UNIÓN EUROPEA
FONDO EUROPEO DE DESENVOLVEMENTO REXIONAL
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Xacobeo 2021 galicia

Charged hadron production at LHCb

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28/07/2021
EPS-HEP

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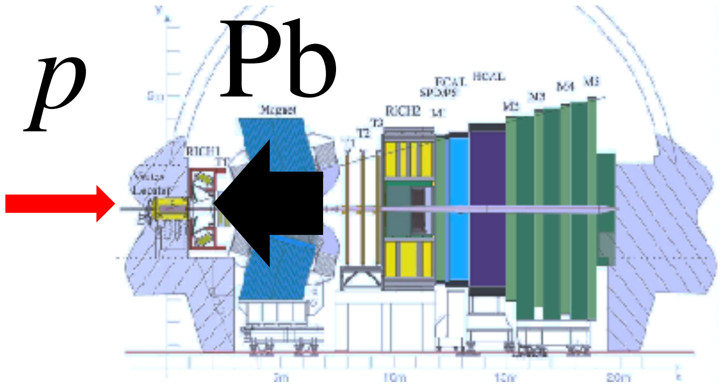
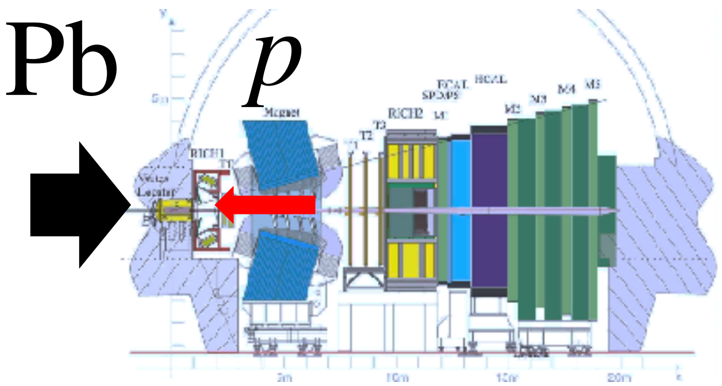
The LHCb detector

- Only LHC detector fully instrumented in $2 < \eta < 5$
- Minimum-bias datasets of pp and $p\mathrm{Pb}$ collisions at different centre-of-mass energies
- Reverse beam directions in $p\mathrm{Pb}$:



Forward $\eta > 0$



Backward $\eta < 0$

Boost of nucleon-nucleon cms system: $\eta = \eta_{lab} - 0.465$

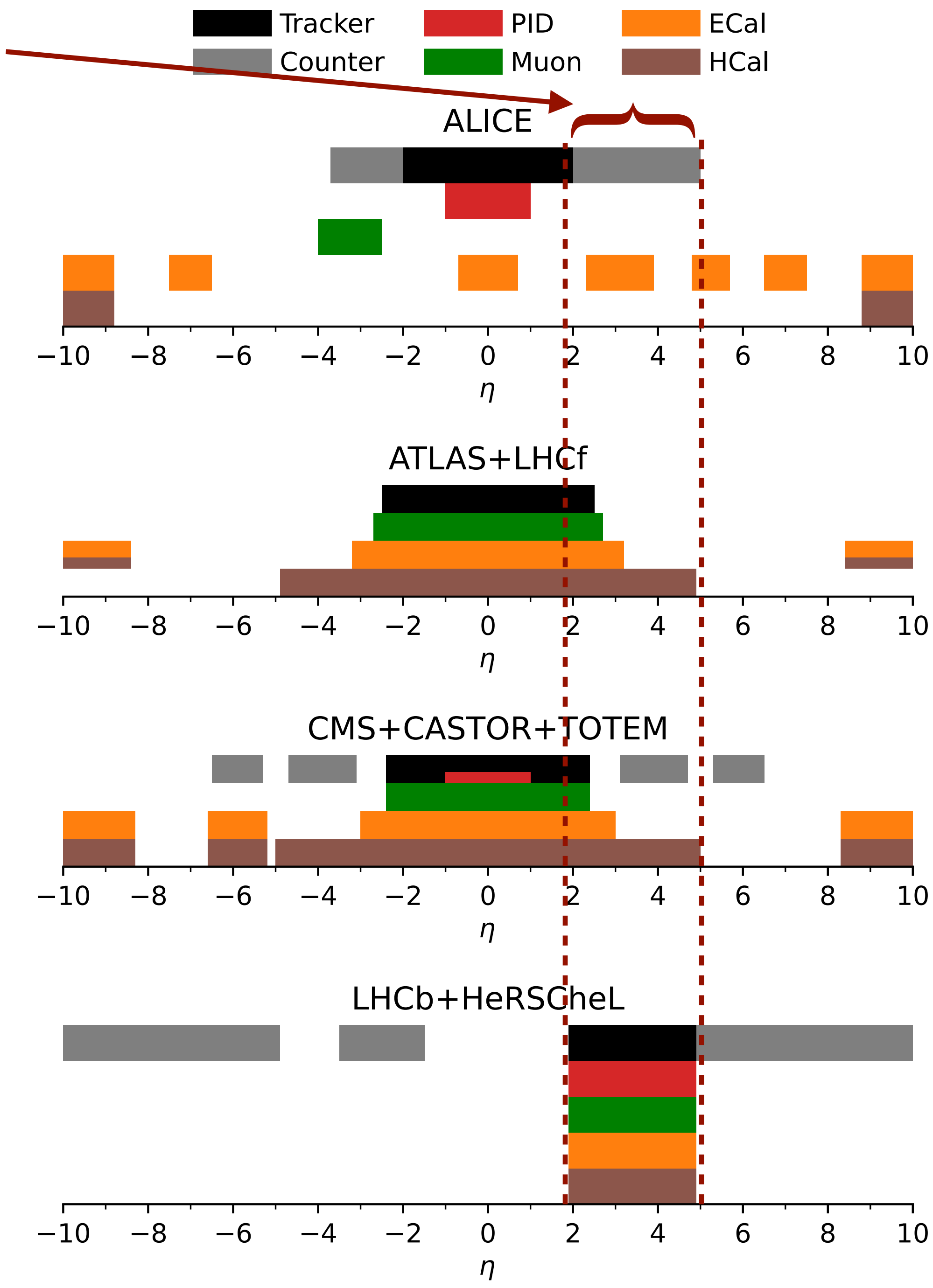


Figure from arXiv:2105.06148v1

Results for today

- Prompt charged particle production in pp collisions at $13\,\mathrm{TeV}$

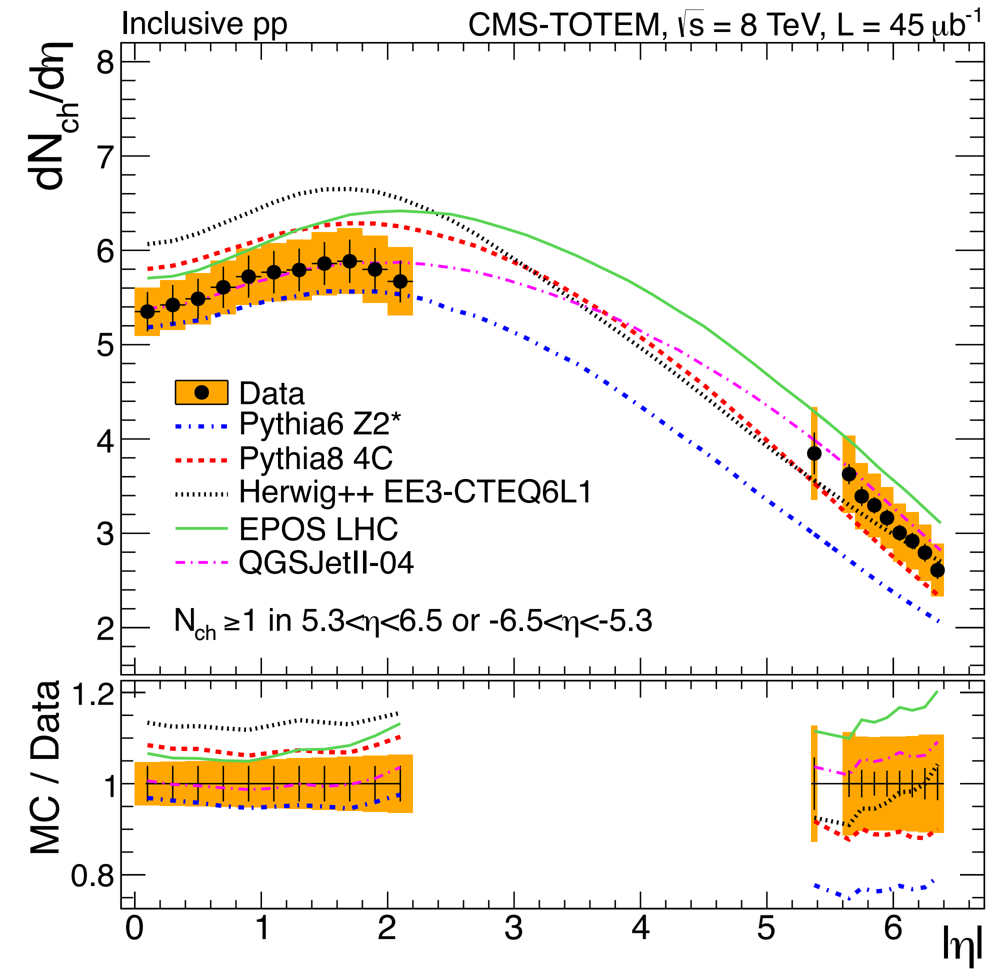
  → arXiv:2107.10090, LHCb-PAPER-2021-010

