Charged particle production in *pp* and *p*Pb collisions at LHCb

HADRON 2021, 27/07/2021, Virtual

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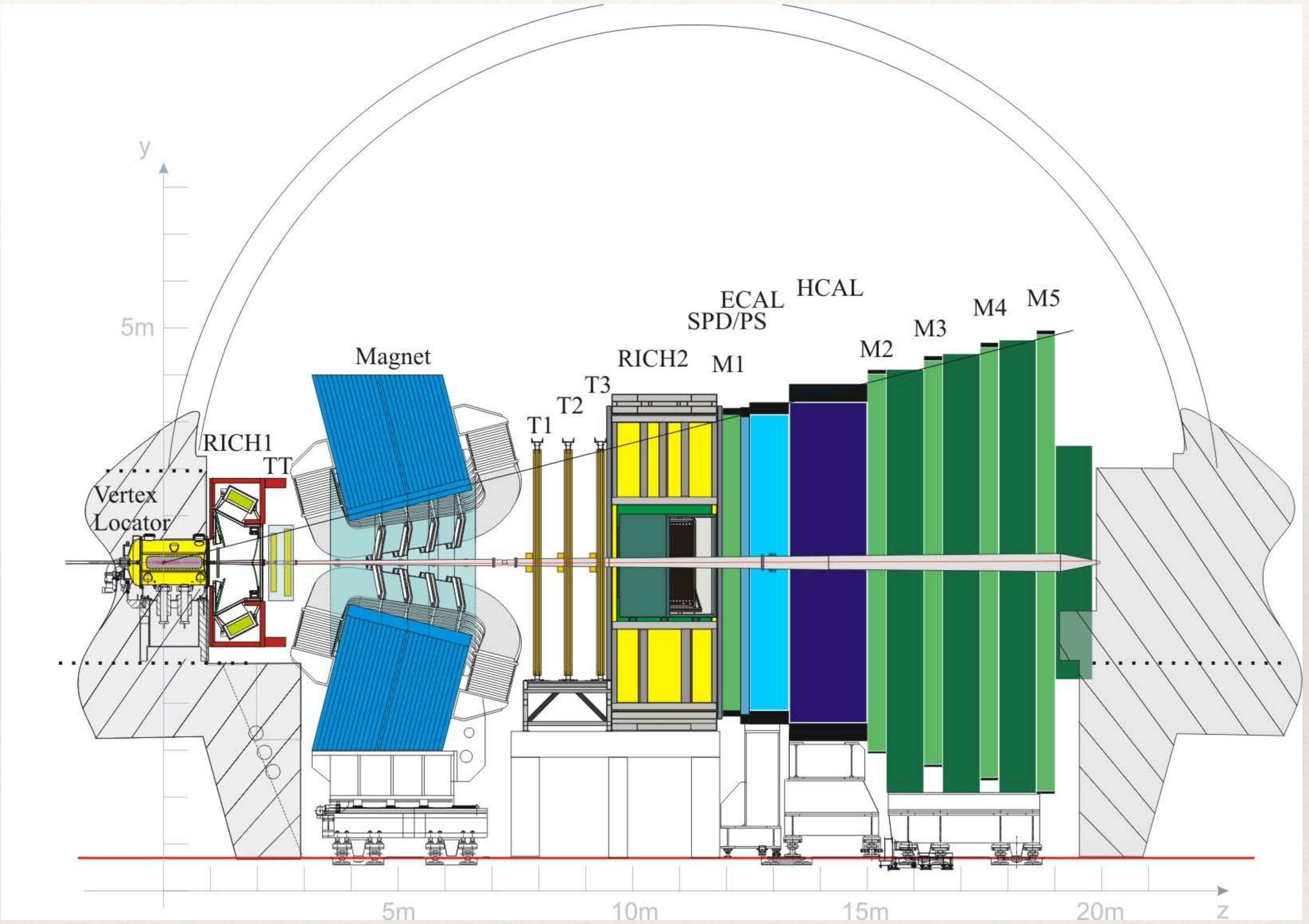
The LHCb detector

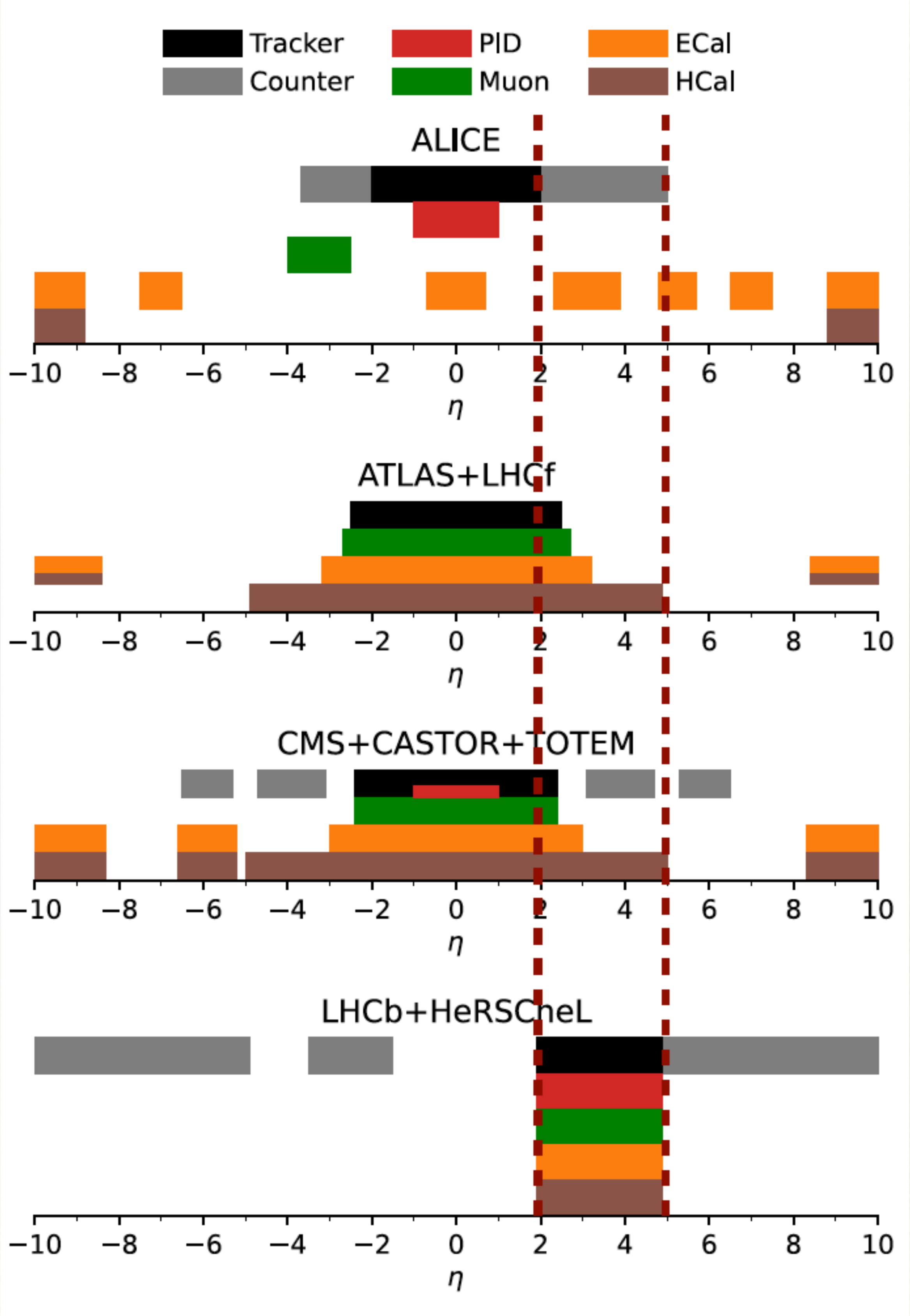
- Single-arm forward spectrometer. Fully instrumented in the region $2<\eta<5$.
- Tracking system with resolution $\delta p/p$=0.5-1% from 2 to 200 GeV.
- Excellent particle identification.
    - Hadron: ~95% efficiency ($K \rightarrow K$) with O(5%) misID ($\pi \rightarrow K$).
    - Muon: ~97% efficiency ($\mu \rightarrow \mu$) with 1-3% misID ($\pi \rightarrow \mu$).
- Excellent vertex resolution $(15 + 29/p_T[\text{GeV}])\mu m$.
- Good calorimeter resolution $\Delta E/E = 1\% + 10\,\%/\sqrt{E[\text{GeV}]}$.
- HeRSCheL detector: veto background in ultra peripheral collisions.
- Flexible trigger, configured to measure very low p_T.



