The Muon Puzzle

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Agenda

What is the Muon Puzzle?

Why do we want to study it?

Cosmic rays and their behaviour with the atmosphere

air shower: trivia and properties

How do we measure these phenomena and which experiments are used?

Other problems related to the muon puzzle

possible solutions

The Muon Puzzle

indirect observation of cosmic rays through air showers in atmosphere

interpretation -> accurate models of air shower physics (QCD extreme)

air showers -> hadronic cascades rich in muons

N_μ key observable for mass composition of CR

Simulation shows drastic Muon deficit compared to measurement! -> why?

visible at TeV scale -> LHC also didn't observe that!

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

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
- come from unknown sources outside the solar system
- shock acceleration (< 1 PeV) in SNR, higher energies have unknown mechanisms, extra-galactic > 1 EeV
- ”Knee” spectrum CR occur 1 per m^2 per year
- ”Ankle” spectrum CR occur 1 per km^2 per century -> hard to study

More about cosmic rays

CR may come from point-like sources, don't appear as such -> isotropic flux

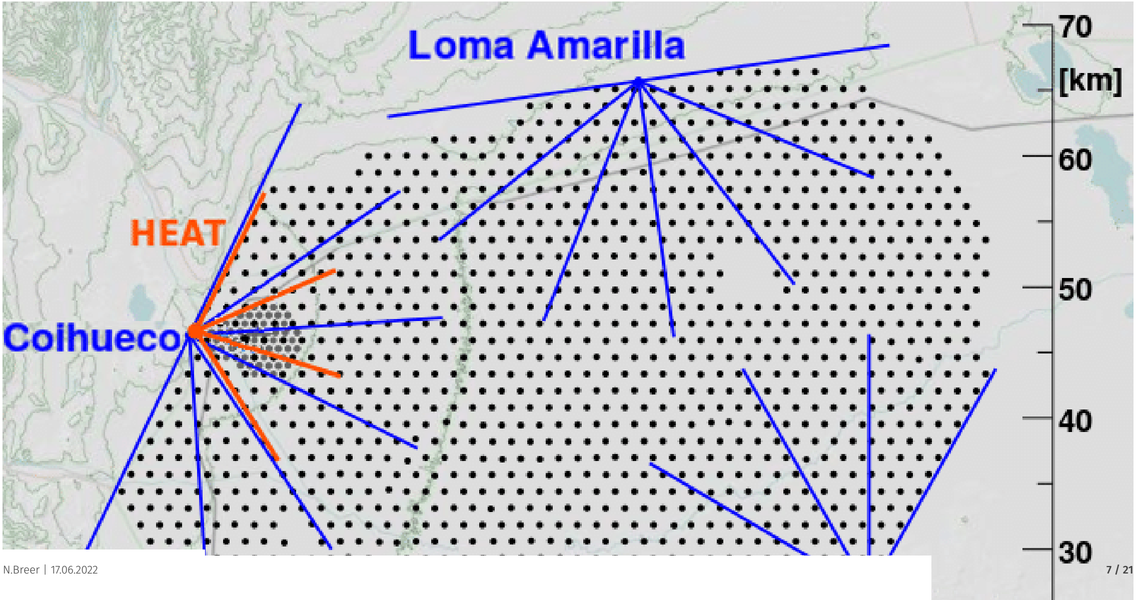
charged and scattered through inhomogenous fields -> random arrival directions

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

Pierre Auger Observatory



Pierre Auger Experiment

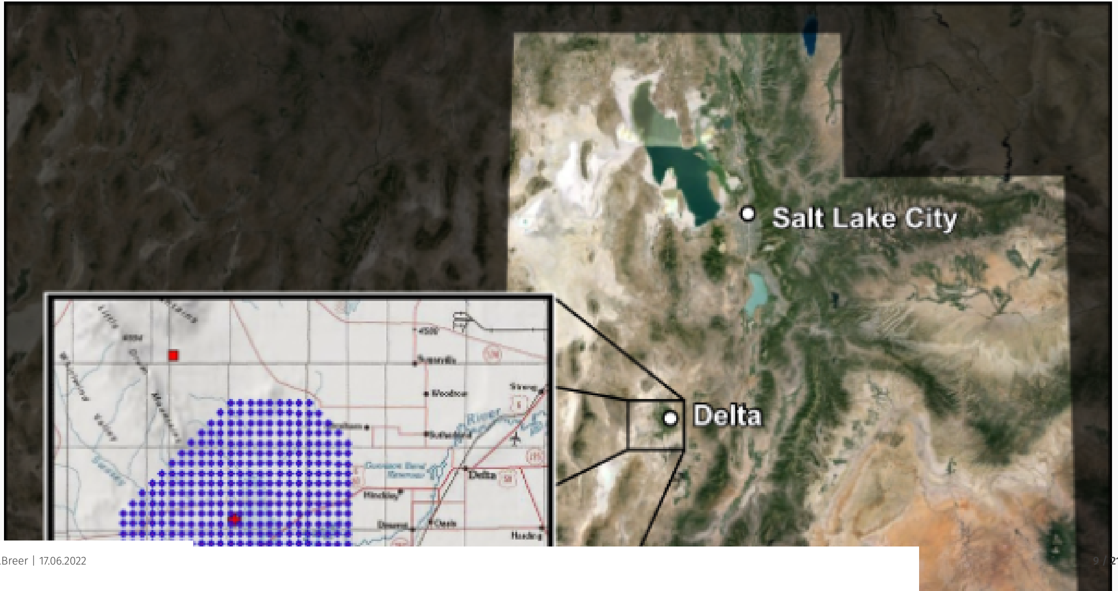
located in Argentina

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

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 groundbased

scintillating trackers (footprint when reaching the surface)

