technische universität dortmund

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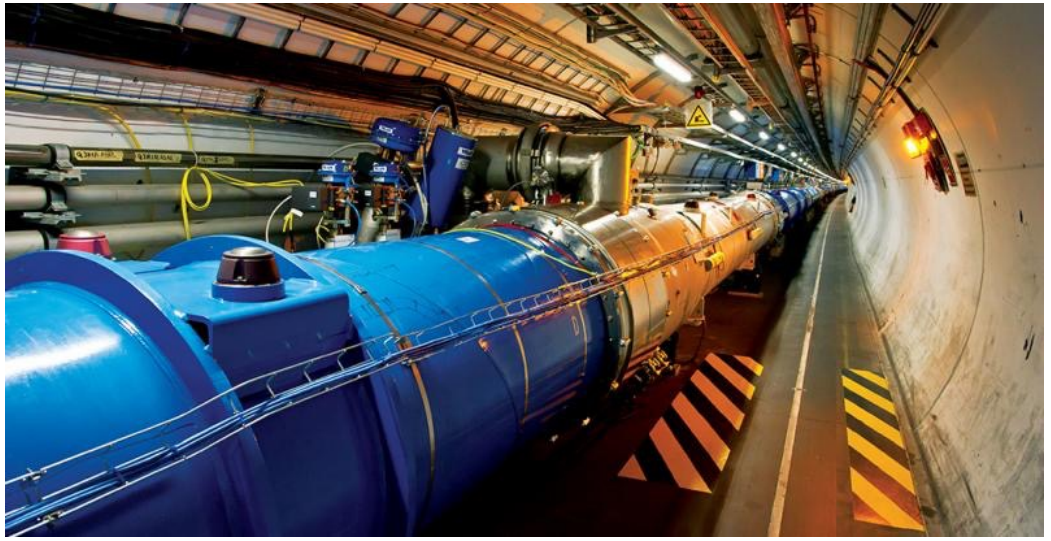
E5a/ Physik

Accelerator input to air shower physics: status and future prospects

Hans Dembinski, TU Dortmund, Germany

CORSIKA 8 Workshop, July 2022, Heidelberg

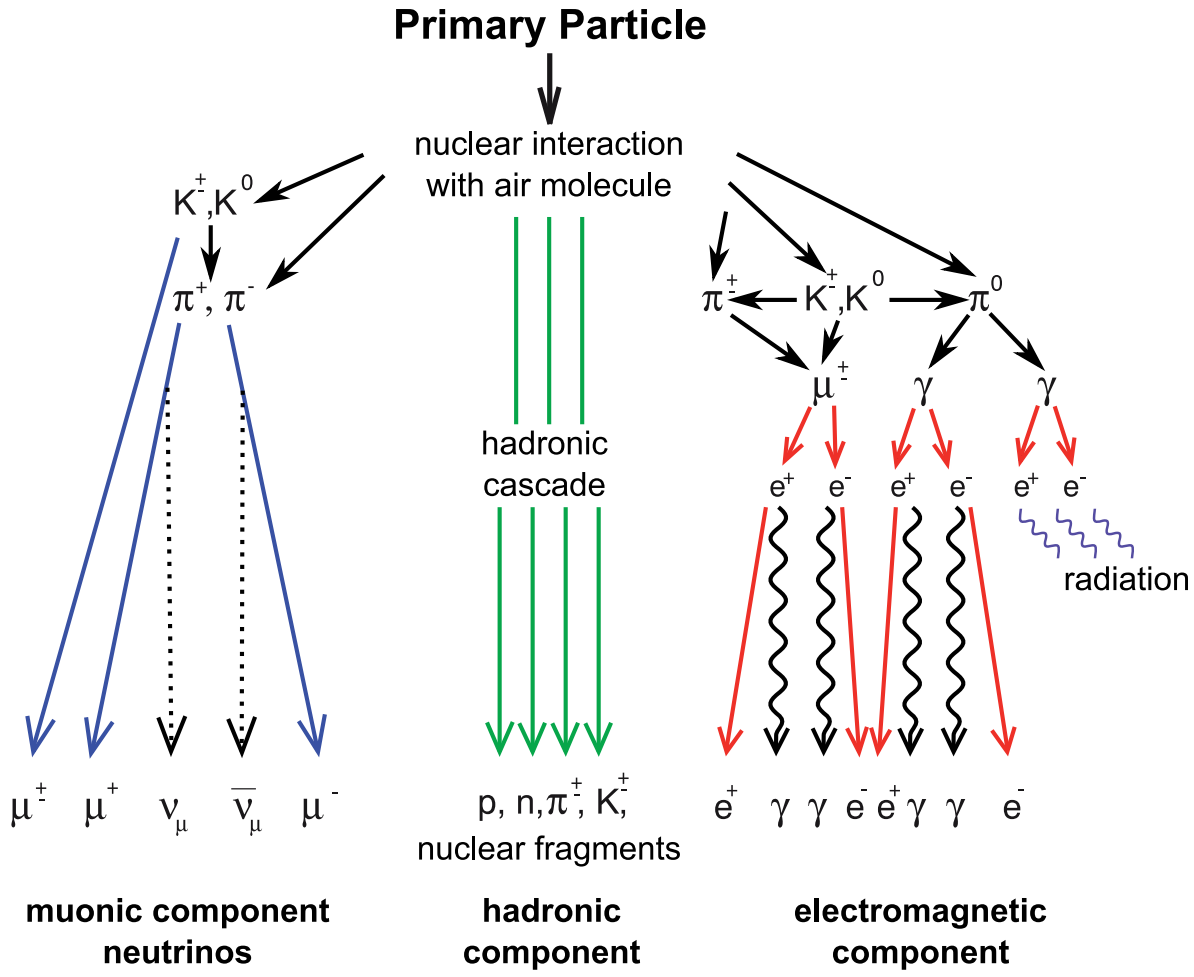
Artist impression of air shower



Overview

- Cosmic-ray induced air showers are driven by hadronic cascades
- CORSIKA 8 should accurately predict
  - First two moments of muon number N_μ and X_{max}
  - Atmospheric neutrino flux
  - Radio/gamma ray production
- Need reference data and and good models of soft-QCD processes
  - Production of long-lived hadrons and π^0
  - Ratio of strange hadrons to unflavored
  - Charm production
- LHC/SPS experiments provide important reference data
  - Challenge: Limited information on forward hadron production
  - Very promising: p-O collisions planned at LHC in 2023/24

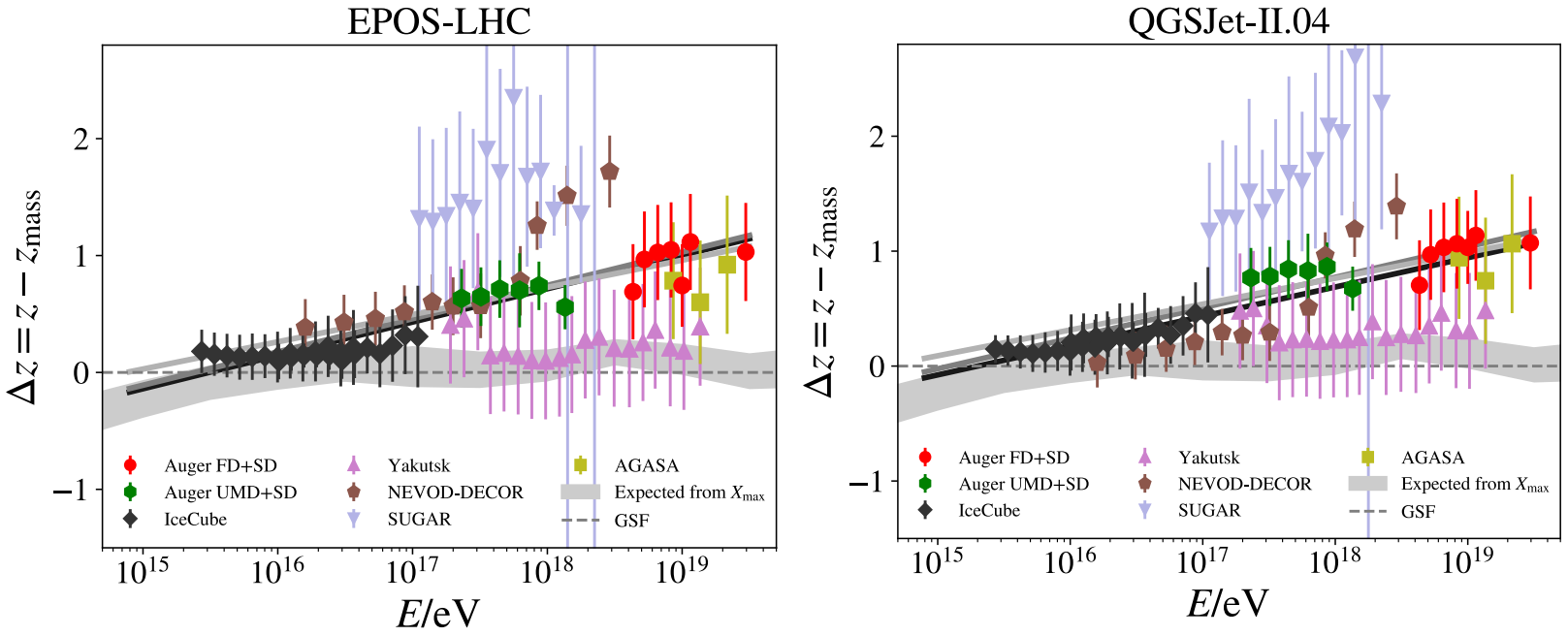
Air shower cascade



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

Muon deficit in simulated showers

PoS(ICRC2021)349



$$z_{\mathrm{mass}} \approx \frac{\langle \ln A \rangle}{\ln 56}$$

- Line model with slope fitted to $\Delta z = z - z_{\mathrm{mass}}$
- Slope is 8σ (10σ) away from zero for EPOS-LHC (QGSJet-II.04)
- Onset of deviation around 40 PeV corresponds to $\sqrt{s} \sim 8$ TeV; **in reach of LHC**

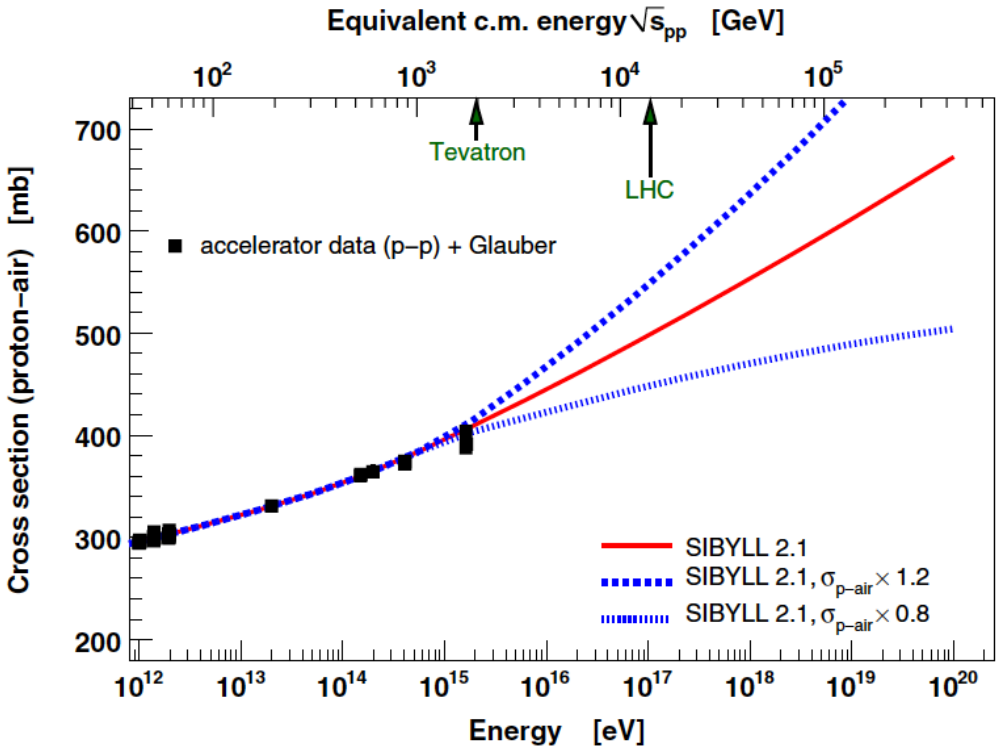
Air showers and QCD

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

- Modify hadronic features in SIBYLL-2.1 and other models with energy-dependent factor $f(E)$
- Study effect in $10^{19.5}$ eV shower simulations

