Forward hadron suppression at the LHC

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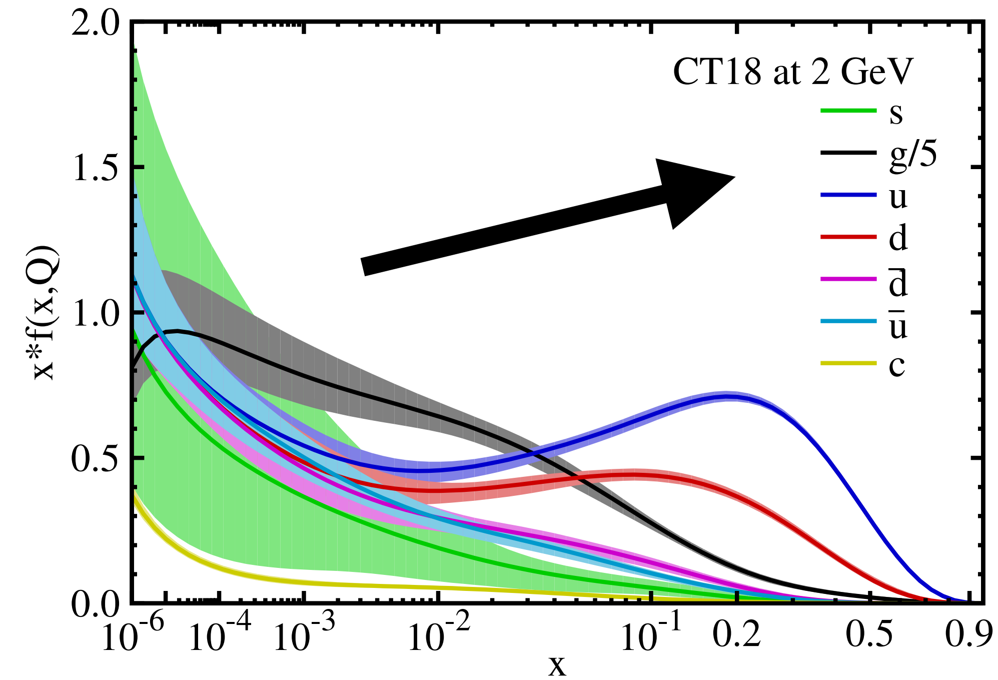
Low-x phenomena

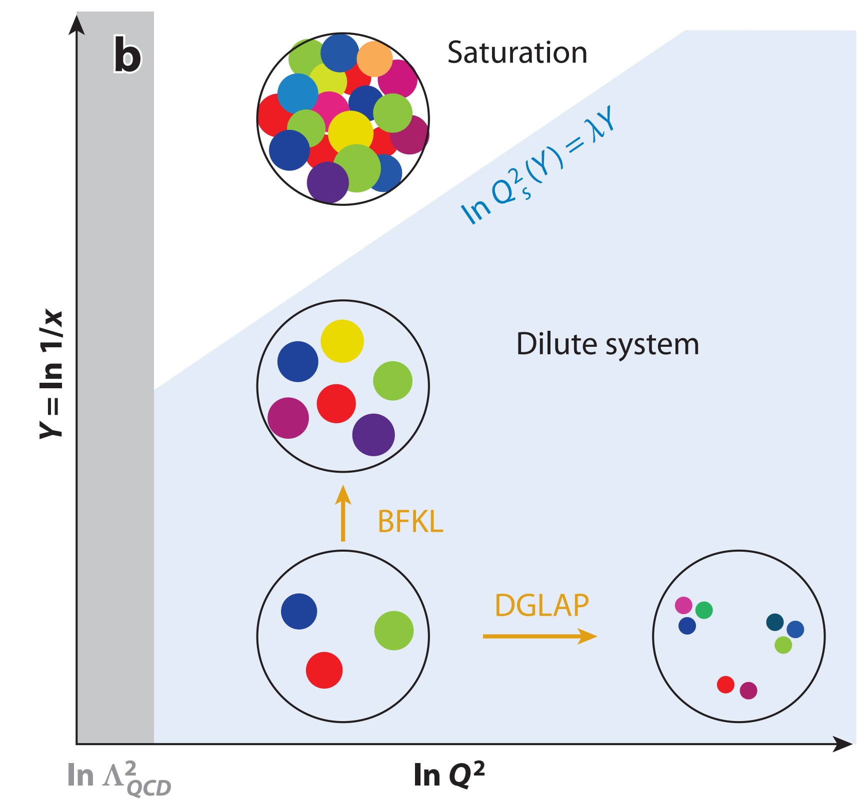
- At large energies and low parton momentum fraction (x) $\rightarrow$ saturation of the gluon density of hadrons
- Base for Color Glass Condensate effective-field theory
- Gluon saturation enhanced in heavy nuclei $\sim A^{1/3}$ (PRL100, 022303 (2008))



Phys.Rev.D 103 (2021) 1, 014013

- Saturation and other nuclear effects can be studied with the particle production ratio in pPb and pp collisions $\rightarrow$ **nuclear modification factor**

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



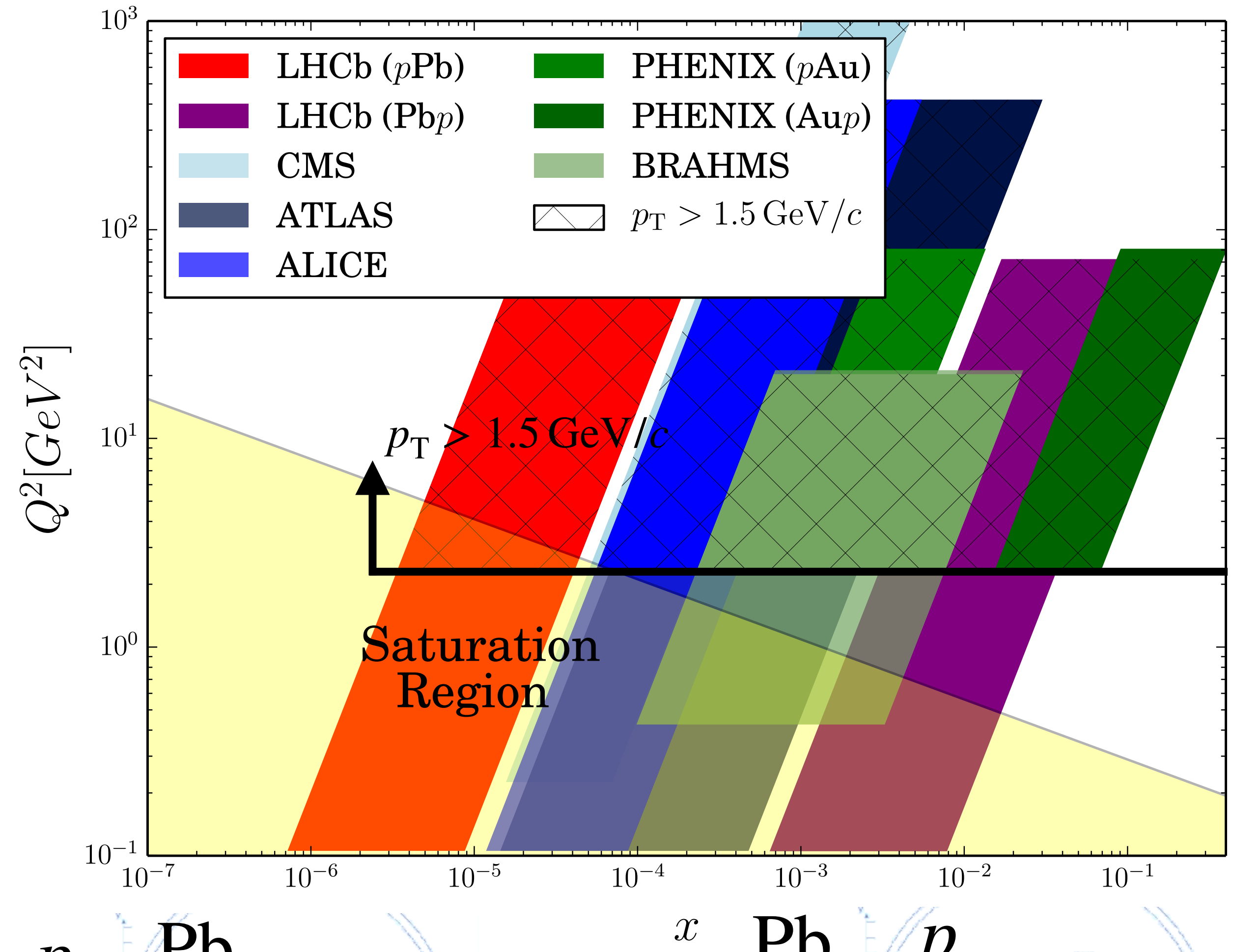
Ann.Rev.Nucl.Part.Sci.60:463-489,2010

Probing low-x at LHC

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

Q^2: exchanged momentum between interacting partons

x: momentum fraction of Pb parton



- Lighter particles provide access to the lowest x
- LHCb coverage:
  - forward, $10^{-6} \lesssim x \lesssim 10^{-4}$
  - backward, $10^{-3} \lesssim x \lesssim 10^{-1}$

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

$$Q_{s,\mathrm{Pb}} \approx 0.26\, A^{1/3} (x_0/x)^{\lambda} \qquad \lambda = 0.288, \quad x_0 = 3 \cdot 10^{-4} \qquad A = 208$$

- Instrumented to detect neutral/charged hadrons
- Excellent performance in pPb and pp collisions

Unique access to the saturation region with LHCb

- This talk → light hadron production measurements to tests of nuclear effects

Measurements for today

1. Charged hadron production in pPb and pp Phys.Rev.Lett. 128 (2022), 142004
2. Neutral pion production in pPb and pp arXiv:2204.10608
3. D^0 production in pPb arXiv:2205.03936

