Light-Ion Physics at LHCb

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on behalf of the LHCb collaboration

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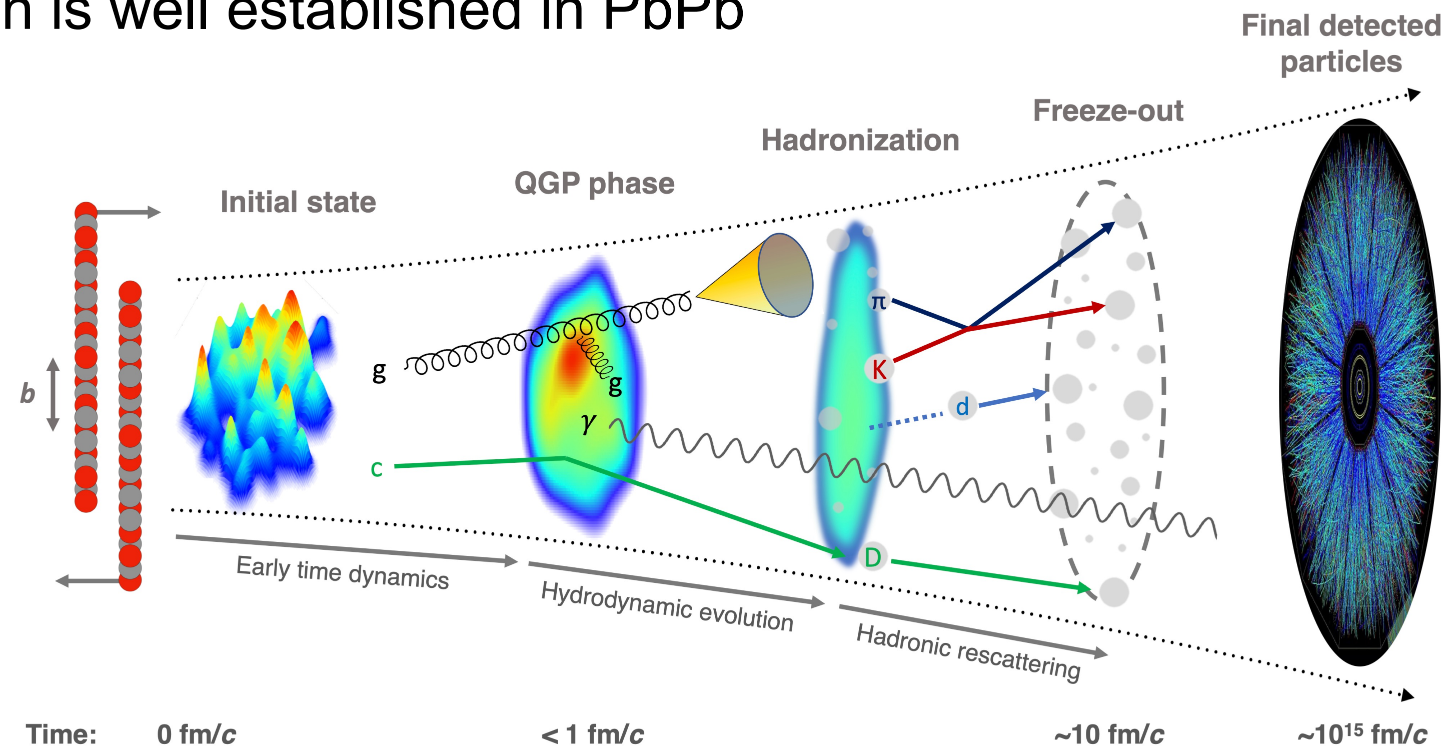
Motivation

- At extremely high temperature and energy density
  - QCD predicts that nuclear matter transitions into a deconfined phase quark–gluon plasma (QGP)
- **Heavy-ion collisions are a laboratory to create and study QGP**
  - QGP formation is well established in PbPb



arXiv:2303.17254

Motivation

- At extremely high temperature and energy density
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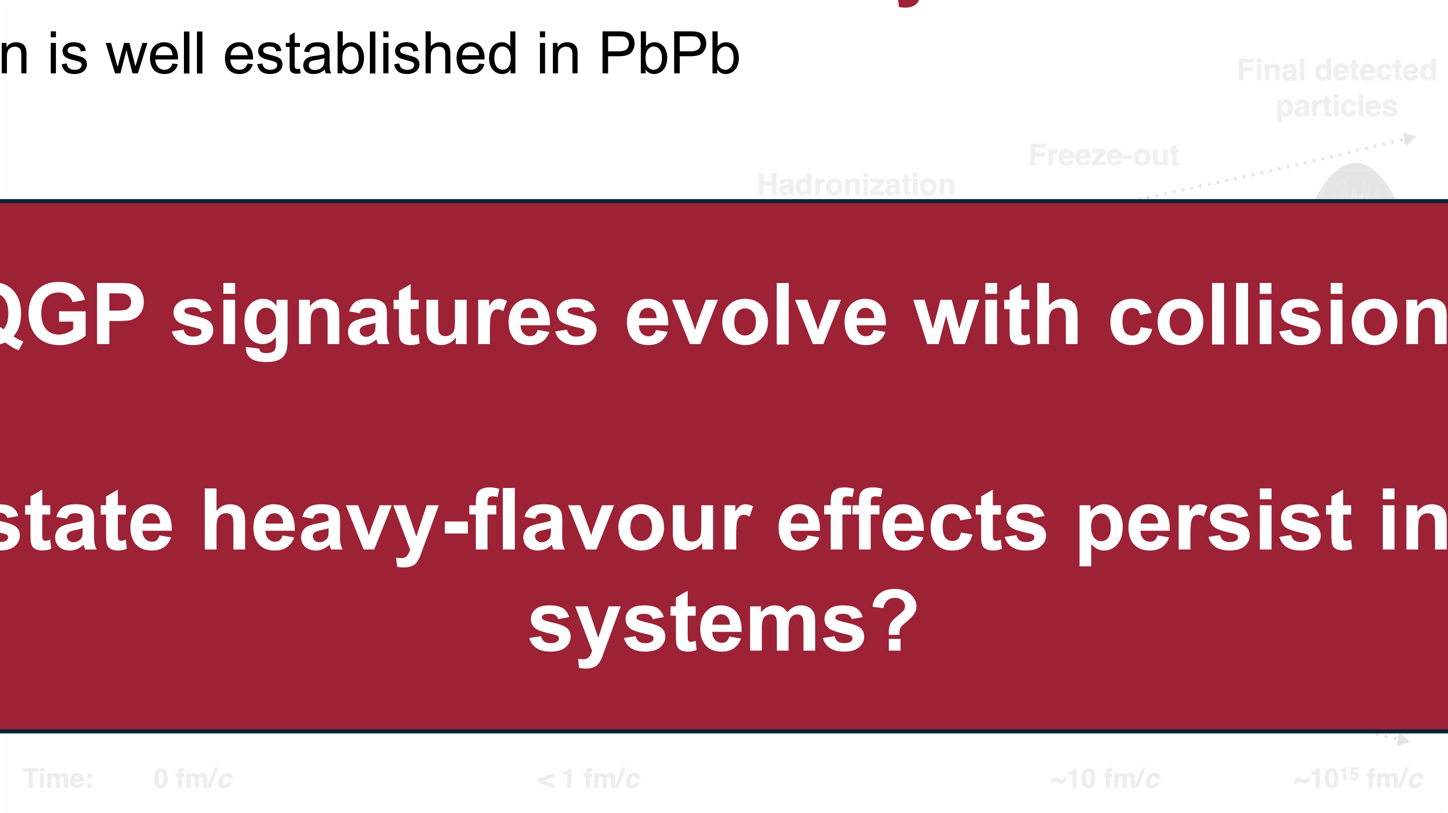


How do QGP signatures evolve with collision system?

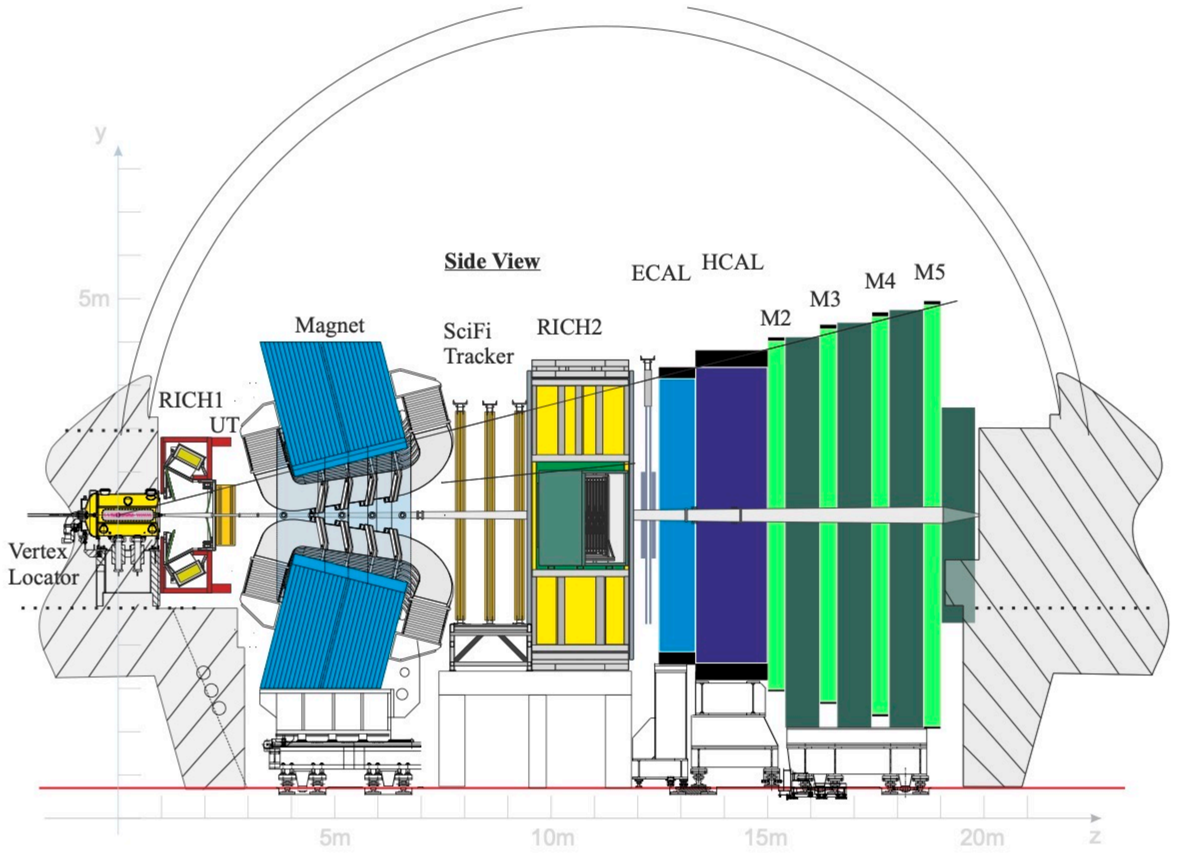
Do final-state heavy-flavour effects persist in light-ion systems?

