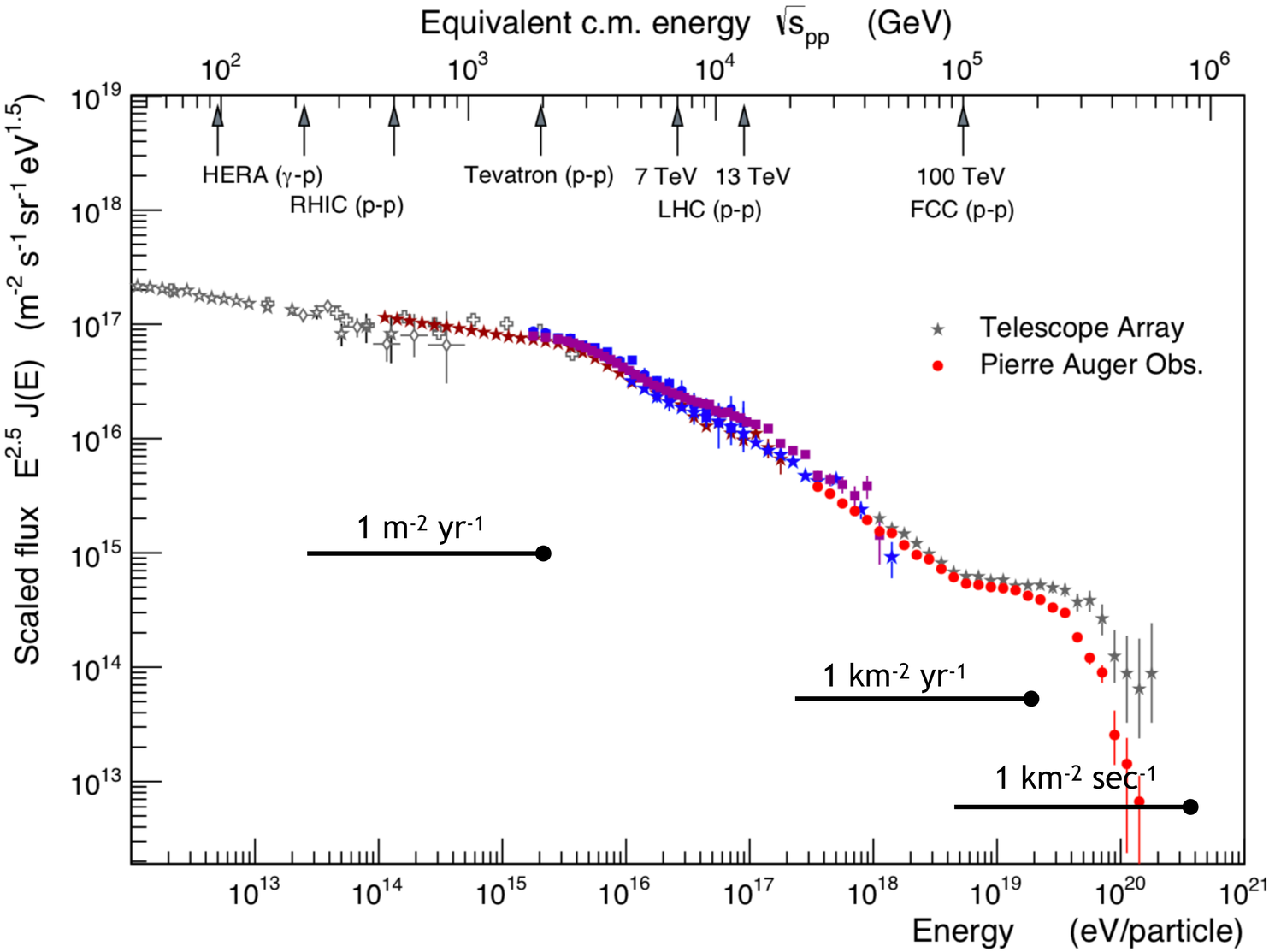
Calibrations at Auger: Paving the Future

Ruben Conceição

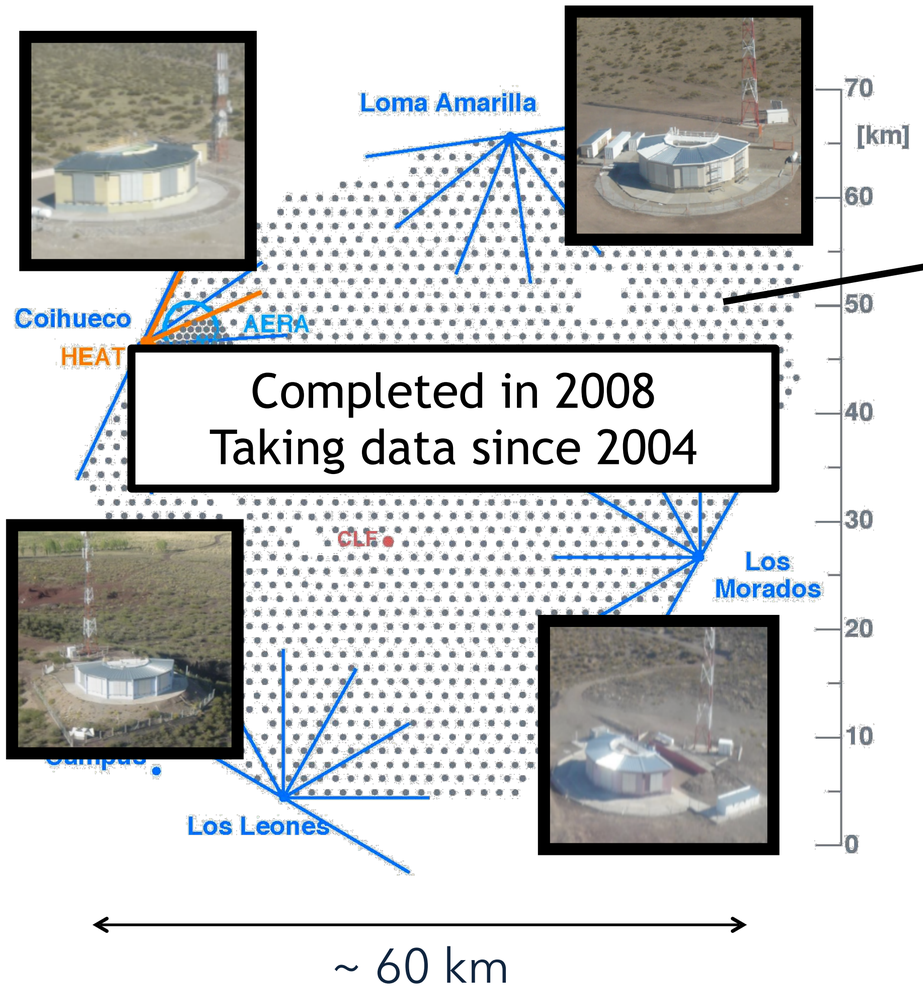
for the Auger-LIP group

Fourth joint LIP/IGFAE workshop, Lisbon, April 13th 2023

Ultra High Energy Cosmic Rays



Pierre Auger Observatory



- ~ 1600 Surface detectors (SD)
- In a 1.5 km hexagonal grid
- 3000 km^2

- 4 Fluorescence Detectors (FD)
- 6 x 4 + 3 Fluorescence Telescopes

Built to detect and study the extremely rare UHECR

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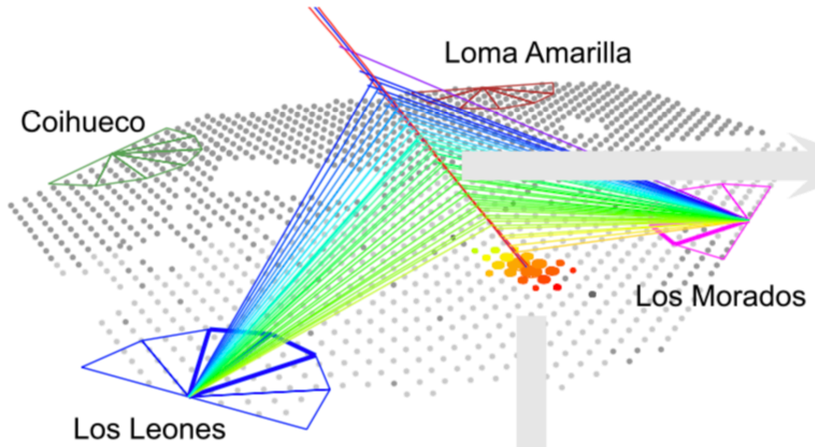
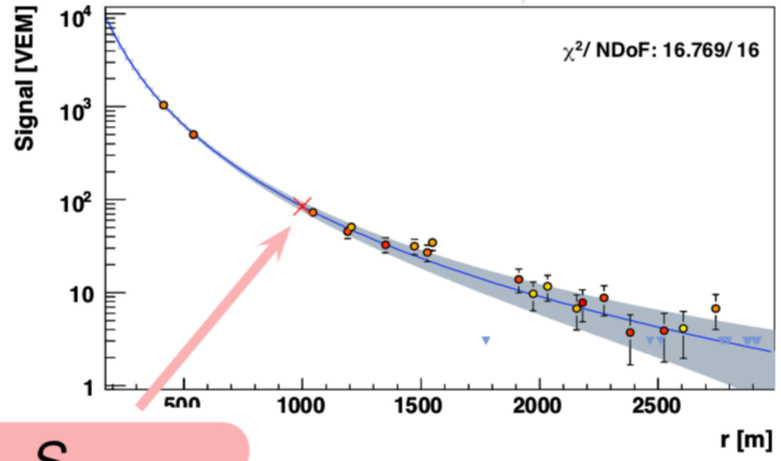
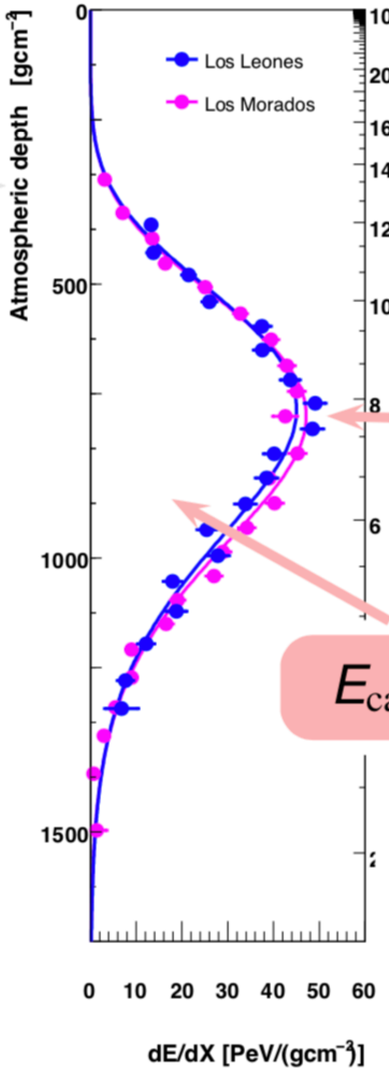
Hybrid Technique (FD + SD)





