technische universität dortmund

Experimentelle Physik V
Teilchenphysik

Astroparticles and Particles

31. May 2022

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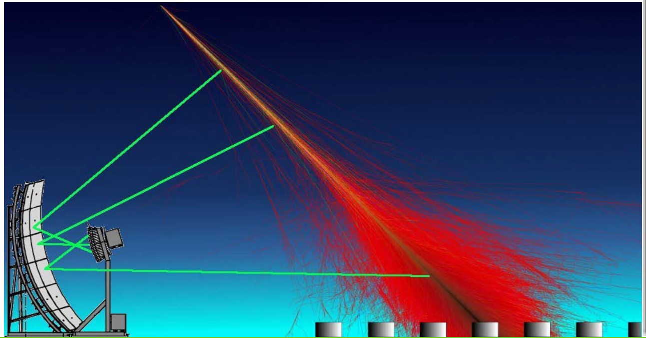
Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

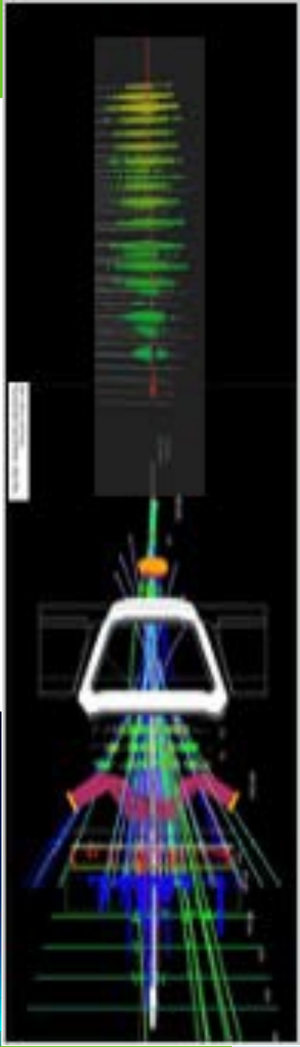
Many slides originally done by K.H. Kampert and H. Dembinski

Particle challenges

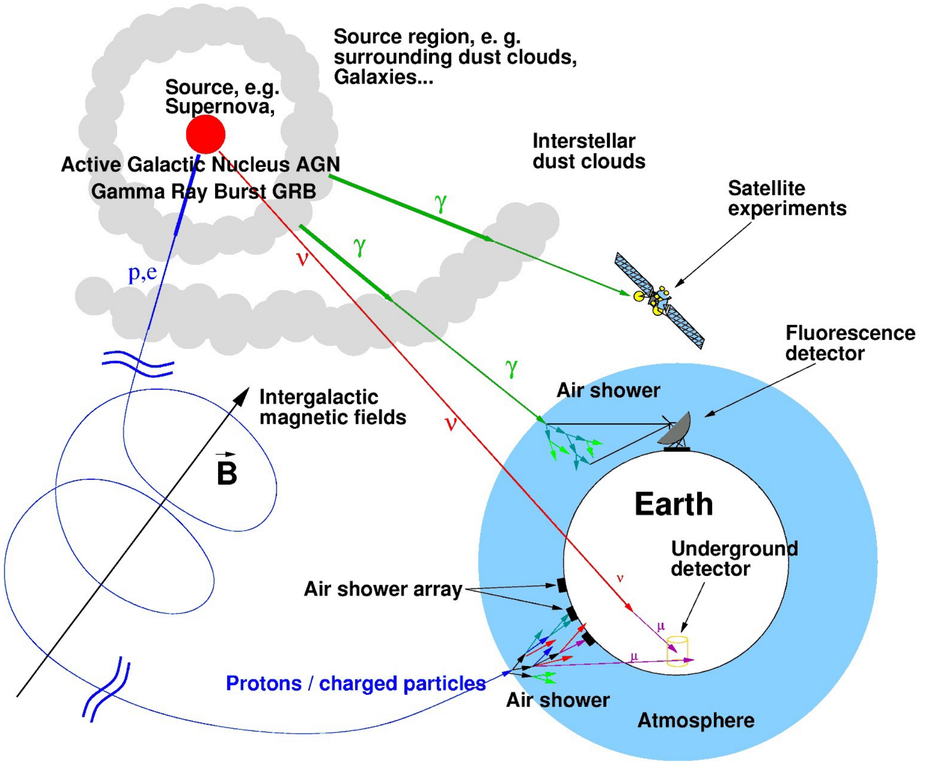
- Overarching Goal:
  Tune hadronic interaction models to consistently describe air shower particles and (LHC) accelerator data to serve a broad field of astroparticle physics

