technische universität dortmund

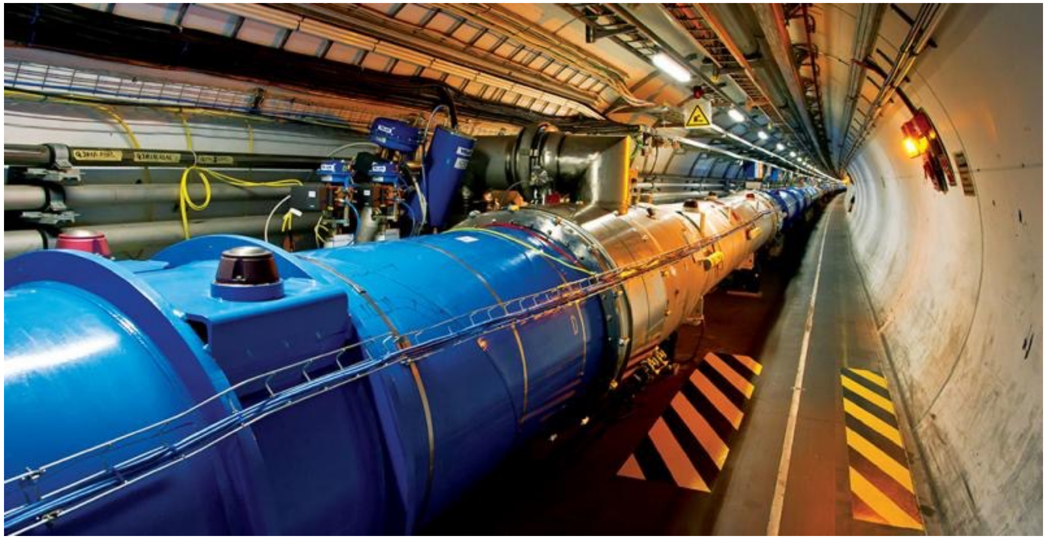
E5a/ Physik

Tuning of event generators with accelerator and astroparticle input

Hans Dembinski, TU Dortmund

Artist impression of air shower

Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0



Overview

- Goal: tune event generators with accelerator & astroparticle input
- Motivation
  - **Muon Puzzle** in cosmic-ray induced air showers
  - Clarify **mass composition** of ultra-high energy cosmic rays
  - Improve **predictive power of generators**
- Astroparticle experiments
  - What kind of data can be used for tuning?
- Accelerator experiments
  - Which measurement are most important?
  - General-purpose experiments vs. specialised experiments
- Tuning
  - How are event generators currently tuned to accelerator input?
  - How could this be extended to astroparticle input?
  - Benefits?

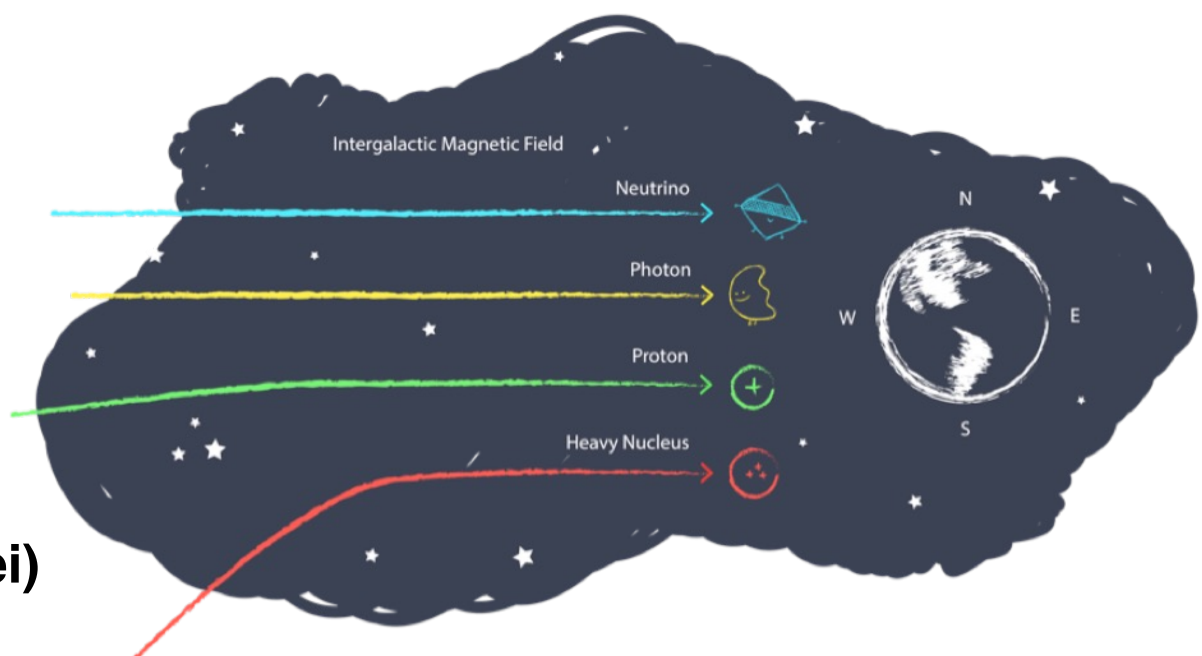
Introduction

Astroparticles

- Messengers of high-energy non-thermal universe
  - Tremendous energies: **TeV** = 10^3 GeV **PeV** = 10^6 GeV **EeV** = 10^9 GeV

- Messengers
  - Gamma rays
    - Pointing ☺
    - Abundant ☺
    - E_{max} 100 TeV ☹
  - **Neutrinos**
    - Pointing ☺
    - Rare ☹
    - E_{max} > 100 EeV ☺
  - **Cosmic rays (nuclei)**
    - No pointing ☹
    - Abundant ☺
    - E_{max} > 100 EeV ☺

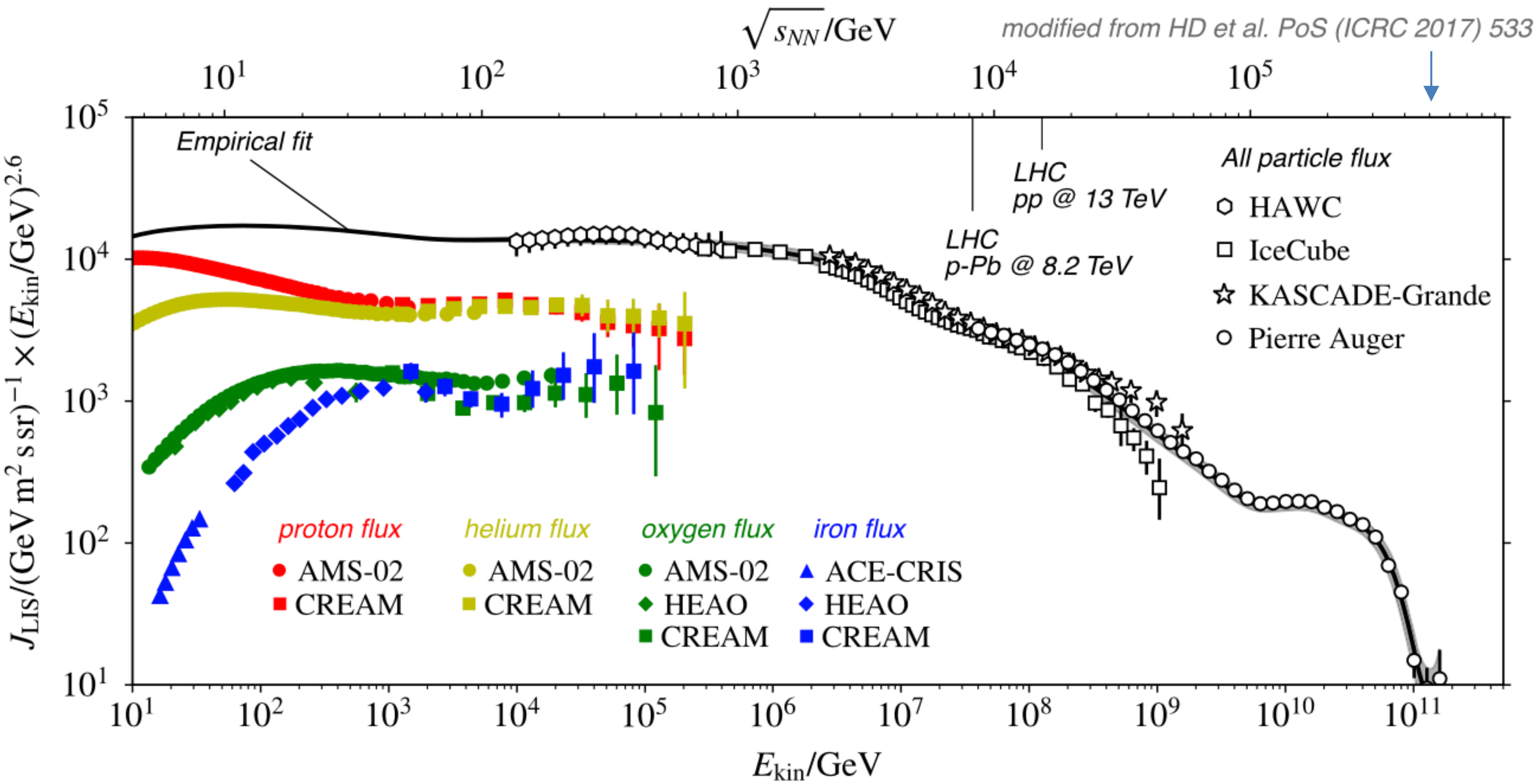
generate background



IceCube Masterclass 2016

Cosmic rays

CR interactions observed up to 500 TeV (**cms**)

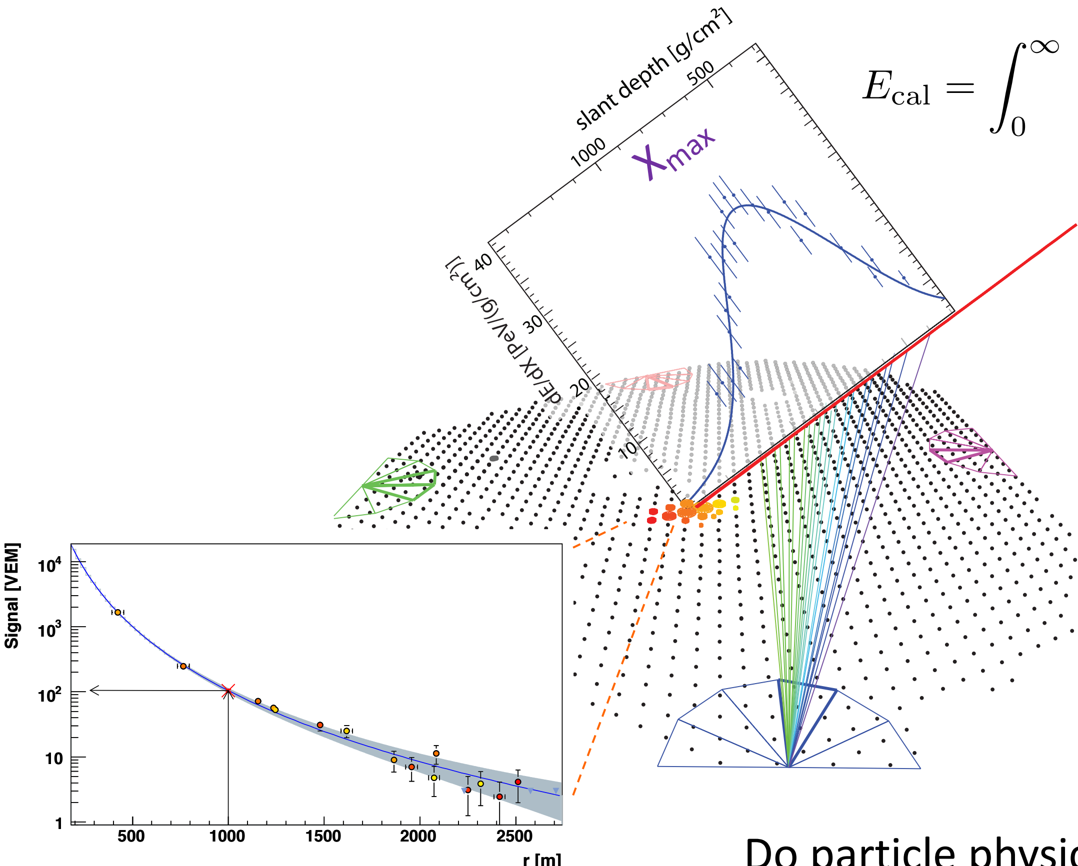


- Direct measurements up to 100 TeV (**lab**)
  - Full information: flux of individual elements & isotopes
- Indirect measurements via **air showers** starting at 10 TeV (**lab**)
  - Resolution of 2-5 mass groups, **model-dependent**

