The Muon Puzzle in Cosmic Ray Induced Air Showers

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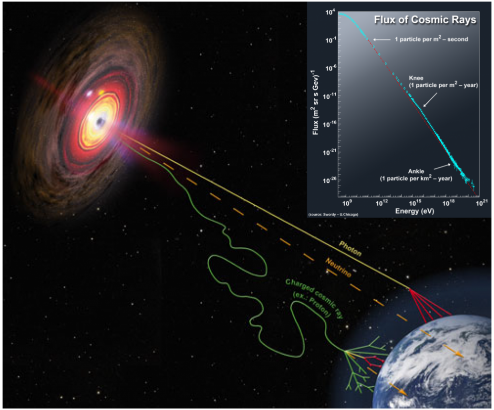
Agenda

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

Cosmic rays



Messengers of high-energy universe

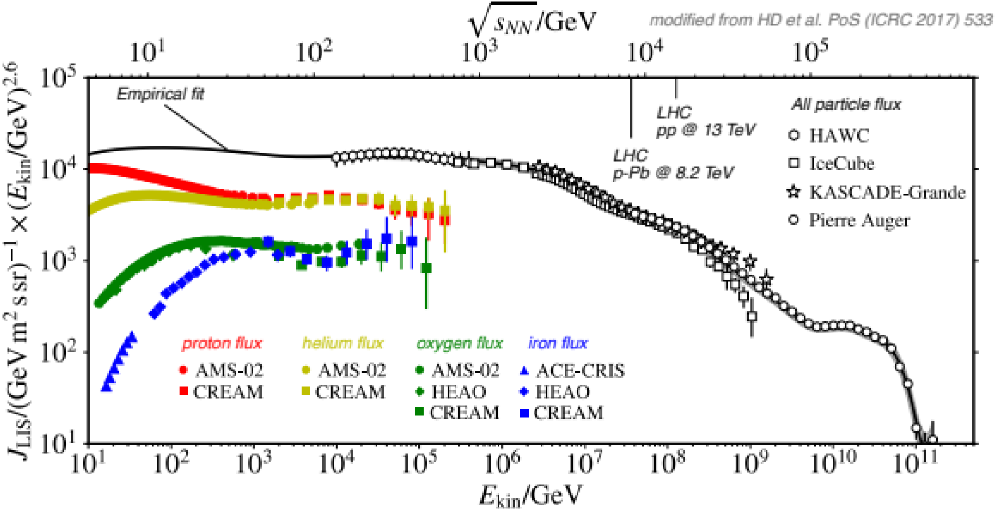
- gamma rays: many of them, straight from the source, E < 100 TeV
- neutrinos: straight from source, very rare but can be high energetic
- Cosmic Rays (CR): high energies, lots of them, path is highly random

Cosmic ray properties

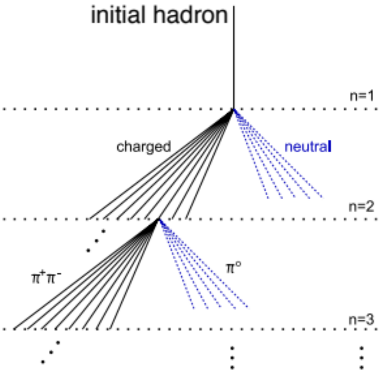
- discovered by Victor Hess in 1912 (balloon experiment)
- Fully ionised nuclei, from protons up to iron, negligible fractions to higher nuclei
- arriving earth with relativistic energies
- origin: unknown sources outside solar system
- shock acceleration (< 1 PeV) in SNR, higher energies have unknown 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)

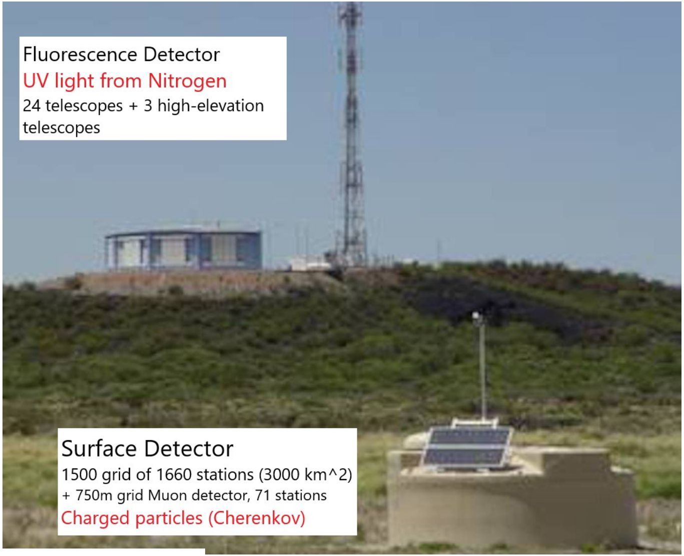


- shower simplified to pions
- charged pions decay to muons at low energies (end of cascade)
- neutral pions decay directly and form em-shower