arXiv:2303.17254

LHCb Detector in Run 3

JINST 19 P05065 (2024)

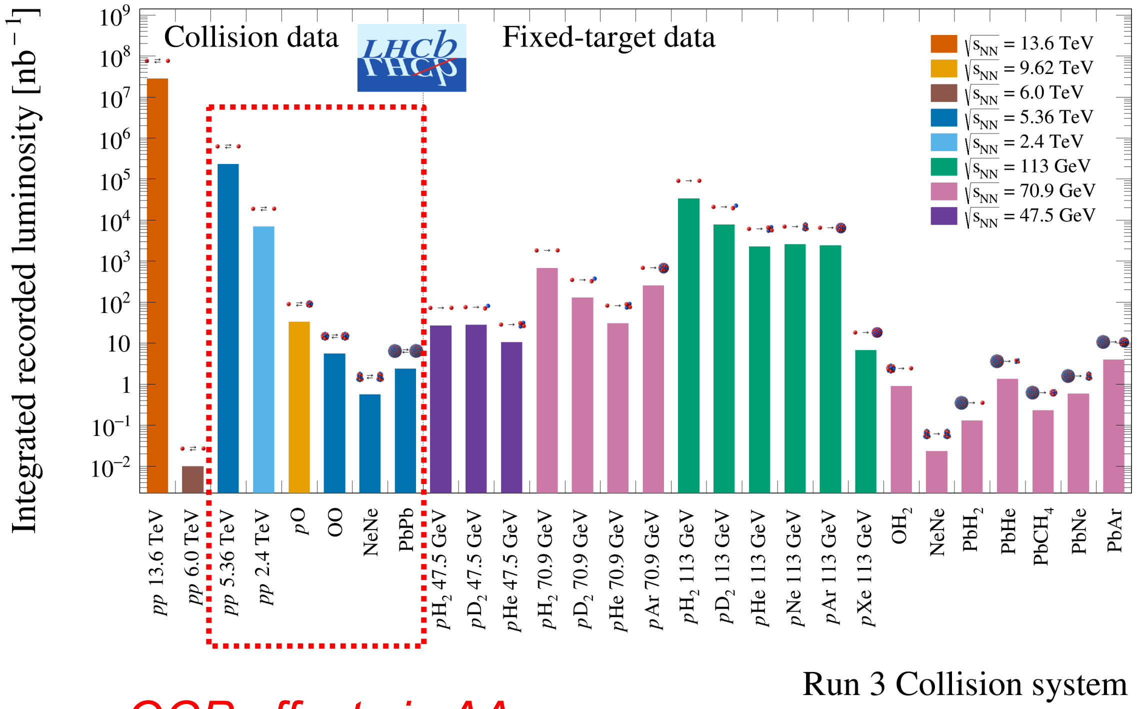
- LHCb: a single-arm forward spectrometer covering $2 < \eta < 5$
- Optimized for heavy-flavor (c, b) physics
- Excellent tracking and particle identification capabilities
  - $\Delta p/p = 0.45\% - 1.1\%$ for $p = 2 - 200$ GeV/c
- In Run 3 the detector was upgraded
  - fully software-based trigger
  - new tracking systems



Collision Systems at LHCb

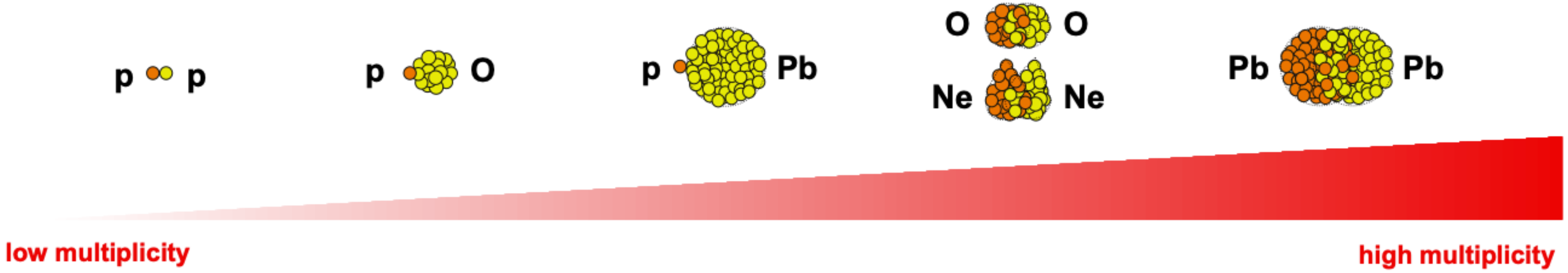
- LHCb collects a diverse data set spanning multiple collision systems
  - a unique opportunity to search for QGP-like effects as a function of system size
- Small systems are interesting
  - challenge the traditional picture that QGP-like behavior appears only in heavy-ion collisions
- Cold Nuclear Matter (CNM)

LHCb Operations Plots



CNM effects in pA:
- *Nuclear PDFs at high and low x*
- *Energy loss in nucleus*

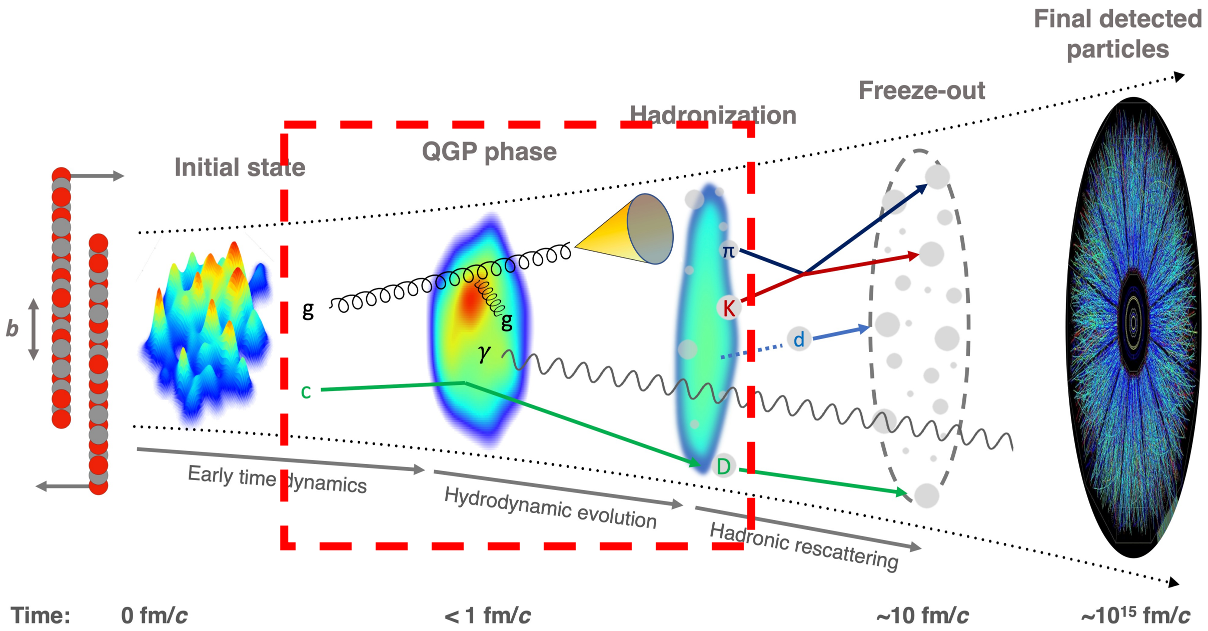
QGP effects in AA:
- *Energy loss in plasma*
- *Hadronization following deconfinement*



How Do We Study Medium Effects?