S_{1000}

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

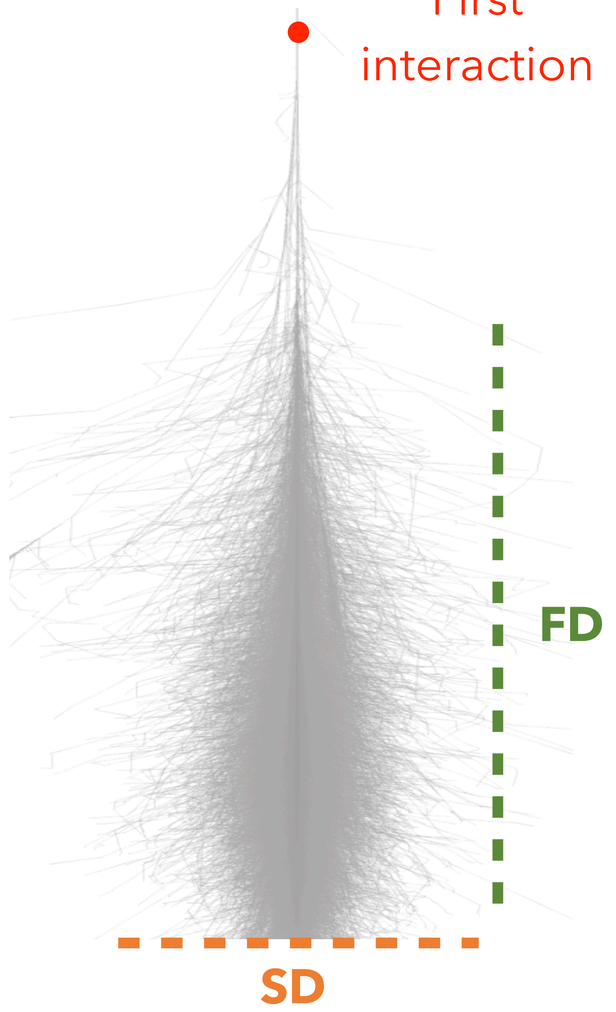


$\sigma X_{\max} \leq 20\ \text{g/cm}^2$
$\Delta_{\text{sys}} \leq 10\ \text{g/cm}^2$

$X_{\max}$

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

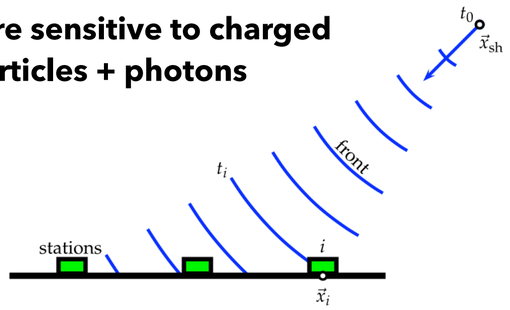
$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$



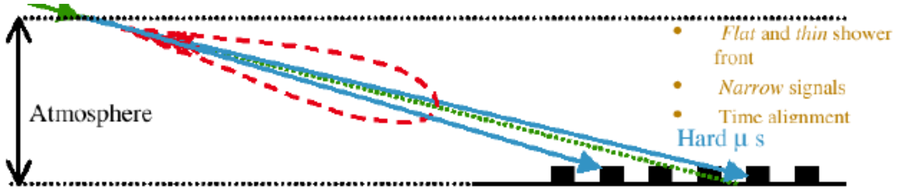
Exploration of inclined showers

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

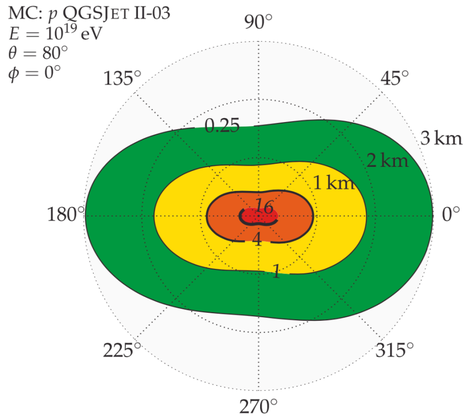
WCDs are sensitive to charged particles + photons

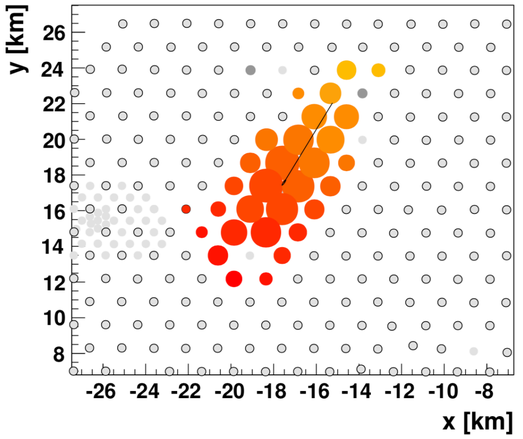


- Inclined shower → Muons



- Energy given by the Fluorescence Detector
- 281 hybrid events





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

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

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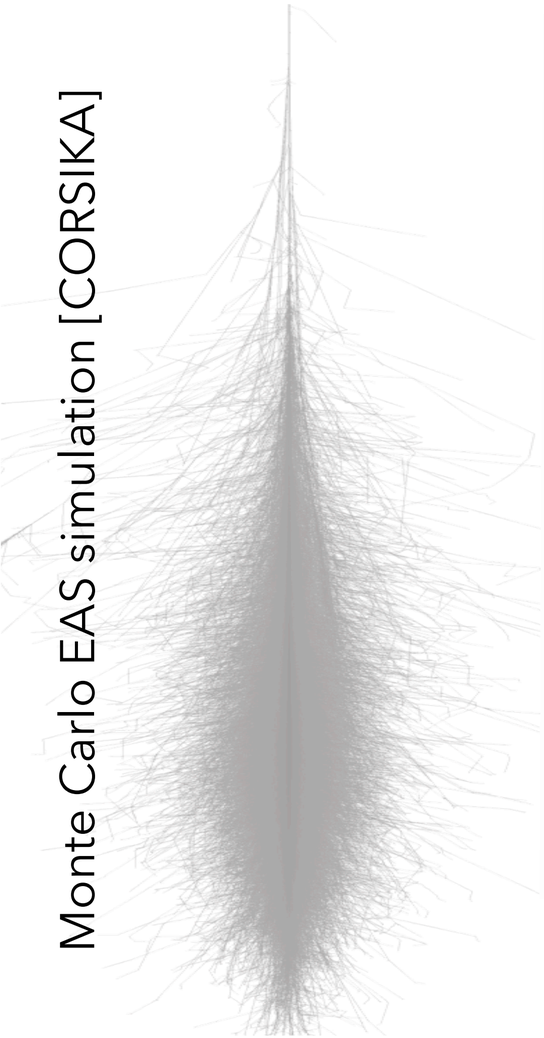
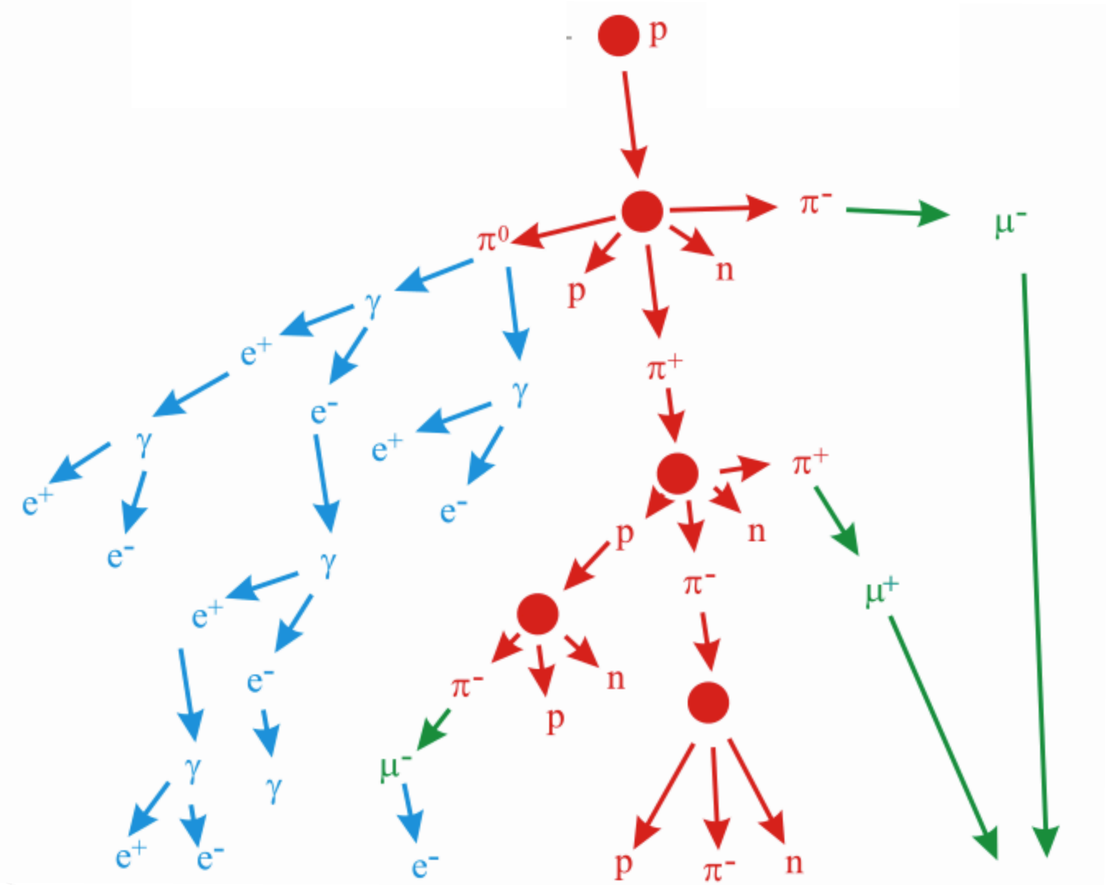
Extensive Air Showers

Monte Carlo EAS simulation [CORSIKA]