- Key Instruments:
  - LHCb @ CERN
  - Pierre Auger Observatory
  - IceCube Observatory

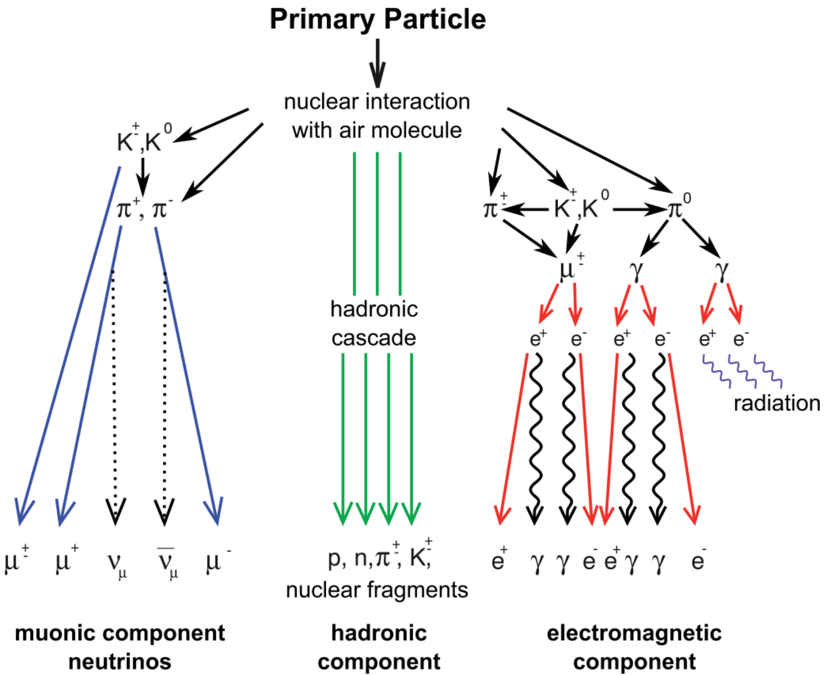




Wofgangs most favorite figure



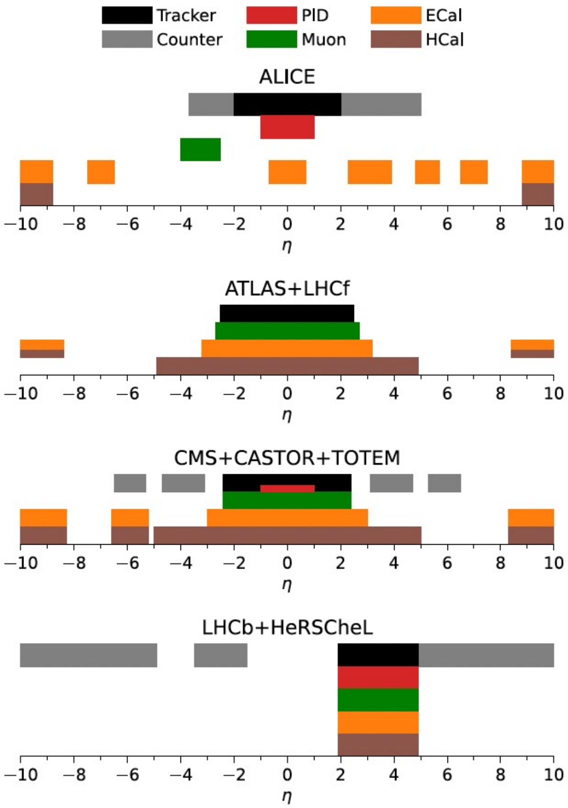
Hadronic interactions in air showers

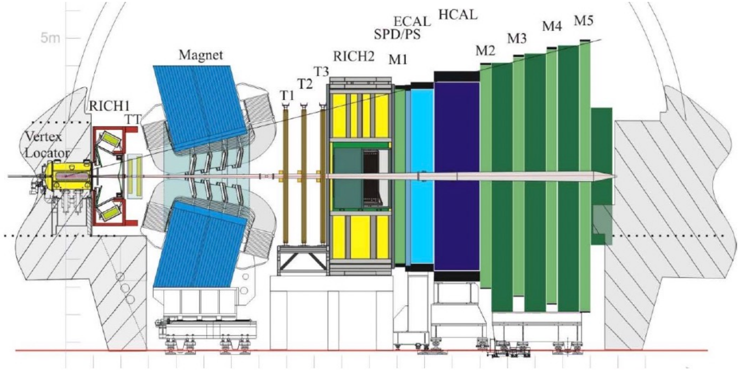


Haungs et al., JoP Conf. Ser. 632 (2015) 012011

Cross section of processes **can and need to be** understood in controlled lab environments

→ Natural interplay between astroparticle and collider experimetns



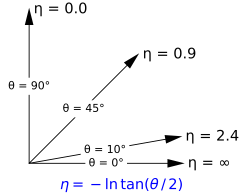


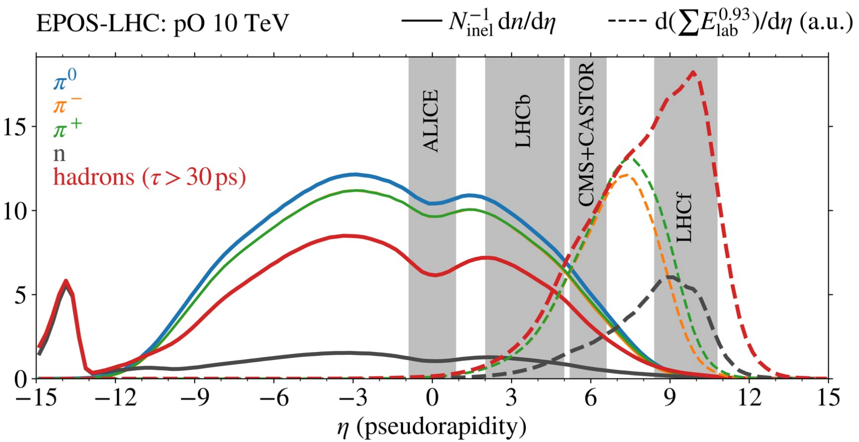
General purpose single-arm forward spectrometer

