Studies of low-x phenomena with the LHCb detector

DIS 2022 - Santiago de Compostela

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Table of contents

1. What do we mean by low-x ?
2. What kind of physics we expect to study
3. Why LHCb is important for this
4. LHCb results:
   - **Measurement of charged hadron production in** pPb **and** pp **collisions,** PhysRevLett.128.142004
   - **Measurement of** π^0 **production in** pPb **and** pp **collisions,** arXiv:2204.10608

Accessing low-x phenomena

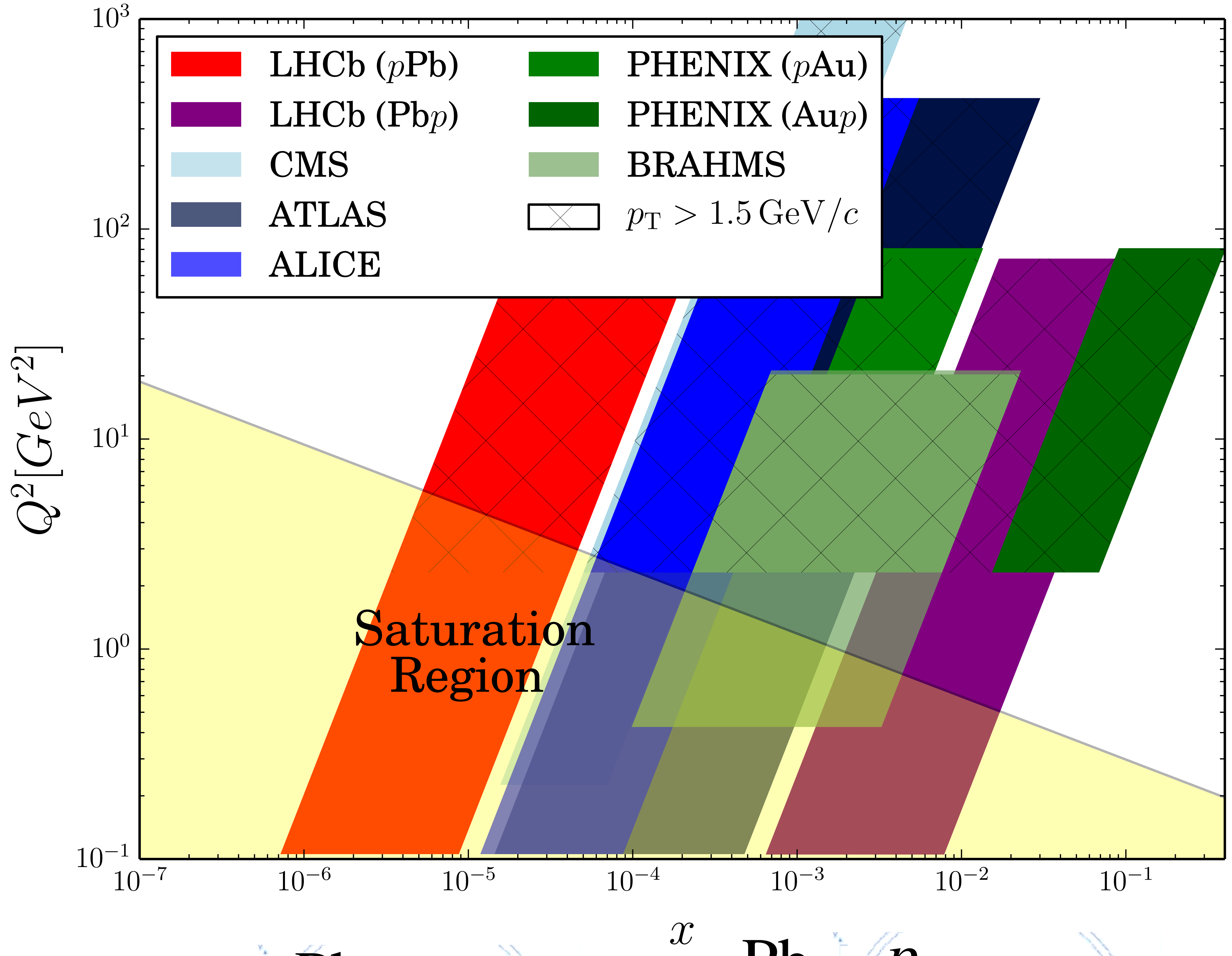
- Q^2: exchanged moments between interacting partons
- x: momentum fraction of the parton with respect to nucleus

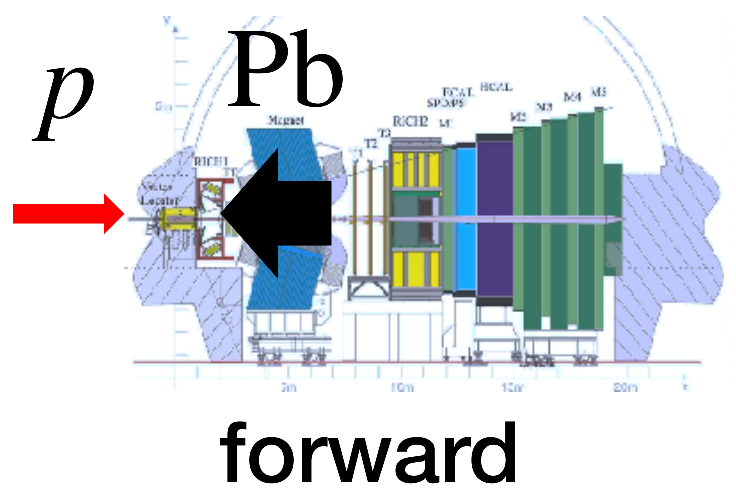
$$Q^2 \sim m^2 + p_T^2, \qquad x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$$

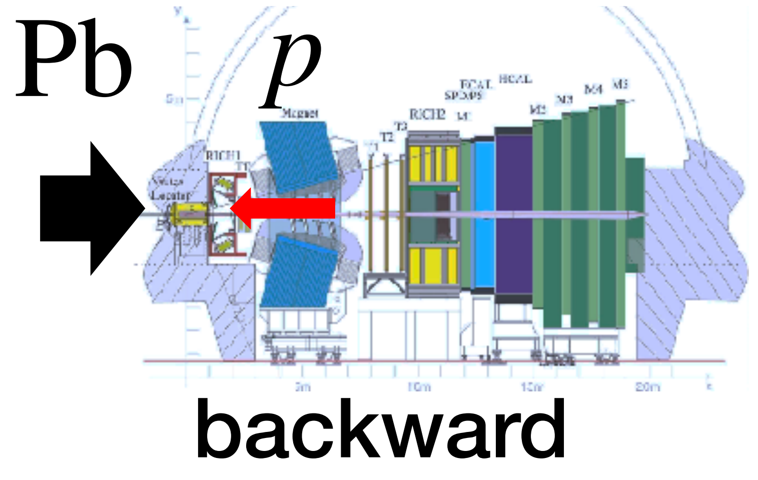
- **LHCb coverage**
  - Forward, $10^{-6} \leq x \leq 10^{-4}$
  - Backward, $10^{-3} \leq x \leq 10^{-1}$

↓

Unique acces to low-x physics







LHCb particular capabilities

- Charged and neutral hadron production at small-x
- Capability to study one system in a wide range of x values:
  - Forward/Backward comparison
- Possible access to the *saturation region* →Non-lineal dynamics

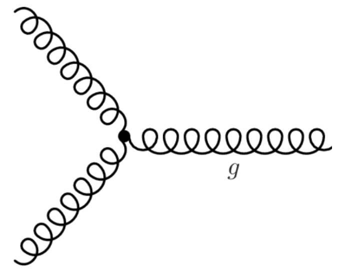
Low-x phenomena

- QCD evolution with ln(1/x) is modeled by BFKL equations
- Due to unitarity, the saturation of gluon PDF's is required

