The Muon Puzzle in Cosmic Ray Induced Air Showers

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Agenda

- What is the Muon Puzzle?
  - Cosmic rays and their behaviour with the atmosphere
  - Air showers and their properties
  - Muon discrepancy between simulation and experiment (8σ offset)
  - experimental validation through WHISP group
- Muon Puzzle might suggest mismodelling QCD
  - Nuclear effects important
  - forwards hadron production studies from LHC data

Where do we see the Muon Puzzle?

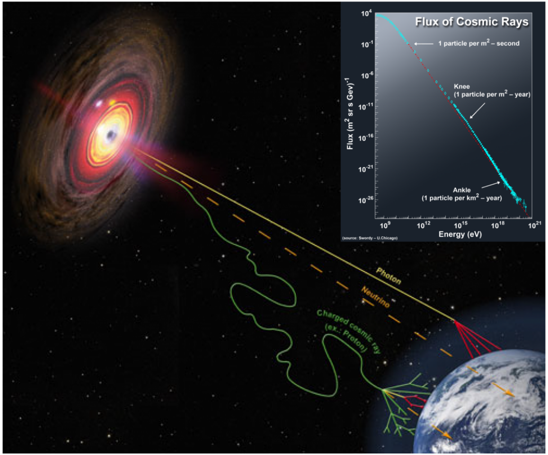
Studies about high-energy cosmic rays through extensive air showers

interpretation through models -> QCD under extreme conditions

understanding the mass composition through N_μ observable

Simulation deficit compared to measurement starting at TeV scale

Cosmic rays



Messengers of high-energy universe

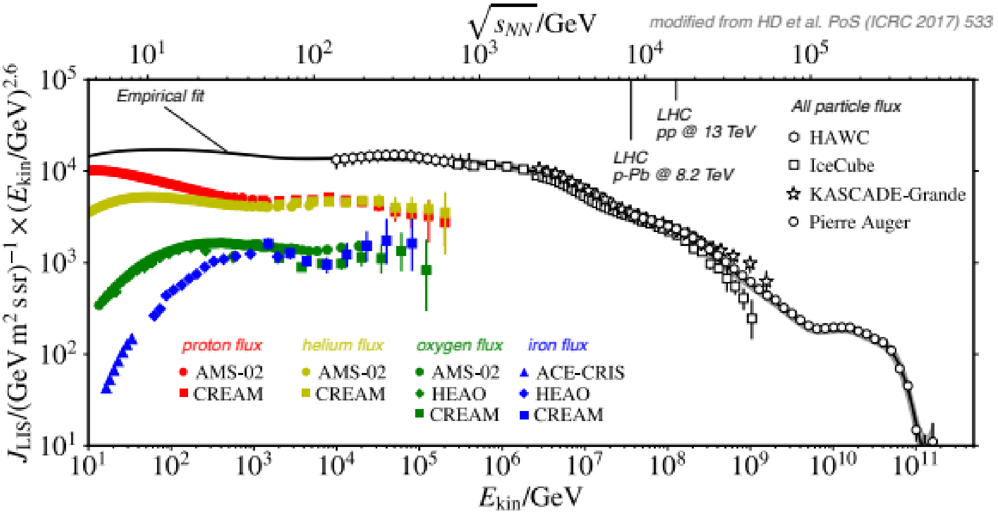
- gamma rays: many of them, straight from the source, E < 100 TeV
- neutrinos: straight from source, very rare but can be high energetic
- Cosmic Rays (CR): high energies, lots of them, path is highly random

Cosmic ray properties

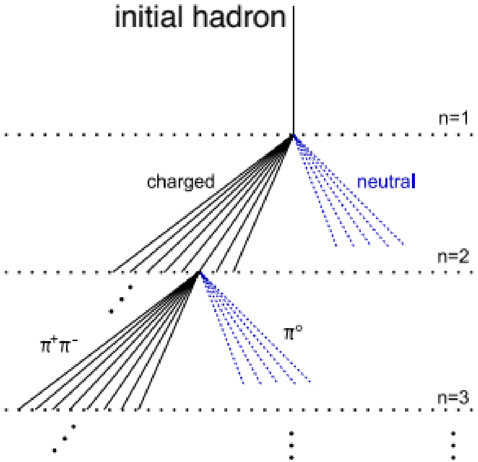
- discovered by Victor Hess in 1912 (balloon experiment)
- Fully ionised nuclei, from protons up to iron, negligible fractions to higher nuclei
- arriving earth with relativistic energies
- origin: unknown sources outside solar system
- shock acceleration (< 1 PeV) in SNR, higher energies have unknown mechanisms, extra-galactic > 1 EeV
- charged and scattered through inhomogenous fields -> random arrival directions
- E < 100 TeV: directly observed by space-based experiments (AMS-02[1])
- higher energies: flux too low -> ground based experiments (Auger, Telescope Array) through particle showers