Electromagnetic component

Hadronic component

Muonic component

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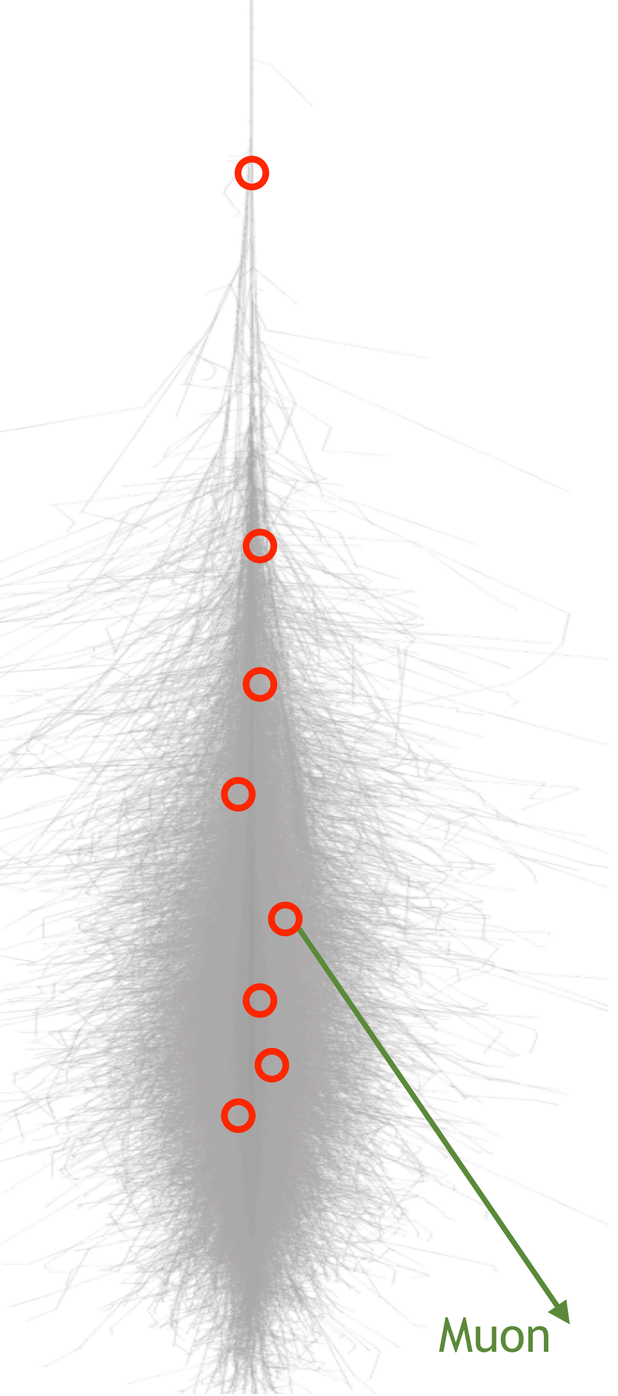
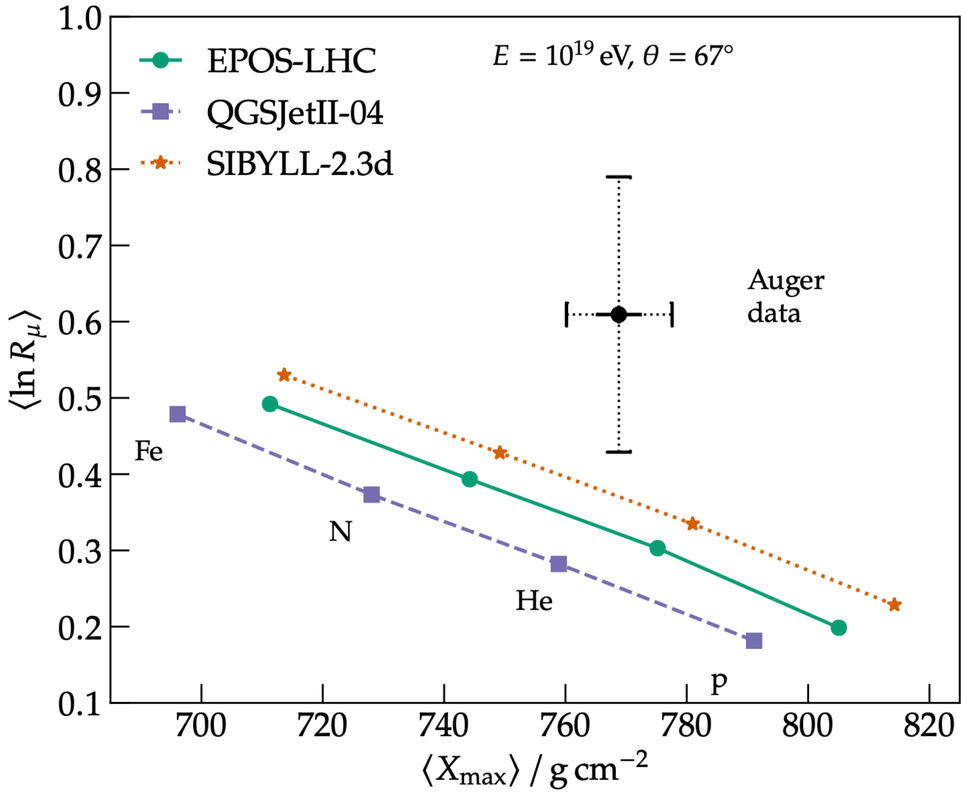
Shower description

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



Surface Detector



Fluorescence Detector

Combination of different measurements **reveals tension between data and all hadronic interaction models**

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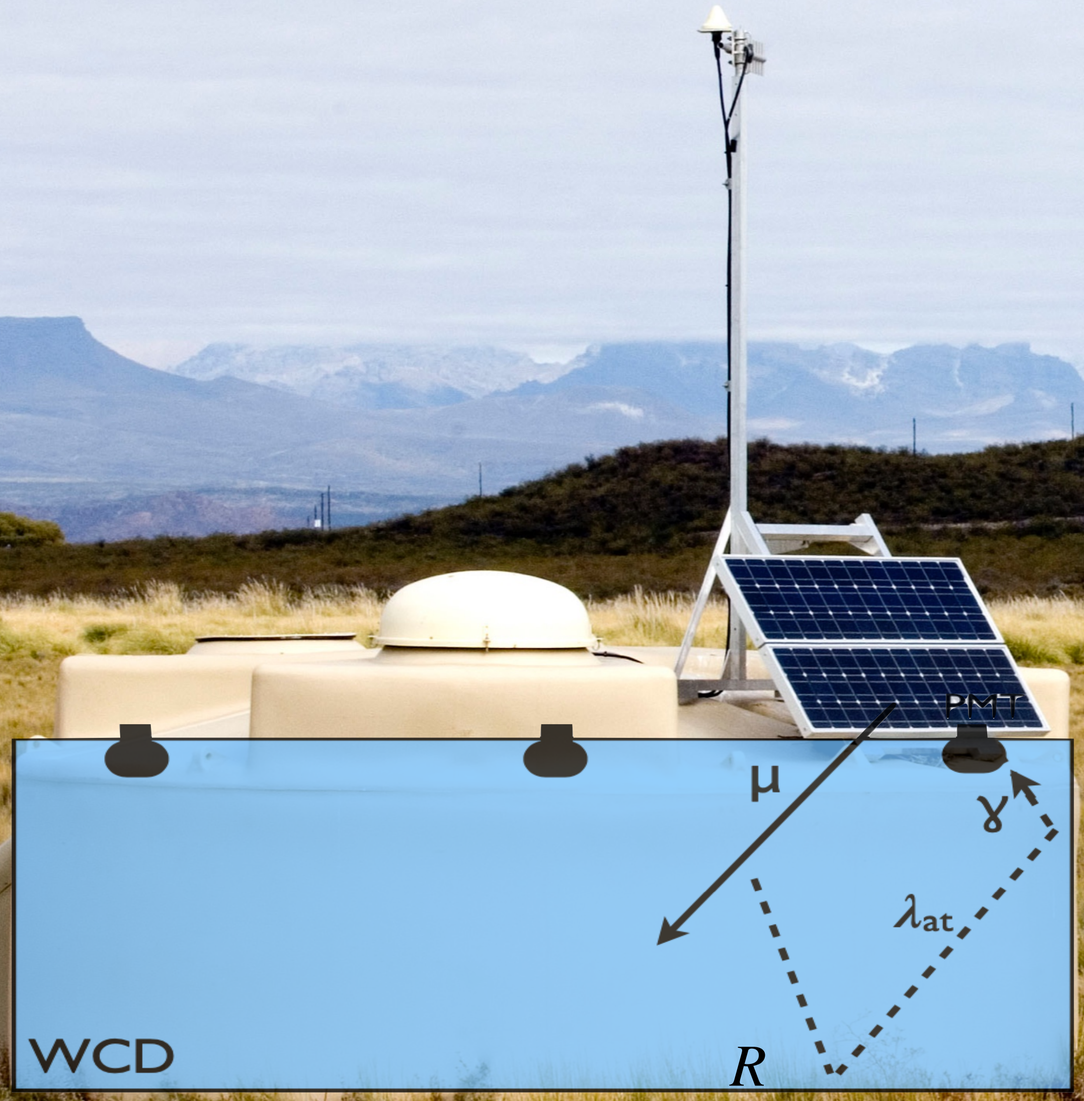

- **Light generation:** Cherenkov yield
- **Light propagation:** attenuation length in water, λ_{at}
- **Light reflection:** Tyvek reflectivity, R
- **Light collection:** PMT geometry, QE
- **Other effects:** water-air transition, ice formation, water level…

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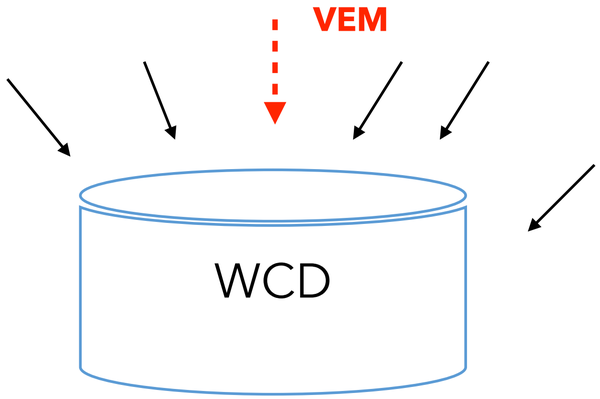
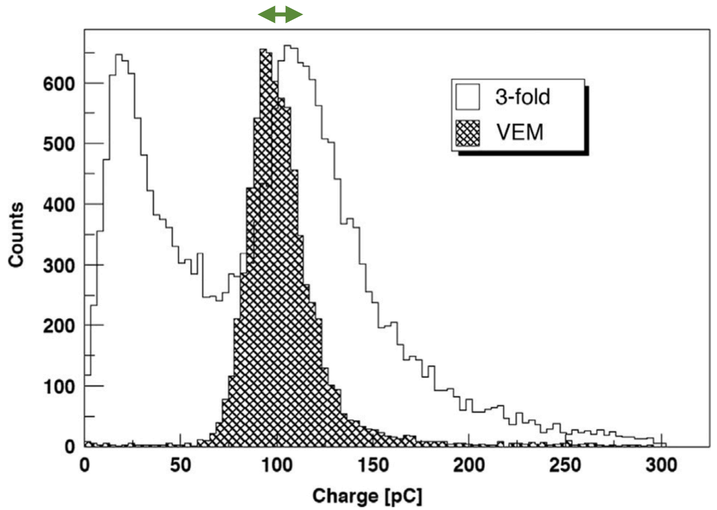
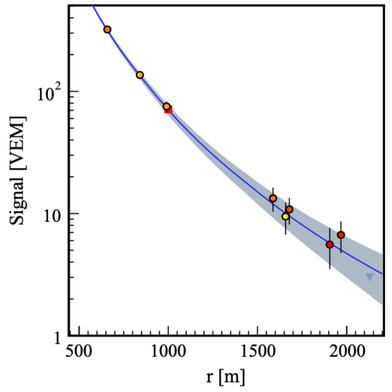
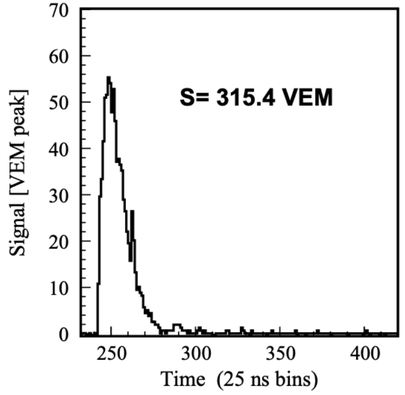
SD calibration (VEM)

