Cosmic Ray

Some highlights from NWO-M, NWO-GO, NWO-XS and eScience proposals

KM3NeT Outing 2025

Dieren

19/11/2025

Ronald

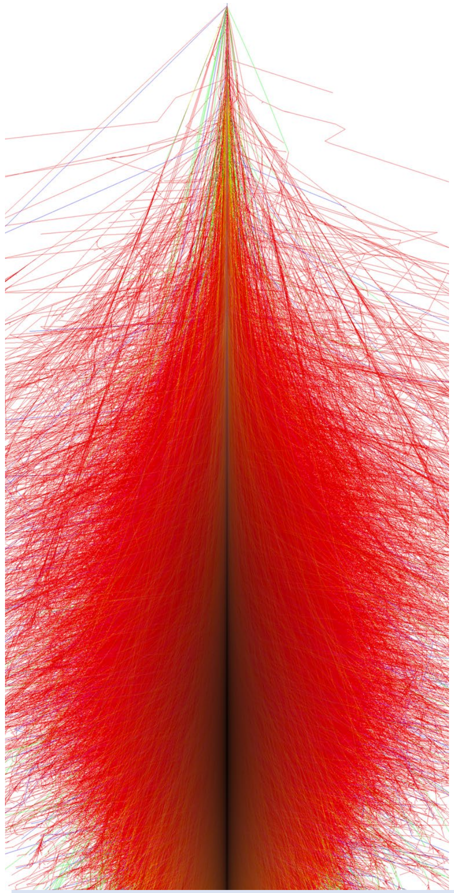
Outline

Short summary of 4 submitted proposals

- Generic CR intro
- NWO-M
- NWO-GO
- NWO-XS
- eScience Open call

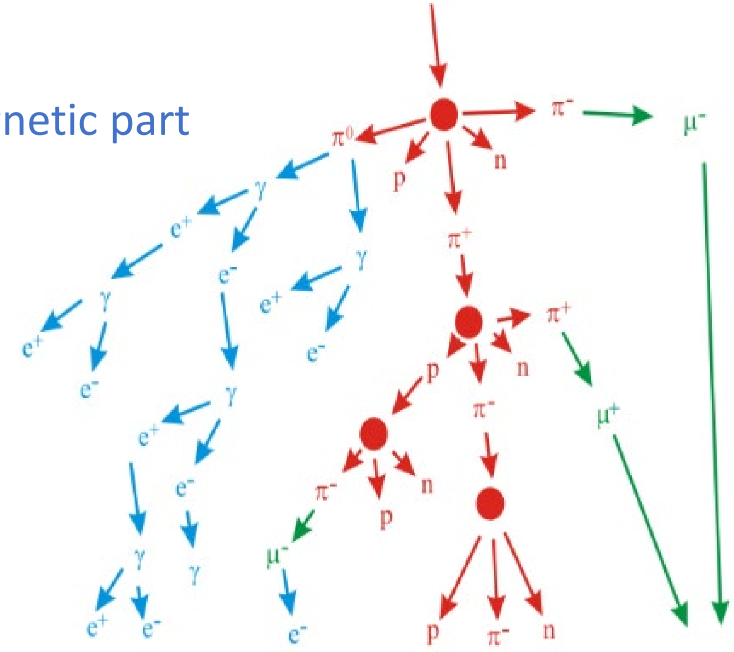
High Energy Cosmic Ray interactions : Air showers

Cosmic Ray (e.g. proton)
Interacts in the top of the atmosphere with Oxygen/Nitrogen …



A cascade of reinteractions occurs until there is not enough energy

π^0 feeds electromagnetic part



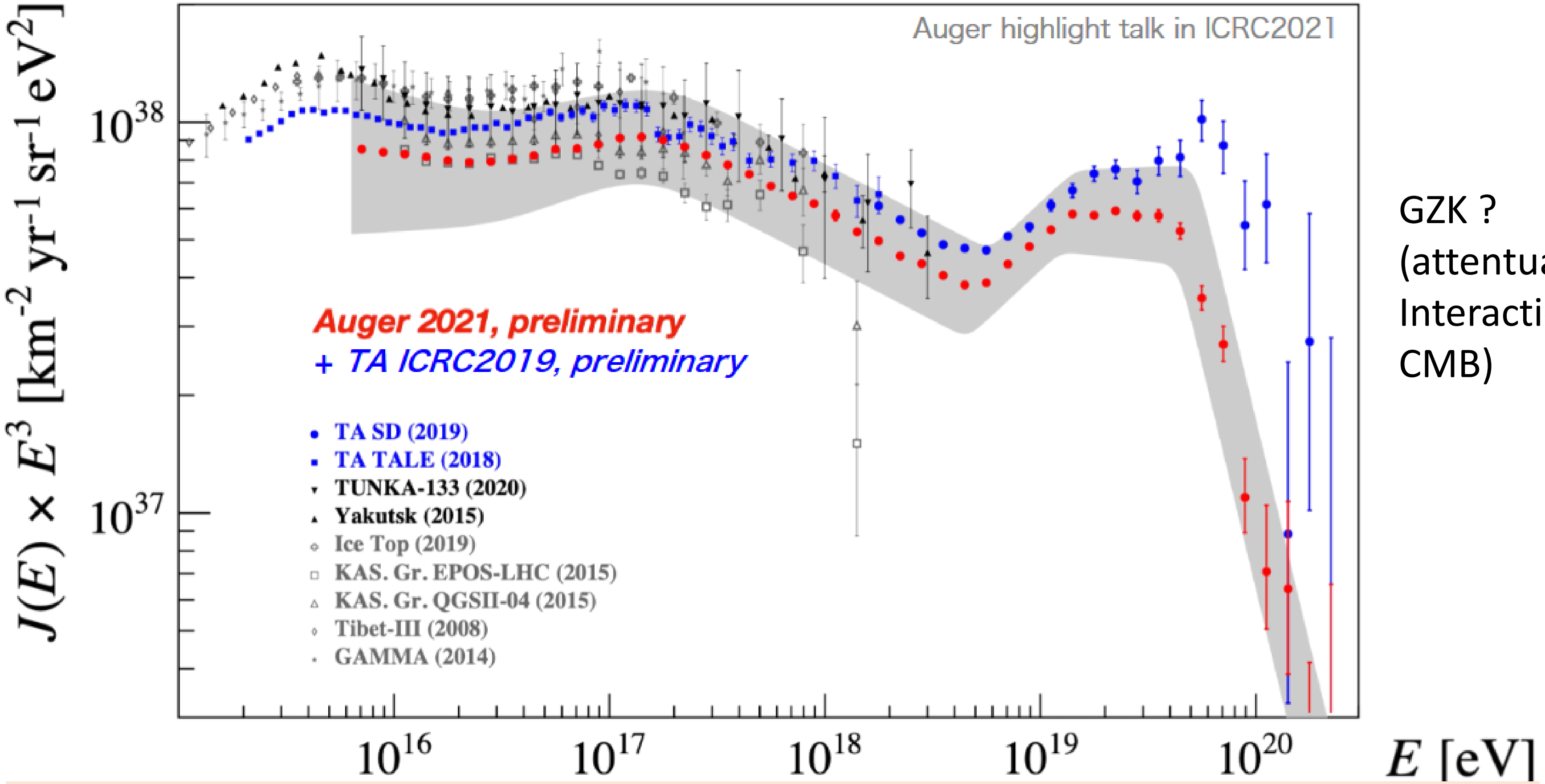
Muons are created along the whole shower from decays
('early' muons have in general larger energy)

Sea-level : ~10^{10} particles for 10^{19} eV proton shower

High Energy Cosmic Ray Spectrum

Transition to extra-galactic sources ?

Bumps and dips … what causes the features ??

