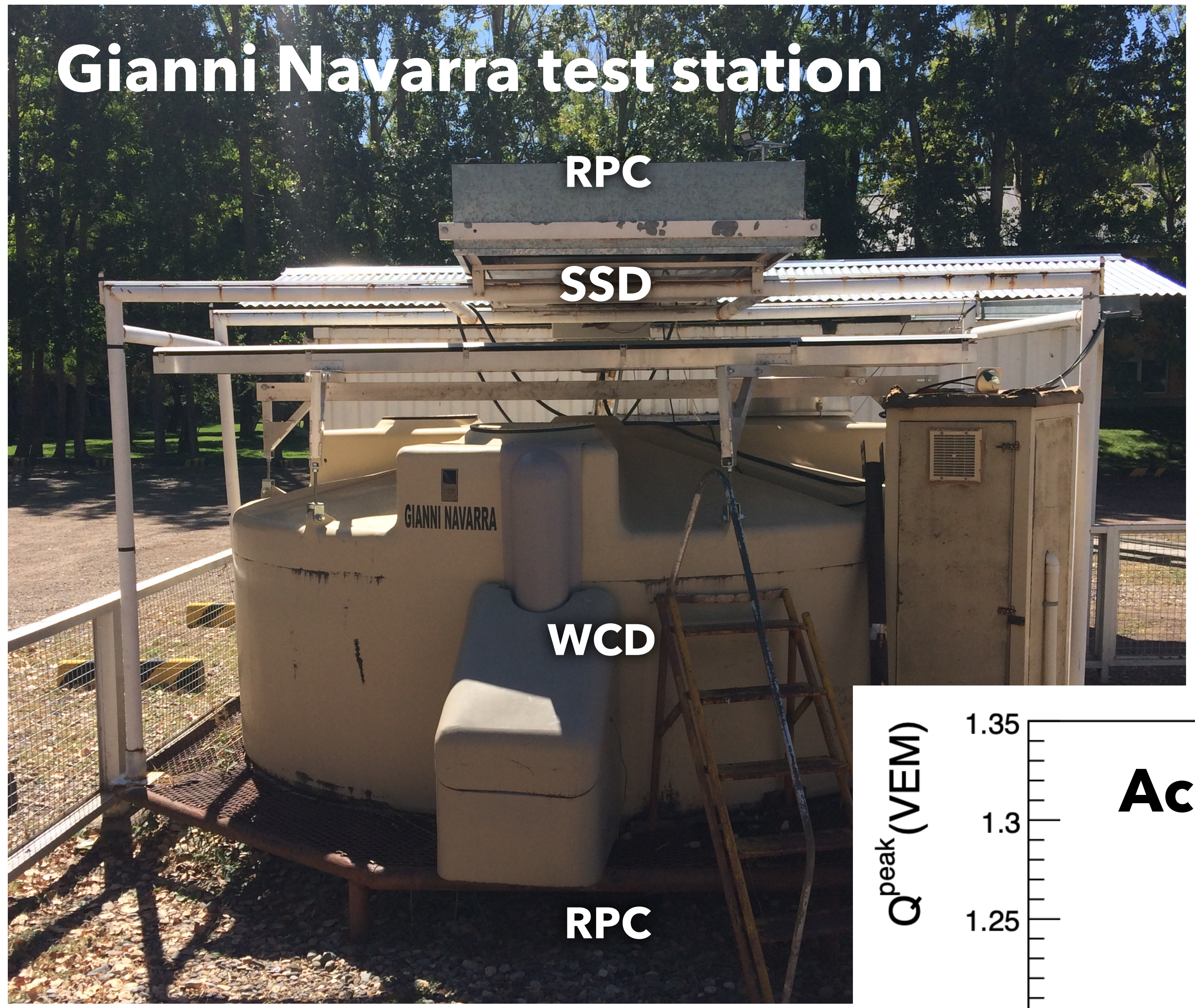


Calibration activities

Use an RPC hodoscope setup to evaluate **WCD-SSD calibration**

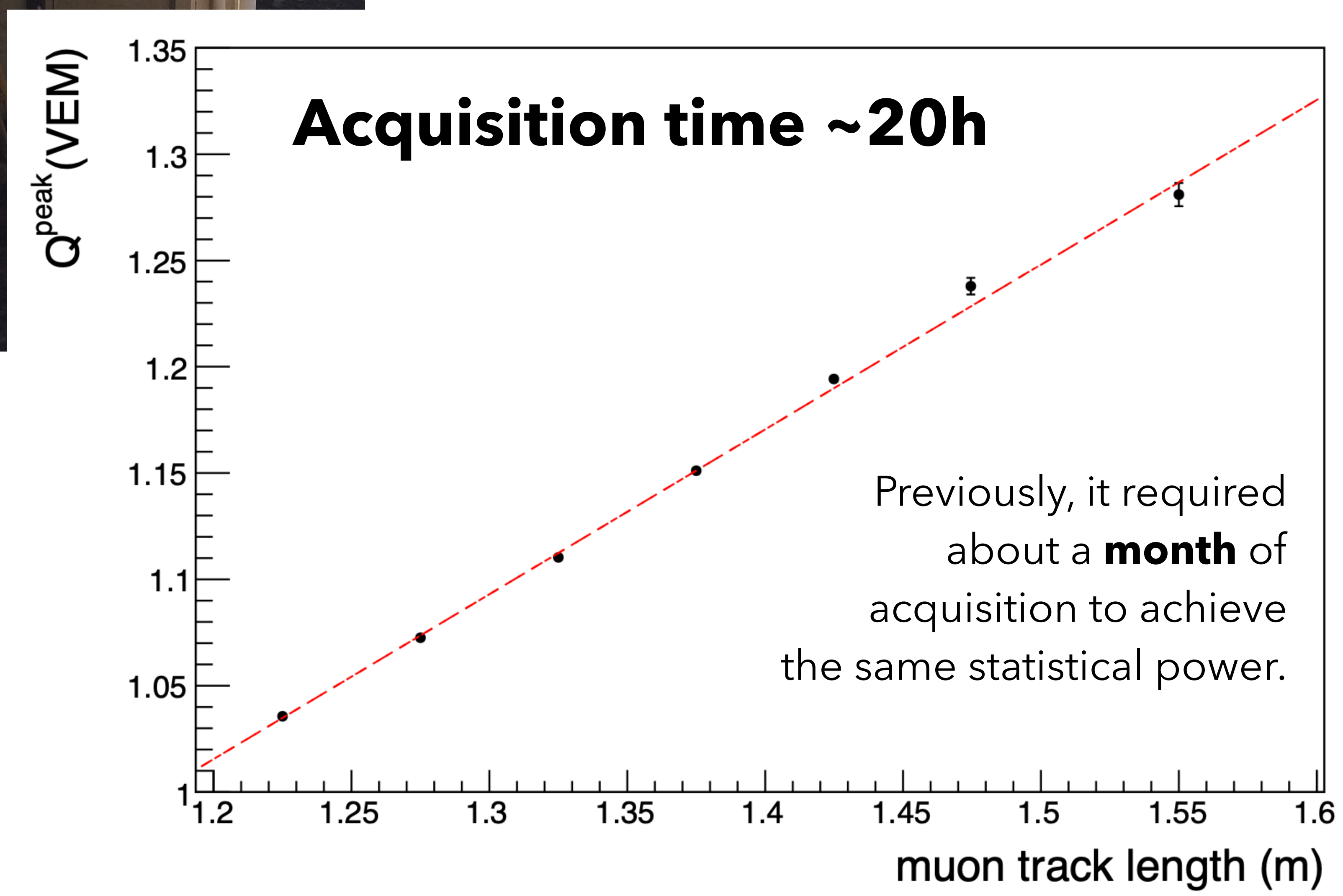
Pierre Auger coll., JINST 15 (2020) 09, P09002

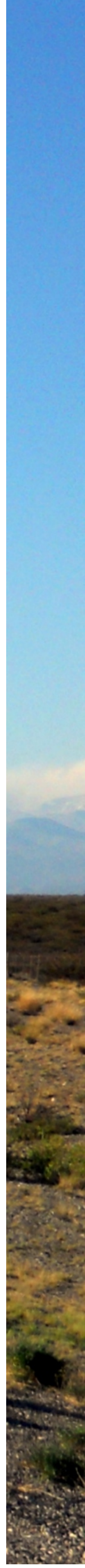




New setup to test/ calibrate the newly installed Scintillator Surface Detector (SSD) and new SD electronics

Development of innovative calibration methods that can be performed directly in the field



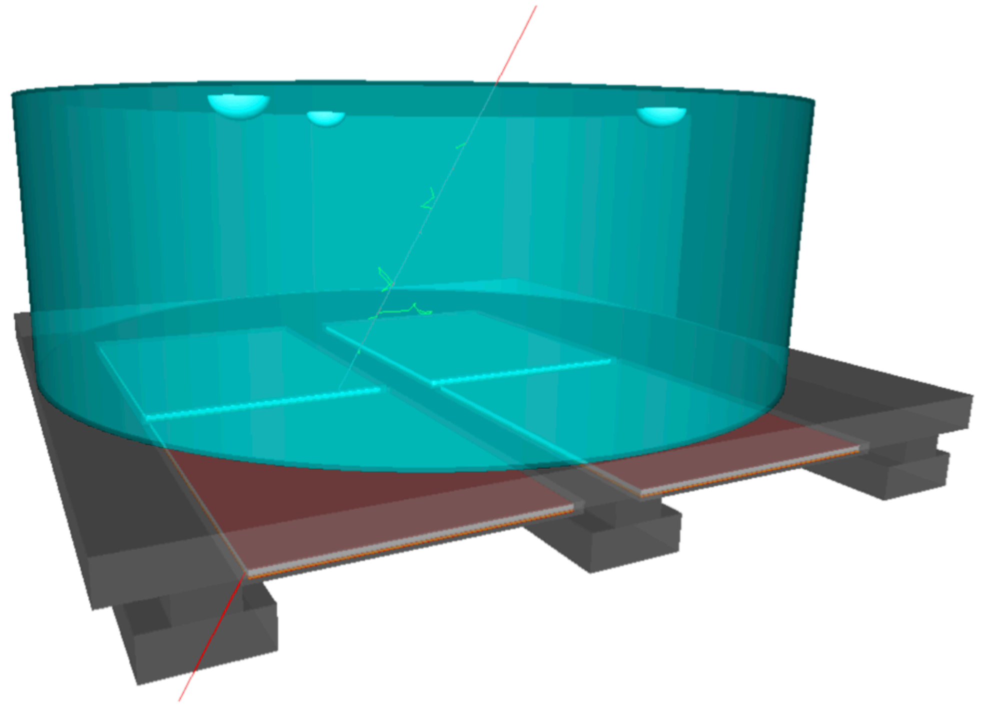


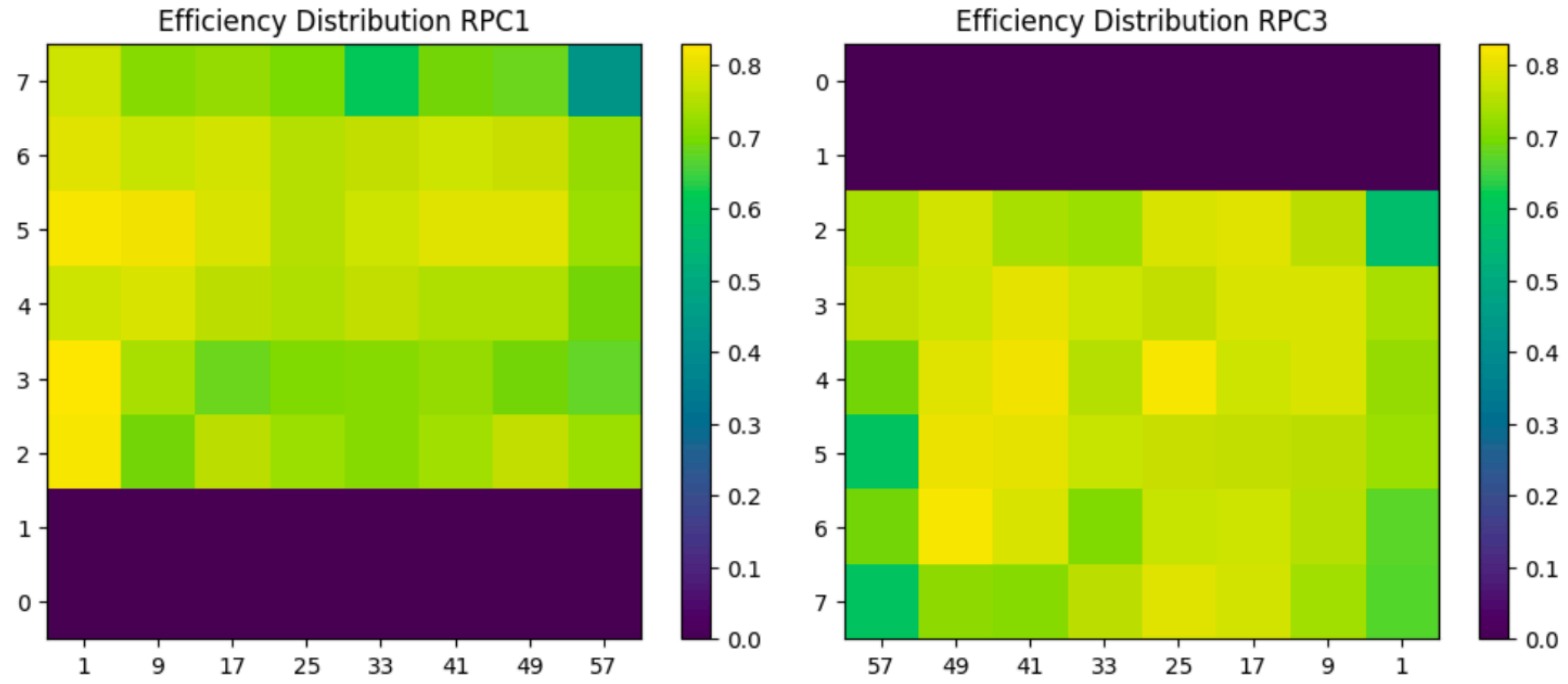
MARTA

Muon Array with RPCs for Tagging Air showers

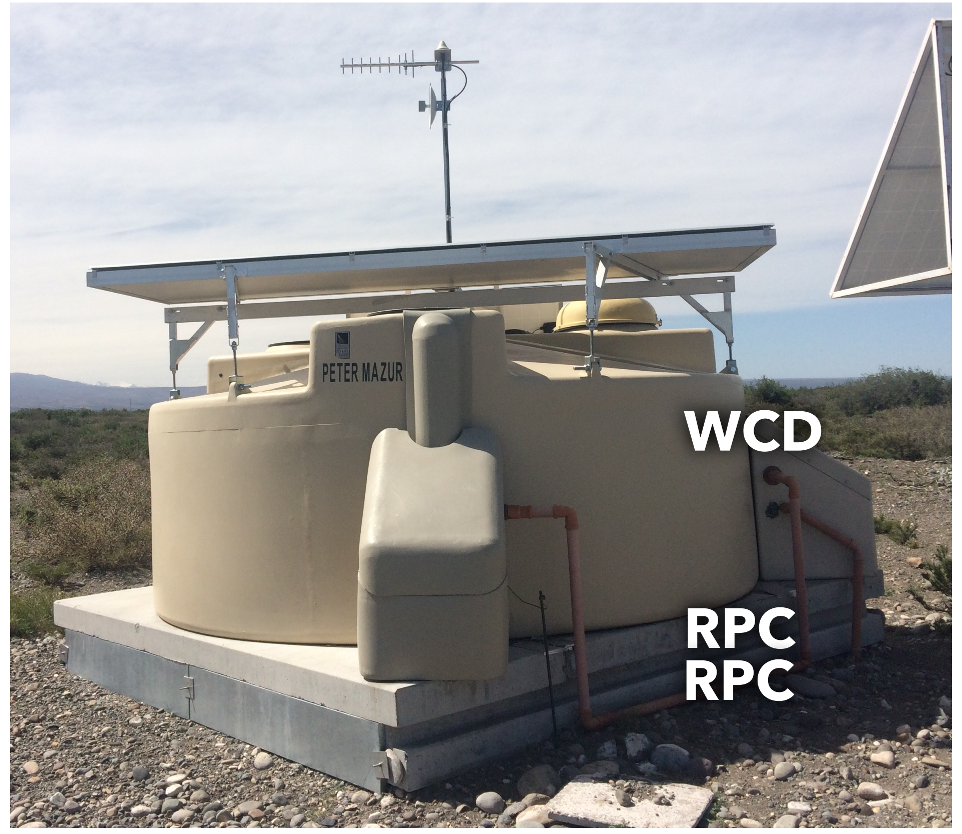
P. Assis, et al Eur.Phys.J.C 78 (2018) 4, 333

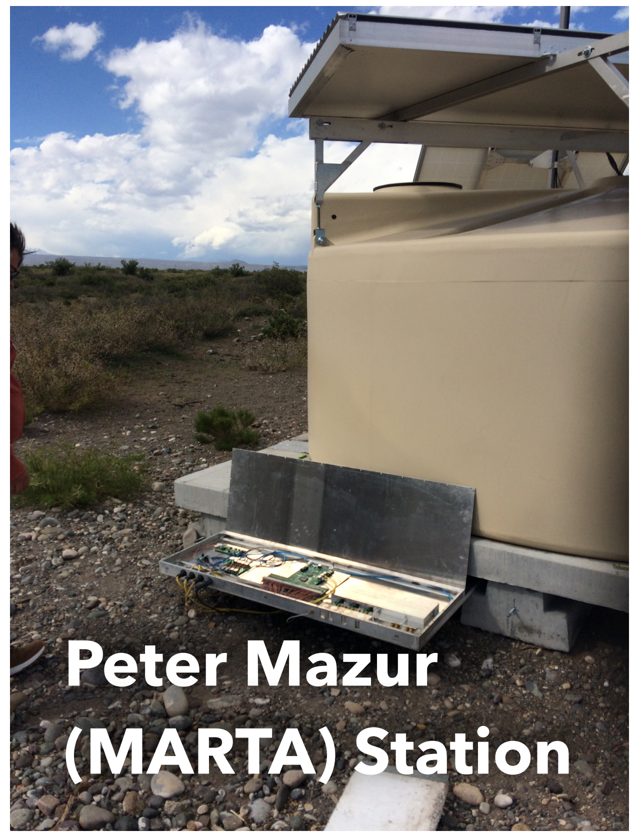
- Place Resistive Plate Chambers below the water Cherenkov tank to directly detect the shower muon component

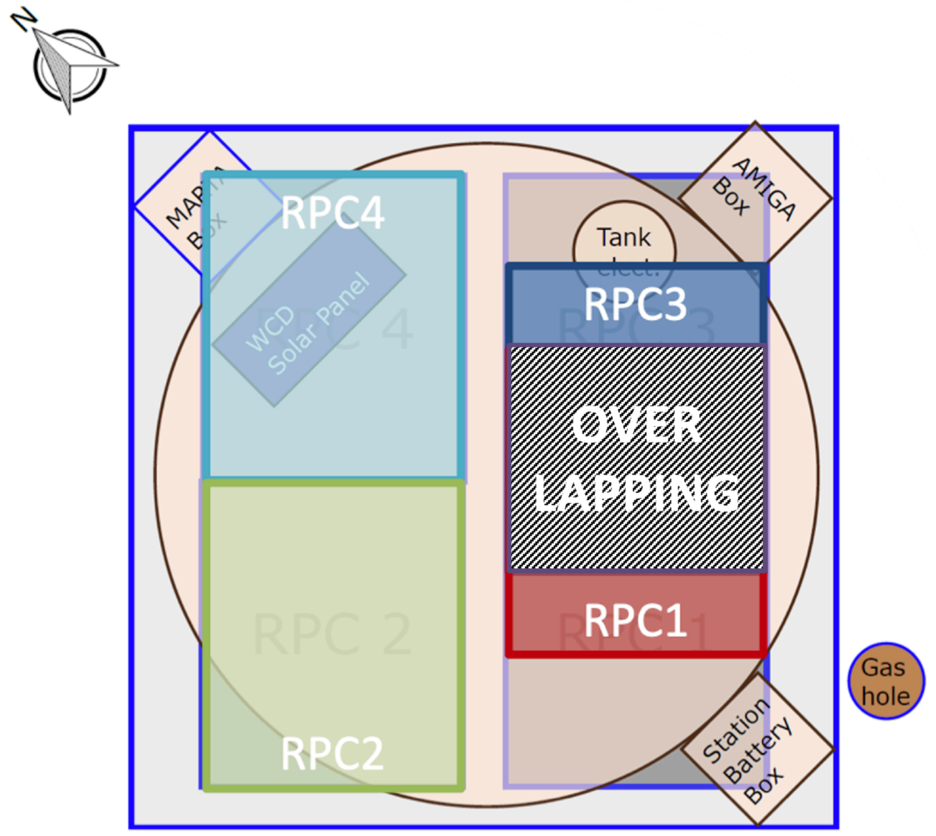


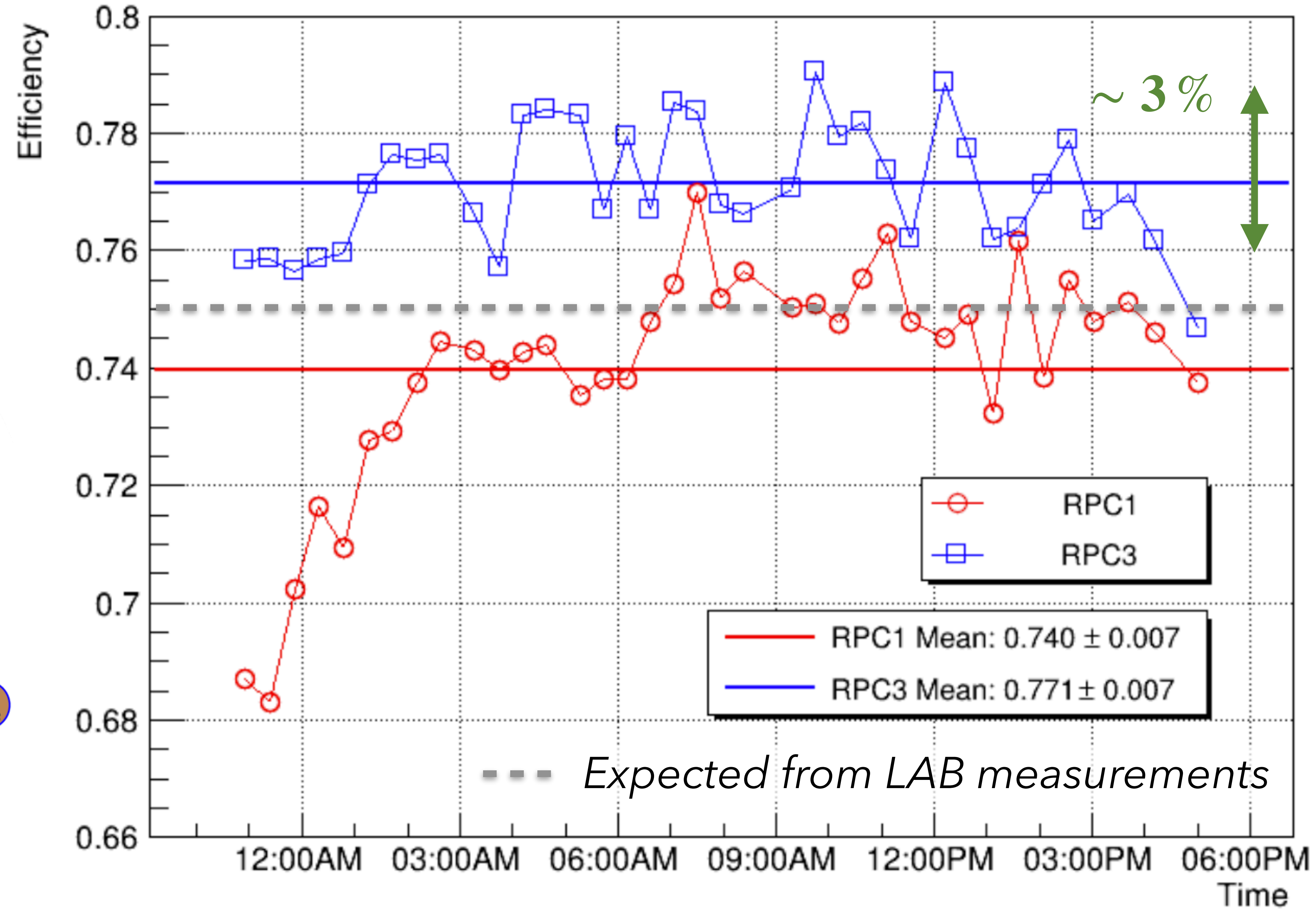


First MARTA station fully commissioned









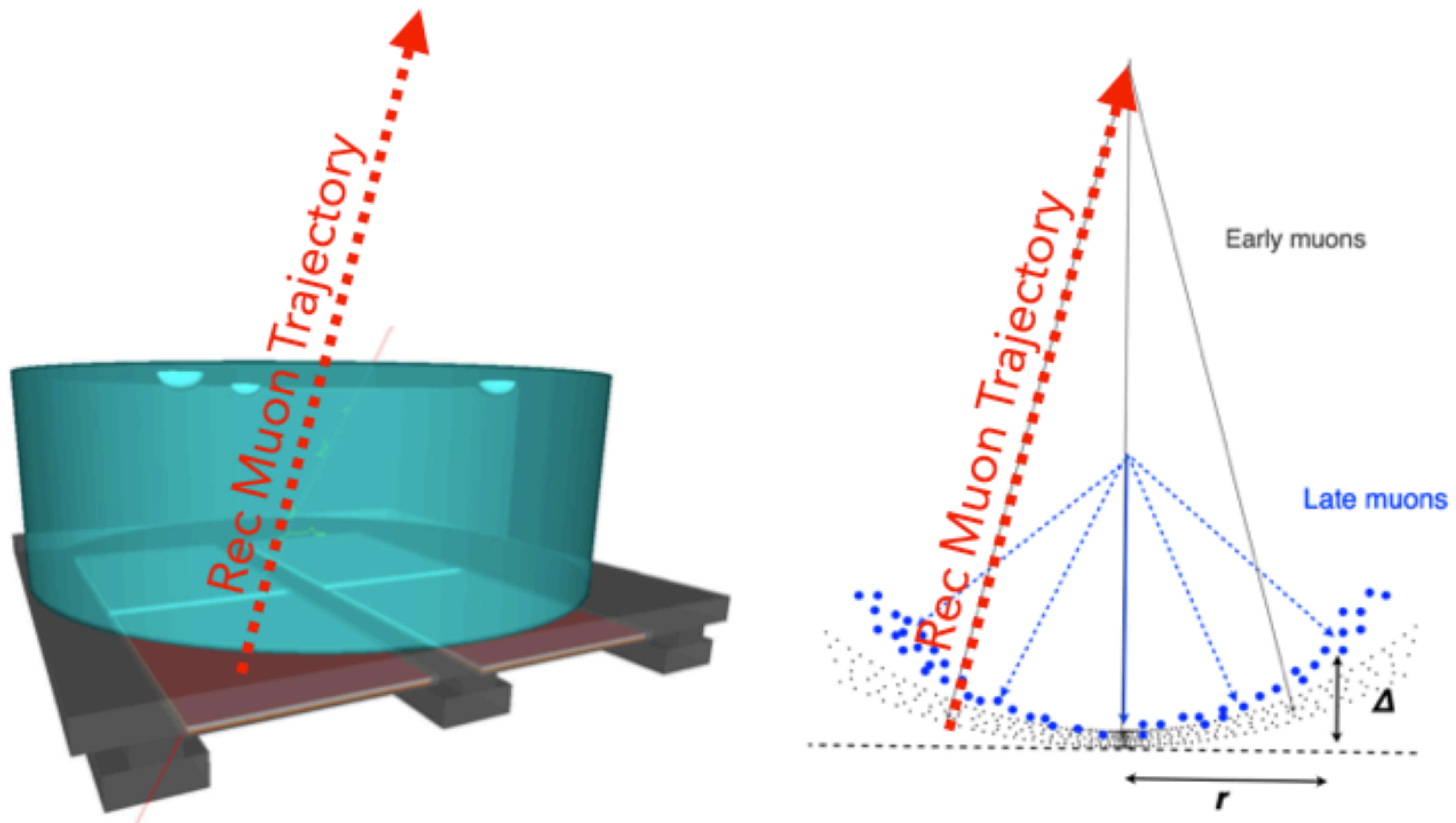
EAS pheno I: EAS particles energy spectrum

Novel strategies being exploited to access for the first time the energy spectrum of the shower e.m. and muon components

Machine Learning WCD analysis + Muon Production Depth

Use ideas developed in SWGO to reconstruct the muon direction analysing the WCD PMTs signal time trace + RPC hit with ML algorithms

Combine with position extract from arrival delay to the shower front (MPD) to access kinematical delay term, i.e. muon energy spectrum

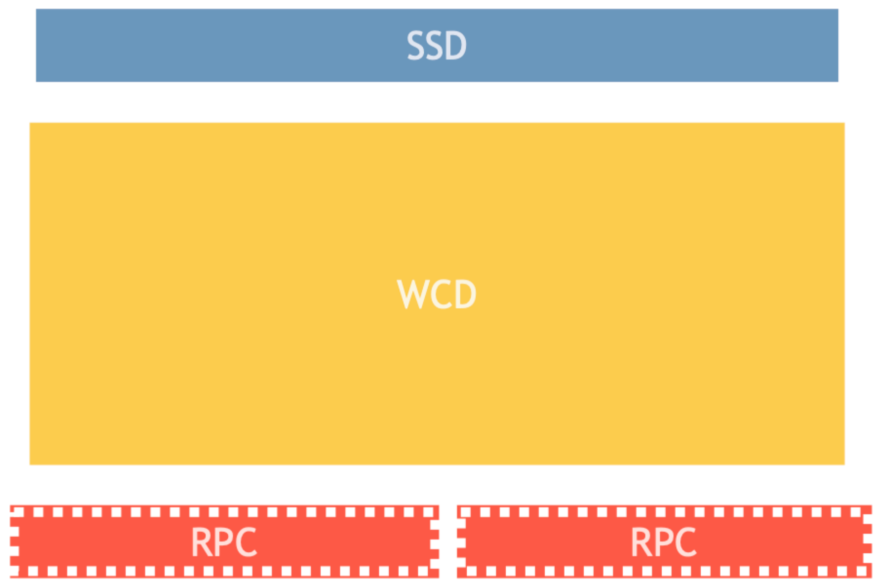


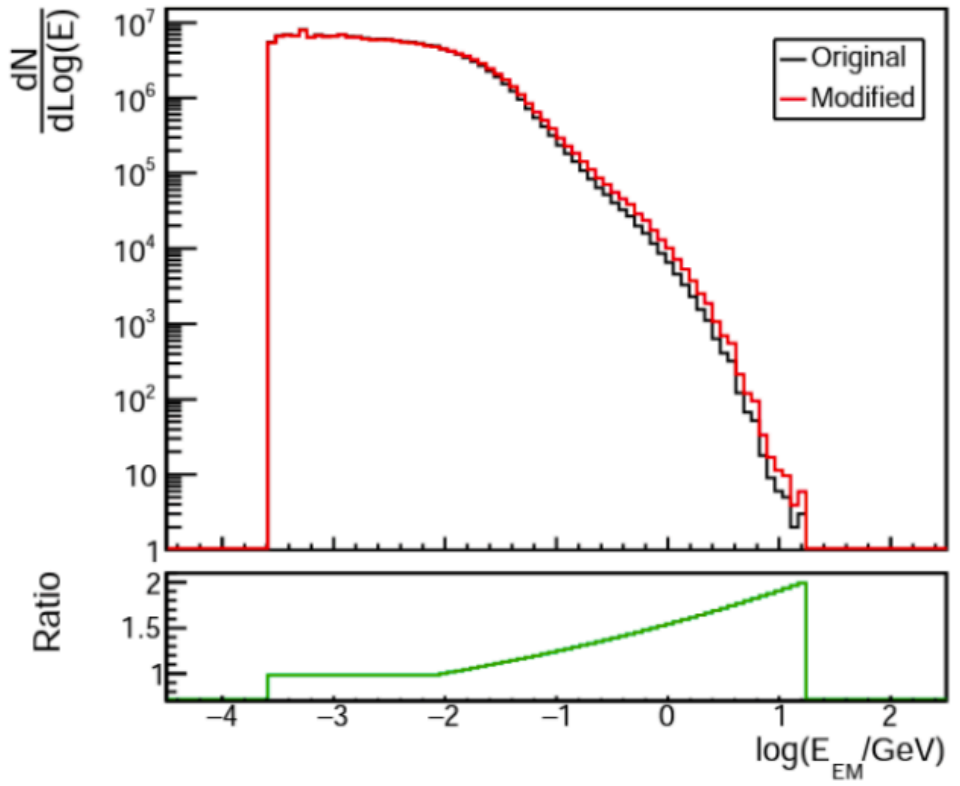
$$z \simeq \frac{1}{2}\left(\frac{r^2}{c\left(t-\langle t_\varepsilon\rangle\right)} - c\left(t-\langle t_\varepsilon\rangle\right)\right) + \Delta - \langle z_\pi\rangle$$

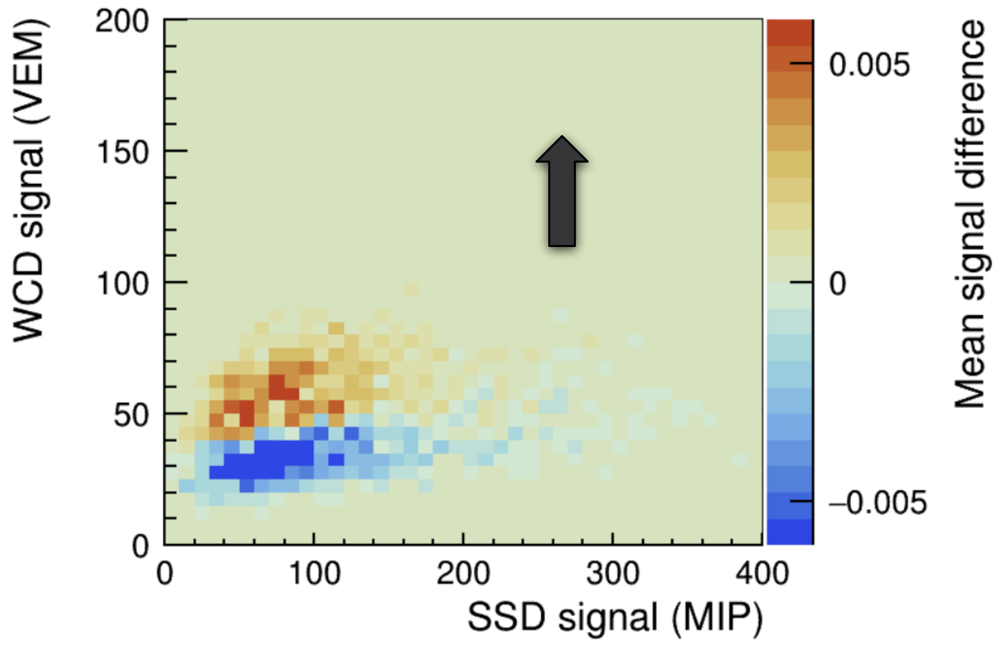
Analysis of MARTA (WCD+RPC) +SSD data

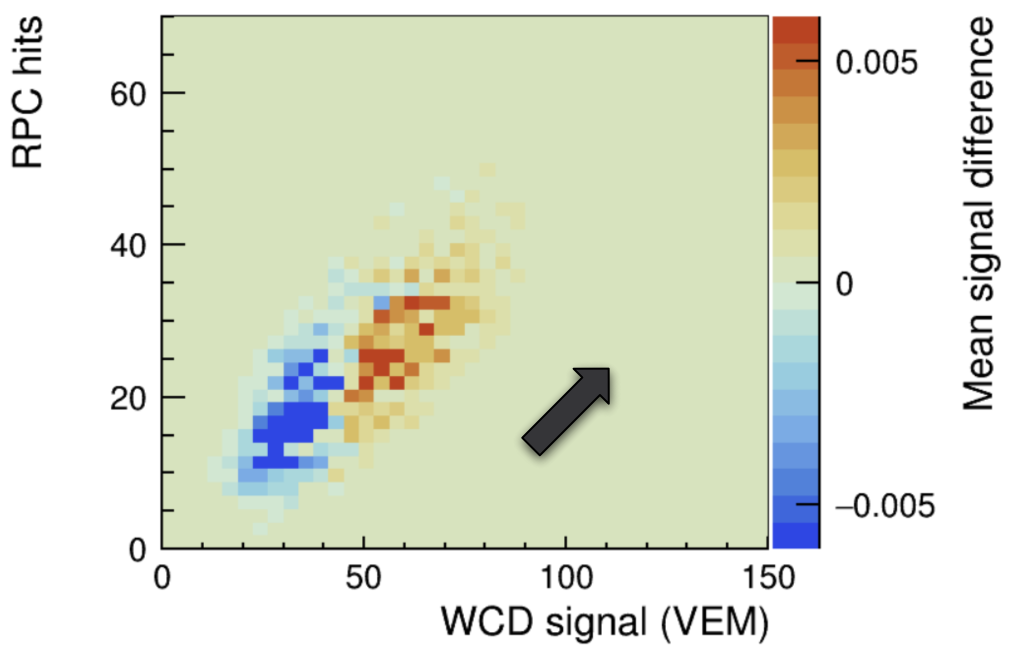
Shower particles are crossing multiple detectors that respond differently to particle type and energy

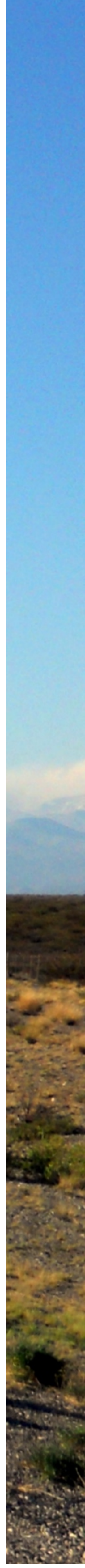
(submitted to JCAP - arXiv:2503.20346)