Color Glass Condensate

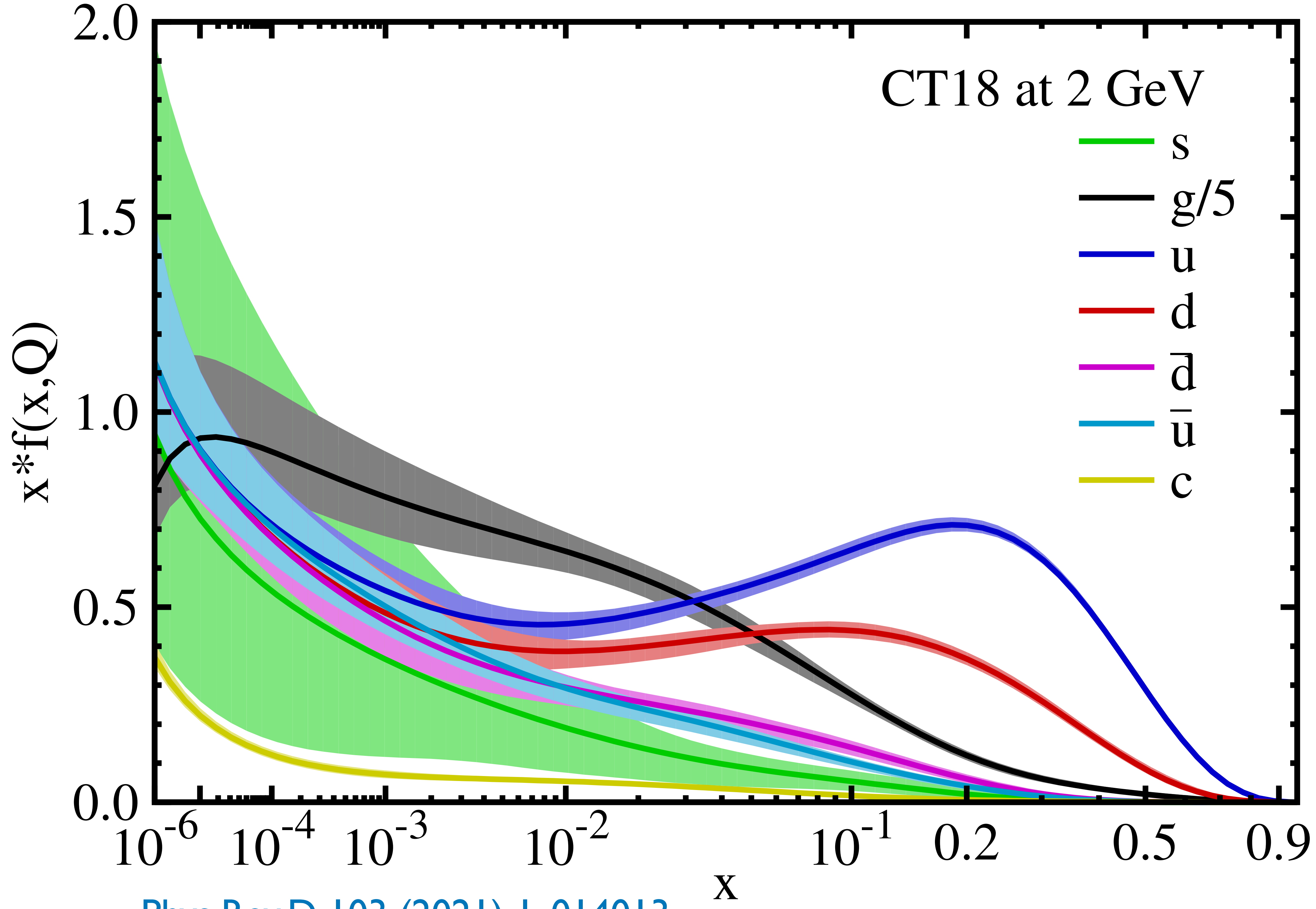
QCD based effective field theory which includes:

- Linear BFKL evolution
- Non-linear process; saturation

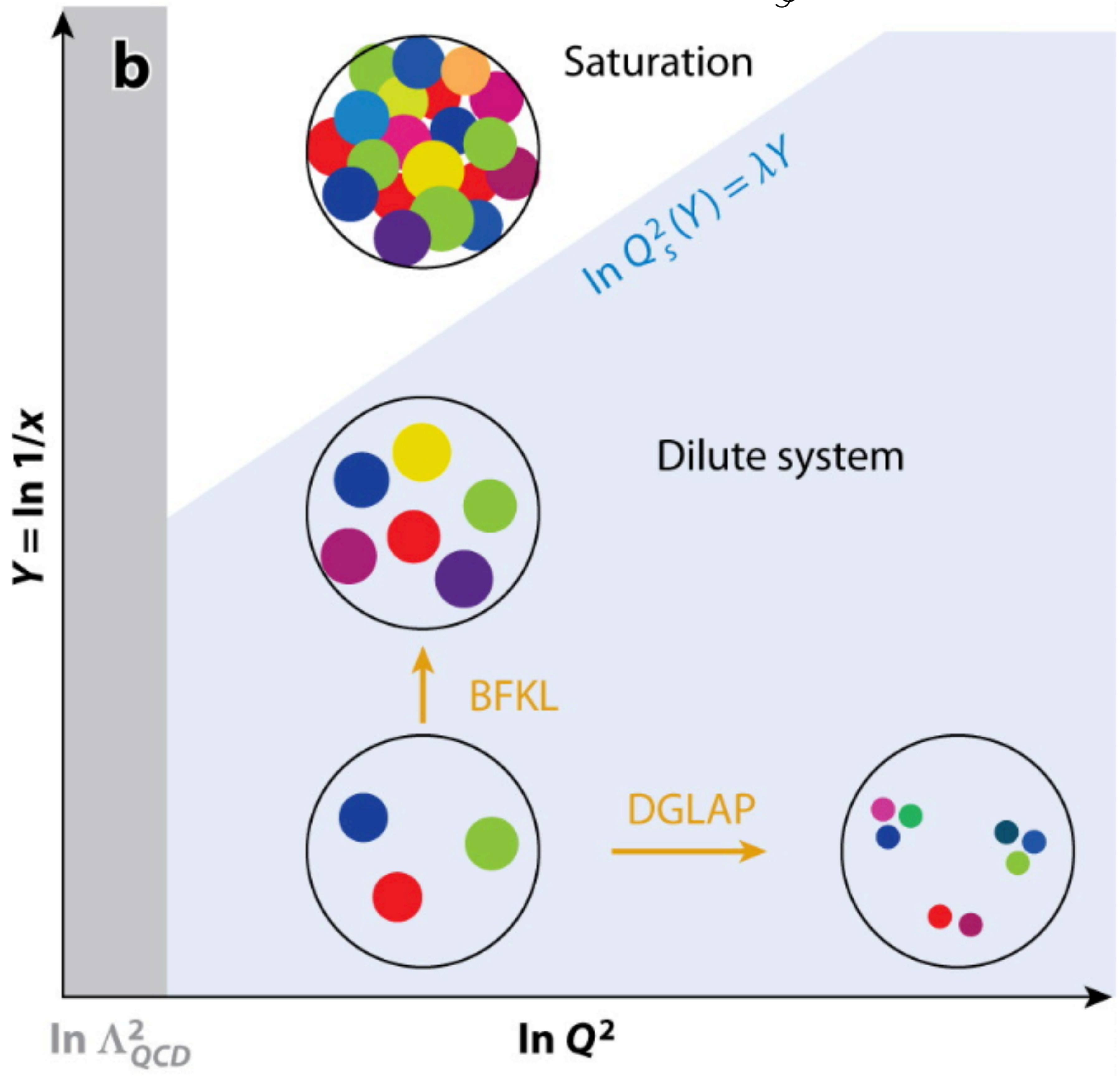


- Nuclear effects can be measured with the nuclear modification factor:

$$R_{pPb}(\eta, p_T) = \frac{1}{A}\frac{d^2\sigma_{pPb}(\eta, p_T)/dp_T d\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_T d\eta}, A = 208$$



