The Muon Puzzle

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Agenda

The Muon Puzzle

indirect observation of cosmic rays through air showers in atmosphere

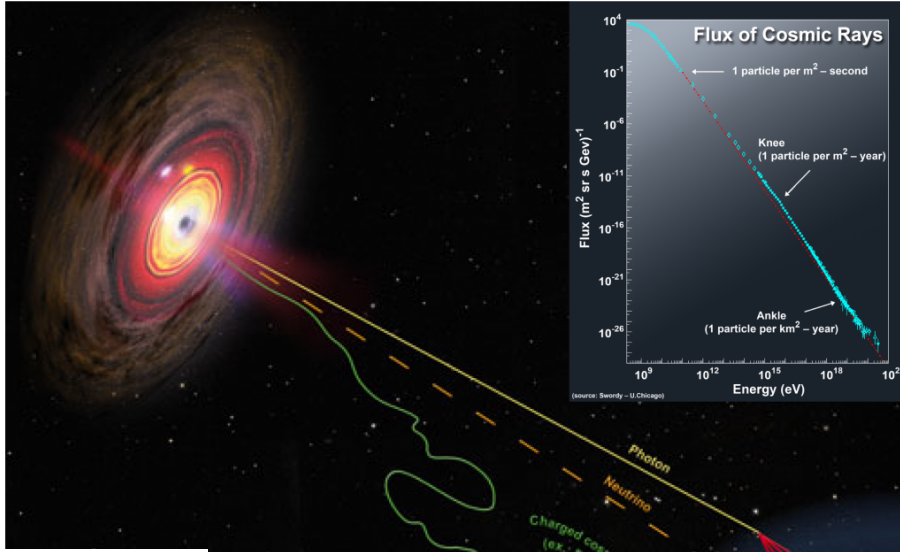interpretation -> models for air shower physics (QCD extreme, large E)

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

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
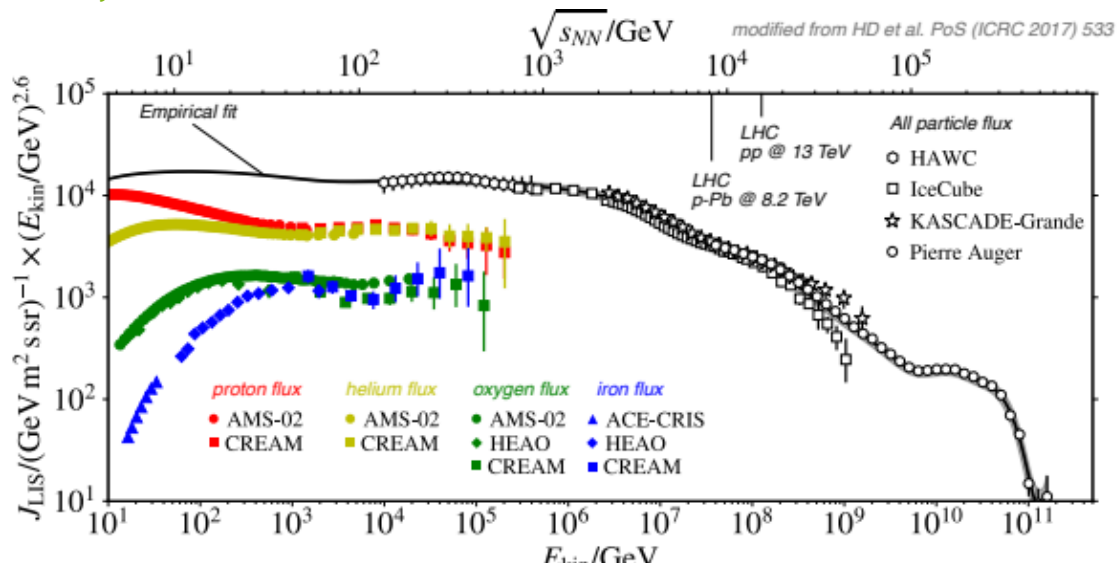
E < 100 TeV: directly observed by space-based experiments (AMS-02[1])

higher energies: flux too low -> ground based experiments (Auger, Telescope Array) through particle showers