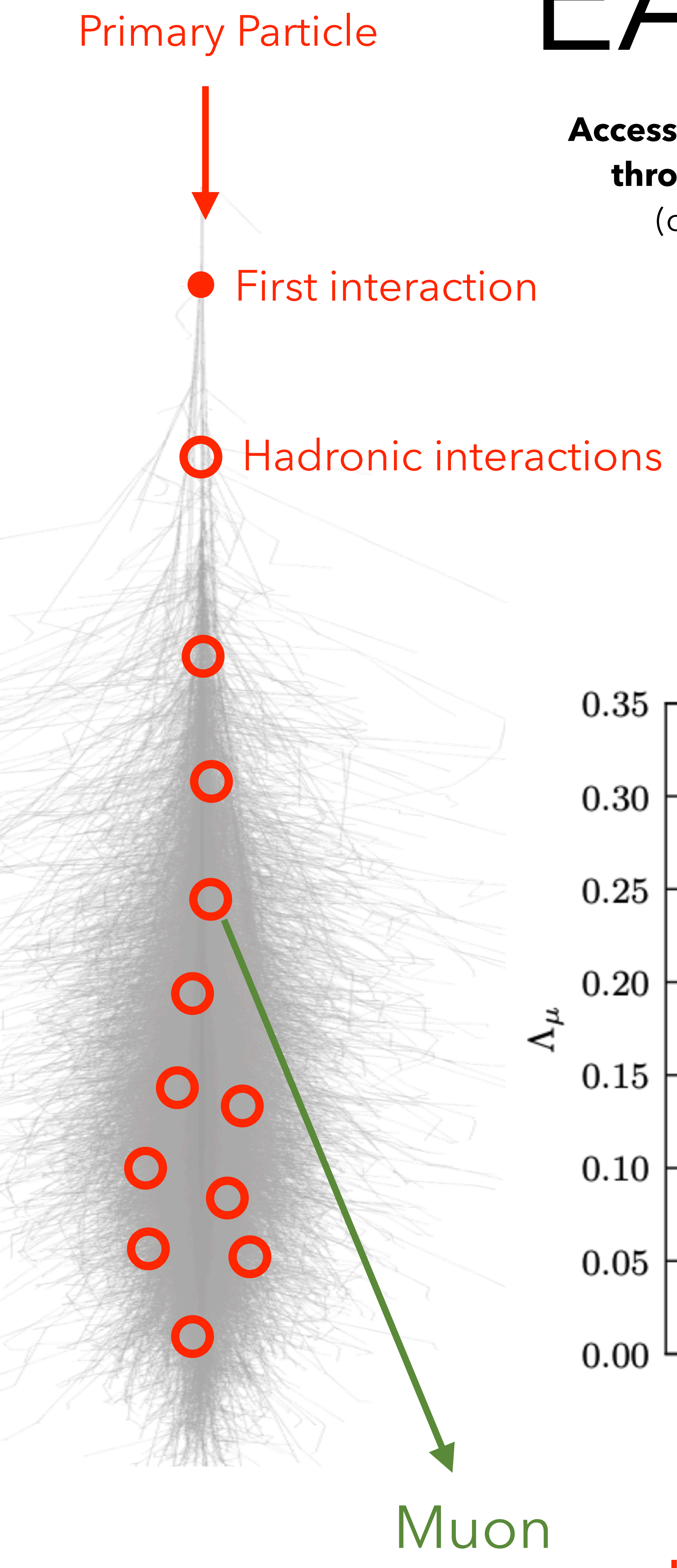




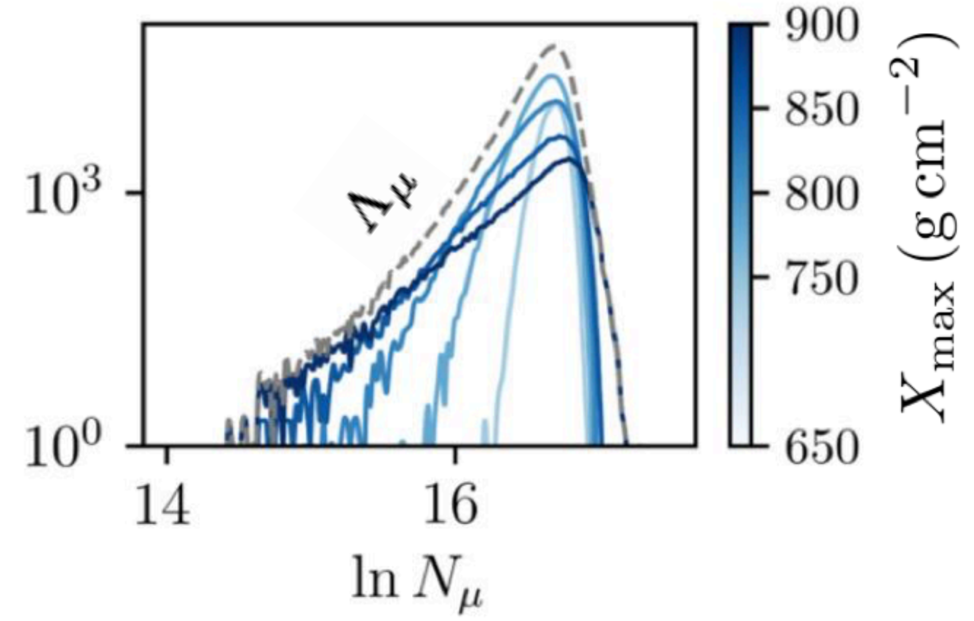


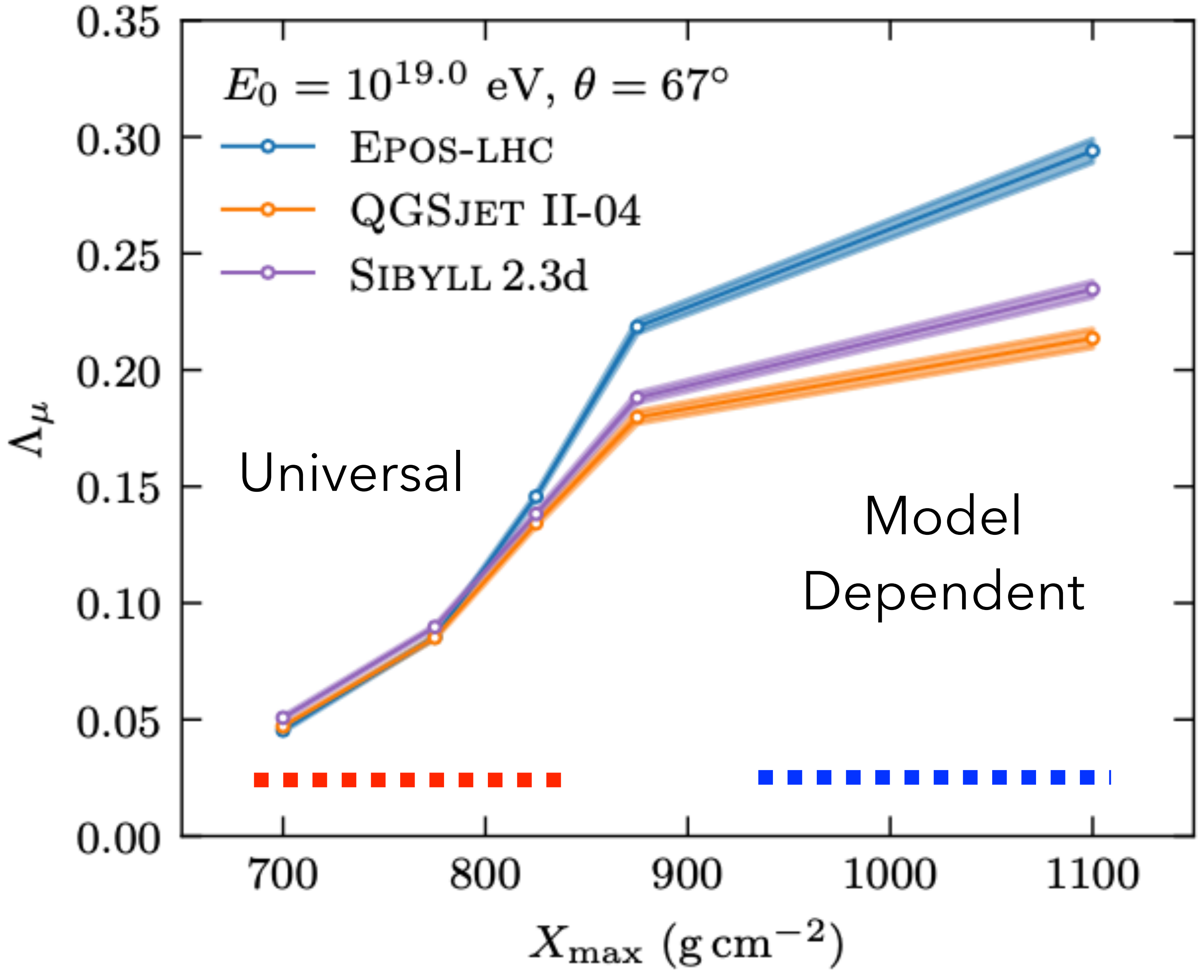


EAS pheno II: Muon distribution



Access the first interaction multi-particle production details through the features of the muon number distribution
(collaboration with Santiago de Compostela group)



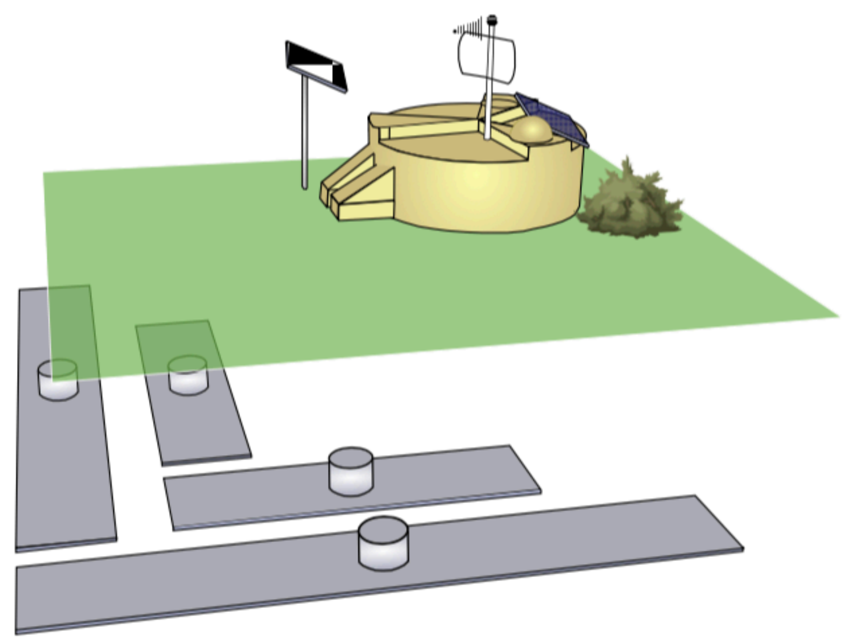


Low hadronic activity - diffractive events

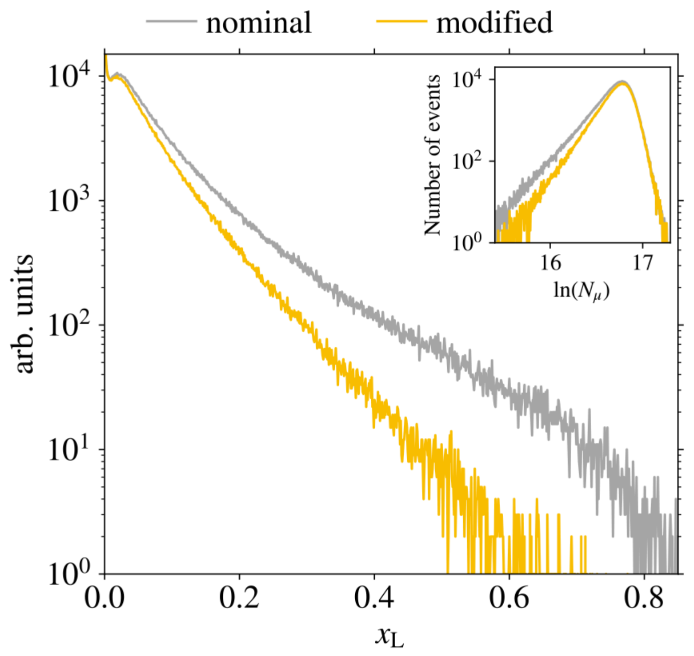
Large hadronic activity - e.g. high multiplicity

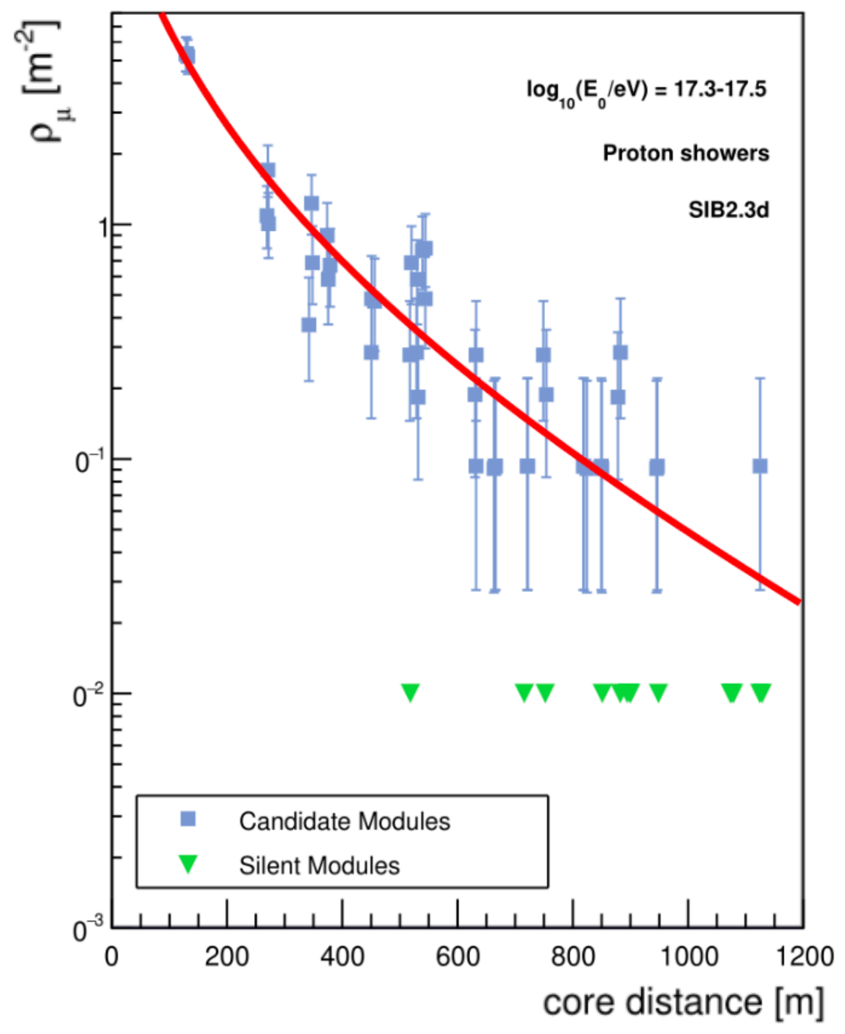
Phys.Lett.B 859 (2024) 139115

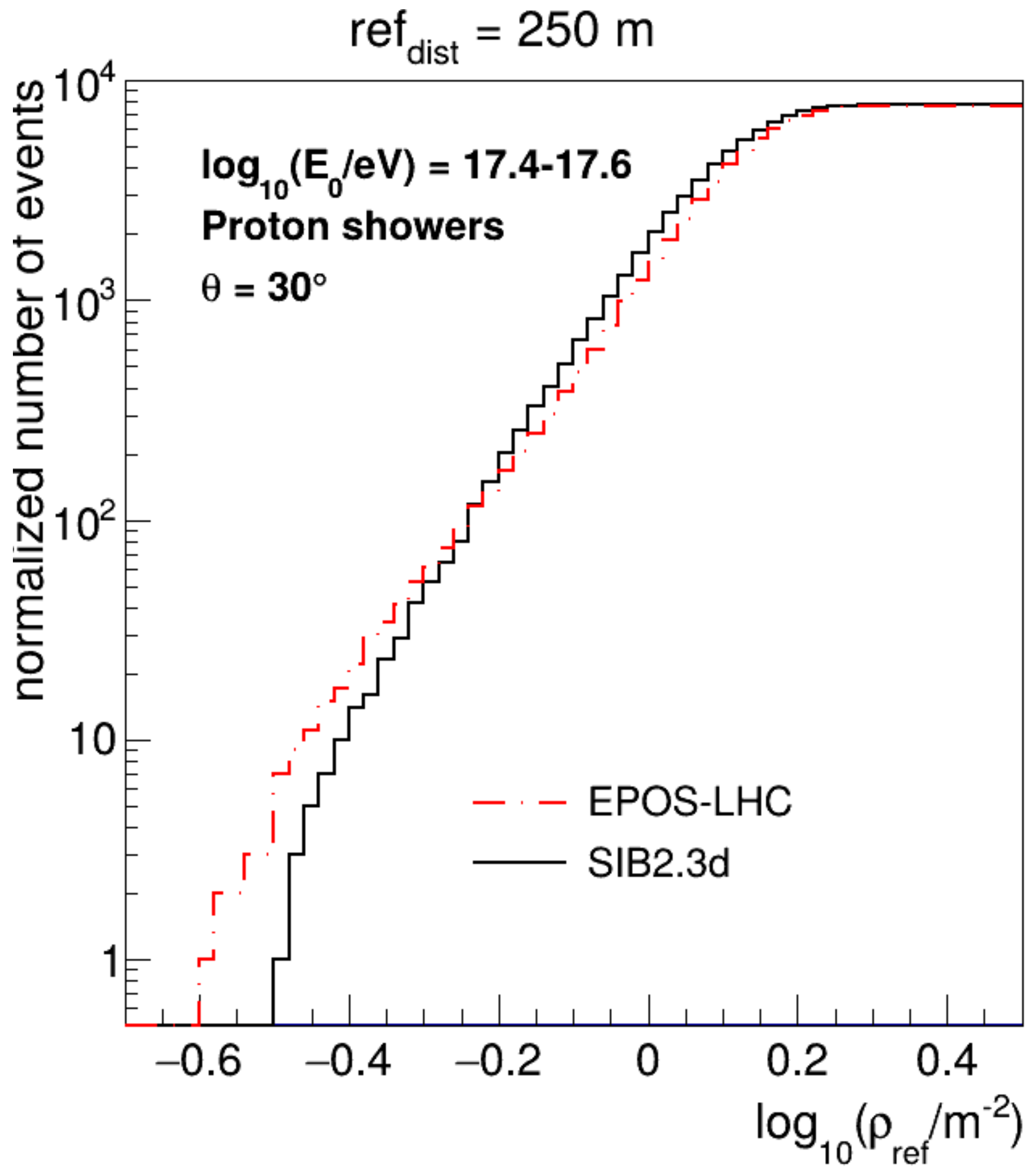
Measurement of the slope of muon number distribution, Λ_μ, through AMIGA data at LHC equivalent energies
(collaboration with Buenos Aires group)



Access the UHE first interaction π^0 energy spectrum



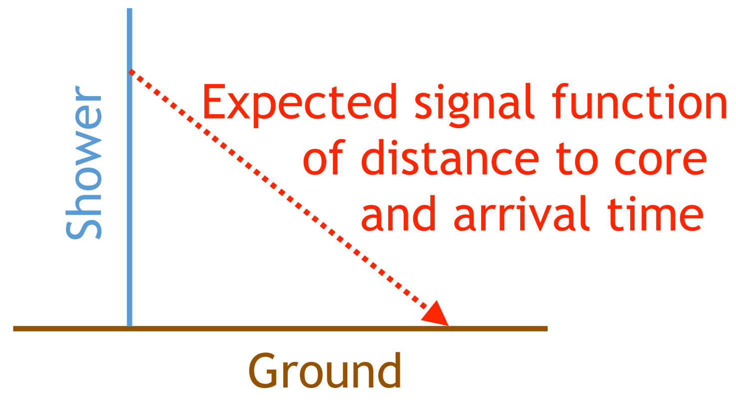




Searches for neutral particles

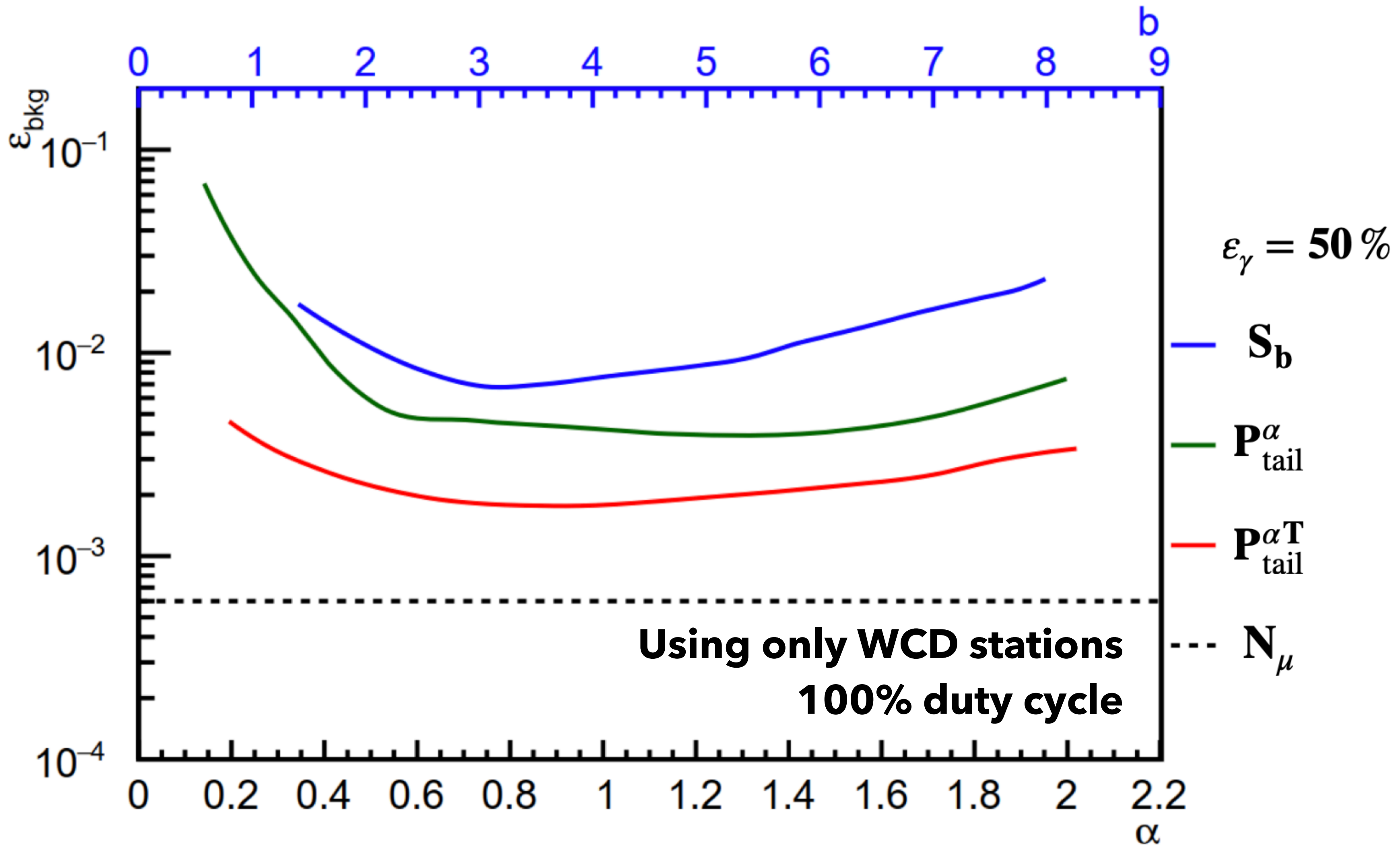
Photons

The Southern Wide-field Gamma-ray Observatory



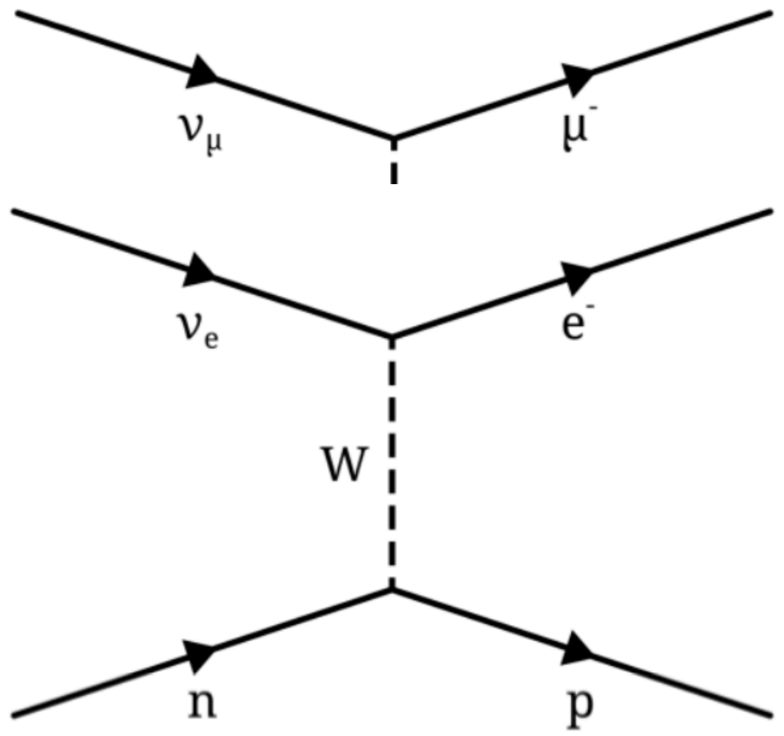
Adapt **innovative gamma/hadron discriminators** created in the context of SWGO for Auger

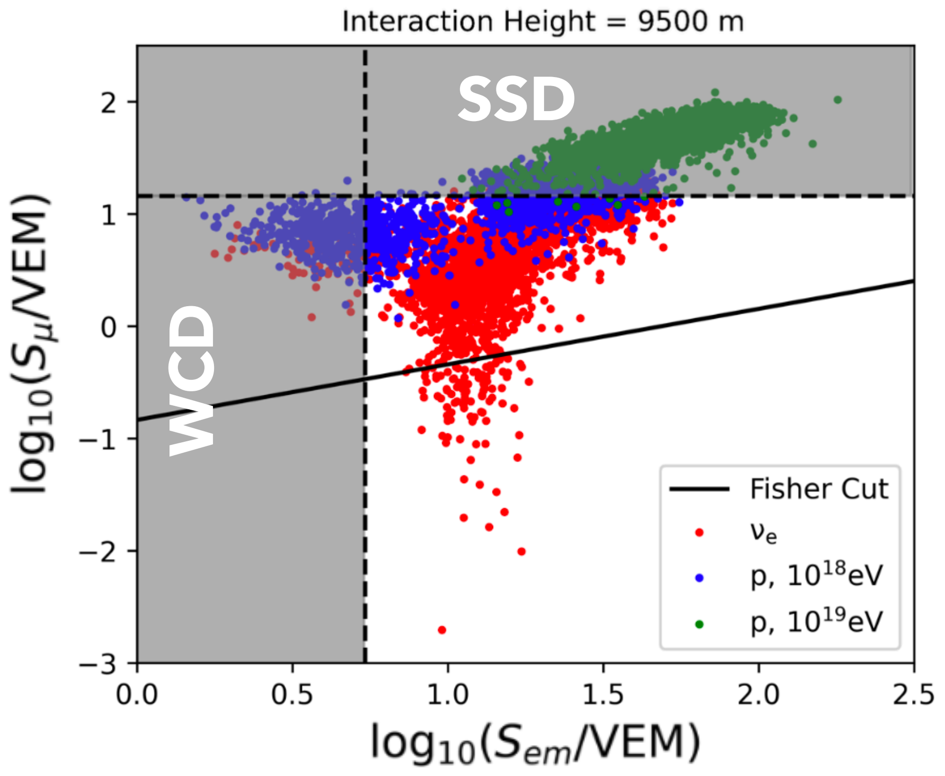
Explore high signal fluctuations in space and **time** - $P_{\text{tail}}^{\alpha T}$

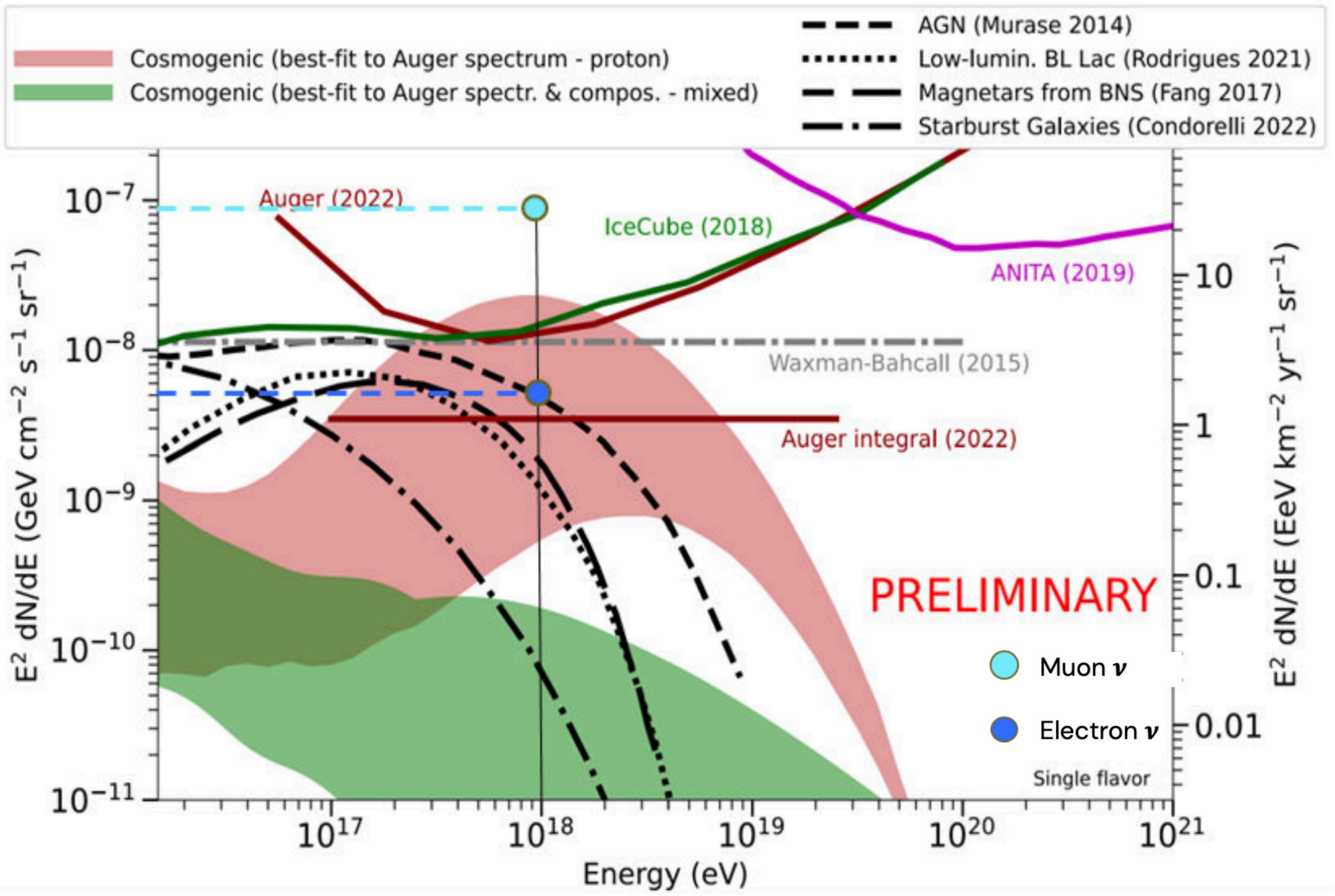


Neutrinos

Explore new detectors (+X_{max} info) to extend **neutrino searches to all zenith angles** and not only for Earth-skimming events

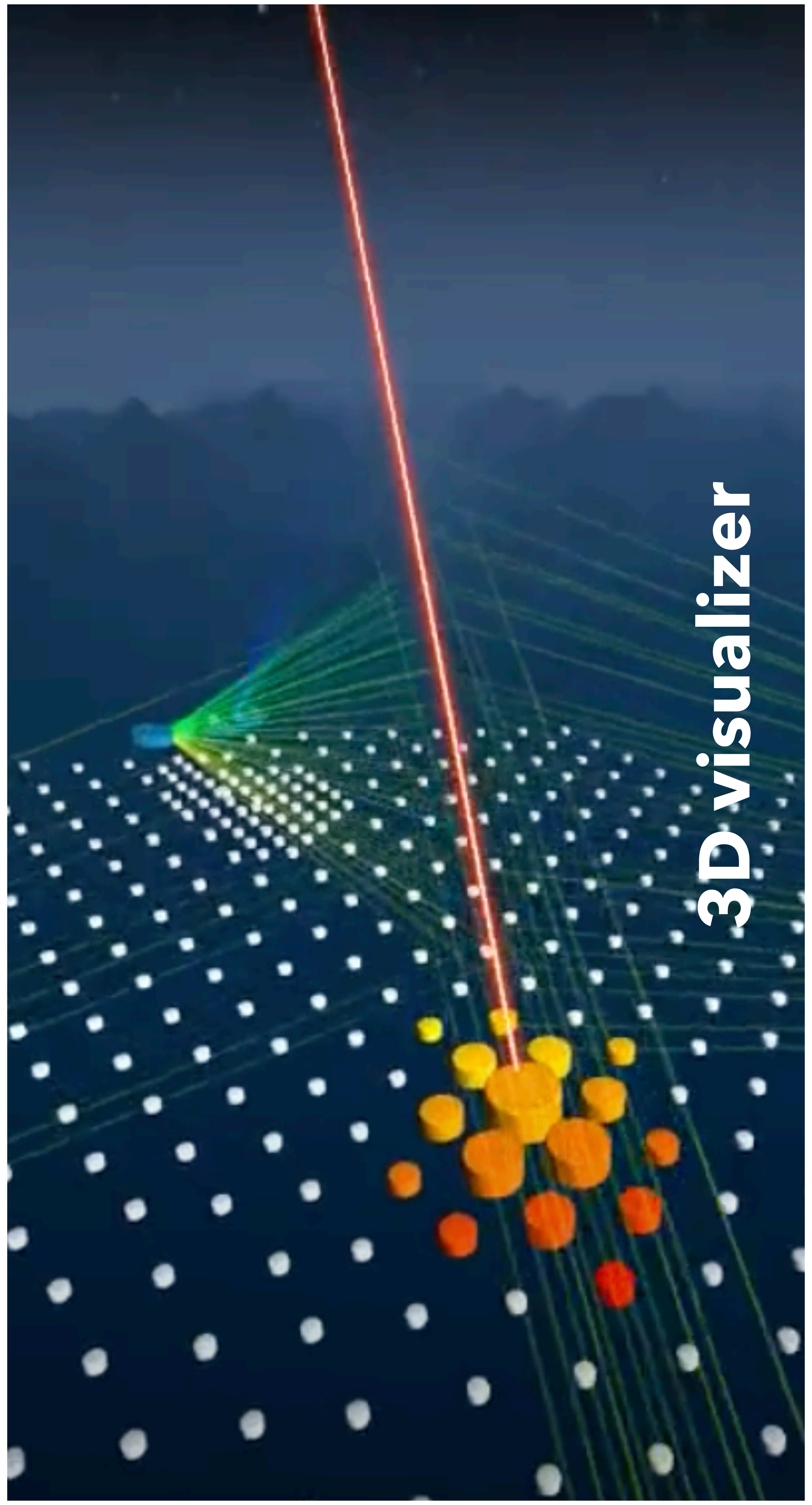




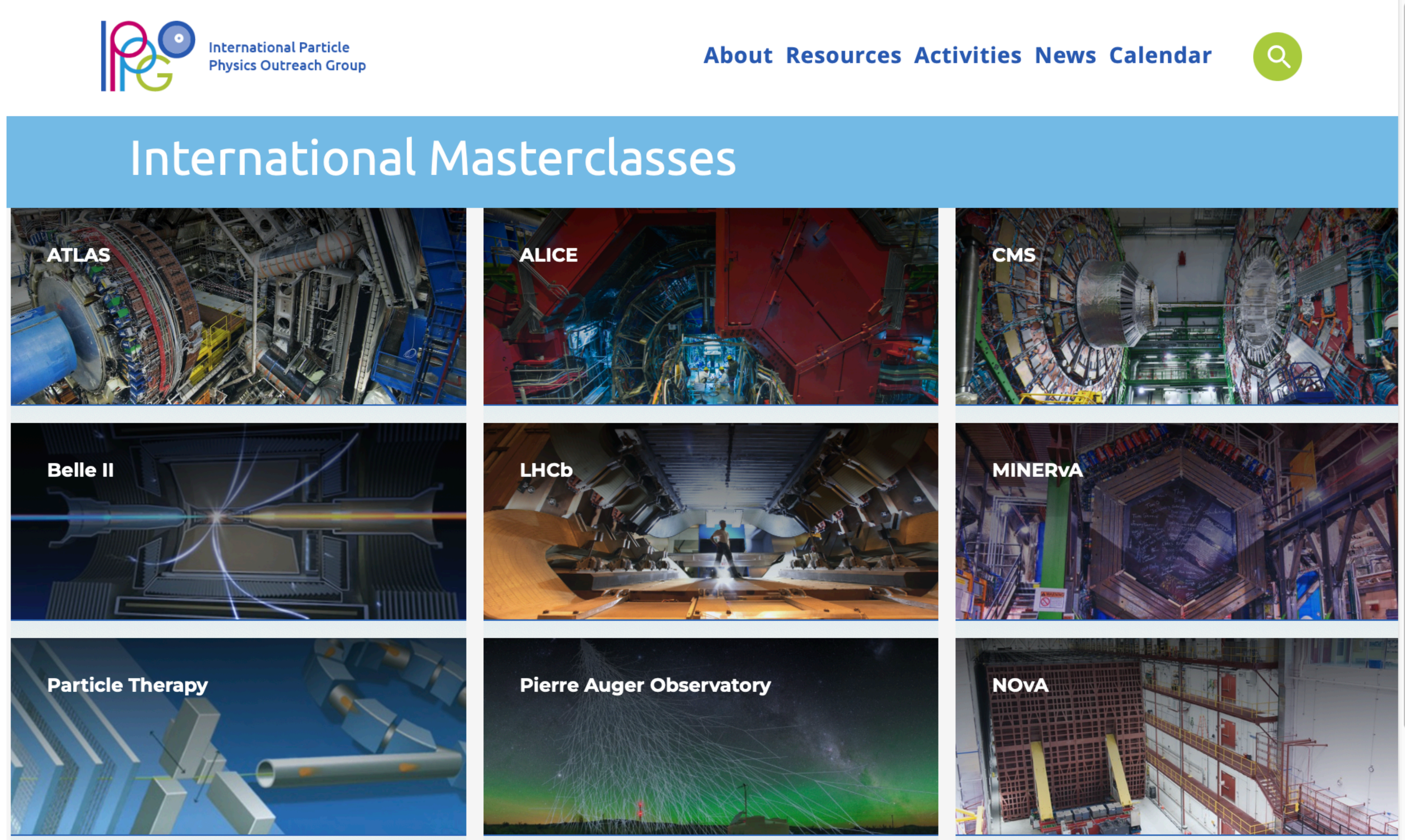


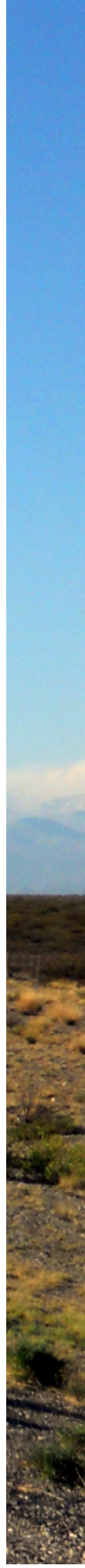
Enhance the Observatory multi-messenger capabilities

Outreach activities



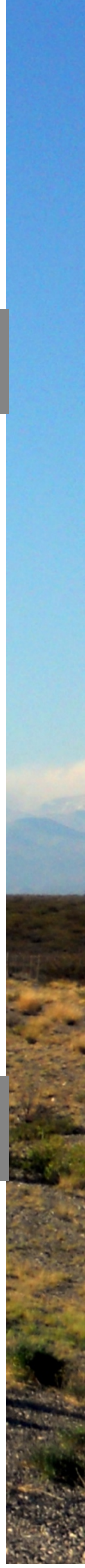
Auger Masterclasses at	IMC 2023	IMC 2024	**IMC 2025**
Events	3	5	**6**
Continents	2	4	**4**
Countries	5	10	**12**
Institutions	12	16	**21**
Institutions within Auger	10	10	**10**
Institutions outside Auger	2	6	**11**
Students	550	534	**660**





New features: *Top100 Catalogue + SD750 + HEAT + …*

SWOT Analysis



Strength

- The LIP team is relatively large, both in terms of membership and expertise, encompassing a diverse range of competencies.
- The long-term commitment by FCT to support Portuguese participation in the Pierre Auger Observatory has been extended through 2035, ensuring the continued payment of the MoU and securing a stable framework for ongoing contributions.

