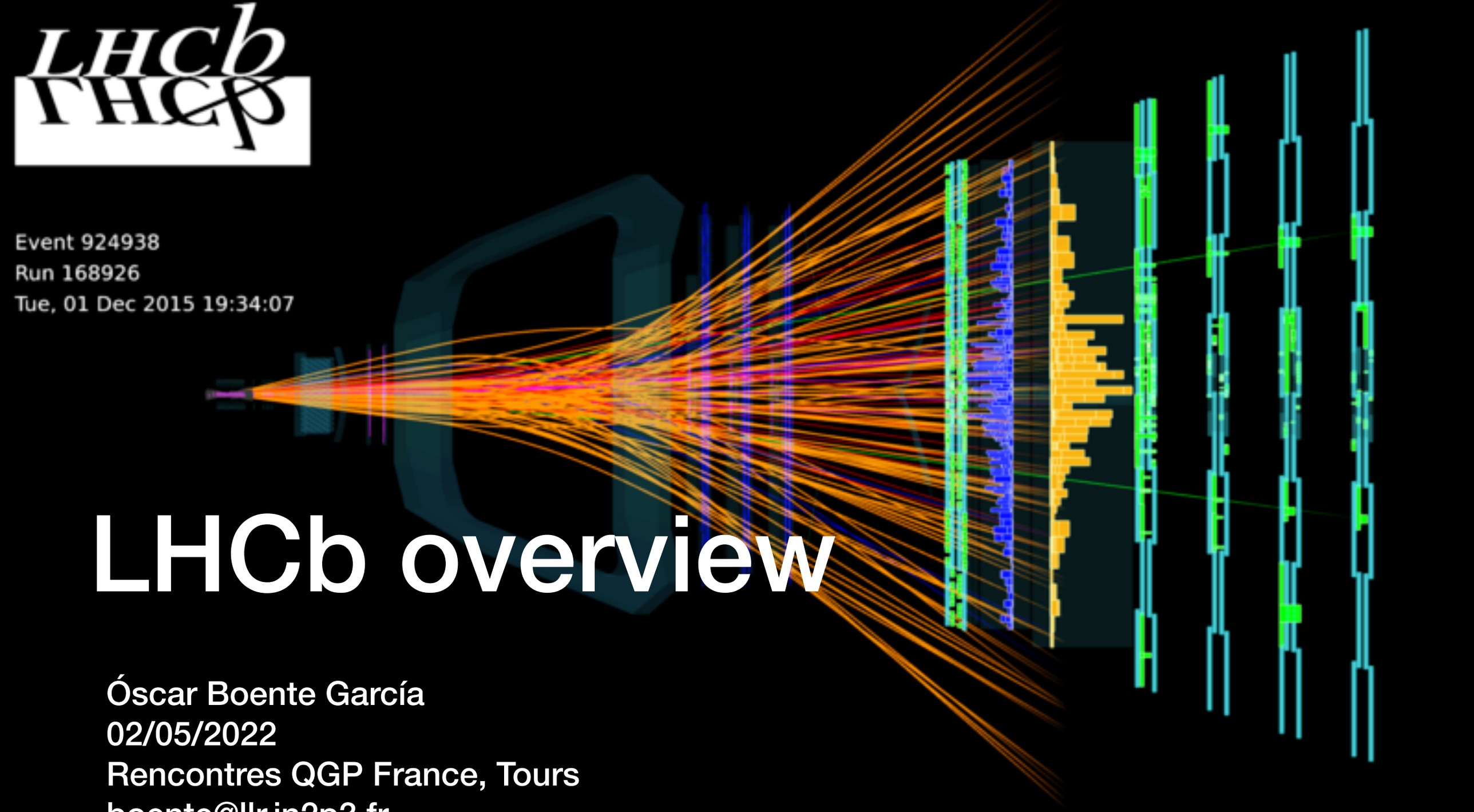


# LHCb overview

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02/05/2022
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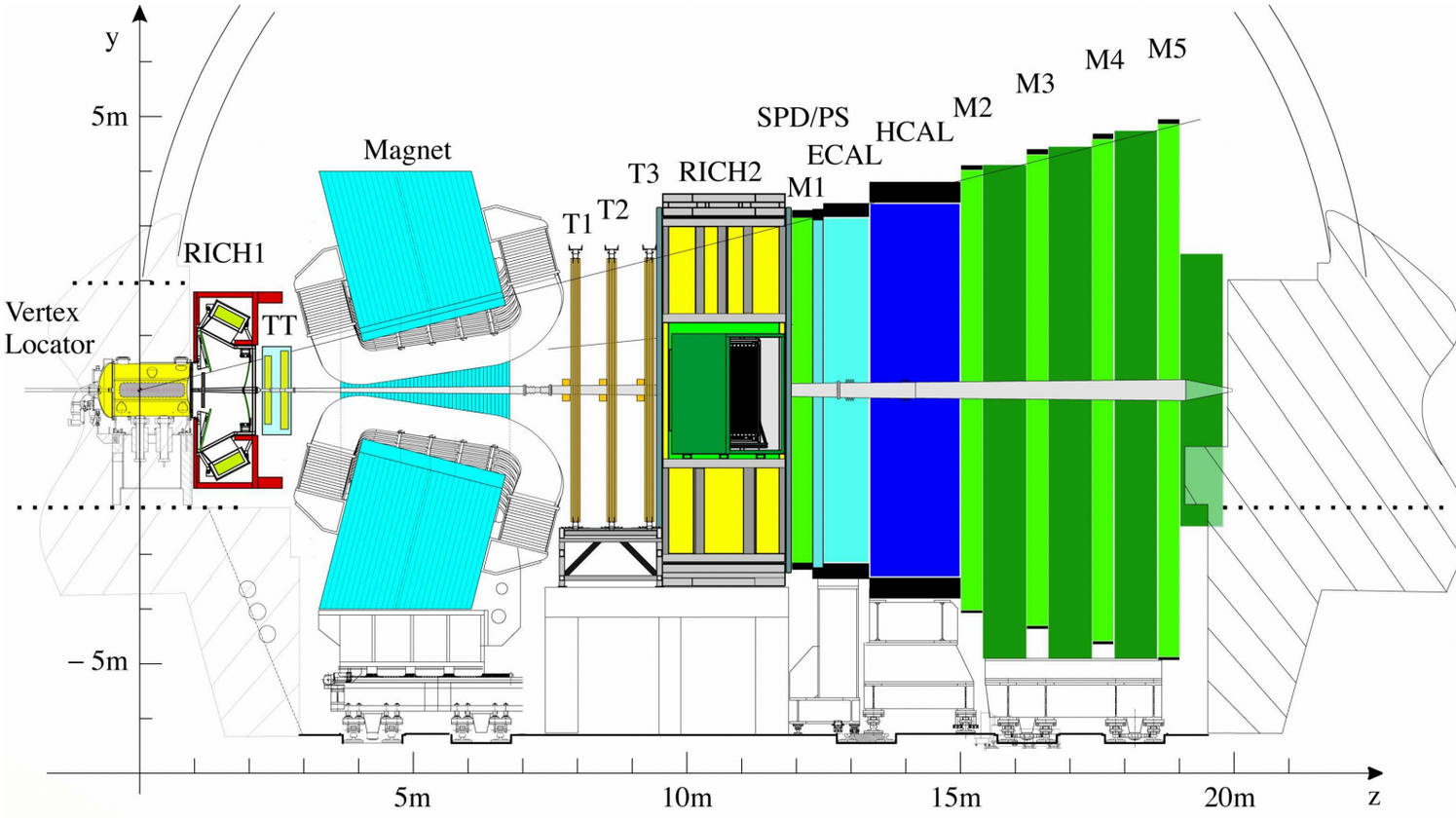
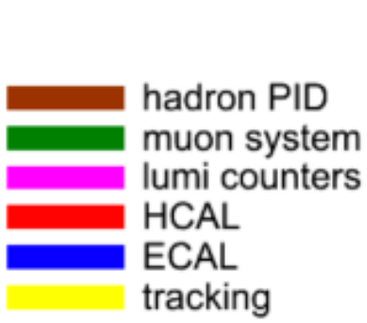
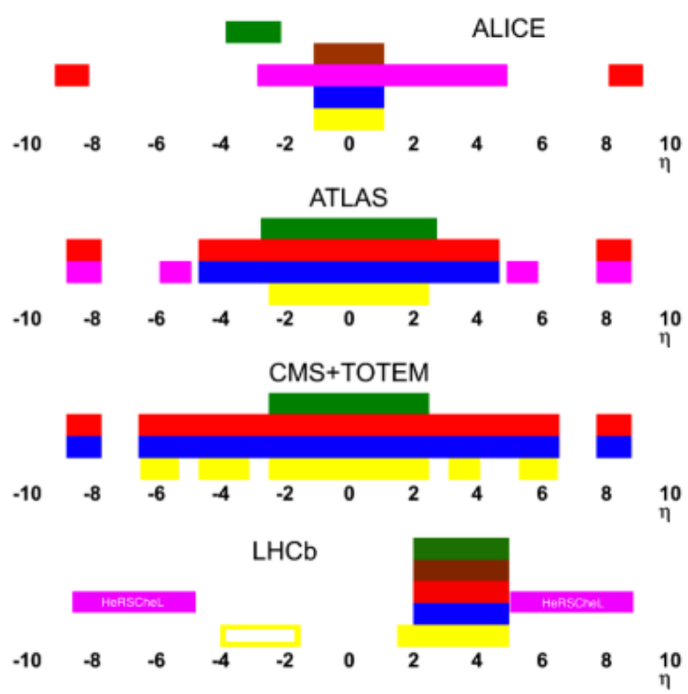
# The LHCb experiment

- One-arm spectrometer at LHC fully instrumented in $2 < \eta < 5$
  - Tracking system with excellent momentum resolution
  - Excellent hadron and muon ID
  - Precise vertex reconstruction, for primary and secondary vertices
  - Calorimeters ECAL, HCAL
  - Flexible trigger, down to low $p_{\mathrm{T}}$