Heavy-flavour Production

- Charm quarks are produced early
  - experience the full medium evolution
- Quantified relative to a pp baseline or small systems
  - how particles are modified through the medium
- p_{T} dependent modification of open-heavy-flavour yields
  - separates initial-state effects from possible final-state effects



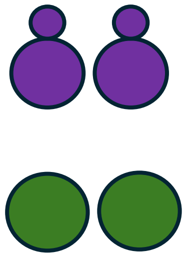
arXiv:2303.17254

Outline

- **D^0 production Ratio NeNe/OO** arXiv:2605.27273
- **Beauty Production in OO, NeNe, and PbPb** LHCB-FIGURE-2025-017
- **Υ suppression in pO, OO** LHCb-PAPER-2026-027 **NEW Preliminary!**

- $\boldsymbol{D^0}$ **production ratio NeNe/OO**

- $$R(p_T) = \frac{\left(dN_{D^0}/dp_T\right)_{\mathrm{NeNe}}}{\left(dN_{D^0}/dp_T\right)_{\mathrm{OO}}}$$



Measure yields per p_T bin

$$\frac{n_{\mathrm{i}}^{\mathrm{NeNe}}}{n_{\mathrm{i}}^{\mathrm{OO}}} \times \frac{\epsilon_{\mathrm{i}}^{\mathrm{OO}}}{\epsilon_{\mathrm{i}}^{\mathrm{NeNe}}} \times \frac{N_{\mathrm{Inel}}^{\mathrm{OO}}}{N_{\mathrm{Inel}}^{\mathrm{NeNe}}}$$

Correct by efficiency

Normalize by number of inelastic collisions

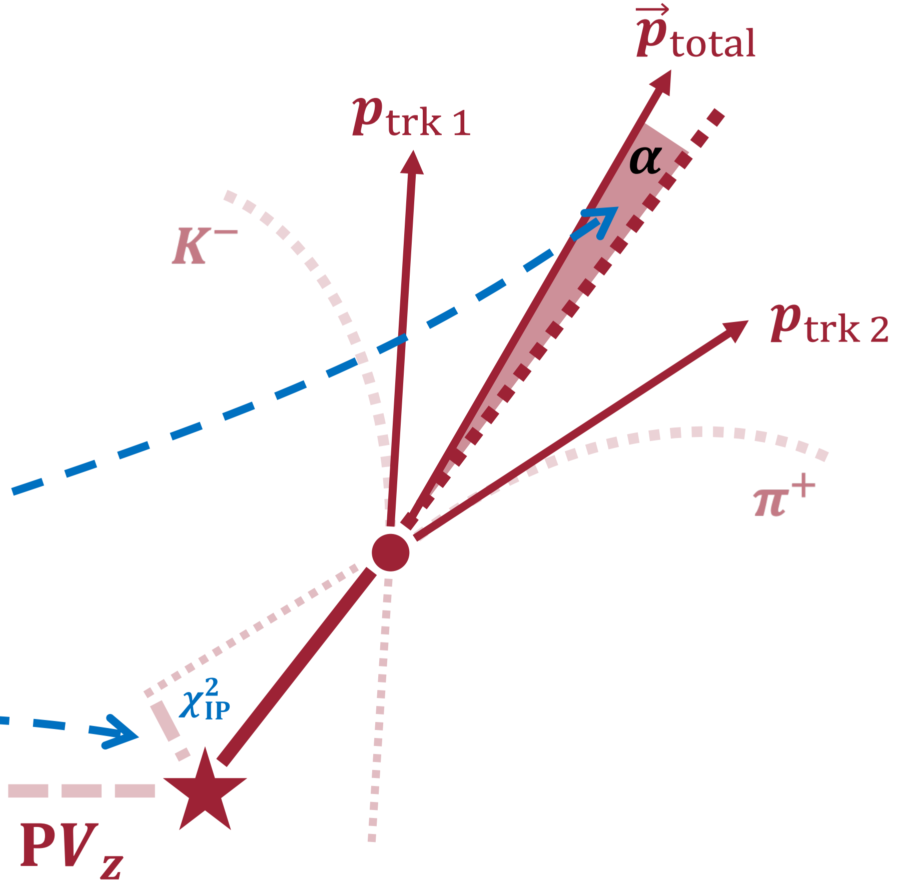
- Many detector and normalization effects partially cancel in the ratio
- The p_T shape is the main observable and isolates nuclear effects
  - $R(p_T) \approx$ constant $\rightarrow$ geometric scaling
  - $R(p_T) \not\approx$ constant $\rightarrow$ differential nuclear modification or QGP formation onset
- **Provides first direct test of system-size dependence of charm production and possible modifications**

Prompt $D^0 \rightarrow K^-\pi^+$ Reconstruction

arXiv:2605.27273

Light-Ion Data at $\sqrt{s_{NN}}$ = 5.36 TeV

- LHCb collected OO and NeNe datasets in 2025 correspond to integrated luminosities
  - OO: $5.5\,nb^{-1}$
  - NeNe: $0.51\,nb^{-1}$
- Displaced decay vertex
- Momentum alignment with PV
- Large impact parameter significance for daughter tracks



Prompt $D^0 \to K^-\pi^+$ Reconstruction

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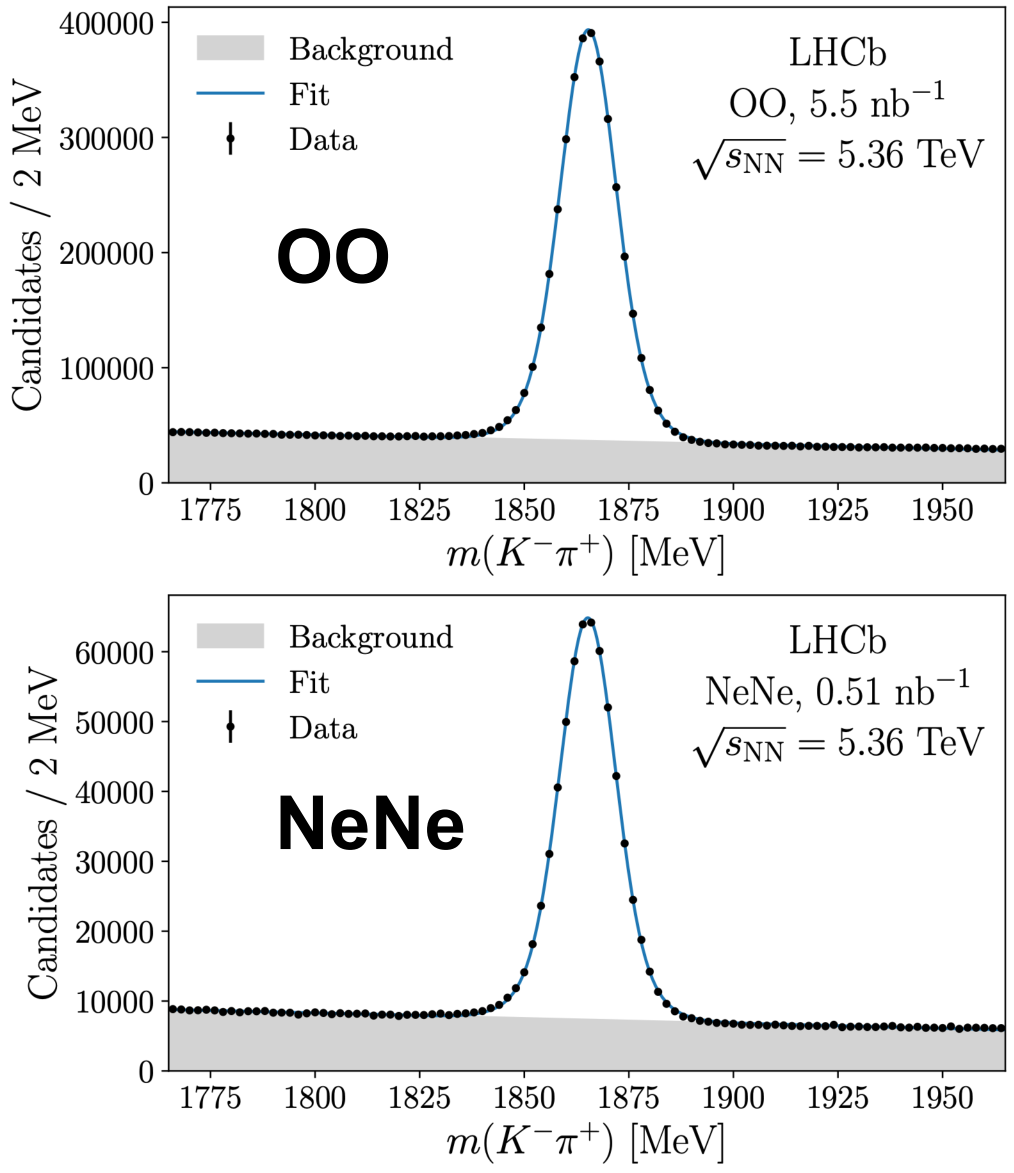
D^0 Acceptance

- Candidates' kinematics
  - $p_T(K,\pi) > 400$ MeV
  - $p(K,\pi) > 5$ GeV
  - $2 < \eta(K,\pi) < 4.7$
  - Particle Identification
- Excellent tracking and vertexing provide very clean D^0
  - 0.5 GeV $< p_T(D^0) < 20$ GeV
  - $2.0 < y\,(D^0) < 4.5$