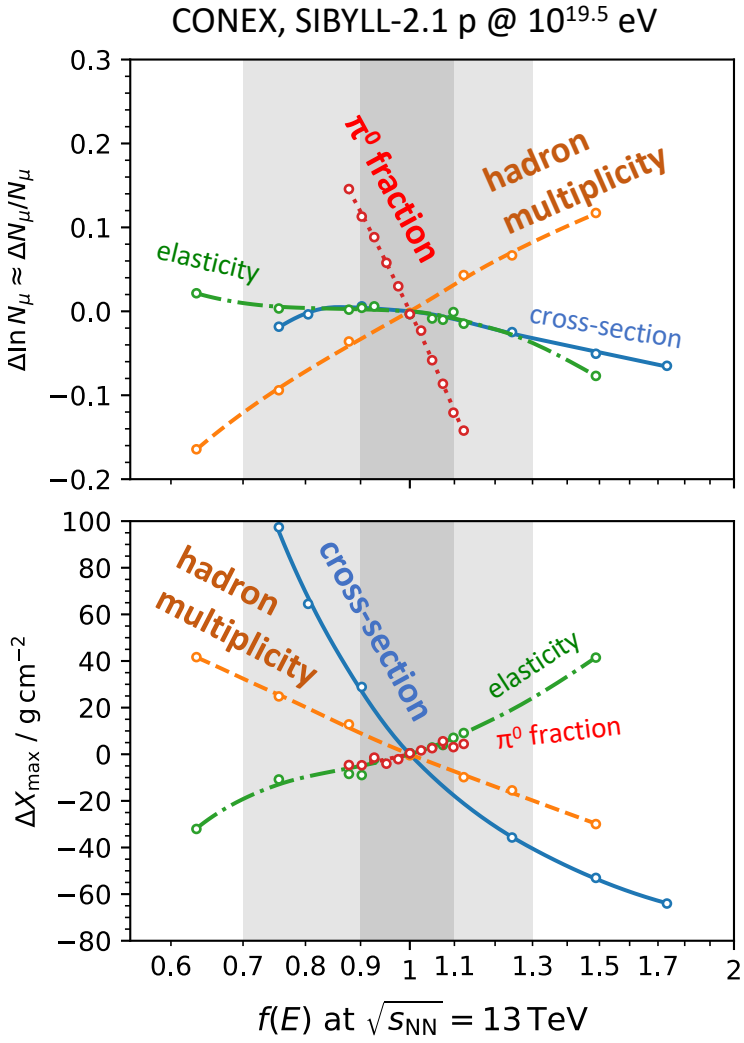
Modified features

- **cross-sections**
  inelastic cross-section of all interactions
- **hadron multiplicity**
  total number of secondary hadrons
- **elasticity** = $E_{\text{leading}}/E_{\text{all}}$
- **π^0 fraction**



From shower muons to QCD

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

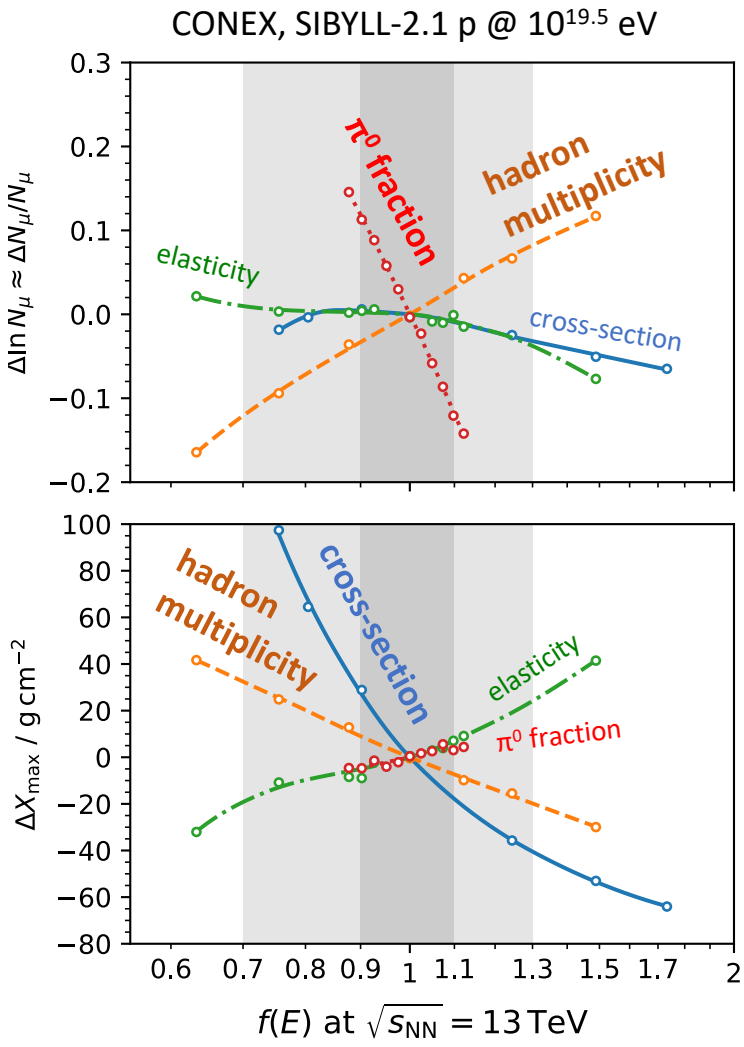


- Number of muons produced, N_μ
  - Very sensitive to π^0 fraction
  - Sensitive to hadron multiplicity

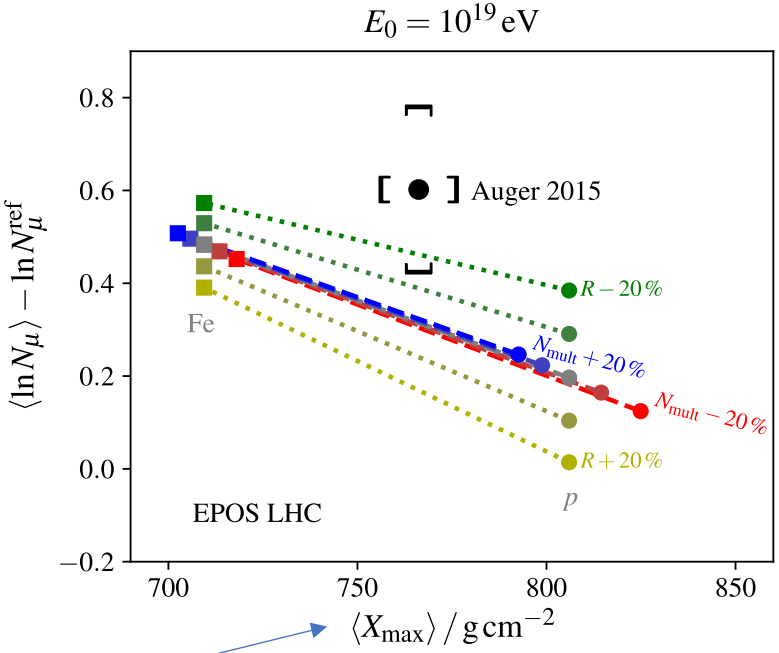
- Depth of shower maximum, X_{max}
  - Very sensitive to cross-section
  - Sensitive to hadron multiplicity

From shower muons to QCD

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



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



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

- Only changes to *R* can solve muon puzzle
- Small changes have large effect,
  R needs to be known to about 5 %

What to measure at the LHC

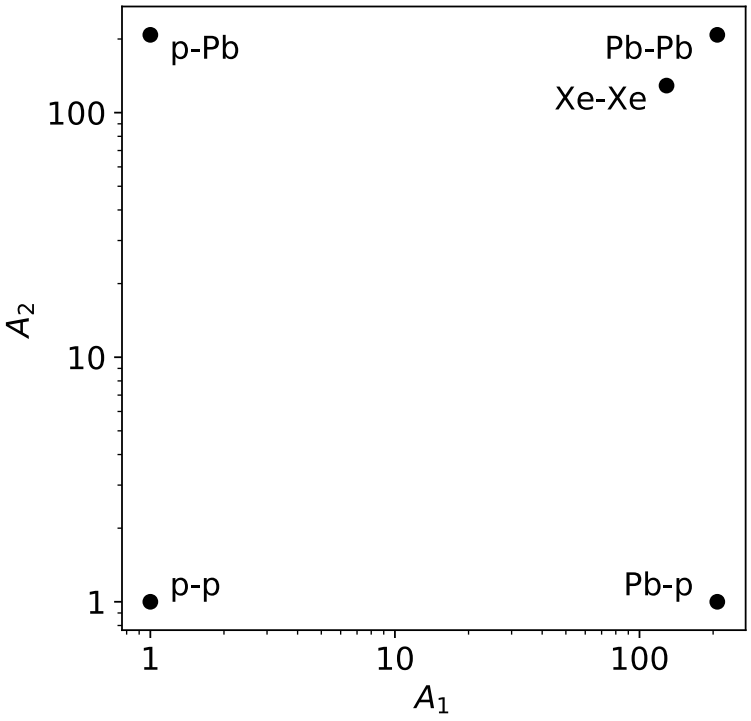
- Inelastic cross-section
- Production of long-lived hadrons and π^0
  - Hadron multiplicity
  - Energy ratio R
- Hadron elasticity
  - Fluctuations of X_{max} and N_μ
- Forward charm production (D^0)

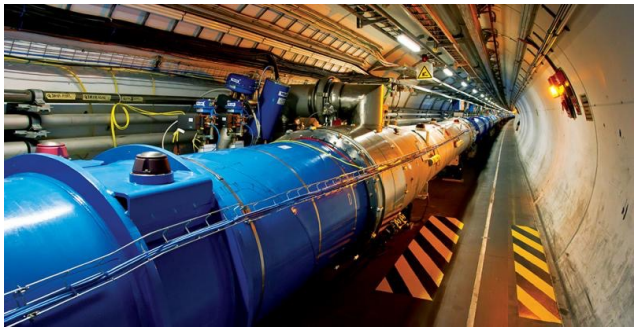
- Need pp, pPb, and pO data to understand nuclear effects

Large Hadron Collider (LHC)

