Particle physics in cosmic rays



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Outline:

- > Introduction
- > Auger measurement
- > Muon puzzle
- > Summary

See for more details: https://arxiv.org/abs/2110.02685

Promienie kosmiczne-Astronarium 120 https://youtu.be/QV6ZbbbV6rY **1912:** Discovery of ionizing radiation of cosmic origin by Victor Hess

> charged particles (mainly proton)

> It increases as the balloon gains altitude

The background radiation is of **cosmic origin!**



A brief history of cosmic rays

Beginning of the *XXth* century: electroscopes are used to measure the radioactivity of materials.

Discharge of electroscopes in the absence of any ionizing source → **existence of background radiation!**

What is its nature ?





2. Altitude variation of ionization. (a) Balloon ascent by Hess (1912) carrying two ion chambers. (b) Ascents by Kolhörster (1913, 1914) using ion chambers. (c) Coincidence counter telescope flown by Pfotzer (1936).

The Ultra-High-Energy Cosmic Ray mystery



Particle physics beyond the reach of colliders

> What's their composition?

> Where do they come from?

→ anisotropies weakly correlated to known possible sources: active galactic nuclei, gamma-ray burst,...

> How do they reach such tremendous energies?

Spectrum suppression:

in the past: the GZK cut-off **now**: rather the efficiency limit of particle acceleration by sources



Need accelerator of size of Mercury's orbit to reach 10²⁰ eV with LHC technology

(Unger, 2006)

UHECRs: Flux of cosmic rays and interaction energies



> At ultra-high-energies (> 10¹⁷ eV) particle physics beyond the reach of colliders Need accelerator of size of Mercury's orbit to reach 10²⁰ eV with LHC technology

UHECRs: Flux of cosmic rays and interaction energies



Different phase space for LHC and air showers:

- > most of the particles produced at midrapidity important for models
- EAS: N_{particle} ~ E, most of energy carried by forward (backward) particles - important for air showers
- > More LHC data needed in the forward directions and for heavier targets to fill required



 $\eta \equiv -\ln(\tan(\theta/2))$

- $\eta=0~(heta=90)$ is midrapdity
- $\eta \gg 1$ is forward $\eta \ll 1$ is backward



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Shower development depends on primary particle



C J.Oehlschlaeger, R.Engel, FZKarlsruhe

PHOTON

Shower development depends on primary particle

muons

electrs

hadrons neutrs





PROTON



Proton 10¹³ eV

21336 m

© J.Oehlschlaeger, R.Engel, FZKarlsruhe

Shower development depends on primary particle

electrs

25000 N 20000 15000 10000 5000 200 150 100 50 0 աստությունությունությունությունություն -20000 -150 -100 -50 0 50 100 150 -200 -50 -100 -150

muons



hadrons neutrs



@ J.Oehlschlaeger, R.Engel, FZKarlsruhe

lron 10 ¹³ eV

IRON

24929 m

Electromagnetic showers: Heitler model



third edition, 1954. Section 38

Electromagnetic showers: Cascade equations

Energy loss
$$\frac{dE}{dX} = -\alpha - \frac{E}{X_0}$$

of electron: $\frac{dE}{dX} = -\alpha - \frac{E}{X_0}$
Radiation length: $X_0 \sim 36 \text{ g/cm}^2$

Cascade equations

$$X_{\text{max}} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad \qquad N_{\text{max}} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}} \frac{E_0}{E_c}$$

(Rossi & Greisen, Rev. Mod. Phys. 13 (1940) 240)

Monte Carlo implementation of Cascade equations:

CORSIKA (COsmic Ray Simulations for KAscade): program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries, see https://www.iap.kit.edu/corsika/

Air shower and its connetions to hadronic interactions



Hadronic interactions models

> Hadronic interaction models commonly used to simulate EAS were updated to take into account LHC data at 7 TeV: QGSJETII-04 Phys. Rev. D 83, 014018, EPOS-LHC Phys. Rev. C 92, 034906, and SIBYLL-2.3C Phys. Rev. D 80, 094003



The p-p cross section is very well described up to the LHC energy (extrapolation up to the highest energies is very similar between models).

... but differences in the extrapolations of the p-air and π -air inelastic cross-sections

> More LHC data needed in the forward directions and for heavier targets.

