Charmonium production from small to large systems at LHCb

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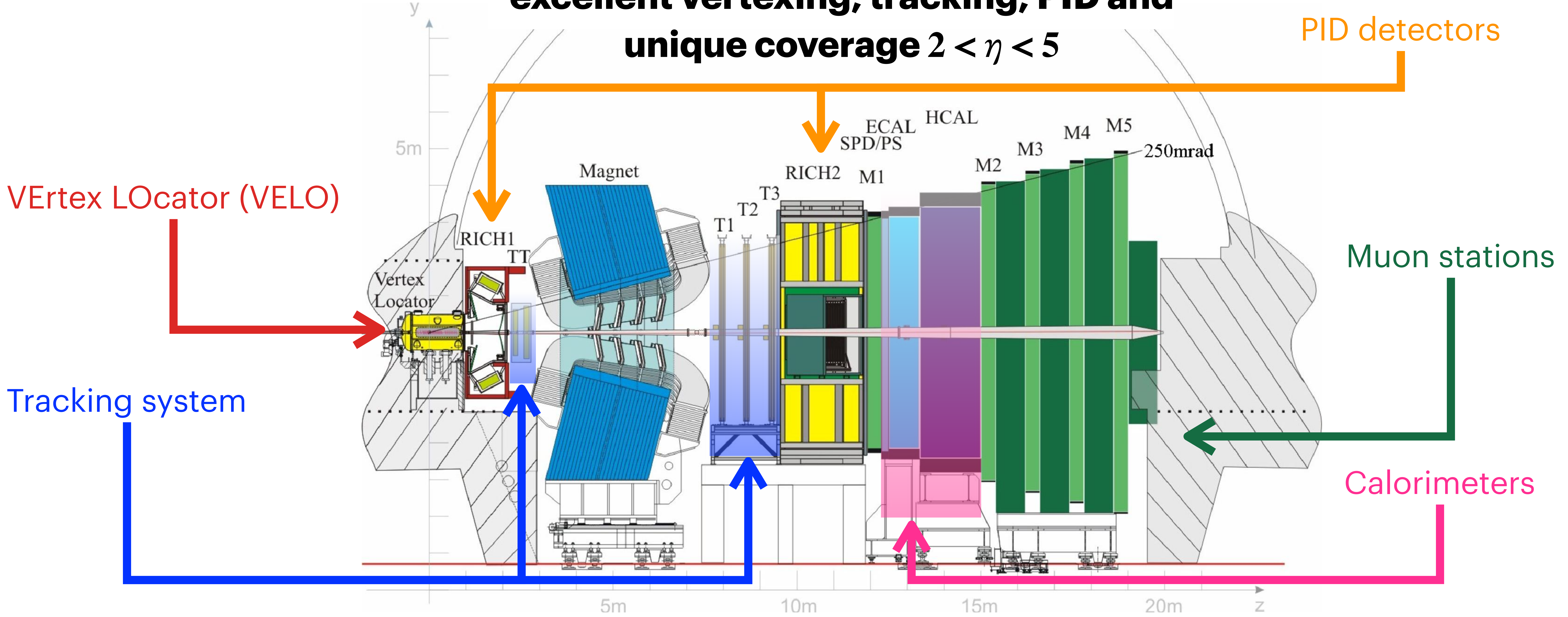
HEP2025 MARSEILLE
07 11 JULY

INTRODUCTION

The LHCb detector
➪ Overview - Run 2

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

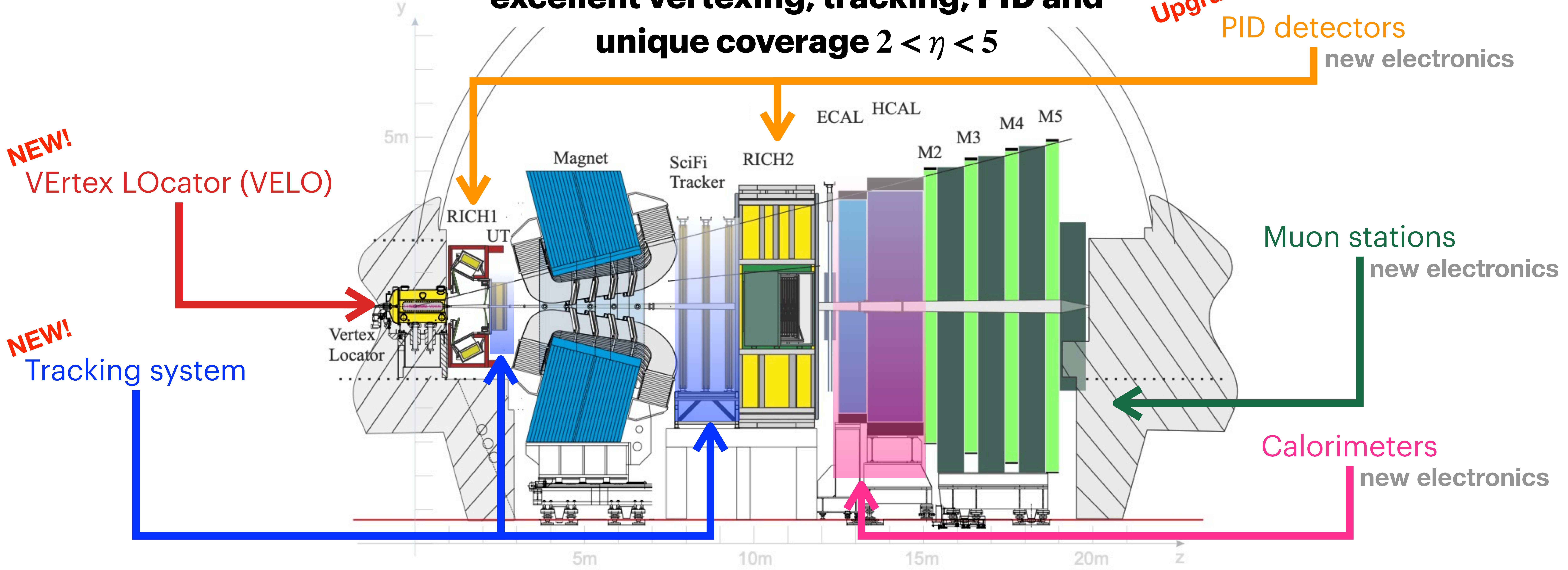
Single arm forward spectrometer with excellent vertexing, tracking, PID and unique coverage $2 < \eta < 5$