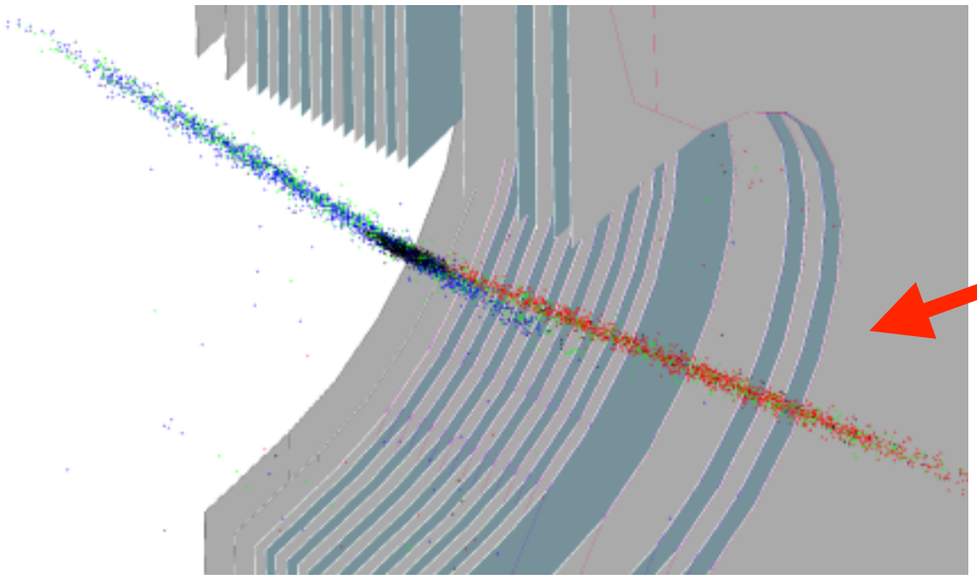



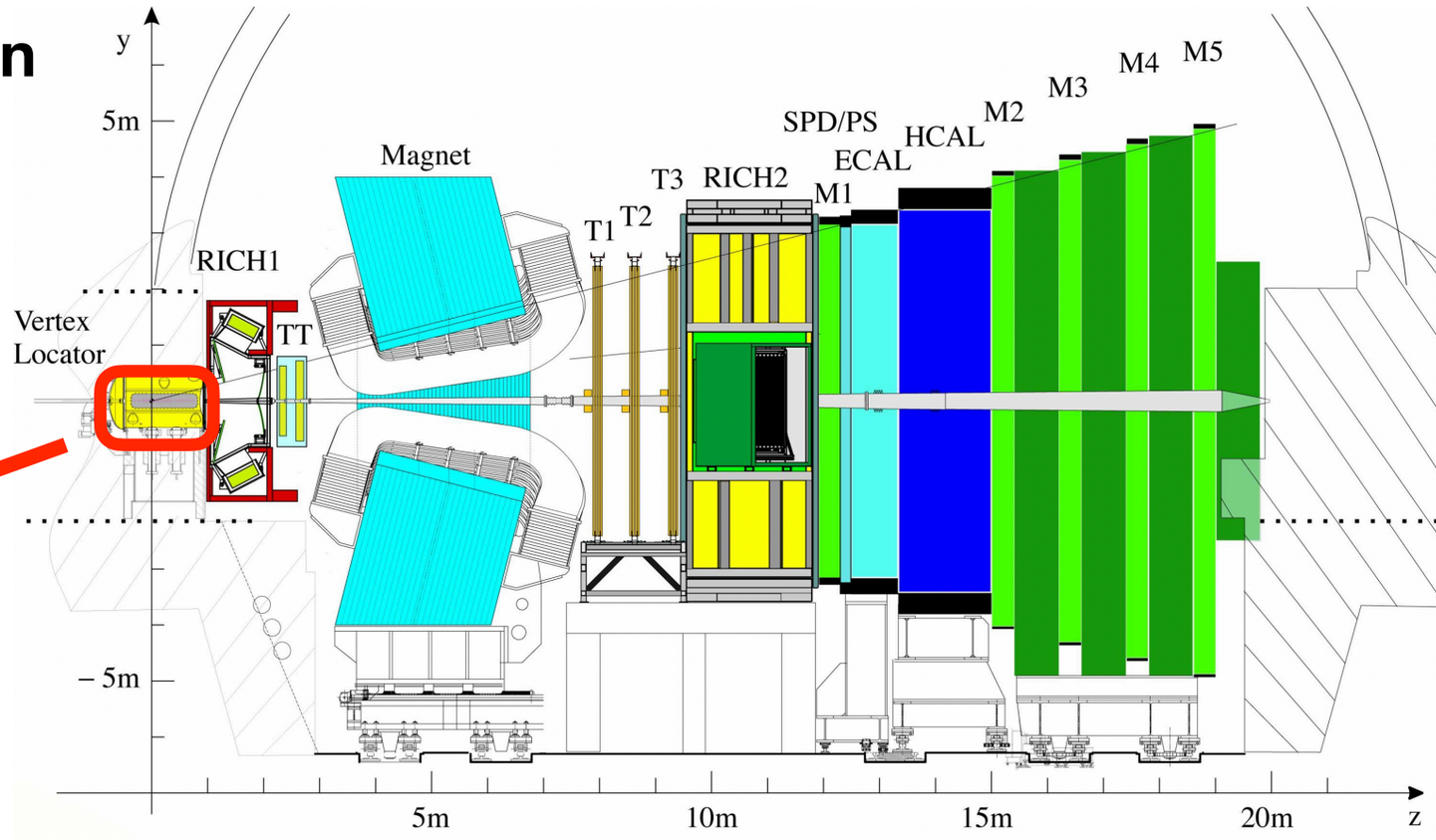

LHCb JINST 3 (2008) S08005

LHCb performance IJMPA 30 (2015) 1530022

# The LHCb experiment

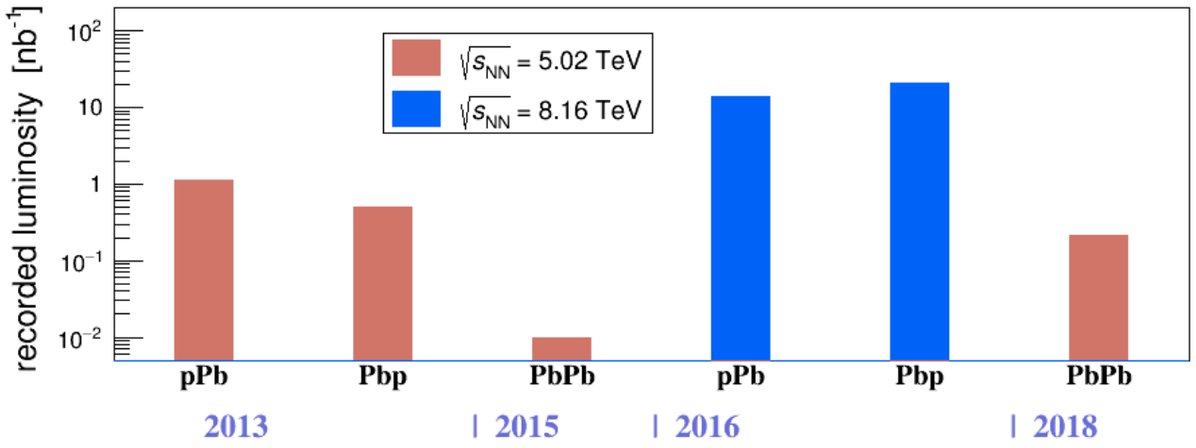
## A unique fixed-target configuration

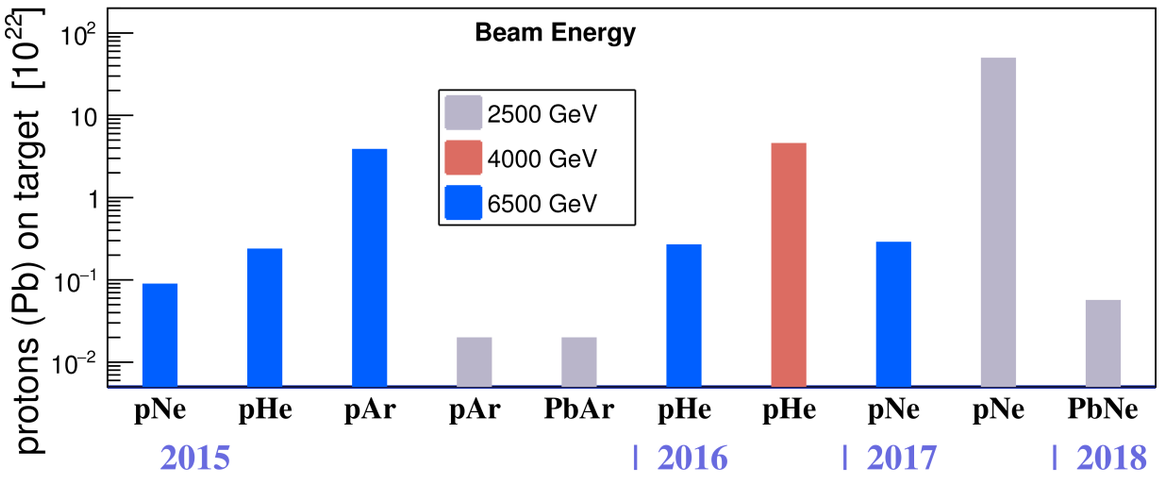




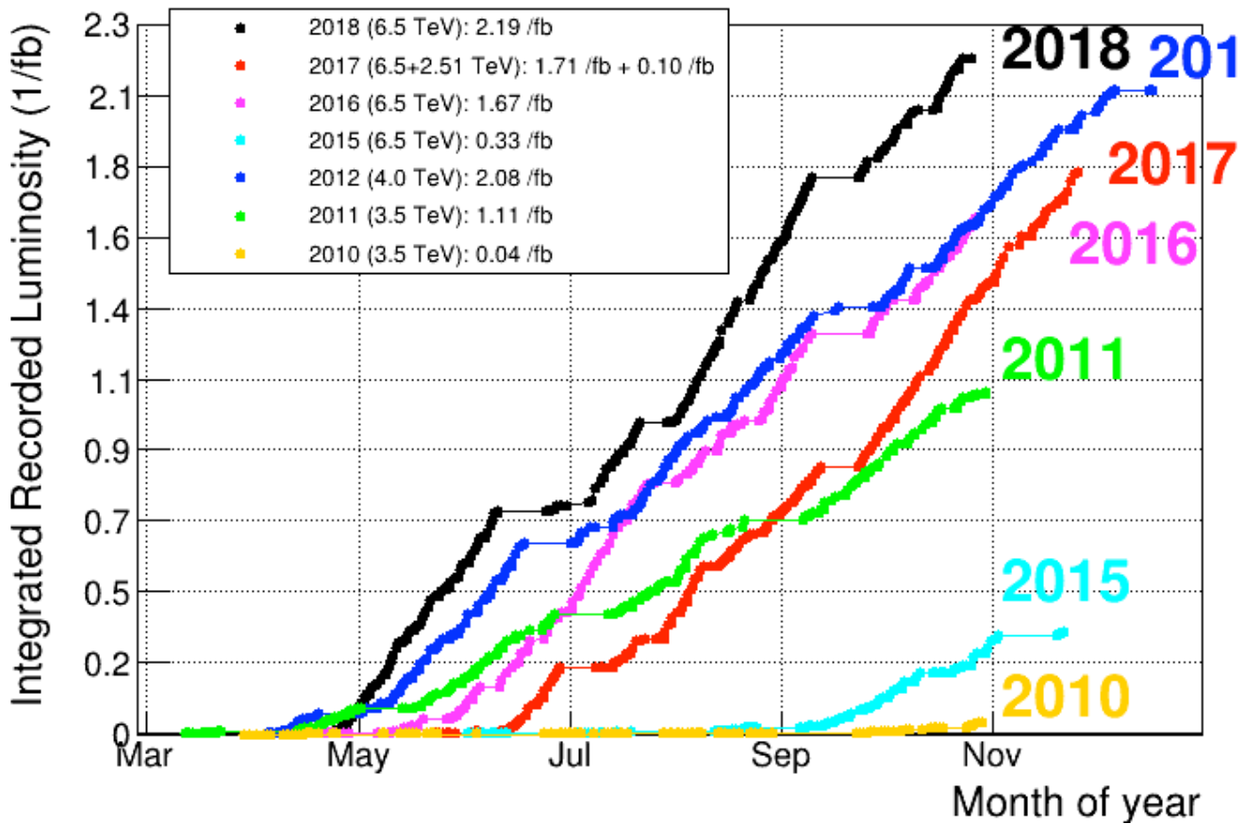

- SMOG system: inject gas inside LHC vacuum, measure collisions between beam and gas nuclei at rest
- Run1&2: noble gas only (He, Ne, Ar)
- $\sqrt{s_{\mathrm{NN}}} = 69$ to $110\,\mathrm{GeV}$, between SPS & RHIC, around $-3.0 < y^* < 0.0$ in cms
- Luminosity measured with $pe$ elastic scattering events

# LHCb datasets from Run1&Run 2

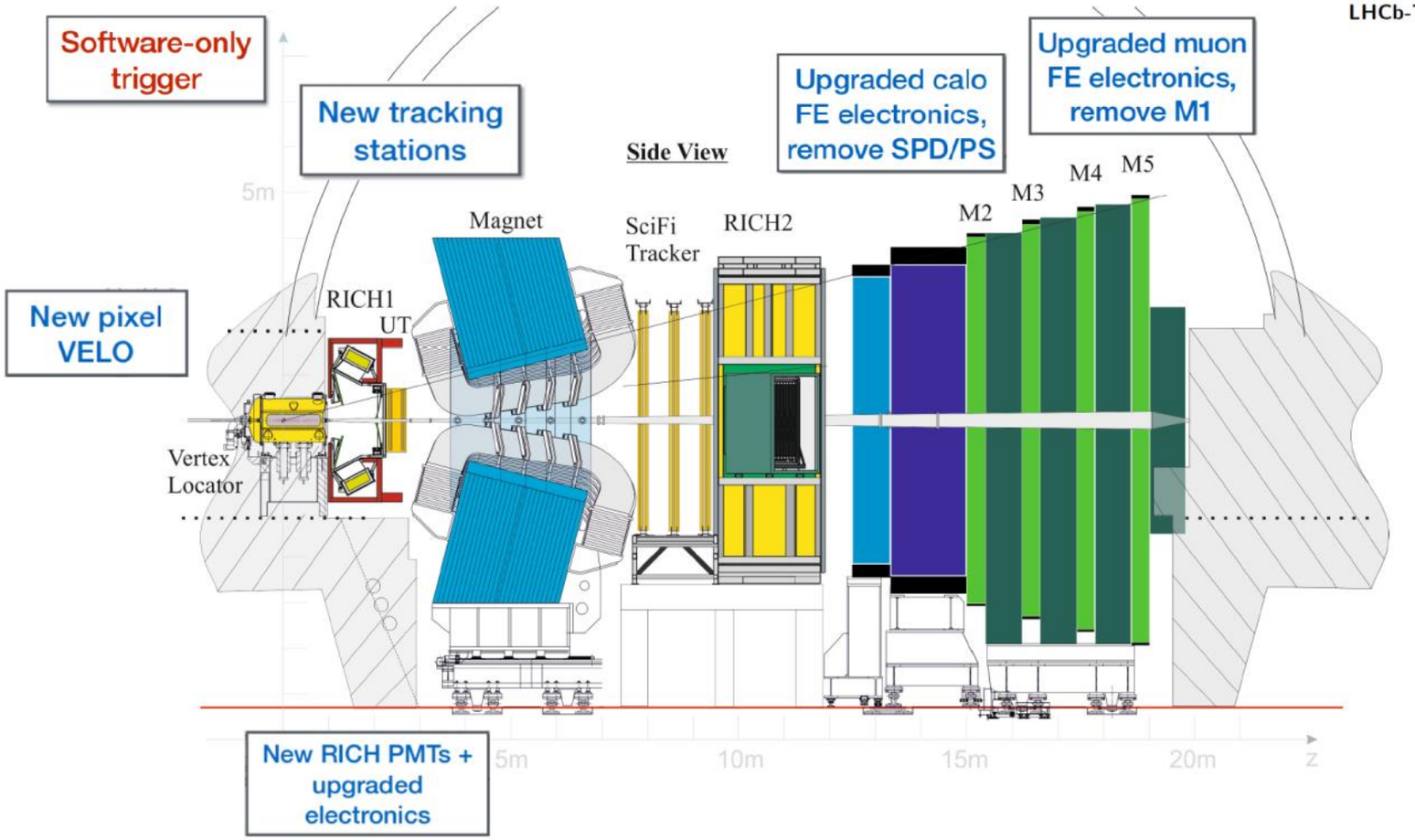


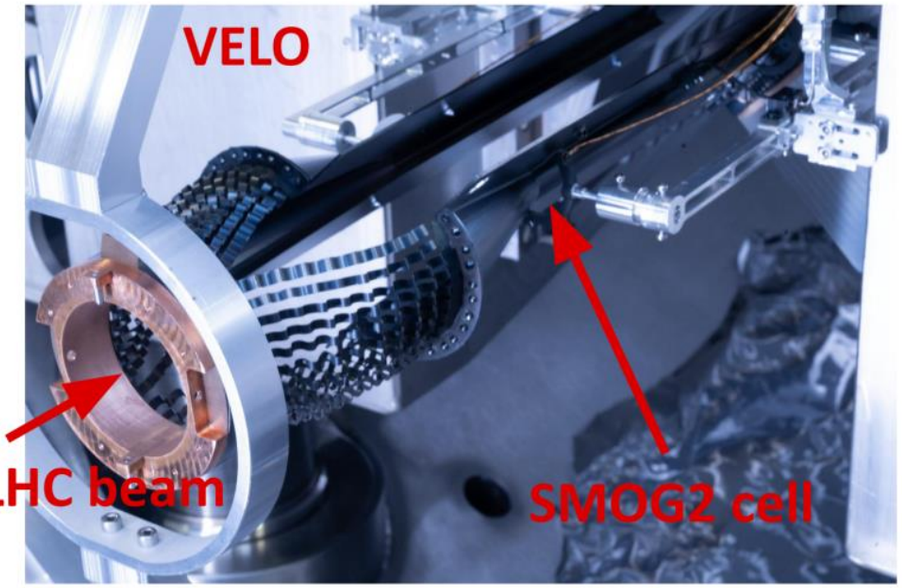

- Reconstruction limited in PbPb up to 60 % centrality



# The LHCb Upgrade I




LHCb-TDR-12



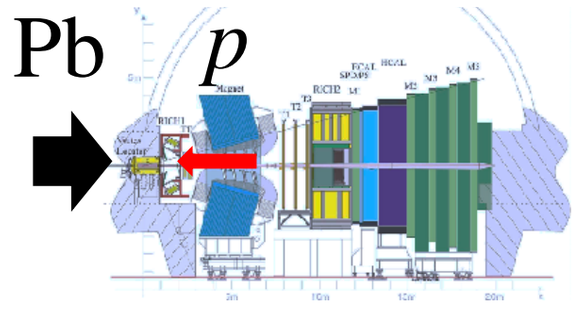

- Major upgrade: replacement of tracking and particle identification detectors
  - New tracking system should reconstruct down to $\approx 30\,\%$ centrality in PbPb
- New SMOG2 system → up to $\times 100$ gas pressure and non-noble gases $(H_2, O_2, D_2, \ldots)$
- More details about in talk by Benjamin Audurier (LHCb prospects)

# Selection of recent LHCb results

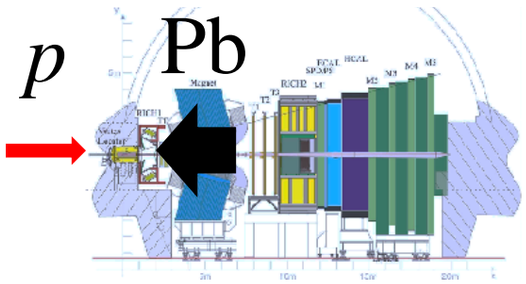
(previous LHCb overview in rencontres QGP )

# Coverage in $(x, Q^2)$

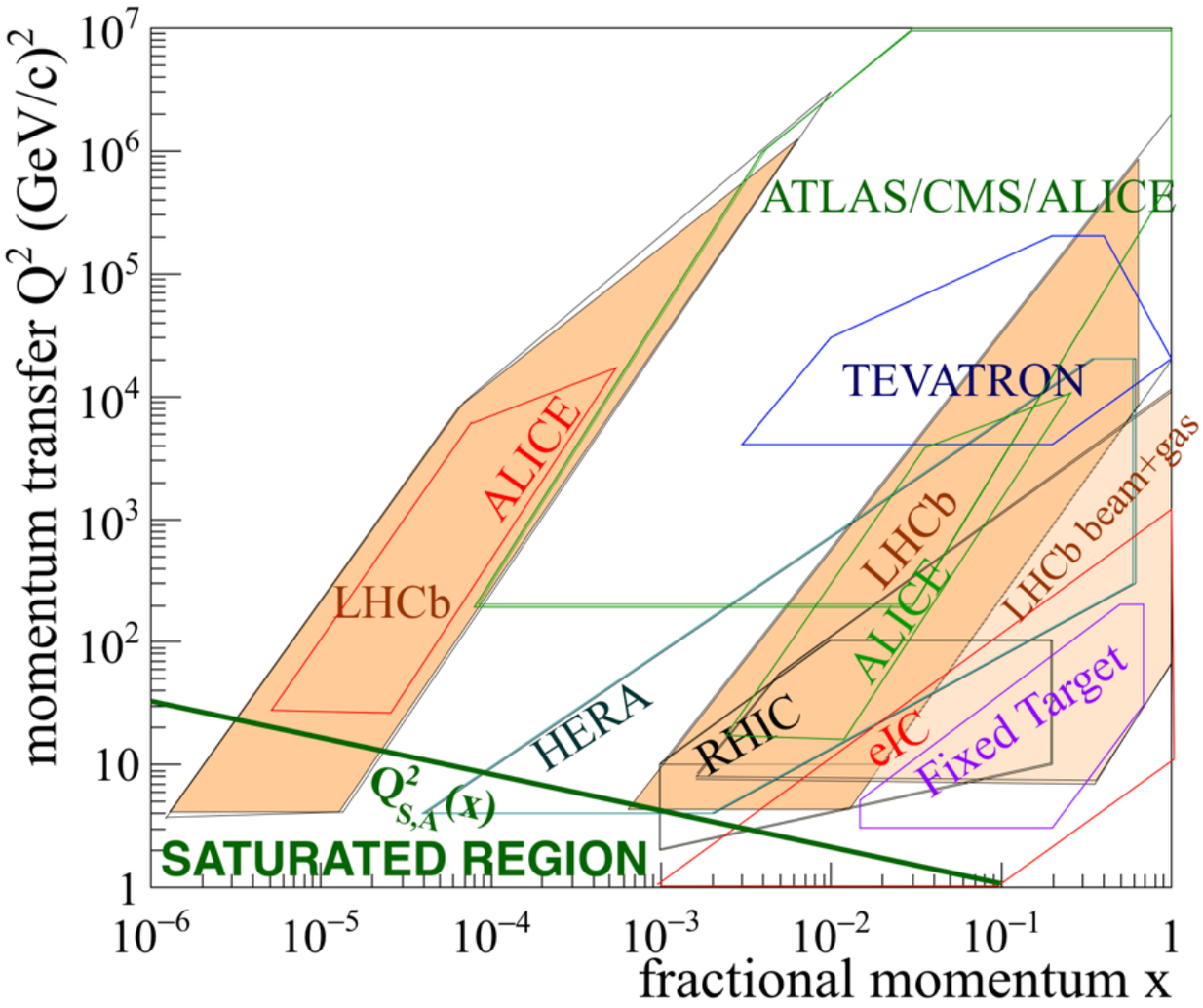
- LHCb has a unique capabilities to study nuclear structure with a wide $(x, Q^2)$ coverage
- Access to the saturation and the high-x regions of nuclei




backward

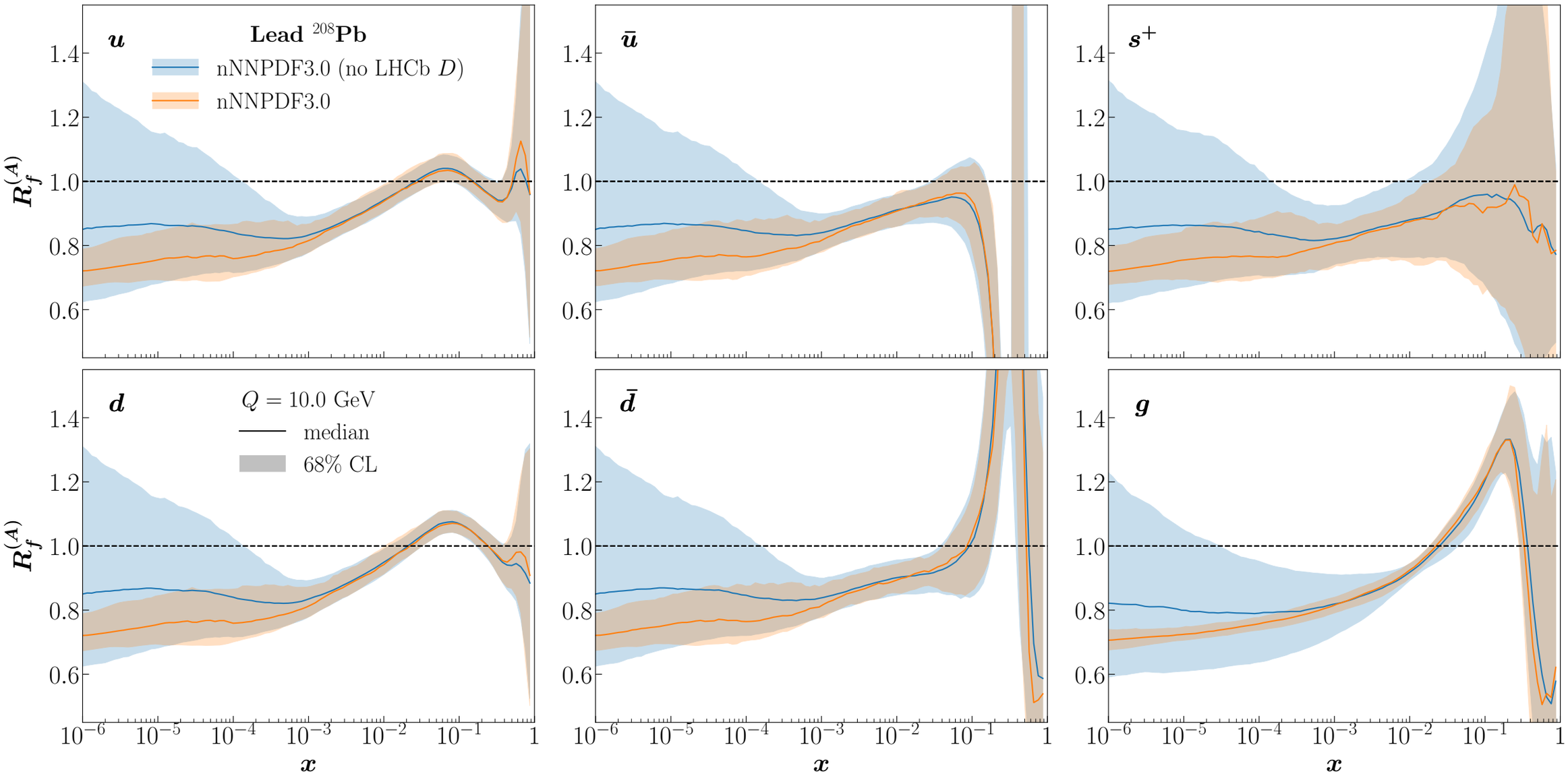



forward



# LHCb constrains in nPDFs

- LHCb $D^0$ production in $p$Pb at 5 TeV: JHEP 10 (2017) 090
- Effect on recent nNNPDF3.0 (arXiv:2201.12363)
- Data also considered in EPPS21