Weakness

- The team is composed primarily of Master's and PhD students, alongside senior researchers, resulting in a relative shortage of mid-level workforce.
- The funding level is low relative to the size of the team, leading to resource constraints. This necessitates careful prioritization of missions for meetings and fieldwork in Argentina to optimize impact.

Opportunities

- The group's expertise in extensive air shower phenomenology, simulations, and RPC hodoscope calibrations positions it well for Phase 2 collaboration activities.
- Increasing visibility in academia, through lecturing and participation in thematic schools, is also creating opportunities to attract new students and raise awareness of the field.

Threats

- The group's funding relies on periodic renewals every two years through the Fund CERN application. Over time, the stability and certainty of this funding source are becoming increasingly uncertain, posing a potential risk to long-term planning and operations.

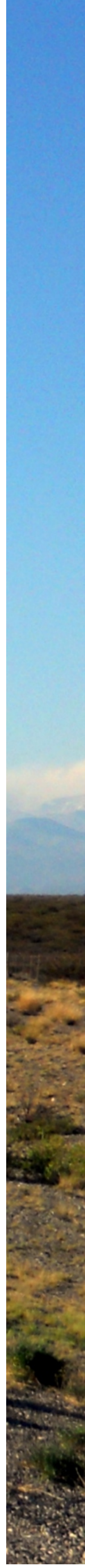
Acknowledgements

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

REPÚBLICA PORTUGUESA

LIP

TÉCNICO LISBOA

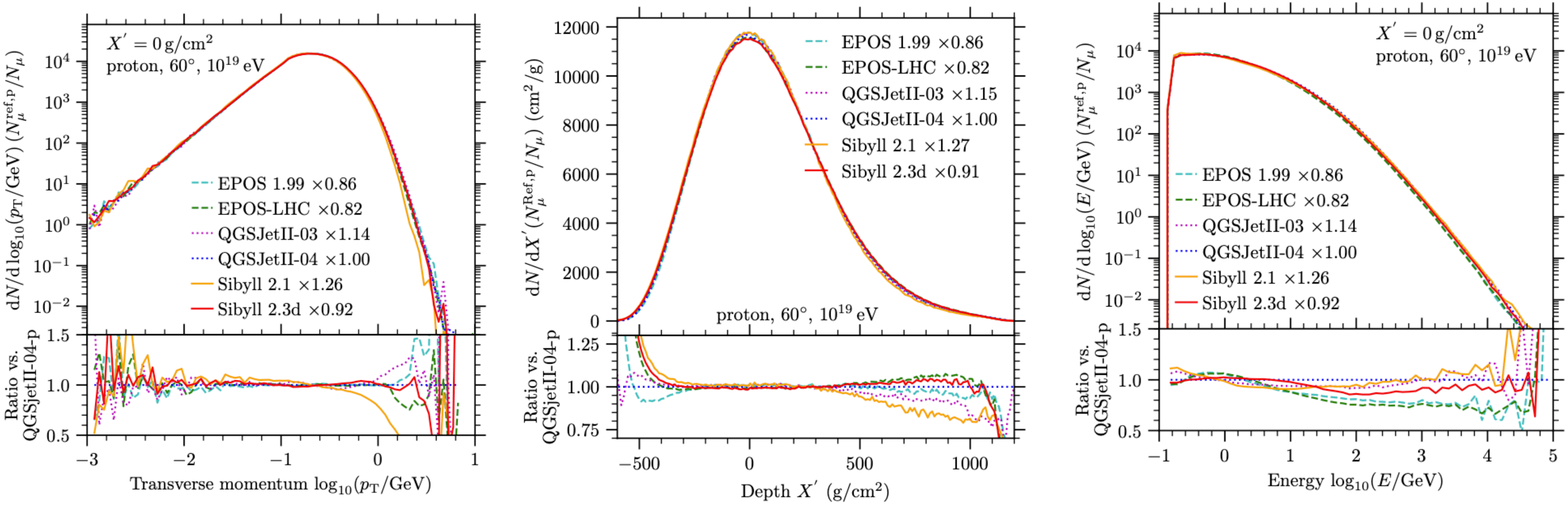


Backup Slides

Universality of the muonic sector

L. Cazon, RC, F. Riehn, JCAP 03 (2023) 022

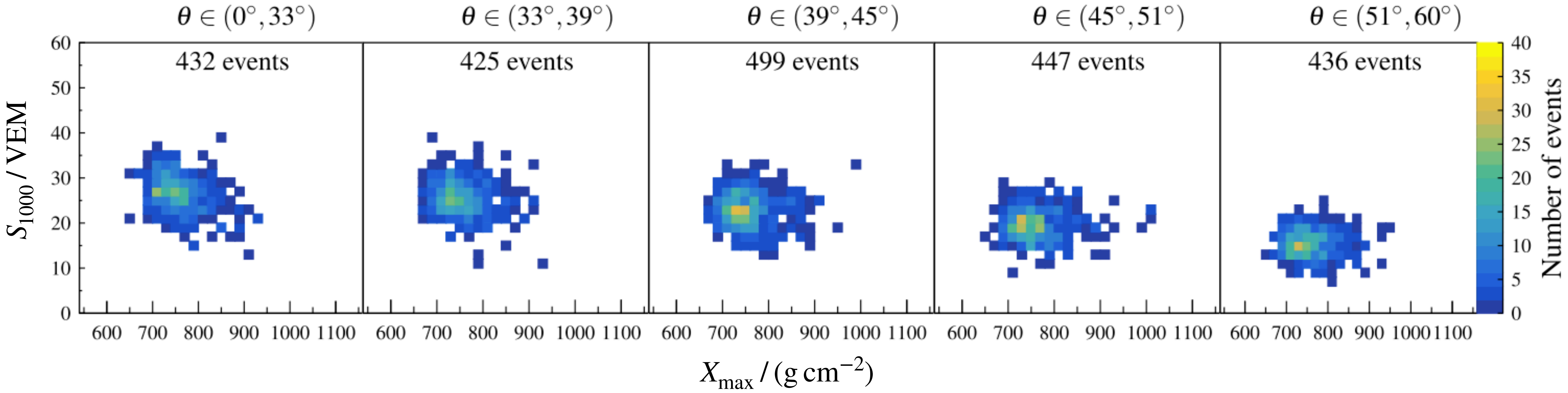
The muon distributions in air shower can be characterized using few key distributions



Most of these distributions are universal with the exception of the muon energy spectrum for $E_\mu > 1\,\mathrm{GeV}$

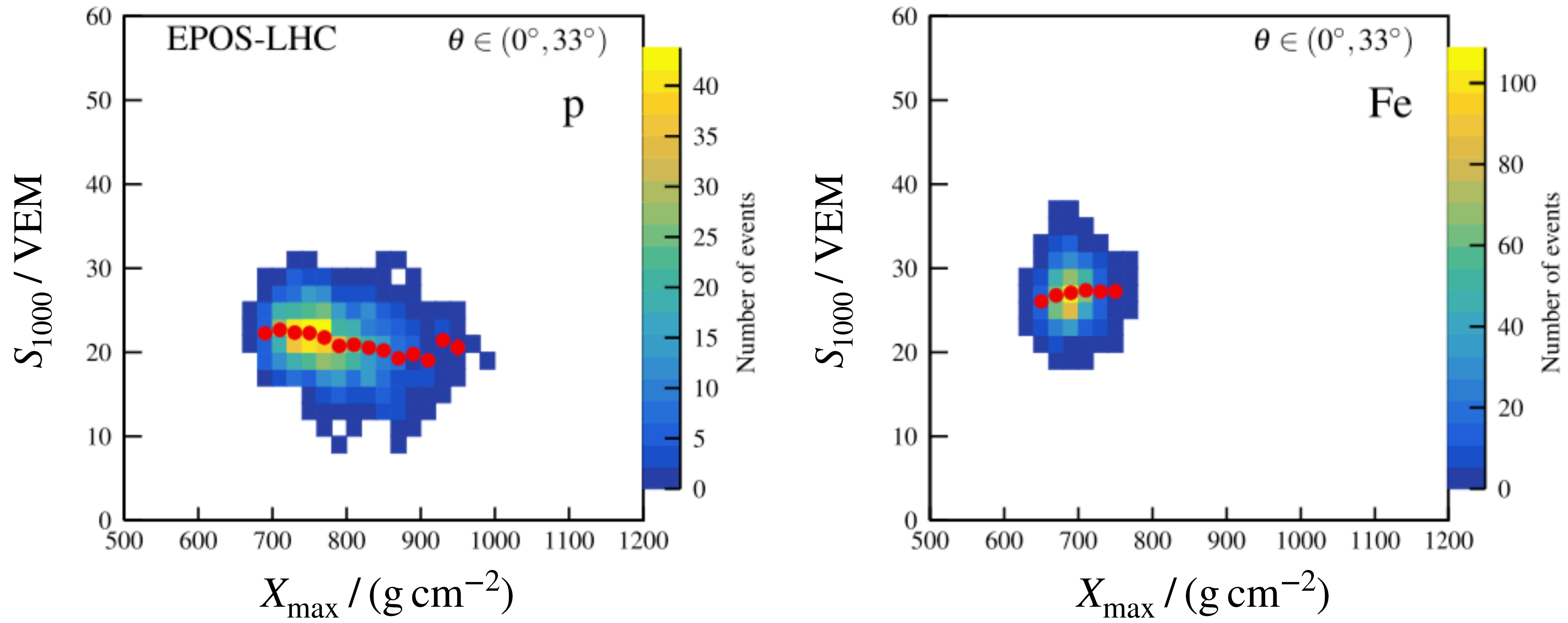
Analysis of the (X_{max}, S_{1000}) distribution

Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001

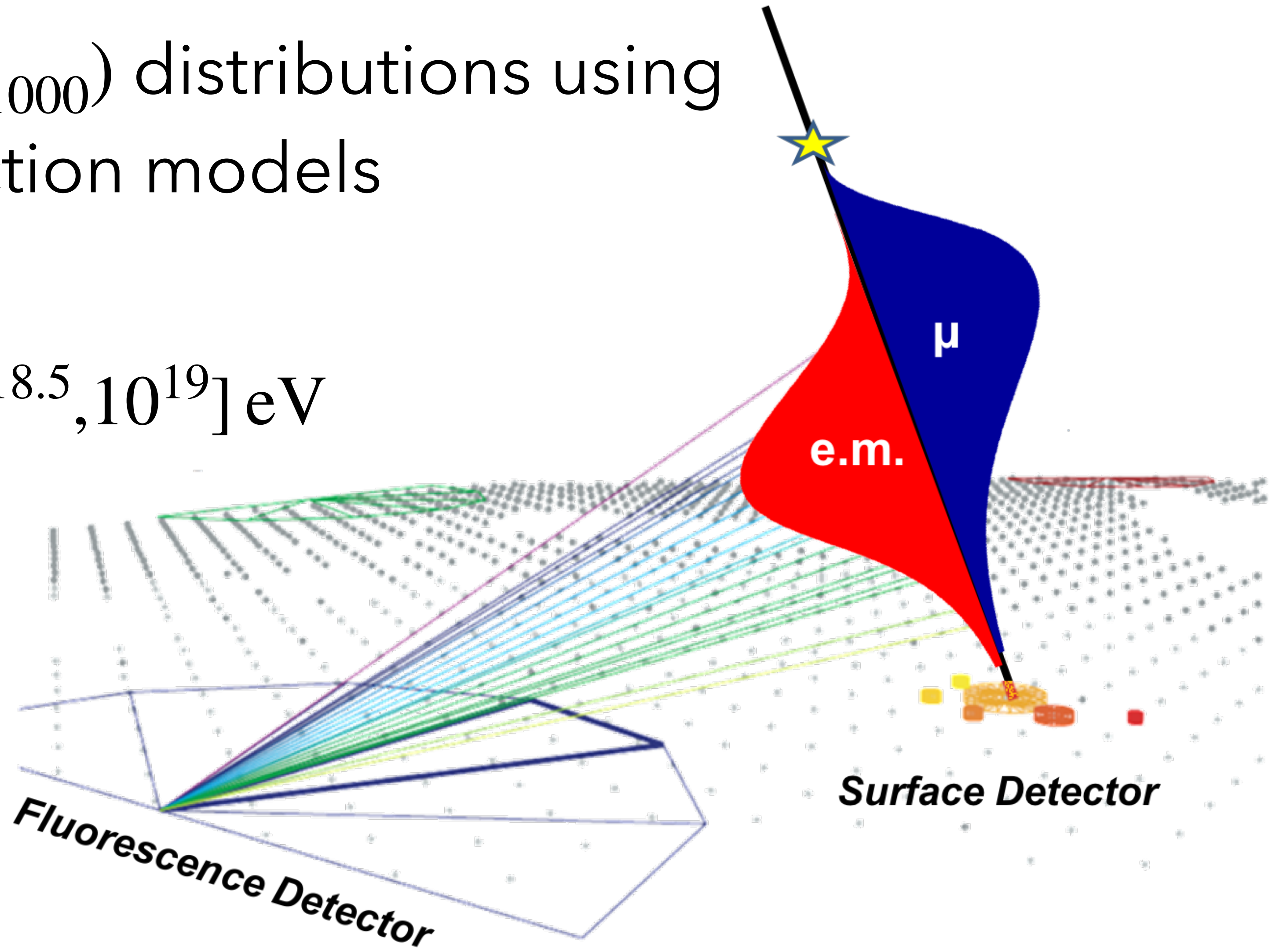


Explore hybrid FD-SD events and **fit the measured two-dimensional** (X_{max}, S_{1000}) distributions using templates for simulated air showers produced with hadronic interaction models

Example of MC templates

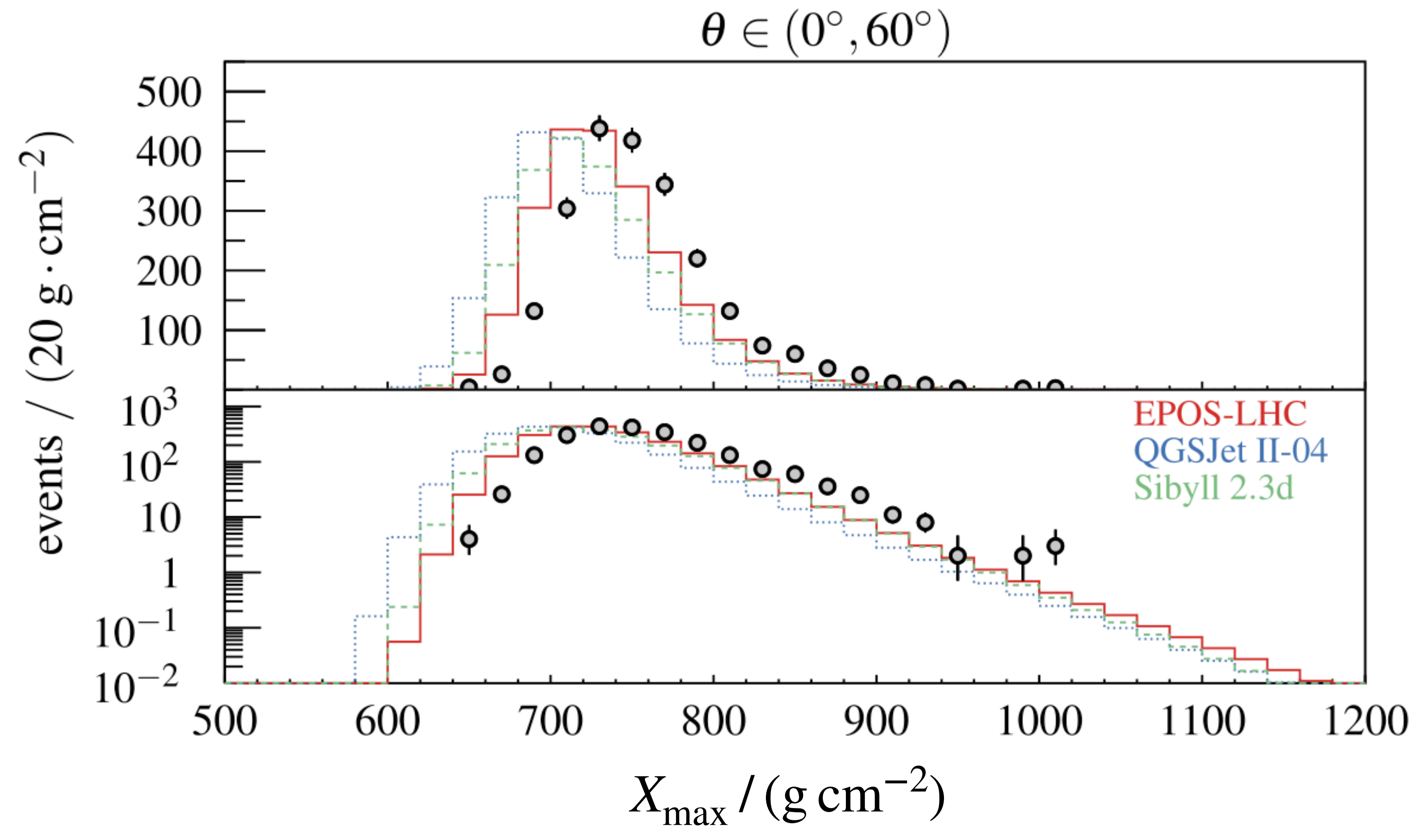


$E \in [10^{18.5}, 10^{19}]$ eV



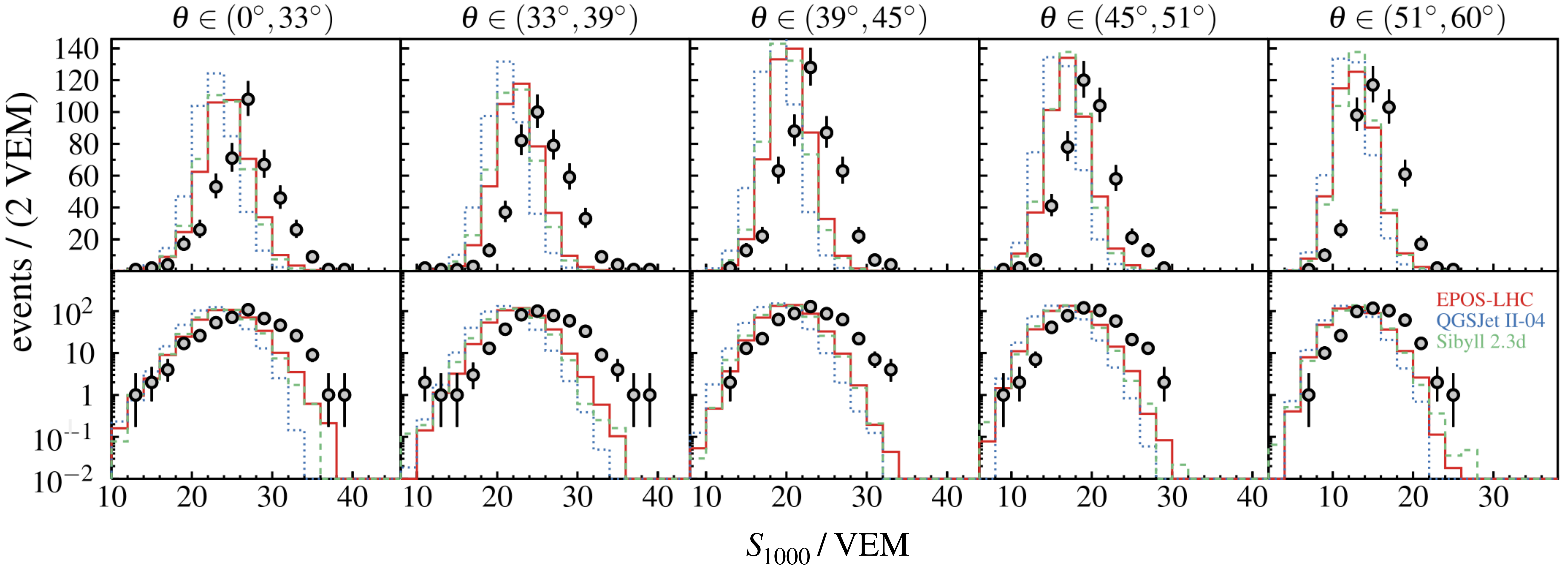
Muon puzzle

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}

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



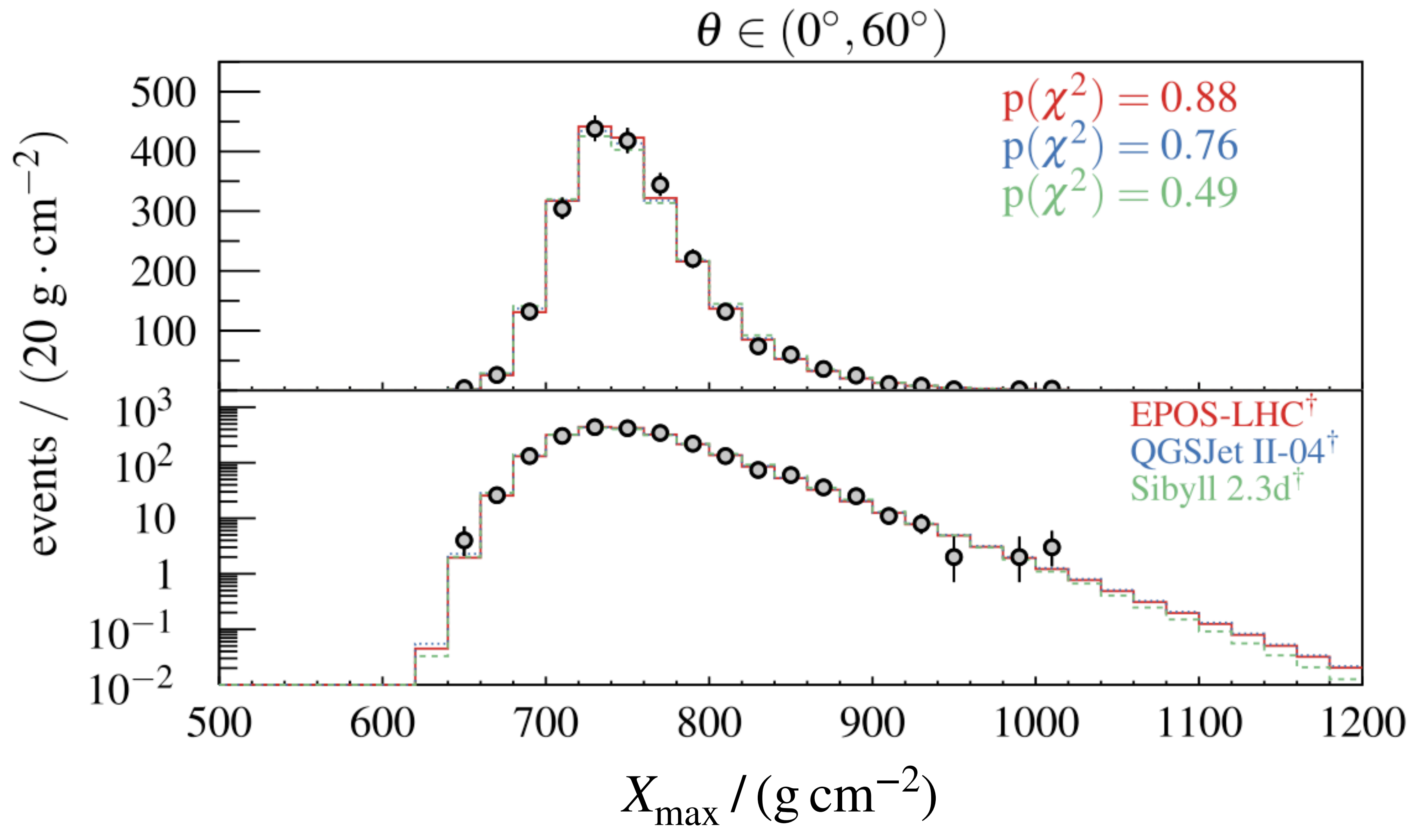
In accordance with previous Auger results
Phys.Rev.Lett. 117 (2016) 19, 192001

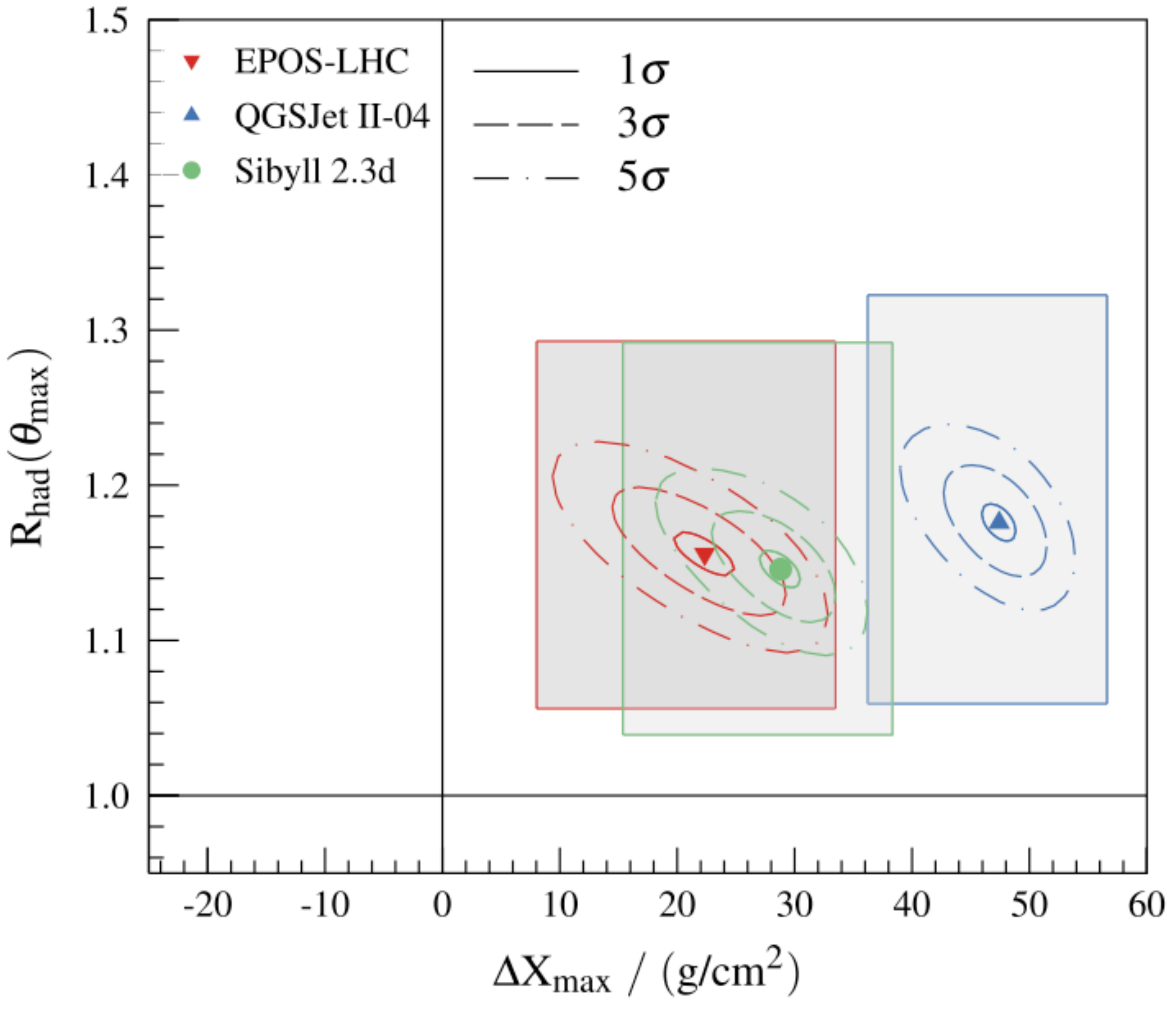
Poor agreement between data and simulations

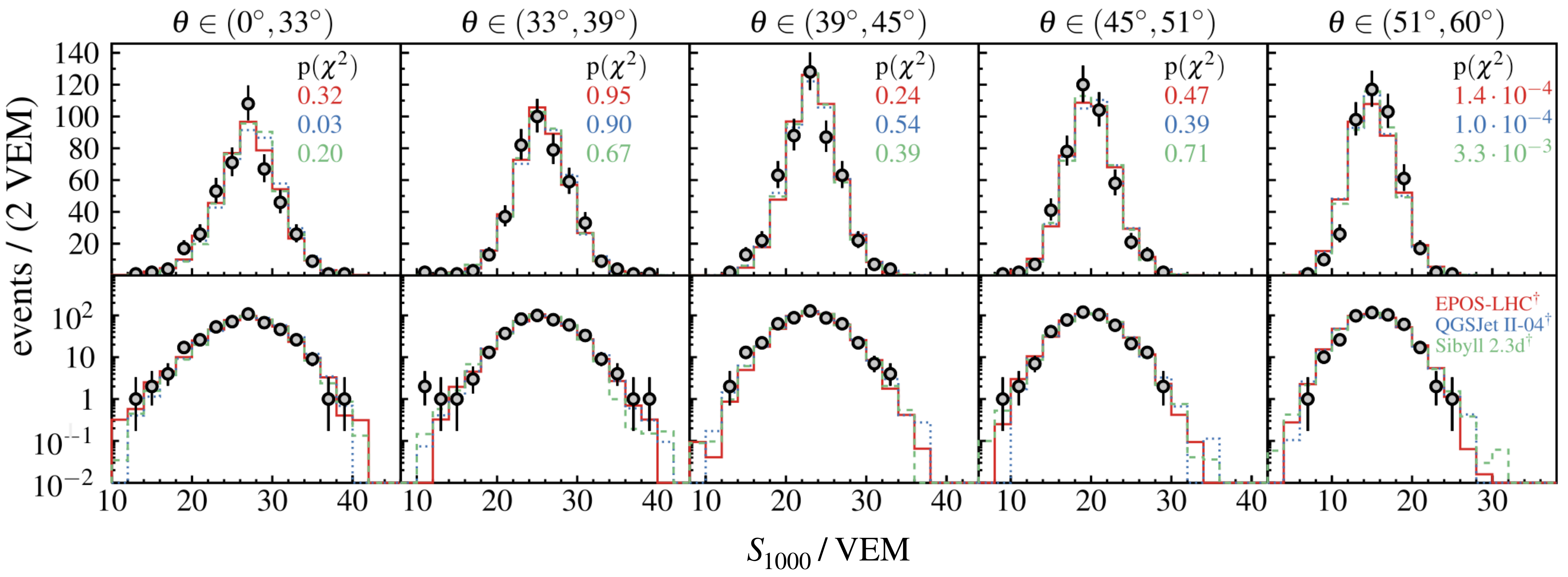
Muon puzzle + Shift in X_{max} scale

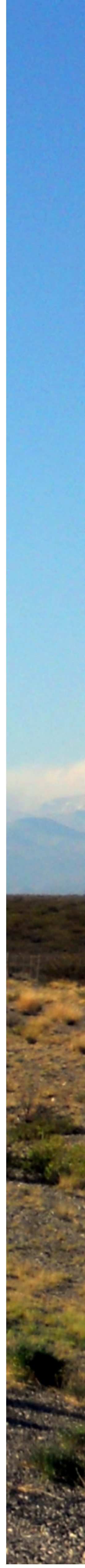
Phys.Rev.D 109 (2024) 10, 102001

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}



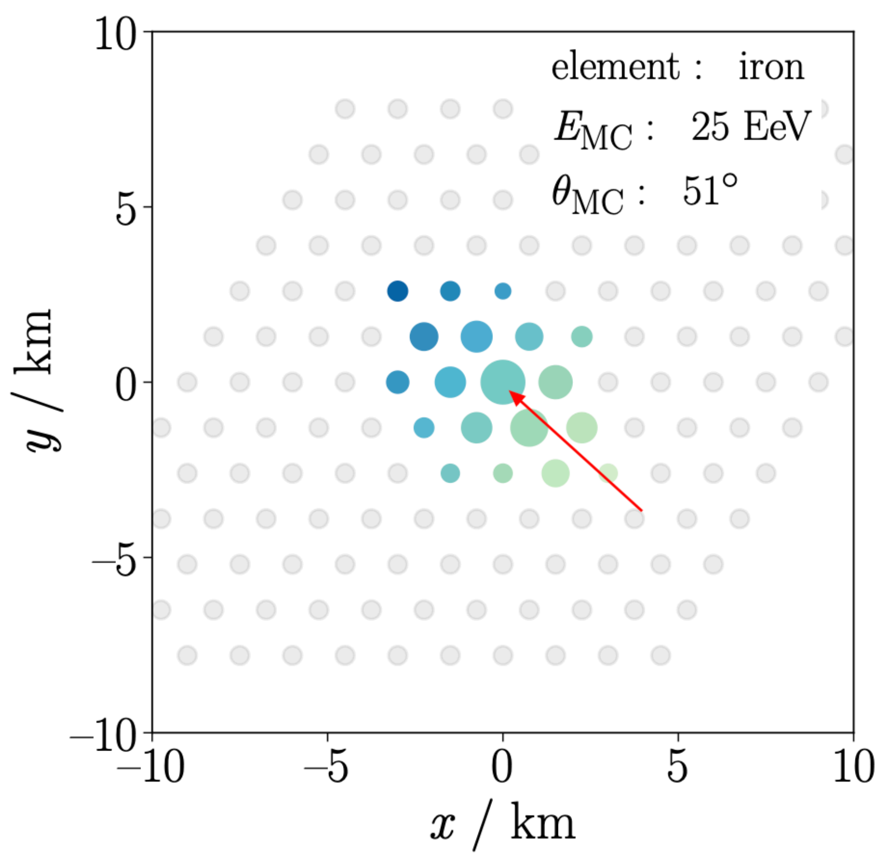


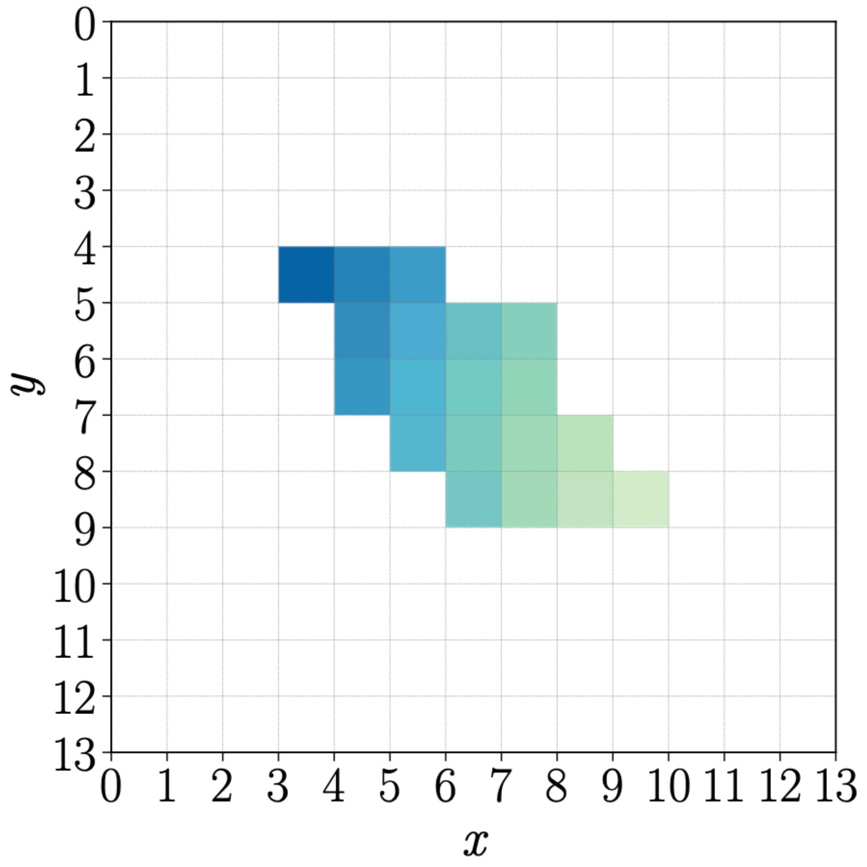


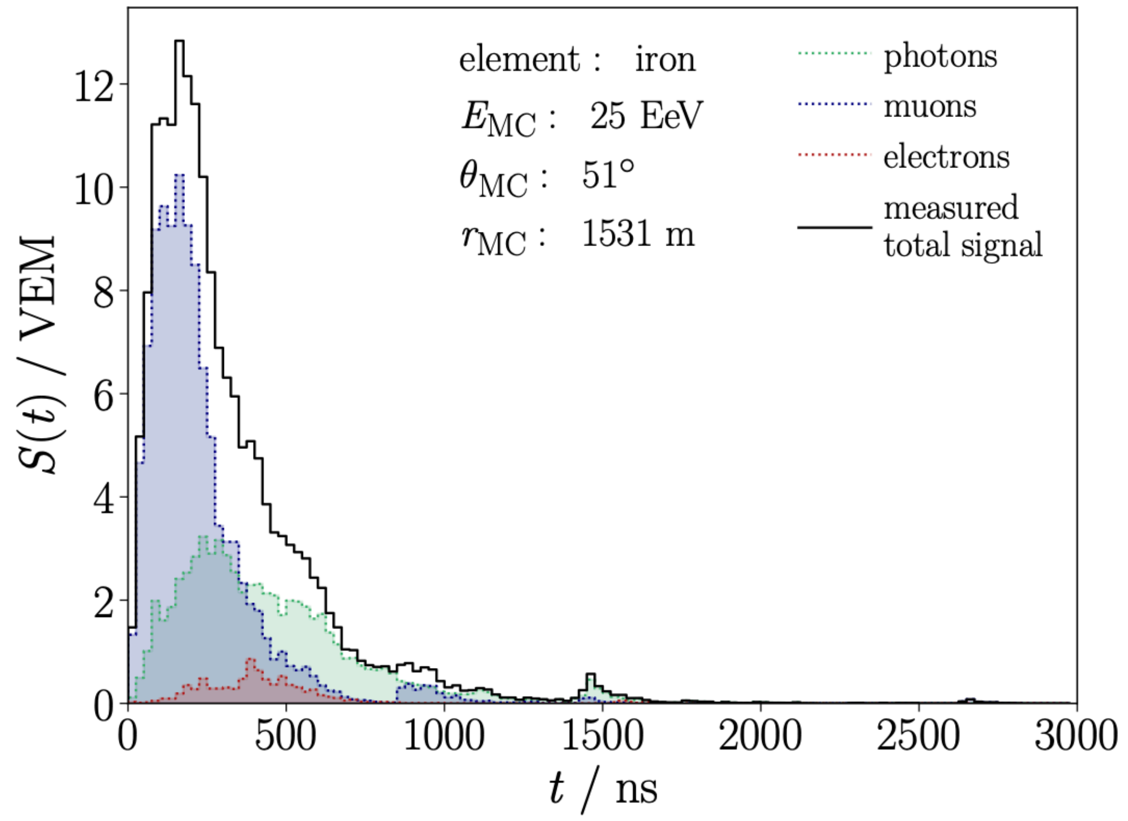


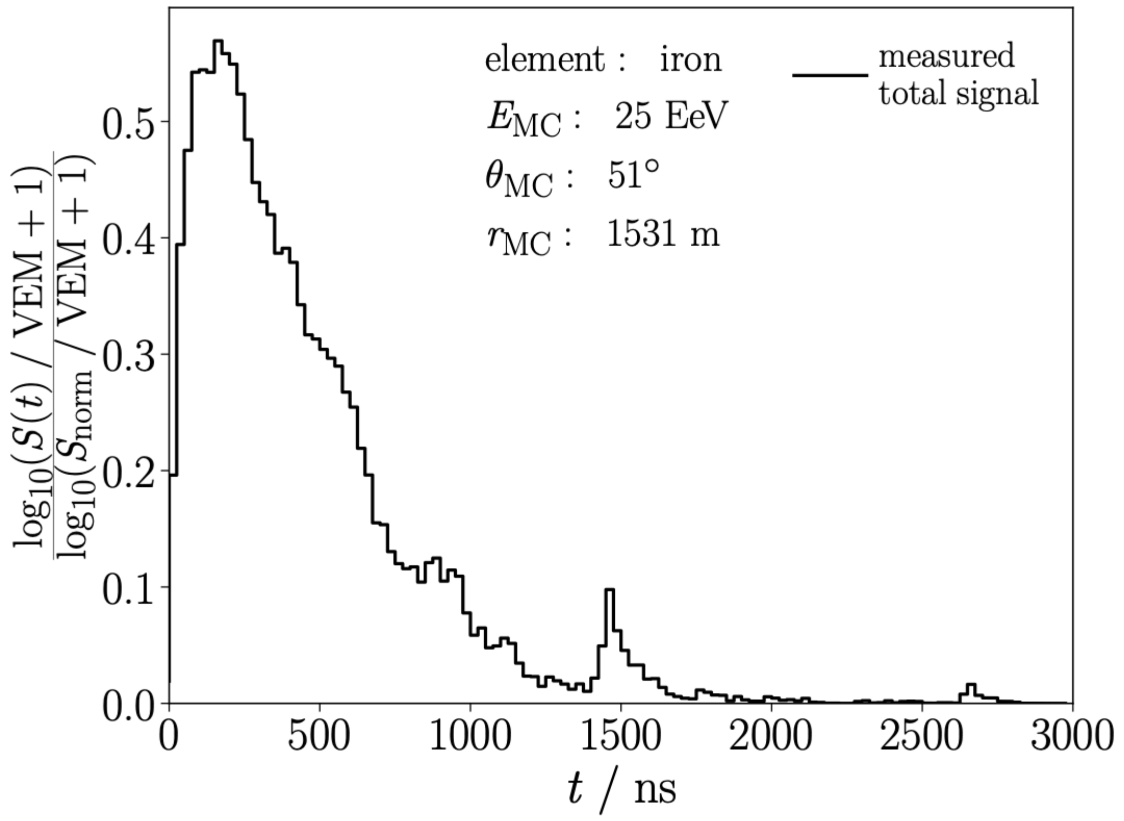
X_{max} from SD trace using a DNN

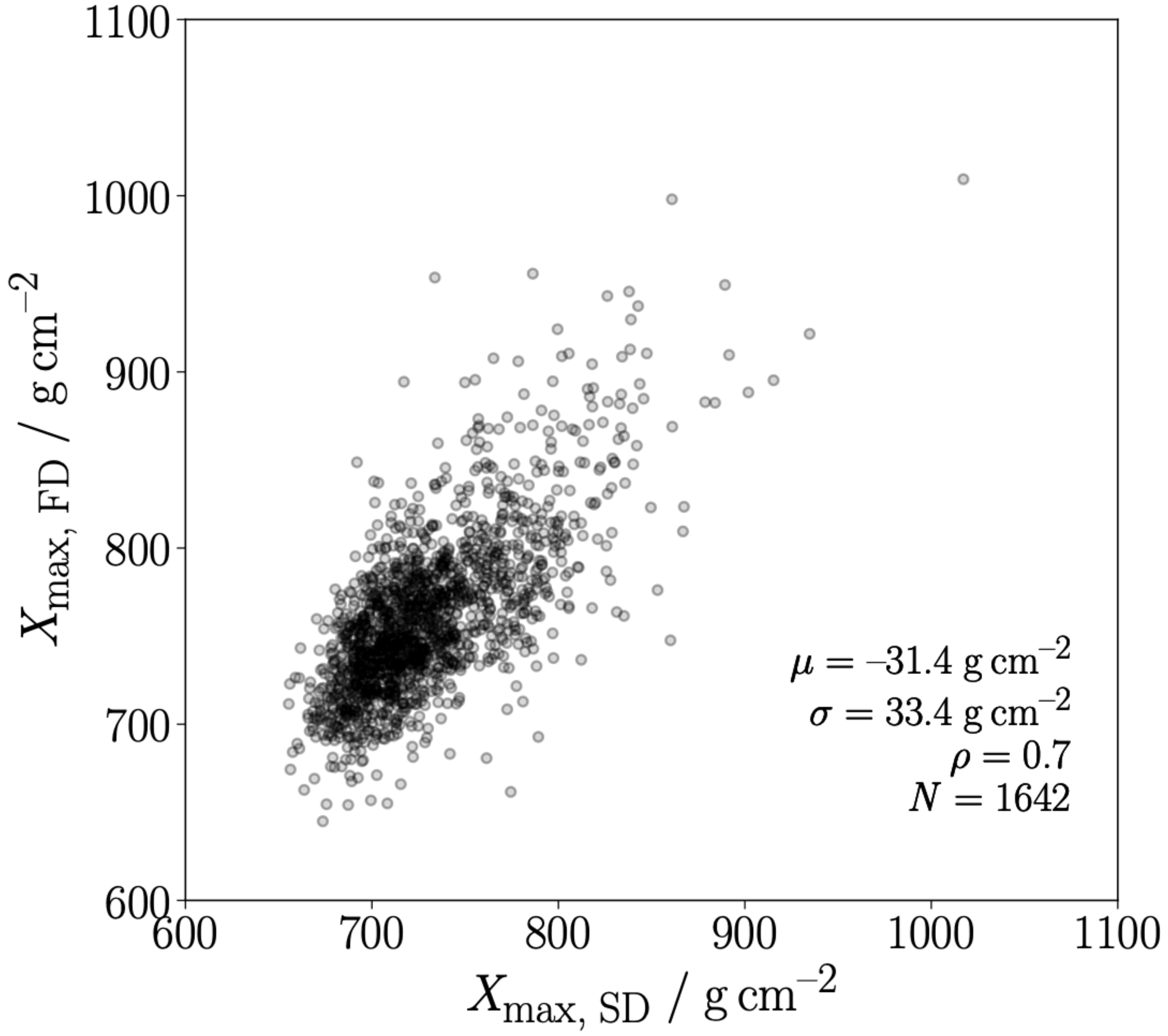
Pierre Auger coll., Phys.Rev.Lett. 134 (2025) 2, 021001 & Phys.Rev.D 111 (2025) 2, 022003







