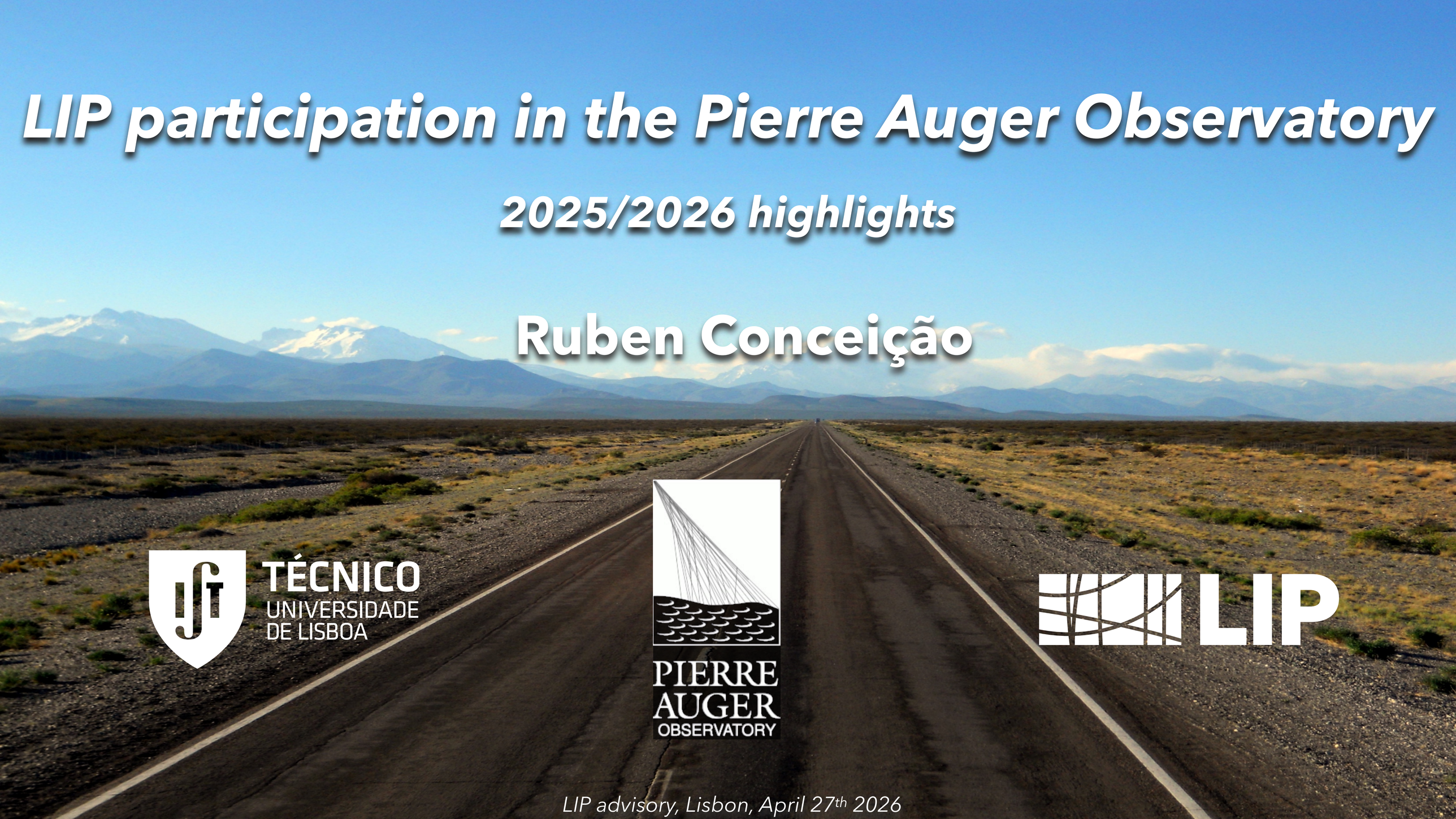
LIP participation in the Pierre Auger Observatory

2025/2026 highlights

Ruben Conceição



TÉCNICO UNIVERSIDADE DE LISBOA

PIERRE AUGER OBSERVATORY

LIP

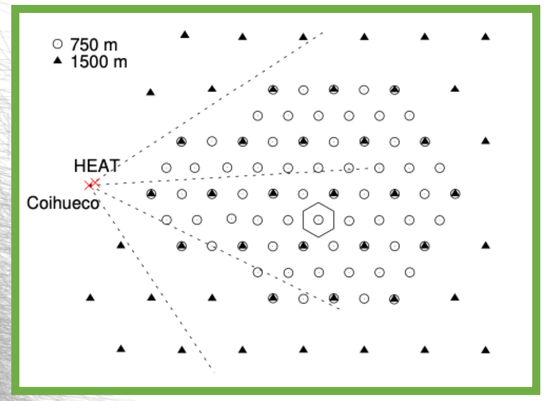
LIP advisory, Lisbon, April 27th 2026

Auger-Phase II: Multi-hybrid shower events

(A plethora of measurements to fully understand the shower)

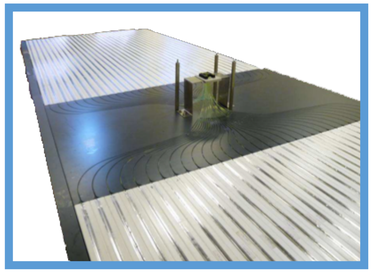
Cosmic Ray

HEAT

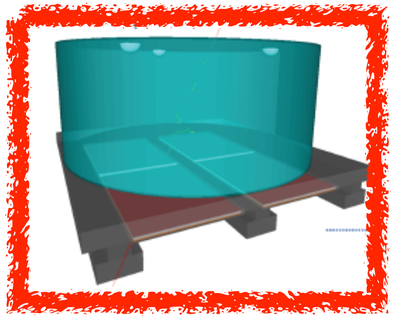


LHC c.m. energy equiv to first interaction

Radio (AERA+RD)



Muon Detectors (UMD)



MARTA R&D

Infill (SD433;SD750)

Auger Prime (SSD)

10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]

Auger-LIP group (current status)

- Members (**11.5** FTEs)
- **7** Senior Researchers
- **2** Technicians
- **4** PhD students
  - Two will finish in 2026
- **1** Master students
- **2** External collaborators
- **5** Undergraduate Trainees

Funding

2024.06879.CERN - 110.300€

Ended Dec 31st 2025

No new fund CERN call yet...

Thesis finished in 2025

Pedro Tomé (MSc, IST)

"*Muon energy spectrum from the analysis of inclined shower footprint*"

Supervisors: R. Conceição and B. Tomé

David Dias (MSc, IST)

"Exploring the electromagnetic shower profile to enhance the Pierre Auger Observatory physics capabilities"

Supervisors: R. Conceição and J. Alvarez-Muñiz (USC)

Miguel Martins (PhD, IST)

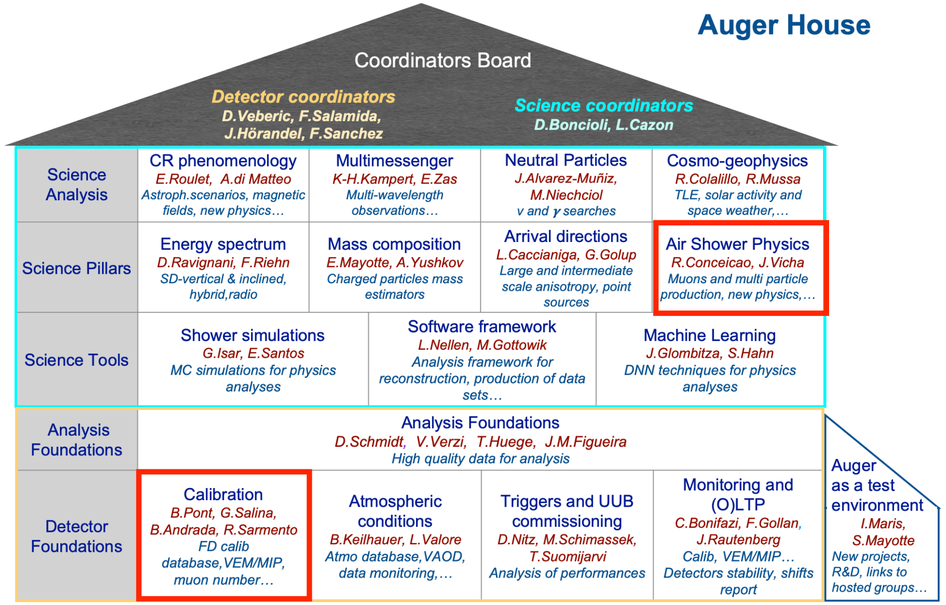
“Inferring hadronic interaction properties from the 2D distribution of muon content and depth of maximum of extensive air showers”

Supervisors: L. Cazon (USC) and R. Conceição

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
  - Calibration SD/SSD task coordinator
  - Ombudsperson *[RENEWED]*
  - Representative Auger member at IPPOG *[RENEWED]*
  - Search committee for Spokesperson election
- Invited plenary talks on EAS physics at IMFP25, ISVHECRI26
- IAC ECRS, Convenership ECRS26 and ICHEP26
- **MoU for the Portuguese participation in Auger has been extended up to 2035**

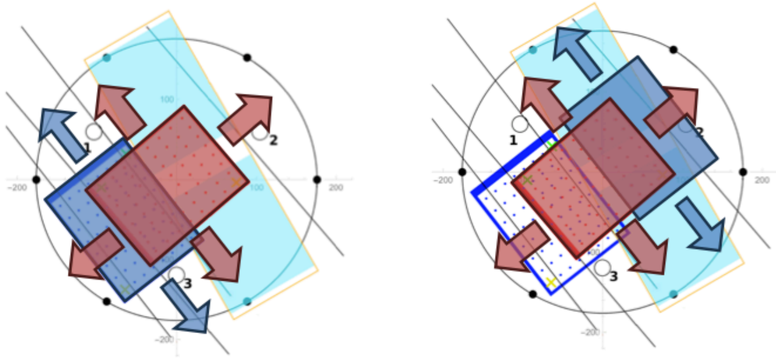


Auger-LIP group main lines of activity

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

Activities in Argentina (@Auger)

Calibration campaign using an RPC hodoscope setup to evaluate **WCD-SSD calibration**



Bottom RPC repositioned to maximize vertical tracks in the SSD

Testing of a new R&D station concept (MARTA)

MARTA **commissioning completed** @ PM station

RPC performance above expectations

Issues with **inter-detector sync** is currently limiting the exploration of shower physics events

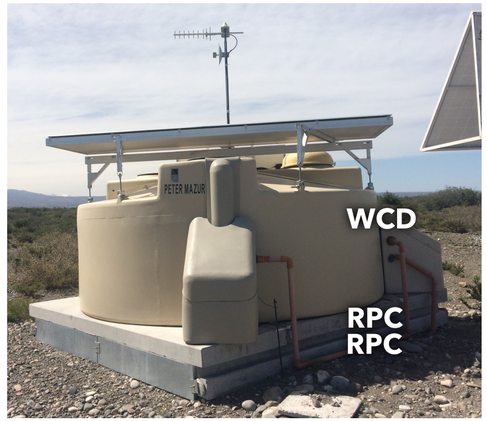
Plans to explore **sealed RPC** technology @ PM station
(synergy with SWGO activities)

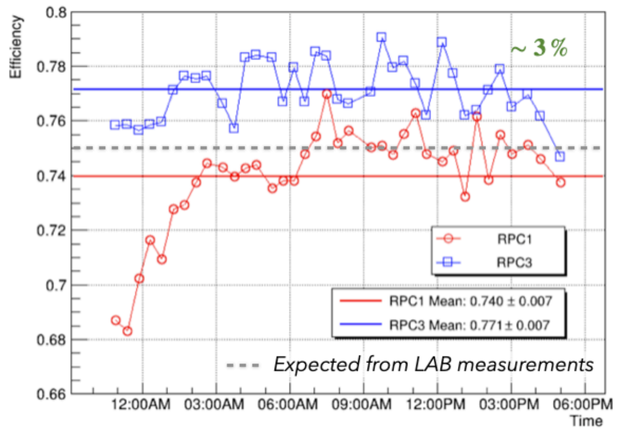
Key measurement for the upgrade

Gas and electronics issues impacted during RPC moving operation

Necessary to identify problems and implement practical fixes

Limited funding → mostly remote operations, minimal on-site support





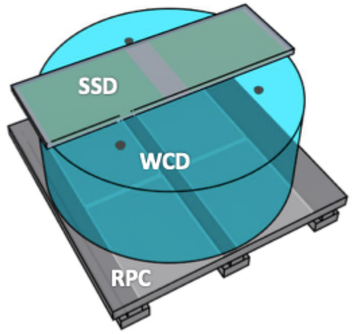
EAS pheno: EAS particles energy spectrum

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

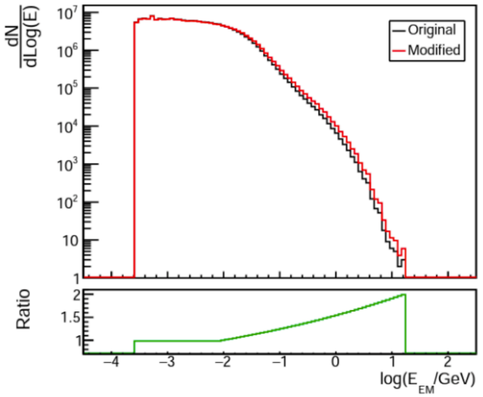
Analysis of MARTA (WCD+RPC) +SSD data

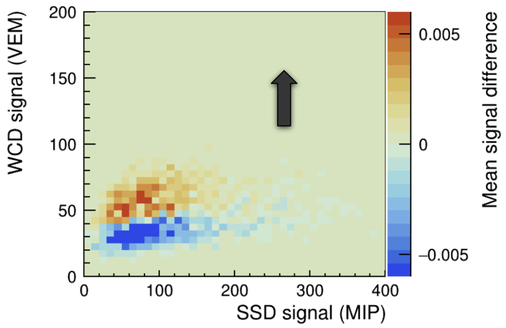
Shower particles are crossing multiple detectors that respond differently to particle type and energy

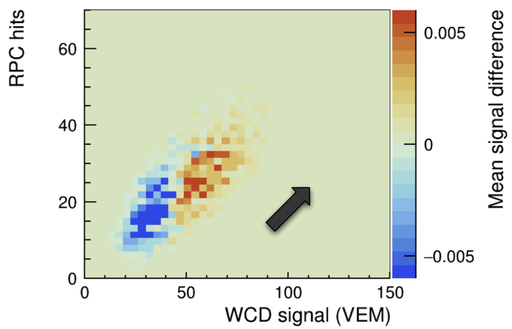
(P. Assis et al, **JCAP 10 (2025) 097**)



MARTA-SSD Station



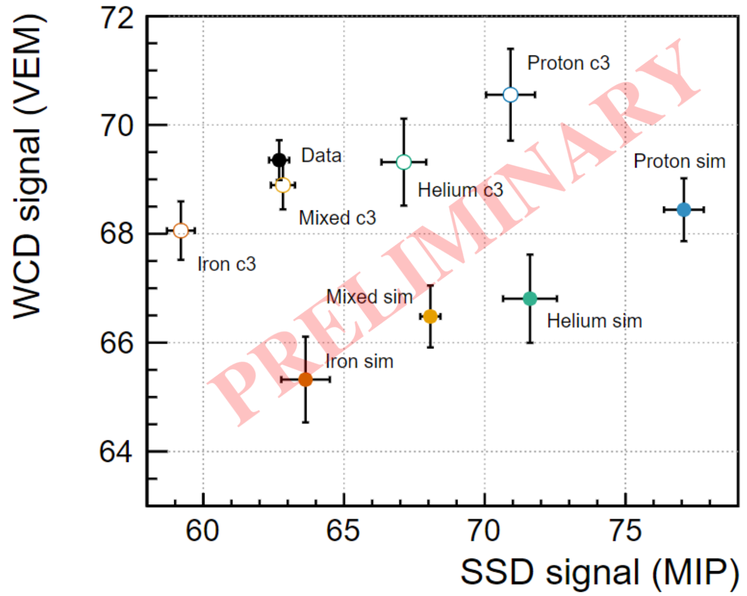




Preliminary results allows us to explore impact of systematic uncertainties and detect potential SSD-related effects

Take advantage of Auger Prime (WCD + SSD)

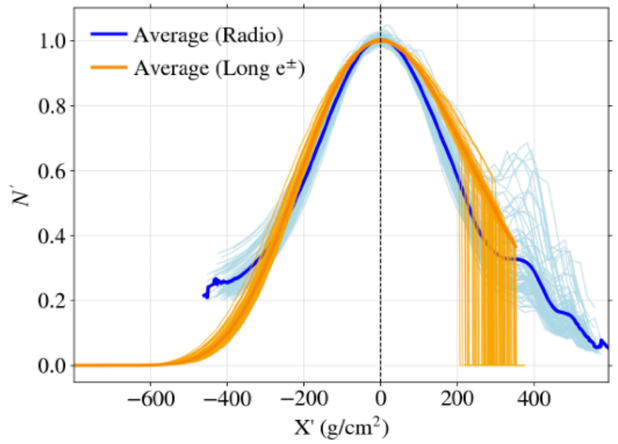
(on-going analysis)



From Radio Profiles to Muon Slopes: New Probes of EAS Physics

Average universal shower profile reconstruction using radio interferometry

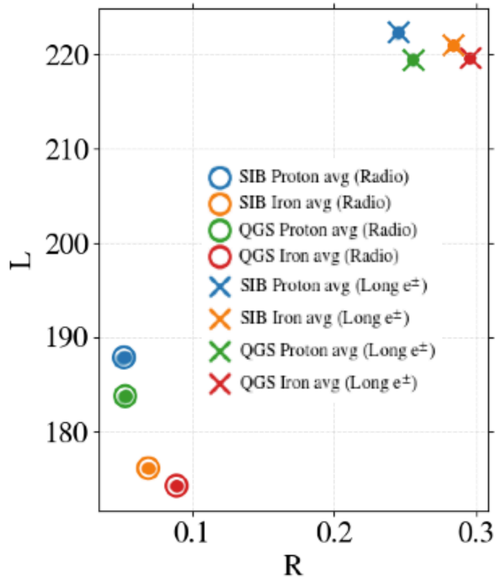
J. Alvarez-Muñiz, W. Carvalho, R. Conceição, **D. Dias**



First demonstration that the average USP can be reconstructed with a radio array

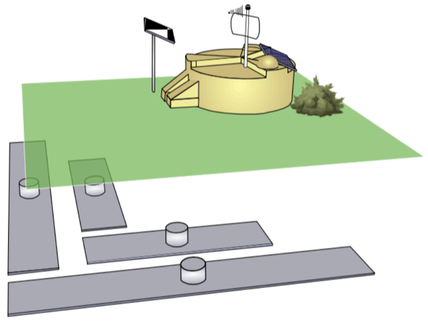
Enhanced sensitivity to primary mass composition and hadronic interaction models

Manuscript ready and about to be submitted for publication

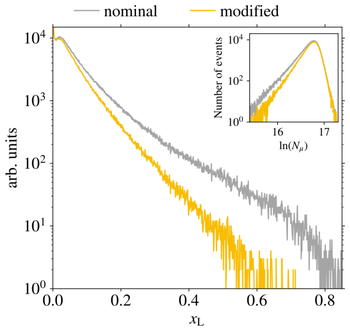


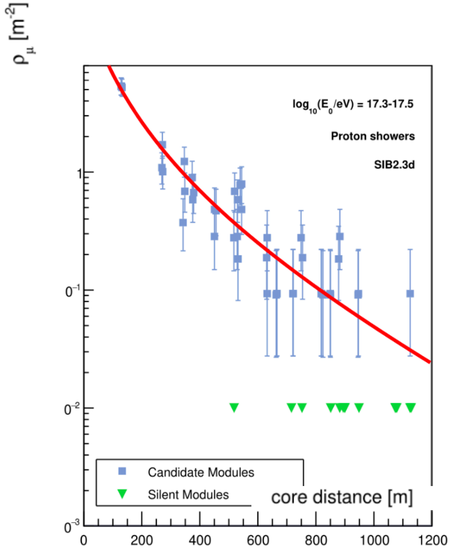
Measurement of the slope of muon number distribution, Λ_μ, through AMIGA data at LHC equivalent energies

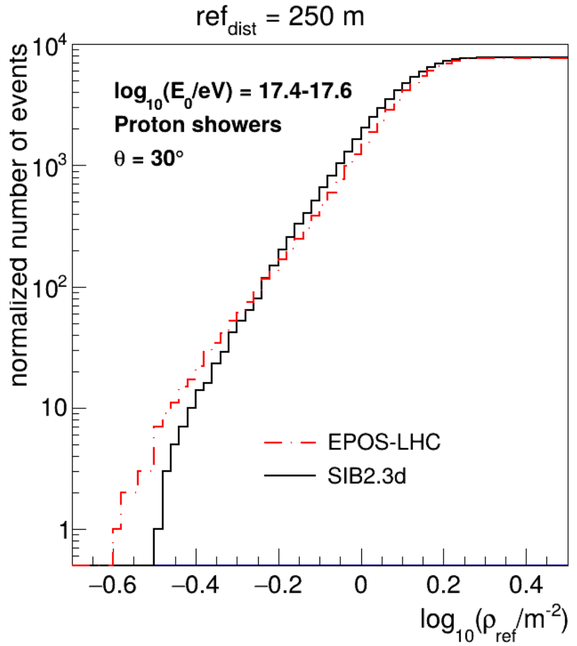
[A. Fernandes PhD (to be completed in 2026)]



Access the UHE first interaction π^0 energy spectrum



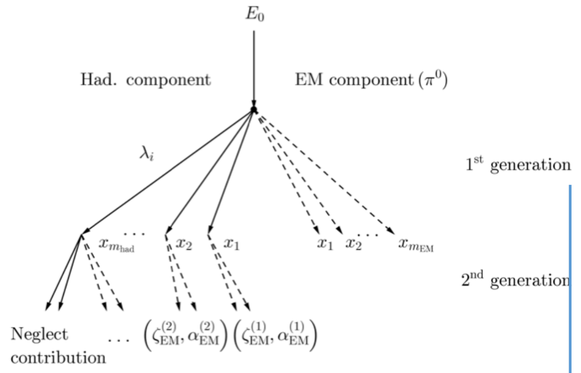




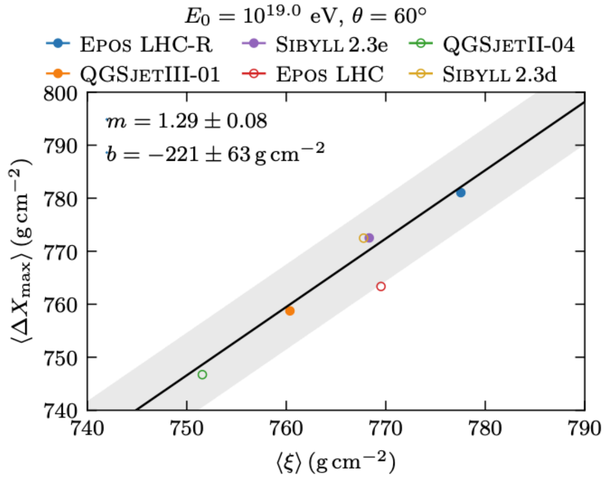
A New Framework to Access First-Interaction Physics

