# Input from LHCb towards understanding air showers

Hans Dembinski, TU Dortmund

# Overview

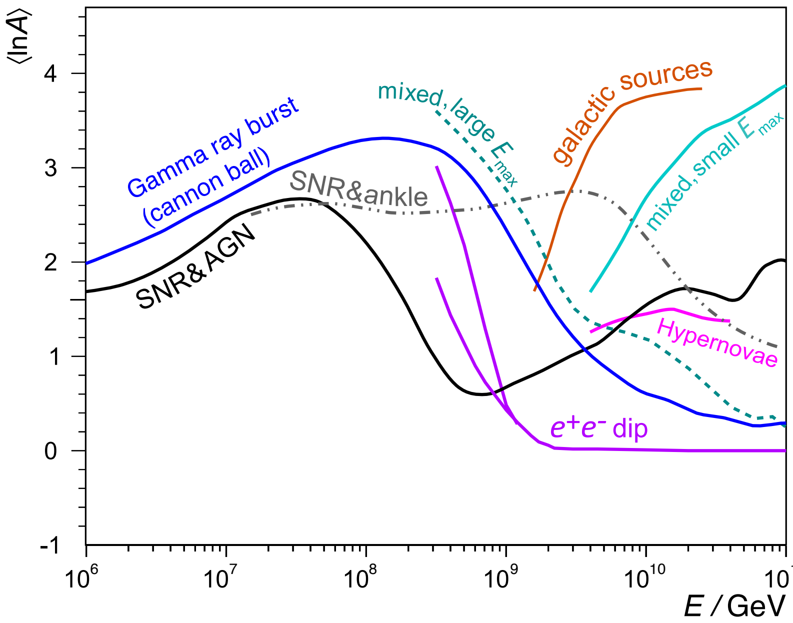
- Muon Puzzle in high-energy cosmic rays
  - Muon production not correctly described in simulations
  - 8$\sigma$ deviation between world data and leading models

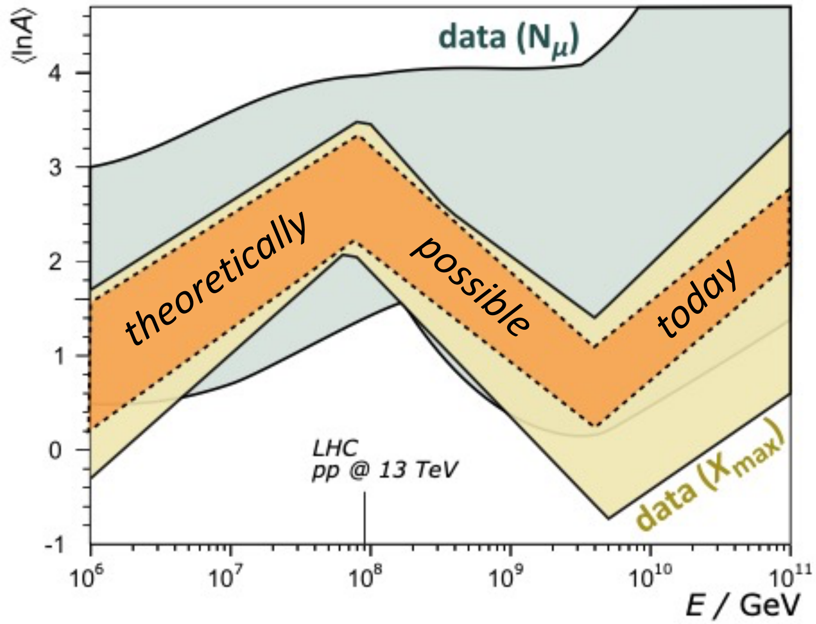
- Muon Puzzle suggests mismodeling of soft-QCD
  - Soft-QCD is based on Gribov-Regge theory and phenomenology
  - Muon Puzzle suggests "new physics" in soft QCD sector
    - QGP formation in small systems or …?

- LHCb ideally suited to address air shower issues
  - Forward spectrometer with particle identification capabilities
  - Can run in fixed-target mode at $\sqrt{s}$ = 110 GeV with He, Ne, Ar gas
    - Anti-proton flux measurement in *p*-He
  - Several other QCD measurements available
  - Studies underway of forward hadron production in *pp @ 13 TeV*, *p*-Pb @ 8.2 TeV
    - Light hadron production
    - Nuclear effects
    - Ratio of electromagnetic and hadronic energy flow is a key variable
  - Study of nuclear effects essential with *p*-O @ 10 TeV in 2023

# CR mass composition

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




Astrophysical origins of cosmic rays?

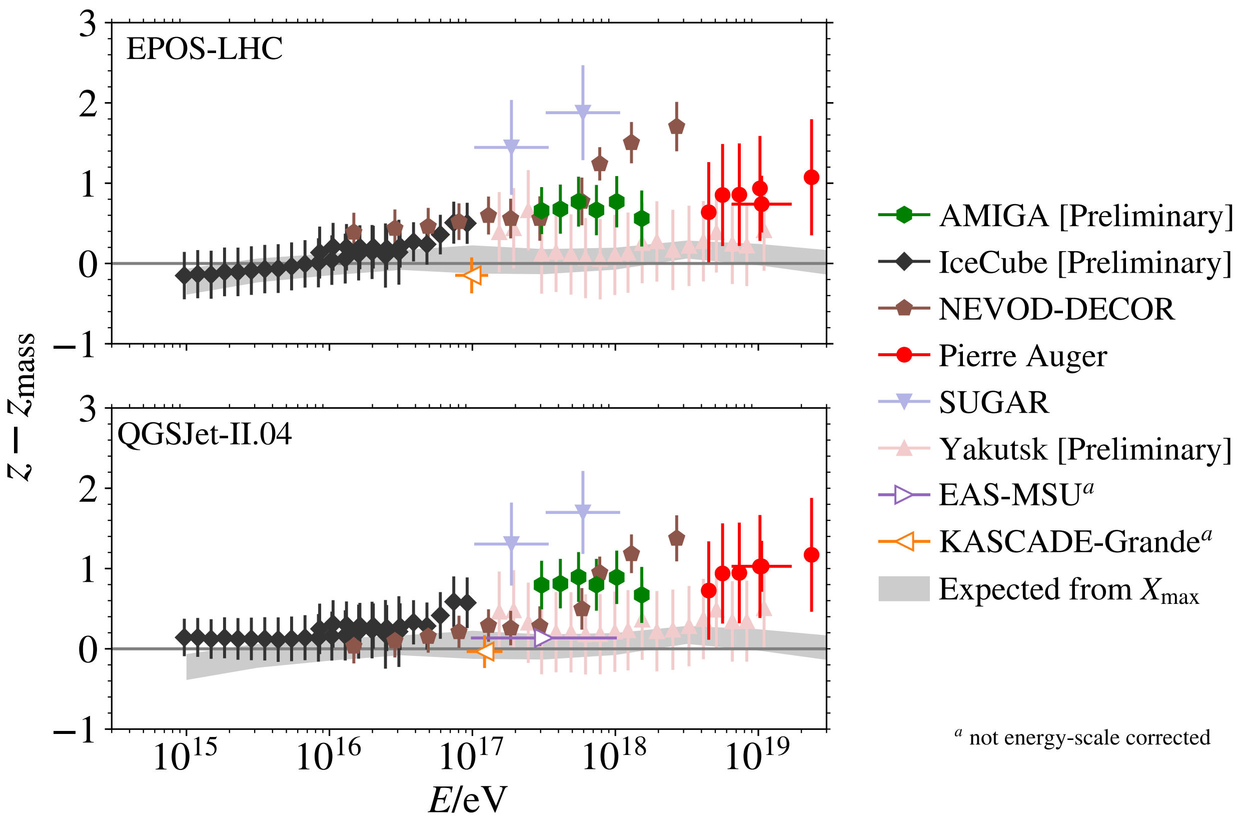
- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
- Uncertainties of <lnA> limited by uncertainty in description of hadronic interactions
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with $X_{max}$