- Acceptance
  - 2 < η < 5 with particle identification (PID)
  - 0.1 < p_T / $\mathrm{GeV}c^{-1}$ < 10
- Very good momentum and vertex resolution
- Accurate luminosity (world record for *p-p* 7 TeV)
- PID optimal for π, K, p, μ
- Flexible software trigger

- **Unique fixed-target mode:** p,Pb+(He, Ne, Ar)gas

Nb.
η related to emission angle





In both cases, need to understand:

- Small Bjorken-x (Need very small x)
- Forward region (Hard to measure at colliders)
- Fragmentation of quarks → hadrons (Non-perturbative, hard to measure)
- Nuclear effects in pA hard interactions

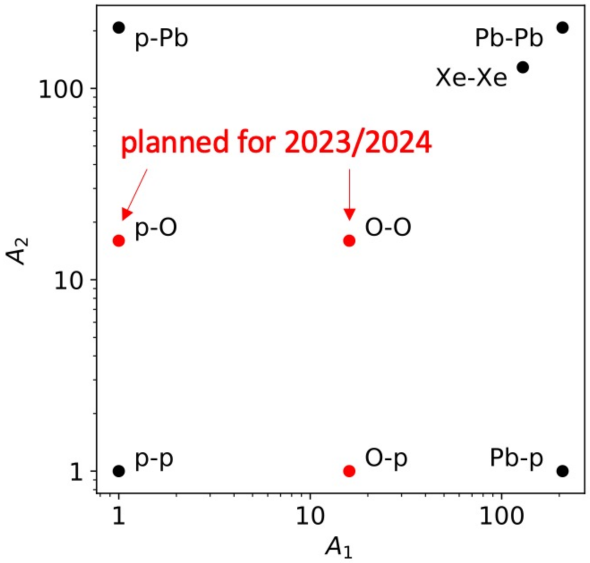
Further Input:

- *Forward cross section for heavy quarks in pp/pA collisions at extremely high energy (pQCD)*
- *Fragmentation of heavy quarks into hadrons*
- Rescattering of nucleons, hadrons (hadronic xsecs) (scattering lengths)
- Decay spectra of charmed mesons & baryons (decay lengths)

LHC(b) collision systems

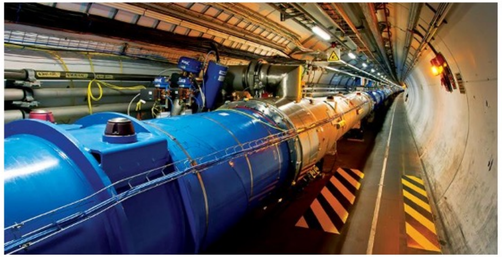
Collision systems at the LHC

Run 3: p-p @ 14 TeV, p-O @ 10 TeV

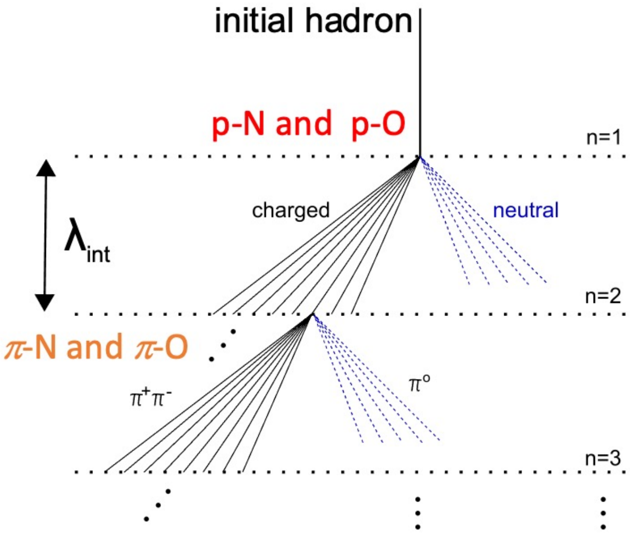


Fixed target data at sub-TeV (LHCb only)

- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)



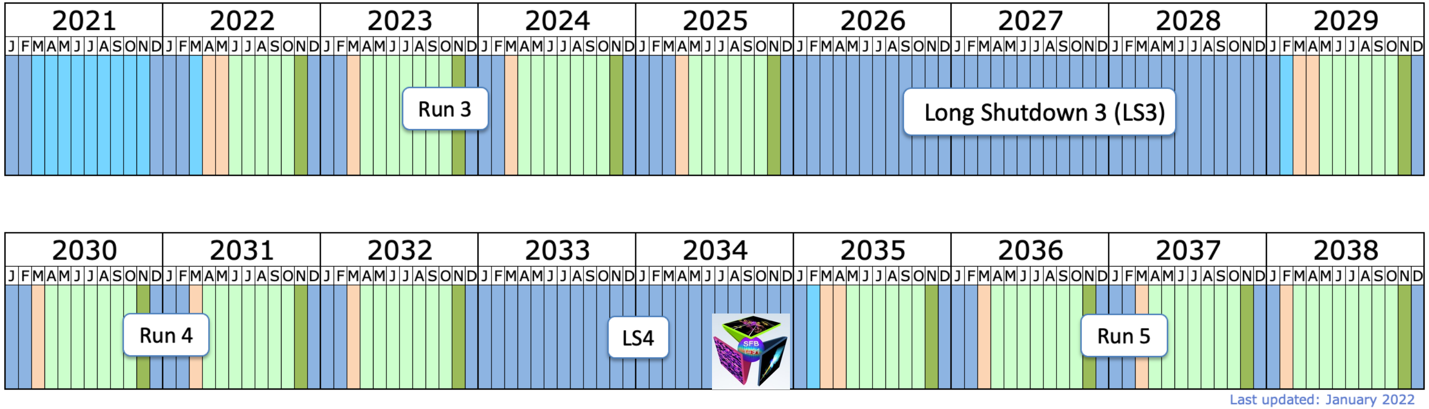
Air shower collision systems



p-O collisions mimic air shower interactions

Datasets used

- LHCb and Auger have a lot of data already available and waiting to be analysed
- Upgraded LHCb and AugerPrime may require some time to be understood
- Availability of Oxygen beam depends on CERN schedule
- Study possibility of LHCb spectrometer forward extension



