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Prompt charged particle production in heavy-ion collisions

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LHCb Implications Workshop

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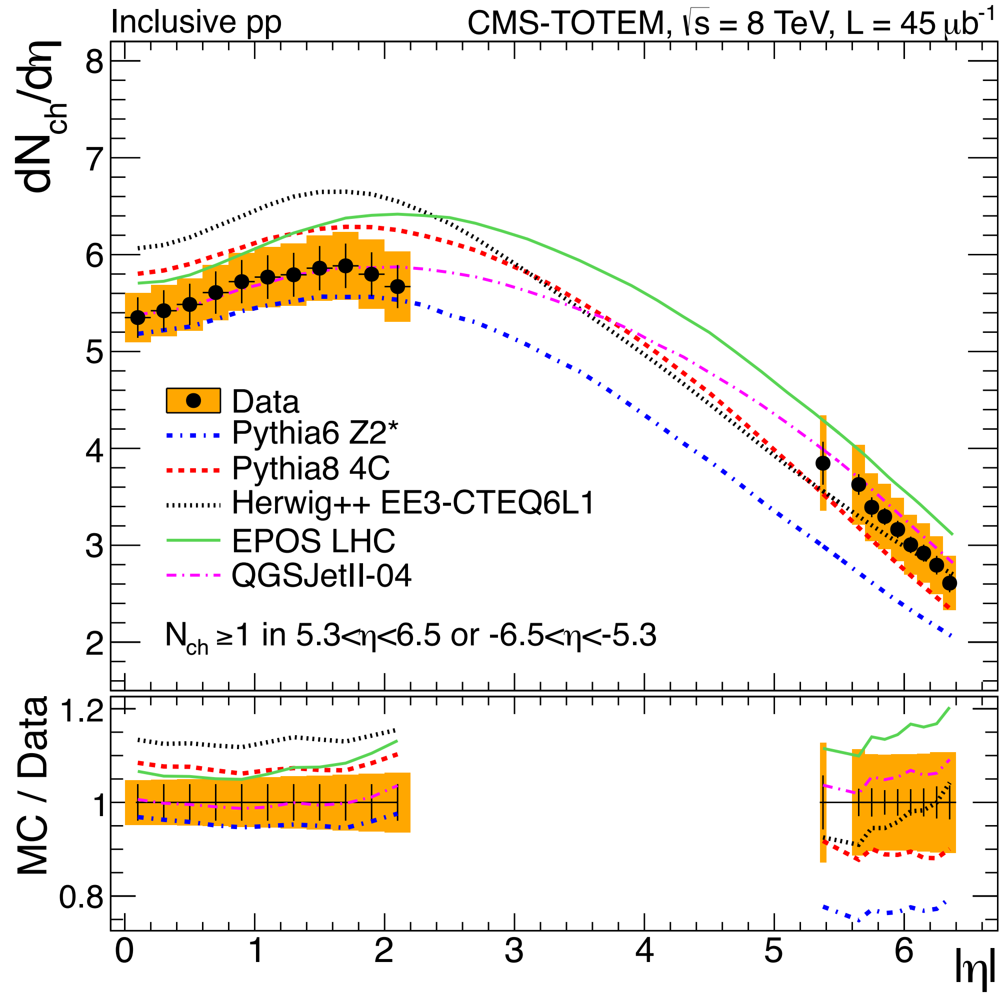
LHCb IGFAE Instituto Galego de Física de Altas Enerxías USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA XUNTA DE GALICIA

Motivation: hadron production

- Hadron production in pp and pA collisions not well understood
- Most production driven by non-perturbative soft-QCD interactions: hadronization, DPS, …
- Predictions of Monte-Carlo generators largely disagree in LHCb acceptance

- Impact in cosmic-ray physics:
  - generators used to study the evolution of hadronic cascades from high-energy cosmic rays
  - uncertainties limited by quality of generators
  - unexplained excess in the number of muons that reach the Earth surface (arXiv:2105.06148v1)

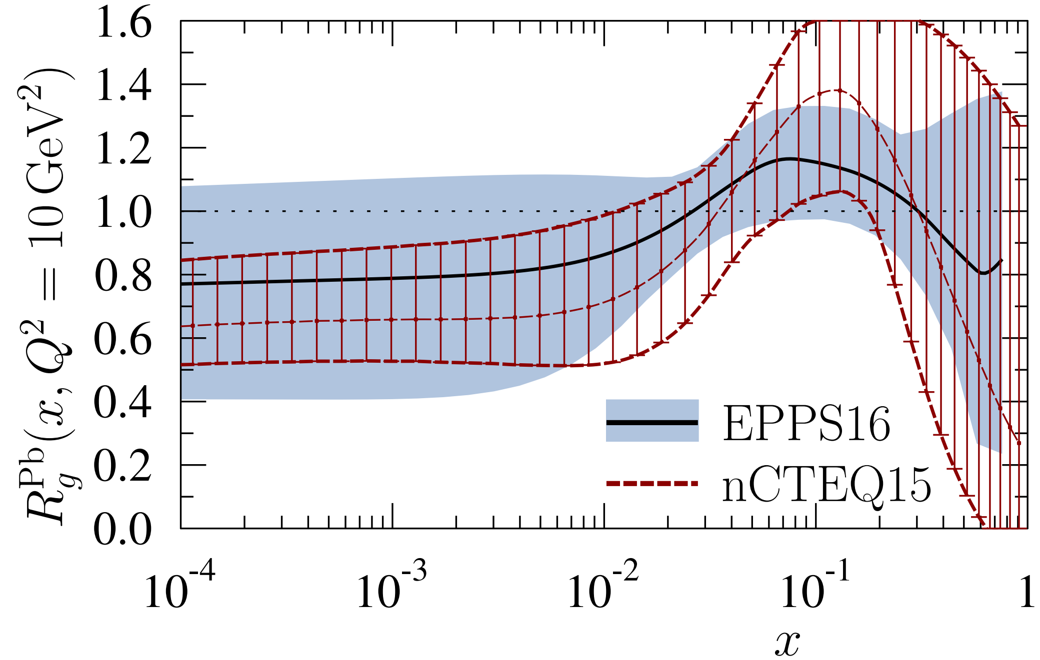


EPJC 74 (2014) 2053

Motivation: CNM effects

- Charged hadron production in $p\mathrm{A}$ collisions influenced by cold nuclear matter (CNM) effects
- Baseline to study AA collisions and quark gluon plasma effects
- Perturbative QCD (pQCD) calculations are only possible for high p_{T} charged particles:
  - Description of shadowing/antishadowing in nuclear PDFs (nPDFs)
  - Study saturation of gluon density → constrains in Color Glass Condensate (CGC) models
  - Are additional CNM effects not described by nPDFs?