- Air shower experts connected inconsistencies to hadronic interaction properties
- Collider community needs to provide dedicated reference measurements

# Muon deficit in simulated showers

HD et al. for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array collaborations, EPJ Web of Conferences **210**, 02004 (2019)

- Converted very diverse measurements from individual experiments into z-values
- Cross-calibrated energy scales of experimented by matching fluxes (main systematic)

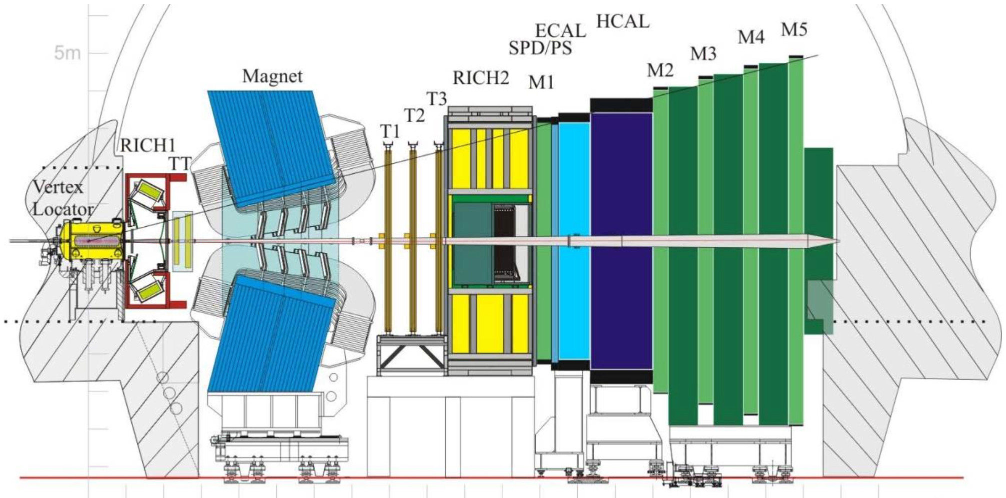


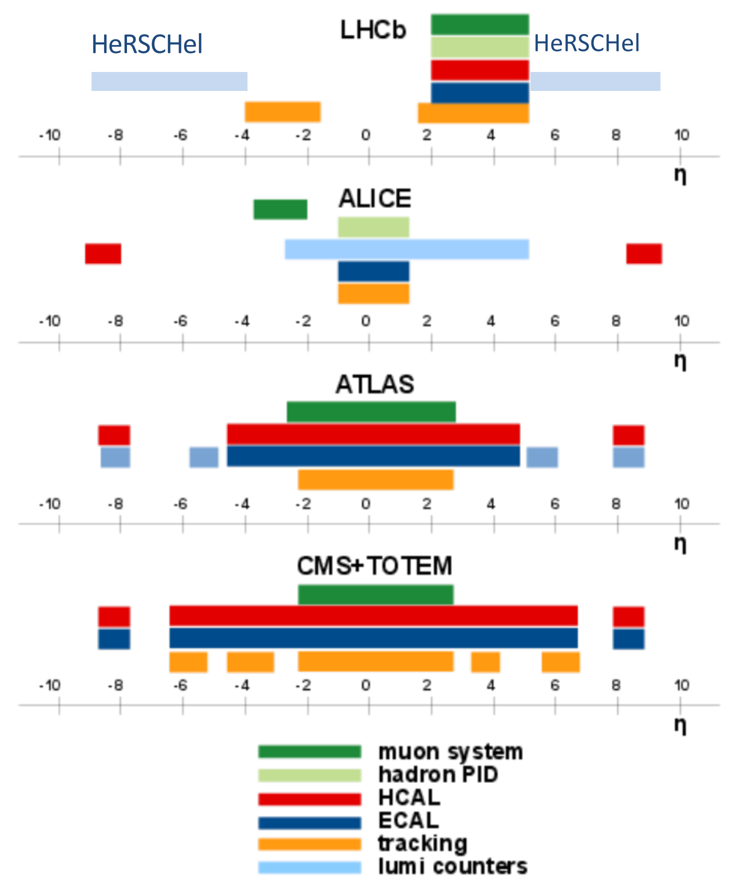

$$z = \frac{\ln N_\mu - \ln N_{\mu,p}^{\mathrm{sim}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{sim}} - \ln N_{\mu,p}^{\mathrm{sim}}}$$

- Slope is non-zero at 8σ
- Deficit in air shower simulations starting around 4 x $10^{16}$ eV or $\sqrt{s}$ ~ **8 TeV**