Pierre Auger Coll., NIM A 798 (2015) 172





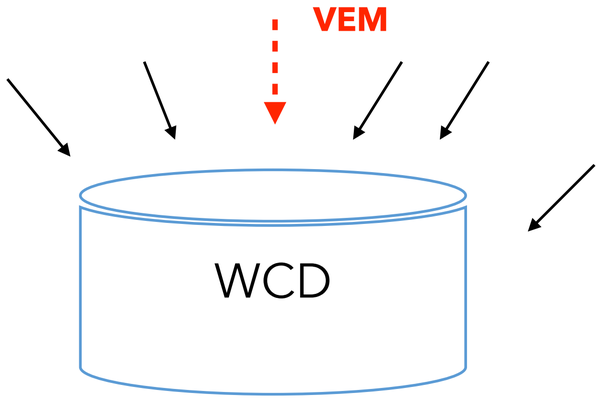


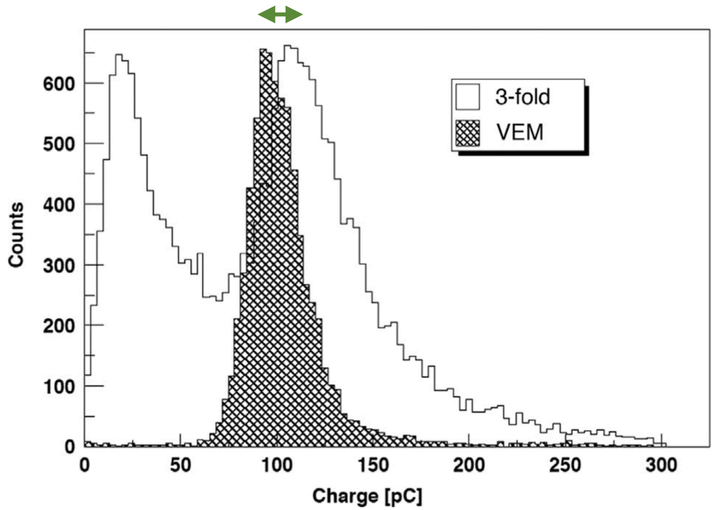


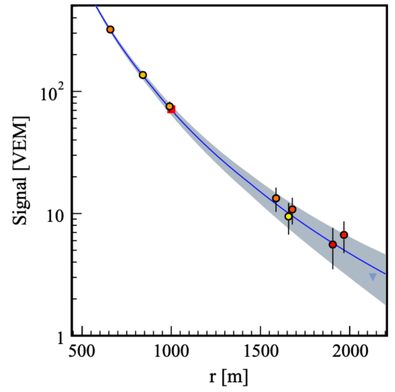
- Use omni-directional atmospheric muons to obtain reference Vertical Equivalent Muon (VEM)

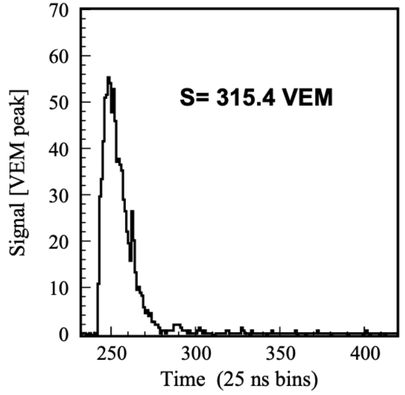
SD calibration (VEM)

Pierre Auger Coll., NIM A 798 (2015) 172

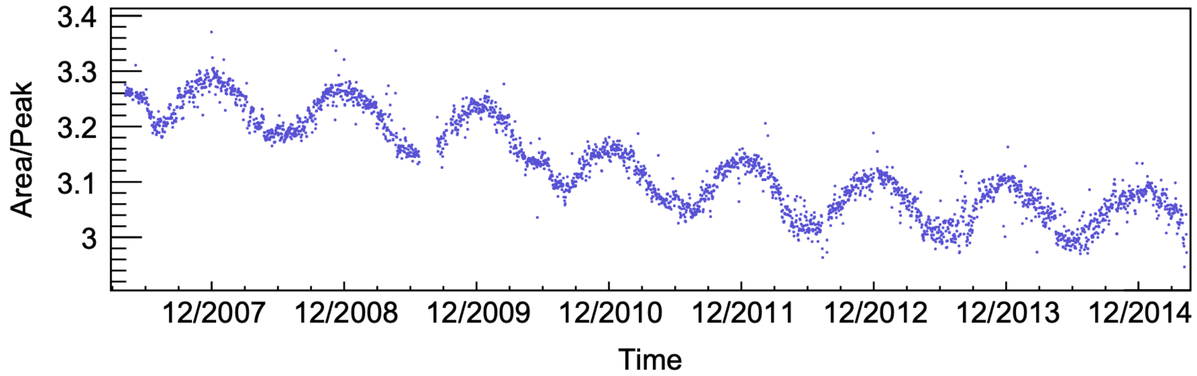








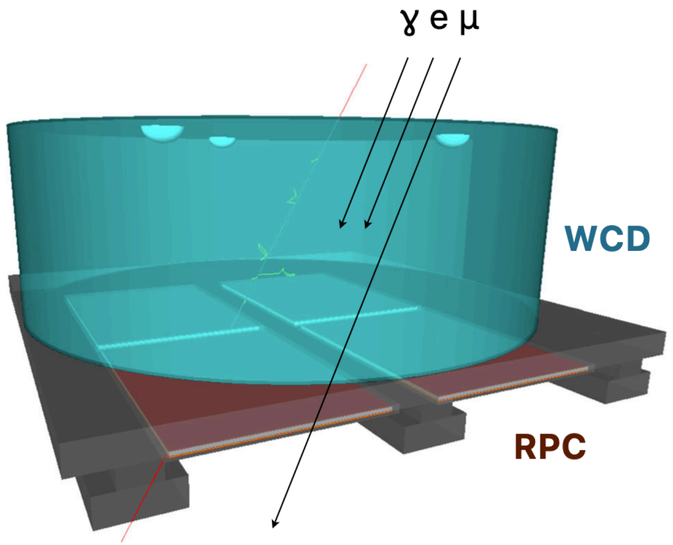
- Use omni-directional atmospheric muons to obtain reference Vertical Equivalent Muon (VEM)
- **There are signs that the WCD stations are ageing**
- Before 2020 it was thought that the systematic uncertainties of the surface detector station alone amounted to $\approx 12\,\%$

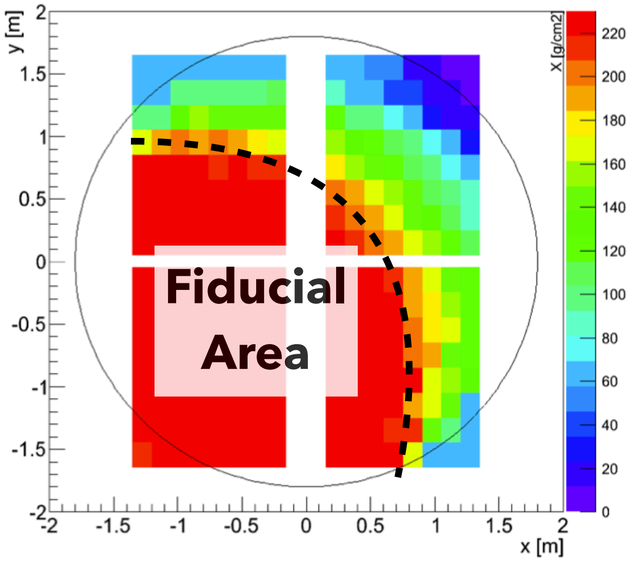


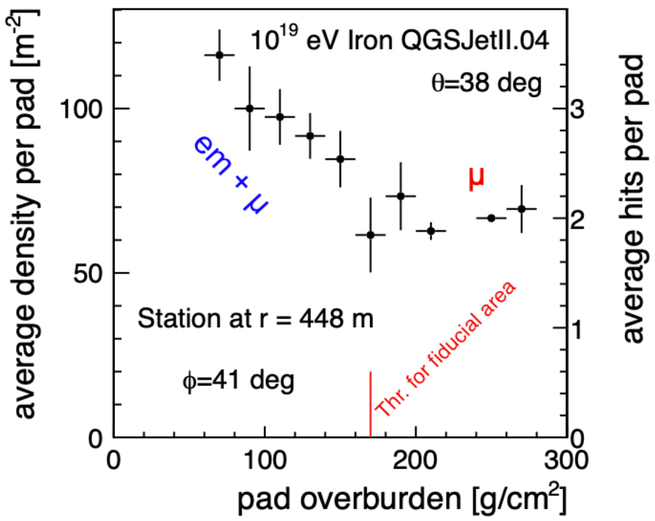
MARTA - **M**uon **A**rray with **R**PCs for **T**agging **A**ir showers