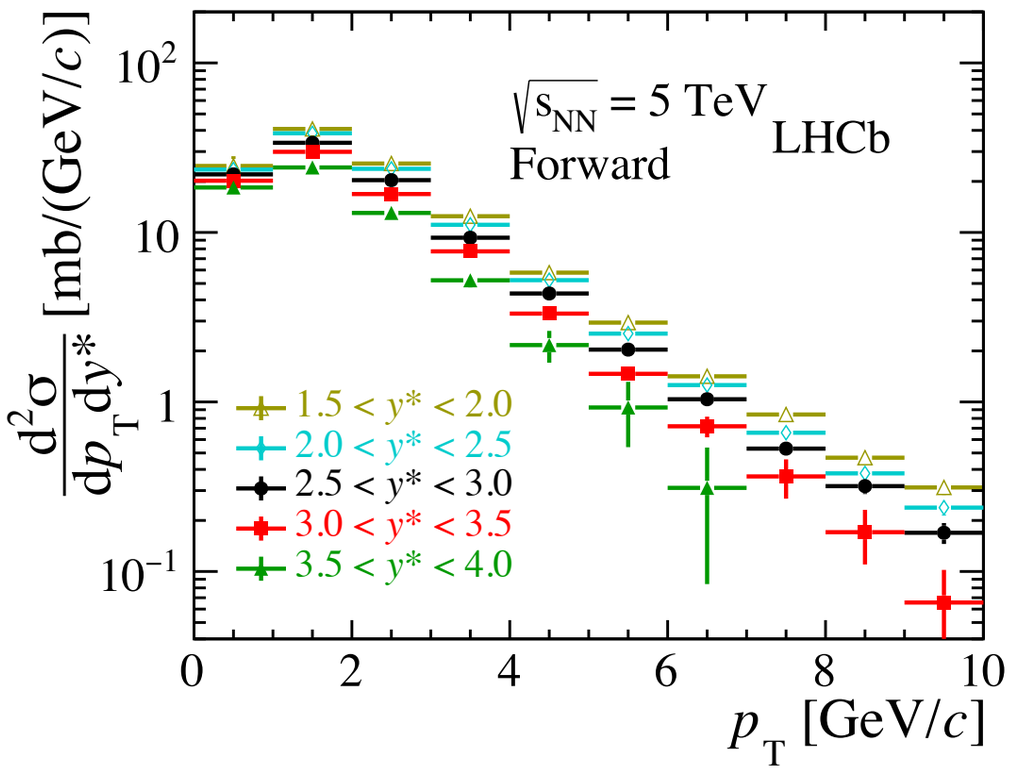


# $D^0$ production in $p$Pb

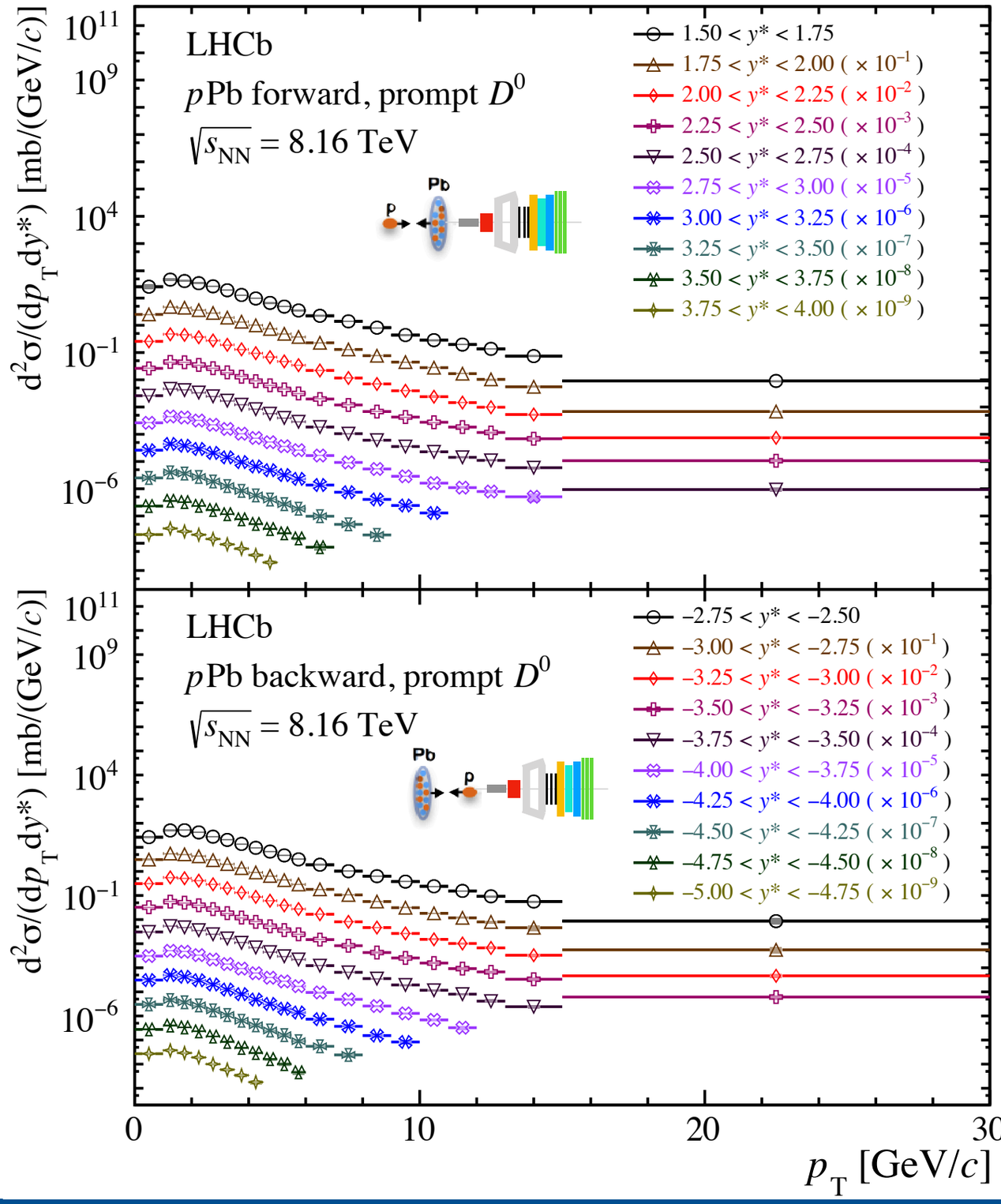
- New measurements of $D^0$ production in $p$Pb
- Using sample x20 larger than previous measurement (JHEP 10 (2017) 090)
- Finer binning and extended kinematic range to $p_{\mathrm{T}} \in [0,30]\,\mathrm{GeV}/c$

**Previous results:**

JHEP 10 (2017) 090



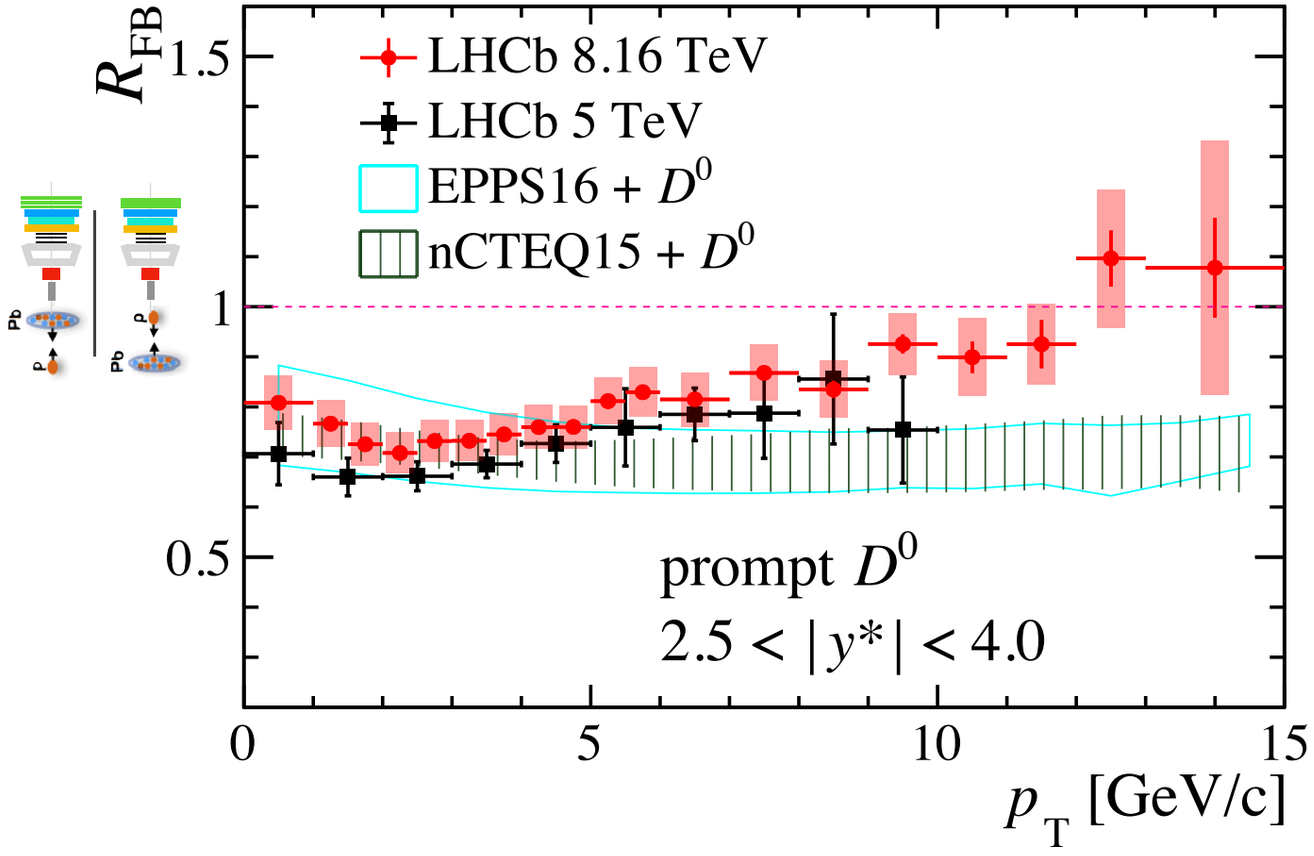

**New result:** LHCb-PAPER-2022-007 (in preparation)



# $D^0$ production in $p$Pb

LHCb-PAPER-2022-007 (in preparation)

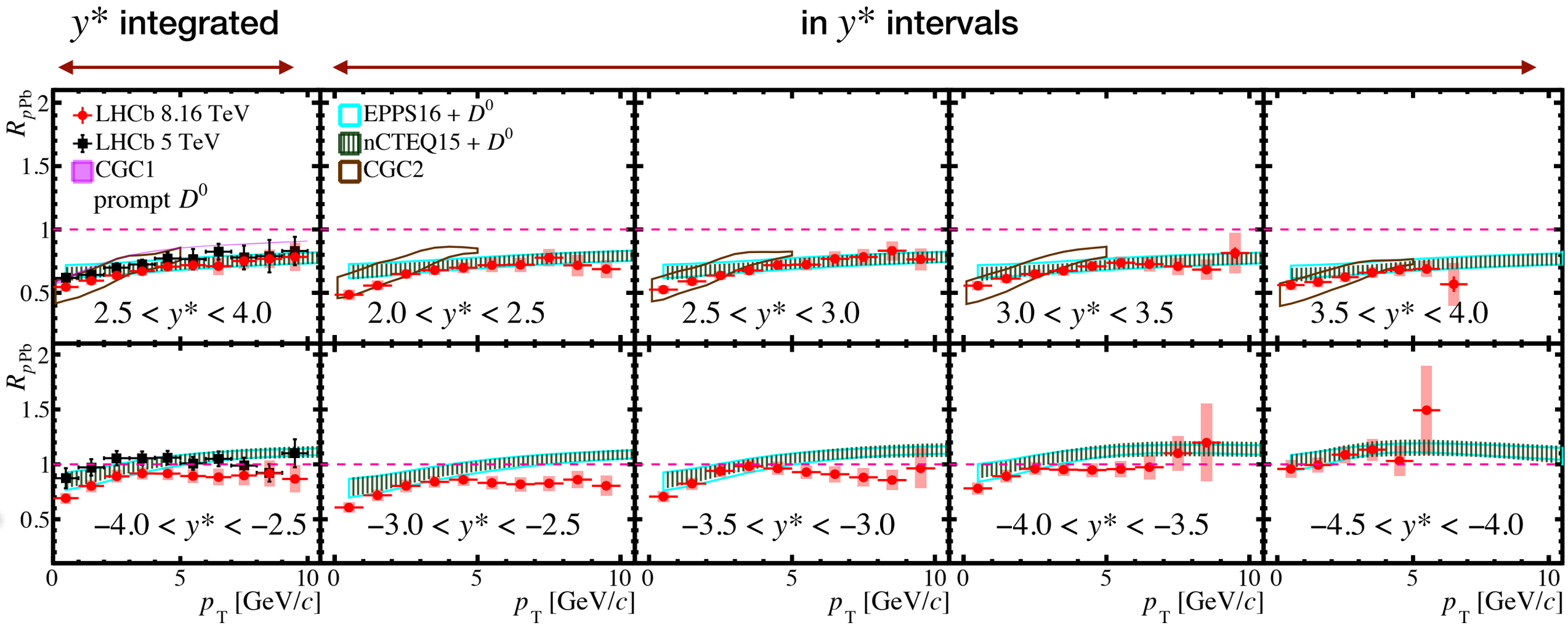
- Forward-to-backward ratio: $R_{\rm FB}(y^*, p_{\rm T}) = \dfrac{d^2\sigma_{p\rm Pb}/dp_{\rm T}dy^*}{d^2\sigma_{\rm Pb}p/dp_{\rm T}dy^*}$
- Comparison with HELAC-Onia predictions with EPPS16 and nCTEQ15 weighted with LHC $D$ measurements
- Discrepancy at high $p_{\rm T}$ with reweighted nPDF predictions
  - Additional effects beyond nPDF?



# $D^0$ production in $p$Pb

LHCb-PAPER-2022-007 (in preparation)

- Nuclear modification factor: $R_{p\mathrm{Pb}} = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}/dp_{\mathrm{T}}dy^*}{d^2\sigma_{pp}/dp_{\mathrm{T}}dy^*}$
- Reference $pp$ cross-section obtained from interpolation of $pp$ results at $\sqrt{s} = 5$ and $13\,\mathrm{TeV}$
- Discrepancy with nPDF predictions in the backward region at high $p_{\mathrm{T}}$



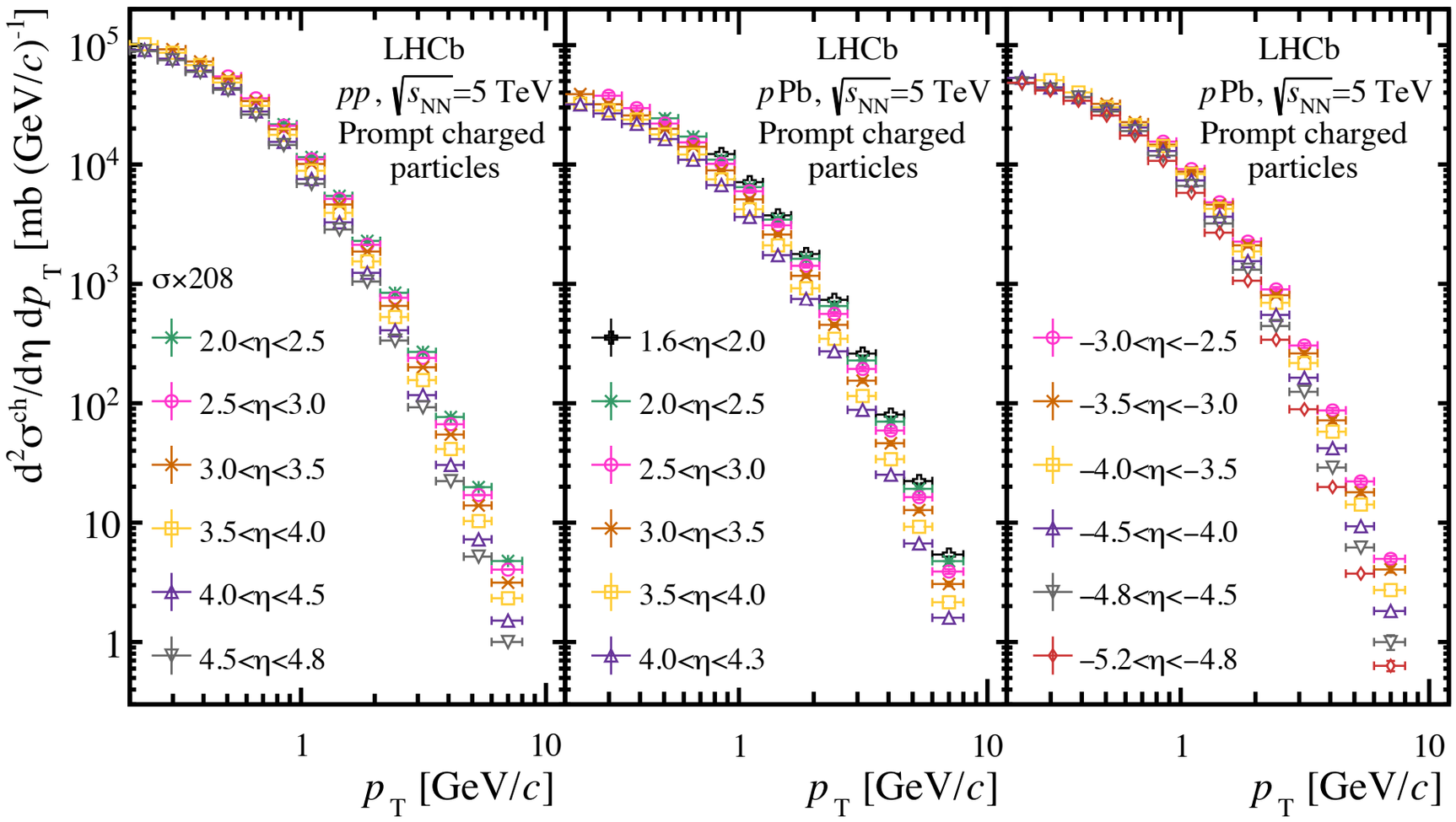
# Charged hadron production in $p$Pb and $pp$

Phys. Rev. Lett. 128, 142004

- Measurement of differential cross-sections and $R_{p\mathrm{Pb}}$
- Constrains to MC generators
- Test models of cold nuclear matter effects: nPDFs, saturation (CGC) models, energy loss, ...