Hadronic interactions models

> Only small differences in p-p model predictions - main difference in high multiplicity tail



> The extrapolations of p-p data to highest energies have large uncertainties

Extended air showers



Pierre Auger Observatory - the largest UHECRs observatory

> Water-Cherenkov stations

→SD1500 : 1600, 1.5 km grid, 3000 km²

⇒SD750 : 61, 0.75 km grid, 25 km²

> Fluorescence Sites:

➡ 4 sites, 24 telescopes, 1-30deg FoV

HEAT: → 3 high elevation FD, 30-60 deg FOV



Surface Water Cherenkov Detectors (SD's)



Fluorescence Telescopes (FD's)



Fluorescence Telescopes (FD's)

FD telescopes at Los Morados





Hybrid reconstruction

> Detection of air shower

Invisible energy fraction



Mass composition with FD

> Depth of shower maximum X_{max} is an observable sensitive to the mass composition



 $X_{max}(Fe) < X_{max}(p) < X_{max}(\gamma)$

$RMS[X_{max}(Fe)] < RMS[X_{max}(p)]$



> The asymmetry, R, and the width, L, in data agree well with the predicted values for all models

Influence of hadronic models parameters



X_{max} and its RMS sensitive to

High-precision measurements from LHC, see e.g.

inelastic cross-section (very sensitive)

X_{max} is dominanted by first interactions and related mostly to electromagnetic component of EAS

The average shape of profile is well reproduced by the Gaisser-Hillas parametrization and agree well with predictions from hadronic interaction models, The Pierre Auger Collaboration, JCAP03(2019)018

Impact of hadronic interaction features on the shower maximum



p-Air cross-section method





> The data agree with an extrapolation from LHC energies to 57 TeV for a limited set of models.

Models show contradictions in the interpretation of X_{max}

> Above E= 2 EeV both X_{max} moments become compatible to MC predictions for heavier nuclei



A.Yushkov for the Pierre Auger Collaboration, ICRC 2019



Method to interpret X_{max} and $\sigma^2(X_{max})$: The Pierre Auger Collaboration, JCAP 02 (2013) 026

$$\langle X_{\text{max}} \rangle = \langle X_{\text{max}} \rangle_p + f_E \langle \Pi A \rangle$$

 $\sigma^2(X_{\text{max}}) = \langle \sigma_{\text{sh}}^2 \rangle + f_E^2 \sigma^2(\ln A)$

- > <In A> and $\sigma^2(\ln A)$ vary depending on hadronic interaction models
- > Trend is similar, but not in absolute value

 > QGSJET-II.04 predicts shower-to-shower fluctuations larger than mass range considered. X_{max} distributions not well
 predicted, leading to unphysical results.

Muon production by low energy interactions



> Muons are produced late in shower cascade, amplified sensitivity to hadronic interactions



Muon production depth



- > Two assumptions:
 - muons are produced in the shower axis
 - muons travel following straight lines

Muon production depth X^{μ}_{max} and X_{max}

Pierre Auger Collaboration, Phys. Rev. D 90, 012012 (2014); M. Mallamaci for the Pierre Auger Collaboration, ICRC 2017



> two independent mass composition measurements, both results should be between p and Fe
 > both results should give the same mean logarithmic mass for the same model
 > ... as we can see results from X^µ_{max} are incompatible with the one from X_{max}

Muon production depth X^{μ}_{max} : discussion

> Data from the Pierre Auger Observatory can be used to constrain diffraction in pion interactions to get consistent results between the mean logarithmic mass extracted from X^µ max and the one deduced from X max

The Pierre Auger Collaboration, Phys. Rev. D 90, 012012 (2014)





- > Idea: compare hybrid data with simulated showers
 - match longitudinal FD light profile data with best simulation profile (p, He, N, Fe)
 - extract S_{EM} and S_{had} from simulation
 - rescale simulated SD signal to match data (extract R_E and R_{had})

Muon studies with hybrid events (<60°)

The Pierre Auger Collaboration, Phys. Rev. Lett. 117, 0192001 (2016)

> Fit adjusting EM and muonic 2 contribution to signal at 1000 m (S_{resc}) 1.8 $\mathbf{R}_{\mathbf{E}}$ and \mathbf{R}_{had} rescaling factors to match 1.6 the SD and FD signals (hybrid data) 1.4 $S_{\rm resc} = R_E S_{\rm EM} + R_{\rm had} R_E^{\alpha} S_{\rm had}$ $\mathsf{R}_{\mathsf{had}}$ 1.2 $\alpha \simeq 0.9$ 1 $R_{\mu} \approx 0.93 \; R_E^{0.9} \; R_{\text{had}} + 0.07 \; R_E$ 0.8 Systematic Uncert. QII-04 p 0.6 **QII-04 Mixed** \odot EPOS-LHC p 0.4 **EPOS-LHC Mixed** • 0.8 0.9 1.2 0.7 1.1 1.3 R_F > Smallest dicrepancy for EPOS-LHC Model R_E $R_{\rm had}$ with mixed composition at level of 1.9σ $1.09 \pm 0.08 \pm 0.09$ $1.59 \pm 0.17 \pm 0.09$ QII-04 p OII-04 mixed $1.00 \pm 0.08 \pm 0.11$ $1.61 \pm 0.18 \pm 0.11$ EPOS p $1.04 \pm 0.08 \pm 0.08$ $1.45 \pm 0.16 \pm 0.08$ Systematic uncertainties **EPOS** mixed $1.00 \pm 0.07 \pm 0.08$ $1.33 \pm 0.13 \pm 0.09$ on R_F and $R_{had} \sim 10 \%$