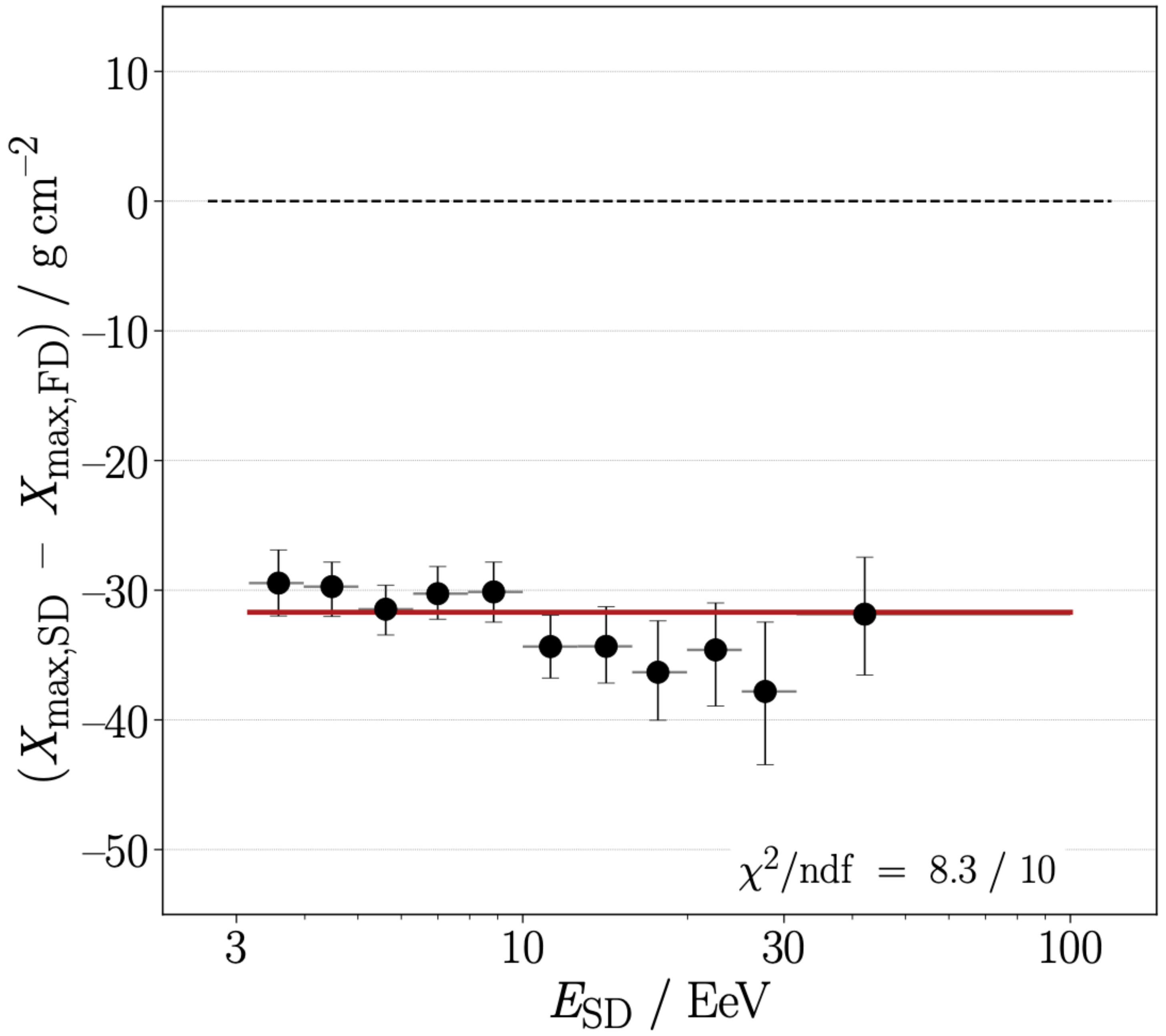


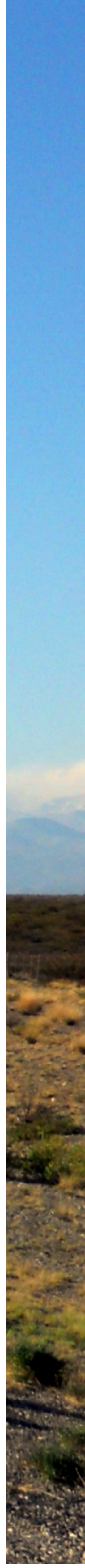


Extract the X_{max} from SD-only events

Exploit the SD traces using a Deep Neural Network

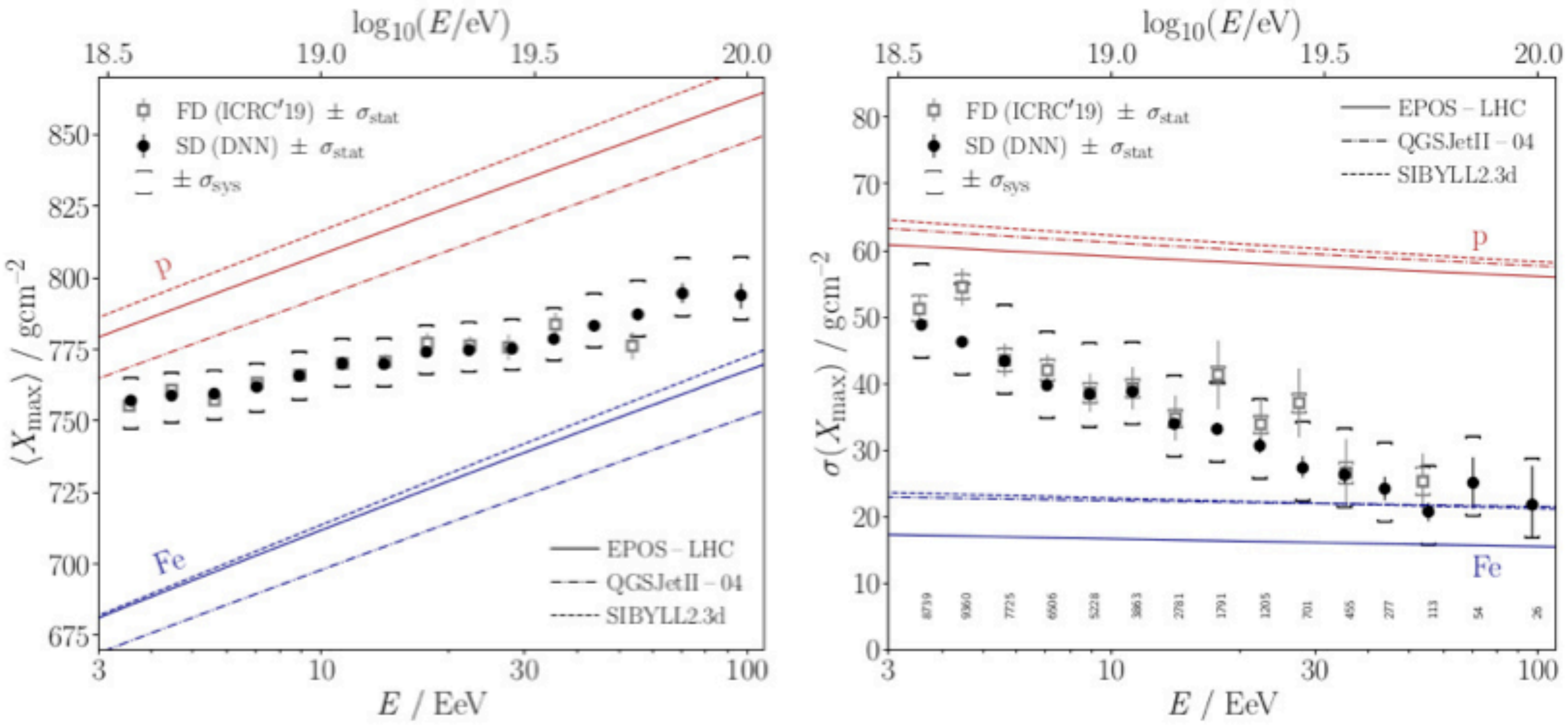
Test DNN performance using FD-SD **hybrid events**

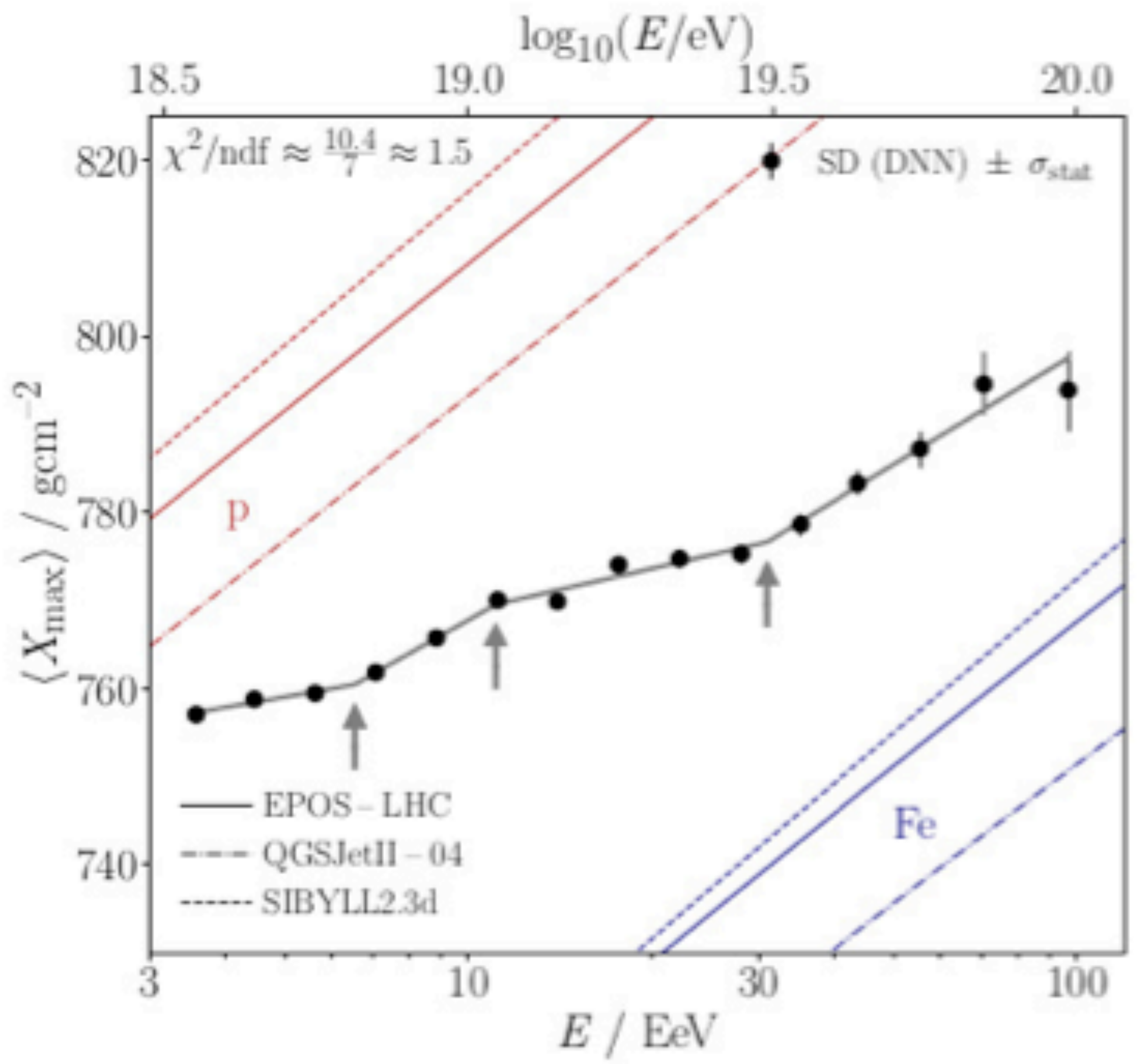


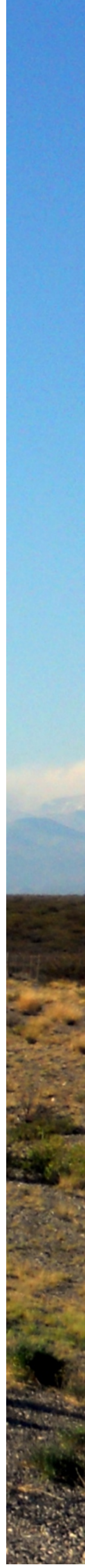


Machine Learning - $X_{\max}$ from DNNs

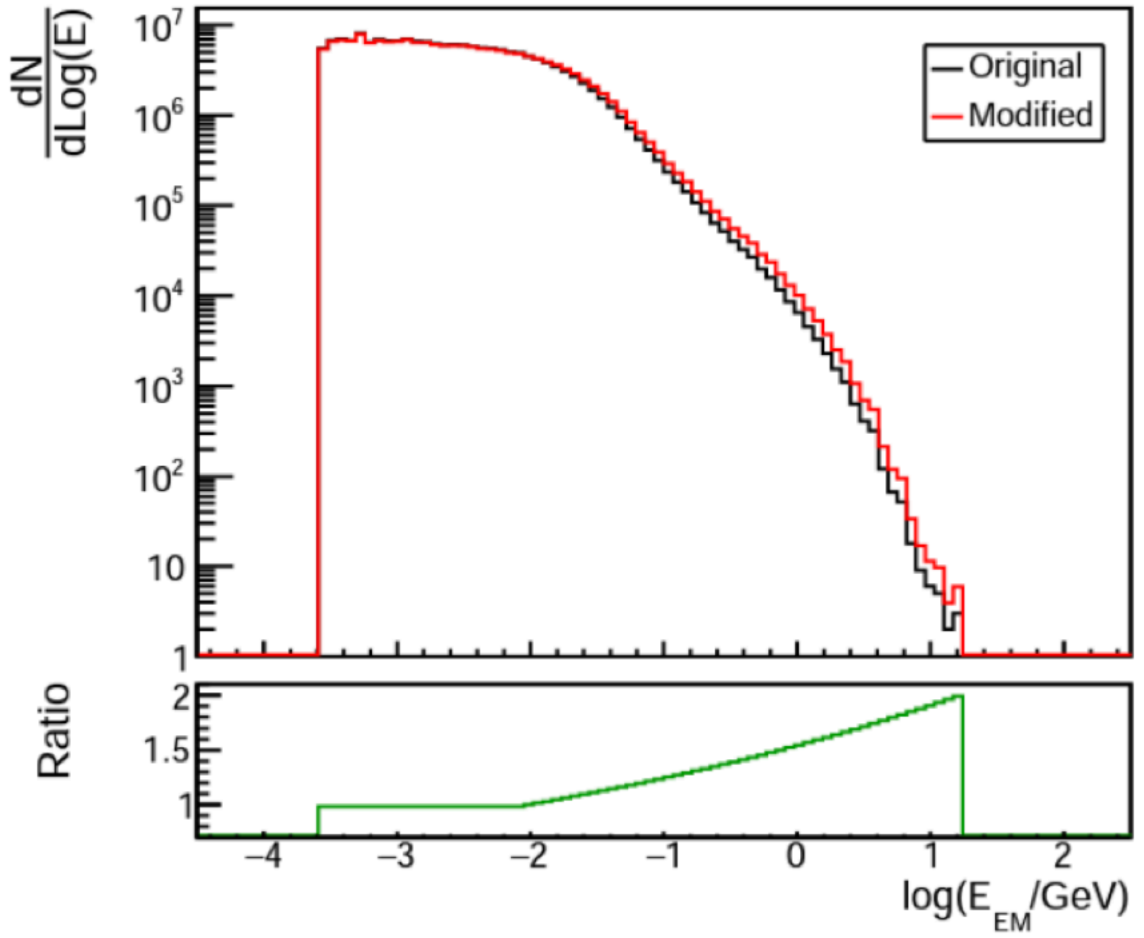
Pierre Auger coll., Phys.Rev.Lett. 134 (2025) 2, 021001 & Phys.Rev.D 111 (2025) 2, 022003

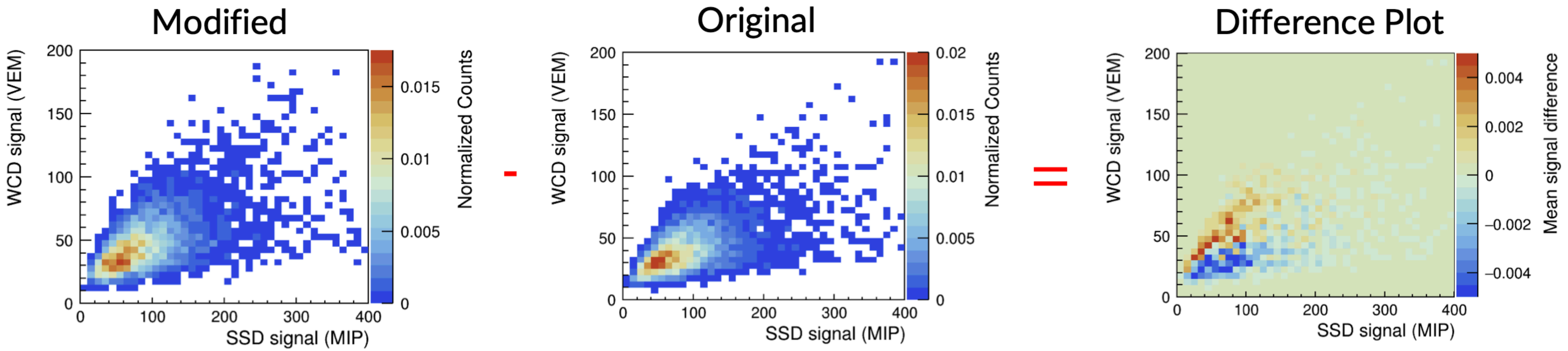


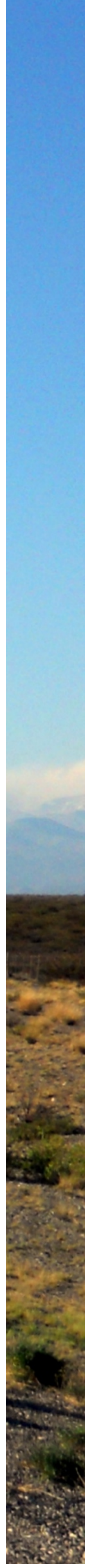




SSD+MARTA - E_{em} extraction

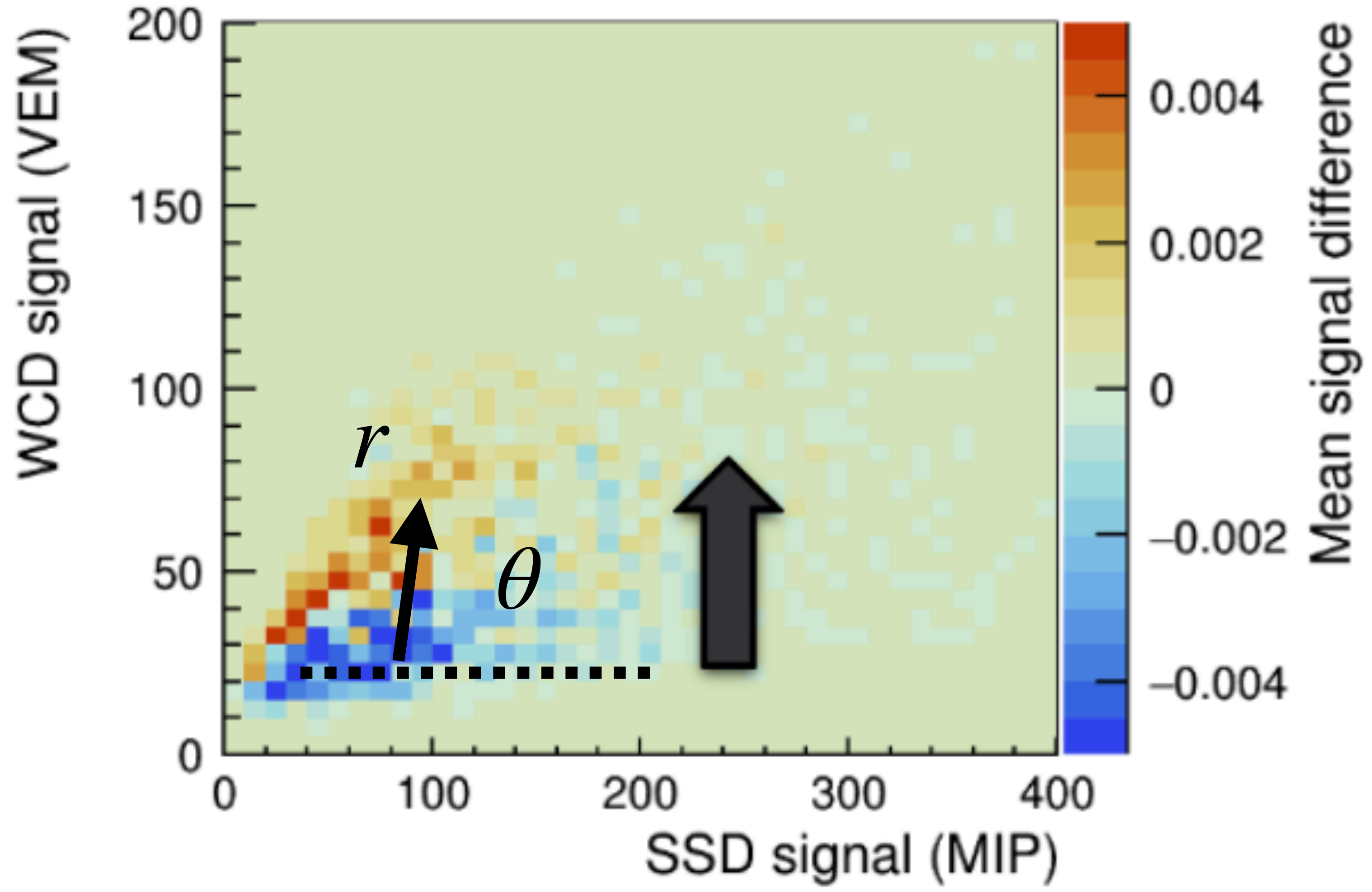


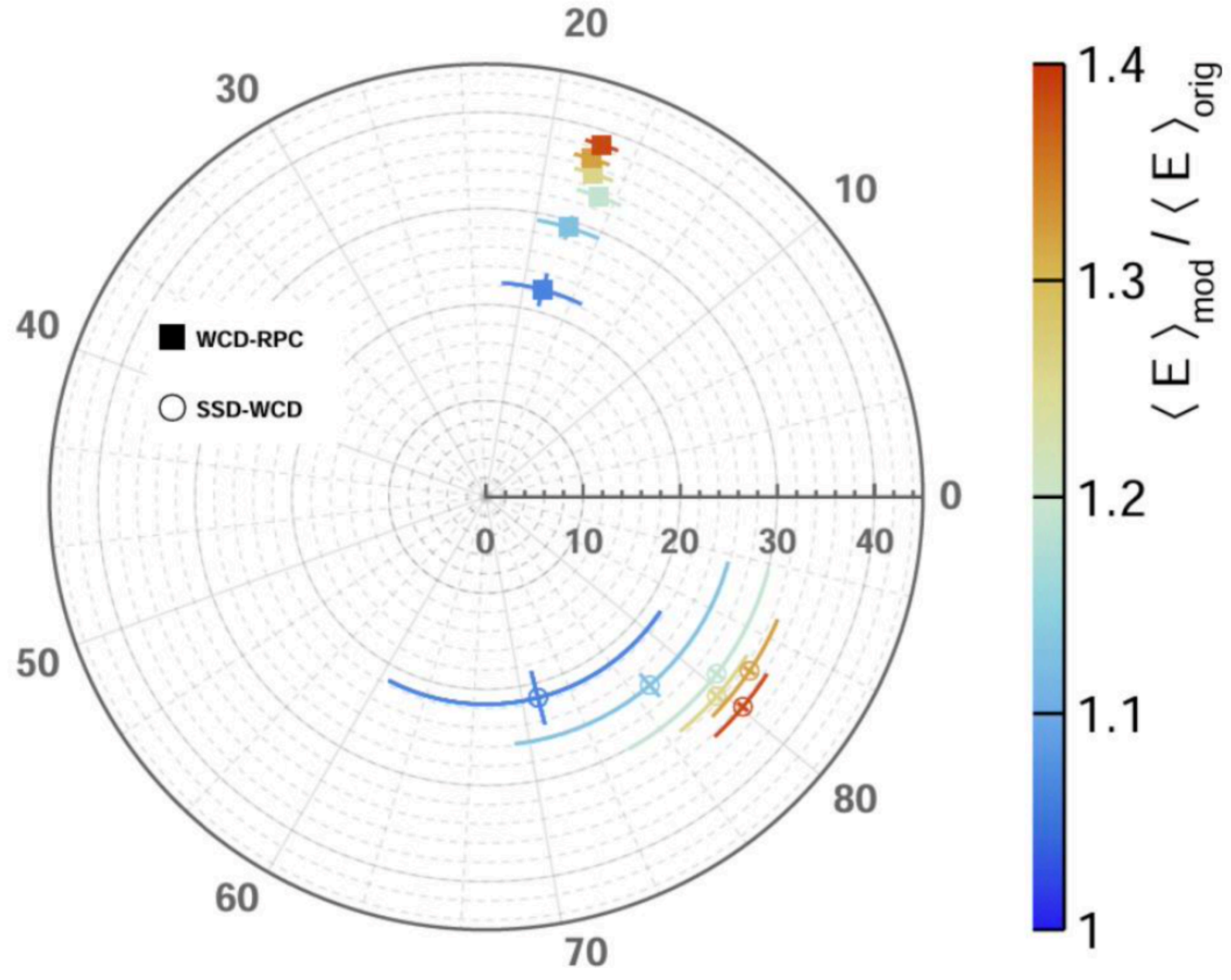


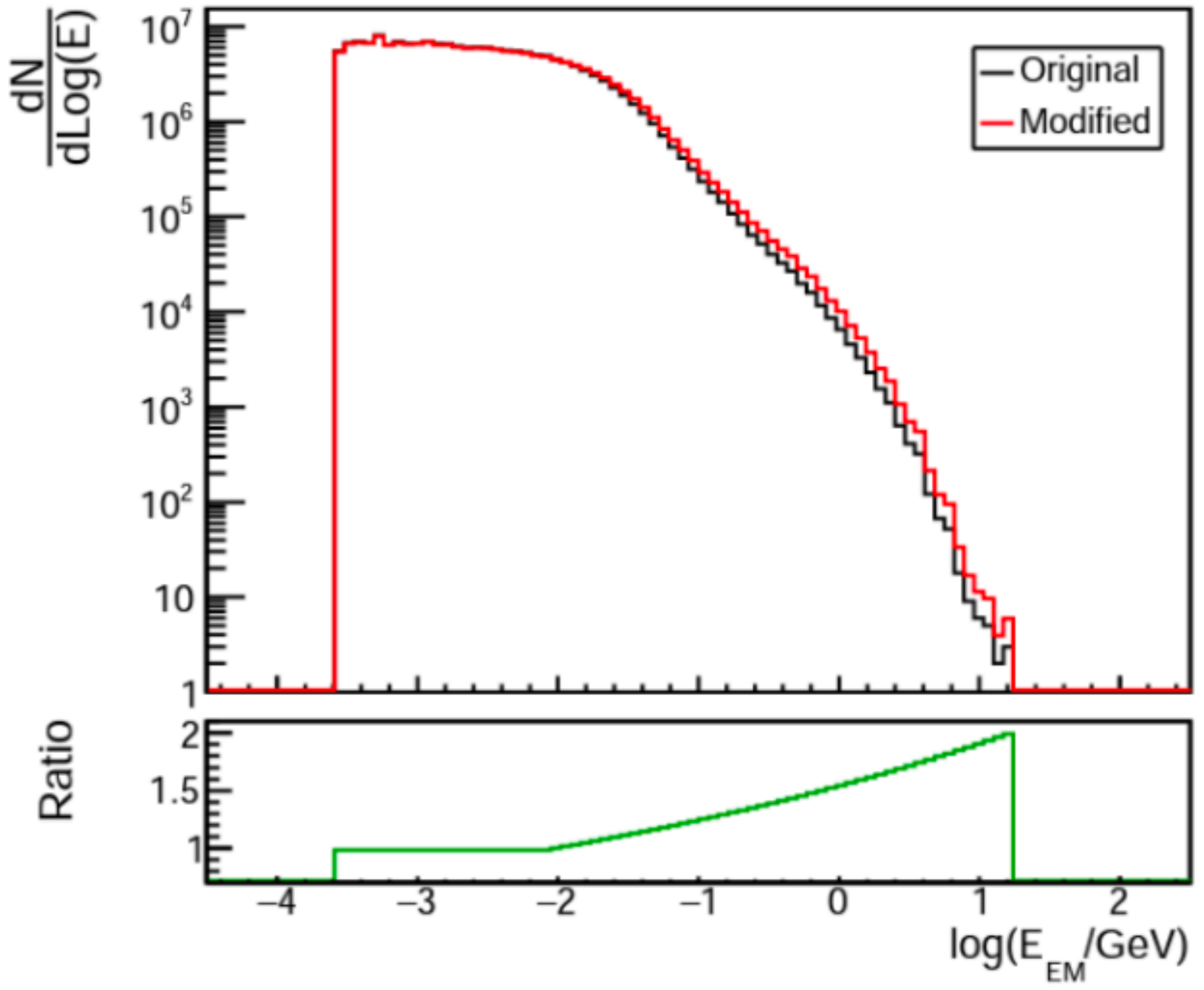


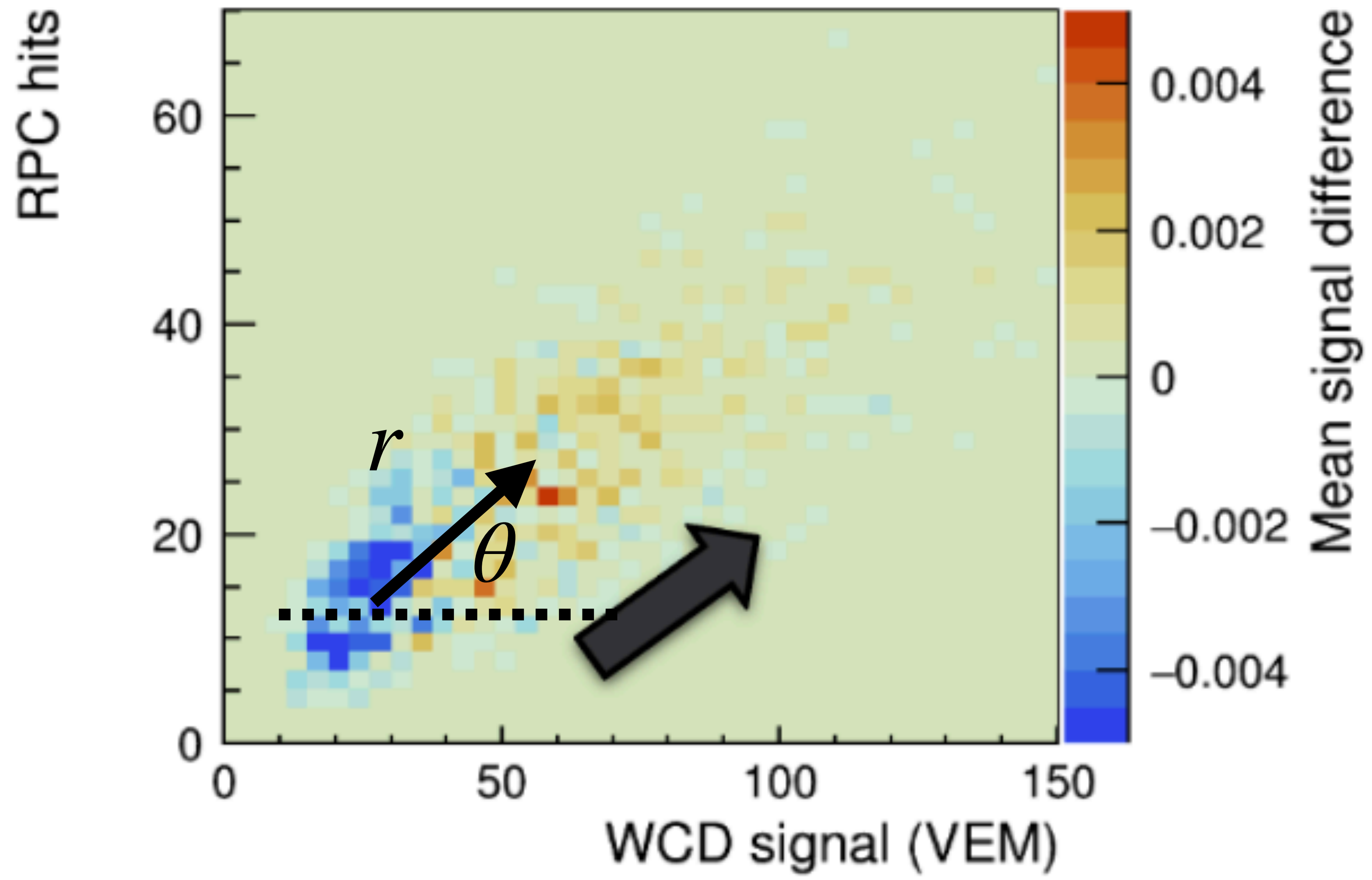
Sensitivity of a MARTA-SSD station to EAS energy Spectrum