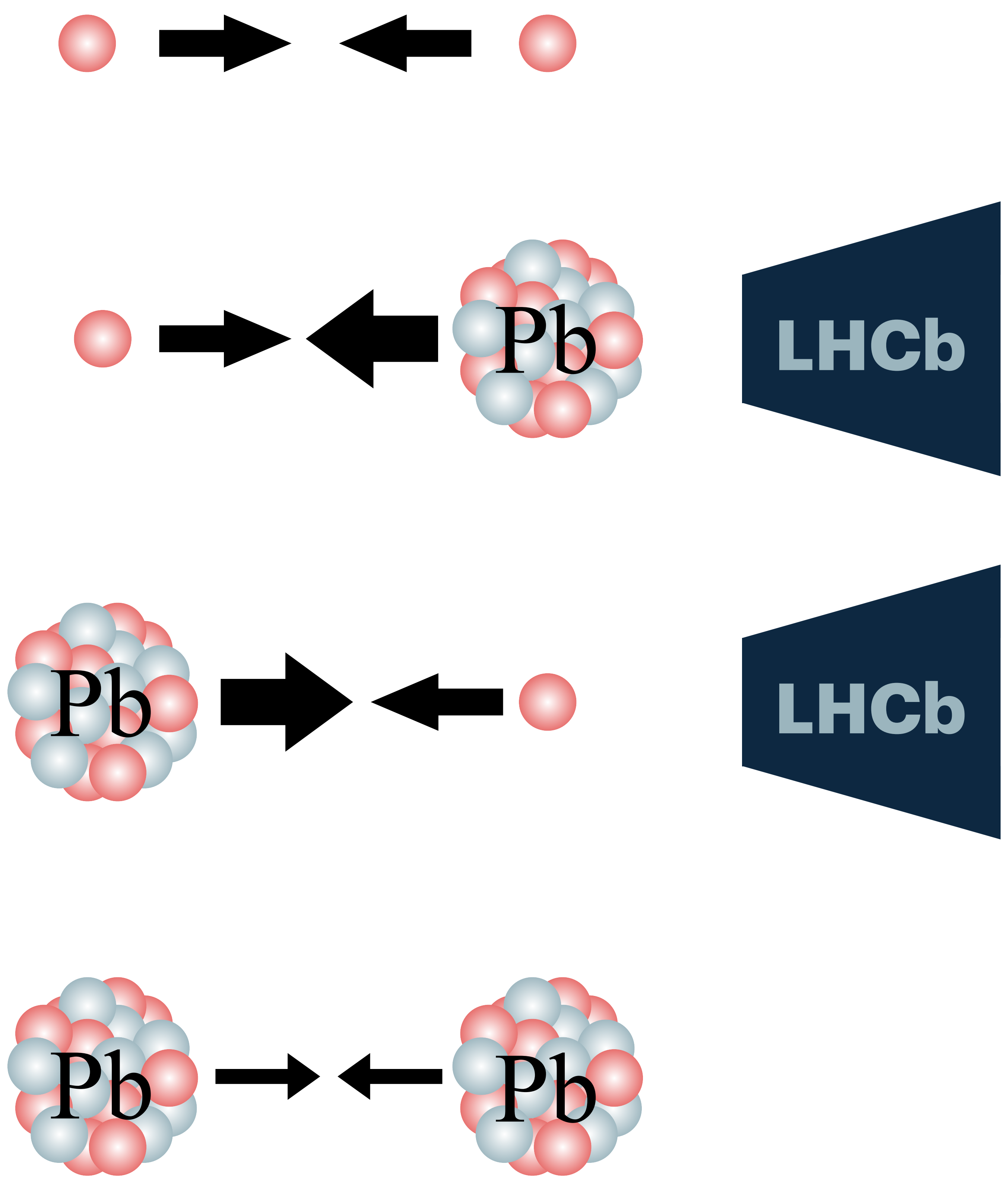
The LHCb detector
➩ Overview - Run 3

Single arm forward spectrometer with excellent vertexing, tracking, PID and unique coverage $2 < \eta < 5$

[JINST 19 P05065]



✴ **Beam colliding** systems:



pp

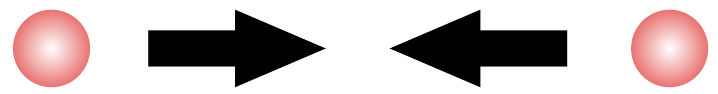
*p*Pb (forward)
$1.5 < y^* < 4.5$

Pb*p* (backward)
$-5.5 < y^* < -2.5$

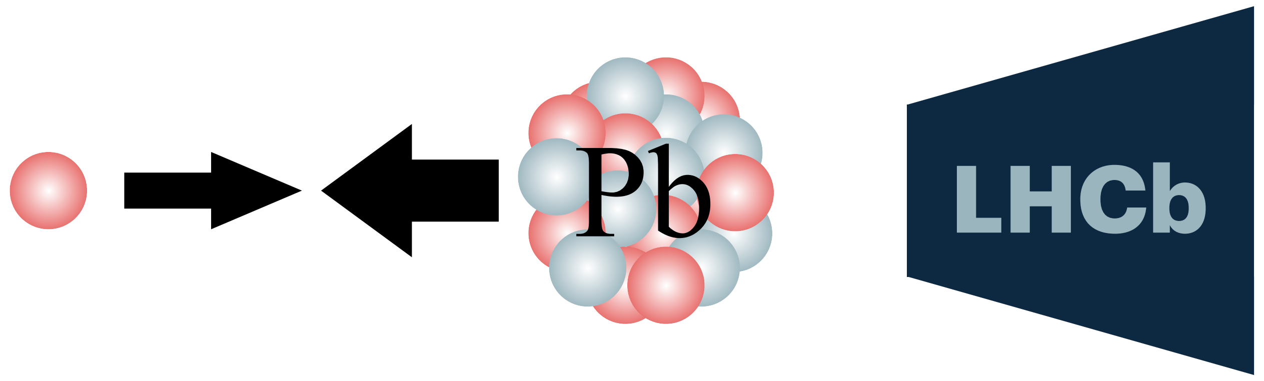
PbPb

Quarkonium production ⇨ QGP

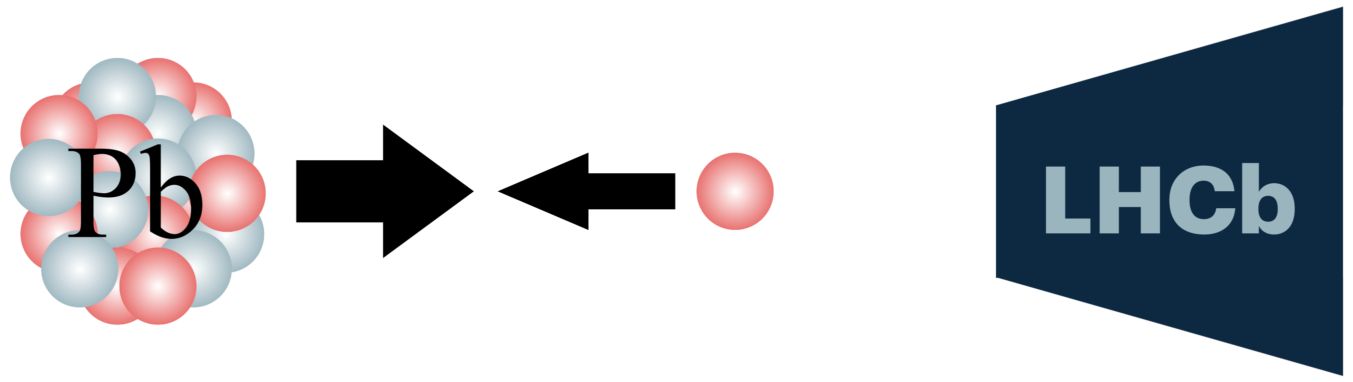
✴ **Beam colliding** systems:



pp



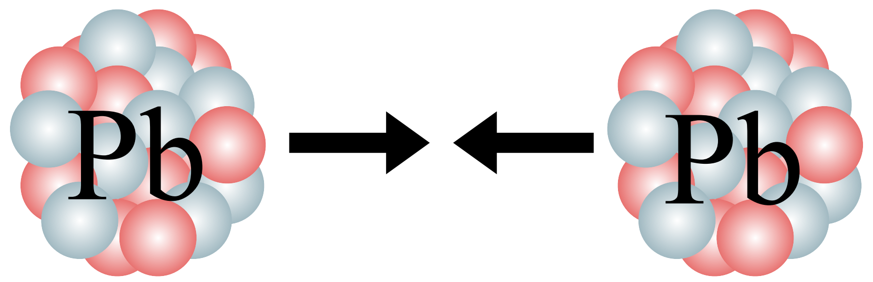
pPb (forward)
$1.5 < y^* < 4.5$



Pbp (backward)
$-5.5 < y^* < -2.5$

State of matter at high temperatures and densities where quarks and gluons are no longer confined but exist as in a deconfined 'liquid-like' configuration
(jet quenching, strangeness enhancement, collective flow phenomena, **quarkonium suppression**)