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

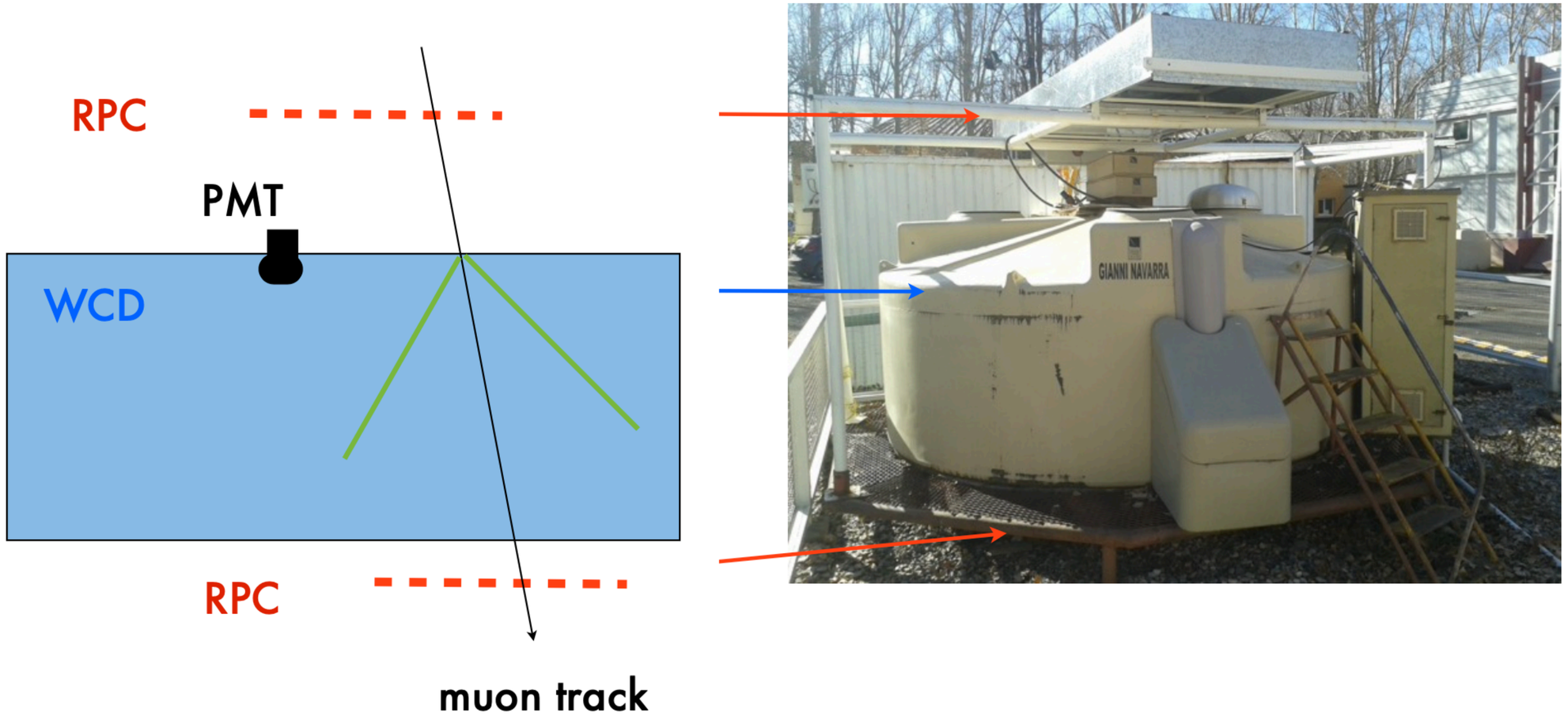
- Combine a water Cherenkov Detector with Resistive Plate Chambers to directly detect the shower muon component
  - Take advantage of the fast timing and segmentation of the RPC





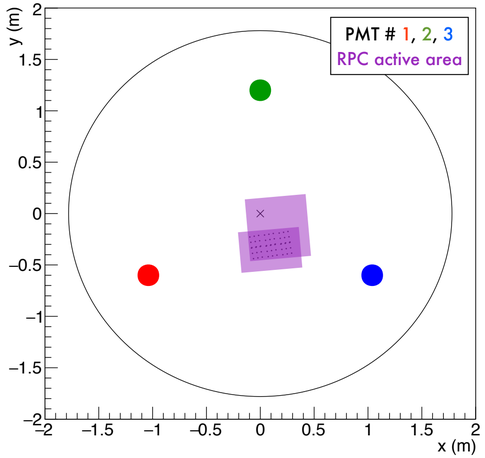


The RPC hodoscope at the Auger test WCD

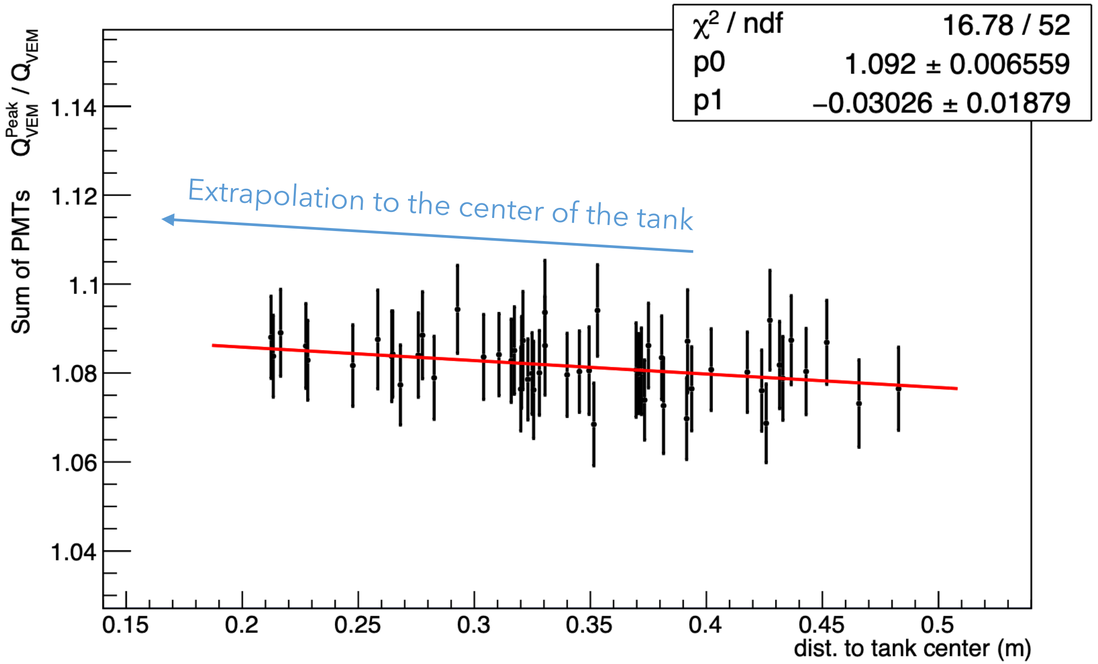


- Resistive Plate Chambers (RPC): position-sensitive detectors
- Trigger on atmospheric muons and study the WCD response for selected trajectories

Results: VEM calibration



- Shower *size* in Auger is given in **VEM unit**
  - The reference is the light detected by the PMTs given the passage a vertical centred muon
  - The ratio omnidirectional/vertical remains the same for a station with more than **10 years** of operation, i.e., no ageing effects on the calibration



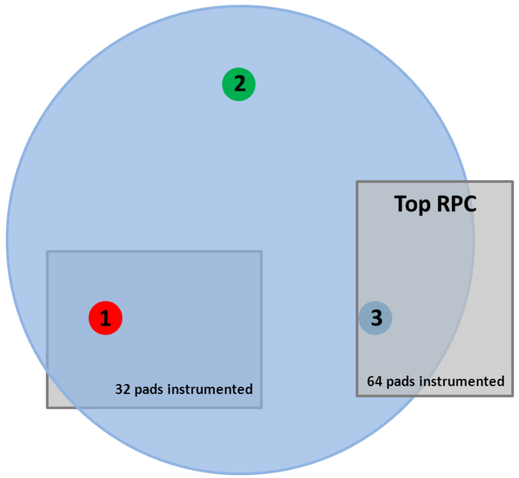
Conversion factor	PMT average	PMT sum
Q^{peak}_{VEM}/Q_{VEM}	1.00 ± 0.02	1.09 ± 0.01
I^{peak}_{VEM}/I_{VEM}	0.92 ± 0.03	

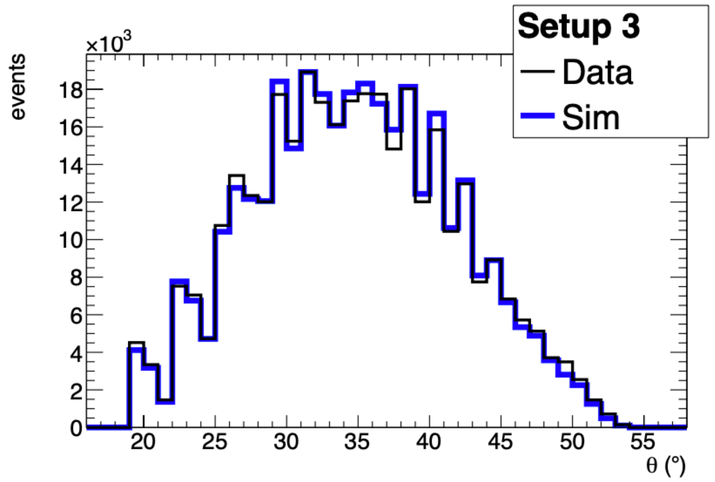
Pierre Auger coll., JINST 15 (2020) 09, P09002