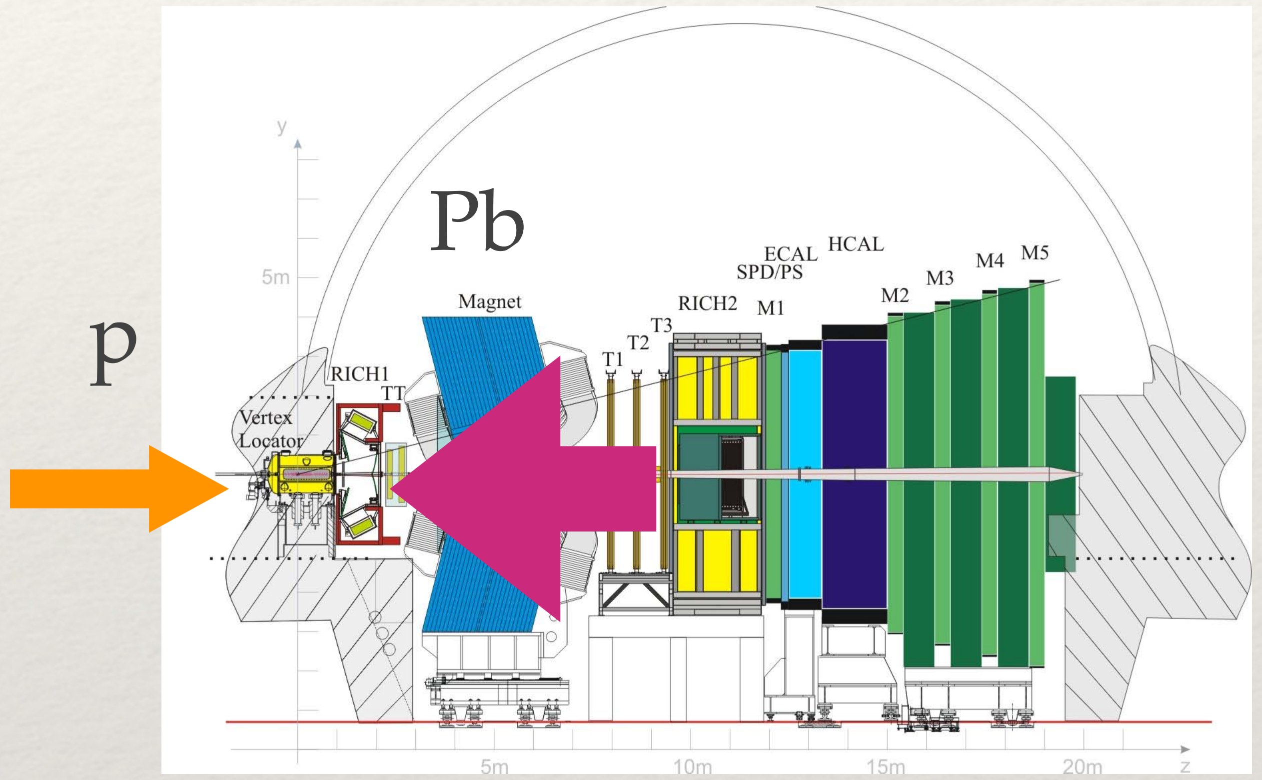
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Heavy Ions at LHCb

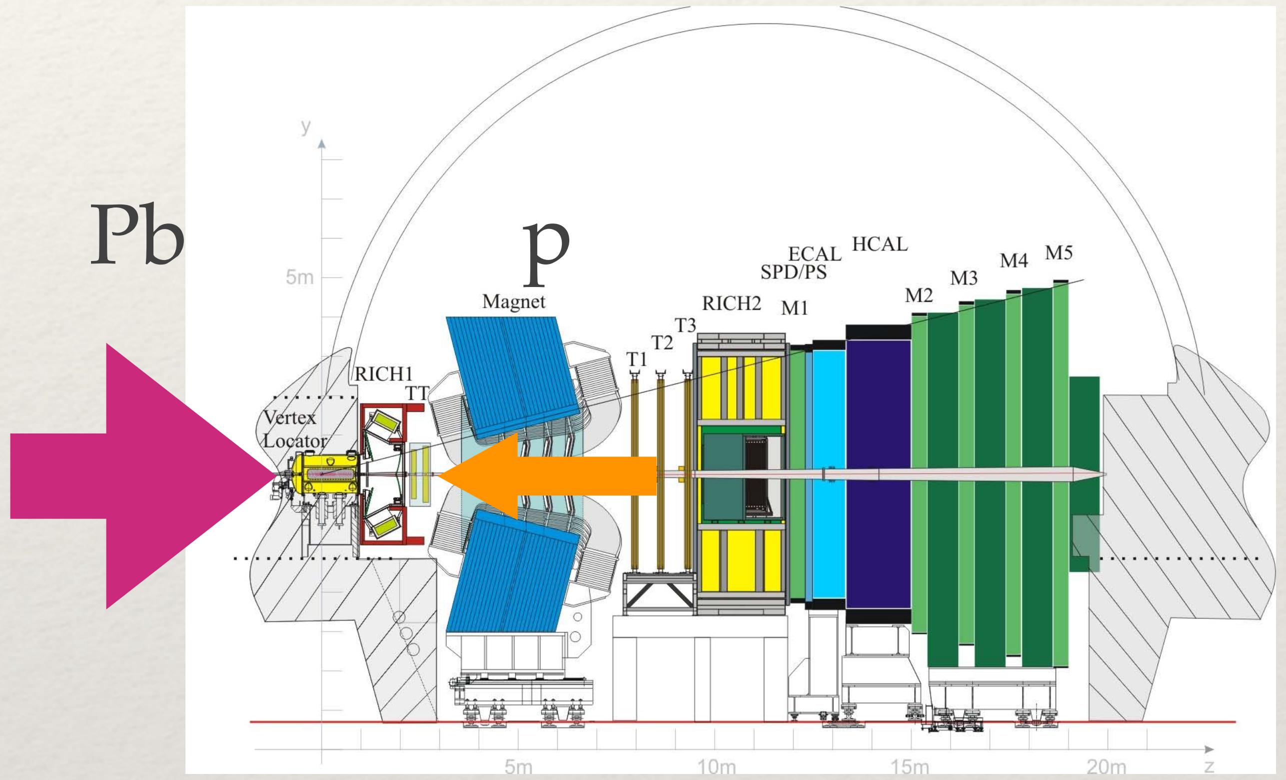
- Only detector at LHC fully instrumented in the forward region.



arXiv:2105.06148v1



Forward η>0



Backward η<0

Different energies of Pb and p beams: boost of nucleon-nucleon cms system $\eta = \eta_{lab} - 0.465$