Air shower measurement

Example: event observed with Pierre Auger Observatory

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\mathrm{ionization}} dX$$



- **Direction** from particle arrival times
- **Energy** from integrated **eγ component** (alternative: ground measurement)
- **Mass** from
  depth of shower maximum X_{max}
  size of muonic component N_μ

Do particle physics with air shower experiments

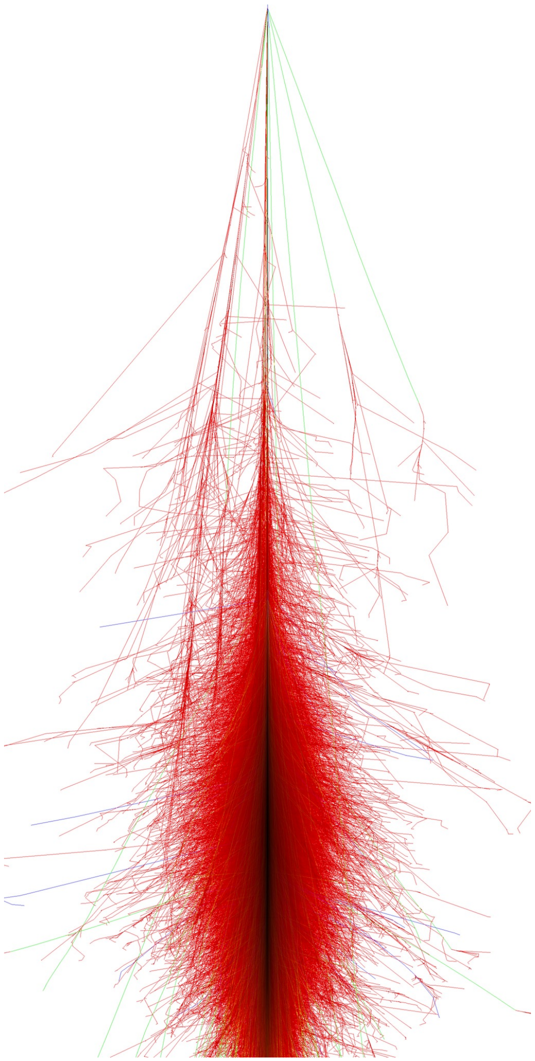
- Predict N_μ from **E** and X_{max} using **air shower simulations**
- Compare with measurement
- Other variables also available: 2nd moments, ...

Simulations

Particle transport in matter

- Simulation codes for Earth's atmosphere (CORSIKA ...) or space (CRPROPA ...)
- Approaches
  - Monte-Carlo simulation (like Geant)
  - Numerical solvers of cascade equations
  - Hybrid
- Components
  - Lepton propagator: EGS4, PROPOSAL ...
  - Hadron interaction & decay via **event generators**
    - **High-energy generator > 10 GeV (cms)** main source of uncertainty
    - Low-energy generator < 10 GeV (cms)

CORSIKA 10 TeV proton

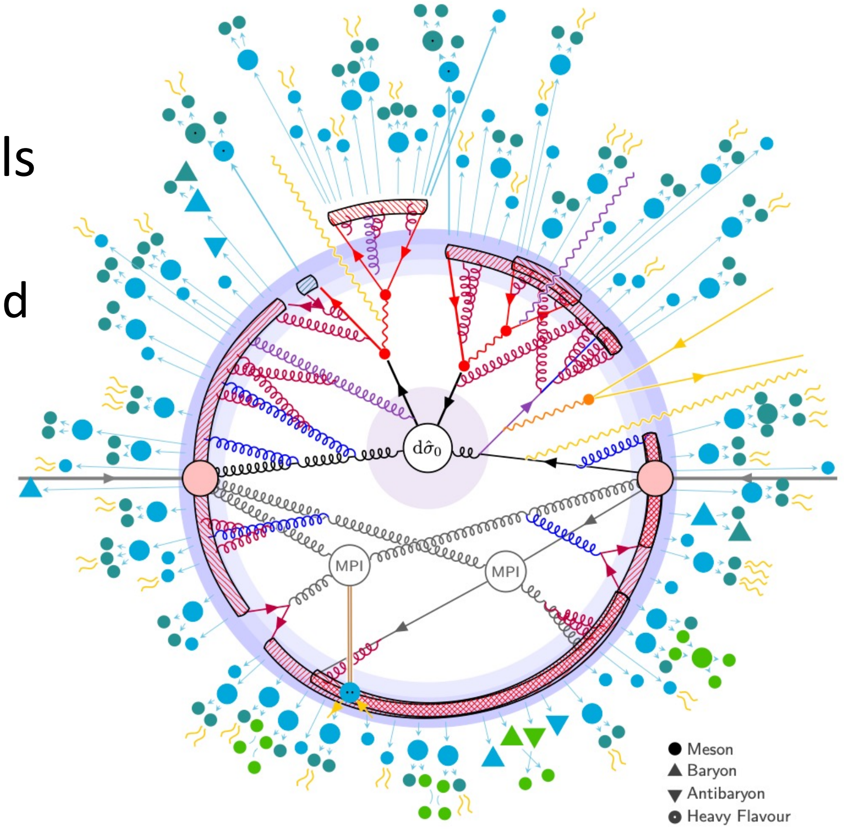


https://www-zeuthen.desy.de/~jknapp/fs/proton_13_0deg.xz.png

Event generators

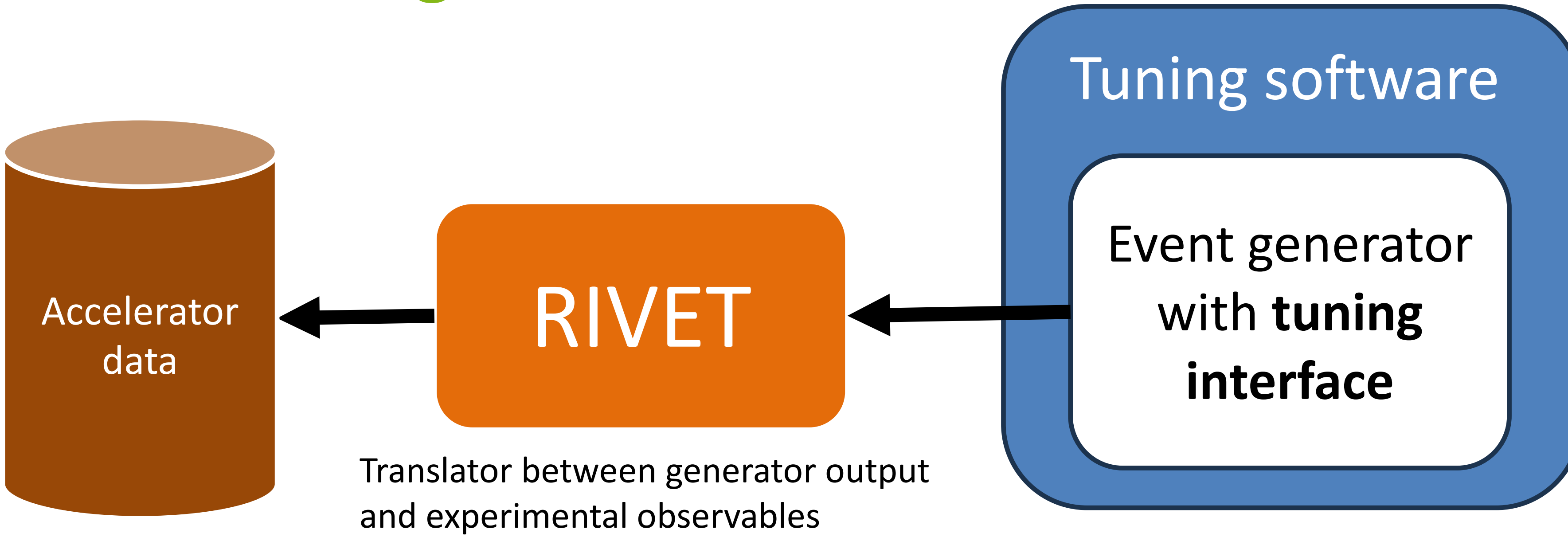
- PYTHIA, FLUKA, UrQMD ...
- SIBYLL, EPOS, QGSJet, DPMJet ...
- Soft QCD described by effective models
  - Many **tunable parameters**
  - Full physics description not guaranteed
  - **Nuclear PDFs** are important input

- Important features for astroparticle experiments
  - Predictive up to 300 TeV (cms)
  - h-ion and ion-ion collisions
  - Diffraction, remnant dissociation
  - Collective effects that modify hadron composition
  - D and B meson production



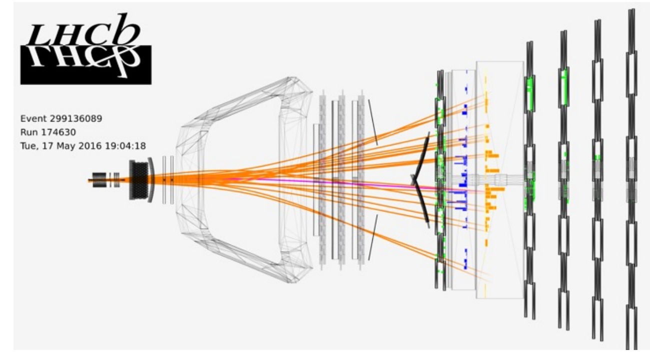
https://skands.physics.monash.edu/research/

Classic tuning

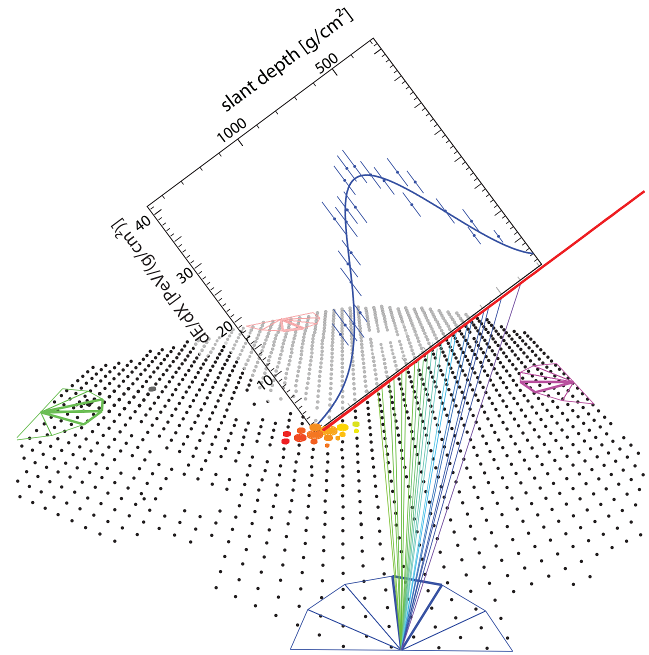


- Tuning software fits parameters of event generator to data
  - Chi-square fit of linearized surrogate model
  - Ideal: tune all parameters at once using all data
  - Practice: tune subset to matching data, requires **expert knowledge**