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

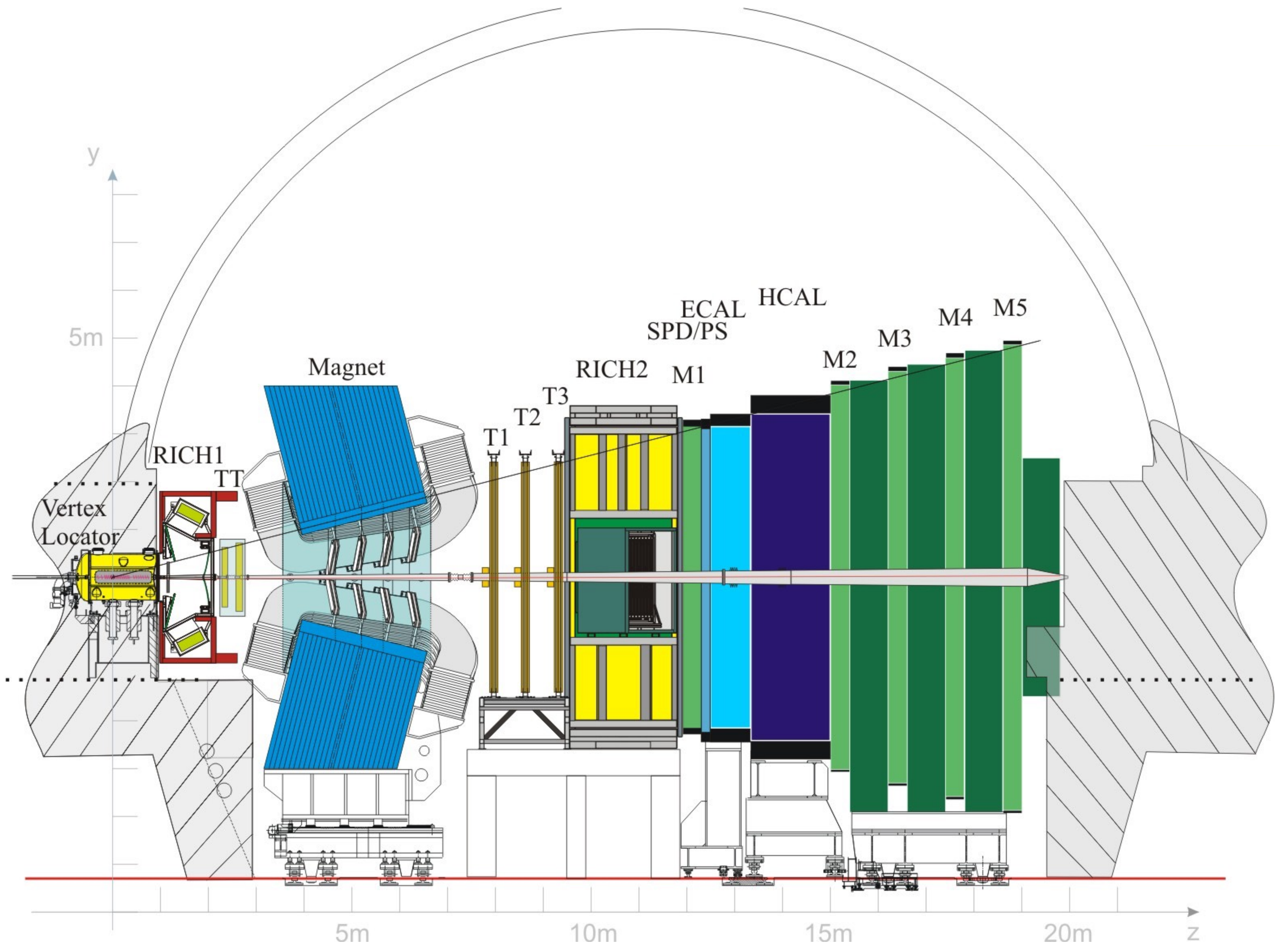


Ann.Rev.Nucl.Part.Sci.60:463-489,2010

About LHCb

LHCb experiment

- General purpose detector *JINST* 3 (2008) S08005
- Single-arm fully instrumented spectrometer in $\eta \in [2, 5]$
- pp, pPb, PbPb and fixed target modes
- Momentum resolution: $\Delta p/p = 0.5 - 1\,\%\,, p \in [2, 200]\,\mathrm{GeV/c}$
- Primary vertex resolution: $\in [10, 35]\,\mu\mathrm{m}$
- ECAL energy resolution: arXiv:2008.11556 $13.5\,\%/\sqrt{E/GeV} \oplus 5.2\% \oplus (0.32\,\mathrm{GeV})/E$



Charged hadron production in pPb and pp

PhysRevLett.128.142004

Nuclear modification factor $R_{pPb}(\eta, p_T) = \frac{1}{A}\frac{d^2\sigma_{pPb}(\eta, p_T)/dp_T d\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_T d\eta}, A = 208$

Prompt charged particles cross section

$$\frac{d^2\sigma}{dp_T d\eta} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta\eta}$$

N^{ch} : Prompt charged particle yield
$\mathscr{L}$: Integrated luminosity of the dataset
$\Delta\eta, \Delta p_T$: Bin size

Prompt charged particles

ALICE-PUBLIC-2017-005

Mean proper lifetime, τ, larger than $\tau > 1$ cm/c:
$\pi^-, K^-, p, \Xi^-, \Sigma^+, \Sigma^-, \Omega^-, e^-, \mu^-(+cc)$

Produced in primary interaction or without long-lived ancestors

$\sqrt{s_{NN}} = 5$ TeV, Datasets:

	Beam	Acceptance	Luminosity
2015	pp	$2 < \eta < 4.8$	$3.49 \pm 0.07\,\mathrm{nb}^{-1}$
2013	pPb	$1.6 < \eta < 4.3$	$42.73 \pm 0.98\,\mu\mathrm{b}^{-1}$
	Pbp	$-5.2 < \eta < -2.5$	$38.71 \pm 0.97\,\mu\mathrm{b}^{-1}$

Charged hadron production in pPb and pp

PhysRevLett.128.142004

- N_{ch} measured with long tracks with:

$p > 2$ GeV/c, $0.2 < p_T < 8$ GeV/c

$$N_{ch} = N^{candidates} \frac{P}{\varepsilon_{reco}\varepsilon_{sel}}$$

  - $N^{candidates}$: selected long tracks
  - P: signal purity
  - ε_{reco}: reconstruction efficiency
  - ε_{sel}: selection efficiency

Dominated by two systematic uncertainties:

- Particle fraction (π, K, p) abundance in pPb
- Tracking efficiency and purity in boundary (η, p_T) bins