Today's results

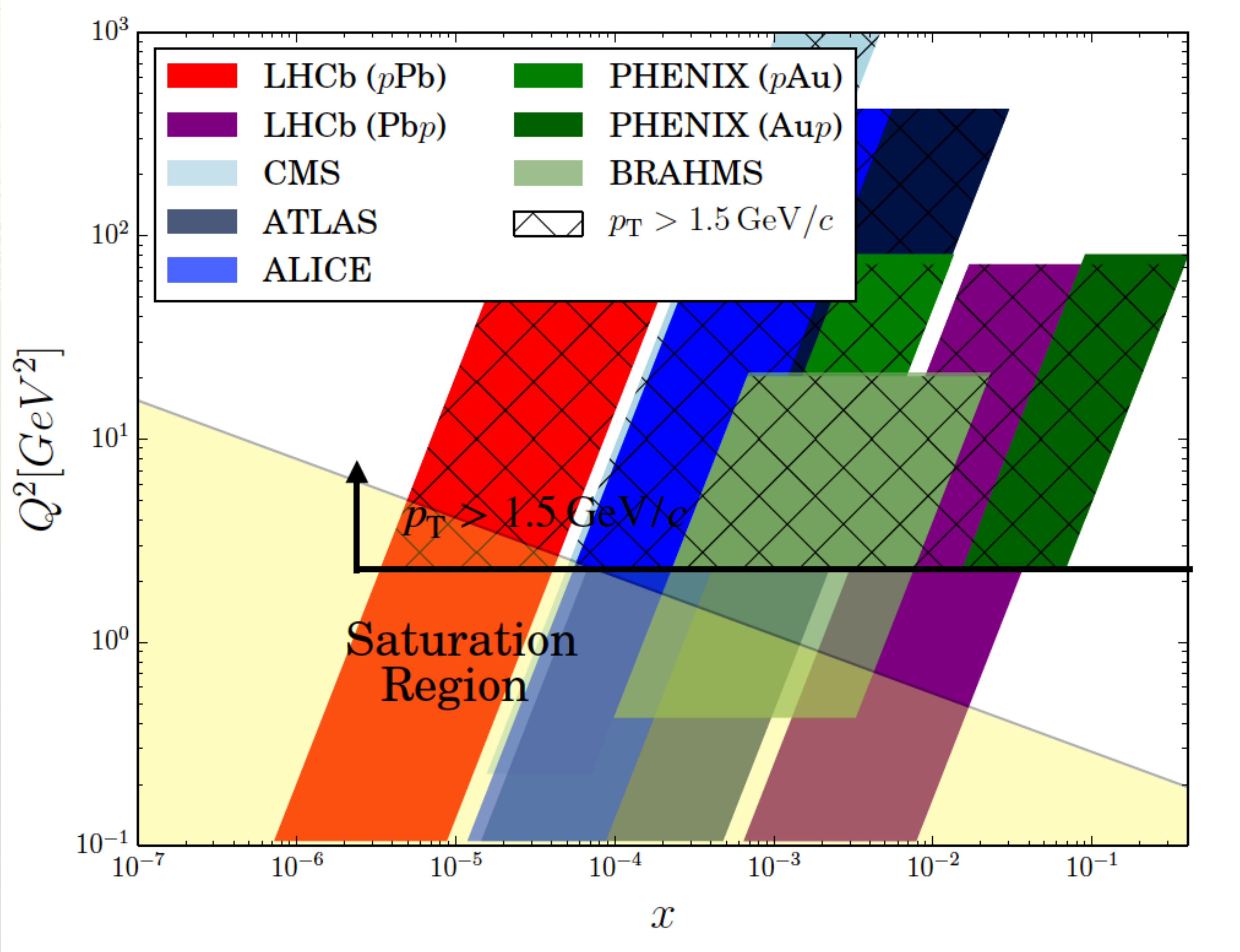
- Prompt-charged particle production in *pp* at 13 TeV.
  - arXiv:2107.10090
- Prompt charged particle production in *p*Pb and *pp* at 5 TeV.
  - LHCb-PAPER-2021-015 (in preparation)

Motivation of the analyses

- Goal: measure inclusive prompt charged particle spectra in *pp* and *p*Pb collisions with respect to (η, p_T).
- Motivation:
  - Description of hadron production in *pp* and *p*A.
    - Impact in cosmic-ray physics. Could explain observed excess in muons from hadronic cascades of high-energy cosmic rays [arXiv:2105.06148v1].
    - MC generator predictions disagree at LHCb acceptance. Important for underlying event simulation.
  - Phenomenology of HI collisions. Measure $R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) = \dfrac{1}{A}\dfrac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/d\eta dp_{\mathrm{T}}}$
    - Measure of Cold Nuclear Matter effects as baseline for PbPb collisions.
    - Description of shadowing/antishadowing in nuclear PDFs.
    - Saturation effects.
    - Cronin effects.

LHCb (x,Q²) coverage

- LHCb has access to unique Bjorken-x range:
  - Q²: exchange momentum between interacting partons.
  - x: momentum fraction from Pb parton:
    - forward, $10^{-6} \lesssim x \lesssim 10^{-4}$
    - backward, $10^{-3} \lesssim x \lesssim 10^{-1}$



- Possible access to saturation region in perturbative scale $p_T > 1.5$ GeV/c.
- Backward acceptance overlaps with (x,Q²) at **central BRAHMS (dAu)** and **backward PHENIX (Aup)**.

PRD 59 (1998) 014017
PRL 100 (2008) 022303

Prompt charged particle production in *pp* at 13 TeV

arXiv:2107.10090

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

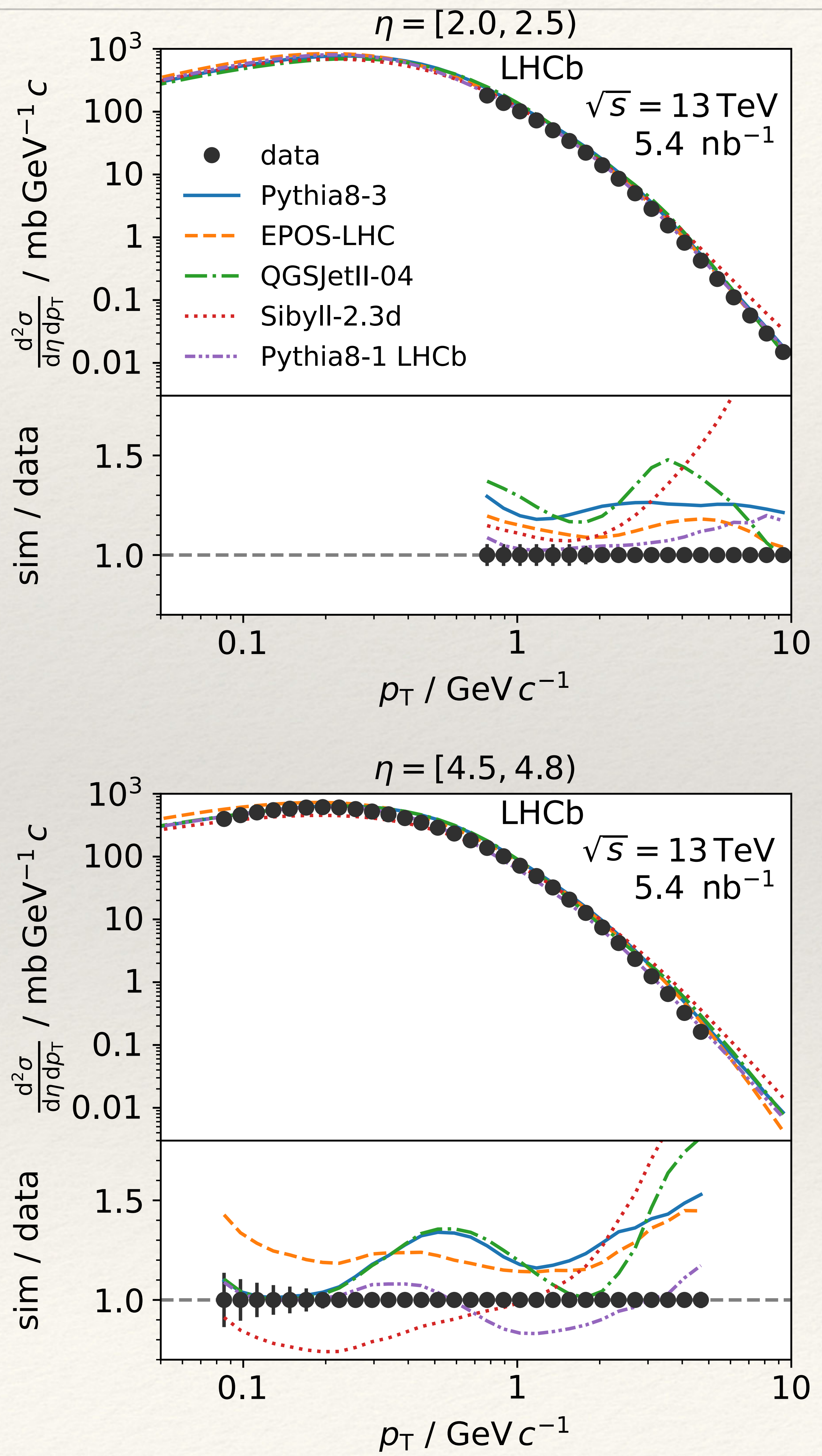
$n_\mathrm{cand} = \epsilon n + \sum_i n_{\mathrm{bkg},i}$: prompt charged particle yield