MARTA-SSD Station





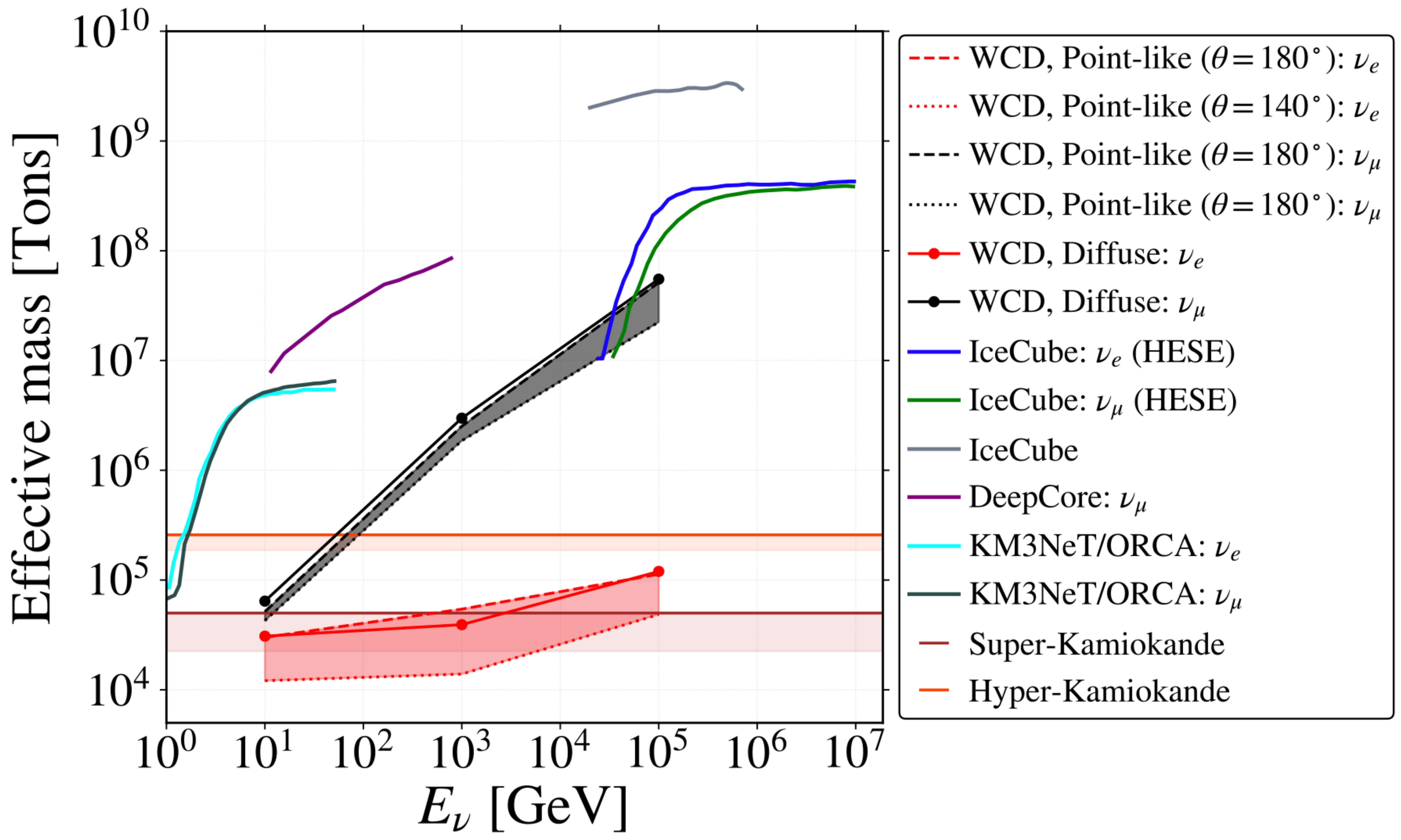


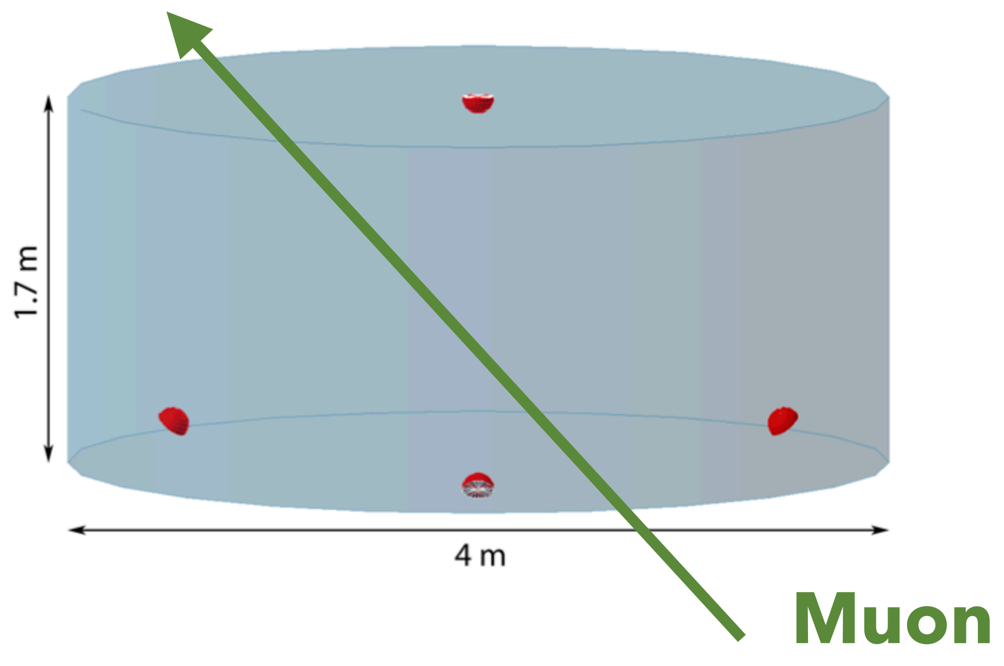


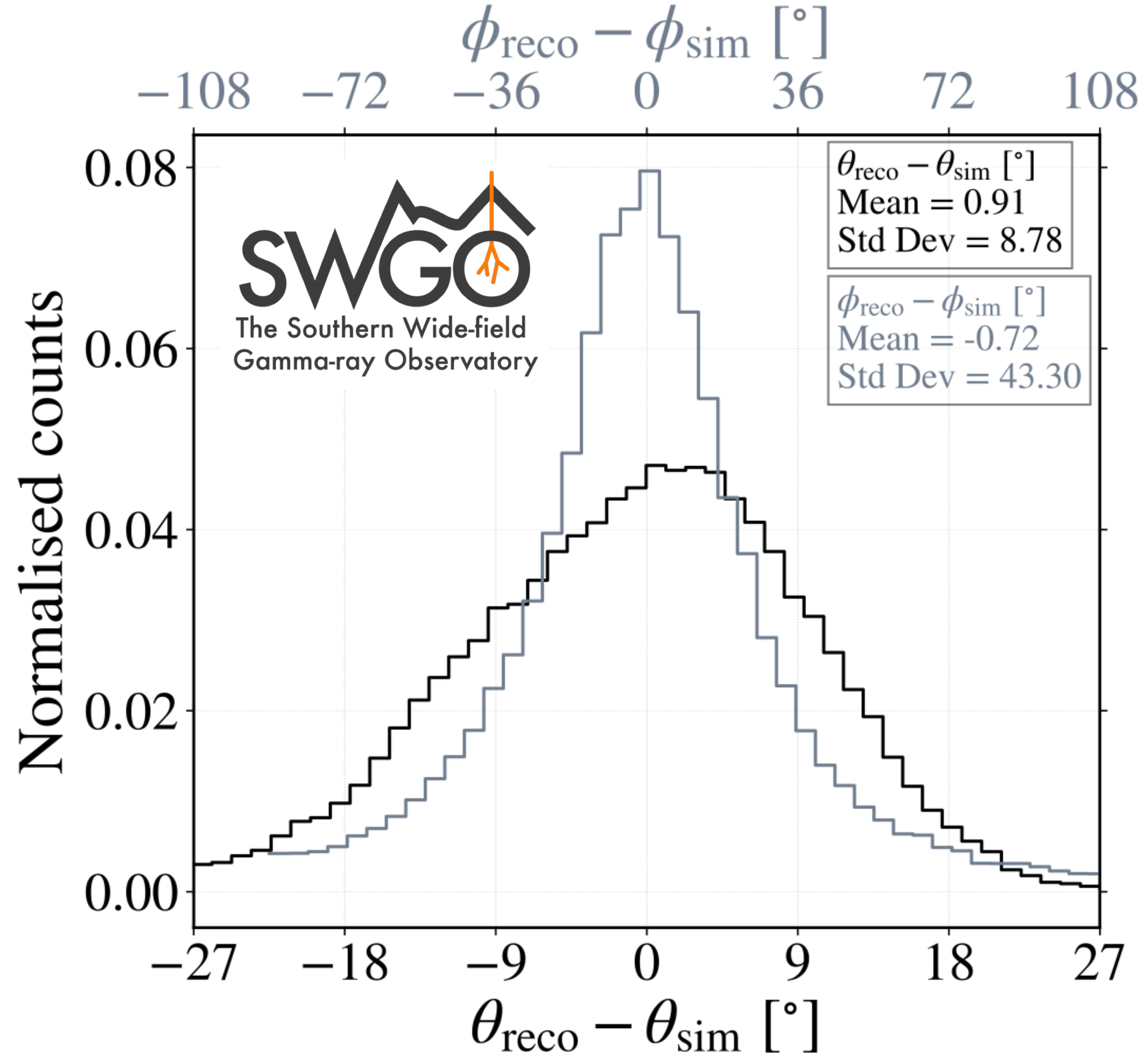
- **Measurement of high-energy e.m. and low-energy muon tail**
- Possibility to perform this measurement with ~ 1 year of data and a single station
- Measurement resilient to experimental conditions:
  - core, primary energy and inclination, shower multiplicity, detector aging effects
- SAL paper to be released soon

Catching neutrinos with a single WCD

J. Alvazez-Muñiz, RC, B. S. González et al., Phys.Rev.D 110 (2024) 2, 023032



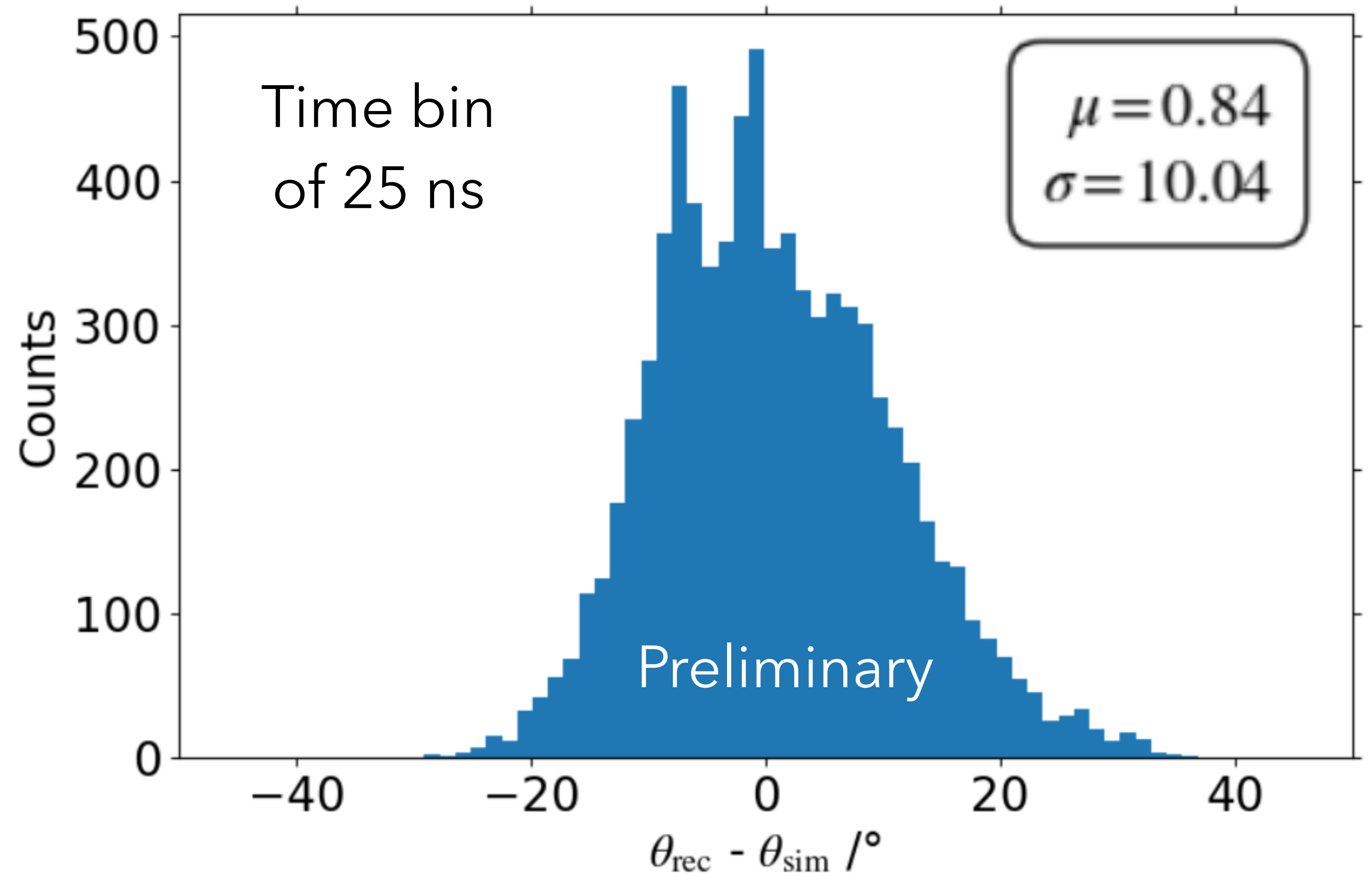


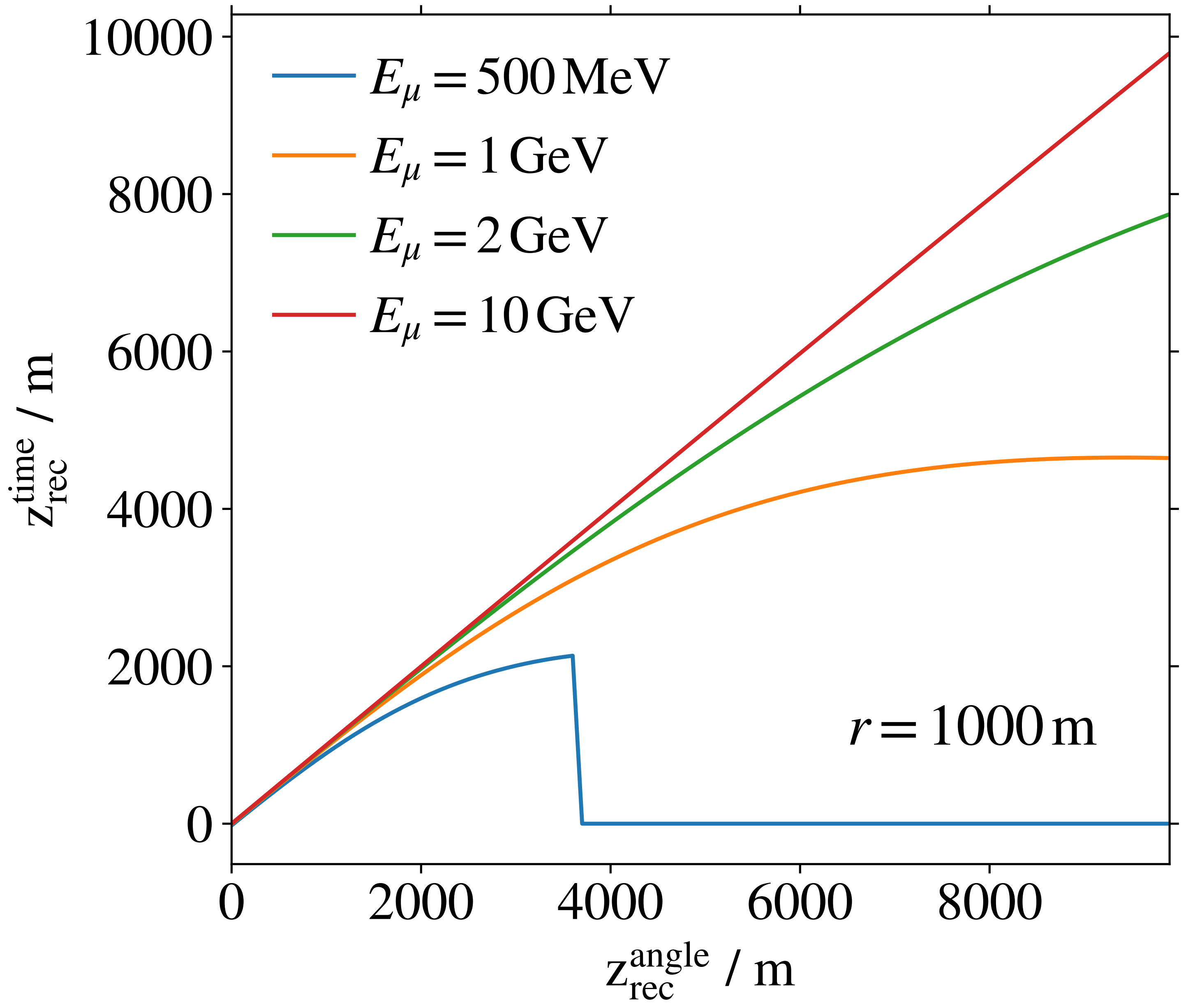


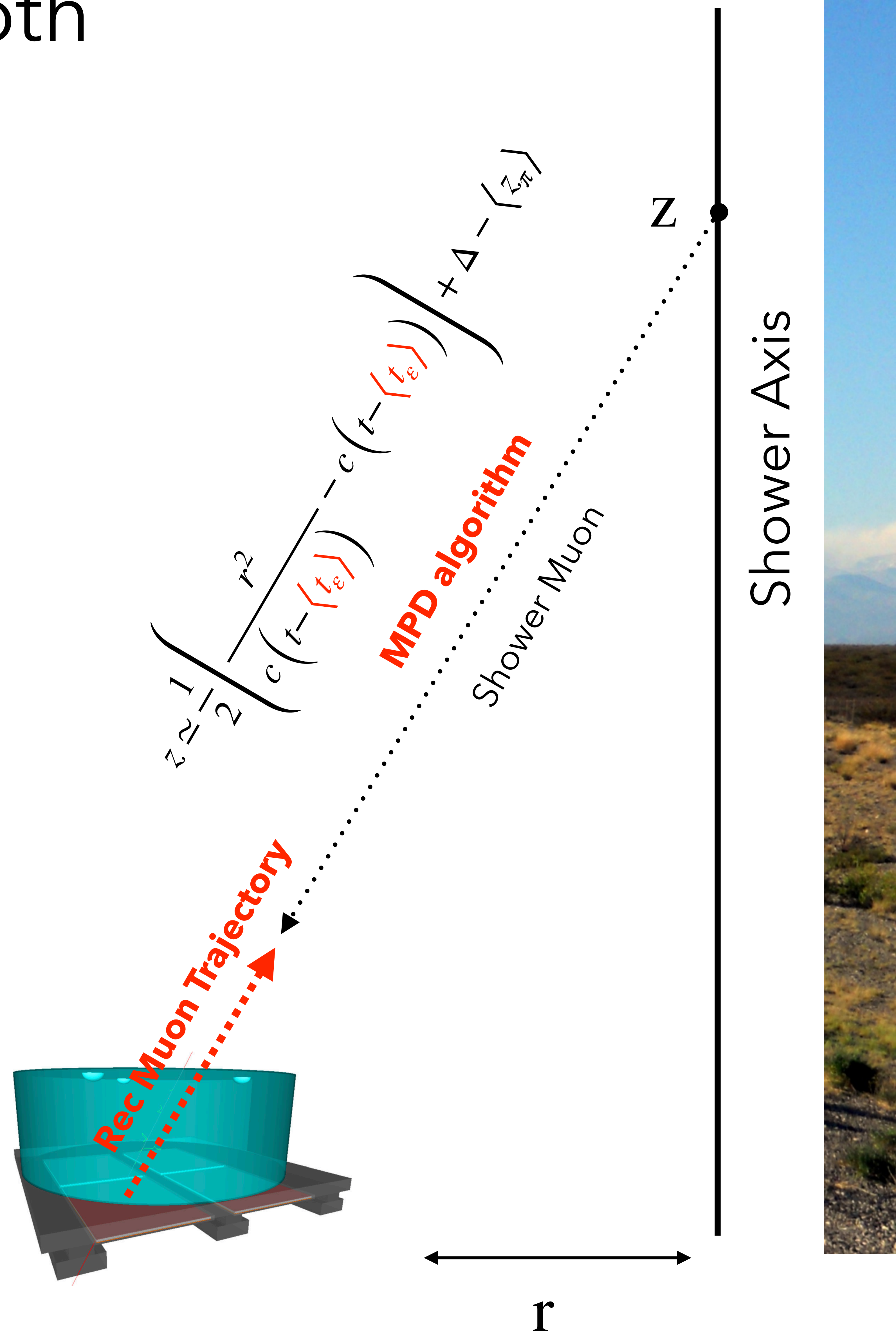
- Explore the PMT signal time trace structure recurring to ML algorithms:
  - Identify up-going ν from CR background
  - Use a CNN to reconstruct the direction of the neutrino (i.e. the muon traversing the WCD)

Extracting the muon energy spectrum from the Muon Production Depth

- **Simple Toy-MC to check method's sensitivity**
- Reconstruction of the muon production height (depth) intersecting the **reconstructed direction with MARTA** with the shower axis - z_{rec}^{angle}
- Reconstruction of the muon production height (depth) with **arrival time delay of muon** w.r.t. shower from - z_{rec}^{time}
- *Interesting first results, lot's of optimizations to be explored*



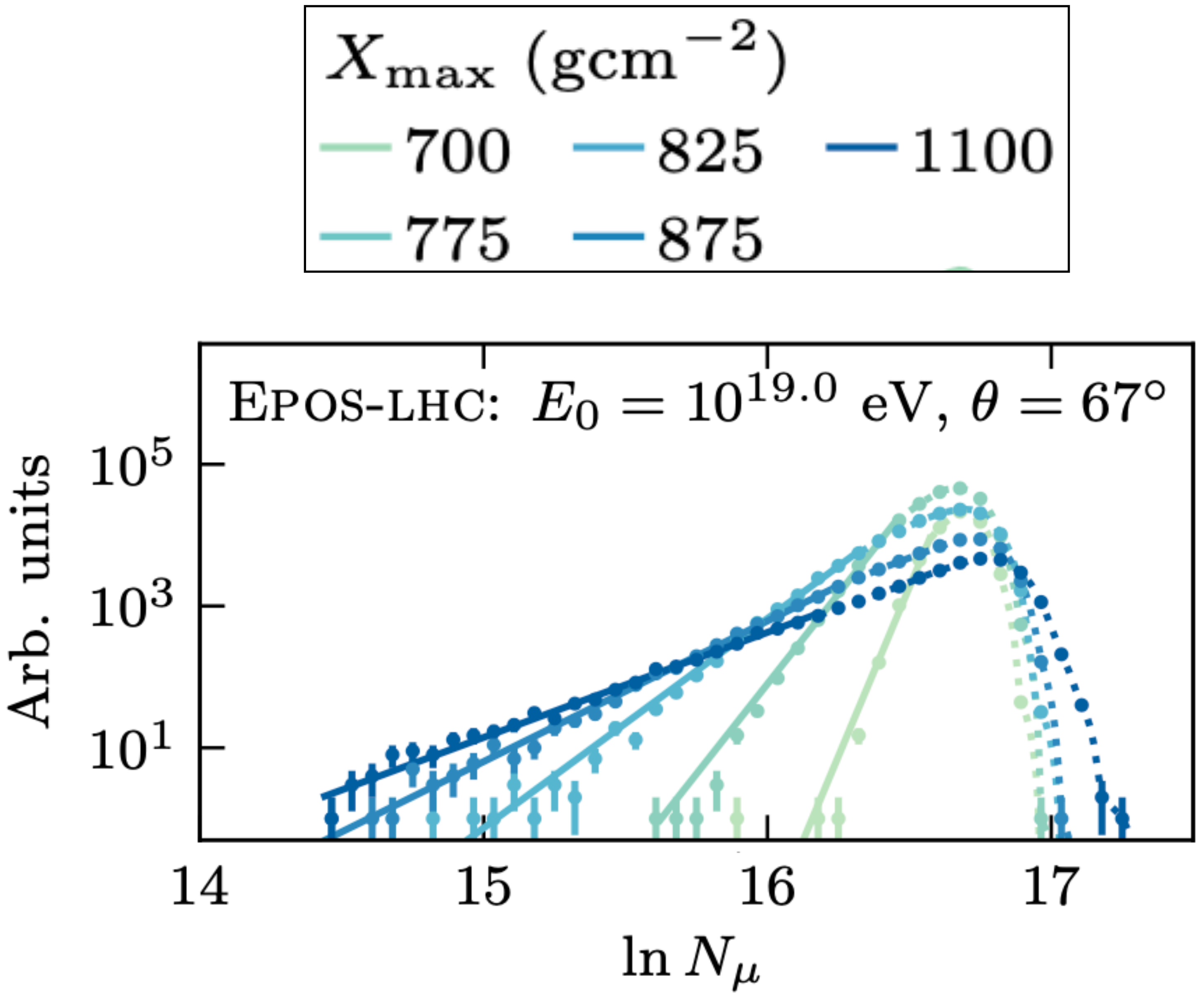




Accessing the first interaction

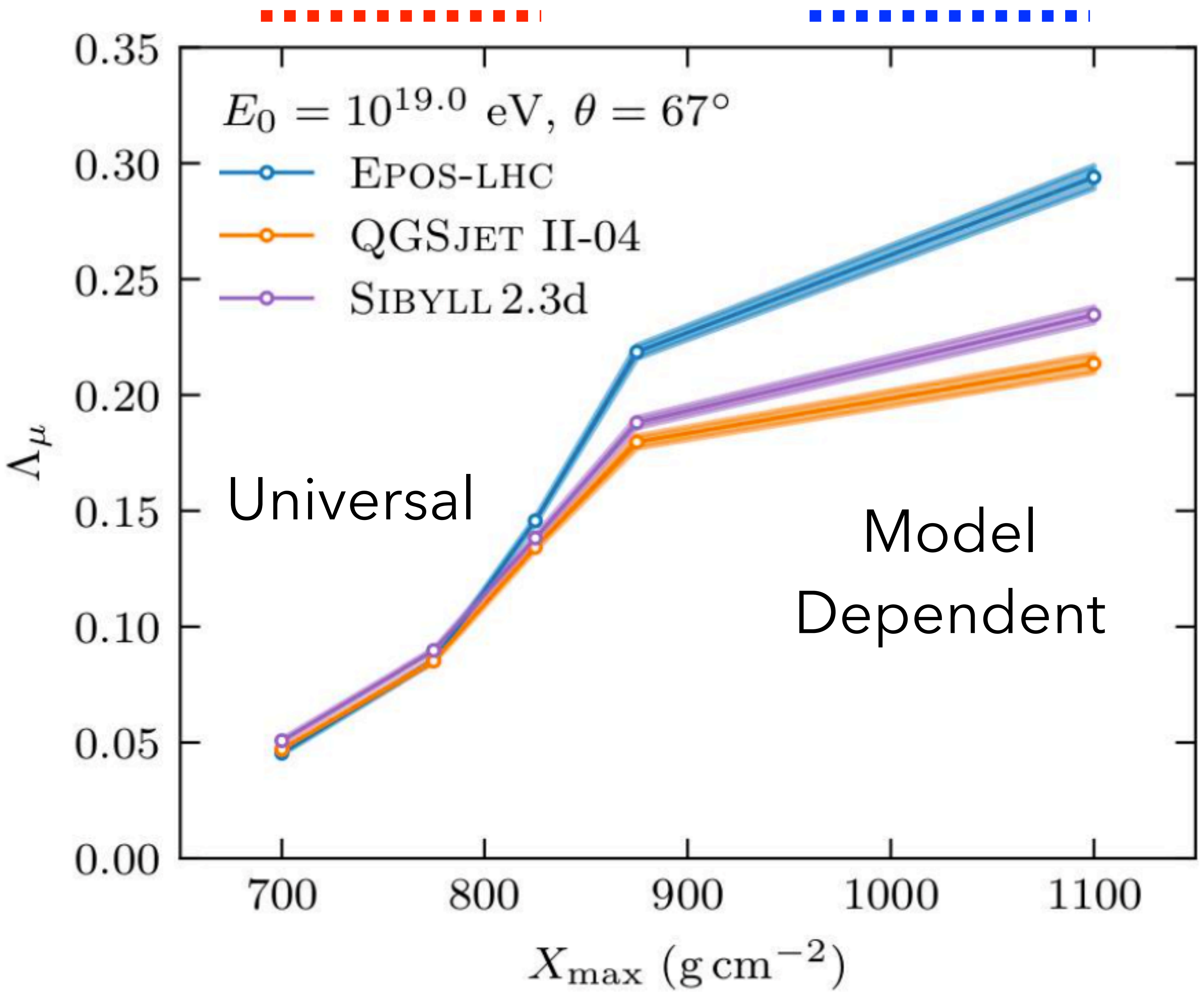
L. Cazon, RC, M. A. Martins, F. Riehn, *Phys.Lett.B* 859 (2024) 139115

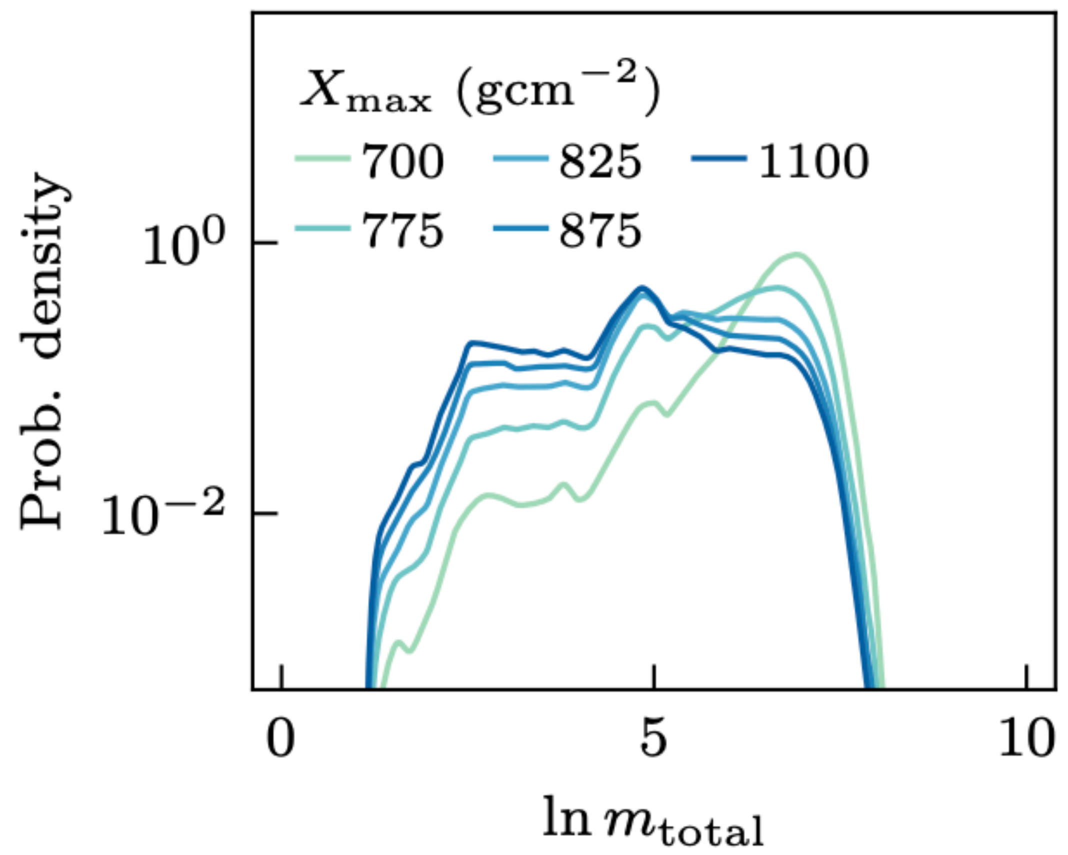
- Hadronic interaction models predict universal value of Λ_μ for shallow showers and highly distinct values for deep showers
- Binning in X_{max} $\Rightarrow$ probe the hadronic activity of the first interaction



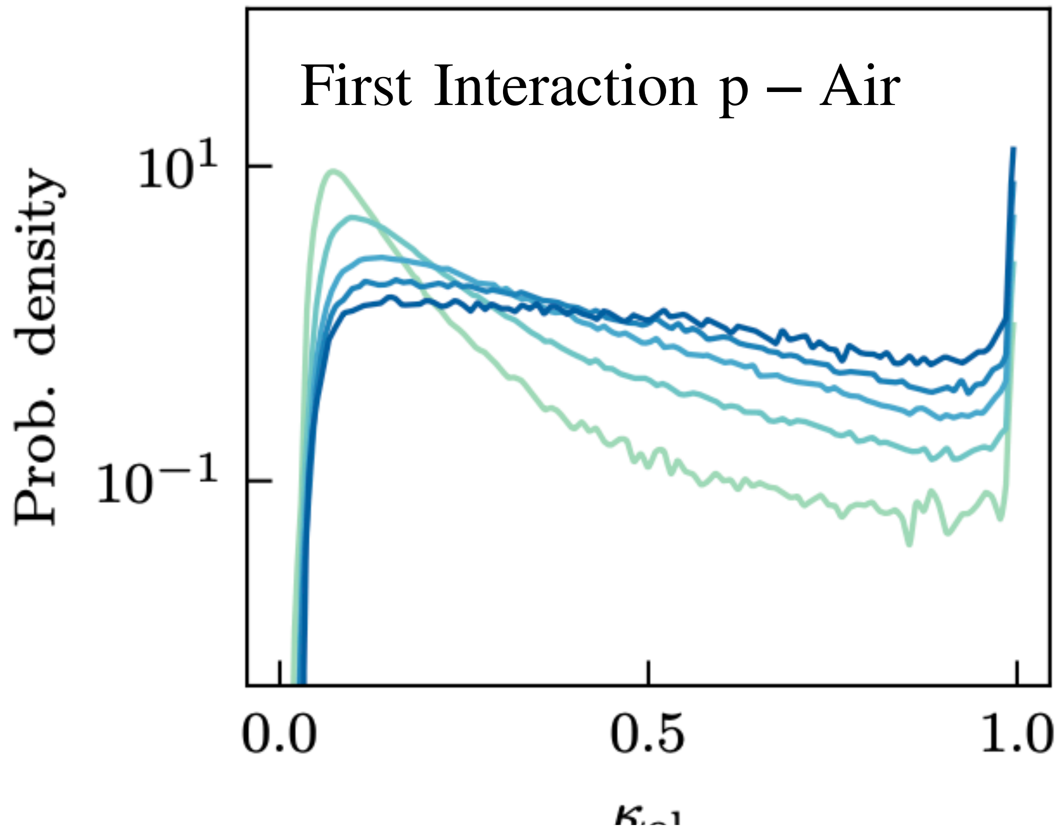
Low hadronic activity - diffractive events