# LHCb detector

JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022

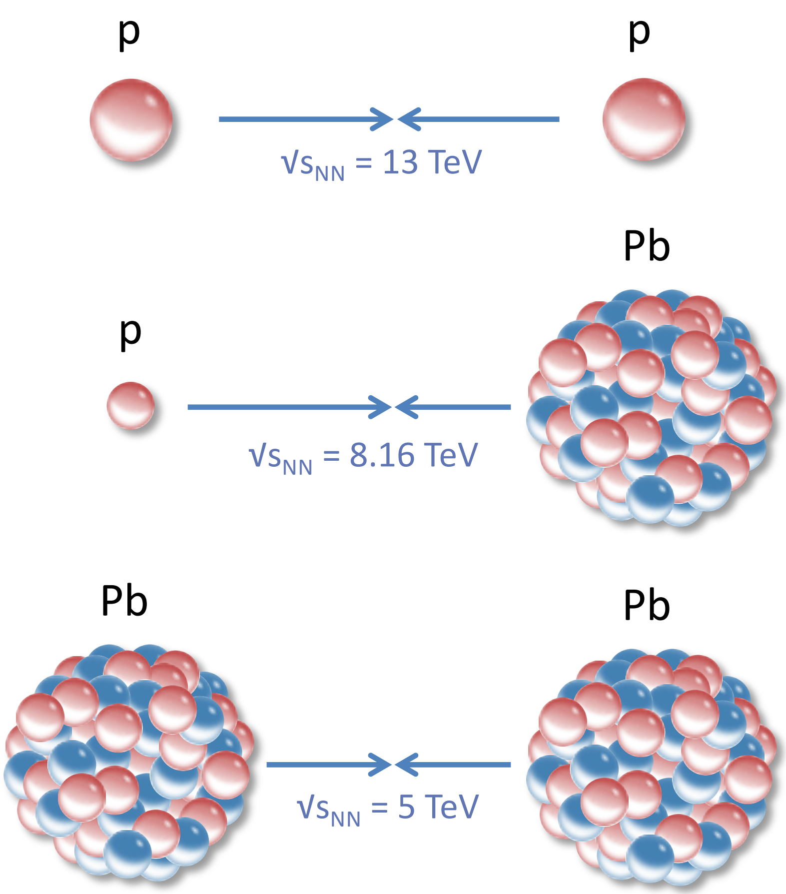


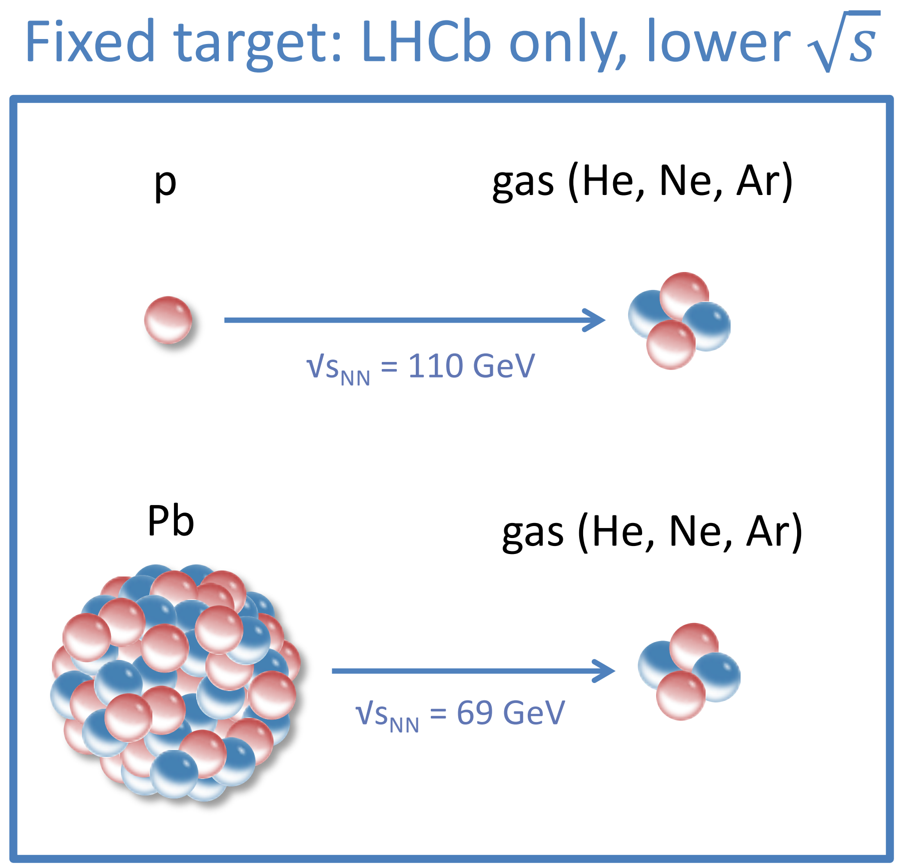

**Single-arm forward spectrometer**

- Fully instrumented at $2 < \eta < 5$
- Very good momentum and vertex resolution
- Good particle identification
- **Optimal**: $\mu$, p, $K^{+-}$, $\pi^{+-}$

# Collisions at the LHC




Short Xe-Xe run in 2017




**Planned**: *p*-O and O-O runs in 2023

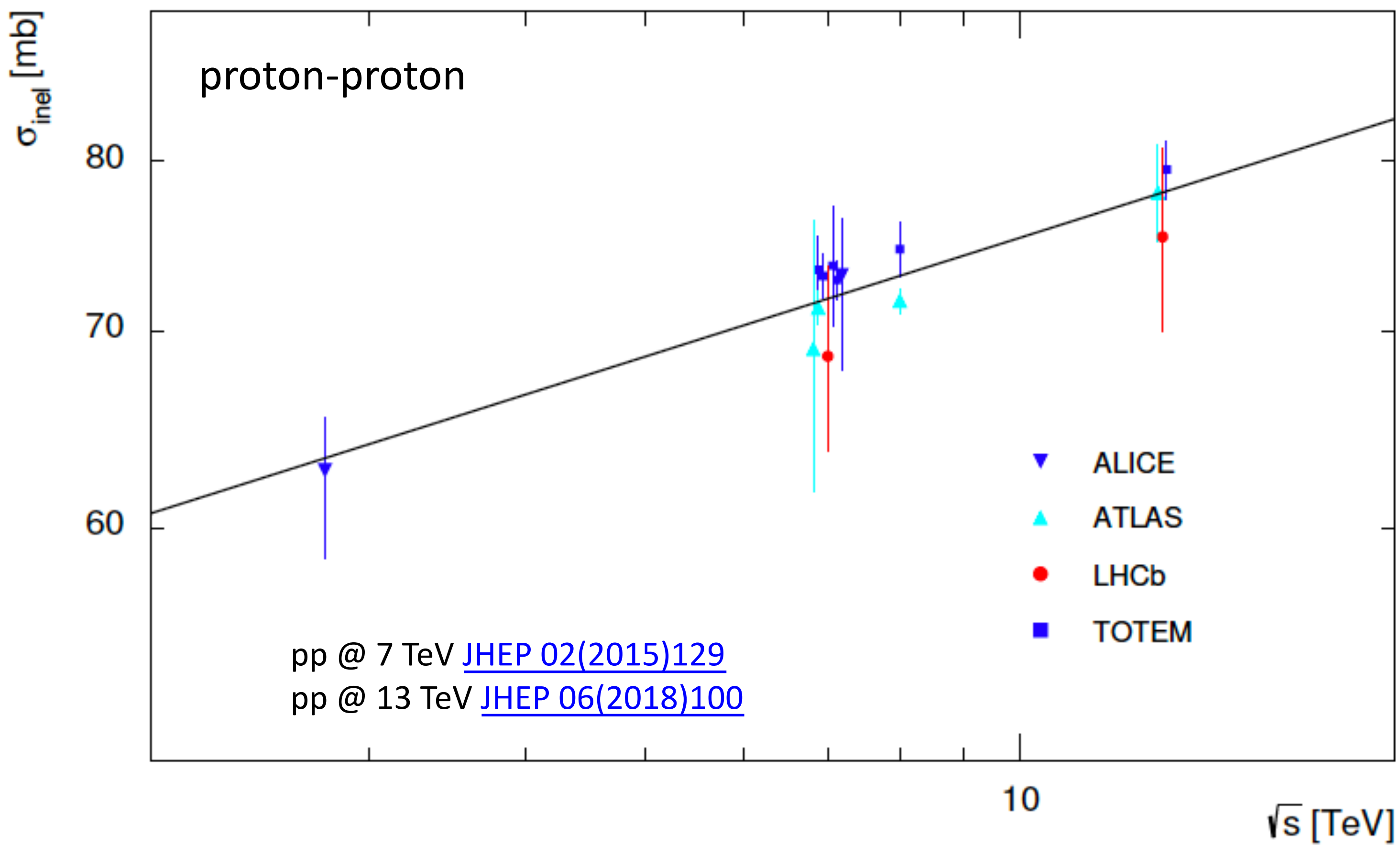
# LHCb and astroparticles

- Heavy flavor contribution to atmospheric lepton flux
  - LHCb measured production cross-sections of c- and b-hadrons
- Anti-proton flux tension
  - LHCb measured anti-proton production cross-section in $p$-He, exploiting opportunity offered by SMOG
  - Results published in PRL
- Further opportunities for cosmic-ray induced air showers