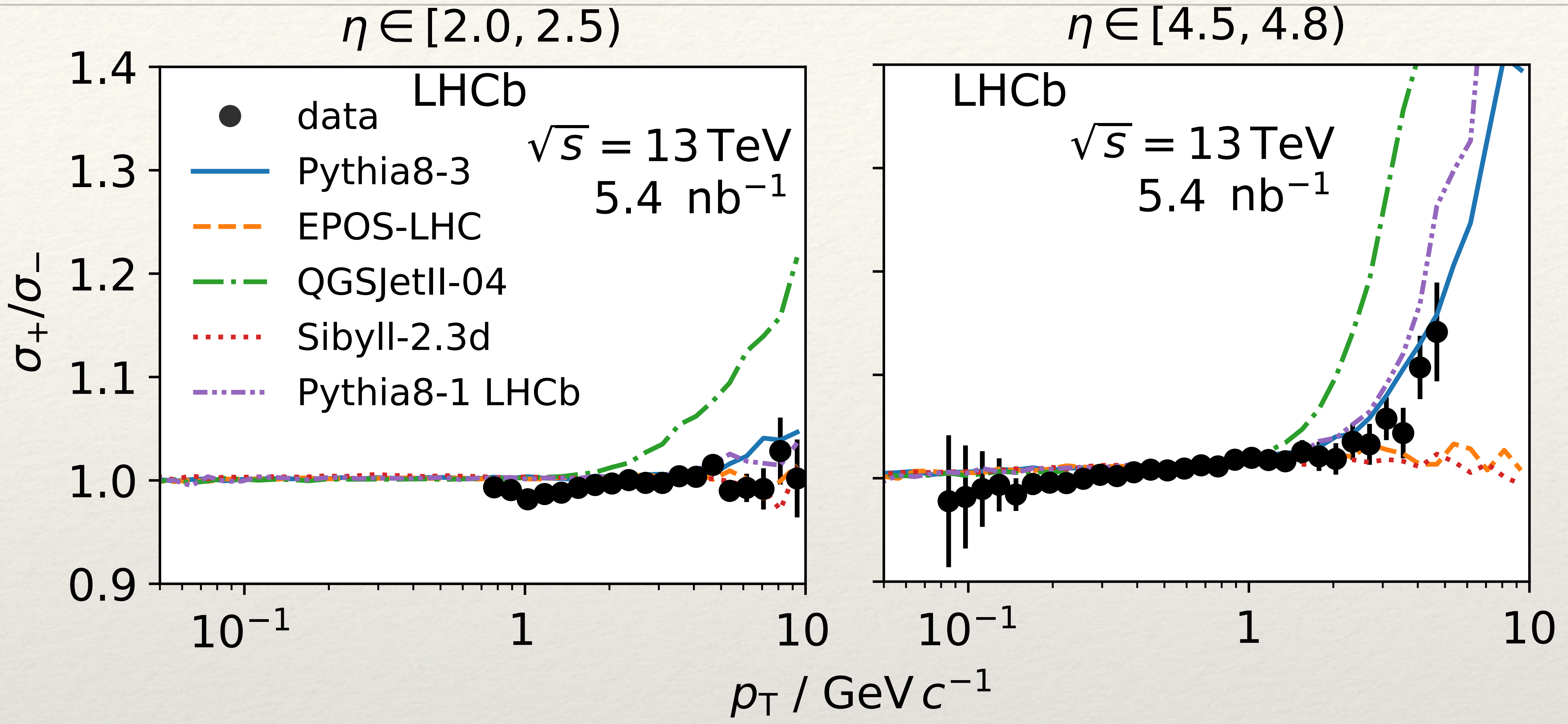
ϵ : detection and selection efficiency

- First double-differential forward charged particle spectrum at 13 TeV.
  - Measured in range $0.08 < p_T < 10\,\mathrm{GeV}$. Unbiased trigger. Separated by charge.
  - Prompt charged particles: charged hadrons and leptons directly from collision or from decays of particles with $\tau < 30\,ps$.
- Crucial measurement for (soft-)QCD, astroparticle physics and generator tuning.
- Loose candidate selection with high efficiency.
- Total efficiency from simulation corrected by data.
- Background subtracted using simulation corrected by data; e.g. fake tracks, tracks from material interactions.

Prompt charged particle production in *pp* at 13 TeV

arXiv:2107.10090





- Uncertainty dominated by systematics. Huge variation across bins.
  - On average less than 5%.
- Comparison with QCD generators.
  - Mostly overestimate forward density.
  - Charge density: best agreement with EPOS-LHC.
  - Charge ratio: best agreement with Pythia-8.3.

Prompt charged particle production in *p*Pb and *pp* at 5 TeV

LHCb-PAPER-2021-015
(in preparation)

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

N^{ch} : prompt charged particle yield
$\Delta\eta, \Delta p_T$: bin size
$\mathscr{L}$: integrated luminosity of the dataset

- Prompt charged particles: charged hadrons and leptons directly from collision or from decays of particles with $\tau < 30\,ps$.
    - Measured from reconstructed tracks, in range $p > 2\,\mathrm{GeV/c}$ and $0.2 < p_T < 8\,\mathrm{GeV/c}$. Unbiased trigger.
- Datasets at 5 TeV:
    - *pp* cover $2 < \eta < 4.8$
    - *p*Pb (Pb*p*) cover $1.5 < \eta < 4.3 (-2.5 < \eta < -5.2)$
    - Measure $R_{p\mathrm{Pb}}$ in common η range.
- Reconstructed tracks need to be corrected from background and reconstruction and selection efficiencies.