[1] Alpha Magnetic Spectrometer

Cosmic ray flux



Air shower model (Heitler-Matthews)

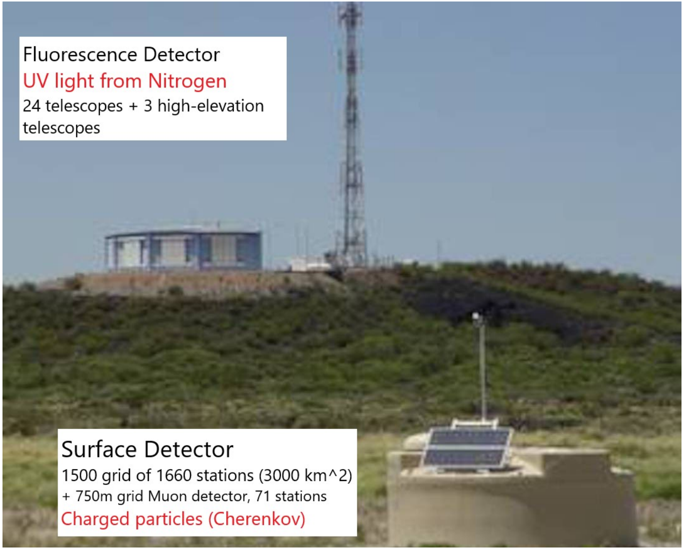


- shower simplified to pions
- charged pions decay to muons at low energies (end of cascade)
- neutral pions decay directly and form em-shower

Most muons and neutrinos produced come from the end of the hadronic cascade

- hadronic interactions need to be studied further
- soft hadronic cascades in forward direction

Pierre Auger Observatory



Pierre Auger Experiment

- located in Argentina
- CR Energies observation between $1 \cdot 10^{17}$ and $1 \cdot 10^{20}$ eV
- studies particle interactions with water tanks at surface
- tracking air showers through UV light in atmosphere
- ground: duty cycle roughly 100%
- fluorescence: roughly 15% (needs to be dark)

Cosmic Ray detection

What is needed for a cosmic rays detection?

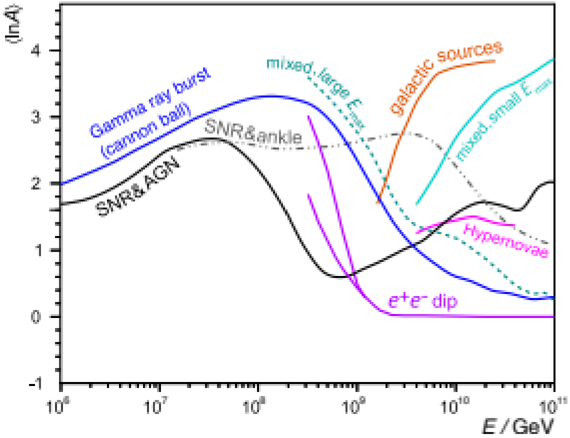
Energy from size of the electromagnetic component

Arrival ***direction*** ϕ, θ from the particles

Mass from depth of shower maximum and muon number

X_{max} = depth where the number of secondary particles reaches a maximum
N_{μ} = Number of muons

mean logarithmic mass prediction



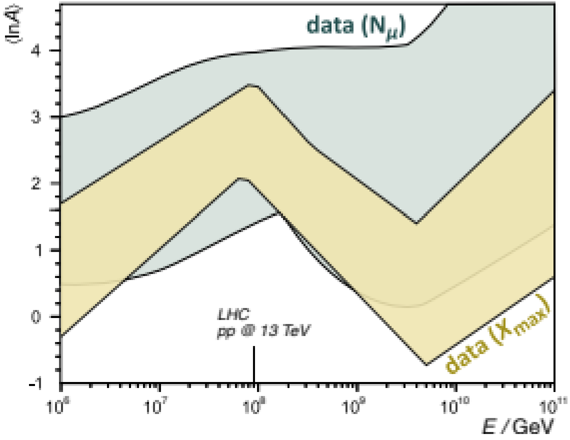
search dominant sources of CR -> for low fluxes need air showers