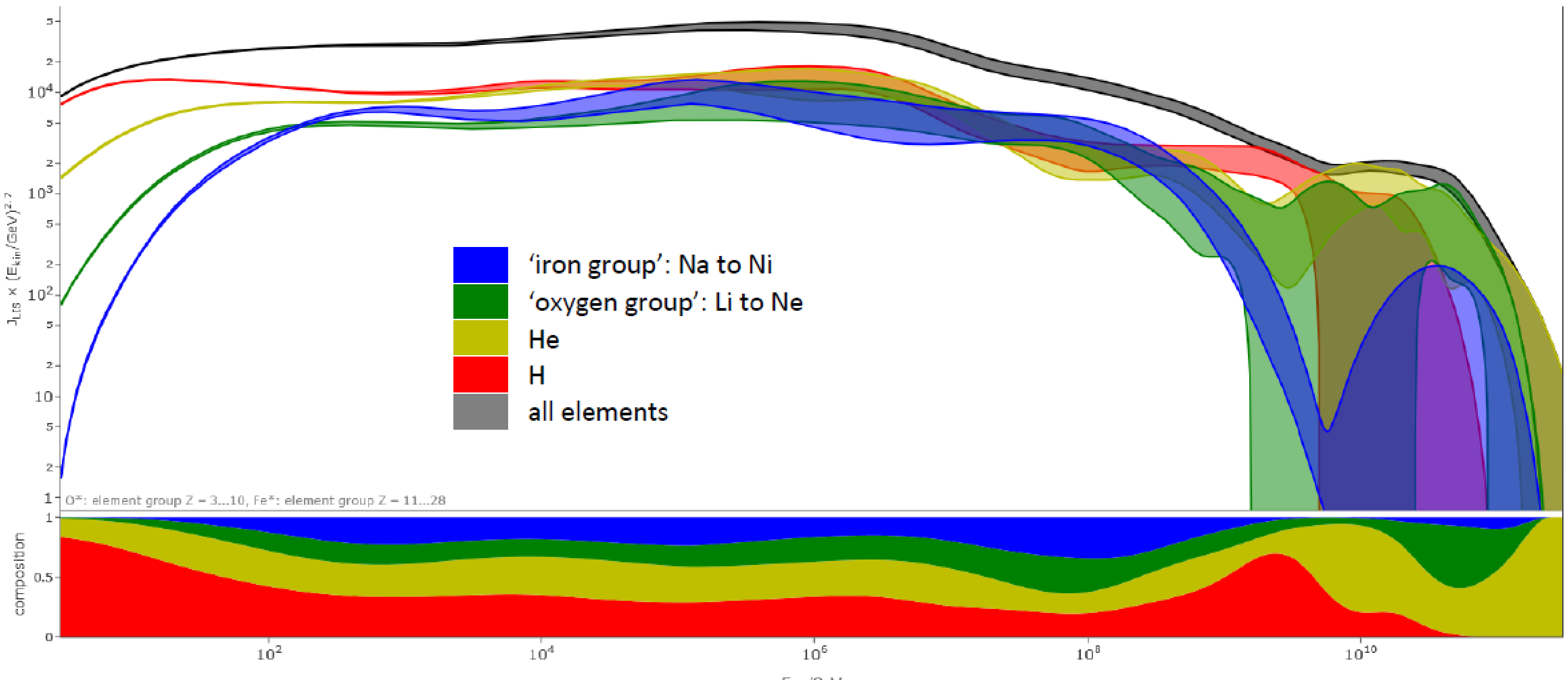


GZK ?
(attentuation through
Interaction with
CMB)

Composition measurements help, as different source and propagation models predict a different energy dependent composition.

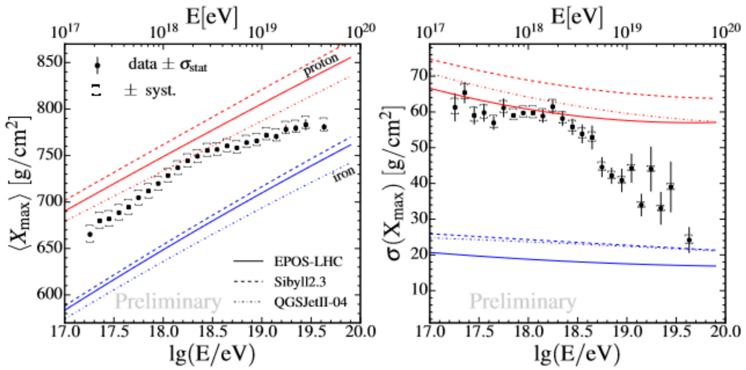
Cosmic Ray Flux

'Global spline fit' : model-free fit to global cosmic ray data



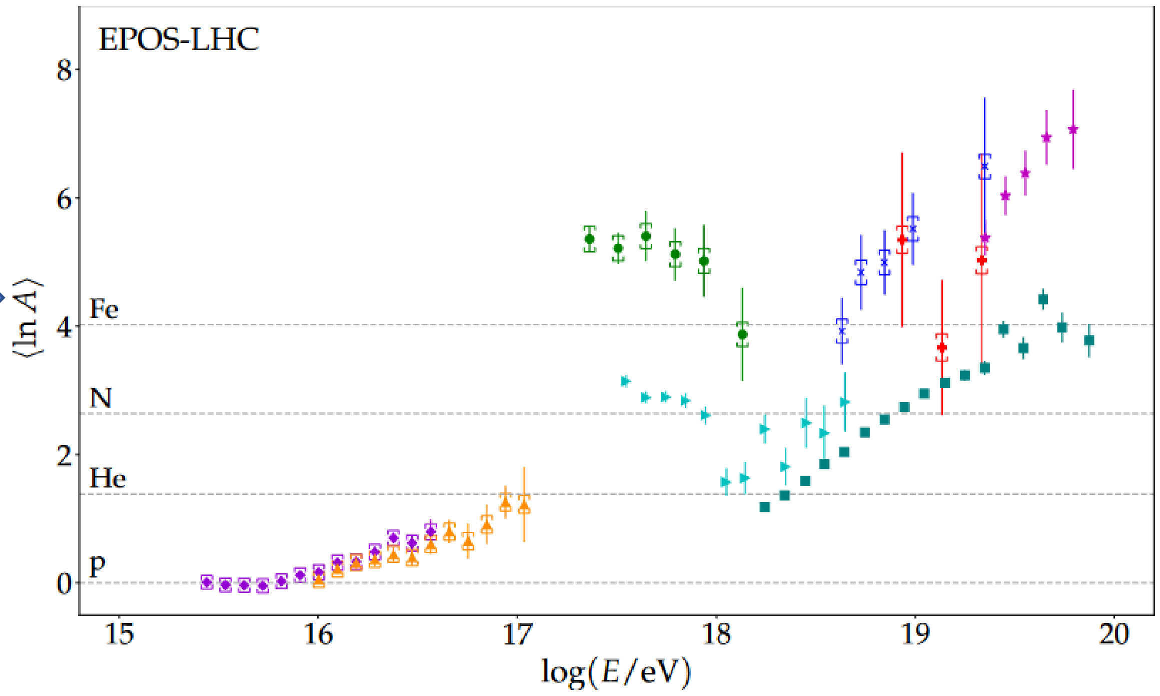
High Energy CR Composition (Simple version)

Measurements :
e.g.:
- Depth of shower maximum
- Muons vs electrons at ground



Models

Composition

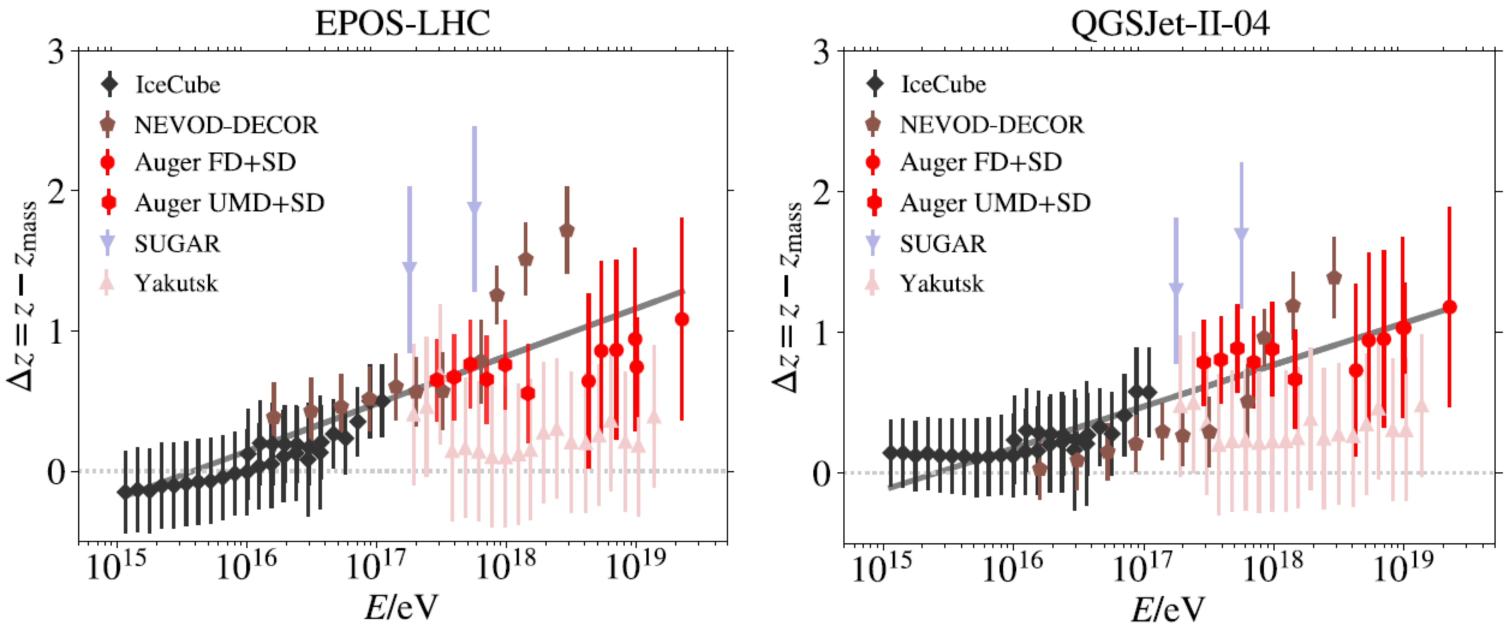


At high energies, models are required to interpret the measurements of cosmic rays in terms of their primary composition

‘The muon puzzle’

- Models predict not enough muons
  - Effect increases with energy

$$z = \frac{\ln(\rho_\mu) - \ln(\rho_{\mu,\mathrm{p}})}{\ln(\rho_{\mu,\mathrm{Fe}}) - \ln(\rho_{\mu,\mathrm{p}})}$$

