Ultra-high energy cosmic rays (UHECRs) and the muon problem – an introduction

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Physics of UHECRs in a nut shell

Deflection in Galactic and extragalactic mag. fields
Energy loss due to interaction with background radiations (GZK effect)

LHC: 27 km circumference

Need accelerator of size of Mercury orbit to reach $10^{20}$ eV with LHC technology

$B \sim 10^{-6} \text{ G}$

$B \leq 10^{-9} \text{ G}$

Kotera & Olinto, ARAA 2011

(Unger, 2006)
The Pierre Auger Observatory

- 3 fluorescence detectors (24 telescopes in total)
- Infill array of 750 m (63 stations, 23.4 km²)
- AERA - Auger Engineering Radio Array
- World’s largest radio experiment for CR-physics.
- Profiting from 3 other nearby CR-detectors:
  - High quality data, ext. trigger, ...
- 100% duty cycle.
- Energy threshold \( \ll 10^{17} \) eV.

- 1665 surface detectors: water-Cherenkov tanks (grid of 1.5 km, 3000 km²)
- Radio antenna array (153 antennas, 17 km²)
- Infill array of 750 m (63 stations, 23.4 km²)
- LIDARs and laser facilities
- 4 fluorescence detectors (24 telescopes in total)
- High elevation telescopes

- 500 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina
Telescope Array (TA)

Northern hemisphere: Delta, Utah, USA

~30 km

- Central Laser
- Lidar, IR camera
- Electron Light Source

Calibration Facilities

507 surface detectors: double-layer scintillators (grid of 1.2 km, 680 km²)

3 fluorescence detectors (2 new, one station HiRes II)

Middle Drum: based on HiRes II

Infill array and high elevation telescopes

LIDAR Laser facility

Electron light source (ELS): ~40 MeV

Beam Operation:
- Sep. 2nd-4th
  - Beam shot into the Sky: Sep. 3rd and 4th
  - # of Shot into the Sky: 1800 pulses
  - Output power = 41.4 MeV
  - 40 MeV
  - 40 pC/pulse
  - 0.5 Hz

Test setup for radar reflection
Hybrid detection of UHECRs

Example: event observed with Auger Observatory

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

$E_{\text{cal}} = \int_0^{\infty} \left( \frac{dE}{dX} \right)_{\text{obs}} dX$
Highlights of flux measurements

(Auger & TA, Deligny et al, ICRC 2019)

Auger and TA data are compatible with each other, highest energies under investigation

New feature at $1.3 \times 10^{19}$ eV

Highlights of composition measurements

Auger and TA data are compatible with each other

Interpretation depends on models

Auger, ICRC 2017 & 2019
Auger, Phys. Rev. D 2014
Highlights of anisotropy measurements

6.5% dipole at 5.2 sigma
Science 357 (2017) 1266

Centaurus A
$E_{th} = 37$ EeV
$\psi = 28^\circ$
$n_{obs} = 203$  $n_{exp} = 141$
local $p$-value=1.5x10^{-7}
post-trial : 3.9$\sigma$

Particle physics (new particles and phenomena)

**Photon limits**

![Photon limits graph]

Auger Letters of Interest related to UHE photons:
SNOWMASS21-CF7_CF3-NF4_NF0_Jaime_Alvarez-Muniz-140
SNOWMASS21-CF1_CF7-203

**Super-heavy particles**

![Super-heavy particles graph]

Violation of Lorentz invariance
(propagation of UHECR, shower development)

CF7 CF0 Yoshiki Tsunesada-265
Particle physics (hadronic interactions)

\[ \sigma_{X_1} = \lambda_{\text{int}} \]

\[ \lambda_{\text{int}} = \frac{\langle m_{\text{air}} \rangle}{\sigma_{p-\text{air}}} \]

Importance of hadronic interactions at different energies

Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

Muons: majority produced in ~30 GeV interactions

Global shower properties and the shower maximum are sensitive to the highest energy interactions. Muons in air showers are sensitive to the hadronic cascade over all energies. → Large problem in predicting the overall muon number is small problem on the level of individual interactions.