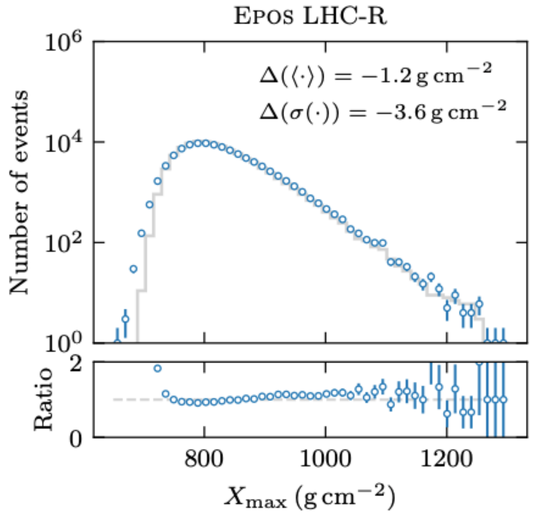
Probabilistic mapping between multiparticle production variables and the depth of maximum in proton-induced extensive air showers

L. Cazon, R. Conceição, M. Martins, F. Riehn
Phys.Rev.D 112 (2025) 4, 043016



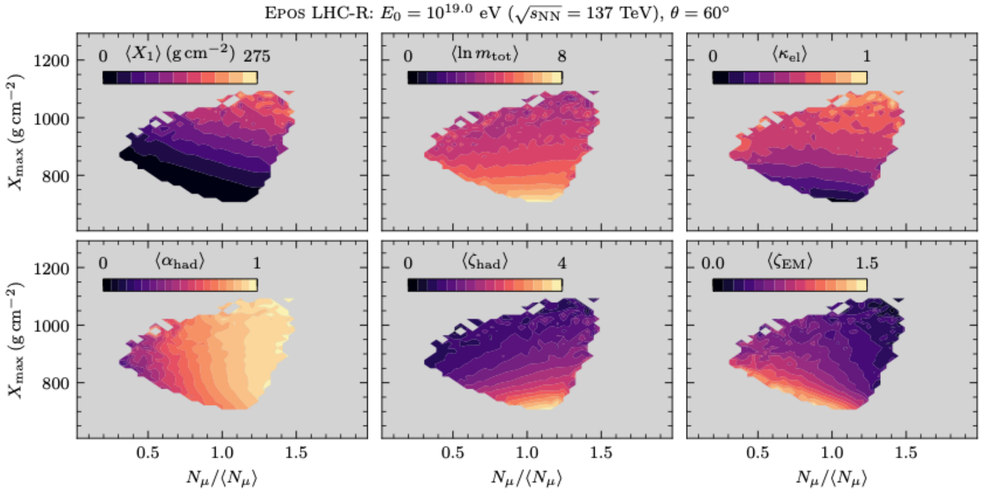
$$\xi = \xi_0 - A(\omega)\,\alpha_{\rm had} - \lambda_r\,(\omega\,\zeta_{\rm had} + \zeta_{\rm EM})$$





Forward hadron production in proton-air collisions above LHC energies through the fluctuations of extensive air showers

L. Cazon, R. Conceição, M. Martins, F. Riehn – submitted to PRL



$$(\xi, \alpha_1) \quad \rightarrow \quad (X_{\rm max}, N_\mu)$$

First interaction properties ⟷ **Shower Observables**

Searches for neutral particles

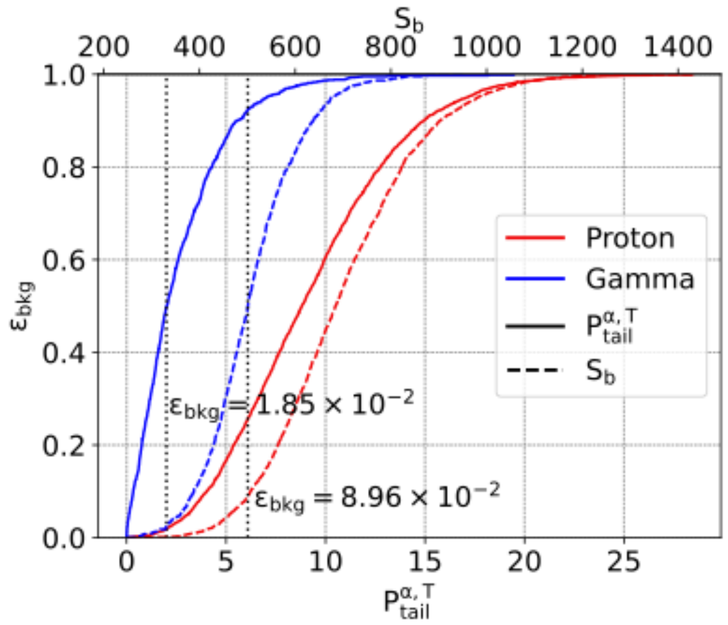
Enhancing the Observatory multi-messenger capabilities

Photons

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

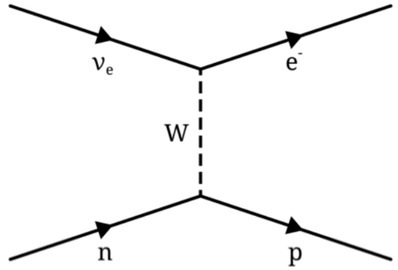
(P. Costa et al., arXiv: 2602.12167)

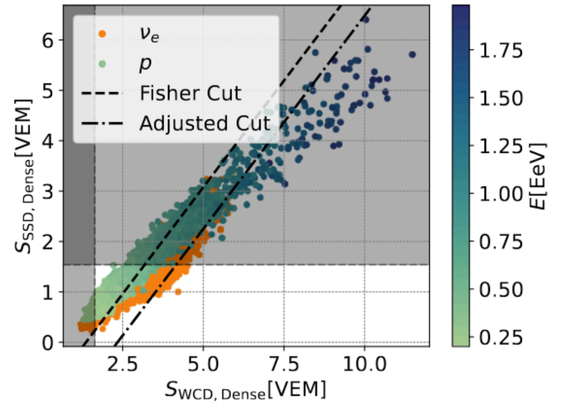
Achieves a fivefold improvement over previous discriminators (S_b) using only WCD stations [100% duty cycle]

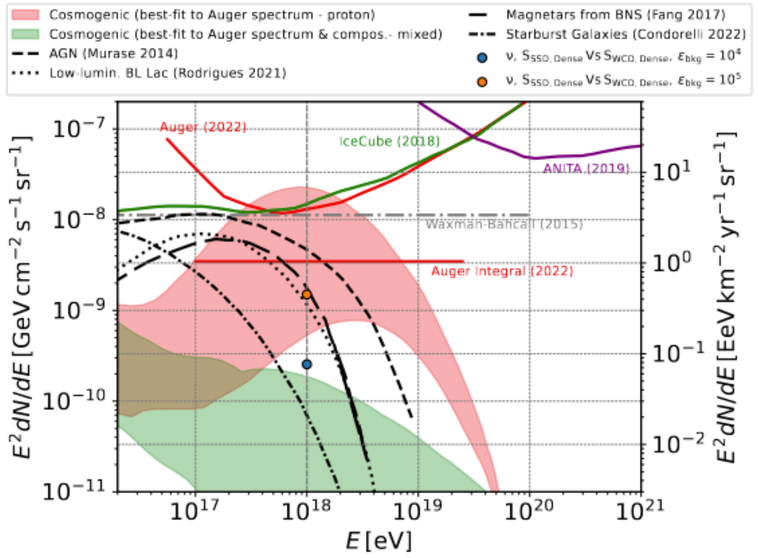


Neutrinos

Explore new detectors to extend **neutrino searches to all zenith angles** and not only for Earth-skimming events

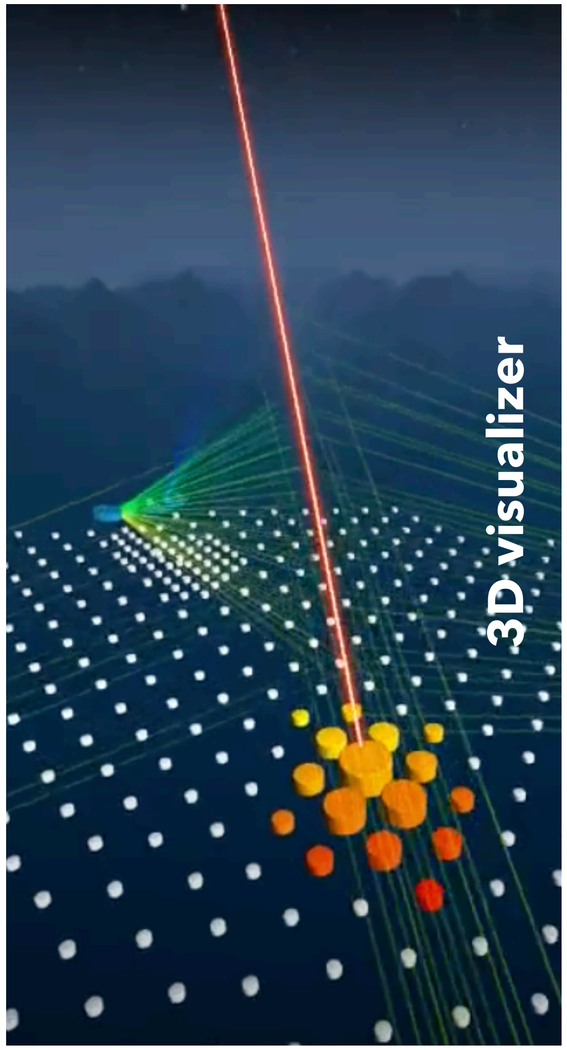




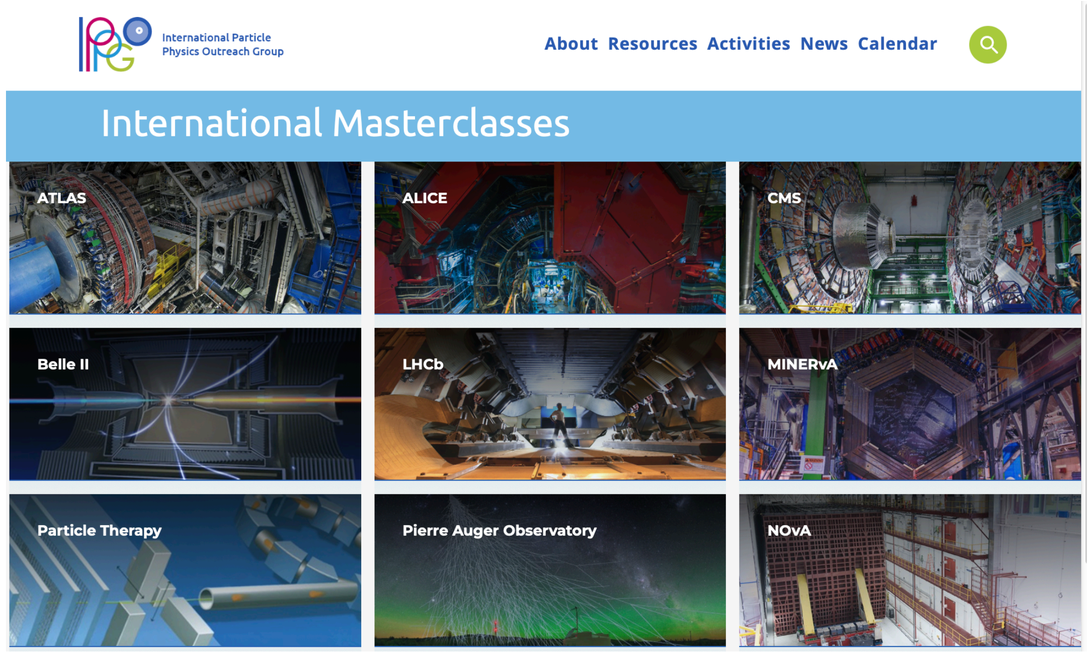


P. Costa, et al. Article ready to be submitted for publication

Outreach activities



Auger Masterclasses at	IMC 2023	IMC 2024	IMC 2025	IMC 2026
Events	3	5	6	8
Continents	2	4	4	3
Countries	5	10	12	14
Institutions	12	16	21	30
Institutions within Auger	10	10	10	14
Institutions outside Auger	2	6	11	16
Students	550	534	660	1280



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

Balance + immediate future

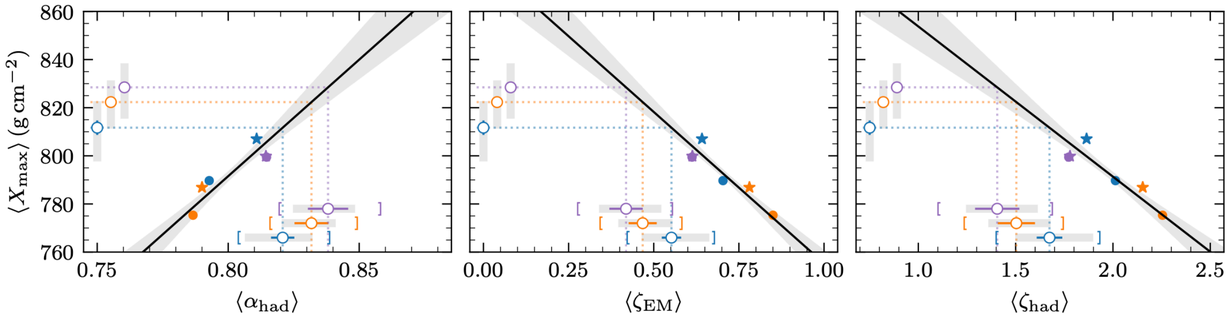
- 17 papers in 2025
  (**8 direct** + 9 indirect)
  - *Strong impact in the community*

- Key milestone: SSD MIP calibration for AugerPrime
- 2 PhD theses to be finalized
- Future Auger PRL publication from the Auger (LIP) team
- Strong involvement in AugerPrime
  - Workshop co-organized between LIP and FZU (Prague)
- Increasing synergistic relations with FZU group

Proton-air interaction properties at $\sqrt{s} \sim 100$ TeV from shower-depth measurements with the Pierre Auger Observatory and connection with the Muon Puzzle

Pierre Auger Coll. – intended for PRL

$E_0 = 10^{18.7}$ eV, $\theta = 55°$



SWOT Analysis

Strength

Strong expertise in air-shower phenomenology, detector calibration, and RPC-based R&D, combined with **visible leadership roles** within the Pierre Auger Collaboration and sustained scientific output in high-impact journals.

Weakness

Very **limited mid-level manpower** and constrained operational **funding** relative to the breadth of activities, requiring careful prioritisation of tasks, travel, and fieldwork to maximise scientific return.

Opportunities

The **AugerPrime** upgrade and extended **operation until 2035** enable precision measurements of shower components, offering **unique opportunities** to address systematic uncertainties, hadronic interaction modeling, and the muon puzzle.

Threats

Strong **dependence on periodically renewed national funding schemes** introduces uncertainty for long-term planning and may limit the group's ability to fully exploit emerging opportunities during the AugerPrime era.

Acknowledgements

Fundação
para a Ciência
e a Tecnologia

REPÚBLICA
PORTUGUESA

TÉCNICO
UNIVERSIDADE
DE LISBOA

LIP

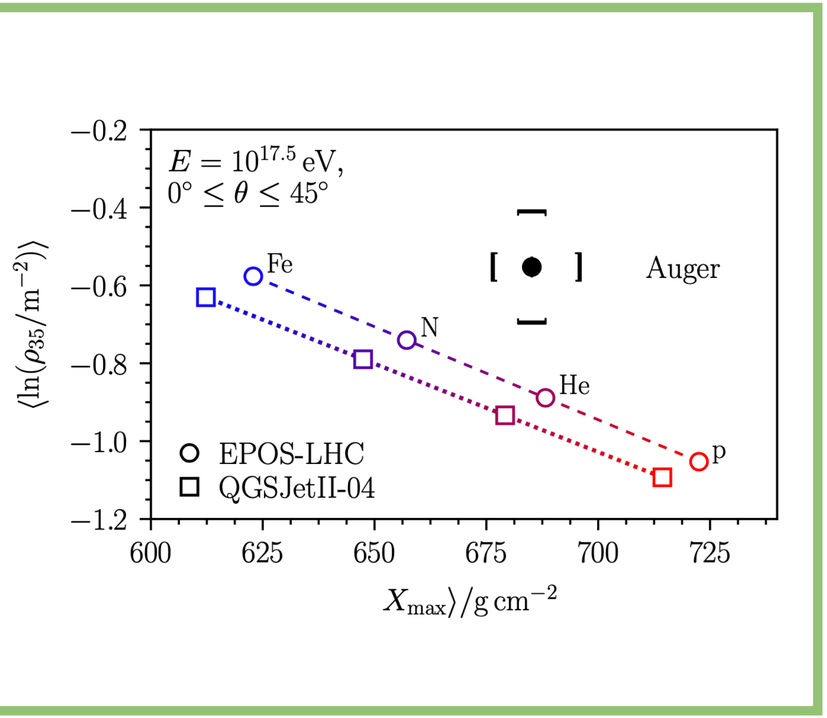
Backup Slides

The EAS muon puzzle @ Auger

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

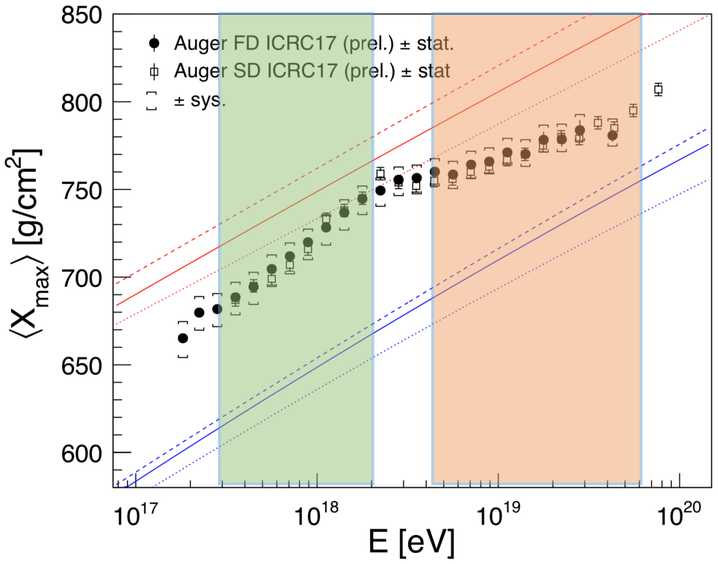
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

