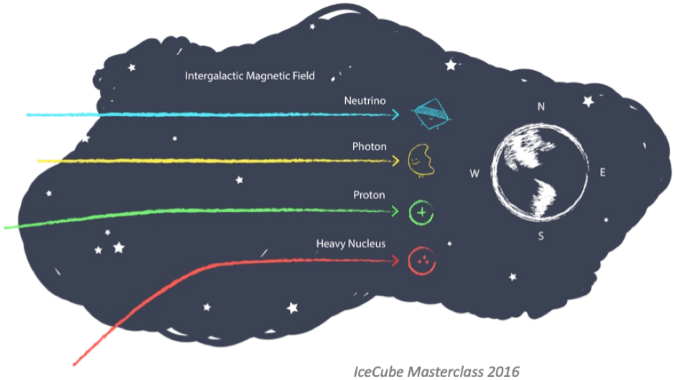
technische universität dortmund

E5a/ Physik

Impact of collider p–A (p-O) measurements for ultra-high energy cosmic rays physics

Hans Dembinski, TU Dortmund, Germany

Physics with high-luminosity proton-nucleus collisions at the LHC
4-5 Jul 2024



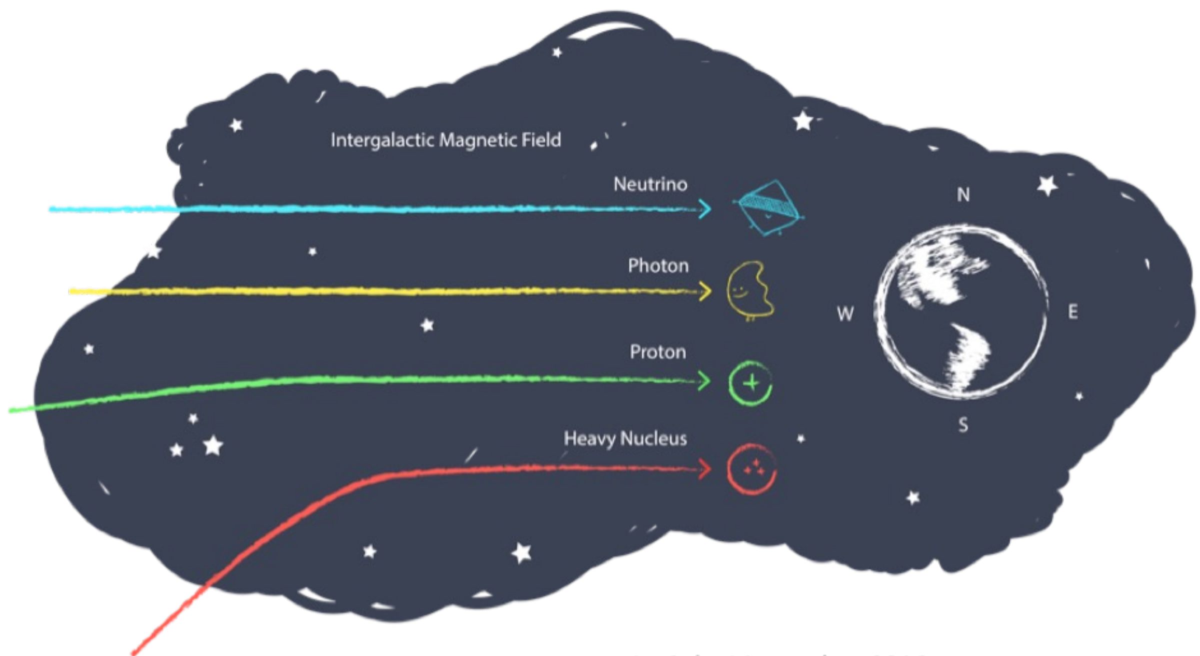
IceCube Masterclass 2016

Astroparticles

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

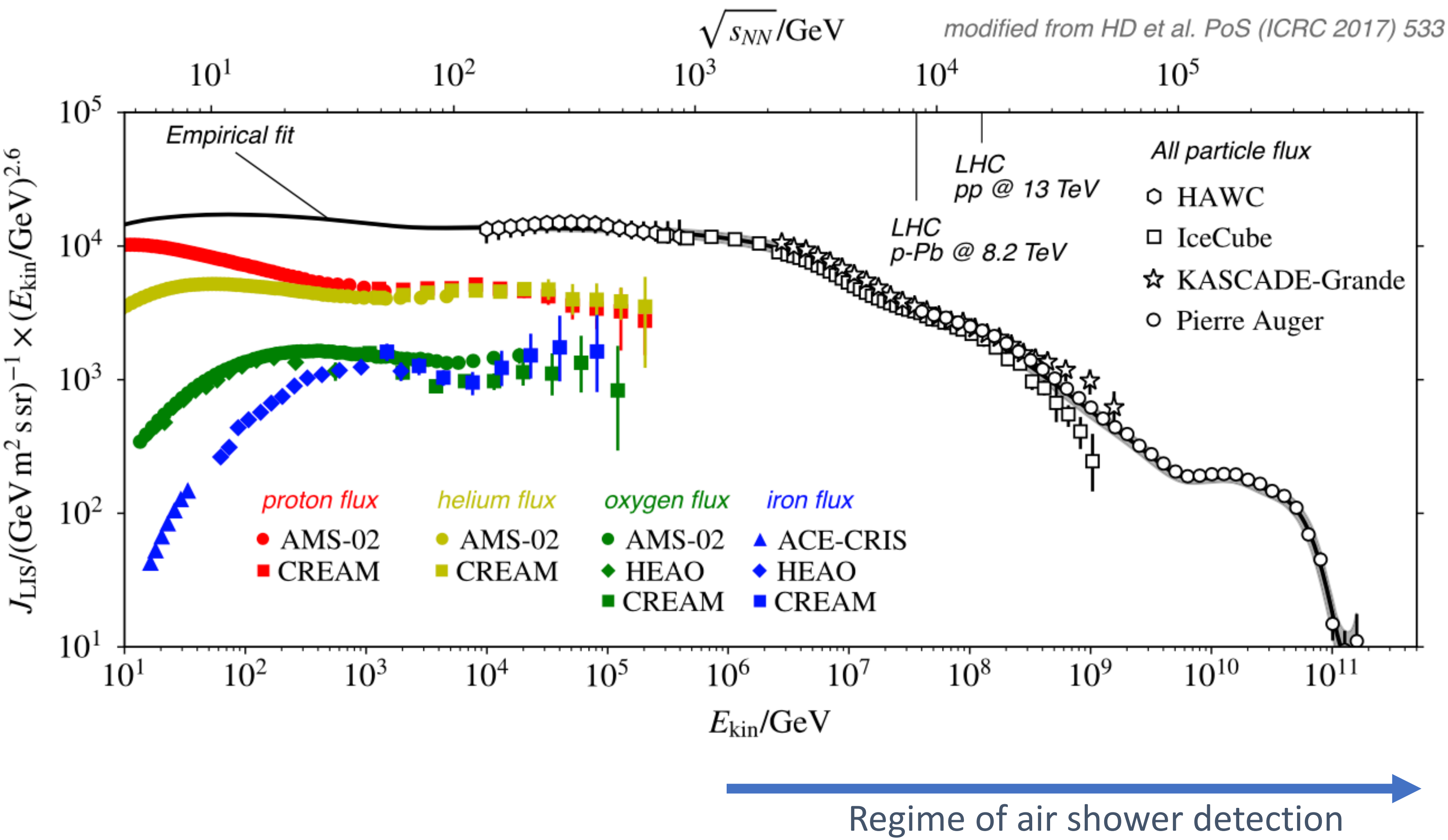
- Messengers
  - Gamma rays
    - Pointing ☺
    - Abundant ☺
    - E_{max} 100 TeV ☹
  - **Neutrinos**
    - Pointing ☺
    - Rare ☹
    - E_{max} > 100 EeV ☺
  - **Cosmic rays (nuclei)**
    - No pointing ☹
    - Abundant ☺
    - E_{max} > 100 EeV ☺