# Related LHCb measurements

- **Inelastic cross-section**
  - pp @ 7 TeV JHEP 02(2015)129
  - pp @ 13 TeV JHEP 06(2018)100
- Charged particle multiplicities
  - pp @ 7 TeV EPJ C (2012) 72:1947
  - pp @ 7 TeV EPJ C (2014) 74:2888
- Energy flow
  - pp @ 7 TeV EPJ C (2013) 73:2421
- Prompt hadron production ratios
  - pp @ 0.9, 7 TeV EPJ C (2012) 72:2168
- **Anti-proton production**
  - pHe @ 110 GeV PRL 121 (2018) 222001
- Long-range near-side angular correlation
  - pPb @ 5 TeV PLB 762 (2016) 473-483
- $K_s^0$ production (s-hadron production)
  - pp @ 0.9 TeV PLB 693 (2010) 69-80
- $\phi$ production (s-hadron production)
  - pp @ 7 TeV PLB 703 (2011) 267-273
- $J/\psi$ production (c-hadron production)
  - pPb @ 5 TeV JHEP 02(2014)072
- $D^0$ production (c-hadron production)
  - pPb @ 5 TeV JHEP 10(2017)090
- $\Lambda_c^+$ production (c-hadron production)
  - pPb @ 5 TeV JHEP 02(2019)102
- $\psi(2S)$ production (c and b-hadron production)
  - pPb @ 5 TeV JHEP 03(2016)133
- $B^+$, $B^0$, $\Lambda_b^+$ production (b-hadron production)
  - pPb @ 8.2 TeV PRD 99(2019)052011
- $\Upsilon$ production (b-hadron production)
  - pPb @ 5 TeV JHEP 07(2014)094
  - pPb @ 8 TeV JHEP 11(2018)194

# Inelastic cross-section



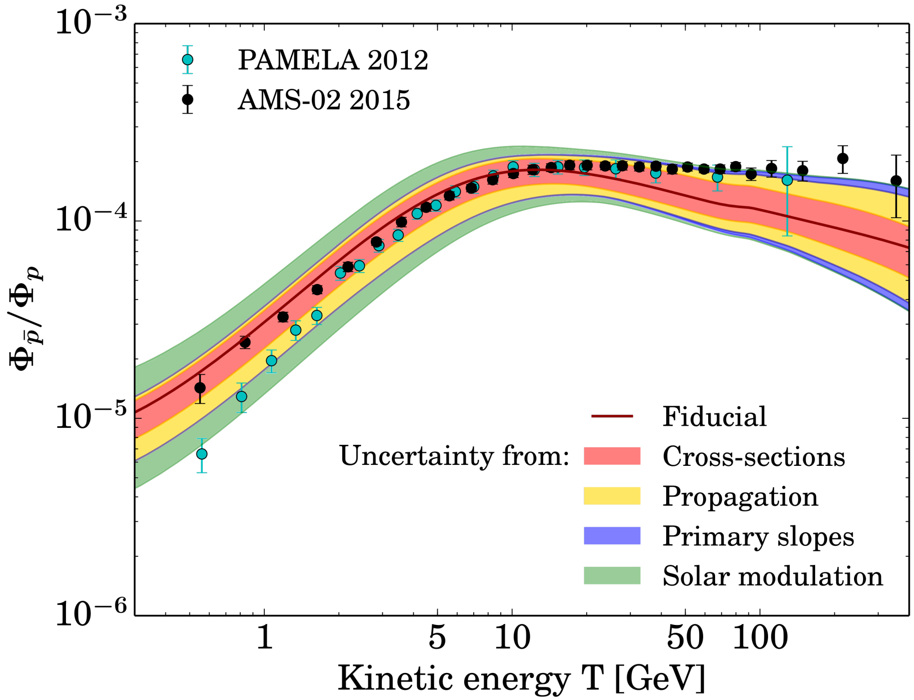

LHCb: $\sigma_{\rm inel}(\sqrt{s} = 13\,{\rm TeV}) = 75.4 \pm 3.0({\rm exp}) \pm 4.5({\rm extr})\,{\rm mb}$

dominated by 4 % luminosity uncertainty

Sizeable extrapolation uncertainty from visible to inelastic cross-section due to LHCb acceptance

# Secondary anti-proton flux

*JCAP 1509 (2015) no.09, 023*

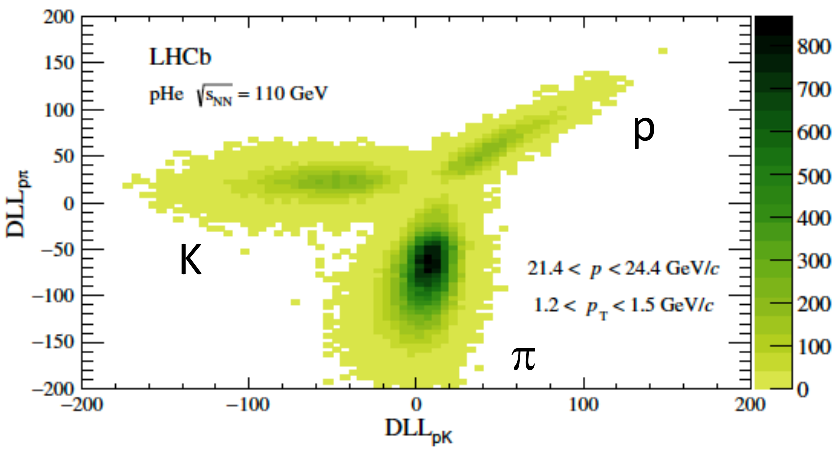


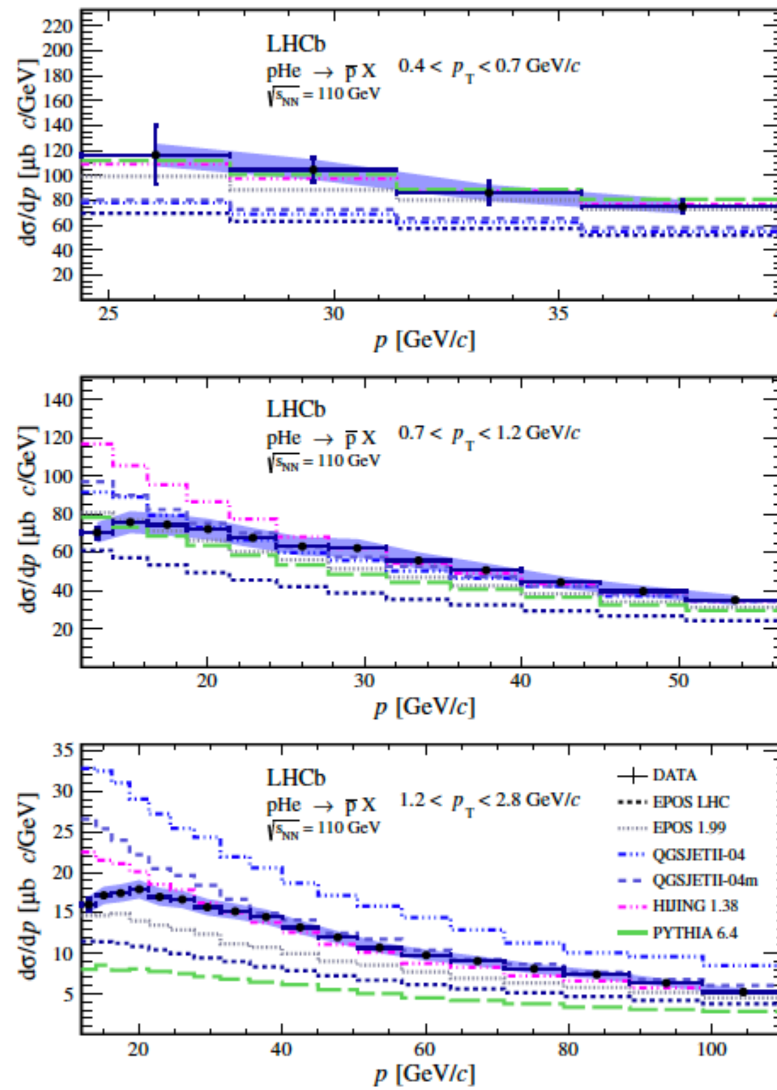

- Anti-proton flux
  - Expected from collisions of cosmic ray protons with interstellar medium (ISM)
  - Excess observed
- Anti-proton production cross-section uncertain
  - ISM 91 % p, 9 % He
  - $pp \rightarrow \bar{p} + X$ **OK**
  - $p\mathrm{He} \rightarrow \bar{p} + X$
    first direct measurement by LHCb