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

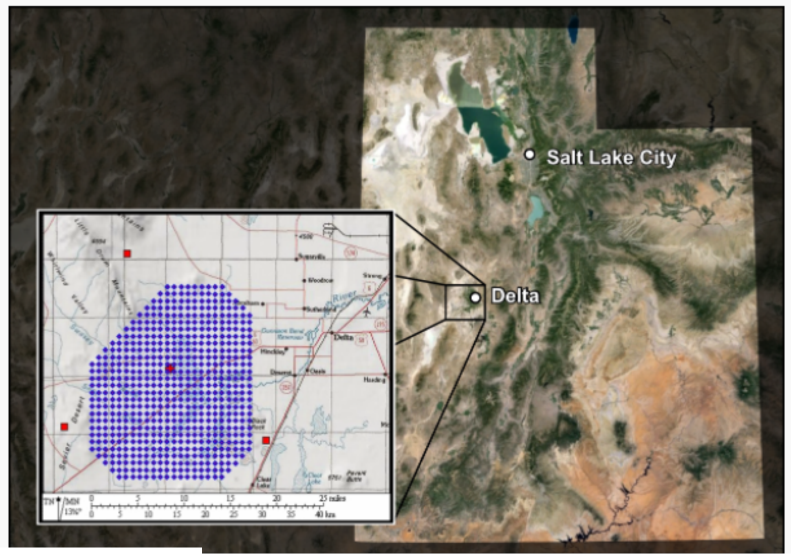
Pierre Auger Observatory



Pierre Auger Experiment

- located in Argentina
- CR Energies 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)

The Telescope Array



Telescope Array

hybrid experiment from many collaborations

observe air showers from CR at highest energies

combination of air-flourescence (atmospheric trace) and ground-based

scintillating trackers (footprint when reaching the surface)

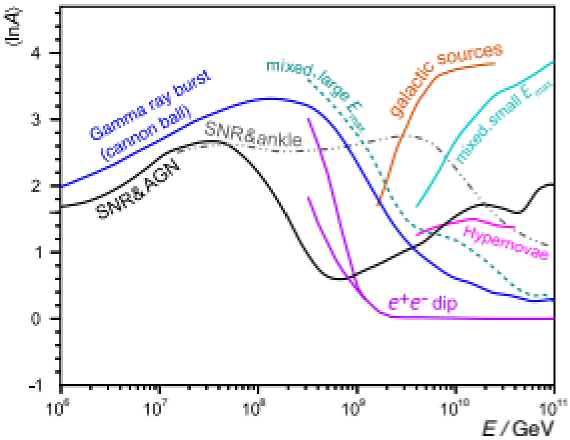
Cosmic Ray detection

What is needed for a cosmic rays detection?

- ***Energy*** from size of of the em-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



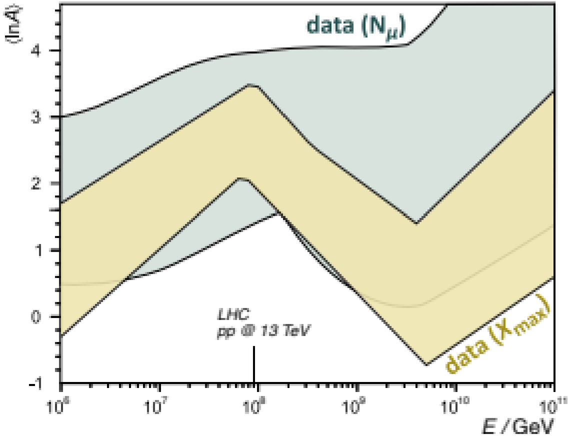
search dominant sources of CR -> for low fluxes need air showers