- Prompt charged particle production in $p\mathrm{Pb}$ and pp collisions at $5\,\mathrm{TeV}$

  → LHCb-PAPER-2021-015 (in preparation)

Motivation

EPJC 74 (2014) 2053



- **Description of hadron production in pp and $p\mathrm{A}$ collisions**
  - ✳ Most production driven by non-perturbative soft-QCD interactions: hadronisation, DPS, …
  - ✳ Predictions of Monte-Carlo generators largely disagree in LHCb acceptance
  - ✳ Impact in cosmic-ray physics, could explain currently observed excess in muons in hadronic cascades of high-energy cosmic rays (arXiv:2105.06148v1)

- **Phenomenology of heavy-ion collisions**
  - ✳ Charged hadron production in $p\mathrm{A}$ collisions influenced by cold nuclear matter effects
  - ✳ Baseline to study AA collisions and quark gluon plasma effects
  - ✳ For high p_{T} charged particles, pQCD predictions are possible
    - Description of shadowing/antishadowing in nuclear PDFs (nPDFs)
    - Influence of gluon saturation in the low x regime

Prompt charged particle production in pp at $13\,\mathrm{TeV}$

arXiv:2107.10090

$$\frac{d^2\sigma}{dp_{\mathrm{T}}d\eta} = \frac{1}{\mathscr{L}} \cdot \frac{n}{\Delta p_{\mathrm{T}}\Delta\eta}$$

n: **prompt charged particle yield**

$\Delta\eta, \Delta p_{\mathrm{T}}$: **bin size**

$\mathscr{L}$: **integrated luminosity of the dataset**

- Dataset of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ and $\mathscr{L} = 5.4\,\mathrm{nb}^{-1}$
- Unbiased trigger selecting leading bunch crossings
- Prompt charged particles: long-lived particles produced in primary interaction or without long-lived ancestors
- Measured from tracks in $2 < \eta < 4.8$ and $0.08 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$
- Loose track selection with high efficiency
- Charged particles separated by charge

selected tracks (candidates) → n_{cand}

background contributions → $n_{\mathrm{backgr,i}}$

- Fake tracks
- Secondary particles

$$n_{\mathrm{cand}} = \varepsilon n + \sum_i n_{\mathrm{backgr,i}}$$

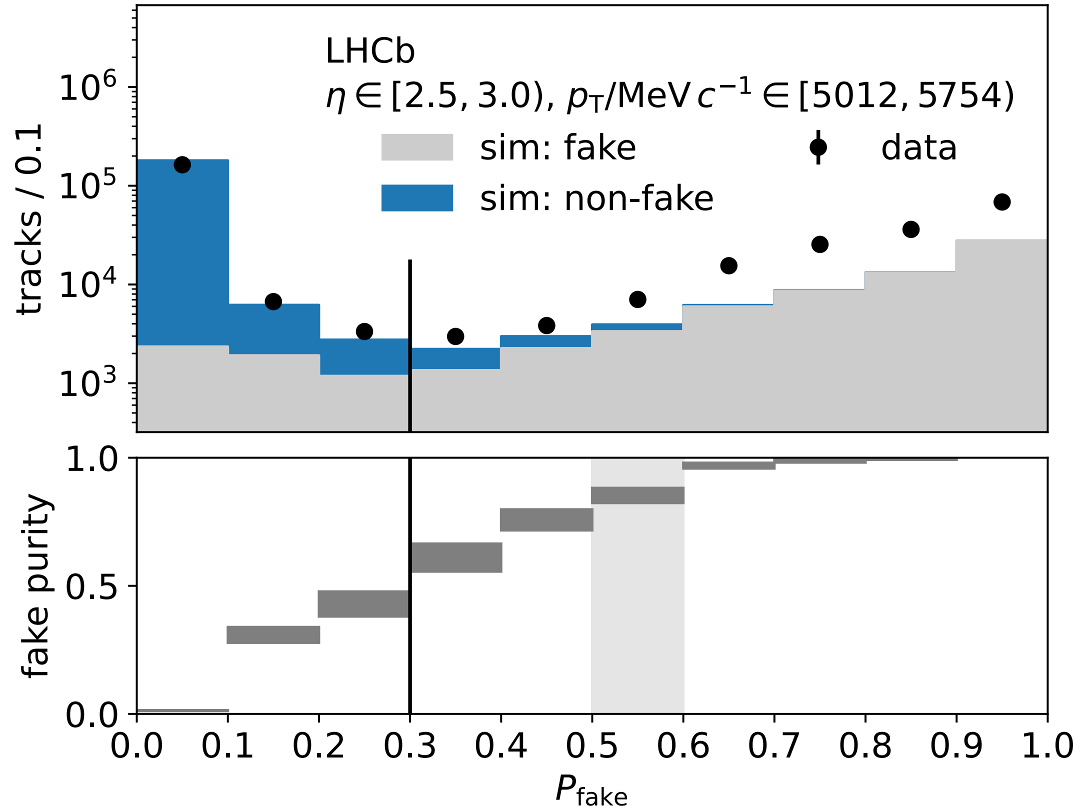
total efficiency → ε

Prompt charged particle production in pp at $13\,\mathrm{TeV}$

arXiv:2107.10090

- Total efficiency from simulation and corrected with data
  - abundance of (π, K, p) extrapolated from LHCb measurement at 0.9 and $7\,\mathrm{TeV}$
    EPJ C72 (2012) 2168

- Background estimated with simulation and corrected by data
  - use proxy samples of tracks enriched with background
  - proxies for fake tracks, material interactions and daughters of Λ, $\overline{\Lambda}$ and K^0_S