Large hadronic activity - e.g. high multiplicity

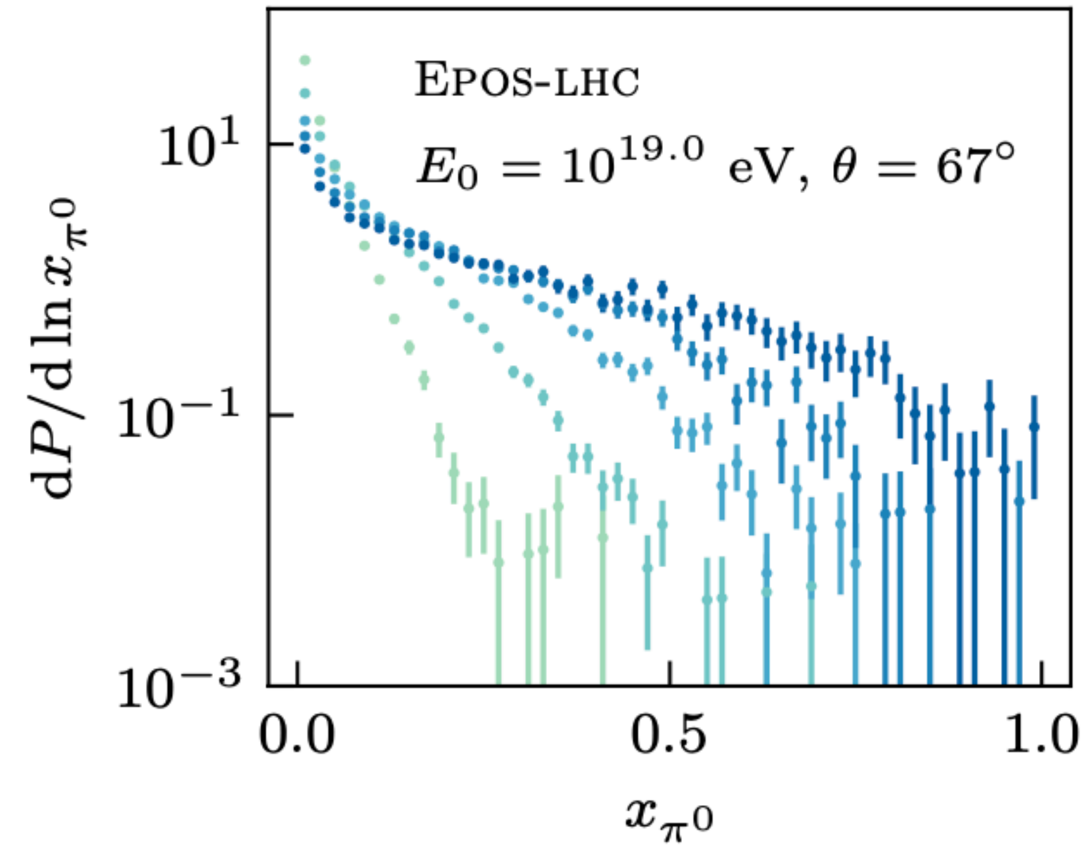




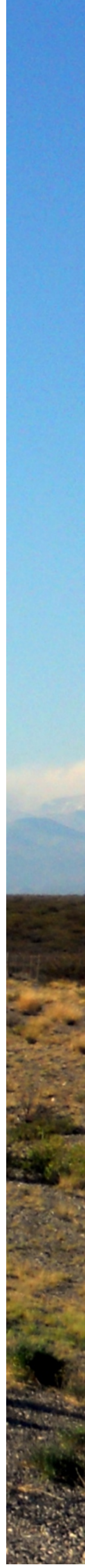
Multiplicity



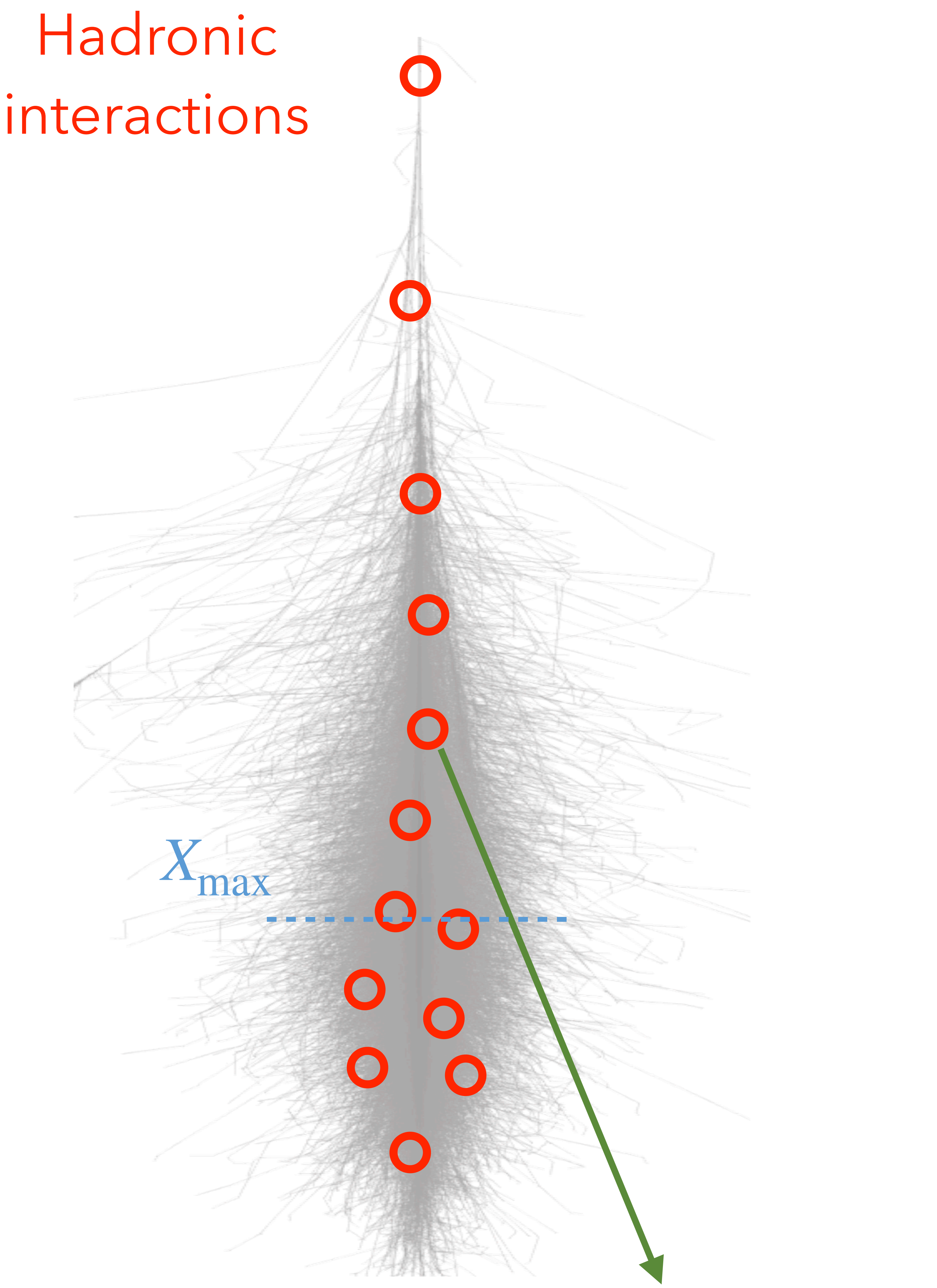
Elasticity



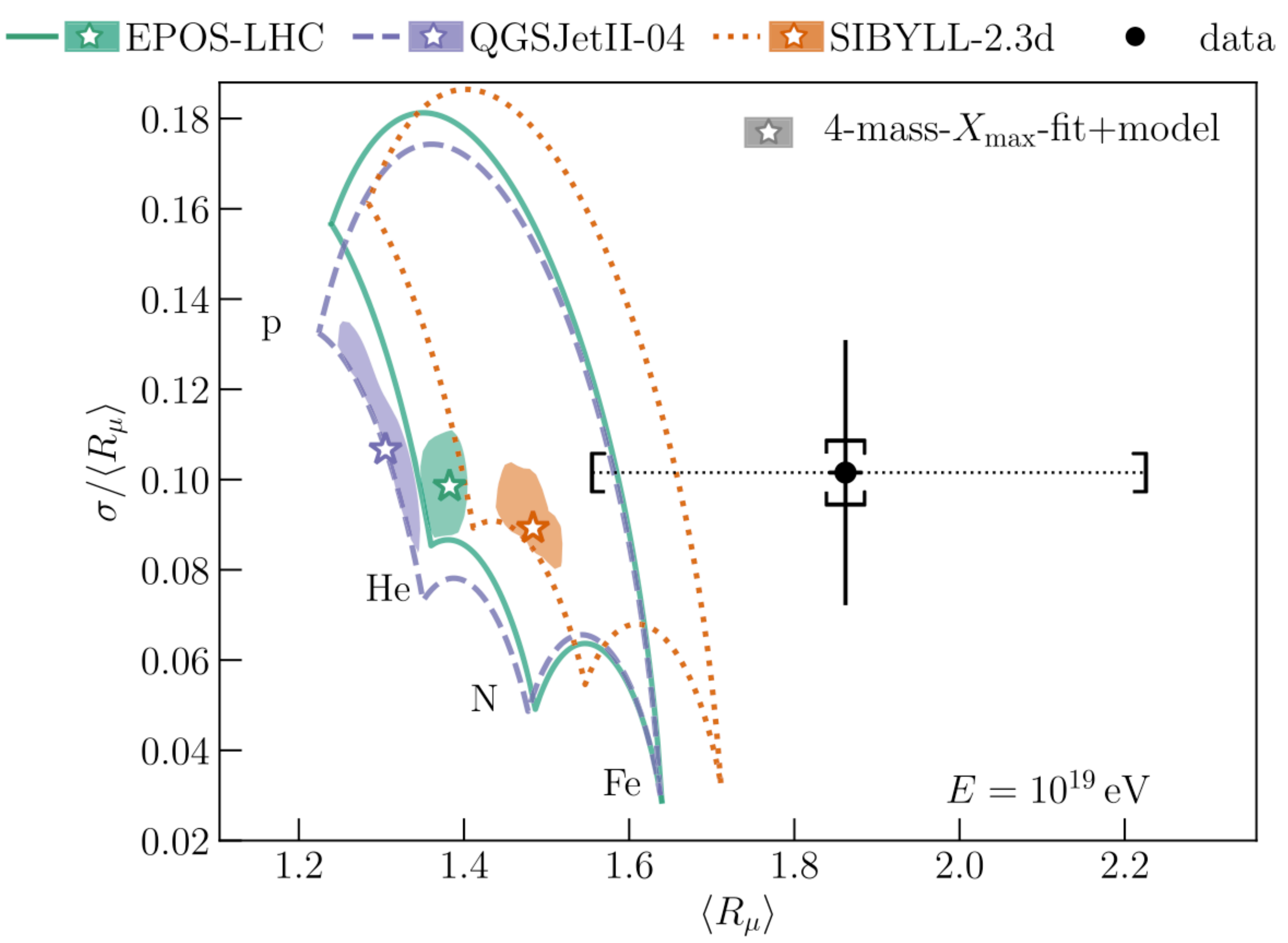
π^0 energy spectrum



EAS Muon Puzzle



Pierre Auger Coll., Phys.Rev.Lett. 126 (2021) 15, 152002

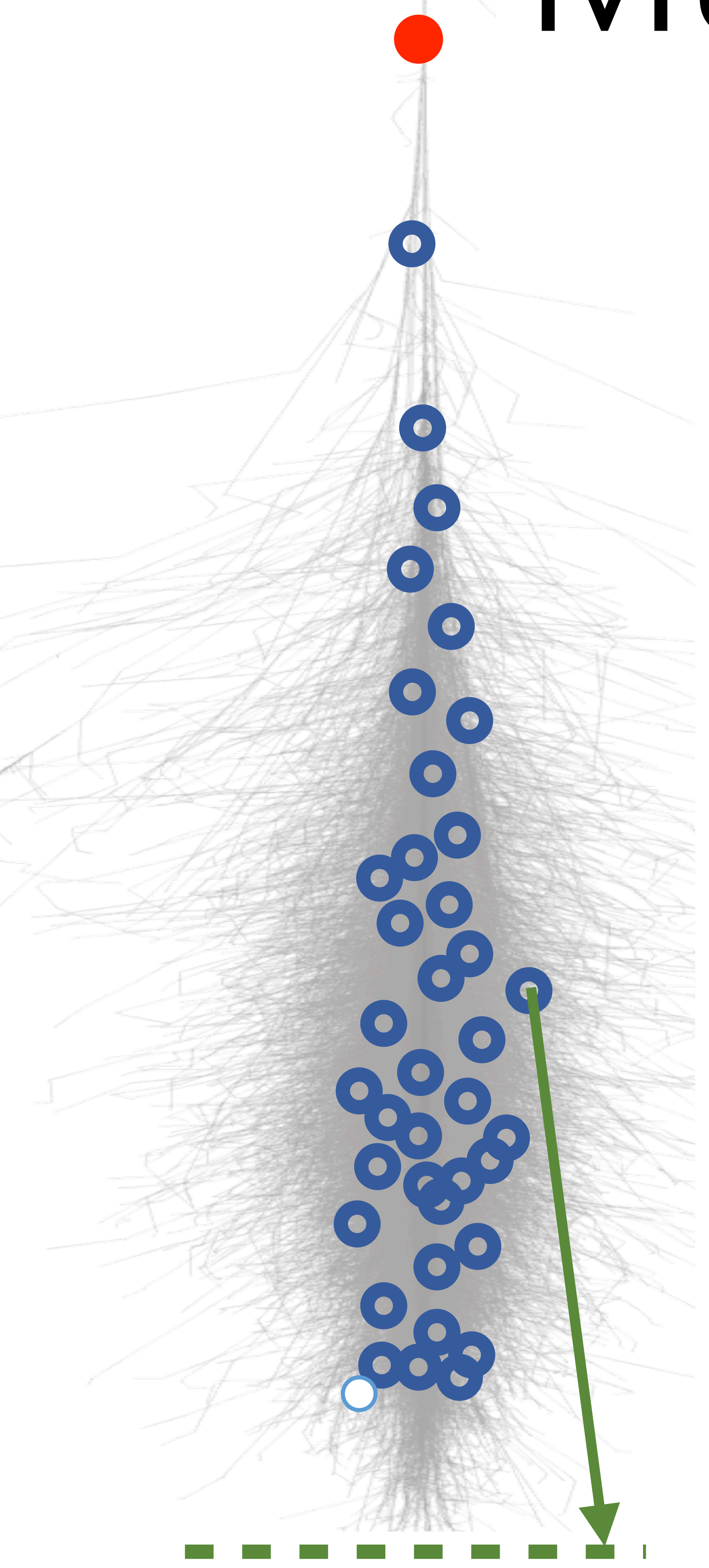


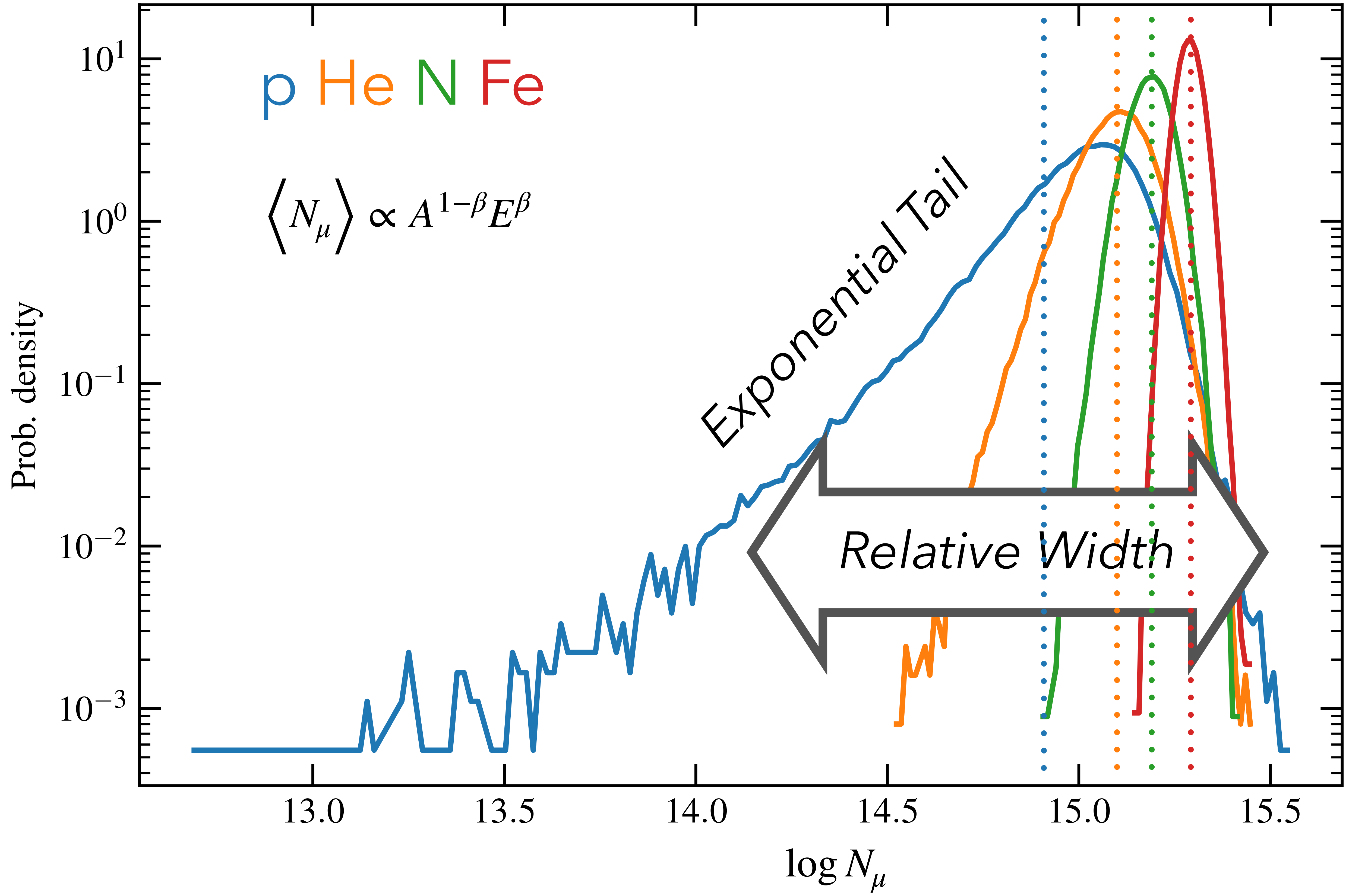
Models unable to consistently describe the average EAS muon content but its relative fluctuations agree with X_{max} expectations!!

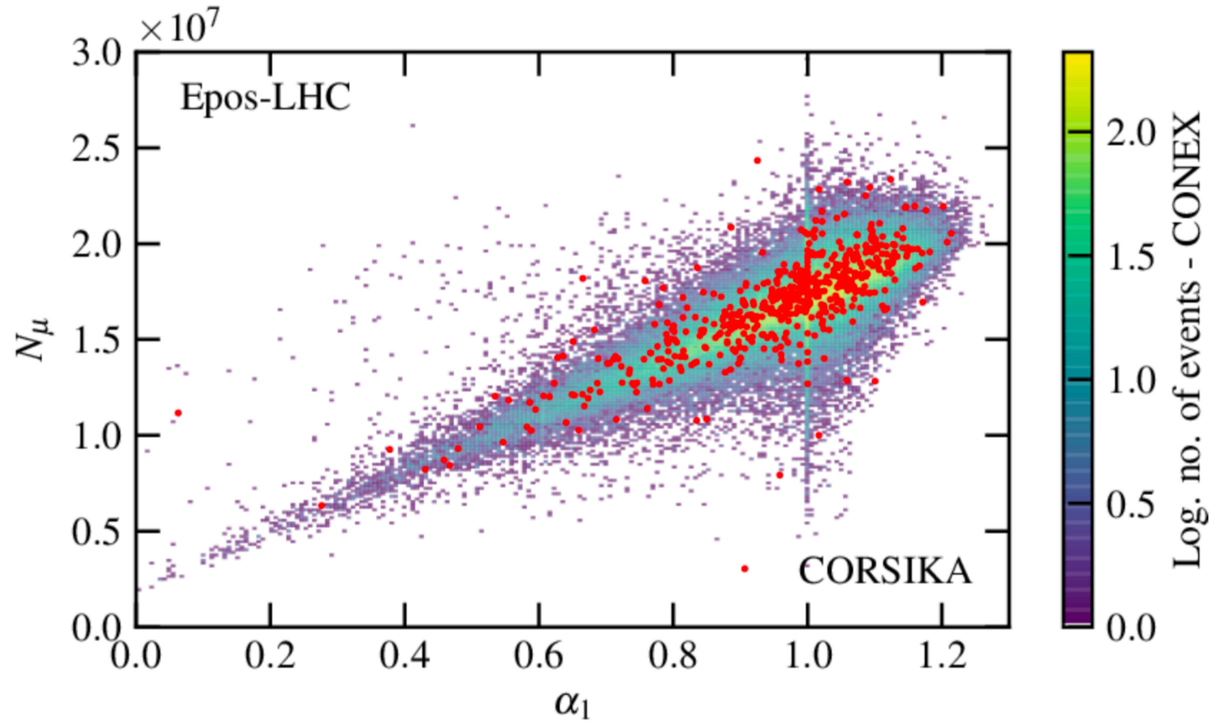
(see also, Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001)

Muon number distribution features

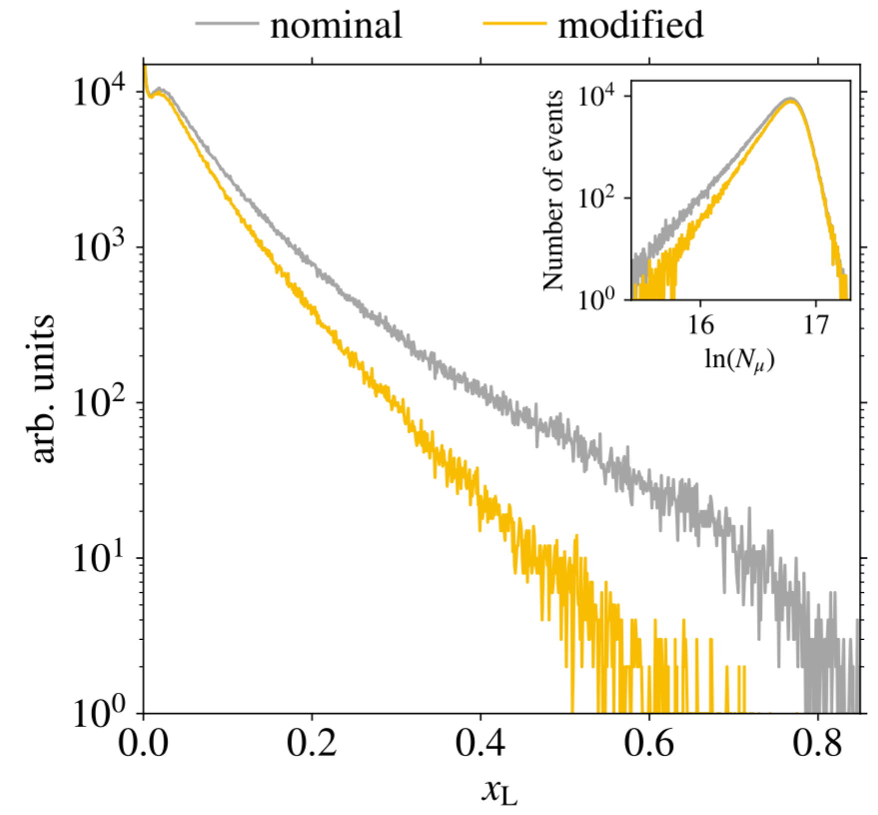
L. Cazon, RC, F. Riehn, Phys.Lett.B 784 (2018) 68-76
L. Cazon, RC, M. Martins, F. Riehn, Phys.Rev.D 103 (2021) 2, 022001
L. Cazon, RC, M. Martins, F. Riehn, Phys.Lett.B 859 (2024) 139115







1^{st} *interaction* π^0 *energy spectrum*



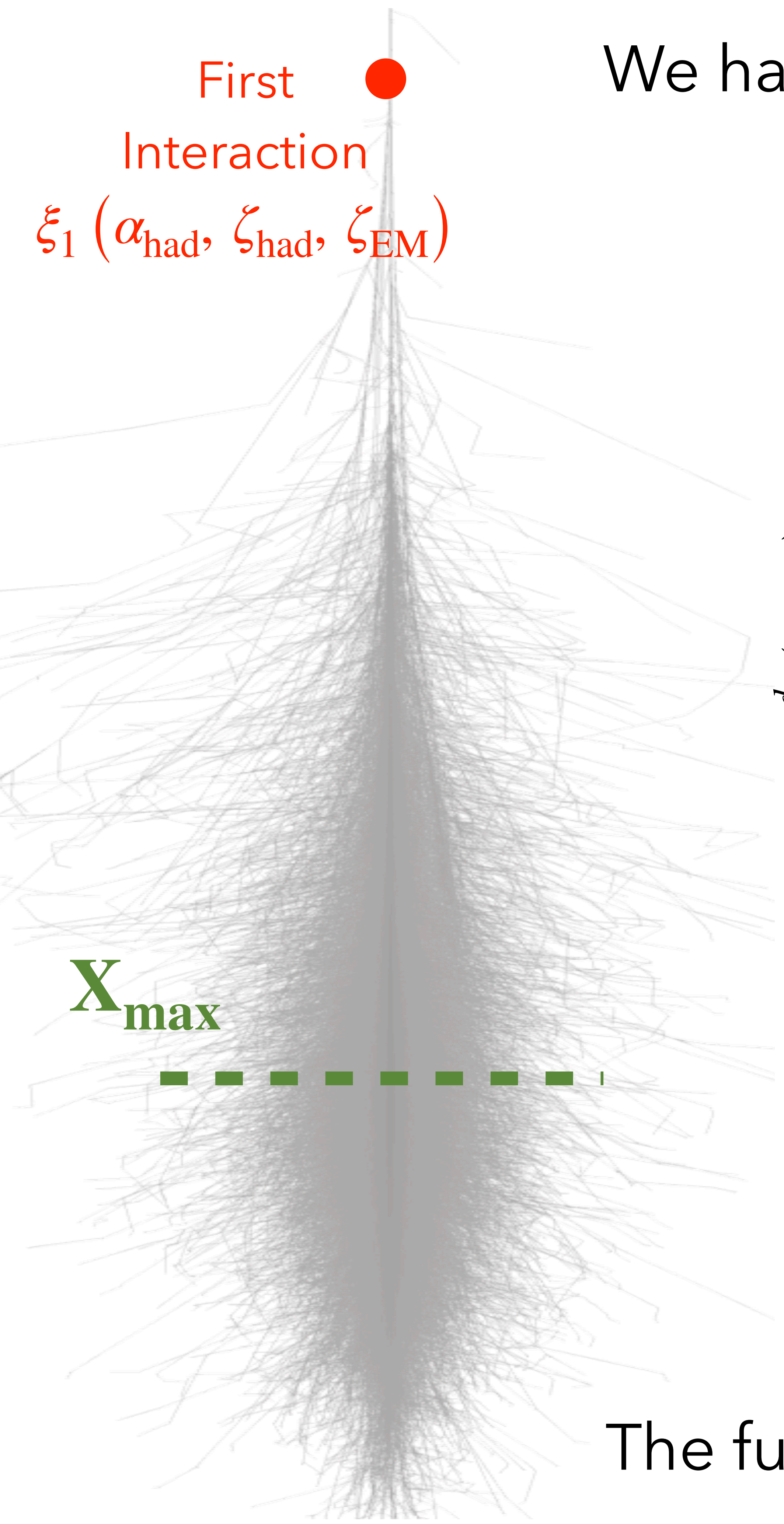
The shape and relative fluctuations of the muon number distribution gives access to the properties of the **FIRST hadronic interaction** (fraction of energy carried by neutral pions - α_1)

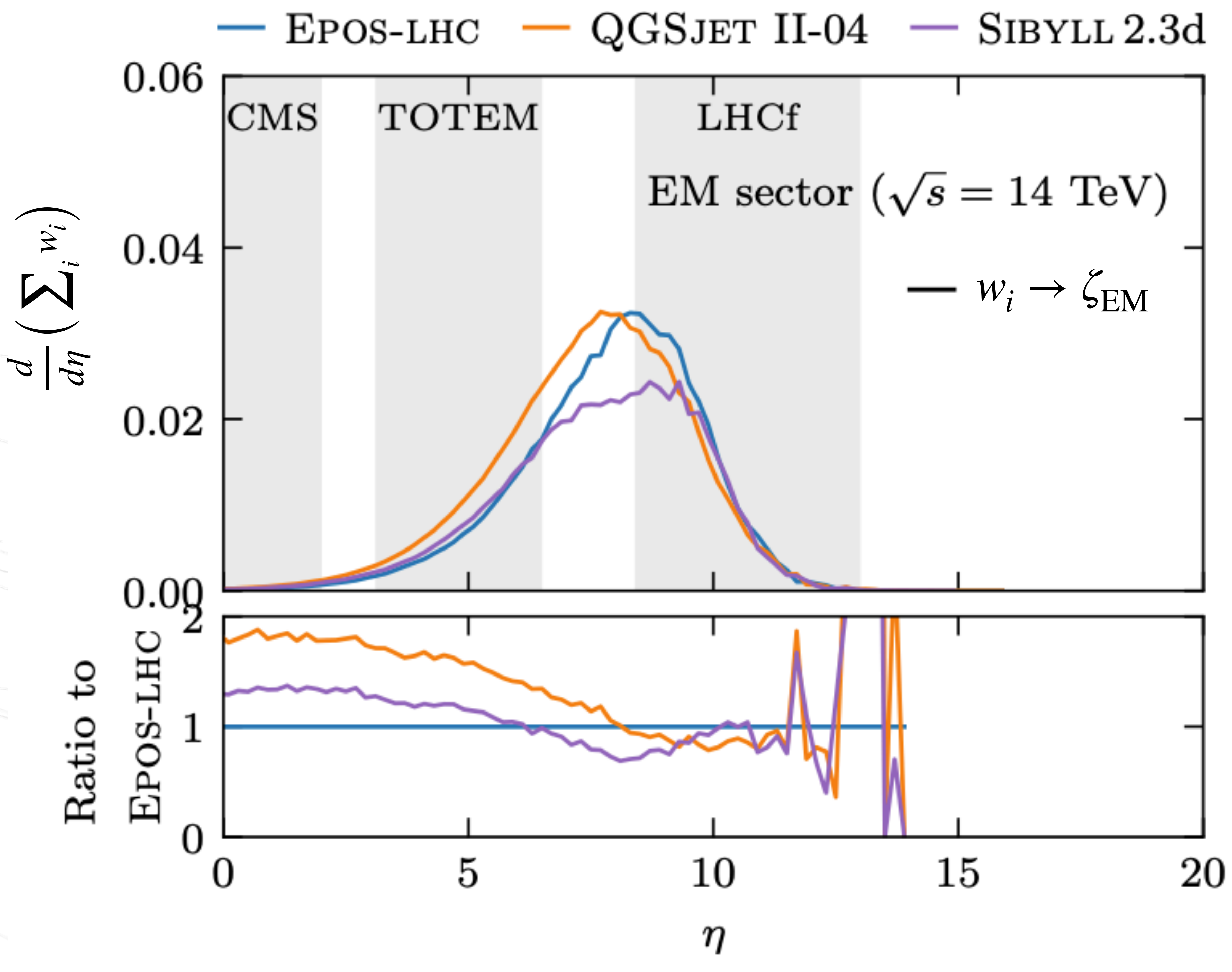
ruben@lip.pt

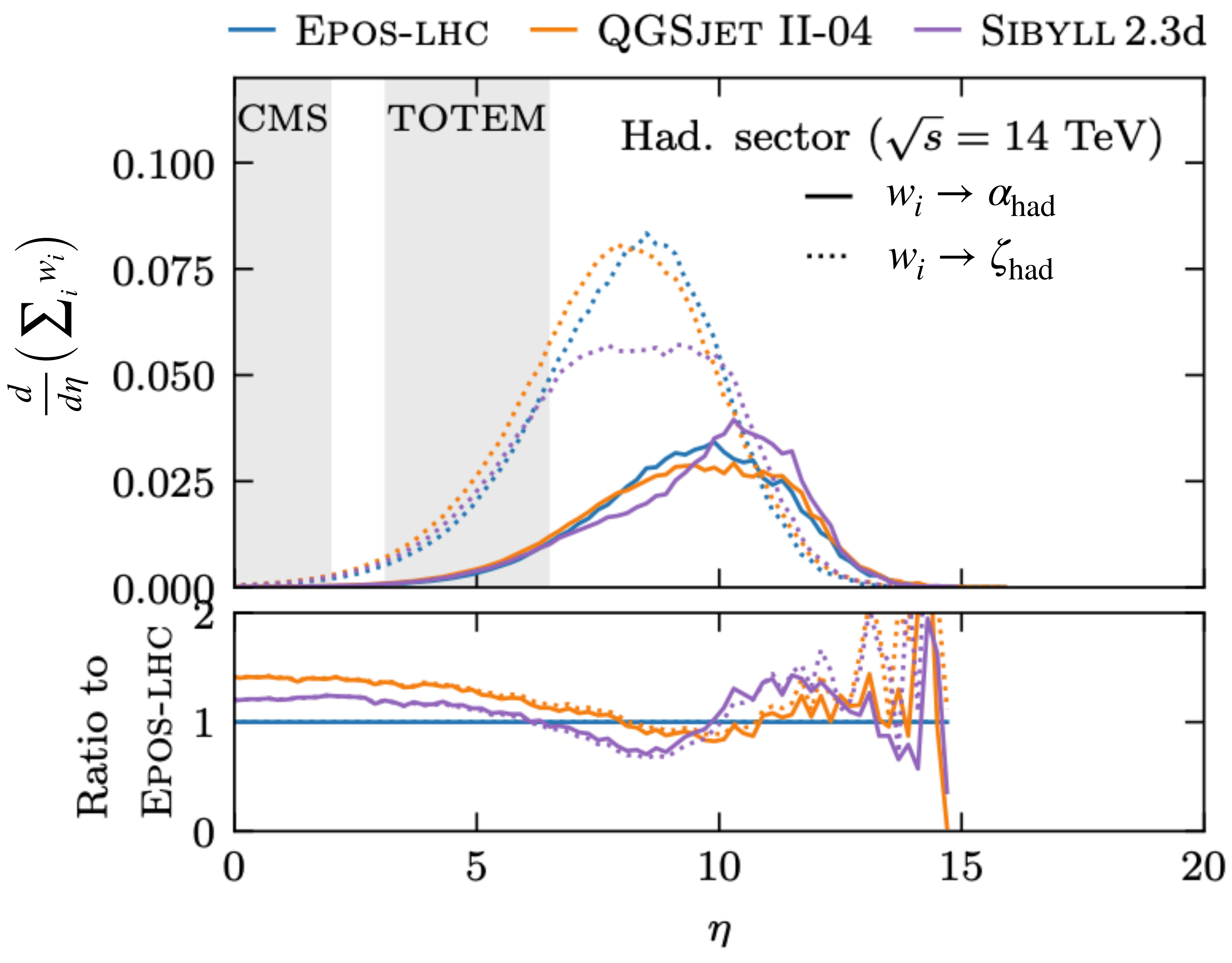
Depth of the shower maximum

L. Cazon, RC, M. Martins, F. Riehn, submitted to Phys. Rev. D

We have shown that $X_{\rm max}$ can be predicted solely from the energy spectra of secondaries by using linear combinations of the following multiparticle production quantities $\alpha_{\rm had}$, $\zeta_{\rm had}$, $\zeta_{\rm EM}$.

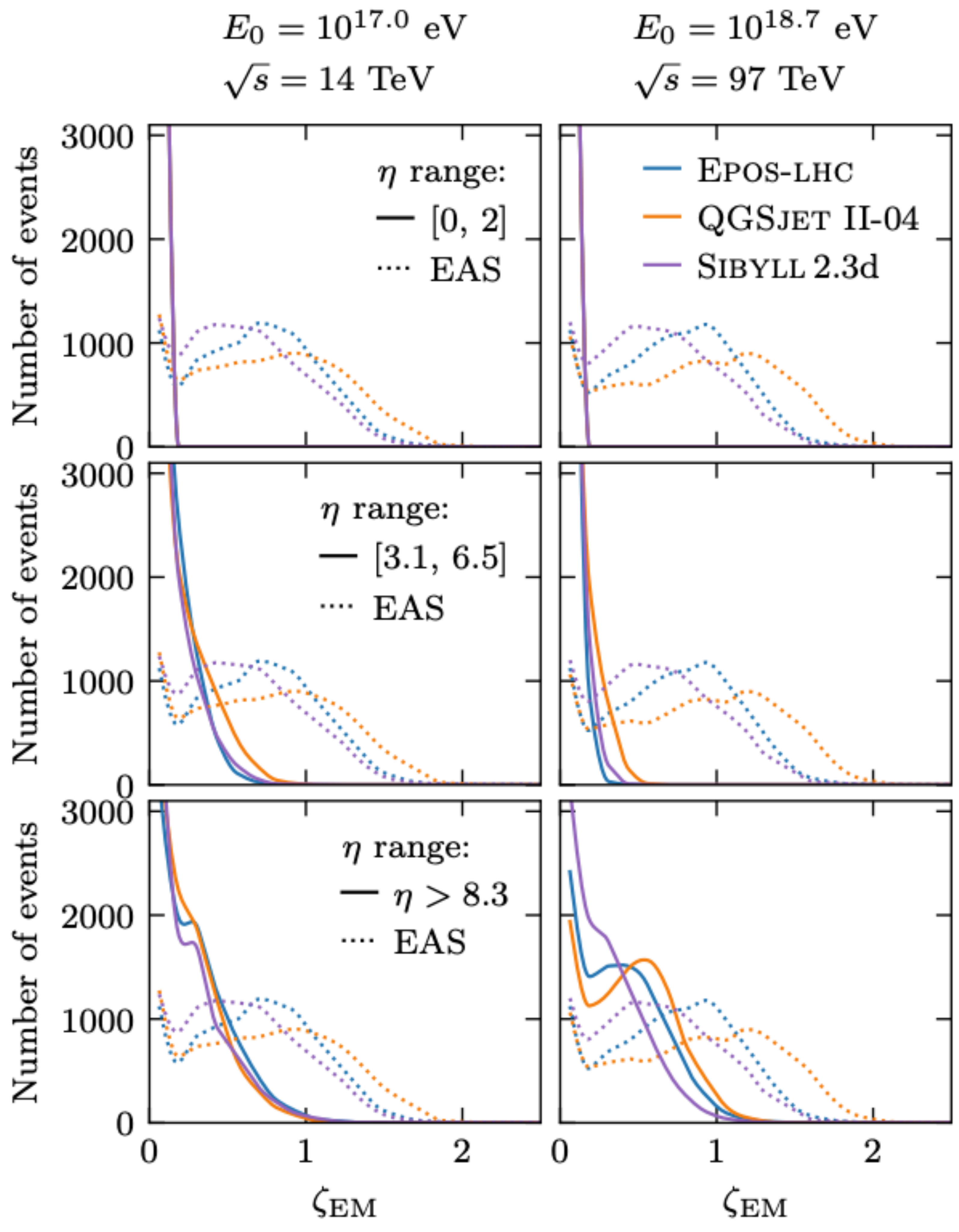






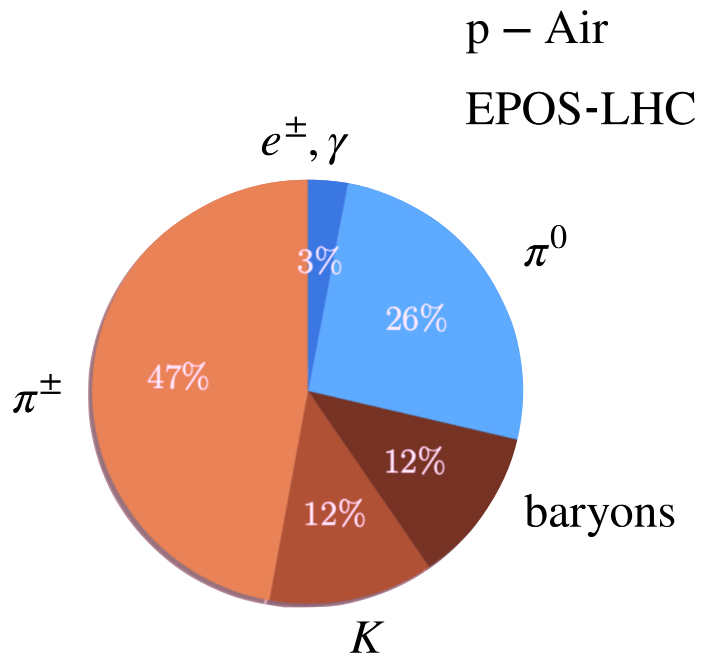
The functional form of $\alpha_{\rm had}$, $\zeta_{\rm had}$, $\zeta_{\rm EM}$ is independent of the hadronic interaction models and the particle contribution to these quantities can be explored at the HL-LHC to exclude models

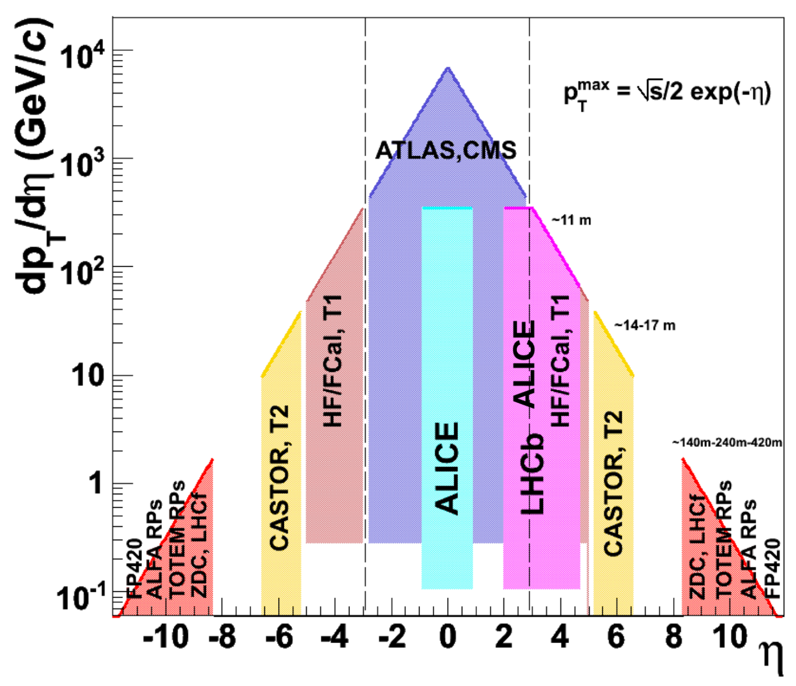
The functional form of ζ_{EM} and ζ_{had}