Astroparticle vs. accelerator measurements

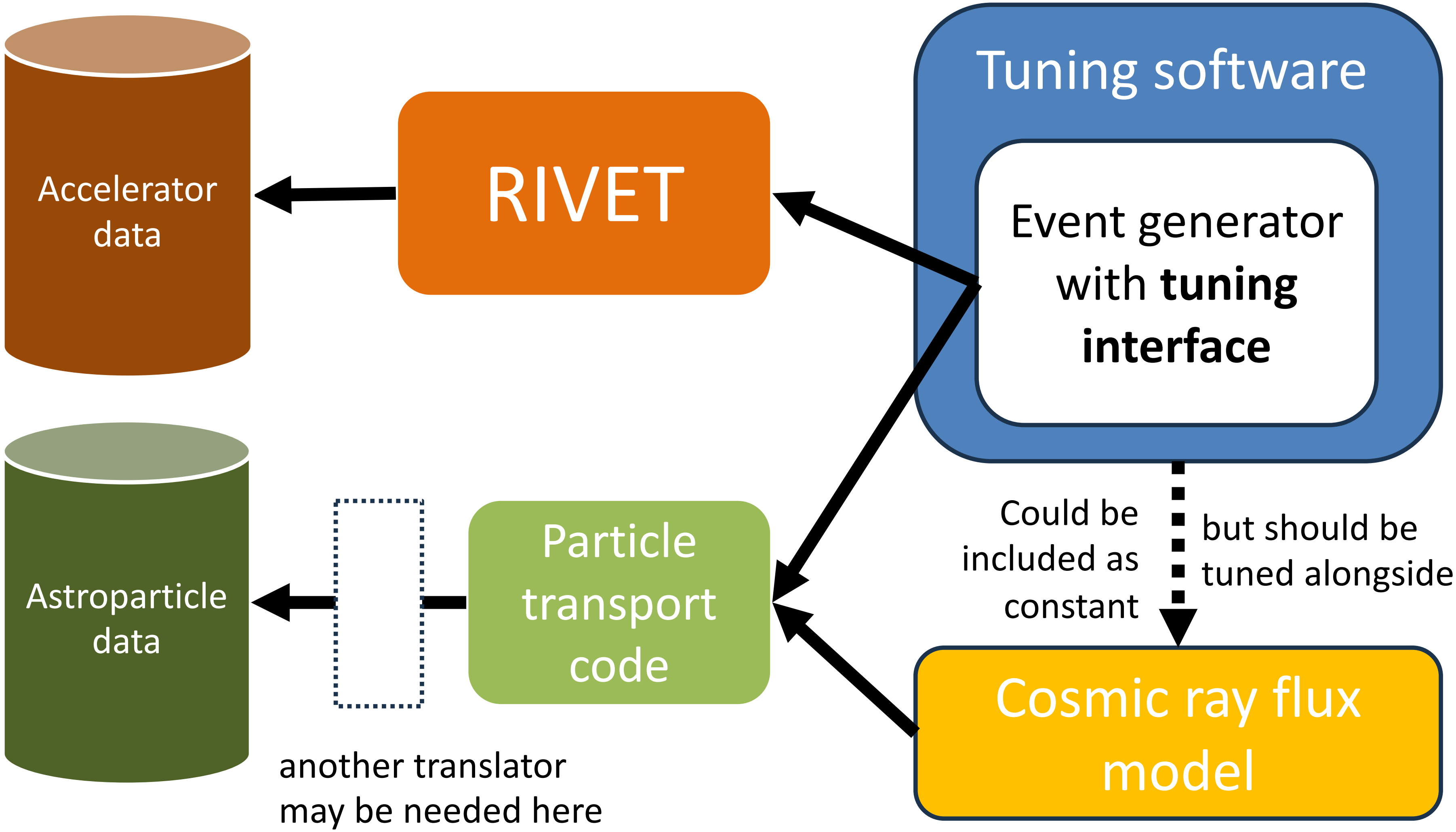


- Accelerator
  - **Identical collision systems** and **mono-energetic beams**



- Astroparticle experiment
  - **Variable collision systems** and **varying beam energies**
  - Cosmic ray flux (composition unknown)
  - 1st interaction, 2nd interaction, ..., n-th interaction
  - TeV particles / prompt flux: after 1rst interaction production of D or B mesons which decay to observable particles
  - GeV particles / conventional flux: after n-th interaction light hadrons decay to observable particles

Global tuning to accelerator & astroparticle data

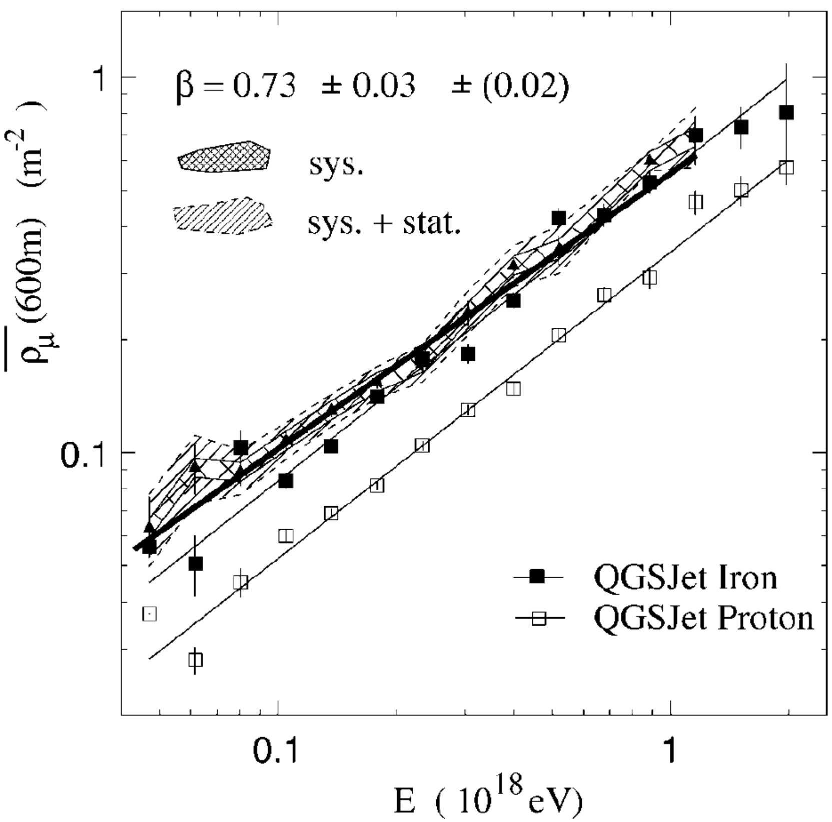


Why should we invest in tuning?

The Muon Puzzle in air showers

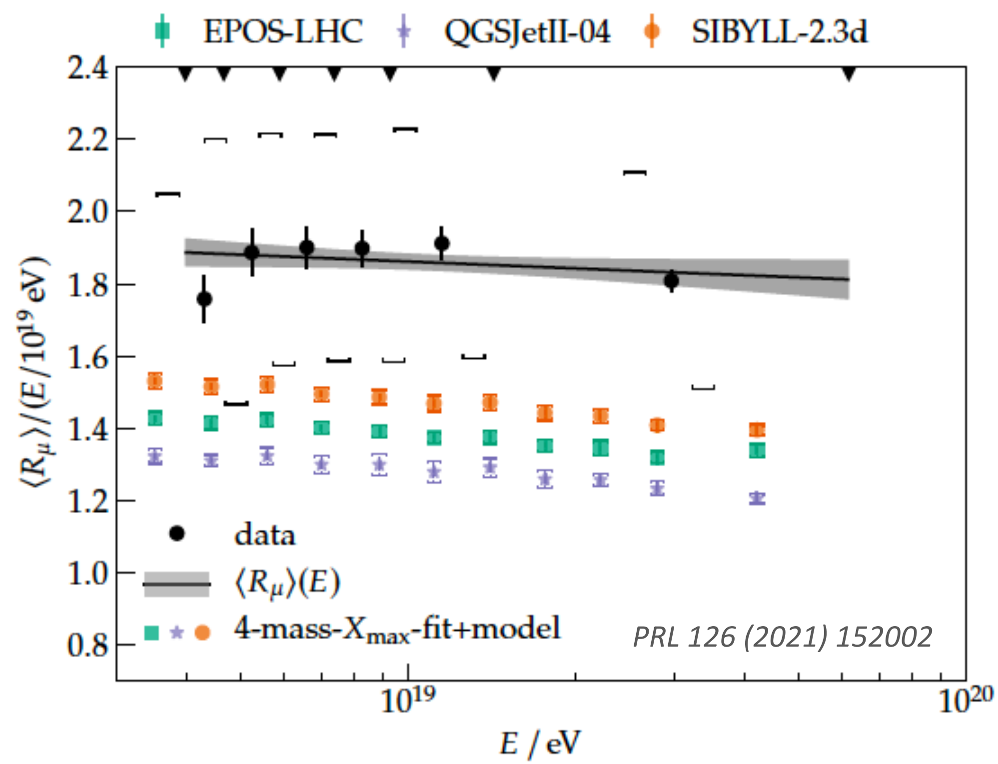
10^{17} eV **HiRes-MIA experiment**
Abu-Zayyad et al. PRL 84 (2000) 4276

Muon content above simulations
(now outdated)



10^{19} eV **Pierre Auger Observatory**
PRD 91 (2015) 032003
PRL 117 (2016) 192001
Eur. Phys. J. C (2020) 80:751
PRL 126 (2021) 152002

Muon content above simulations
(state-of-the-art)

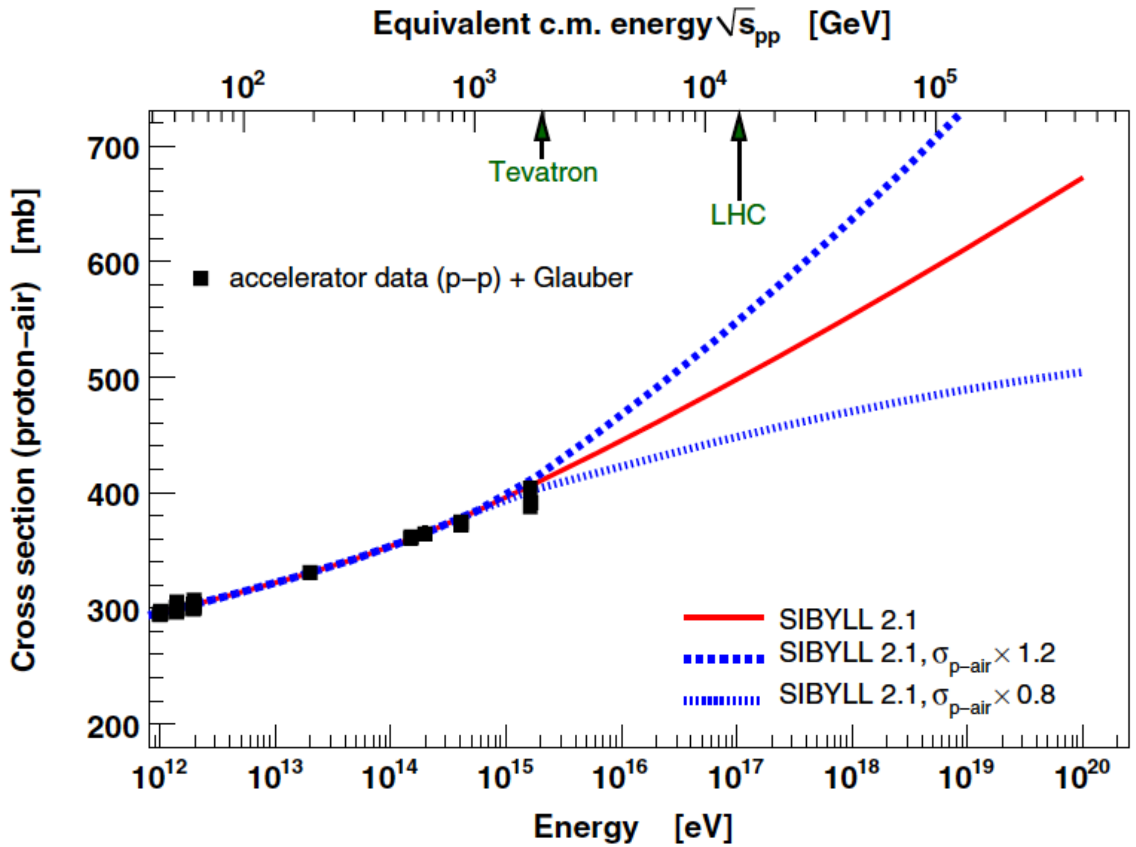


From QCD to shower muons

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- Modify predictions of event generator with energy-dependent factor $f(E)$
- Study effect in simulations of $10^{19.5}$ eV air showers (CORSIKA)