generate background



IceCube Masterclass 2016

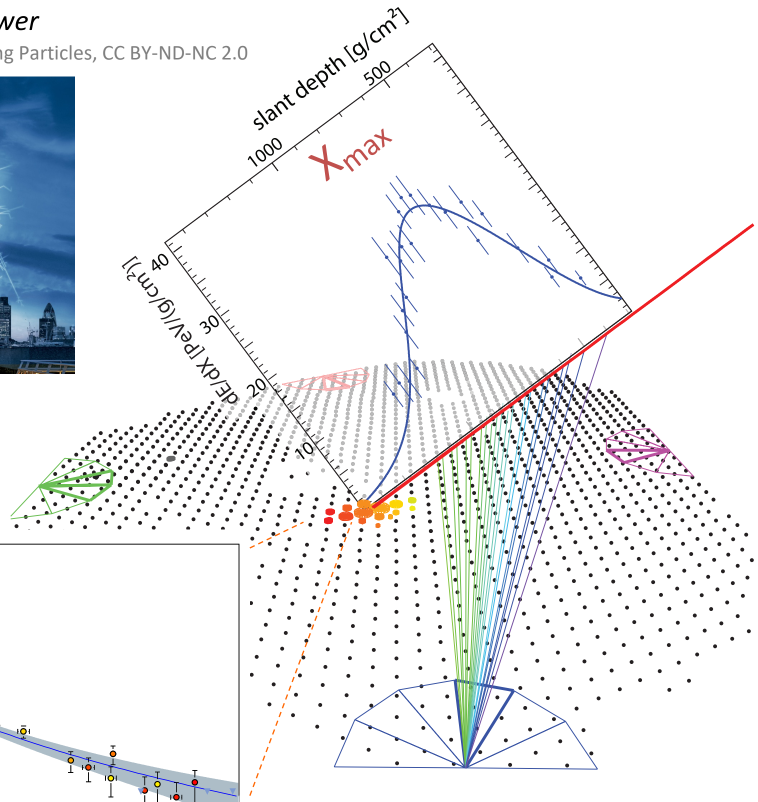
Ultra-high energy cosmic rays

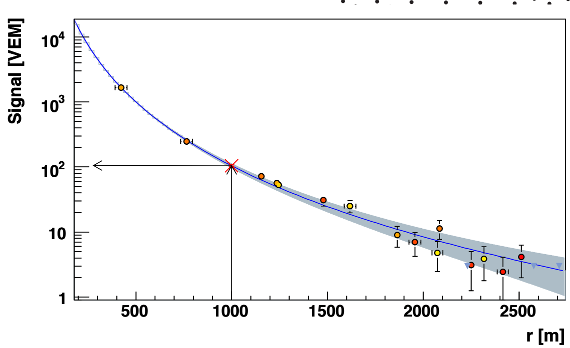


Air shower detection

Example: event observed with Pierre Auger Observatory

Artist impression of air shower





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

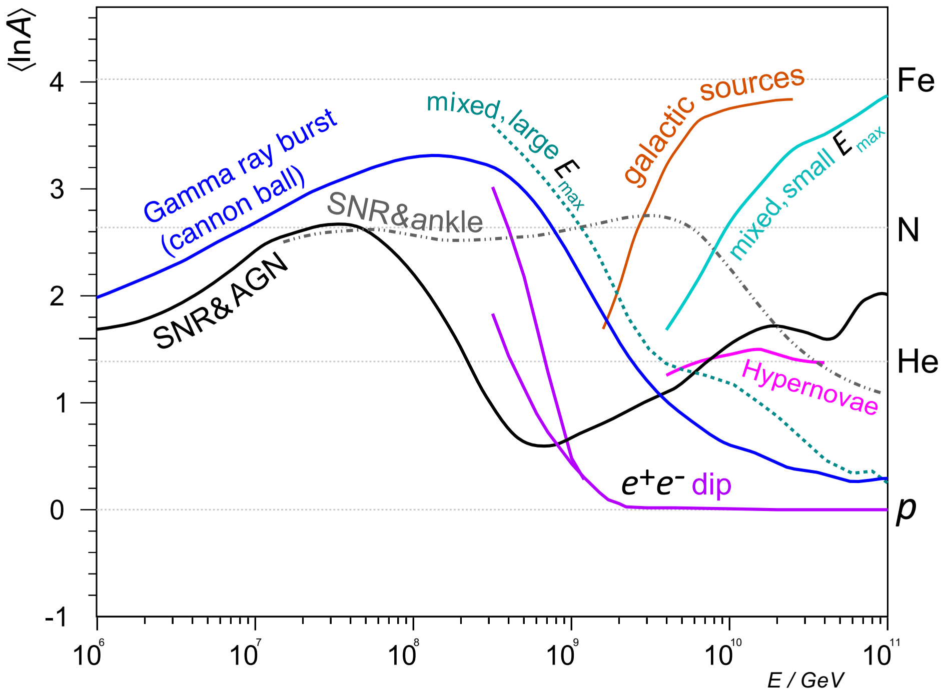
- **Direction** from particle arrival times
- **Energy** from size of **fluorescence light**
- **Mass** from **depth of shower maximum** X_{max} or size of **μ component** N_μ

Ground signal = **e** + **γ** + **μ**

Accurate measurements, limited by QCD theory

Mass composition of cosmic rays

Indirect search for dominant sources of ultra-high energy 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

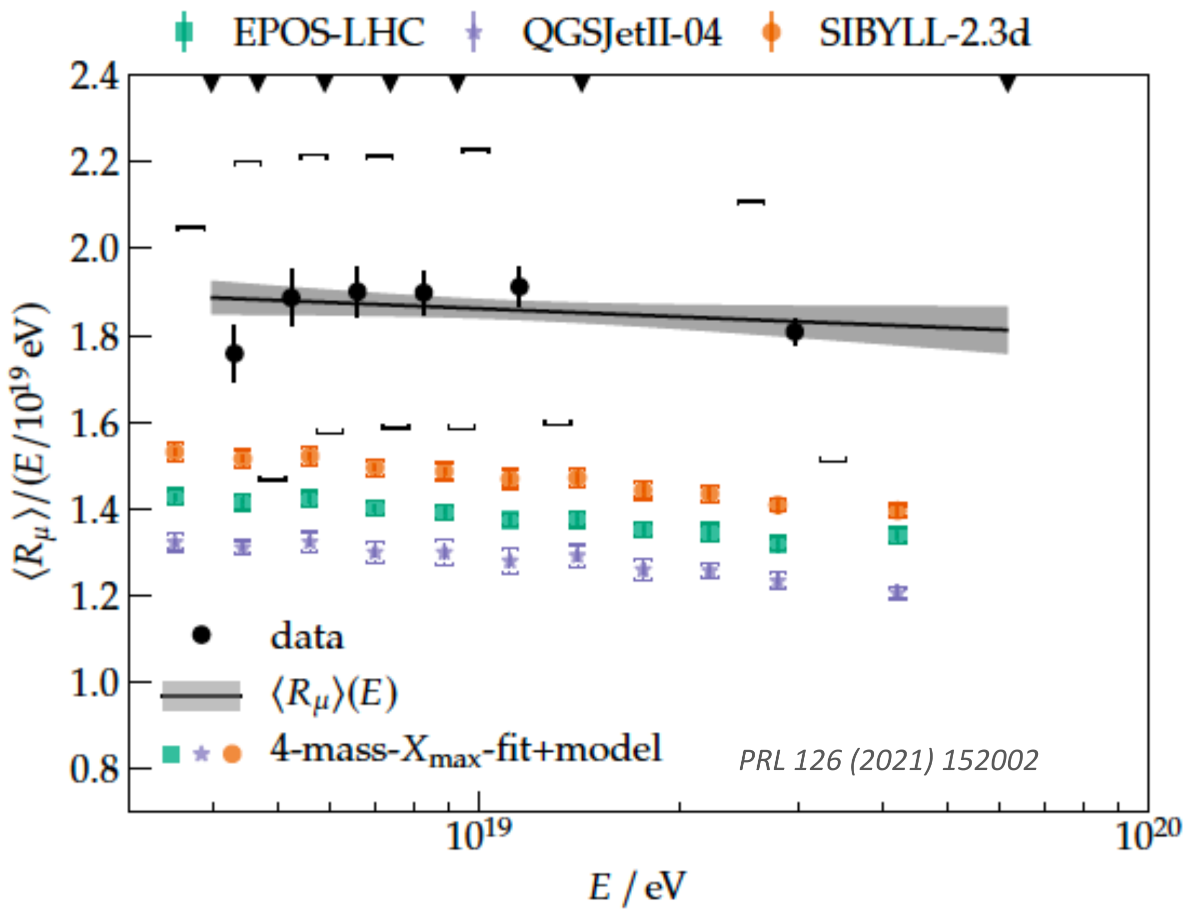
- **Muon Puzzle:** <lnA> from N_μ and X_{max} inconsistent
  → problem with theory

Muon deficit in air shower simulations

10^{19} eV (lab energy)

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)