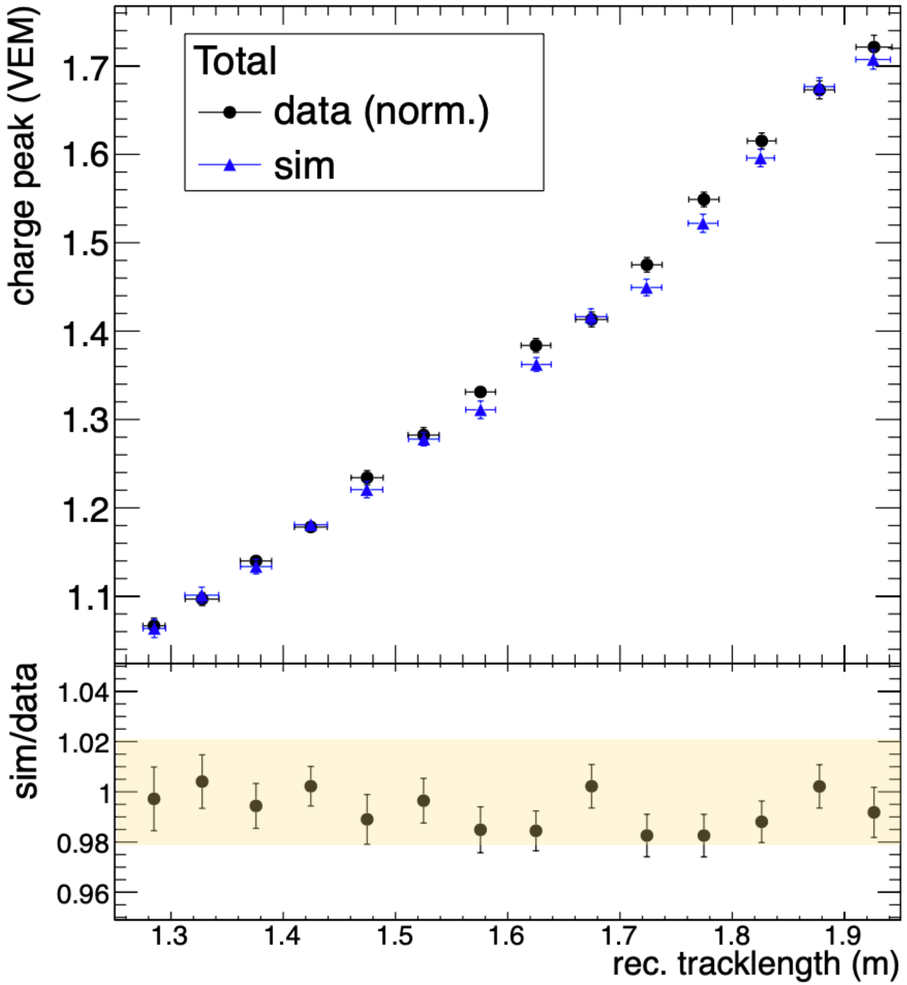
Results: inclined muons

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

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



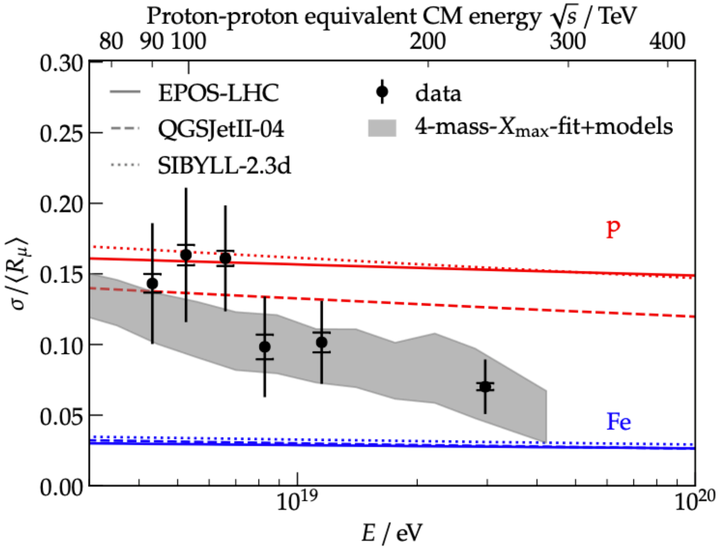


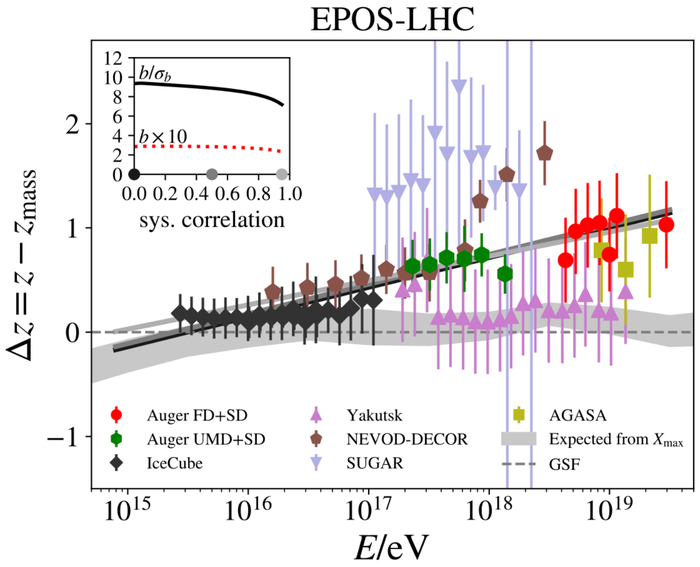


EAS muon puzzle

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

- There's no easy way to explain the apparent excess of muons in data
- SD calibration well understood and allowed to investigate the relative muon fluctuations
  - Whose agreement with model predictions suggest that the problem might be connected to lower energy hadronic interactions
- Confirmed by the combination of the data of 9 cosmic ray experiments (WHISP)

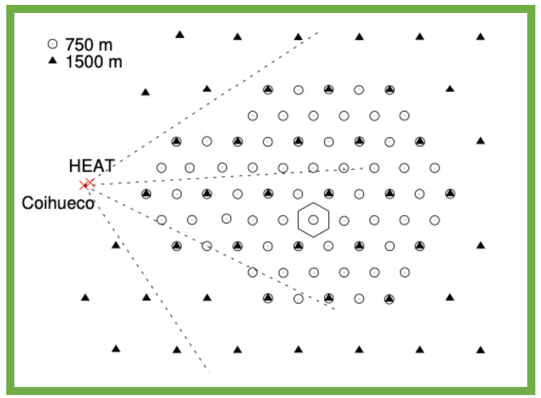




Multi-hybrid shower events

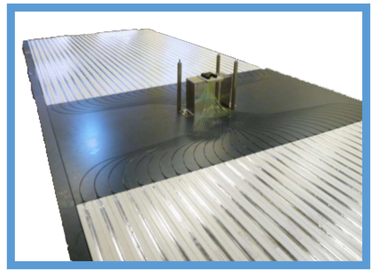
(A plethora of measurements to fully understand the shower)

HEAT



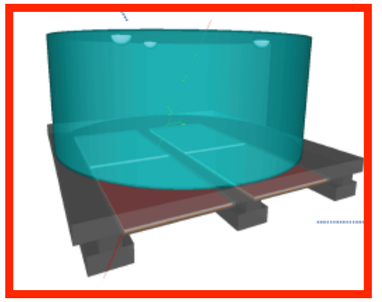
LHC c.m. energy equiv to first interaction

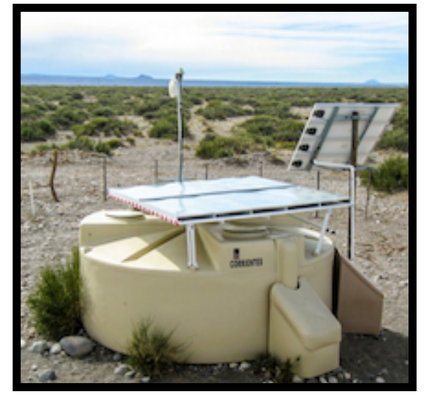
Radio



AMIGA

MARTA



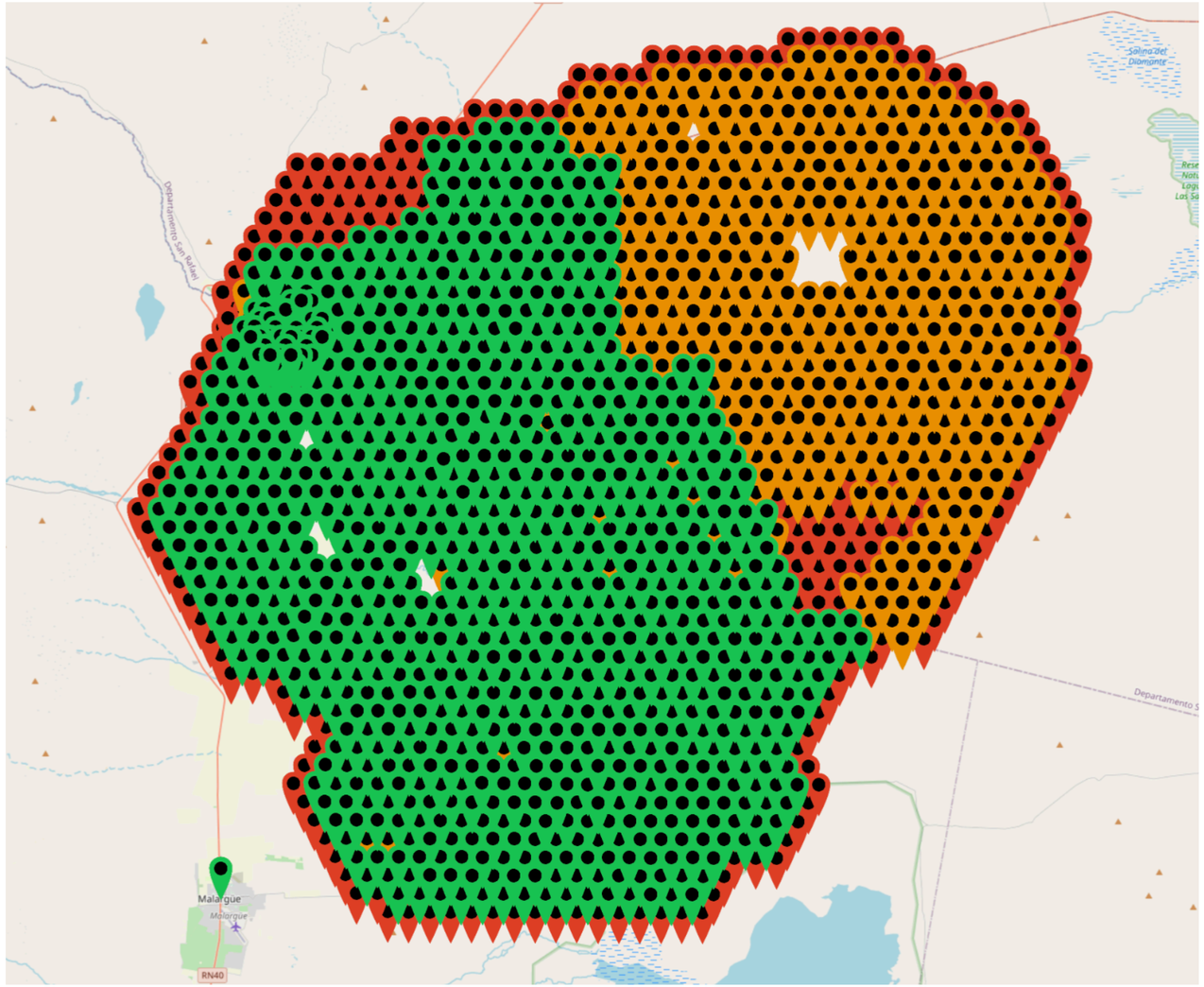


Infill

Auger Prime (SSD)

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

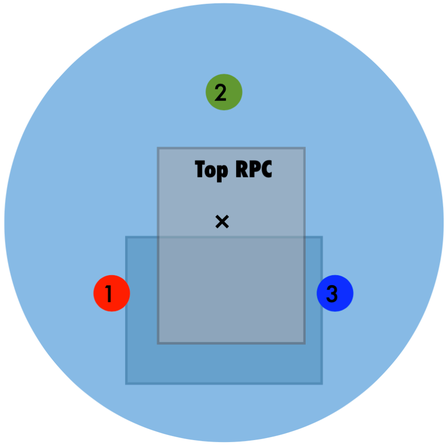
Auger Prime (SSD + WCD)