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

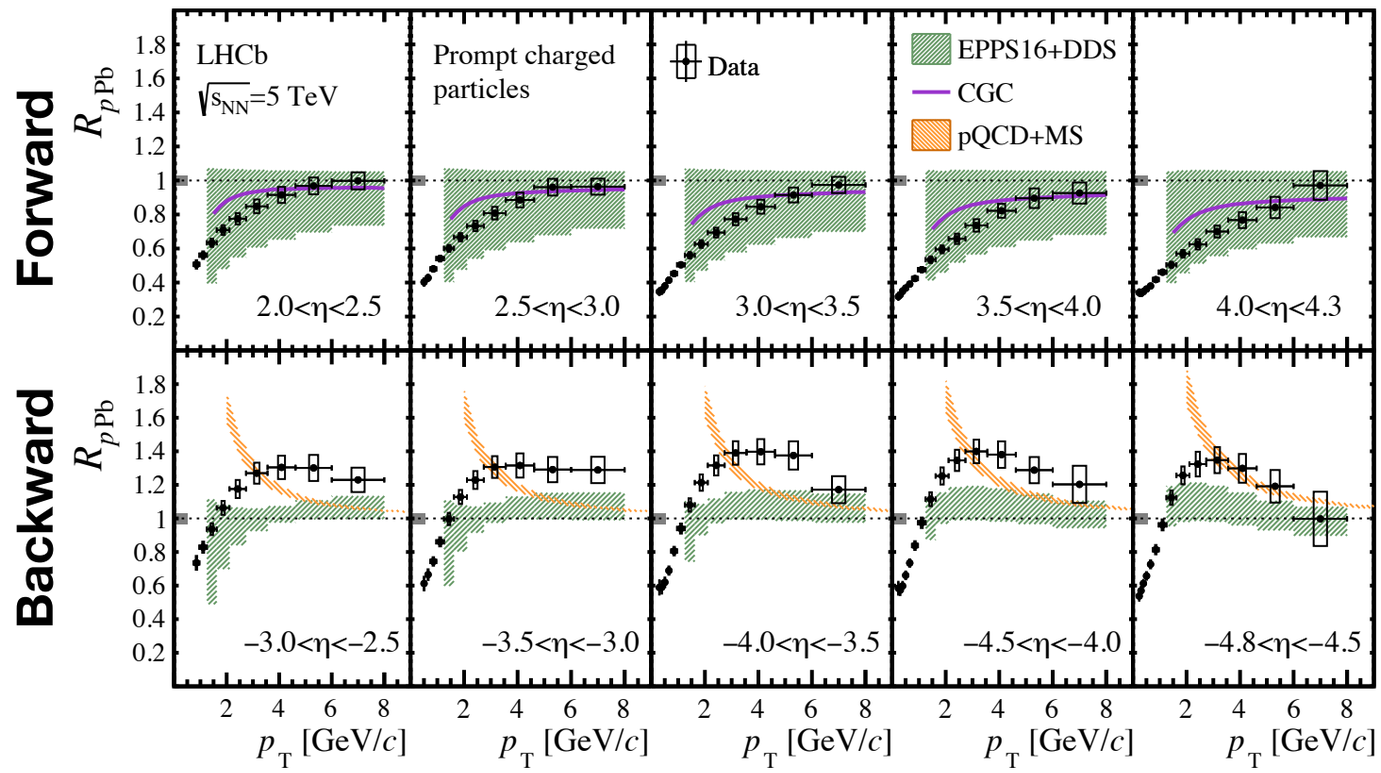
$$R_{p\mathrm{Pb}}(\eta,p_{\mathrm{T}}) = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta,p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}{d^2\sigma_{pp}(\eta,p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}$$



# Charged hadron production in $R_{p\mathrm{Pb}}$: $(x_{exp}, Q^2_{exp})$ dependence

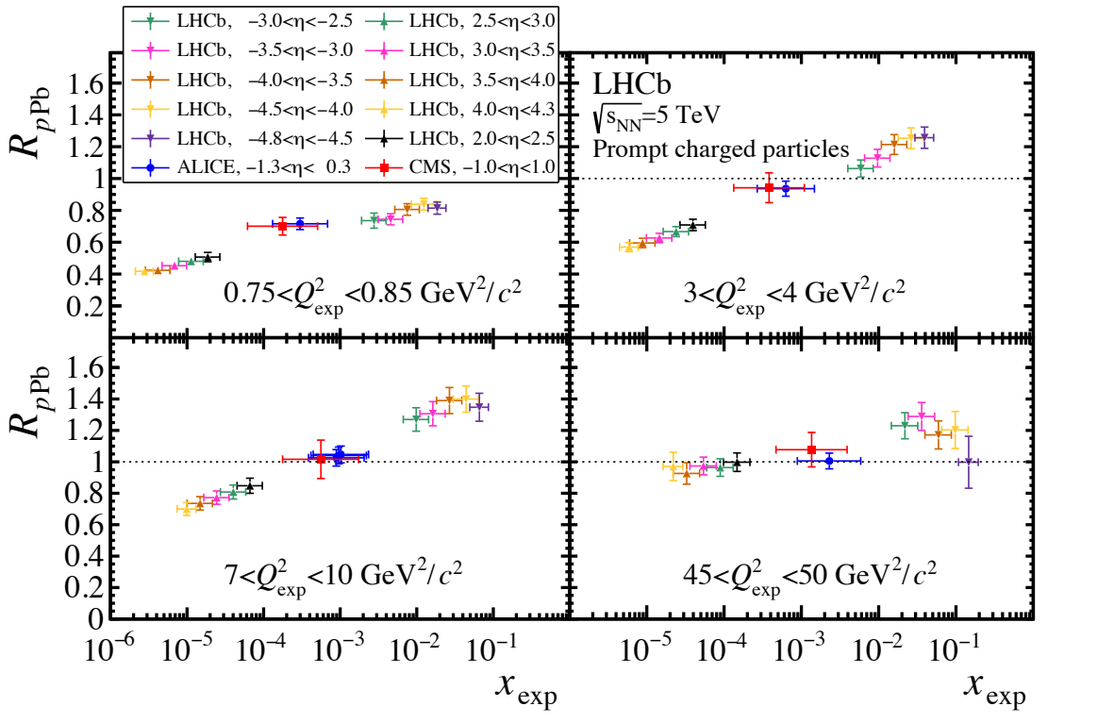
Phys. Rev. Lett. 128, 142004

- **Strong suppression** at forward $\eta$, down to $\sim 0.3$ at low $p_{\mathrm{T}}$
- **Enhancement** at backward for $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$
  - Not reproduced by EPPS16 prediction
  - Clear pseudorapidity dependence




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

- Continuous evolution of $R_{p\mathrm{Pb}}$ with $x_{exp}$ at different $Q^2_{exp}$, compatible with CMS and ALICE data
- Next step:
  - Measure identified $(\pi, K, p)$ spectra



# Neutral pion production in $p$Pb and $pp$

arXiv:2204.10608

- **New measurement** of $\pi^0$ production cross-section:
  - Disentangle effects from different hadrons → understand enhancement in backward
  - Input to fragmentation functions (hadronization)
  - Additional constrains to nPDFs and test of saturation effects
  - Input needed for direct photon production measurement

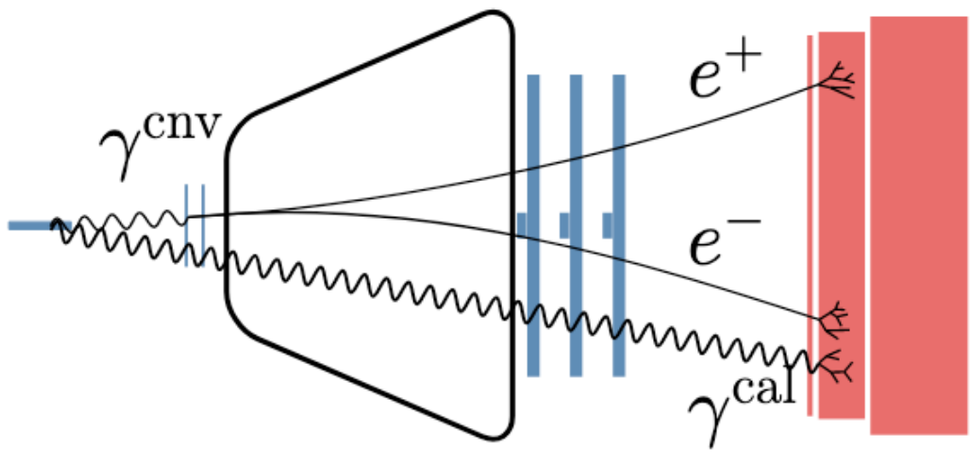
- Datasets:
  - $p$Pb and Pb$p$ data at $8.16\,\text{TeV}$
  - $pp$ reference interpolated with $5$ and $13\,\text{TeV}$ datasets

**Kinematic coverage:**

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

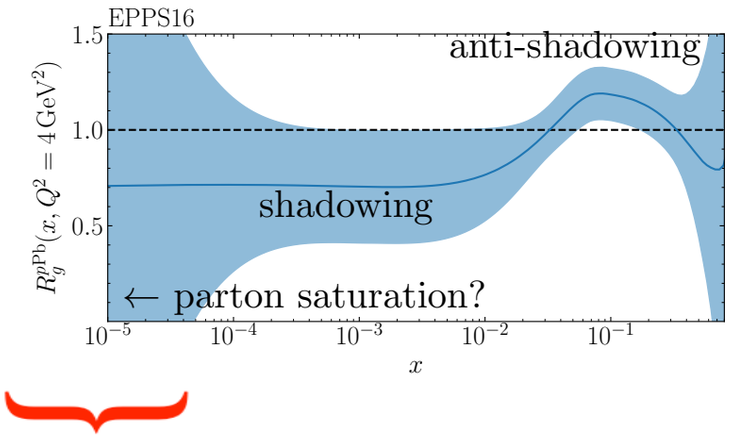
$$\begin{cases} 2.5 < \eta_{\text{CM}} < 3.5 \\ -4.0 < \eta_{\text{CM}} < -3.0 \end{cases}$$

- 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



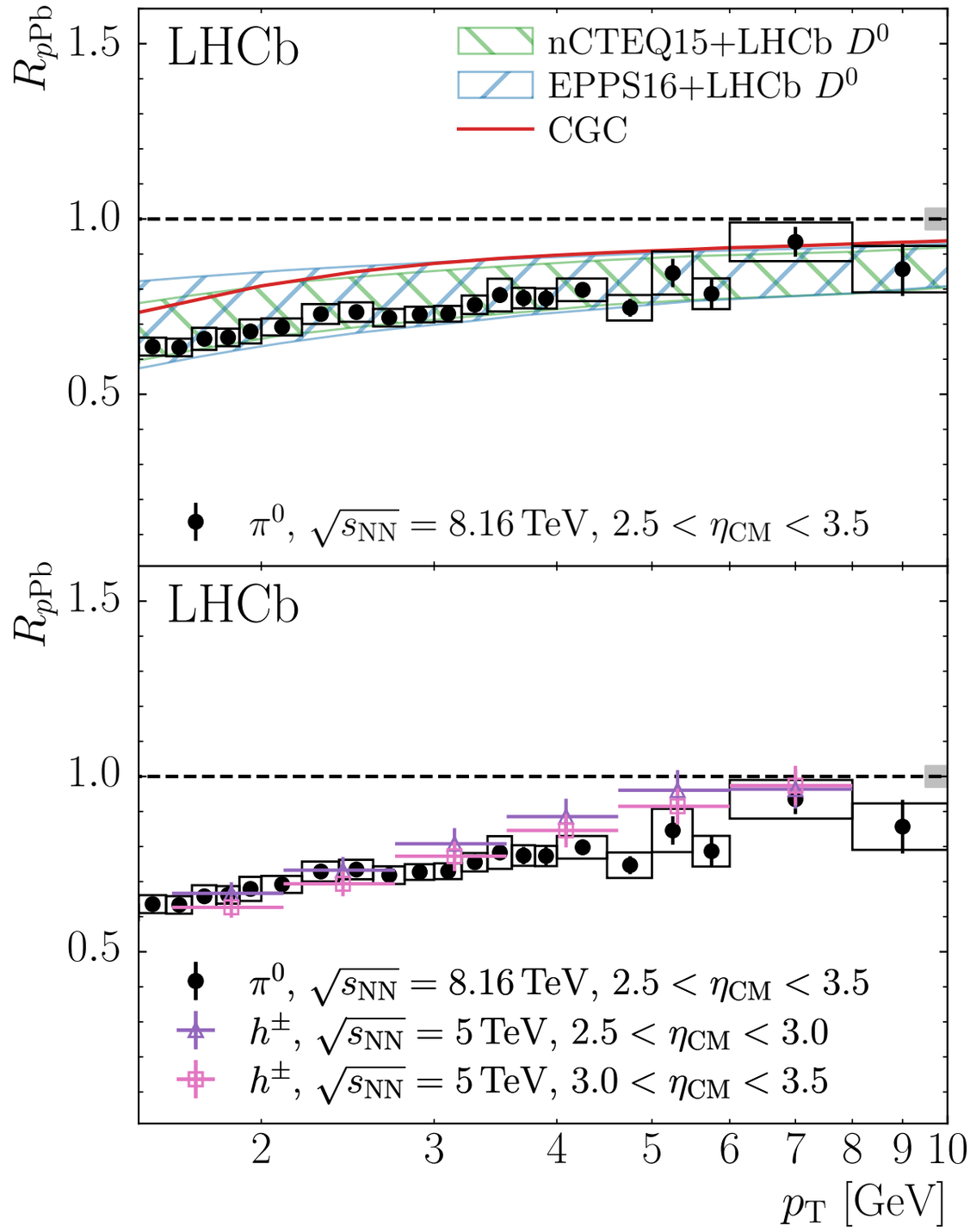
# Neutral pion $R_{p\mathrm{Pb}}$: forward region

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



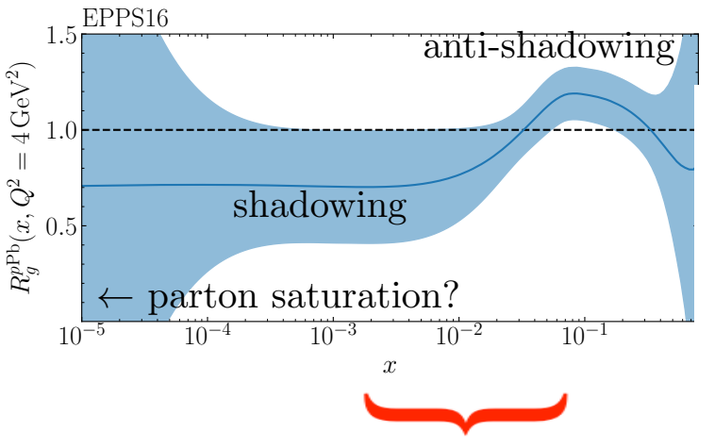

- Strong suppression of $\pi^0$ production
  - $R_{p\mathrm{Pb}}$ compatible with charged hadron result
  - similar shadowing/saturation effects affecting all hadrons
- In agreement with nPDFs (reweighted with LHCb $D^0$ data) JHEP 05 (2020) 037 JHEP 1710 (2017) 090
- CGC LO prediction underestimates $\pi^0$ suppression PR D88, 114020

arXiv:2204.10608



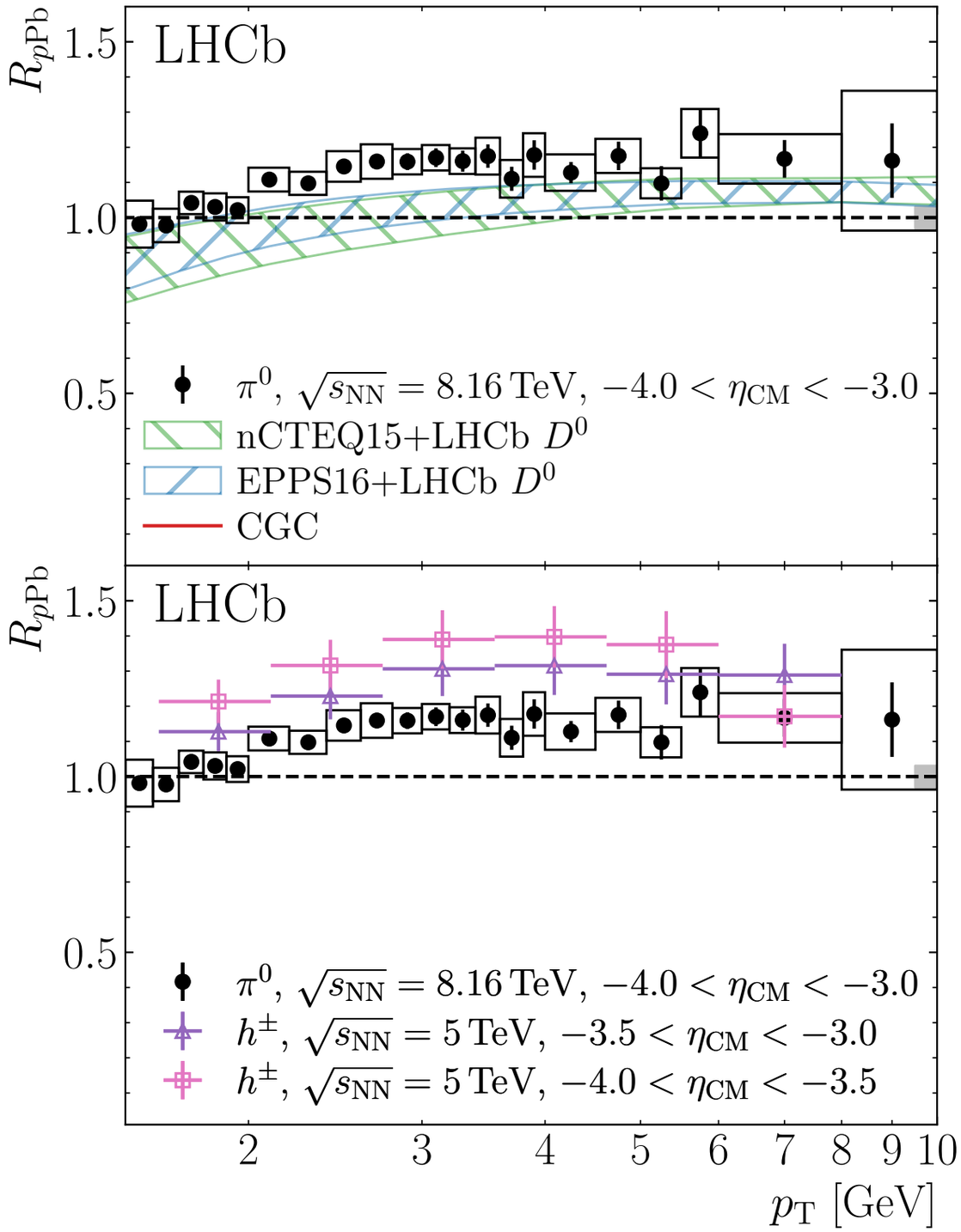
# Neutral pion $R_{p\mathrm{Pb}}$: backward region

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




- Cronin-like enhancement of $\pi^0$ 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 $4\,\mathrm{GeV}/c$
  - contributions from additional effects?

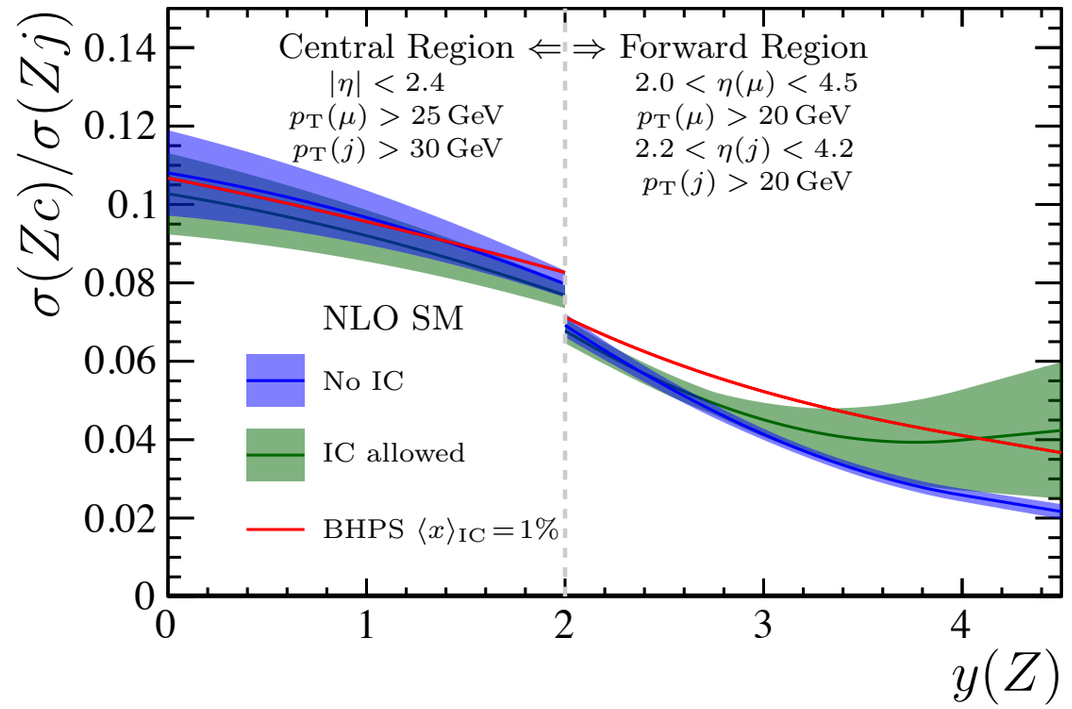
arXiv:2204.10608



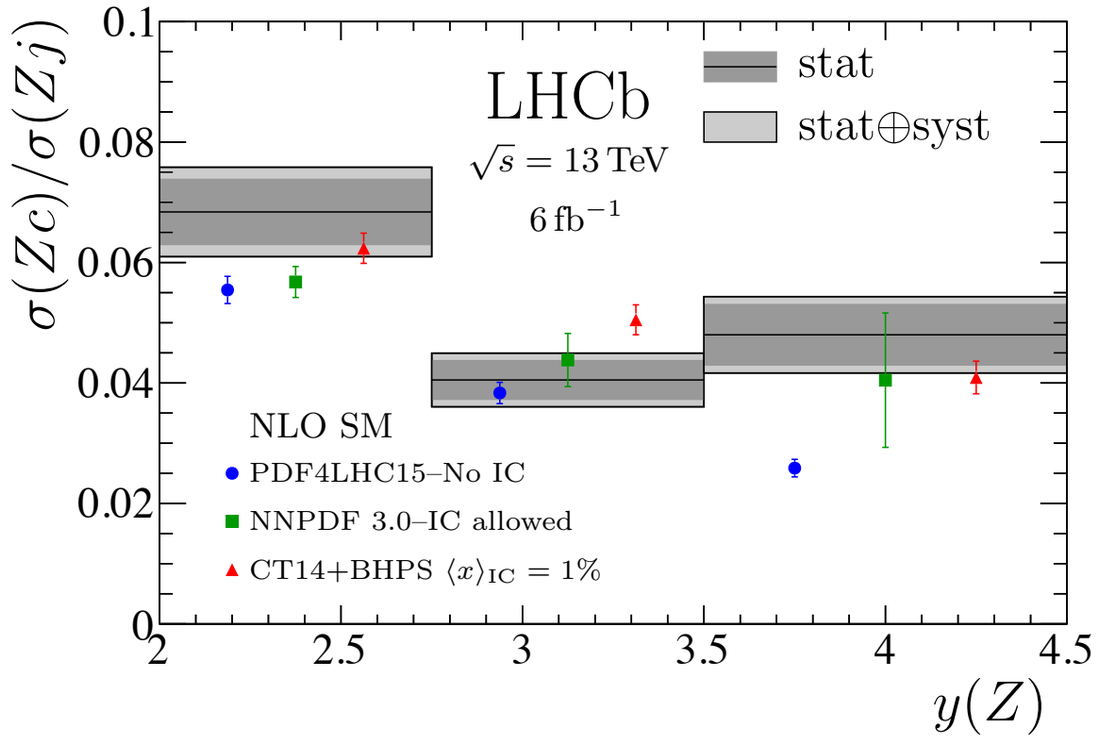
# $Z$ boson production with charm

Phys.Rev.Lett. 128 (2022) 8, 082001

- Measurement of $Z$ boson associated with charm jet
- $R_j^c = \dfrac{\sigma(Zc)}{\sigma(Zj)}$ → Events with $Z$ boson + charm jet
  → Events with $Z$ boson + any jet
- Data of $pp$ collisions, $\sqrt{s} = 13\,\text{TeV}, 6\,\text{fb}^{-1}$