Example of modified inelastic proton-air cross-section



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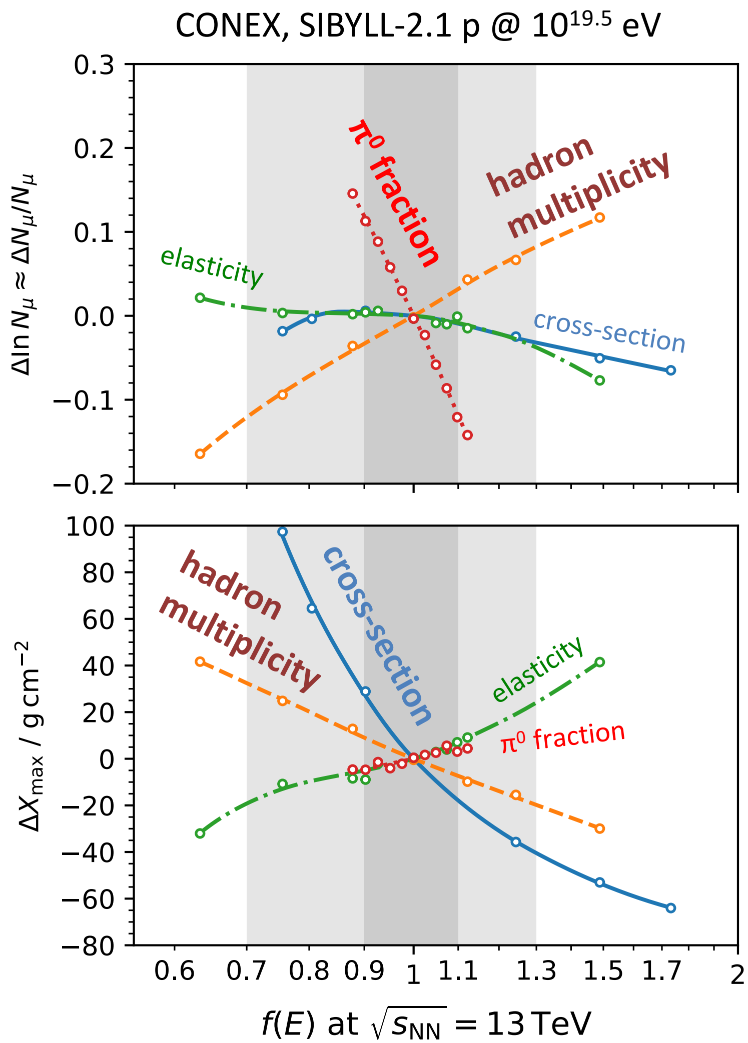
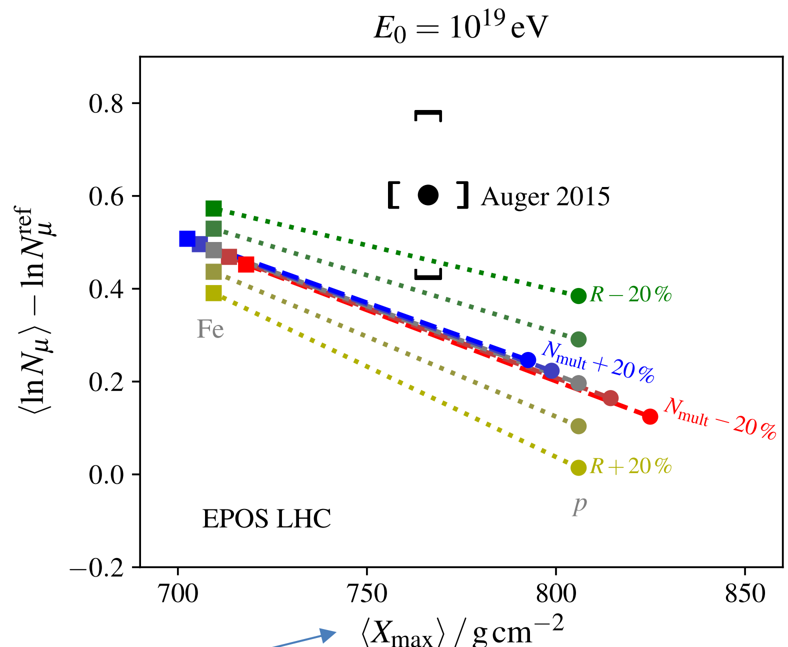
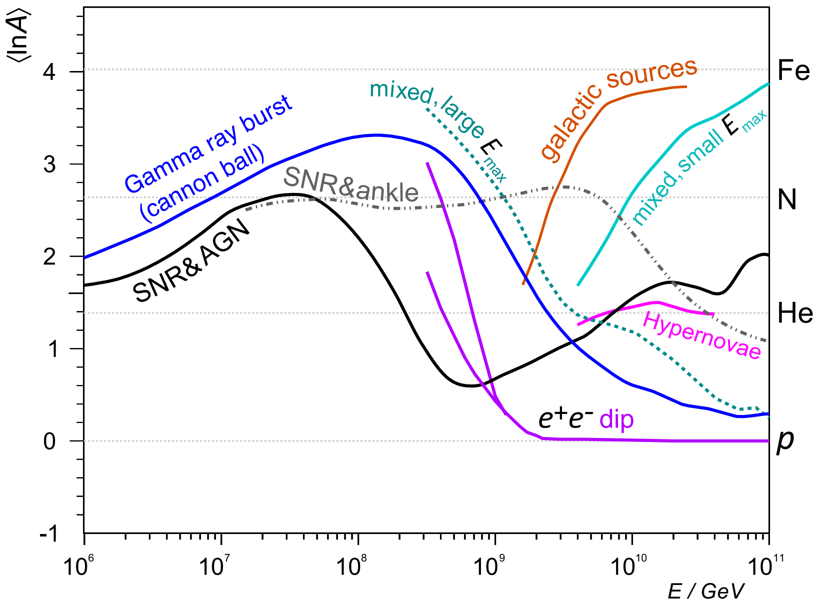


S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, PRD 107 (2023) 9, 094031



$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Mass composition of cosmic rays

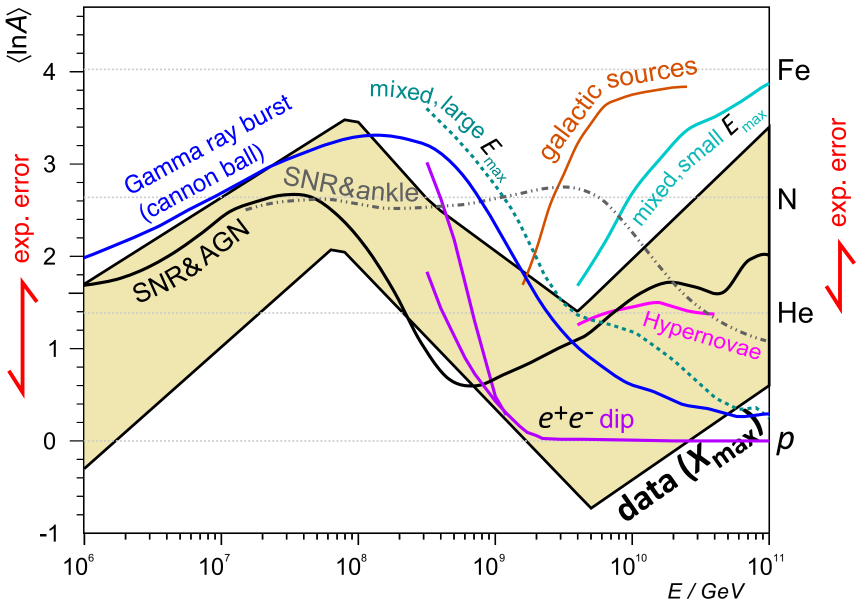


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation

Mass composition of cosmic rays



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

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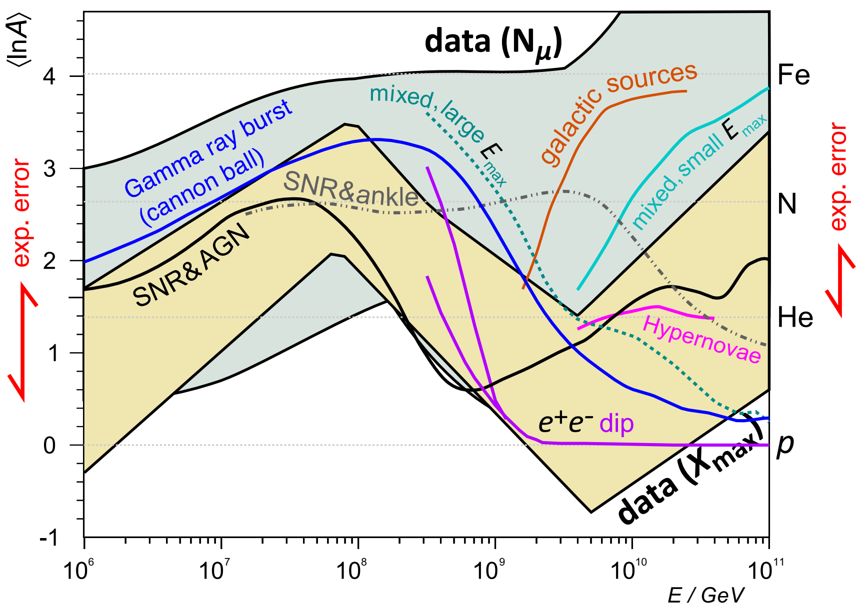
Mass composition of cosmic rays

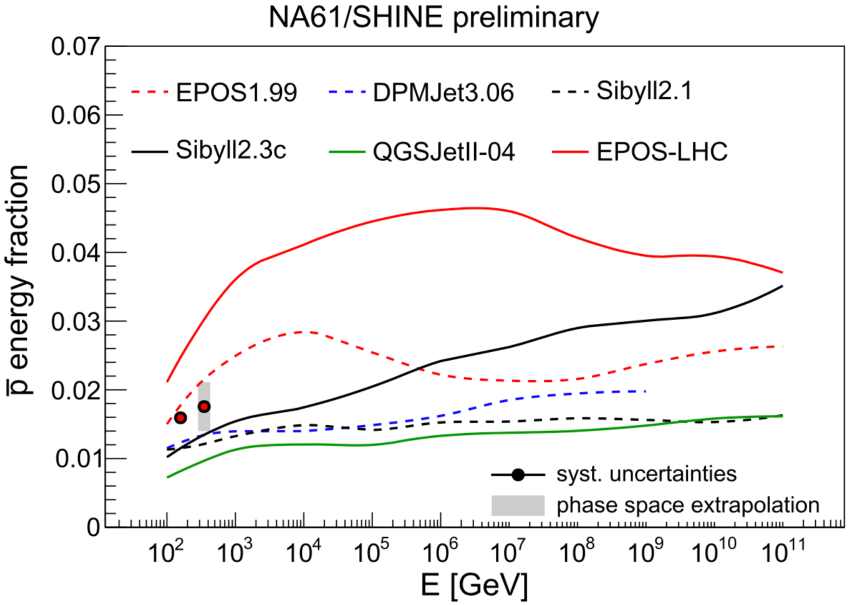


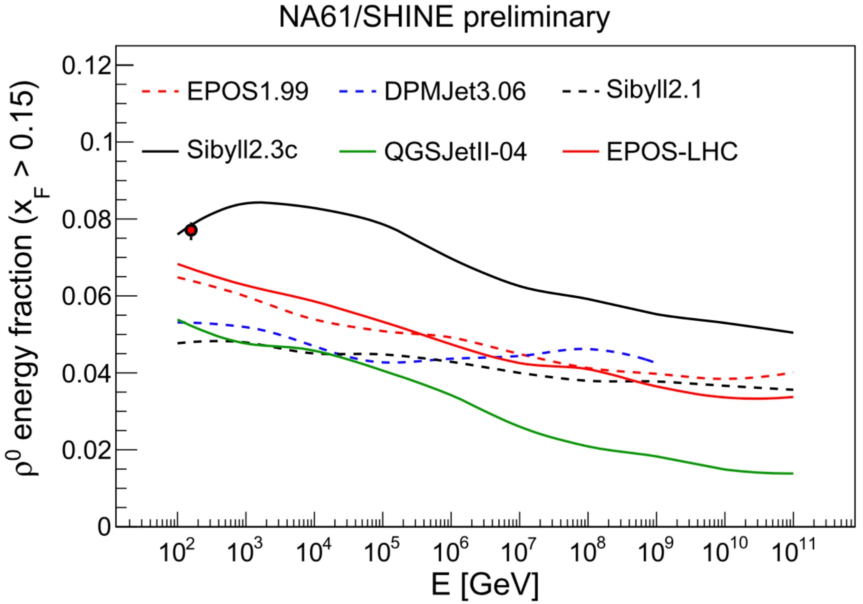
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
- Uncertainties of <lnA> limited by uncertainty in description of hadronic interactions
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with X_{max}

