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The Muon Puzzle

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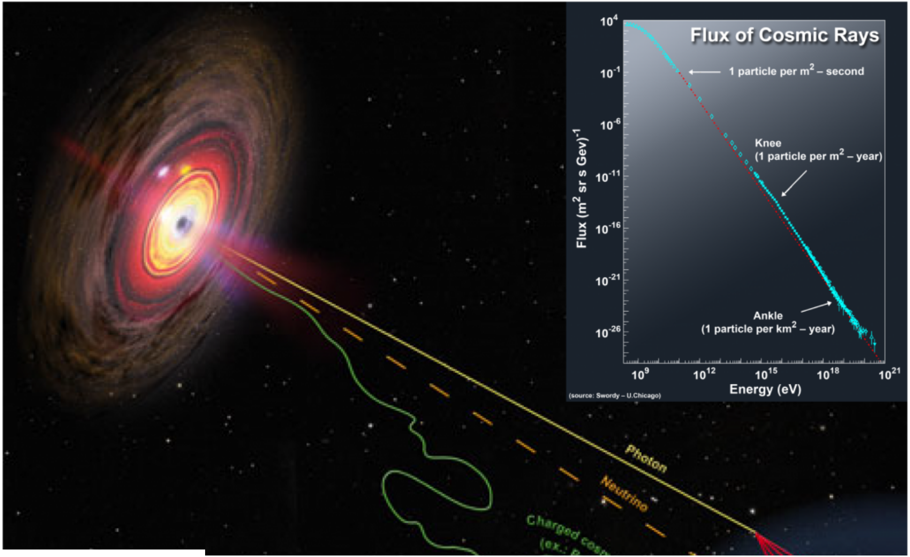
Agenda

- What is the Muon Puzzle?
- Cosmic rays and their behaviour with the atmosphere
- air shower: trivia and properties
- How do we measure these phenomena and which experiments are used?
- Why do we want to study it?
- Other problems related to the muon puzzle
- possible solutions

The Muon Puzzle

- indirect observation of cosmic rays through air showers in atmosphere
- interpretation -> models for air shower physics (QCD extreme, large E)
- N_μ key observable for mass composition of CR
- Simulation shows drastic Muon deficit compared to measurement
- Muon discrepancy starts right after the ”knee”, increases with $ln(showerE)$
- Discrepancy also seen in showers where first interaction of the CR has cms = 8 TeV

Cosmic rays

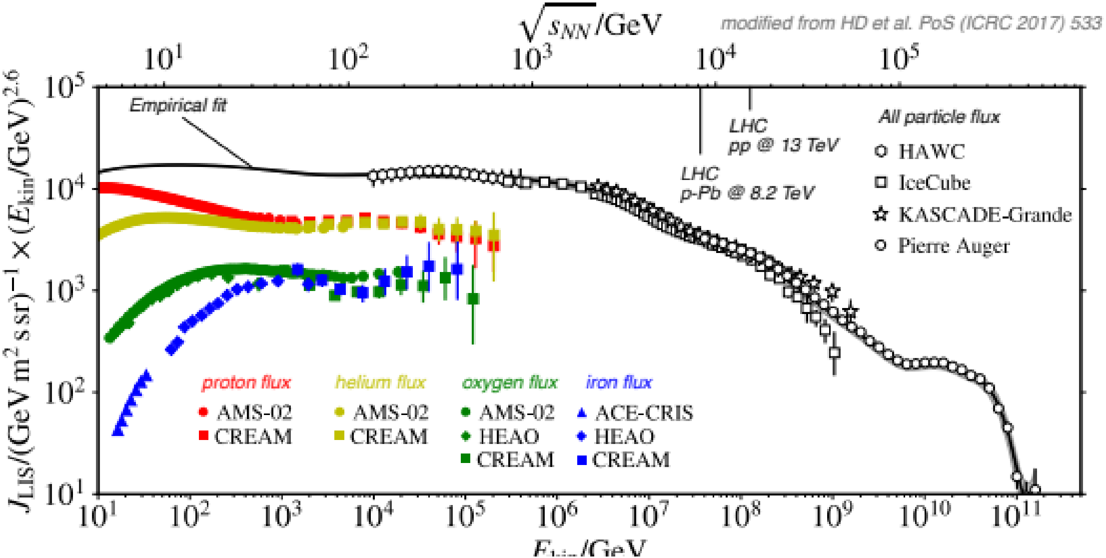

Flux of Cosmic Rays
1 particle per m^2 – second
Knee
(1 particle per m^2 – year)
Ankle
(1 particle per km^2 – year)
Flux (m^2 sr s Gev)$^{-1}$
10^4
10^{-1}
10^{-6}
10^{-11}
10^{-16}
10^{-21}
10^{-26}
10^9
10^{12}
10^{15}
10^{18}
10^{21}
Energy (eV)
(source: Swordy – U.Chicago)
Photon
Neutrino

What are cosmic rays?