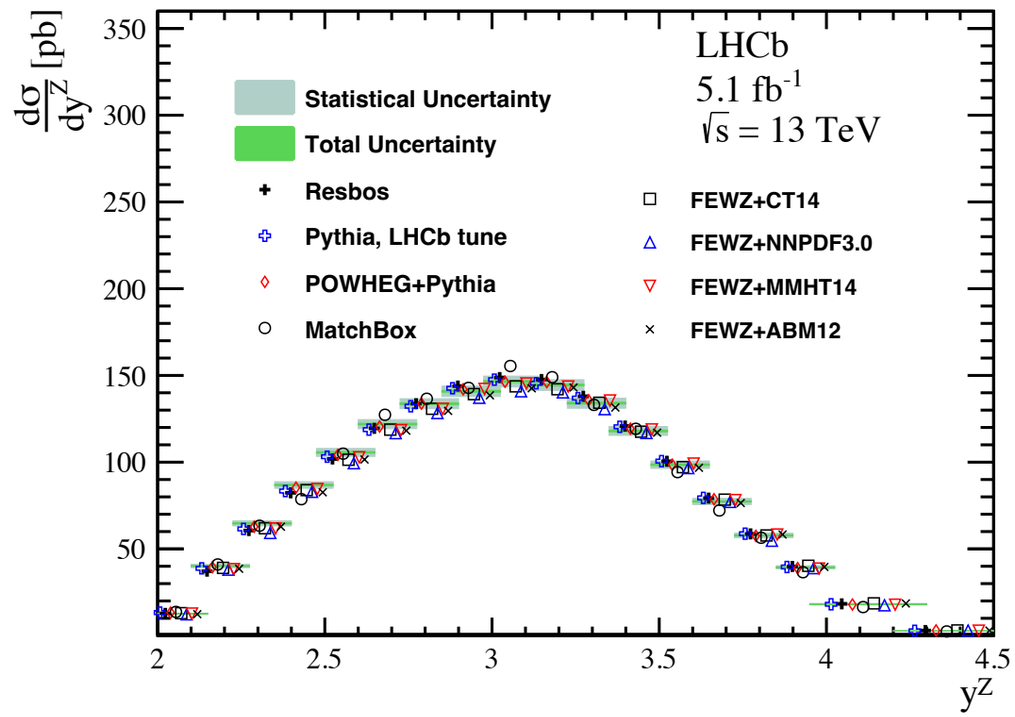

- $\sigma(Zc)$ measured by tagging secondary vertices
- Sensitivity to intrinsic charm at forward rapidity
- Result favours PDF prediction including intrinsic charm

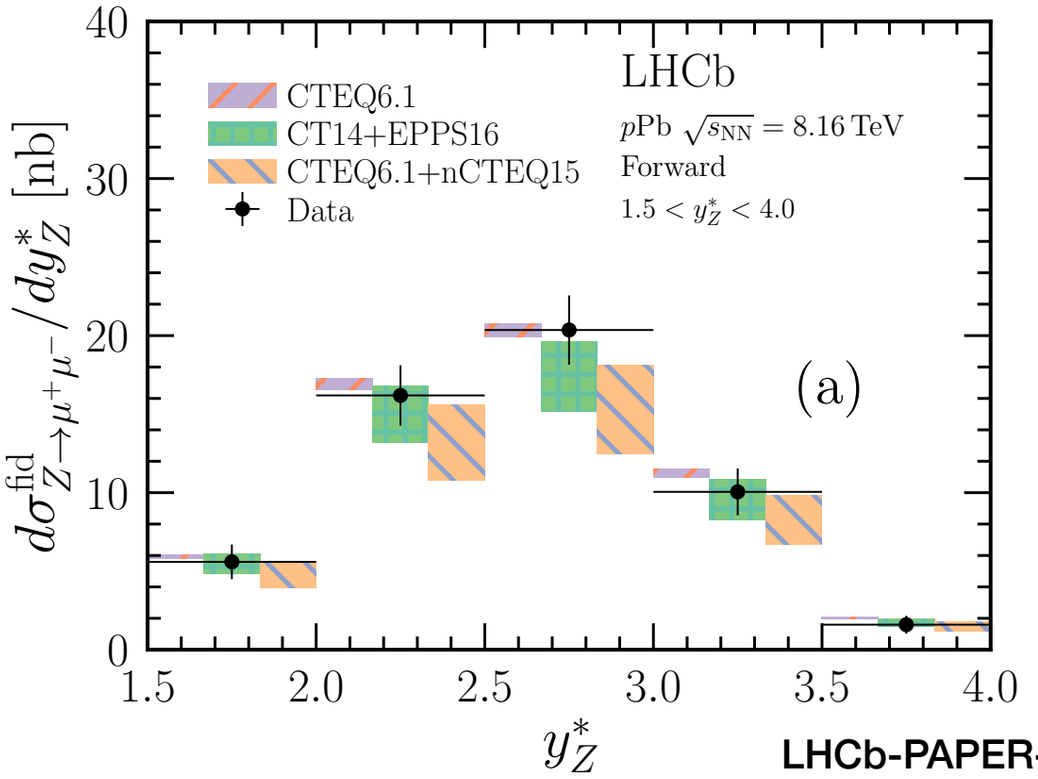


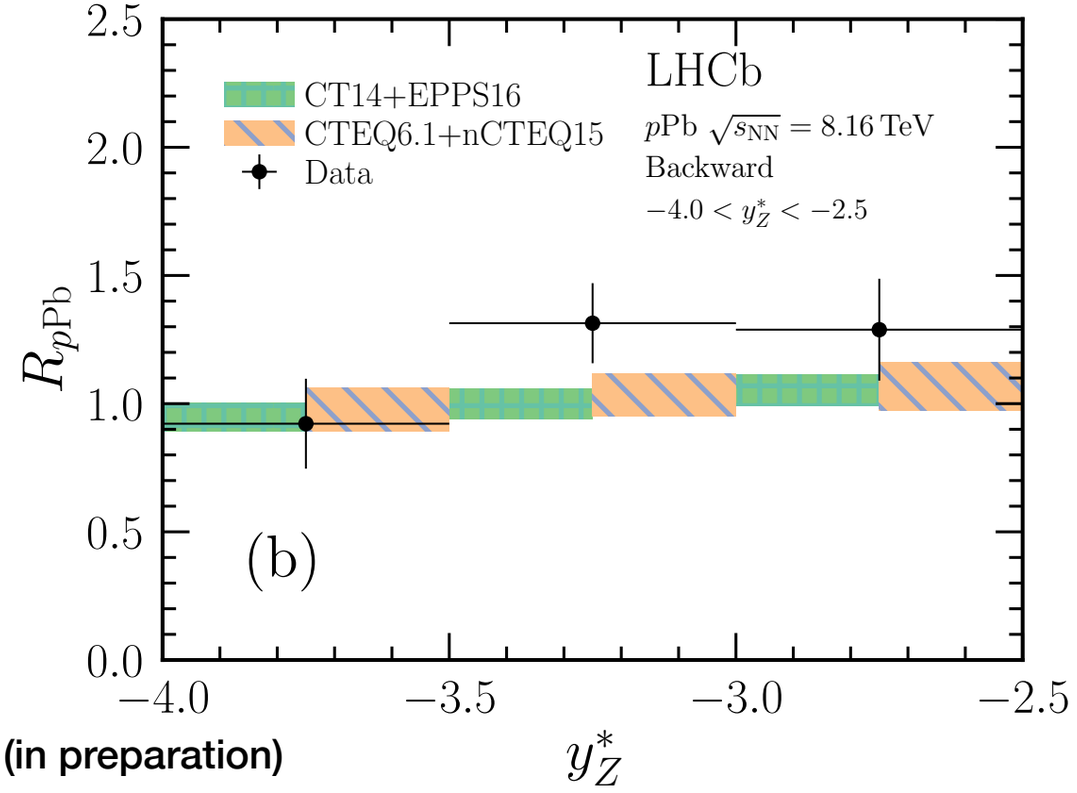
# $Z^0$ boson production in $pp$ and $p$Pb

arXiv:2112.07458

- Clean constrains to PDFs & nPDFs
- $Z$ cross-section in $pp$ at $\sqrt{s} = 13\,\text{TeV}$
  - Uncertainty of $2.15\,\%$ ($0.77\,\%$ excl. lumi)
  - First double-differential measurement in forward region
- $Z$ cross-section in $p$Pb at $\sqrt{s_{\text{NN}}} = 8.16\,\text{TeV}$ and $R_{p\text{Pb}}$



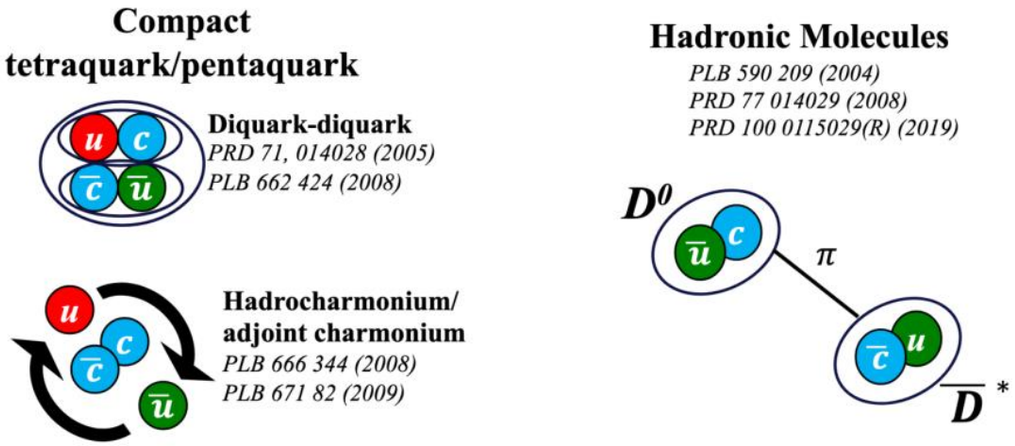




LHCb-PAPER-2022-009 (in preparation)

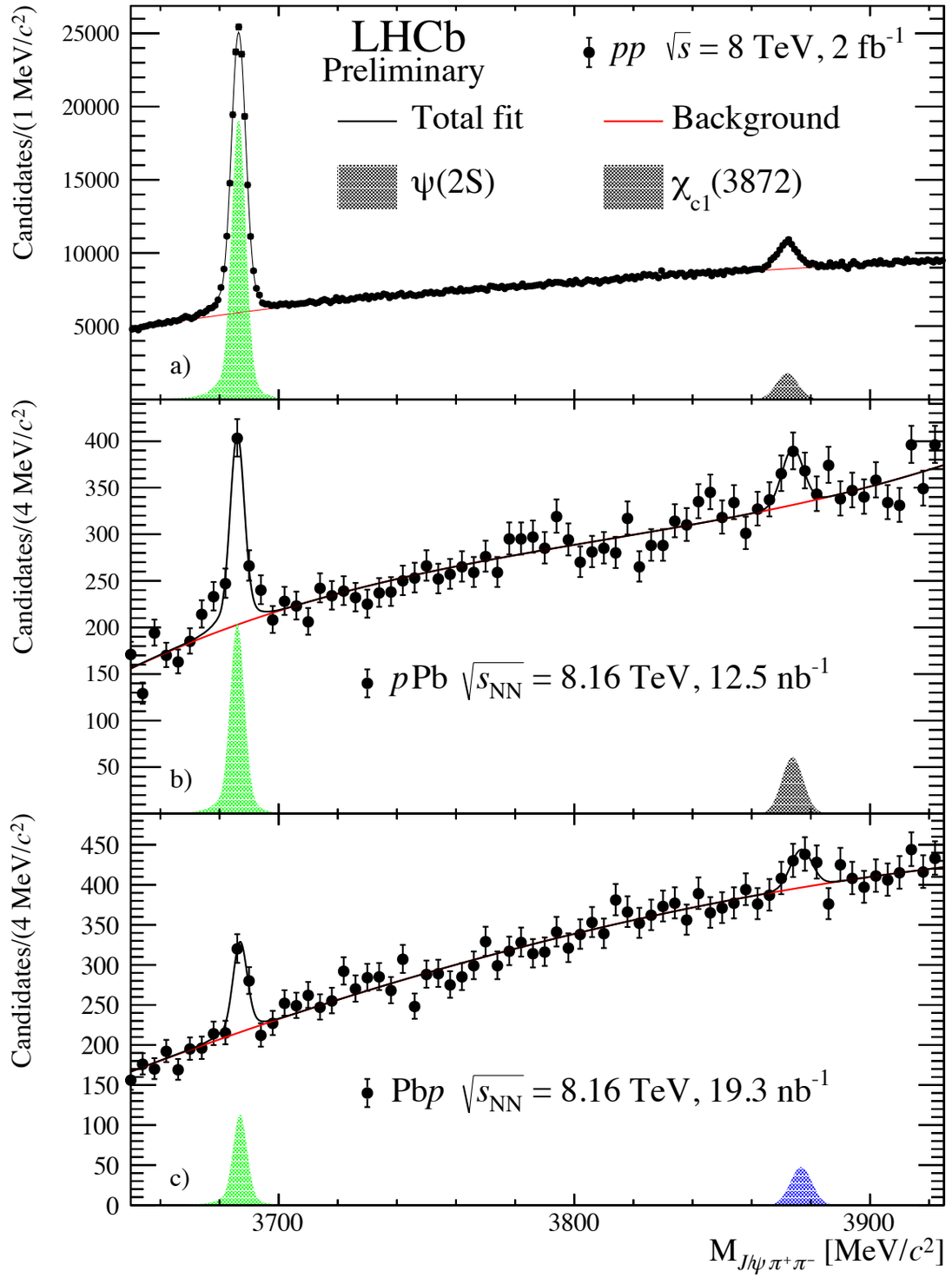
# Production of $\chi_{c1}(3872)$ in $p$Pb

- Nature of $\chi_{c1}(3872)$ not clear (tetraquark, molecule, combination?)
  - Study production with respect to the QCD medium
  - Non conventional hadrons → new probes of hadronization mechanisms




- Measure ratio of prompt $\chi_{c1}(3872)$, $\psi(2S)$with $\chi_{c1}(3872), \psi(2S) \rightarrow J/\psi\pi^+\pi^-$
- Use full $\sqrt{s_{NN}} = 8.16\,\mathrm{TeV}$ dataset