Hard to close gaps in accelerator data



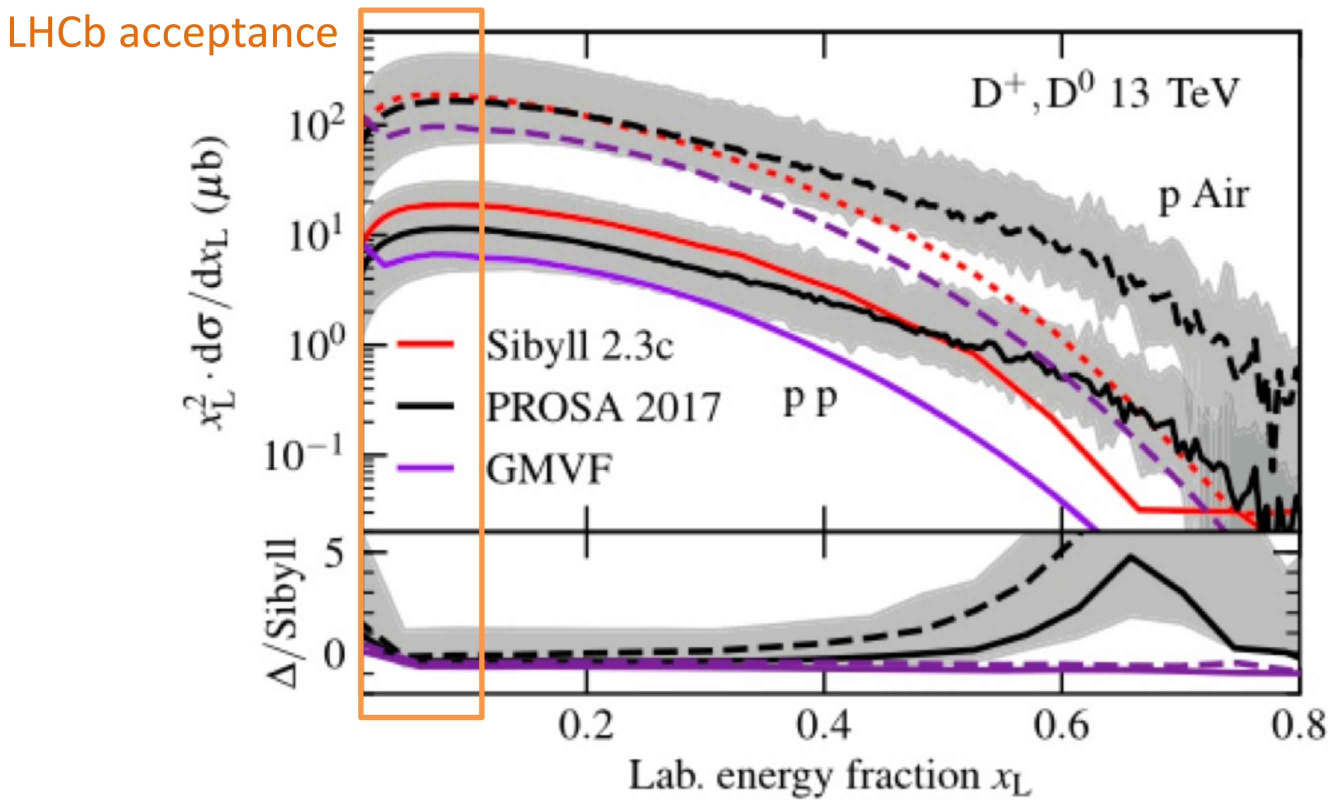


- No π collider in foreseeable future
- Forward baryon and ρ^0 production affect for muon yield in air showers

T. Pierog, K. Werner, PRL 101 (2008) 171101
M. Unger for NA61/SHINE, PoS ICRC2019 (2020) 446
R. Prado for NA61/SHINE, EPJ Web Conf. 208 (2019) 05006
F. Riehn, R. Engel, A. Fedynitch, TK. Gaisser, T. Stanev, Phys.Rev.D 102 (2020) 6, 063002
F. Riehn et al. PoS ICRC2023 (2023) 429

Hard to close gaps in accelerator data

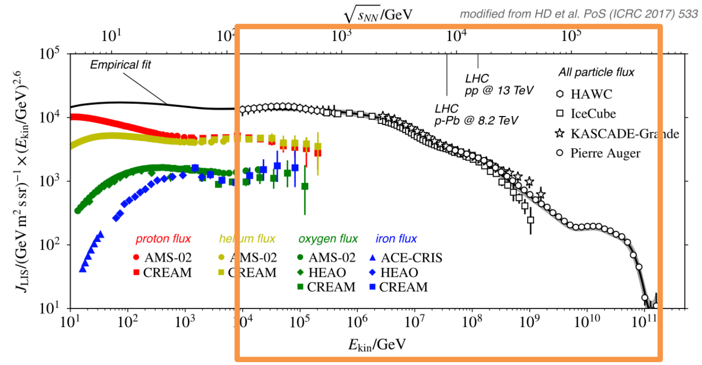
A. Fedynitch, F. Riehn, R. Engel, TK. Gaisser, T. Stanev, Phys.Rev.D 100 (2019) 103018



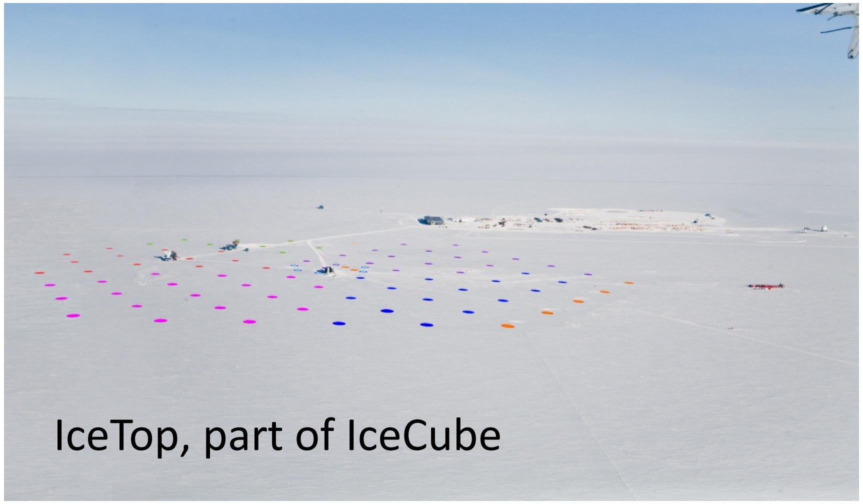
- No charm data at η > 5 from accelerators in near future
- IceCube lepton flux measurements sensitive to forward charm production

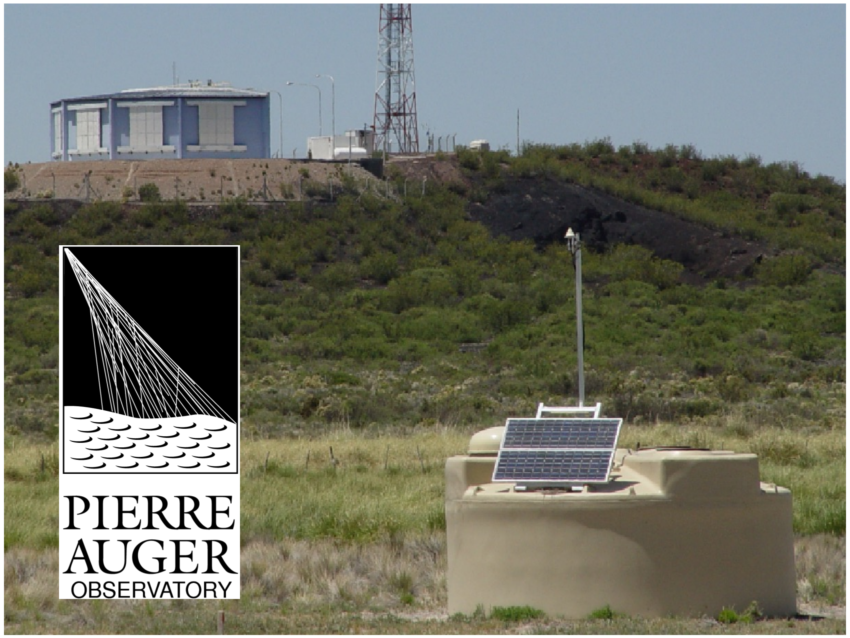
Astroparticle experiments

Cosmic ray experiments



- Pierre Auger Observatory, Telescope Array, HAWC, LHAASO...
- Indirect measurement of cosmic rays via air showers > 10 TeV (lab)
- Ideal for tuning: independent measurements of E, X_{max}, N_μ
  - Pierre Auger Observatory is ideally equipped for this
- High-altitude ground arrays can measure E, N_μ independently


IceTop, part of IceCube

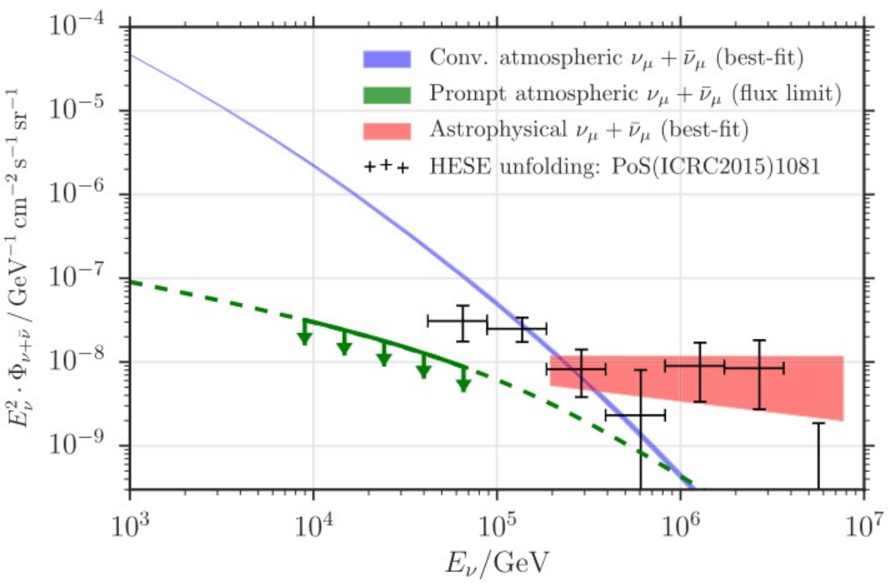


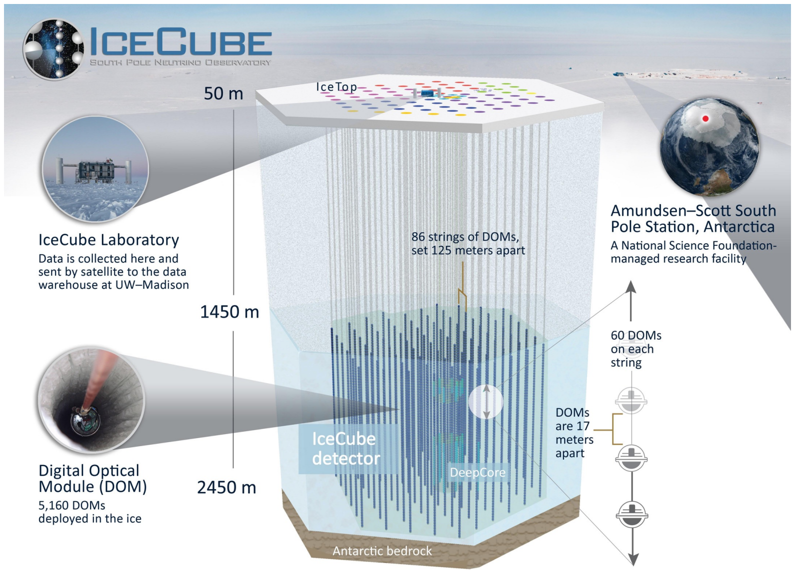
Neutrino experiments

- IceCube Neutrino Observatory, ANTARES, KM3NET, ...
- IceCube is ideal
  - Surface detector at 2.9 km a.s.l. near shower maximum measures shower energy with very low systematic uncertainty
  - Combined measurements on surface GeV muons and in-ice TeV muons
- Lepton flux = conventional (π, K decay) + **prompt** (D, B decay) + astro