- 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



Cosmic ray flux

Flux is scaled with $E^{2.6}$ -> many orders of magnitude

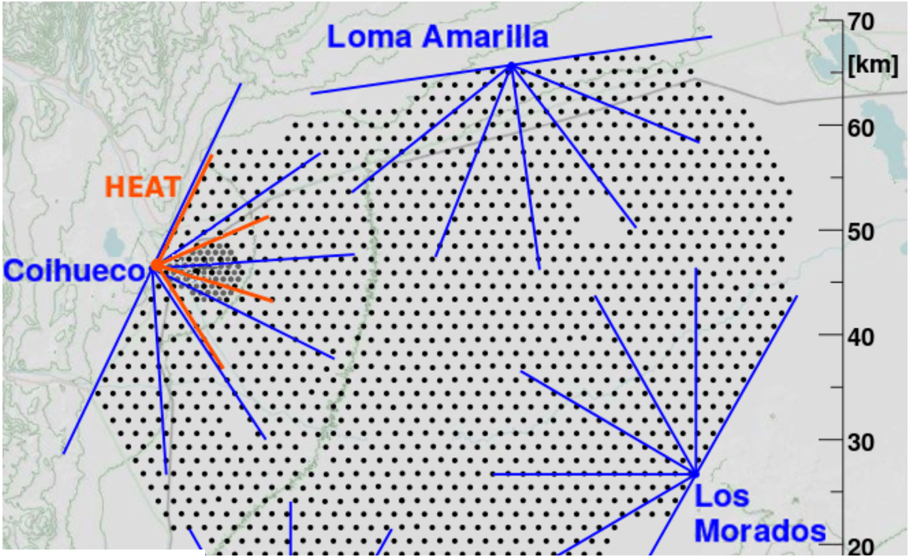
open sybols: shower experiments measuring ”all particle CR flux”

coloured: flux of individual balloon and satelite measurements

empirical fit to the data (what is empirical?)

interesting part from above the knee at $1 \cdot 10^6$ GeV.

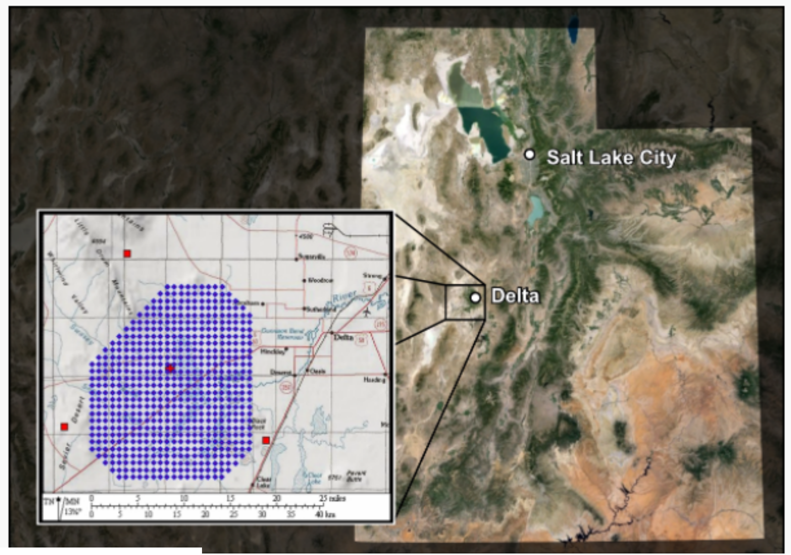
Pierre Auger Observatory



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

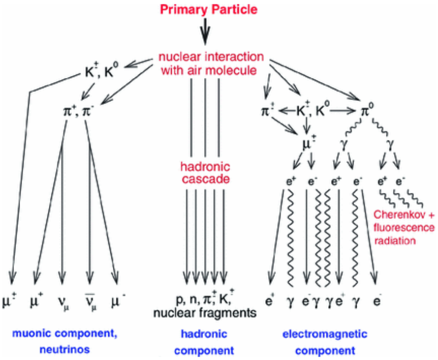
hybrid experiment from many collaborations

observe air showers from CR at highest energies

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

scintillating trackers (footprint when reaching the surface)

Air showers



CR interaction with atmosphere; production of daughter particles

generation of em- and hadronic cascades

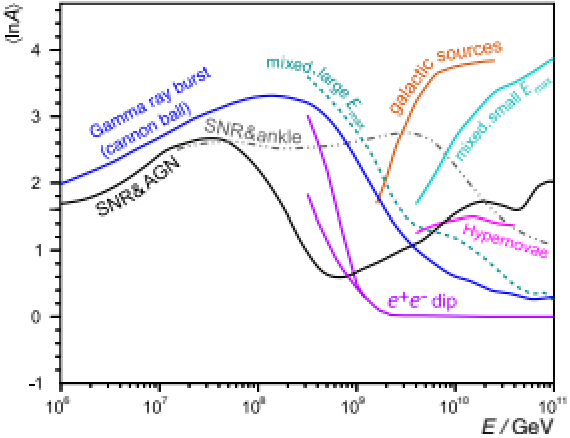
primary particles: $\pi^0 \rightarrow \gamma \rightarrow e^{\pm}$...