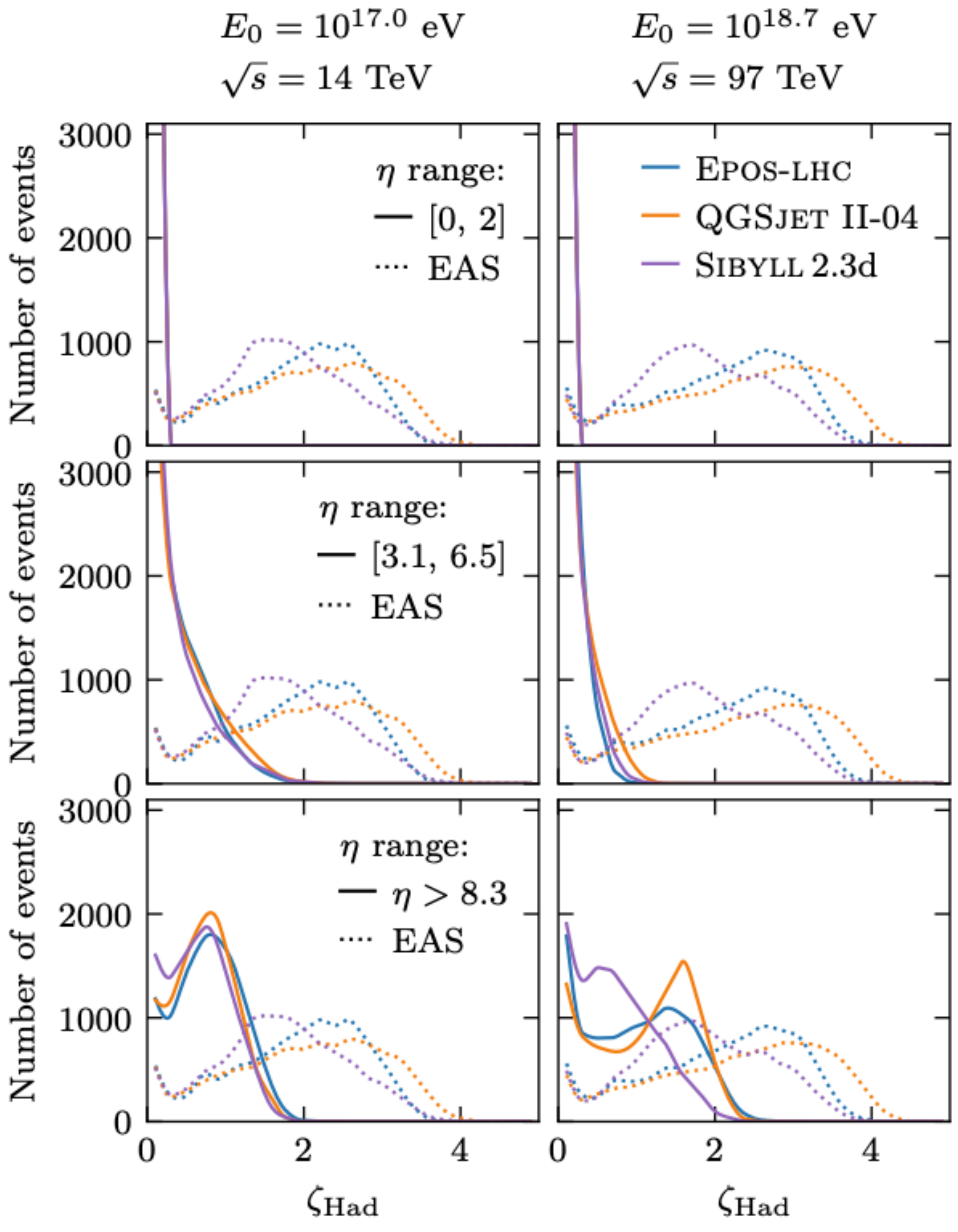


Shower electromagnetic sector

The **shape** of ζ_{EM} and ζ_{had} can only be differentiated across models in **Cosmic Ray experiments** or at the **FCC-hh**



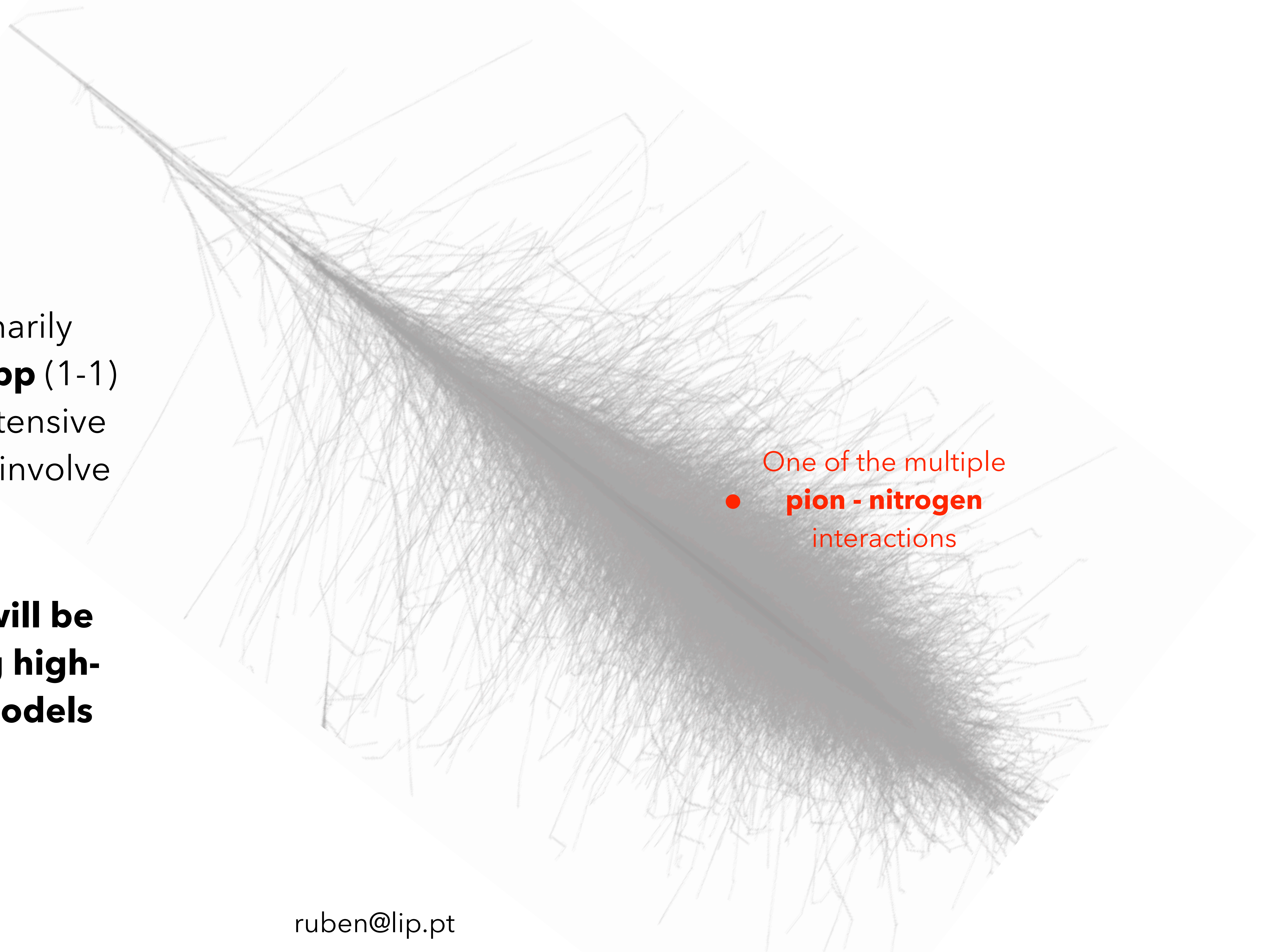




Shower hadronic sector

ruben@lip.pt

Extensive Air Showers



Available accelerator data primarily cover collisional systems such as **pp** (1-1) and **PbPb** (208-208), whereas extensive air showers (EAS) predominantly involve **p/$\pi^{\pm}$-N** (1-14) interactions

The upcoming p-O collisions will be highly valuable in constraining high-energy hadronic interaction models

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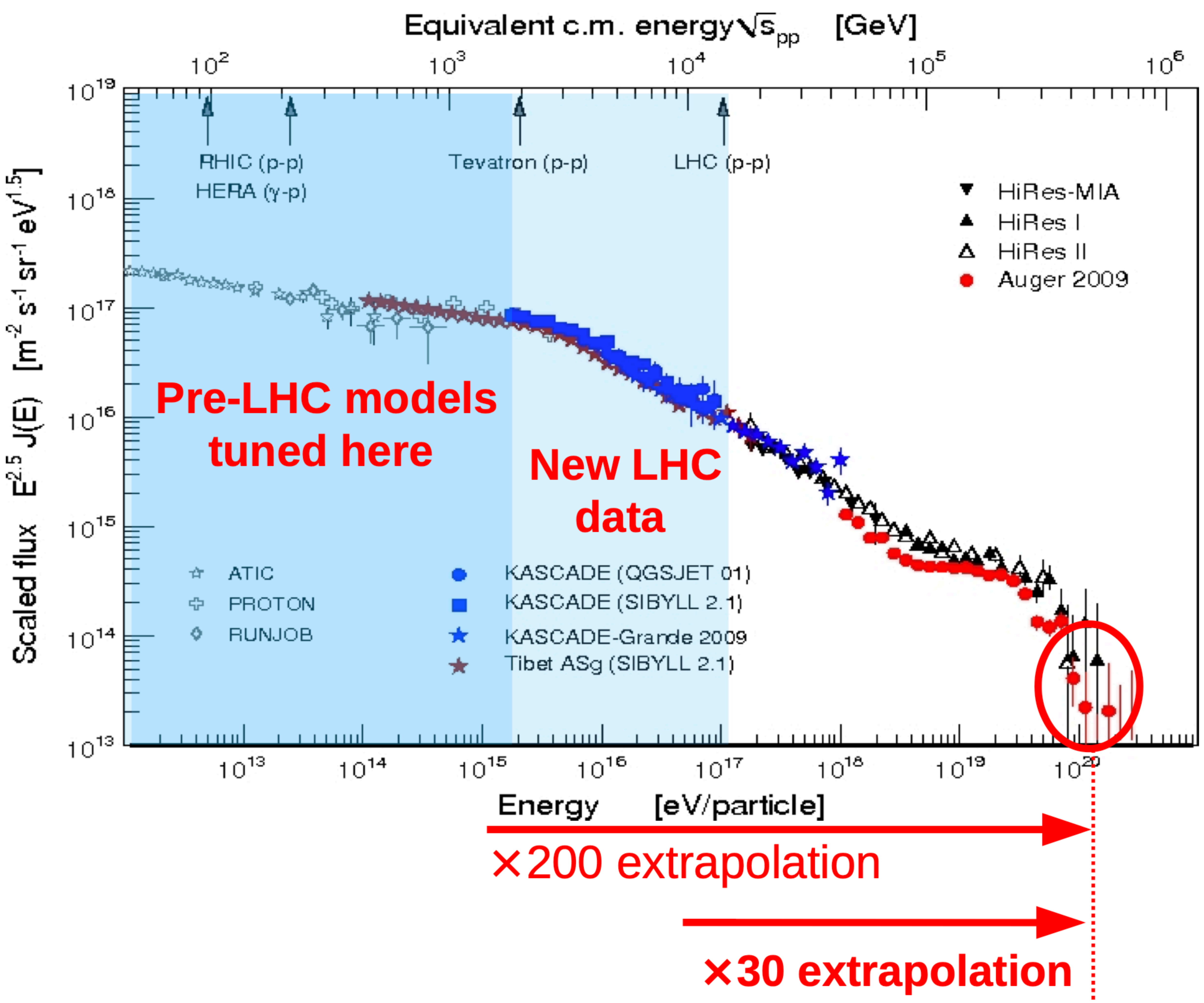
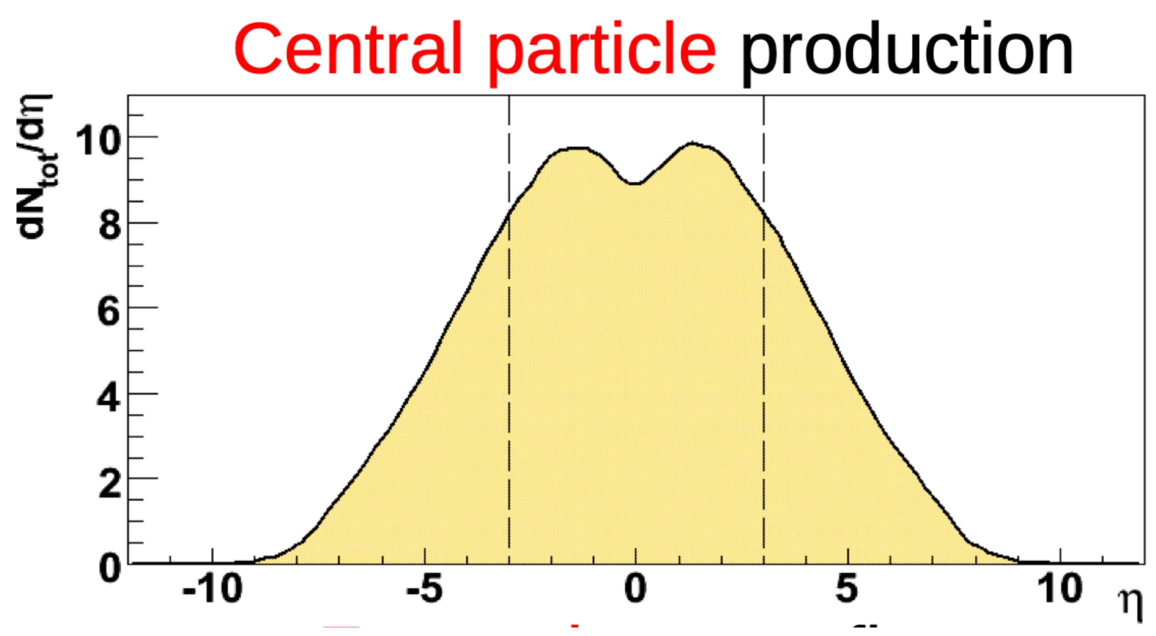
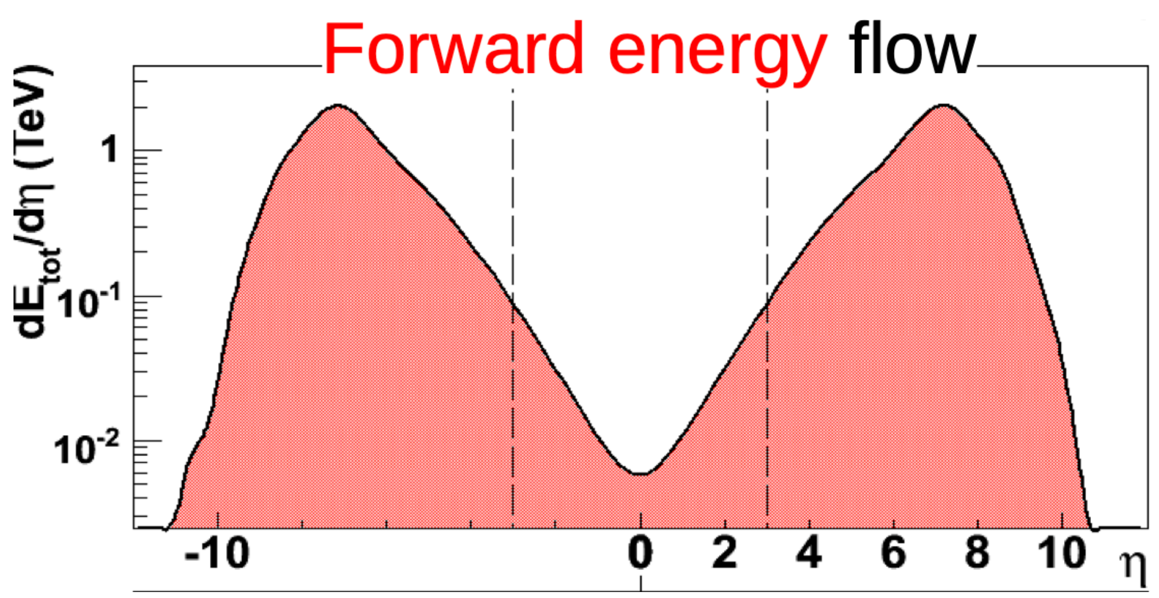
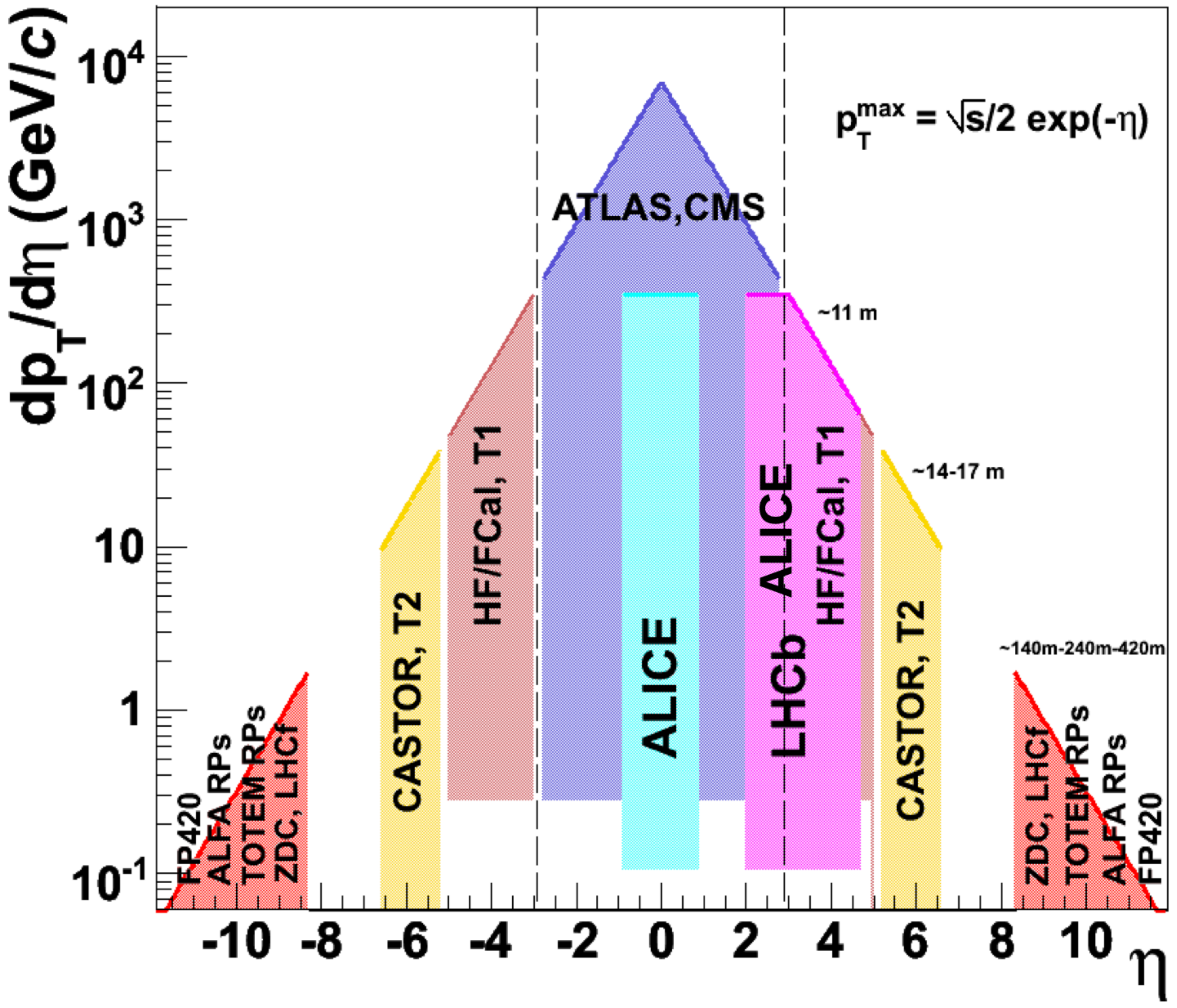
The challenge

p-p @ 14 TeV

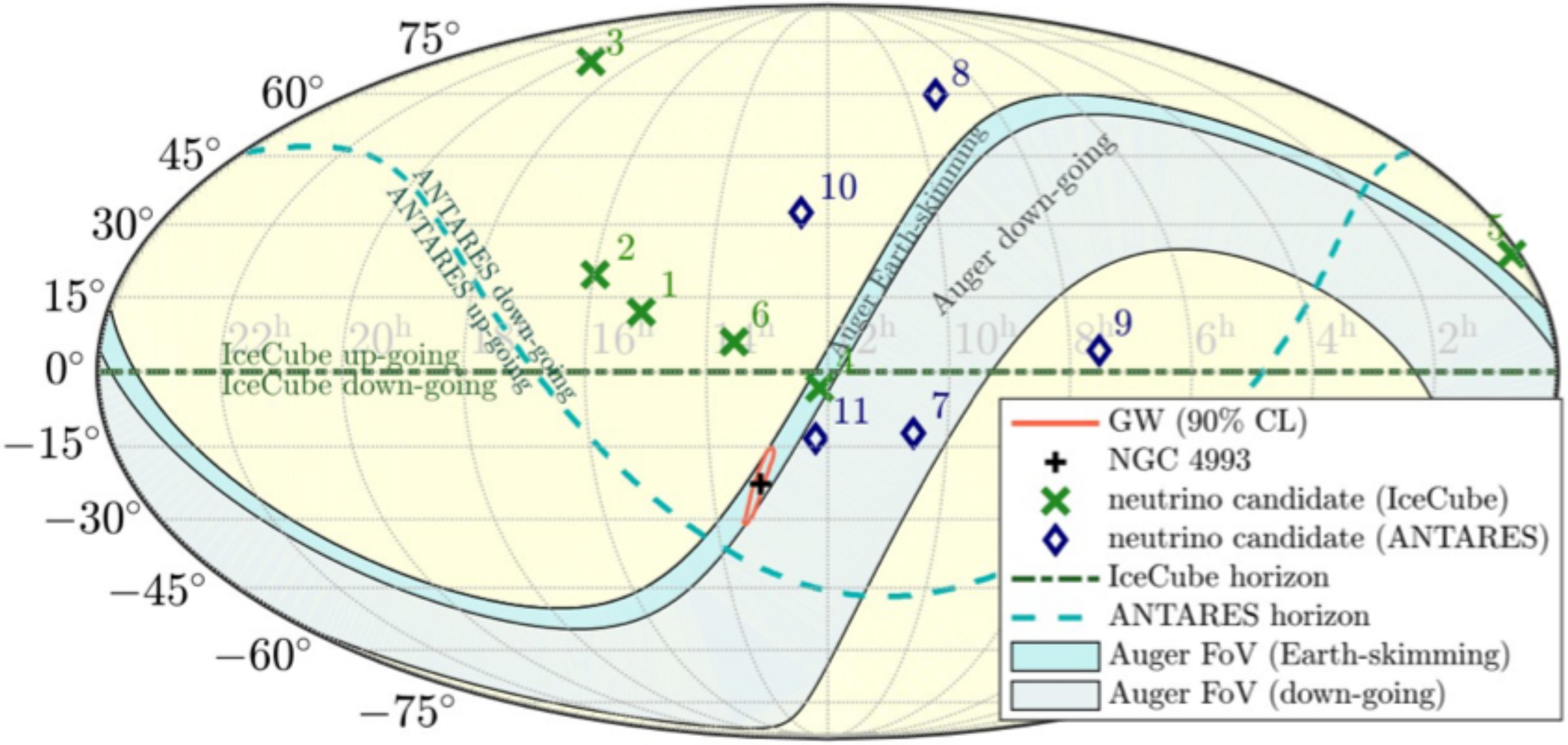






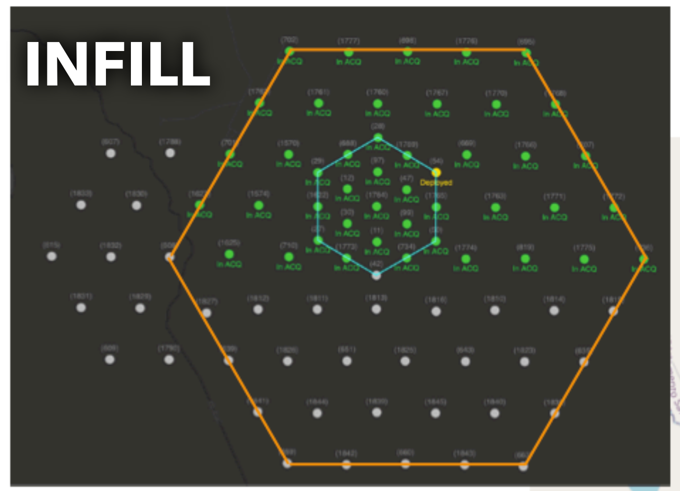


GWs and neutrinos - GW170817

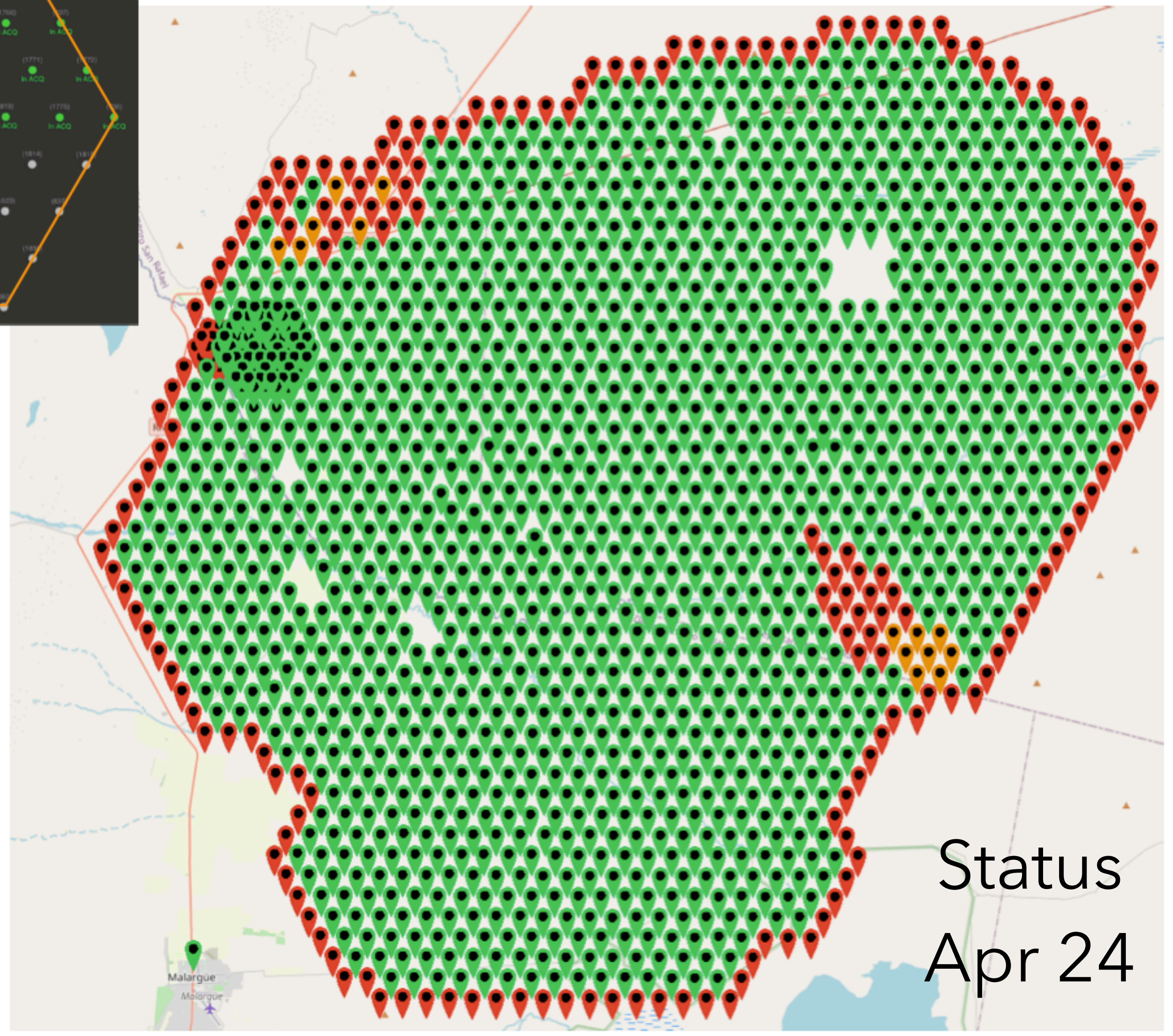


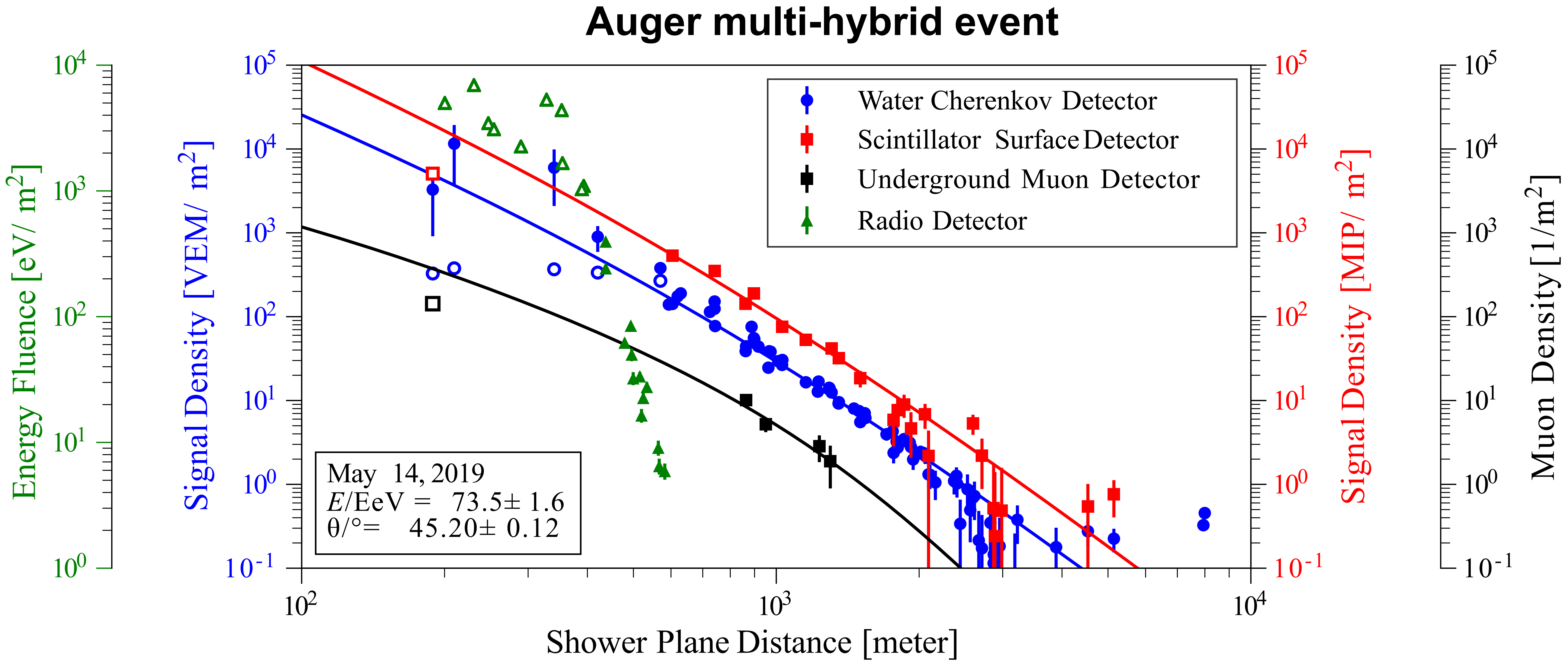
AugerPrime timeline

2019	Start of the Upgrade phase
2020	end of PMTs fabrication
2021	end of SSD shipment on site
2022	end of SSD deployment
2023	end of UUB production and shipment
2023–2024	end of UUB + PMTs deployment
2024	end of Radio+ UMD deployment
… 2035	