Bound heavy quark pairs: $c\bar{c}$ charmonium and $b\bar{b}$ bottomonium

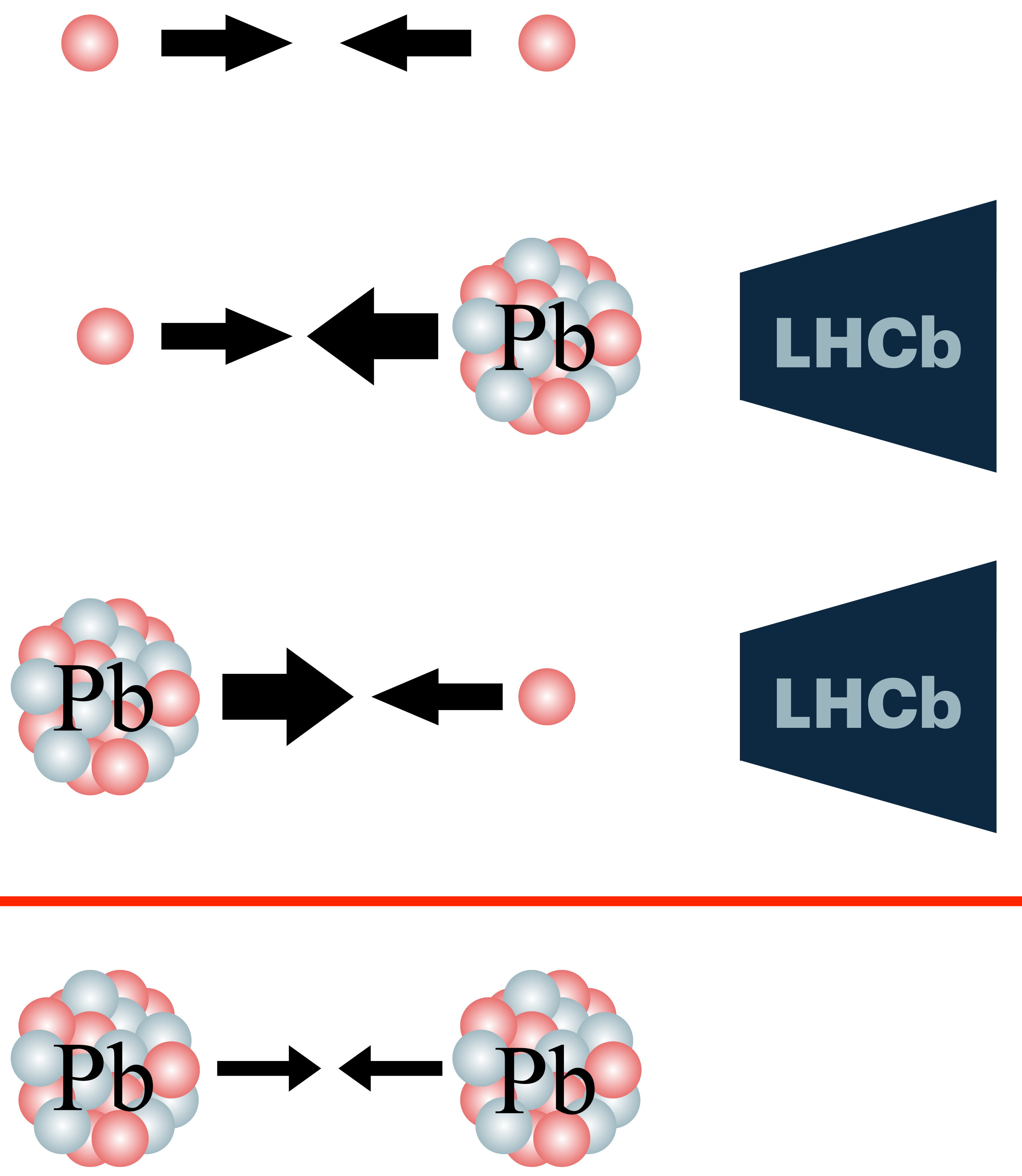


PbPb

QUARK-GLUON PLASMA (QGP)

Quarkonium production
⇨ QGP - Quarkonium production

✴ **Beam colliding** systems:



pp

*p*Pb (forward)
$1.5 < y^* < 4.5$

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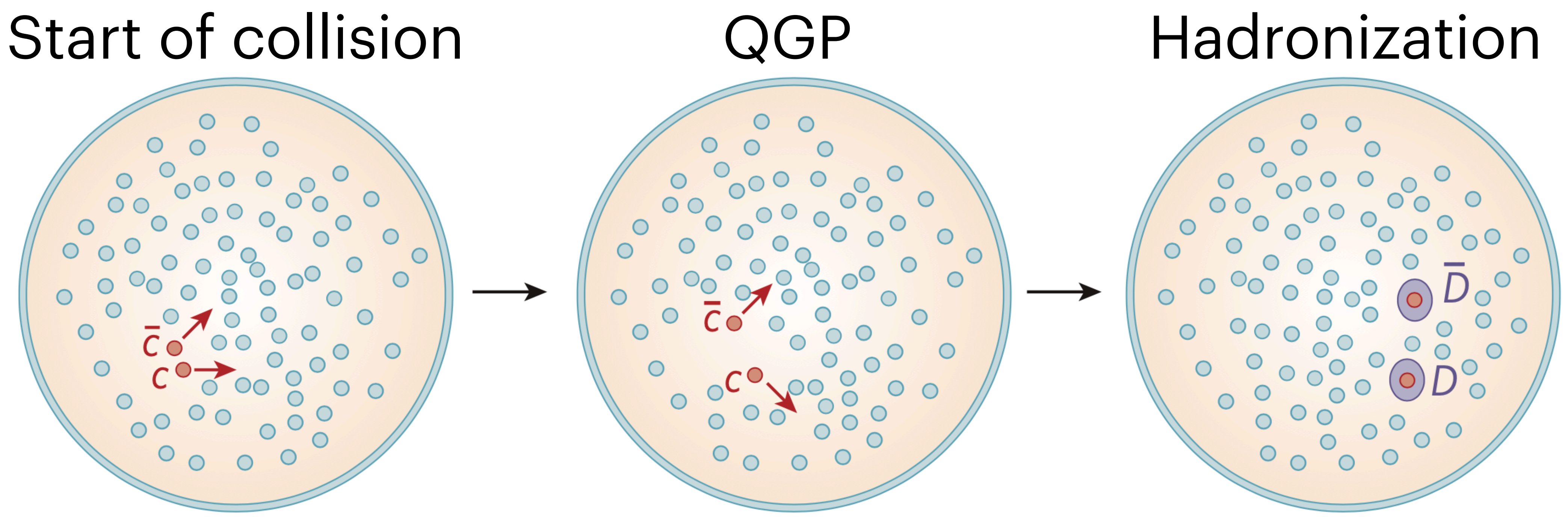
PbPb