Differential cross-sections results

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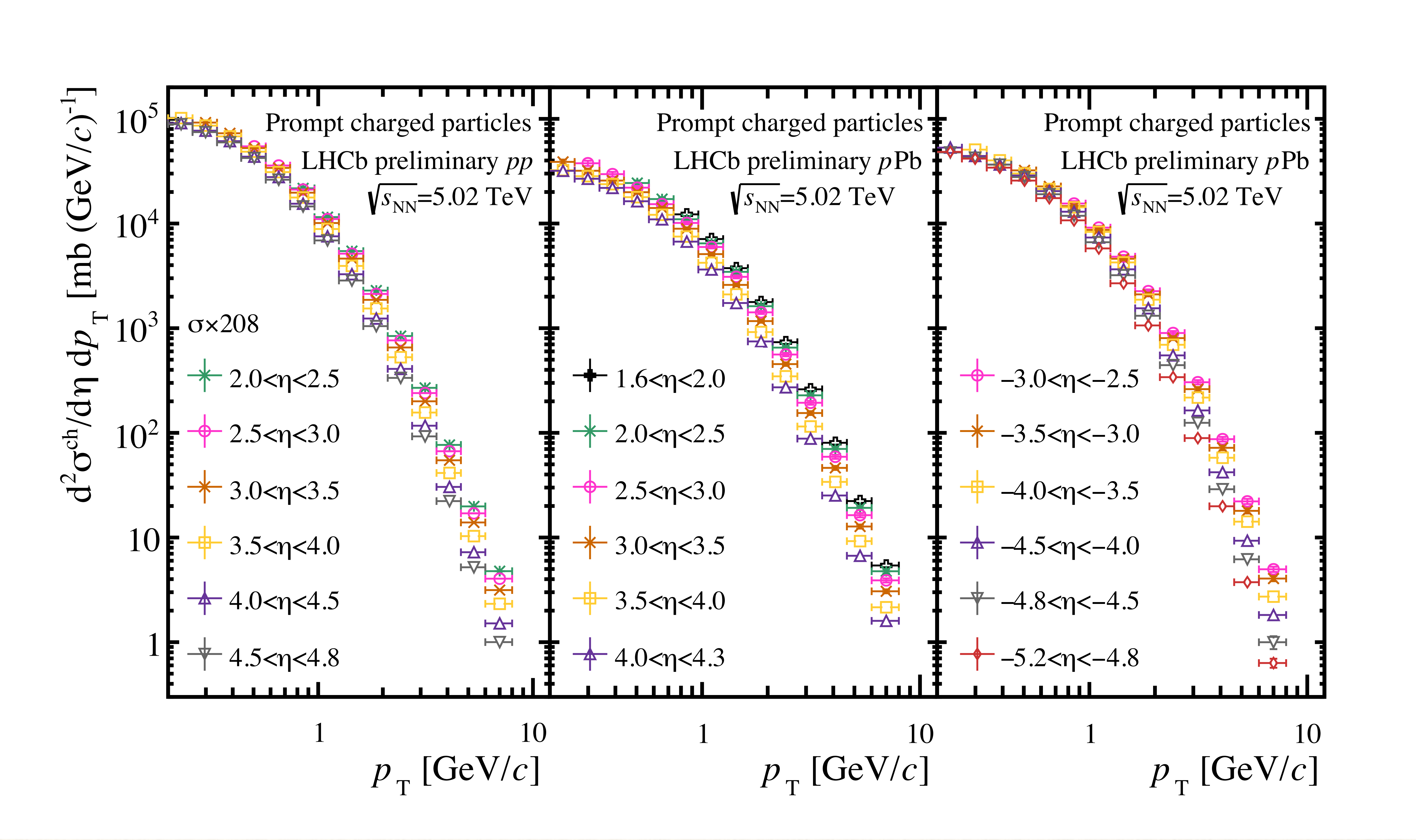
(in preparation)

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

Measured in *pp*, *p*Pb and Pb*p*.



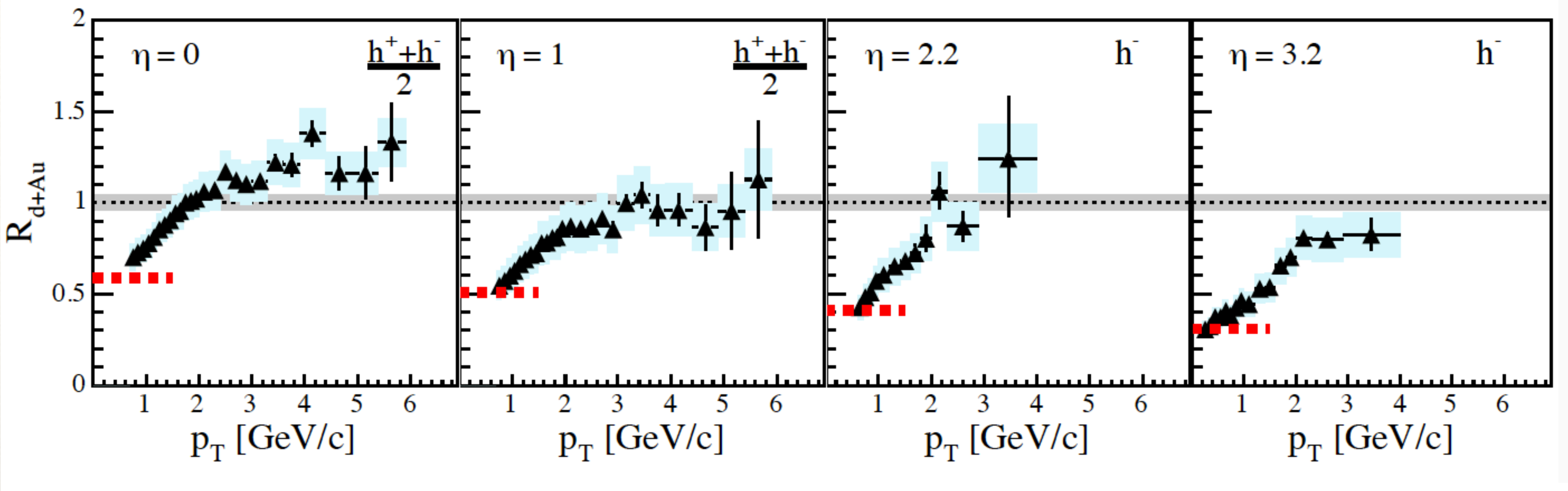
Compatible with the result at 13TeV.

Measurement dominated by systematic uncertainties. Most (η, p_T) bins with uncertainty <3% in cross-section and <5% in R_{pPb}.

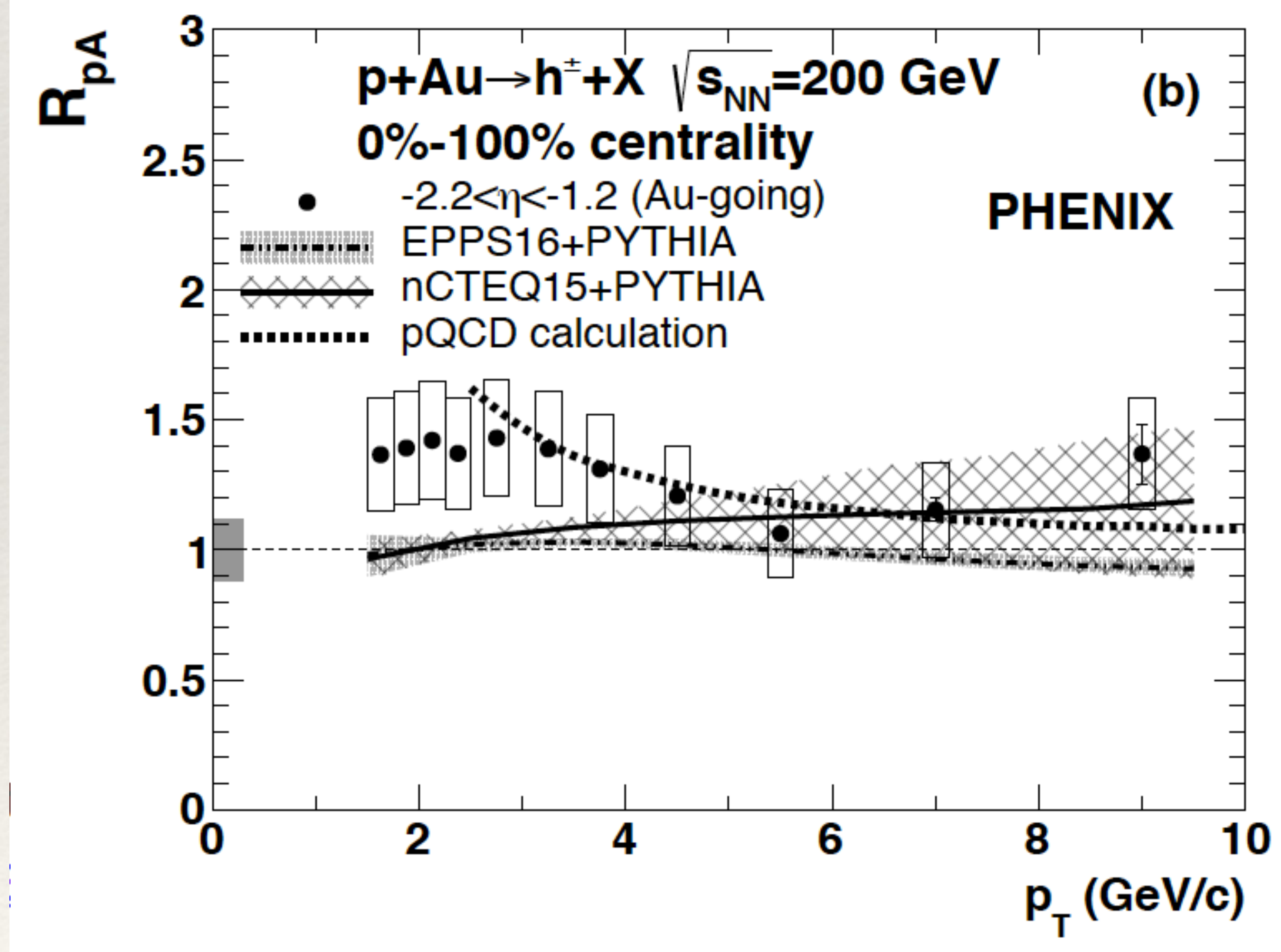
Uncertainty source	*p*Pb [%] (forward)	*p*Pb [%] (backward)	*pp* [%]
Track-finding efficiency	1.5 – 5.0	1.5 – 5.0	1.6 – 5.3
Detector occupancy	0.0 – 2.8	0.6 – 2.9	0.1 – 1.6
Particle composition	0.4 – 4.1	0.4 – 4.6	0.3 – 2.4
Selection efficiency	0.7 – 2.2	0.7 – 3.0	1.0 – 1.7
Purity	0.1 – 1.8	0.1 – 11.7	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 $d^2\sigma/d\eta dp_T$)	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	–