SFB end phase 3

Why is model tuning important

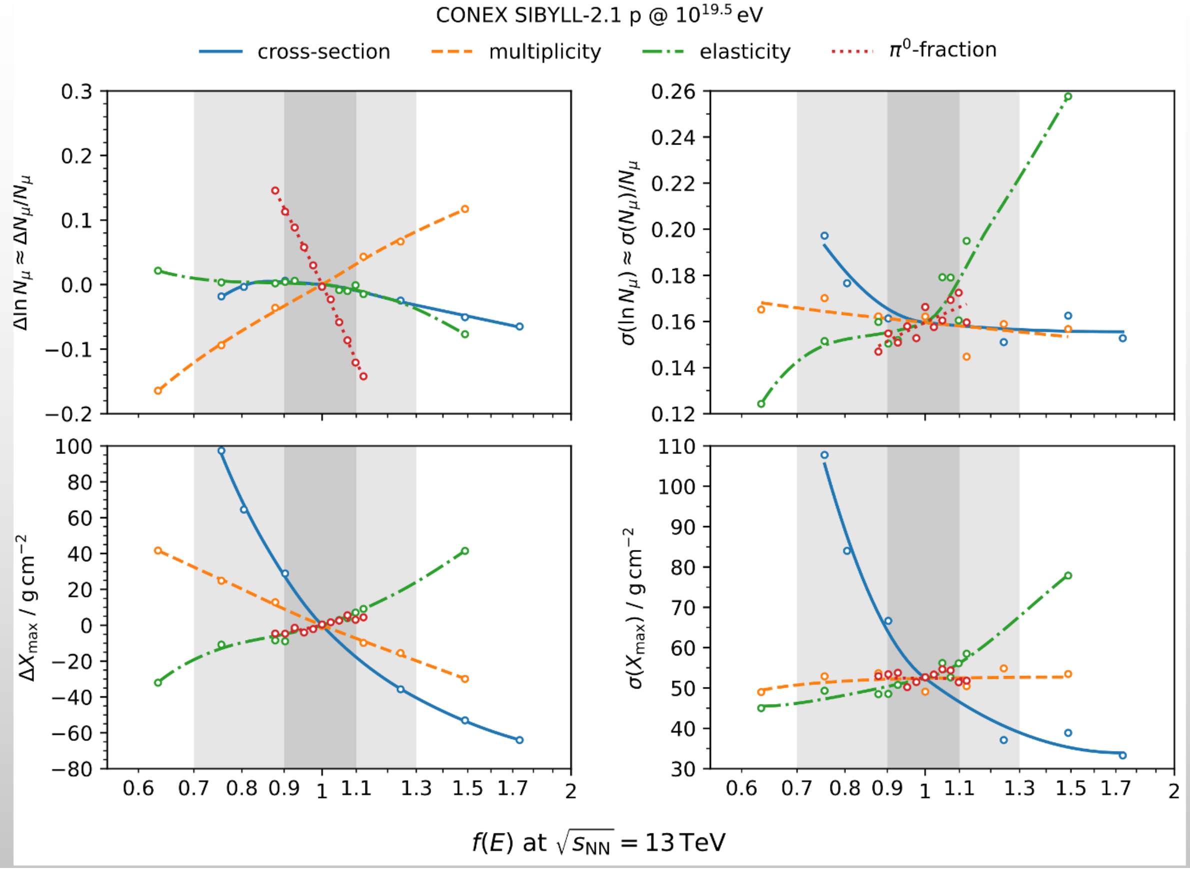
A: Understanding UHECR sources

- Knowing the cosmic ray mass composition at high energies is of key importance for understanding the origin of UHECR, i.e. origin of most energetic particles in the Universe
- Cosmic ray mass composition also key ingredient to UHECR Multi-Messenger observations, e.g. for predicting cosmogenic neutrino and photon fluxes, a goal for many next generation experiments
- „Progress of high energy astroparticle physics depends on progress in measuring the UHECR composition reliably“
- Unfortunately, UHECR mass composition is the most poorly known quantity as it is the most difficult one to measure…
- … because it is inferred from comparison of EAS data with EAS simulations, with the latter being dependent on hadronic interaction models