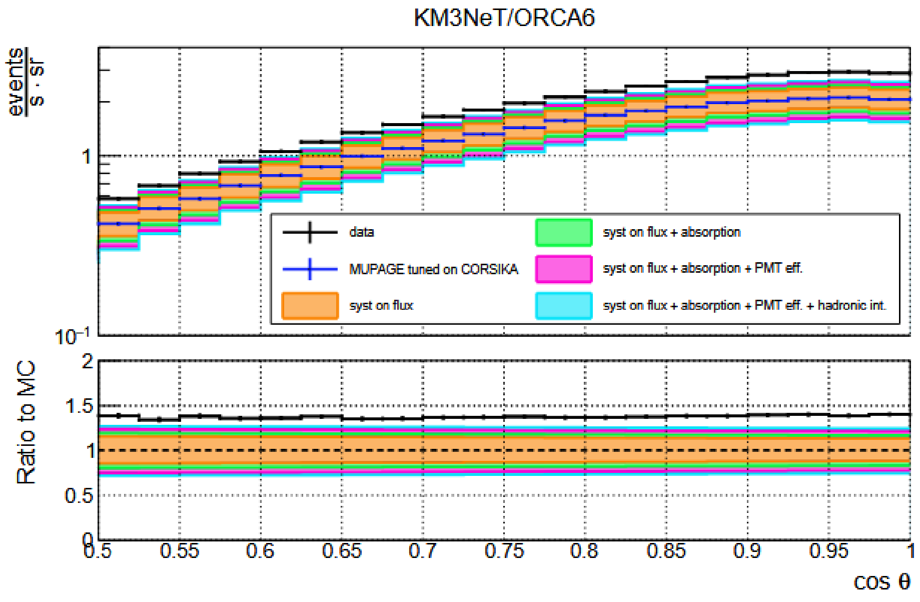


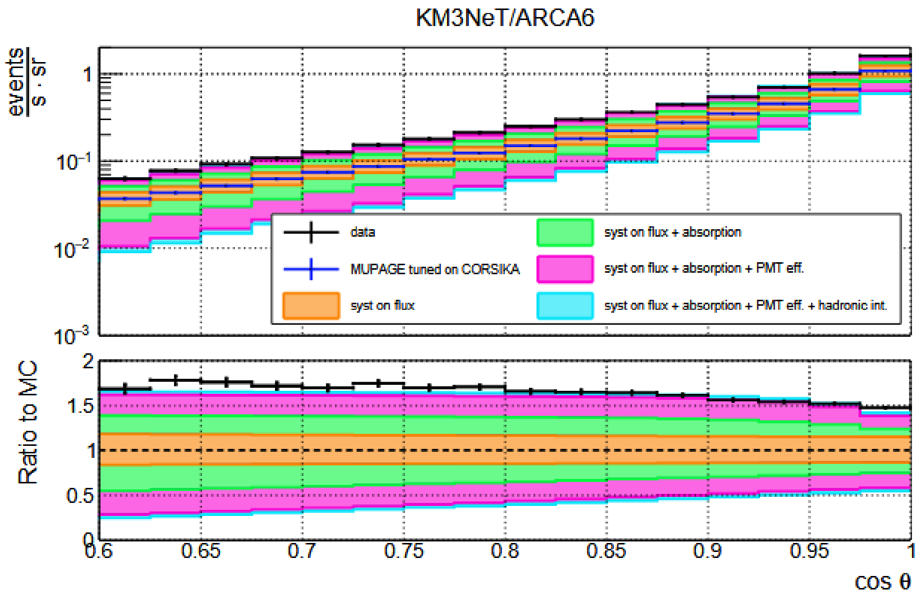
[H.P. Dembinski et al. (WHISP), EPJ Web Conf. 210 (2019)]

0 : Predicted from Xmax measurements

WHISP: Working group on Hadronic Interactions and Shower Physics

Muon deficit measured in KM3NeT





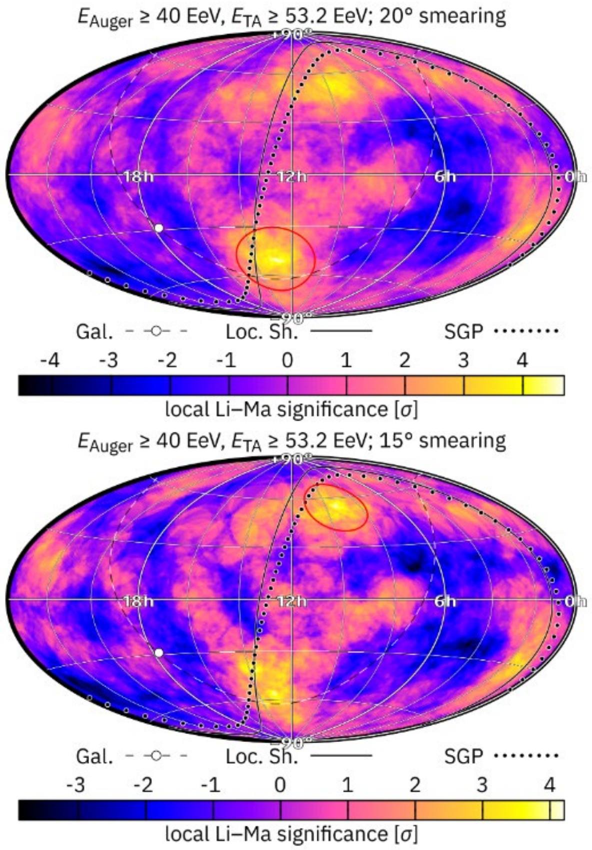
KM3NeT also sees a muon-deficit (in MC).

Note: this does not reflect the improvements in data/MC
when using a data-driven model for flux and hadronic interactions

High Energy CR - Arrival directions

Magnetic field deflect charged cosmic rays – at high energies (rigidities) deflection is less.

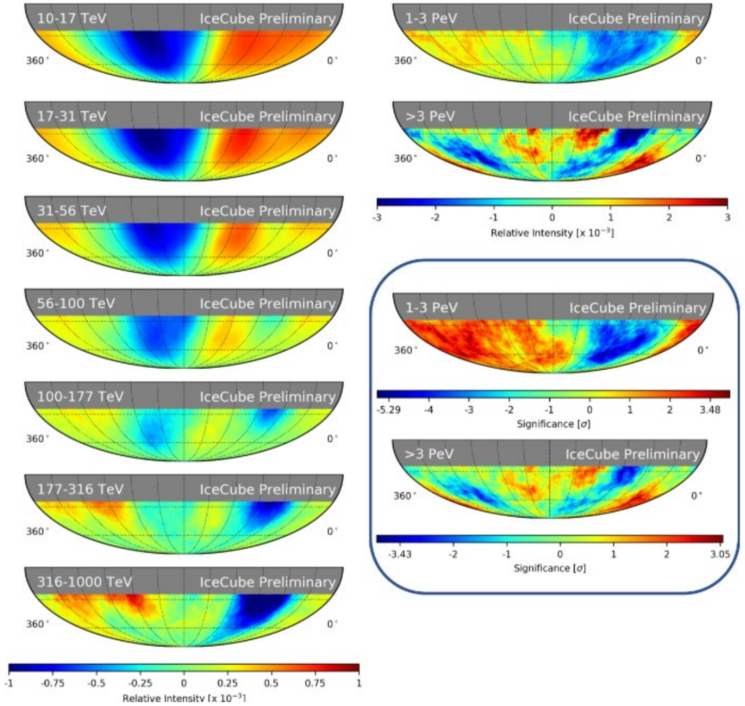
Auger+TA



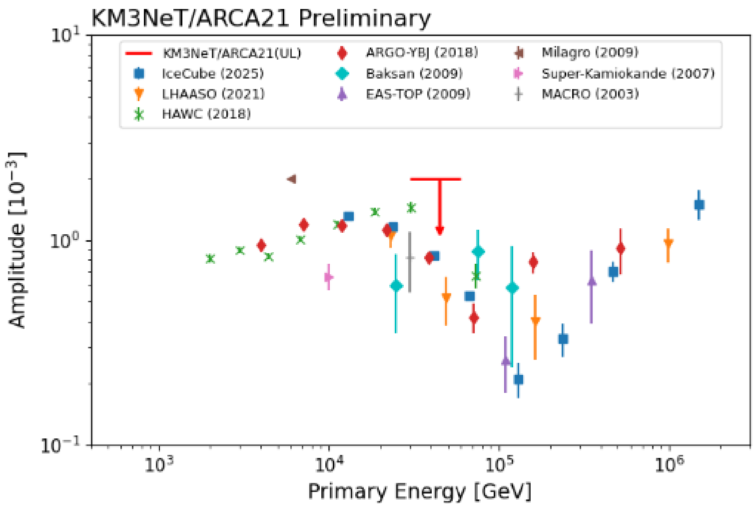
Anisotropies and correlations with source candidates are seen at the highest energies (CenA, Starburst)

PoS(ICRC2019)439

IceCube
Low Energy
Local ?



(ICRC 2021) arXiv:2107.11454v1



KM3NeT/ARCA
PoS(ICRC2025)202

NWO-M

The call

- Continuously open
  - Subdivided in 3 to 4 batches/year
- Total budget 40M/year
- One can request 400.000 euro
  - More if 2 applicants, or can argue for investments
  - Single scientific position; PhDs,Post-Docs, …
  - + some for travel, computing, equipment,….

NWO-M

Goals

- Provide a contribution to the understanding of hadronic interactions at high energies
  - Input for solving ‘muon puzzle’
- Measure composition of the primary cosmic ray flux
- Reduce uncertainties in the atmospheric muon and neutrino flux for the benefit of KM3NeT analyses

Objectives

By making use of KM3NeT, this project aims to 1) provide a crucial contribution to particle physics by understanding of hadronic interactions at high energies, including to solving the ‘muon puzzle’, 2) measure the composition of the primary cosmic ray flux in the energy range accessible to KM3NeT, and 3) as a collateral reduce the uncertainties in the atmospheric muon and neutrino flux in KM3NeT and other observatories, catalysing discoveries in searches for neutrino origins and their properties. To achieve these aims, we will (Task 1) develop and implement sophisticated reconstruction algorithms—machine learning and ‘traditional’ ones—that will extract signatures of hadronic interactions, including muon multiplicity, energy and transverse momentum, and (Task 2) integrate the aforementioned algorithms with existing ones to scrutinize data from the KM3NeT detectors, and to perform multifaceted, multi-parameter fits to cosmic ray composition and hadronic interaction models.