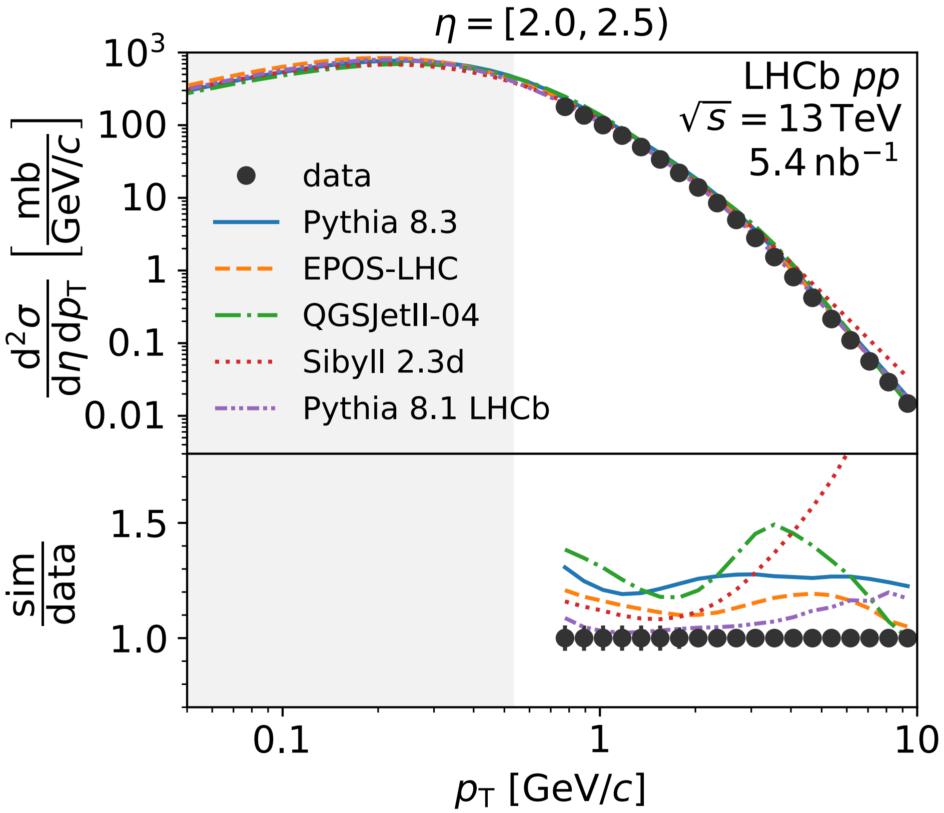


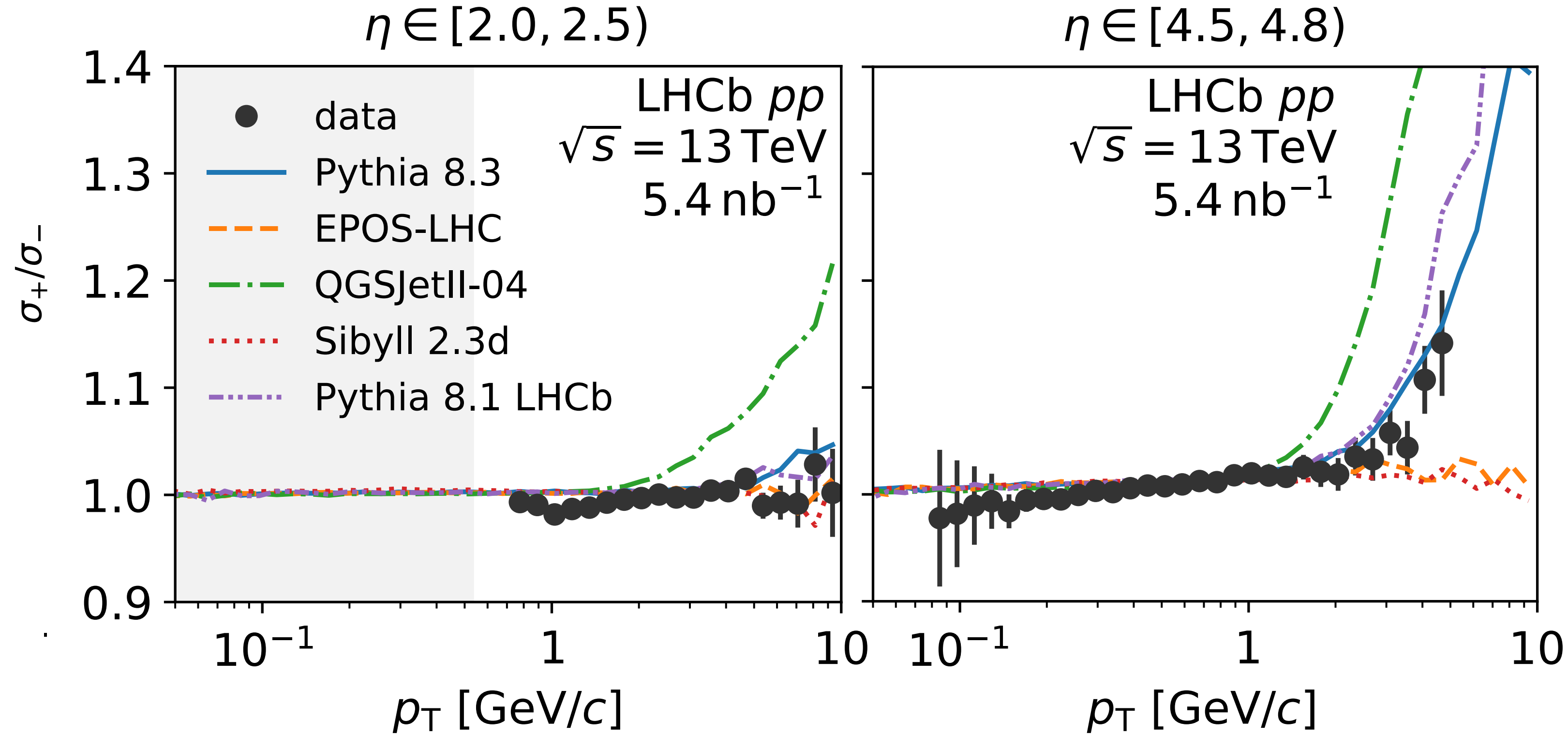
P_{fake}: fake track probability, obtained with NN classifier (LHCb-PUB-2017-011)

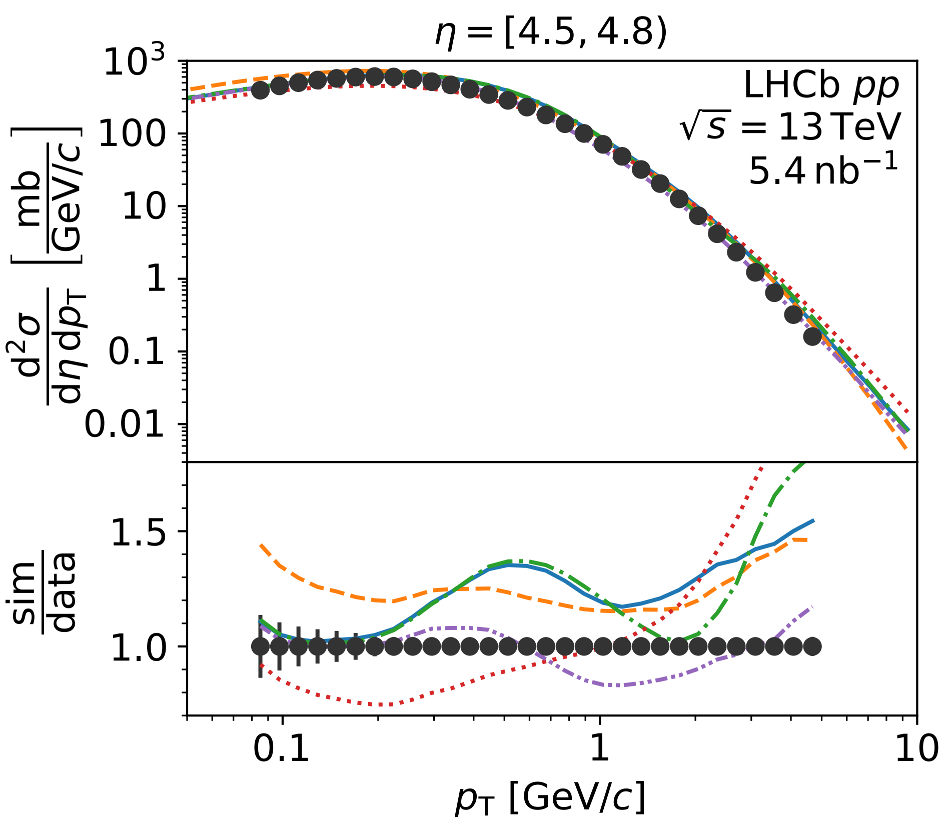
- Measurement dominated by systematic uncertainties:
  - Total uncertainty between $2 - 15\,\%$, most bins below $5\,\%$
  - Generally dominated by background estimation procedure
  - Computation of full covariance matrix for uncertainties

Double-differential cross-sections at 13 TeV

arXiv:2107.10090







- Generators mostly overestimate forward particle production
- Particle density: best agreement with EPOS-LHC and Pythia8-1 tuned for LHCb (occupancy weighted)
- Charged ratio: best agreement with Pythia 8.3

Prompt charged particle production in pPb, pp at 5 TeV

LHCb-PAPER-2021-015
(in preparation)

Nuclear modification factor $\rightarrow$ $R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) = \frac{1}{A} \frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}$, $A = 208$

$$\left.\frac{d^2\sigma}{dp_{\mathrm{T}}d\eta}\right|_{p\mathrm{Pb},\,pp} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_{\mathrm{T}})}{\Delta p_{\mathrm{T}} \Delta\eta}$$