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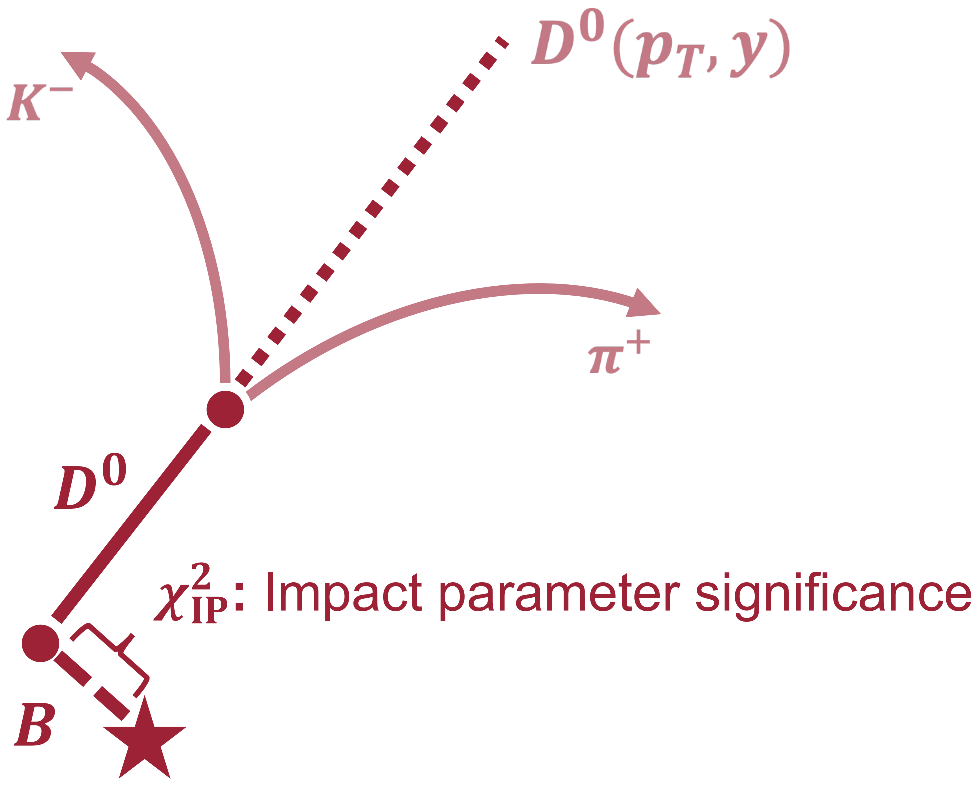
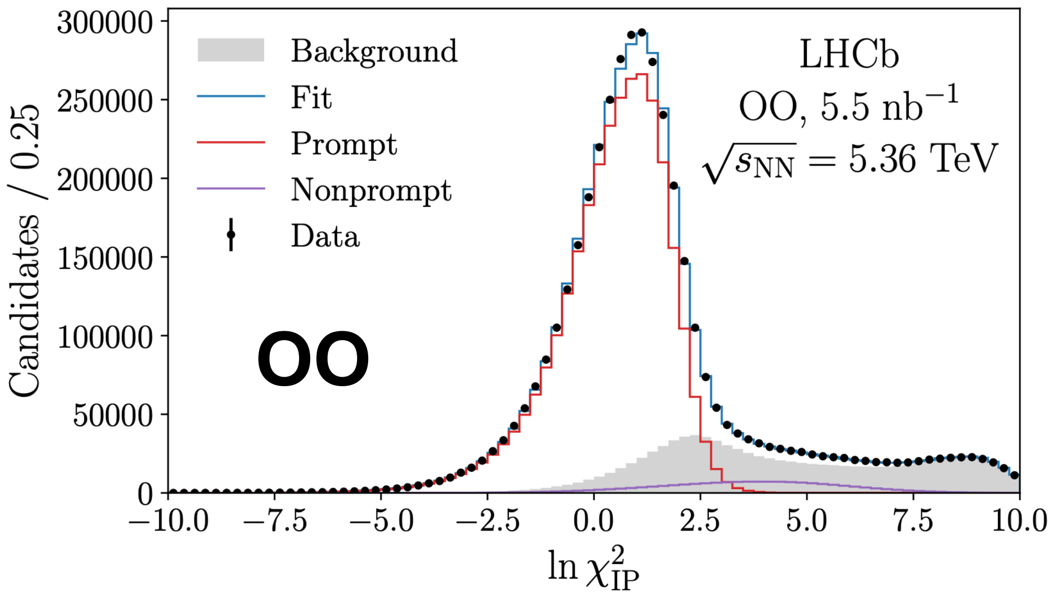
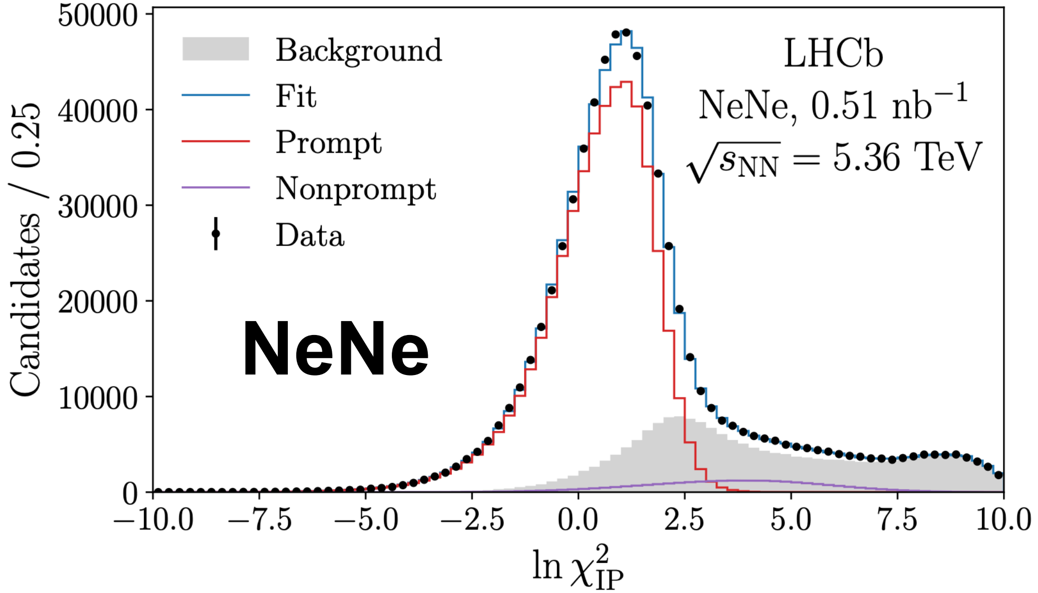
$\log(\chi^2_{\mathrm{IP}})$ Fit

- Prompt and nonprompt components are separated using fits to χ^2_{IP}







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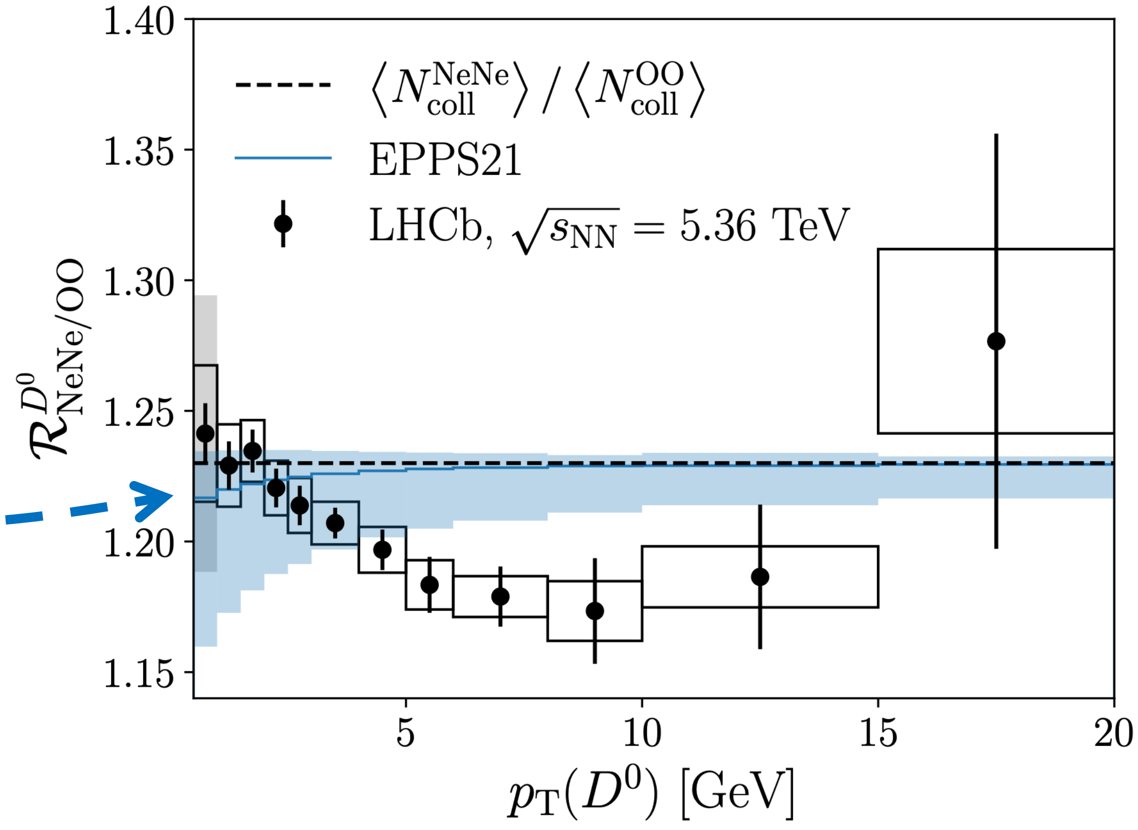
First charm measurement in light-ion collisions

- $R(p_T) = \frac{n_i^{NeNe}}{n_i^{OO}} \times \frac{\epsilon_i^{OO}}{\epsilon_i^{NeNe}} \times \frac{N_{Inel}^{OO}}{N_{Inel}^{NeNe}}$

  Yields efficiency Normalization

- The measured p_T dependence is not described by nPDF-only EPPS21 expectations
  - $R(p_T) \approx \langle N_{coll}^{NeNe} \rangle / \langle N_{coll}^{OO} \rangle$ by binary collision scaling expectation
  - suggests that a simple geometric-scaling picture is insufficient