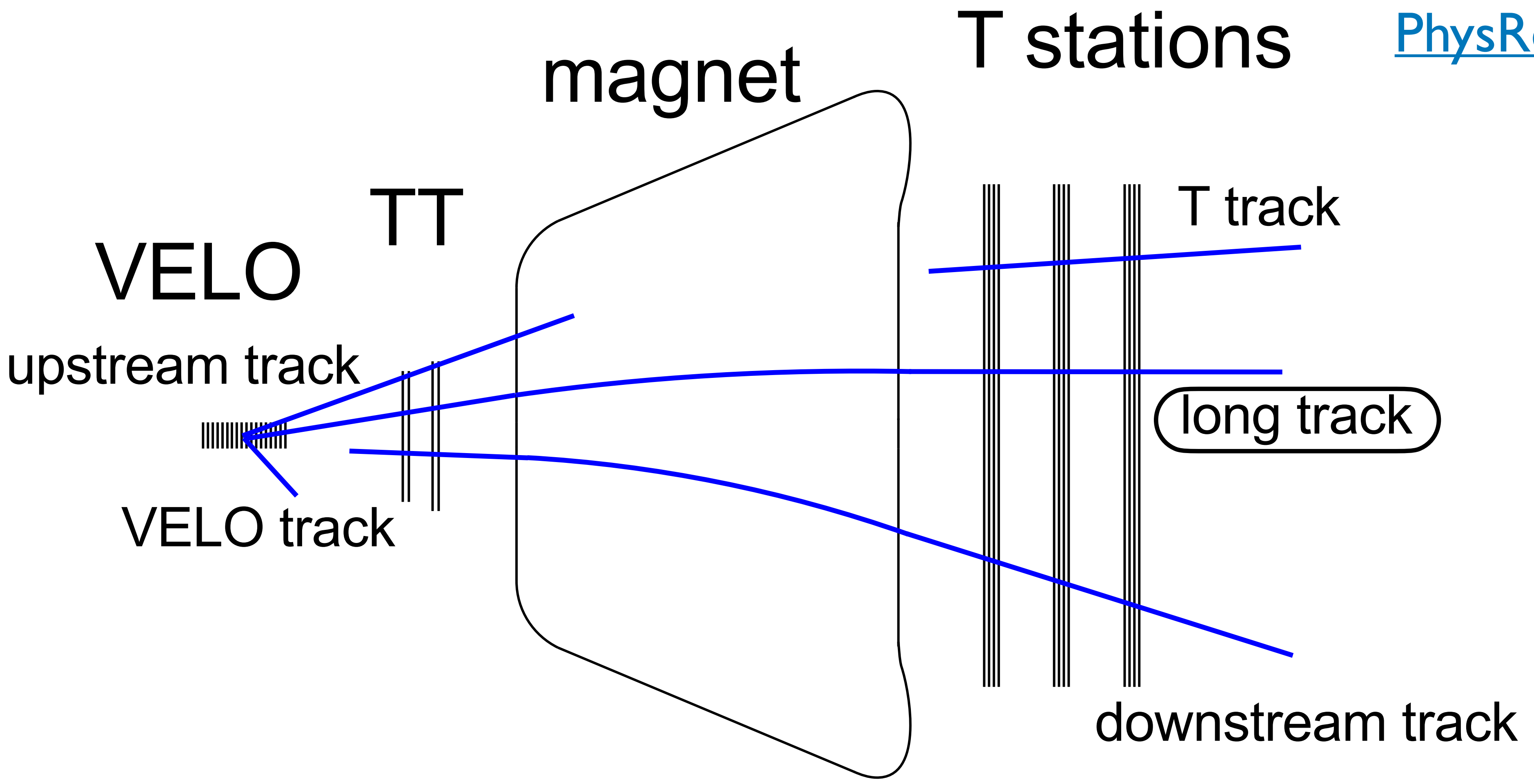


Figure from JINST 10 (2015) 02, P02007

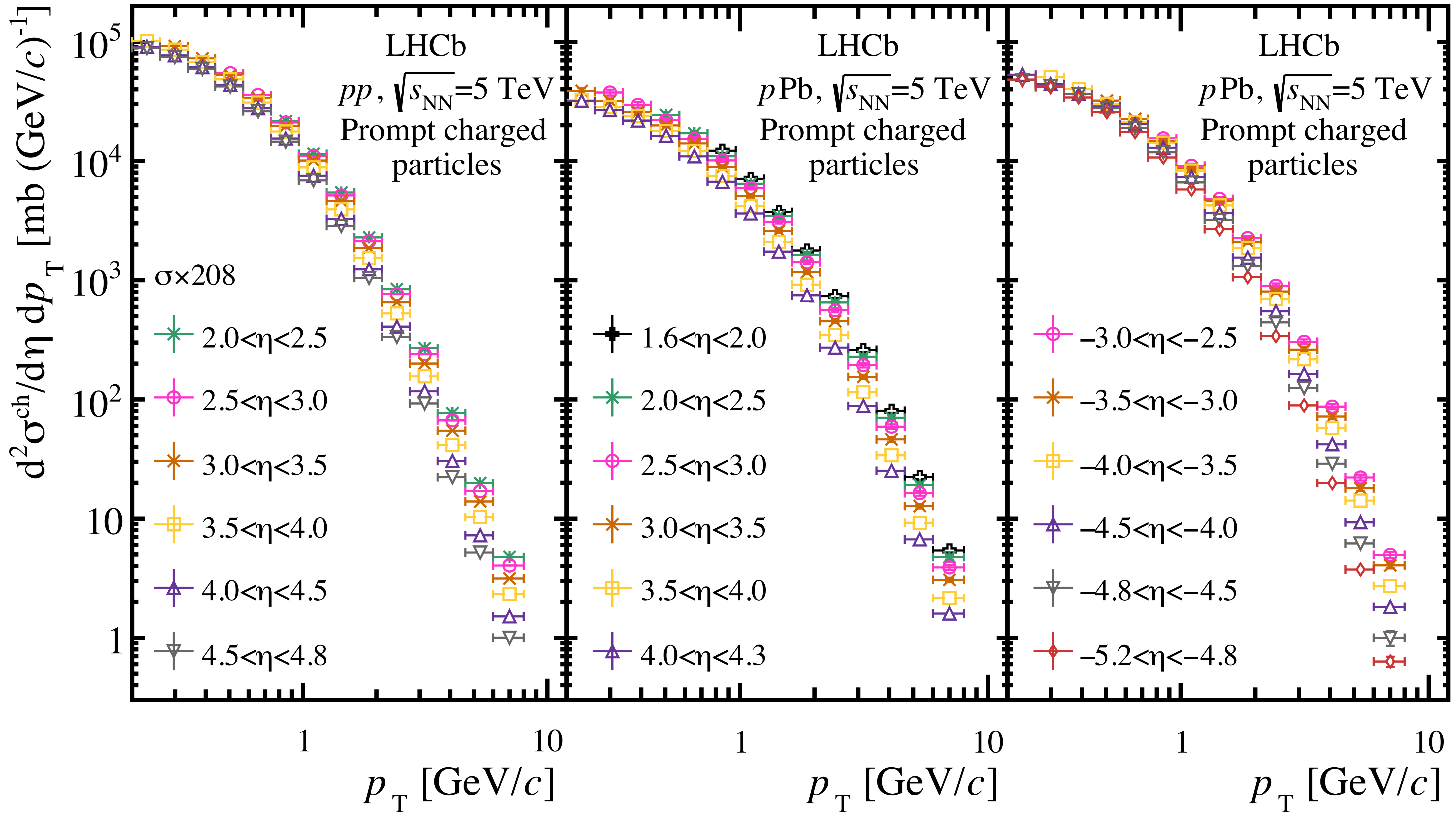
Uncertainty source	pPb [%] (forward)	pPb [%] (backward)	pp [%]
Track-finding efficiency	1.5 – 5.0	1.5 – 5.0	1.6 – 5.3
Detector occupancy	0.0 – 2.8	0.6 – 2.9	0.1 – 1.6
Particle composition	0.4 – 4.1	0.4 – 4.6	0.3 – 2.4
Selection efficiency	0.7 – 2.2	0.7 – 3.0	1.0 – 1.7
Signal purity	0.1 – 1.8	0.1 – 11.7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

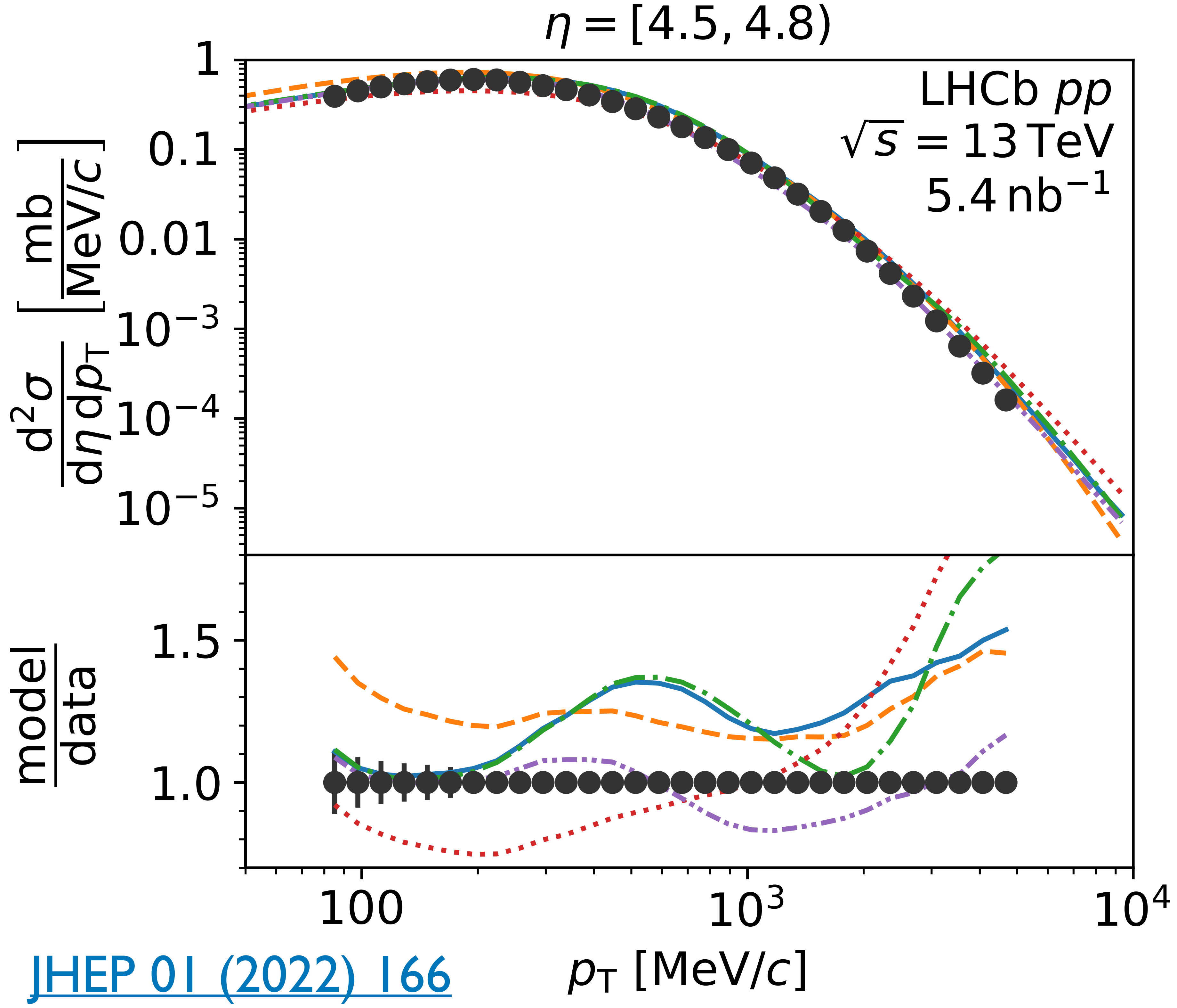
Charged hadron production in pPb and pp

Prompt charged particles cross section results:

$$\frac{d^2\sigma}{dp_T d\eta} = \frac{1}{\mathscr{L}} \cdot \frac{N^{ch}(\eta, p_T)}{\Delta p_T \Delta \eta}$$

PhysRevLett.128.142004





JHEP 01 (2022) 166

- Also measurement at $\sqrt{s_{NN}} = 13$ TeV for pp
- Down to very low p_T

Charged hadrons R_{pPb}: Forward

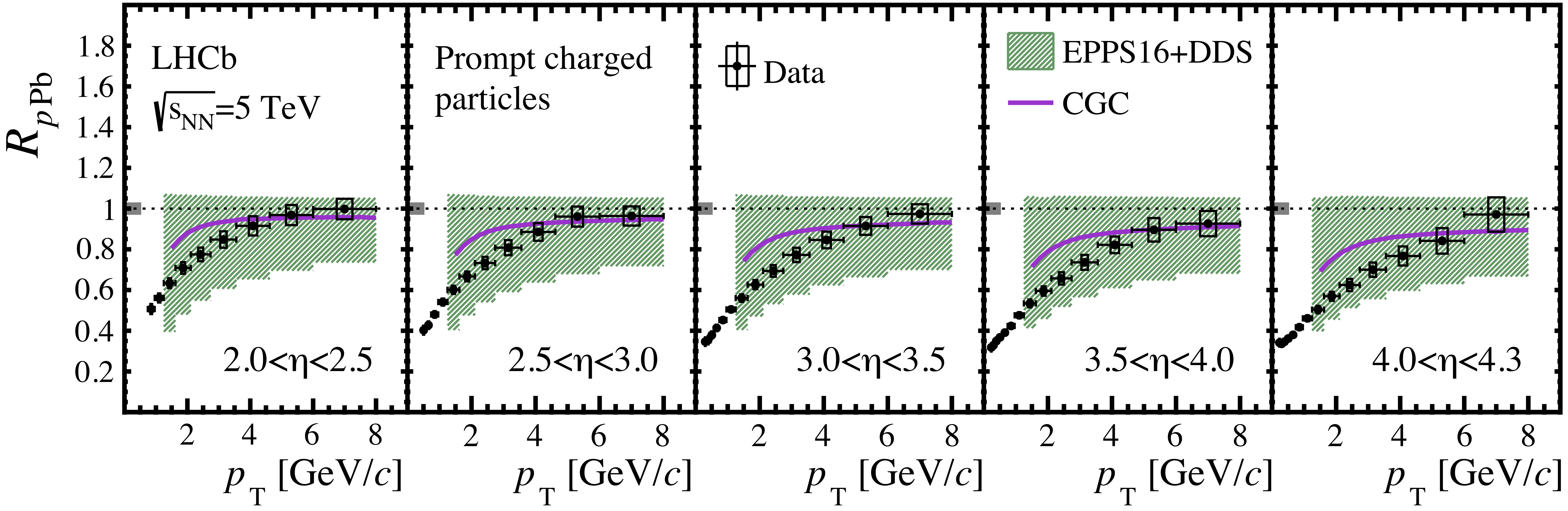
PhysRevLett.128.142004

- Nuclear modification factor results: $R_{pPb}(\eta, p_T) = \frac{1}{A}\frac{d^2\sigma_{pPb}(\eta, p_T)/dp_T d\eta}{d^2\sigma_{pp}(\eta, p_T)/dp_T d\eta}$, $A = 208$