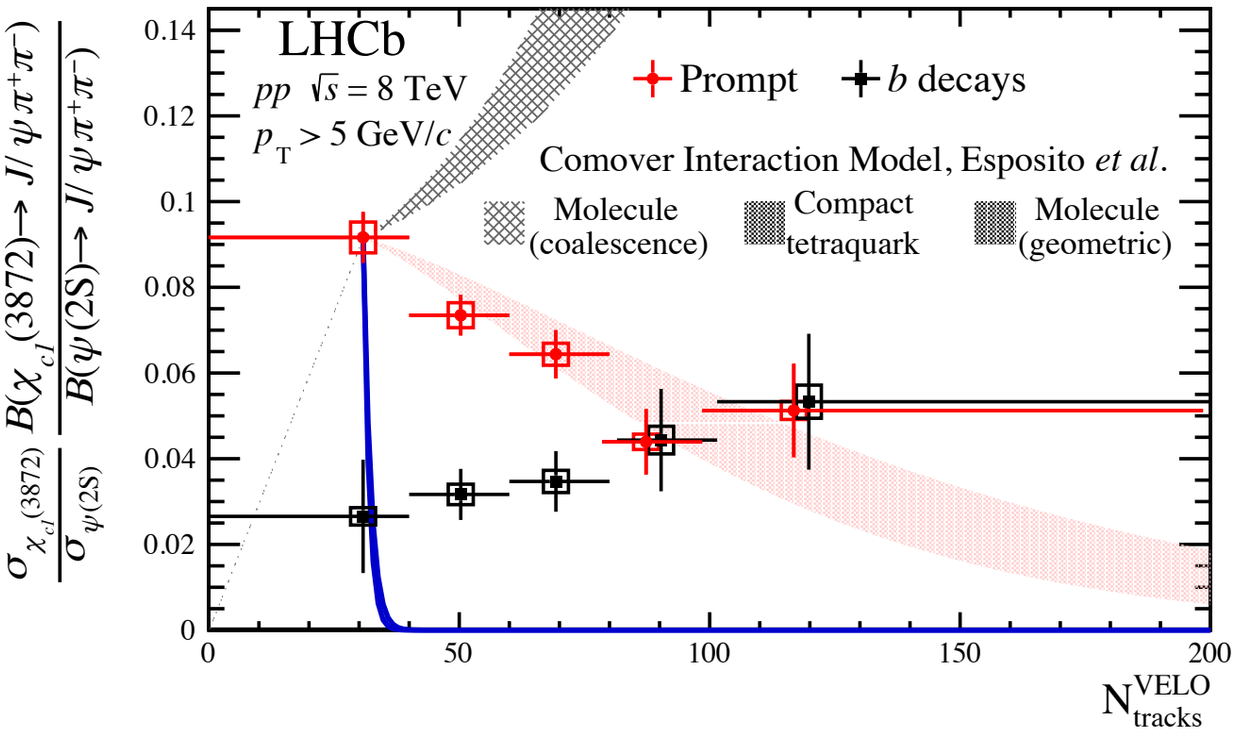
LHCb-CONF-2022-001



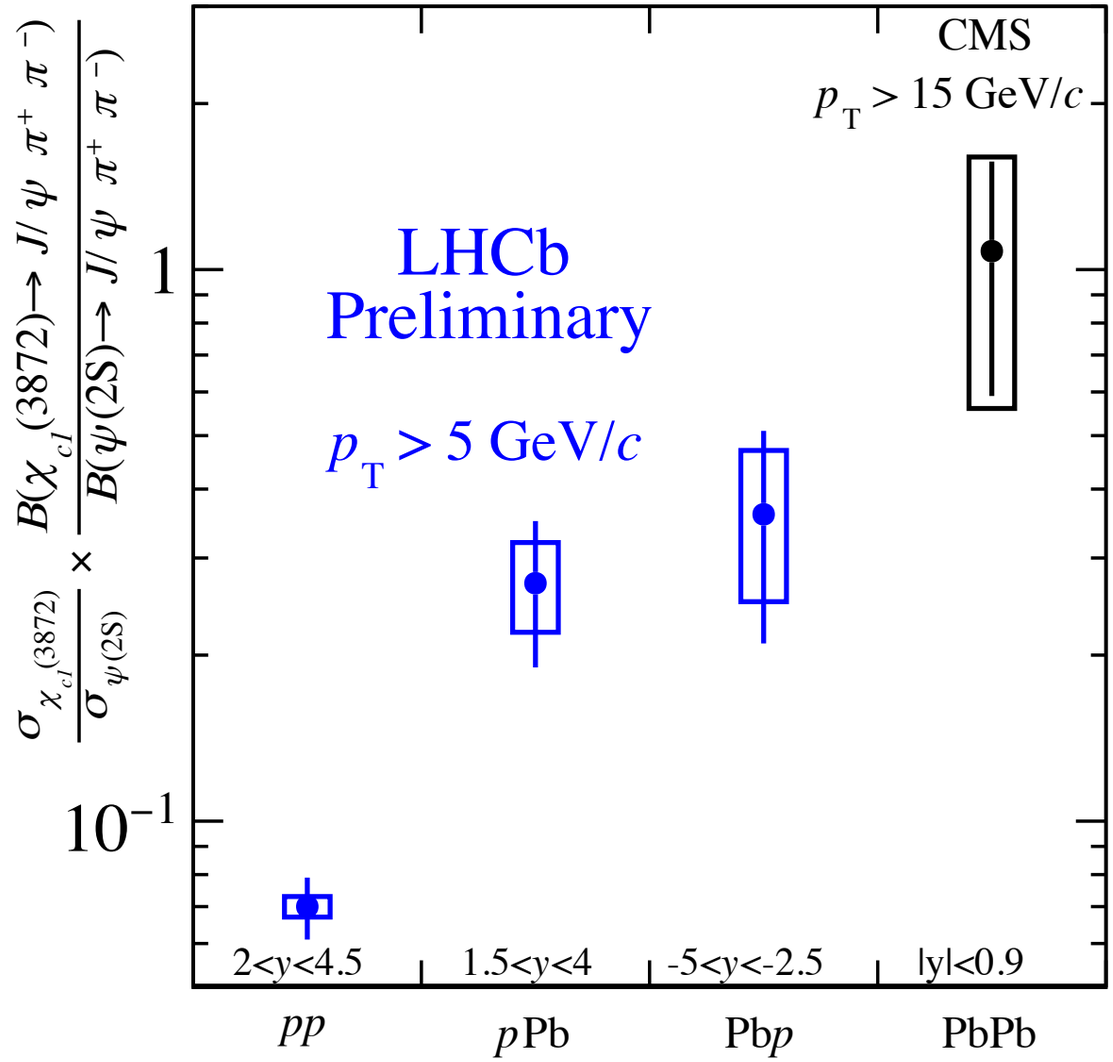
# Production of $\chi_{c1}(3872)$ in $p$Pb

- Increase of the $\chi_{c1}(3872)/\psi(2S)$ ratio with system size
- Different behaviour of $\chi_{c1}(3872)$ and $\psi(2S)$
  - $\psi(2S)$ suppressed in $p$Pb
  - Enhancement of $\chi_{c1}(3872)$?
- Contrast with trend in $pp$ with multiplicity

Phys. Rev. Lett. 126 (2021) 092001




LHCb-CONF-2022-001

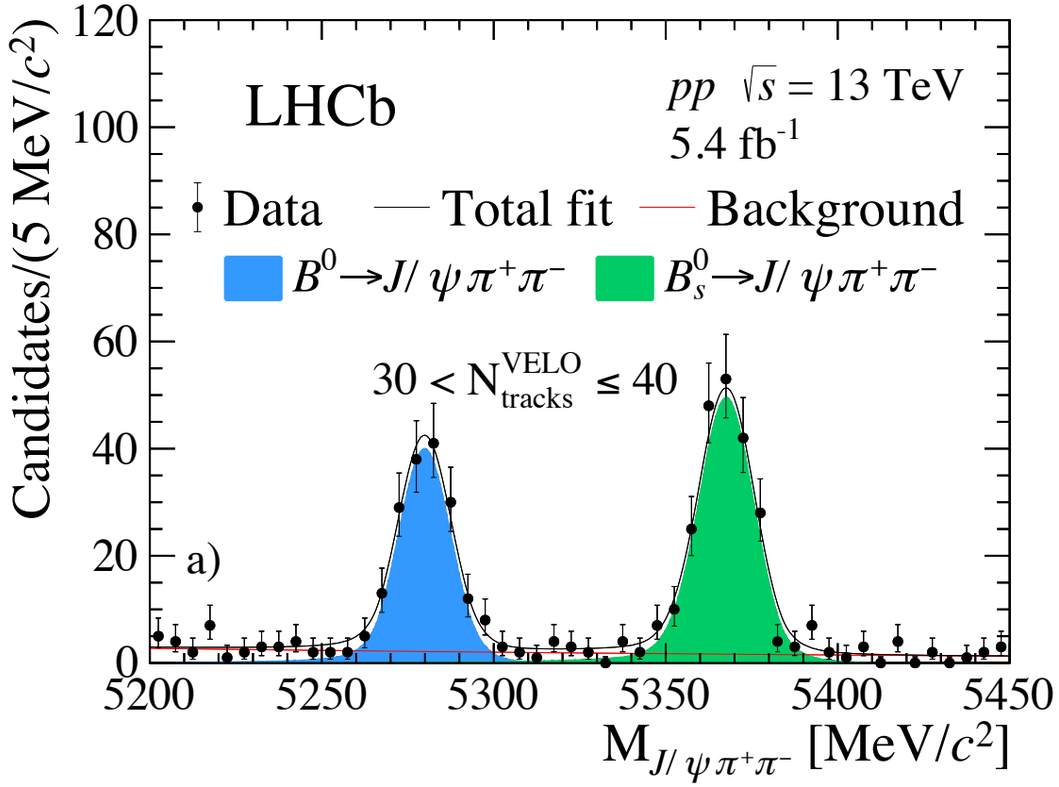


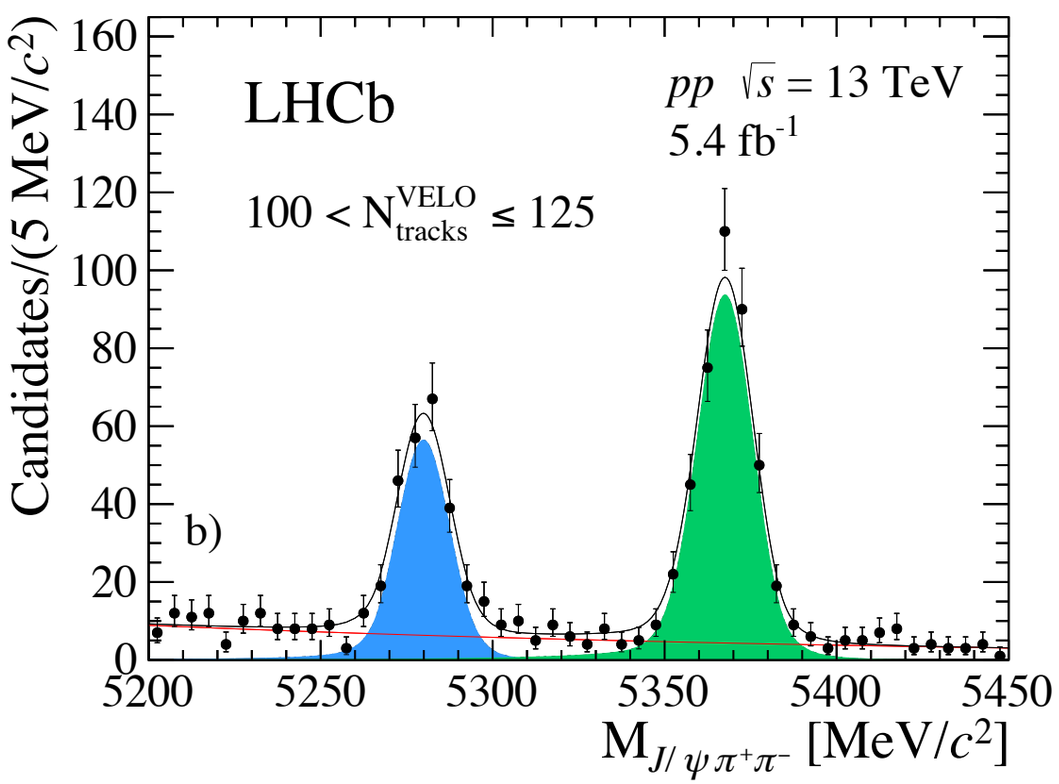
# $B_s^0/B^0$ ratio with event multiplicity in $pp$

arXiv:2204.13042

- Event multiplicity-dependent measurement tests dense medium effects
- $B_s^0/B^0$ could be modified due to b-hadronization via quark coalescence
- Study of $\sigma(B^0)_s/\sigma(B^0)$ ratio with $B^0_{(s)} \to J/\psi\pi^+\pi^-$, using $pp$ collisions, $5.4\,\text{fb}^{-1}$
- Use two multiplicity metrics:

$$\begin{cases} N^{\text{VELO}}_{\text{tracks}} : \text{tracks in } -3.5 < \eta < -1.5 \text{ and } 2 < \eta < 5 \\ N^{\text{backward}}_{\text{tracks}} : \text{tracks in } -3.5 < \eta < -1.5 \end{cases}$$

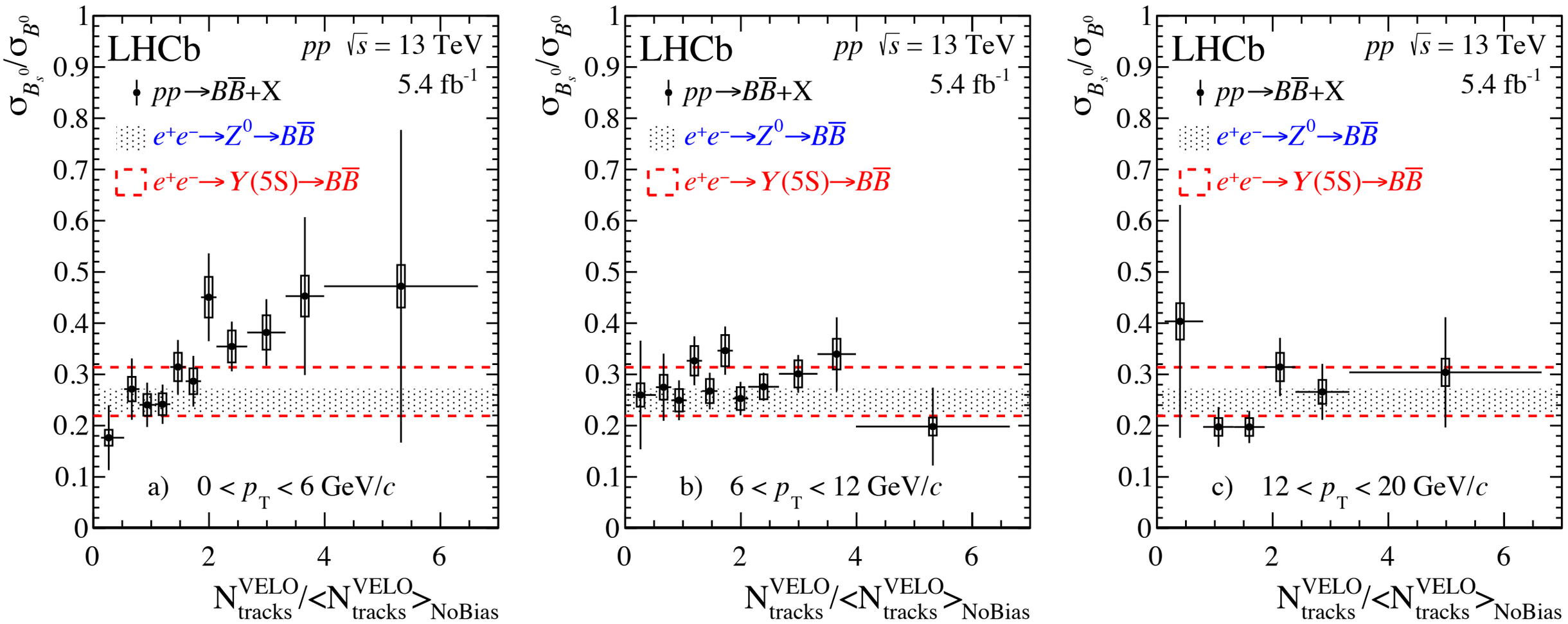


# $B_s^0/B^0$ ratio with event multiplicity in $pp$

arXiv:2204.13042

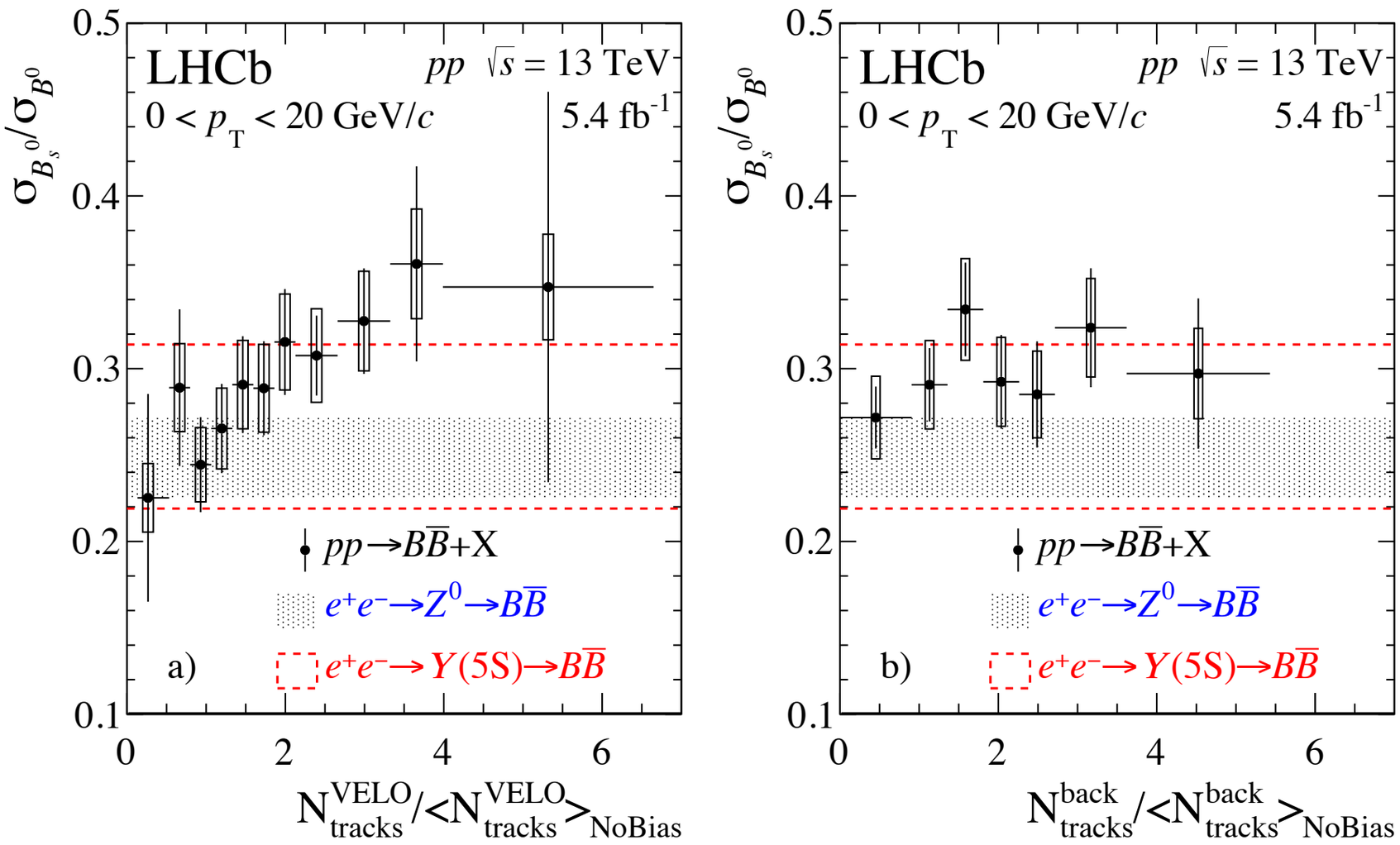
- Result in several $p_{\mathrm{T}}$ bins:
  - Increase of $B_s^0/B^0$ with multiplicity at low $p_{\mathrm{T}}$ (slope significance = 3.4 sigma)
  - modification occurs at low $p_{\mathrm{T}}$, where most of the bulk particles are produced
  - high $p_{\mathrm{T}}$ and low-multiplicity consistent with $e^+e^-$ result



# $B_s^0/B^0$ ratio with event multiplicity in $pp$

arXiv:2204.13042

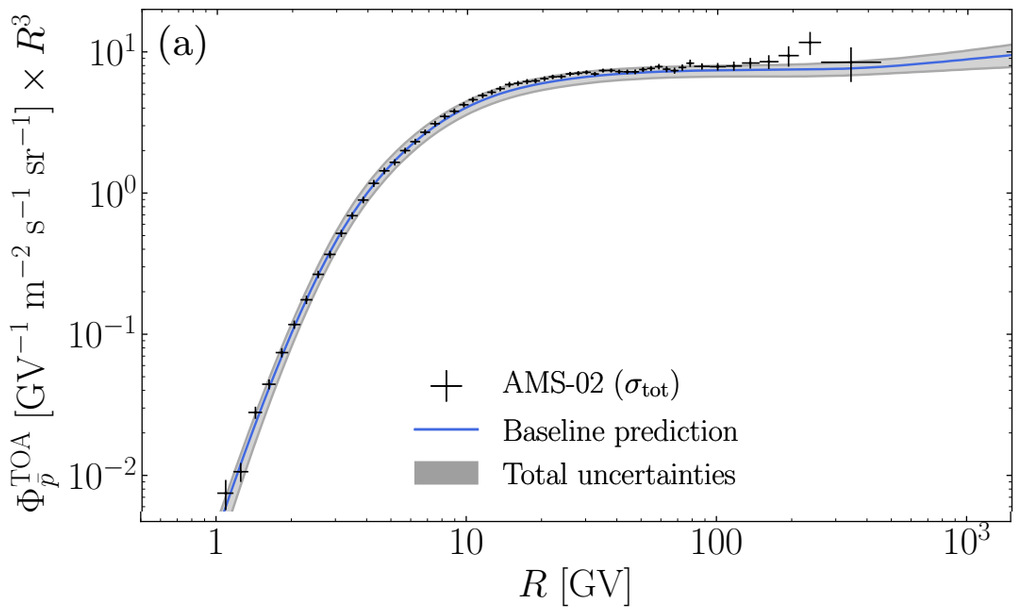
- Comparison between different multiplicity metrics
- No significant enhancement is observed for $N_{\text{tracks}}^{\text{backward}}$
  - Indication that mechanism behind enhancement is related with multiplicity in similar rapidity as $B$ meson