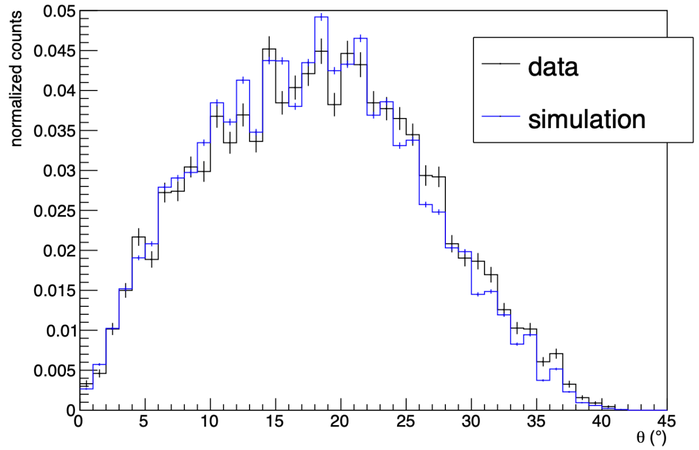


- Upgrade should be completed at the beginning of next year
- Crucial assess the calibration of the scintillator (SSD) and the WCD

Back to the calibration with the RPC hodoscope

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





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

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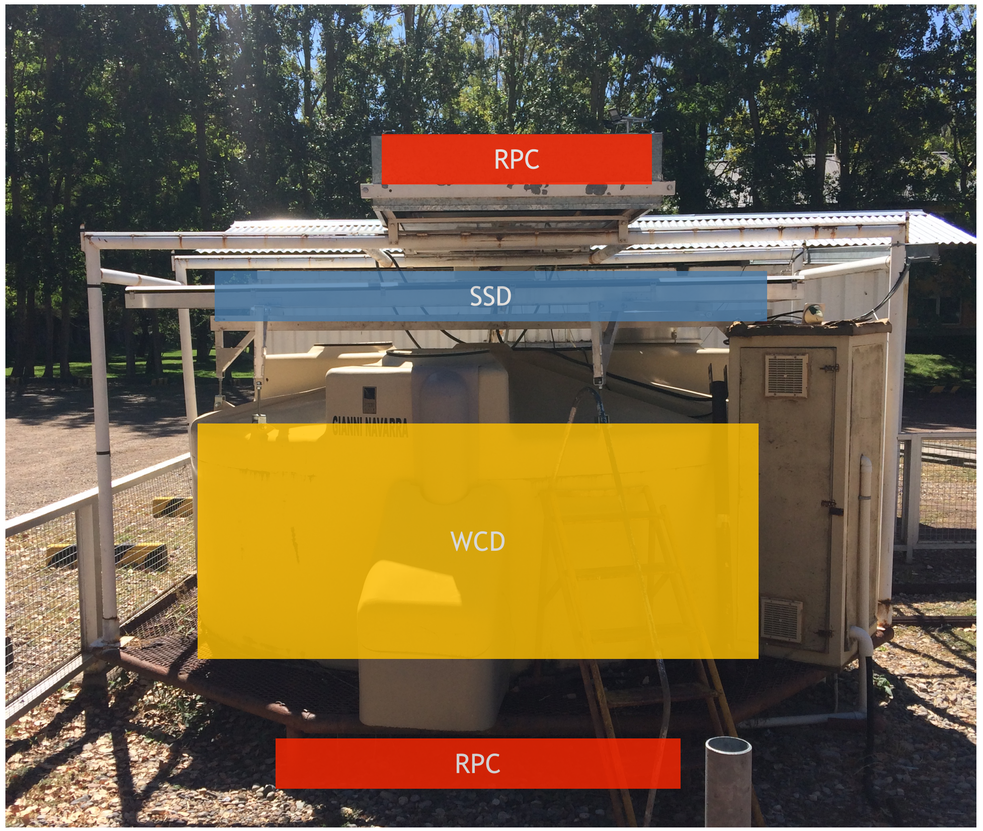
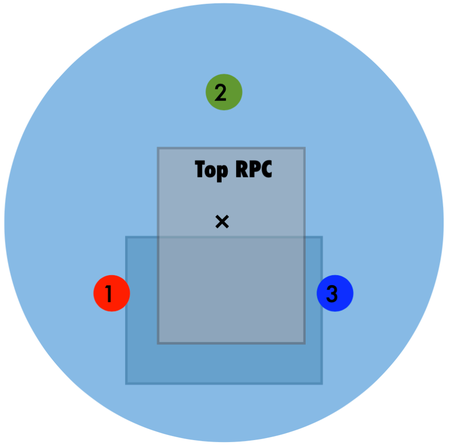
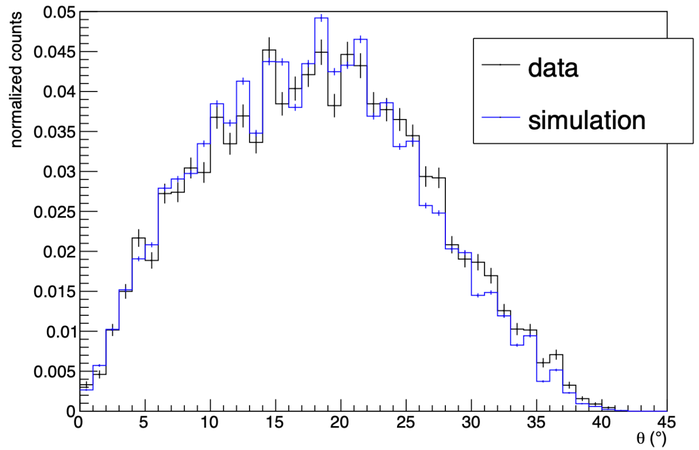


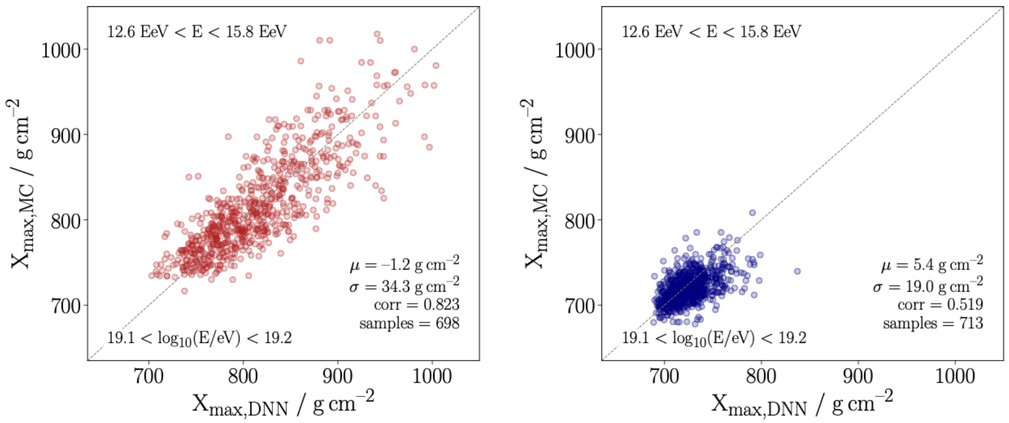




- The data acquisition system was also upgraded to cope with the new electronics board of the WCD and have a more robust/faster acquisition system

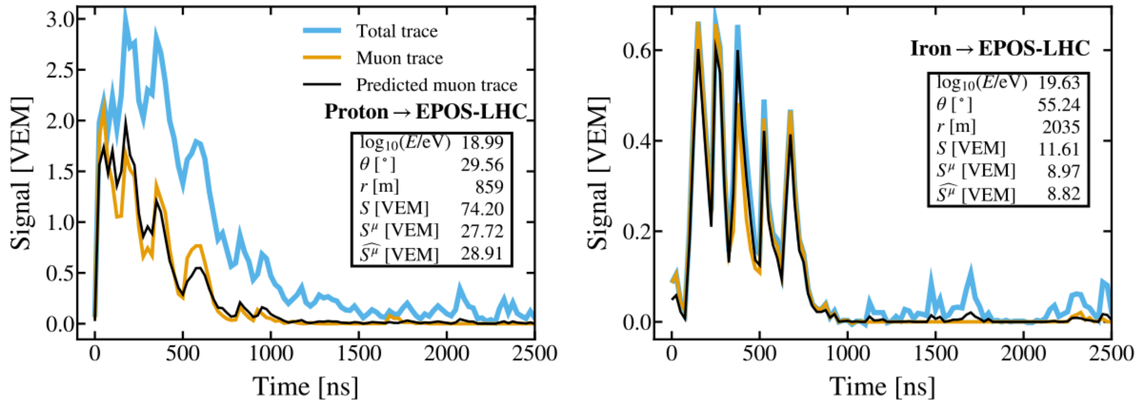
The dawn of Machine Learning @ Auger

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



Extraction of Xmax from the SD ground signal

Pierre Auger coll., JINST 16 (2021) 07, P07016



Extraction of Nmu from the WCD signal for vertical showers

- Both method have good resolutions comparable to those achieved with hybrid events
- Algorithms highly dependent of simulations and might be picking up unknown less controlled shower characteristics
- It is vital to create strategies to achieve self consistent solutions ⇒ RPC hodoscope

Summary

The ability of Auger to scrutiny the shower physics mechanisms will dramatically improve in the coming years

To take the full potential of multi-hybrid events calibration and detector systematic uncertainties will need to be mitigated

The RPC hodoscope will certainly take an important part on this endeavour

Acknowledgements

FCT Fundação para a Ciência e a Tecnologia

Lisb@20[20]