Gluon nuclear modification in nPDFs

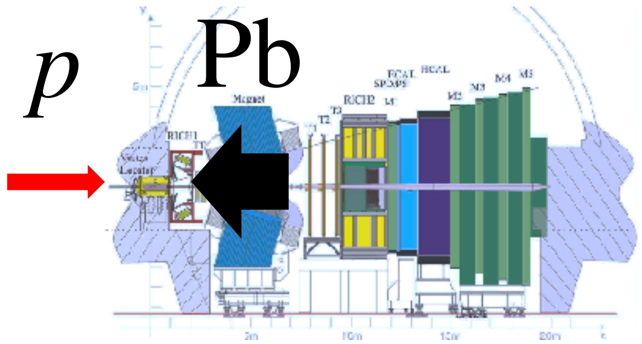


Eur.Phys.J.C 77 (2017) 3

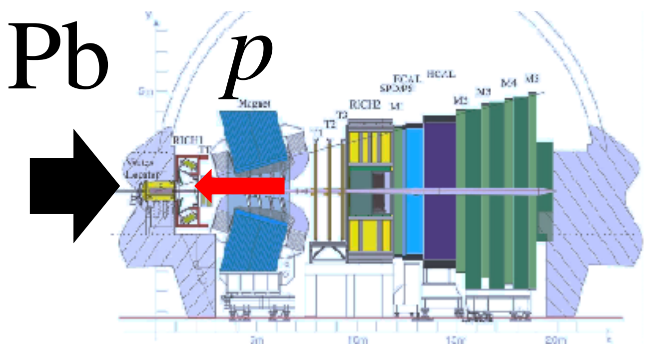
Nuclear modification factor → $R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}, \quad A = 208$

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: $\eta = \eta_{lab} - 0.465$