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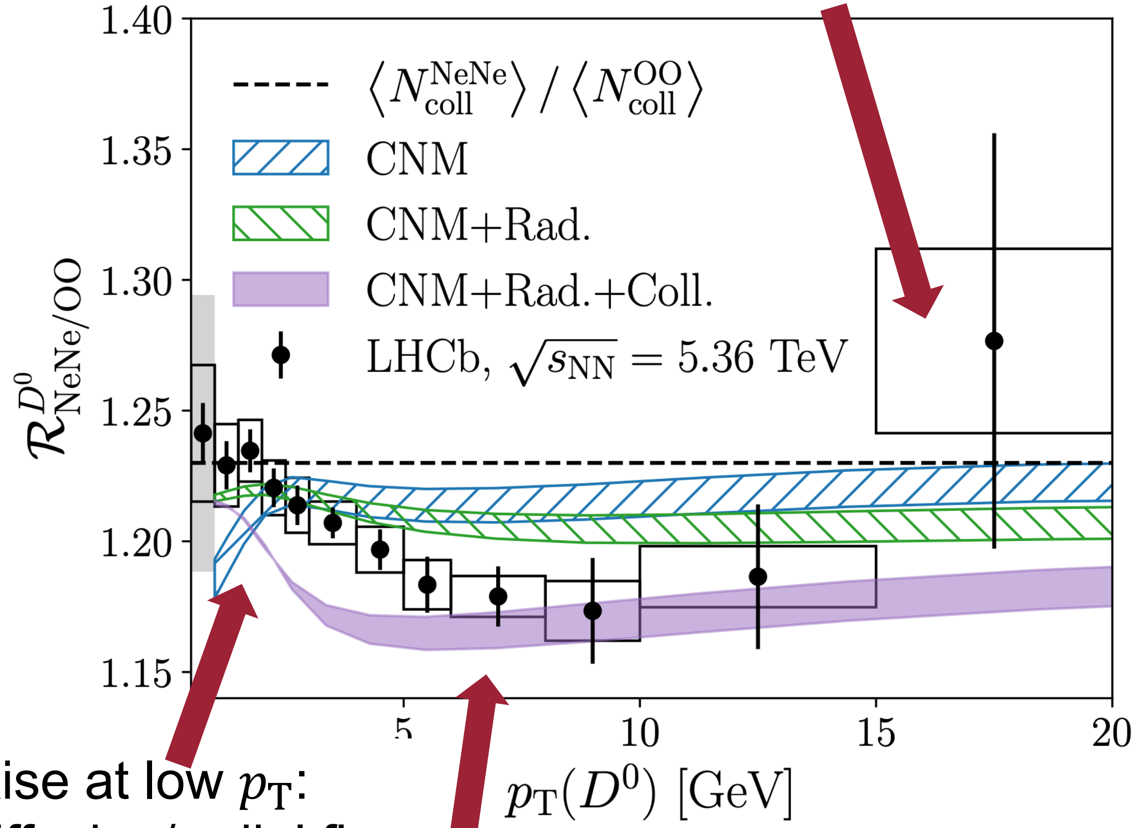
Theory models with QGP effects…

- Predict a non-constant p_T dependence
- CNM-only
  - decreasing toward p_T
- CNM + radiative loss
  - weak p_T dependence
- CNM + radiative + collisional loss
  - best describes the observed trend
- **The data favor calculations including final-state charm-quark energy loss over CNM-only expectations**
  - consistent with QGP-like effects
  - in the model, the larger NeNe system produces stronger modification

Possible recovery at high p_T: radiative loss regime



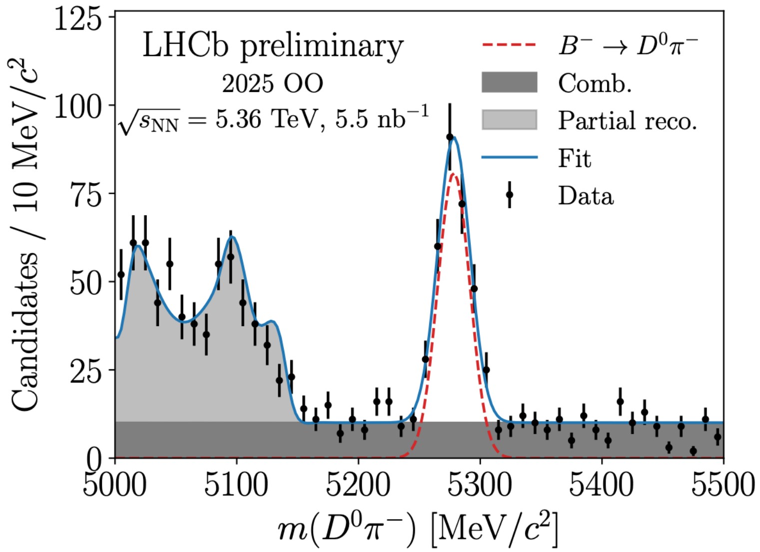
Rise at low p_T: diffusion/radial flow

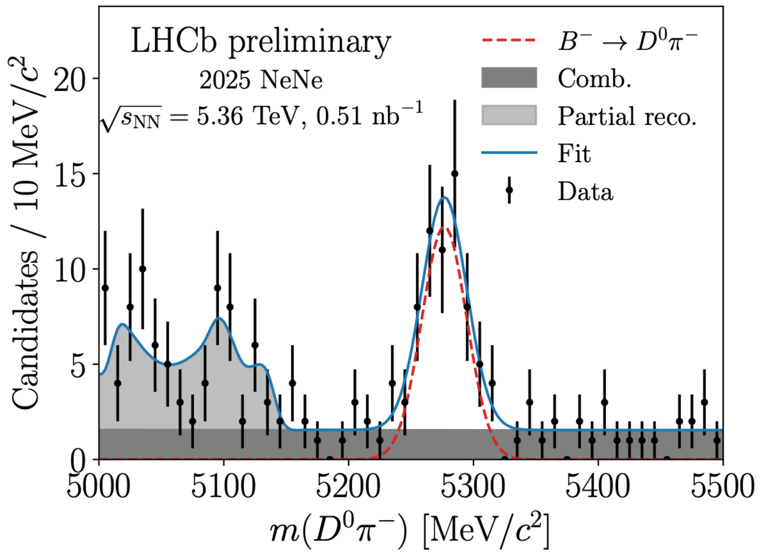
Dip near 5-10 GeV: strongest sensitivity to energy loss

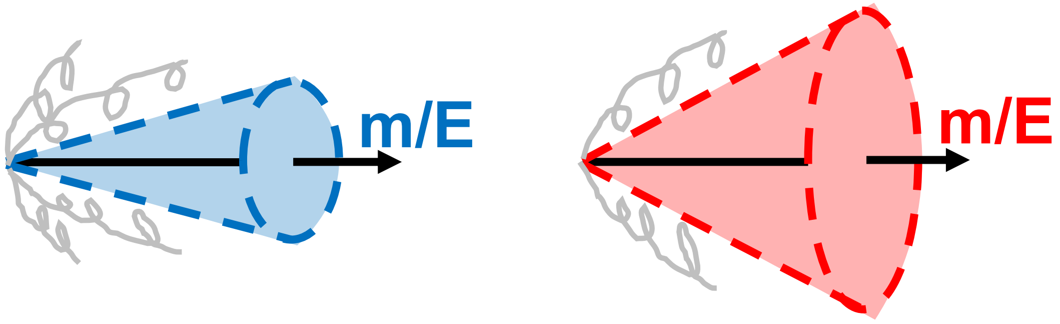
Beauty Production

LHCB-FIGURE-2025-017

- Prompt D^0 establishes a handle in OO and NeNe
  - beauty is the natural next step
- B^- is reconstructed with $D^0(\rightarrow K^-\pi^+)\,\pi^-$
  - feasibility of fully reconstructed hadronic B meson measurements
- Enabling a future test of the mass dependence of energy loss
  - is the medium dense and long-lived enough to modify a heavier, less easily quenched probe?







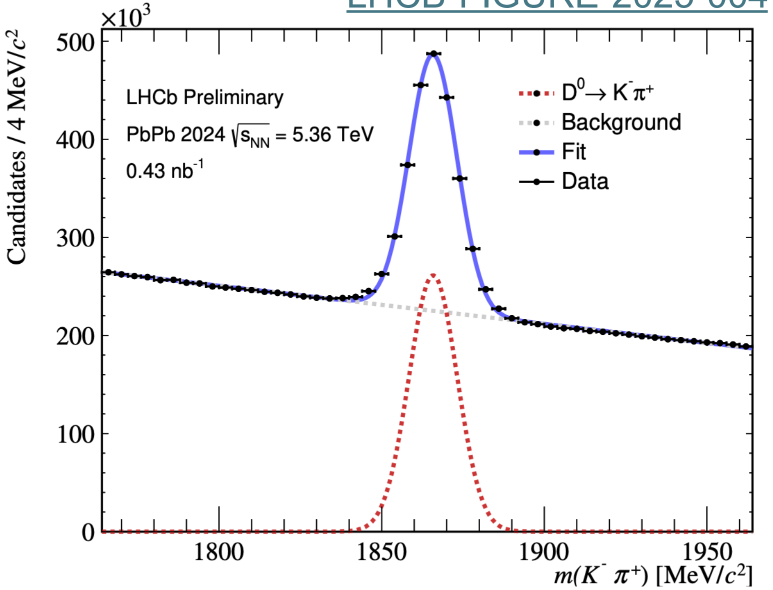
Larger energy loss

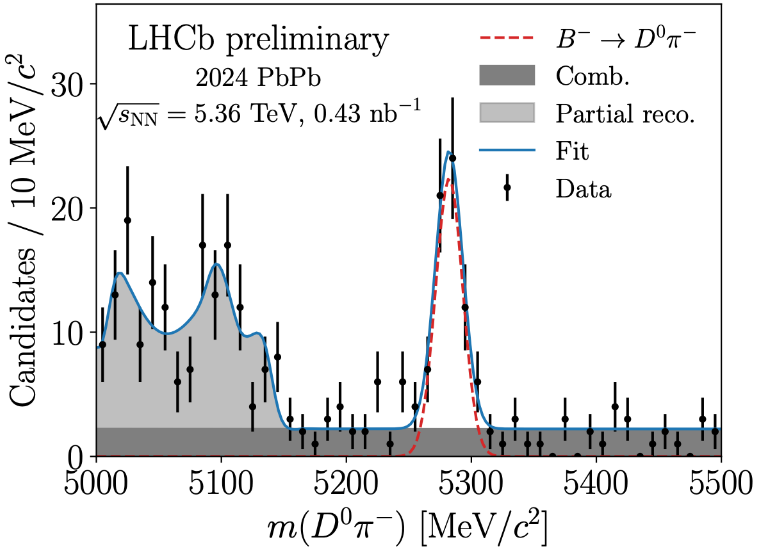
Smaller energy loss

From OO/NeNe to PbPb: Large-System Anchor

- LHCb collected its largest ever sample of PbPb data in Run 3
  - $\mathcal{L}_{\mathrm{int}} = 2.2\ \mathrm{nb}^{-1} \longrightarrow \times 10$ compared to Run 2
- OO/NeNe onset regime $\longrightarrow$ PbPb large QGP regime
  - where beauty modification is expected
- The ability to reconstruct D^0 and B^- demonstrates LHCb's potentials
  - access previously unexplored kinematic regions using heavy-flavor probes