COMPETE 2020
PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

PORTUGAL 2020

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

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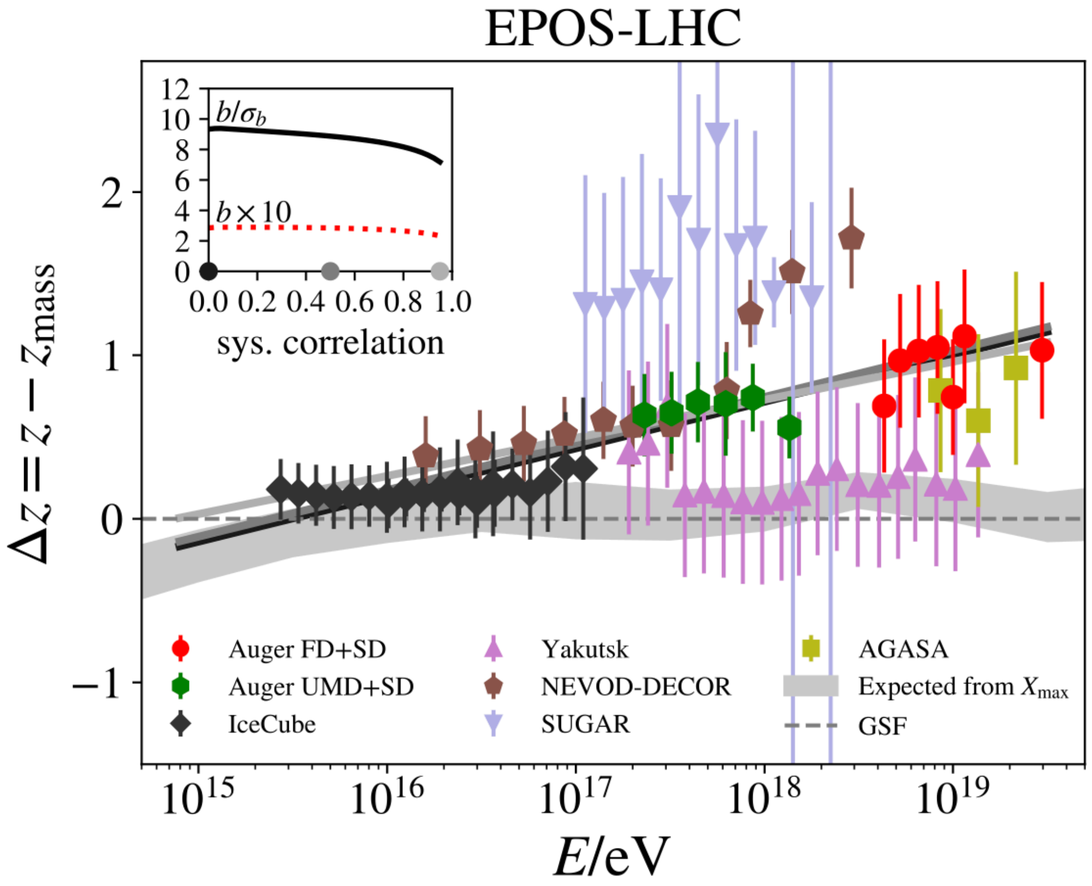
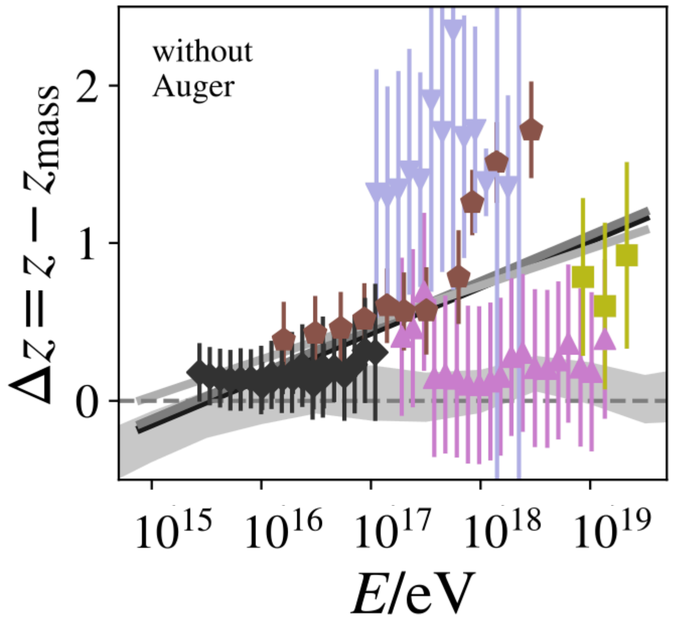
Backup Slides

WHISP muon excess

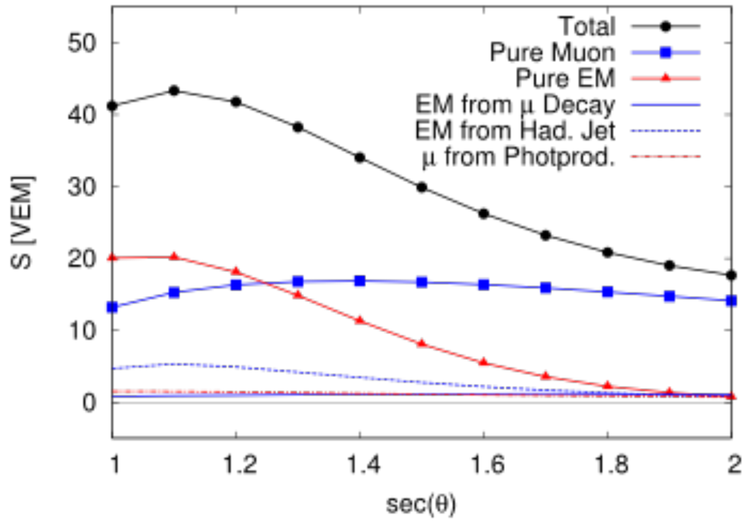


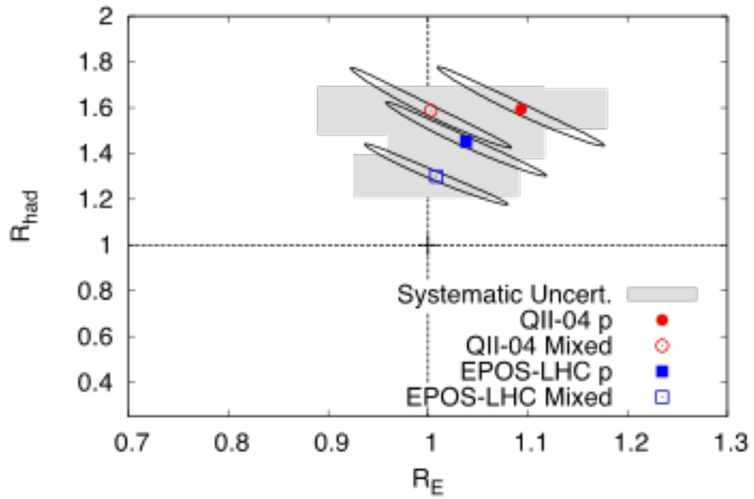


Explore hybrid events

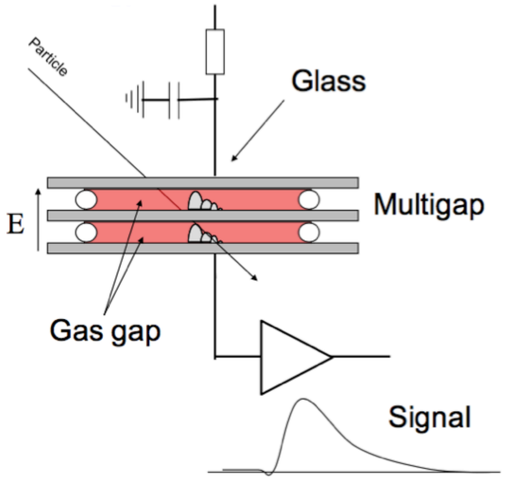
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had})
  - $S_{\rm resc}(R_E, R_{\rm had})_{i,j} \equiv R_E S_{EM,i,j} + R_{\rm had} R_E^{\alpha} S_{{\rm had},i,j}$
- Findings:
  - No need for an energy rescaling
  - Hadronic signal in data is significantly larger with respect to simulations

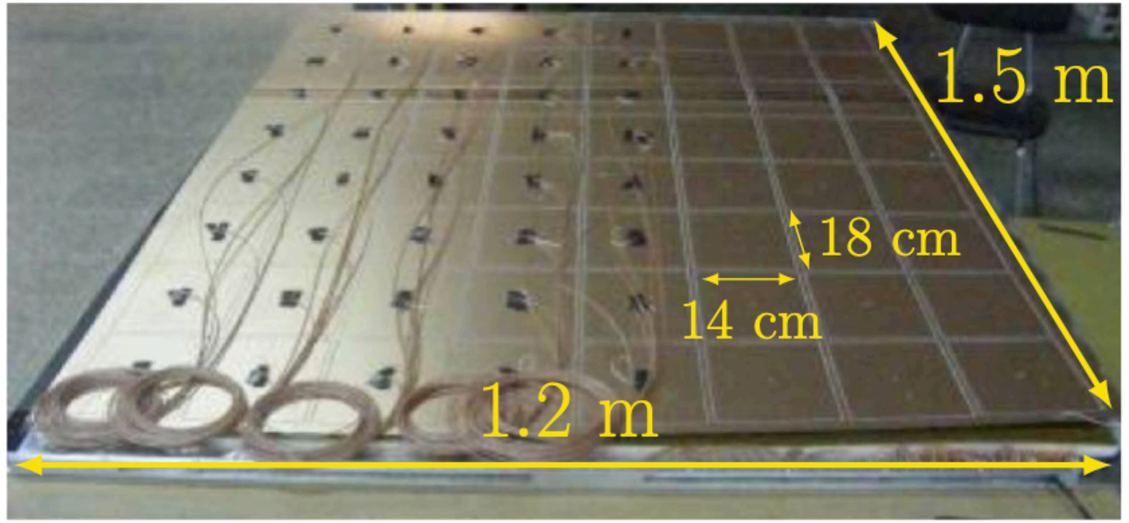
Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

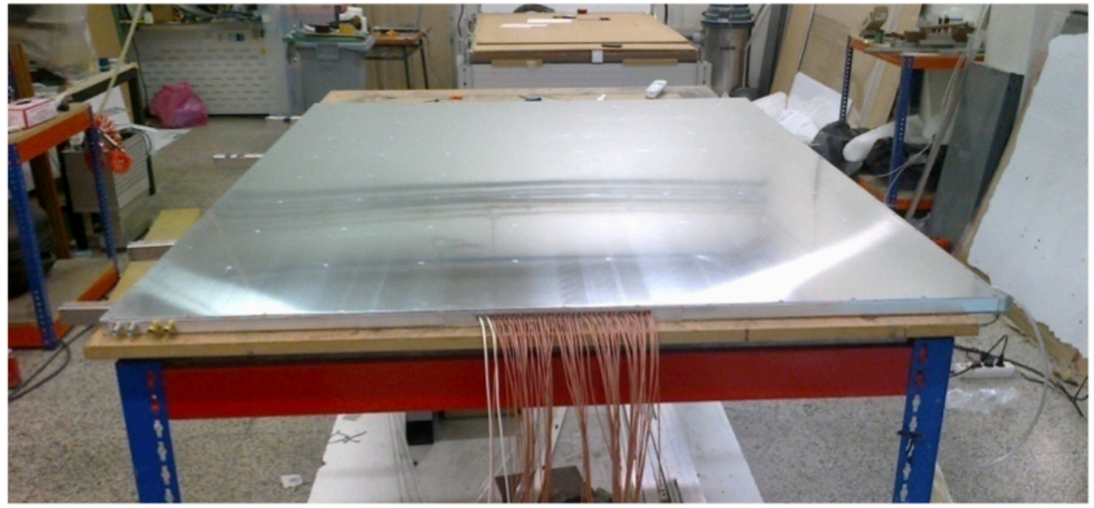




RPCs







Peter Mazur WCD station