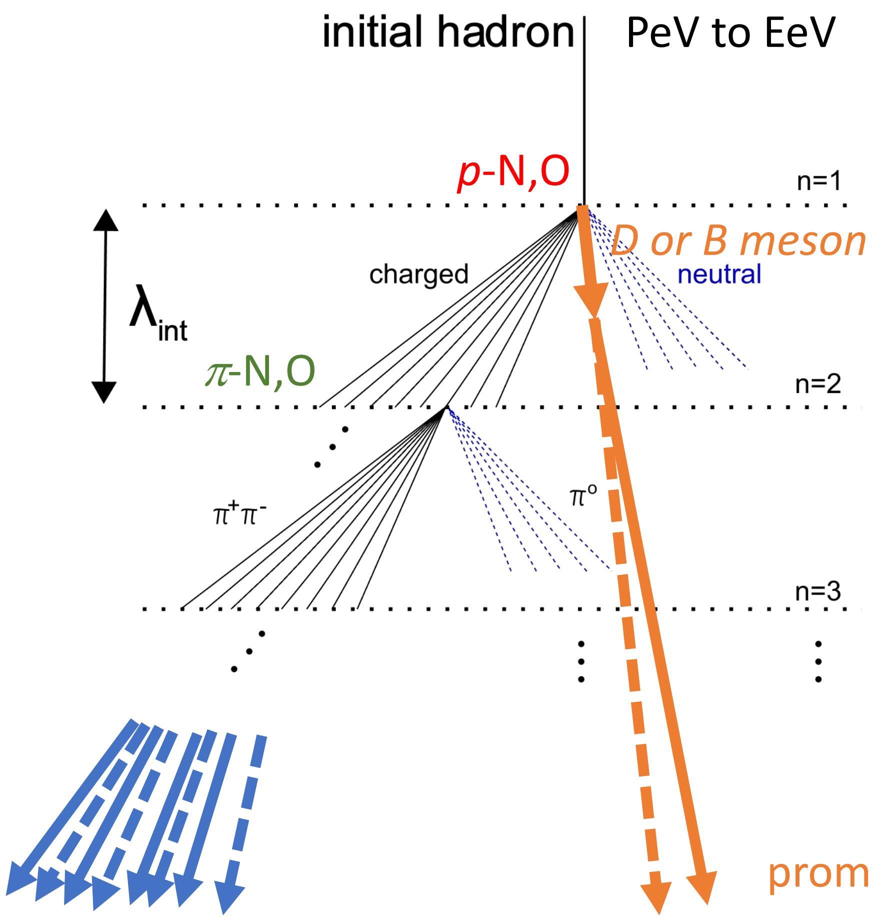


Also seen in other experiments:
Meta analysis by WHISP group presented at

- ICRC 2023
- ICRC 2021
- ICRC 2019
- UHECR 2018

Review on Muon Puzzle Albrecht et al, Astrophys. Space. Sci. 367, 27 (2022)

Muon and neutrino production in air showers



Conventional μ ν_μ ν_e
produced when mesons decay,
$\langle E \rangle \approx 10$ GeV

prompt
μ ν_μ ν_e
$E \gg 1$ TeV

Conventional lepton production

- **Hadronic cascade** with 5-10 steps
- Origin of **Muon Puzzle**
- **Theory: Soft-QCD**

Prompt lepton production

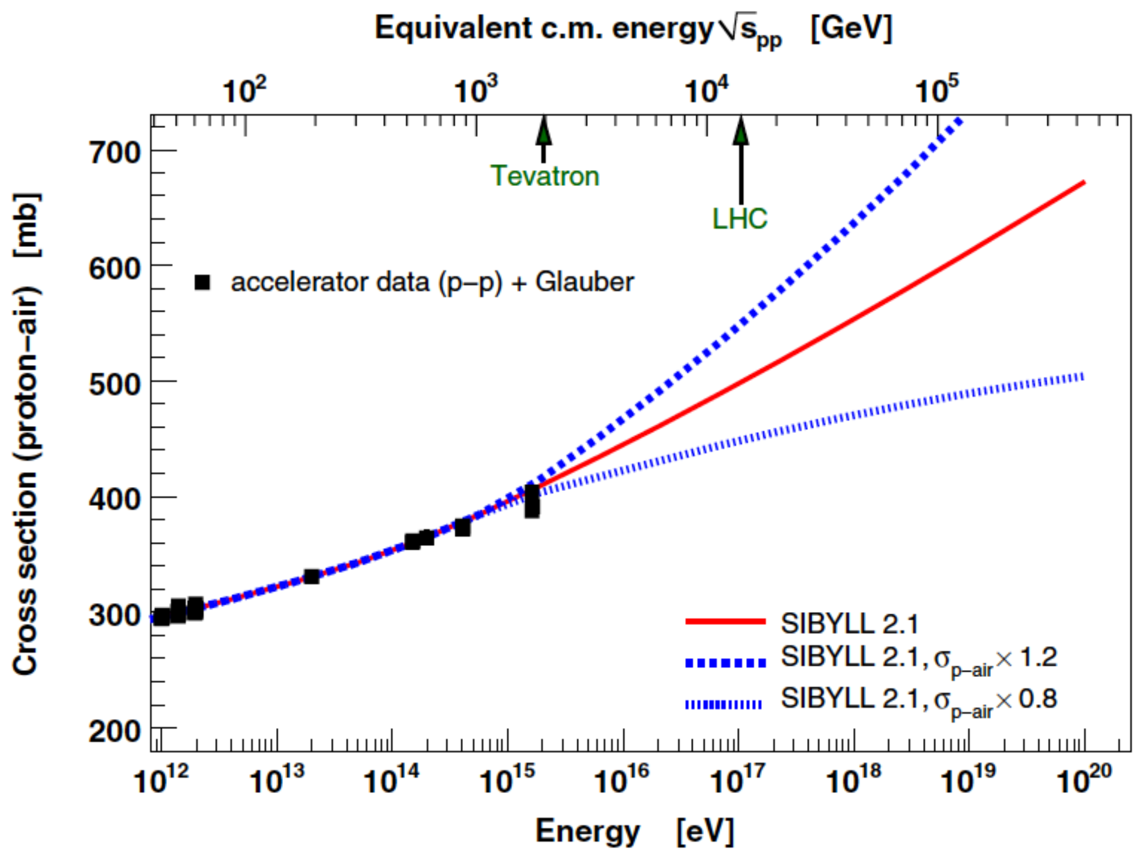
- Rare, but very high energy
- Source: first p+O interaction
- **Theory: pQCD**

QCD and conventional lepton production

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

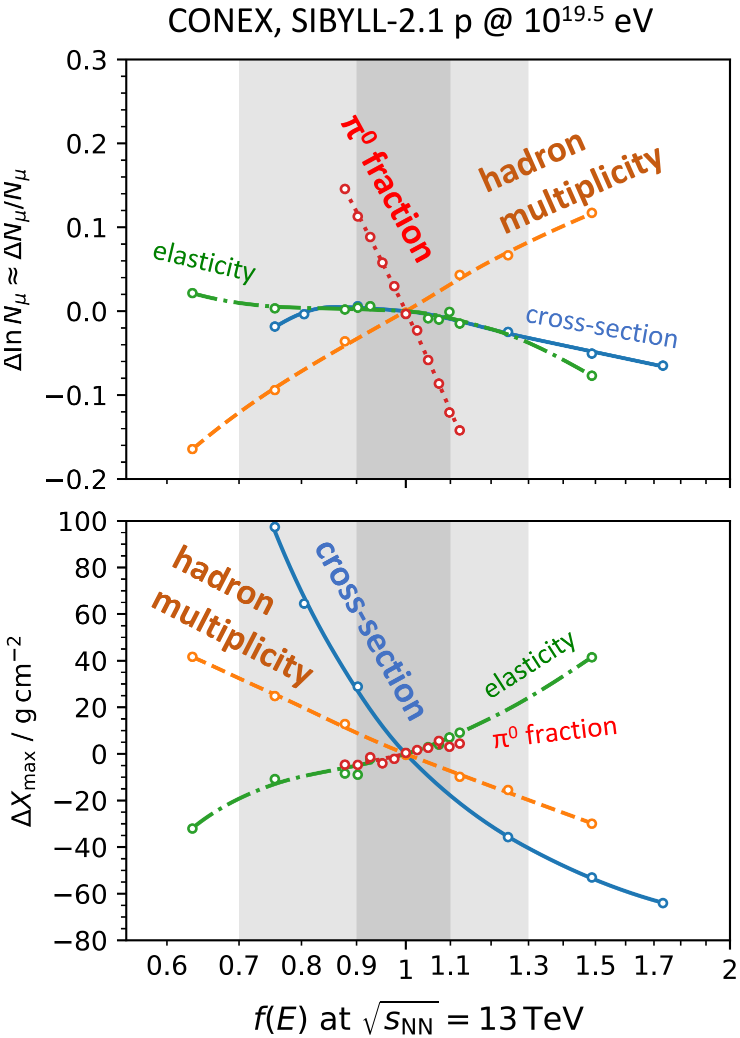
- Modify predictions of event generator with energy-dependent factor $f(E)$
- Study effect in simulations of $10^{19.5}$ eV air showers (CORSIKA)