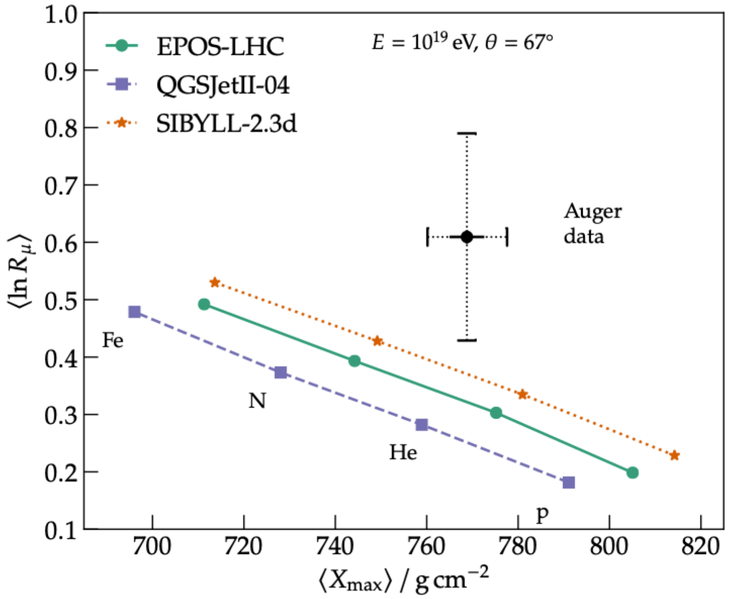
Phys.Rev.Lett. 126 (2021) 15, 152002



AMIGA

FD data





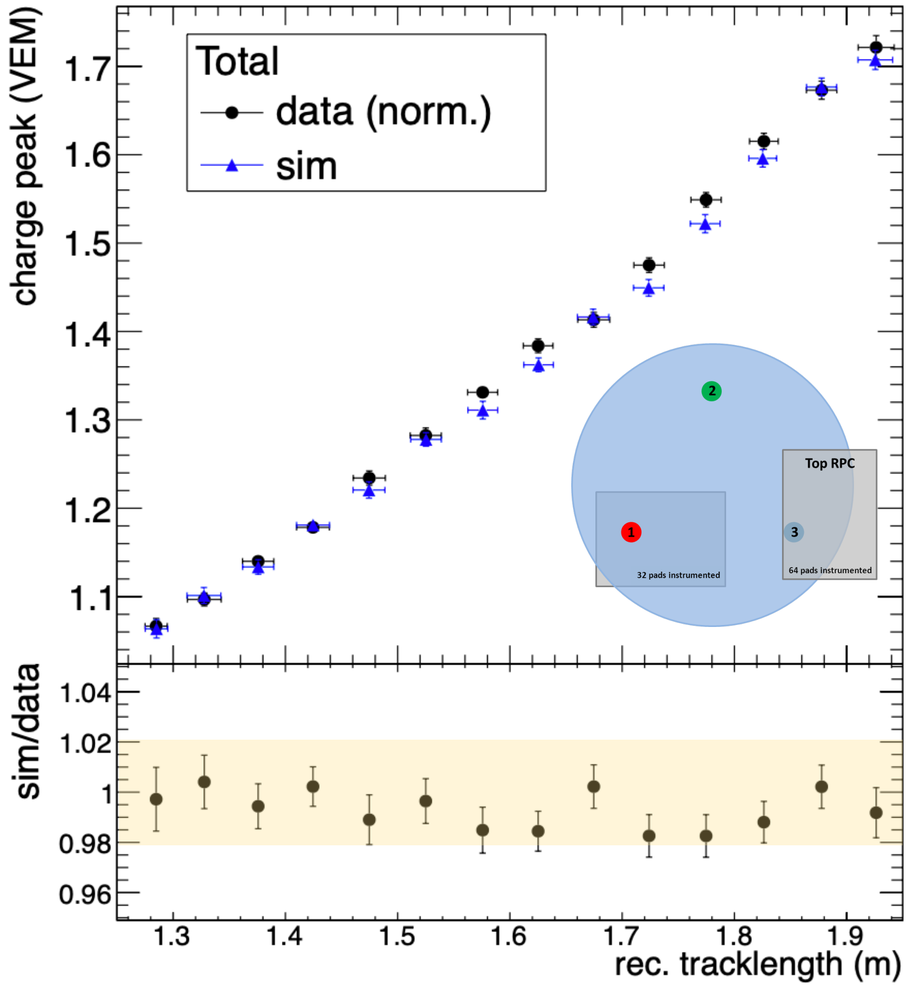
SD inclined

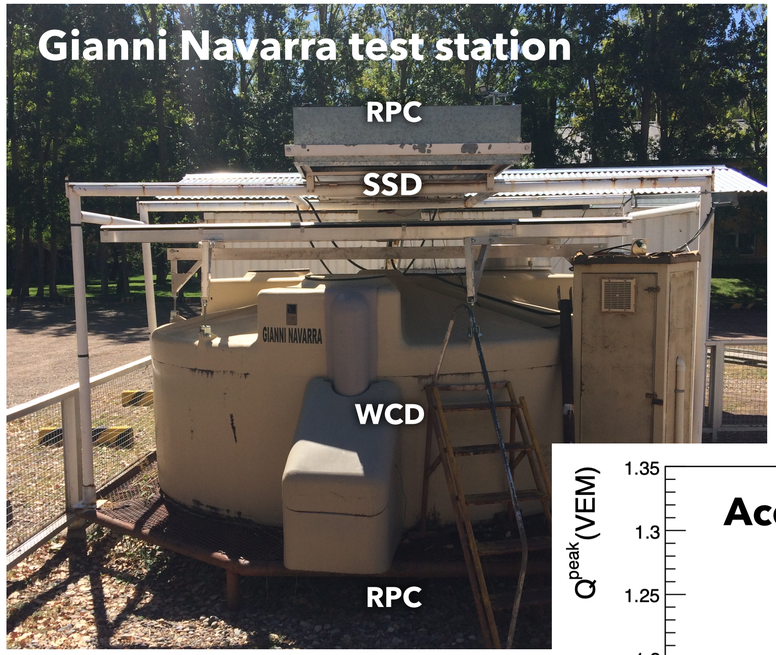
ruben@lip.pt

Calibration activities

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

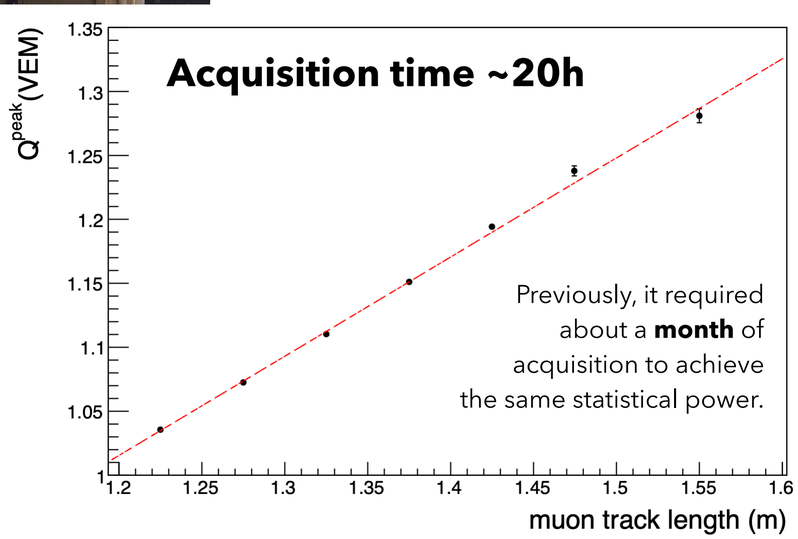
Pierre Auger coll., JINST 15 (2020) 09, P09002





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

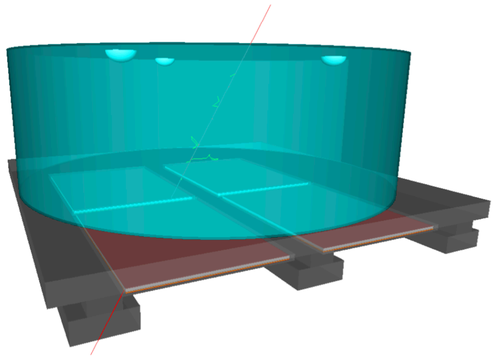


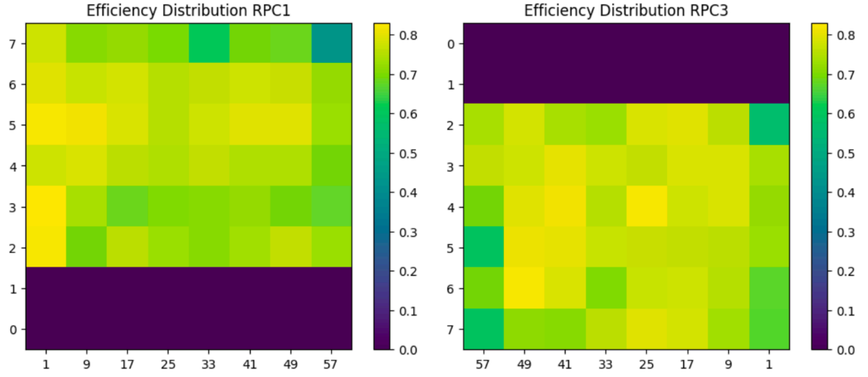
MARTA

Muon Array with RPCs for Tagging Air showers

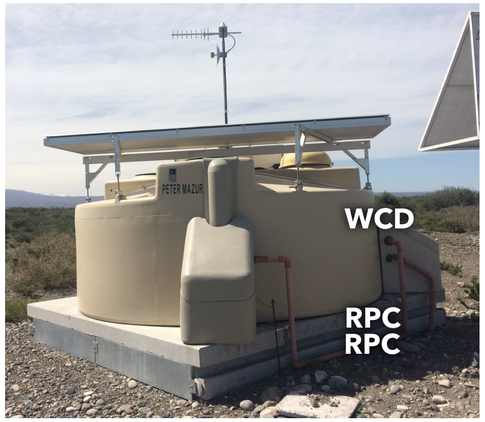
P. Assis, et al Eur.Phys.J.C 78 (2018) 4, 333

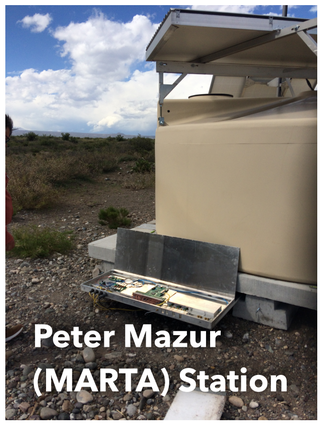
- Place Resistive Plate Chambers below the water Cherenkov tank to directly detect the shower muon component

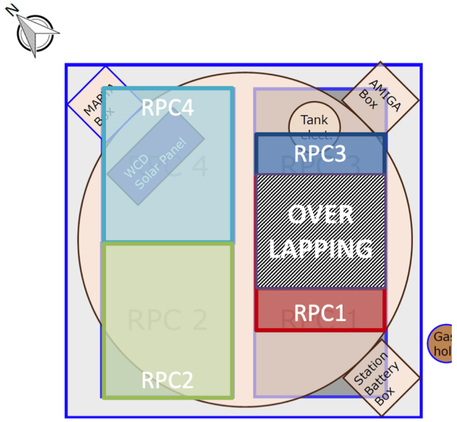


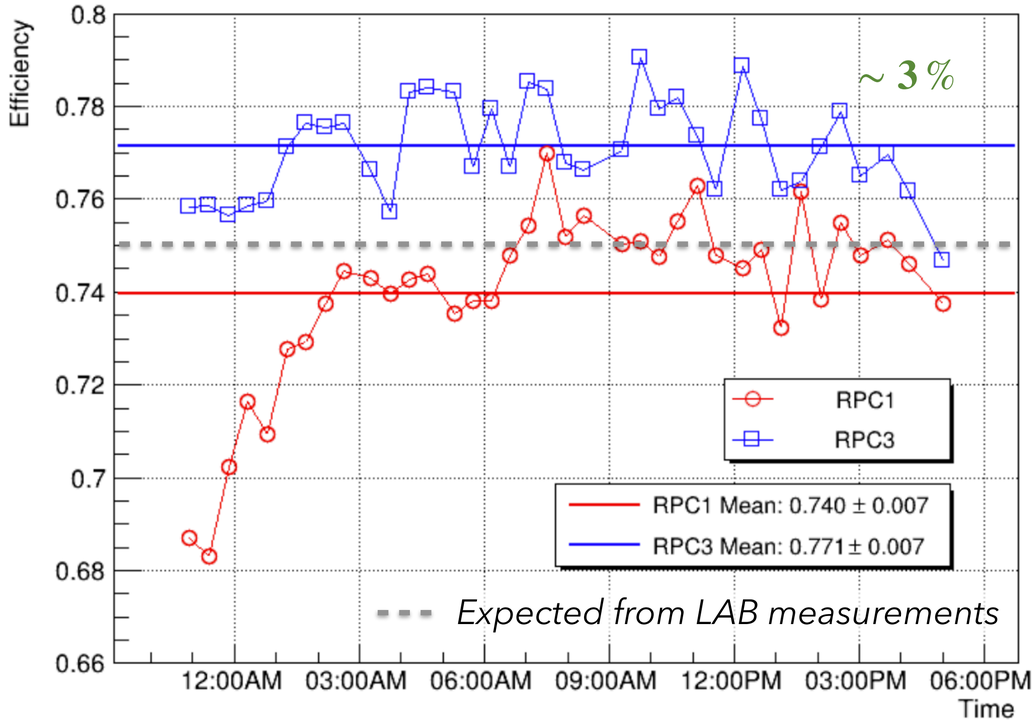


First MARTA station fully commissioned



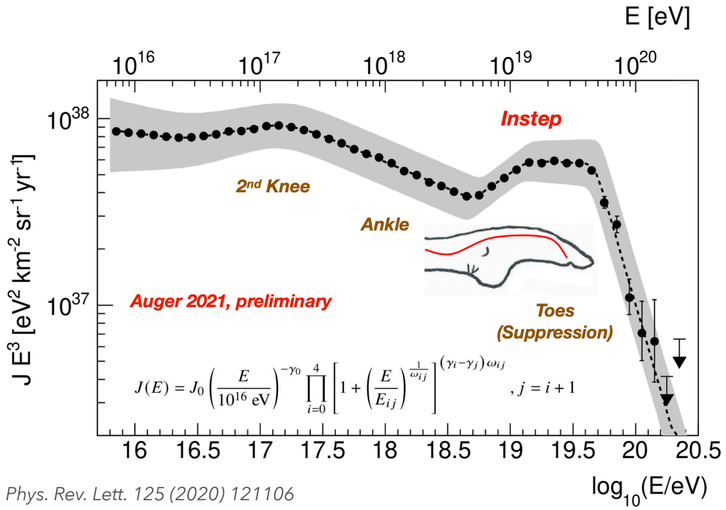






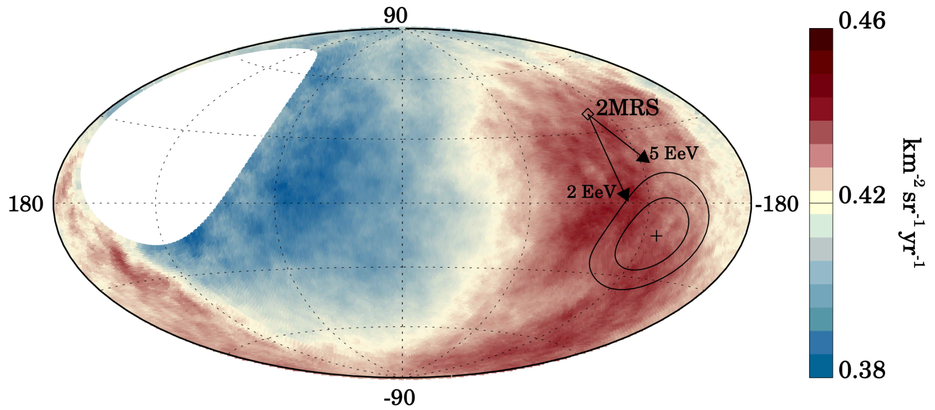
Pierre Auger collaboration results in a nutshell

UHECR energy spectrum features



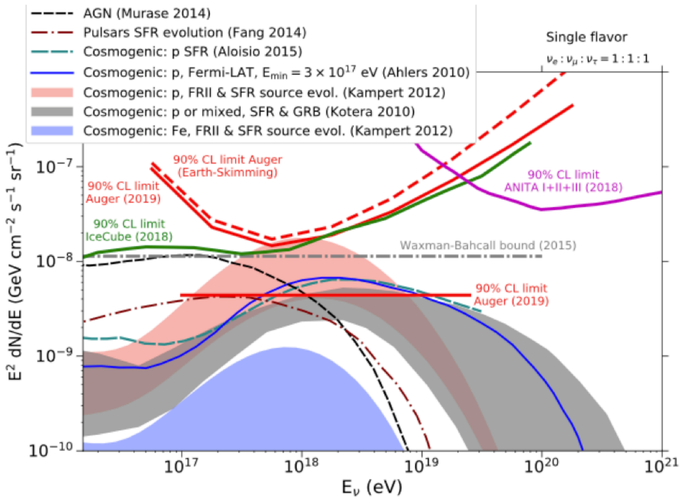
Phys. Rev. Lett. 125 (2020) 121106

UHECR have an extra-galactic origin



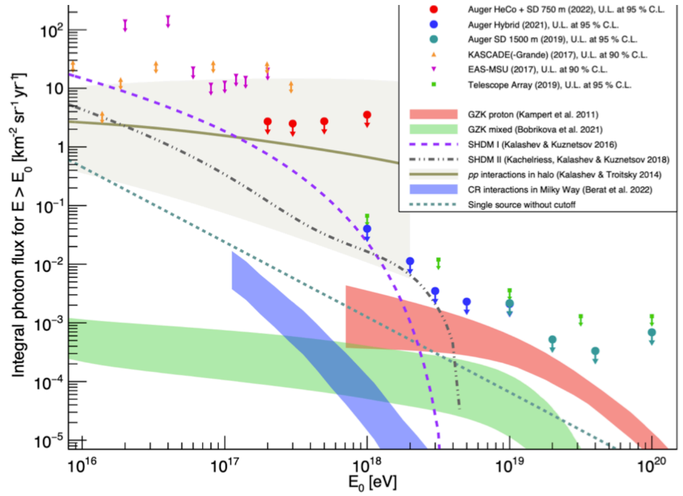
Science 357 (2017) 6537, 1266-1270

Stringent limits on UHE neutrinos



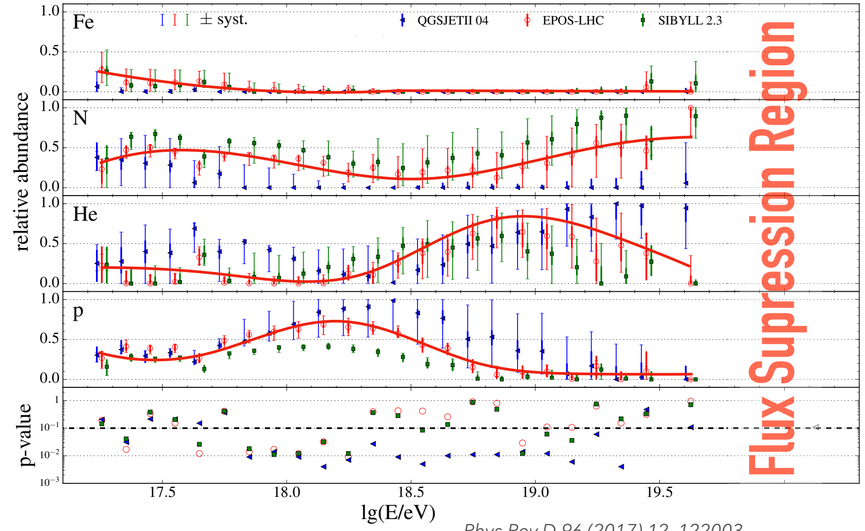
ApJ 902 (2020)105

Stringent limits on UHE photons



Astrophys.J. 933 (2022) 2, 125

Mass composition evolution towards heavier elements

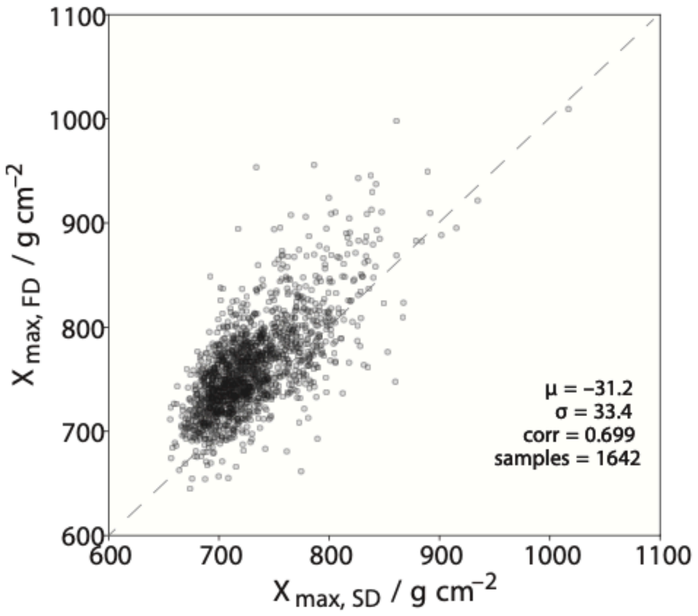


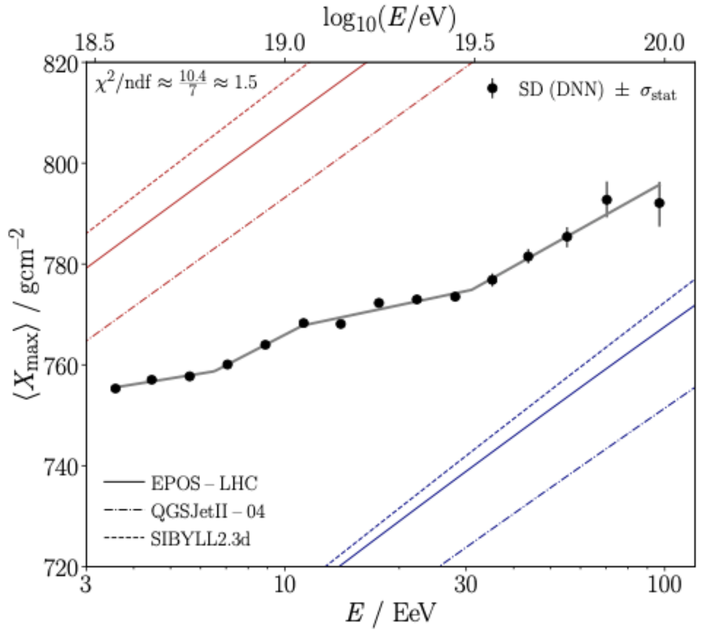
Phys.Rev.D 96 (2017) 12, 122003

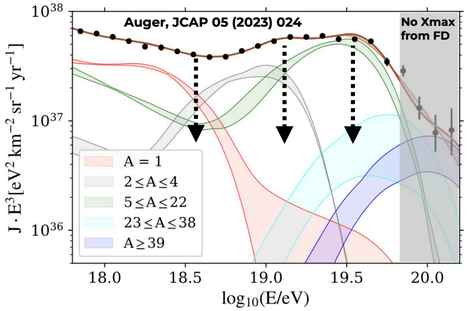
The rise of Machine Learning @ Auger

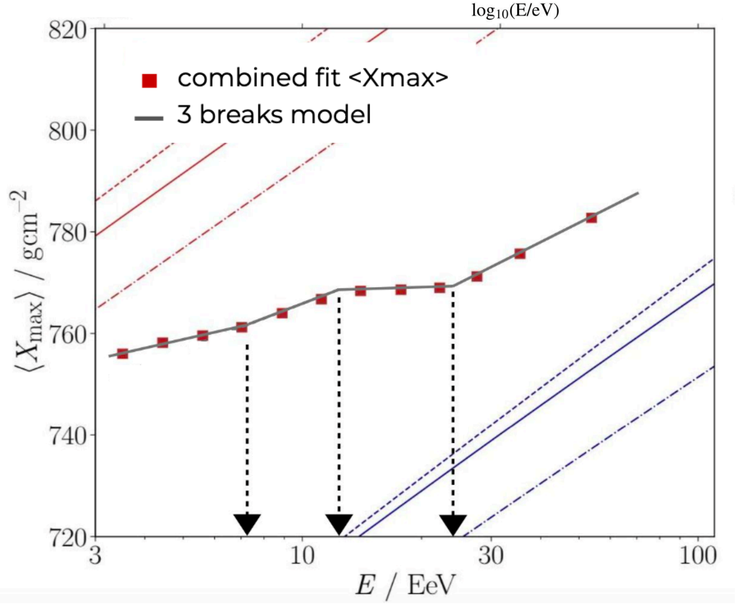
Extraction of Xmax from the SD ground signal