LHC collision systems

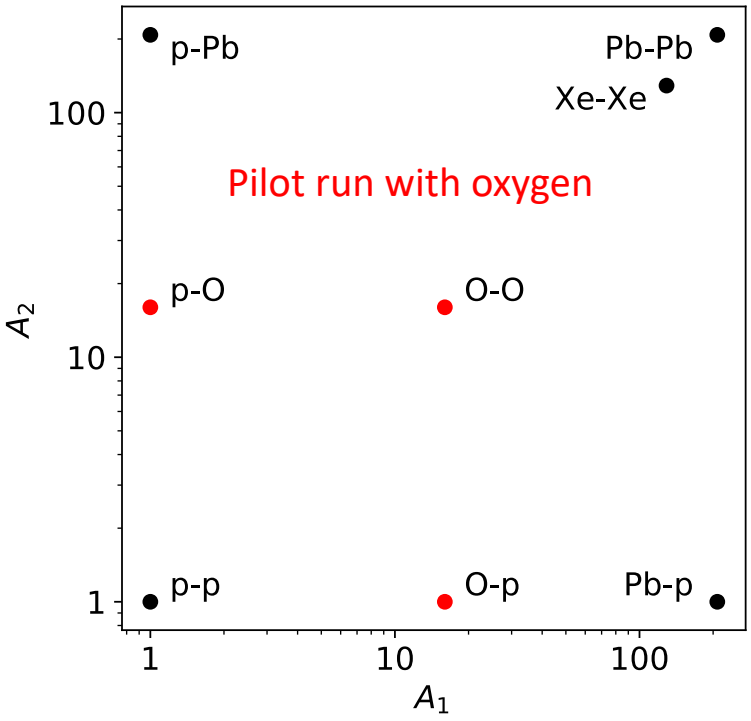
Collision systems at the LHC

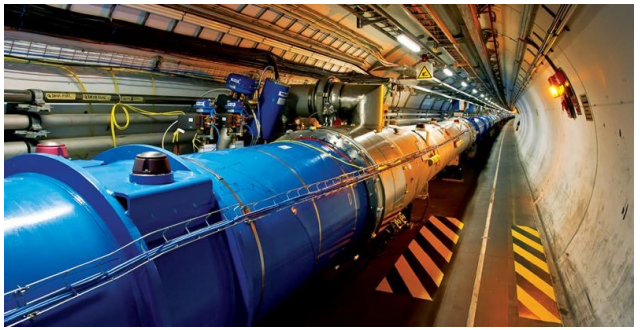




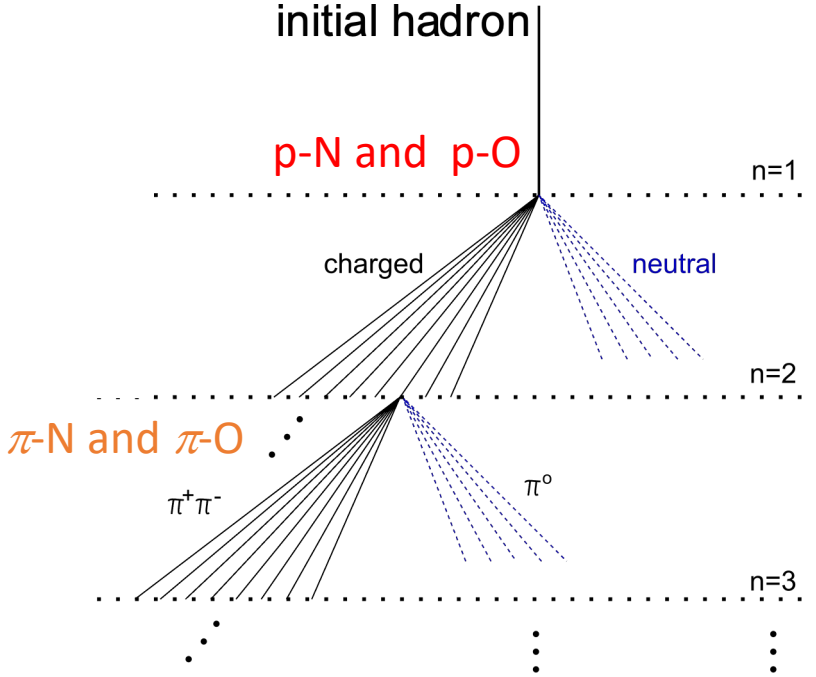
LHC collision systems

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





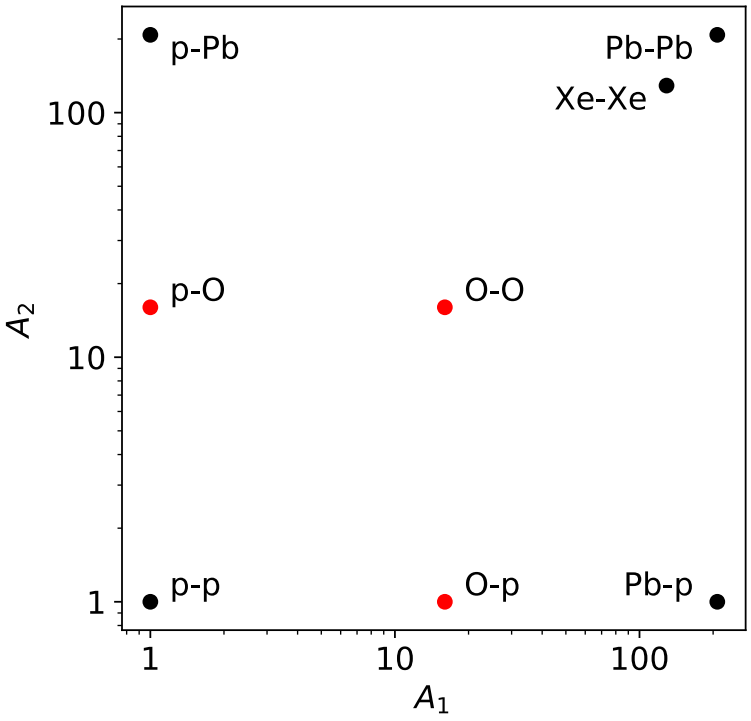
Air shower collision systems

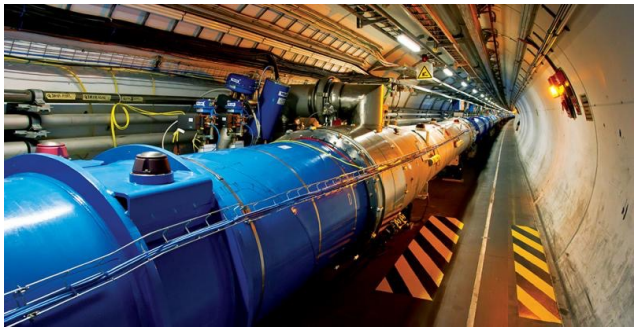


p-O collisions mimic air shower interactions

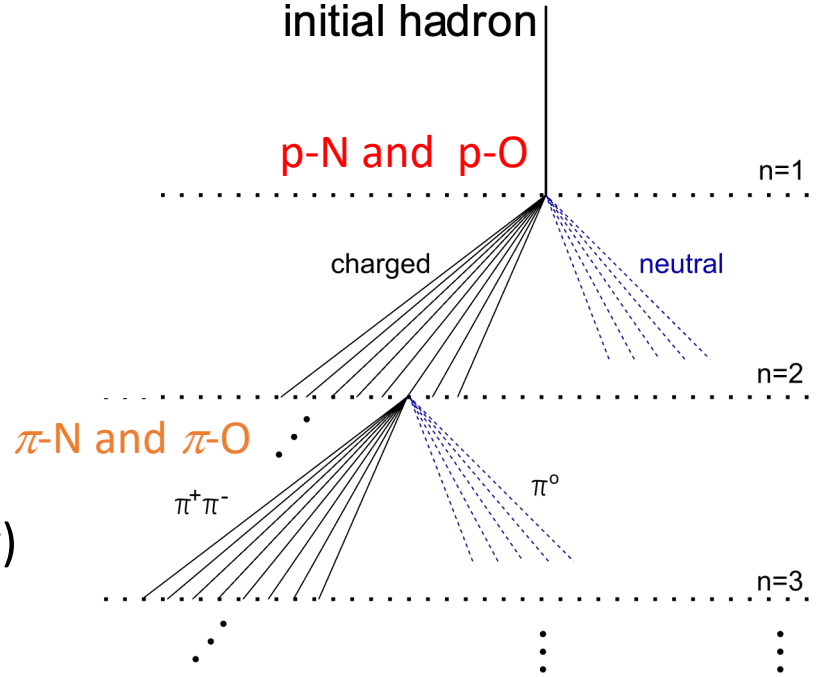
LHC collision systems

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





Air shower collision systems



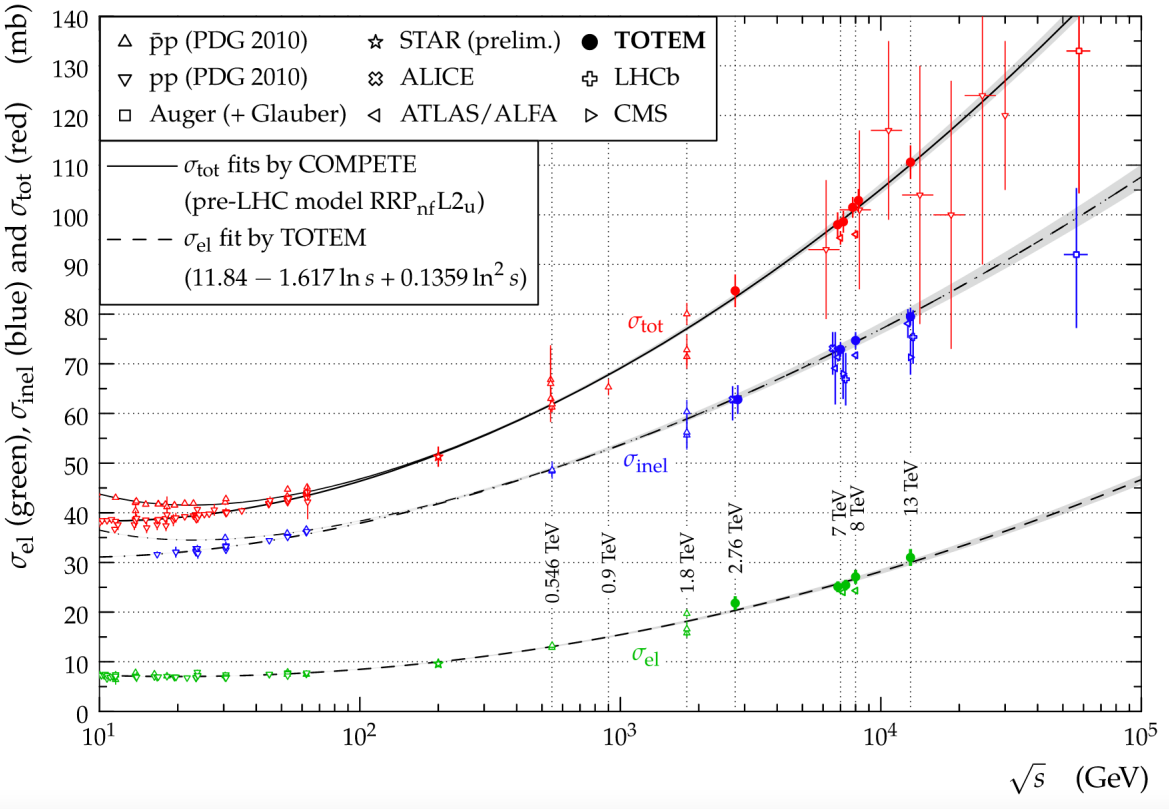
p-O collisions mimic air shower interactions

Fixed target data at sub-TeV (LHCb only)

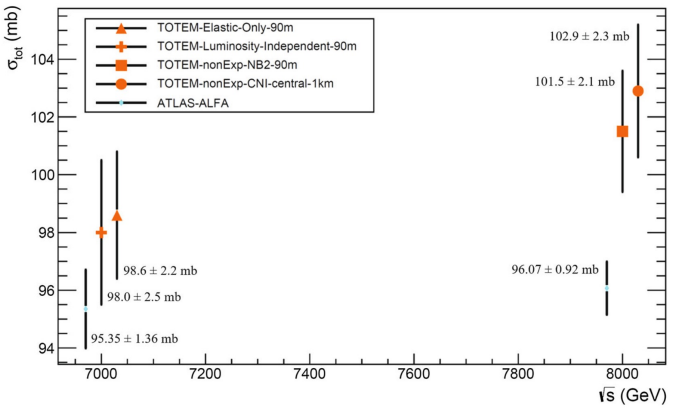
- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)

Inelastic cross-section

TOTEM, EPJC (2019) 79:103 (see references therein for ALICE, ATLAS, CMS, LHCb)