Example of modified inelastic proton-air cross-section

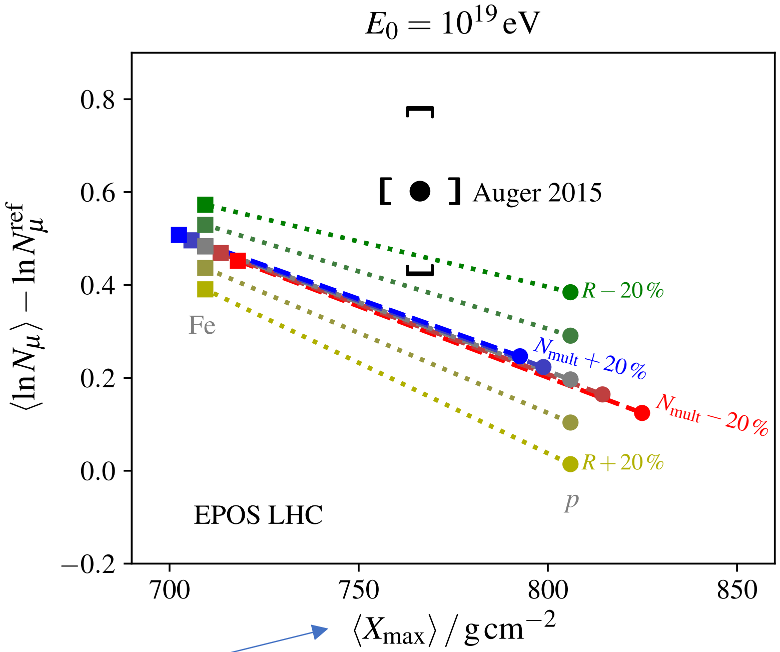


QCD and conventional lepton production

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



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

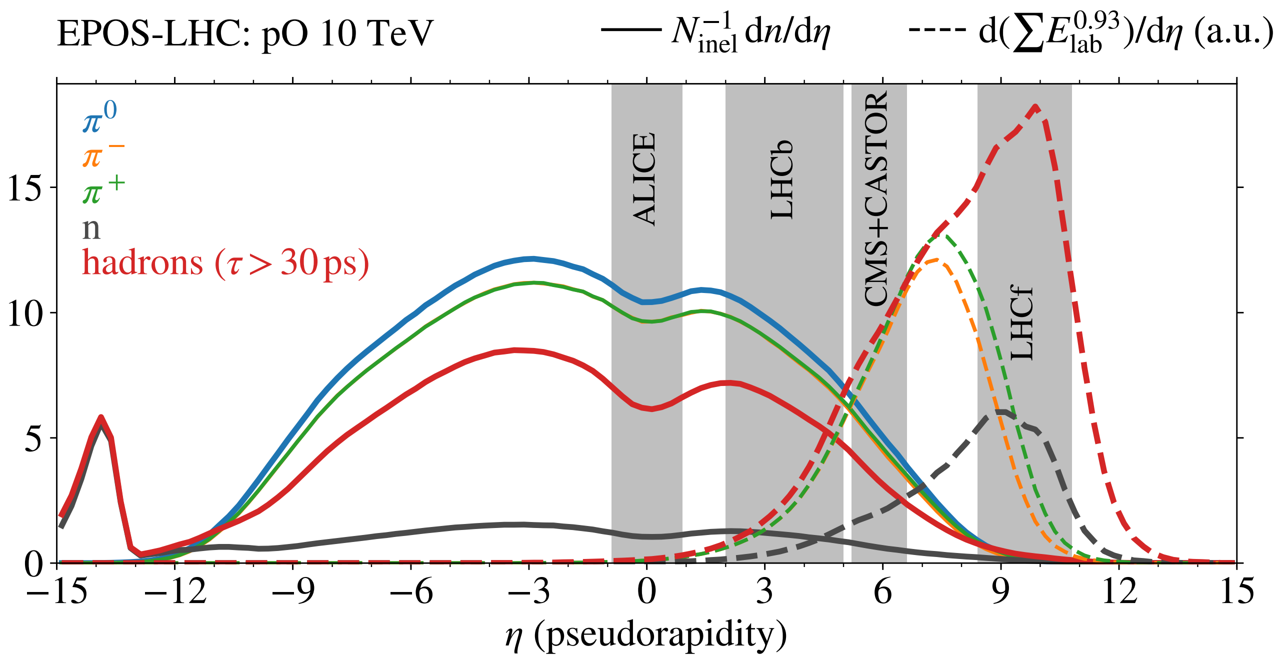


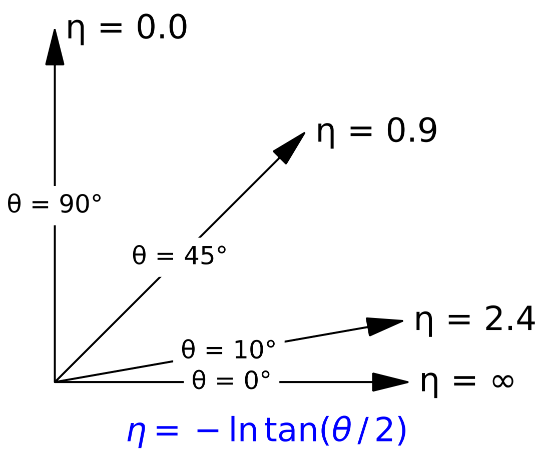
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Importance of forward acceptance

Albrecht et al, Astrophys. Space. Sci. 367, 27 (2022)
Also see PoS(ICRC2021)463 in arXiv:2112.11761

„Muon production weight“





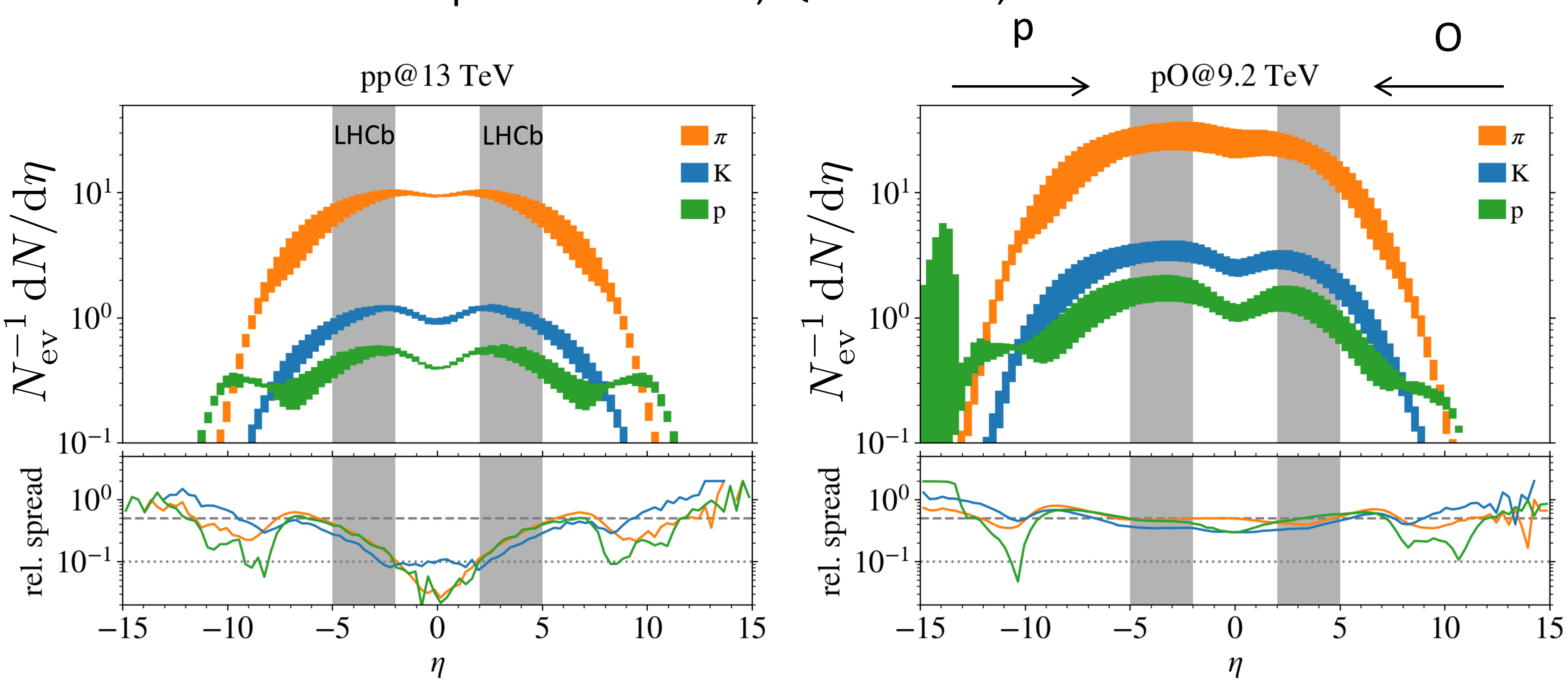
general-purpose experiments
with particle identification (PID)