> The observed muon signal is a factor 1.33 (EPOS-LHC) to 1.61 (QGSJET-II.04) larger than predicted by models

Muon studies with inclined hybrid events (60° -80°)

> Inclined showers: only the muon components survive to the ground.



The Pierre Auger Collaboration, PRD D91 (2015) 3, 032003



> Hadronic models underestimate the number of muons produced in showers.

Update ICRC 2019: Muon studies with inclined hybrid events (60° -80°)

> Hadronic models underestimate the number of muons produced in showers.



> Muon fluctuations however appears to fit expectation.

Could be an indication that first interaction may not be responsible for the muon deficit in models. Small difference that accumulates over particle generations?

Direct muon measurement with AMIGA



- 1 full year of data with PMTs
- PMTs to be replaced by SiPMs



Direct muon measurement with AMIGA

> First direct measurement of the muon densities at energies $10^{17.3} \text{ eV} < \text{E} < 10^{18.3} \text{ eV}$



> Hint to muon deficit in simulations at lower energies (from X_{max} dominated by light elements!)



Muon number estimator

$$z_{\alpha} = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_{p}}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_{p}}$$

one composition-sensitive from various measurement



F. Sánchez for the Pierre Auger Collaboration, ICRC 2019



> Within the statistical and systematic uncertainties, the z-factors derived by the two muon studies seem to be in agreement at the intermediate energies between their distinct energy ranges

The combined muon measurements match the trend of z derived from X_{max} measurements as a function of the energy

Muon deficit in simulations (aka muon excess in data)

Muon number estimator

$$z_{\alpha} = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_{p}}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_{p}}$$

one composition-sensitive from various measurement $\begin{cases} \mathsf{SD} \longrightarrow R_{\mu} \\ \mathsf{FD} \longrightarrow X_{max} \\ \mathsf{UMD} \longrightarrow \rho_{35} \end{cases}$



> Muon deficit seen also in other experiments

Muon deficit: Possible solutions

Chiral Symmetry Restoration

Lorentz Invariance Violation

Quark Gluon Plasma



EPJ Web Conf. 53(2013) 07007

Phys. Rev. D 59, 116008 (1999)

PoS(ICRC2019)387

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Auger prime – upgraded surface detector

Need measurement of electromagnetic and muonic component event-by-event

Open questions

- > Origin of the flux suppresion
- > Proton fraction at UHE
- > Rigidity-dependence of anisotropies
- > Hadronic physics above sqrt(S)=140 TeV

Need large-exposure detector with composition sensitivity

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

The Pierre Auger Observatory Upgrade

"AugerPrime"

Preliminary Design Report

The Pierre Auger Collaboration April, 2015

Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

Auger Prime: Increased Composition Sensitivity

with SSD

Detector Upgrades for AugerPrime

Complementary response

Plans

2016: Engineering Array

2018-2019: deployment of 1200 SSD

2019-2025: data taking (almost double exposure)

Goal: composition measurement at 10²⁰ eV ● composition-enhanced anisotropy studies

particle physics with air showers

Summary

- > Auger measurements:
 - FD: EM shower is fairly well described by models, our best mass estimator is X_{max}
 - FD+SD: Measurements of muon content;
 no need for energy rescaling, thus muon problem
 - Muon rescaling factor 1.3-1.6
 - SD: R_{μ} in inclined showers Increasing MC deficit with increasing energy
 - SD: Muon Production Depth mismatch provides further constraints in hadronic models
 - AMIGA (new): extending down to 3x10¹⁷ eV

> Muon Puzzle

Experimentally established at 8o

- statement by eight leading air shower experiments
- problem not in the data, theory has to change

> Future:

Key measurements to be done at the LHC

- energy ratio R of π^0 to other hadrons at forward rapidity
- nuclear modification in forward hadron production
- Proton+oxygen collisions planned about ~2023

Auger Prime: Increased accuracy of muon measurements