Charged hadron production in pPb and pp

Phys.Rev.Lett. 128 (2022), 142004

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

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

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

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

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

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

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

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

Charged hadron production in pPb and pp

Phys.Rev.Lett. 128 (2022), 142004

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

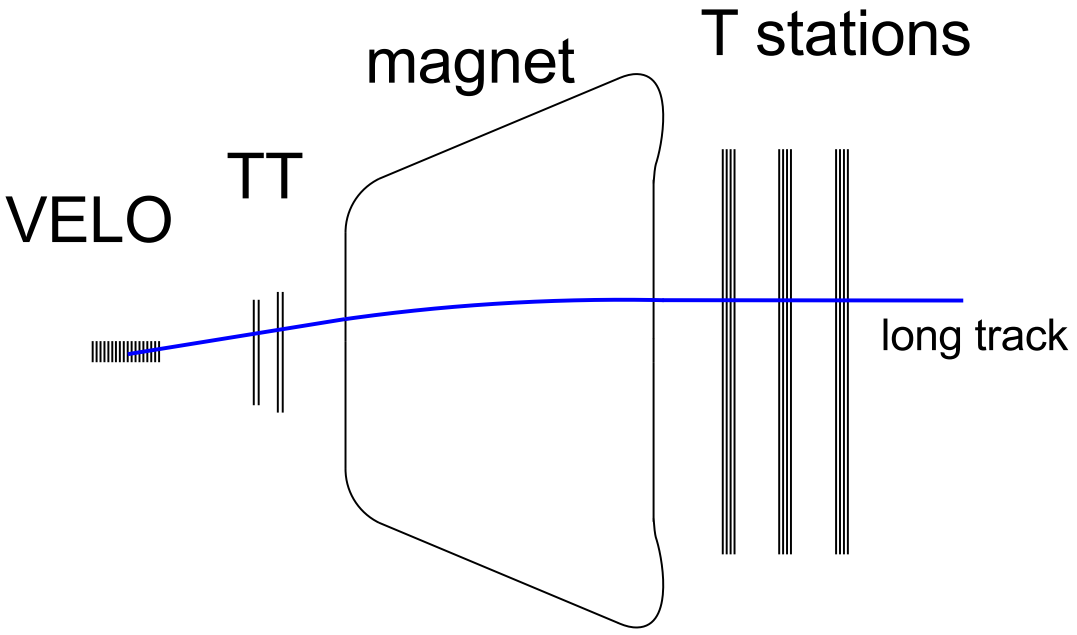


Figure from JINST 10 (2015) 02, P02007

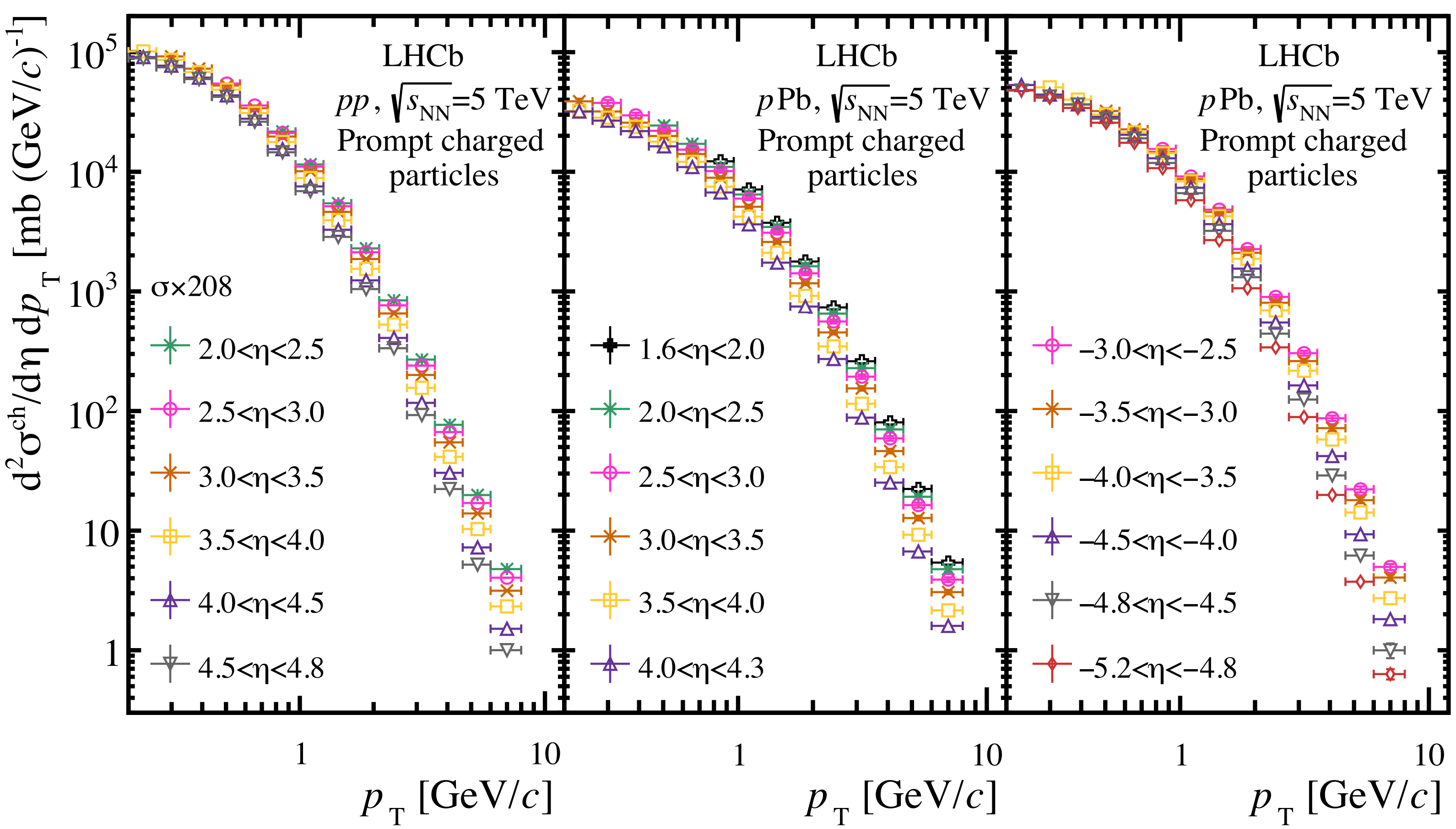
- Measurement dominated by systematic uncertainties:
  - particle composition (π, K, p) abundance in pPb for most bins
  - tracking efficiency and signal purity in boundary $(\eta, p_{\rm T})$ bins

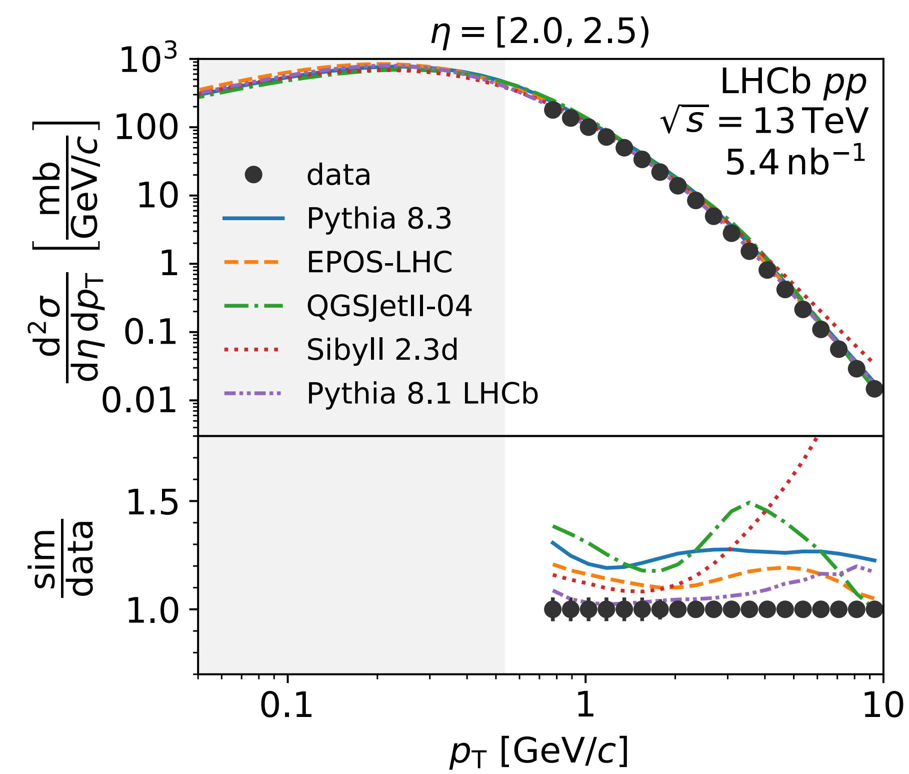
Uncertainty source	pPb [%] (forward)	pPb [%] (backward)	pp [%]
Track-finding efficiency	1.5 – 5.0	1.5 – 5.0	1.6 – 5.3
Detector occupancy	0.0 – 2.8	0.6 – 2.9	0.1 – 1.6
Particle composition	0.4 – 4.1	0.4 – 4.6	0.3 – 2.4
Selection efficiency	0.7 – 2.2	0.7 – 3.0	1.0 – 1.7
Signal purity	0.1 – 1.8	0.1 – 11.7	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 $d^2\sigma/d\eta dp_{\rm T}$)	3.0 – 6.7	3.3 – 14.5	2.8 – 8.7
Total (in $R_{p\rm Pb}$)	4.2 – 9.2	4.4 – 16.9	–

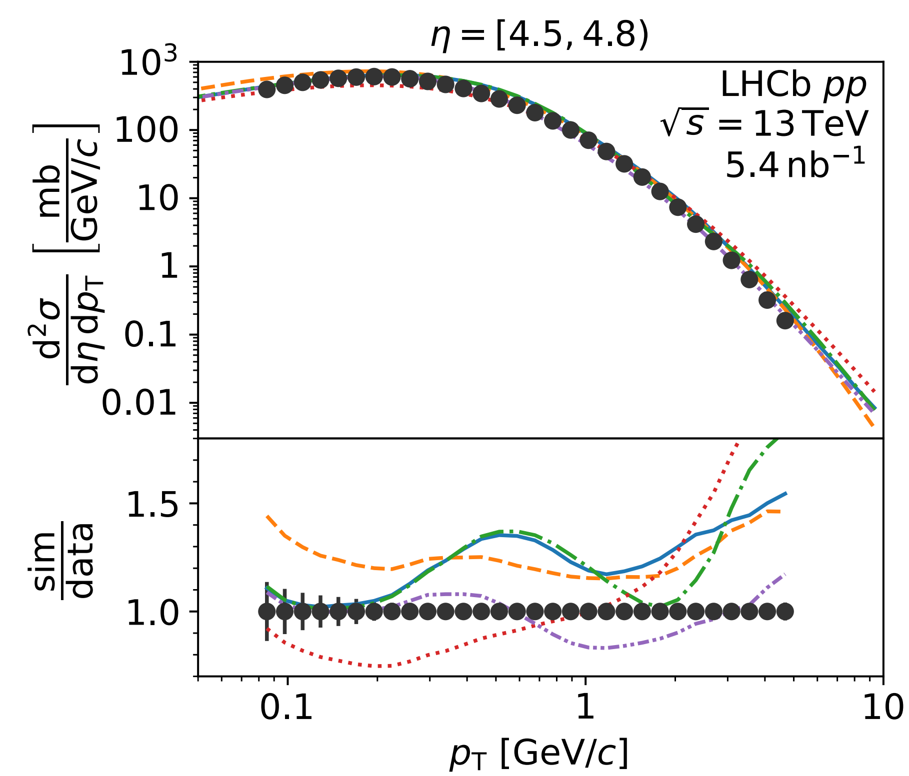
Charged hadron production in pPb and pp

[Phys.Rev.Lett. 128 (2022), 142004](#)

- $$\left.\frac{d^2\sigma}{dp_T d\eta}\right|_{p\mathrm{Pb},\,pp} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta\eta}$$
- Precise double-differential cross-sections measured over a wide η range
- Recent LHCb measurement at $\sqrt{s} = 13\,\mathrm{TeV}$ for pp ([JHEP 01 (2022) 166](#))







Charged hadrons $R_{p\mathrm{Pb}}$: backward region

Phys.Rev.Lett. 128 (2022), 142004

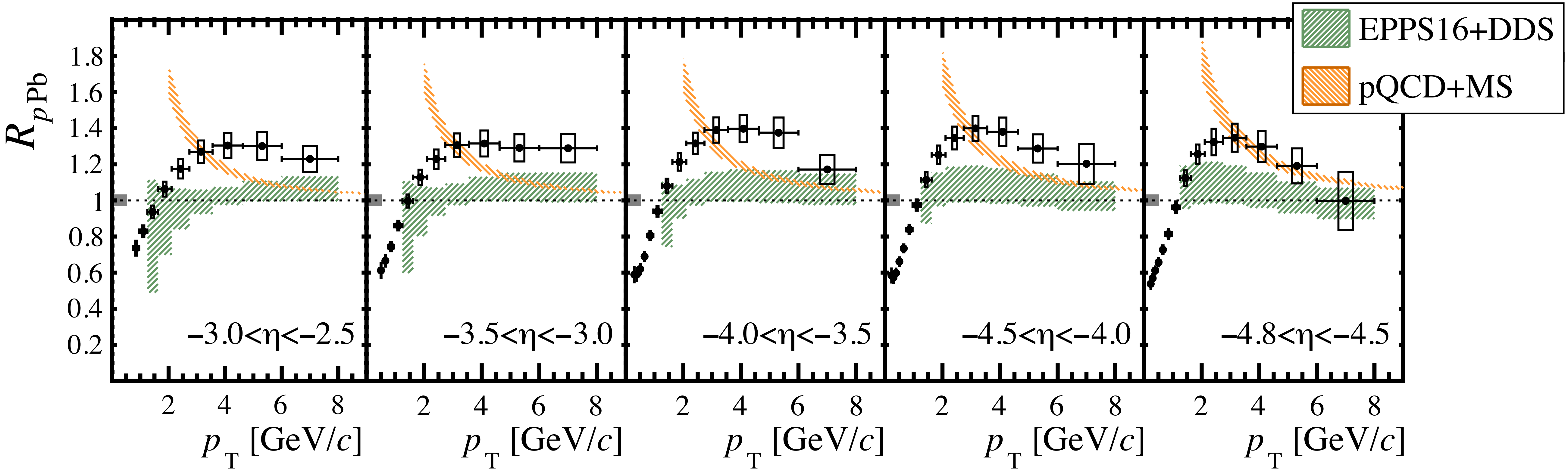
- **Nuclear modification factor**: $R_{p\mathrm{Pb}}(\eta, p_\mathrm{T}) = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_\mathrm{T})/dp_\mathrm{T}d\eta}{d^2\sigma_{pp}(\eta, p_\mathrm{T})/dp_\mathrm{T}d\eta}, \quad A = 208$