- Strong suppression (~ 0.3) at forward and low p_T
- Growing up to 1 at high p_T
- High precision in comparison with theoretical calculations

Models:

- EPPS16+DDS: JHEP09(2014)138
- CGC (LO): PhysRevD.88.114020
  - CGC NLO: Better agrement arXiv:2112.06975



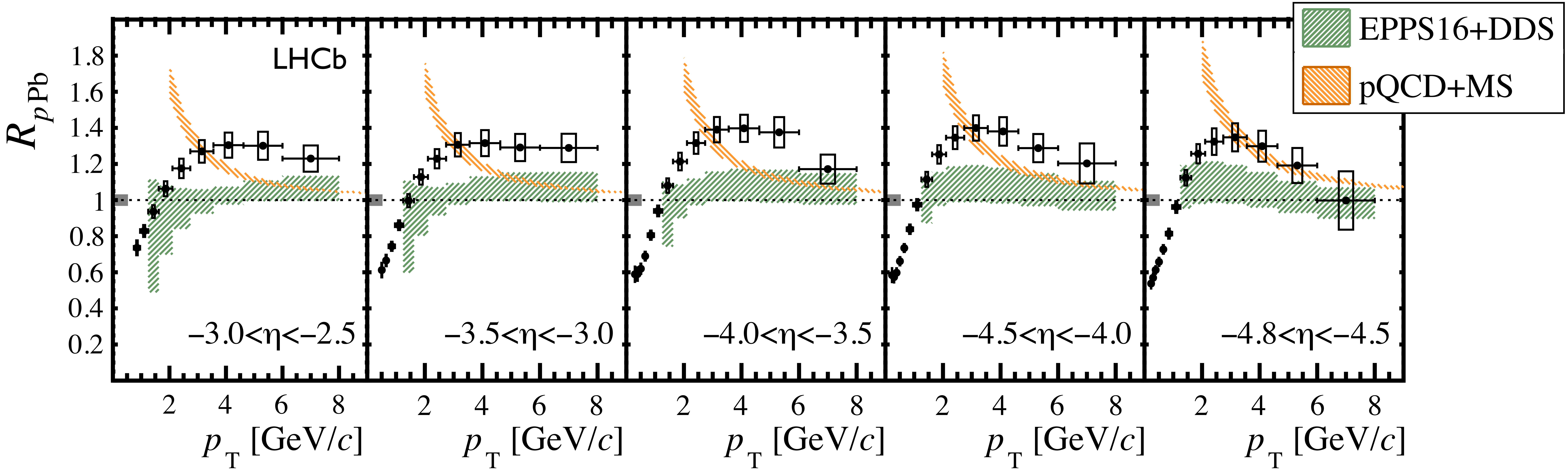
Charged hadrons R_{pPb}: Backward

PhysRevLett.128.142004

- Enhancement at backwards, $p_T > 1.5$ GeV/c
- Pseudo-rapidity dependent shape
- No current model describe data

Models:

- EPPS16+DDS: JHEP09(2014)138
  - Undervalues enhancement effect
- pQCD+MS: PR D88(2013) 054010
  - Multiple scattering effects
  - Reproduces tendency at most backward region and $p_T > 2.5$ GeV/c



Charged hadrons: $R_{pPb}(x_{exp}, Q^2_{exp})$

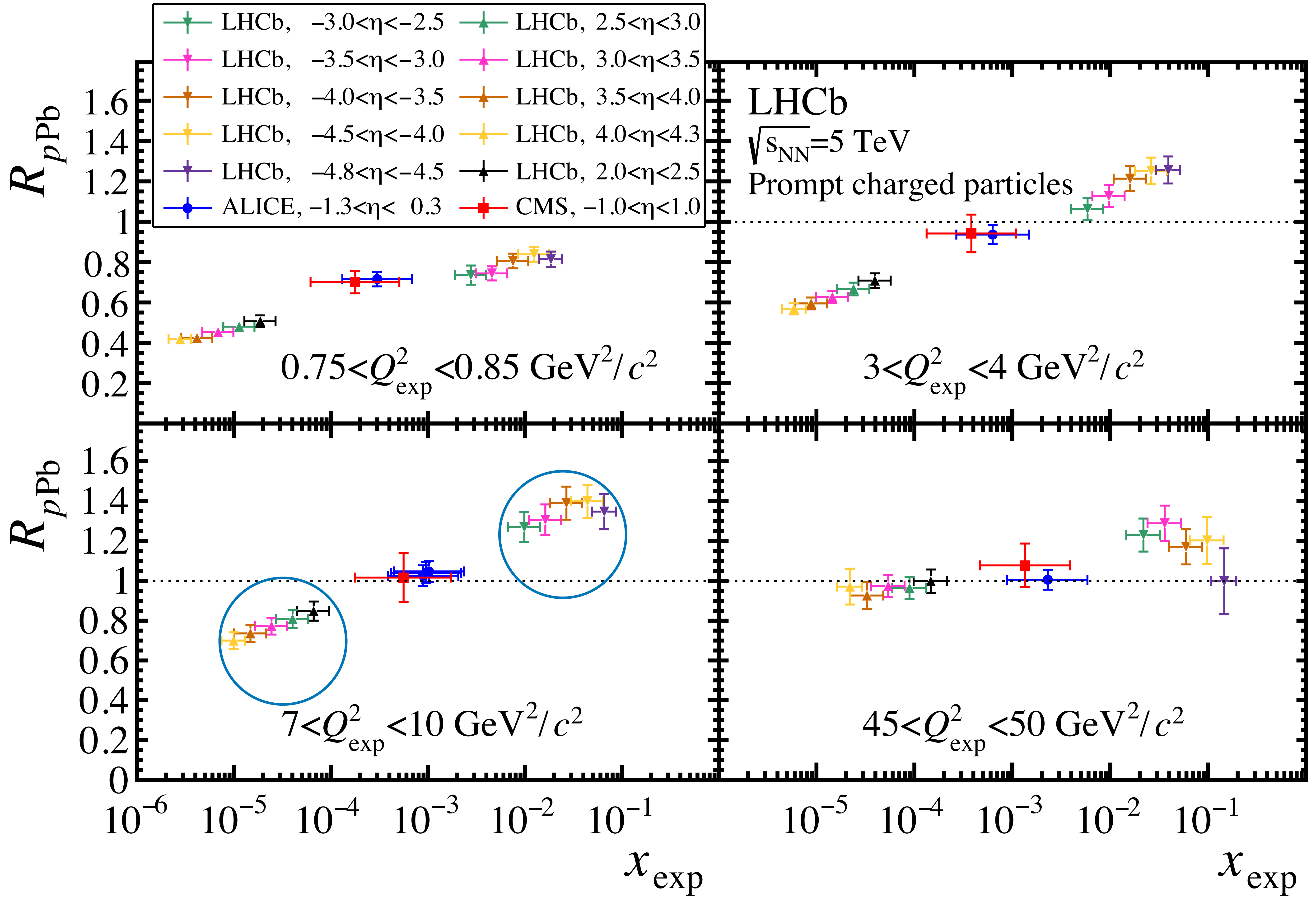
PhysRevLett.128.142004

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

- Approximations to (x, Q^2)
- (η, p_T) the center of each bin

- Averaged mass, $m = 256$ MeV

- Continuous evolution of R_{pPb} with x_{exp} between backward, central and forward region
- LHCb data expands the tendency in the (x_{exp}, Q^2_{exp}) phase space