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[1]Alpha Magnetic Spectrometer

Cosmic ray flux

Cosmic ray flux

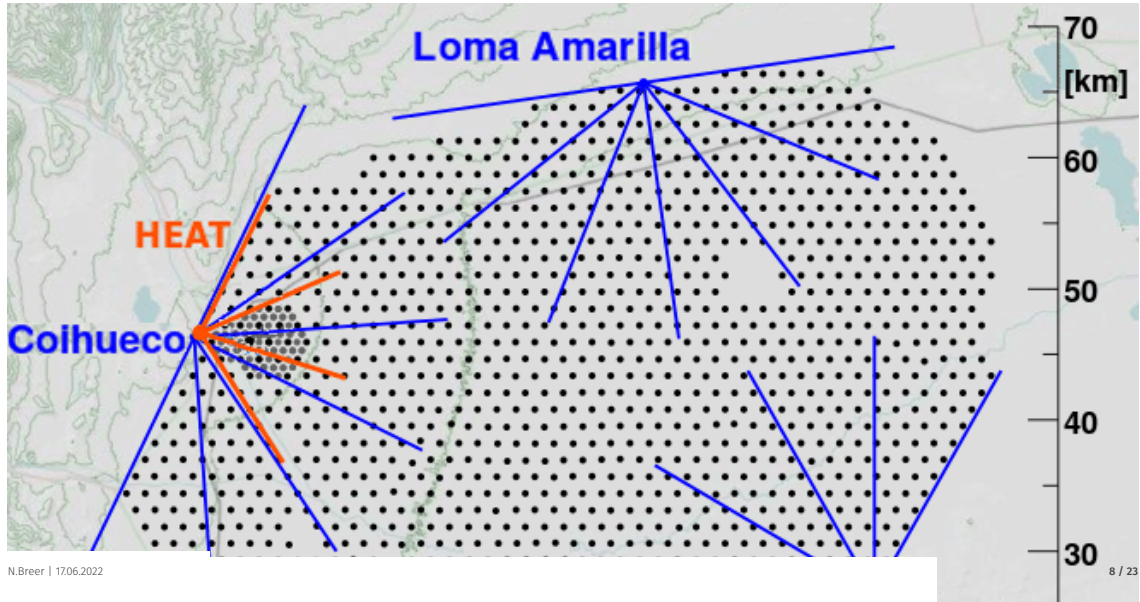Flux is scaled with $E^{2.6}$ -> many orders of magnitude

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%
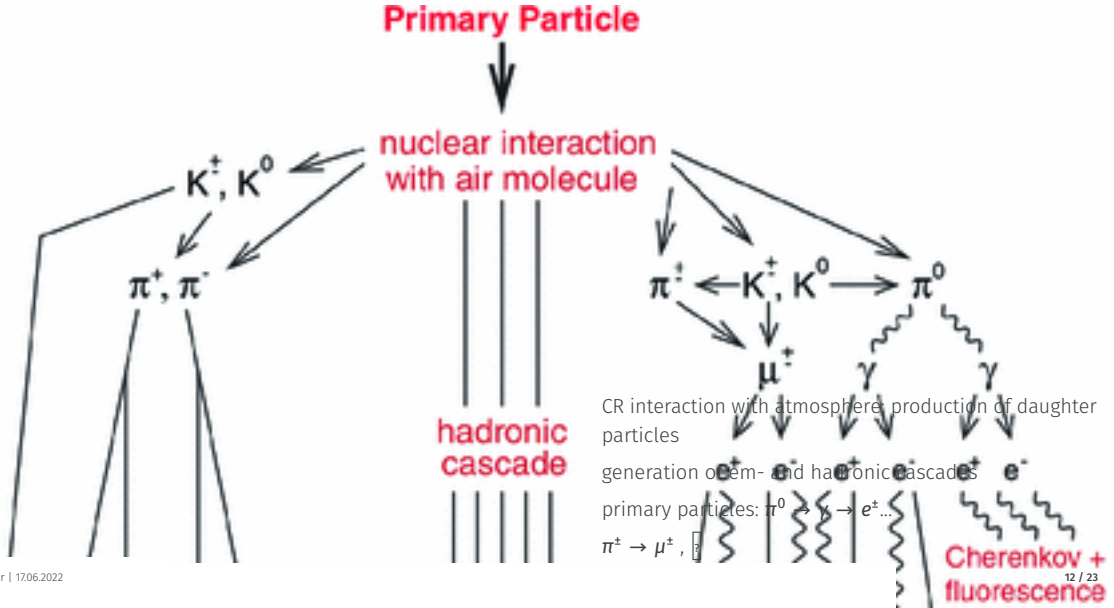
fluorescence: roughly 15% (needs to be dark)