N^{ch}: **prompt charged particle yield**

$\Delta\eta, \Delta p_{\mathrm{T}}$: **bin size**

$\mathscr{L}$: **integrated luminosity of the dataset**

- Datasets at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$:
- Measure $R_{p\mathrm{Pb}}$ in common η range

Beam	Acceptance	Luminosity
pp	$2 < \eta < 4.8$	$3.49 \pm 0.07\,\mathrm{nb}^{-1}$
pPb	$1.6 < \eta < 4.3$	$42.73 \pm 0.98\,\mu\mathrm{b}^{-1}$
Pbp	$-5.2 < \eta < -2.5$	$38.71 \pm 0.97\,\mu\mathrm{b}^{-1}$

- N^{ch} measured with reconstructed tracks, covering $p > 2\,\mathrm{GeV}/c,\ 0.2 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$
- Events selected with minimum-bias trigger
- Reconstructed tracks corrected from background and reconstruction and selection efficiencies, measured with simulation and corrected with data

Prompt charged particle production in pPb, pp at 5 TeV

LHCb-PAPER-2021-015
(in preparation)

- Background from fake tracks specially important
  - Increases with event occupancy, large contribution in Pbp
  - Contribution rises strongly with p_{T}
- Tighter track selection than in 13 TeV analysis
- Selection efficiency measured on data using a calibration sample of $\phi(1020) \to K^+K^-$ decays
- Charged particle composition not yet measured in LHCb acceptance for pPb → use EPOS-LHC simulation validated with ALICE data (Phys. Lett. B760 (2016) 720)

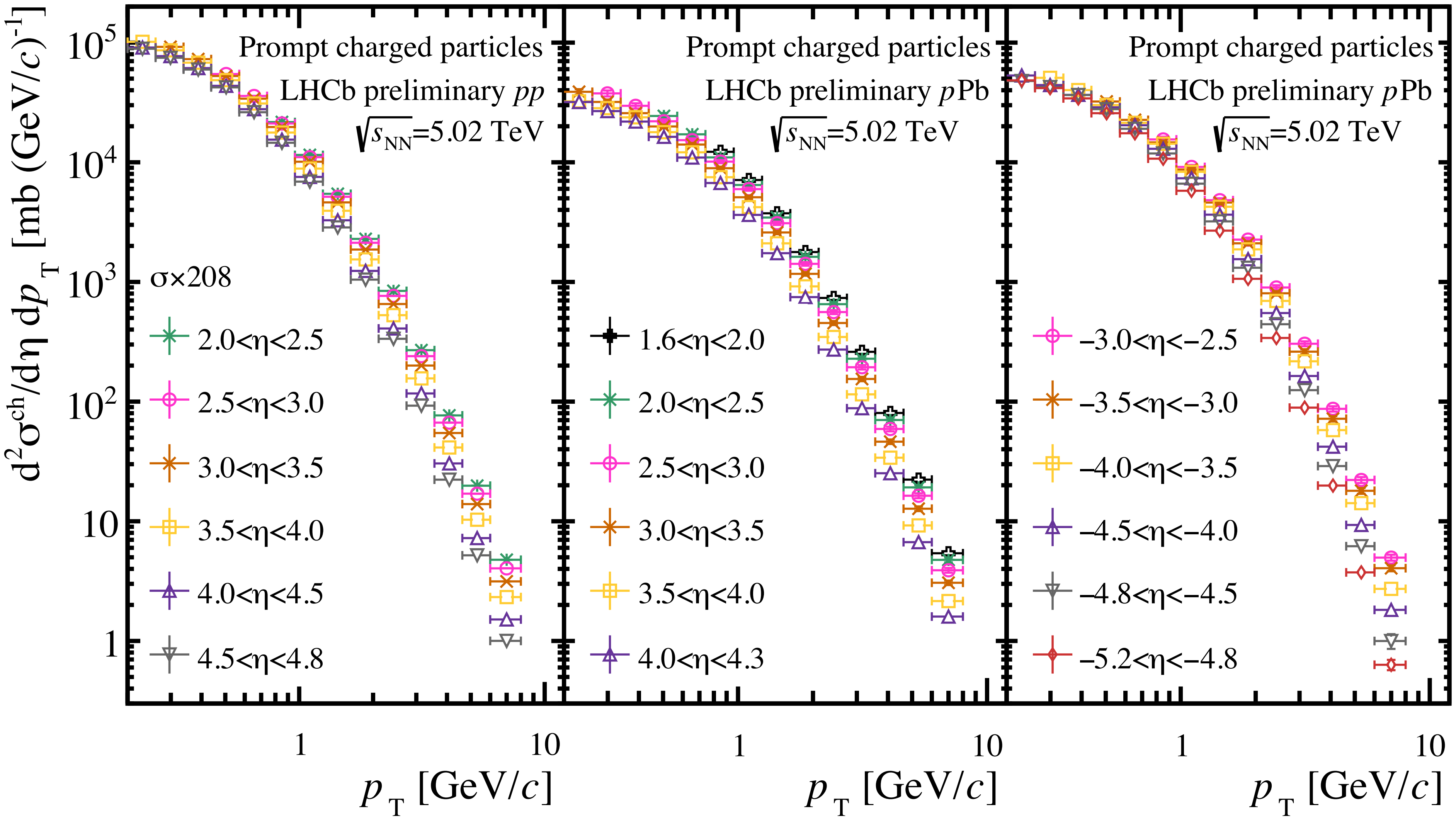
- Total uncertainty:
  - down to 2.8 % in $\mathrm{d}^2\sigma/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}$
  - down to 4.2 % in $R_{p\mathrm{Pb}}$
- Dominated by systematic uncertainties:
  - particle composition in pPb for most bins
  - tracking efficiency and signal purity in boundary (η, p_{T}) bins

Uncertainty source	pPb [%]	Pbp [%]	pp [%]
Track finding efficiency	1.5-5.0	1.5-5.0	1.6-5.3
Detector occupancy	0.0-2.8	0.6-2.9	0.1-1.6
Particle composition	0.4-4.1	0.4-4.6	0.3-2.4
Selection efficiency	0.7-2.2	0.7-3.0	1.0-1.7
Purity	0.1-1.8	0.1-11.7	0.1-5.8
Truth-matching	0.0-0.1	0.0-0.1	0.1-0.2
Luminosity	2.3	2.5	2.0
Statistical uncertainty	0.0-0.6	0.0-1.0	0.0-1.1
Total (in $\mathrm{d}^2\sigma/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}$)	3.0-6.7	3.3-14.5	2.8-8.7
Total (in $R_{p\mathrm{Pb}}$)	4.2-9.2	4.4-16.9	

Double-differential cross-sections at $5\,\mathrm{TeV}$

LHCb-PAPER-2021-015
(in preparation)

- $$\left.\frac{d^2\sigma}{dp_\mathrm{T} d\eta}\right|_{p\mathrm{Pb},\,pp} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_\mathrm{T})}{\Delta p_\mathrm{T} \Delta\eta}$$
  - pp result consistent with measurement at $\sqrt{s} = 13\,\mathrm{TeV}$ (LHCb-PAPER-2021-010)
  - cross-section at $13\,\mathrm{TeV}$ from $5\,\mathrm{TeV}$ increases a factor $1-3$ depending on p_T



LHCb (x, Q^2) coverage

LHCb-PAPER-2021-015
(in preparation)

- $R_{p\mathrm{Pb}}$ probes nuclear effects
- Depends on (x, Q^2) of the probed Pb parton