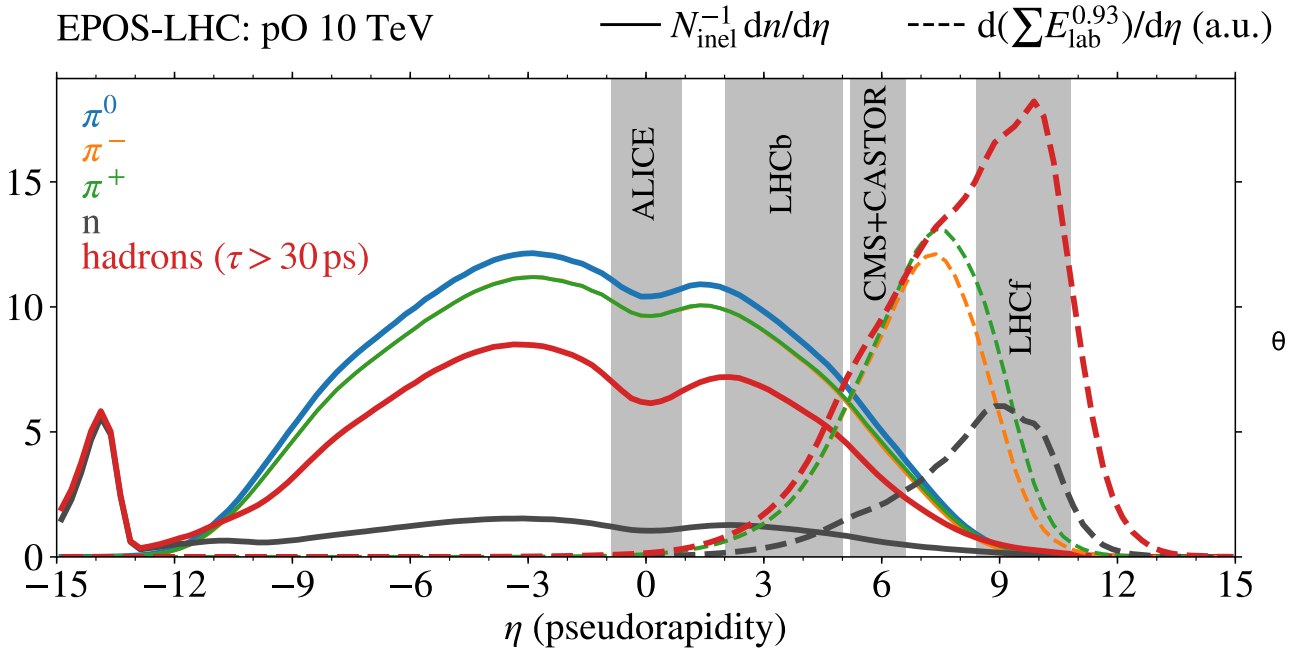


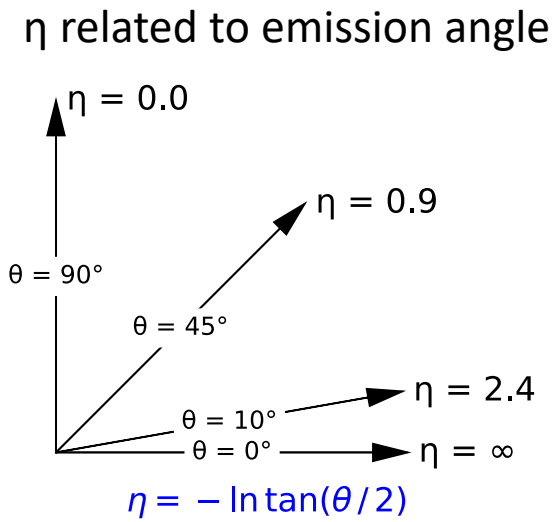
- Precision of 1 to 2 % achieved
- Data up to 13 TeV
- Allows for very accurate extrapolation
- Tevatron ambiguity resolved
- Potential new tension between ATLAS and TOTEM



Importance of forward acceptance

„Muon production weight“
how many muons would be produced in shower
by secondaries in this collision



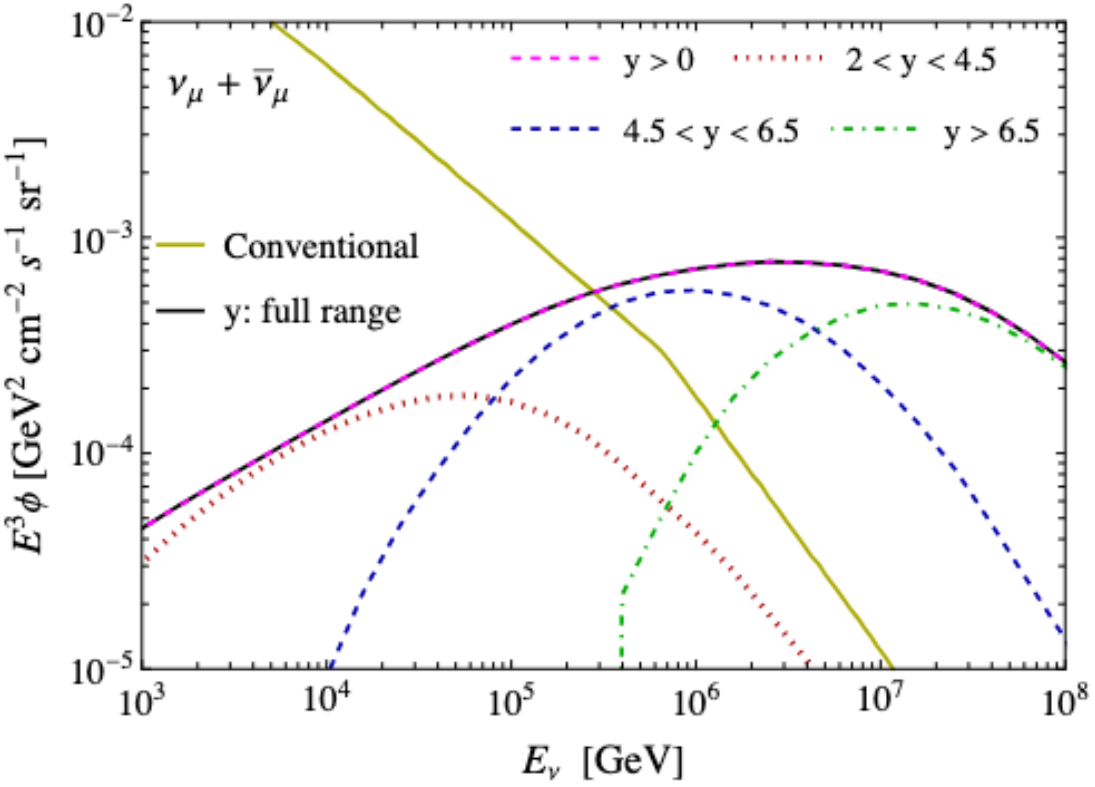


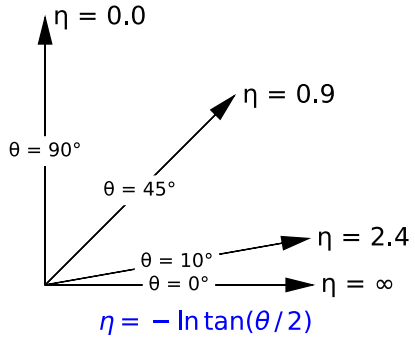
J. Albrecht, HD, et al., Astrophys. Space. Sci. **367,** 27 (2022)
PoS(ICRC2021)463 in arXiv:2112.11761

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 open charm and beauty

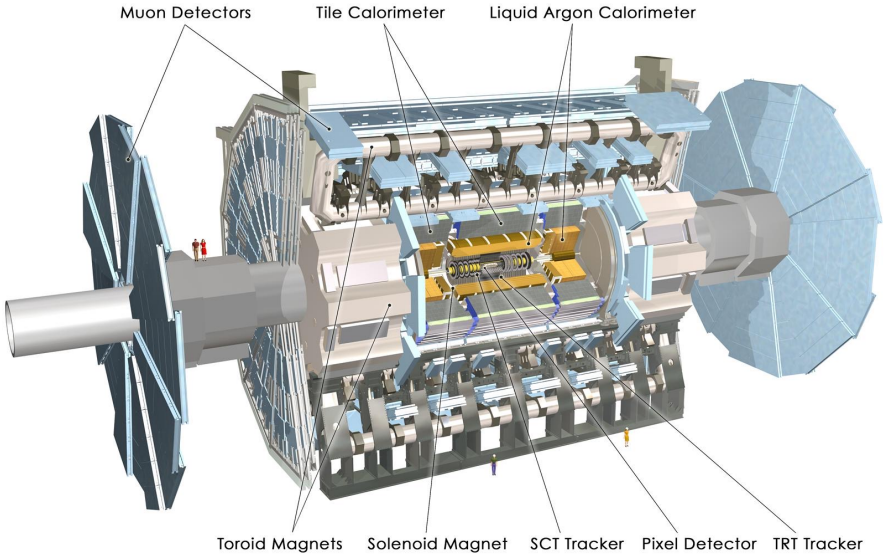




Pseudorapidity η
related to emission angle

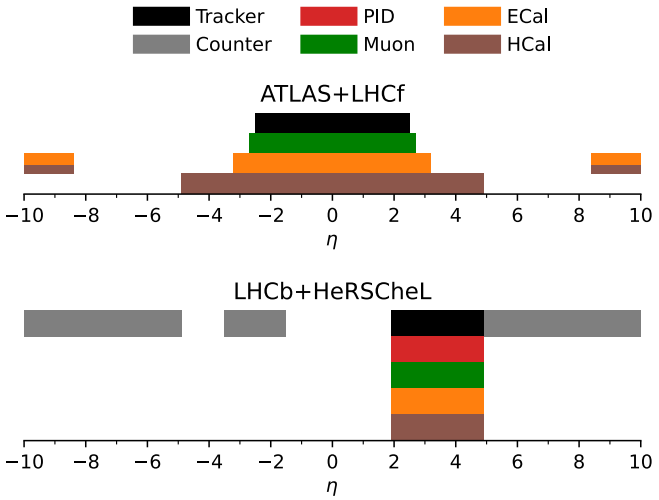
M. Garzelli: "We mostly need charm data at y = 4 to 7"

ATLAS vs. LHCb



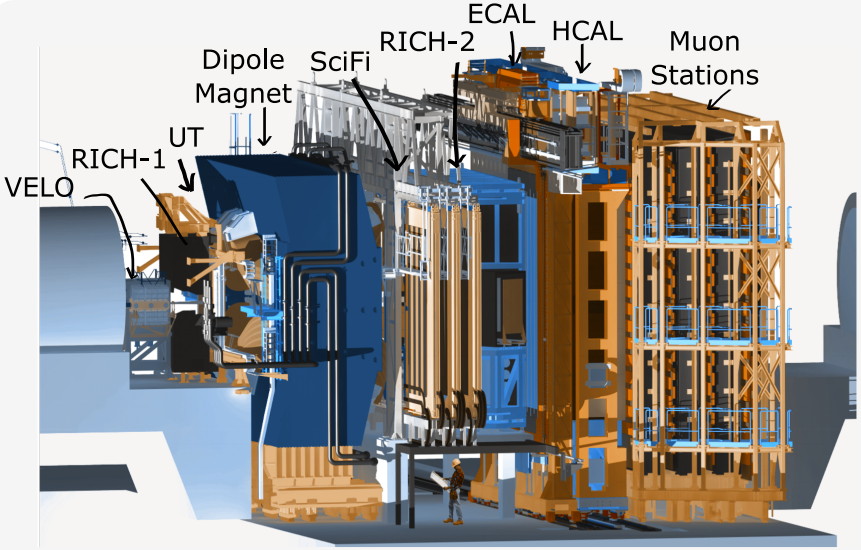
ATLAS: Symmetric spectrometer

- Optimized for study of new heavy particles



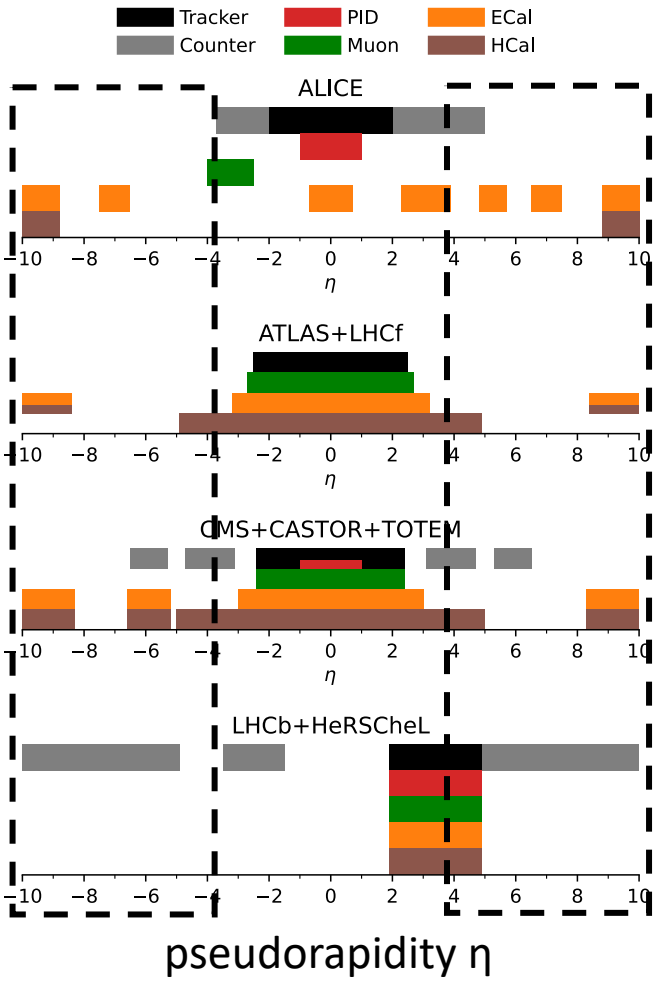
LHCb: Forward spectrometer

- Optimized for study of charm and beauty
- Life-time of c,b quarks stretched by forward boost