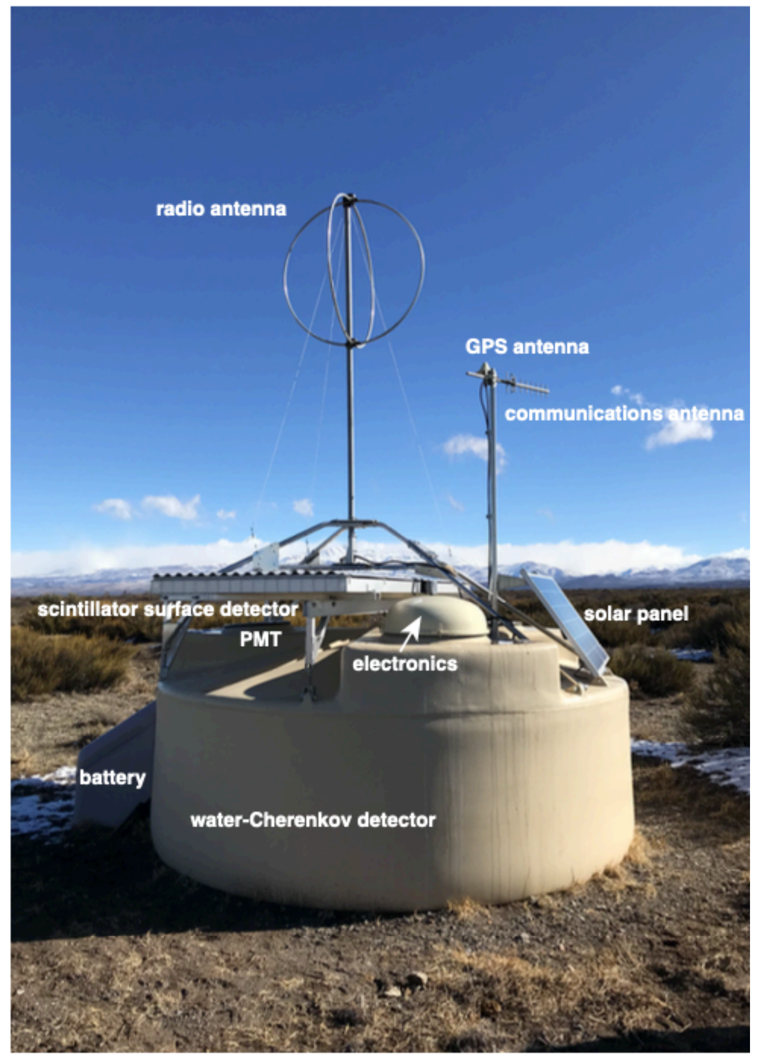


UMD
— SD433 95%
— SD750 59%

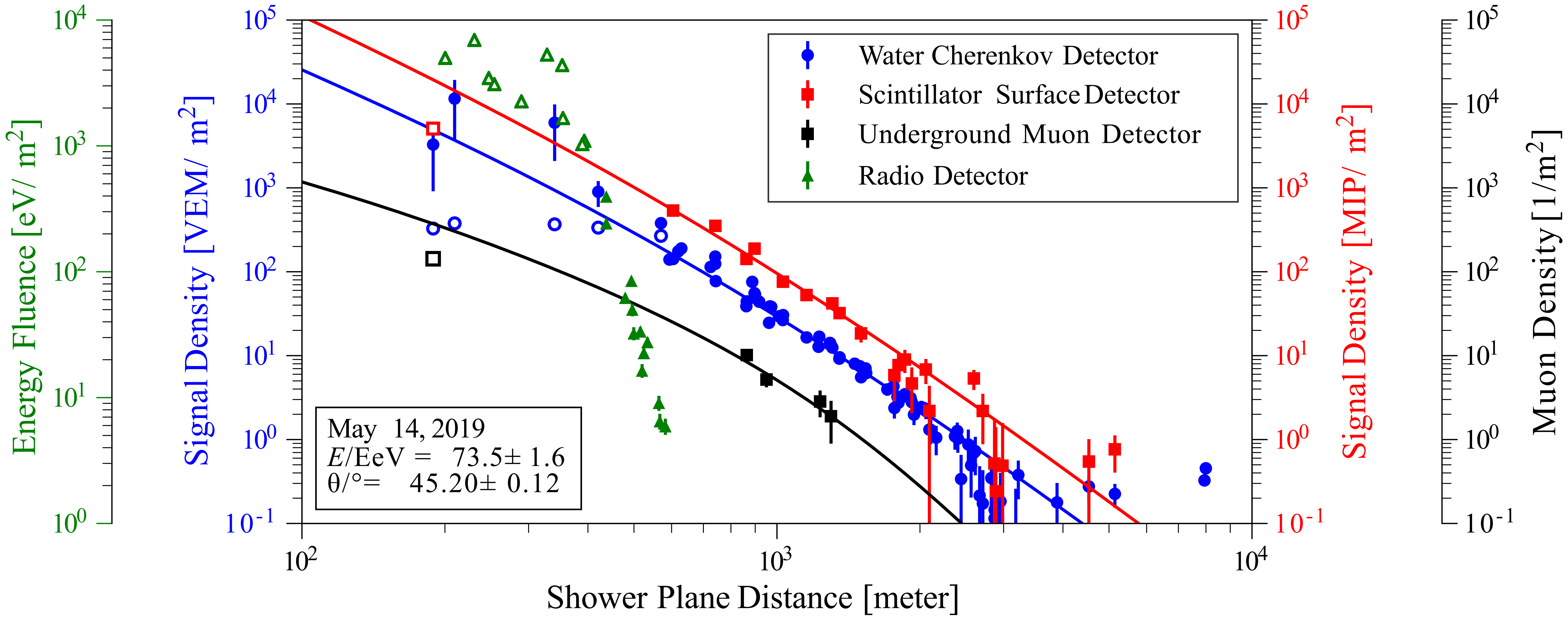




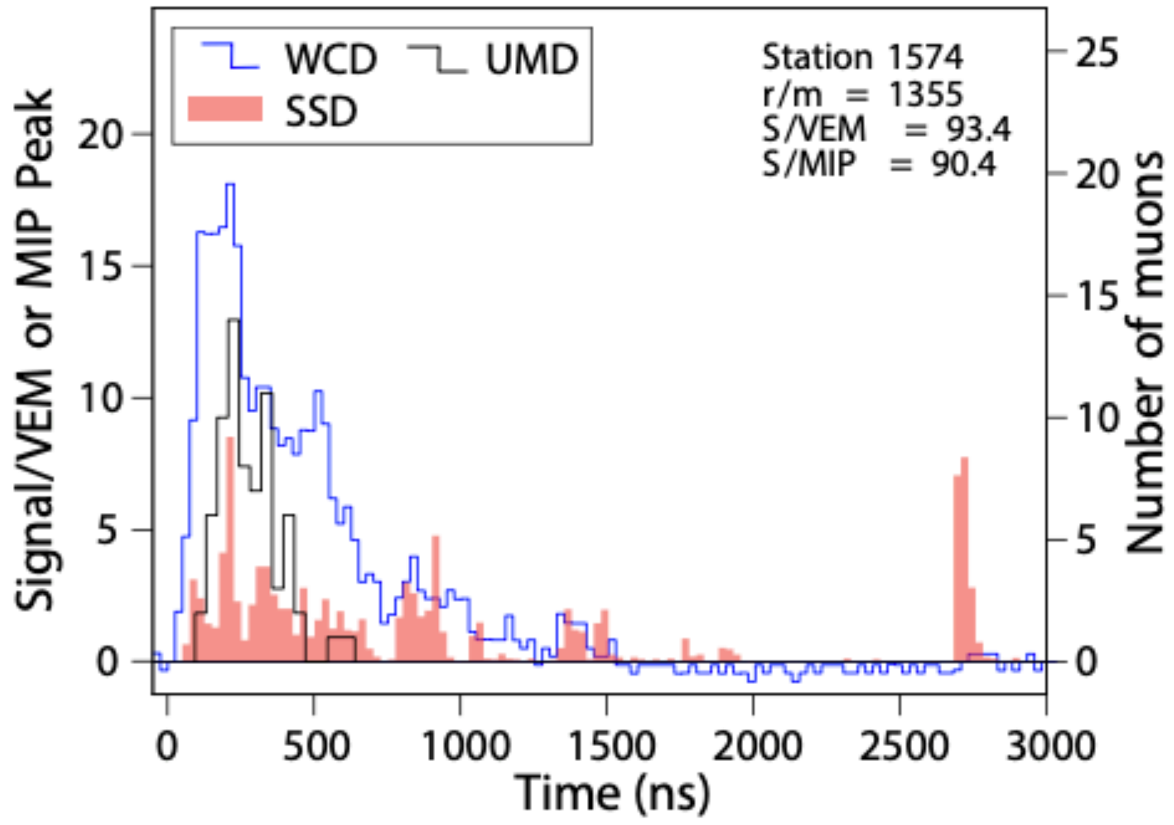
AugerPrime: A Wealth of Information



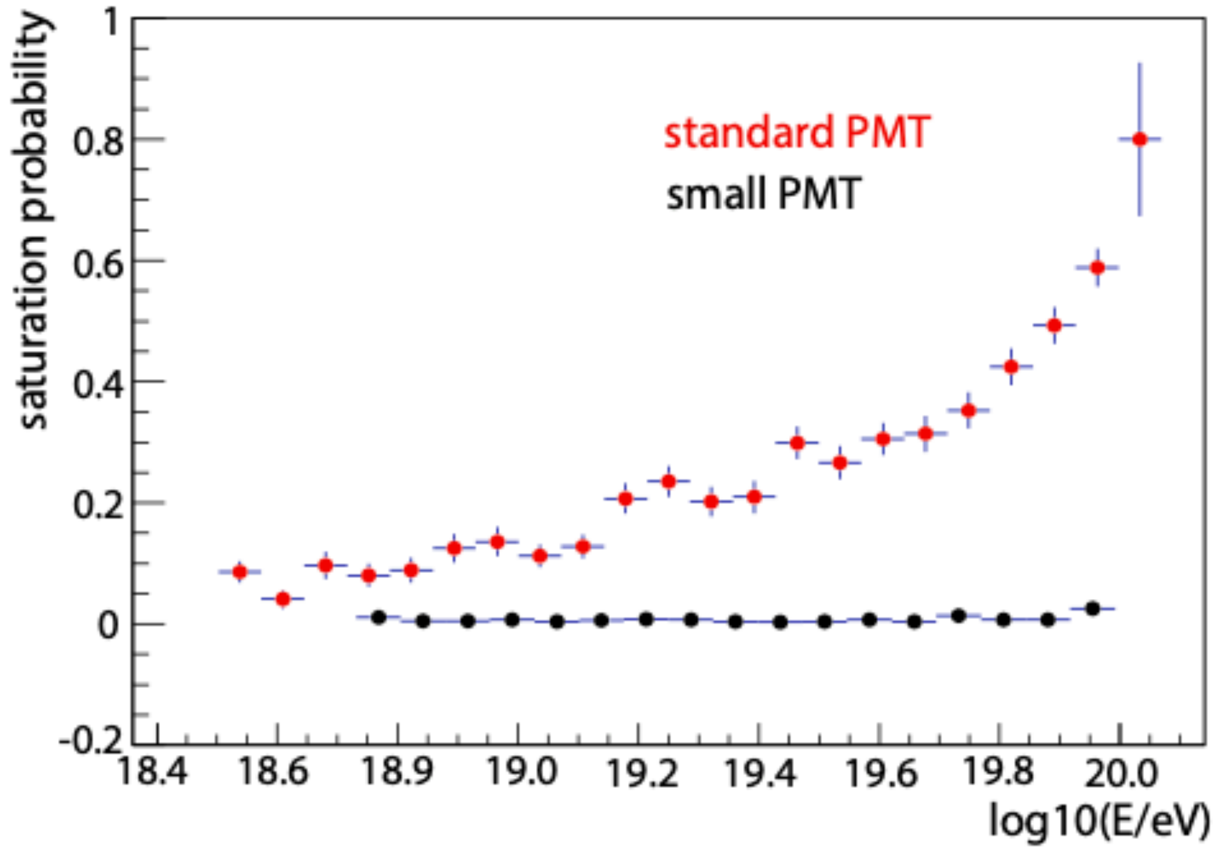
Auger multi-hybrid event

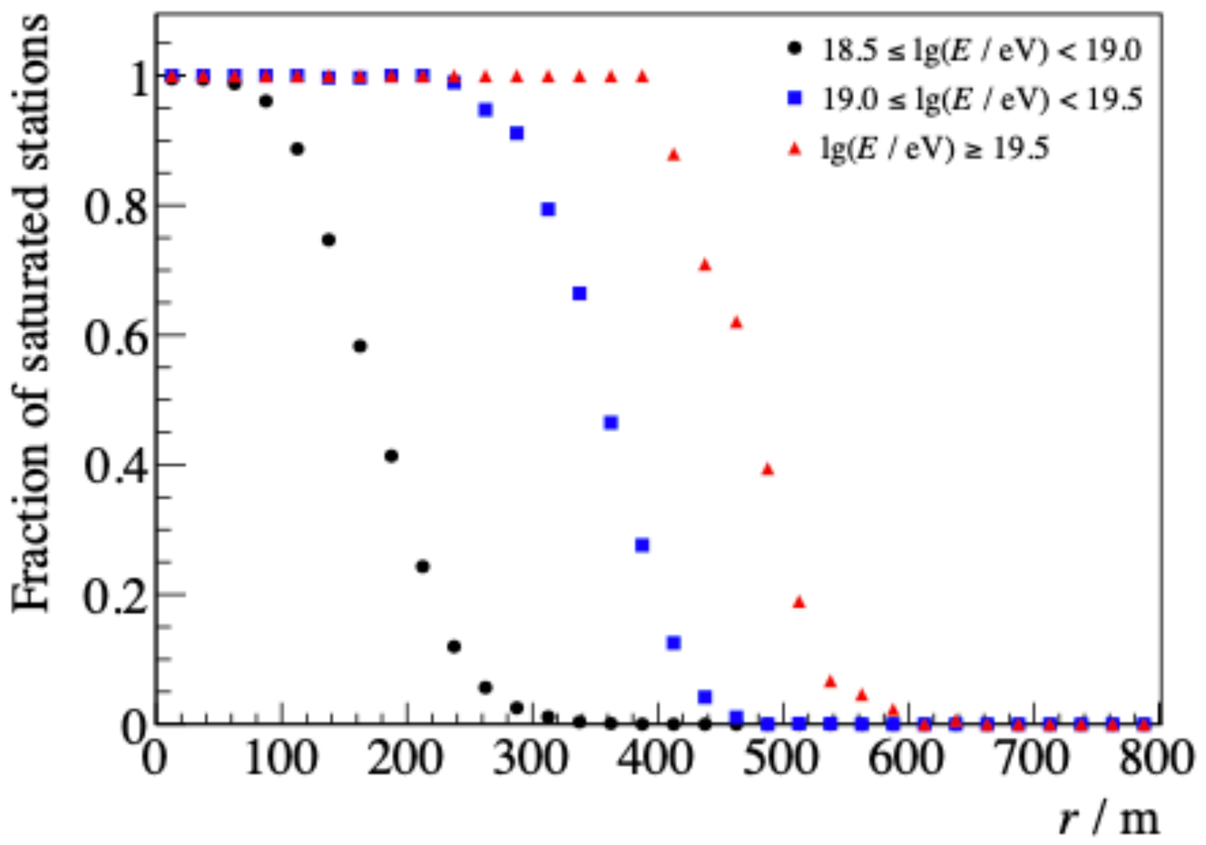


PMTs signal time trace

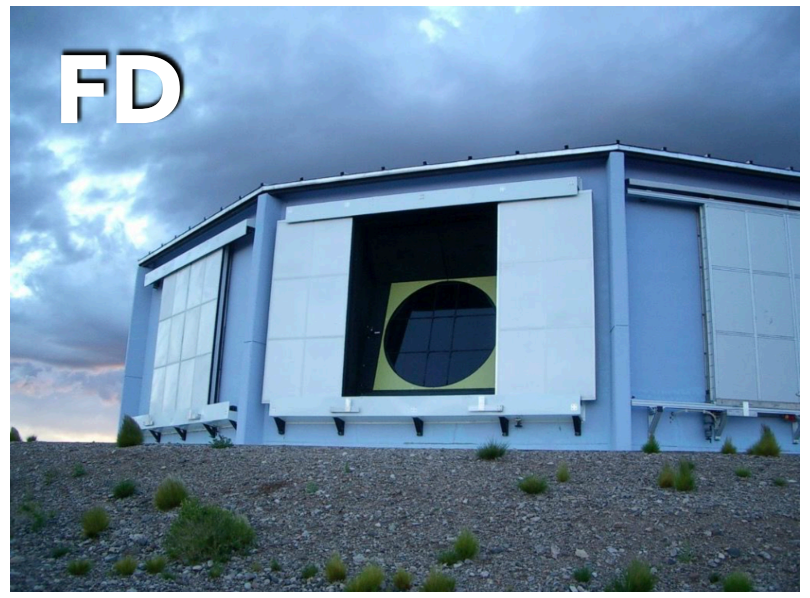


Small PMT in the WCD



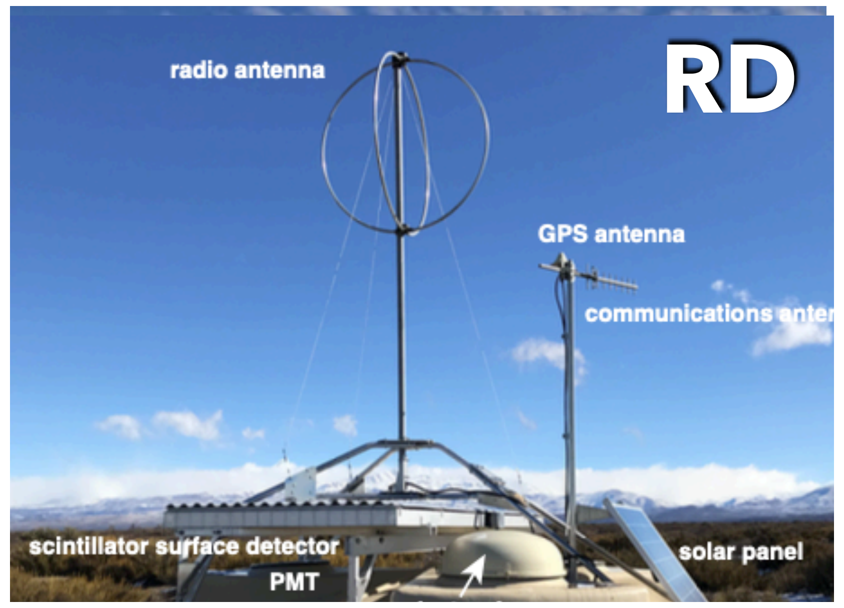


More events than ever…



Vertical
Events

Horizontal
Events

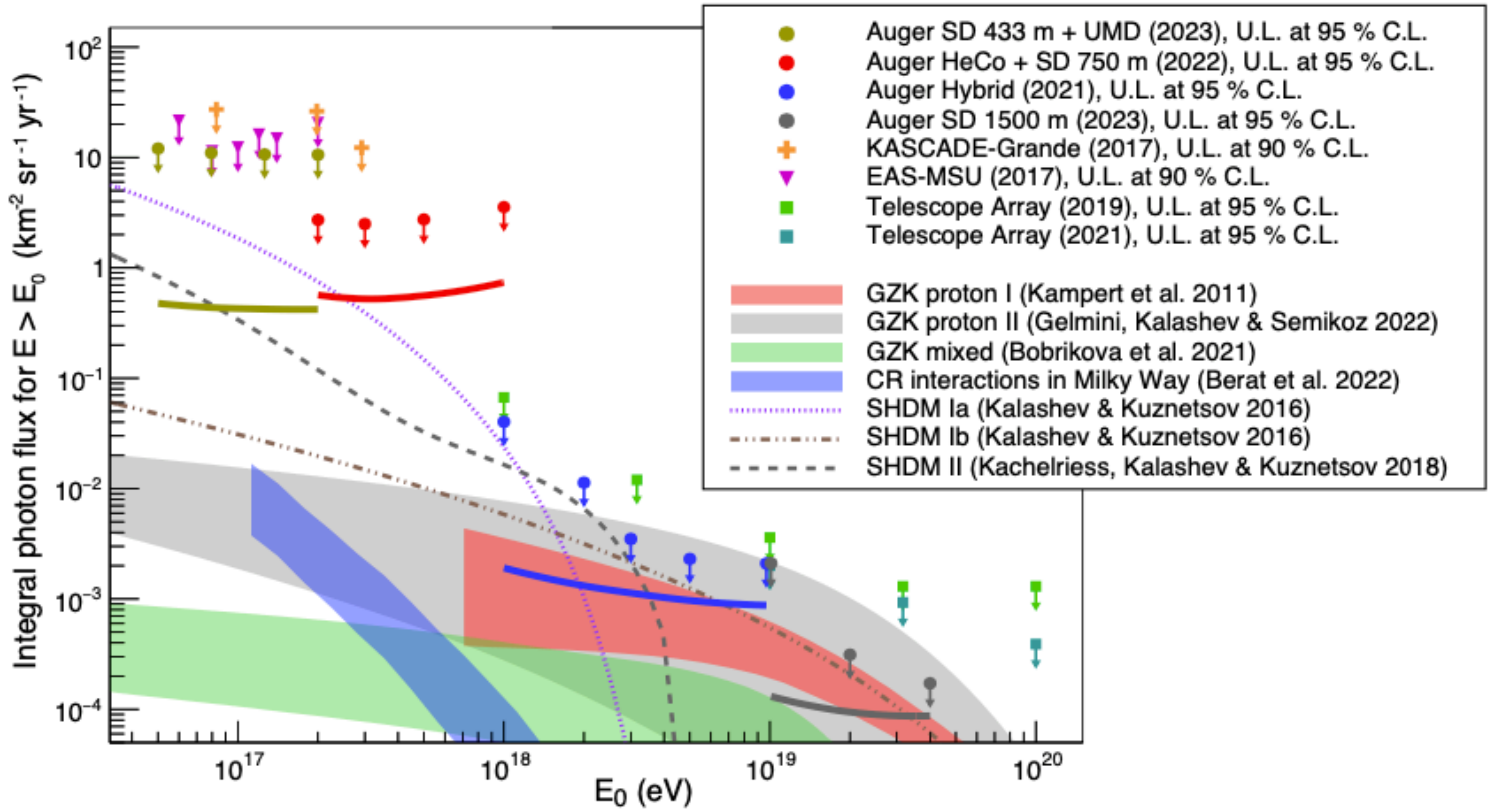


Energy scale

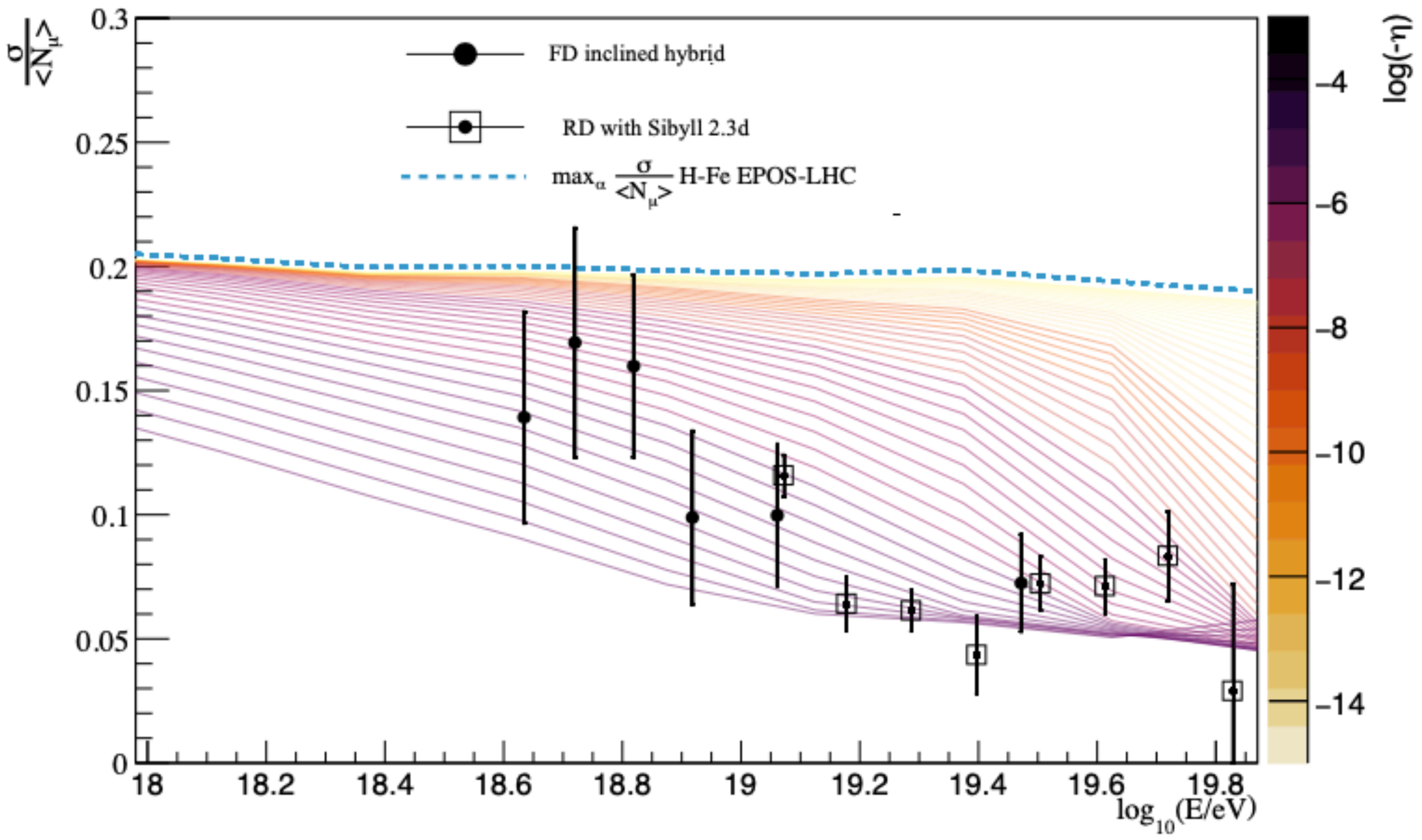
Particles at the ground

Energy scale

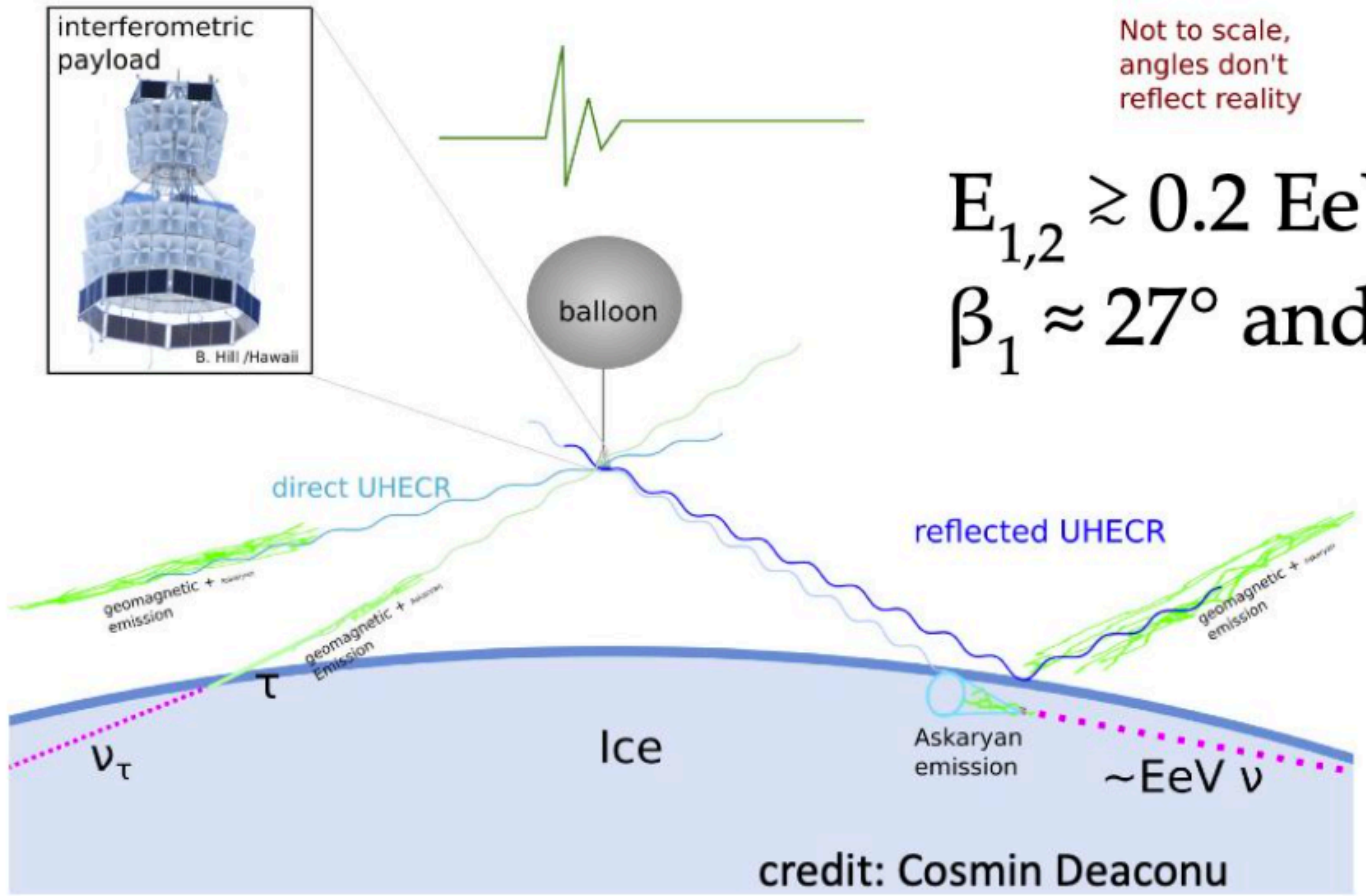
Photon Limits



Lorenz Invariance Violation

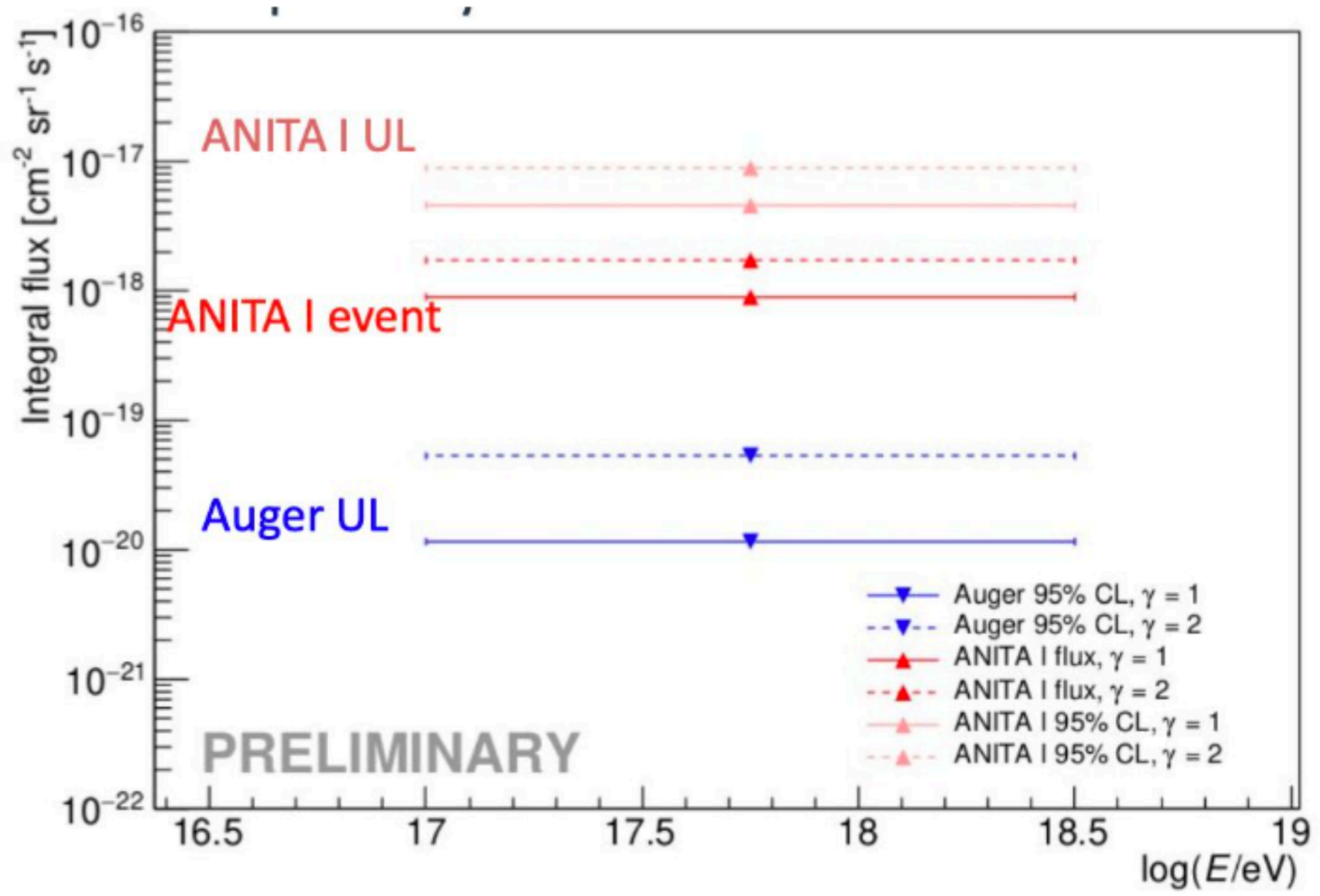


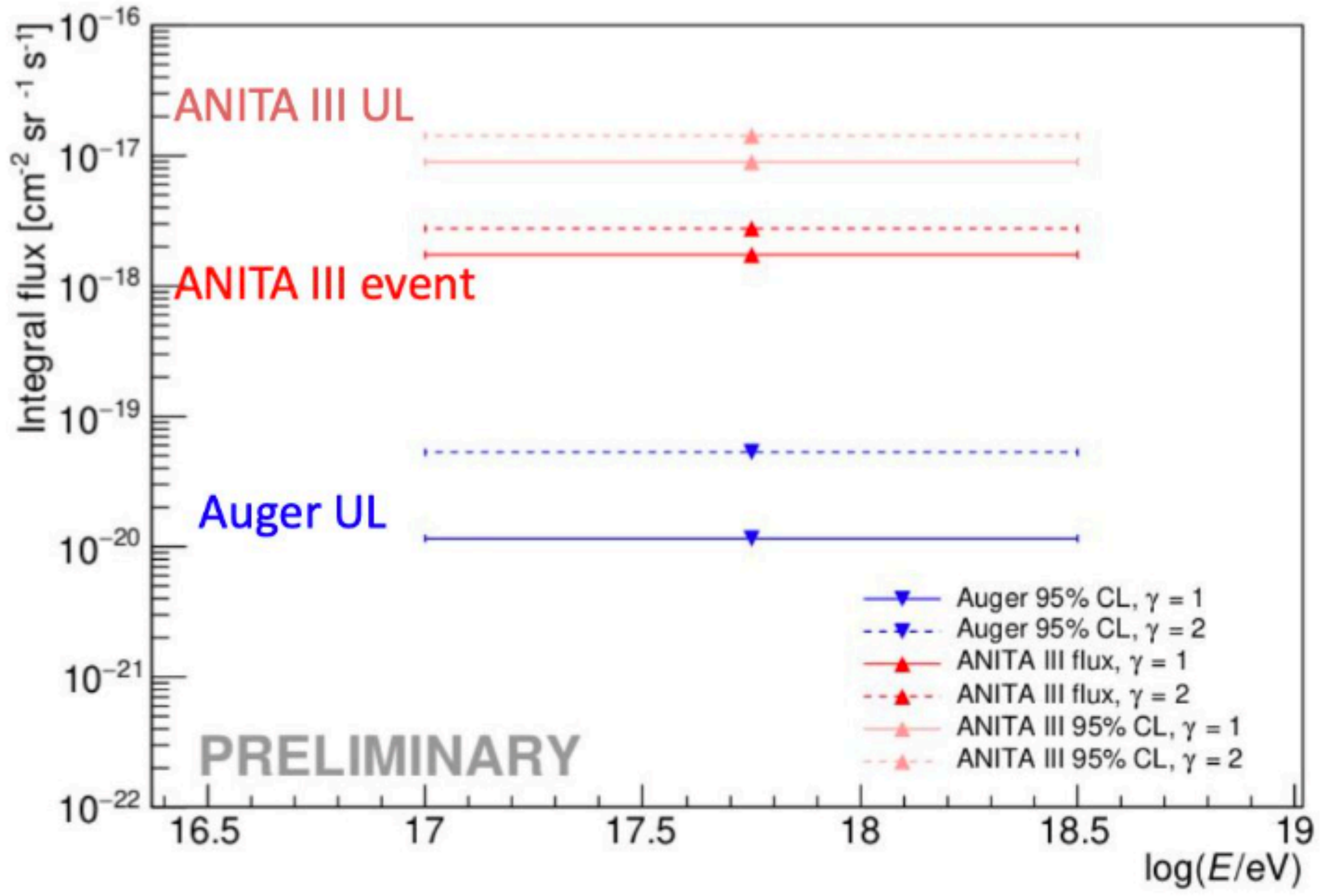
Beyond Standard Model Physics



$$E_{1,2} \gtrsim 0.2\ \text{EeV} \approx 10^{17.8}\ \text{eV}$$
$$\beta_1 \approx 27° \text{ and } \beta_2 \approx 35°$$

(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

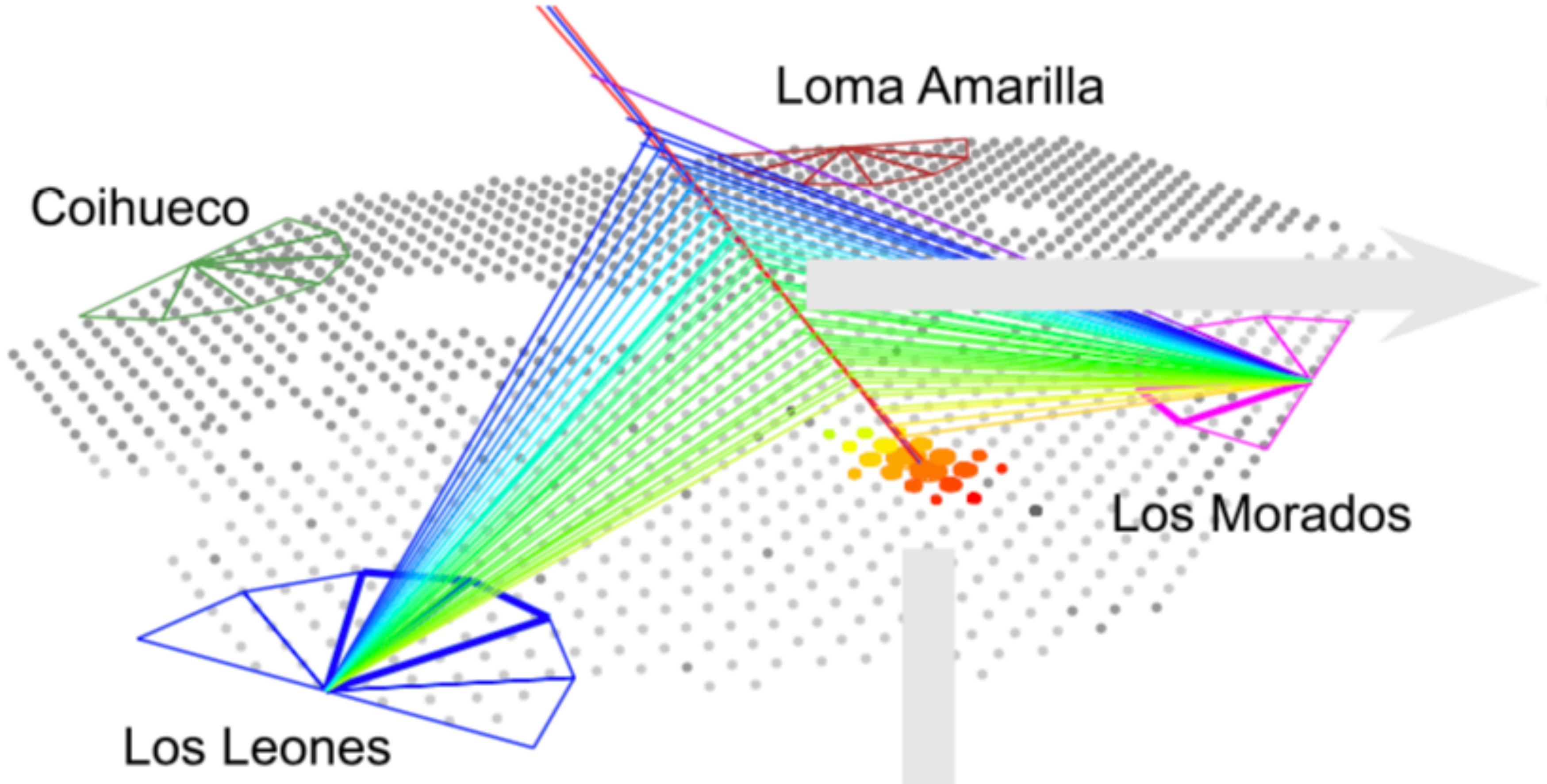


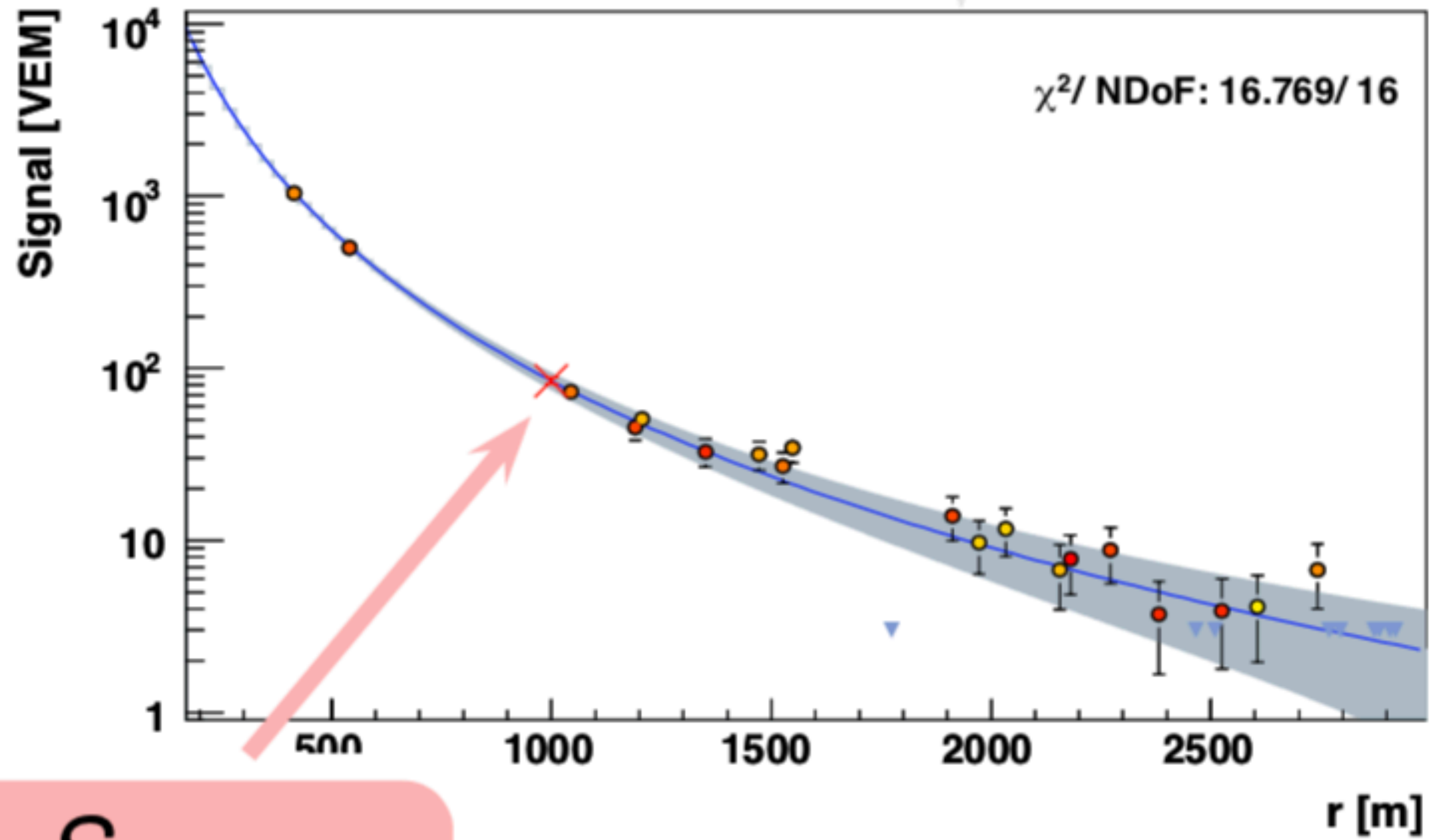


- Search of up-going events with FD

- one event observed (compatible with background)
- Auger upper limits are significantly lower than the inferred ANITA fluxes
- FD exposure for up-going shower also used for others BSM studies

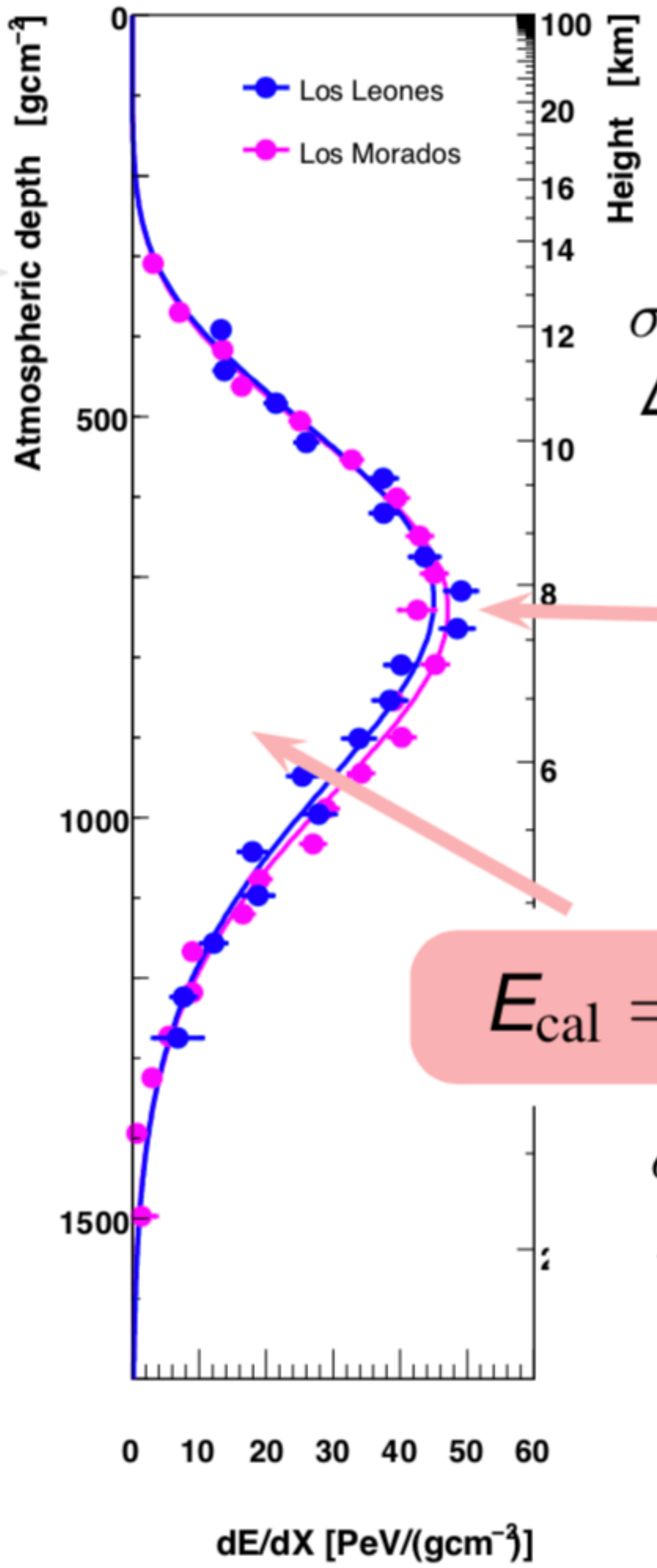
Hybrid Technique (FD + SD)





S_{1000}

$E_{\text{surface}} = f(S_{1000},\ \theta)$



$\sigma X_{\text{max}} \leq 20\,\text{g/cm}^2$
$\Delta_{\text{sys}} \leq 10\,\text{g/cm}^2$

X_{max}

$E_{\text{cal}} = \int \frac{dE}{dX}\,dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$