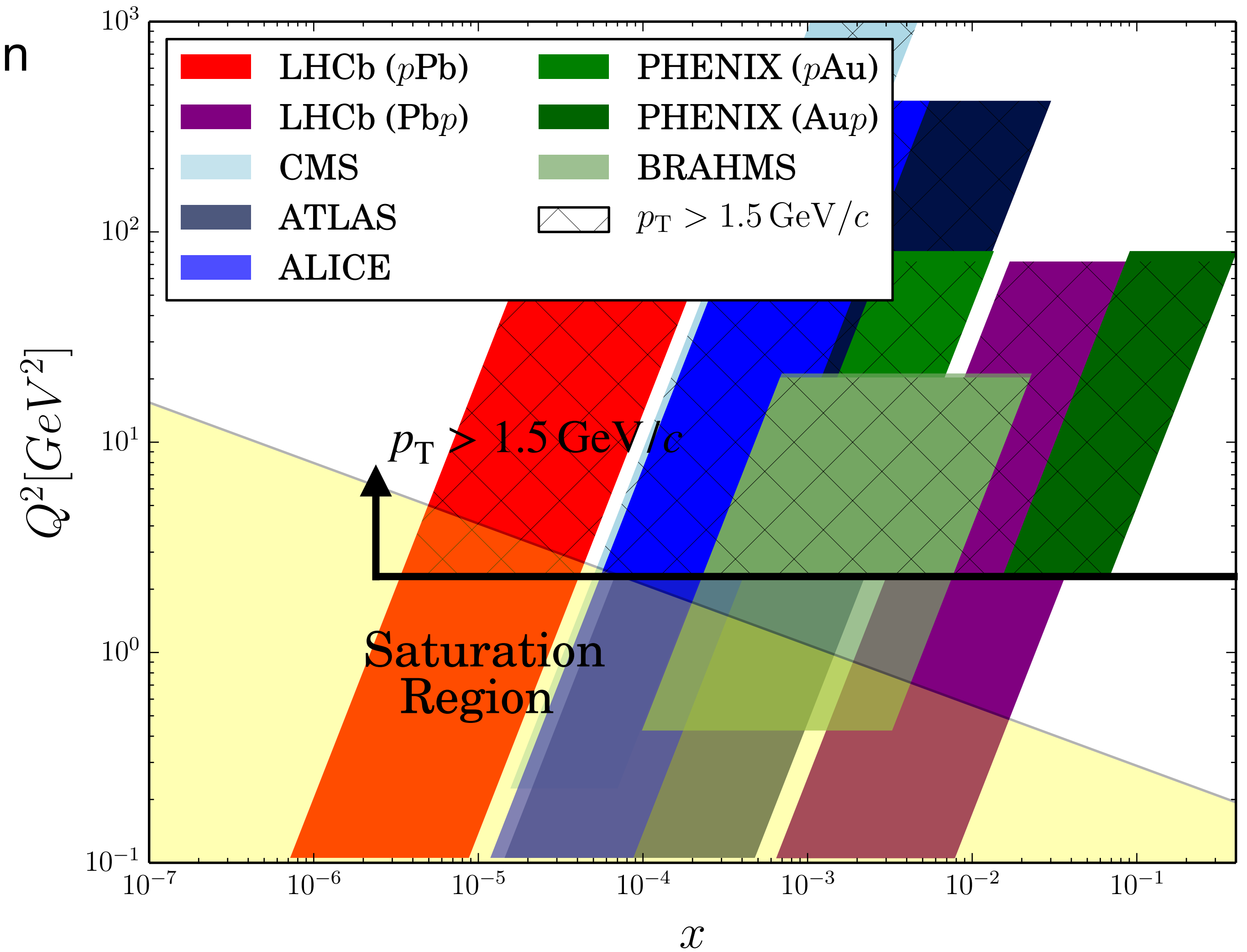
Q^2: exchanged momentum between interacting partons

x: momentum fraction of Pb parton

$$Q^2 \sim m^2 + p_T^2, \qquad x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$$

$$m = 256\,\mathrm{MeV}/c^2$$

- LHCb can probe unprecedented Bjorken-x range:
  - forward, $10^{-6} \lesssim x \lesssim 10^{-4}$
  - backward, $10^{-3} \lesssim x \lesssim 10^{-1}$
- Possible access to saturation region in perturbative scale $p_T > 1.5\,\mathrm{GeV}/c$
- Backward acceptance overlaps with (x, Q^2) at central BRAHMS (dAu) and backward PHENIX (Aup)



Saturation region:
PRD59, 014017 (1998), PRL100, 022303 (2008)

$$Q^2_{s,\mathrm{Pb}} \approx 0.26\, A^{1/3} (x_0/x)^{\lambda}\,\mathrm{GeV}^2$$

$\lambda = 0.288$
$x_0 = 3 \cdot 10^{-4}$
$A = 208$

Results of $R_{p\mathrm{Pb}}$

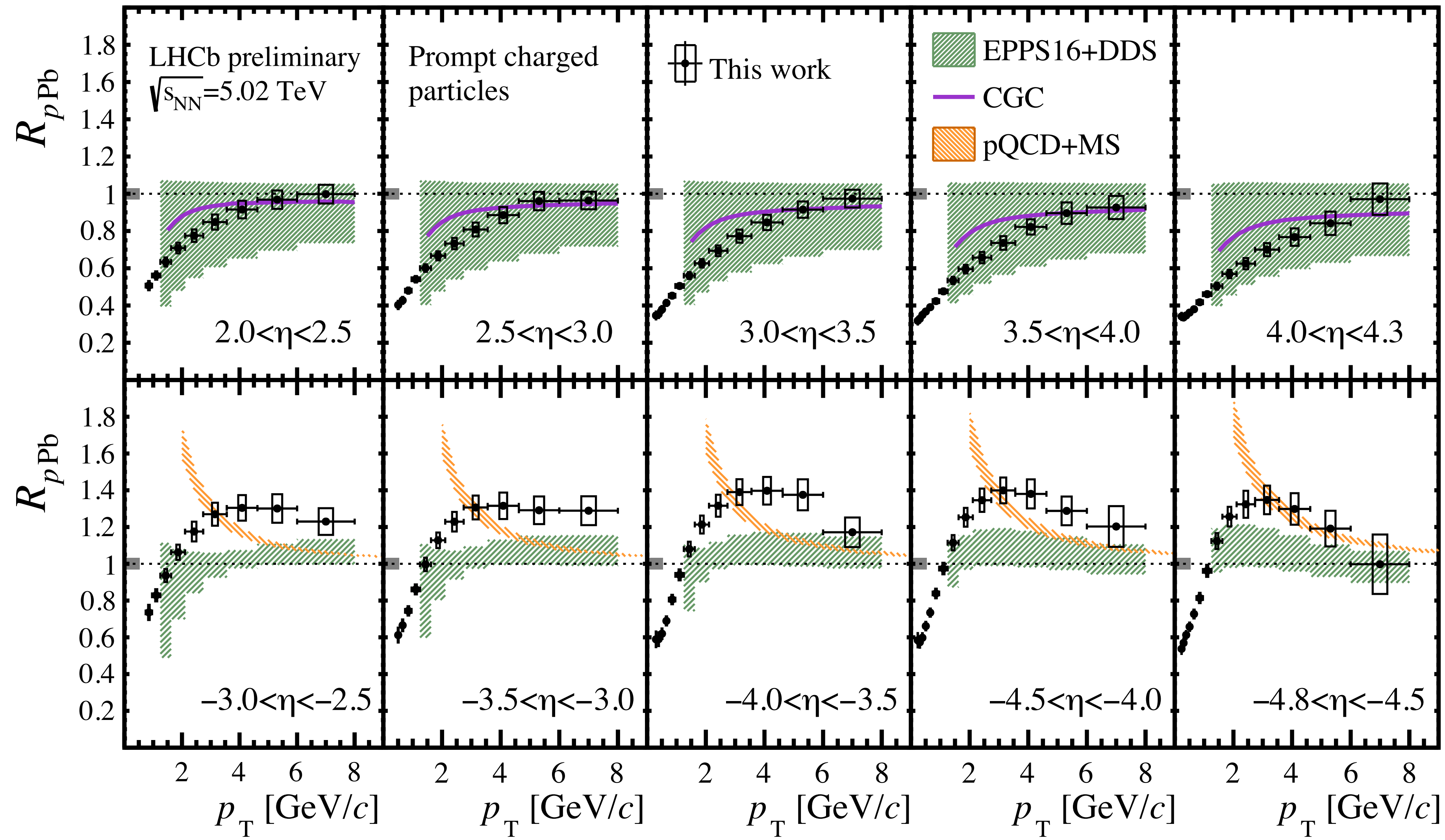
LHCb-PAPER-2021-015 (in preparation)

- **Strong suppression** at forward η, down to ~ 0.3 at low p_T and most forward rapidity
- **Enhancement** at backward for $p_T > 1.5\,\mathrm{GeV}/c$, as observed by PHENIX in $\mathrm{Au}p$ Phys. Rev. C101 (2020) 034910

Models:
- EPPS16+DDS: I. Helenius *et. al.* JHEP09(2014) 138
- Color Glass Condensate (CGC): T. Lappi *et. al.* PR D88, 114020
- pQCD calculation with MS: Z. B. Kang *et. al. (reproduced PHENIX enhancement)* PL B740(2015) 23, PR D88(2013) 054010