LHCB-FIGURE-2025-004





Υ Suppression in Small Systems

- Υ Cross Section Ratio

- $$\frac{\sigma_{\Upsilon(nS)}}{\sigma_{\Upsilon(1S)}} = \frac{N_{\Upsilon(nS)}}{N_{\Upsilon(1S)}} \cdot \frac{BR[\Upsilon(1S)\to\mu^+\mu^-]}{BR[\Upsilon(nS)\to\mu^+\mu^-]} \cdot \frac{\epsilon_{\Upsilon(1S)}}{\epsilon_{\Upsilon(nS)}}$$

Inclusive yields | Branching Ratio | Efficiency

$$\frac{\epsilon^{acc}_{\Upsilon(1S)}}{\epsilon^{acc}_{\Upsilon(nS)}} \times \frac{\epsilon^{trig}_{\Upsilon(1S)}}{\epsilon^{trig}_{\Upsilon(nS)}} \times \frac{\epsilon^{rec}_{\Upsilon(1S)}}{\epsilon^{rec}_{\Upsilon(nS)}} \times \frac{\epsilon^{PID}_{\Upsilon(1S)}}{\epsilon^{PID}_{\Upsilon(nS)}}$$

- LHCb measured sequential suppression of bottomonia by studying $\Upsilon(1S, 2S, 3S)$ in pp, pO, OO
  - Ratios: $\Upsilon(nS)/\Upsilon(1S)$
  - Double ratios:
  - $[\Upsilon(nS)/\Upsilon(1S)]_{pO,OO}/[\Upsilon(nS)/\Upsilon(1S)]_{pp}$
- Evaluate CNM vs hot-medium effects in small systems.
- **Explore QGP formation threshold in light ion systems**

ϒ Suppression in Small Systems

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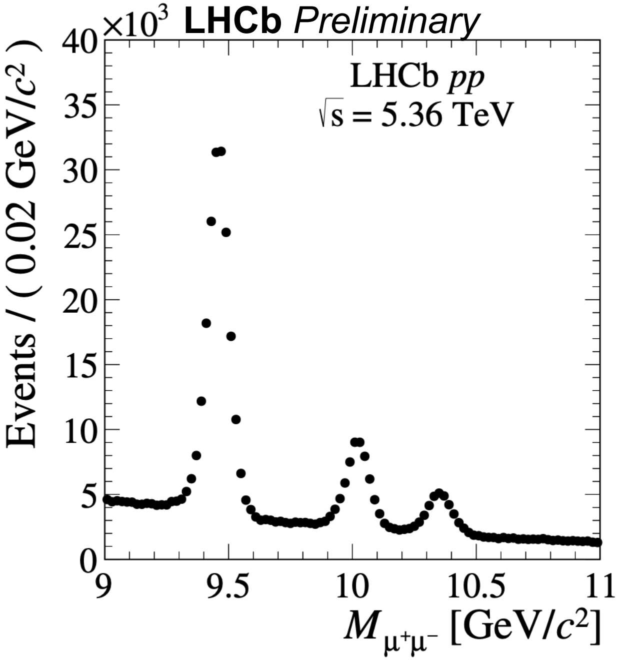
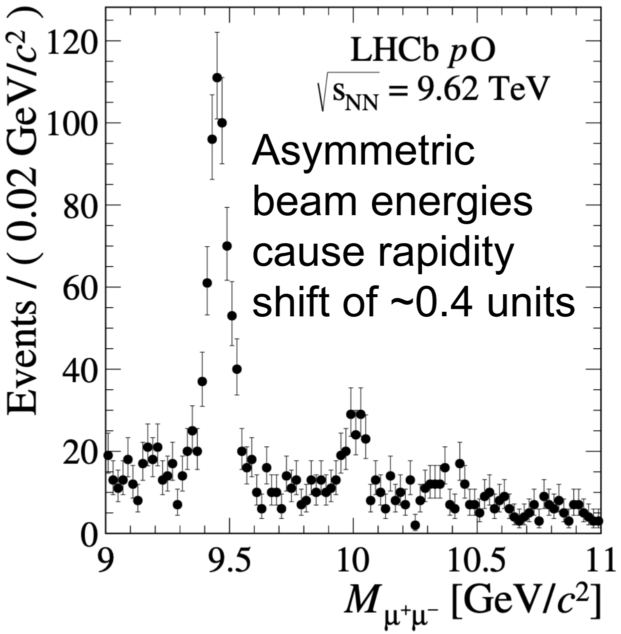
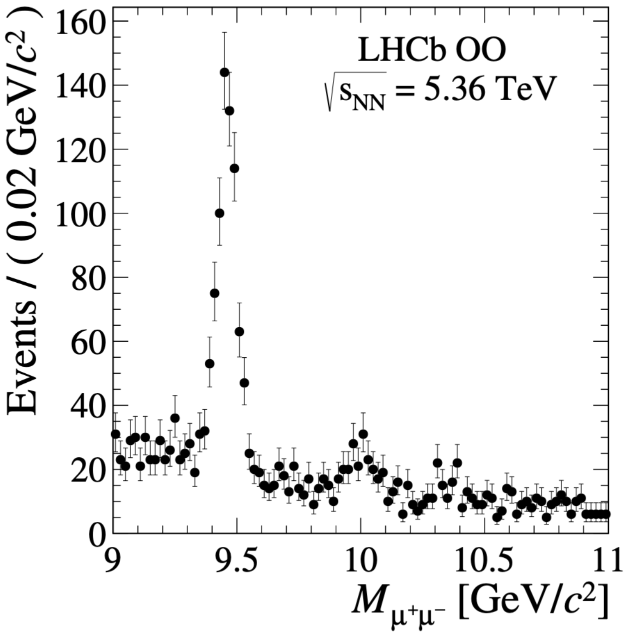
- pp: baseline $\Upsilon(1S, 2S, 3S)$ production in vacuum
- pO: controls for cold nuclear matter effects
- OO: may have evidence for additional suppression in QGP







Υ Suppression in Small Systems

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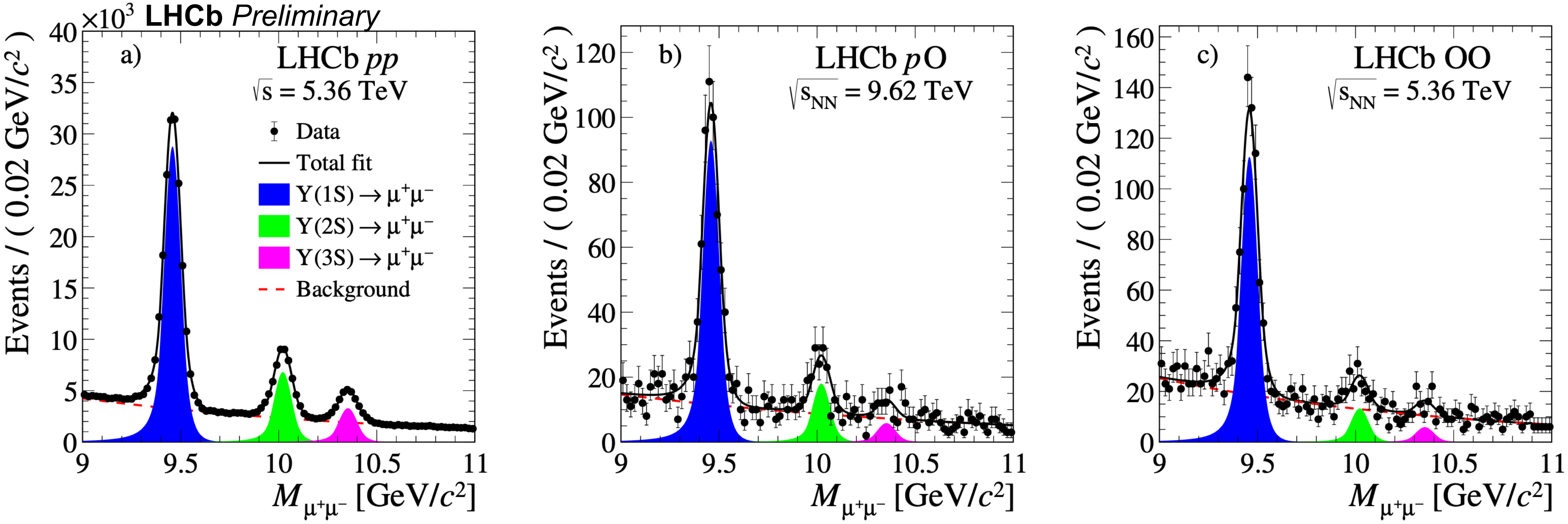
- Fit $\mu^+\mu^- \rightarrow$ extract yields & ratios
- Simultaneous fit across all systems, allowing yields and background to vary
  - Signal: Double sided Crystal Ball, shape fixed to MC.
  - Background: exponential



The dominant systematics comes from the background parameterization, driven by limited OO statistics

ϒ Ratios in pp

- pp gives baseline ϒ production in vacuum
  - agrees very well with previous data
- No $\sqrt{s_{NN}}$ dependence
  - much of the energy dependence cancels in ratios
  - the initial hard $b\bar{b}$ production is common to all ϒ states