# Anti-proton production in *p*He(gas)

*LHCb collab. PRL 121 (2018) 222001*

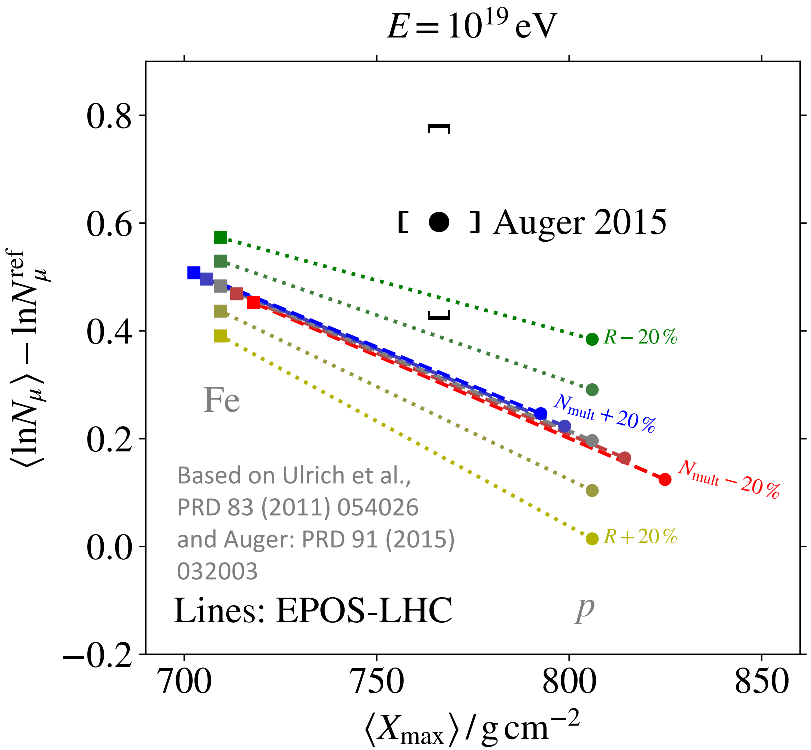
- Excellent anti-proton separation with multivariate LHCb PID
- Precise normalization of cross-section
  - Reference: single electon-scattering p+e(gas)
  - Only 6 % uncertainty
- Total uncertainty < 10 % for most bins
- Model variation up to factor 2

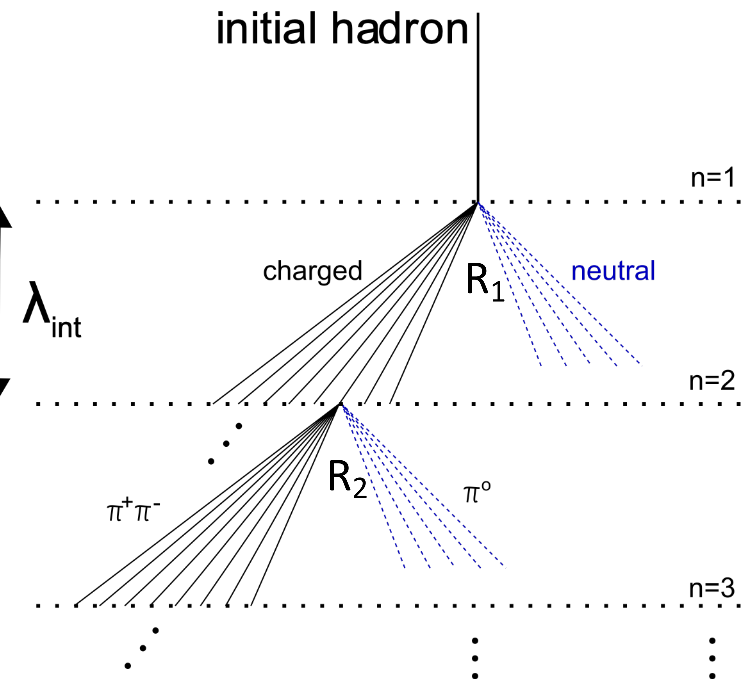


# Impact of LHC measurements

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026
S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265




- $X_{max}$ sensitive to: inel. cross-section, hadron multiplicity
- $N_\mu$ sensitive to: **energy ratio R**, hadron multiplicity
- **Strong nuclear modification in forward-produced hadrons**

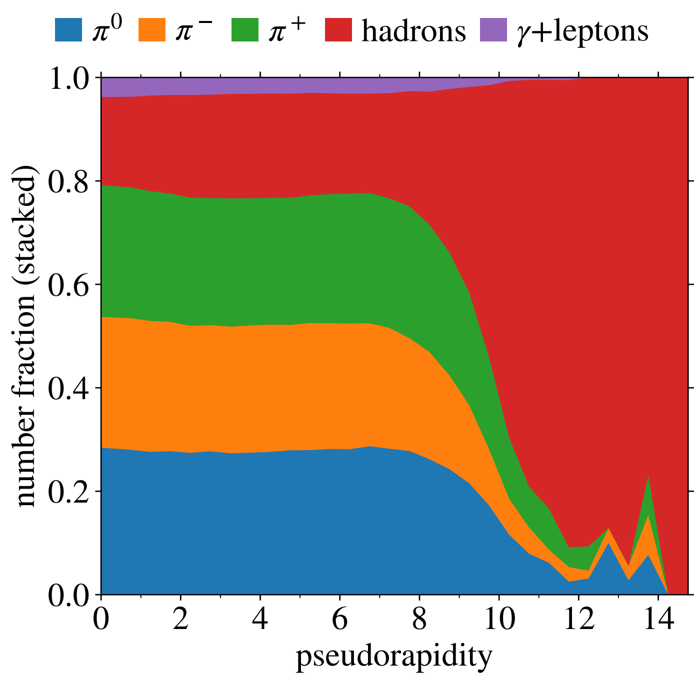
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