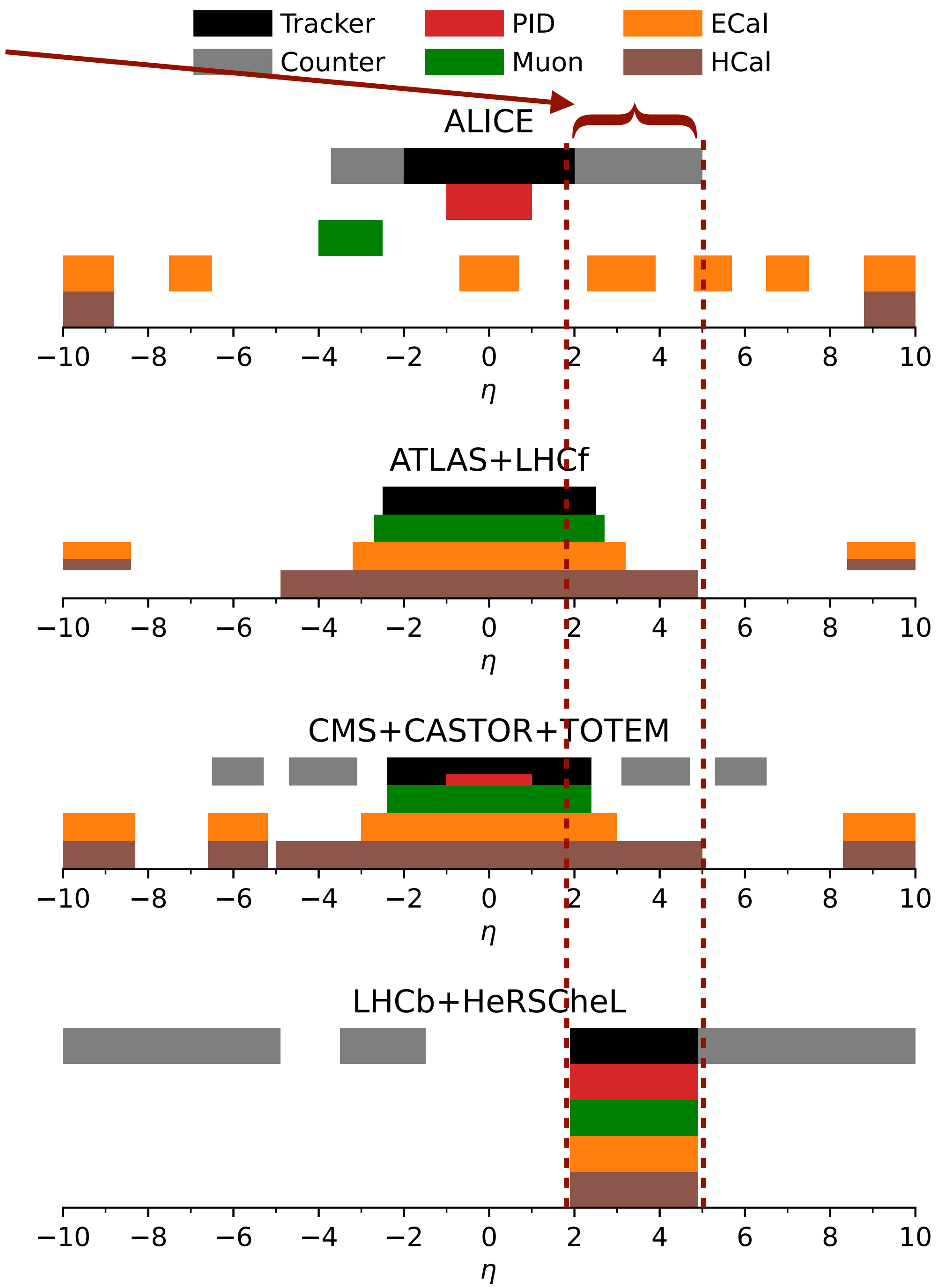


Figure from arXiv:2105.06148v1

LHCb (x, Q^2) coverage

- Nuclear effects depend on (x, Q^2) of the probed Pb parton

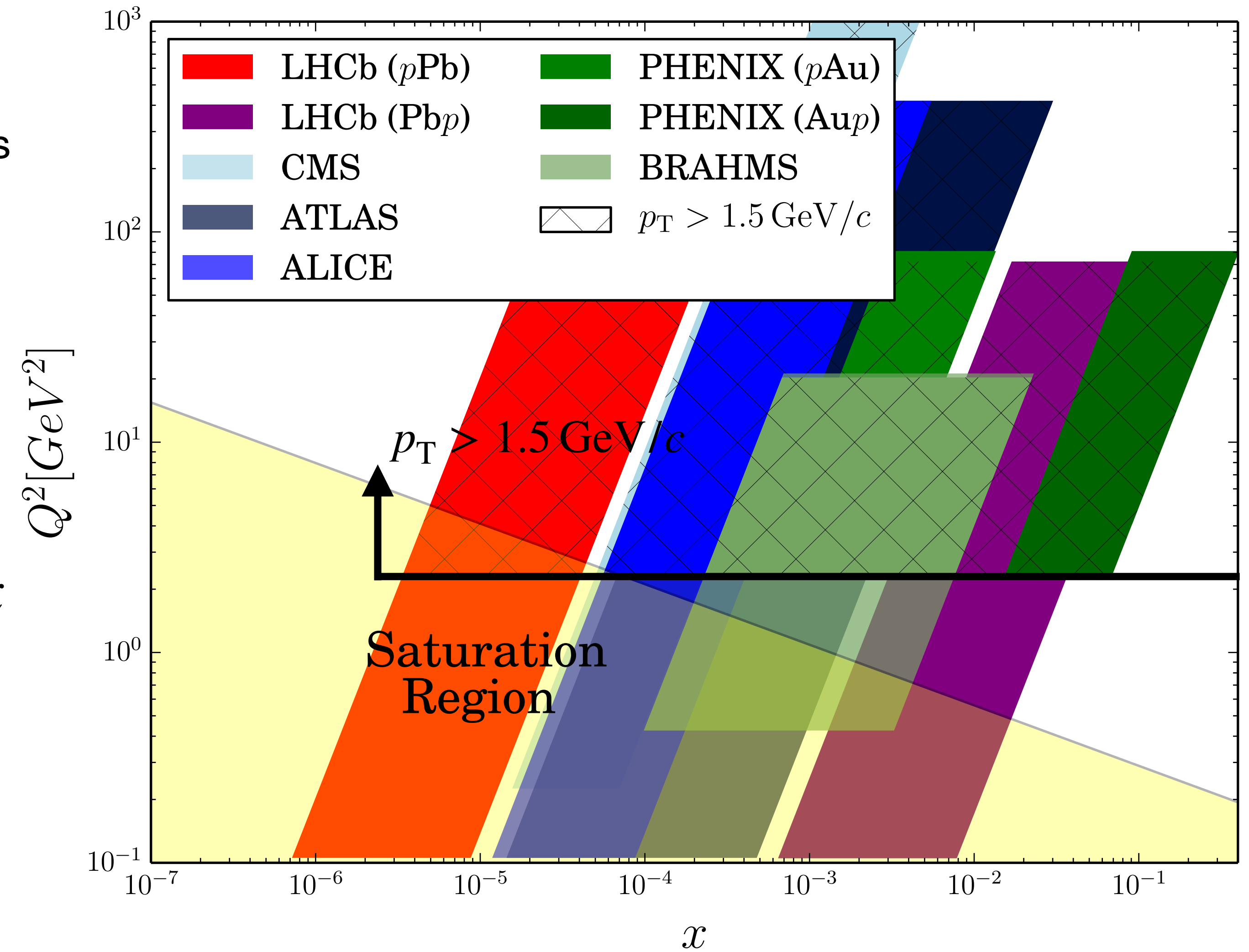
Q^2: exchanged momentum between interacting partons

x: momentum fraction of Pb parton

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

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

- 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 $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$
- Backward acceptance overlaps with (x, Q^2) at central BRAHMS (dAu) and backward PHENIX (Aup)



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

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

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

Prompt charged particle production in pPb and pp

arXiv:2108.13115

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

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

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

$\Delta\eta$, Δp_T: **bin size**

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

- Prompt charged particles:
  - long-lived particles (lifetime $< 30\,\mathrm{ps}$)
  - produced in primary interaction or without long-lived ancestors
- Long-lived charged particles: $\pi^-, K^-, p, e^-, \mu^-, \Xi^-, \Sigma^+, \Sigma^-, \Omega^-$ $(+cc.)$

- 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	$-5.2 < \eta < -2.5$	$38.71 \pm 0.97\,\mu\mathrm{b}^{-1}$

Analysis overview

arXiv:2108.13115

- N^{ch} measured with long tracks, covering $p > 2\,\mathrm{GeV}/c,\ 0.2 < p_{\mathrm{T}} < 8\,\mathrm{GeV}/c$
- $N^{\mathrm{ch}} = N^{\mathrm{candidates}} \dfrac{P}{\varepsilon_{\mathrm{reco}}\varepsilon_{\mathrm{sel}}}$
  - $N^{\mathrm{candidates}}$: selected long tracks
  - P: signal purity
  - $\varepsilon_{\mathrm{reco}}$: reconstruction efficiency
  - $\varepsilon_{\mathrm{sel}}$: selection efficiency