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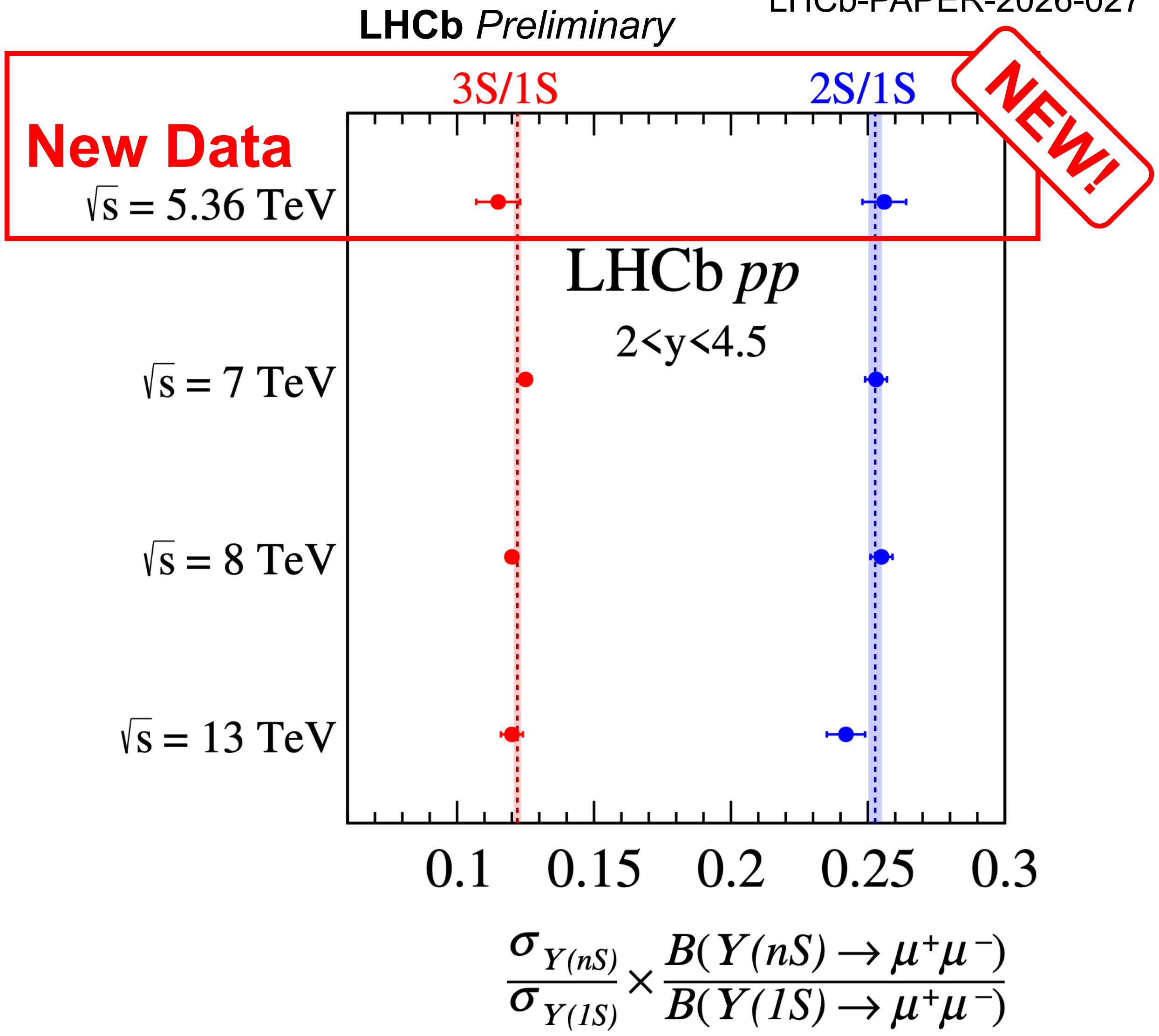

Υ Ratios Across Systems

- pO: moderate suppression relative to pp
  - due to CNM effects
- OO: stronger suppression by a factor of ~ 2 (4.8σ from pp)
- Hard to say much about the 3S with these uncertainties, but still interesting.
- Sequential suppression of $\Upsilon(nS)$ beyond the CNM baseline
- Could be due to emergence of QGP!

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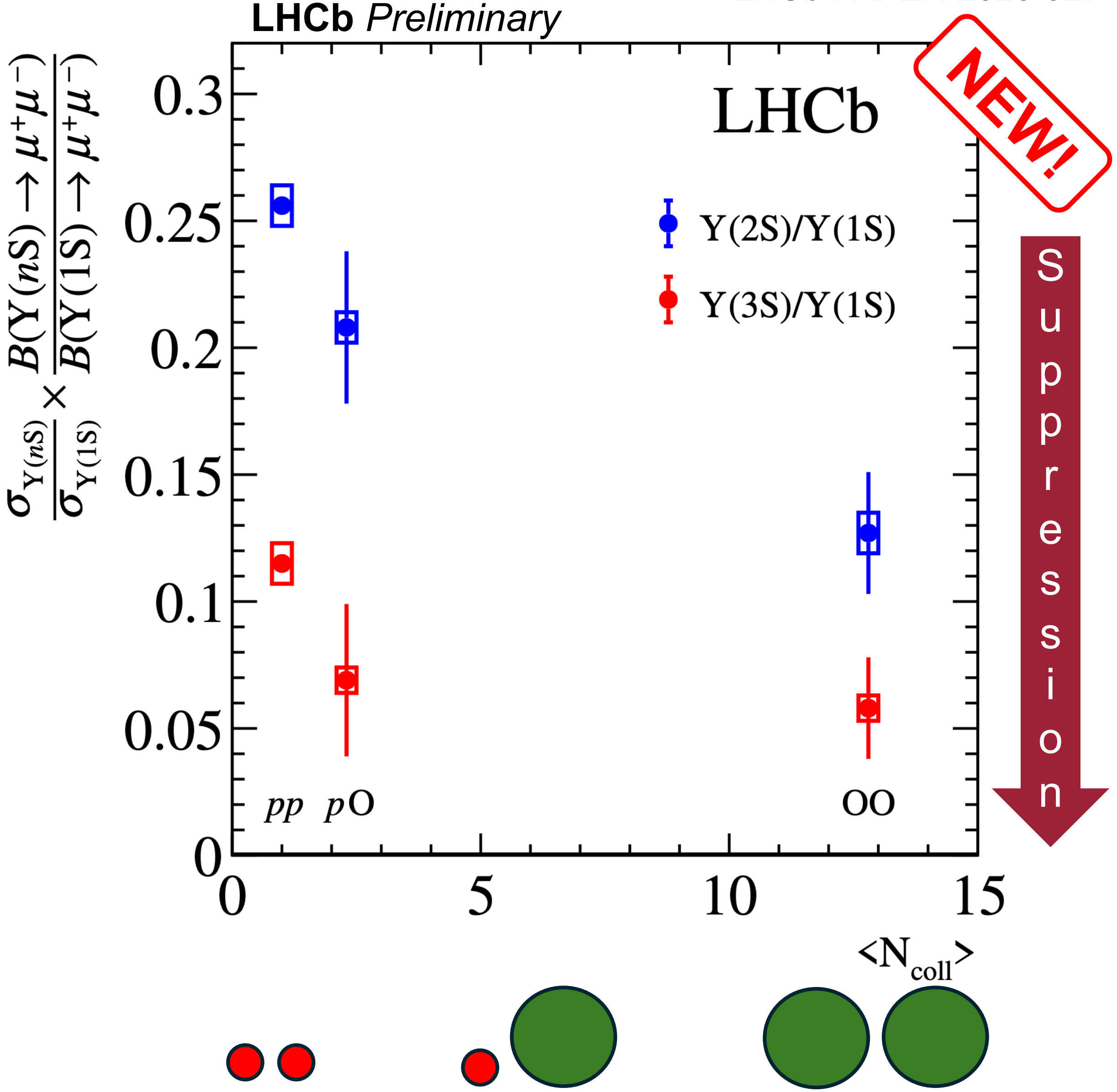