needs to be known to 5 %

# 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 enhanced in hadron-nuclear collisions, reducing π yield?

*pp 13 TeV, EPOS-LHC*



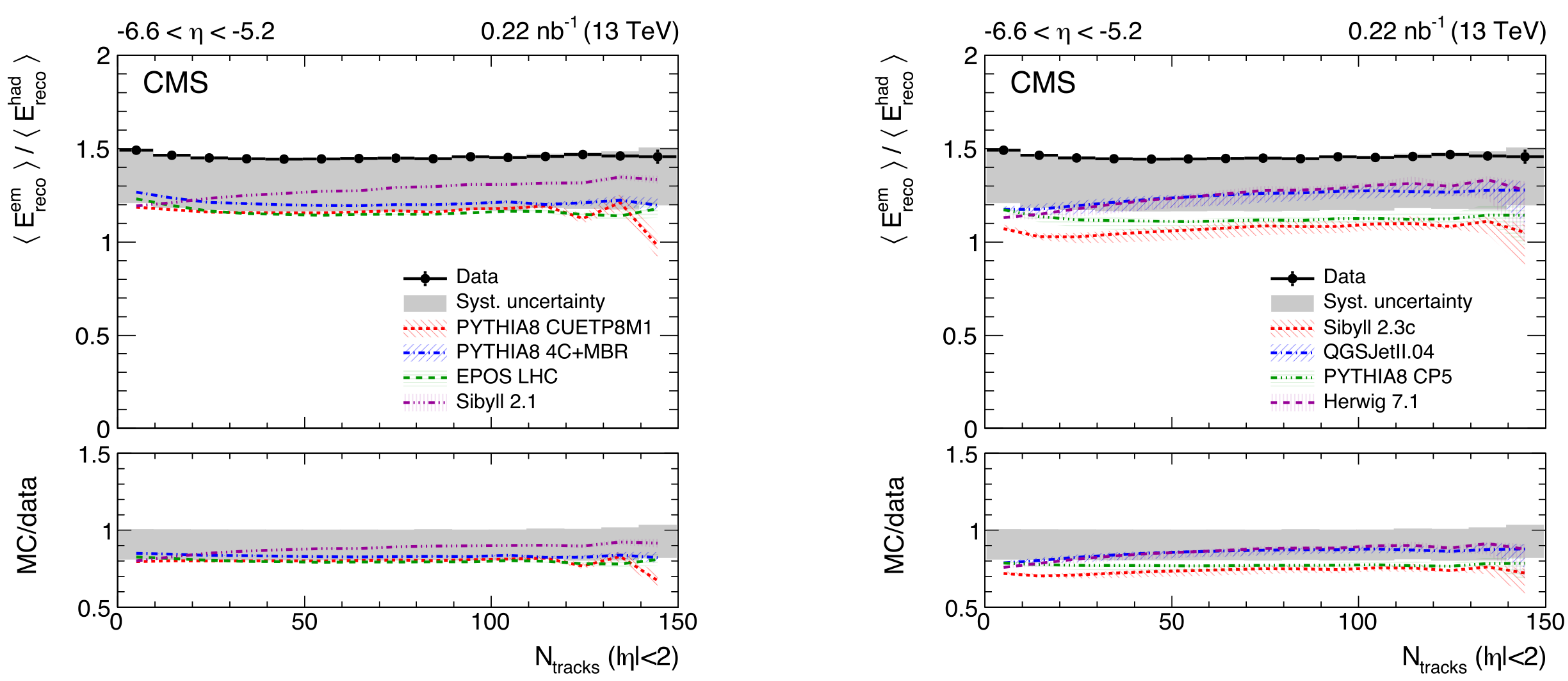

Collective effects may reduce pion fraction, EPOS-LHC predicts drop in *R* at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

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*

# *R* in models seems too low in pp

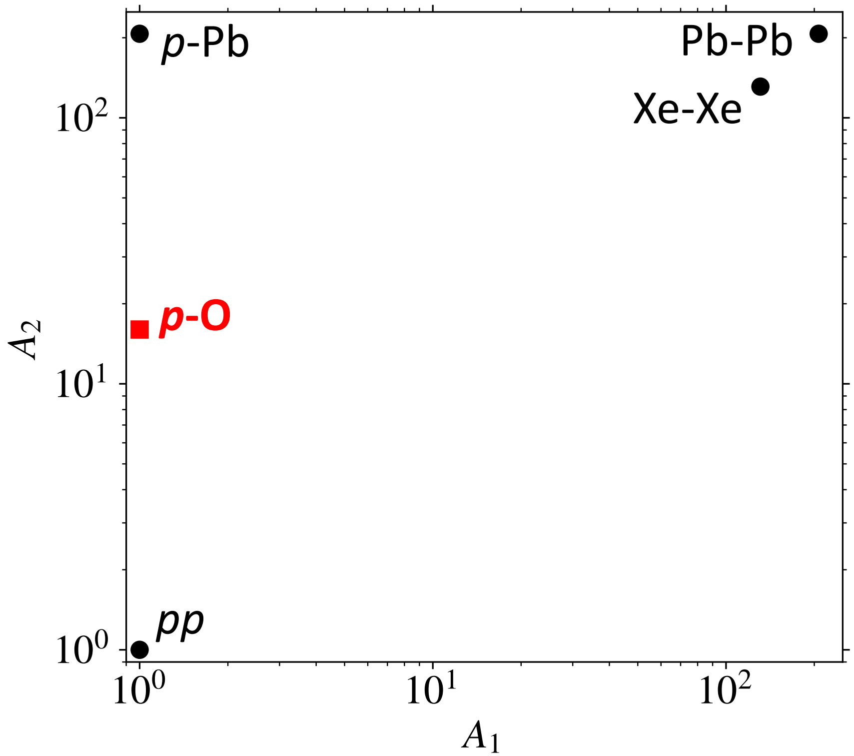
*pp @ 13 TeV* *CMS collab. Eur.Phys.J. C79 (2019) no.11, 893*



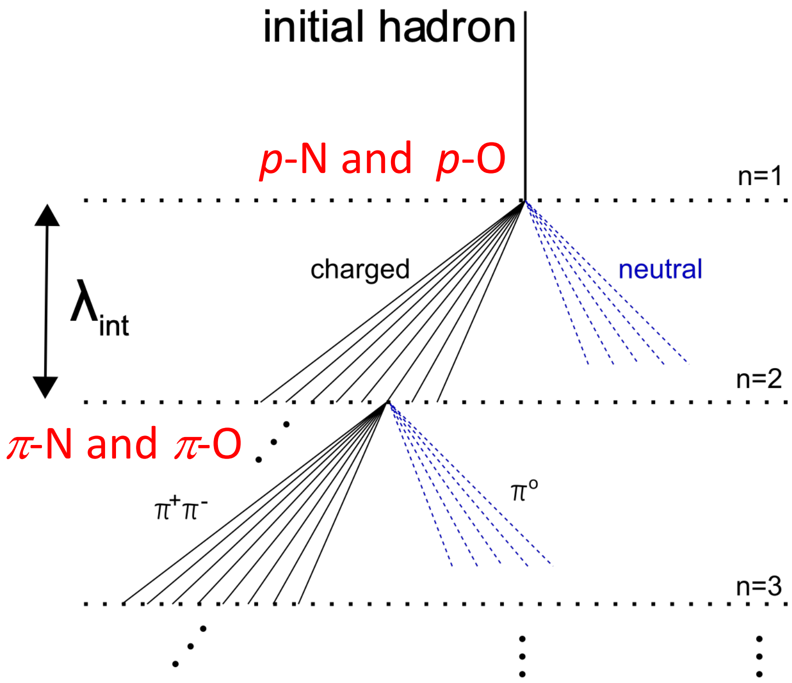

- CMS measurements give higher R than models for 5.2 < |eta| < 6.6
- Models should have higher R and should yield even fewer muons!
- Evidence points to nuclear effects