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

Models:

- EPPS16+DDS: JHEP09(2014) 138
  - does not reproduce enhancement
- pQCD+MS (MS = Multiple Scattering effects):
  - same calculation reproduces enhancement in Aup collisions at PHENIX

PR C101 (2020) 034910 PL B740(2015) 23 PR D88(2013) 054010



Charged hadrons $R_{p\mathrm{Pb}}$: forward region

Phys.Rev.Lett. 128 (2022), 142004

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

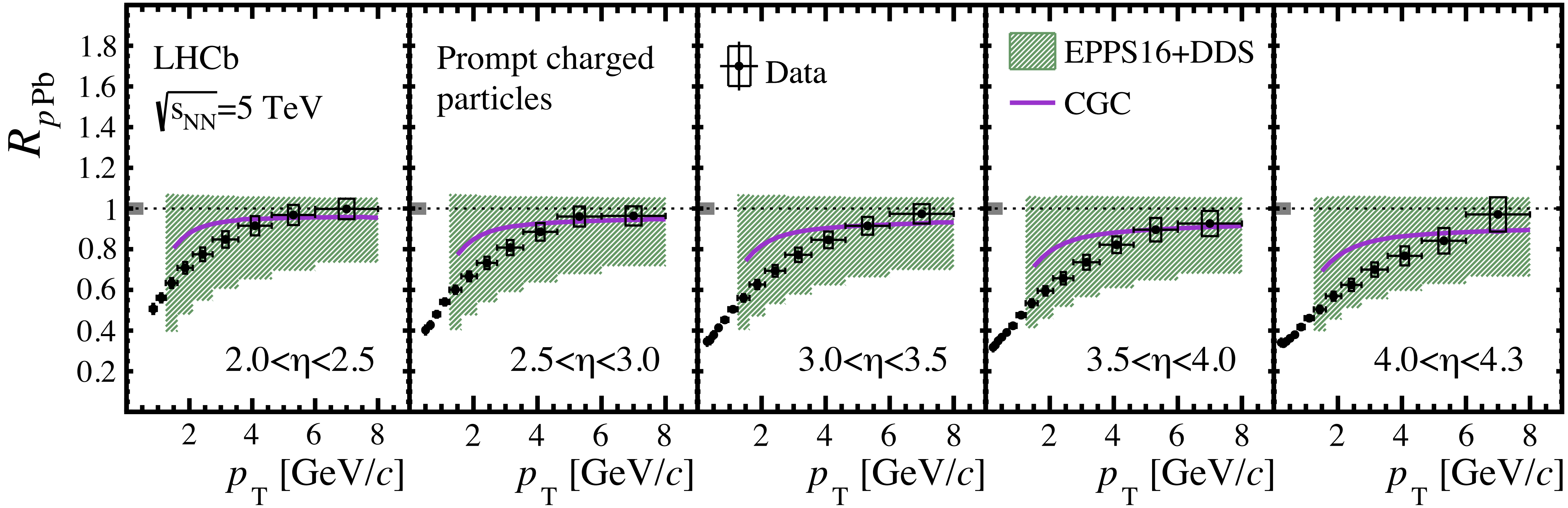
- **Strong suppression** at forward η, down to ~ 0.3 at low p_T and most forward rapidity
- Discrepancy at low p_T with CGC LO calculation

Models:

- EPPS16+DDS: JHEP09(2014) 138
- CGC (LO): PR D88, 114020

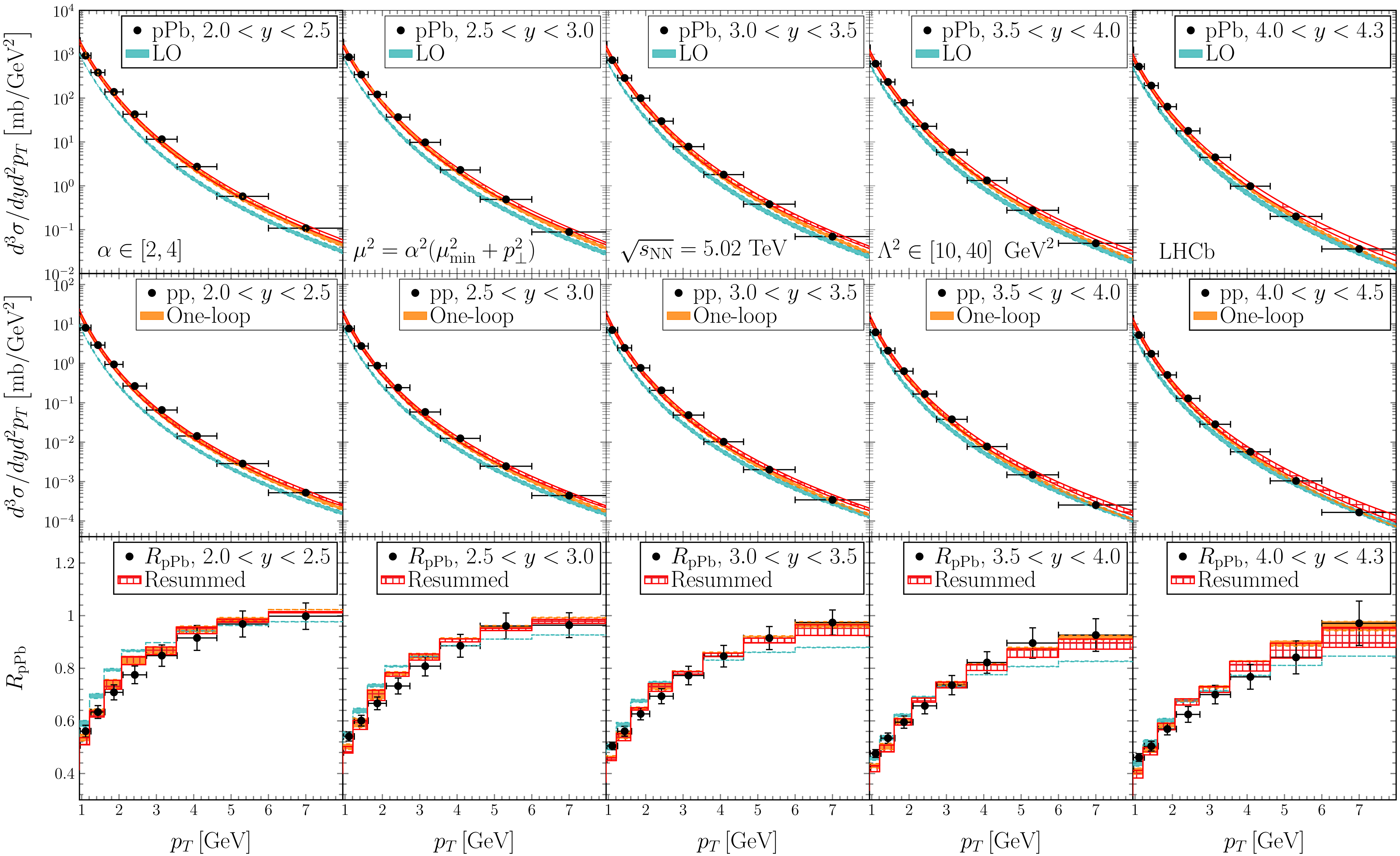
✳CGC NLO: better agreement with data

Phys. Rev. Lett. 128, 202302



Comparison with CGC NLO

Plot and prediction: Phys. Rev. Lett. 128, 202302 **Data:** Phys.Rev.Lett. 128 (2022), 142004



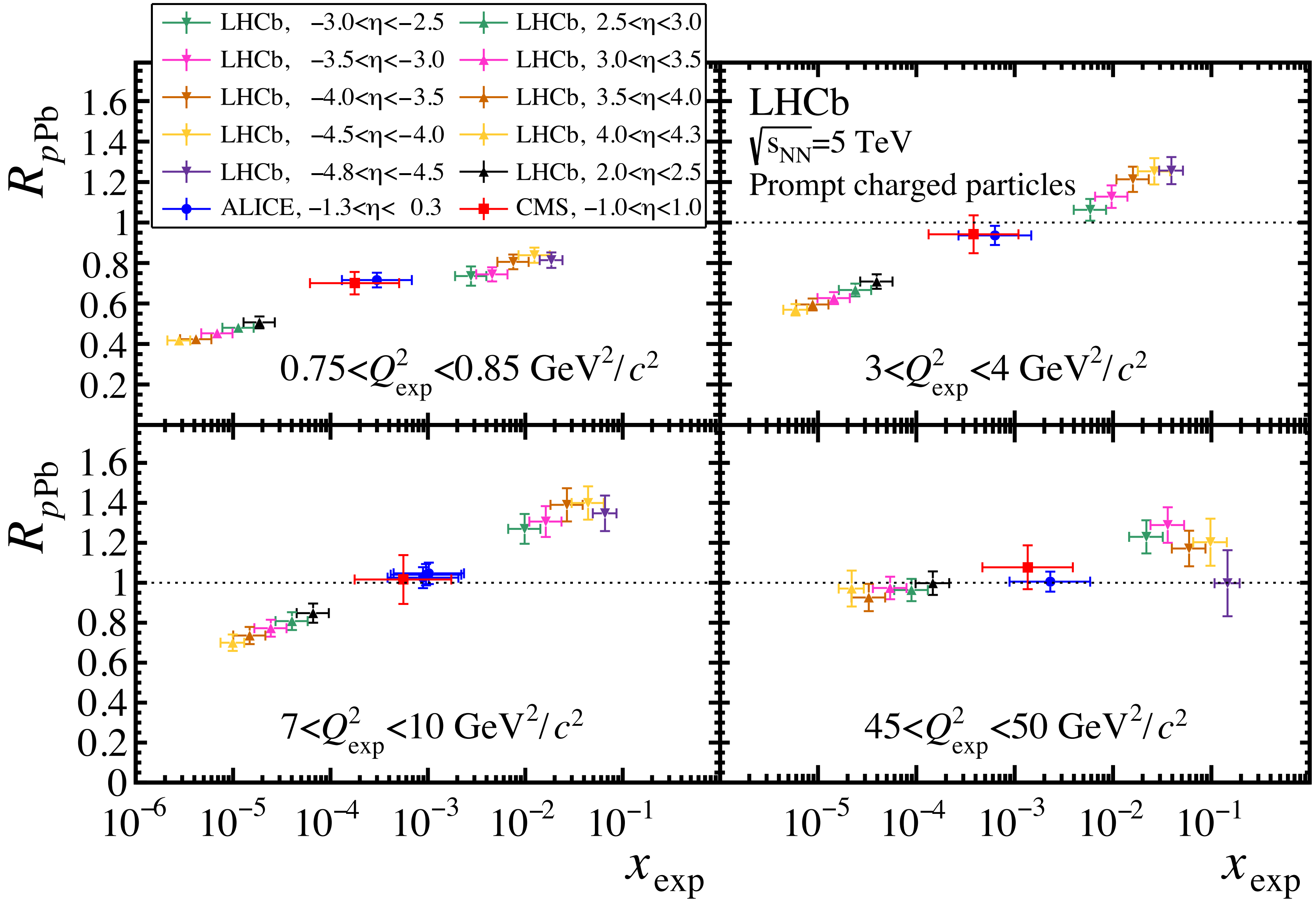
Charged hadrons $R_{p\text{Pb}}$: (x_{exp}, Q^2_{exp}) dependence

Phys.Rev.Lett. 128 (2022), 142004

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

- 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 $R_{p\text{Pb}}$ with x and Q^2