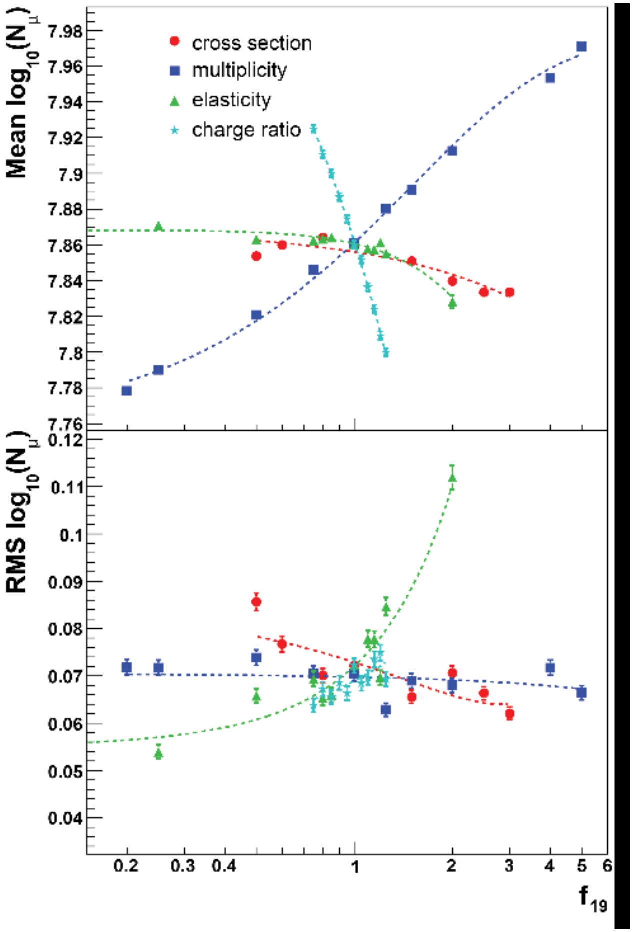
How to achieve these ?

- Develop reconstruction algorithms to extract signatures of hadronic interactions
  - Muon multiplicity
  - Muon energies
  - Transverse momentum/Lateral separation
- Combine with existing ones and perform ‘global’, simultaneous fits to cosmic ray composition and hadronic interaction models
  - E.g. template based with distributions of zenith,energy, multiplicity, lateral separation (and zenith dependent)

Observables in KM3NeT

- Typical air-showers detectors only have access to particle densities
  - Dominated by low energy muons - sub TeV
  - Very limited or no energy measurement of individual muons
- KM3NeT can measure (individual) high-energy muons from the initial interactions

Modifying interaction properties



Scaling of particular property

Multiplicity and fluctuations: Muons from initial interactions

Energy from hadronic interactions carried away by neutral mesons, in particular neutral pions, versus charged mesons and baryons will affect the total number of muons reaching sea-level and beyond.

$$\alpha_1 \equiv \sum_i^m \left(\frac{E_i^{\mathrm{had}}}{E_0} \right)^\beta$$

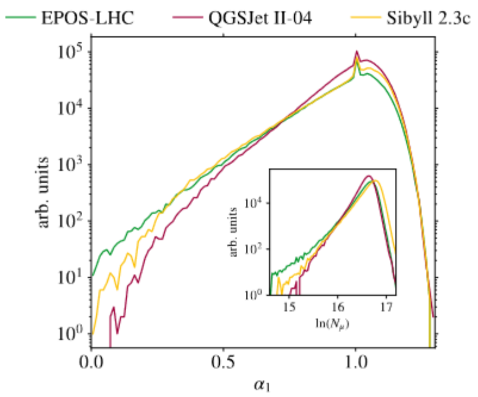
Fraction of energy in hadronically interacting particles at primary interaction

Air-shower experiments measure fluctuations in total number

$$N_\mu \propto \alpha_1 \alpha_2 \ldots \alpha_g \ldots \alpha_n$$

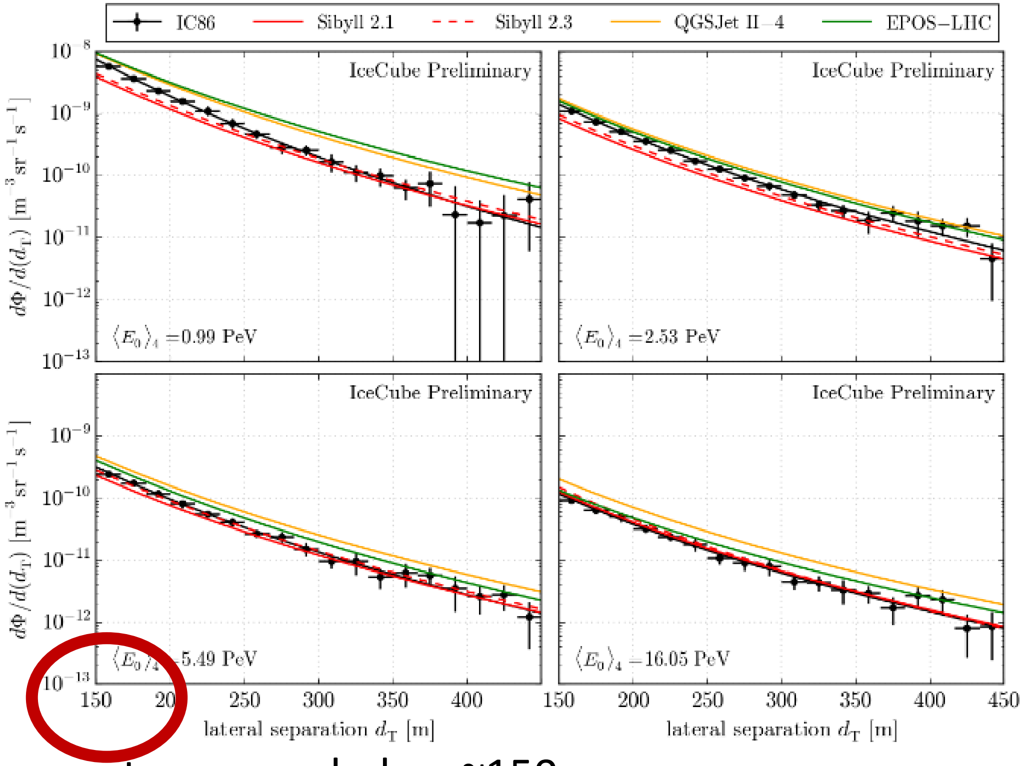
Narrower distributions as there are more particles

We can measure this

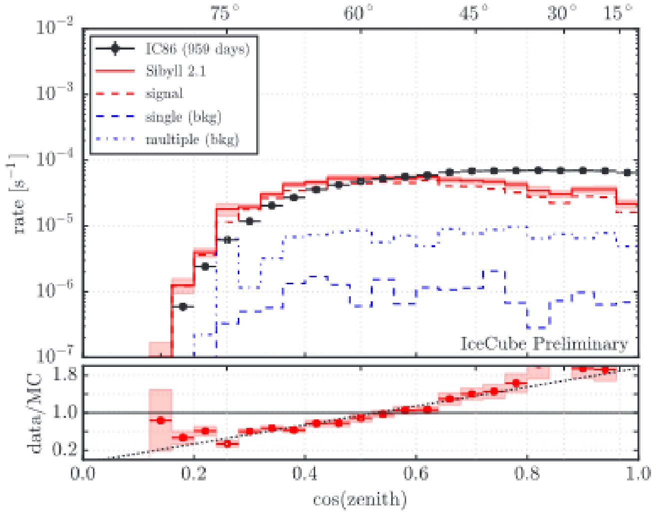


Lateral separation

Muons a large distance away from the cosmic ray shower axis result from fragments with relatively high transverse momentum. These muons directly trace the transverse momentum distribution of mesons created in the first interaction are sensitive to the primary particle species



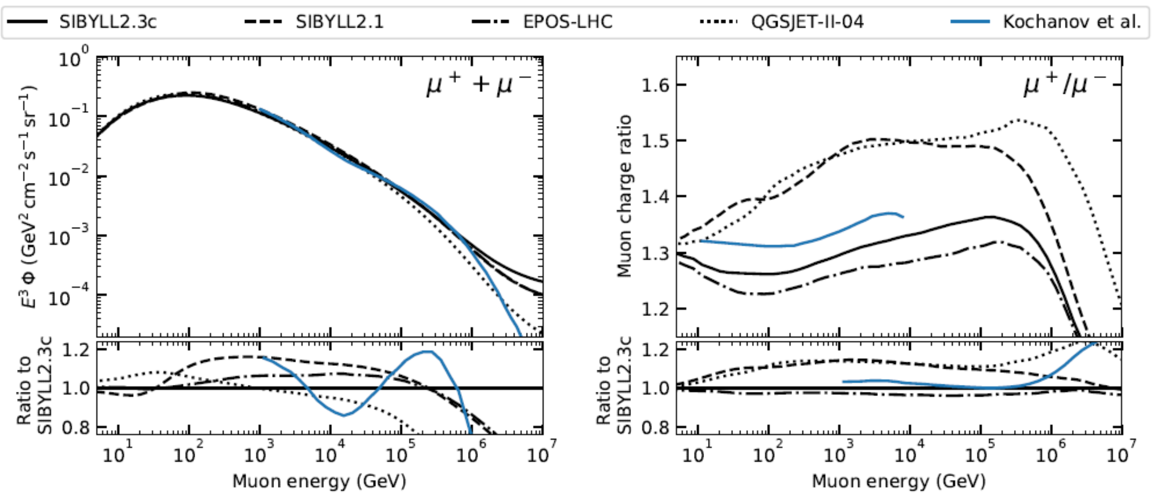
Icecube cannot measure below ~150m
This is also where it cannot be calculated pertubatively