specialized forward experiments

Nuclear effects and hadron spectra

Brewer, Mazeliauskas, van der Schnee (2021) arXiv:2103.01939

Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3



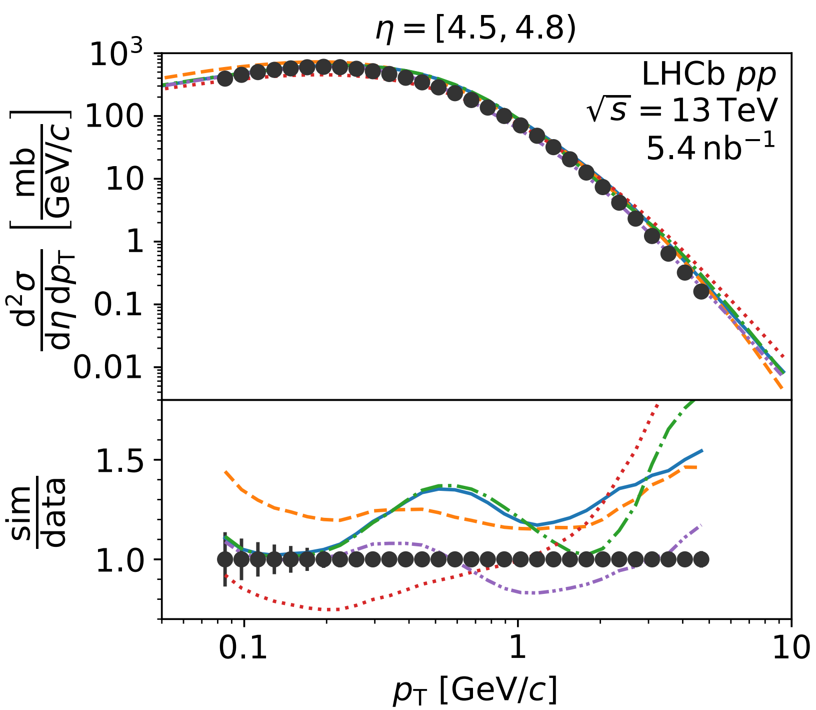
- *p-p* 10 % model spread, but 50 % spread at eta = 5
- 50 % spread everywhere in *p*-O

Forward hadron spectra

Prompt charged particles

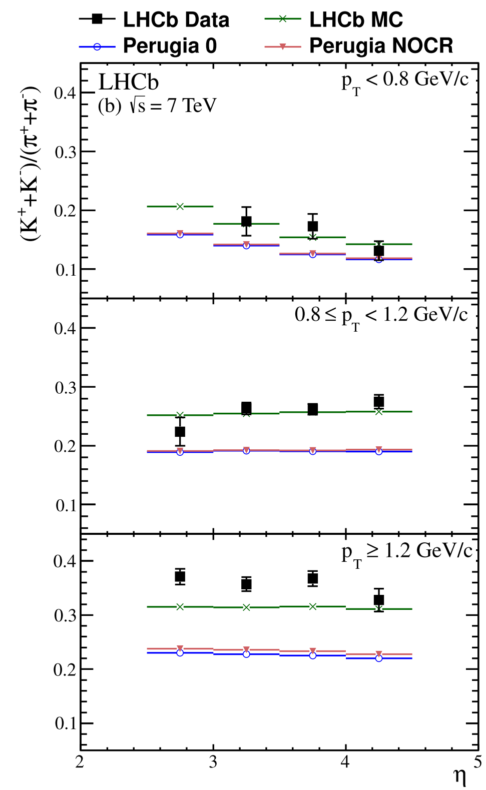
LHCb-PAPER-2021-010, arXiv:2107.10090
p-p @ 13 TeV

LHCb-PAPER-2021-015, arXiv:2107.10090
p-p, p-Pb @ 5 TeV



Hadron ratios (will be updated soon)

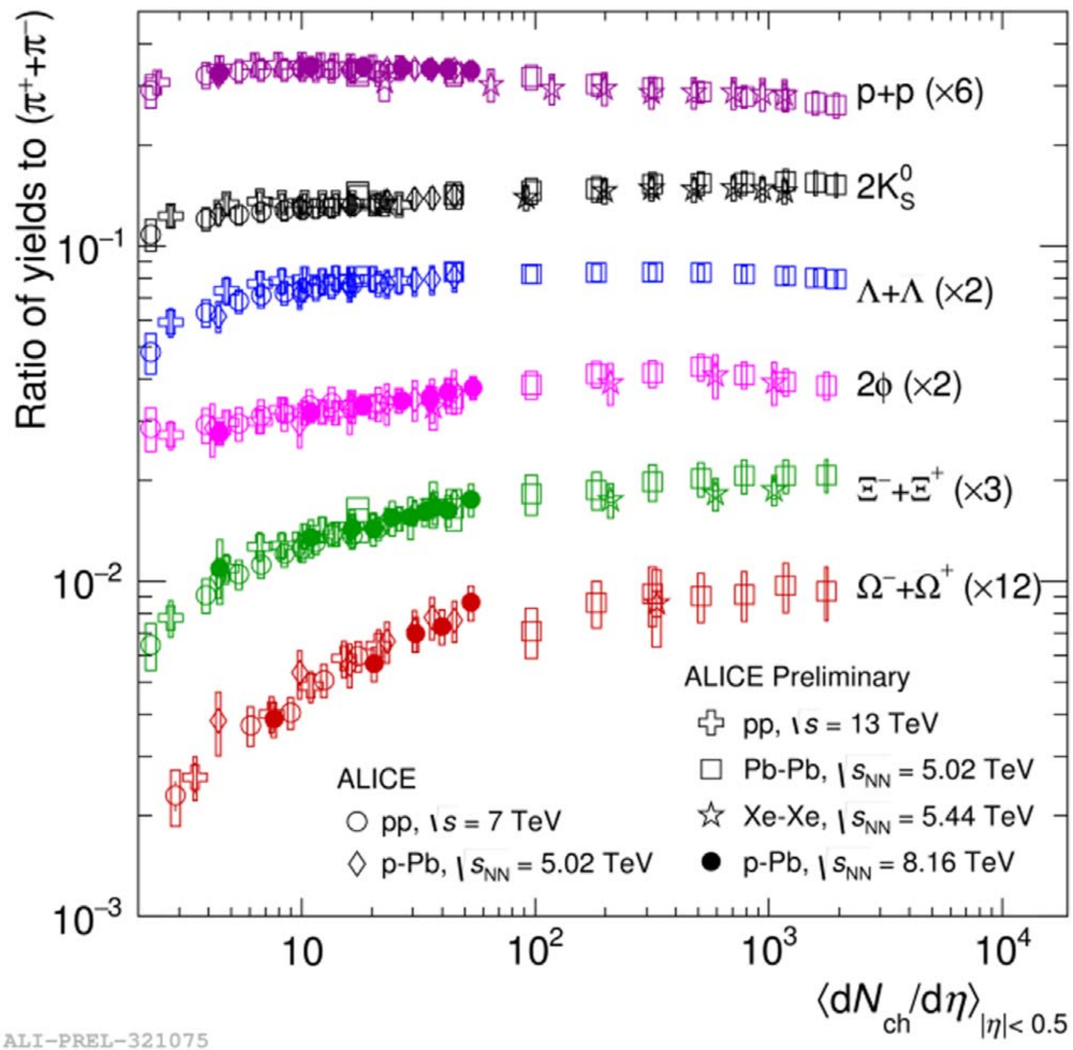
LHCb, EPJC (**2012**) 72:2168
p-p @ 0.9, 7 TeV