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

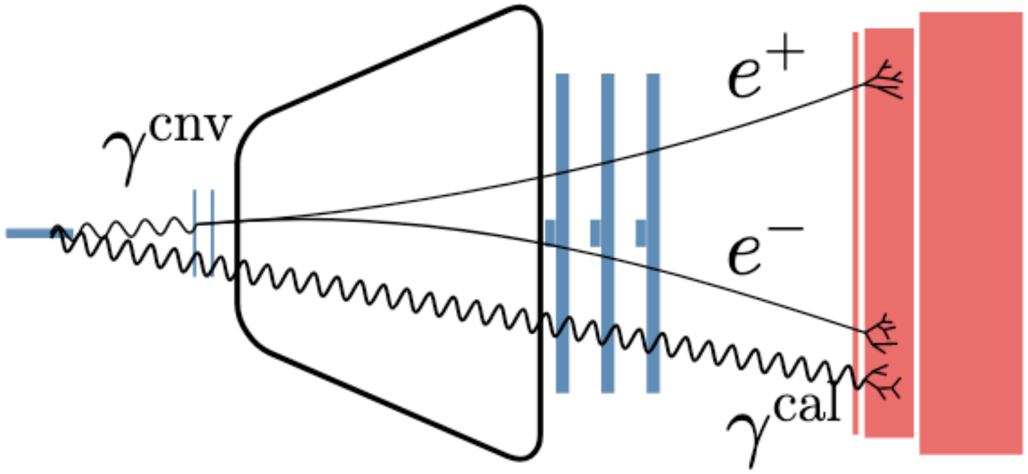


Neutral pion production in pPb and pp

arXiv:2204.10608

- **Measurement** of π^0 production cross-section:
  - Disentangle effects from different hadrons → understand enhancement in backward
  - Input to fragmentation functions (hadronization)
  - Constrains to nPDFs and test of saturation
  - Input needed for direct photon production measurement

- Detection technique fully independent from charged particle analysis:
  - Measure $\pi^0 \to \gamma^{\text{cnv}}\gamma^{\text{cal}}$
    - ✳ use $\pi^0 \to \gamma^{\text{cal}}\gamma^{\text{cal}}$ as cross-check and efficiency calibration



- Datasets:
  - pPb and Pbp data at $8.16\,\text{TeV}$
  - pp reference constructed with 5 and $13\,\text{TeV}$ datasets

Kinematic coverage:

$$1.5 < p_{\text{T}} < 10.0\,\text{GeV}/c$$

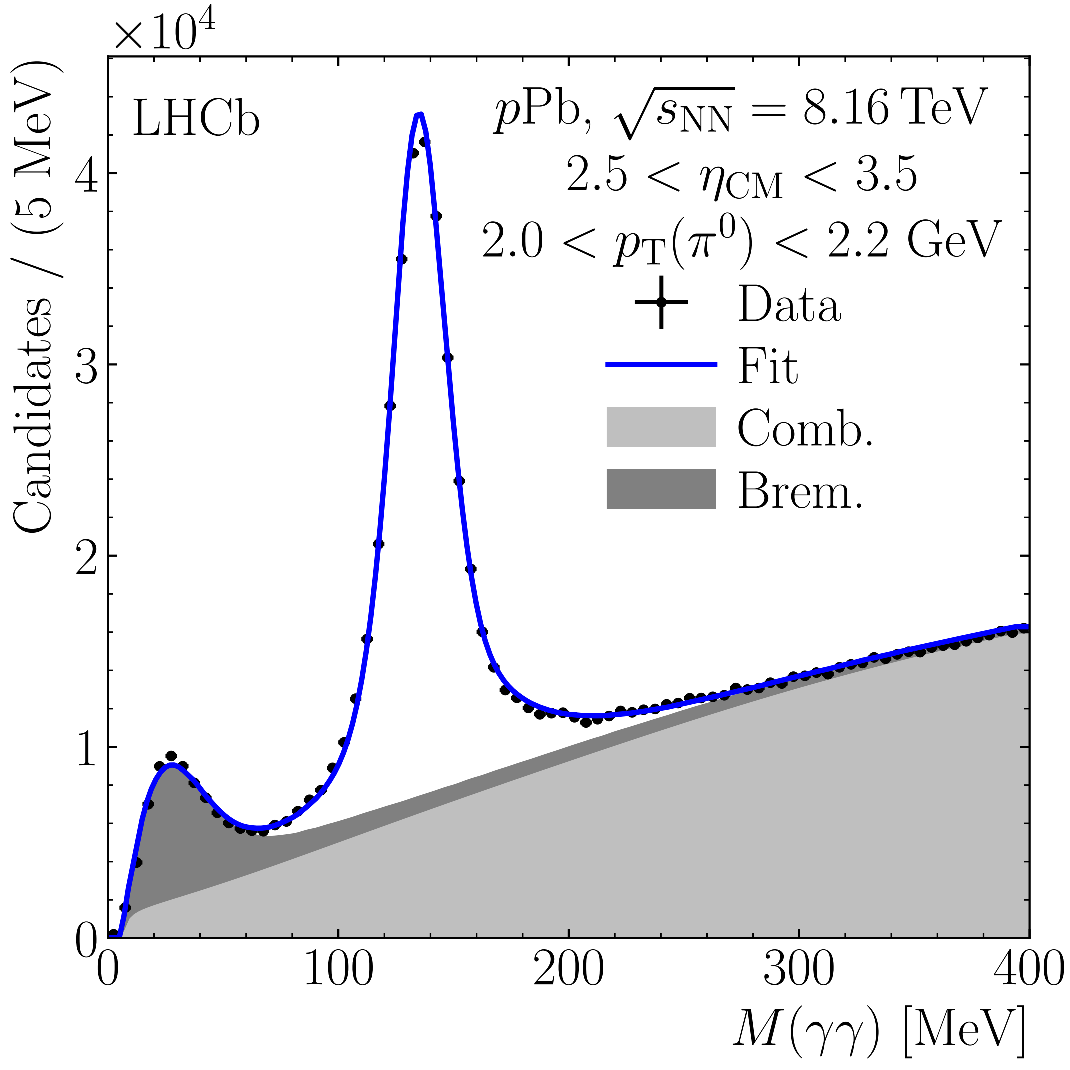
$$\begin{cases} 2.5 < \eta_{\text{CM}} < 3.5 \\ -4.0 < \eta_{\text{CM}} < -3.0 \end{cases}$$

Neutral pion production in pPb and pp

arXiv:2204.10608

- Yields of π^0 extracted from fit to mass spectrum for each kinematic bin
  - Signal: two-sided Crystal Ball function
  - Combinatorial background: constructed with proxy sample of charged tracks
  - Bremsstrahlung: combination of the converted photon and its own brem. radiation

- Yields of π^0 corrected by detector effects using simulation:
  - Calibration to correct data-simulation differences (JINST 14 (2019) P11023)
  - Iterative unfolding technique used to correct efficiency and resolution effects

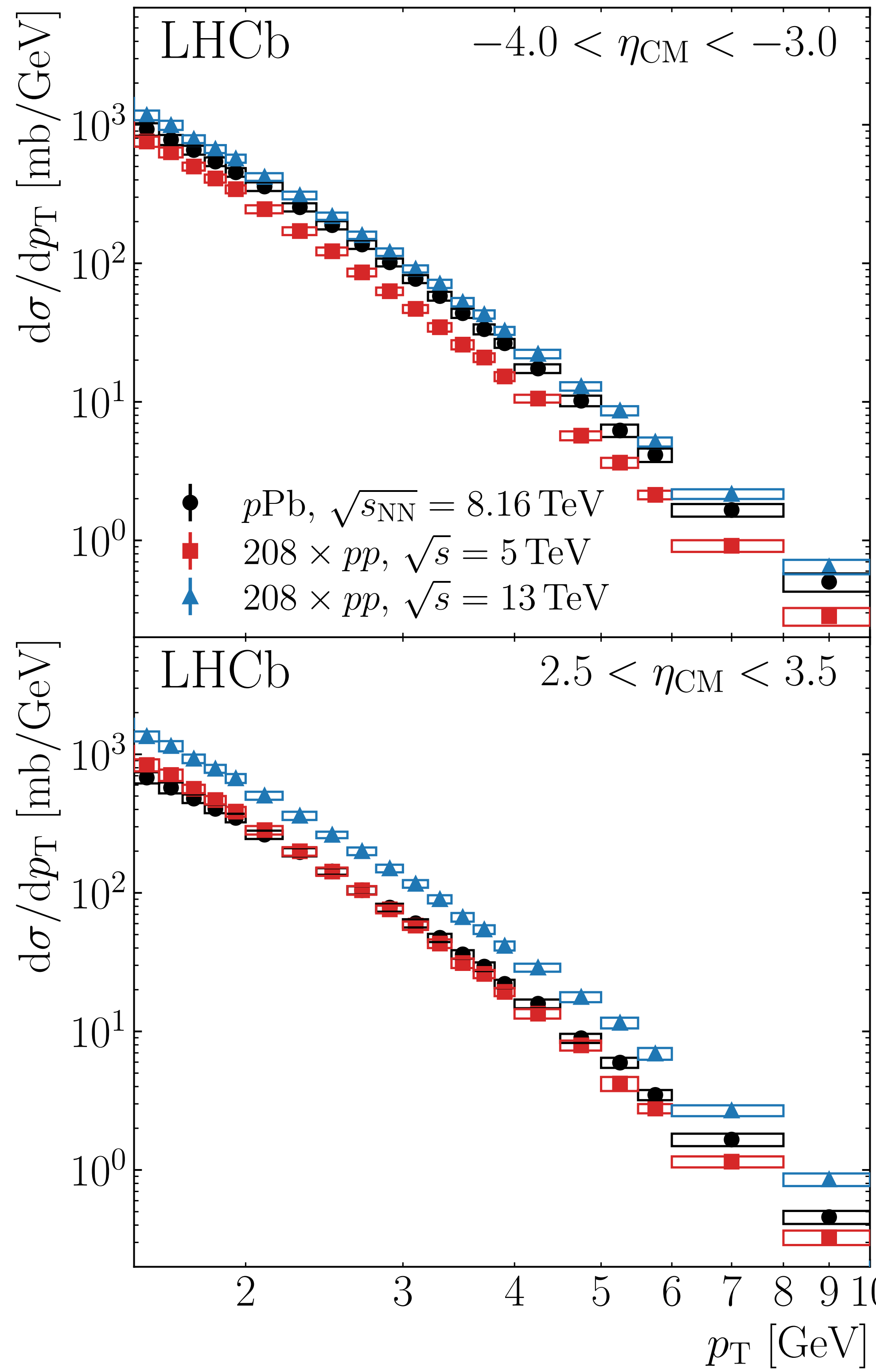


Neutral pion production in pPb and pp

arXiv:2204.10608

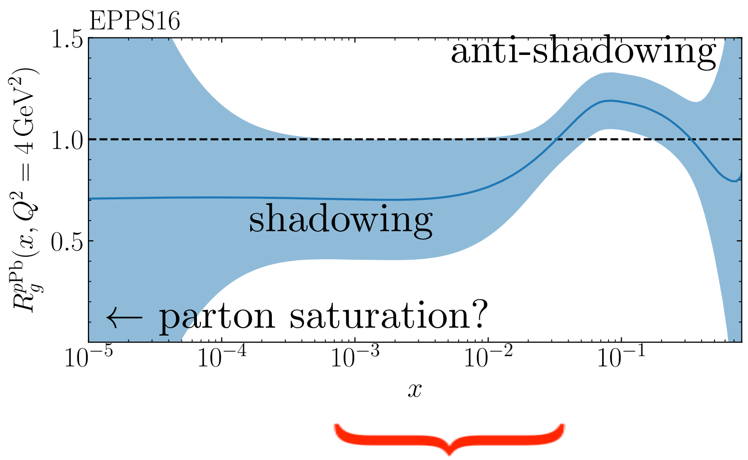
- Result for $d\sigma/dp_{\mathrm{T}}$ cross-section
- Interpolation of $5\,\mathrm{TeV}$ and $13\,\mathrm{TeV}$ cross-section to construct the reference for $R_{p\mathrm{Pb}}$
- Correlated uncertainties across datasets cancel in $R_{p\mathrm{Pb}}$:
  - total uncertainty less than $6\,\%$ in most p_{T} intervals

Source	$\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$ [%]	$R_{p\mathrm{Pb}}$ [%]
Fit model	2.0–12.6	0.9–15.8
Unfolding	0.3–6.4	0.4–6.4
Interpolation	–	0.9–4.5
Material	4.0	–
Efficiency	1.3–1.9	1.9–2.1
Luminosity	2.0–2.6	2.2–2.3
Total systematic	5.4–15.0	4.3–17.4
Statistical	1.0–9.6	1.4–9.1