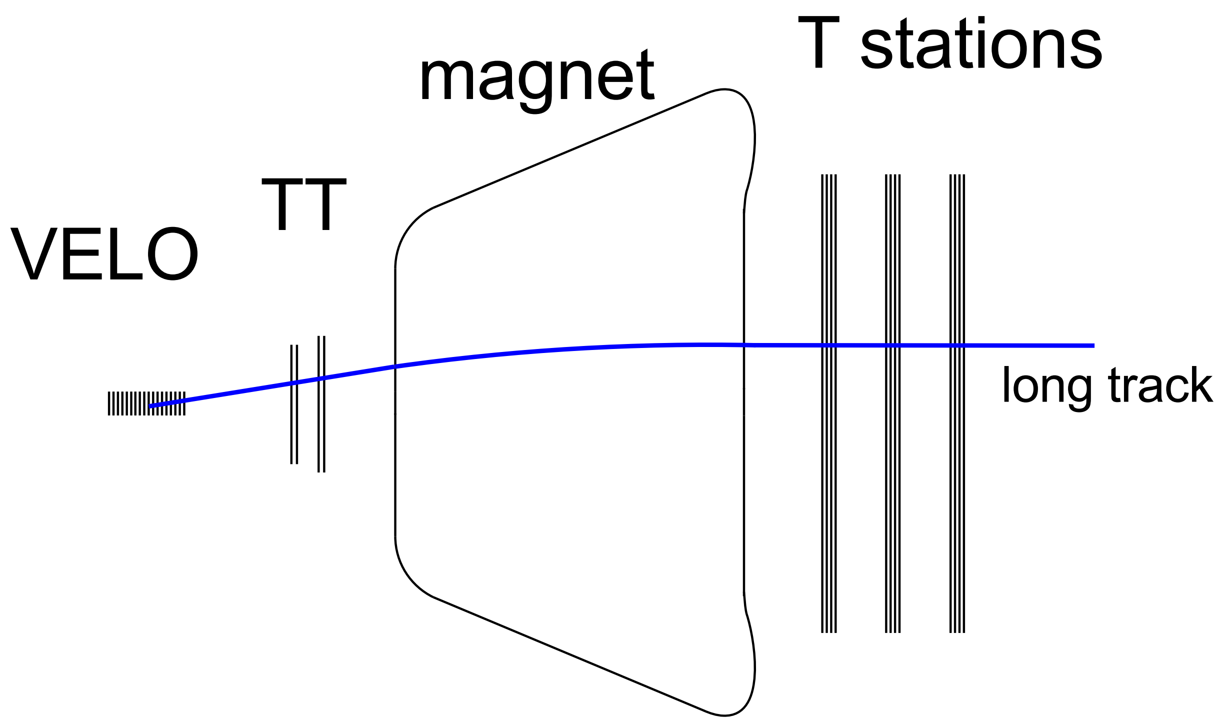


Figure from JINST 10 (2015) 02, P02007

- **Background contributions**:
  - Fake tracks, reconstruction artifacts 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 ($\Lambda^0, K^0_S, \Sigma^+ \ldots$)

Analysis overview

arXiv:2108.13115

Background description

- Background from fake tracks specially important
  - Increases with event occupancy, large contribution in $\mathrm{Pb}p$
  - Contribution rises strongly with p_{T}
- Remove most background with a tight track selection
- Selection efficiency measured on data using a calibration sample of $\phi(1020) \to K^{+}K^{-}$ decays
- Remaining background estimated with simulation and corrected with data
  - use background-enriched proxy samples

Relative particle composition

- Reconstruction efficiency depends on relative particle composition
- Charged particle composition not yet measured in LHCb acceptance for $p\mathrm{Pb}$ → use EPOS-LHC simulation validated with ALICE data (Phys. Lett. B760 (2016) 720)

Systematic uncertainties

arXiv:2108.13115

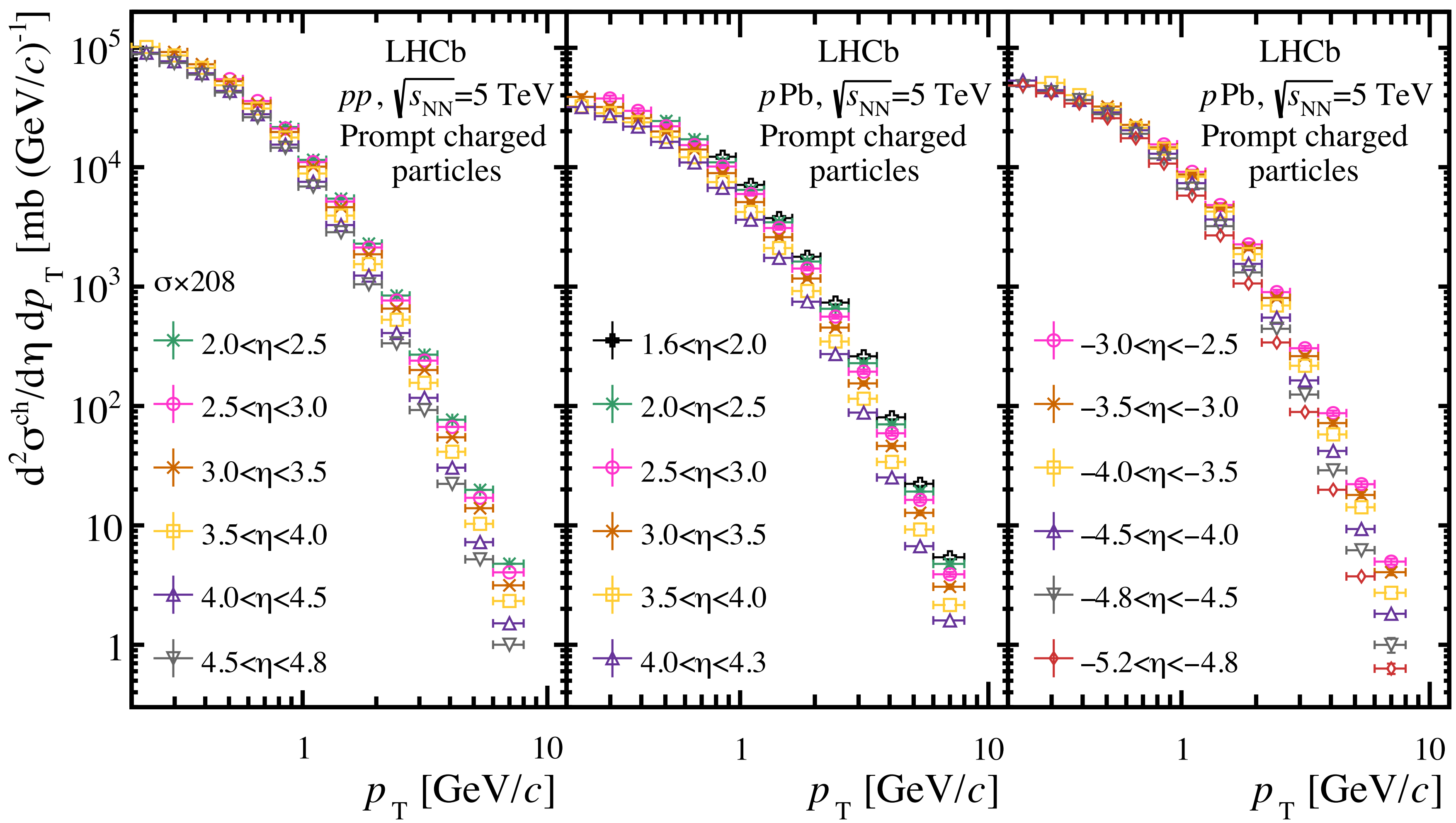
- Measurement dominated by systematic uncertainties:
  - particle composition in pPb for most bins
  - tracking efficiency and signal purity in boundary (η, p_{T}) bins
- Total uncertainty shown in the table:
  - down to $2.8\,\%$ in $\mathrm{d}^2\sigma/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}$
  - down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