Neutral pion production in pPb and pp

arXiv:2204.10608

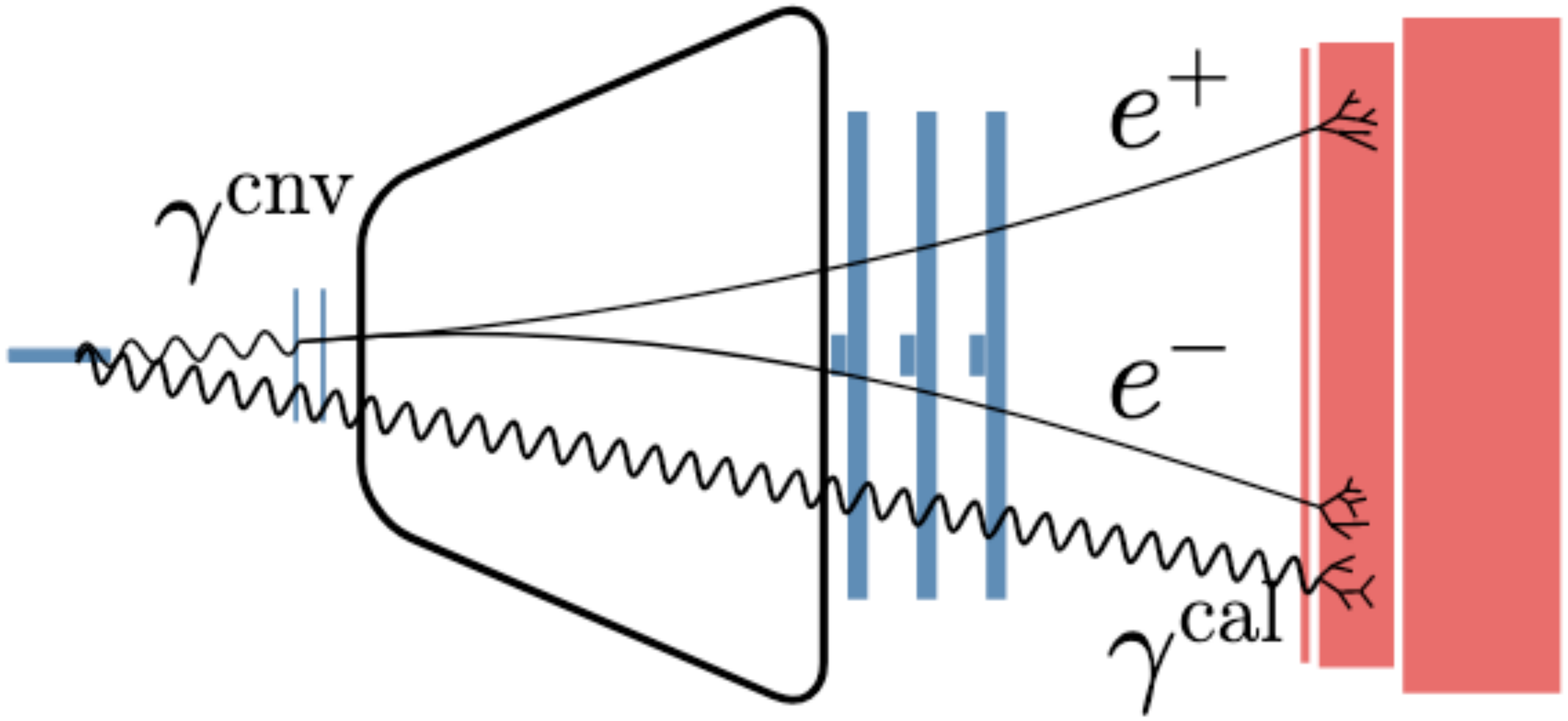
- Neutral pion production is important first step to perform direct photon measurements
- Particularly sensitive to cold nuclear matter (CNM) effects →nuclear parton distribution functions (nPDFs)
- First π^0production measurement in forward and backward rapidities at LHC

<u>Data sets:</u>

- pPb and Pbp data at $\sqrt{s_{NN}} = 8.16$ TeV
- pp reference constructed with and interpolation between $\sqrt{s_{NN}} = 5$ TeV and $\sqrt{s_{NN}} = 13$ TeV

<u>Technique</u>:

- Reconstructing the neutral pion with one converted photon and one ECAL photon, $\pi^0 \to \gamma^{cnv}\gamma^{cal}$ → Better momentum resolution than using only ECAL
  - Use $\pi^0 \to \gamma^{cal}\gamma^{cal}$ as cross-check and efficiency calibration



<u>Kinematic coverage:</u>

- $1.5 < p_T < 10.0$ GeV/c
- $2.5 < \eta < 3.5$ →Both photons in the detector
- $-4.0 < \eta < -3.0$

Neutral pion production in pPb and pp

arXiv:2204.10608

- π^0 yields extracted from binned maximum likelihood fits to di-photon mass spectra in bins of the π^0 p_T:
  - Two-sided Crystal Ball:
    - Tail parameters from MC
    - Gaussian parameters are left free

Combinatorial background:
- Correlated: π^0's are produced in a jet with other π^0's
- Uncorrelated: Combining converted photons with ECAL photos from uncorrelated underlying event

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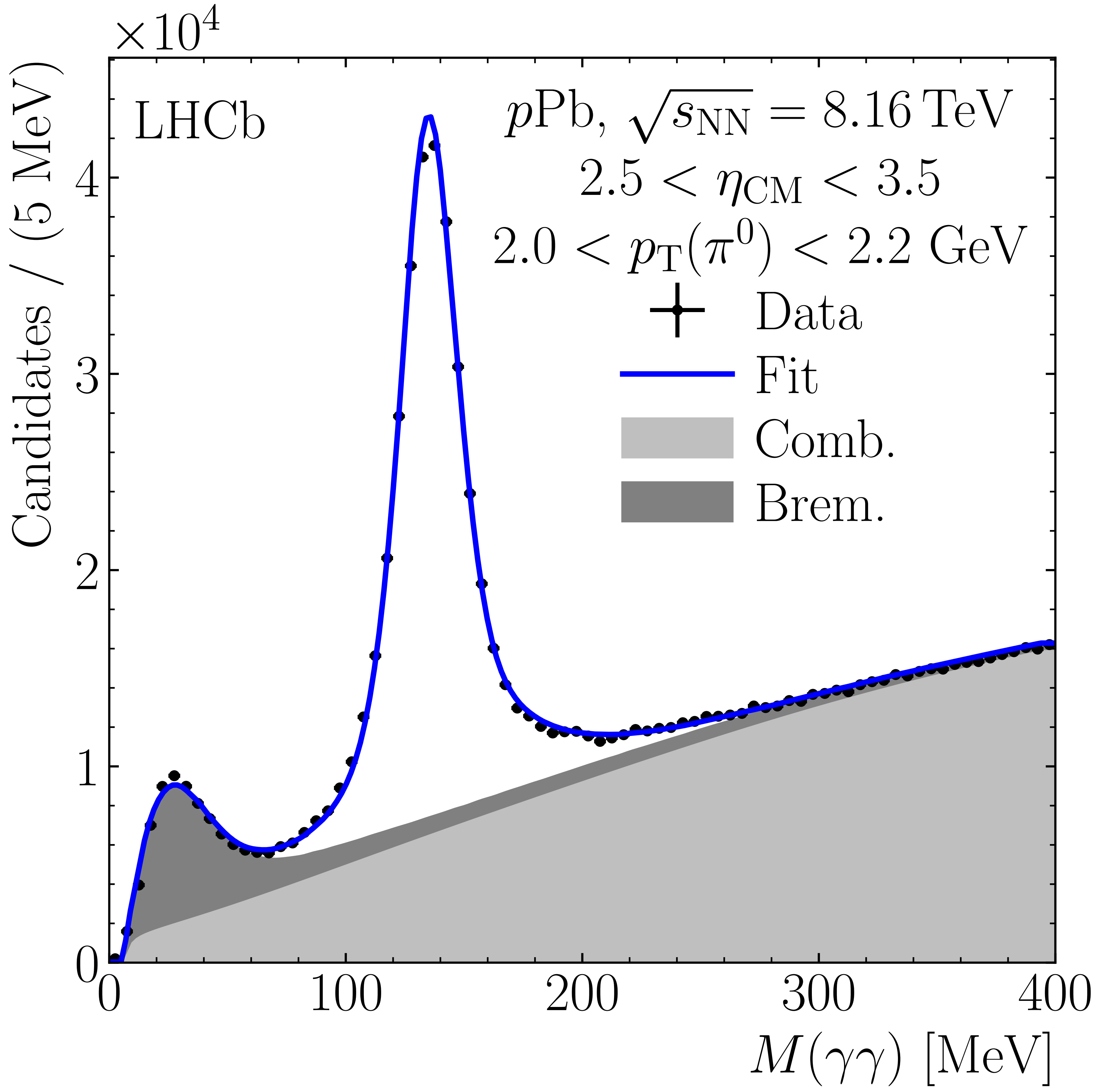
Modeled using charged tracks from MC