Forward region →

Backward region →



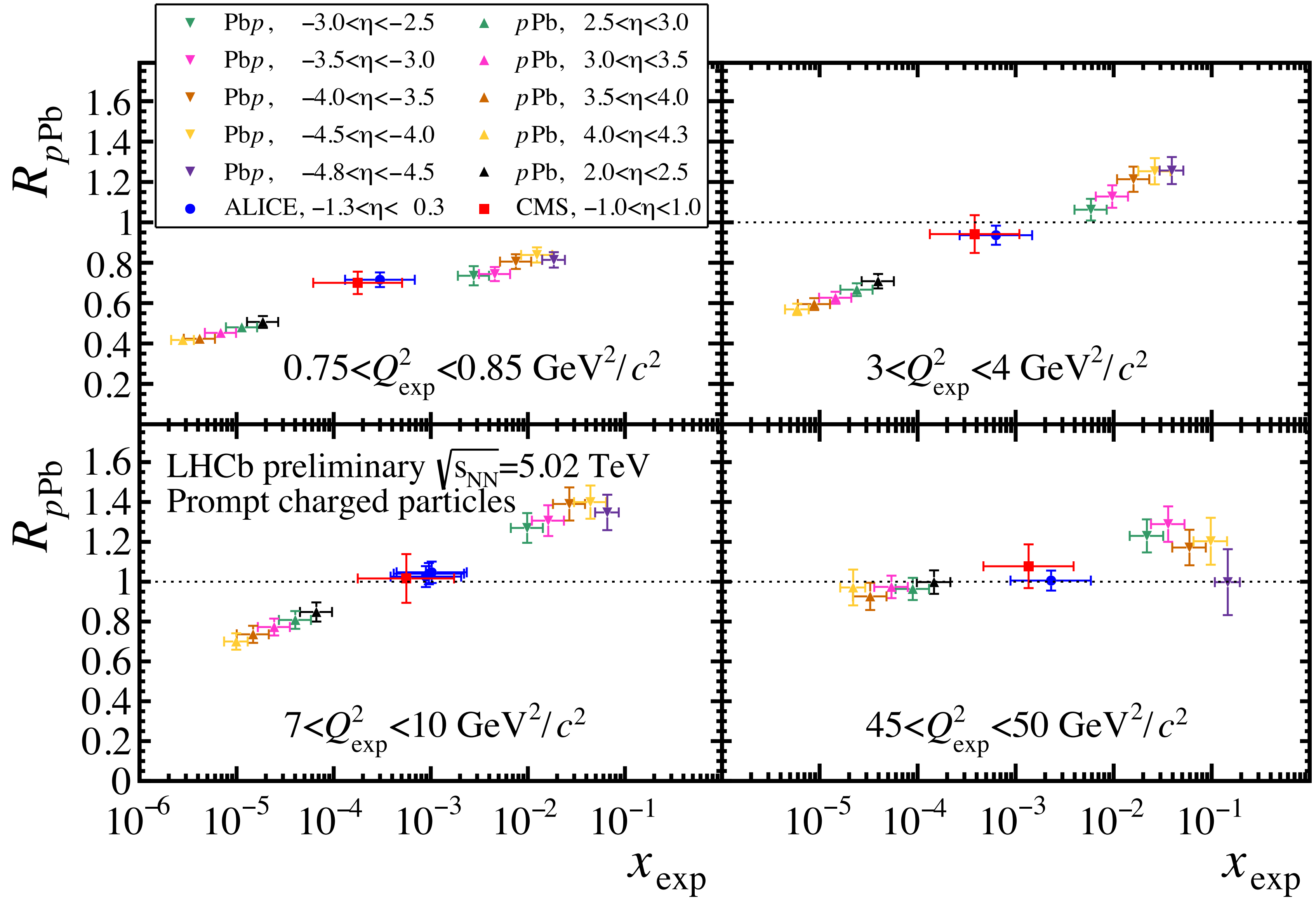
Results of R_{pPb} - dependence with (x_{exp}, Q^2_{exp})

LHCb-PAPER-2021-015 (in preparation)

$$Q^2_{exp} \equiv m^2 + p_T^2 \quad \text{and} \quad x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$

- experimental proxies for (x, Q^2)
- with η and p_T the center of each bin and $m = 256\,\text{MeV}/c^2$
- indirect study of the evolution of R_{pPb} with x and Q^2

- Continuous evolution of R_{pPb} with x_{exp} at different Q^2_{exp}, between forward, central and backward η regions



Conclusions

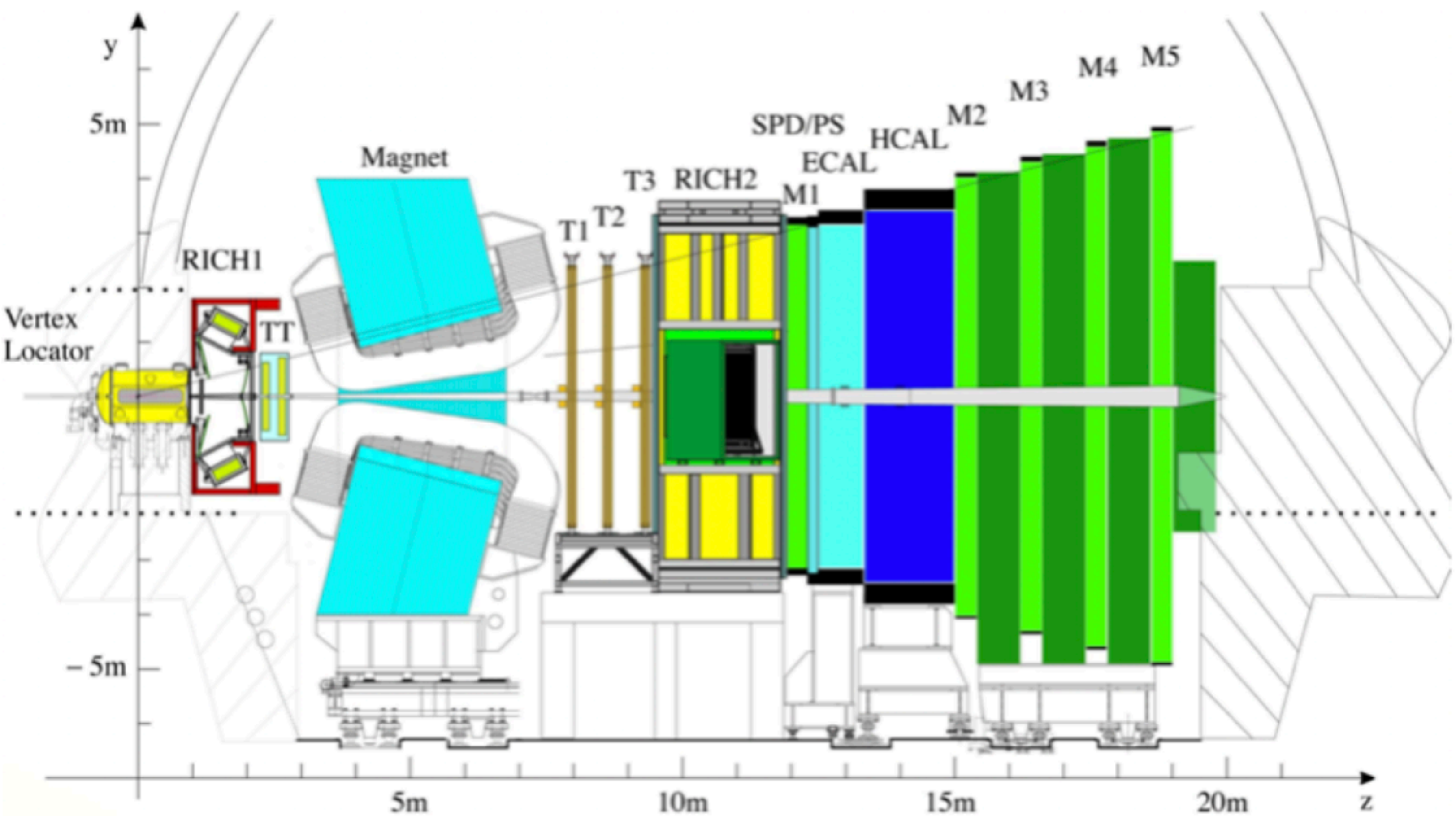
Recent results of charged particle production in *p*Pb and *pp* collisions were presented

