The Pierre Auger Observatory





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• Particles from above:

- Charged
 - electrons
 - Protons
 - Nuclei
- Neutral
 - Photons
 - neutrinos



Cosmic Rays – (rare) free energetic particles

Cosmic Ray Spectra of Various Experiments



https://web.physics.utah.edu/~whanlon

10²¹

Cosmic Rays – particle physics in space



https://web.physics.utah.edu/~whanlon



Extensive Air Showers





Extensive Air Showers (EAS) – a disk of particles to be sampled





...a hybrid detector











Auger – Fluorescence detector quasi calorimetric measurement

An UV telescope observing the atmosphere

Particles from shower ionize Nitrogen Nitrogen de-excitation emit UV light









Auger – Surface detector Sample the particle disk

Cherenkov Water Tank Detectors



vertical muon







Cosmic Rays – particle physics in space

The GZK effect

Energy/10²⁰ eV



Some questions answered

How Many?





At the same time...

Elongation rate, the development of shower



Transition to shallower showers



Combined fit



2

Can we explain the spectrum suppression via source exhaustion

Ups...

The change in spectra can be due to source exhaustion Primary composition is changing... Muons can give a hint to the composition... Let's look at the muons!



AUGER needs to upgrade: Auger Prime



Upgrades

The Pierre Auger Observatory Upgrade

"AugerPrime"

Preliminary Design Report



The Pierre Auger Collaboration April, 2015



arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

AugerPrime

- 3.8 m² scintillators (SSD) on each 1500-m array station
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750-m array (AMIGA)
- increased FD uptime



SSD – More sensitive to e.m. Tank – More sensitive to muons But... No perfect separation Add a segmented detector under the tank \rightarrow get only the muons





The amount of material crossed can be accurately computed for each pad and each shower geometry

The chosen detector - RPC

Resistive Plate Chamber

- Gaseous detector
- Planar geometry
- uniform electrical field imposed.
- High resistive plates in between the electrodes limit the avalanche current.
- Signal is picked up by the induction of the avalanche in the readout pads.



Avalanche mode





SIGNAL PICKUP MODULE



Total area $150x120 = 18000 \text{ cm}^2$

Area covered with pads, "efficient" area 64x18x14=16128 cm² ⇔ 90 % of the total area

Area covered with guard rings, 18000 - 16128 = 1872 cm² \Leftrightarrow 10 % of the total area





The RPC module





Electronics box (1285 x 407 mm²)

Designed, developed, built @ LIP



LIP Group Activities



• Get better data with a new detector

1

• "Calibrate" the standard detector

Approach #2:

- Develop new observables
- Study the interactions in the atmosphere

2

Development of new observable

- Shower Physics and Data Analysis
 - Focus on the EAS muon distributions
- Hadronic Models and interface with accelerator measurements
 - Impact on showers
- Example:

Lorenzo Cazon, Ruben Conceição, Miguel Alexandre Martins, and Felix Riehn: <u>"Constraining the energy</u> <u>spectrum of neutral pions in ultra-high-energy protonair interactions"</u>, *Phys. Rev. D 103, 022001*

• Exploring the relation between tail of muon distribution and energy spectrum of pions from first interactions.

Shown for the first time that it is possible to access the first interaction multi-particle production properties!



 $\Lambda_{\mu} \Lambda_{\alpha}$ are the slopes of exp. fit

Measure Muons and its fluctuations

Improve the analysis to measure the fluctuation on the number of muons

For a limited set of events (inclined events), Auger can measure the muon content

Average is not compatible with models Underestimated in simulations

Fluctuations is compatible with models



The Muon Puzzle



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

Group Activities

- Detector performance and calibration
 - Study the tank performance; Measure response to muons Hodoscope installed in test-tank
 - Test and calibrate SSD detectors: follow up of detailed tank studies
- MARTA RPCs R&D
 - R&D for MARTA and future experiments
- MARTA Engineering Array
 - Operate a small array of RPC underneath the tank (Comissioning in a couple of weeks)
 - Study the muon component
 - Explore capabilities near the core
 - Cross-calibrate detectors (tank, Marta, Amiga, SSD)
- Shower Physics and Data Analysis
 - Measurement of muon distributions and EAS muon energy spectrum
 - Impact of novel physics in EAS
- Hadronic Models and interface with accelerator measurements
- Low energy extensions (Multi-messenger events)
 - Possible synergies with SWGO
- Education and Public Outreach
 - Masterclasses