$\pi^{\pm} \rightarrow \mu^{\pm}$, ?

air shower detection

- fluorescence light from nitrogen
- Cherenkov light in water tanks at ground level
- accurate arrival direction and particle composition at ground -> muon number (10 - 100 GeV)
- better accuracy: build ground array close to X_{max} (maximum number of secondary particles)
- golden standard: use both to test hadronic interaction models

mean logarithmic mass prediction



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

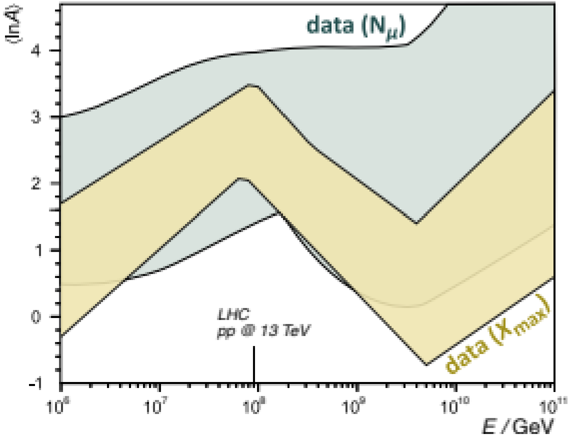
Air showers are indirectly observed and mass composition can only be sumarized by the logarithmic mass ln(A) (for E above PeV)

-> why? because of the intrinsic fluctuations inside the air showers

ln(A) for several source classes shown

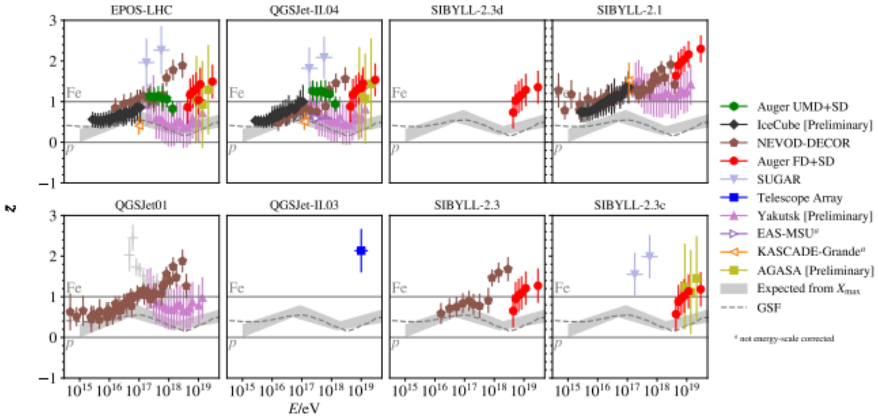
precise measurements can rule out competing theories (e.g CR with highest energies are light or heavy)

logarithmic mass prediction



- bands constructed from several measurements on air showers
- mass-sensitive features: shower depth maximum X_{max} and muon Number 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
- experimental uncertainy is 10%

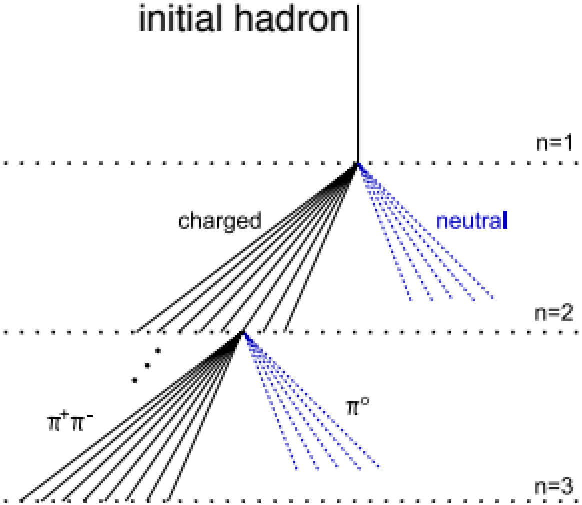
experimental uncertainty



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

N_μ calculation from simulation



Solving the puzzle requires improvements of simulation -> solving cascade equations

Heitler-Matthews model connects quantities: primary E, N_μ, X_{max}

low energiy event generators have small impact on muon number (too small to be tye cause) -> look at higher energies

hadronic interaction model largest source of uncertainties

WHISP group and discrepancy measurements

- WHISP : Working group for Hadronic Interactions and Shower Physics
- formed by several experiments to increase significance by viewing more phase space
- develop common framework to compare measurements, direct comparison often not possible (shower age, E, lateral distance from axis, ...)
- Pierre Auger was first with nearly model-independent measurement
- abstract muon z-scale: $z = \frac{ln(N_\mu) - ln(N_\mu)_p}{ln(N_\mu)_{FE} - ln(N_\mu)_p}$
- to cancel potential biases, insensitive to mismodelling of N_μ
- range: $0 < z < 1$

Now what is puzzling?

LHC has state-of-the-art soft hadronic interaction models = generators

generators always predict a lower muon Number than seen in measurements

prediction is nearly model-independent →only small wiggle room

why not observed yet at LHC?

have not looked at the right spot! wrong eta range for soft hadronic interactions (eta >= 2)

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
https://doi.org/10.1007/978-3-319-63411-1_1