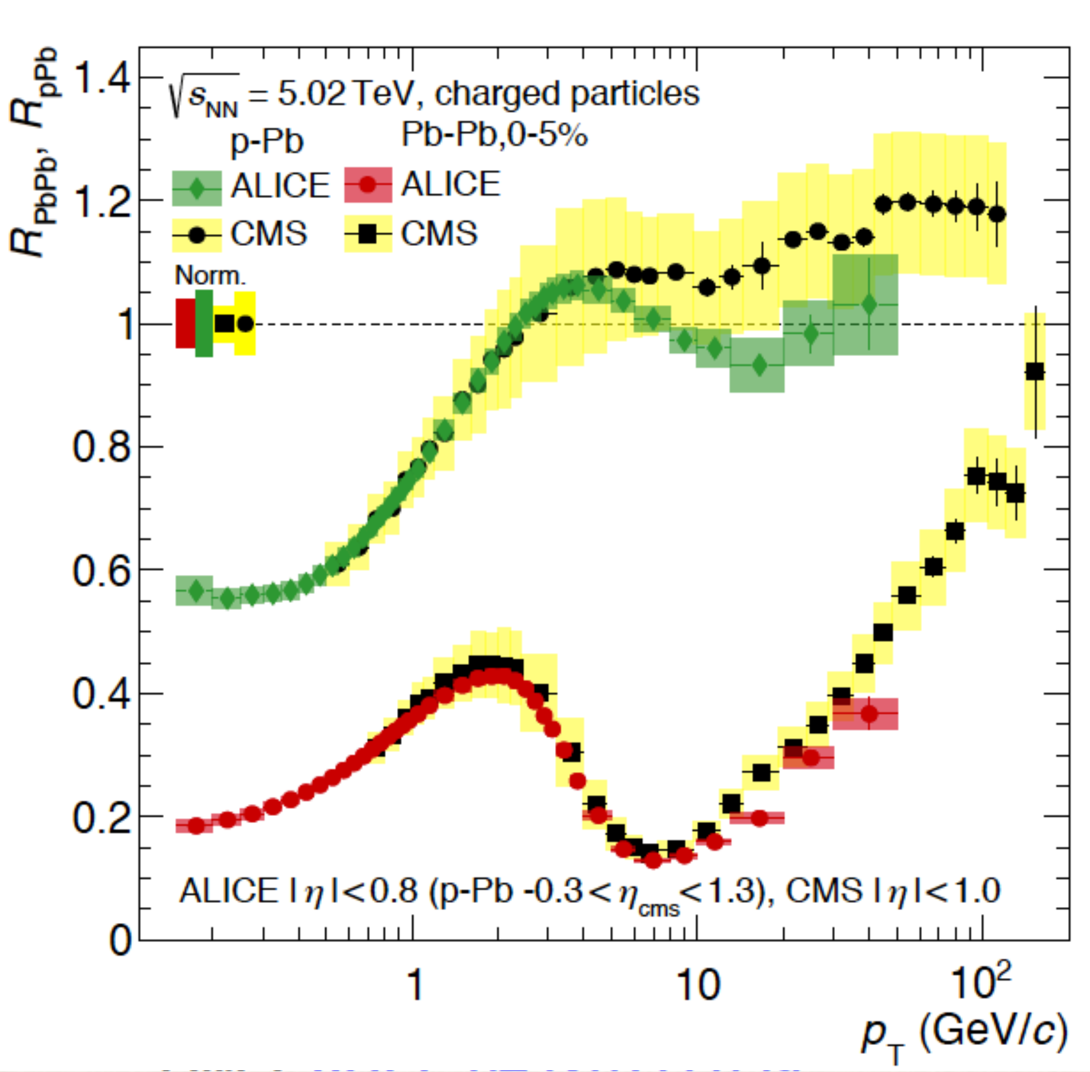
Previous measurements of $R_{pA,dA}$

BRAHMS R_{dAu} (2004)
[PRL 93 (2004) 242303]



PHENIX R_{pAu} (2020)
-2.2<η<-1.2
[PRC 101 (2020) 034910]





CMS R_{pPb} (2018)
|η|<1.0
[JHEP 04 (2017) 039]

ALICE R_{pPb} (2020)
0.3<η<1.3
[JHEP 1811 (2018) 013]

Also measurements from ATLAS [PRL 763 (2016) 313] and PHENIX R_{dAu} [PRL 91 (2003) 072303]