- Published: precise measurements of charged particle density at 1-2 % level
- **Soon**: hadron ratio measurements in pp, pPb

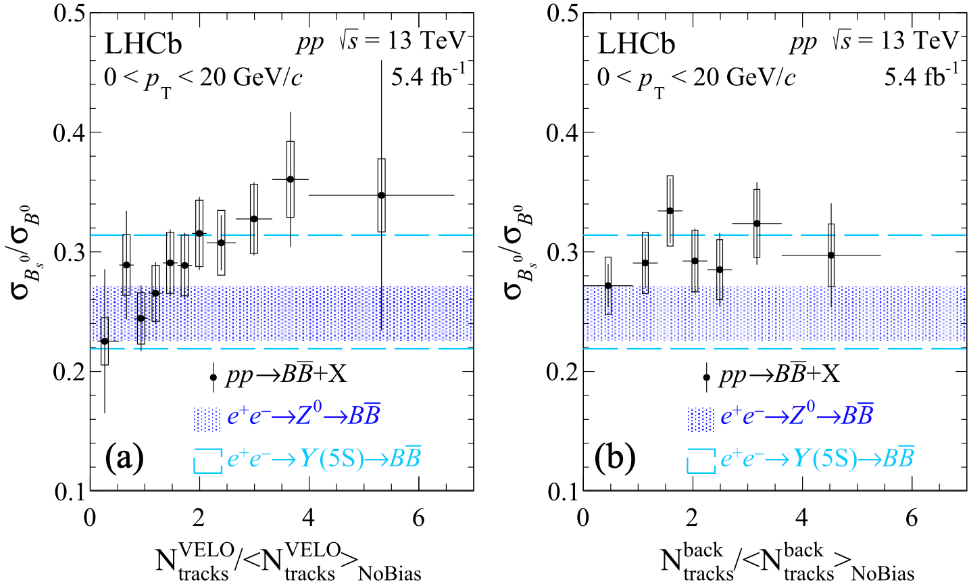
Nuclear effects and strangeness production

M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007

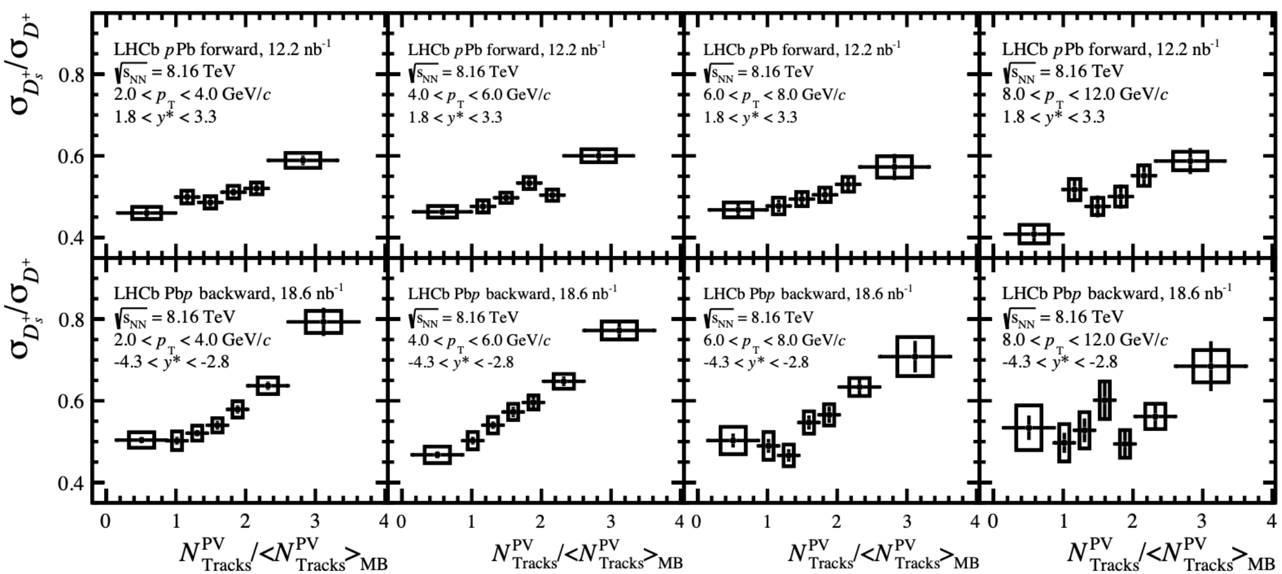


$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

Nuclear effects and strangeness production

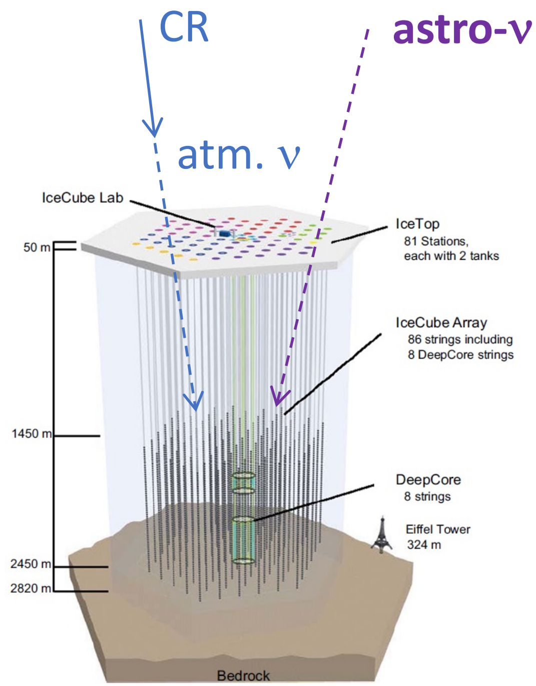


Association with b:
LHCb (2023) PRL 131, 061901 (2023)