LHC experiments and Muon Puzzle

arXiv:2105.06148



Regions of interest for air showers

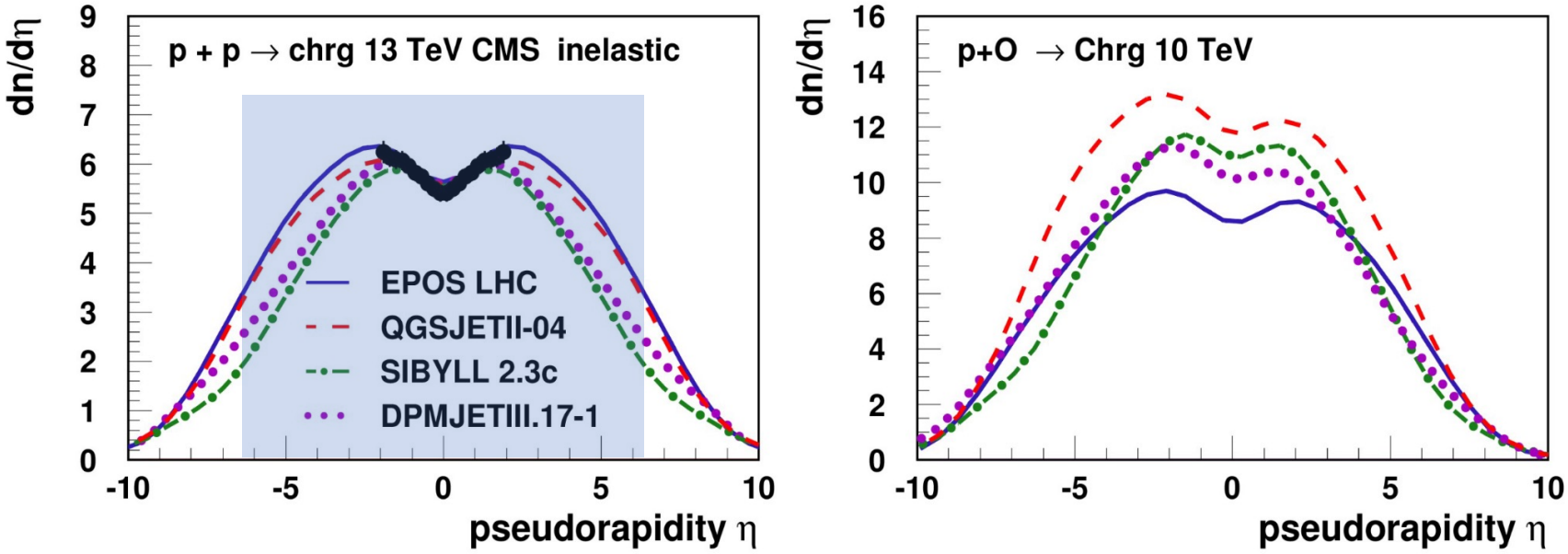
- Most LHC experiments focus on |η| < 2 region
- Forward capabilities |η| > 2
  - ALICE (counters)
  - **CMS-CASTOR:** calorimeter
  - TOTEM
  - **LHCb**: full tracking and PID
  - LHCf: neutral particles
  - (Forward Physics Facility)

Can constrain R

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

Forward charged particle spectra

pp T. Pierog, ISVHECRI 2018 p-Oxygen



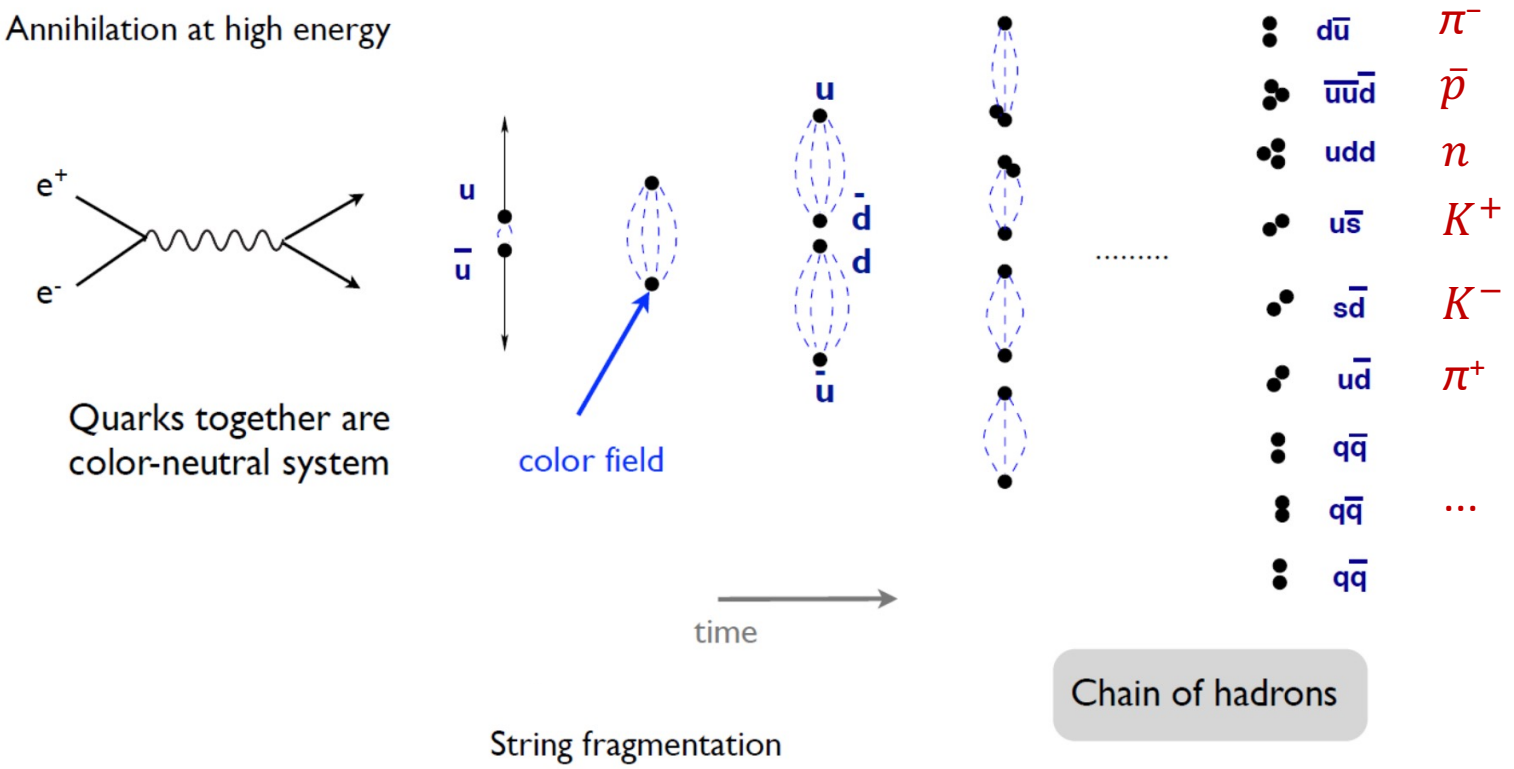
- Data available up to $|\eta| = 6.4$ in p-p and partially in p-Pb
  ALICE, Eur.Phys.J.C 77 (2017) 12 CMS & TOTEM, Eur.Phys.J.C 74 (2014) 10, 3053
  LHCb, JHEP 01 (2022) 166 ...
- Models agree at mid-rapidity in p-p, but not in the forward region
- Models do not agree on extrapolation from p-p to p-O; new LHC data will fix this

QCD factorisation

- 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



QCD factorisation breaking effects

- Collinear framework cannot describe rich phenomenology found in pPb at LHC
  - Strangeness enhancement & collective fluid-like phenomena observed in pPb and pp
  - Enhanced strangeness and baryon production observed at mid-rapidity (Muon Puzzle!)

- Alternative hadronization models
  - Become important when density of produced partons is high:
    heavy-ion collisions, high-energy collisions → collisions in air showers!
  - Not constrained by data from ee colliders
  - LHCb data provides evidence for alternatives models in forward region

- Core-Corona model (e.g. EPOS)
  - Statistical hadronization from Quark Gluon Plasma (QGP) at midrapidity (core)
  - String and remnant fragmentation in the forward region (corona)

- String-string interactions (e.g. DIPSY)
  - Strings overlapping in space-time interact with each other

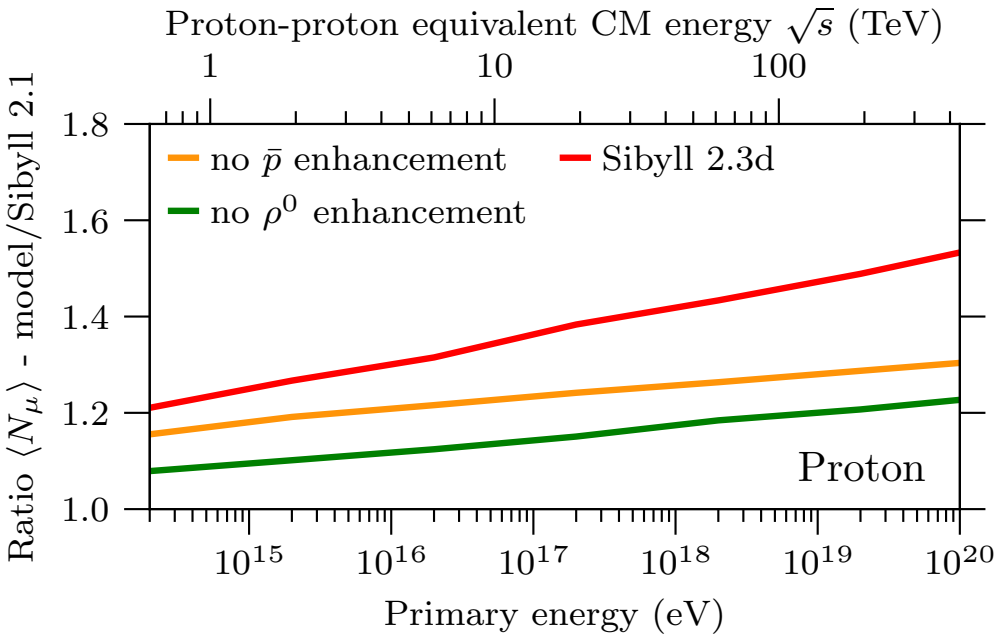
- Quark coalescence model
  - Hadrons directly formed from pairs of quarks produced in collision