Bremsstrahlung: Combination of converted photons with bremsstrahlung radiation

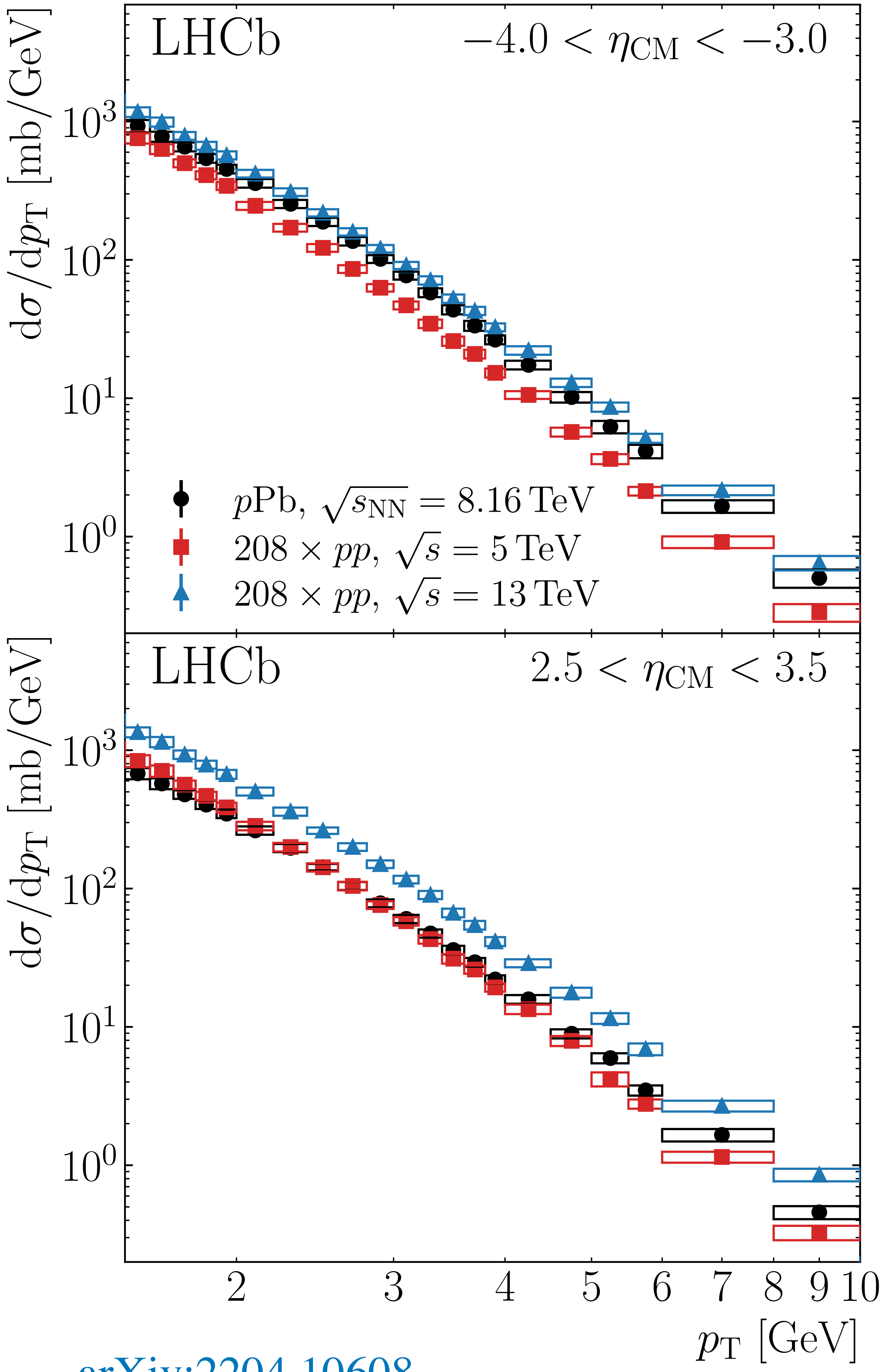


- Both background models are validated by fitting to only-background MC
- Data corrected by reconstruction efficiency and finite momentum resolution using MC

Neutral pion production in pPb and pp

- Neutral pion cross-section result, $\left.\frac{d\sigma}{dp_T}\right|_{\pi^0}$
  - Total uncertainty less than 6 % in most p_T intervals:
  - Main systematic uncertainty sources:
    - Fit model and pp interpolation

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



arXiv:2204.10608

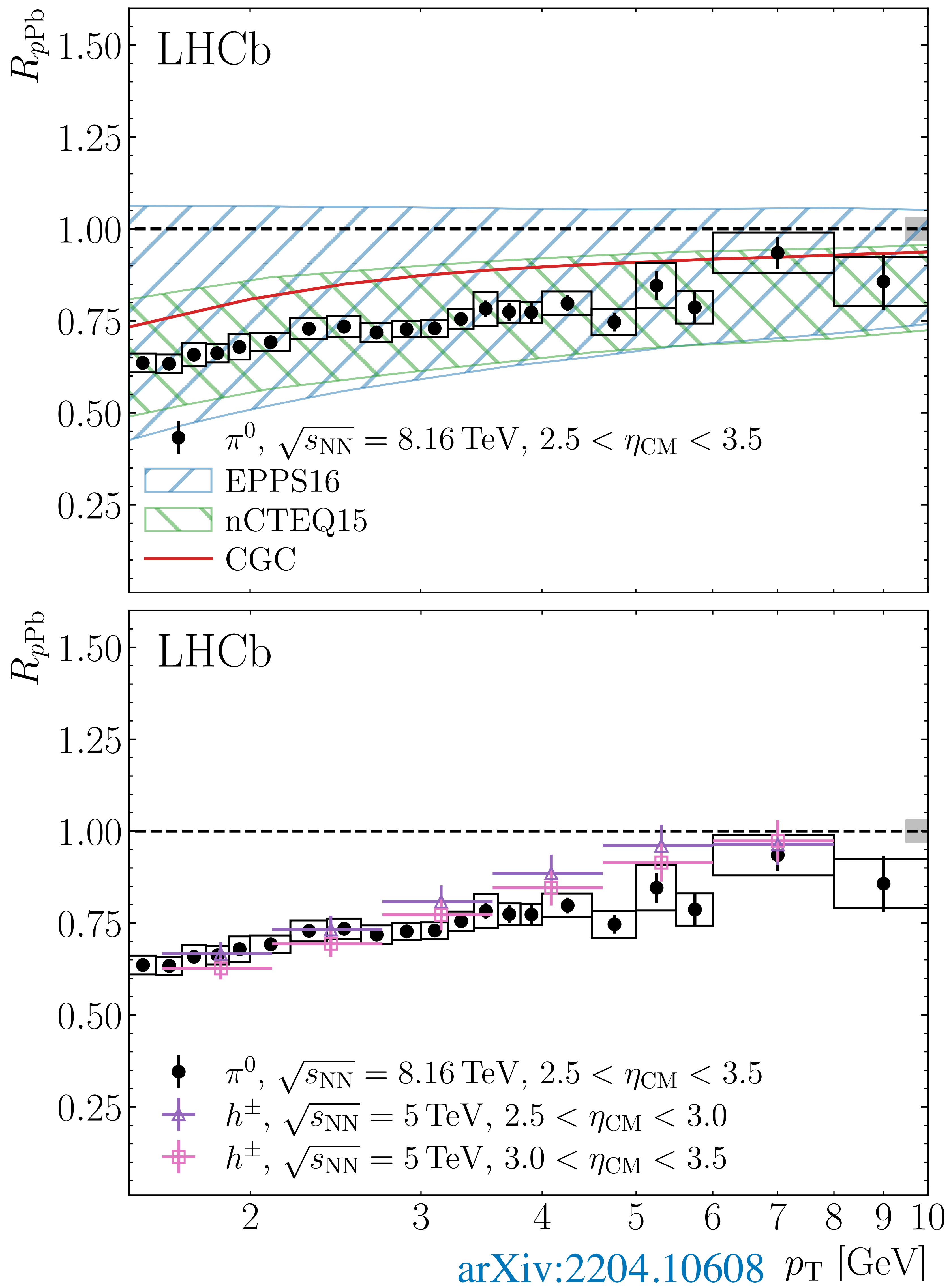
Neutral pion R_{pPb}: Forward

$$R_{pPb}(p_T) = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}, A = 208$$

- Suppression down to 0.6
- Compatible with charged hadron results

<u>Comparing with theory</u>

- CGC LO underestimates suppression, but follows the tendency
  Phys. Rev. D 88, 114020
- In agreement with NLO pQCD nPDFs (reweighted with LHCb D^0 data)
  JHEP1710(2017)090 JHEP05(2020)037
  - Constrain nPDFs computation at low p_T



arXiv:2204.10608

Neutral pion R_{pPb}: Backward

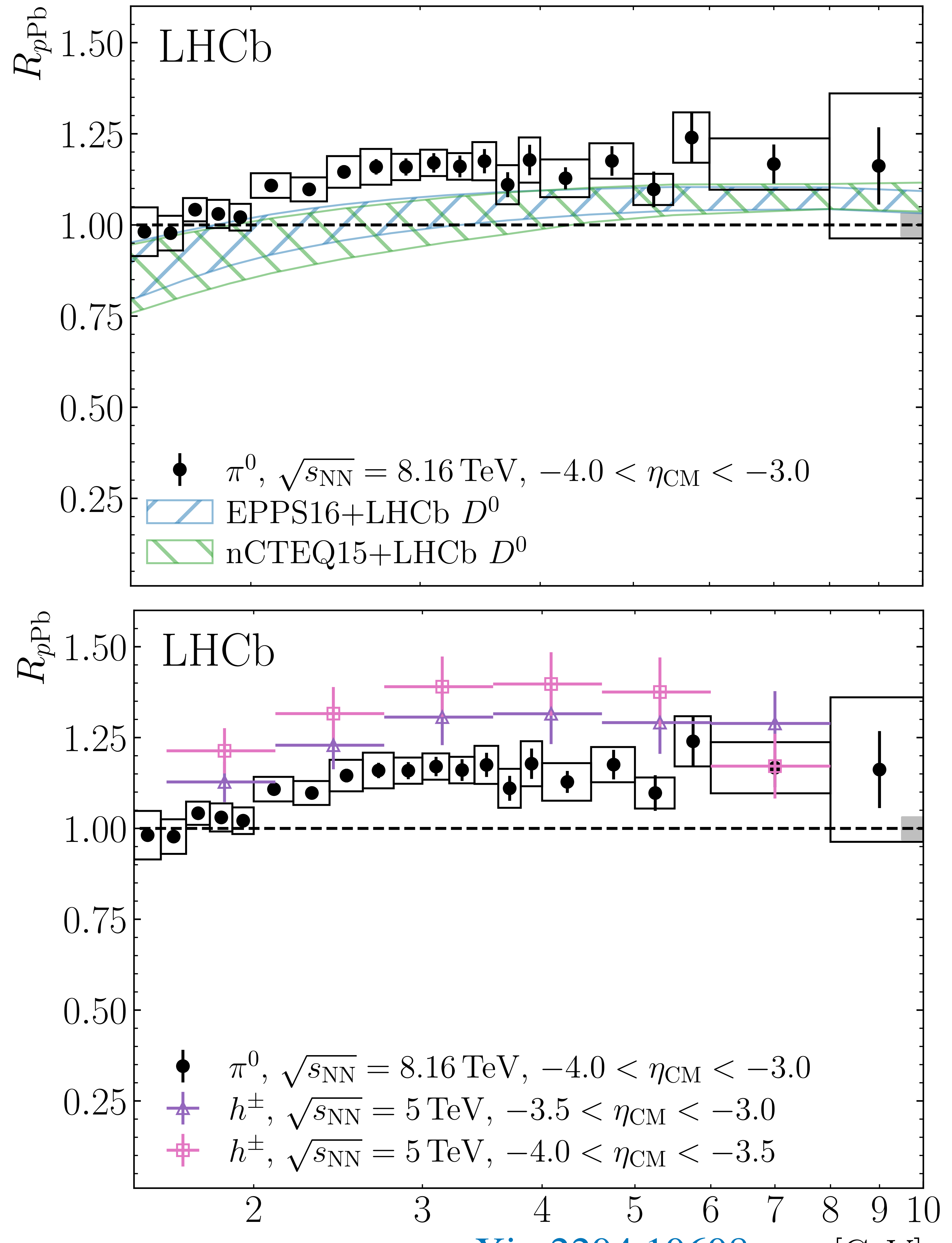
$$R_{pPb}(p_T) = \frac{1}{A}\frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T}, A = 208$$