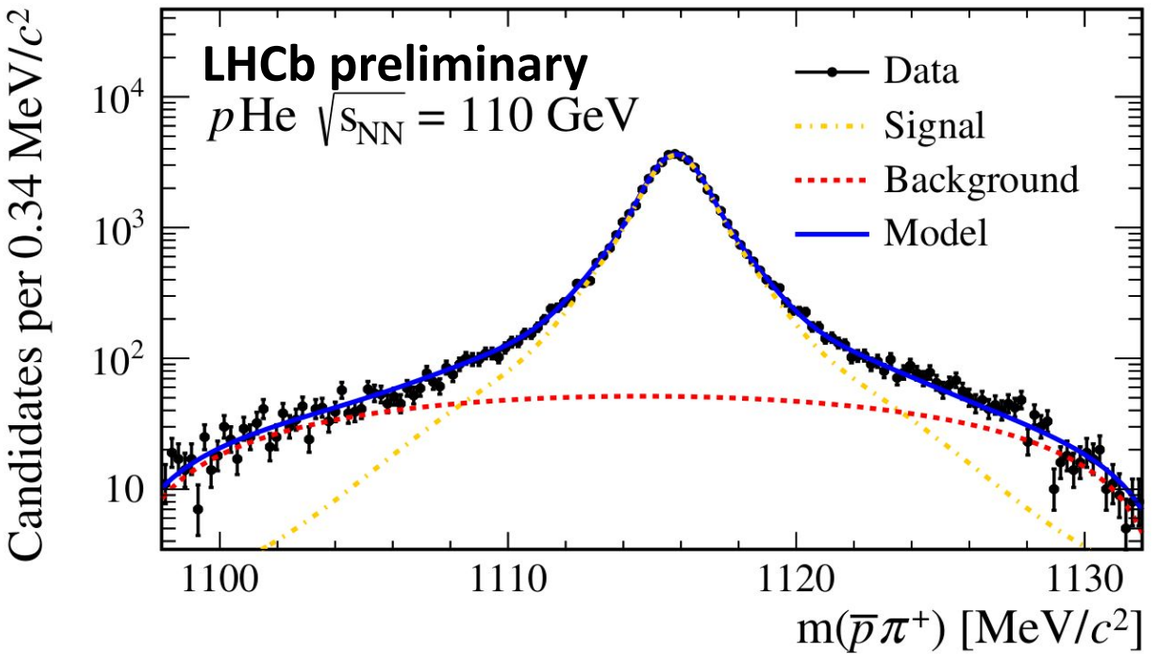
# Detached antiproton production in $p$He

Phys.Rev.Res. 2 (2020) 2, 023022

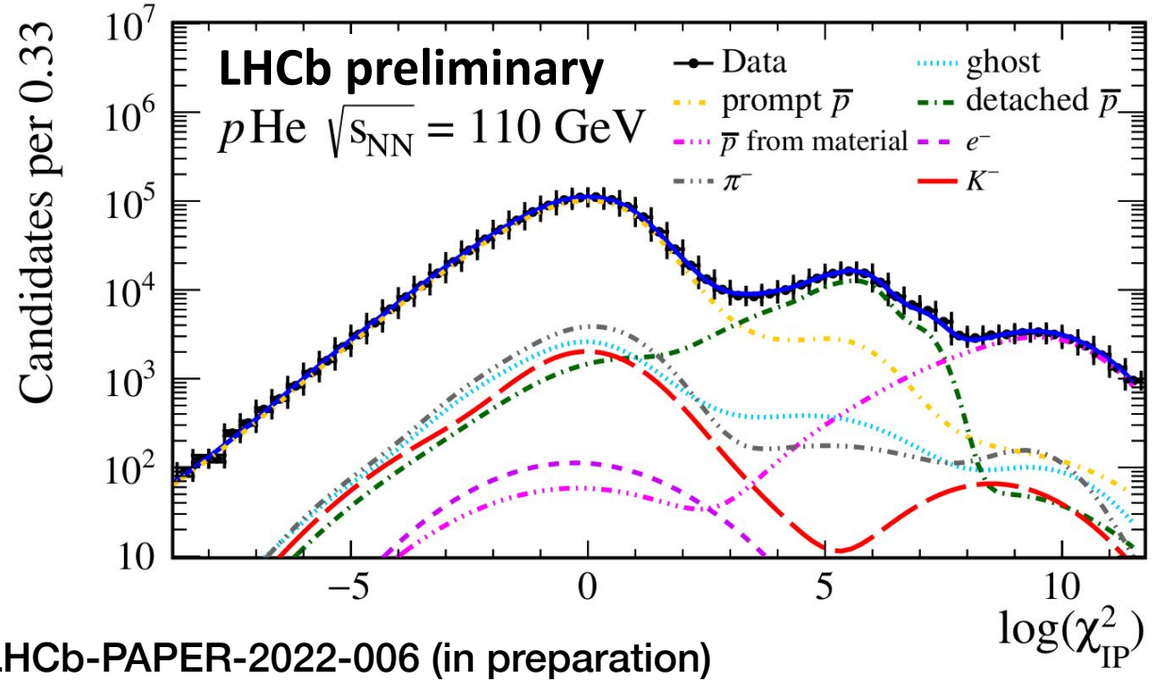
- LHCb measured $\overline{p}$ production in $p$He at $\sqrt{s_{NN}} = 110\,\text{GeV}$ (PRL 121 (2018) 222001)
  - Study of AMS excess of $\overline{p}$
  - Predictions rely on cross-sections of prompt and detached $\overline{p}$
- Measure now antiprotons from detached sources (hyperon decays)
- Two approaches:




**Exclusive approach, measure $\overline{\Lambda} \to \overline{p}\pi^+$**




**Inclusive approach, measure full detached contribution**



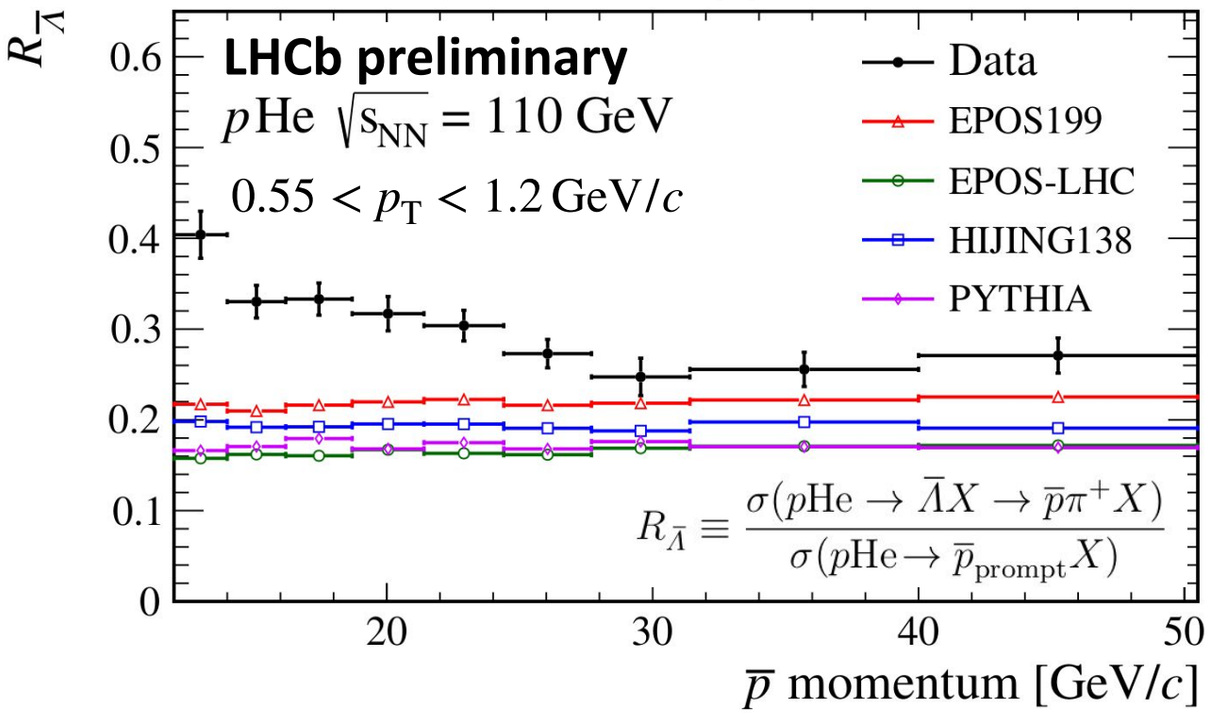

LHCb-PAPER-2022-006 (in preparation)

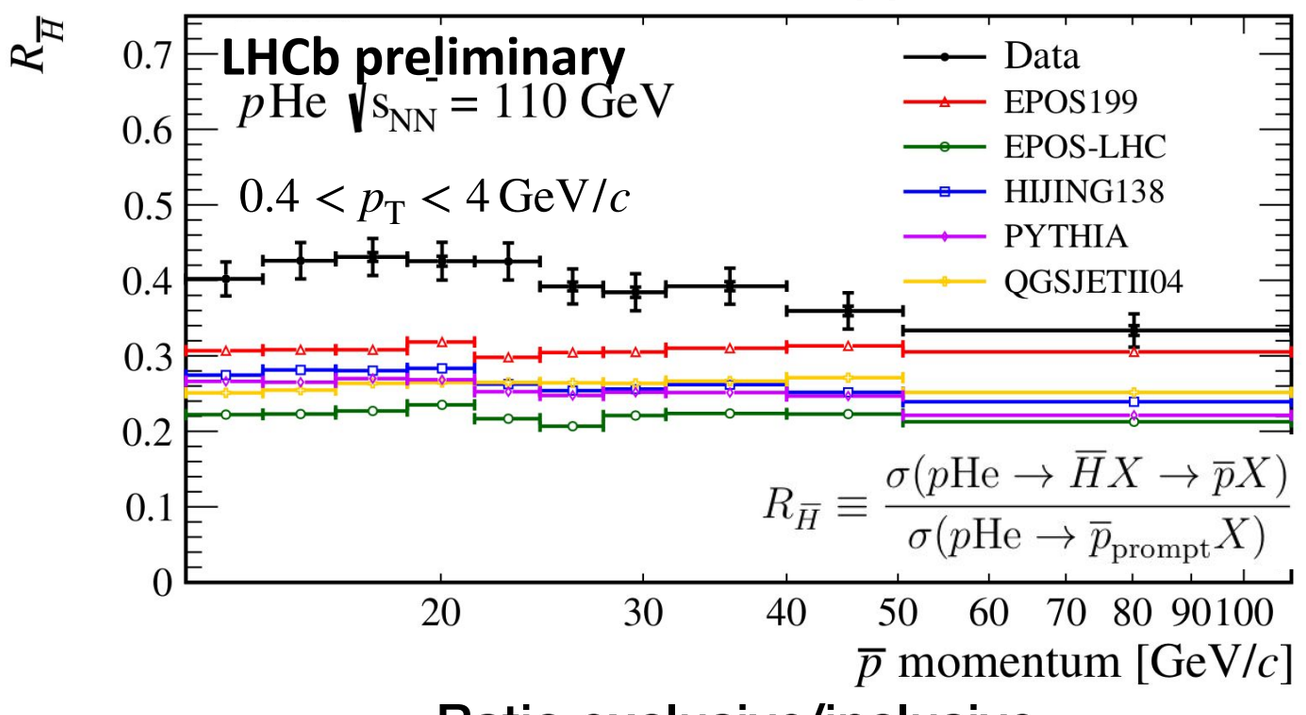
# Detached antiproton production in $p$He

Exclusive approach

LHCb-PAPER-2022-006 (in preparation)

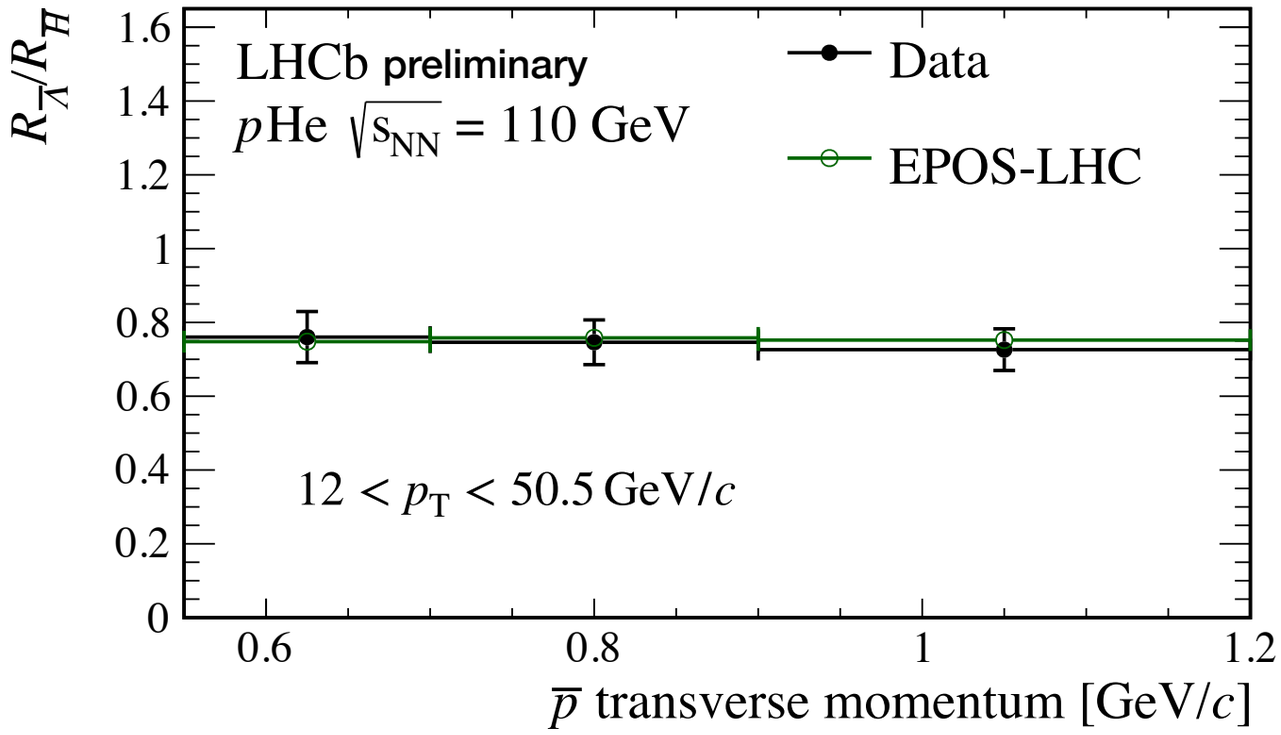
Inclusive approach



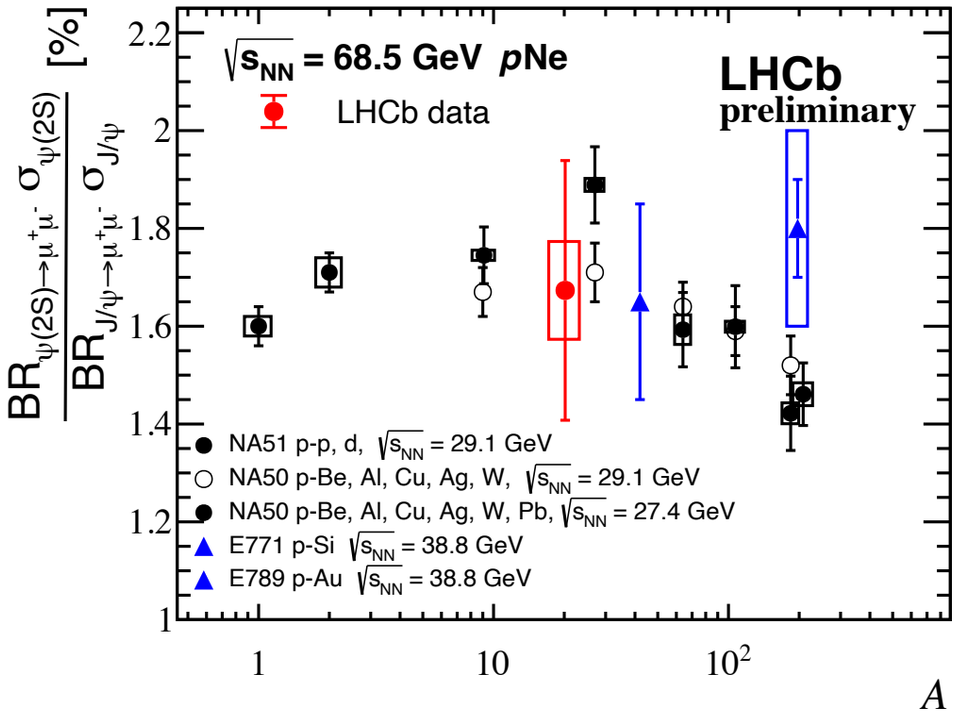

- Generators largely underestimate anti-hyperon contribution
- Dependency with $\bar{p}$ kinematics not predicted by models
- Ratio $R_{\bar{\Lambda}}/R_{\bar{H}}$ well described by generators