QCD factorisation breaking effects

- Enhanced forward baryon and ρ^0 production in π-air collisions

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

Observed at NA61/SHINE

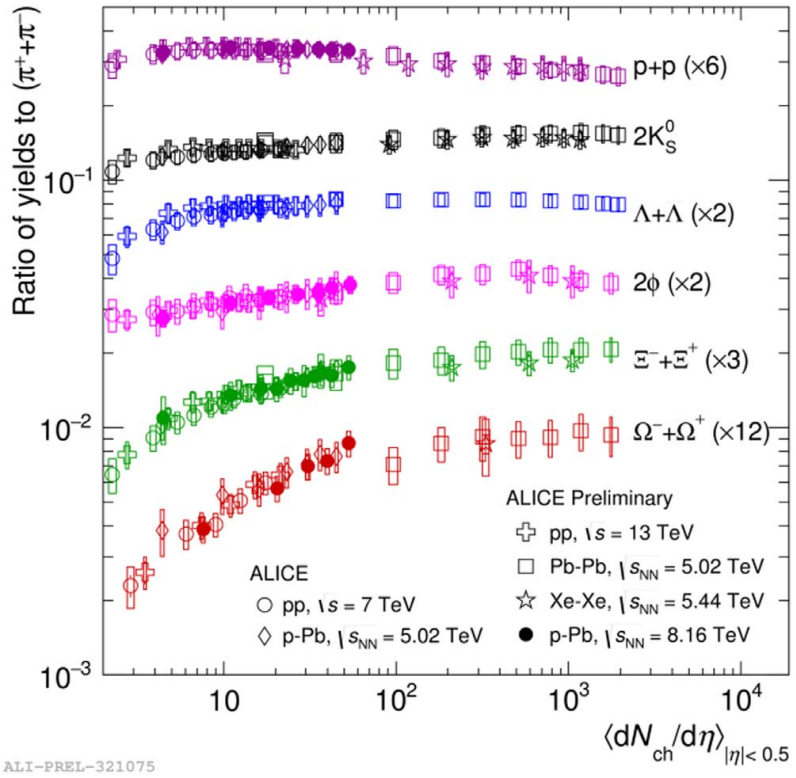


- More baryons and ρ^0 → less π^0 → more muons in air showers
- Large increase of muon number in SIBYLL model, but not enough to solve muon puzzle
- Effect also included by EPOS (core-corona model)

Strangeness enhancement

- Enhanced strangeness production observed at mid-rapidity

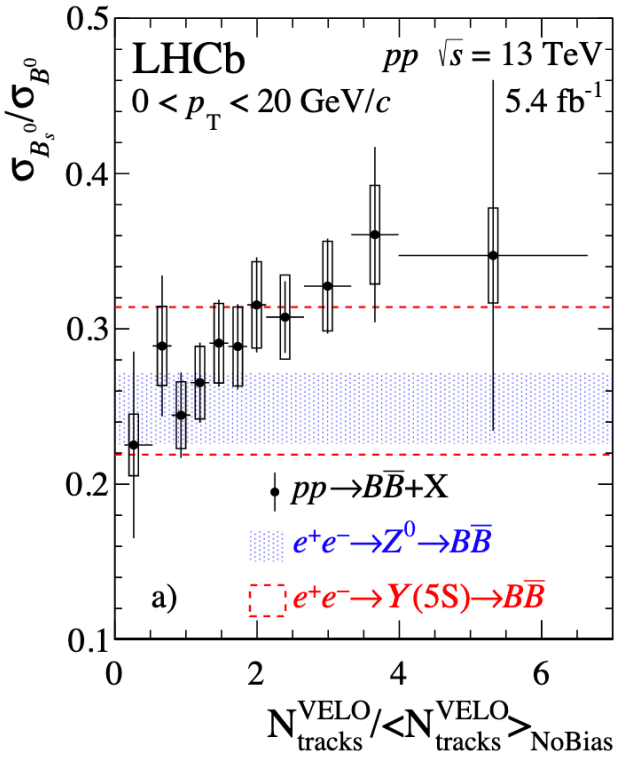
M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007

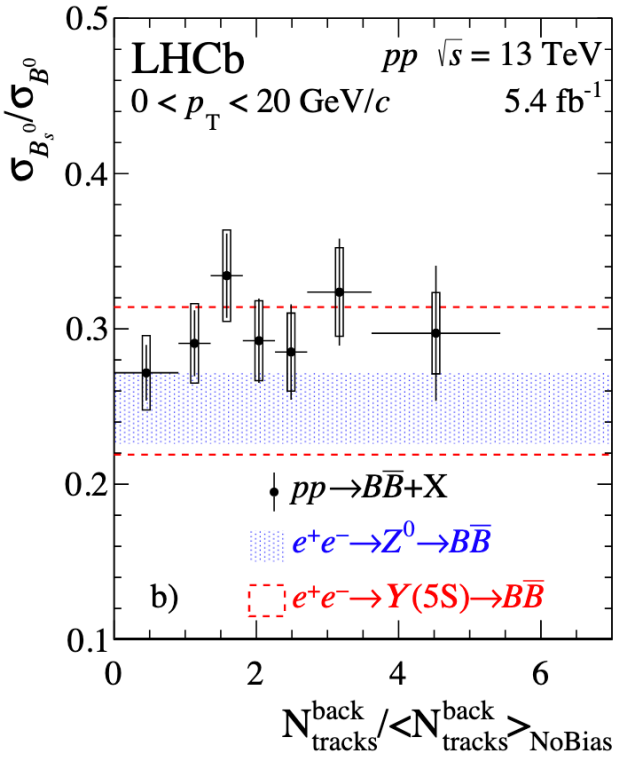


- ALICE discovered universal enhancement of strangeness production in *pp*, *p*Pb, PbPb
  ALICE, Nature Phys. 13 (2017) 535
- More strangeness → less π^0
  → more muons in air showers
  $R \approx 0.41 - 0.45$ (low density)
  $R \approx 0.34$ (high density) (≈ -20 %!)
  arXiv:1902.09265
  arXiv:2202.03095
- Enhancement seems to depend **only** on density of charged particles → predictive power!
- Does it extend forward to $\eta \gg 1$?
  - Data from CMS inconclusive
    CMS, Eur.Phys.J.C 79 (2019) 11, 893
  - Many studies started in LHCb; first results next slide

Forward strangeness enhancement

LHCb-PAPER-2022-001, arXiv:2204.13042

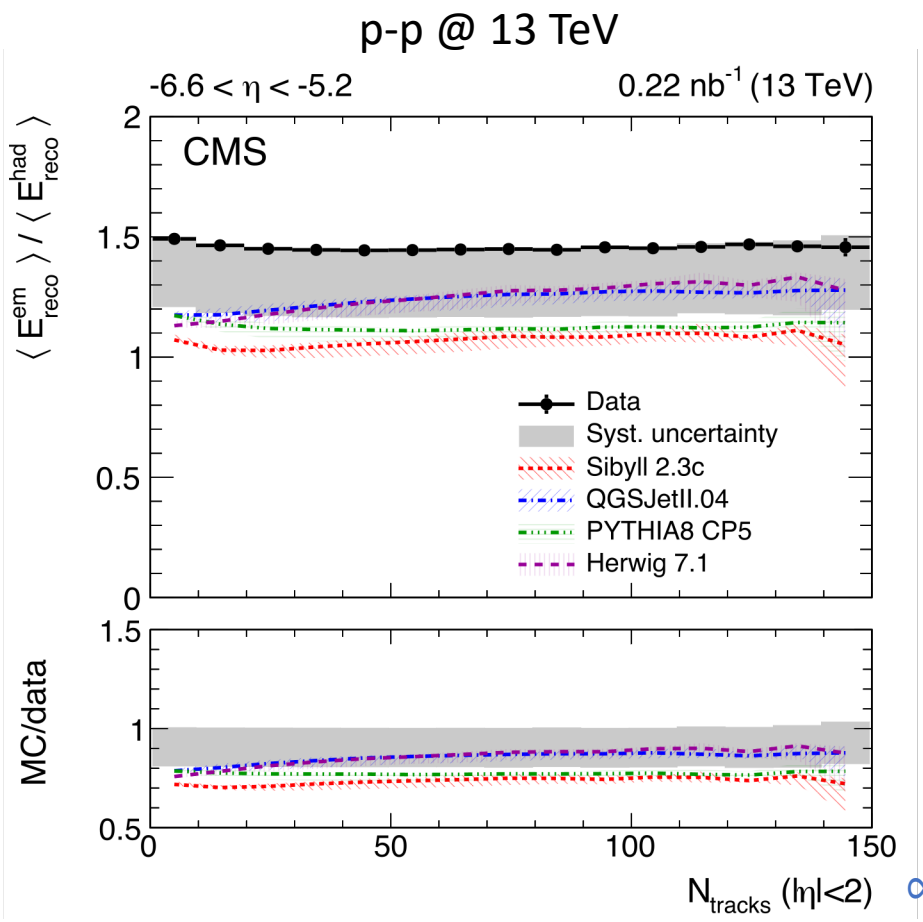




- B_s^0/B^0 ratio proxy for probability ratio to form hadron with ***d* or *s*** quark (*b* quark irrelevant)
- **3.4σ evidence** for multiplicity-dependent strangeness enhancement
- No trend if ratio plotted vs. backward-going tracks
- Effect local in rapidity?

Direct very forward measurement of *R*

CMS, Eur.Phys.J. C79 (2019) no.11, 893



- Ideal measurement for muon puzzle
- Strangeness enhancement should show decline in *R* with $dN_{ch}/d\eta$
- Surprise: Measured R_{reco} value higher than predicted by models in p-p and "flat"! But:
  - Important is p-O and not p-p
  - Systematic uncertainty large...

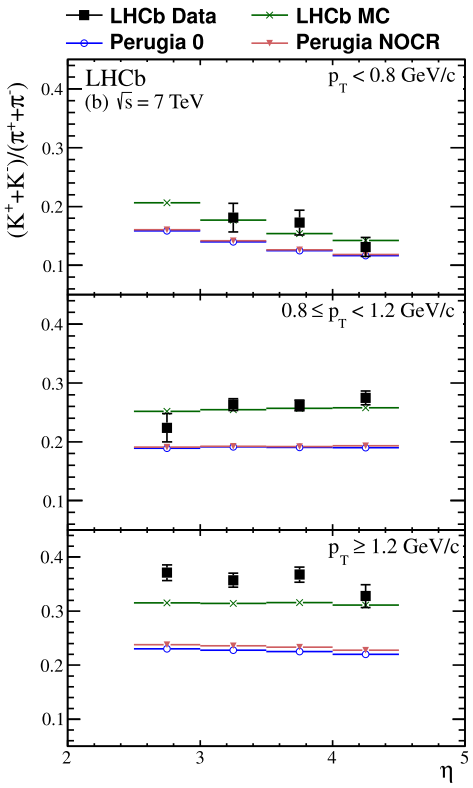
R_{reco} > *R* here, because of detector effects