Nuclear modification factor $R_{p\mathrm{Pb}}$

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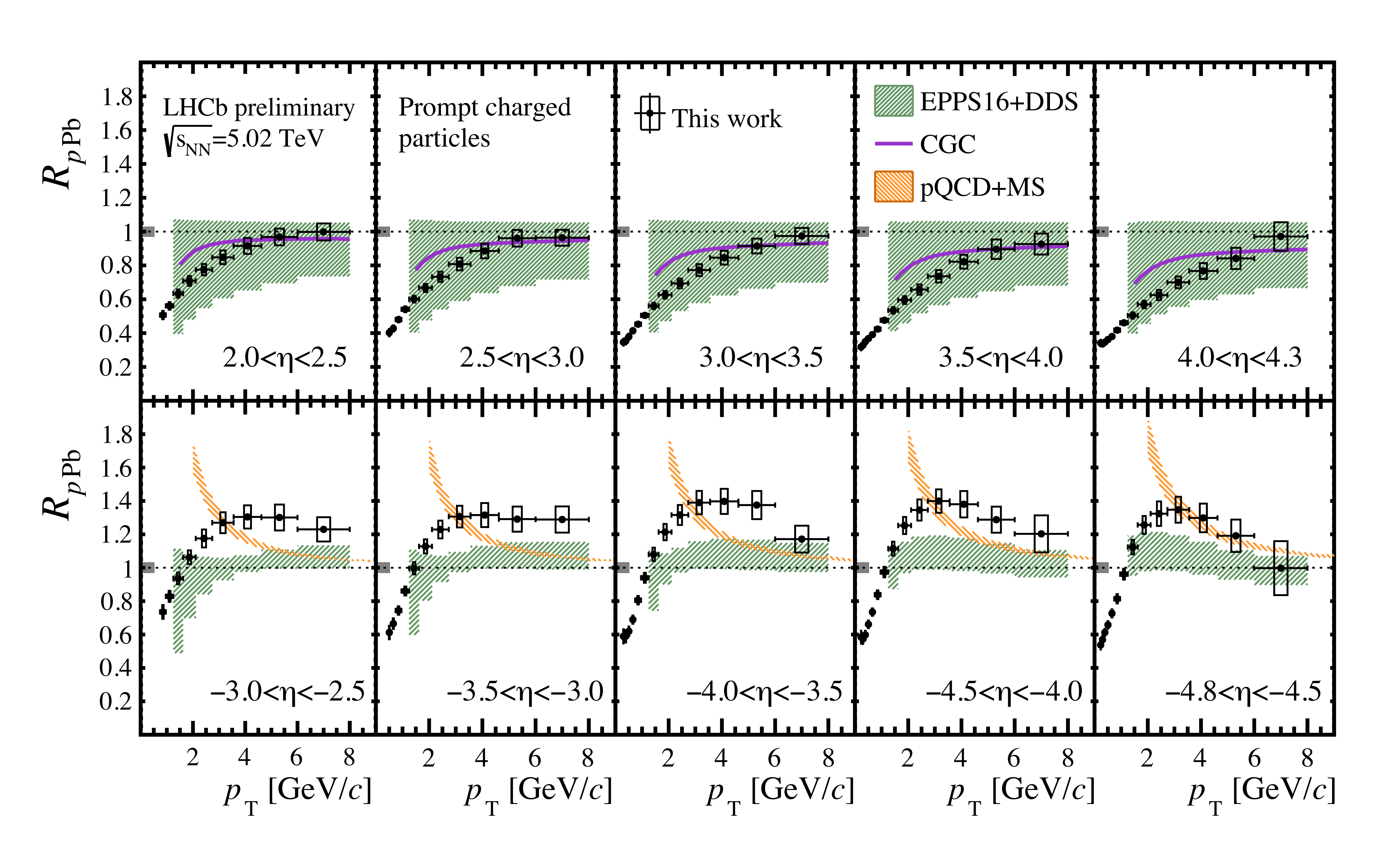
(in preparation)

- Nuclear modification factor

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

- Strong suppression at forward η.
- Enhancement at backward for $p_T > 1.5\,\mathrm{GeV/c}$ as observed by PHENIX in Aup.
  - Models:
    - **EPPS16+DDS**: I. Helenius et al. [JHEP09(2014)138].
    - **CGC (Color Glass Condensate)**: T. Lappi et al. [PRD88(2013)114020].
    - **pQCD calculation with MS**: Z.B. Kang et al. [PRD88(2013)054010, PLB740(2015)23].



Comparison with ALICE and CMS

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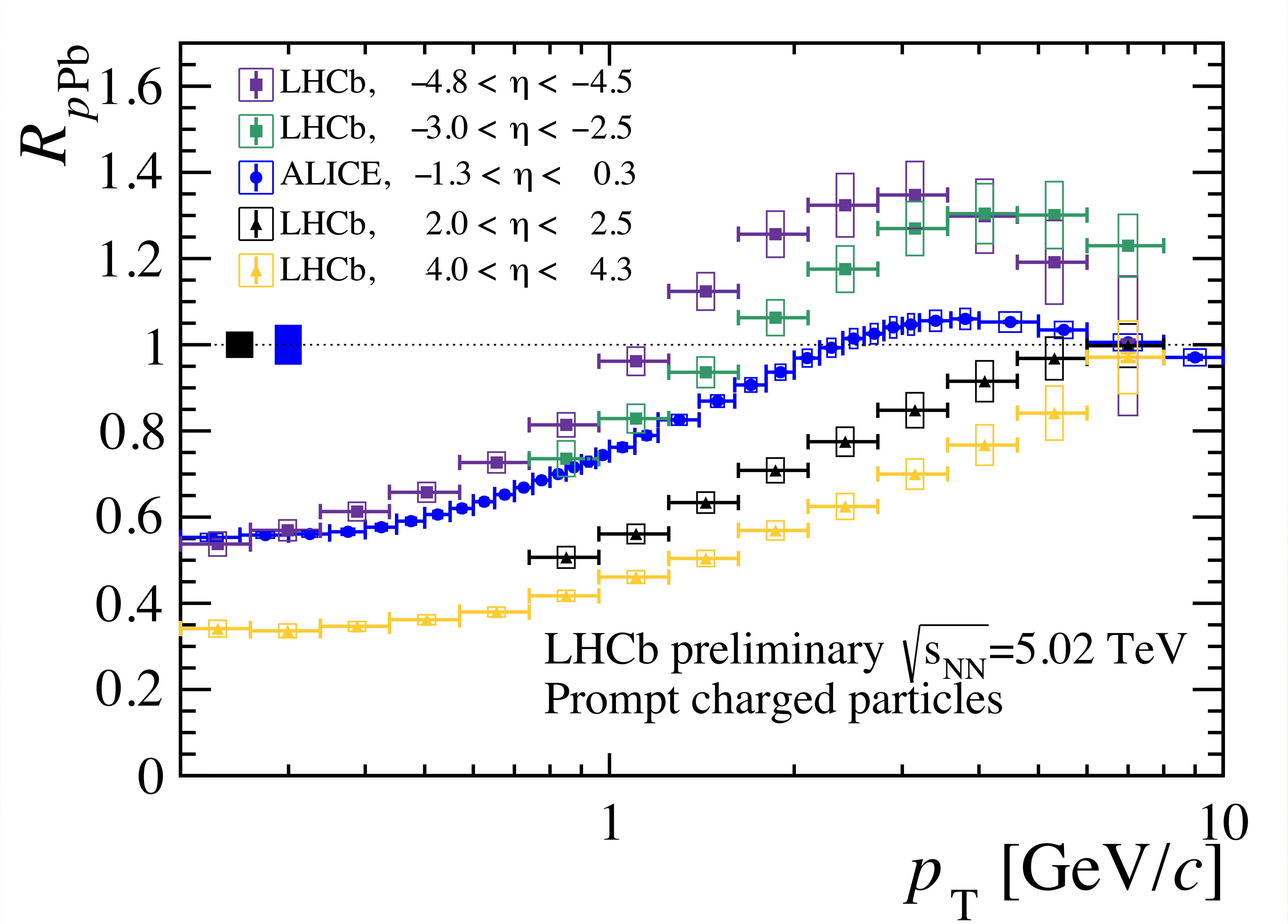
(in preparation)



- Continuous trend from forward to backward η including ALICE results [JHEP 1811 (2018) 013].
- Enhancement in backward regions starts at different p_T for different η.