B: Precise measurement of atmospheric neutrino flux

- Cosmic ray composition also key ingredient to atmospheric neutrino-flux calculations
- Flux of prompt neutrinos depends on charm (bottom) production cross section

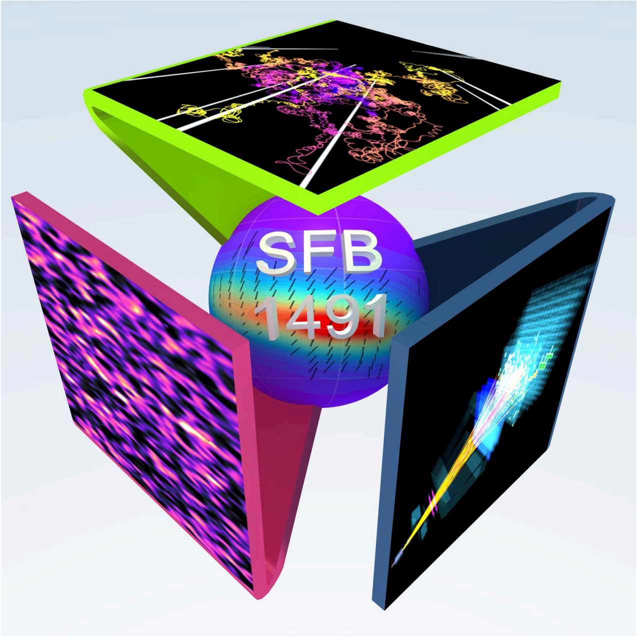
Complexity of model tuning



Modifications of models based on LHCb data may not improve description of EAS data, may even lead to conflicts…

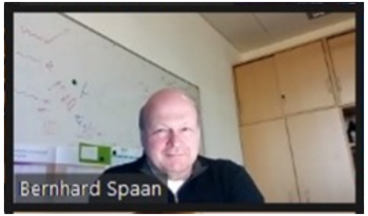
<u>If we are lucky:</u>
Will find a consistent picture that describes all EAS observables

Particle Projects in SFB1491



Particle challenges

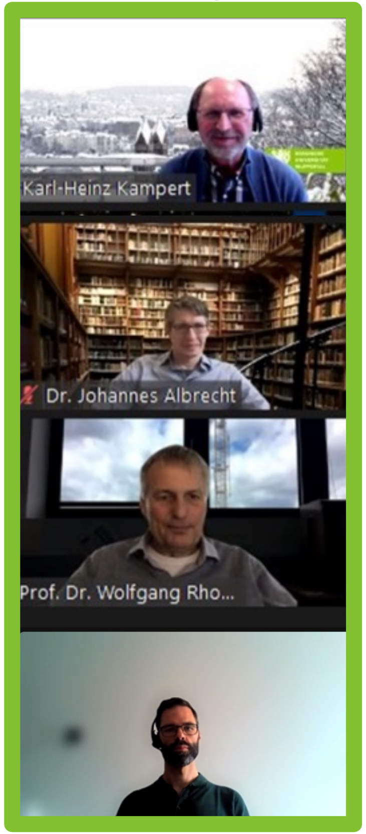
- Two „particle“ projects in SFB1491

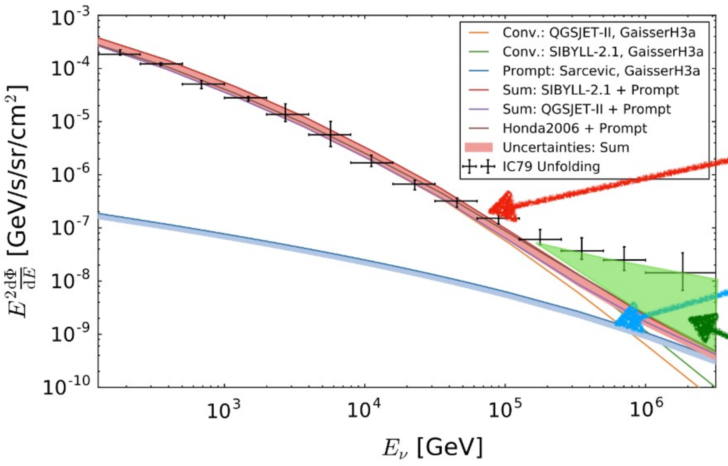


- F3: Prompt Lepton Production in Hadronic Interactions
  - PIs: Wolfgang Rhode, Johannes Albrecht
  - Consultant: Hans Dembinksi, Jan Ellbracht
  - DFG: Nicole Schulte (TUD), Mirco Hünnefeld (TUD)