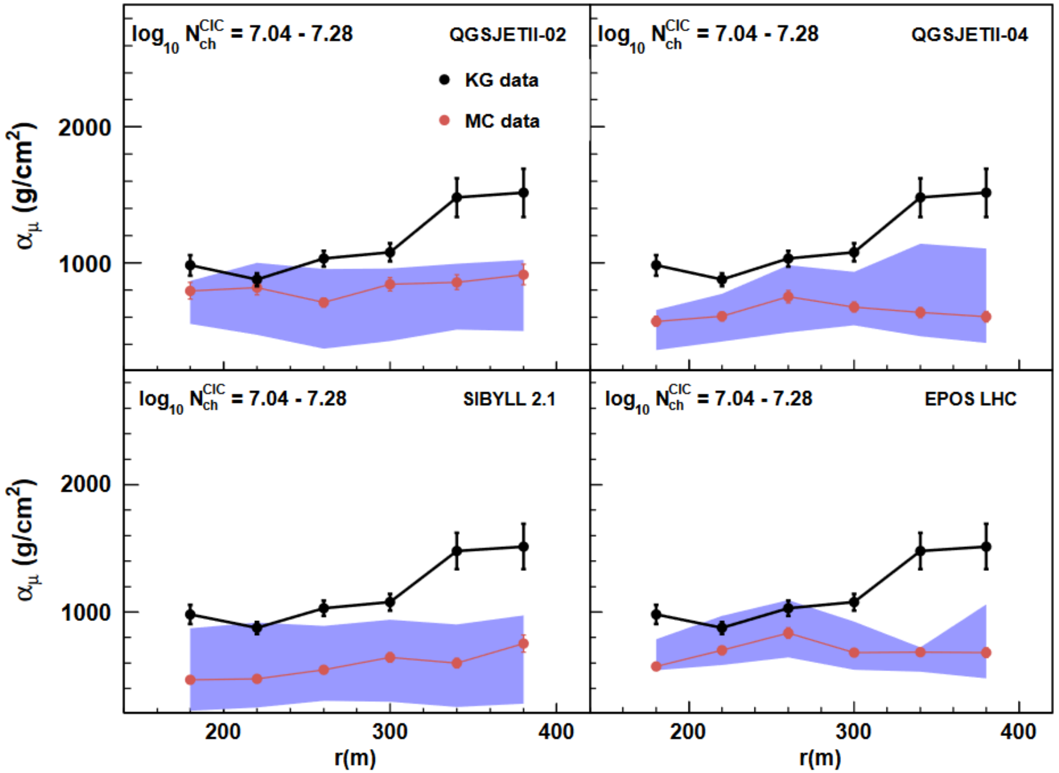


Distribution of lateral separated muons shows data/mc discrepancy

Muon energy spectrum and zenith dependence

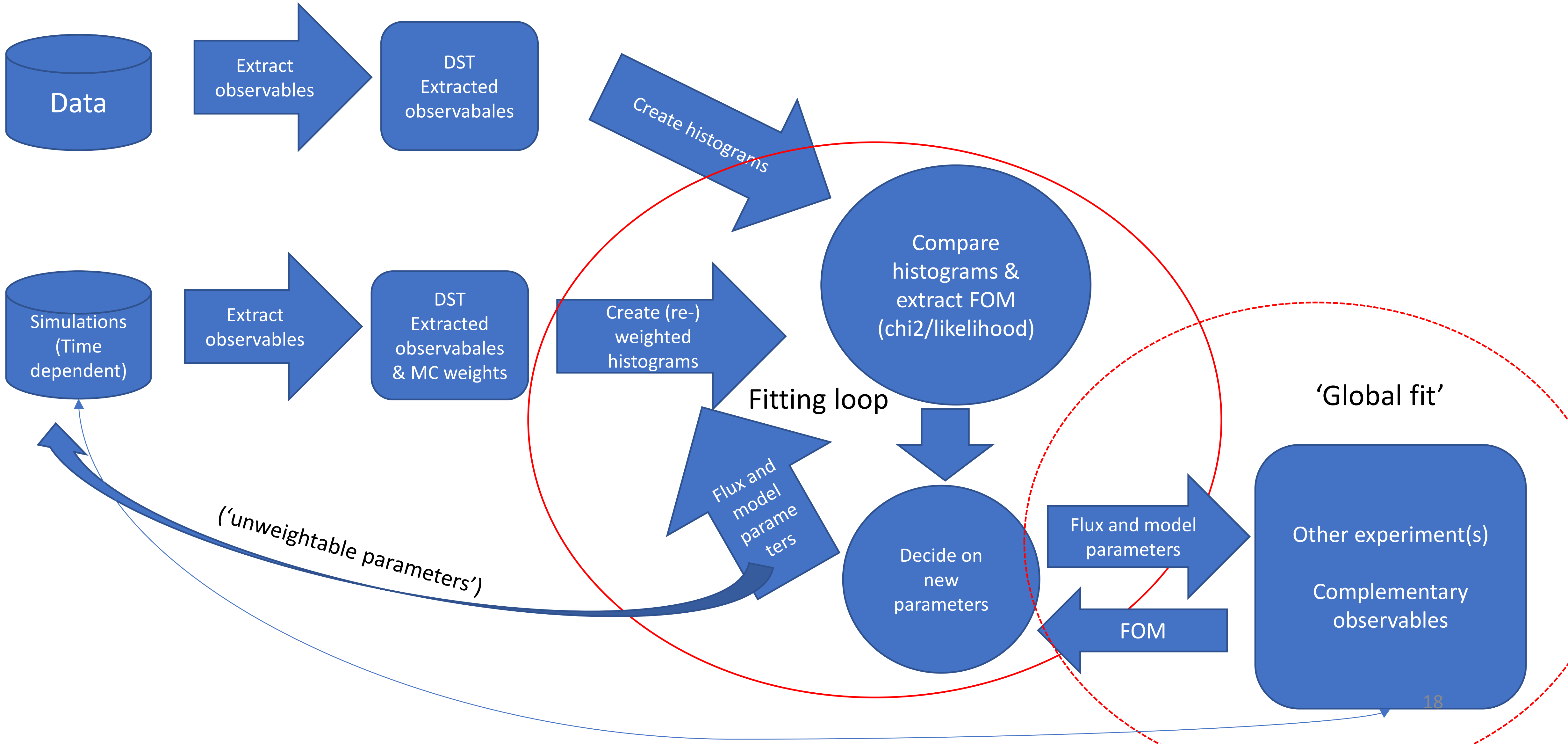
$$\bar{\rho}_{\mu}(r,\theta) = \bar{\rho}^{\circ}_{\mu}(r)e^{-X_0 \sec\theta/\alpha_{\mu}(r)}$$





Kascade-Grande

Analysis/Fitting



NWO-GO ‘Space Infrastructure’

The call

- Total budget : 3.240.000 euro
- One can request 360.000 euro
  - Single Scientific position + some pocket money
- Purpose :
  - This funding instrument is intended to support high-quality scientific research **that makes substantial use of infrastructure in space**. The infrastructure can be both (current or past) existing and planned infrastructure. Within this objective, the GO programme is open for **scientific research in the area of Earth observation** and planets (and other objects) within our solar system.

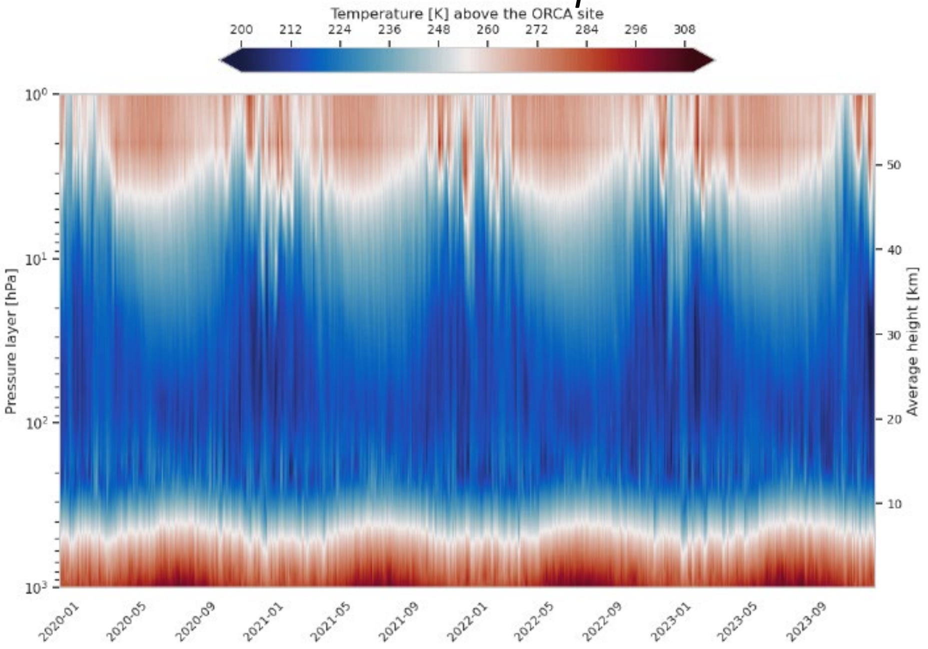
So, <u>no</u> (astro-)particle physics !!
(I called to check…)