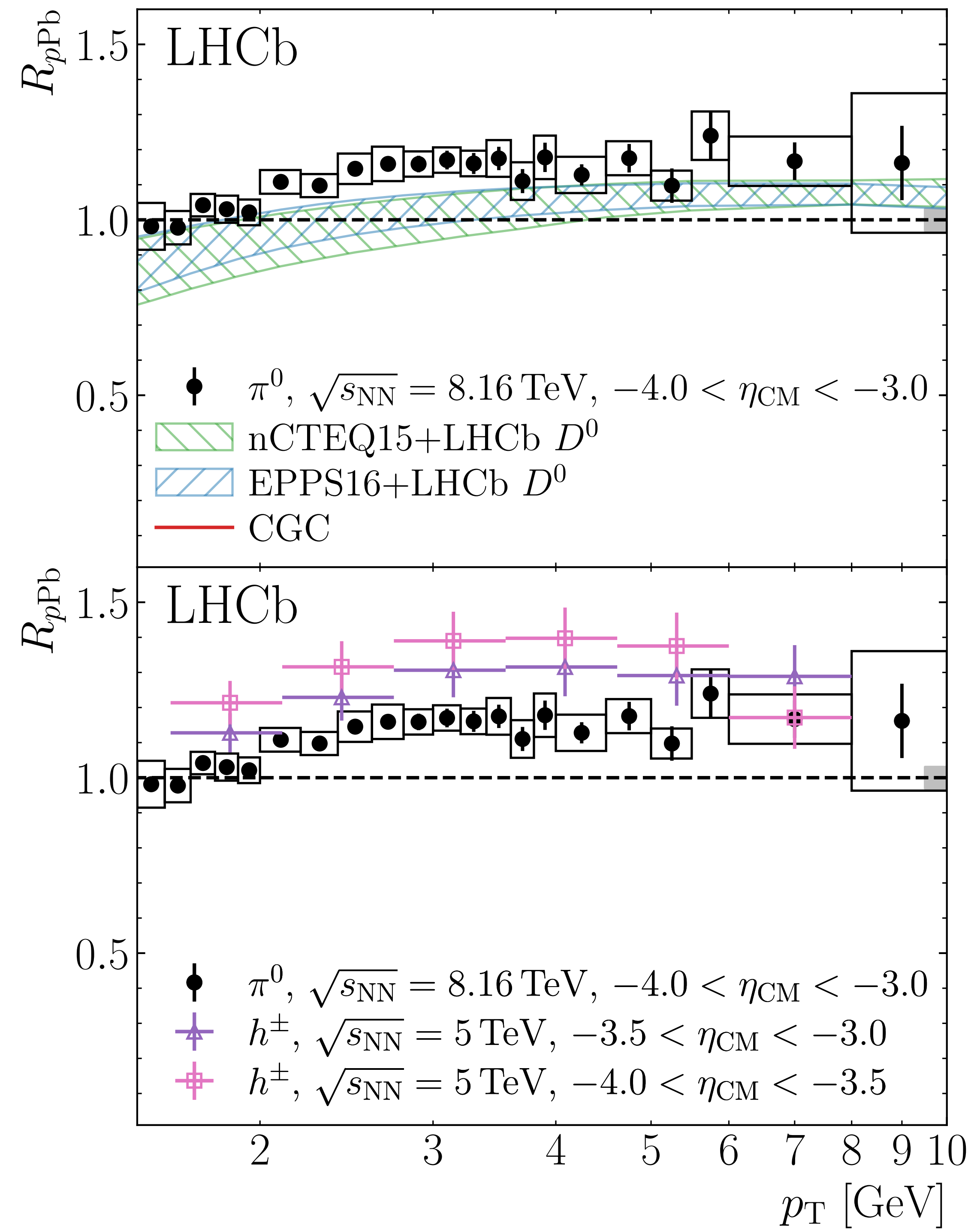
Neutral pion R_{pPb}: backward region

$$R_{pPb} = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$



- Cronin-like enhancement of π^0 production
  - Enhancement less pronounced than for charged particles ($\pi^-, K^-, p, \ldots$ mixture)
  - Indication of a mass-ordering in the Cronin enhancement, as observed by other experiments
  - compatible with final-state recombination picture (Phys. Rev. Lett. 93, 082302)
- Excess over reweighted nPDFs predictions between 2 and $4\,\mathrm{GeV}/c$

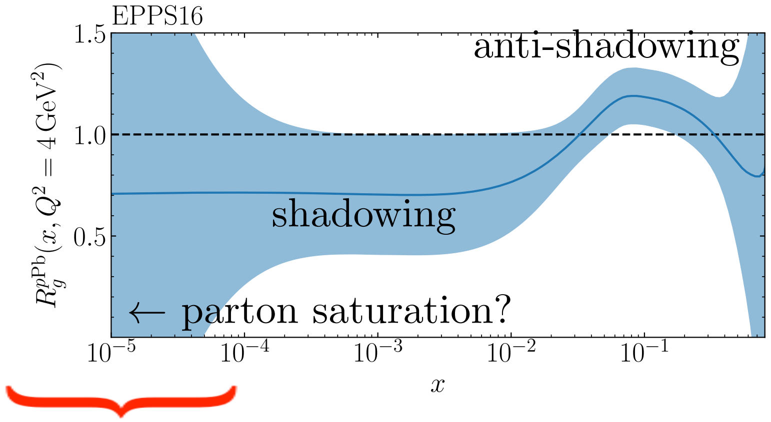
arXiv:2204.10608



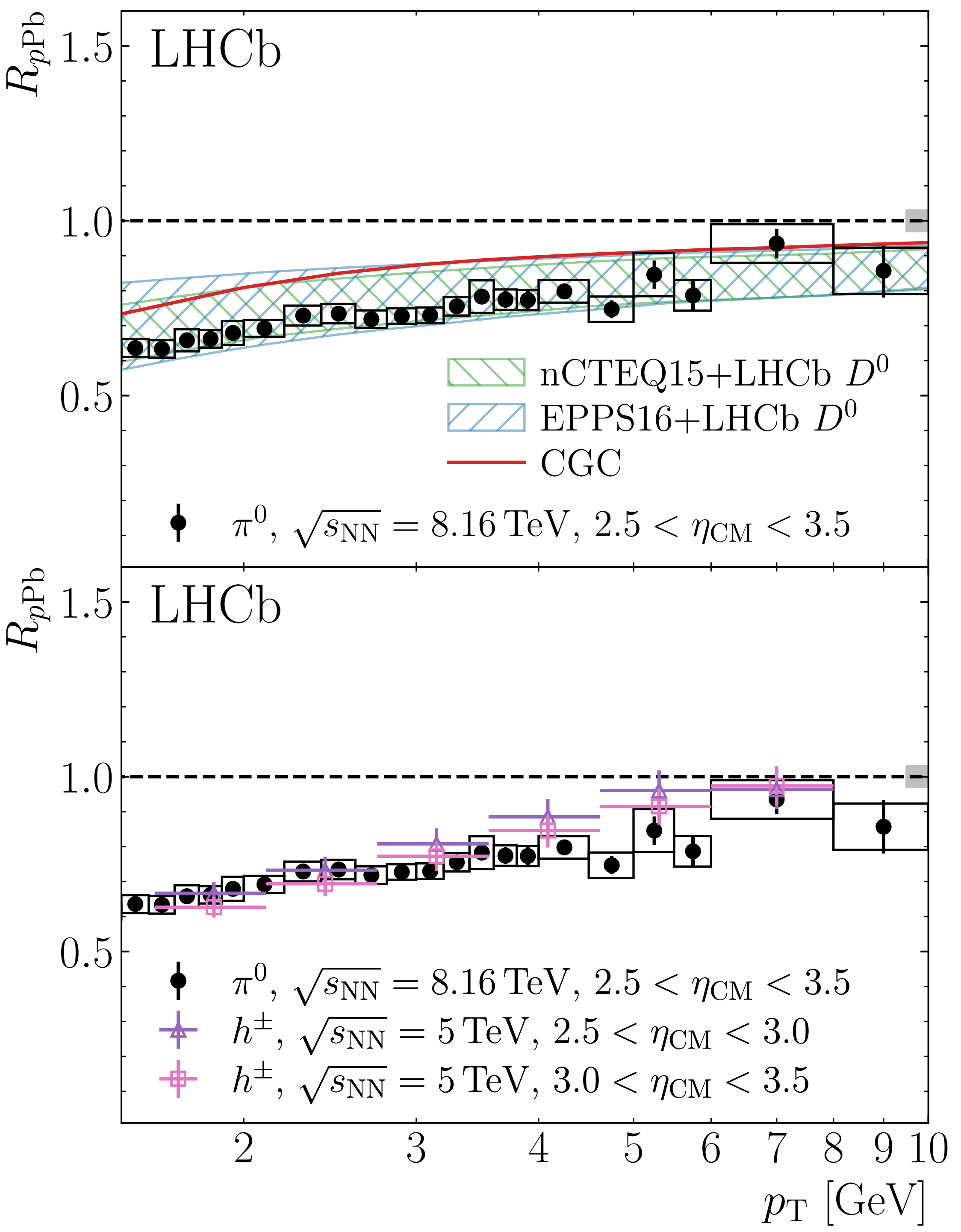
Neutral pion $R_{p\mathrm{Pb}}$: forward region

arXiv:2204.10608

$$R_{p\mathrm{Pb}} = \frac{1}{A}\frac{d\sigma_{p\mathrm{Pb}}/dp_{\mathrm{T}}}{d\sigma_{pp}/dp_{\mathrm{T}}}$$



- Strong suppression of π^0 production
  - $R_{p\mathrm{Pb}}$ compatible with charged hadron result
  - could indicate that saturation affects similarly all hadrons, needs confirmation
- In agreement with nPDFs (reweighted with LHCb D^0 data) JHEP 05 (2020) 037 JHEP 1710 (2017) 090
- CGC LO prediction underestimates π^0 suppression PR D88, 114020
  - no comparison yet with CGC NLO