# Collisions at the LHC and air showers

Collision systems at the LHC



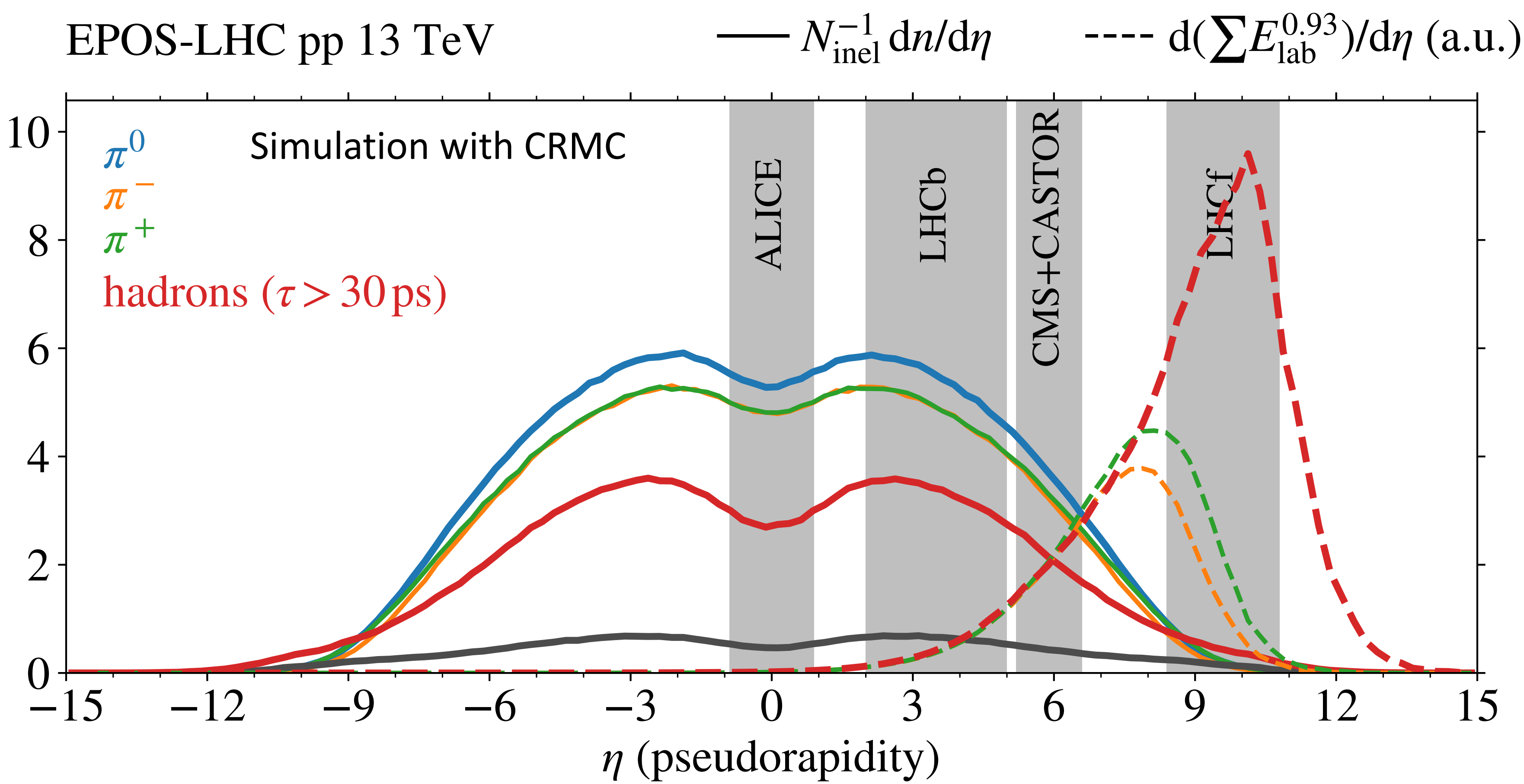

Air shower collision systems




- *p*-O collisions mimic air shower interactions
- Need *pp*, *p*-Pb, and *p*-O to understand nuclear effects