NWO-GO - goal

- Goal:
  - '… develop and demonstrate a innovative technique to monitor global atmospheric conditions through measured fluxes of subatomic particles'

Color indicates temperature

Altitude

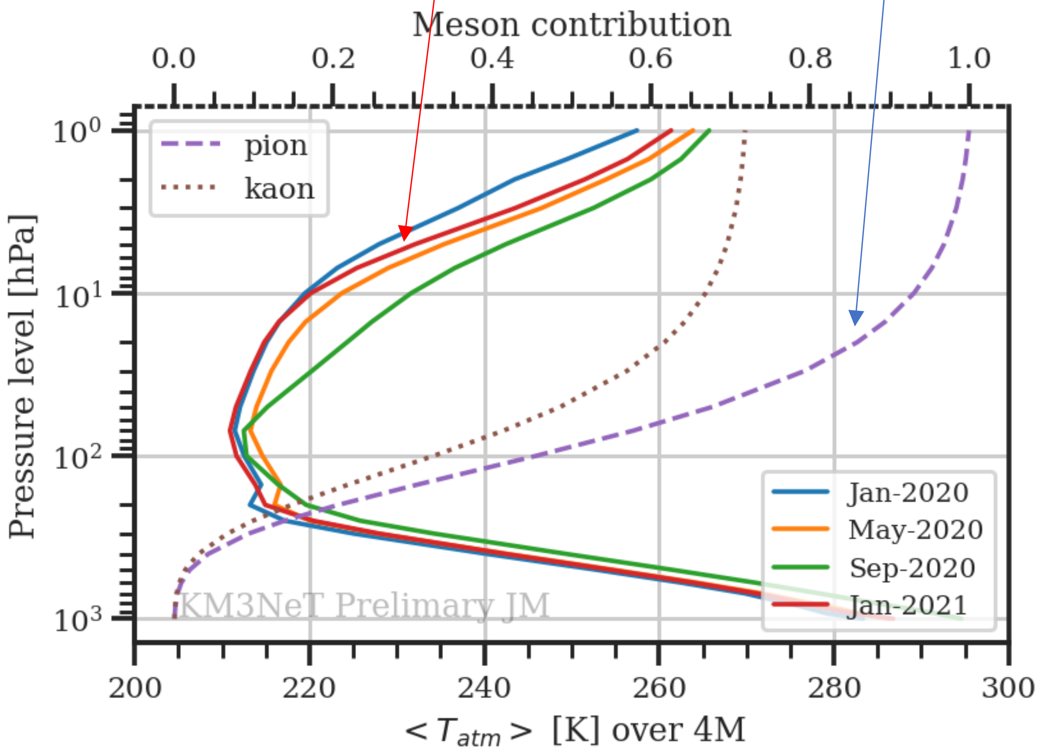


Time

Atmospheric conditions (here, temperature) vary over time and influence lepton fluxes.

Muon 'seasonal'variations

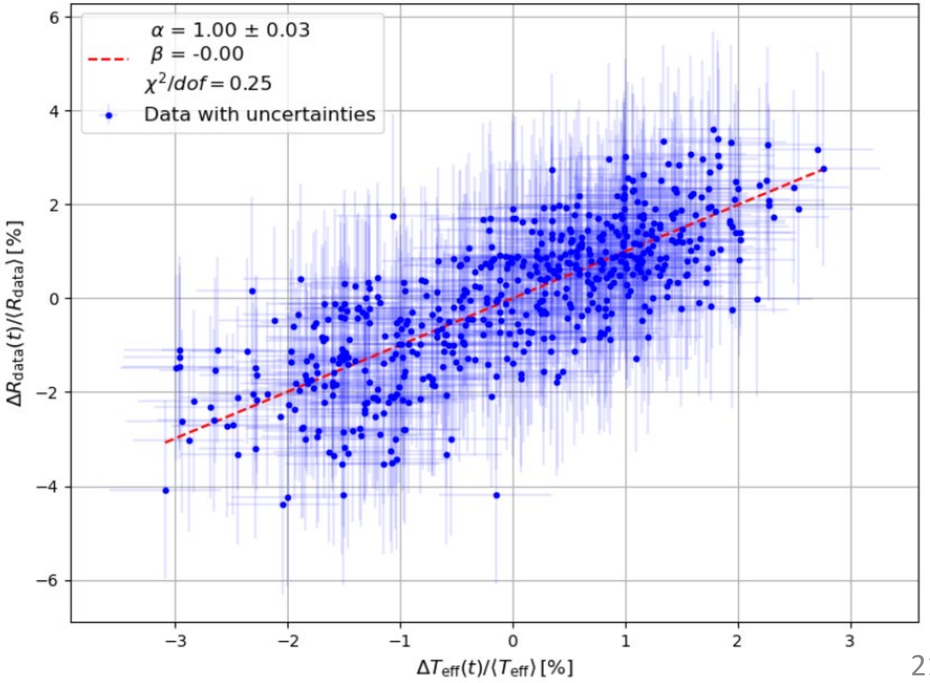
$$T_{eff} = \frac{\int_0^\infty d\chi T(\chi) \int_0^\infty dE_\mu \eta^0(E_\mu, \theta, \chi)}{\int_0^\infty d\chi \int_0^\infty dE_\mu \eta^0(E_\mu, \theta, \chi)}$$



Change in muon rate

Change in temperature

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$



Neutrino Seasonal Variations

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Observation of Seasonal Variations of the Flux of High-Energy Atmospheric Neutrinos with IceCube

PROCEEDINGS OF SCIENCE

Seasonal Variations of the Atmospheric Neutrino Flux measured in IceCube

The IceCube Collaboration
(a complete list of authors can be found at the end of the proceedings)

PROCEEDINGS OF SCIENCE

12-Years Observation of Seasonal Variation of Atmospheric Neutrino Flux with IceCube

The IceCube Collaboration
(a complete list of authors can be found at the end of the proceedings)

Time variation of the atmospheric neutrino flux at dark matter detectors

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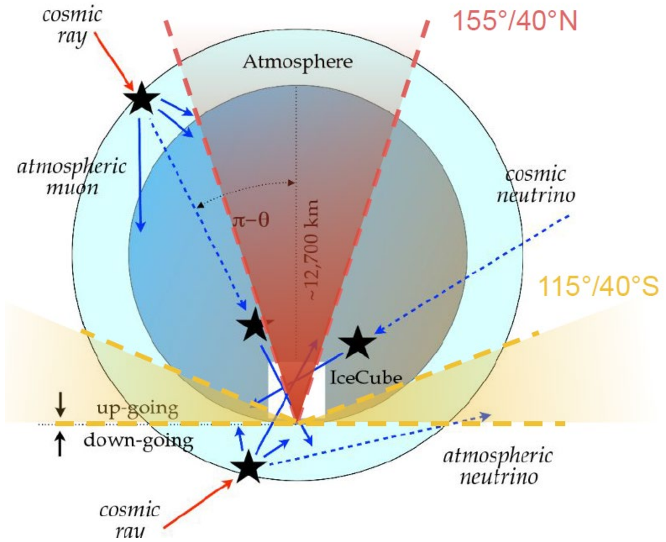
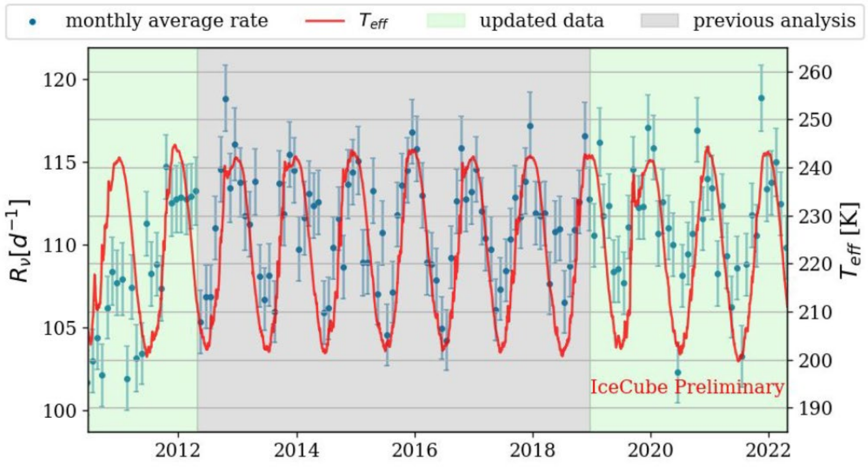
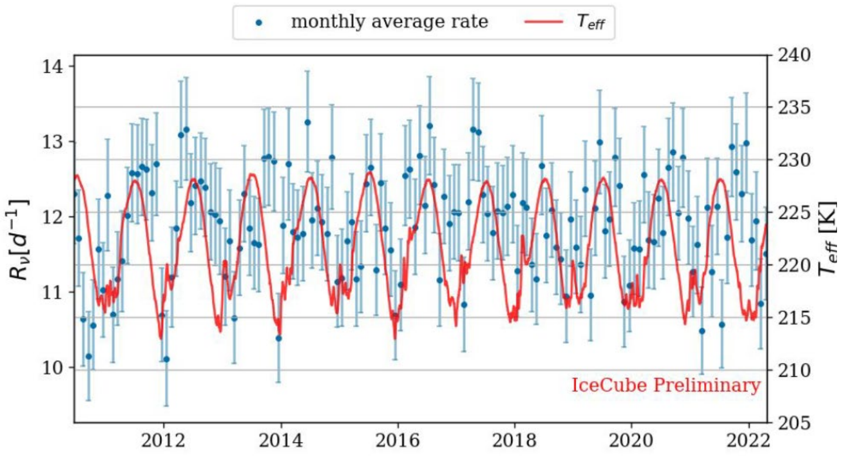
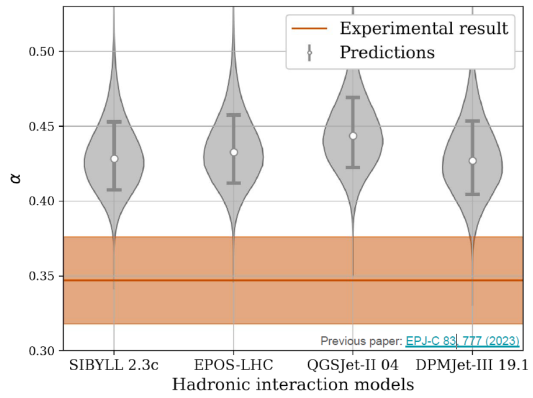
Neutrino seasonal variations