- First measurement of double-differential prompt charged particle cross-section in pp collisions in forward region at $\sqrt{s} = 13\,\text{TeV}$ (arXiv:2107.1009, LHCb-PAPER-2021-010)
  - Separation of negatively and positively charged particles
  - total uncertainty $2 - 15\,\%$, full error correlation matrix will be published
  - Crucial input for hadron production modeling in atmospheric showers in cosmic-ray physics
- First determination of $R_{p\text{Pb}}$ for prompt charged particles in forward and backward regions at LHC (LHCb-PAPER-2021-015, in preparation)
  - double-differential prompt charged particle cross-section in pp and $p\text{Pb}$ at $\sqrt{s_{\text{NN}}} = 5\,\text{TeV}$
  - total uncertainty down to $4.2\,\%$ in $R_{p\text{Pb}}$
  - Study of cold nuclear matter effects over a wide range of x
  - Strong constrains to nuclear PDFs and saturation models at intermediate and very low x
- Prospects: exploit excellent (π, K, p) PID at LHCb to measure cross-sections by species in pp and $p\text{Pb}$ collisions

Backup slides

The LHCb detector

- Forward spectrometer at LHC fully instrumented in $2 < \eta < 5$
  - Tracking system with excellent momentum resolution
  - Identification of charged hadrons (π, K, p), neutrals (γ, π^0), and leptons (μ, e)
- Resolution of B and D decay vertices from primary collision
- Highly flexible trigger, configured to measure very low p_{T}
- Accurate luminosity determination (uncertainty $\sim 2\,\%$, JINST 9 (2014) 12, P12005)



LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

Key ideas of the analyses

- Study hadron production with inclusive prompt charged particle spectra in (η, p_{T}) bins
  - long-lived particles (lifetime $< 30\,\mathrm{ps}$)
  - produced in primary interaction or without long-lived ancestors
- Long-lived charged particles are: $\pi^-, K^-, p, e^-, \mu^-, \Xi^-, \Sigma^+, \Sigma^-, \Omega^-(+cc.)$

- **LHCb tracking system** used to detect charged particles
- Long tracks with $p > 2\,\mathrm{GeV}/c$

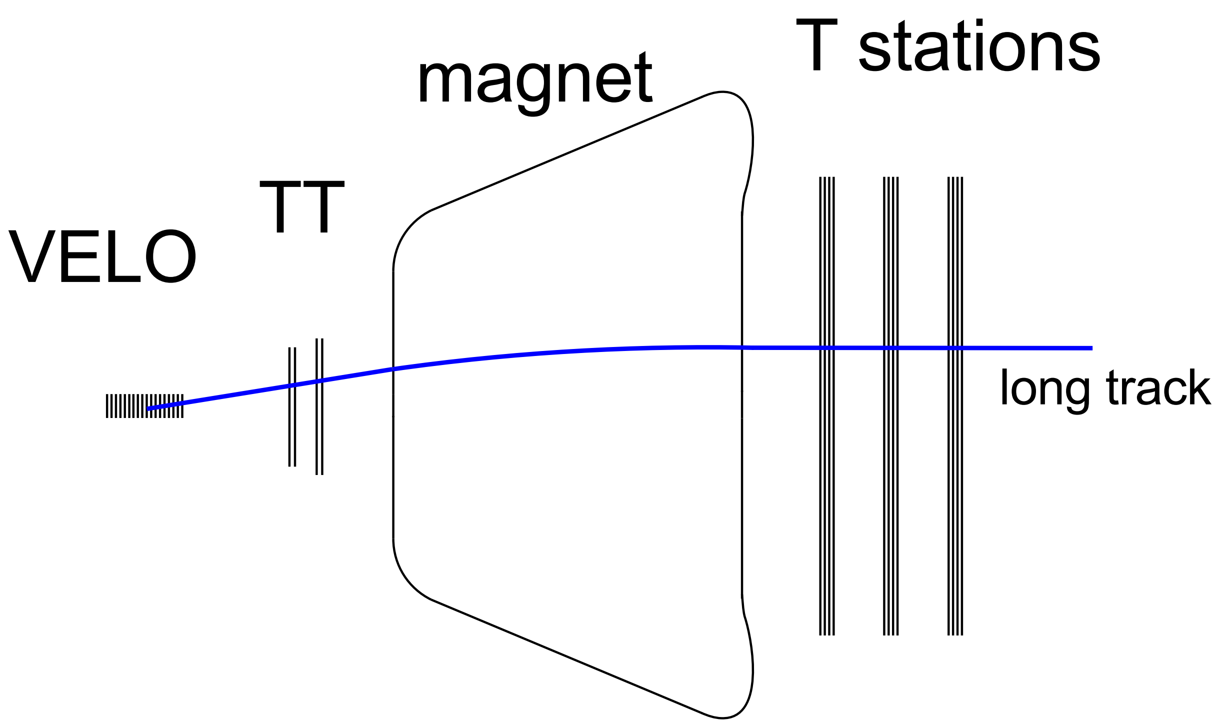


Figure from JINST 10 (2015) 02, P02007

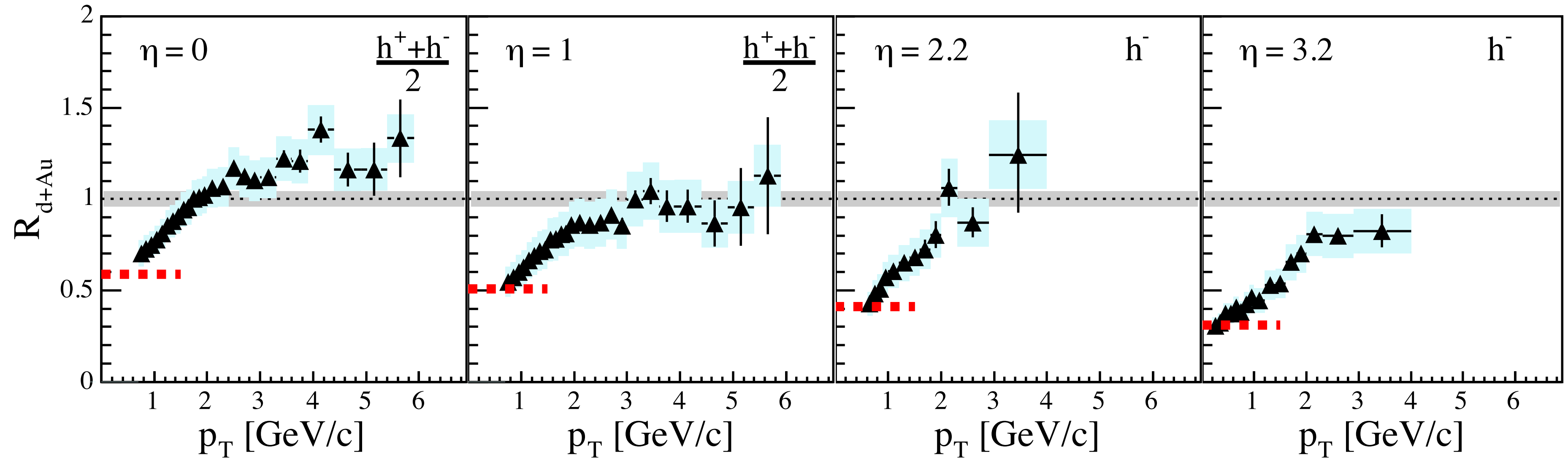
Main inputs:

- reconstruction and selection efficiencies
- background contributions
  - Fake tracks, not produced by charged particles
  - Secondary particles: particles from
    - ✳ interactions with the detector material (e^- from γ conversions and hadrons from hadronic interactions)
    - ✳ daughters of long-lived particles ($\Lambda^0, K^0_S, \Sigma^+ \ldots$)