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





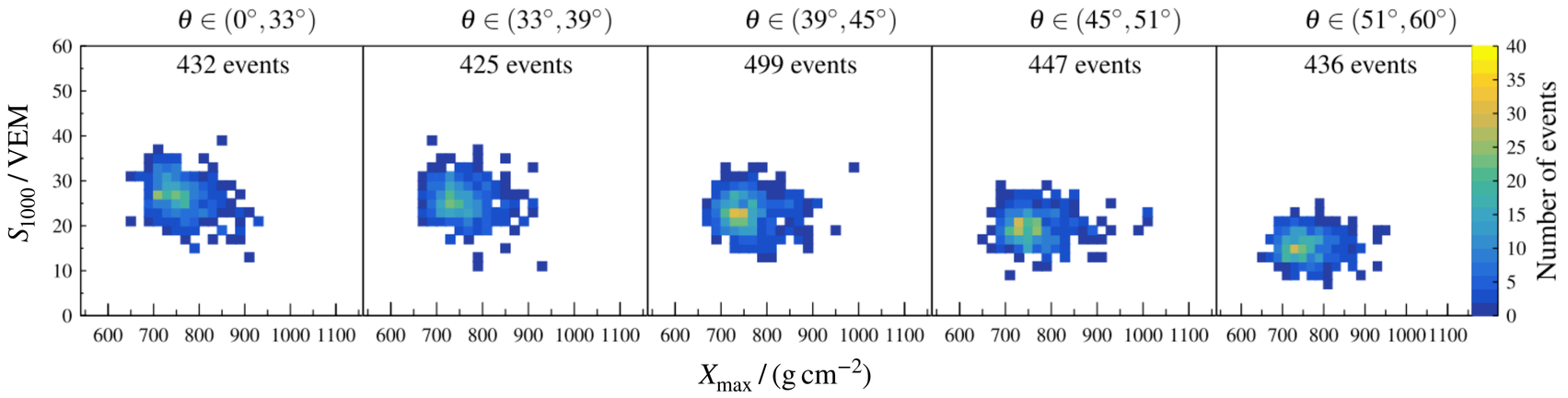




- **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- Algorithms highly **dependent of simulations** and might be picking up unknown less controlled shower characteristics
- **It is vital to control the Extensive Air Showers and detector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

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

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



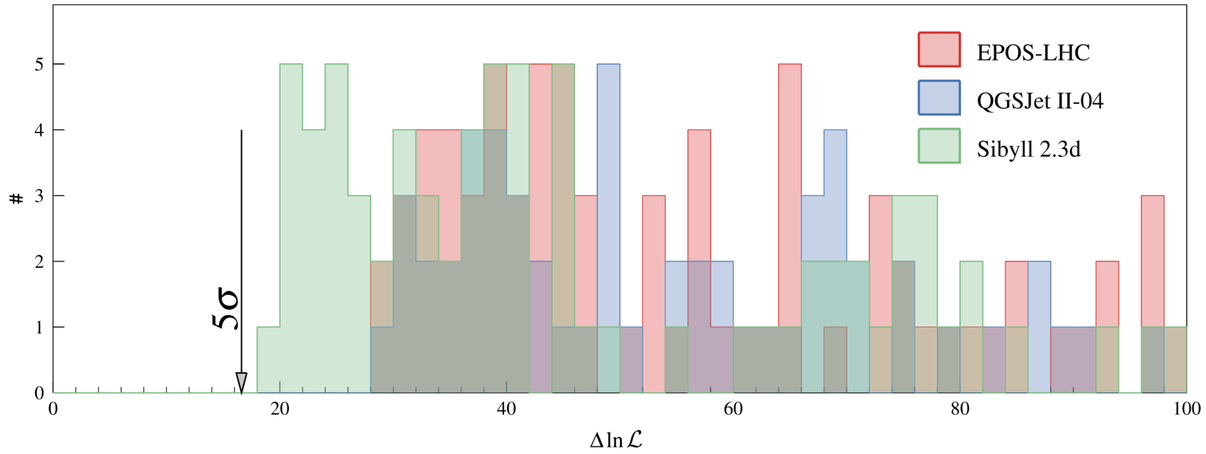
Systematic uncertainties

E − 14%

E + 14%

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

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



Systematic uncertainties

S(1000) − 5%

S(1000) + 5%

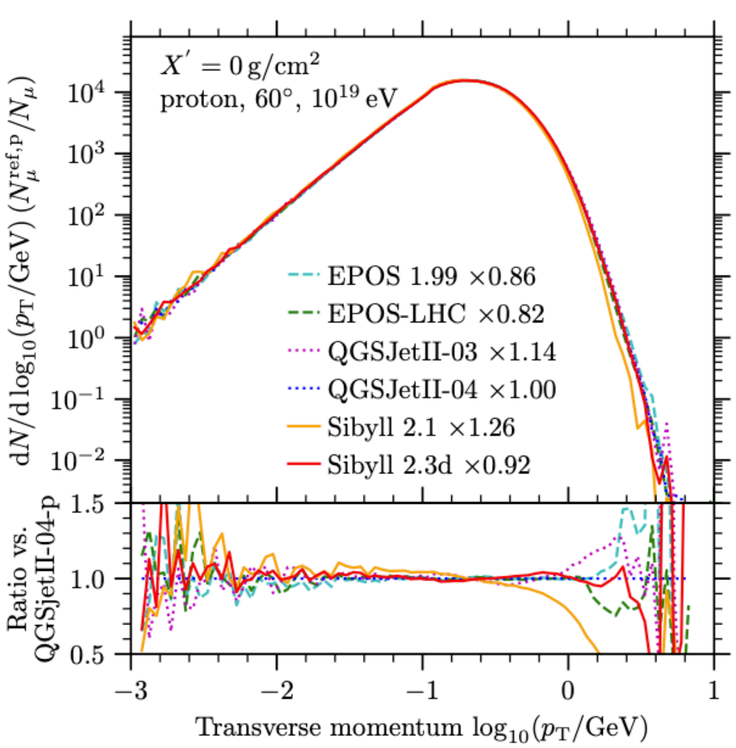
Method

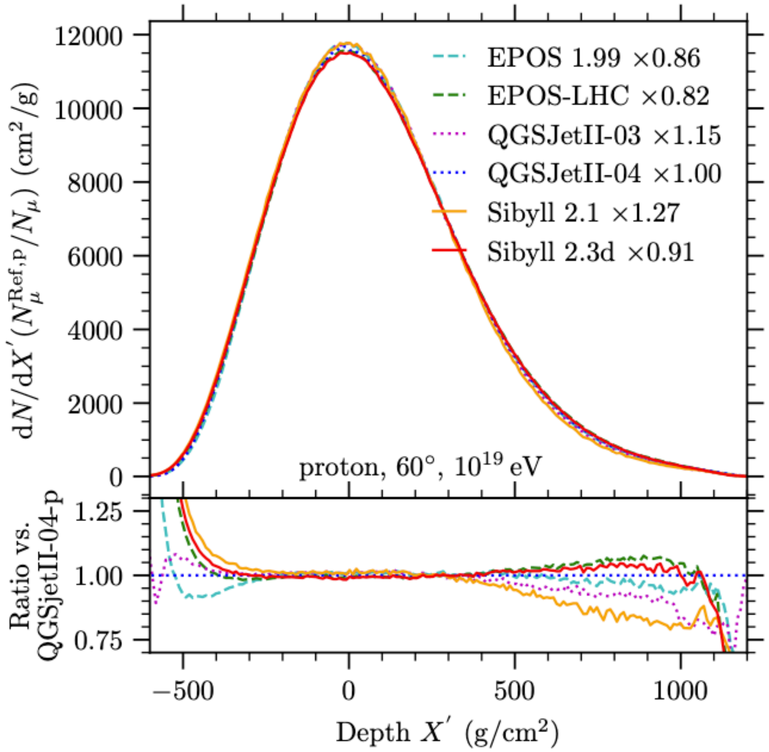
None of the **post-LHC tuned hadronic interaction models** can describe the Auger $(X_{\max}, S_{1000})$ data, even considering the systematic uncertainties - **Shift on muon and $X_{\max}$ scale needed?!**

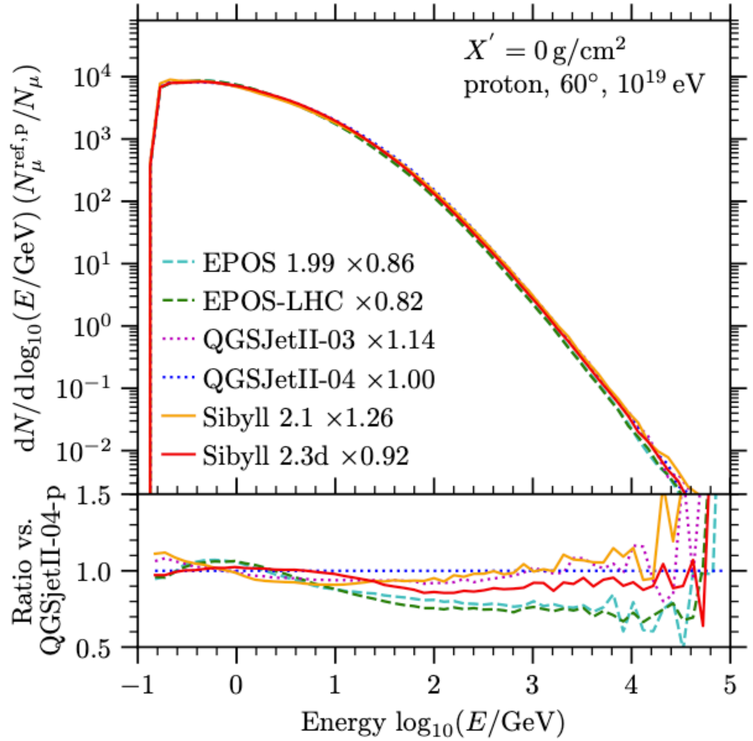
Universality of the muonic sector

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

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



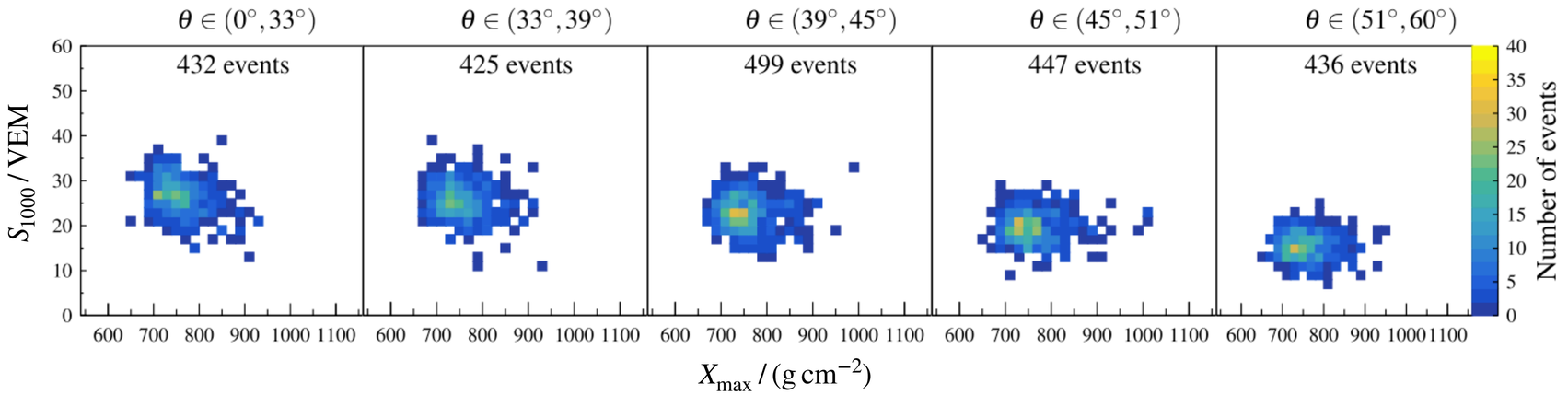




Most of these distributions are universal with the exception of the muon energy spectrum for $E_\mu > 1\,\mathrm{GeV}$

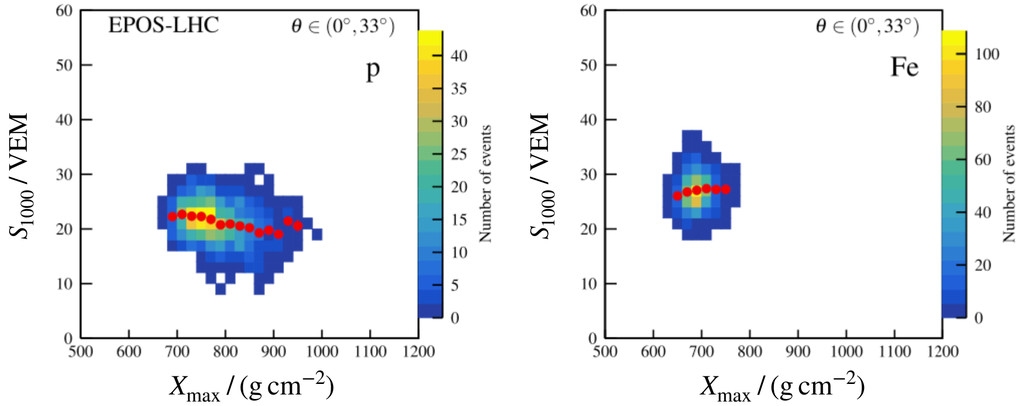
Analysis of the $(X_{\mathrm{max}}, S_{1000})$ distribution

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

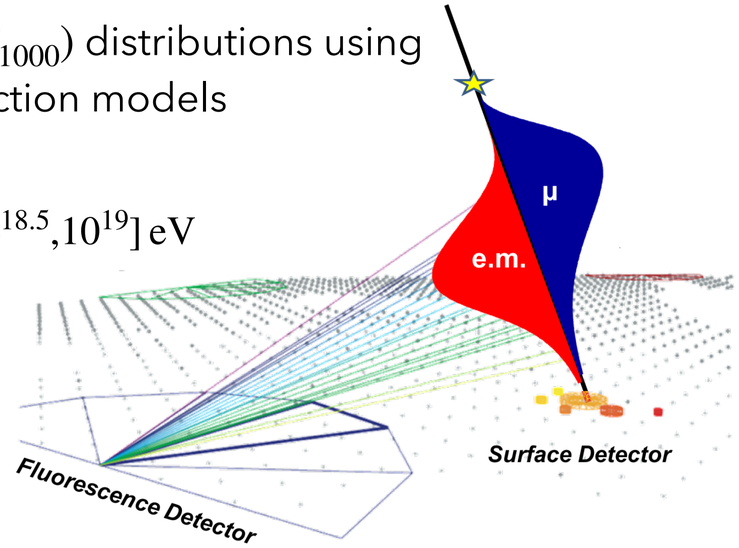


Explore hybrid FD-SD events and **fit the measured two-dimensional** $(X_{\mathrm{max}}, S_{1000})$ distributions using templates for simulated air showers produced with hadronic interaction models

Example of MC templates



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



Muon puzzle

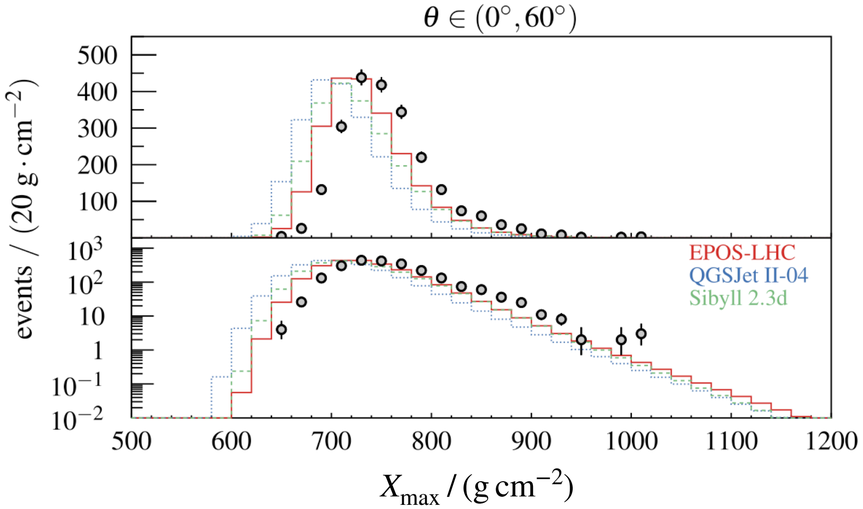
Phys.Rev.D 109 (2024) 10, 102001

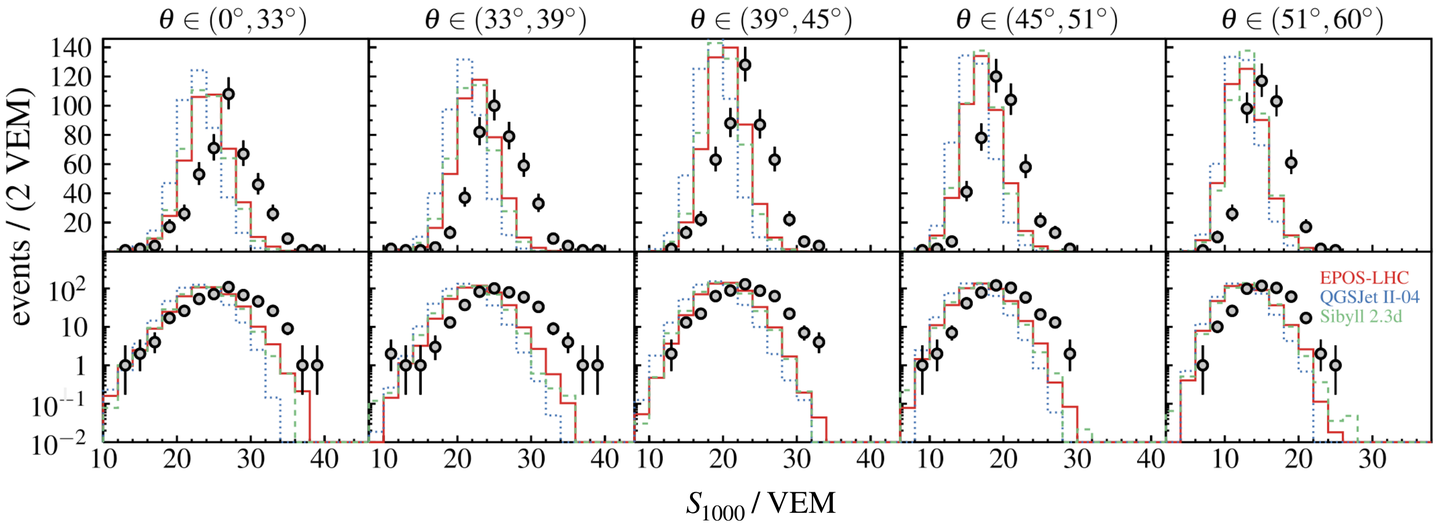
Allow for a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}