Observations in tension with predictions



NWO-XS

The call

- Total budget : 2.400.000 euro
- One can apply for 50.000 euro
    - Personnel and equipment
- 3 times per year (was 4)
- You have to anonimize your application (!) and assess other applications

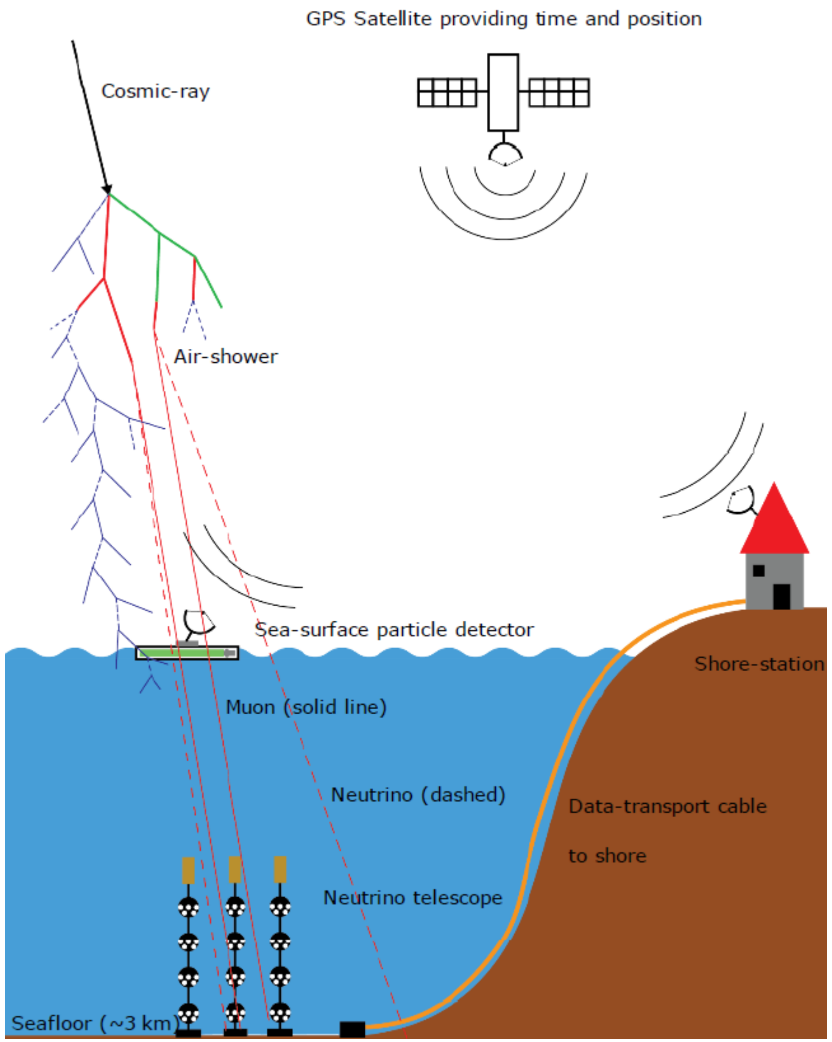
Demonstrator of a sea-surface detector

Goal:

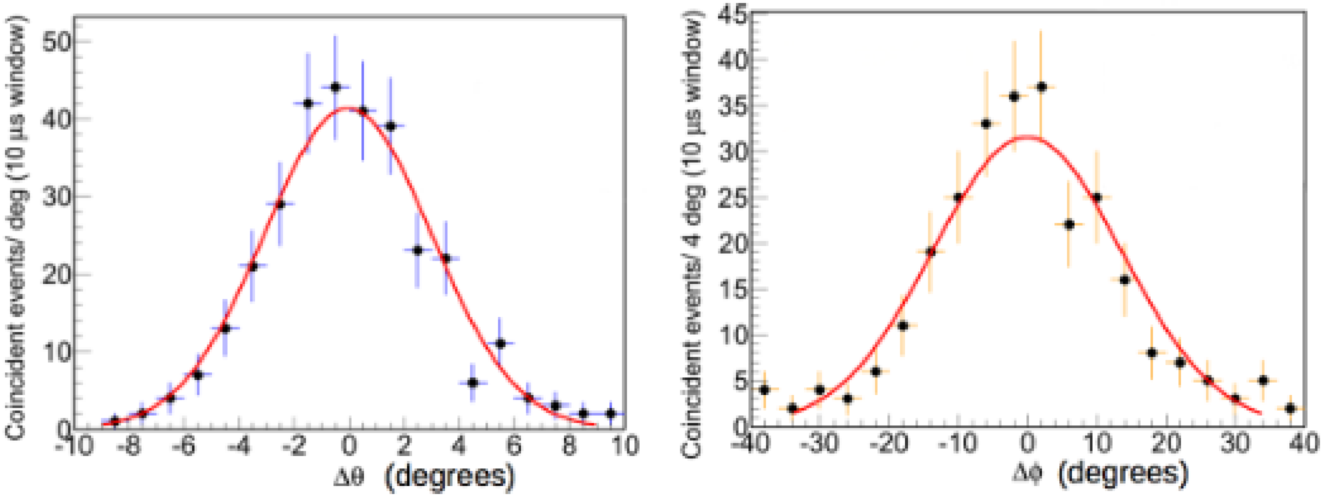
- '…to demonstrate the feasibility of a sea-surface detector for cosmic-ray induced particles'
  - 'Prototype' or 'demonstrator'
  - For orientation calibration of our detectors
  - Could be expanded to array for cosmic ray research
    - Measure electro-magnetic component of air-showers

Requested:

- Technical personnel and material cost



Antares: array on ship



Difference between reconstructed muon angle and ship-Antares axis

Side note : Gamma-ray detectors

Instrumenting a Lake as a Wide-Field Gamma-ray Detector

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[a]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, Heidelberg 69117, Germany.*

Abstract

Ground-level particle detection has recently emerged as an extremely powerful approach to TeV-PeV gamma-ray astronomy. The most successful observatories of this type, HAWC and LHAASO, utilise water-Cherenkov based detector units, housed in tanks or buildings. Here we explore the possibility of deploying water-Cherenkov detector units directly in to a natural or artificial lake. Possible advantages include reduced cost and improved performance due to better shielding. The lake concept has been developed as an option for the future Southern Wide-view Gamma-ray Observatory, and is now under consideration for a possible future extension of the observatory, beyond its recently selected land site. We present results from prototypes operated in a custom built facility, and concepts for full-scale array deployment and long-term operation.

(Uses ANTARES PMTs)

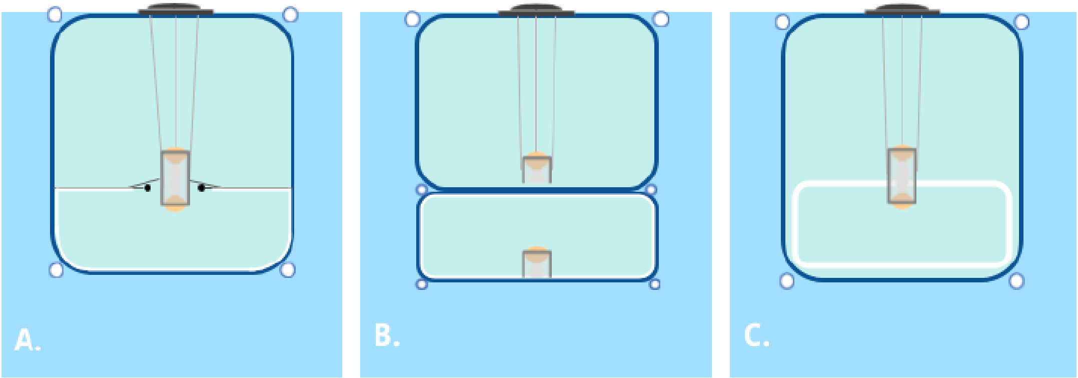


Figure 1: Three design options, from left to right: A) internal divider, B) independent volumes, C) the matryoshka, or nested solution.