- Enhancement of π^0production in pPb with respect to pp in backward region at intermediate $p_T \rightarrow$ Cronin-like enhancement ?
  - Less pronounced than in charged particles:
    - Mass-dependent enhancement consistent with radial flow or baryon enhancement from final state recombination

<u>Comparing with theory</u>

- Excess over reweighted nPDFs predictions:

  JHEP1710(2017)090 JHEP05(2020)037
  - More contributions to enhancement ?

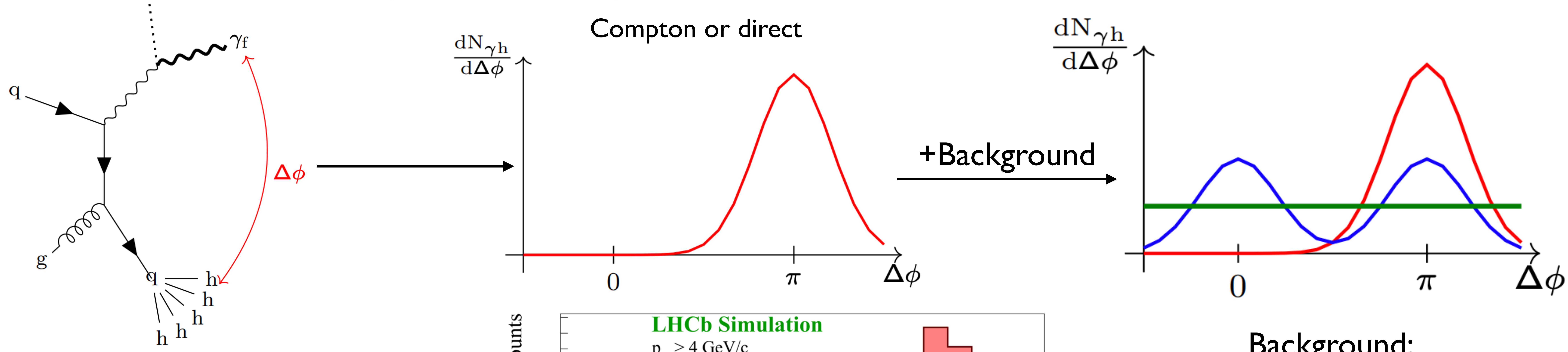


arXiv:2204.10608

Direct γ-hadron correlations

Ongoing work !

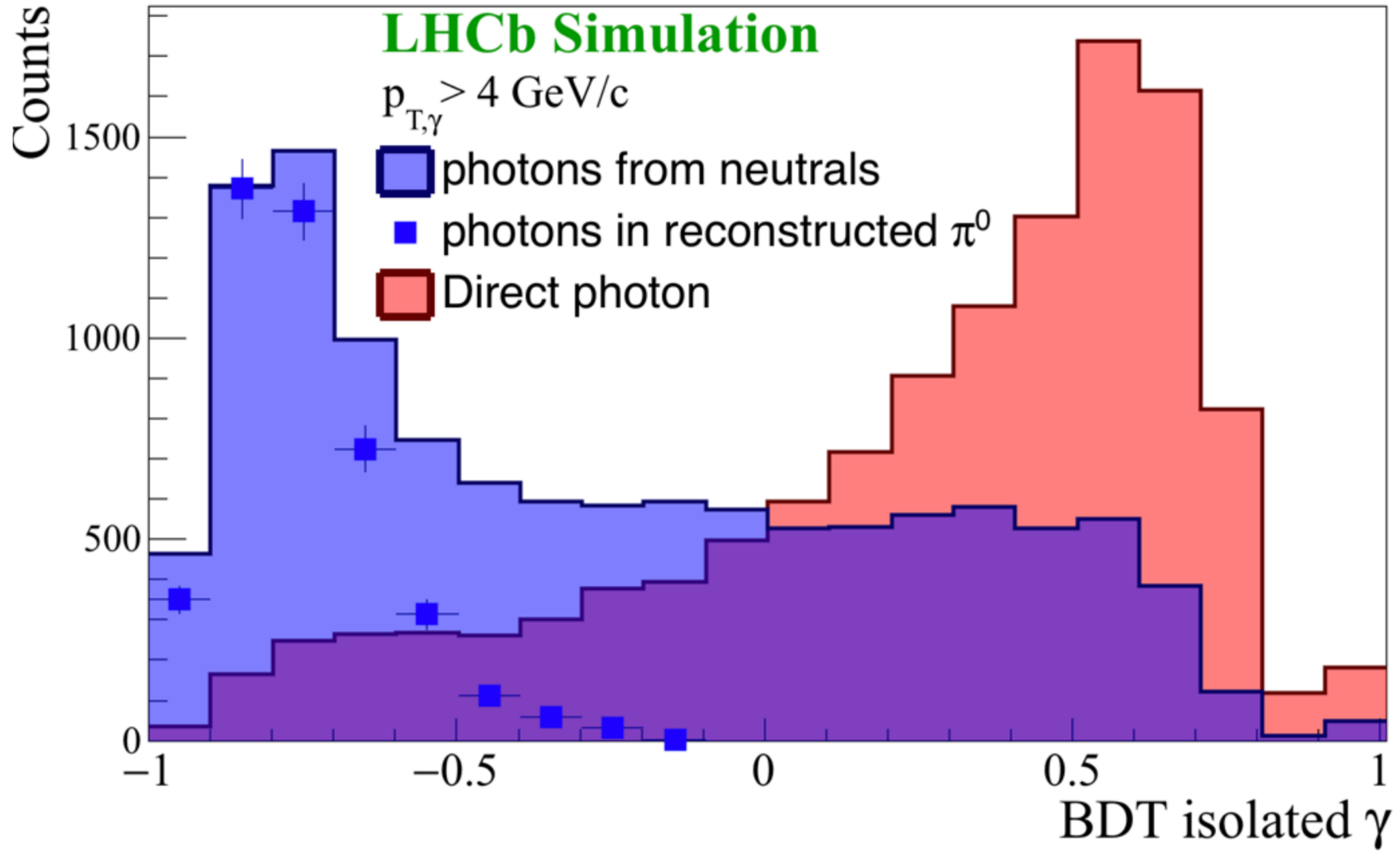
- One of the most direct ways to access the gluon PDF
- Inverse Compton signal will show up as an away-side peak in γ-hadron correlations
- Minimal activity around the photon, isolated photon



Background:

- Neutral decays
- Fragmentation
- Bremsstrahlung
- Thermal

Boost Decision Tree for Isolated Photons



Summary

- LHCb measurements provided unique access to low-x physics:
  - **Measurement of charged hadron production in pPb and pp collisions,**

    PhysRevLett.128.142004 **NEW PRL!**
  - **Measurement of π^0 production in pPb and pp collisions,** arXiv:2204.10608 **NEW!**

→ Compatible results from different approach ←

- Precise data to:
  - Constrain nPDF's →Better modeling nuclear effects
  - Tune saturation models and non-lineal effects
  - Understand enhancement in $x \sim 10^{-2}$

More LHCb results will come in the future →Stay tuned

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LHCb constrains in nPDFs EXTRA!

JHEP10(2017)090

- Impact of LHCb measurements in the nNNPDFs arXiv:2201.12363
- From LHCb D^0 production in pPb at $\sqrt{s_{NN}} = 5$ TeV
- Important reduction of uncertainties down to $x \sim 10^{-6}$. Specially gluon nPDFs

$$R_f^{(A)}(x,Q) \equiv \frac{f^{(N/A)}(x,Q)}{\frac{Z}{A} f^{(p)}(x,Q) + \frac{(A-Z)}{A} f^{(n)}(x,Q)}$$

Using neural networks (NN)