Uncertainty source	pPb [%] (forward)	pPb [%] (backward)	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
Signal purity	0.1 – 1.8	0.1 – 11.7	0.1 – 5.8
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 TeV

arXiv:2108.13115

- $$\left.\frac{d^2\sigma}{dp_T d\eta}\right|_{p\text{Pb},pp} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta\eta}$$
  - pp result compared with measurement at $\sqrt{s} = 13\ \text{TeV}$ (arXiv:2107.10090)
  - cross-section at $13\ \text{TeV}$ from $5\ \text{TeV}$ increases a factor $1-3$ depending on p_T, consistent with expectations



Results of $R_{p\mathrm{Pb}}$: forward region

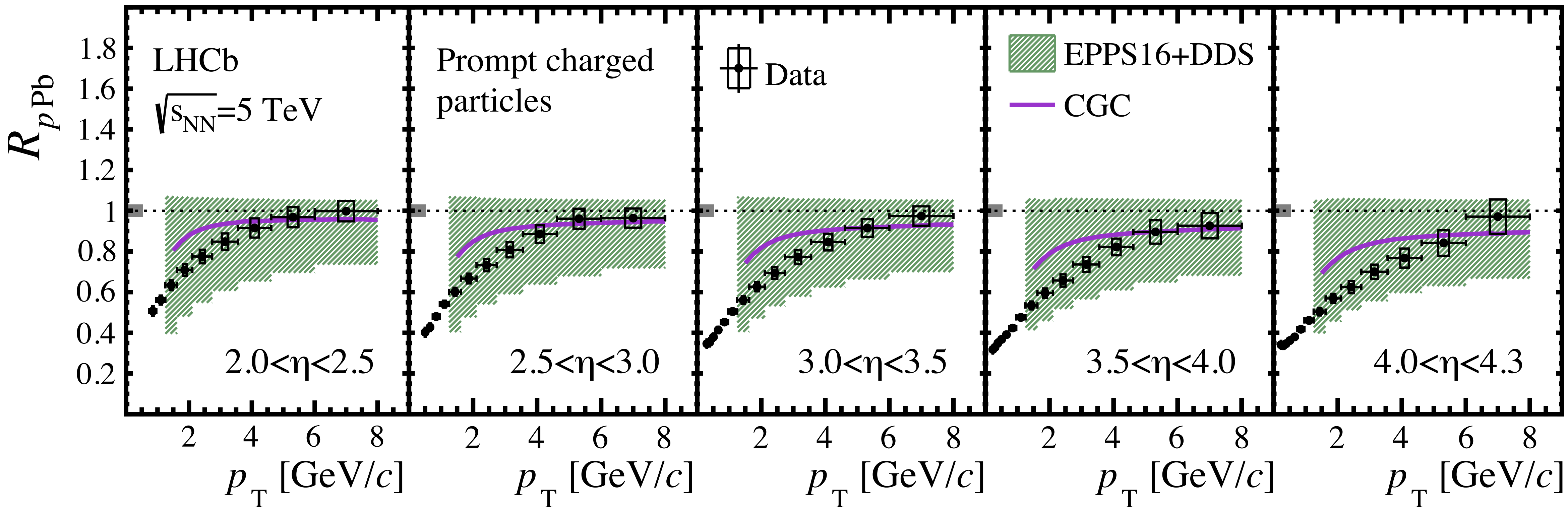
arXiv:2108.13115

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

- **Strong suppression** at forward η, down to ~ 0.3 at low p_T and most forward rapidity
- Discrepancy at low p_T with CGC calculation

Models:

- EPPS16+DDS: I. Helenius *et. al.* JHEP09(2014) 138
- CGC: T. Lappi *et. al.* PR D88, 114020



Results of $R_{p\mathrm{Pb}}$: backward region

arXiv:2108.13115

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

- **Enhancement** at backward for $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$, as observed by PHENIX in $\mathrm{Au}p$
- Observed a η dependence of the enhancement

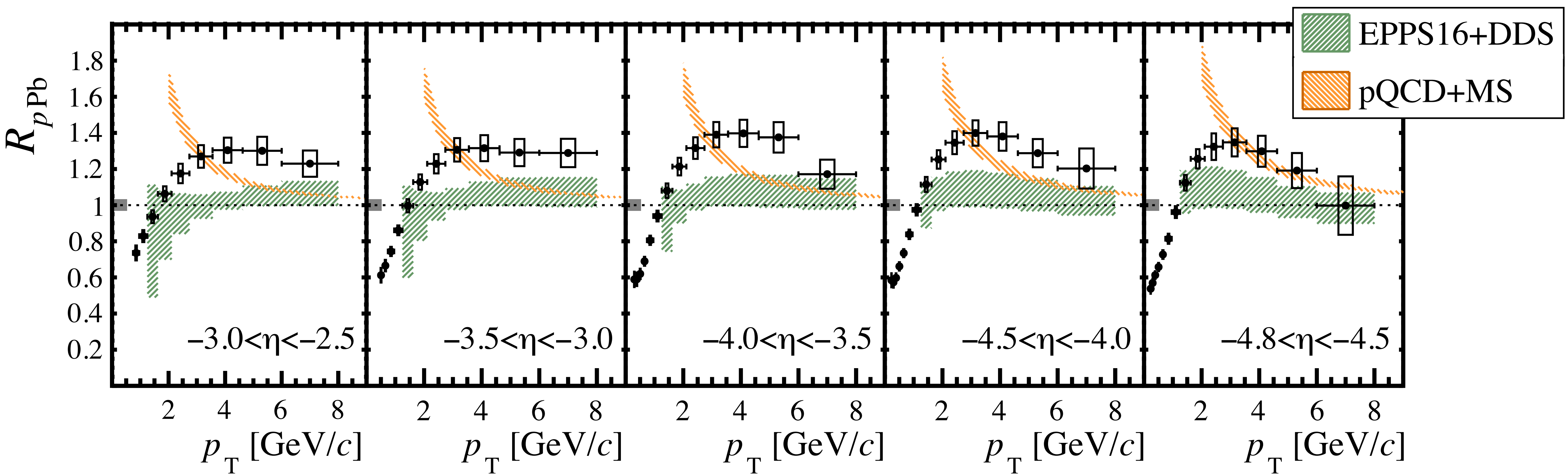
Models:

- EPPS16+DDS: I. Helenius *et. al.* JHEP09(2014) 138
  - does not reproduce enhancement
- pQCD calculation with MS: Z. B. Kang *et. al.*
  - same calculation reproduces enhancement in $\mathrm{Au}p$ collisions at PHENIX

PR C101 (2020) 034910

PL B740(2015) 23

PR D88(2013) 054010



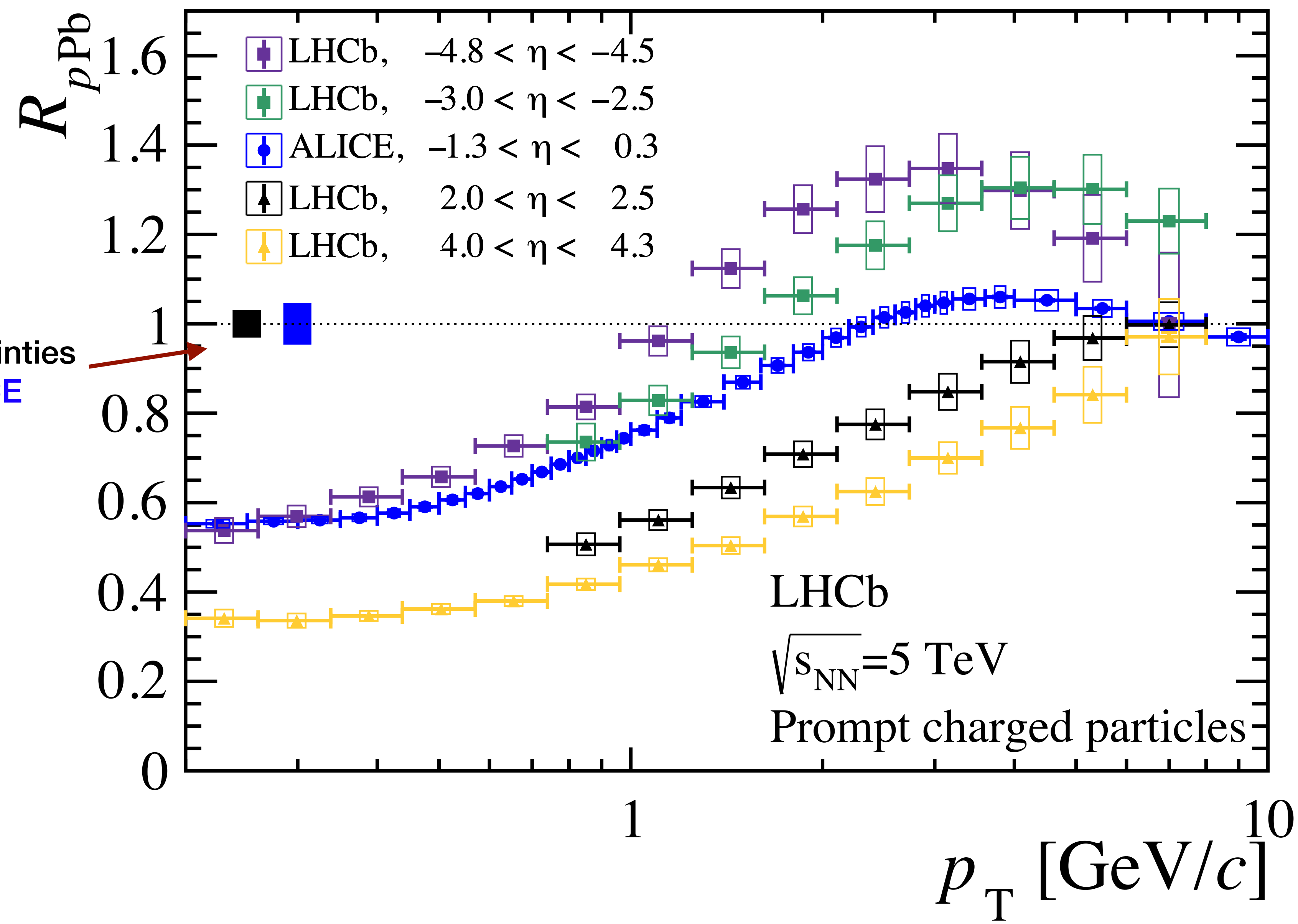
Results of $R_{p\text{Pb}}$: comparison with ALICE

arXiv:2108.13115

ALICE: JHEP 1811 (2018) 013

- Continuous trend of $R_{p\text{Pb}}$ from forward to backward η rapidity, including CMS and ALICE results