Figure 7: The test facility at MPIK: A 10 m diameter, 7 m height lake simulation tank, here with two bladders deployed. Next to the tank the water filtration system, and a small container for electronics and DAQ.

eScience Open Call

The call

- Total budget : ??
- One can apply for 3 FTE of eScience engineer personpower over 3 years
  - Some pocket money
  - Requirement of organising workshop
- Purpose of call:
  - *‘This call for proposals supports research that requires the development and application of advanced research software. Each proposal should address an urgent methodological research challenge that can count on broader support from the research community in which the applicants are active. ‘*

Air-shower simulations are required to interpret measurements

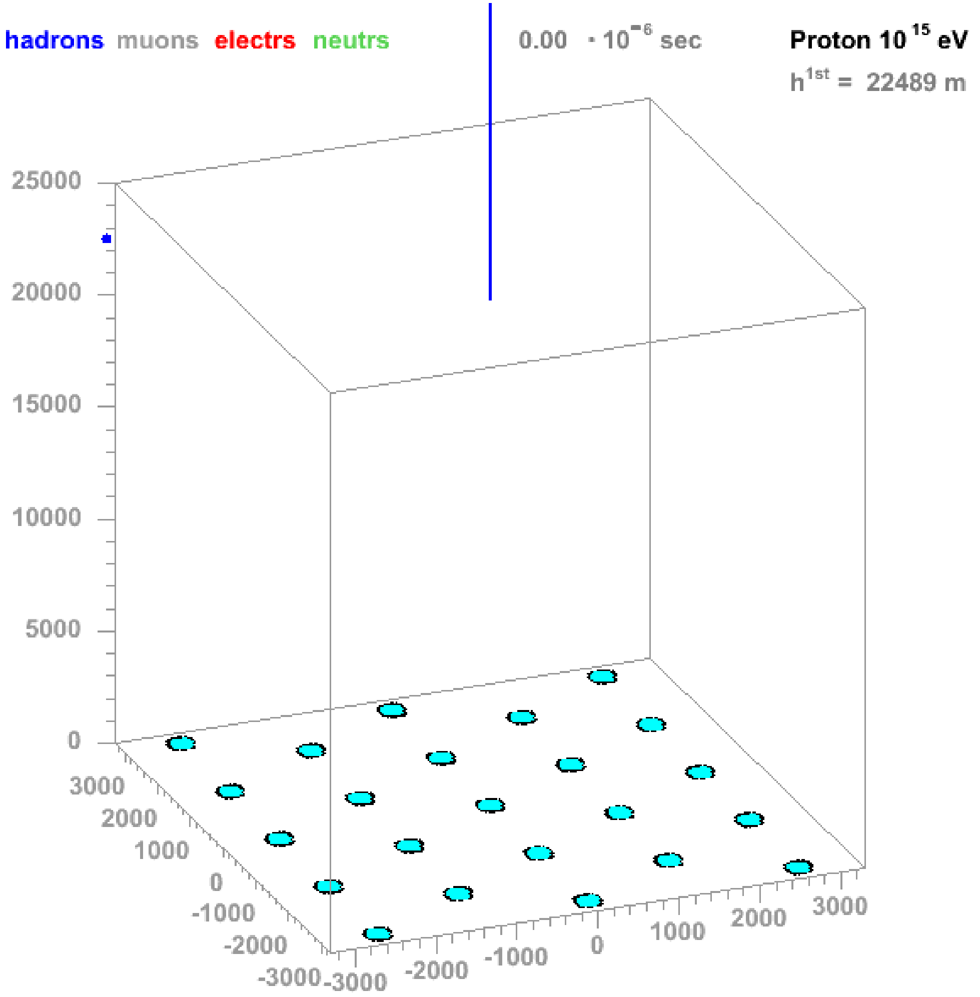
Air-shower simulations model the particle cascade following an cosmic-ray interaction in the atmosphere. This includes particle (re-)interactions, decays etc.

Inputs:
- Models for particle interactions
    - Provide cross-sections, particle yields etc.
- Atmosphere through which the showers develop

Outputs:
- List/Distribution of particles at observation levels, including type, energy, direction
- Energy losses in medium (for e.g. fluorescence, acoustic)

Most commonly used method is Monte-Carlo simulation

They are required due to the complex relation between the microscopic physics and the observables, combined with the large amount of particles and interactions.



J.Oehlschlaeger,R.Engel,FZKarlsruhe

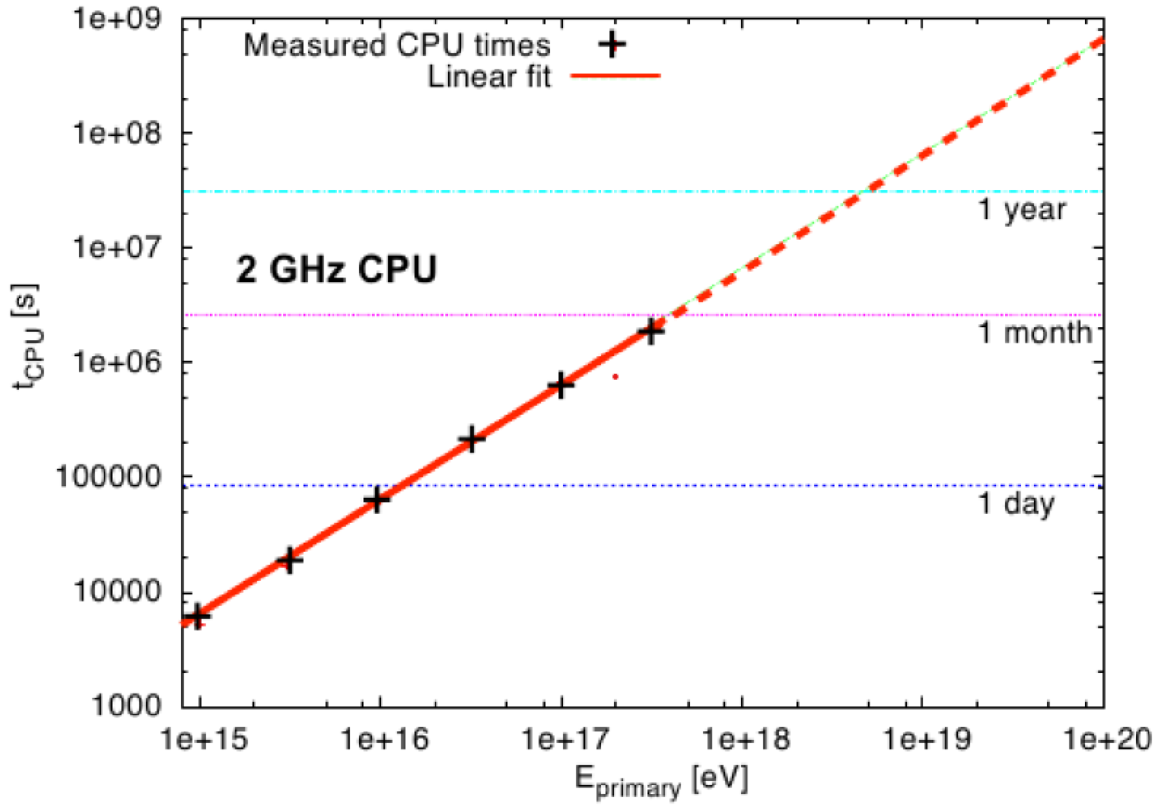
Air-shower simulations are compute intensive

Required computation time is large, and scales directly with particle energy (storage too).

Computation time can be mitigated to small extent using weighting schemes, thinning.

Simulating one month of data, with mitigating options (!) requires many hundreds of thousands of hours of CPU time.

Parametric simulations are fast, but do not capture the physics. There is e.g. no relation between primary and particle flux.



So, let's make things faster (and better for the environment!)

(Generative) Neural Networks

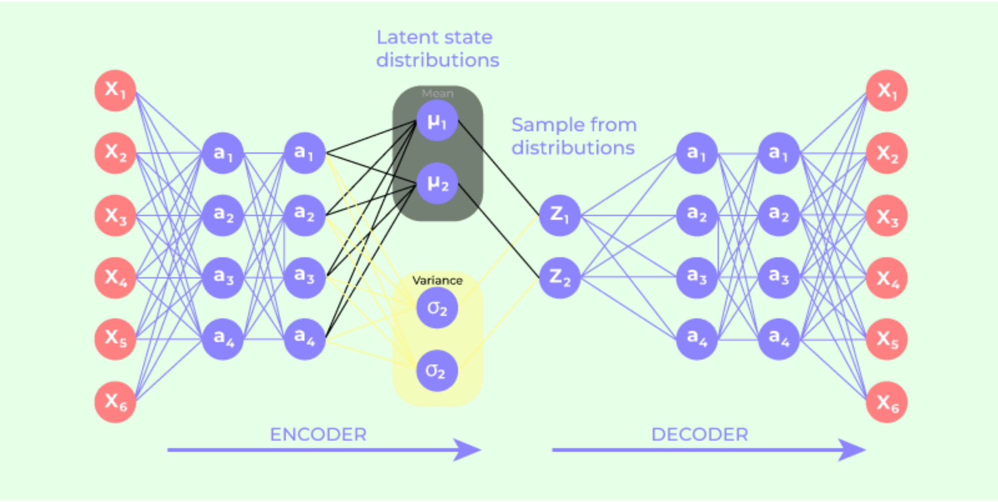
Neural Networks can be used to generate fake data.
(You probably have seen fake images or videos …)

Several architectures are candidates to deal with the stochastic nature of air-shower simulations

The goal:
A neural network based method to generate air-shower Particle distributions many orders of magnitude faster than Simulations.

The idea is to train networks on data generated by CORSIKA for different parameters (e.g. primary particle, atmosphere, hadronic interaction model) with the goal of them learning to make such distributions themselves.

Variational auto-encoder



Generative adversarial network