Air showers are indirectly observed; mass composition sumarized by mean logarithmic mass <lnA>

because of the intrinsic fluctuations inside the air showers

precise measurements can rule out competing theories (e.g CR with highest energies are light or heavy)

logarithmic mass prediction



- bands constructed from several measurements on air showers
- mass-sensitive features: X_{max}, N_μ
- band width →theoretical uncertainties (forward hadron production)
- uncertainties prevent exclusion of theories on the CR origin
- N_μ good discrimination between light and heavy rays at EeV scale
- more usefull than X_{max} because of few statistics of flourescence

CR mass composition

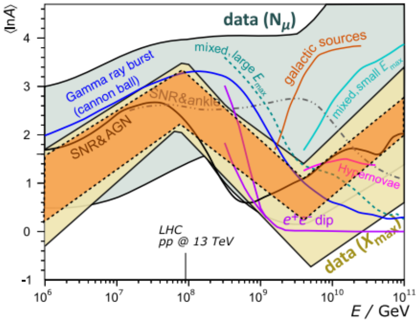


Abbildung: Based on Kampert and Unger, Astropart. Phys. 35 (2012) 660

What are the origins of cosmic rays?

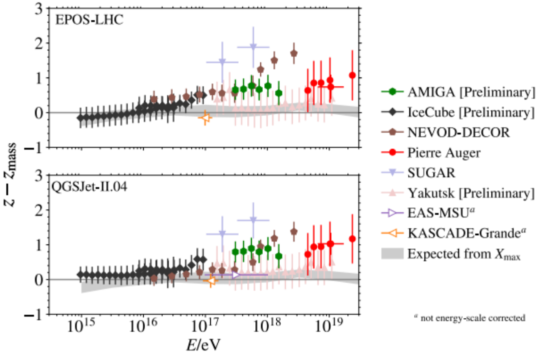
- Mass composition (<lnA>) of CR provides information about source and propagation
- uncertainties of <lnA> confined by uncertainty of hadronic interaction model
- **Muon Puzzle**: Predicted number of muons in air showers higher than in simulations

Possible solution from already taken data at the LHC

- forward production cross-section of π, K, p
- forward measurements of $R = (E_{\pi^0})/(E_{\text{other hadrons}})$ of em-cascades

Muon deficit in simulation

WHISP: Working group for Hadronic Interactions and Shower Physics
formed by several experiments to increase significance by viewing more phase space



Calibrate diverse measurements to common, abstract z-scale

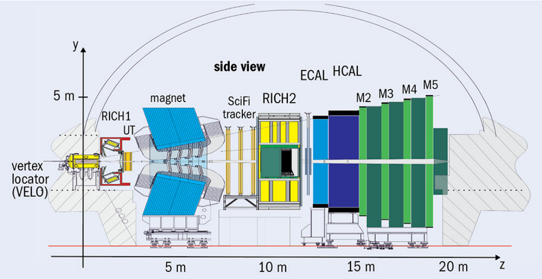
$$z = \frac{\ln N_\mu - \ln N_{\mu,p}^{\mathrm{sim}}}{\ln N_{\mu,FE}^{\mathrm{sim}} - \ln N_{\mu,p}^{\mathrm{sim}}}$$

to cancel potential biases, insensitive to mismodelling of N_μ

Deficit in air shower sim. visible around $8 \cdot 10^{16}$ eV (8 TeV)