neutrinos, muons

no astro component for muon flux



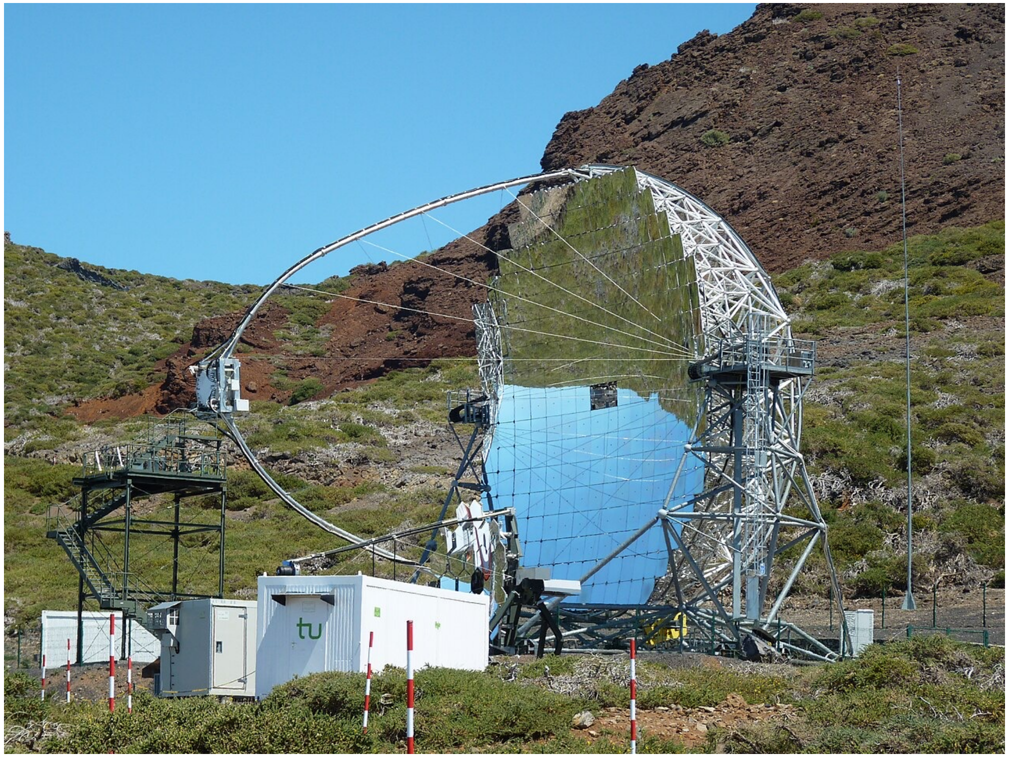


Gamma-ray telescopes

- H.E.S.S., MAGIC, CTA, ...
- Gamma flux = conventional (π^0 decay) + astro
- E < 100 TeV (lab) too low for tuning QCD models, better to use direct measurements at accelerators

IACTs can measure muons in air showers, but CTA aperture needed

AMW Mitchell, HD, RD Parsons, *Astropart.Phys.* 111 (2019) 23-34

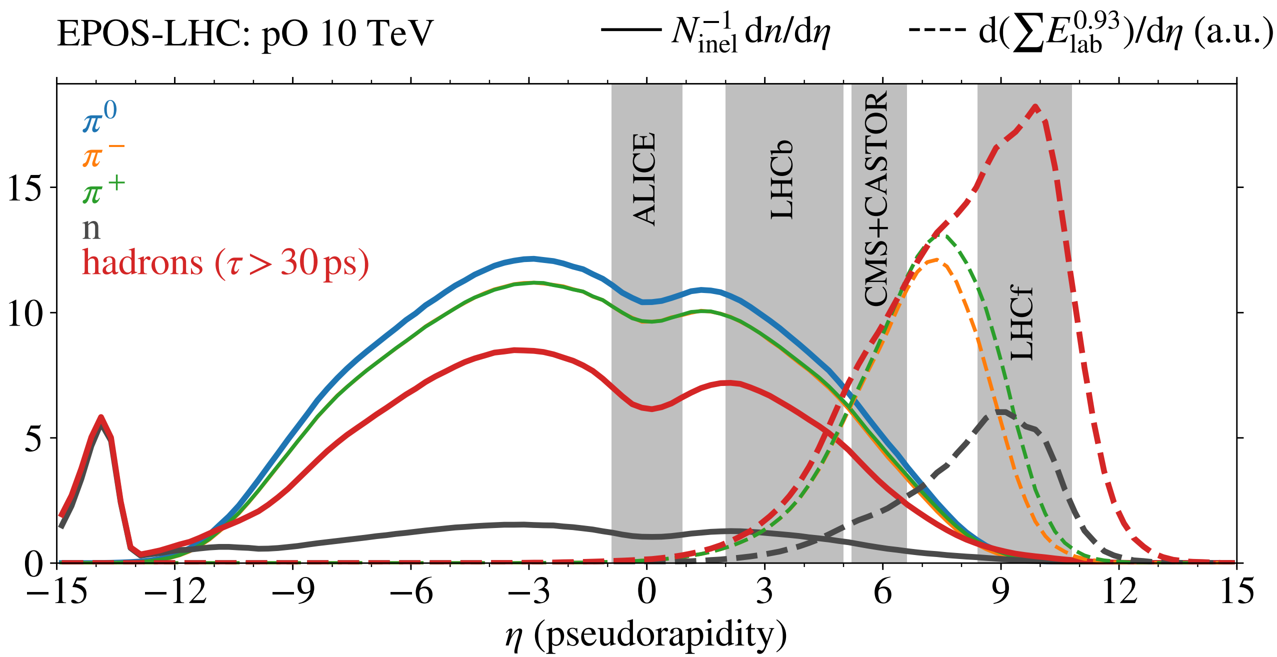


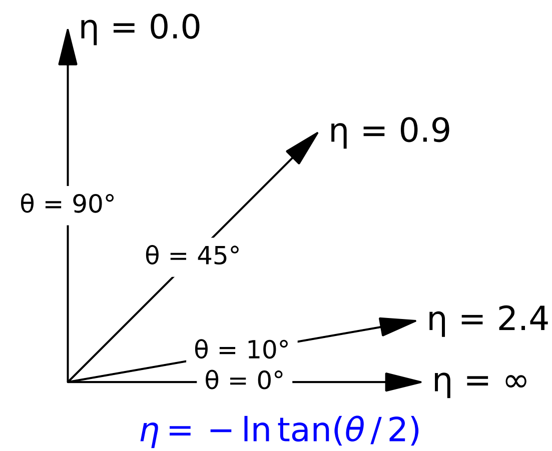
Accelerator experiments

Importance of forward acceptance

HD, J. Albrecht, W. Rhode, B. Spaan, ..., Astrophys. Space. Sci. 367, 27 (2022)
Also see PoS(ICRC2021)463 in arXiv:2112.11761

„Muon production weight“





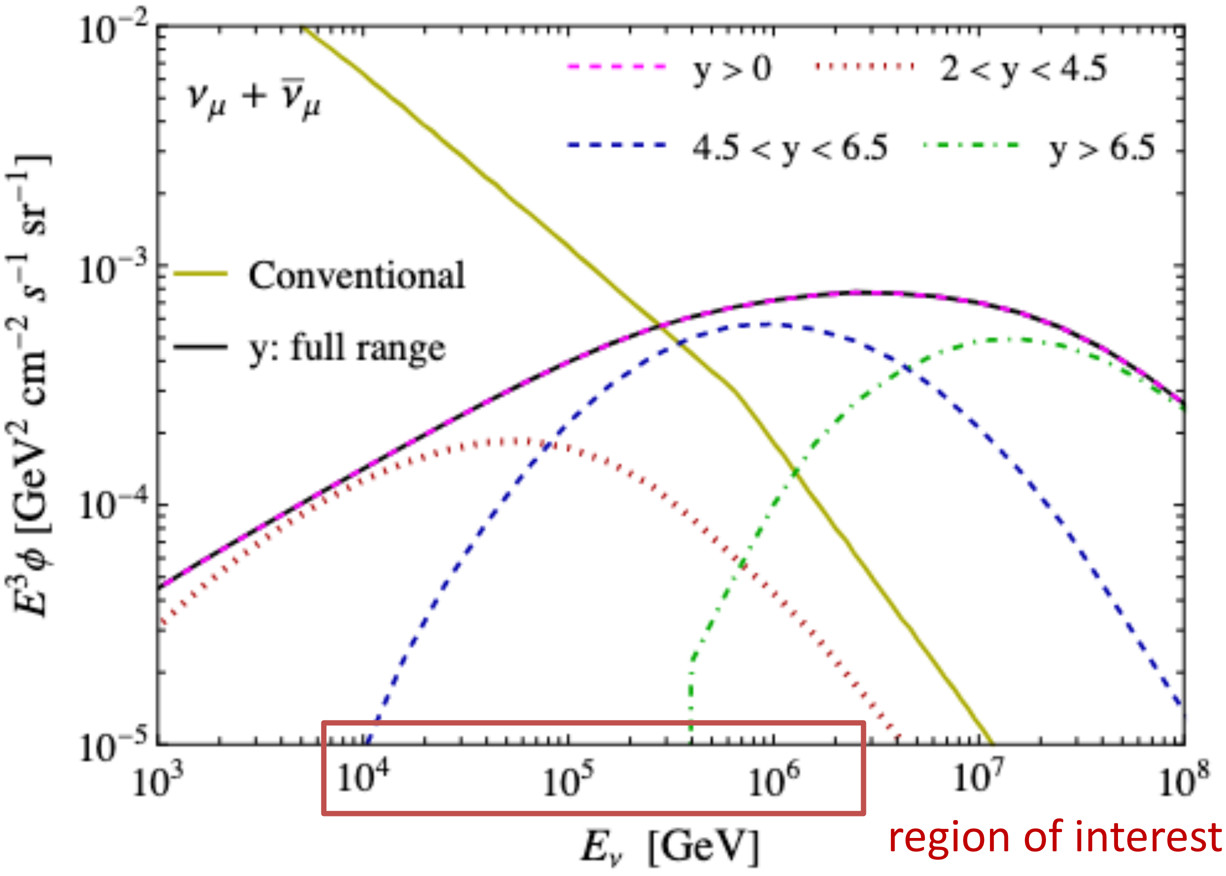
general-purpose experiments
with particle identification (PID)