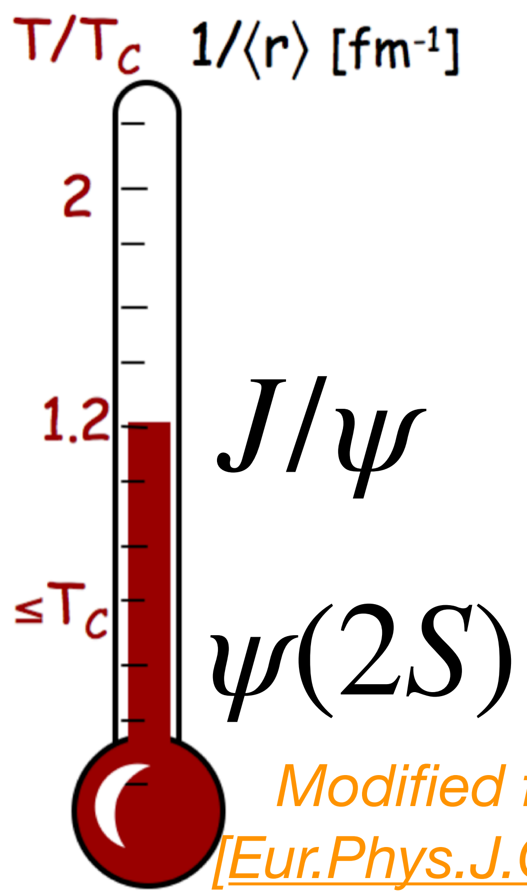
QGP

COLOUR SCREENING
Quarkonium production suppression



[Nature 448 (2007) 302]

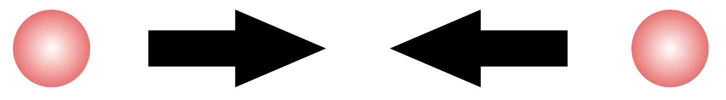
- Colour screening in QGP prevents binding of $c\bar{c}$ pair
- The amount of suppression is related to the properties of the QGP, such as its temperature



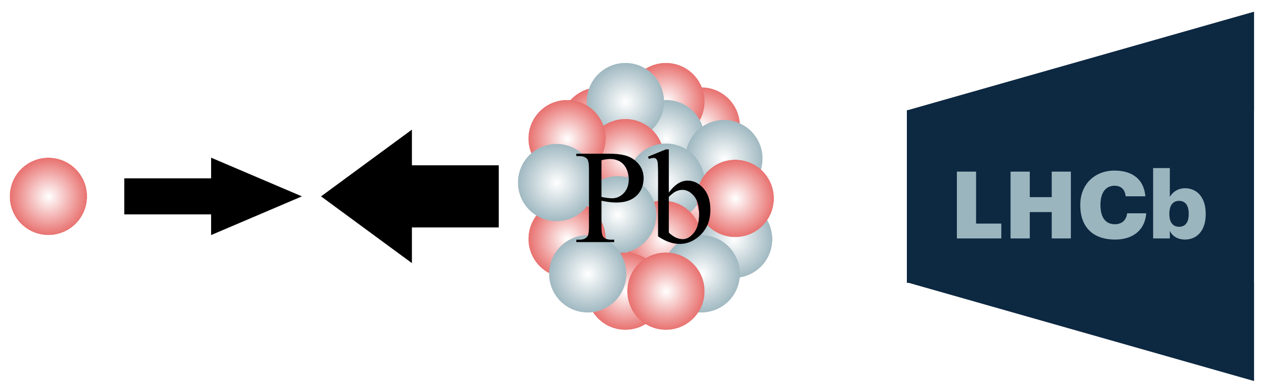
Modified from [Eur.Phys.J.C61: 705-710,2009]

Quarkonium production
➪ QGP - Quarkonium production

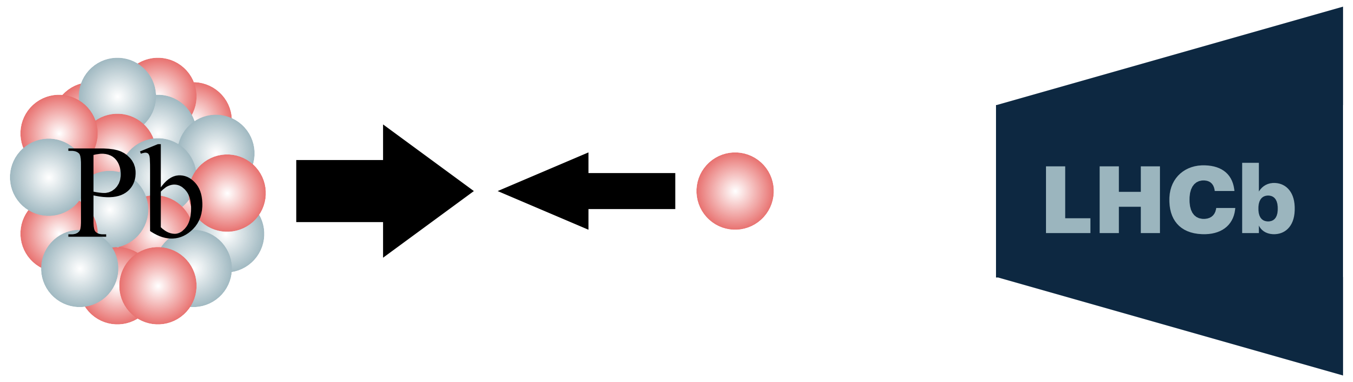
✴ **Beam colliding** systems:



pp



pPb (forward)
$1.5 < y^* < 4.5$



Pbp (backward)
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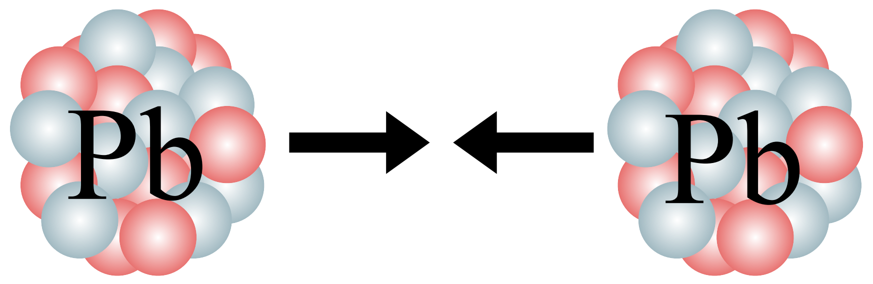
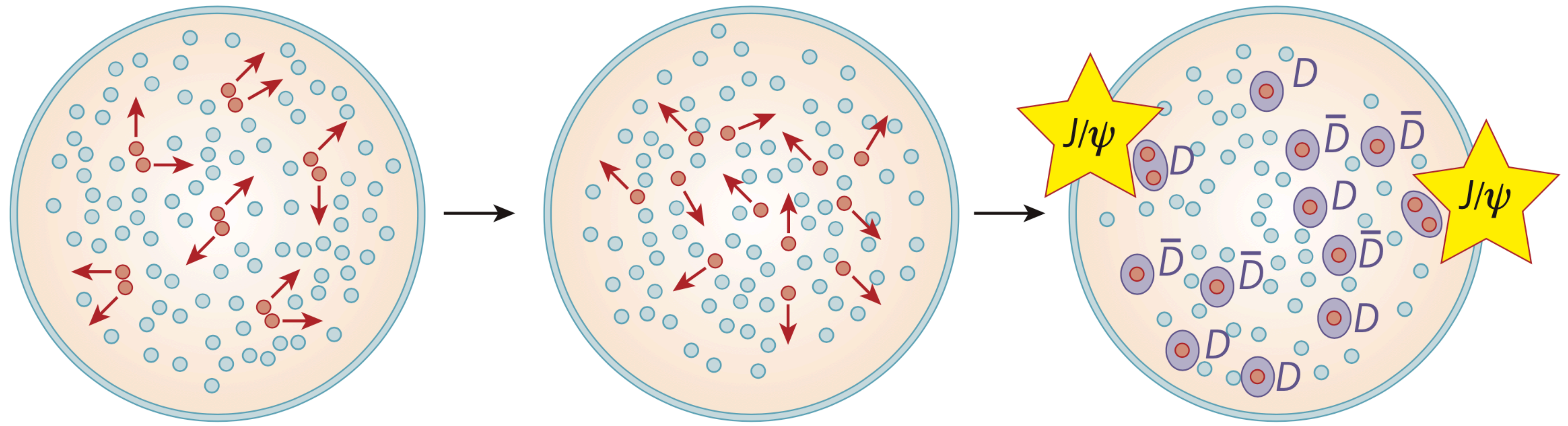


PbPb

QGP

RECOMBINATION

Quarkonium production enhancement

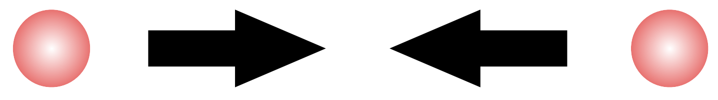


[Nature 448 (2007) 302]

- At sufficiently high $\sqrt{s_{NN}}$, c and $\bar{c}$ are abundantly produced (>100 pairs at LHC)
- These c and $\bar{c}$ quarks in the QGP can be recombined to form quarkonium states

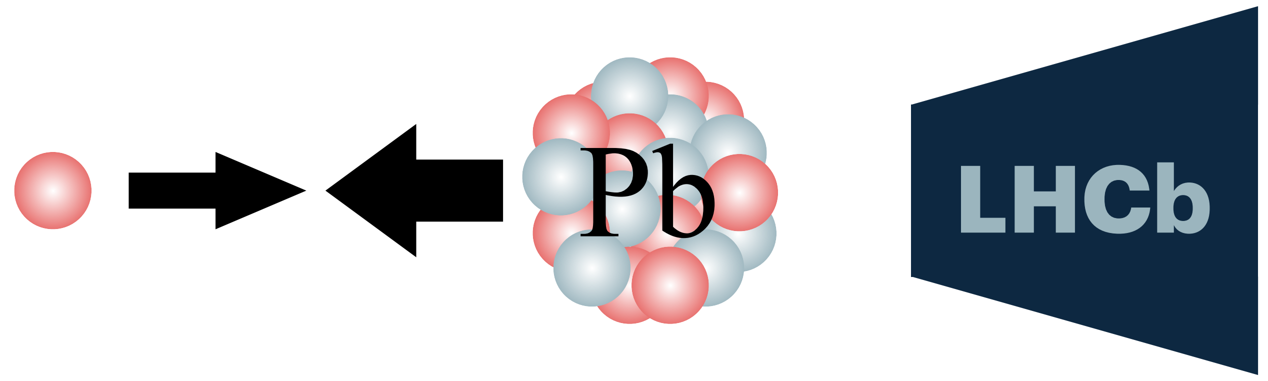
Quarkonium production ➯ CNM effects

✴ **Beam colliding** systems:



pp

Modifications to particle production and propagation in a nucleus due to the nucleus' presence, independent of QGP formation



pPb (forward)
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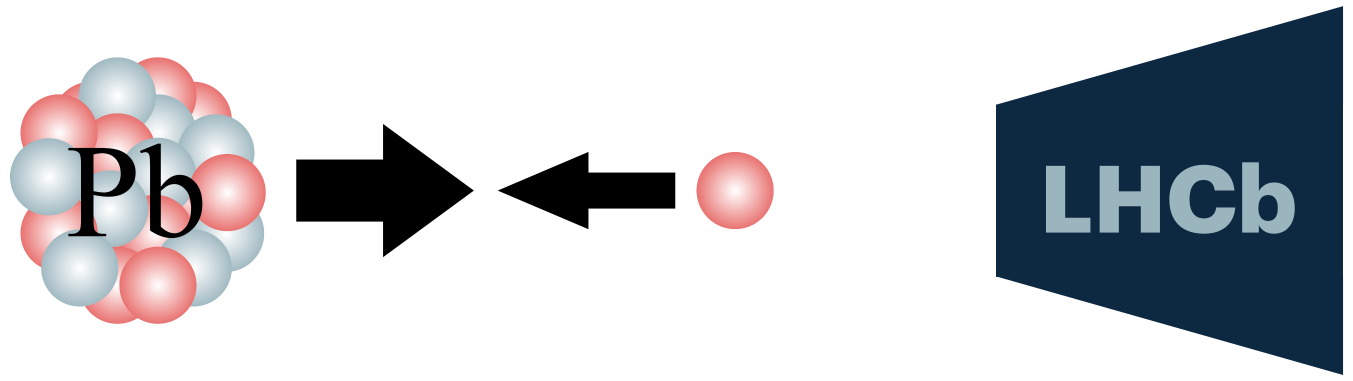
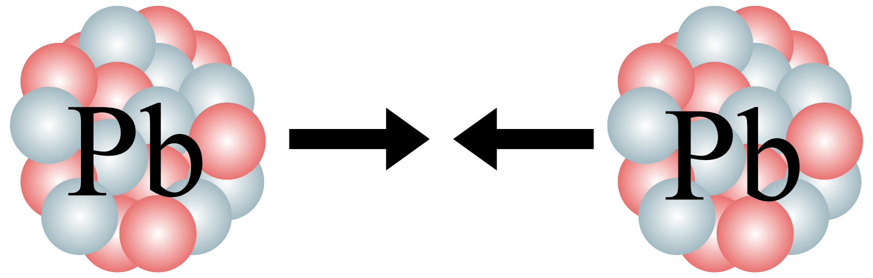


Pbp (backward)
$-5.5 < y^* < -2.5$

COLD NUCLEAR MATTER (CNM)