$R_{\mathrm{had}} > 1$ **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

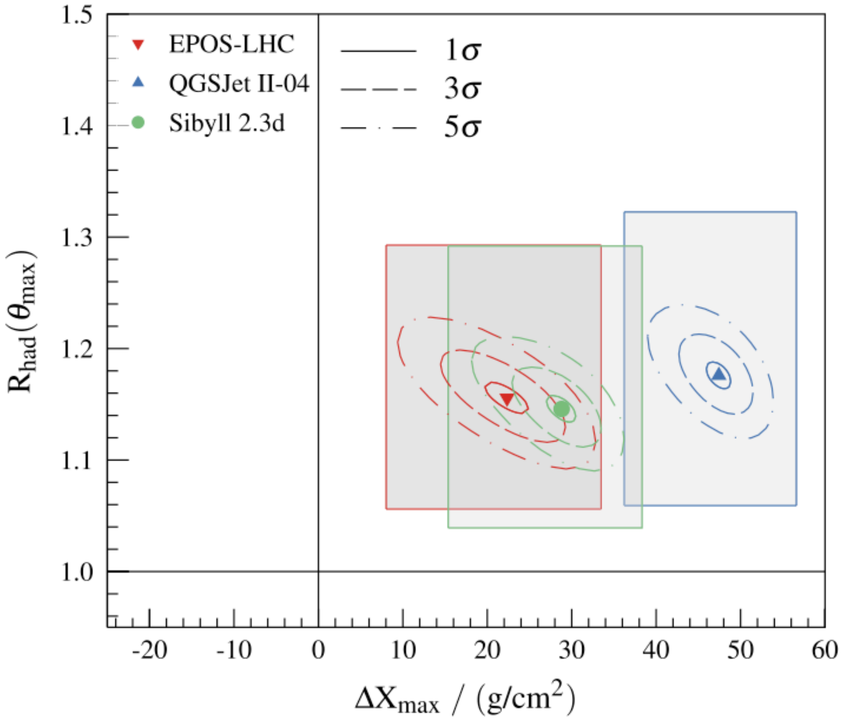


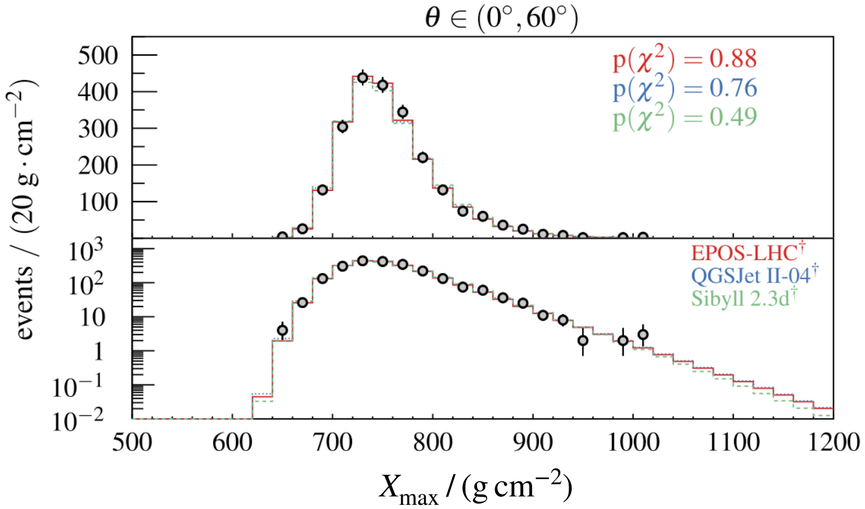


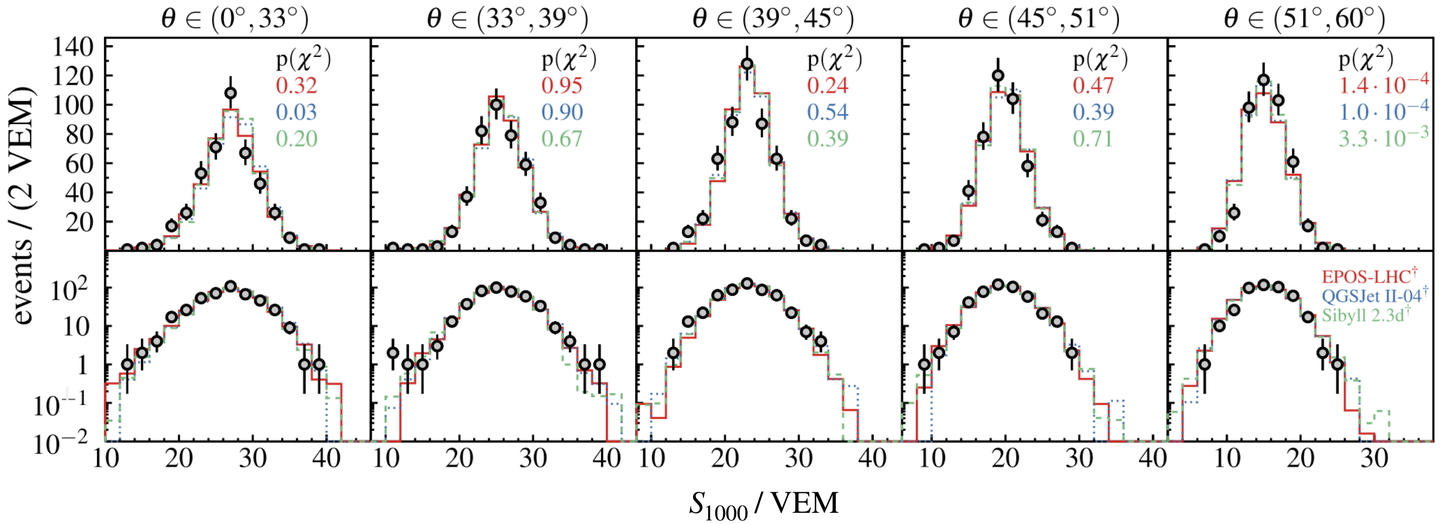
Muon puzzle + Shift in X_{max} scale

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}

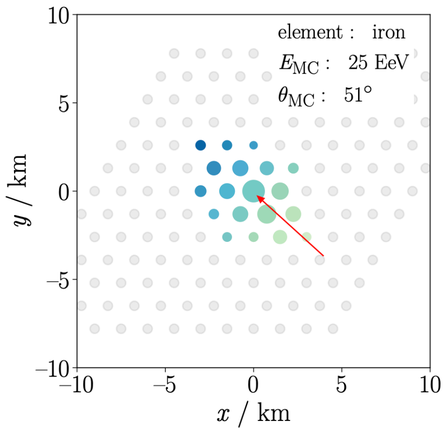


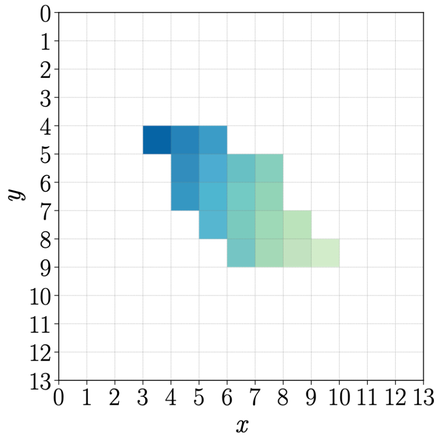


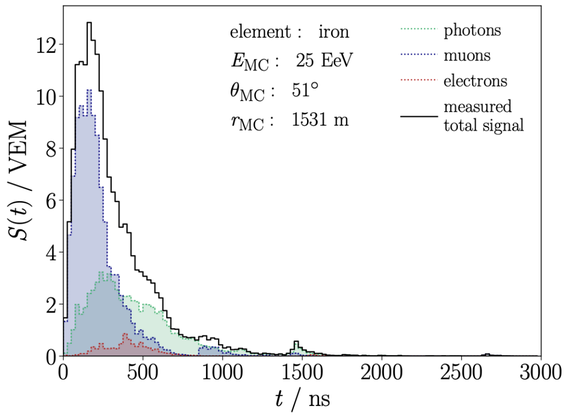


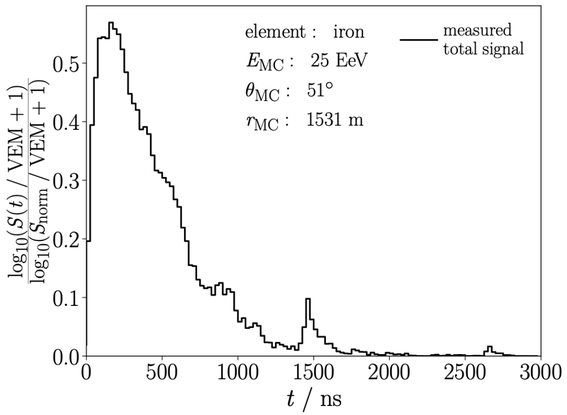
X_{max} from SD trace using a DNN

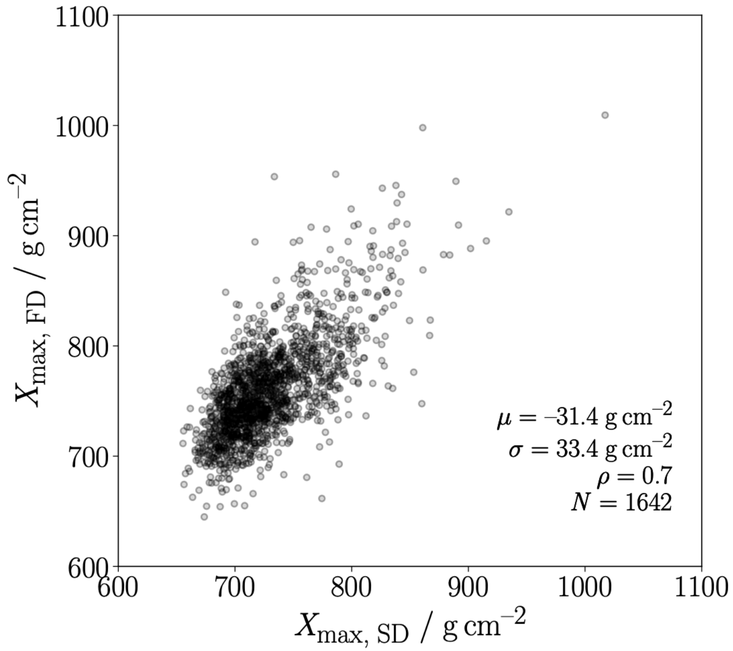
Pierre Auger coll., Phys.Rev.Lett. 134 (2025) 2, 021001 & Phys.Rev.D 111 (2025) 2, 022003







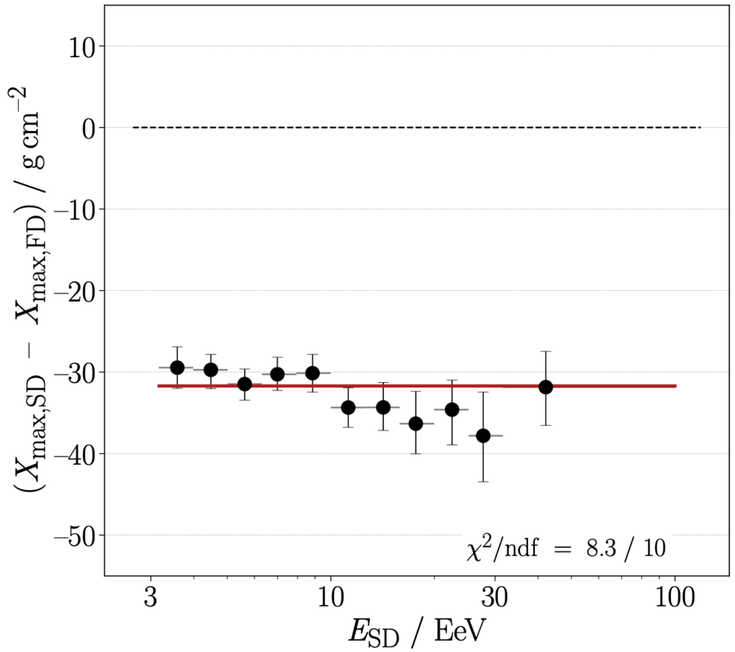




Extract the X_{max} from SD-only events

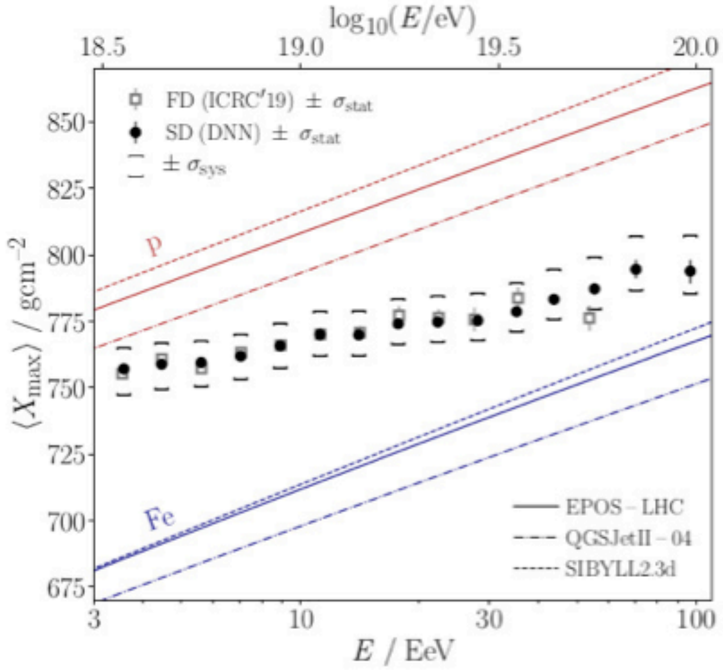
Exploit the SD traces using a Deep Neural Network

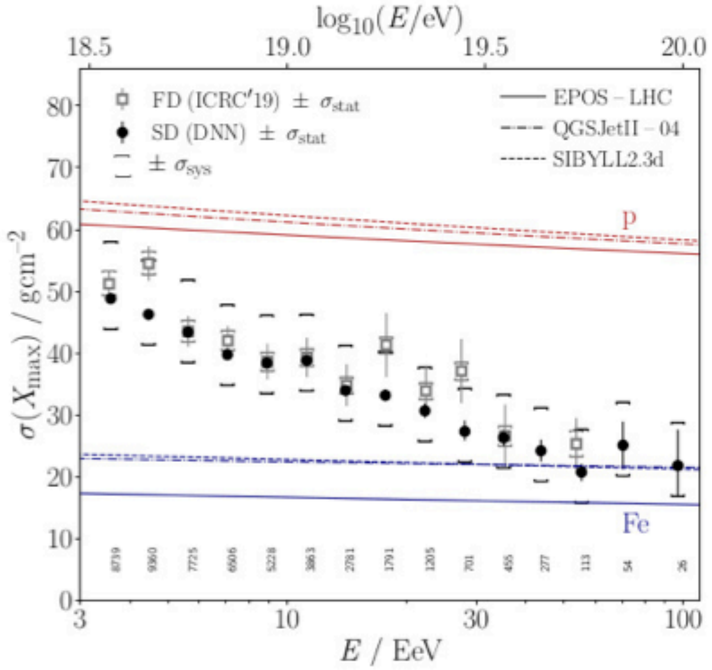
Test DNN performance using FD-SD **hybrid events**

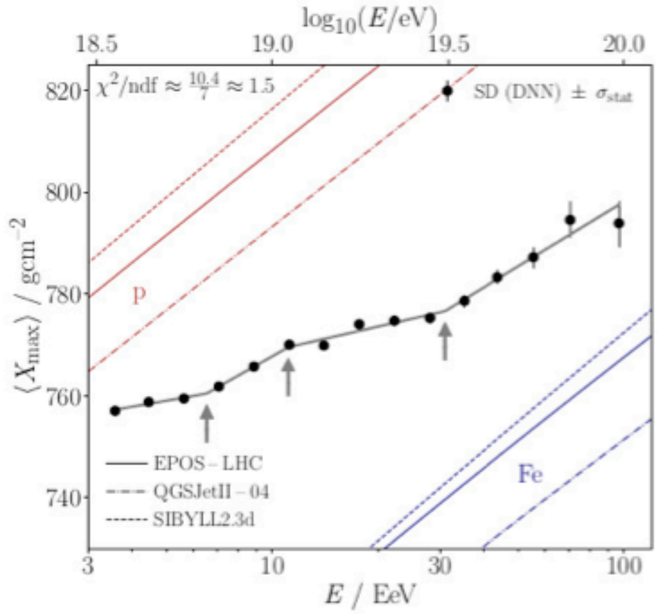


Machine Learning - X_{max} from DNNs

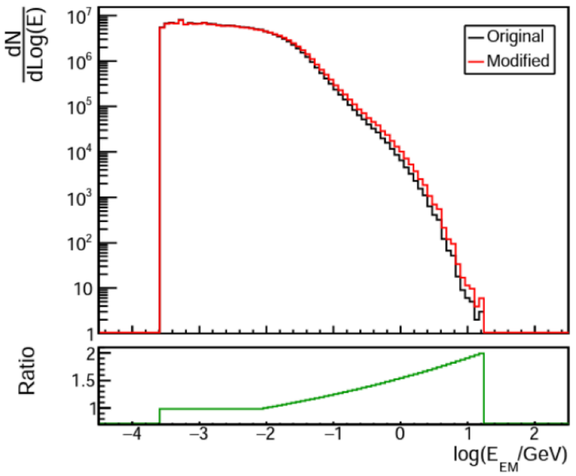
Pierre Auger coll., Phys.Rev.Lett. 134 (2025) 2, 021001 & Phys.Rev.D 111 (2025) 2, 022003

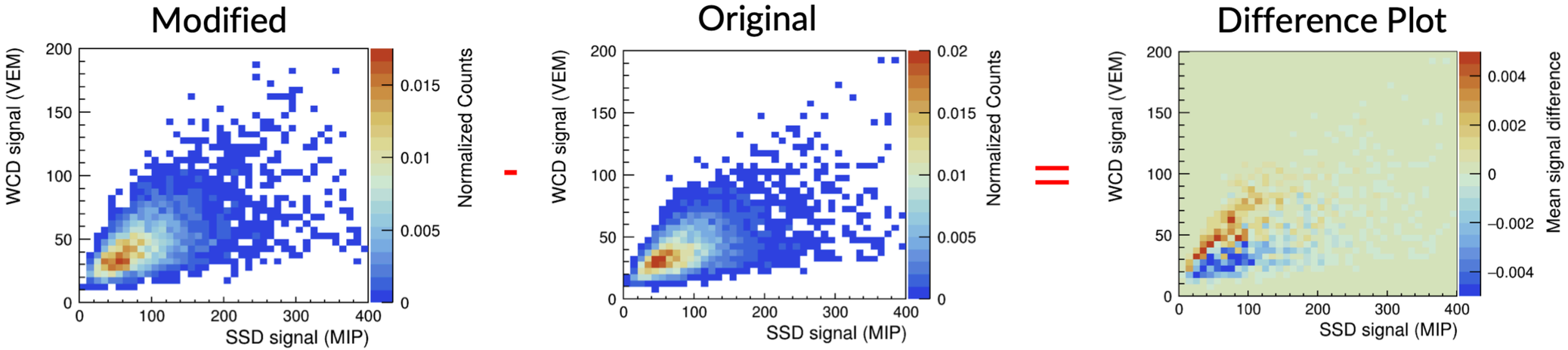






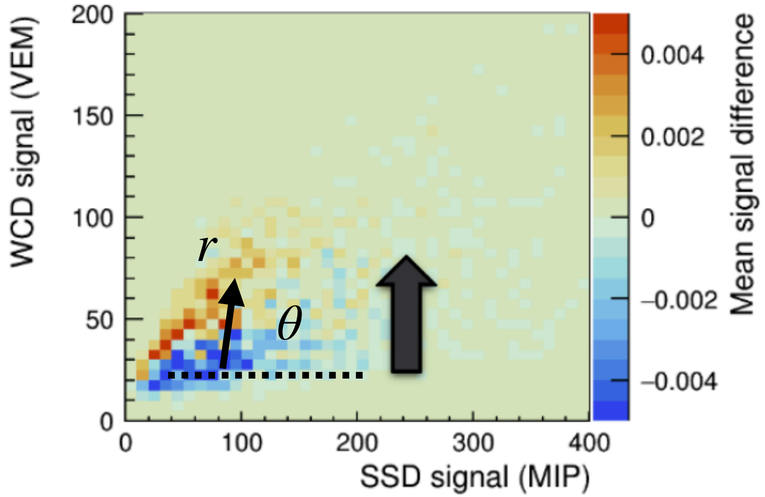
SSD+MARTA - E_{em} extraction

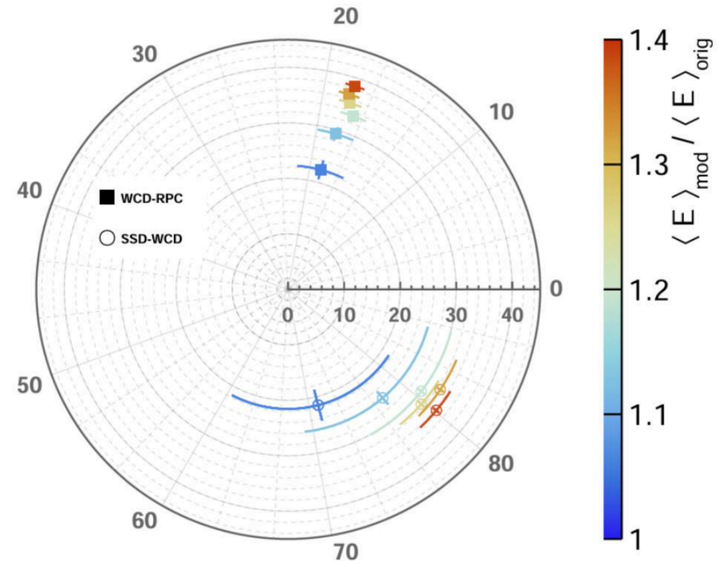


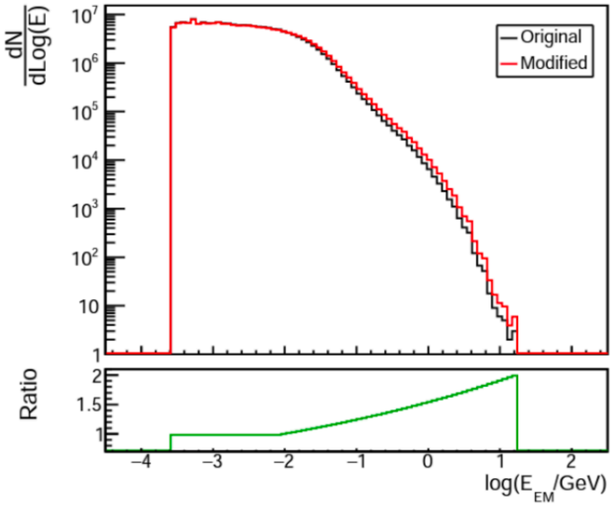


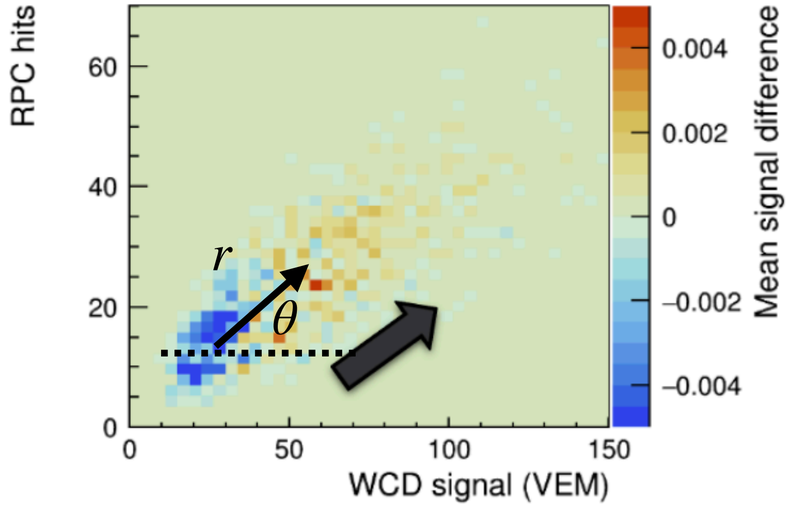
Sensitivity of a MARTA-SSD station to EAS energy Spectrum

MARTA-SSD Station







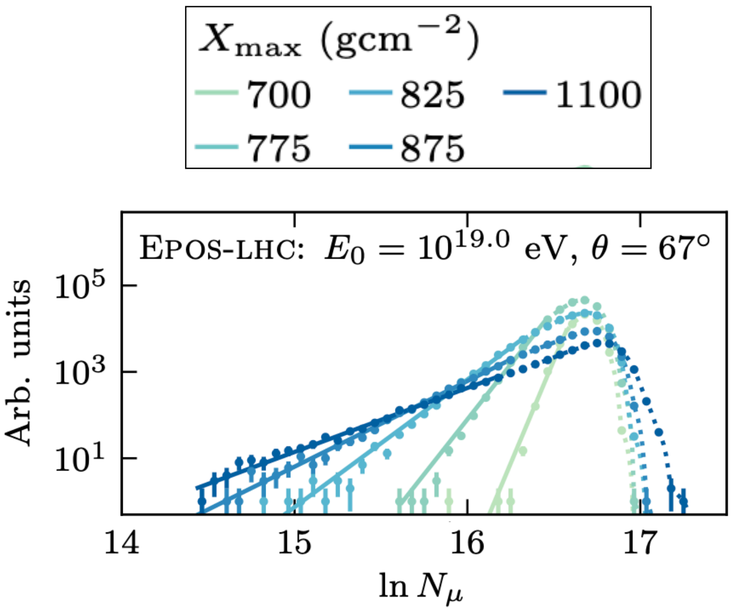


- **Measurement of high-energy e.m. and low-energy muon tail**
- Possibility to perform this measurement with ~ 1 year of data and a single station
- Measurement resilient to experimental conditions:
  - core, primary energy and inclination, shower multiplicity, detector aging effects
- SAL paper to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