Forward identified hadron spectra

Hadron ratios

LHCb, EPJC (2012) 72:2168

p-p @ 0.9, 7 TeV



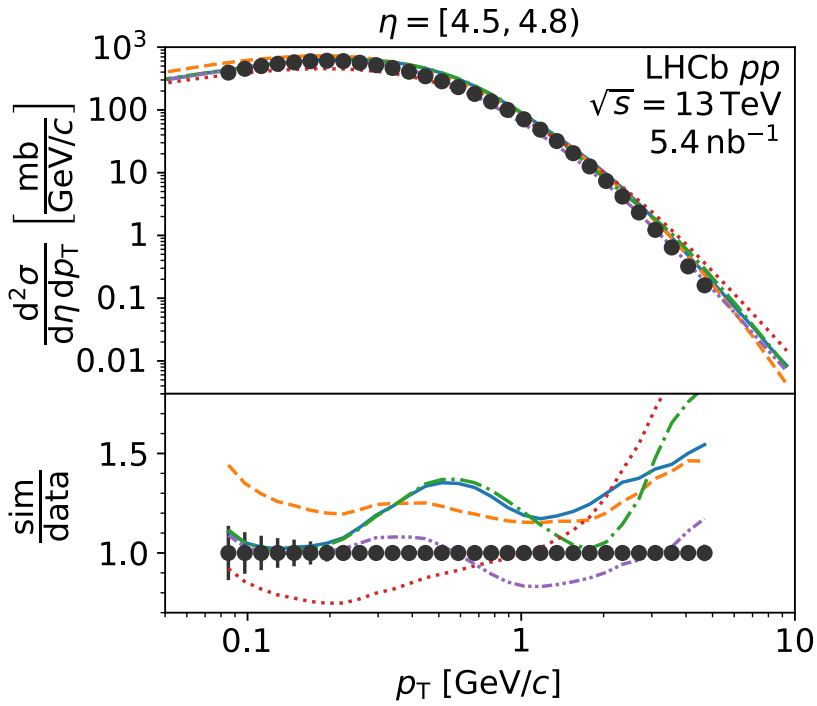
Prompt charged particles

LHCb JHEP 01 (2022) 166

p-p @ 13 TeV

LHCb PRL 128 (2022) 14, 142004

p-p, p-Pb @ 5 TeV



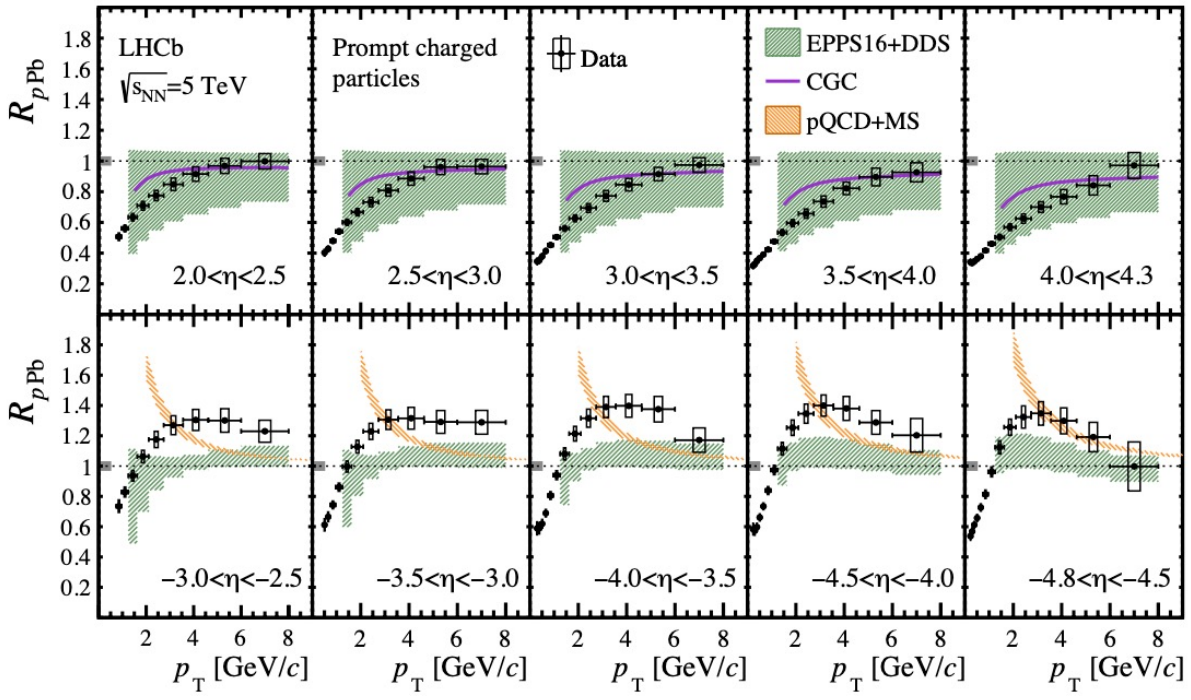
- Just published: precise measurements of charged particle density at 1-2 % level
- *R* constrained by π, K, p ratios measured in p-p at 0.9 and 7 TeV; analysis of 13 TeV data in progress
- Potential of fixed target studies: $\bar{p}$ production in p-He at 0.11 TeV LHCb, PRL 121 (2018) 22, 222001

Forward charged particle production

LHCb PRL 128 (2022) 14, 142004 p-p, p-Pb @ 5 TeV

- Nuclear modification
  - Suppression at small pT in forward region
  - Enhancement in backward region
- Collinear model not consistent with backward region

$$R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{ch}}_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2\sigma^{\mathrm{ch}}_{pp}(\eta, p_{\mathrm{T}})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$



Forward

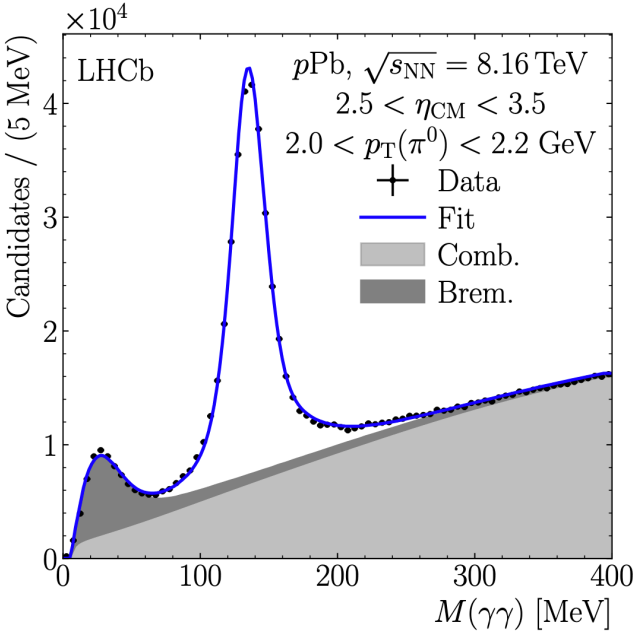
Backward

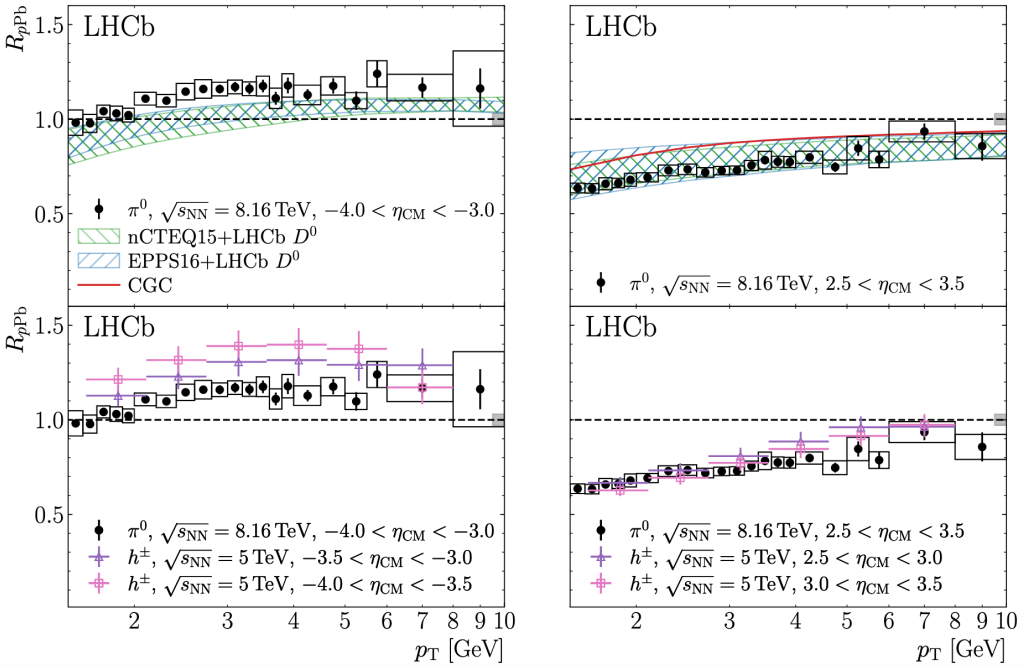
Forward π^0 production

LHCb-PAPER-2021-053, arXiv:2204.10608 pPb 8.16 TeV

Special π^0 reconstruction

- Photon 1 detected in ECal
- Photon 2 detected as converted ee pair
- Better momentum resolution
- No bias from overlapping ECal hits



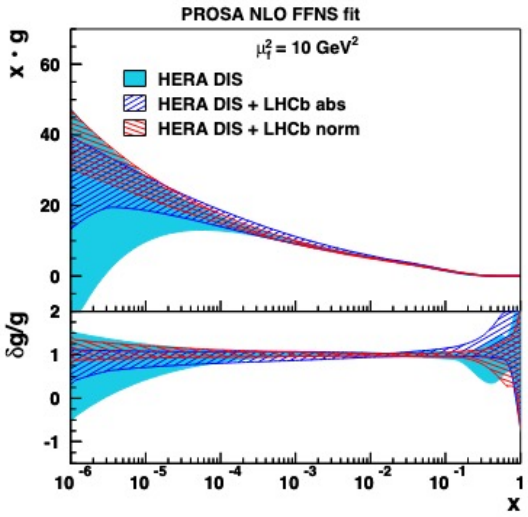


- Total uncertainty < 6 % in most bins
- Forward suppression similar to that of charged particles

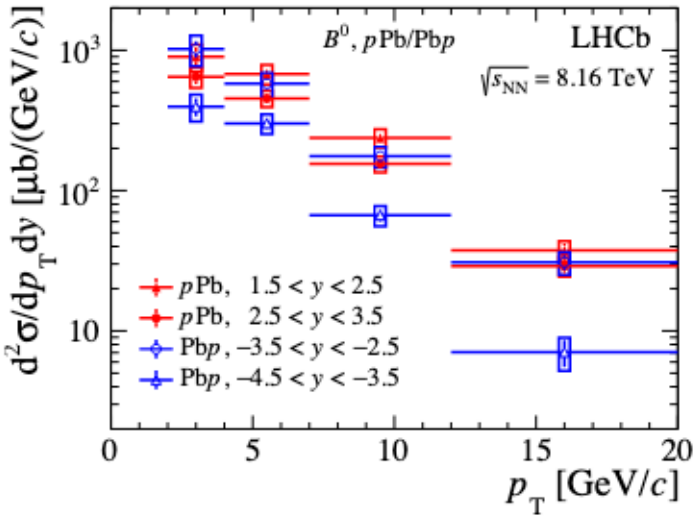
Forward D and B production

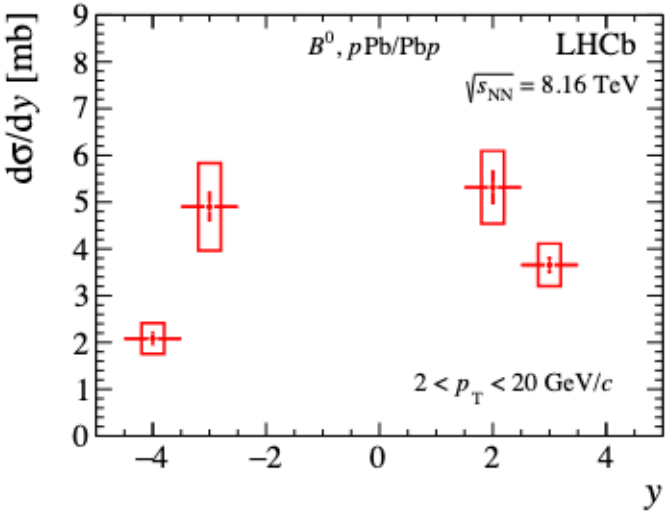
- LHCb designed to study forward heavy-flavor production
- Detailed data on forward D and B meson production
  - Forward open charm production in p-p, p-Pb
    - LHCb: Nucl.Phys.B 871 (2013) 1-20; JHEP 10 (2017) 090; ...
  - Forward open beauty production in p-p, p-Pb
    - LHCb: JHEP 08 (2013) 117, PRL 118 (2017) 5, 052002; PRD 99 (2019) 5, 052011; ...
  - Constraints on gluon PDF in nucleon up to x = 10^{-6}

PROSA, EPJ C 75 (2015) 8, 396



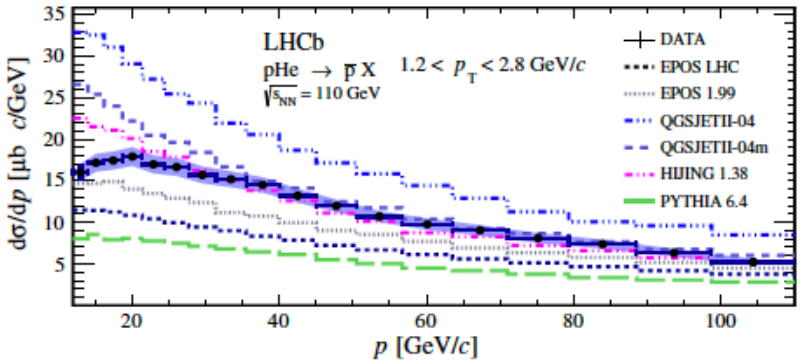
LHCb, PRD 99 (2019) 5, 052011



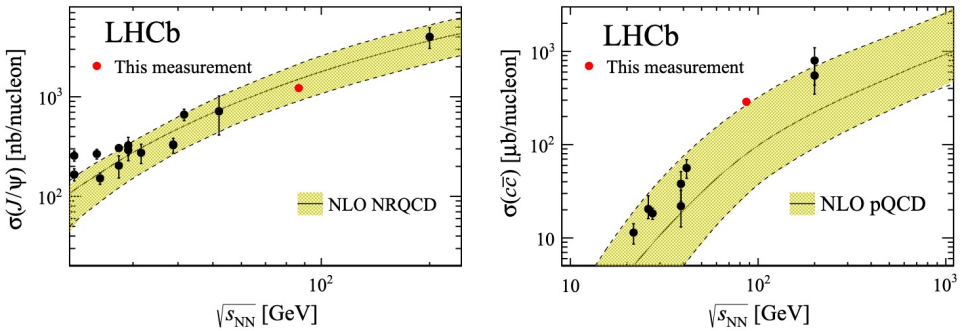


Fixed-target experiments with LHCb

- SMOG device at LHCb
  - Injects noble gas into vertex detector
  - Former precision luminosity record
    LHCb, JINST 9 (2014) P12005
  - Physics potential: Study nuclear effects at $\sqrt{s}$ = 0.1 TeV with different targets