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

-> why? 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

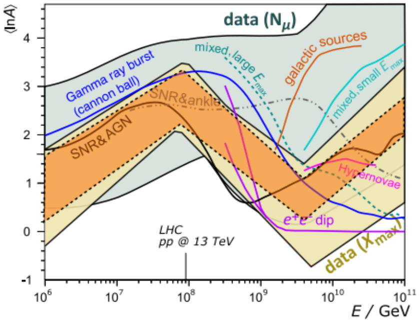


Abbildung: Based on Kampert and Unger, Astropart. Phys. 35 (2012) 660

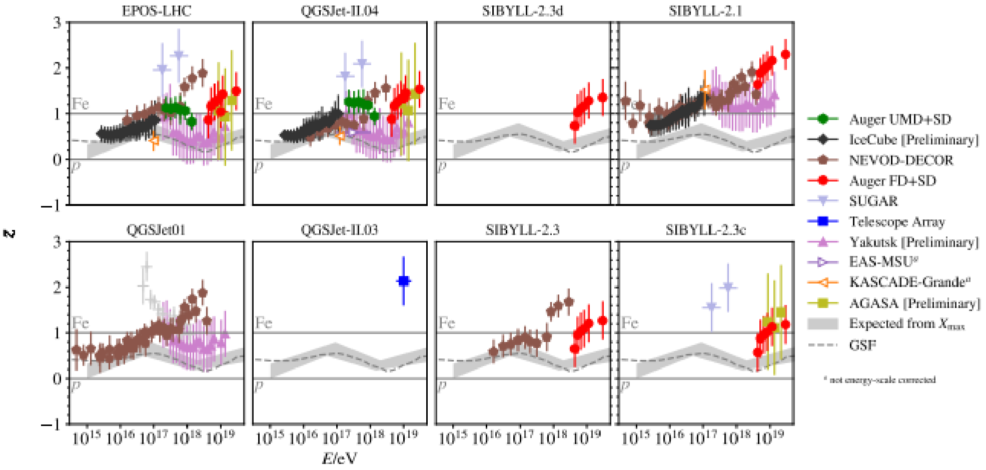
What are the origins of cosmic rays?

- 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

experimental uncertainty

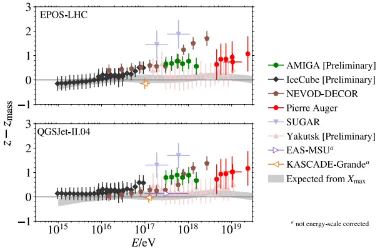


experimental uncertainty measurements

- precise air shower measurements
- experimental uncertainty is 10%
- factor 2.5 to 4 (E dependent) small than band width (theoretical unc.)
- theo. unc. comes from shower simulation used to infer $ln(A)$ from X_{max} and N_μ
- simulation essential: no way of calibrating since mass composition of any astrophysical source unknown
- uncertainty from evolution of hadronic cascades; responsible for muon production at the end

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

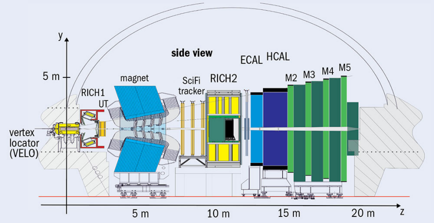
$$z = \frac{\ln N_\mu - \ln N_{\mu,p}^{\text{sim}}}{\ln N_{\mu,FE}^{\text{sim}} - \ln N_{\mu,p}^{\text{sim}}}$$

to cancel potential biases, insensitive to mismodelling of N_μ

Deficit in air shower sim. visible around $1 \cdot 10^{16}$ eV or 8 TeV

Slope is non-zero at 8?

The LHCb experiment

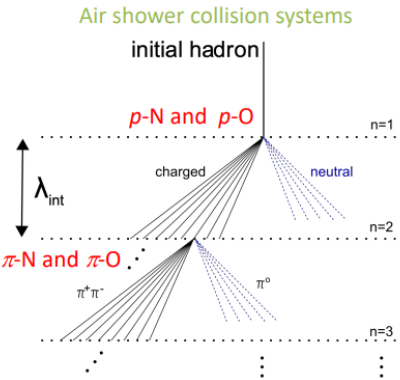


fully instrumented at 2 < ? < 5

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

very good momentum and vertex resolution

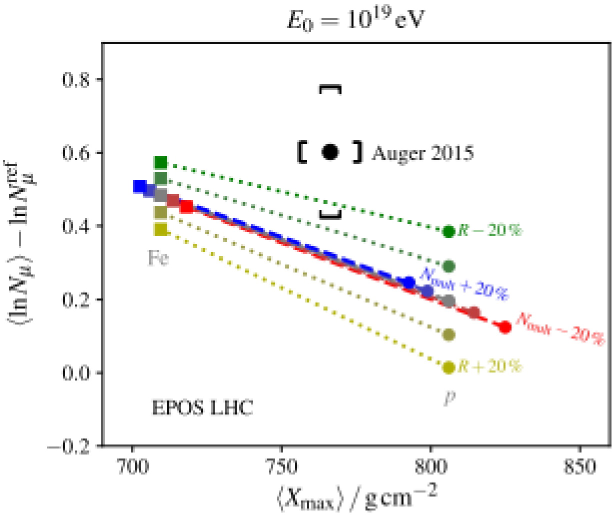
Using the LHC for air showers



p-O collisions similar to air shower interactions

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

impact of LHC measurements



impact of R ratio (fig 11 in paper)

Why is solving the puzzle necessary?

- reduce the size of N_μ bands by a factor of 2.5 to 4
- resolve ambiguity (mehrdeutigkeit) 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 to the Puzzle

use LHCb as instrumentation device because it has the correct eta range (2 to 5)

Recap

Muon deficit clearly visible in air showers with 8

IceCube and the Pierre Auger experiment made huge contributions to model-dependent measurements

$\sqrt{s_{NN}} \approx 8$ TeVwith linear increase in $\log(E)$ -> high energy measurements at LHC

small modifications in hadron production reduce energy contribution of photons, coming from π^0 decays

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/