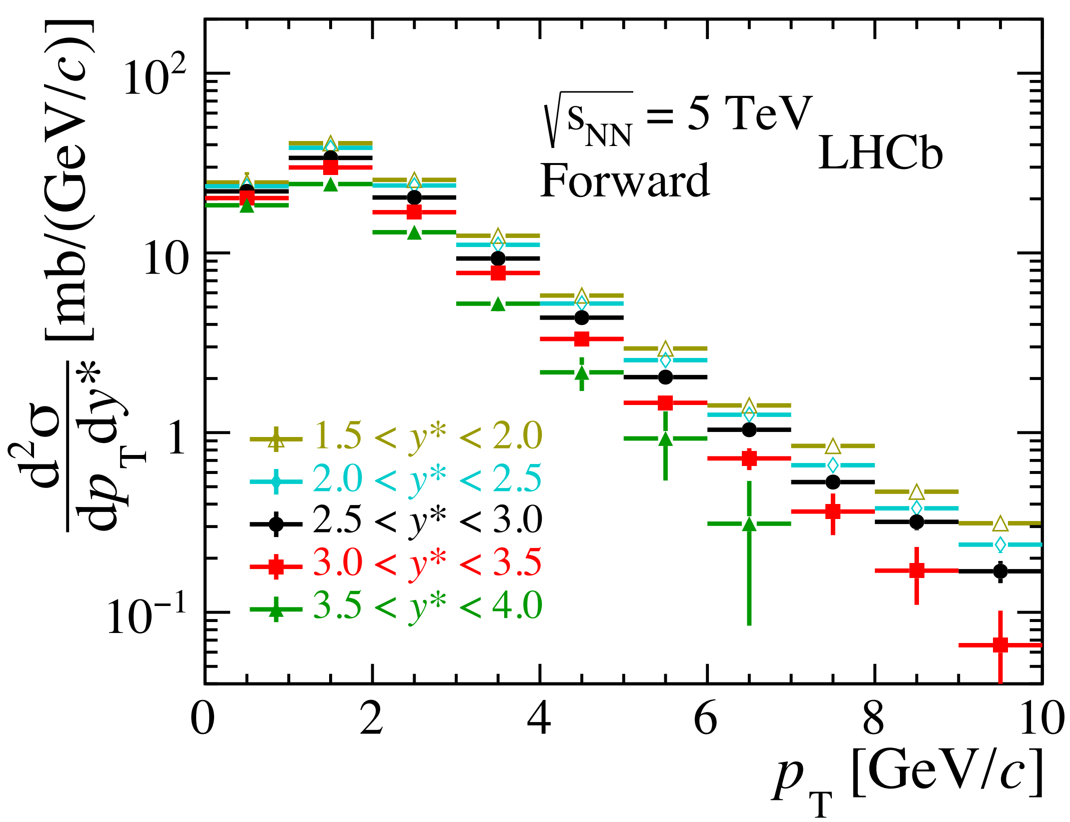


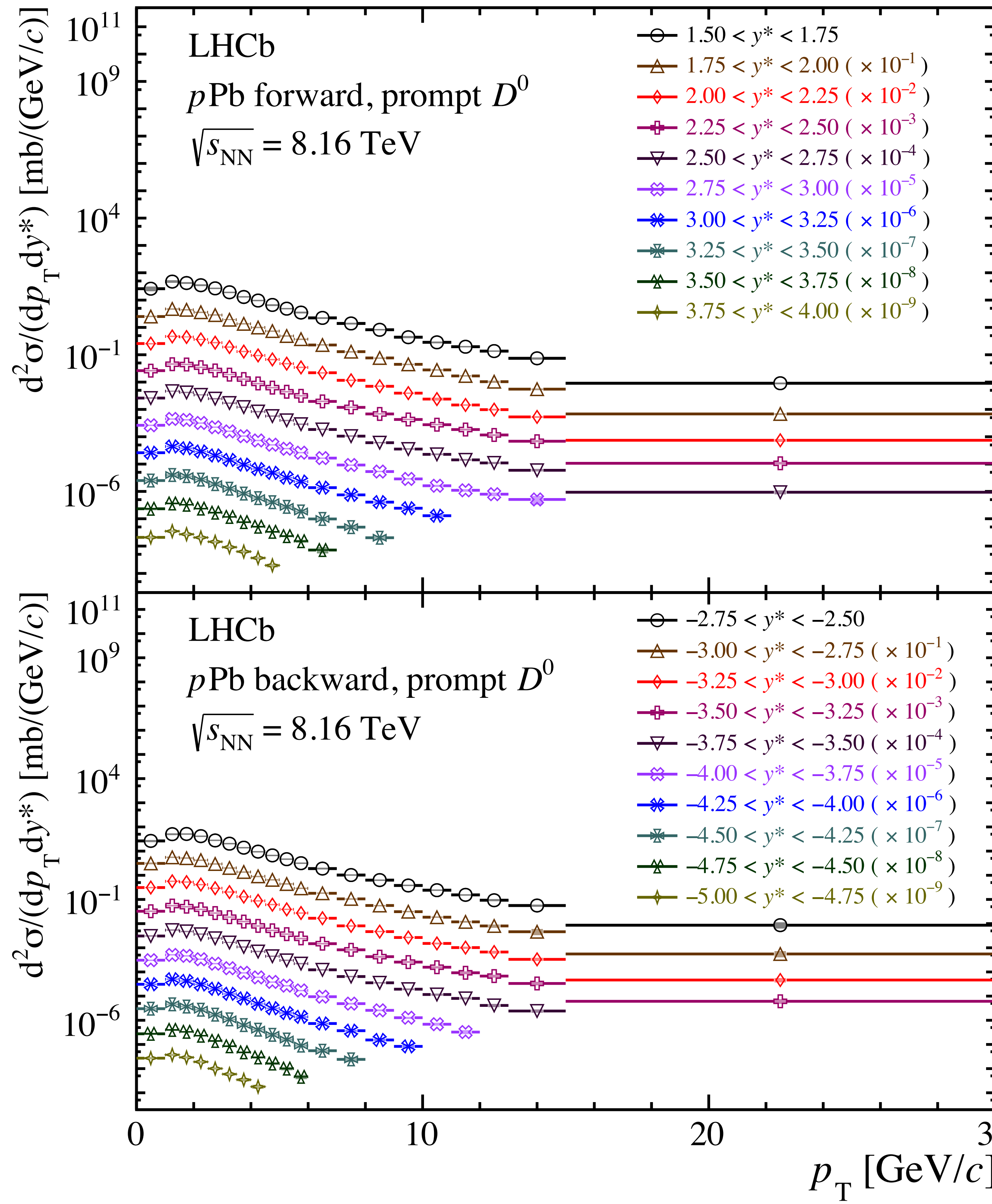
arXiv:2205.03936

- Measurements of D^0 production in pPb with Run 2 data
- Using sample x20 larger than previous measurement (JHEP 10 (2017) 090)
- Finer binning and extended kinematic range to $p_T \in [0,30]\,\text{GeV}/c$

Previous results:

JHEP 10 (2017) 090

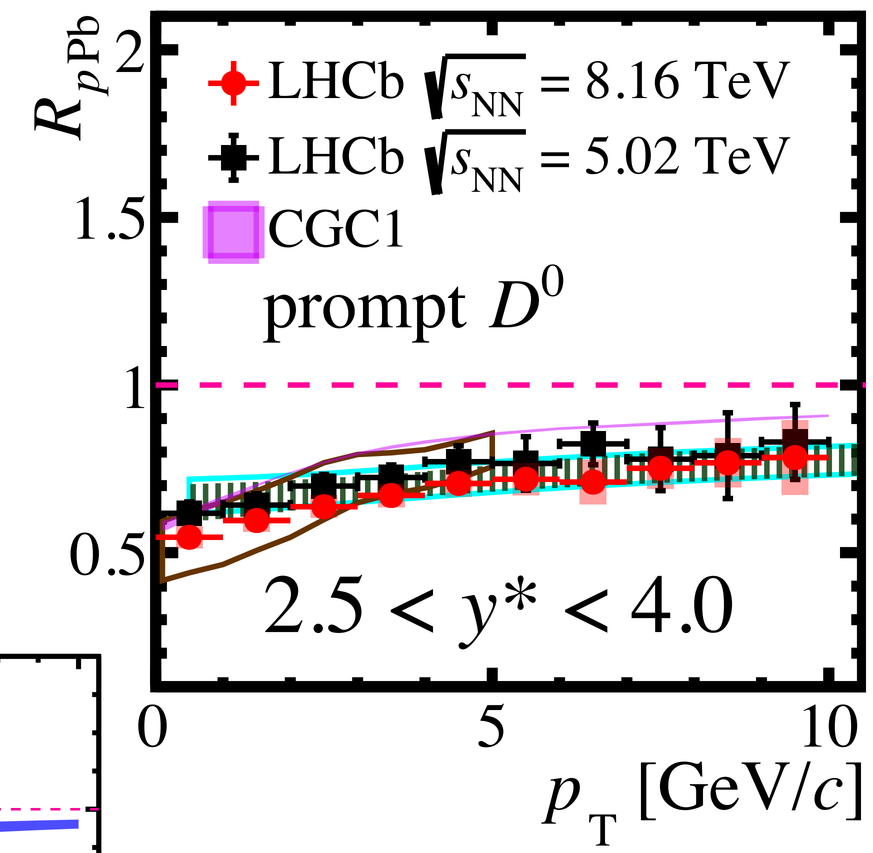


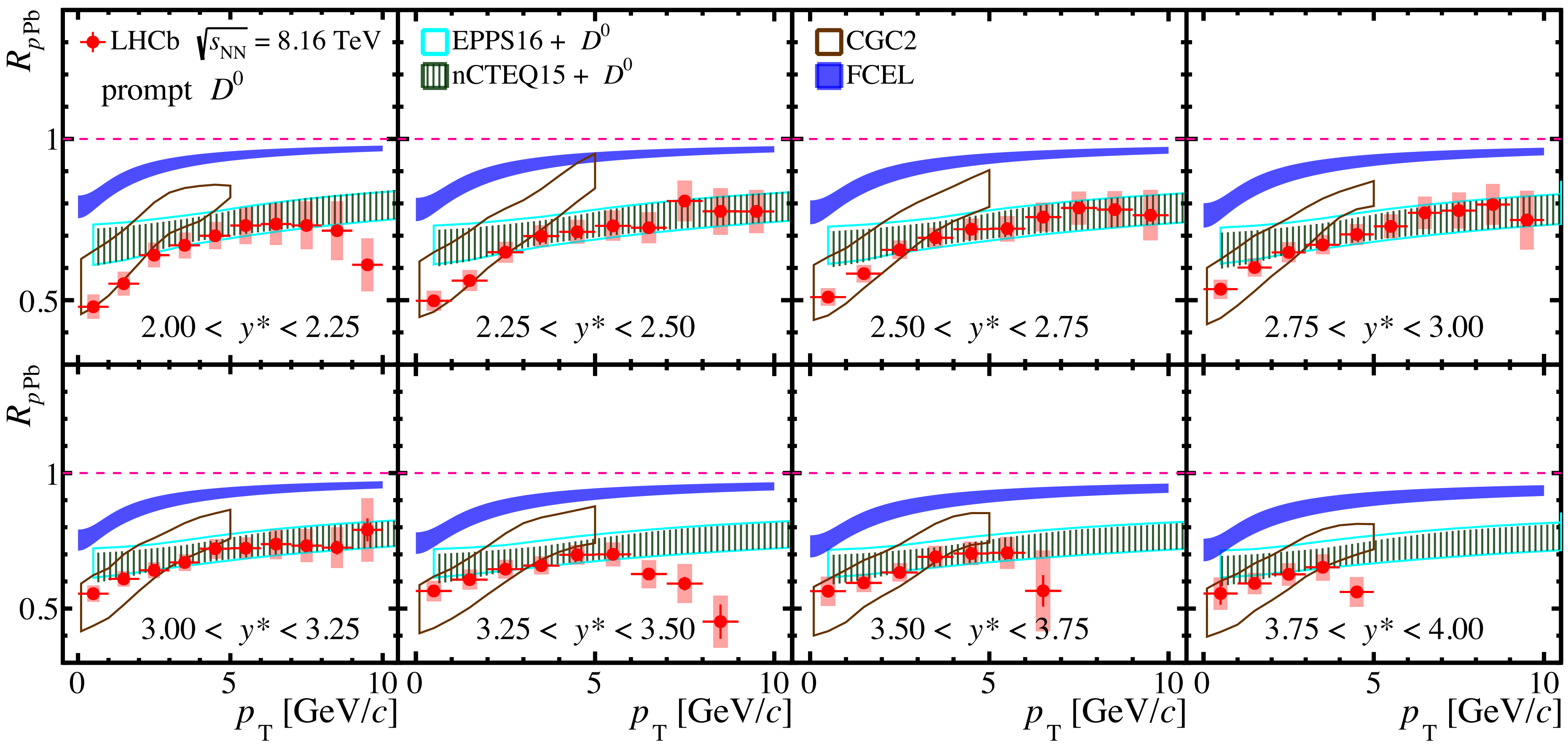


D^0 production in pPb

arXiv:2205.03936

- $R_{p\mathrm{Pb}}$ probes low-x region in the forward region
- Data compared with two CGC calculations, overall good agreement:
  - CGC1 → PR D91, 114005 (2015) arXiv:1612.04585
  - CGC2 → PR D98, 074025 (2018)