Slope is non-zero at 8σ

The LHCb experiment

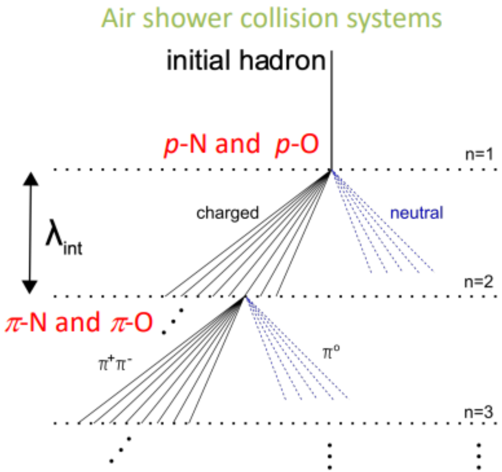


fully instrumented at 2 < η < 5 -> soft hadronic interactions

good particle identification (optimal for μ, p, $K^{\pm}$, $\pi^{\pm}$)

very good momentum and vertex resolution

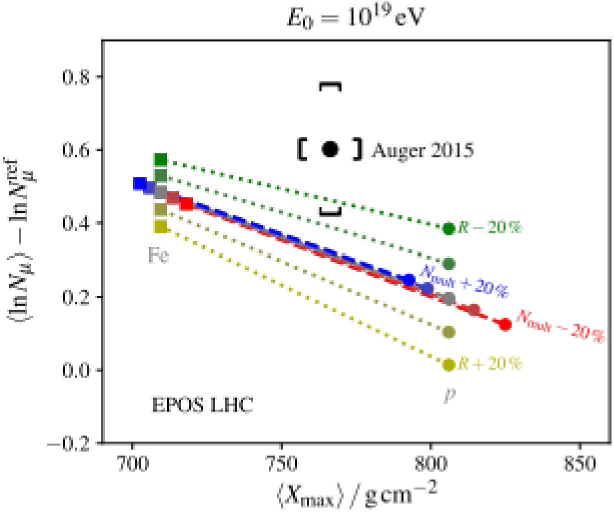
Using the LHC for air showers



p-O collisions similar to air shower interactions

needed: pp, p-Pb, p-O for nuclear effects

impact of LHC measurements



modified hadron multiplicity N_{mult}

modified R ratio = $\frac{E_{\pi^0}}{E_{\text{other hadrons}}}$

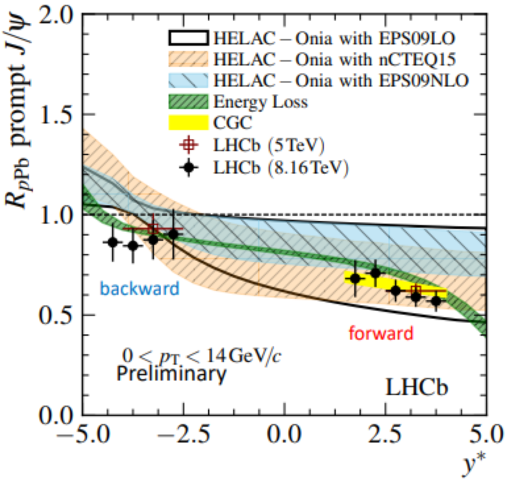
top left: pure iron shower, bottom right: pure proton shower

grey: standard prediction from EPOS-LHC model

muon discrepancy: distance between auger data and grey

-> nuclear modifications for forward-produced hadrons

Nuclear effects in forward production



close to 50% suppression for forward direction

strong suppression in CR pseudorapidity range

Why is solving the puzzle necessary?

- resolve ambiguity of cosmic ray mass composition at EeV level
- improve hadronic interaction models for CR mass composition in simulation
- more precision of lepton flux, main background for IceCube

Possible solutions

increase muon number by reducing energy fraction lost to photon production (π^0 decay)

highest energy CR have heavy nuclei -> first interaction creates quark-gluon plasma -> shift equilibrium to an enhanced strangeness state (40% more muons)

Summary

- muon deficit experimentally established with 8σ evidence
- $\sqrt{s_{NN}} = 8$TeV: should be observable at LHC
- most likely explanation: modification in hadron production (photon energy fraction)
- ALICE observed enhanced strangeness in mid-rapidity which would match but needs to be studied further
- LHCb needed to perform missing measurements

Quellen

http://www.telescopearray.org/index.php/about/telescope-array
https://www.researchgate.net/figure/A-schematic-of-the-Pierre-Auger-Observatory-where-each-black-dot-is-a-water-Cherenkov_fig1_319524774
https://www.cta-observatory.org/pevatrons-hunt-for-galactic-cosmic-rays/
https://arxiv.org/pdf/2105.06148.pdf
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https://cerncourier.com/a/lhcbs-momentous-metamorphosis/