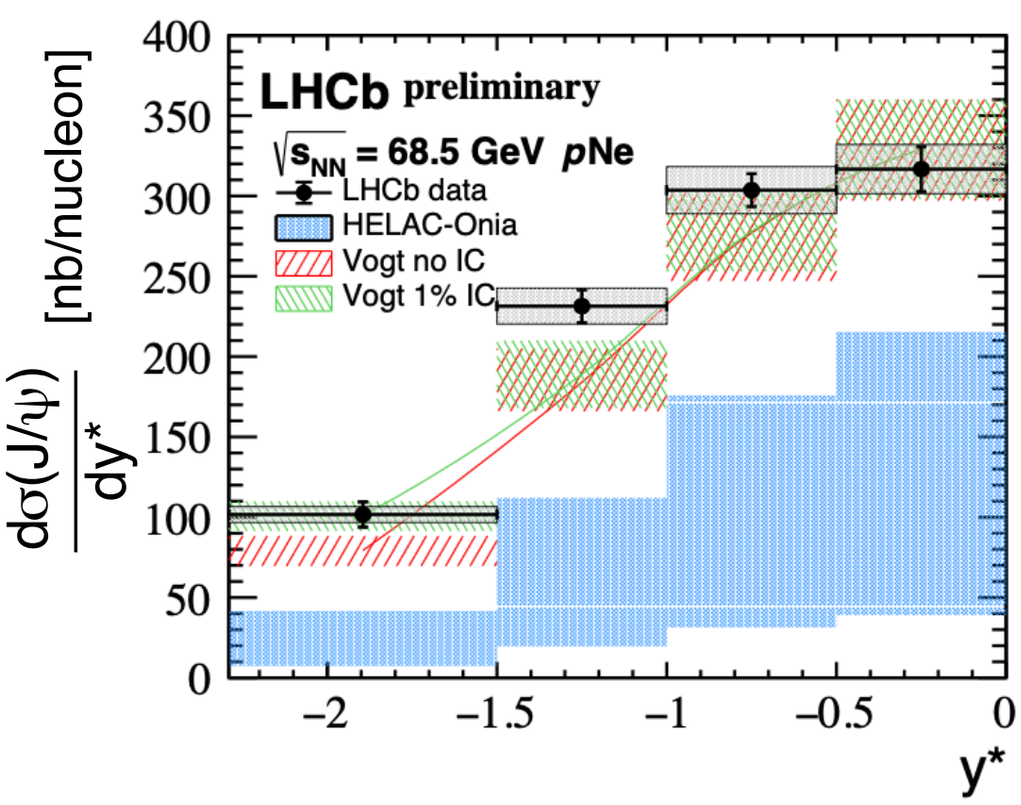
Ratio exclusive/inclusive

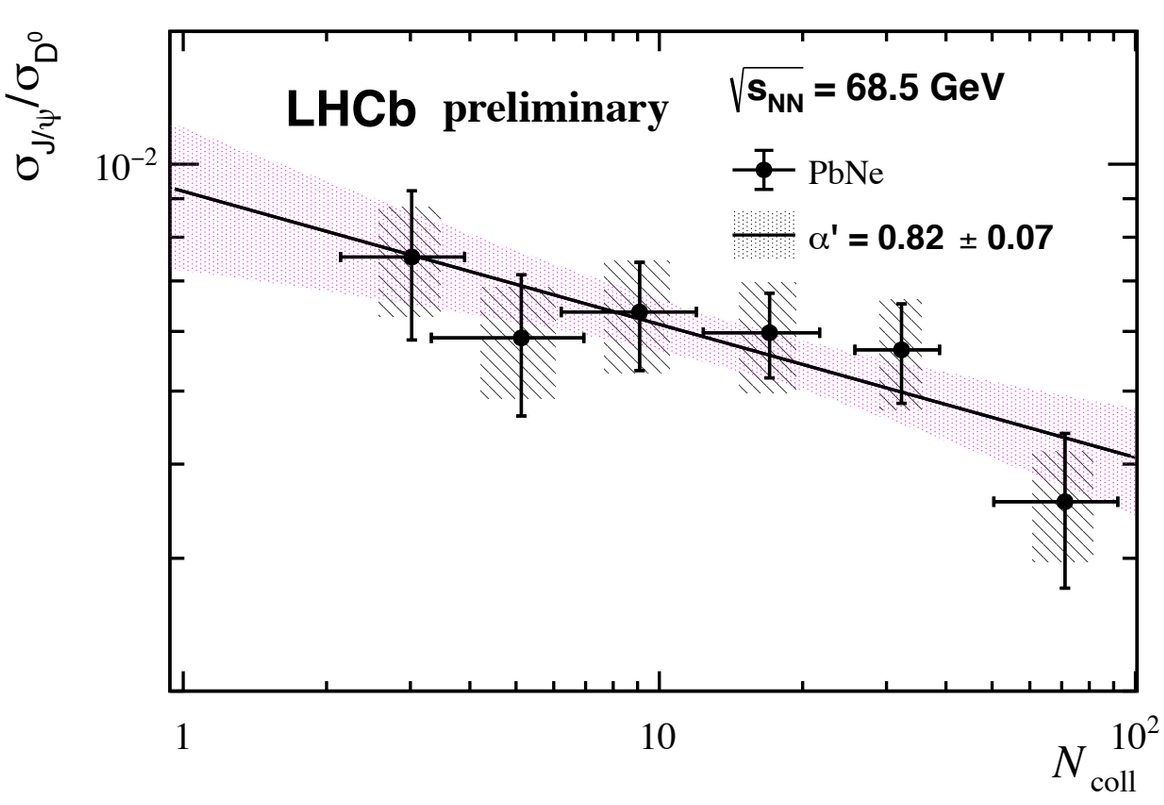


# Charm in fixed-target mode

- New results of charm production in $p$Ne and PbNe:
  - $J/\psi$ and $\psi(2S)$ production in $p$Ne at $\sqrt{s_{\rm NN}} = 68.5\,\text{GeV}$ (LHCb-PAPER-2022-014)
  - $J/\psi$ and $D^0$ production in PbNe at $\sqrt{s_{\rm NN}} = 68.5\,\text{GeV}$ (LHCb-PAPER-2022-011)
- See talk by Élisabeth Niel about charm in fixed target



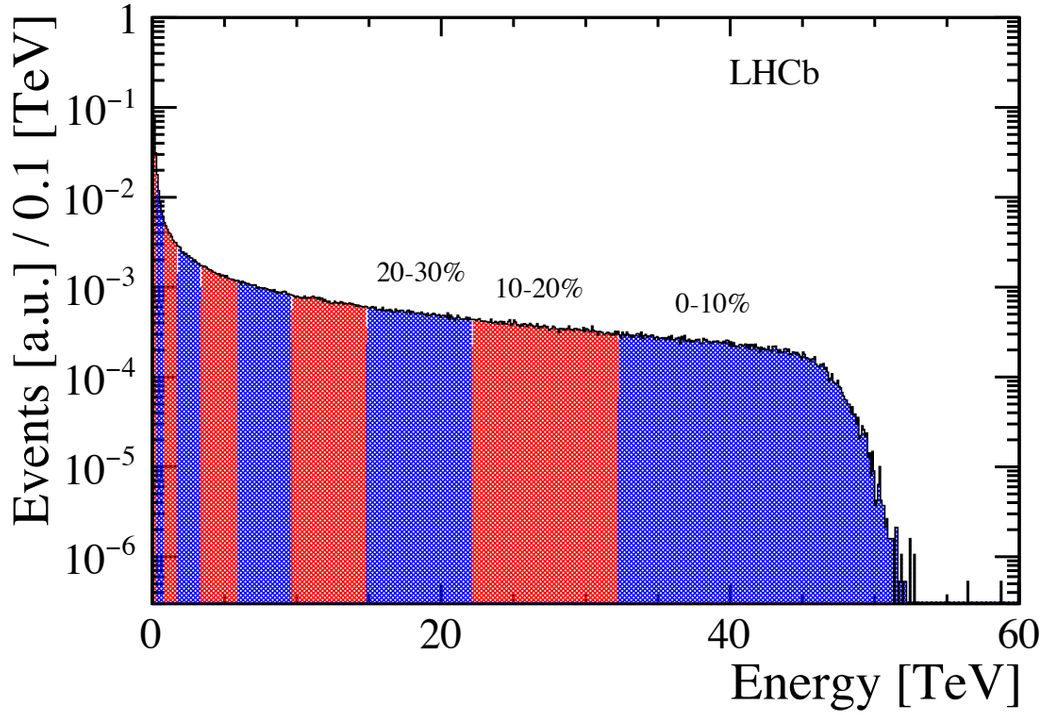



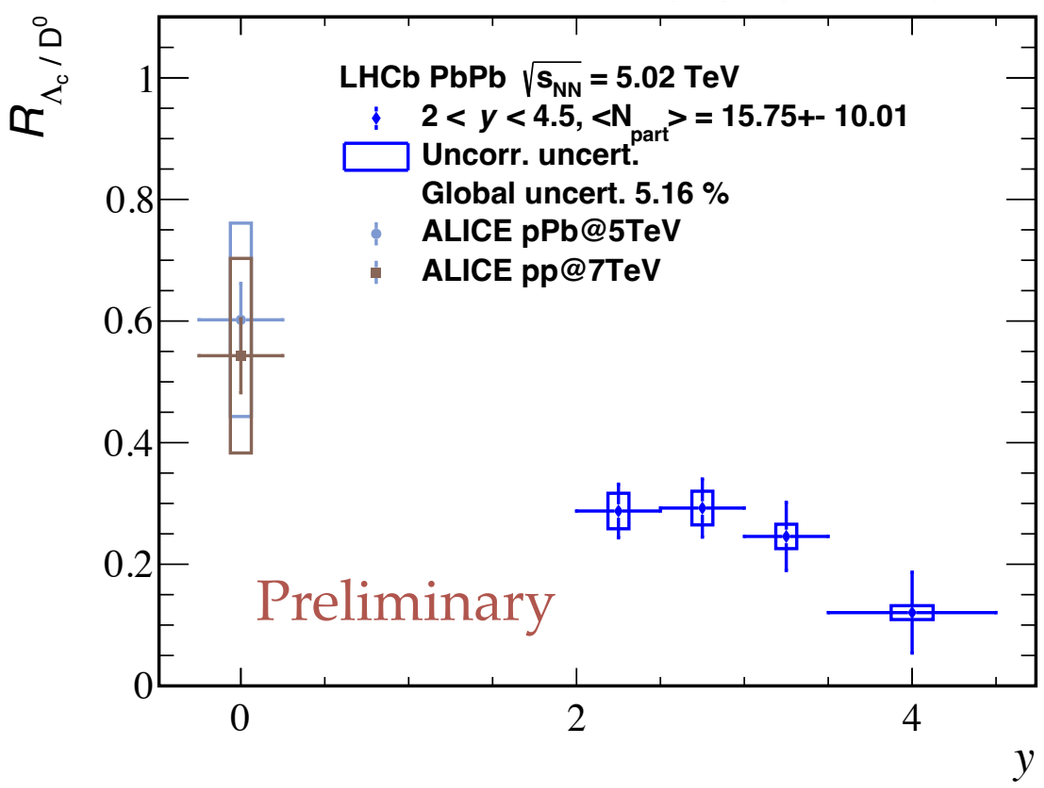
# Results in PbPb collisions

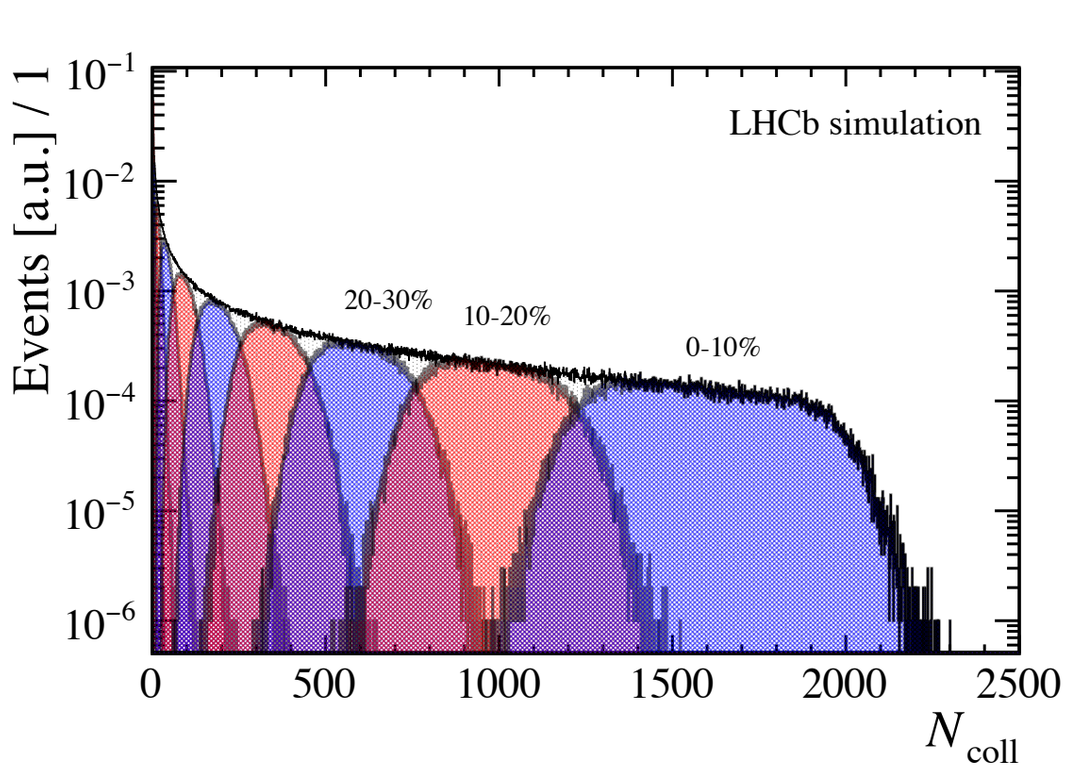
- New results in PbPb collisions:
  - Centrality determination in PbPb and PbNe
  - $J/\psi$ photo-production in peripheral collisions (Phys. Rev. C 105, L032201)
  - $\Lambda_c/D^0$ ratio in peripheral collisions
- See talk by Samuel Belin

arXiv:2111.01607




LHCb-PAPER-2021-046 (in preparation)



# Summary

- LHCb has unique capabilities for measurements in QCD & Heavy Ion physics
- Very interesting new measurements were presented (incomplete list!)
  - Charged hadrons and $\pi^0$production in $p\mathrm{Pb}$ and $pp$ collisions
  - New $D^0$ production measurement in $p\mathrm{Pb}$ at 8TeV
  - $Z$ boson production with charm jets and $Z$ boson cross-sections in $pp$ and $p\mathrm{Pb}$ collisions
  - Production of $\chi_{c1}(3872)$ and $\psi(2S)$ in $p\mathrm{Pb}$ collisions
  - $B_s^0/B^0$ ratio with respect multiplicity in $pp$ collisions
  - antiproton production from hyperons in $p\mathrm{He}$ collisions
- Additional constrains to nPDFs and some tensions with predictions
- Better performance and larger datasets expected for Run 3

- Other LHCb-related talks:
  - Élisabeth Niel (Charm in fixed target)
  - Samuel Belin (Charm production in PbPb collisions)
  - Benjamin Audurier (Physics prospects & detector improvements)

# Backup

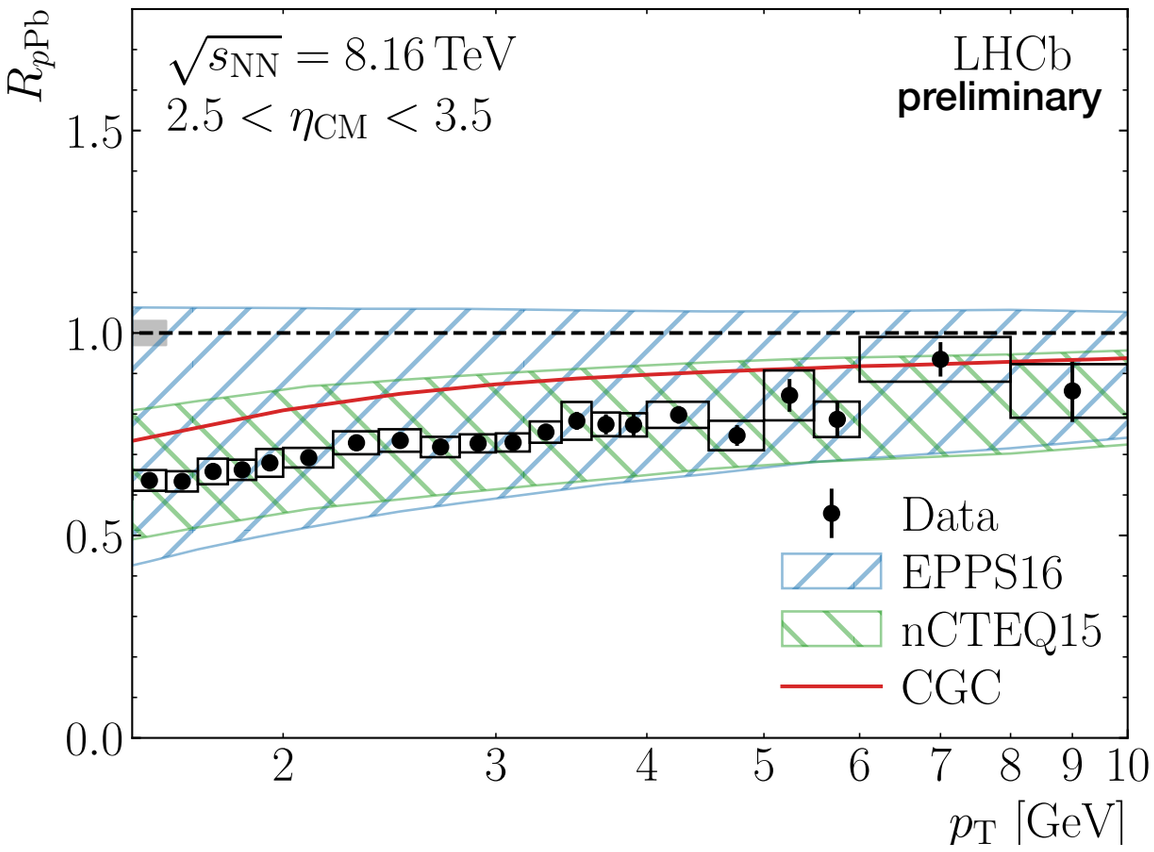
# Heavy-ion and QCD physics at LHCb

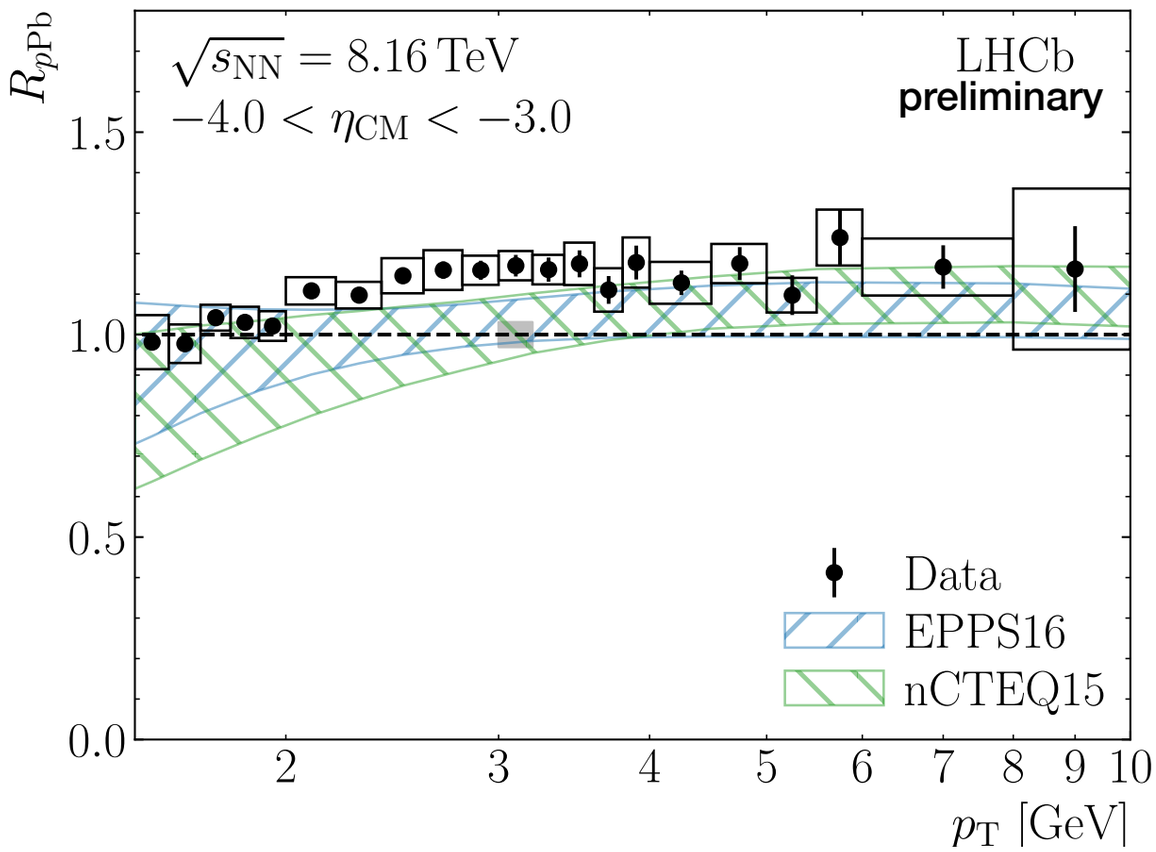
**Some of the LHCb strong points:**

- Unique coverage in $(x, Q^2)$
  - constrains to nPDFs
- Precision and unique heavy-flavour measurements down to low $p_{\mathrm{T}}$
  - clean separation of prompt-nonprompt, angular measurements
- Study of the saturation region
  - full capabilities in the very low-x region at forward region (charged hadrons, photon and neutral hadron reconstruction with very low $p_{\mathrm{T}}$ coverage)
- Spectroscopy and exotic hadrons
- UPC and CEP measurements
  - excellent $p_{\mathrm{T}}$ resolution

# Neutral pion production in $p$Pb

LHCb-PAPER-2021-053 (in preparation)




- Comparison with non reweighted nPDF predictions

# $D^0$ production in $p$Pb at 5 TeV