Accessing the first interaction

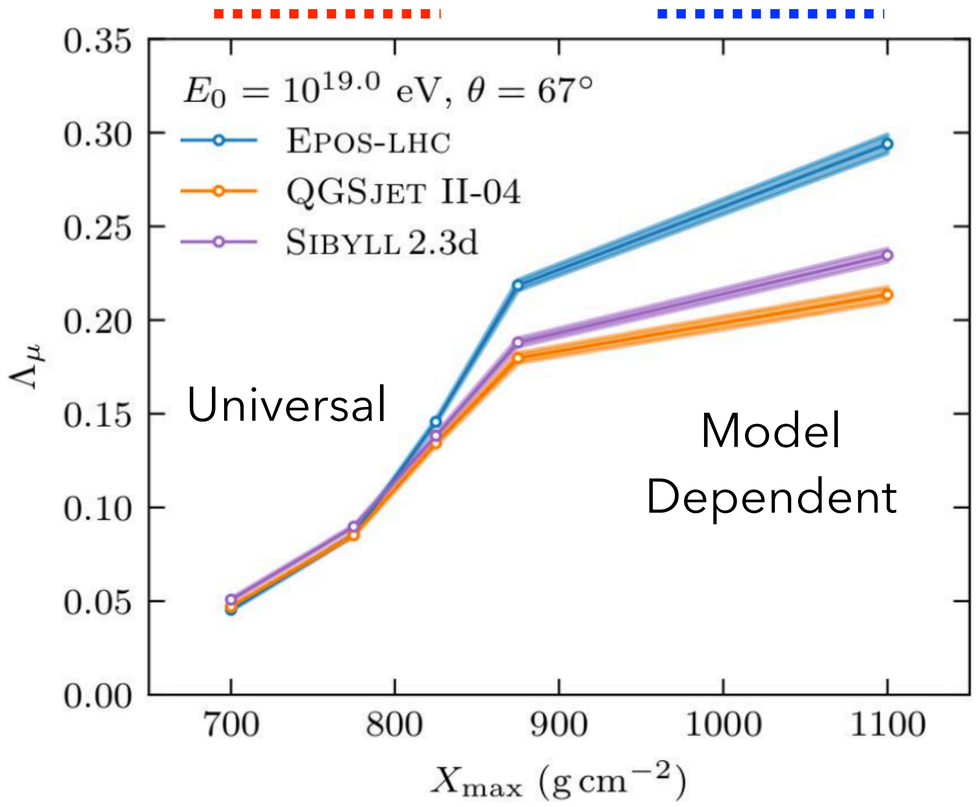
L. Cazon, RC, M. A. Martins, F. Riehn, *Phys.Lett.B* 859 (2024) 139115

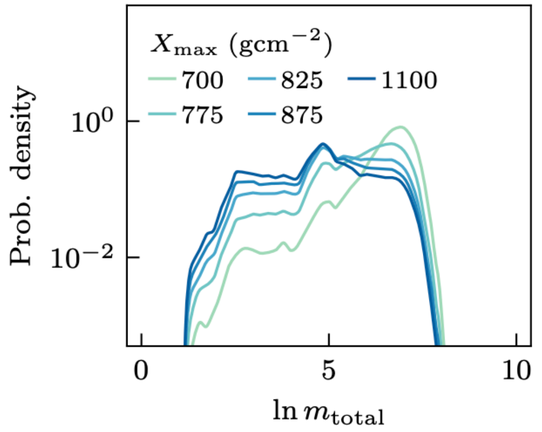
- Hadronic interaction models predict universal value of Λ_μ for shallow showers and highly distinct values for deep showers
- Binning in $X_{\rm max}$ ⇒ probe the hadronic activity of the first interaction



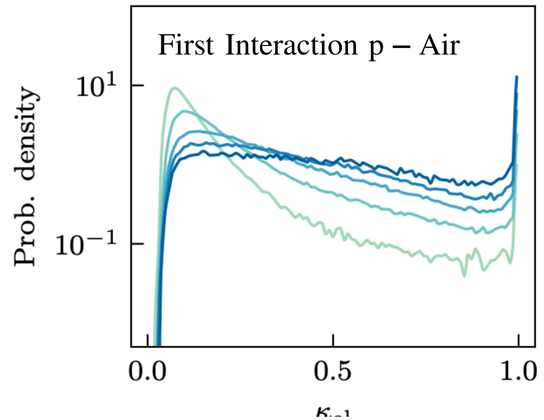
Low hadronic activity - diffractive events

Large hadronic activity - e.g. high multiplicity

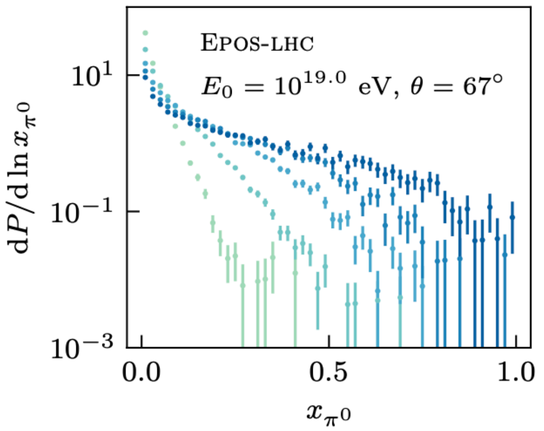




Multiplicity



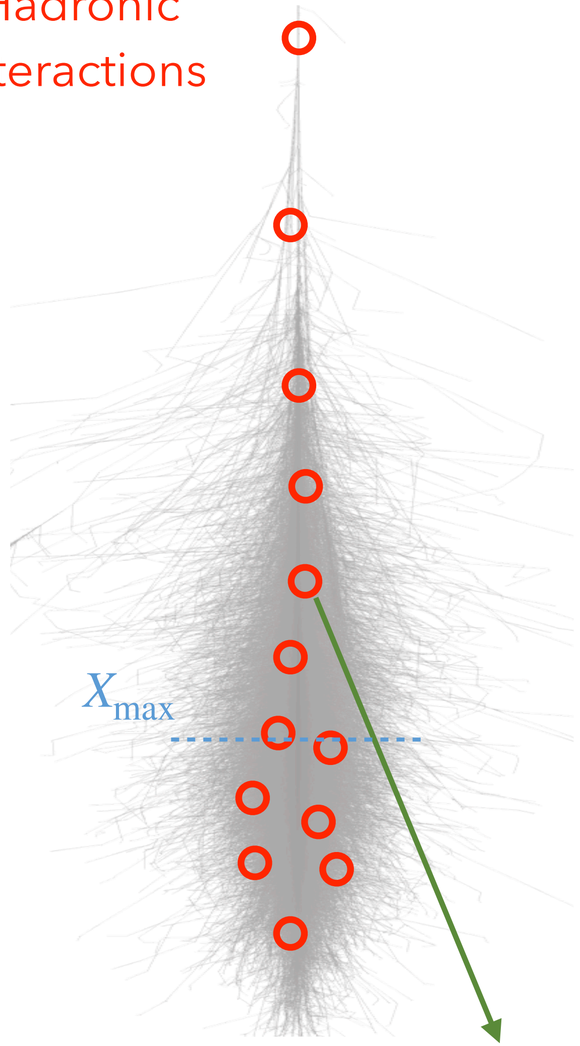
Elasticity



π^0 energy spectrum

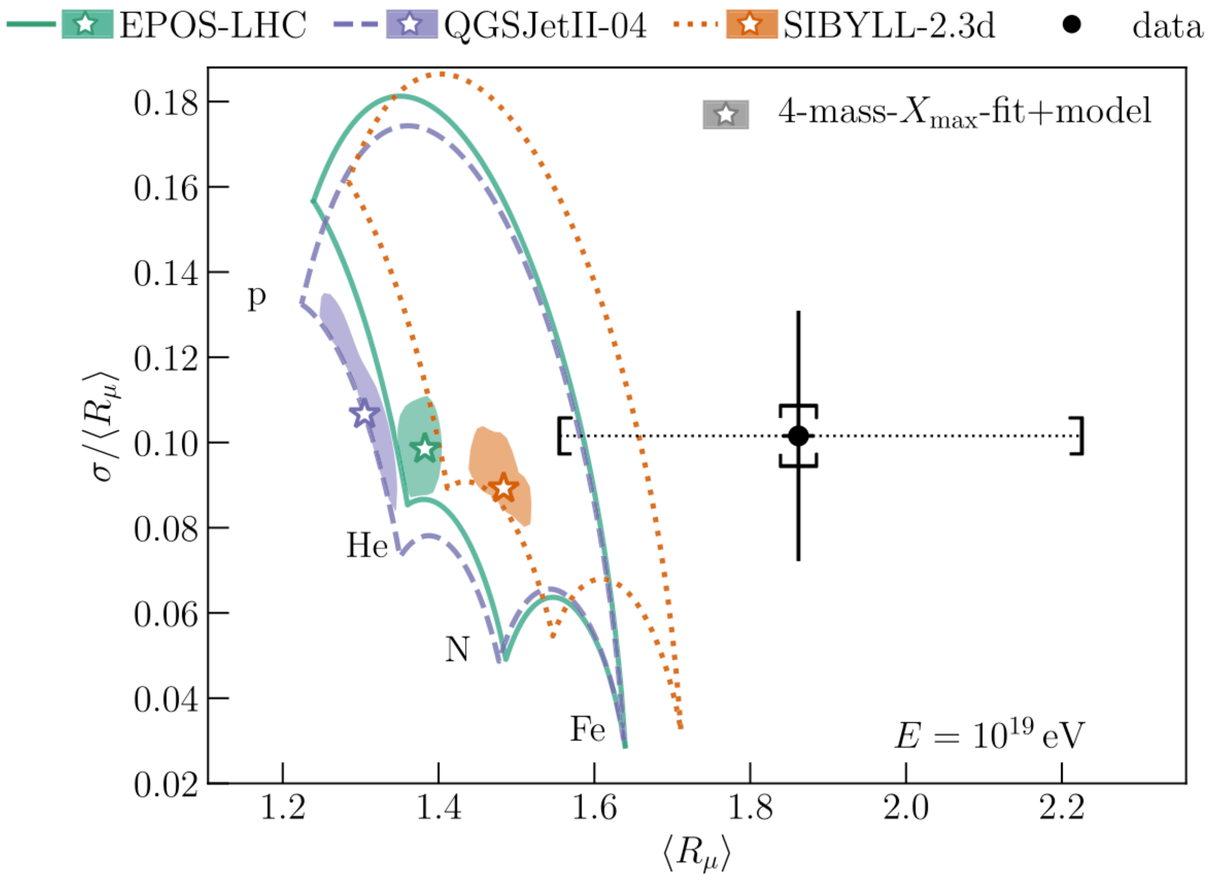
EAS Muon Puzzle

Hadronic interactions



Number of muons at ground, R_μ

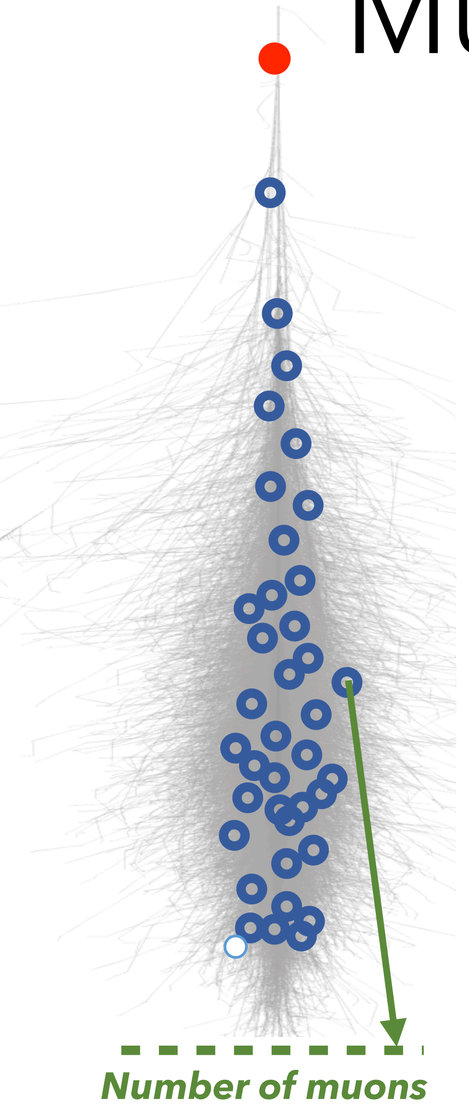
Pierre Auger Coll., Phys.Rev.Lett. 126 (2021) 15, 152002

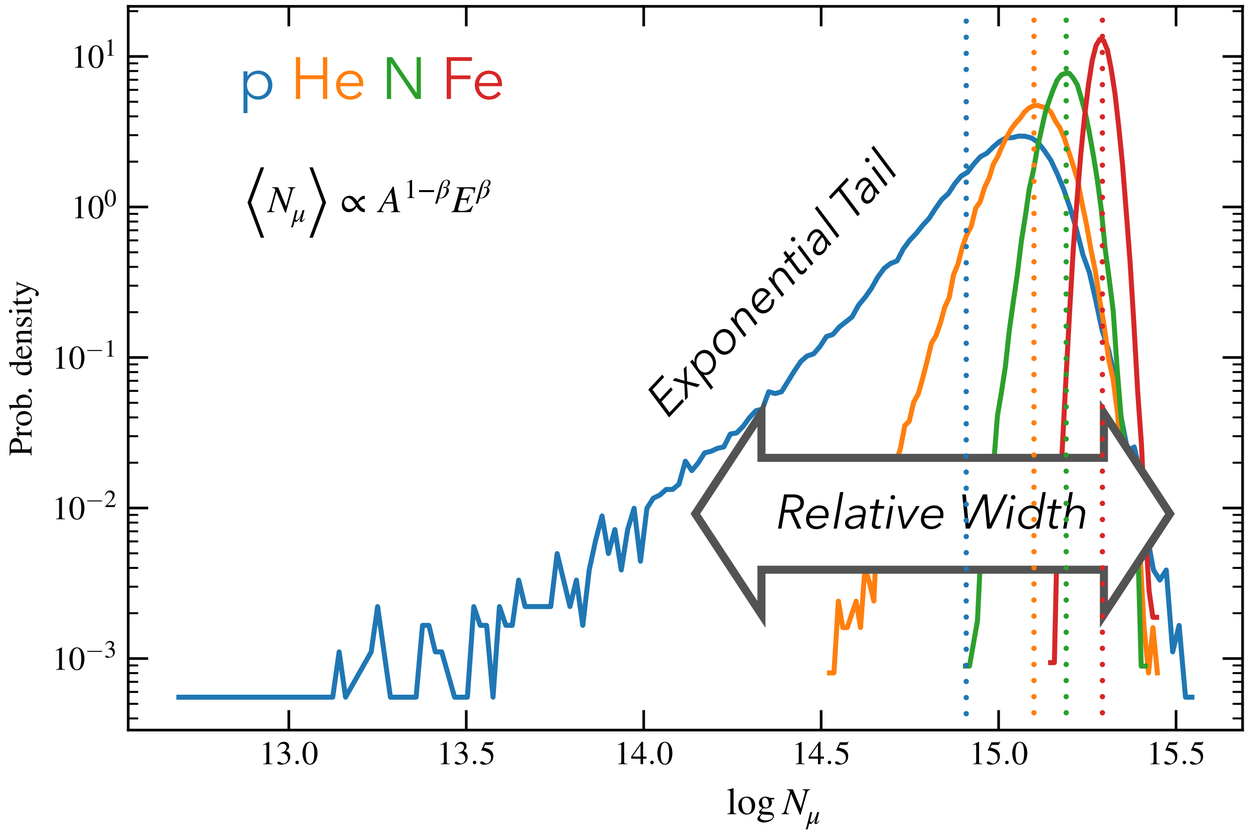


Models unable to consistently describe the average EAS muon content but its relative fluctuations agree with $X_{\max}$ expectations!!

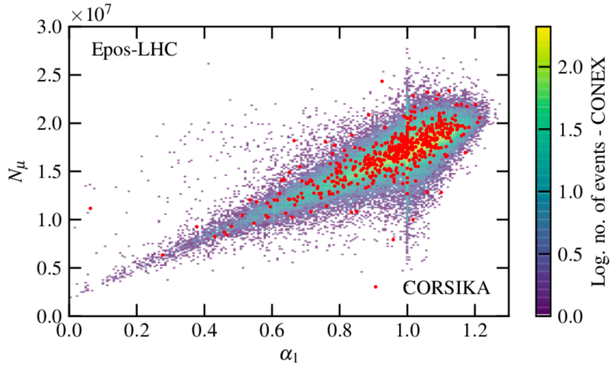
(see also, Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001)

Muon number distribution features

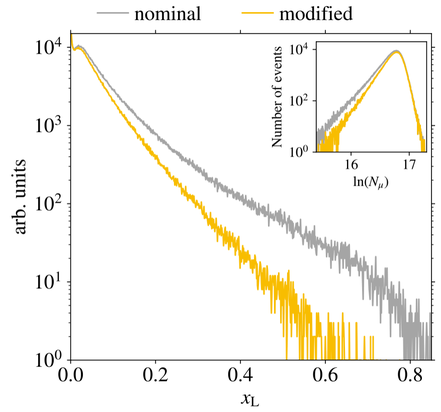




L. Cazon, RC, F. Riehn, Phys.Lett.B 784 (2018) 68-76
L. Cazon, RC, M. Martins, F. Riehn, Phys.Rev.D 103 (2021) 2, 022001
L. Cazon, RC, M. Martins, F. Riehn, Phys.Lett.B 859 (2024) 139115



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

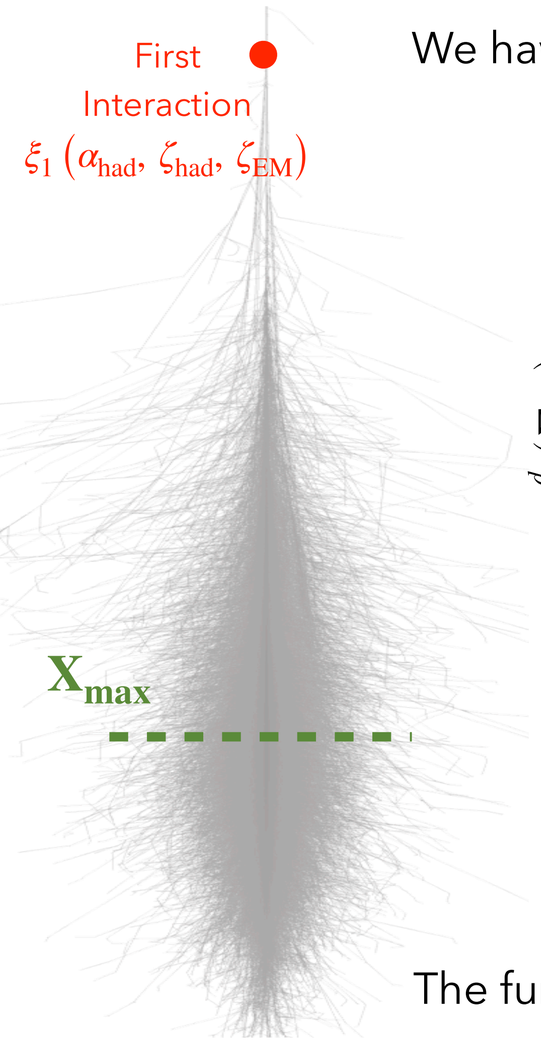


The shape and relative fluctuations of the muon number distribution gives access to the properties of the **FIRST hadronic interaction** (fraction of energy carried by neutral pions - α_1)

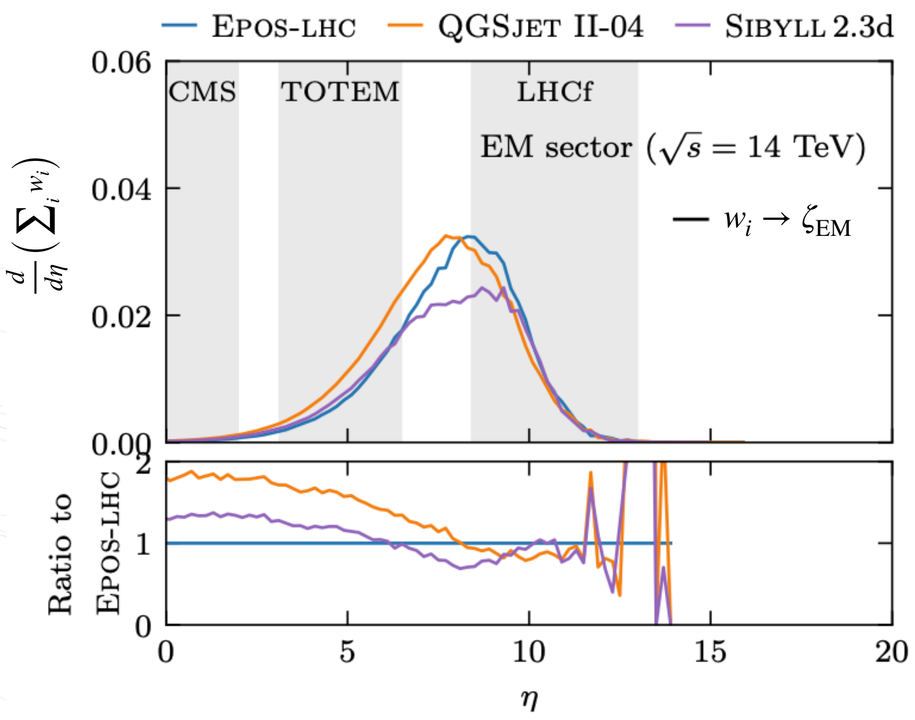
ruben@lip.pt

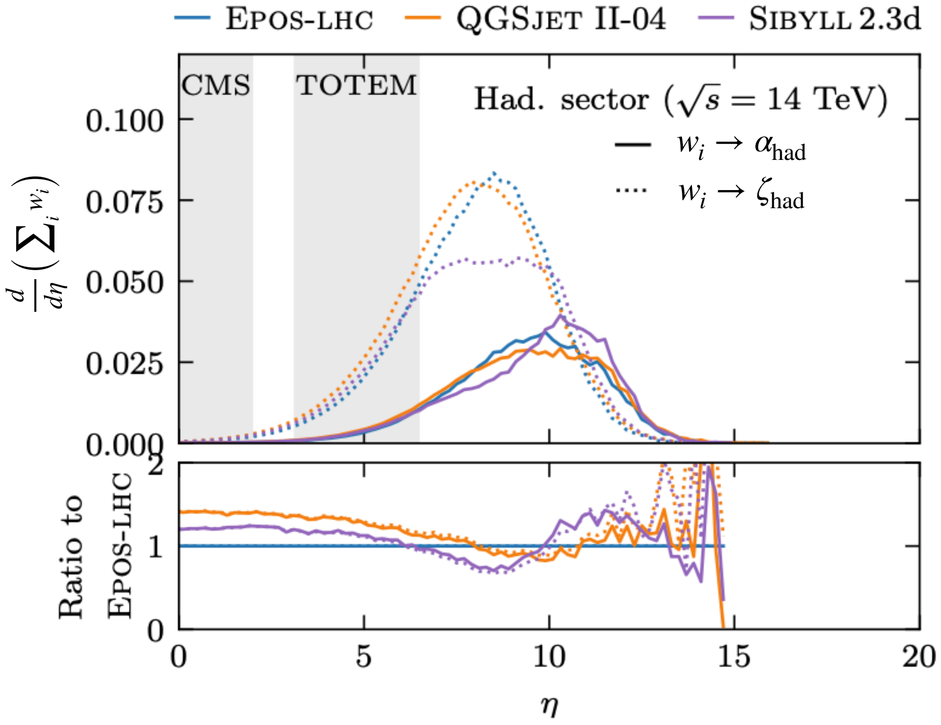
Depth of the shower maximum

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



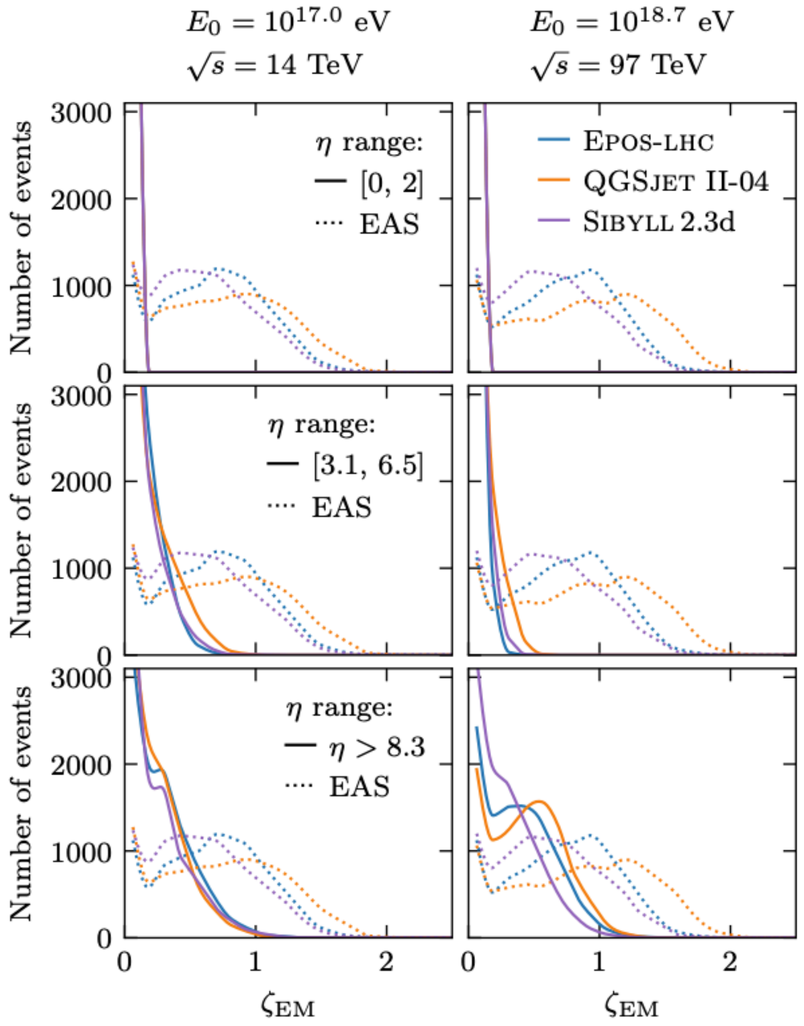
We have shown that $X_{\rm max}$ can be predicted solely from the energy spectra of secondaries by using linear combinations of the following multiparticle production quantities $\alpha_{\rm had}$, $\zeta_{\rm had}$, $\zeta_{\rm EM}$.