Comparison with ALICE and CMS

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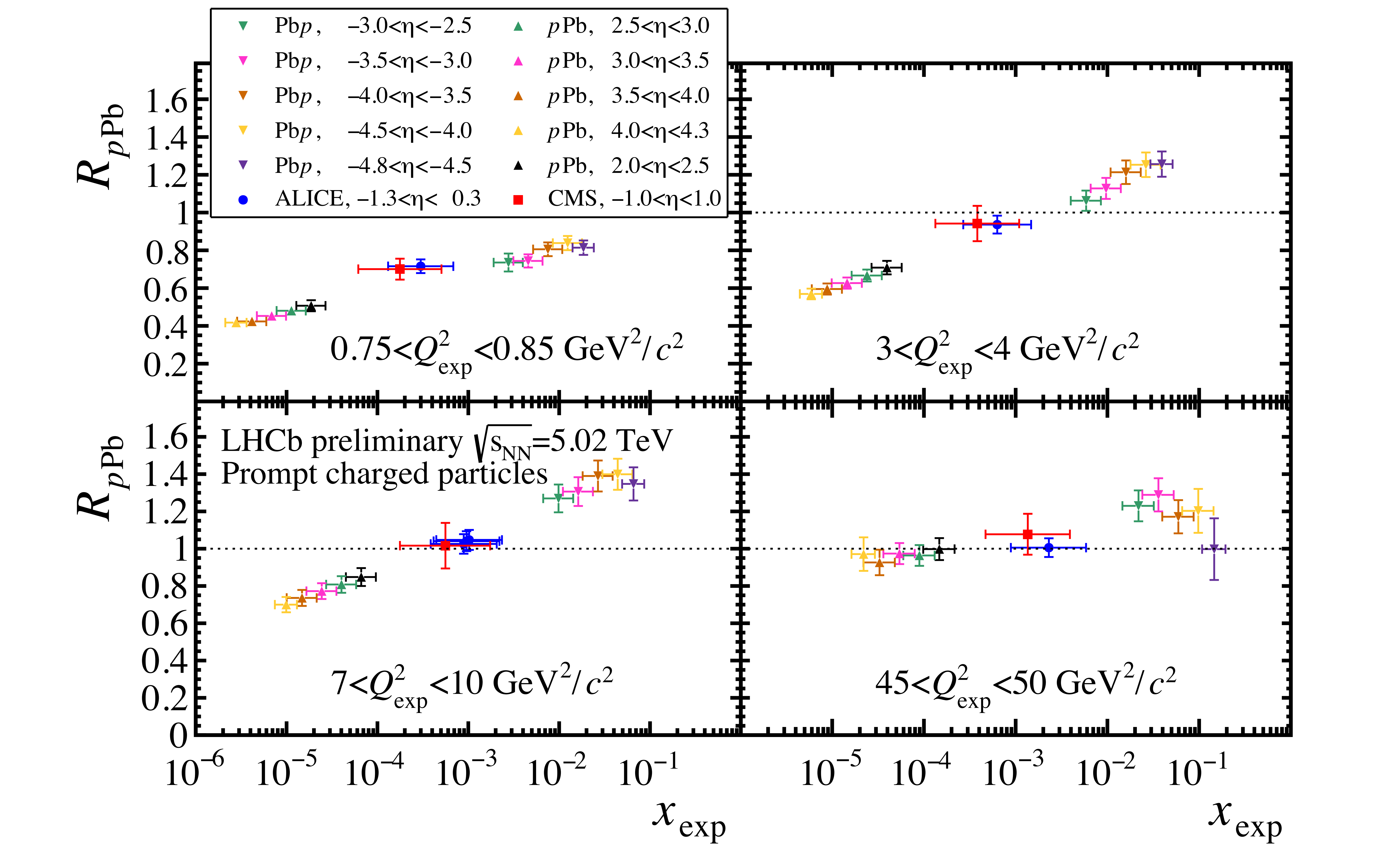
(in preparation)

- Q^2_{exp} and x_{exp} are proxies for Q^2 and x.
  - $Q^2_{exp} \equiv m^2 + p_T^2$, with $m = 256\,\text{MeV}$
  - $$x_{exp} \equiv \frac{Q^2_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$
- 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.



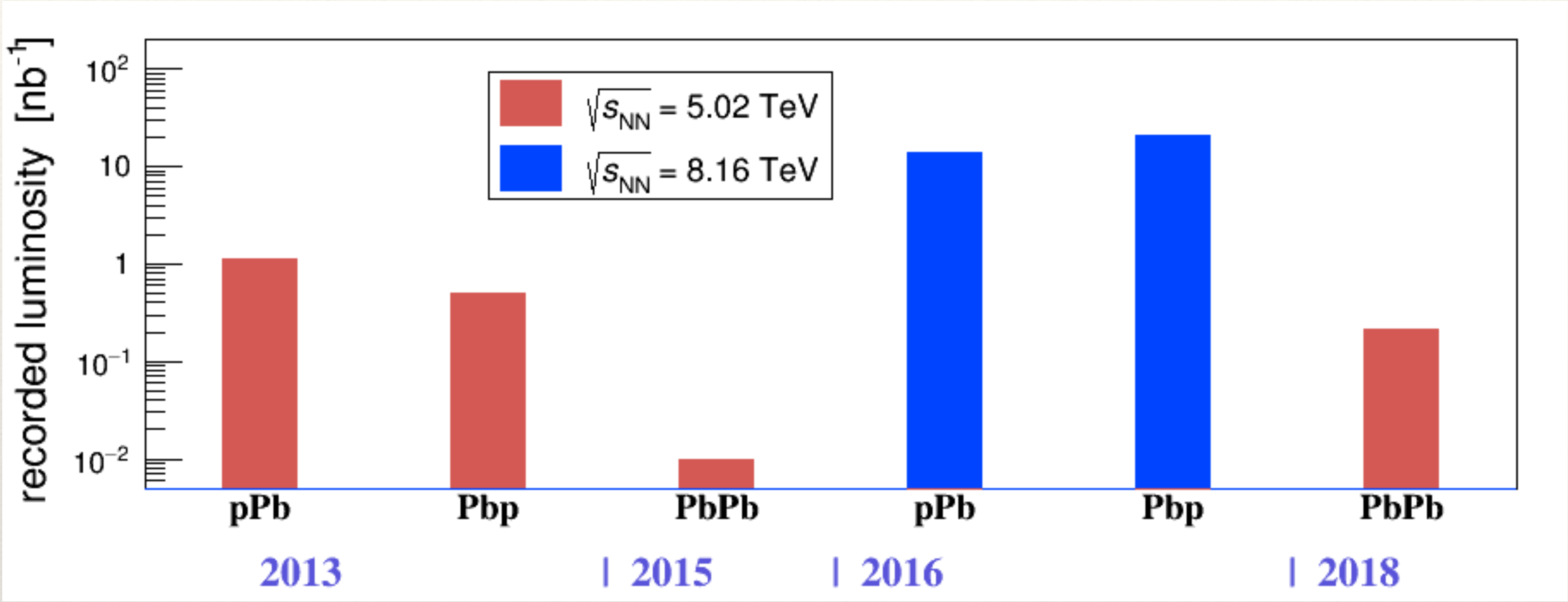
Conclusions

- Recent results of charged particle production in *pp* and *p*Pb collisions presented.
  - First measurement of double differential cross-section in forward region at 13 TeV.
    - Important input for astroparticle physics and generator tuning.
  - First determination of $R_{p\mathrm{Pb}}$ for prompt charged particles in forward and backward regions at LHC.
    - Measure prompt charged particle production cross-section in *pp* and *p*Pb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$.
    - Relative uncertainty in $R_{p\mathrm{Pb}}$ below 5%.
    - Study of cold nuclear matter effects over wide range of Bjorken-x.
    - Strong constraint to nuclear PDFs and saturation models down to very low Bjorken-x.

Backup

Available datasets

- Full Run 1+2 dataset from Heavy Ion collisions:



- Also pp data at 5, 7, 8 and 13 TeV samples available. Total of 9 fb^{-1}.
- Data from pPb collisions are an ideal benchmark to study cold nuclear matter effects and collectivity in small systems.

Prompt charged particle production in *pp* at 13 TeV

LHCb-PAPER-2021-010
(in preparation)

- Measurement dominated by systematic uncertainties.
- Systematic uncertainties vary heavily across the bins.
  - Overall below 5%.
  - Typically dominated by the proxy samples for efficiency calculations.
- Uncertainty (2.3 to 15) %:
  - Fake tracks < 9.5%.
  - Material interactions < 12%.
  - Tracking efficiency < 5.1%.