MARTA capabilities

- Muon distributions with MARTA
- Can we measure the distribution tail and access the first interaction pion energy spectrum?
- Yes, provided that we get enough muons
 - Need to measure muons near the shower core



Miguel Martins

Use MARTA to get near the shower

- At low energies (10¹⁷eV)
- Saturation prevents us to have measurements near the shower core
- Lower number of muons far from core
- Extend MARTA DAQ mode to get into the shower core



Apply novel analysis

- Novel analysis for shower classification (shower azimuthal fluctuations)
 - Developed in the context of SWGO
 - Can it be applied in Auger?
- Can we extend the shower identification? Measure the muon content by higher level analysis?



QGP?

- Cosmic Rays provide a very high energy environment
- Could QGP get turned on?
- What are the influence in the shower development?
- What are the signatures on ground?
- Tweak the hadronic simulation codes to include the phenomena



Look at sky

- Auger provides a unique instrument to look for very high energetic particles from the sky
- The upgrade will boost shower classification
- Can we search the sky? Namely look at photon sources? Do we have sufficient discriminant power? Can we improve it with new instruments?

Thank you



Acknowledgements









Pedro Assis - SWGO meeting NOV2020

Participation in the Pierre Auger Observatory



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- CERN/FIS-PAR/0020/2021: UHECR Physics with the Pierre Auger Observatory, Ruben Conceição
- CERN/FIS-PAR/0012/2021: Enhancement of the measurement capabilities of the Pierre Auger Observatory, Pedro Assis
 - R. Conceição is leader of the Shower Physics task

Lorenzo Cazon, Ruben Conceição, Miguel Alexandre Martins, and Felix Riehn: <u>"Constraining the energy</u> <u>spectrum of neutral pions in ultra-high-energy protonair interactions"</u>, *Phys. Rev. D 103, 022001*

Pierre Auger Collaboration Measurement of the Fluctuations in the Number of Muons in Extensive Air Showers with the Pierre Auger Observatory. Phys. Rev. Lett. **126**, 152002

Pierre Auger Collaboration "Extraction of the muon signals recorded with the surface detector of the Pierre Auger Observatory using recurrent neural networks", J. Instrum. 16 (2021) P07016

Pierre Auger Collaboration "Calibration of the underground muon detector of the Pierre Auger Observatory", J. Instrum. 16 (2021) P04003

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The Pampa Argentina



The Detector field



Making precision measurements to shed light on what's the muon content

The muons "problem"

"number" of muons Measured by tanks



Depth of shower – Measured by FD

The MARTA Engineering Array

FCT – FAPESP project

(Portugal – Brasil)

Results from a specific call FAPESP-FCT

- RPC R&D
- RPC technology @ Brasil
- Build RPC detectors
- Install EA (hexagon) in Auger

Synergies with AugerPrime

- RPC hodoscopes for testing SSD
- Cross-calibration
- Physics at E=10^17 eV





Install a unitary cell (hexagon) In the infill area, in AMIGA tanks

The support structure

Precast structure built at the observatory Transported to the field Installed in a couple of hours (Emptying/Filling the tank is more time consuming)

















The modules

4 modules of RPC to be installed in each station Triggered by the WCD

The active medium







Read-out: Segmentation





The MARTA module

Each module contains:

- Sensitive volume
- Pickup system
- sensors
- Enclosure
- Annex:
 - •DAQ
 - •HV
 - •PSU
 - Control Board
 - Bubbler



The MARTA module



MARTA Readout System



RPC channel



RPC channel



First field station



Spin-offs

Hodoscopes to test other detectors







Telescopes for muon-graphy





<u>www.lip.pt</u> pages.lip.pt/auger/

Thank you