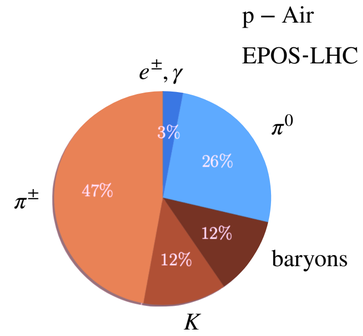
The functional form of $\alpha_{\rm had}$, $\zeta_{\rm had}$, $\zeta_{\rm EM}$ is independent of the hadronic interaction models and the particle contribution to these quantities can be explored at the HL-LHC to exclude models

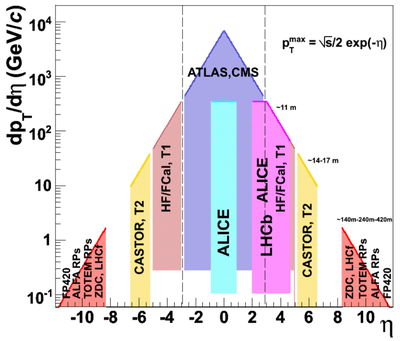
The functional form of ζ_{EM} and ζ_{had}

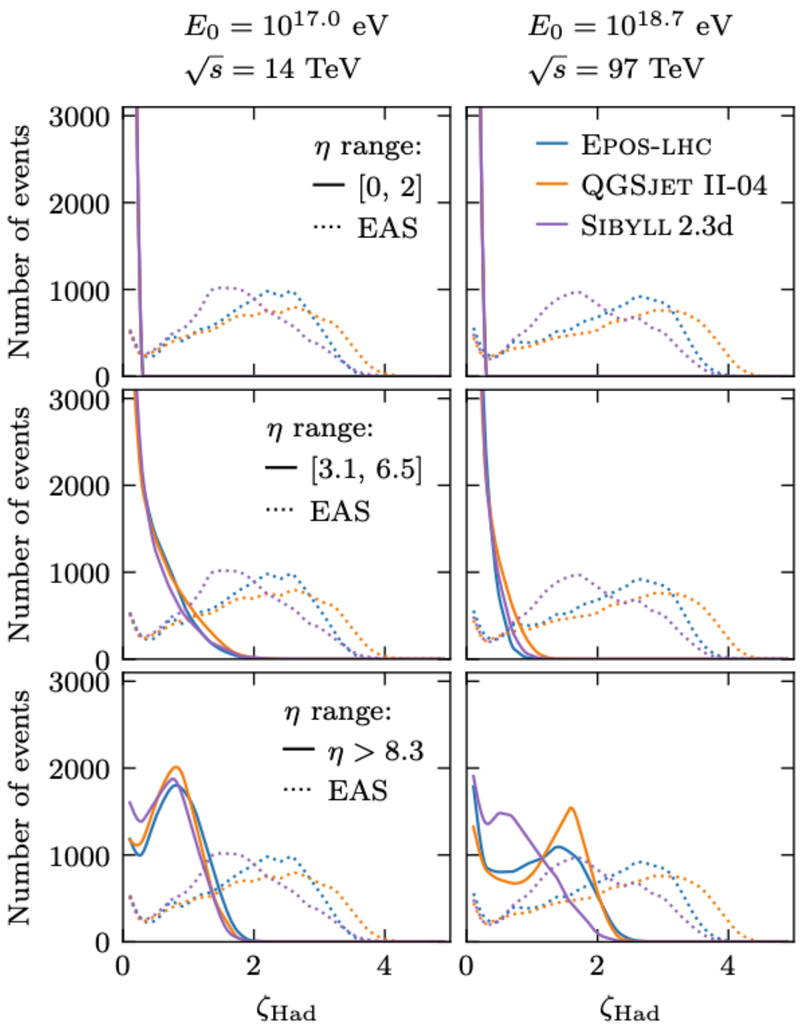


Shower electromagnetic sector

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

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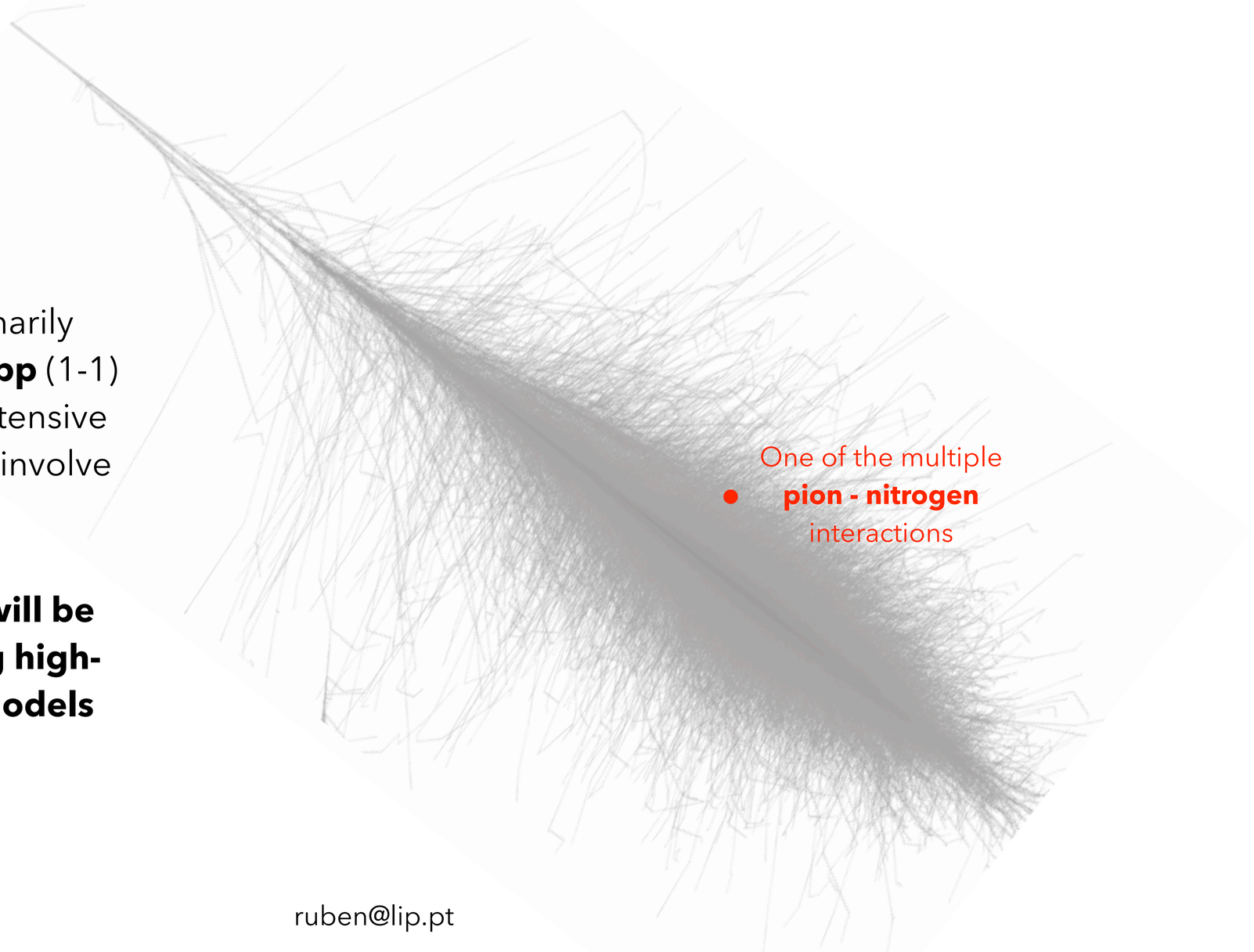
Extensive Air Showers

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



One of the multiple
- **pion - nitrogen** interactions

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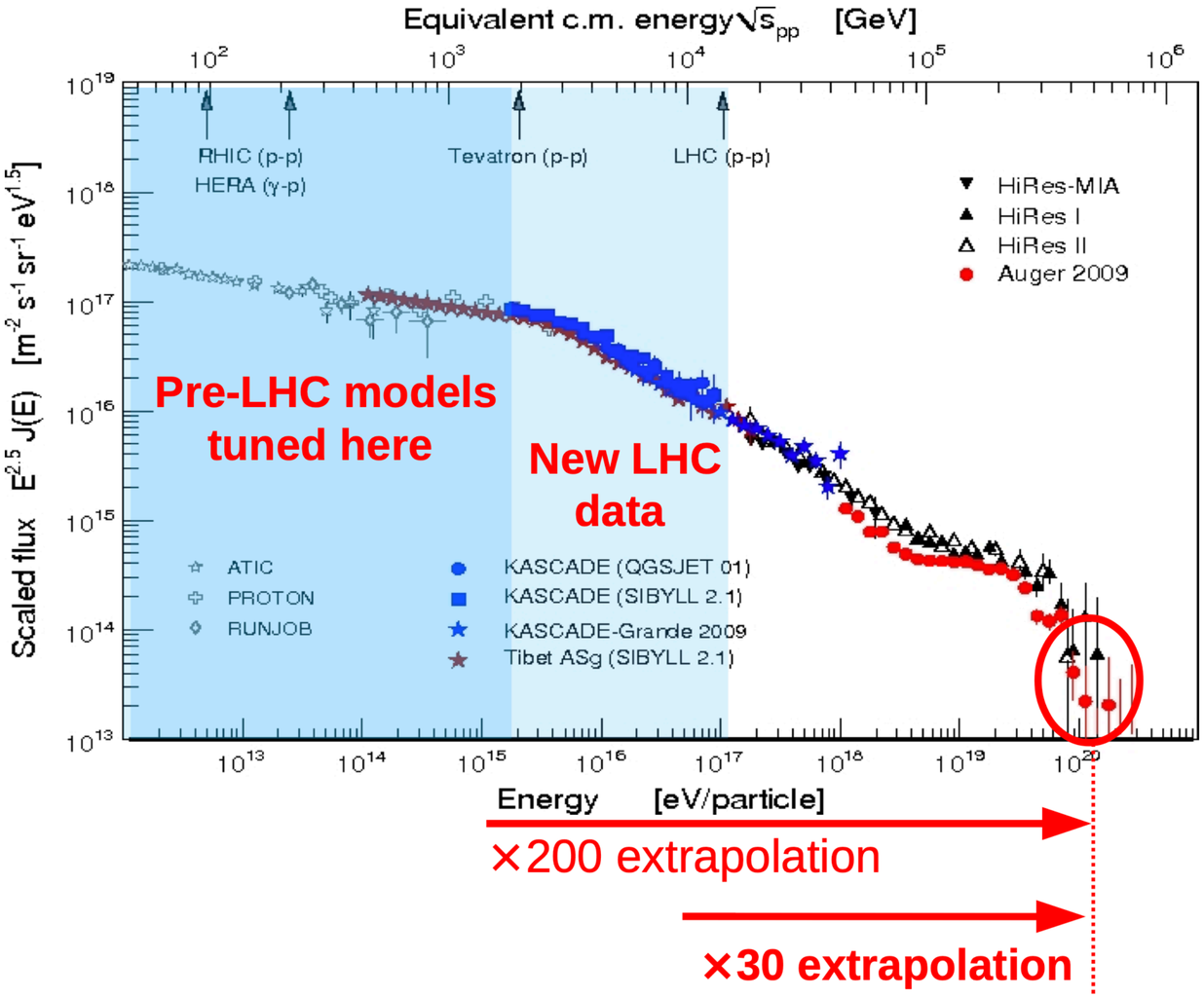
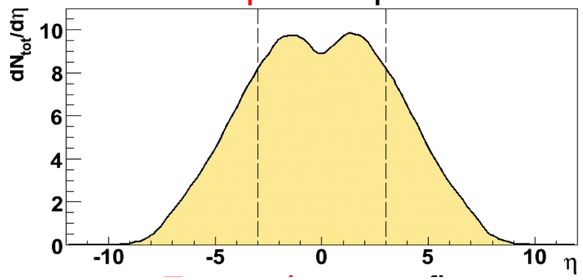
The challenge