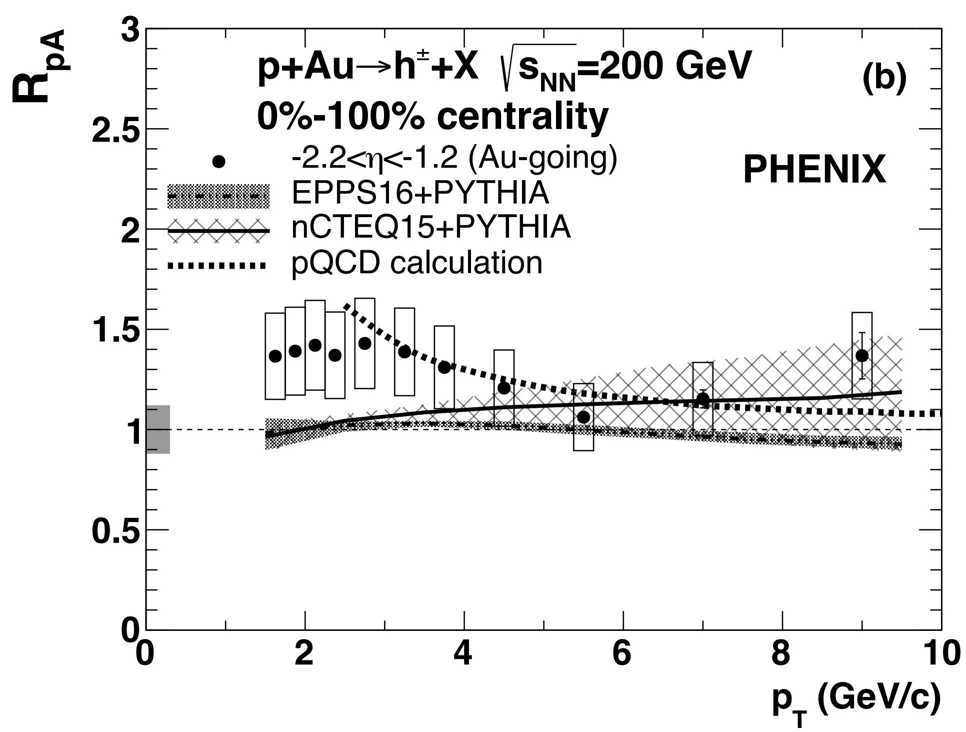
Previous results of $R_{pA,dA}$

BRAHMS R_{dAu}

Phys.Rev.Lett. 93 (2004) 242303



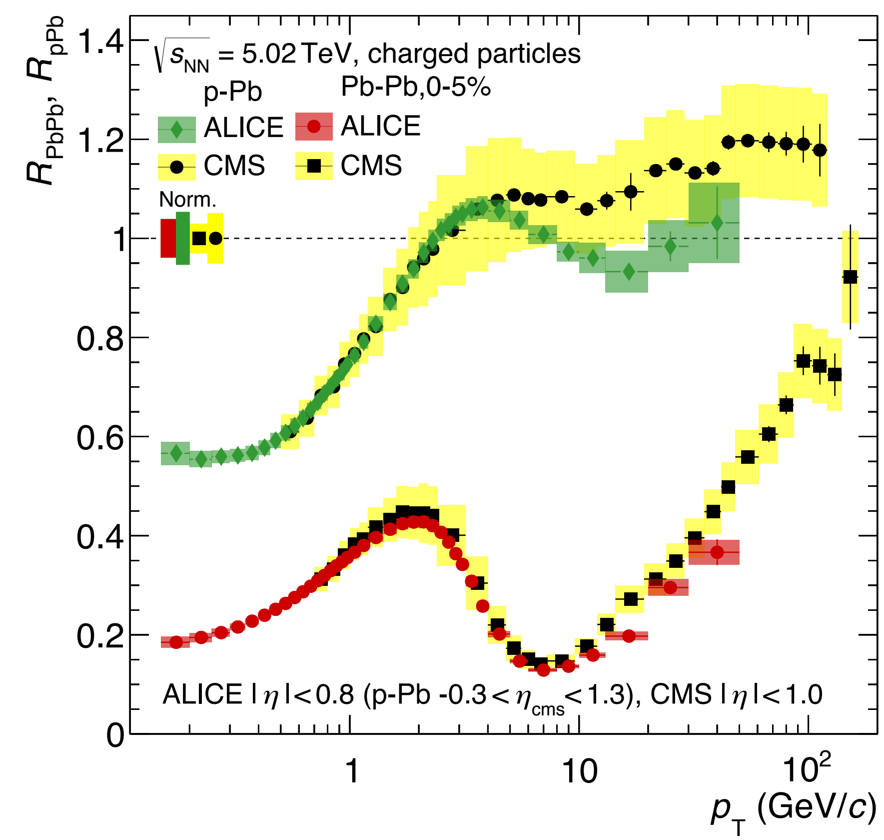
PHENIX R_{pAu} Phys. Rev. C101 (2020) 034910



CMS, ALICE R_{pPb}

JHEP 04 (2017) 039

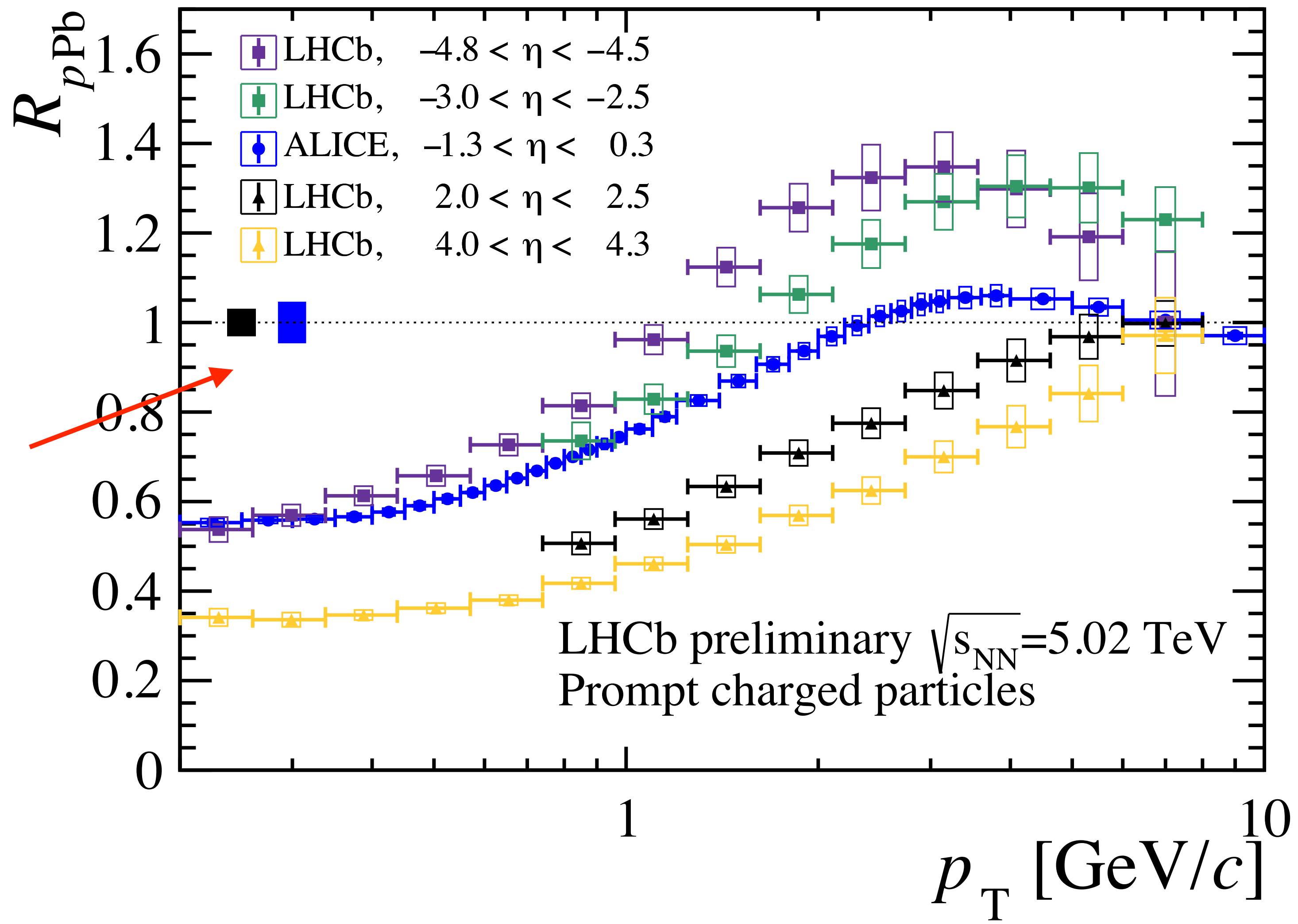
JHEP 1811 (2018) 013



Comparison of $R_{p\mathrm{Pb}}$ from ALICE and LHCb

- Continuous trend of $R_{p\mathrm{Pb}}$ at different η

Global uncertainty from normalization



LHCb-PAPER-2021-010 (in preparation)

ALICE: JHEP 1811 (2018) 013