- F4: Cross sections and hadronic interactions in particle- and astroparticle physics
  - PIs: Johannes Albrecht, Kevin Kröninger, Karl-Heinz Kampert
  - Consultant/Staff: Hans Dembinksi, Julian Rautenberg, Leonel Morejon, Lars Kolk
  - DFG: Salvatore La Cagnina, Michael Windau, Julian Boelhauve (TUD), Chloé Gaudu (BUW)

PI‘s





The Issue:

Atmospheric neutrinos (arising from air showers induced by Cosmic Rays), mostly π **decays, long lived** $\rightarrow dJ/dE \propto E^{-3.7}$

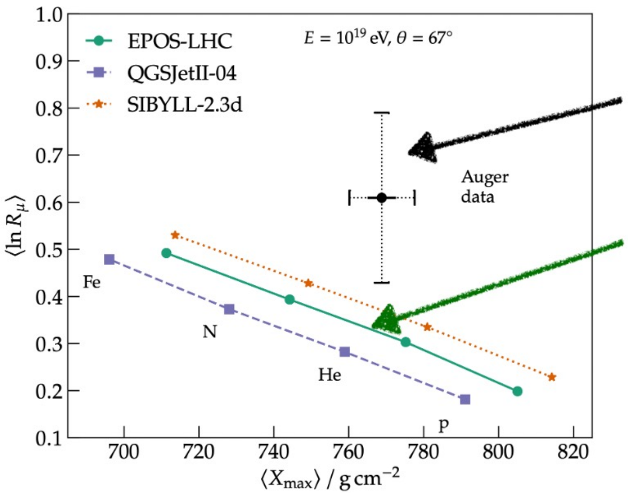
„Prompt“ flux of neutrinos, mostly charmed particles, short lived, no energy loss $\rightarrow dJ/dE \propto E^{-2.7}$

The difference is the astrophysical flux
→ need to understand the atmospheric including its prompt flux very well

Objectives:

- What is the energy spectrum of leptons produced in extensive air showers?
- What is the energy spectrum of prompt muons produced in hadronic interactions?
- How can the highest-energy part of the spectrum of astrophysical neutrinos be described?

F4: Cross Sections and Hadronic Interactions and beyond LHC



The Issue

Auger measures both muon number and depth of shower maximum as a fct of CR energy

Air shower simulations fail to describe muon number, unless primary CR composition would be trans iron

known as „Muon Puzzle“

Objectives and key questions:

- Can interaction models be tuned to provide a consistent description of air shower observables?
- How do nuclear effects in proton and ion collisions impact hadron generation at high energies?
- Is there universal strangeness and baryon enhancement in high-multiplicity proton and ion collisions in the forward region and how would it affect extensive air showers?

Astrophysics and Space Science (2022) 367:27
https://doi.org/10.1007/s10509-022-04054-5

Further reading

REVIEW ARTICLE

Check for updates

The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider

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Abstract
High-energy cosmic rays are observed indirectly by detecting the extensive air showers initiated in Earth's atmosphere. The interpretation of these observations relies on accurate models of air shower physics, which is a challenge and an opportunity to test QCD under extreme conditions. Air showers are hadronic cascades, which give rise to a muon component through hadron decays. The muon number is a key observable to infer the mass composition of cosmic rays. Air shower simulations with state-of-the-art QCD models show a significant muon deficit with respect to measurements; this is called the Muon Puzzle. By eliminating other possibilities, we conclude that the most plausible cause for the muon discrepancy is a deviation in the composition of secondary particles produced in high-energy hadronic interactions from current model predictions. The muon discrepancy starts at the TeV scale, which suggests that this deviation is observable at the Large Hadron Collider. An enhancement of strangeness production has been observed at the LHC in high-density events, which can potentially explain the puzzle, but the impact of the effect on forward produced hadrons needs further study, in particular with future data from oxygen beam collisions.

Astroparticles and particles @ SFB1491