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Shower particles produced in 100 interactions of highest energy

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(Ulrich APS 2010)
Muon production at large lateral distance

\[ E_{\pi^\pm, \text{dec}} \sim 30 \text{GeV} \]

Typically 8-10 interactions

Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon

\[ E_0 = 10^{19} \text{ eV} \]

(Maris et al. ICRC 2009)
Ultimative test: simulation of individual events

Phenomenological model ansatz

Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

Full detector simulation after re-scaling

None of the models gives a really good description
Muon number in inclined showers

Shower size attenuation

Number of muons in showers with $\theta > 65^\circ$

Combination of information on mean depth of shower maximum and muon number at ground

Several measurements: strong indications (evidence?) for muon discrepancy

(Auger, PRD91, 2015)
AMIGA – buried muon detectors

- Direct counting of muons
- Energy range overlapping with LHC c.m. energy
- Composition and hadronic interactions

Scintillation counters:
- 61 positions
- 30 m² each
- 750 m spacing
- 2.5 m of soil

(Auger, EPJ 2020)
Muon excess seen by many experiments

Other effects also present: possible dependence on shower age, lateral distance, energy threshold.

Subtracting mass-effect (here estimated by GSF, other choices possible) to make energy-dependent trend more visible.

Correlation or causation?

Average lateral distance of data also increases with energy (WHISP working group, Cazon et al., ICRC 2019).

What we have learned:

- Combining measurements is very powerful
  - Greatly extends phase-space coverage
  - Allows for cross-checks
  - Reasonable agreement in very diverse experiments

- Challenges and solutions
  - Muon measurements differ in many details
  - Convert to comparable quantity $z$
    - Muon density depends on uncertain mass composition
  - Subtract effect using other variable (e.g. $X_{\text{max}}$) or model (e.g. GSF)
  - Alternative: Select protons (only deep showers) or iron (via direct Cherenkov light)
    - Muon density offset almost proportional to energy scale offsets
  - Cross-calibrate relatively by matching fluxes of air shower experiments
  - Cross-calibration globally with model like GSF

Mathematical expression:

$$z = \frac{\ln N_{\mu}^{\text{det}} - \ln N_{\mu,\mu}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,\mu}^{\text{det}}}$$

Graphs showing data from EPOS-LHC and QGSJet-II.04 for different energy ranges.

Legend:
- Pierre Auger
- AMIGA [Preliminary]
- IceCube [Preliminary]
- NEVOD-DECOR
- SUGAR
- Yakutsk [Preliminary]
- Kampert & Unger 2012

(WHISP working group, Cazon et al., ICRC 2019)
Shower-to-shower fluctuation of number of muons

Mean number of muons depend on whole chain of hadronic interactions
Fluctuations are driven by multiplicity & energy distribution fluctuations of first interaction

Model scenarios for increasing number of muons

1 Baryon-Antibaryon pair production  
(Pierog, Werner 2008)
- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly low-energy muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Leading particle effect for pions  
(Drescher 2007, Ostapchenko 2016)
- Leading particle for a $\pi$ could be $\rho^0$ and not $\pi^0$
- Decay of $\rho^0$ to 100% into two charged pions
- Unknown leading particle effects?

3 New hadronic physics at high energy  
- Quark-gluon plasma formation (collective effects)
- Inhibition of $\pi^0$ decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

30% chance to have $\pi^0$ as leading particle

Decay of leading particle
**TAX4 Project**

**TA SD (~3000 km²): Quadruple area**
- Approved in Japan 2015
- 500 scintillator SDs
- 2.08 km spacing
- 3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

**2 FD stations (12 HiRes Telescopes)**
- Approved US NSF 2016
- Telescopes/electronics being prepared at Univ. Utah
- Site construction underway at the northern station.

**Get 19 TA-equiv years of SD data by 2020**
- Get 16.3 (current) TA years of hybrid data

*(Kido, Matthews ICRC 2017)*
Upgrade of Auger Observatory: AugerPrime

- Scintillators (3.8 m²) and radio antenna on top of each array detector
- Composition measurement up to $10^{20}$ eV
- Composition selected anisotropy
- Particle physics with air showers

(AugerPrime design report 1604.03637)
AugerPrime – first data

![AugerPrime site](image1)

![AugerPrime setup](image2)

**Energy Fluence [eV/m²]**

**Signal Density [VEM/m²]**

**Muon Density [1/m²]**

**Shower Plane Distance [meter]**

- Water Cherenkov Detector
- Scintillator Surface Detector
- Underground Muon Detector
- Radio Detector

May 14, 2019

\[ \frac{E}{E_{\text{eV}}} = 73.5 \pm 1.6 \]

\[ \theta / \circ = 45.20 \pm 0.12 \]