Normalization uncertainties for LHCb and ALICE



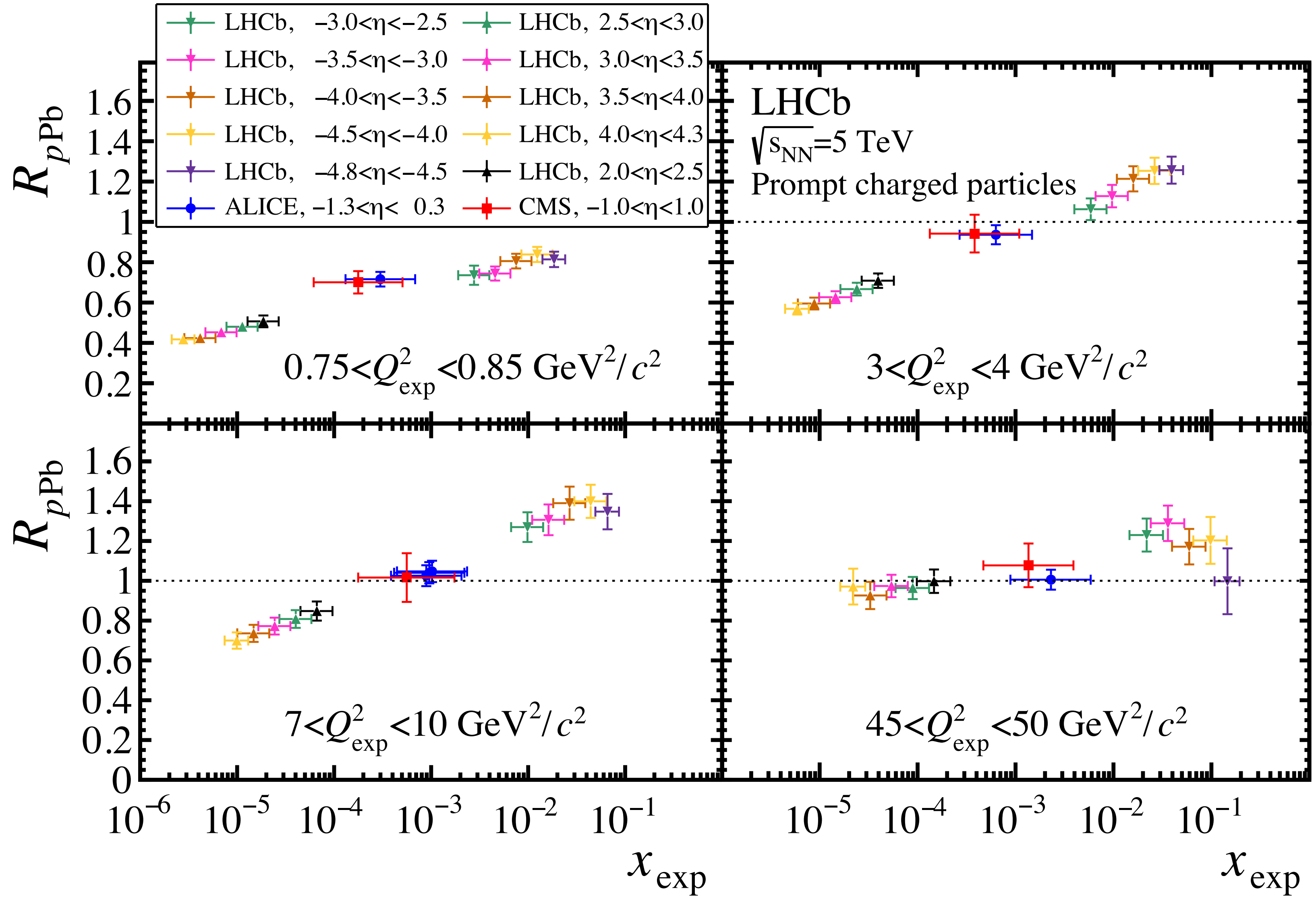
Results of $R_{p\mathrm{Pb}}$: dependence with (x_{exp}, Q^2_{exp})