specialized forward experiments

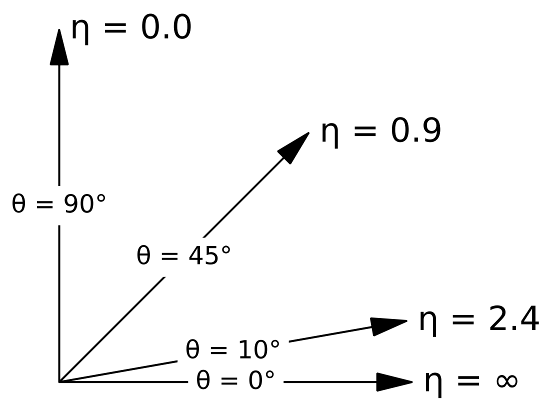
Importance of forward acceptance

Y.S. Jeong et al. + Honda et al.
from L. Anchordoqui et al. arXiv:2109.10905

Conventional flux: ν_μ from light flavor
Prompt flux: ν_μ from charm and beauty



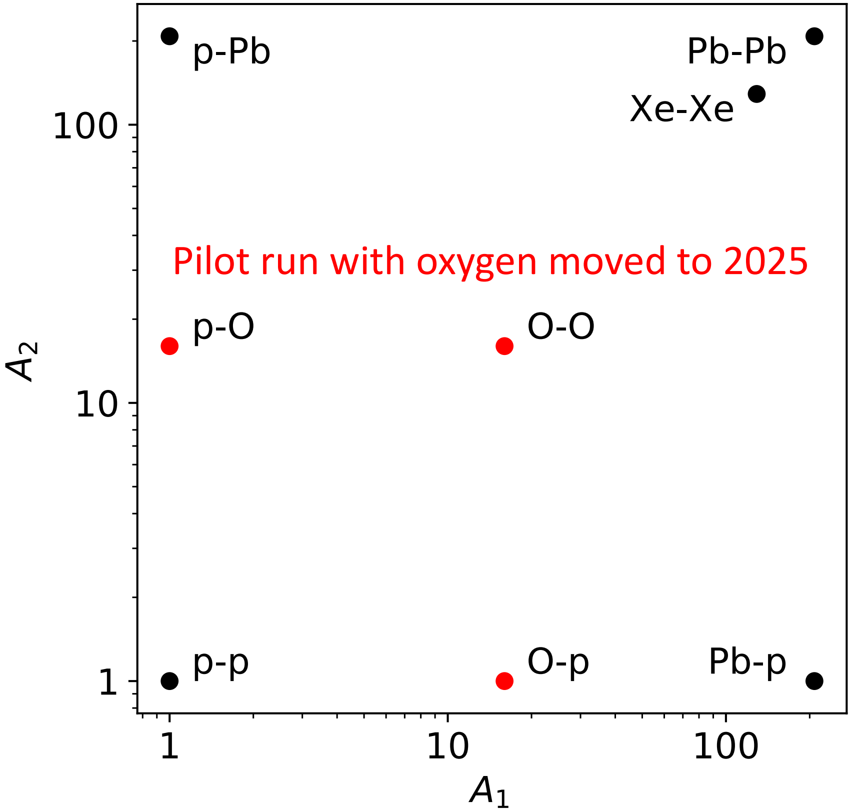
region of interest

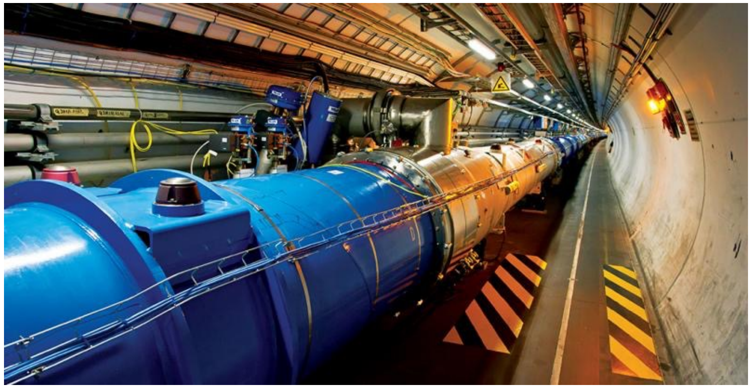


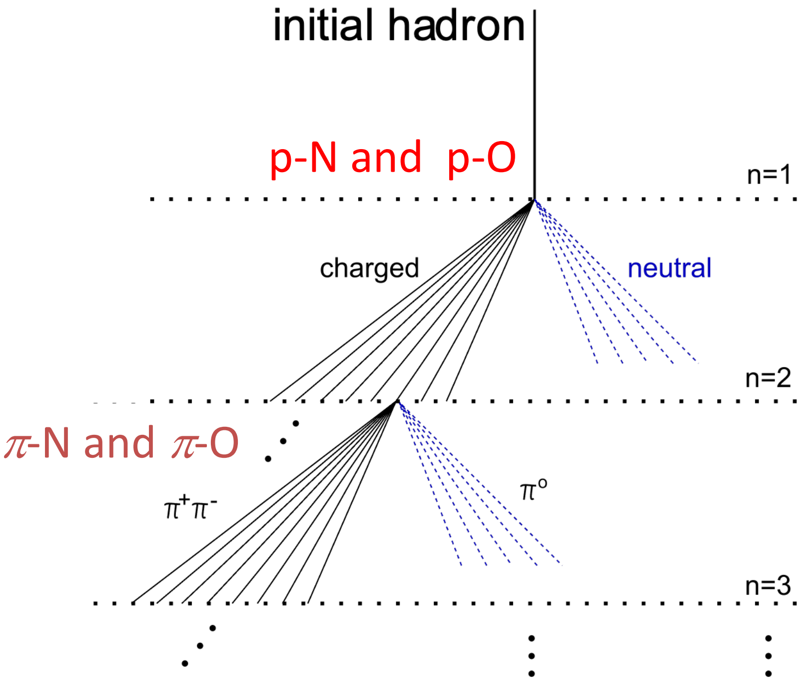
$\eta = -\ln\tan(\theta/2)$

LHC collision systems

Collision systems at the LHC
Run 3: p-p @ 14 TeV, p-O @ 10 TeV





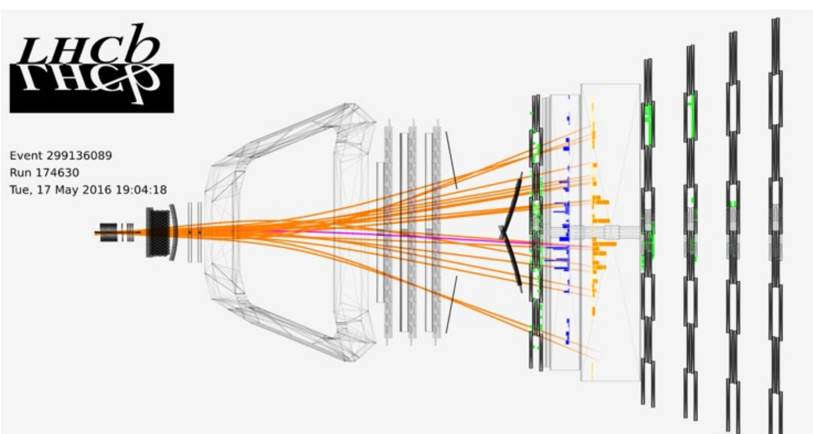


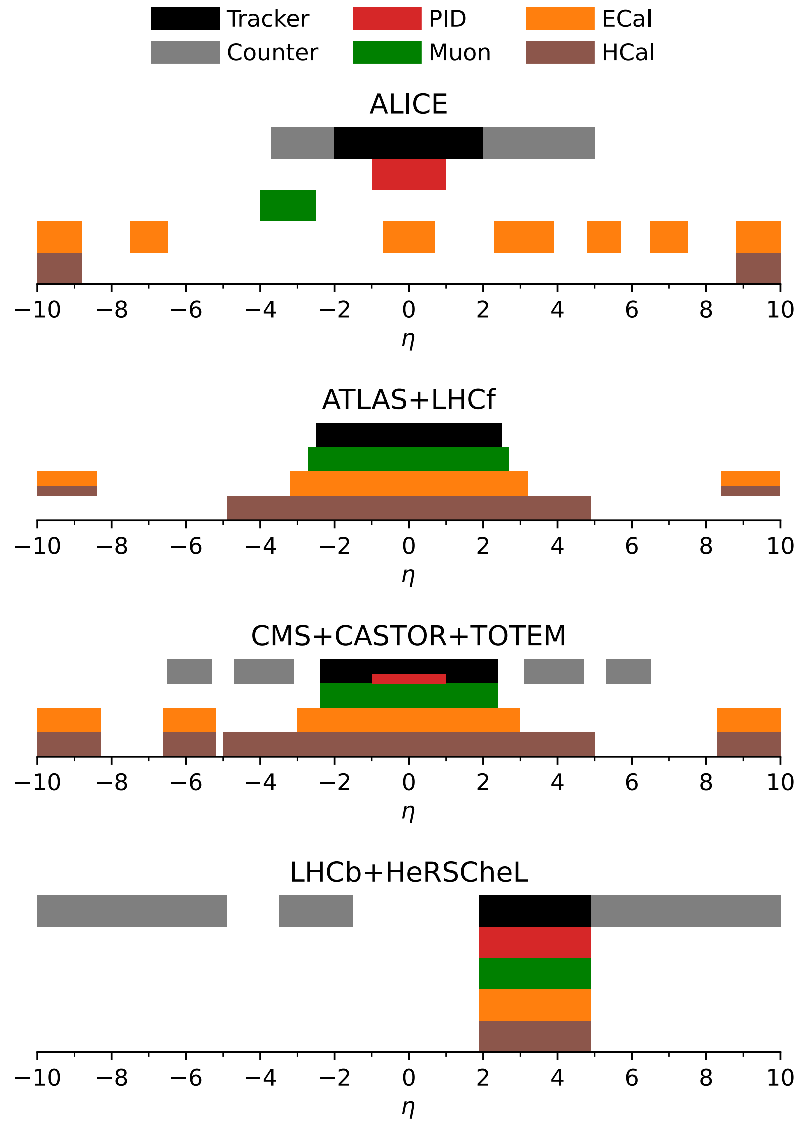
p-O collisions mimic air shower interactions

General-purpose collider experiments

- LHC: ATLAS, **CMS**, **ALICE**, **LHCb**
- RHIC: PHENIX, STAR
- …

- Study of Soft-QCD requires
  - Access to low p_T
  - Particle identification (PID)

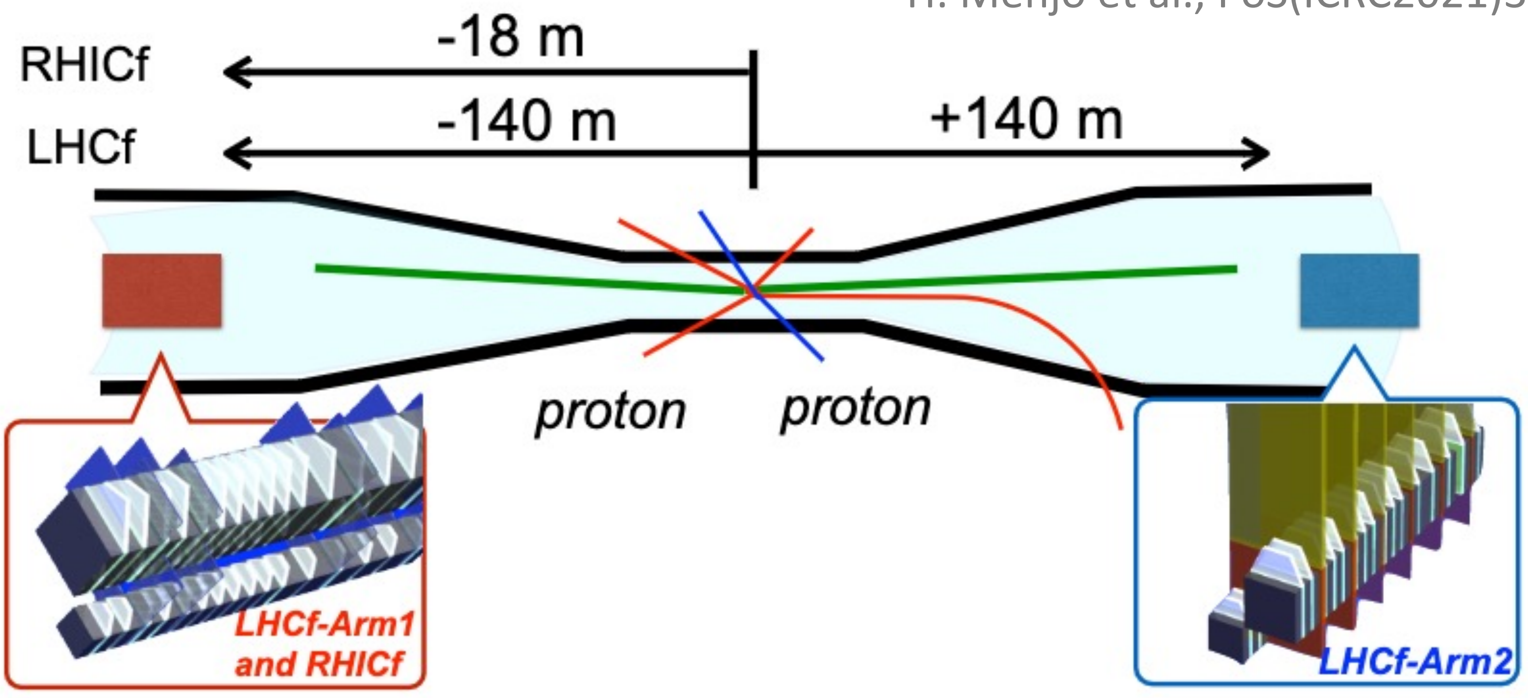




Very-forward experiments

- LHCf, RHICf, FASER, ...