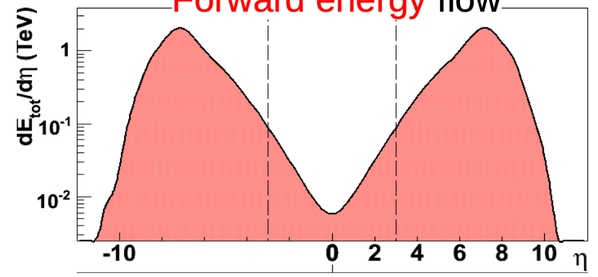
p-p @ 14 TeV

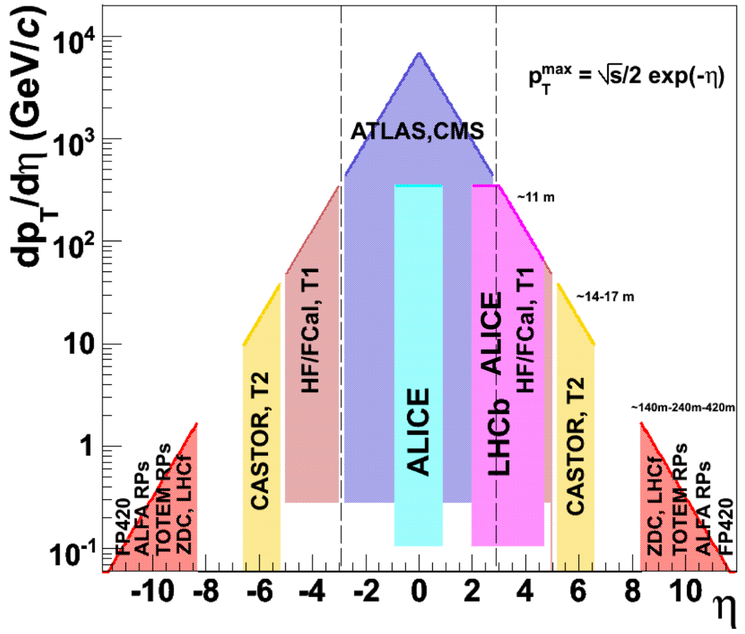


Central particle production



Forward energy flow

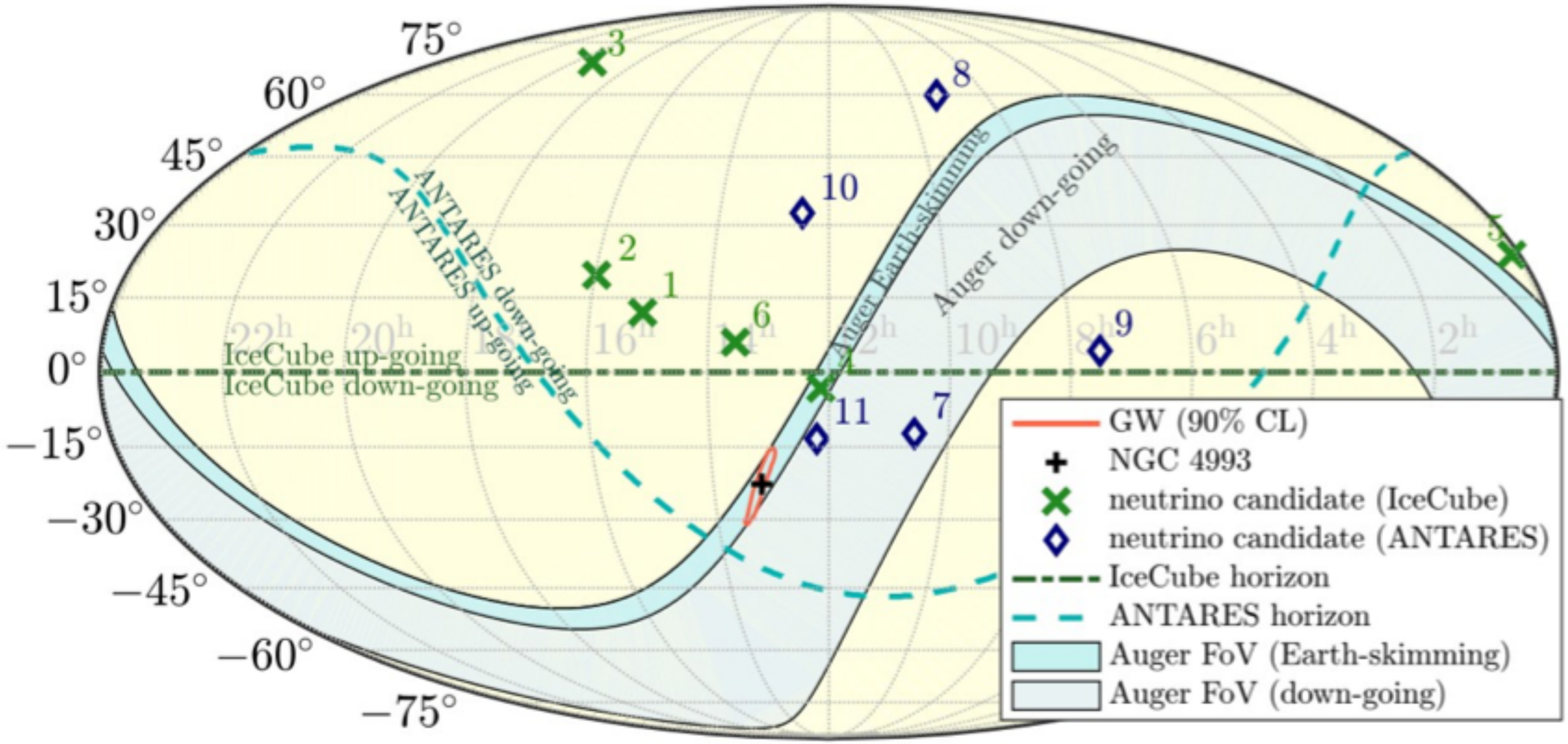




From D. d'Enterria

ruben@lip.pt

GWs and neutrinos - GW170817



AugerPrime timeline

Start of the Upgrade phase — 2019

end of PMTs fabrication — 2020

end of SSD shipment on site — 2021

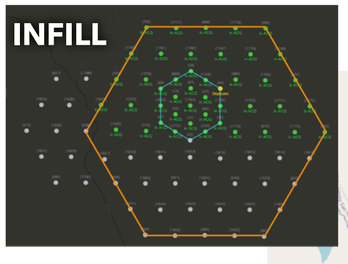
end of SSD deployment — 2022

end of UUB production and shipment — 2023

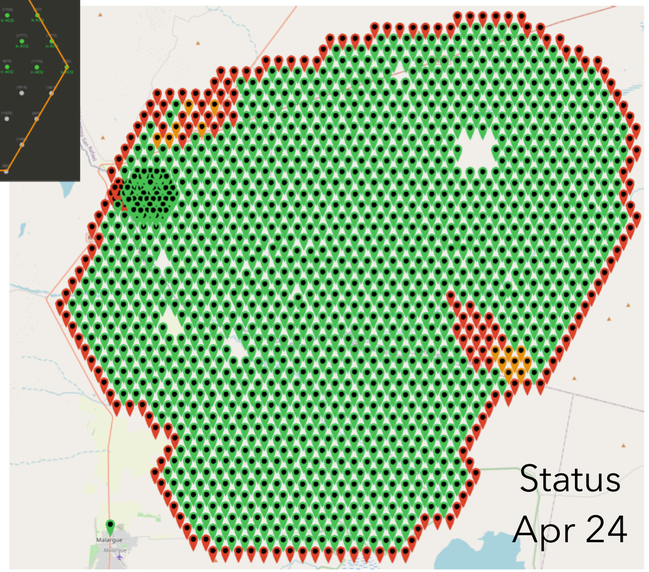
end of UUB + PMTs deployment — 2024

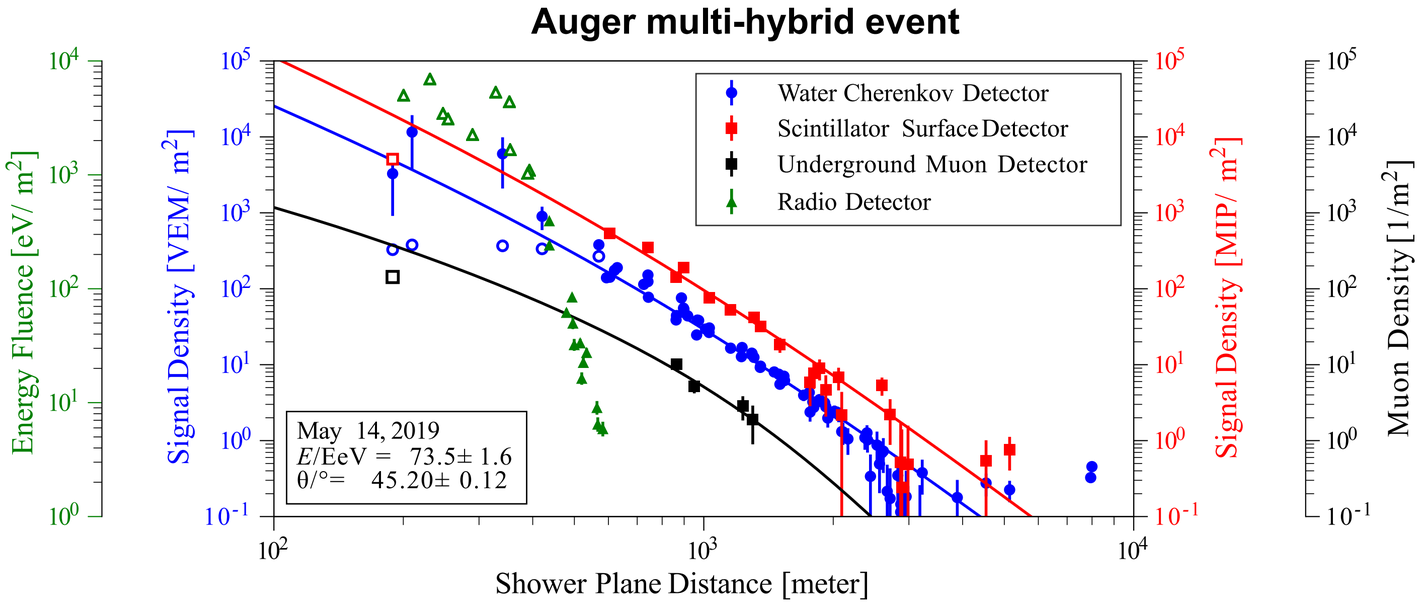
end of Radio+ UMD deployment — 2024

••• 2035

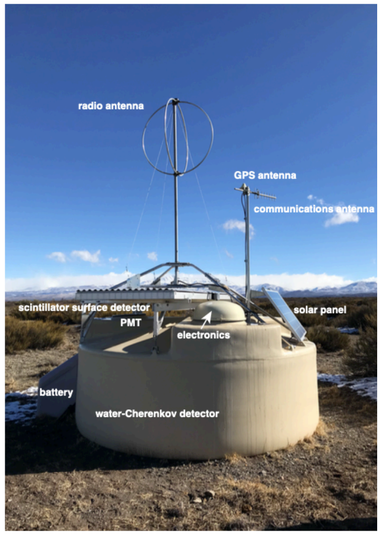


UMD
— SD433 95%
— SD750 59%

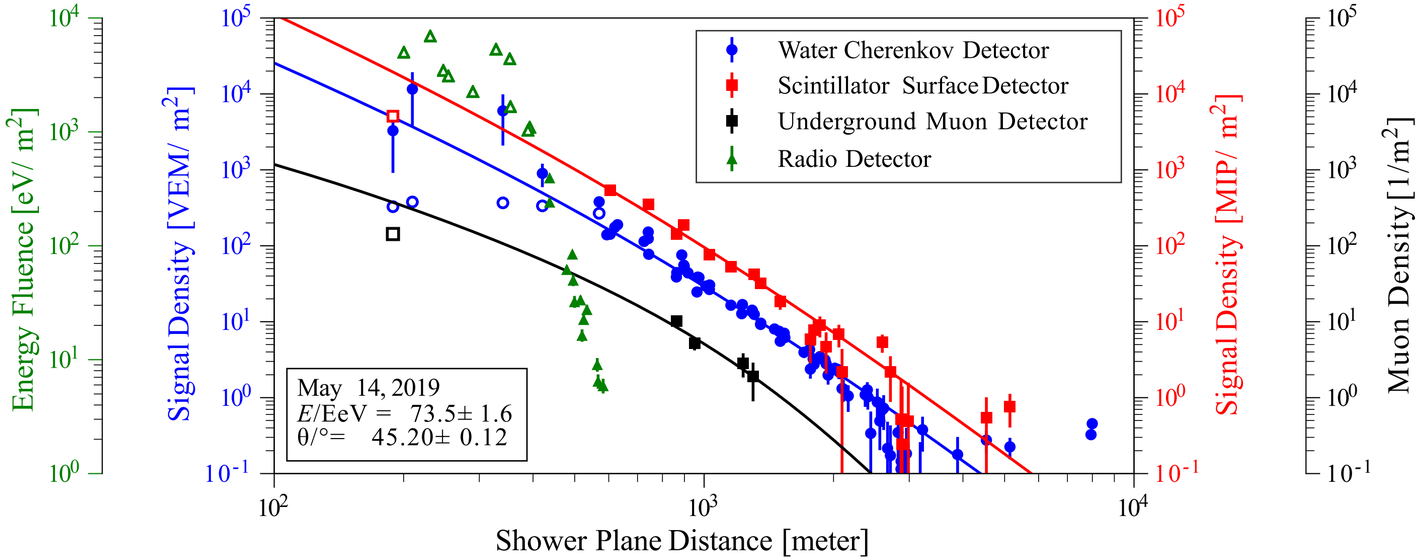




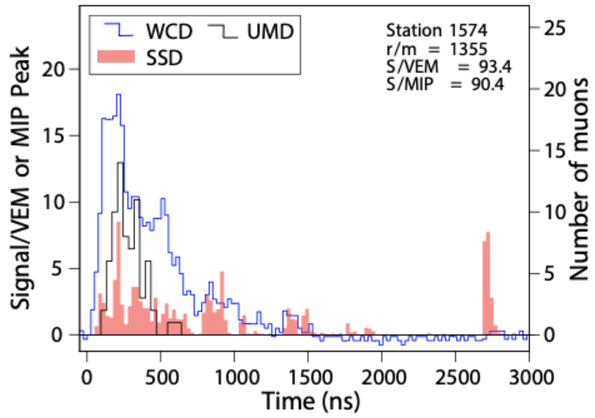
AugerPrime: A Wealth of Information



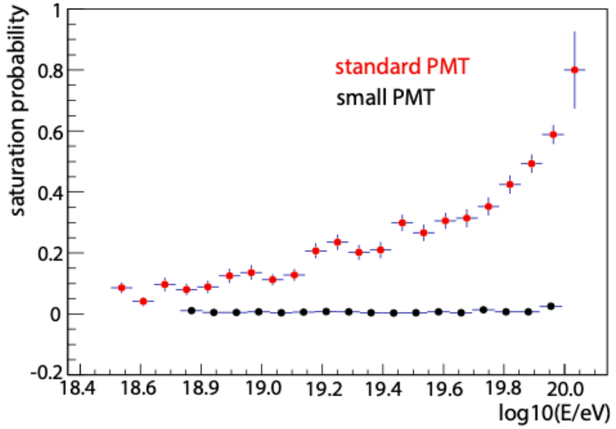
Auger multi-hybrid event

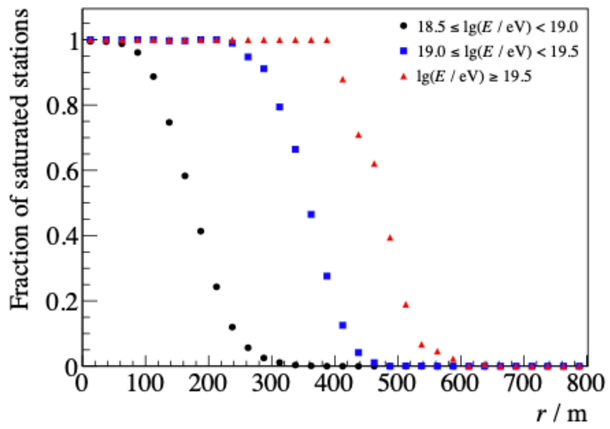


PMTs signal time trace

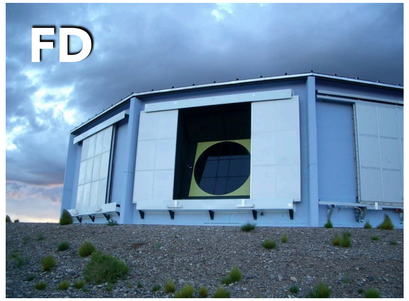


Small PMT in the WCD



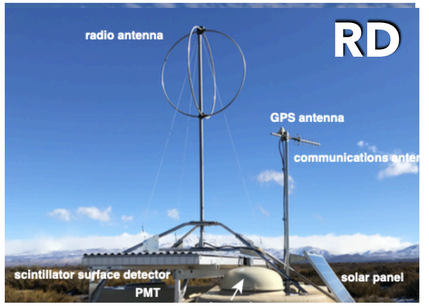


More events than ever…



Vertical Events

Horizontal Events

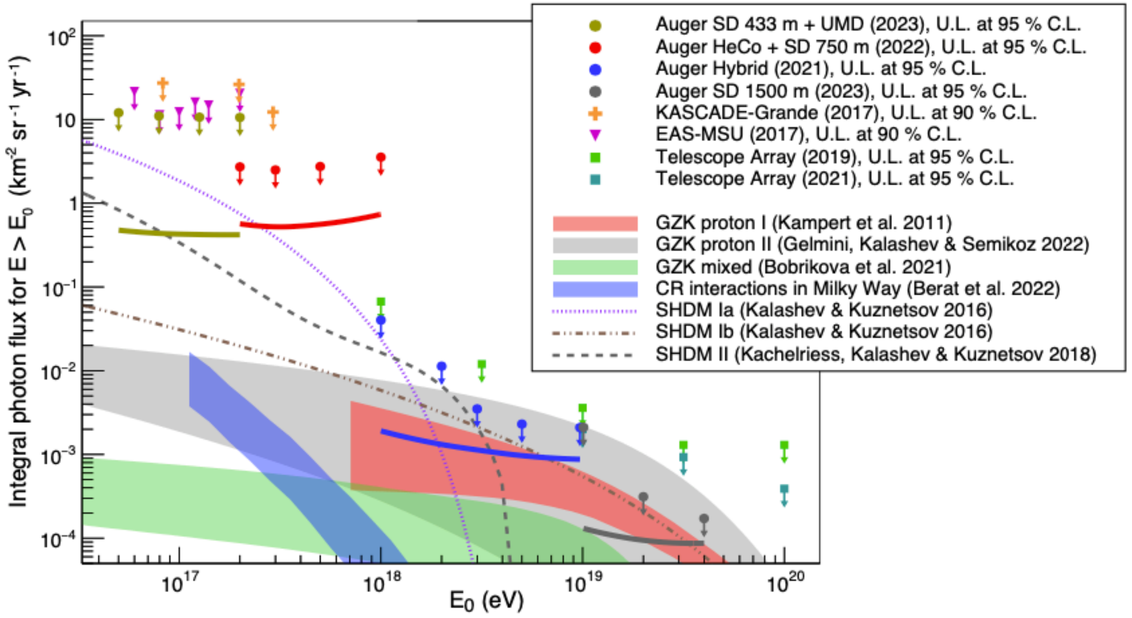


Energy scale

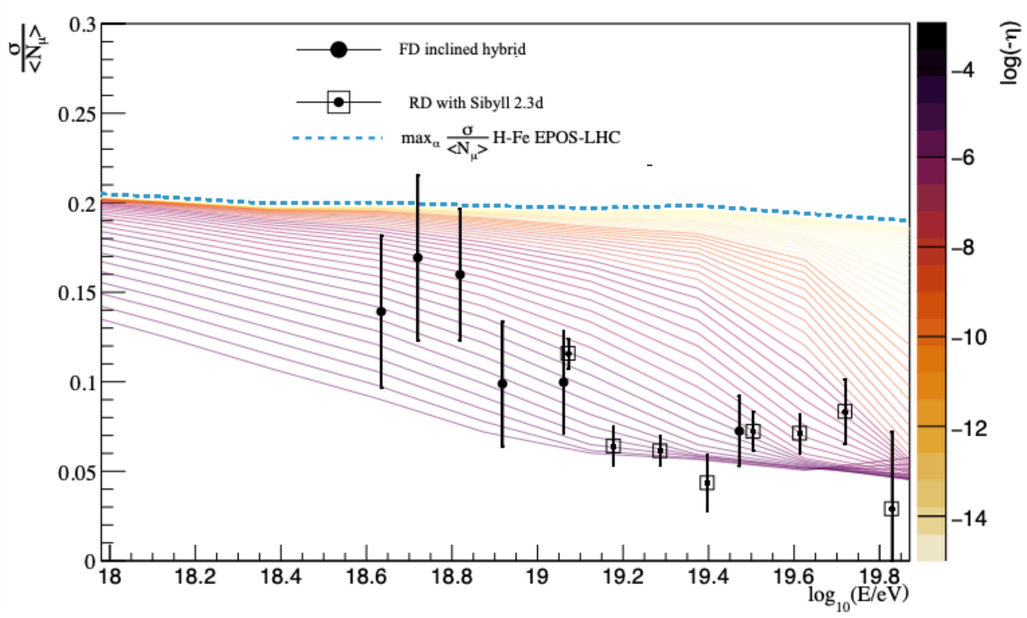
Particles at the ground

Energy scale

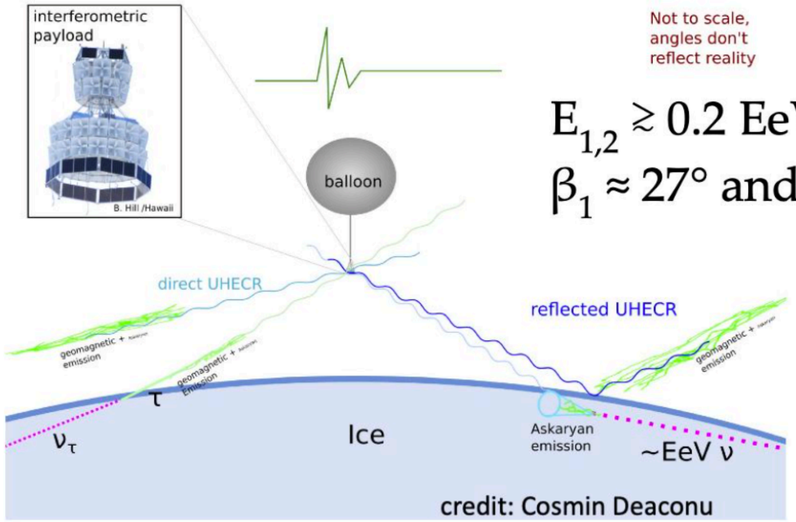
Photon Limits



Lorenz Invariance Violation



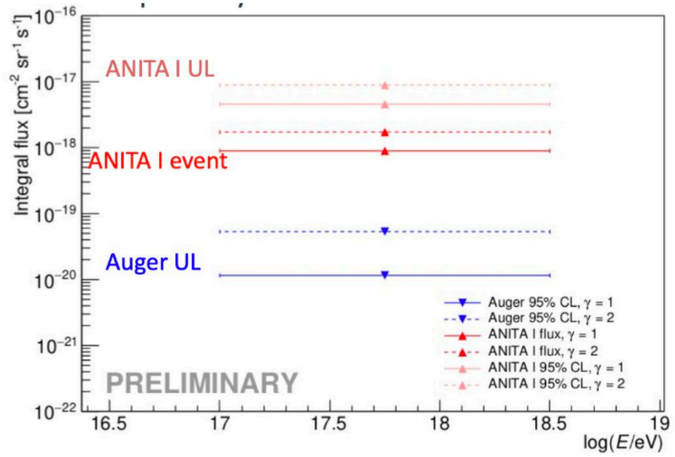
Beyond Standard Model Physics

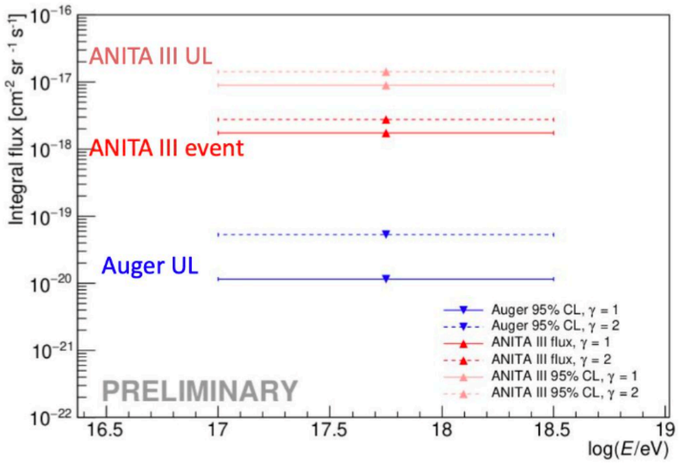


Not to scale, angles don't reflect reality

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

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

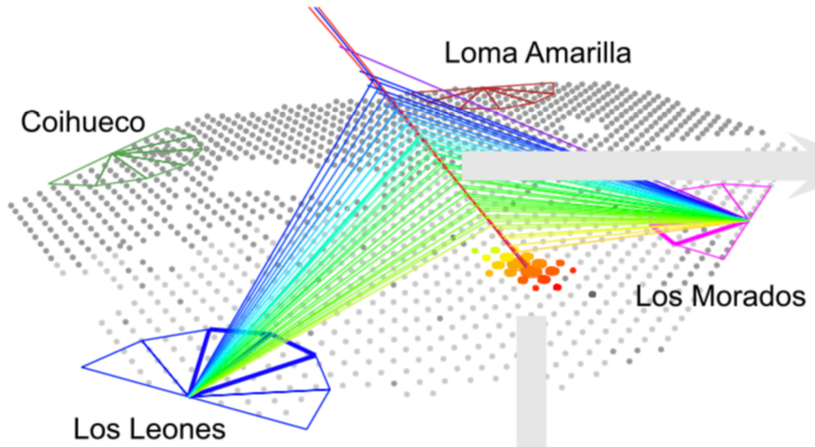


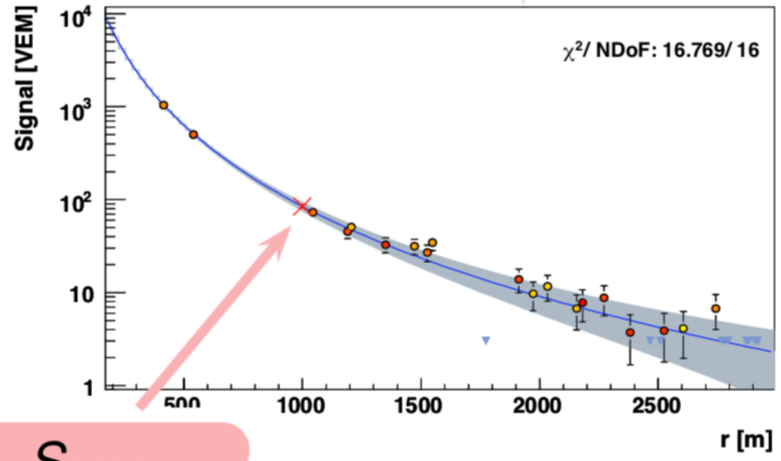


- Search of up-going events with FD

- 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

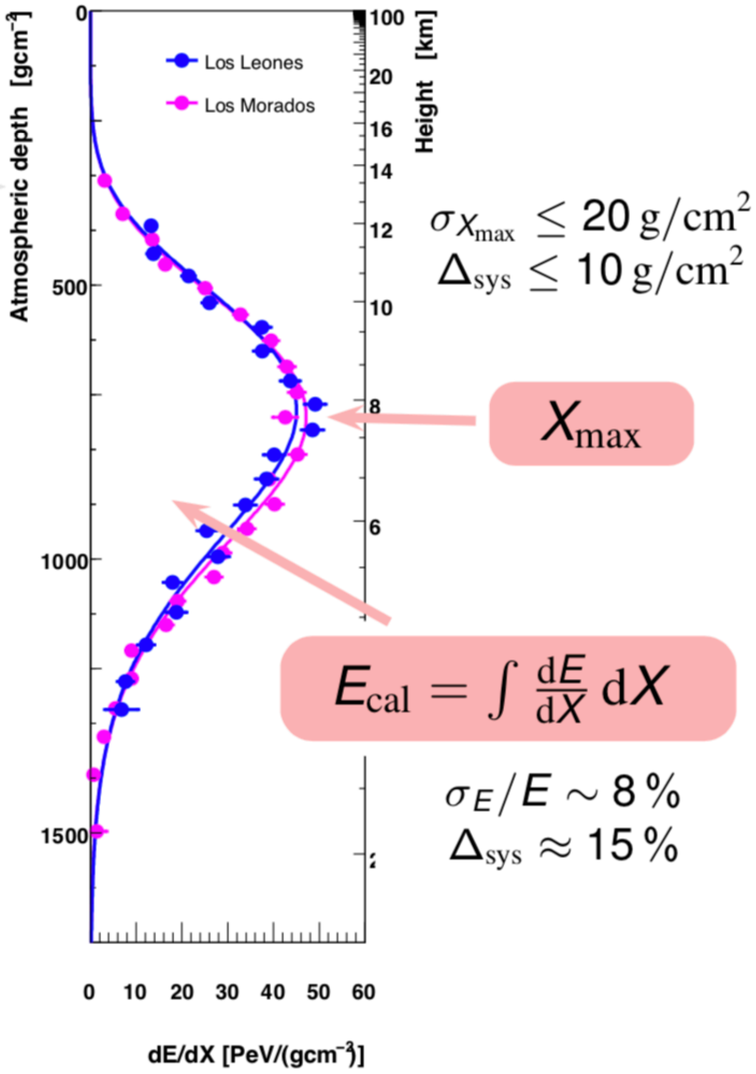
Hybrid Technique (FD + SD)





S_{1000}

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



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

$X_{\max}$

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

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