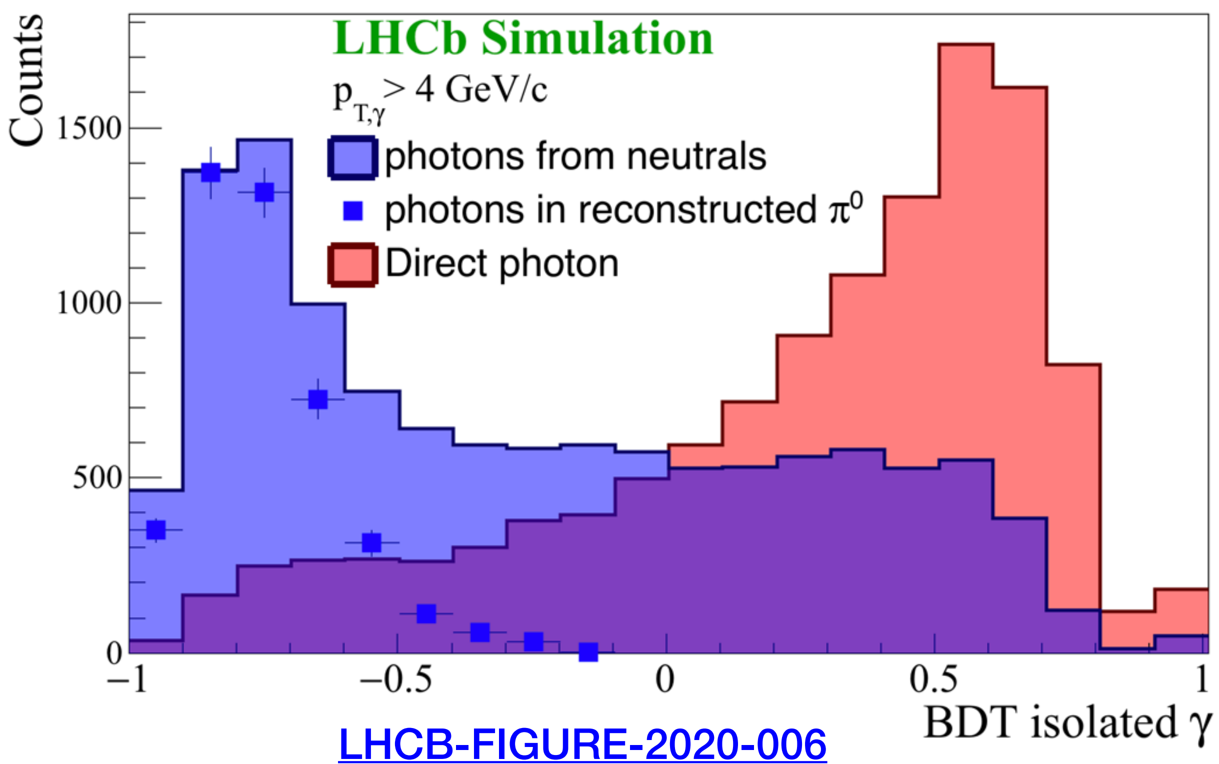
Future prospects

- Neutral side:
  - other neutral mesons (η and η')
  - direct photon production
  - direct gamma - hadron correlation

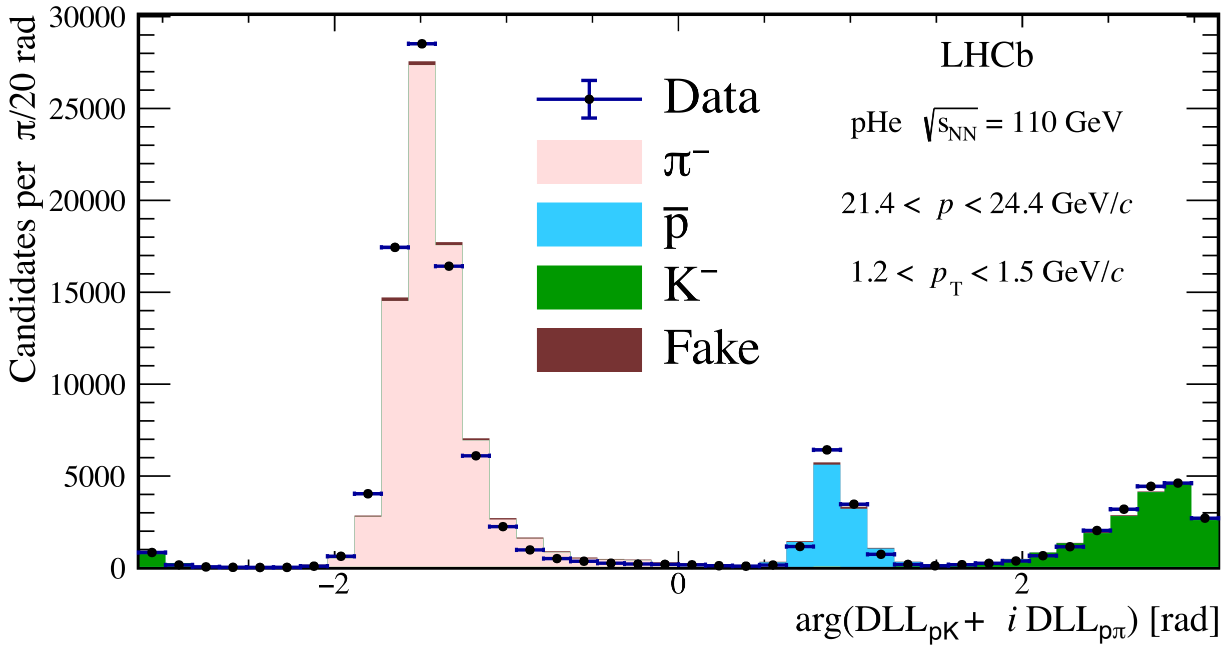
- Charged side:
  - Identified hadron spectra: (π^-, K^-, p)
    - ✳ good prospects: PID systematic in similar measurement in pHe system below $5\,\%$
    - ✳ Reduce one of the main systematic uncertainties in inclusive charged hadron measurement

- For Run3/Run4
  - Larger pPb sample
  - Short pO run possible, saturation in mid-size nucleus
  - LHCb upgrade: improved detector performance

- **New ideas to exploit LHCb data always welcome!**



LHCB-FIGURE-2020-006



Phys. Rev. Lett. 121 (2018) 222001

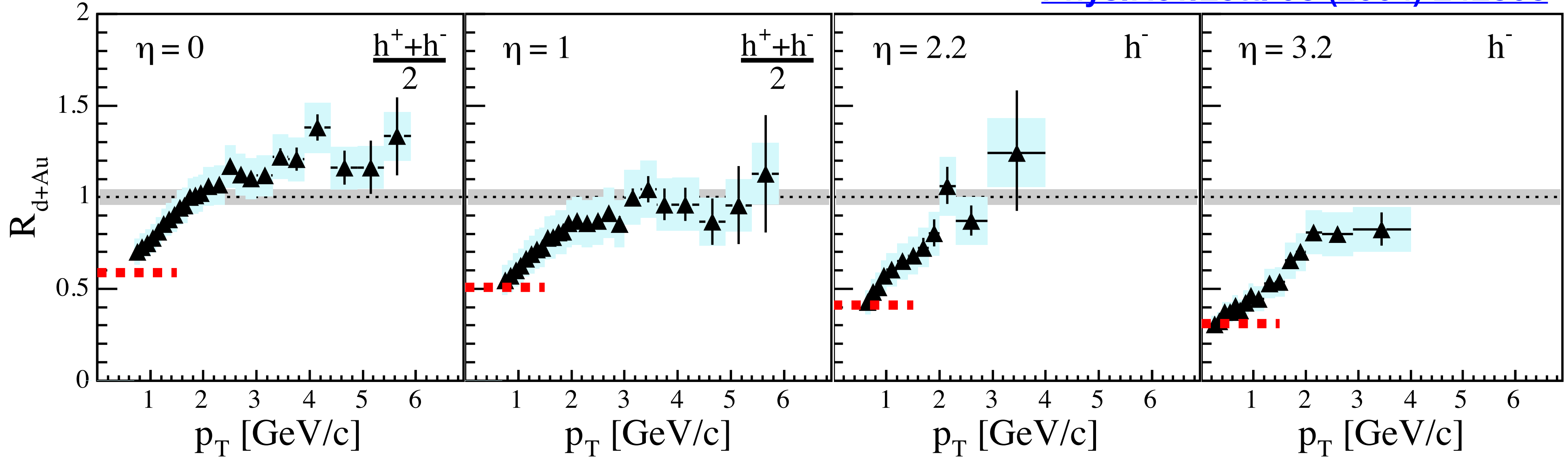
Summary

- Hadron production measurements at LHCb provide a unique access to the saturation region:
  - **Charged hadron production in pPb and pp collisions** Phys.Rev.Lett. 128 (2022), 142004
  - **π^0 production in pPb and pp collisions** arXiv:2204.10608 *accepted by PRL*
  - **D^0 production in pPb collisions** arXiv:2205.03936
- All measurements show a significant hadron suppression in the forward region
  - compatible results with independent experimental techniques
- Data has high precision and can constrain CGC-based calculations
- Several oncoming Run2 analyses will improve precision and/or provide additional information on saturation
- Several interesting prospects beyond: pO and pPb runs, new upgraded detectors