The Telescope Array
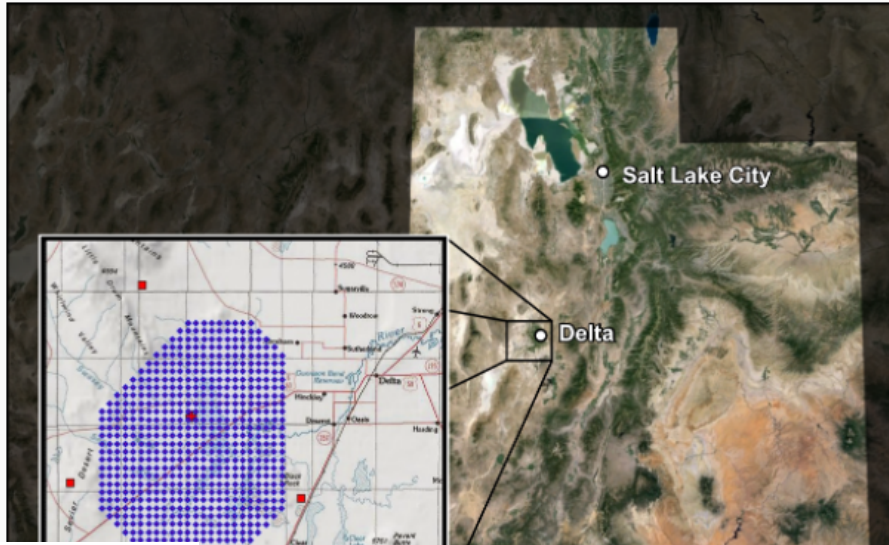
Telescope Array

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

Primary Particle

nuclear interaction with air molecule

$K^{\pm}, K^0$

π^+, π^-

hadronic cascade

$\pi^{\pm} \leftarrow K^+, K^0 \longrightarrow \pi^0$

$\mu^{\pm}$

γ γ

CR interaction with atmosphere production of daughter particles

generation of em- and hadronic cascades

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

$\pi^{\pm} \to \mu^{\pm}$, ...

$e^{\pm}$ e^-

Cherenkov + fluorescence

air shower detection
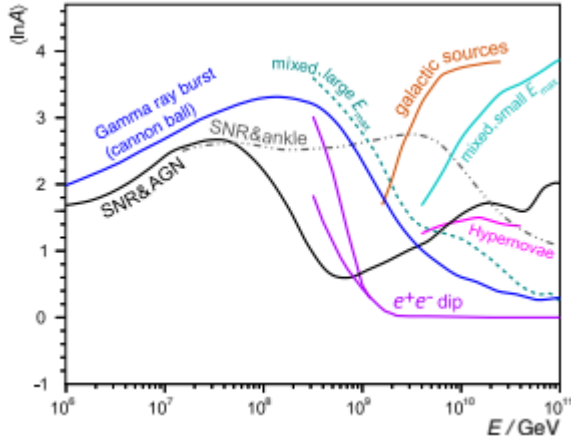
fluorescence light from nitrogen