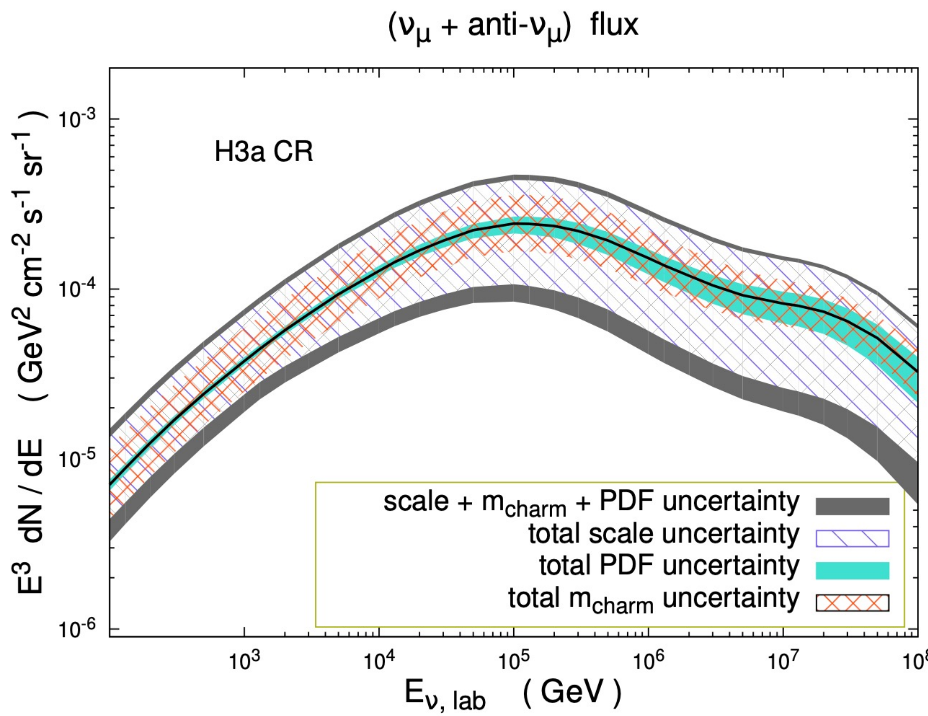


Association with c:
LHCb (2023)
arXiv:2311.08490

Neutrino measurements and theory



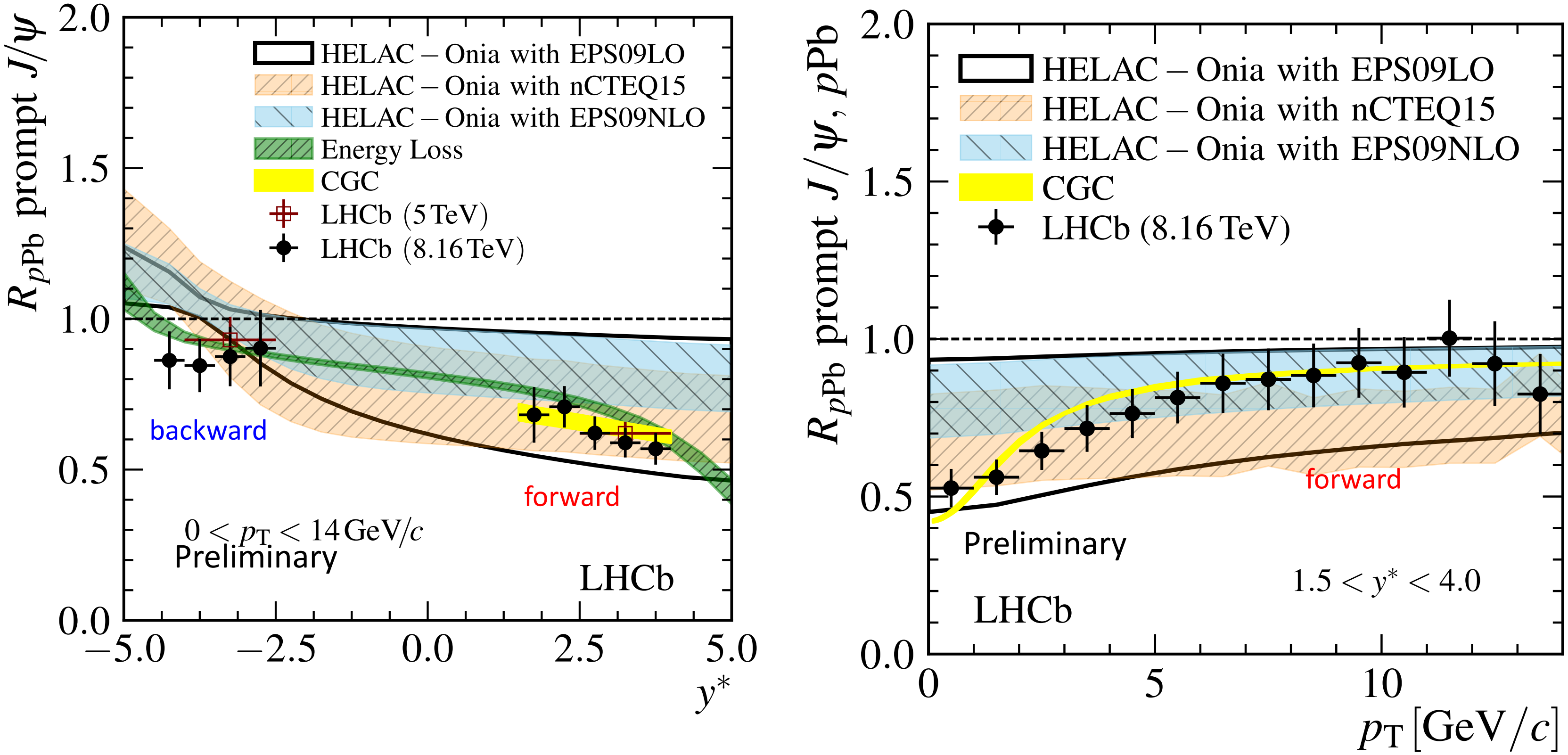
PROSA collab., JHEP04 (2020) 118



- **>50 %** uncertainty in atmospheric neutrino flux
  - Dominant uncertainty: **pQCD scale** (reduce with **forward D, B measurements**)
  - About **30 %** from uncertain CR mass composition
- **Double benefit** from better LHC measurements
  - Direct: More accurate prompt lepton production
  - Indirect: More accurate cosmic ray composition

Nuclear effects and charm production

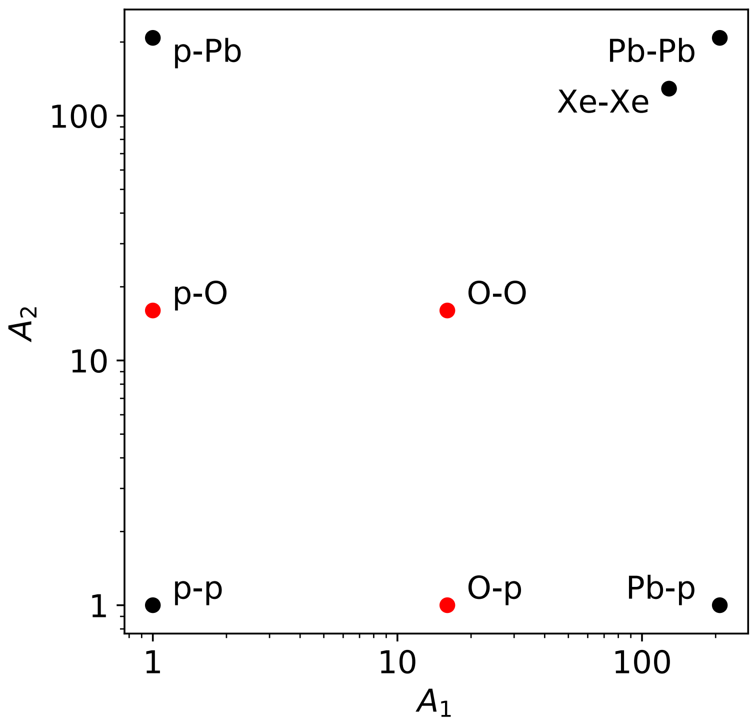
LHCb collab., Phys. Lett. B 774 (2017) 159

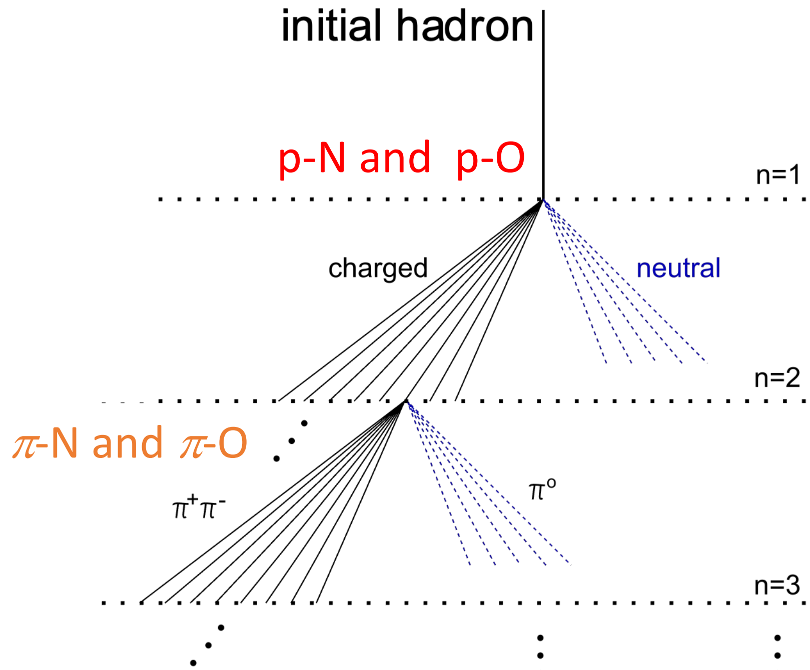


Up to 50 % suppression in forward direction

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

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)

Major physics topics in p-A, A-A

Altman et al. "QCD challenges from pp to AA collisions: 4th edition" Eur.Phys.J.C 84 (2024) 4, 421

Astroparticle physics p-O (cosmic ray composition, Muon Puzzle)
- Identified hadrons (double differential absolute cross-section η, p_T)
- D, B mesons

Fluid dynamics in collective flow
- Identified hadrons
- D, B meson v_n
- Quarkonia v_n

Jet quenching/energy loss
- Charged track R_{AA} (identified hadrons?)
- D, B meson R_{AA}

Modification of hadron chemistry
- Identified strange hadrons, ϕ, K^0_s
- D_s, B_s
- Multi strange baryons

Quarkonia suppression
- $J/\psi, \psi(2S)$ vs p_T, centrality

Legend
Red = needs high luminosity

Thermal photons
- Direct photons
- Converted photons

Summary

A = light nucleus, like oxygen

- Muon puzzle in astroparticle physics
  - Not enough muons produced by hadronic cascades
  - Origin in **Soft-QCD** in hadronic cascade from TeV to GeV
  - Most likely solution: **modified forward hadron composition** in p-A collisions beyond "standard model" (more strangeness and baryons)