arXiv:2108.13115

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

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

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



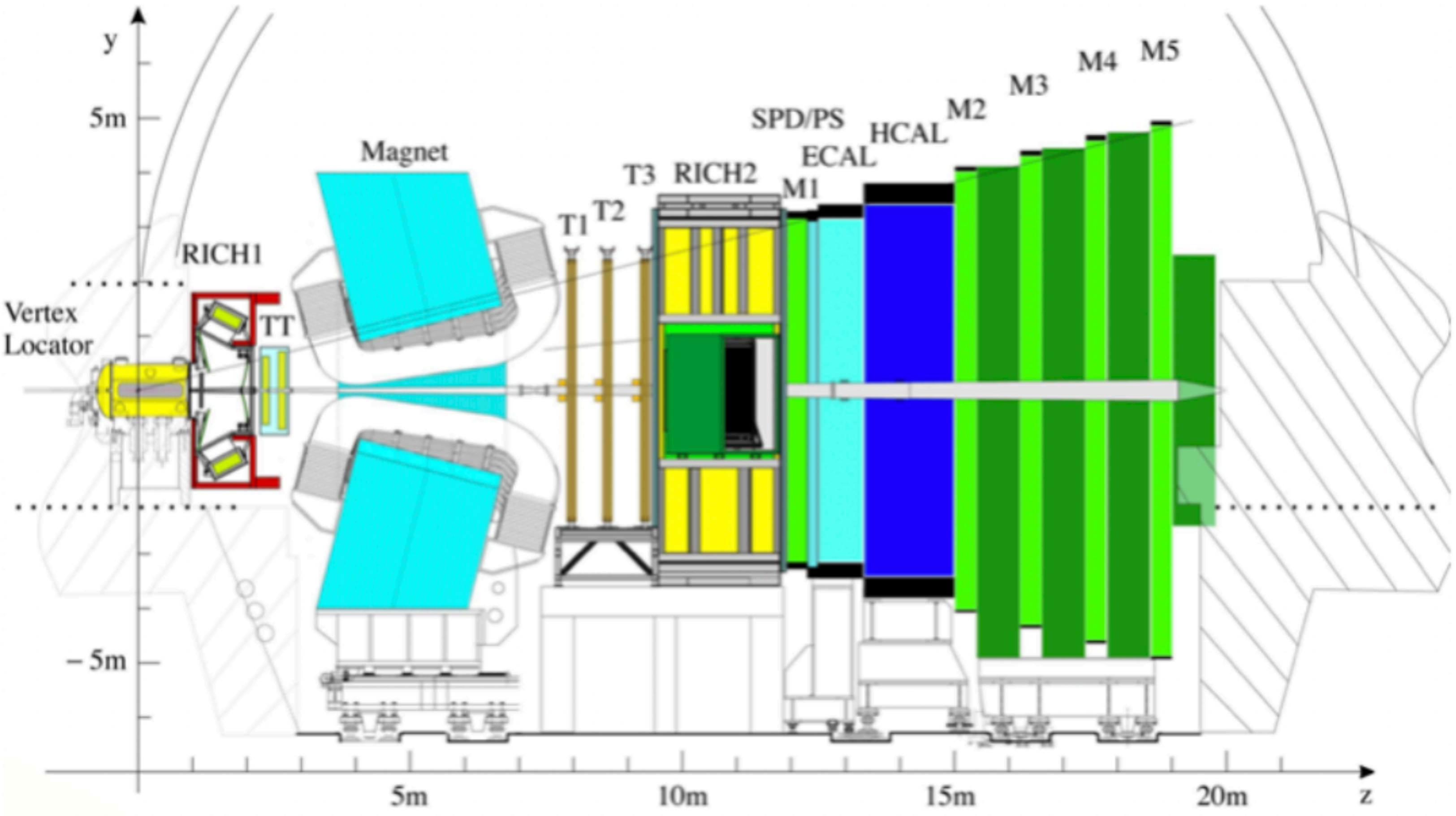
Conclusions

- First determination of $R_{p\mathrm{Pb}}$ for prompt charged particles in forward and backward regions at LHC
  - double-differential prompt charged particle cross-section in pp and $p\mathrm{Pb}$ at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$
  - total uncertainty down to $4.2\,\%$ in $R_{p\mathrm{Pb}}$
  - 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 $p\mathrm{Pb}$ collisions
  - Reduction of systematic uncertainty in this measurement
  - Input to understand enhancement in backward region

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)



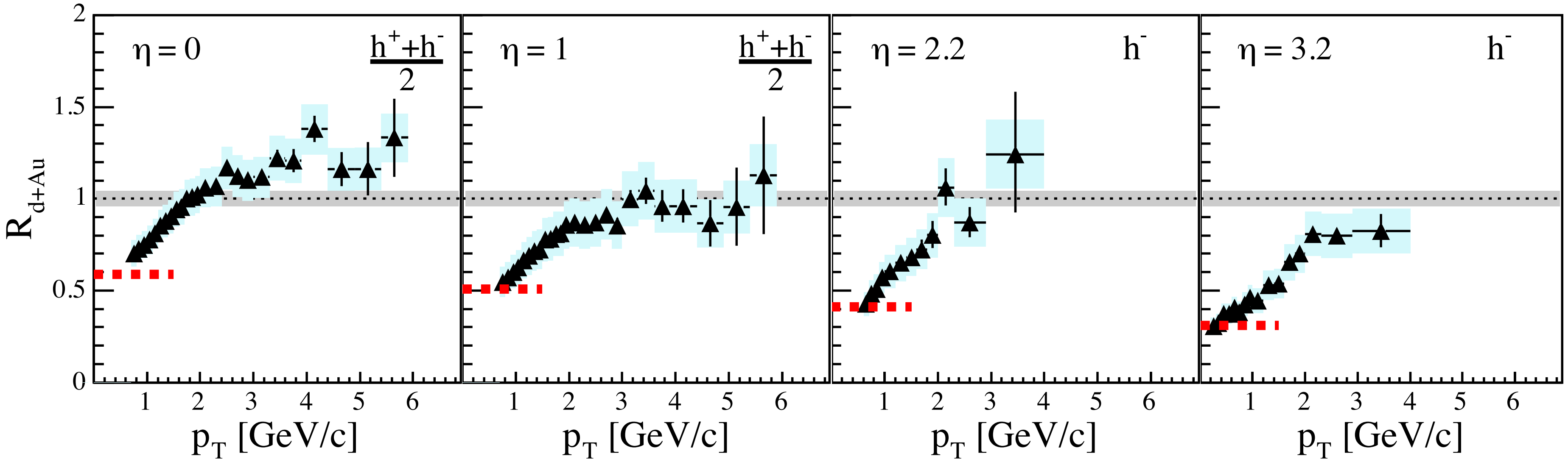
LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

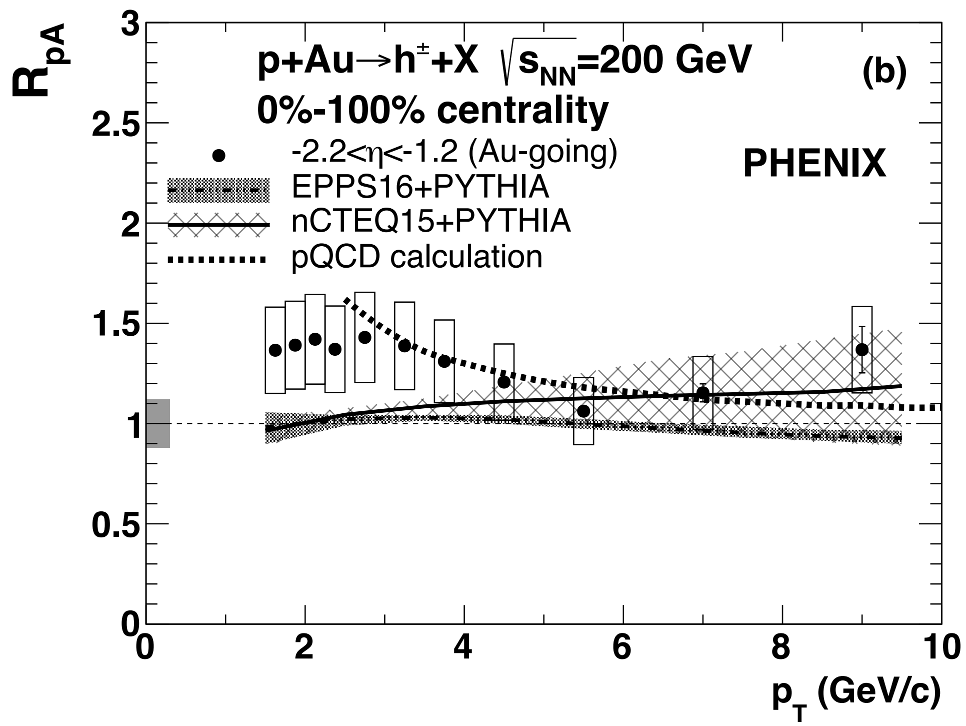
Previous results of $R_{pA,dA}$

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]