ϒ Double Ratios

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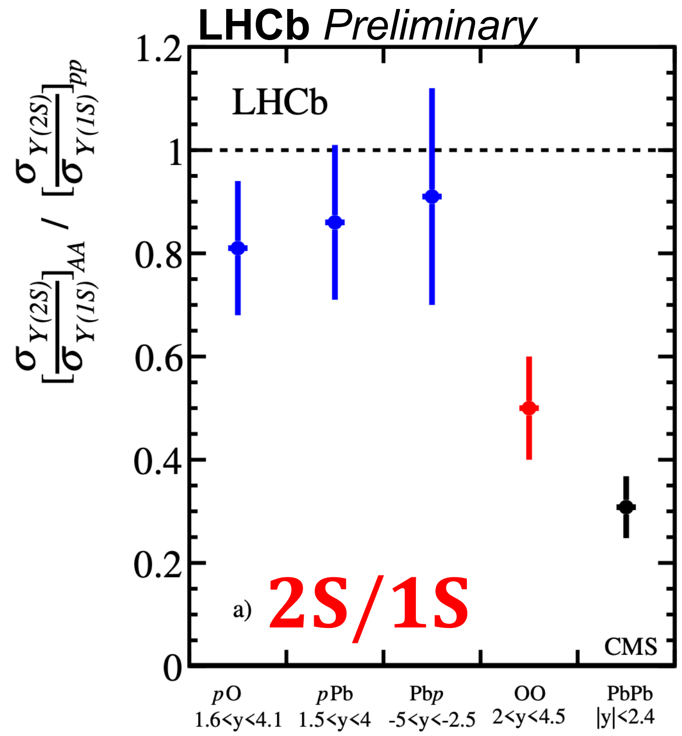
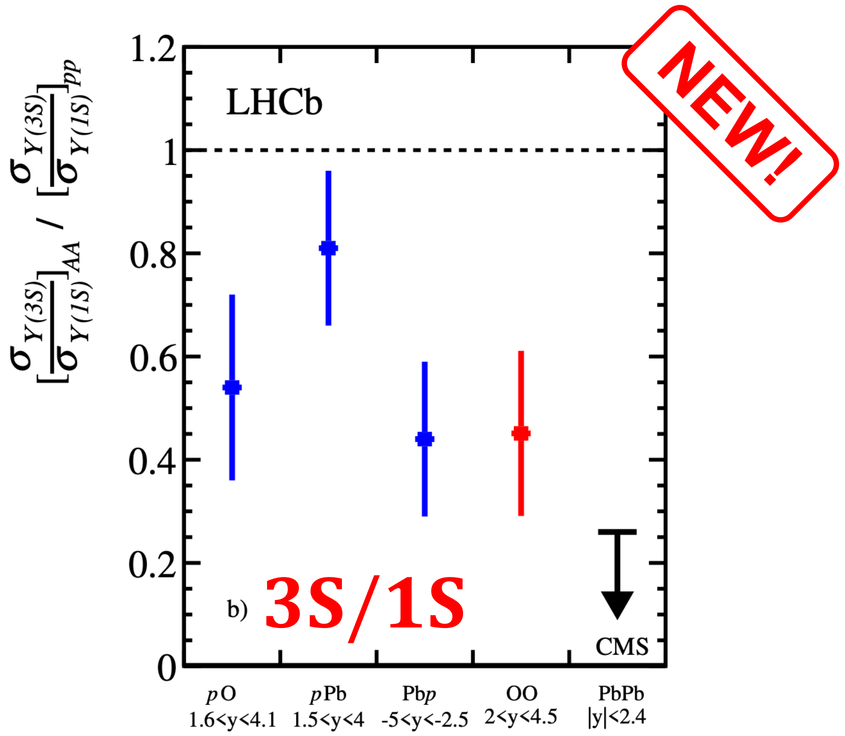
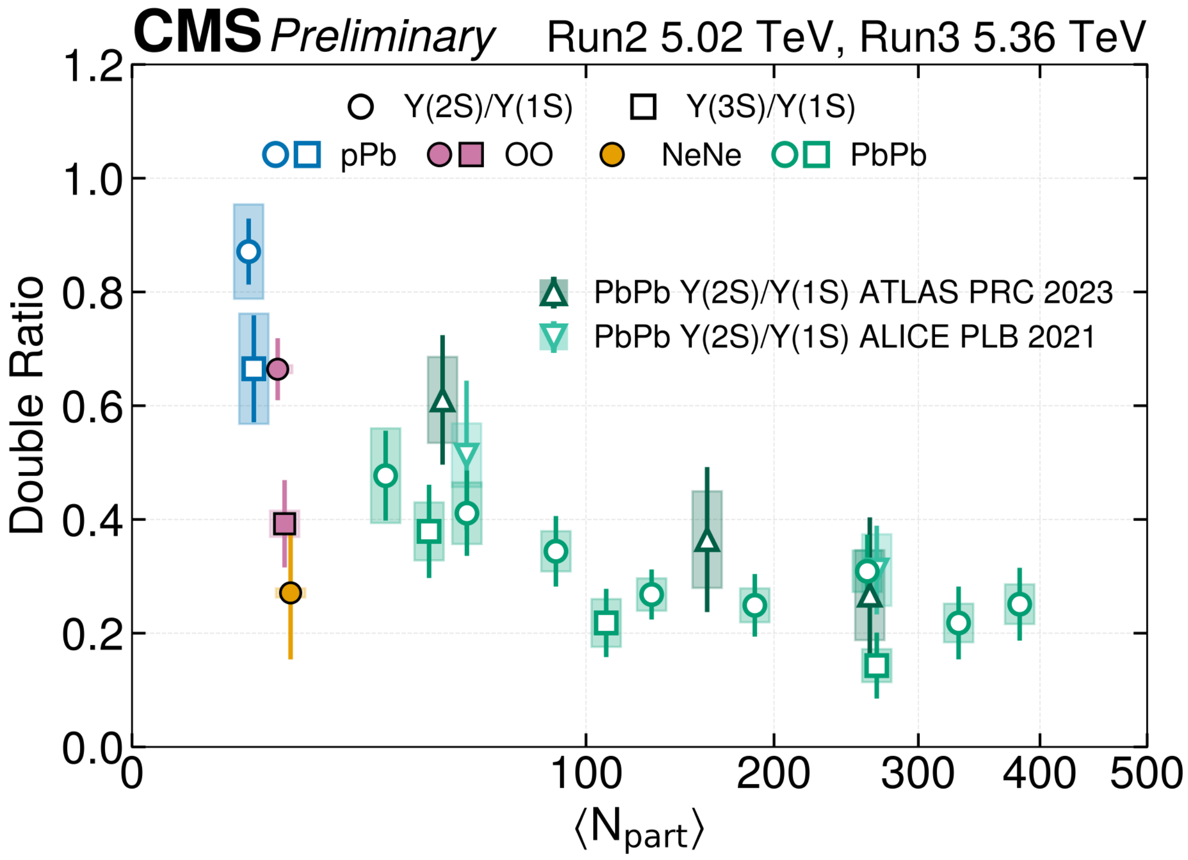
- 2S double ratio in OO has 5σ difference from pp
  - OO, PbPb data different trend from pO, pPb
- 3S double ratio suppressed across systems.
  - Weaker binding energy, more susceptible to CNM and QGP effects.
  - 3S in OO has 3.3σ difference from pp





Compare to CMS Preliminary

CMS-PAS-HIN-25-015



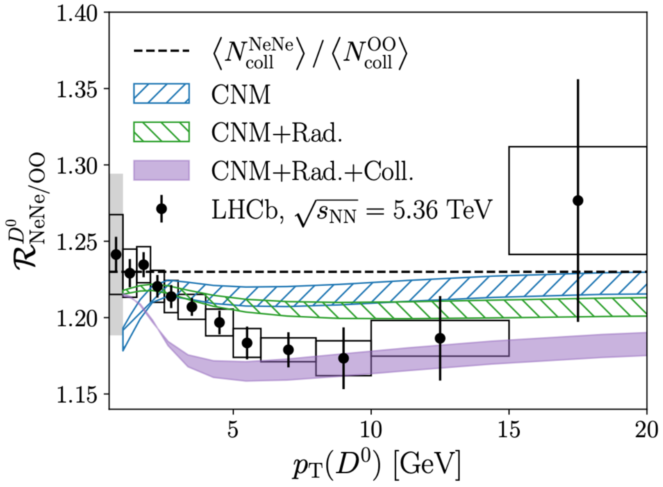
Double Ratio	LHCb Prelim	CMS Prelim
2S/1S OO	0.50 ± 0.1 ± 0.03	0.664 ± 0.055 ± 0.007
3S/1S OO	0.45 ± 0.15 ± 0.05	0.392 ± 0.077 ±0.023

- **OO shows good agreement within uncertainties**
  - **CMS has no pO results**

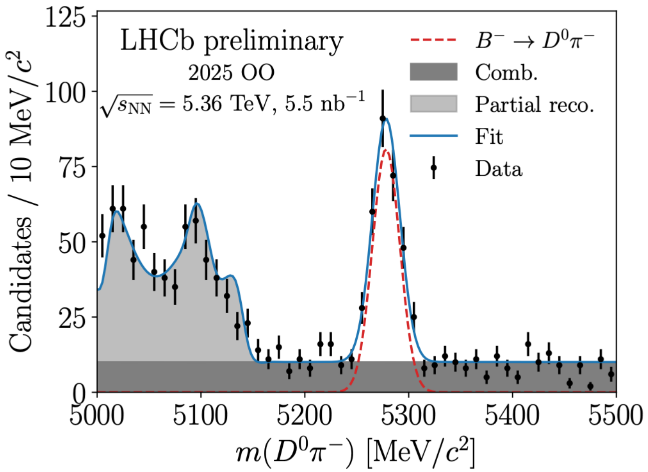
Summary

- First D^0 production ratio in OO and NeNe shows non-constant p_{T} dependence
  - suggests QGP-like effects may be present
- Clear $B^- \to D^0\pi^-$ signals in OO, NeNe, and PbPb
  - open the possibility of future mass-dependent energy-loss studies
- Υ measurements show stronger excited-state suppression in OO than in pp and pO
  - consistent with a possible final-state contribution

arXiv:2605.27273



LHCB-FIGURE-2025-017



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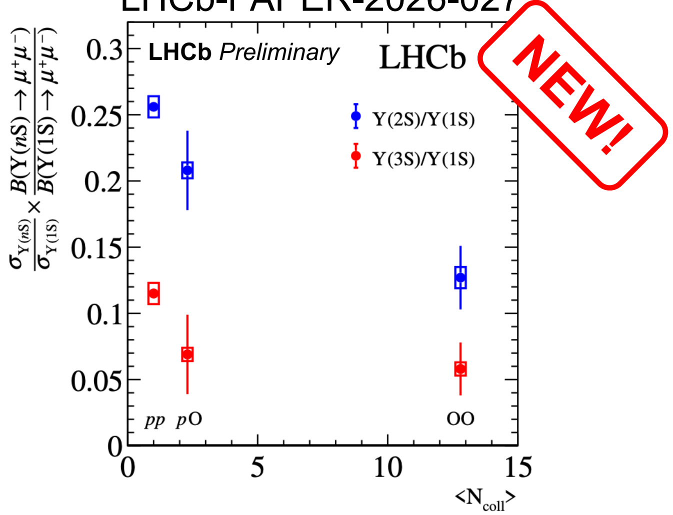

Backup