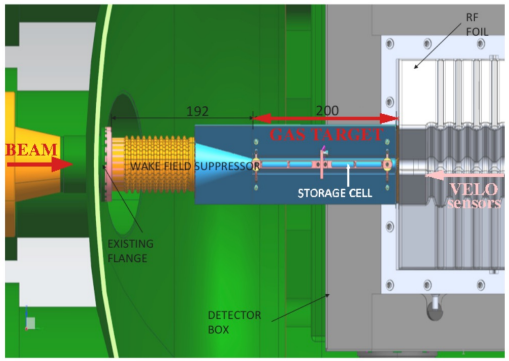


- Anti-proton production in p-He
  - LHCb, PRL 121 (2018) 222001
  - LHCB-PAPER-2022-006-002
  - Used to predict background for DM searches in cosmic $\bar{p}$/p ratio

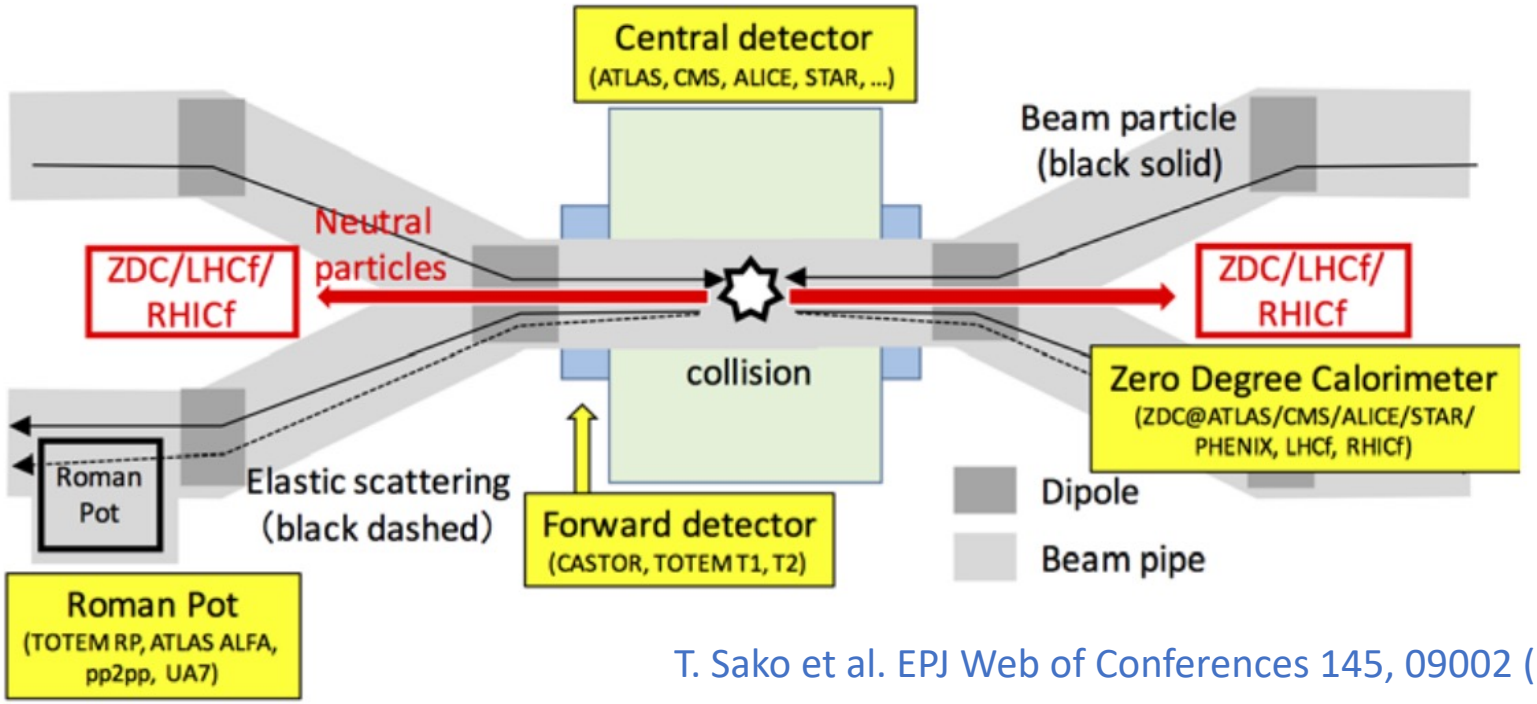


- First look at charm production in p-He, p-Ar
  - LHCb, PRL 122 (2019) 13, 132002
  - Study potential intrinsic charm in proton

- SMOG2 Upgrade for Run 3 CERN-LHCC-2019-005
  - Window-less storage cell
  - Well-controlled gas density, 100x higher
  - Non-noble gases possible: oxygen, nitrogen!



Zero-degree measurements



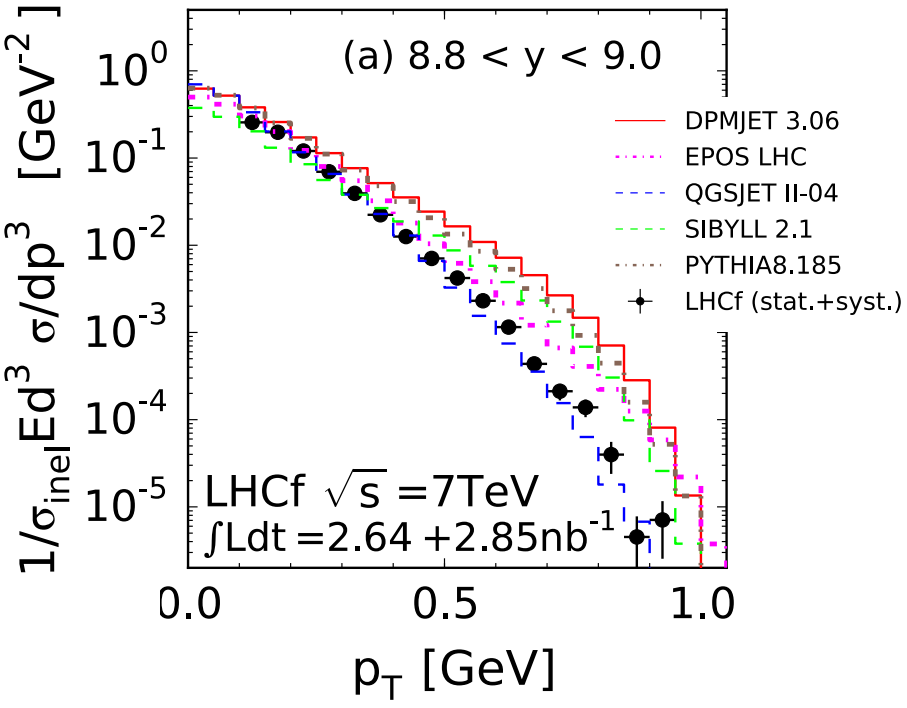
T. Sako et al. EPJ Web of Conferences 145, 09002 (2017)

- LHCf: zero degree calorimeters ($\eta > 8$) around ATLAS to detect neutral particles
- RHICf: Similar detector at RHIC to study p-p at 0.51 TeV PoS(ICRC2021)301

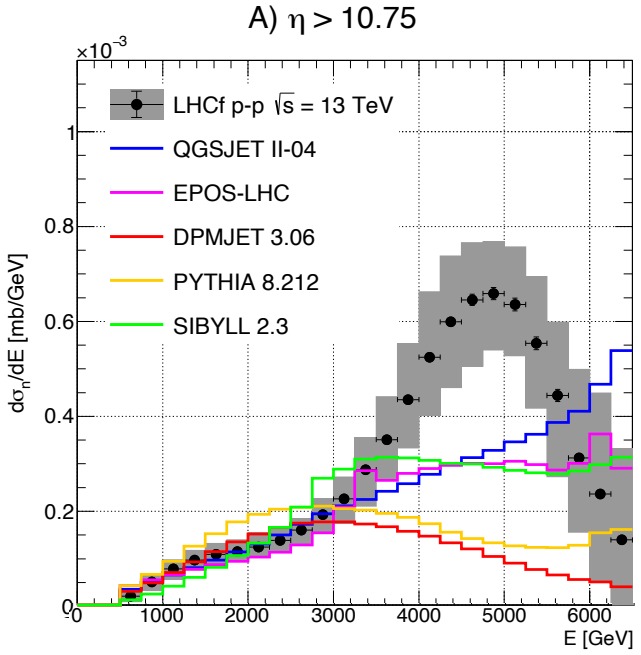
Zero-degree measurements with LHCf

- LHCf constraints R by photon, π^0, neutron production cross-sections in p-p, p-Pb
  - LHCf, PRD 94 (2016) 3, 032007, LHCf, JHEP 07 (2020) 016, ...
- Plans to study strangeness production via $K^0_S \longrightarrow 4\gamma$ in Run 3 PoS(ICRC2021)301

LHCf, PRD 94 (2016) 3, 032007
π^0 production in p-p @ 7 TeV



LHCf, JHEP 07 (2020) 016
neutron production in p-p @ 13 TeV



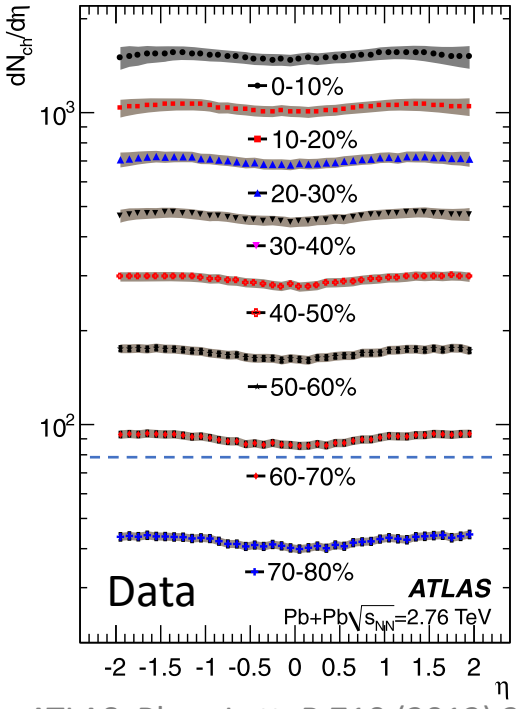
Summary & outlook

J. Albrecht, HD, et al., Astrophys. Space. Sci. **367,** 27 (2022)

- Cosmic-ray induced air showers are driven by hadronic cascades
- Primarily need reference data at y = 4 to 10 for air showers
- LHC/SPS experiments provide important reference data
  - Extremely precise pp cross-section
  - NA61/SHINE results on ρ^0 and anti-p production in π-C
  - ALICE and LHCb results on strangeness enhancement
  - LHCb precision results on forward prodution of long-lived hadrons and π^0
  - LHCf results on π^0 and neutron production, neutron-elasticity
- LHC data show QCD factorization breaking effects important for air showers
- **Collaborative Research Center 1491** (Dortmund, Bochum, Wuppertal) funded
  - Fully exploit LHCb data
  - Tune generators used in astroparticle simulations with collider and air shower data
- LHC outlook
  - Measurements with p-O collisions in 2023/24
  - Forward strangeness production with LHCf
  - Forward physics facility (FPF)
  - FoCal, forward calorimeter for ALICE
  - Forward calorimeter for LHCb?

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