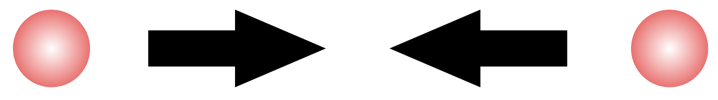


PbPb

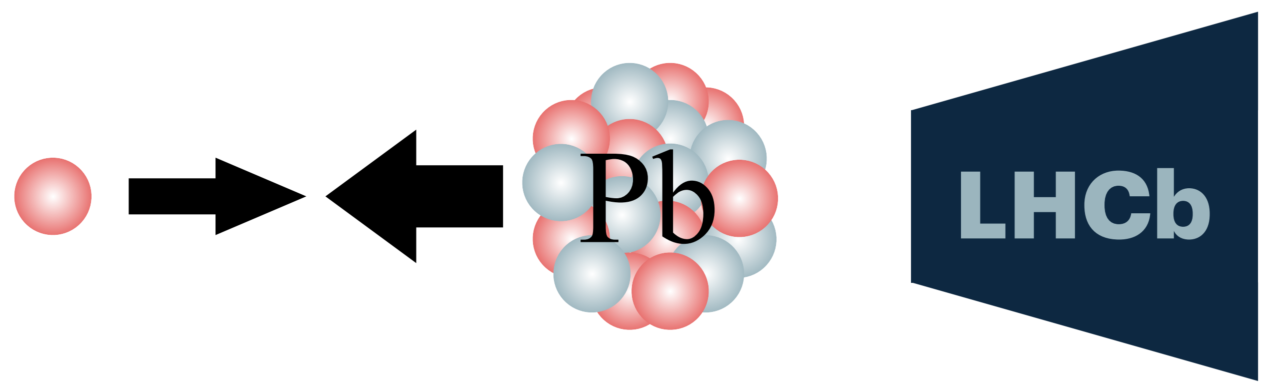
Reference point for understanding how the QGP affects particle production
(nuclear shadowing, parton energy loss, Cronin effect)

Quarkonium production
➾ Small-systems

✳ **Beam colliding** systems:



pp **BASELINE**



pPb (forward)
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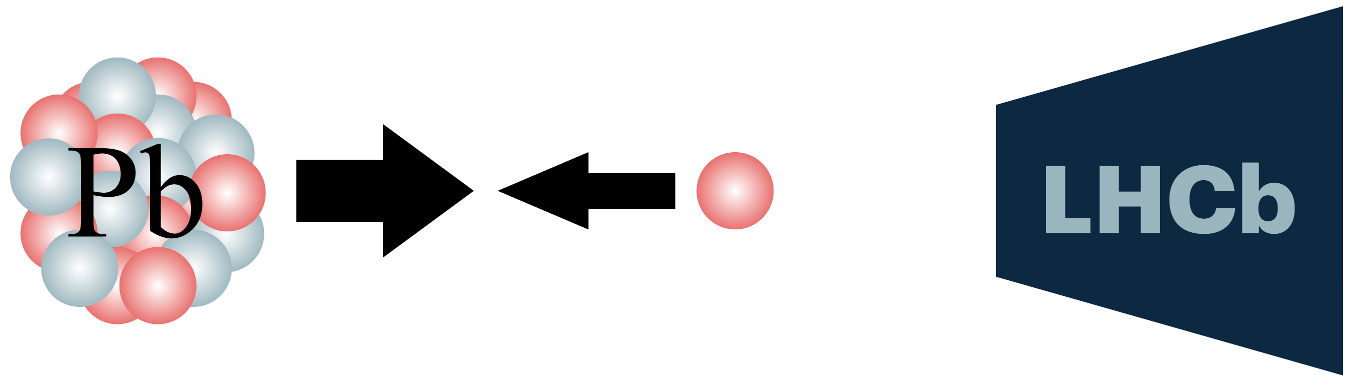

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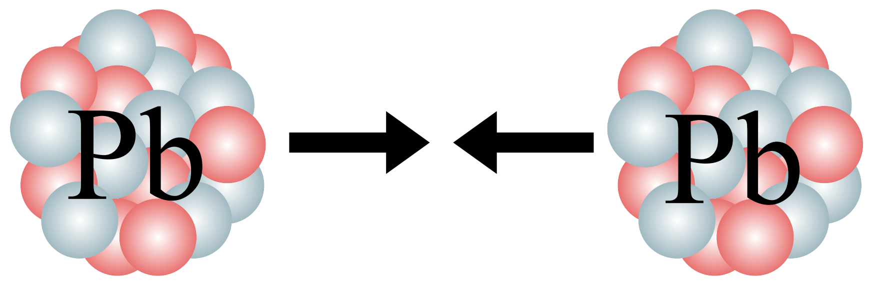
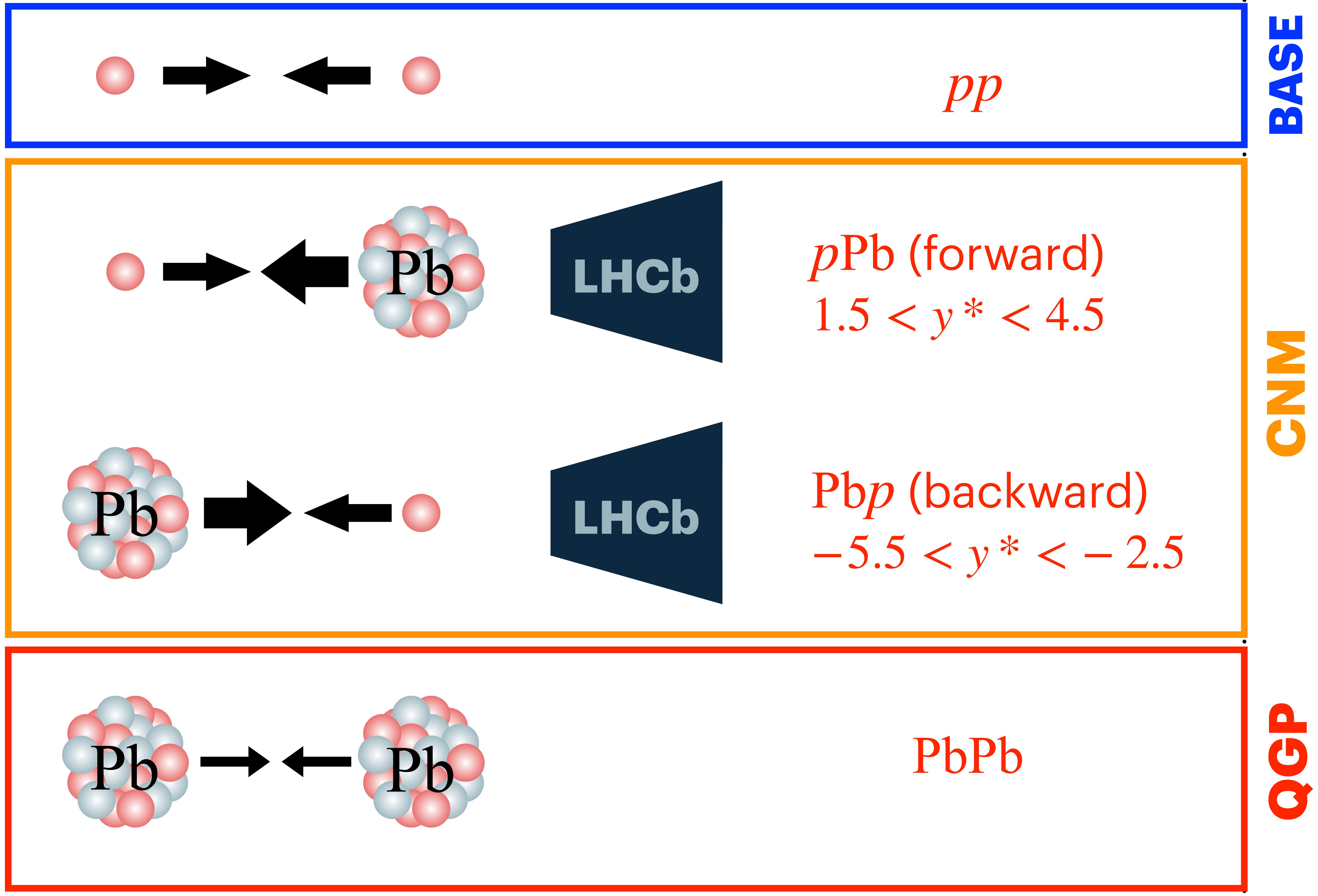


PbPb

Quarkonium production
➡ From small to large systems

✳ **Beam colliding** systems:



QGP-like signatures have been observed in small collision systems at high multiplicity!