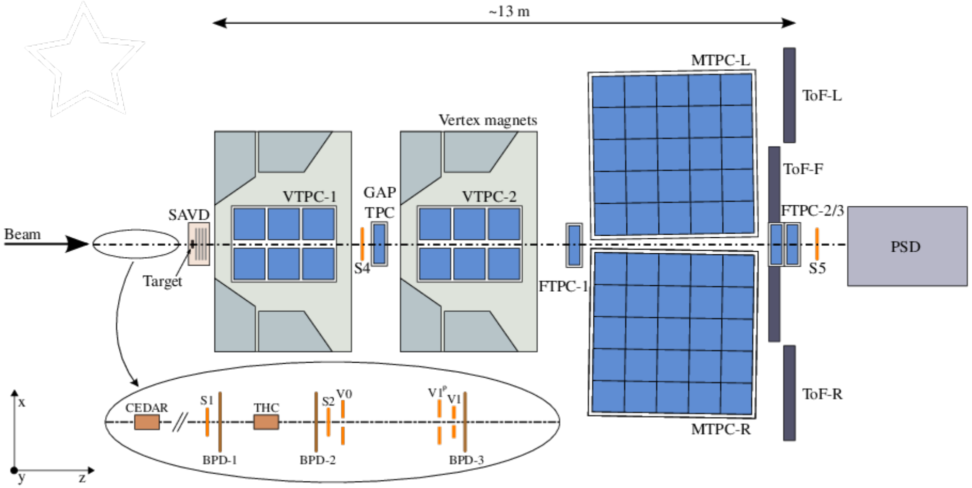
H. Menjo et al., PoS(ICRC2021)301



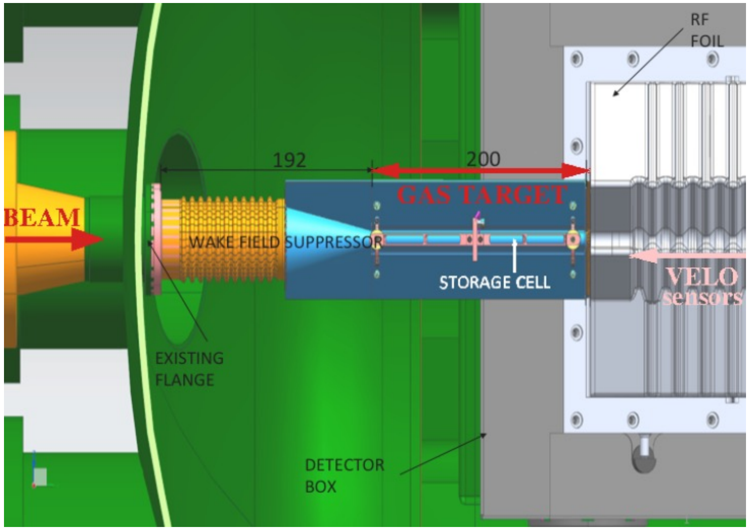
- Zero degree experiments (η > 7-8) measure subset of all particles
- LHCf, RHICf: **not shielded**; detects π^0, neutrons
- FASER: **shielded**; detects neutrinos, high-energy muons, exotics

Fixed-target experiments

- Tracker with PID systems
- Flexible targets: C, N, O, ...
- Study nuclear PDFs at large *x*



- NA61/SHINE @ SPS
  - SPS: max E = 350 GeV (lab), about 25 GeV (cms)
  - Full coverage of pseudorapidity



- LHCb SMOG @ LHC
  - LHC: max E = 6.8 TeV (lab), about 112 GeV (cms)
  - Pseudorapidity coverage $-2.5 < \eta_{cms} < 0.5$

Conclusions

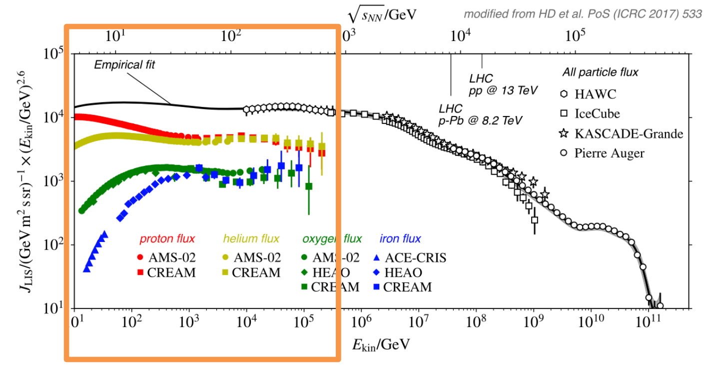
- **Global tuning** needed to make progress in astroparticle physics
  - Potential solution to muon puzzle & mass composition ambiguity
- Astroparticle input closes blind spots of accelerator experiments
- Strong test of soft QCD models employed in event generators
  - Recent surprises: QGP-like effects in high-multiplicity p-p collisions
  - New soft QCD physics needed to describe global data?

- Tools matter
  - Accelerator data: HepData, RIVET, tuning software
  - Astroparticle data: CRDB, cosmic flux models, transport codes
  - **In progress:** tuning software which connects to both worlds

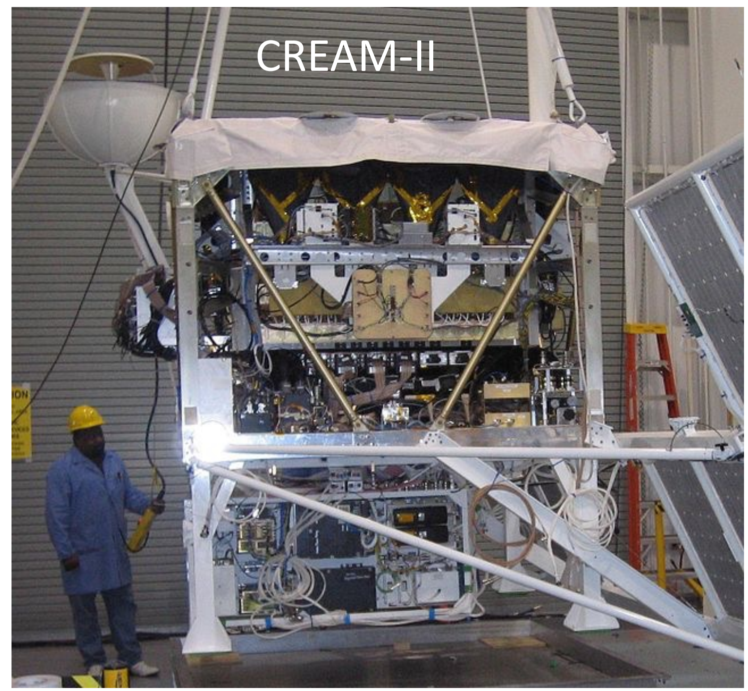
- Looking forward to your input and the discussions!

Backup

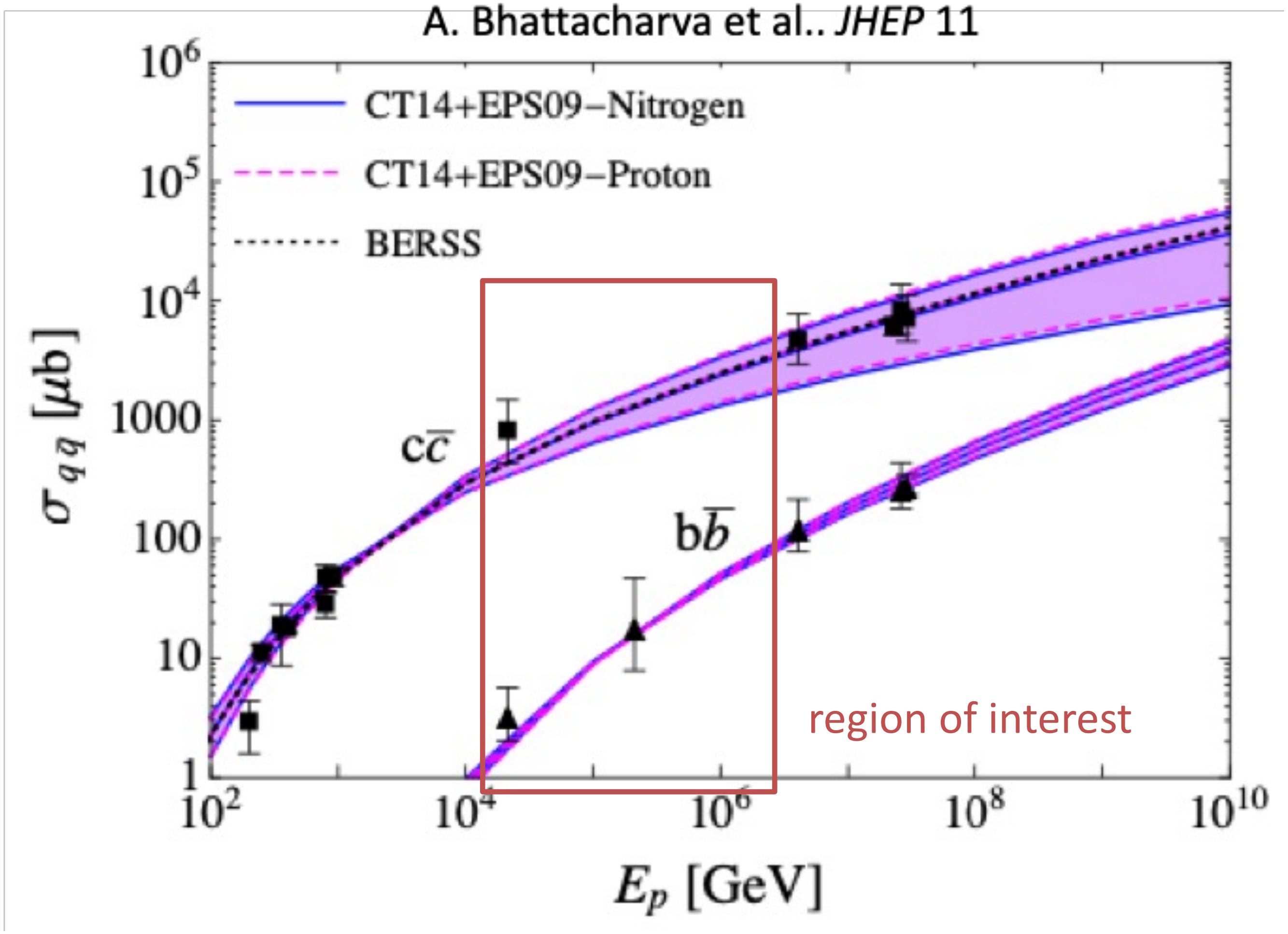
Air and space experiments



- AMS, PAMELA, CREAM, ...
- Cosmic rays < 100 TeV (lab)
- Single element or isotope resolution
- No dependence on hadronic physics, no tuning data



Prompt neutrino flux



- Charm production 10 x more important than bottom production