- Prompt atmospheric lepton flux
  - Use data on **forward c,b-production** in p-A as input for **nPDFs**
  - Universal fragmentation functions?
  - High-luminosity measurements

- Outlook: Global tuning of event generators
  - Workshop with particle/astroparticle experts in Feb 2024
  - In preparation: Workshop report and white paper
  - Ongoing: demonstrate tuning to air shower data
  - Proposal to develop RIVET-like tool for astroparticle data

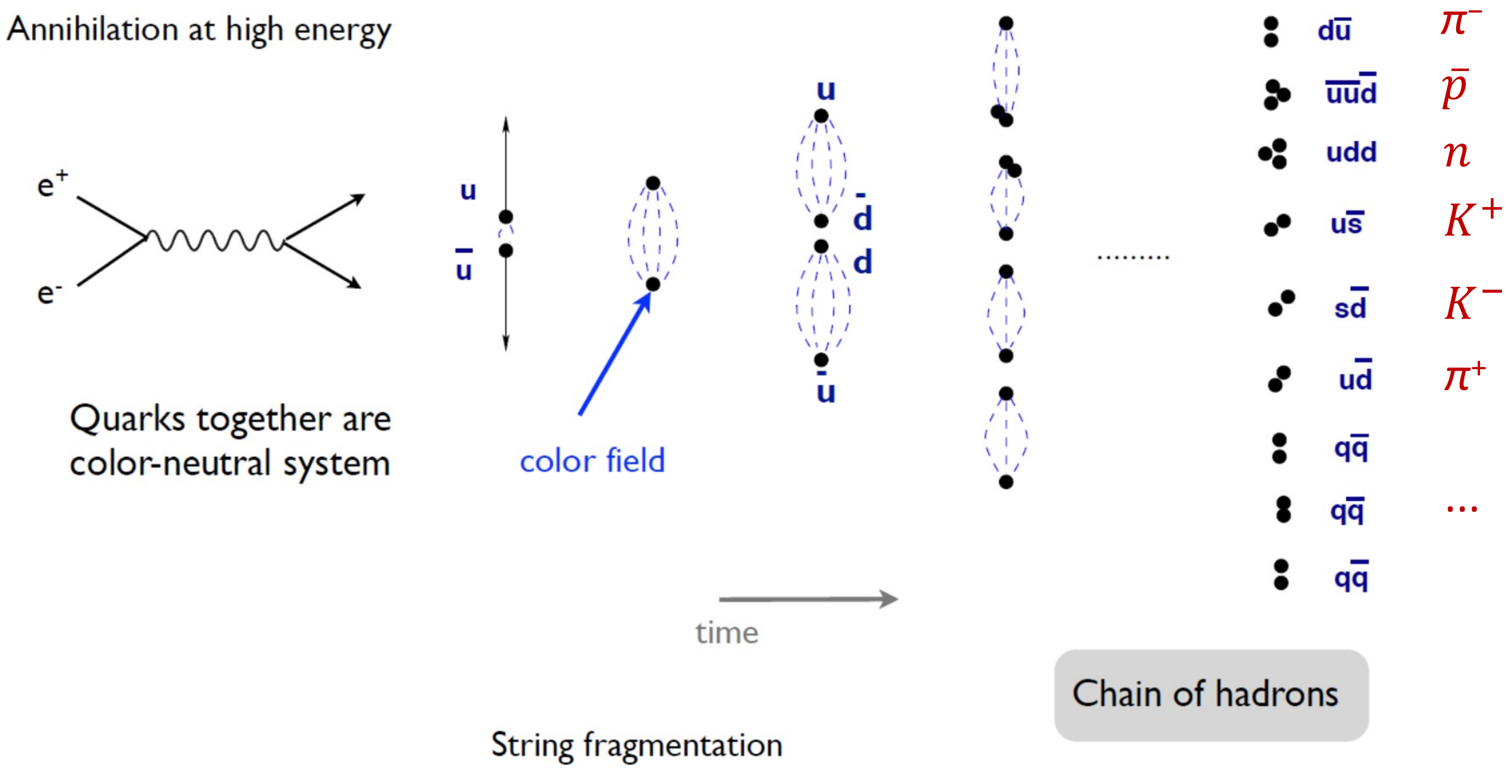
Backup

Possibilities to reduce energy ratio *R*

- Difficult to change *R* within standard QCD
  - String fragmentation universal → hadron ratios universal
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$

Probabilities to generate quark pairs independent of collision details

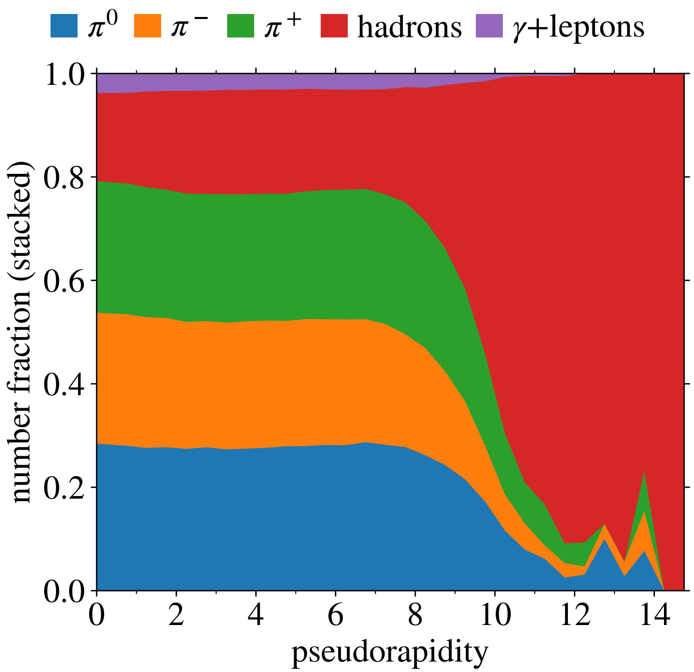
T. Pierog, K. Werner, NA61-theory talk (2015); figure from R. Engel



Possibilities to reduce energy ratio *R*

- Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$ so need to reduce π production
- Is strangeness yield enhanced in hadron-nuclear collisions, reducing π yield?

pp 13 TeV, EPOS-LHC



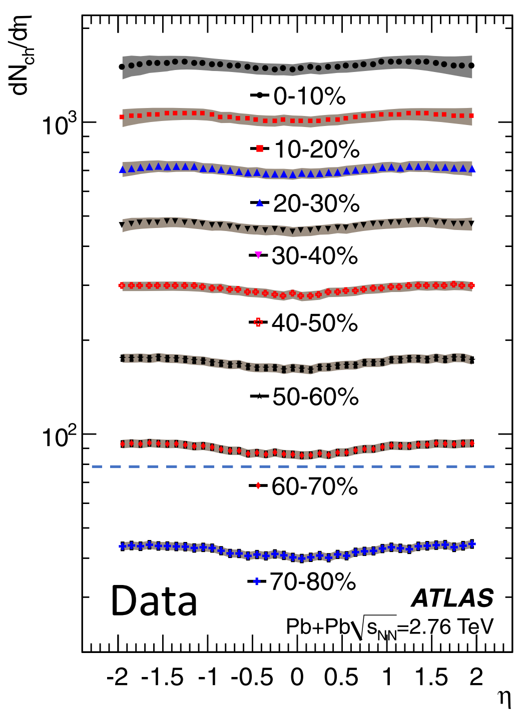
Collective effects may reduce pion fraction, EPOS-LHC predicts drop in *R* at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

QGP in air showers could enhancing strangeness production, reducing pion fraction
https://arxiv.org/pdf/1612.07328.pdf

Unexpected enhancement of strangeness observed in central collisions in *pp*, *p*Pb
ALICE, Nature Phys. 13 (2017) 535

Predictive power of universality

- Multiplicity increases with *number of nucleons* and with *sqrt(s)*
- Average p-air collision at sqrt(s) = 100 TeV $dN_{ch}/d\eta \approx 80$
- Peripheral Pb-Pb collisions at the LHC sqrt(s) = 2.76 TeV $dN_{ch}/d\eta \approx 80$
- If universality holds for forward production:
  Predict collisions of *lighter nuclei at energies beyond the LHC* using data from *heavier nuclei at LHC energies*



ATLAS, Phys. Lett. B 710 (2012) 363