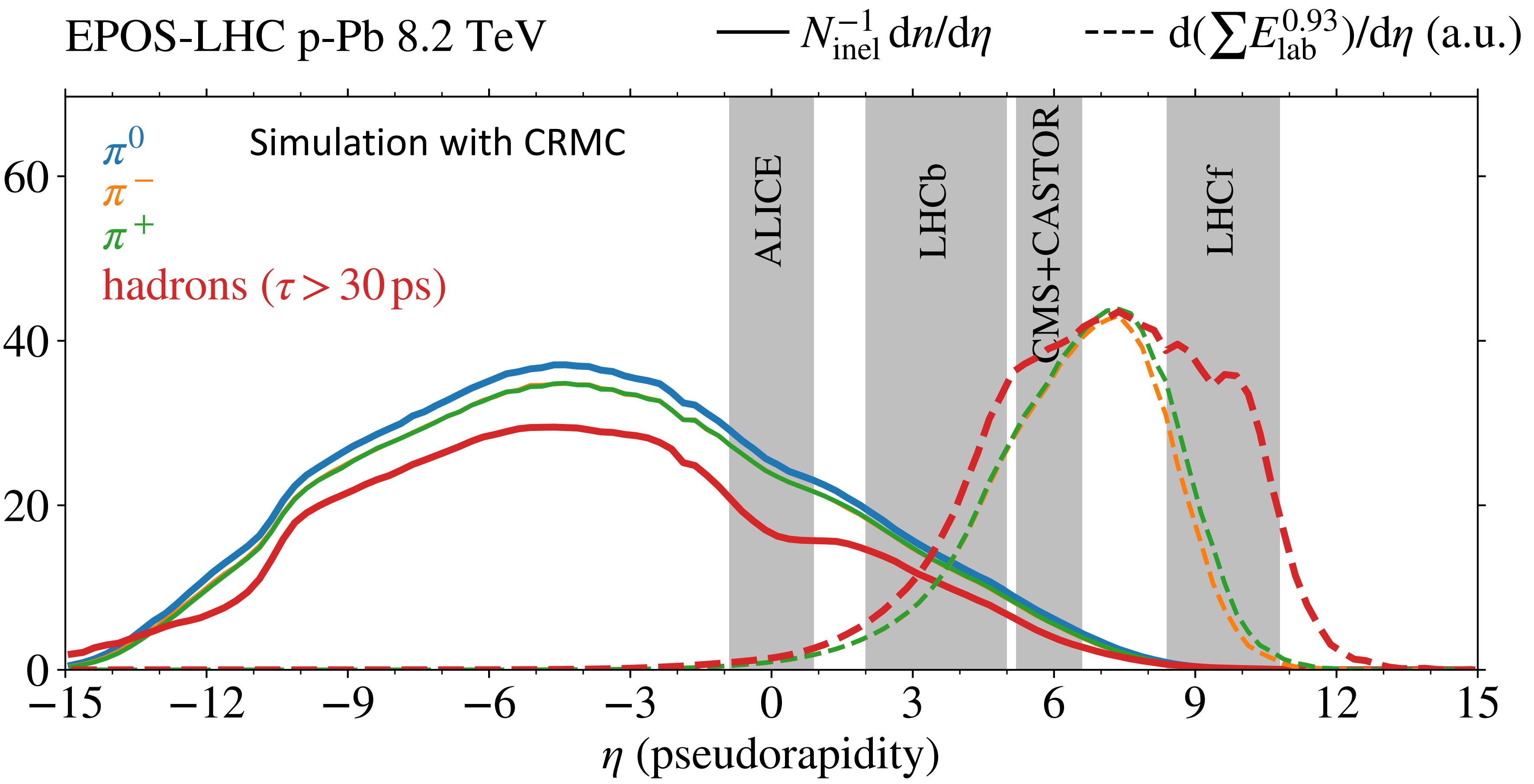
# Forward production pp

„Muon weight“



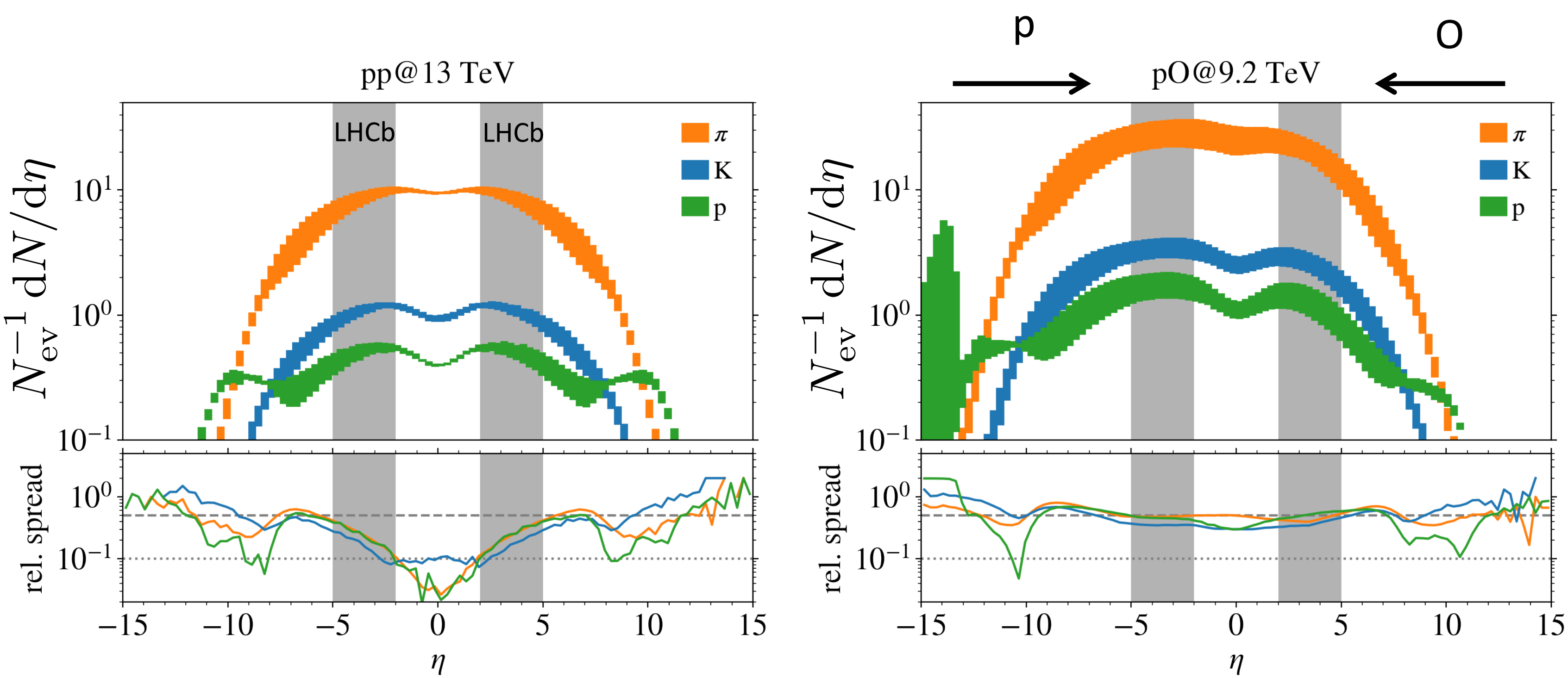
# Forward production pPb

„Muon weight“



# Model variation in hadron spectra

- Simulations done with CRMC
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3




- Models mostly tuned to *pp* data at |η| < 2
- *pp* 10 % model spread, but 50 % spread at eta = 5
- 50 % spread also in *p*-O

# Proton-oxygen collisions at the LHC

CERN Yellow Report
Z. Citron et al., *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*
https://doi.org/10.23731/CYRM-2019-007.1159

| Year | Systems, $\sqrt{s_{NN}}$ | Time | $L_{int}$ |
|---|---|---|---|
| 2021 | Pb–Pb 5.5 TeV | 3 weeks | 2.3 $nb^{-1}$ |
| | pp 5.5 TeV | 1 week | 3 $pb^{-1}$ (ALICE), 300 $pb^{-1}$ (ATLAS, CMS), 25 $pb^{-1}$ (LHCb) |
| 2022 | Pb–Pb 5.5 TeV | 5 weeks | 3.9 $nb^{-1}$ |
| | O–O, p–O | 1 week | 500 $\mu b^{-1}$ and 200 $\mu b^{-1}$ |
| 2023 | p–Pb 8.8 TeV | 3 weeks | 0.6 $pb^{-1}$ (ATLAS, CMS), 0.3 $pb^{-1}$ (ALICE, LHCb) |
| | pp 8.8 TeV | few days | 1.5 $pb^{-1}$ (ALICE), 100 $pb^{-1}$ (ATLAS, CMS, LHCb) |
| 2027 | Pb–Pb 5.5 TeV | 5 weeks | 3.8 $nb^{-1}$ |
| | pp 5.5 TeV | 1 week | 3 $pb^{-1}$ (ALICE), 300 $pb^{-1}$ (ATLAS, CMS), 25 $pb^{-1}$ (LHCb) |
| 2028 | p–Pb 8.8 TeV | 3 weeks | 0.6 $pb^{-1}$ (ATLAS, CMS), 0.3 $pb^{-1}$ (ALICE, LHCb) |
| | pp 8.8 TeV | few days | 1.5 $pb^{-1}$ (ALICE), 100 $pb^{-1}$ (ATLAS, CMS, LHCb) |
| 2029 | Pb–Pb 5.5 TeV | 4 weeks | 3 $nb^{-1}$ |
| Run-5 | Intermediate AA | 11 weeks | e.g. Ar–Ar 3–9 $pb^{-1}$ (optimal species to be defined) |
| | pp reference | 1 week | |

- 200 $\mu b^{-1}$ is enough statistics to push statistical error below 5 % in LHCb
- 2 $nb^{-1}$ (10 x minimum) will be requested, also allows to measure charm
- Latest plans moved oxygen-week to 2023

# Summary

- Muon Puzzle suggests mismodeling of soft-QCD
- LHC + LHCb great for studying forward production
- Many LHCb measurements relevant for astroparticle physics
  - Production cross-sections for b- and c-hadrons
  - Light hadron production cross-sections
  - Anti-proton production cross-section in *p*-He
- LHCb data has potential to solve Muon Puzzle
  - Ongoing
    - Light hadron production cross-sections in pp @ 13 TeV and pPb @ 8.2 TeV
  - Planned
    - Study *p*-O @ 10 GeV in 2023
    - Use CORSIKA 8 to compute effect of LHCb data on air showers ($X_{max}$, $N_{\mu}$)