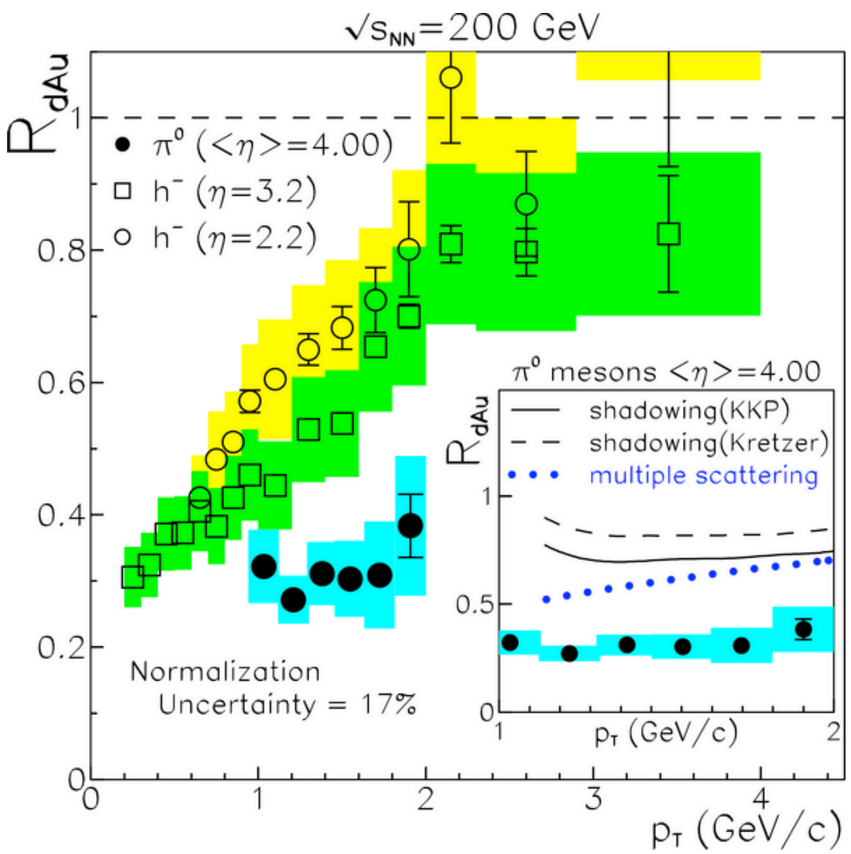
Backup

Forward suppression at RHIC

Phys.Rev.Lett. 93 (2004) 242303



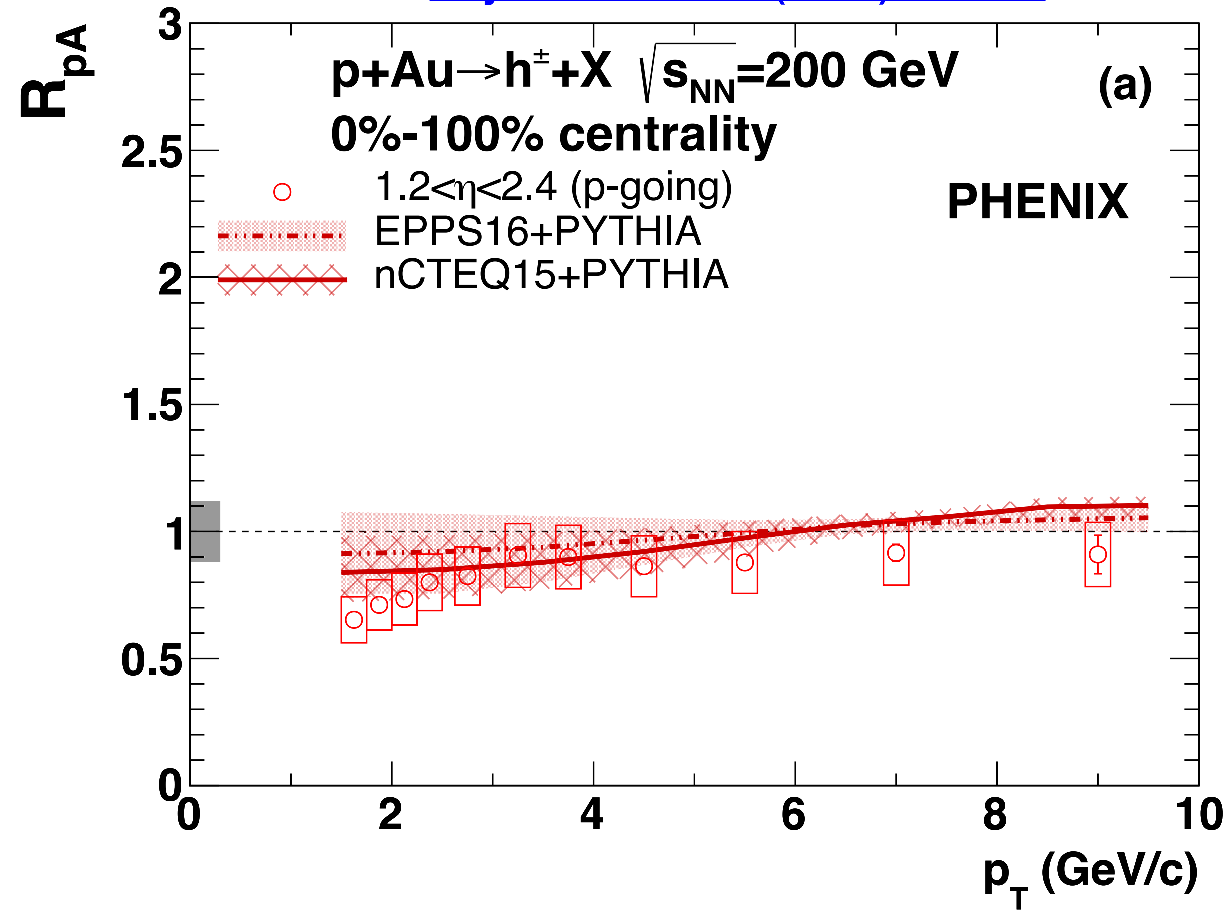
BRAHMS
h^-



STAR
π^0

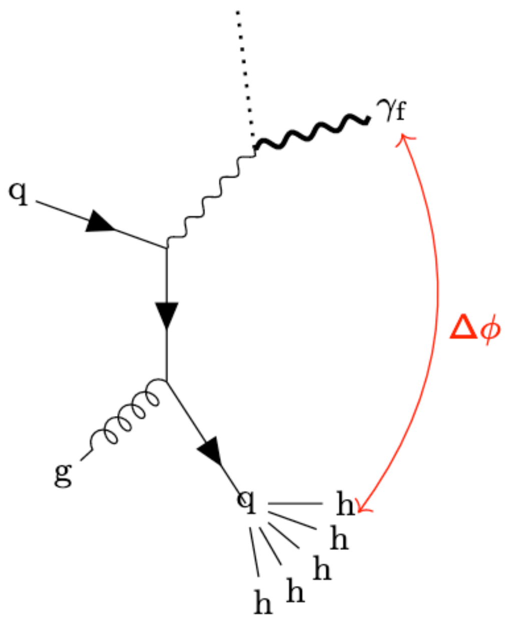
Phys. Rev. Lett. 97 (2006) 152302

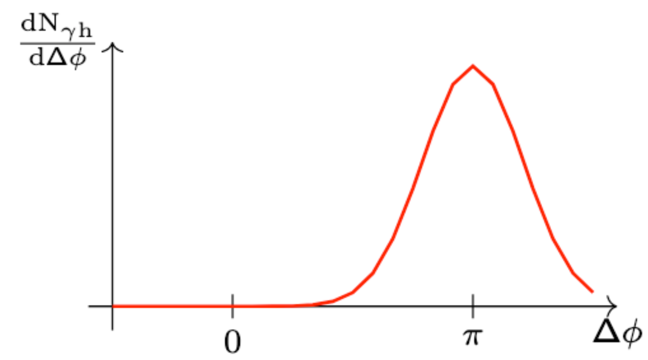
Phys. Rev. C 101 (2020) 034910



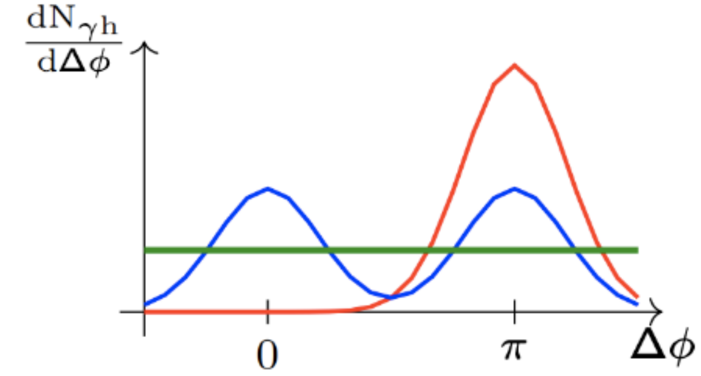
Hadron - photon correlation in pPb

- Cleaner access to saturation region
  Compton-scattering process

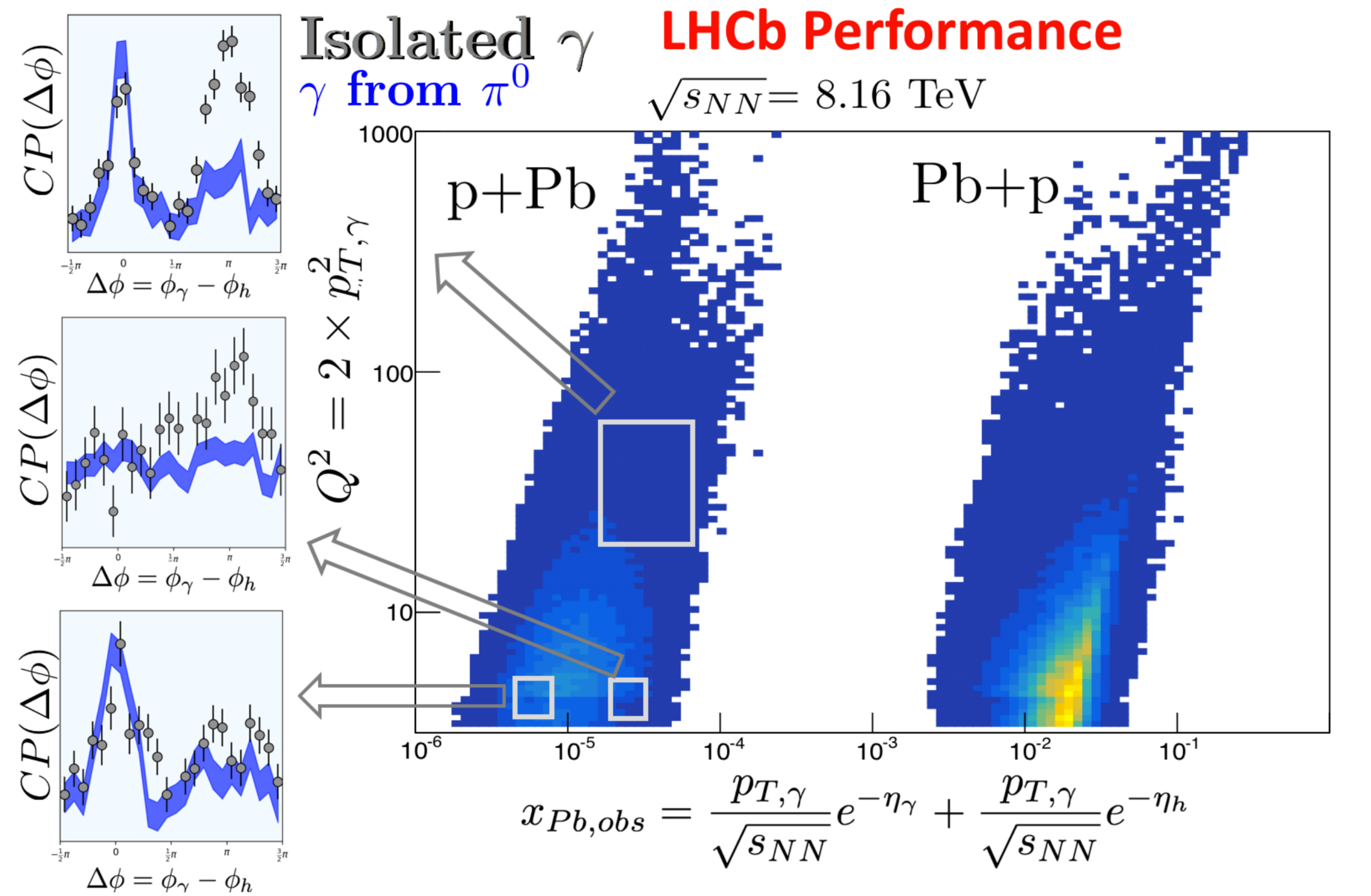




Compton or direct



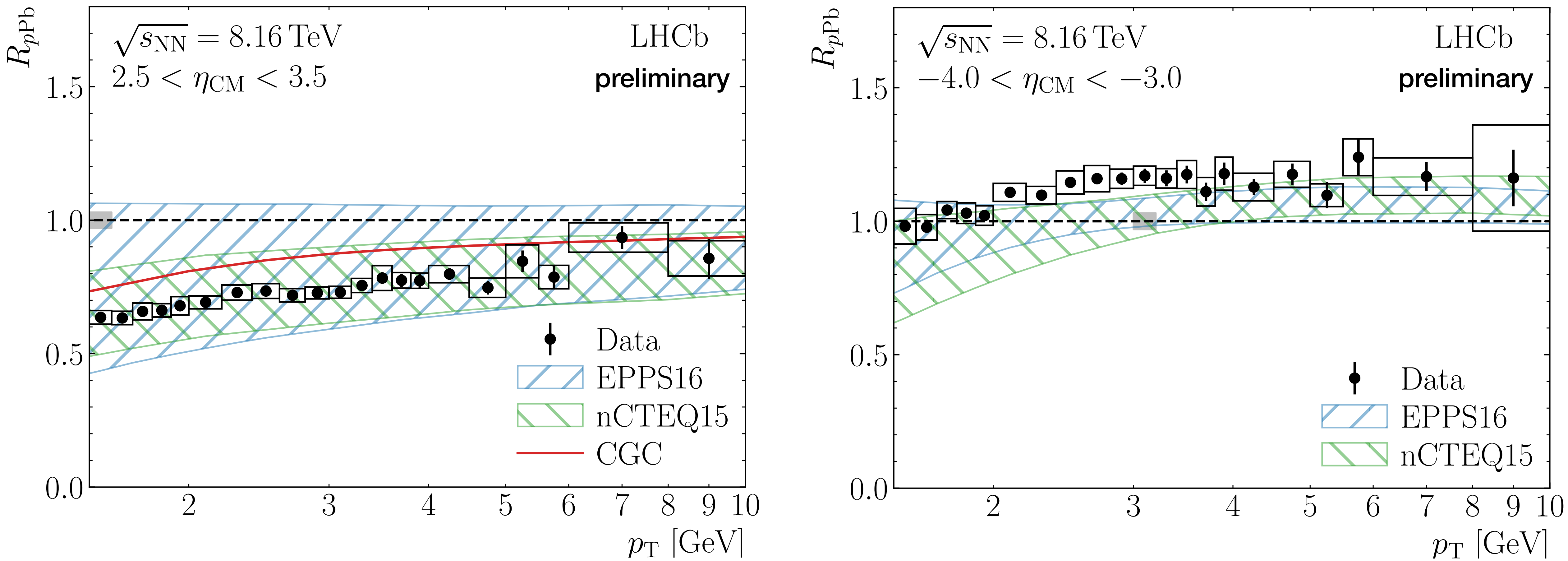
Compton or direct + backgrounds



Poster by Cesar Luiz Da Silva in QM 2018

Neutral pion production in pPb

LHCb-PAPER-2021-053 (in preparation)



- Comparison with non-reweighted nPDF predictions