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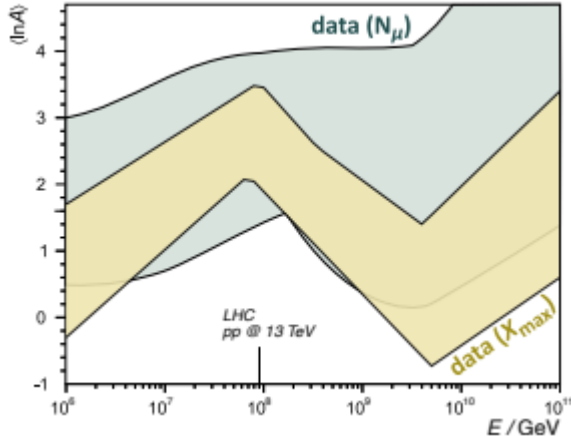
Air showers are indirectly observed and mass composition can only be sumarized by the logarithmic mass ln(A) (for E above PeV)

-> 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

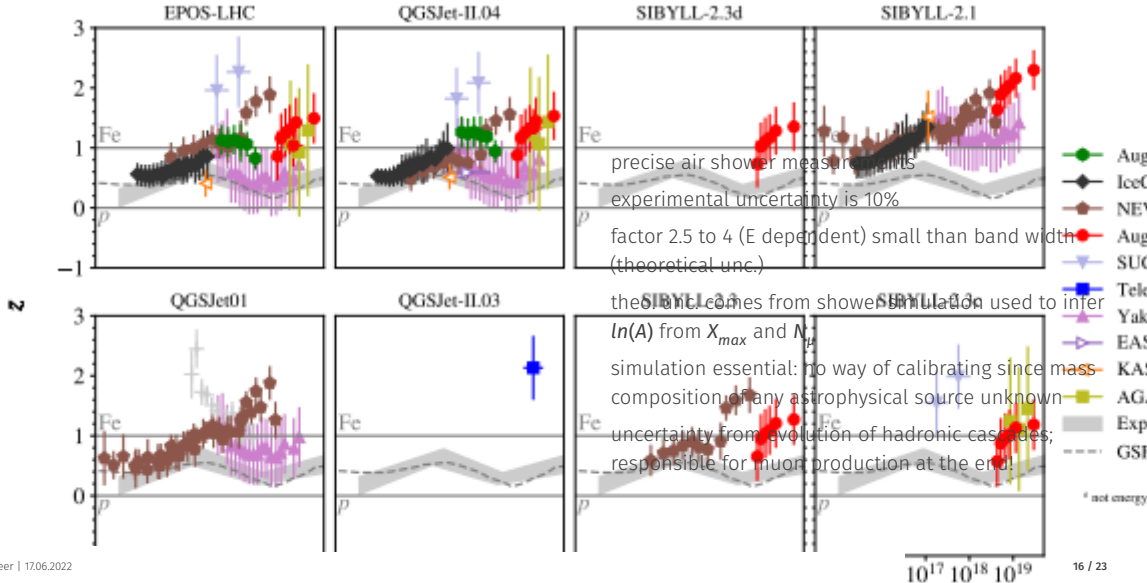band width →theoretical uncertainties (forward hadron production)

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 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

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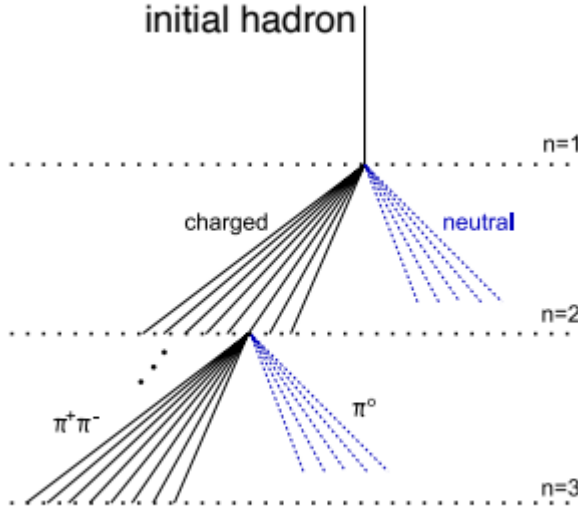
Solving the puzzle requires improvements of simulation -> solving cascade equations

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 interesting

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

$\sqrt{S_{NN}} \approx 8\,\text{TeV}$ with 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