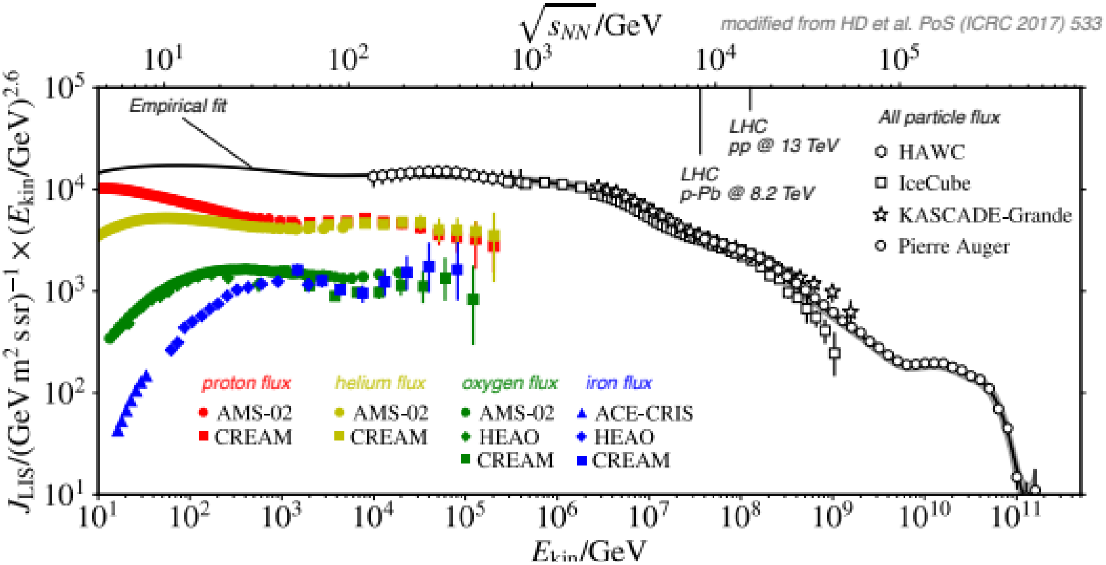
Air Showers

- picture?
- description
- more details

Muon Messungen und Modelle

d

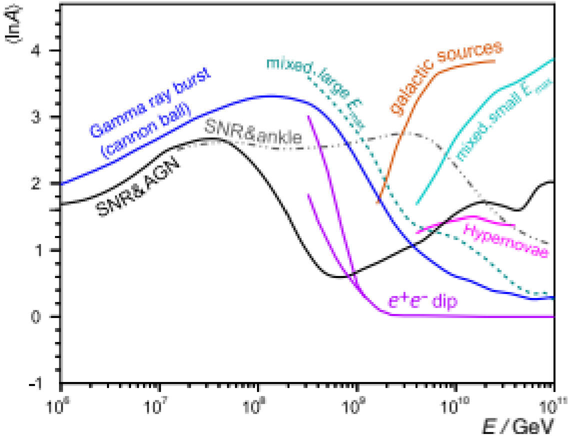
flux


$\sqrt{s_{NN}}$/GeV
modified from HD et al. PoS (ICRC 2017) 533
10^1 10^2 10^3 10^4 10^5
Empirical fit
LHC
pp @ 13 TeV
LHC
p-Pb @ 8.2 TeV
All particle flux
HAWC
IceCube
KASCADE-Grande
Pierre Auger
proton flux
AMS-02
CREAM
helium flux
AMS-02
CREAM
oxygen flux
AMS-02
HEAO
CREAM
iron flux
ACE-CRIS
HEAO
CREAM
$J_{LIS}/(\mathrm{GeV\,m^2\,s\,sr})^{-1} \times (E_{kin}/\mathrm{GeV})^{2.6}$
E_{kin}/GeV

heel and knee plot, flux

- Flux is scaled with $E^{2.6}$ -> many orders of magnitude
- open sybols: shower experiments measurring ”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.

logarithmic mass prediction



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

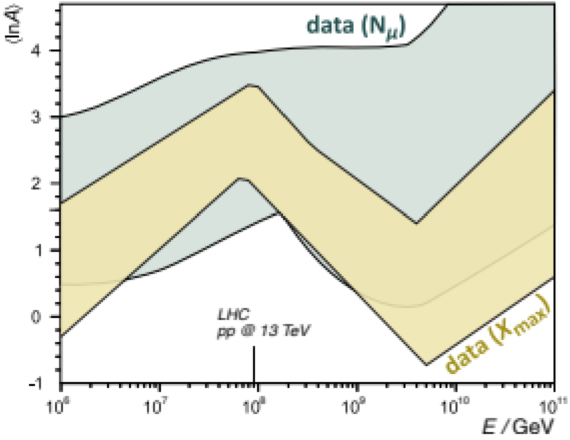
Air showers are indirectly observed and mass composition can only be sumarized by the logarithmic mass ln(A) (for E above PeV)

-> 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



important features are shower depth maximum X_{max} and muon Number N_μ

describe

right side

plot

with the

bands

even more puzzling

something missing in generators for soft hadronic interactions

cms energy in atmosphere is approx. 8 TeV -> low enough for LHC to observe but not found yet

why? have not looked at the right spot!

cause is in the realm of soft hadronic interactions which occur at eta >= 2 range

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

more to N_μ

N_μ is sensitive to energy fraction of carried away photons from π_0 decays

ALICE saw universal strangeness enhancement in final states, resulting in less pions in mid rapidity range

this was only seen in heavy ion collisions! hint?

Possible solutions to the Puzzle

e

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