[Phys. Lett. B 765 (2017) 193] *CMS 2017, pp, Collective flow*

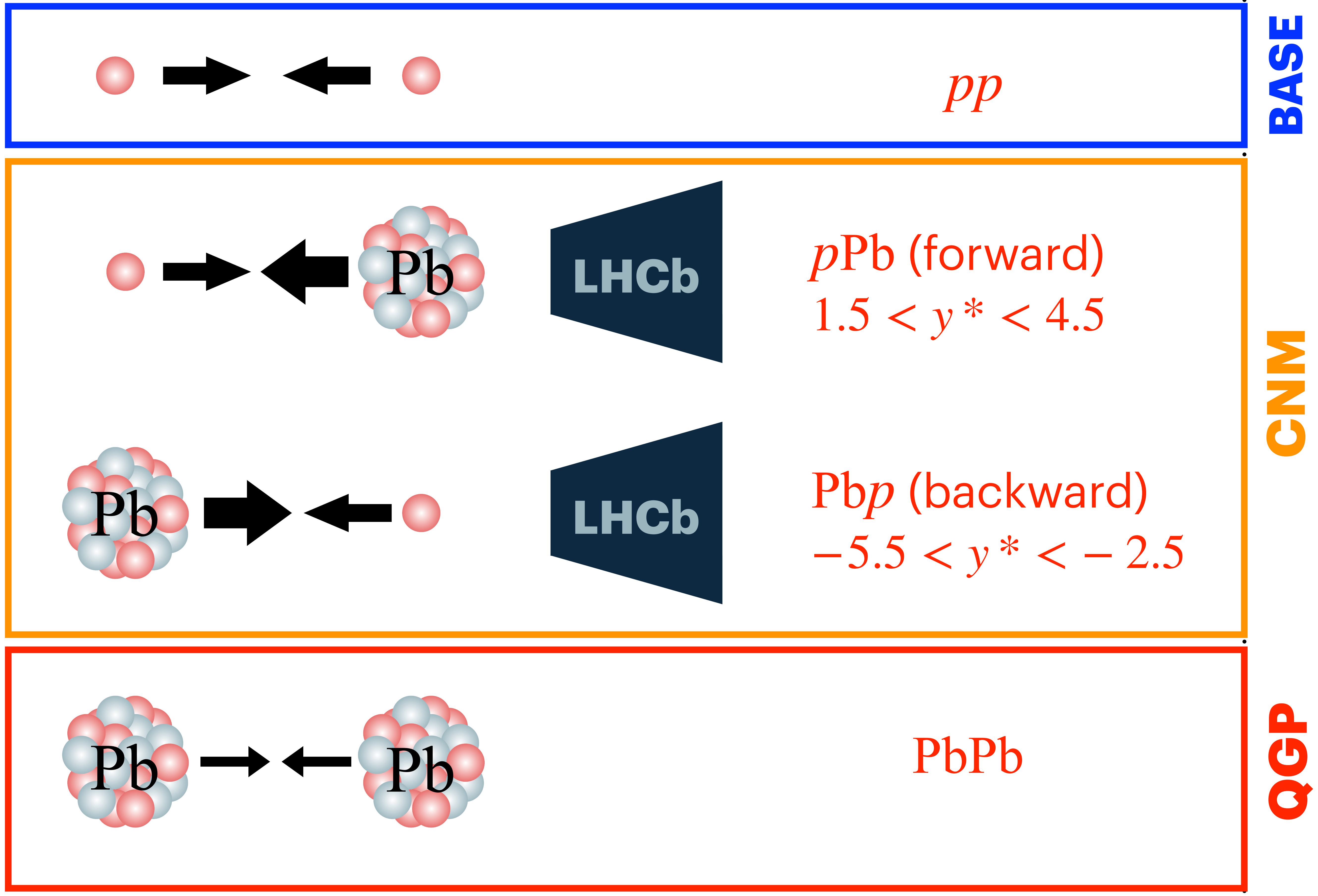
[Nature Phys 13, 535–539 (2017)] *ALICE 2017, pp, Strangeness enhancement*

What about quarkonium suppression?

This motivates the study of quarkonium production as a function of multiplicity / centrality from small - medium - large systems

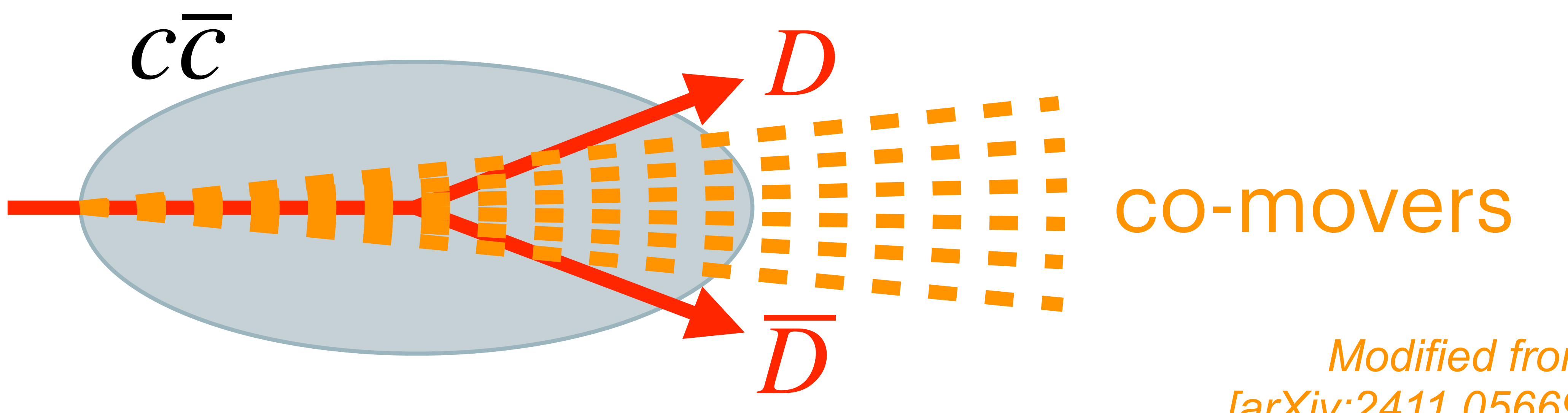
Quarkonium production
⇨ The co-mover model

✴ **Beam colliding** systems:



Co-mover interaction model

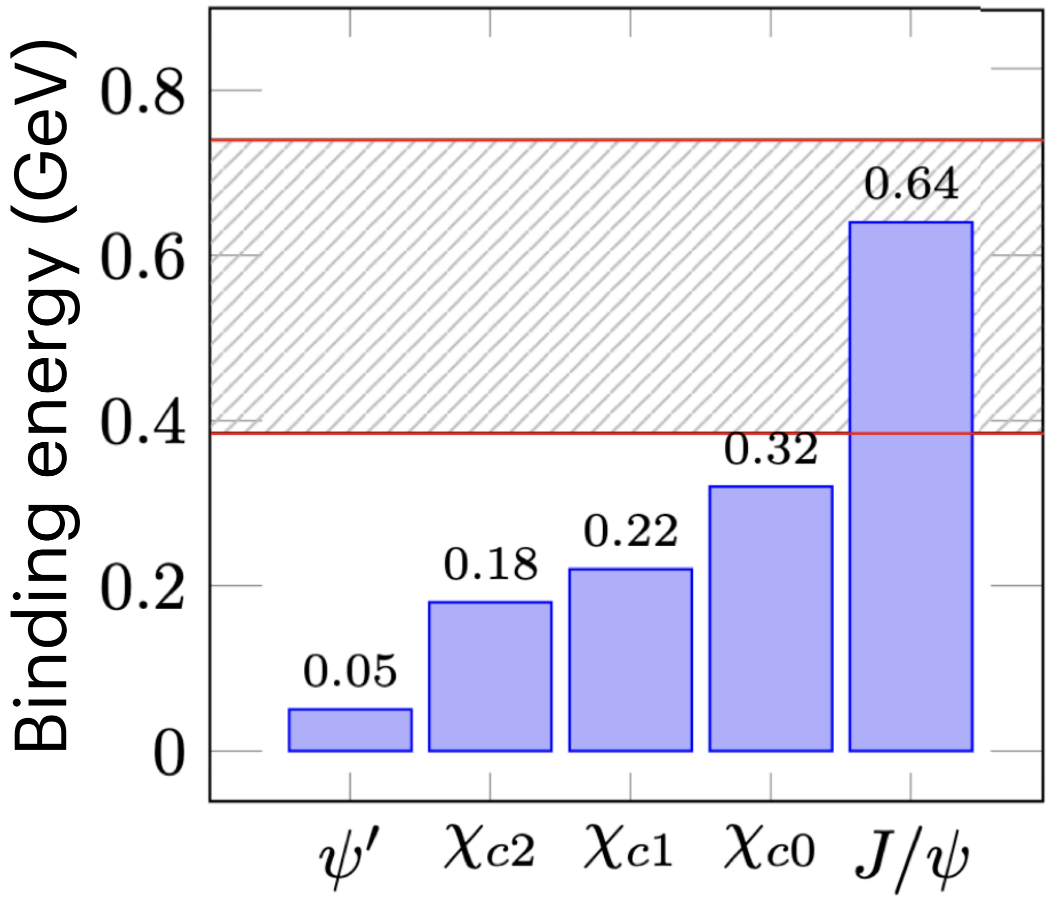
Quarkonium suppression is caused by final-state interactions with soft particles (co-movers) produced in the same collision



Modified from [arXiv:2411.05669]

The $\psi(2S)$ is more suppressed than the J/ψ due to its larger size

The suppression increases with the density of the medium



Quarkonium production
⇨ Observable in pp and pPb

More details in the backup

* $\psi(2S)$-to-J/ψ **cross-section ratio** → $$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{tot,J/\psi}}{\varepsilon_{tot,\psi(2S)}} \times \frac{\mathcal{B}_{J/\psi}}{\mathcal{B}_{\psi(2S)}}$$

Yields — Efficiencies

* As a function of multiplicity → $N^{PV}_{tracks} \equiv$ number of VELO tracks used to reconstruct the PV

Primary Vertex

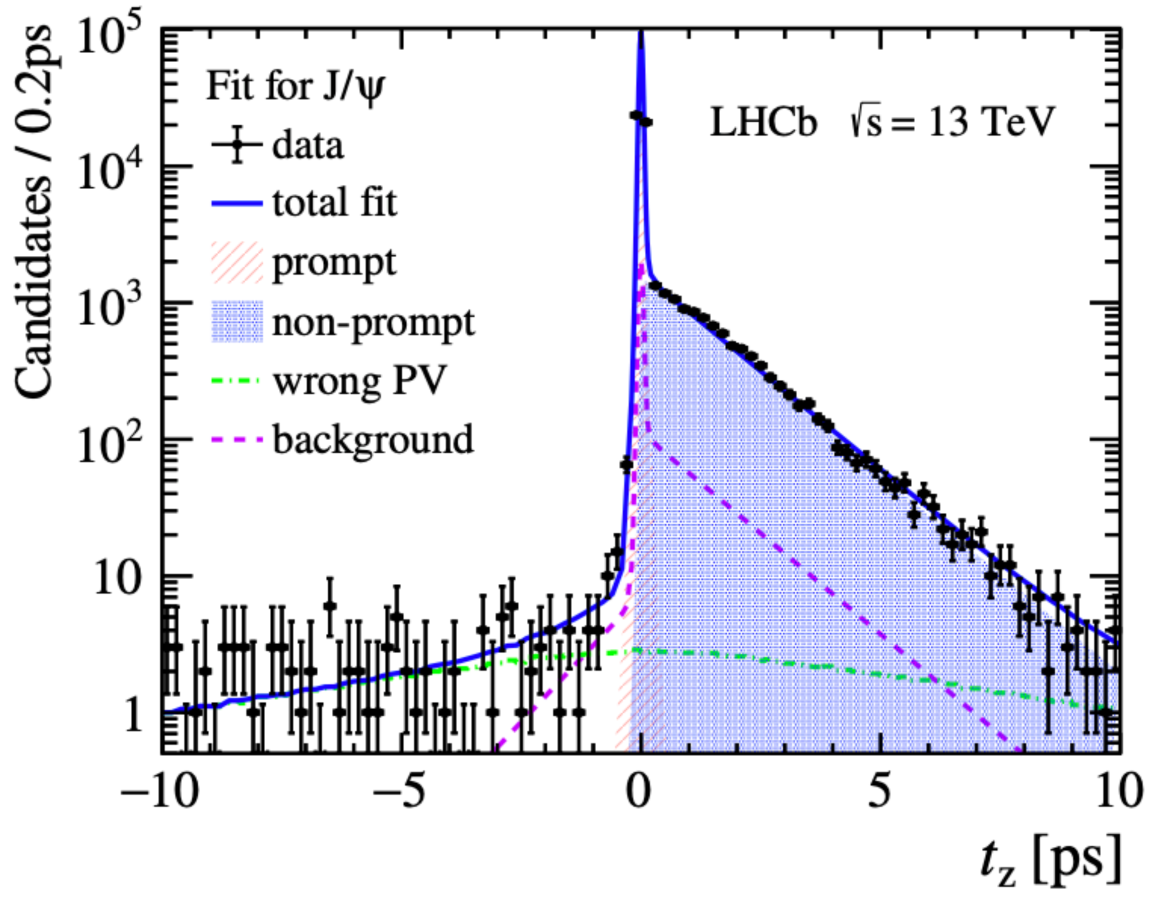
Quarkonium production
➩ Observable in pp and pPb

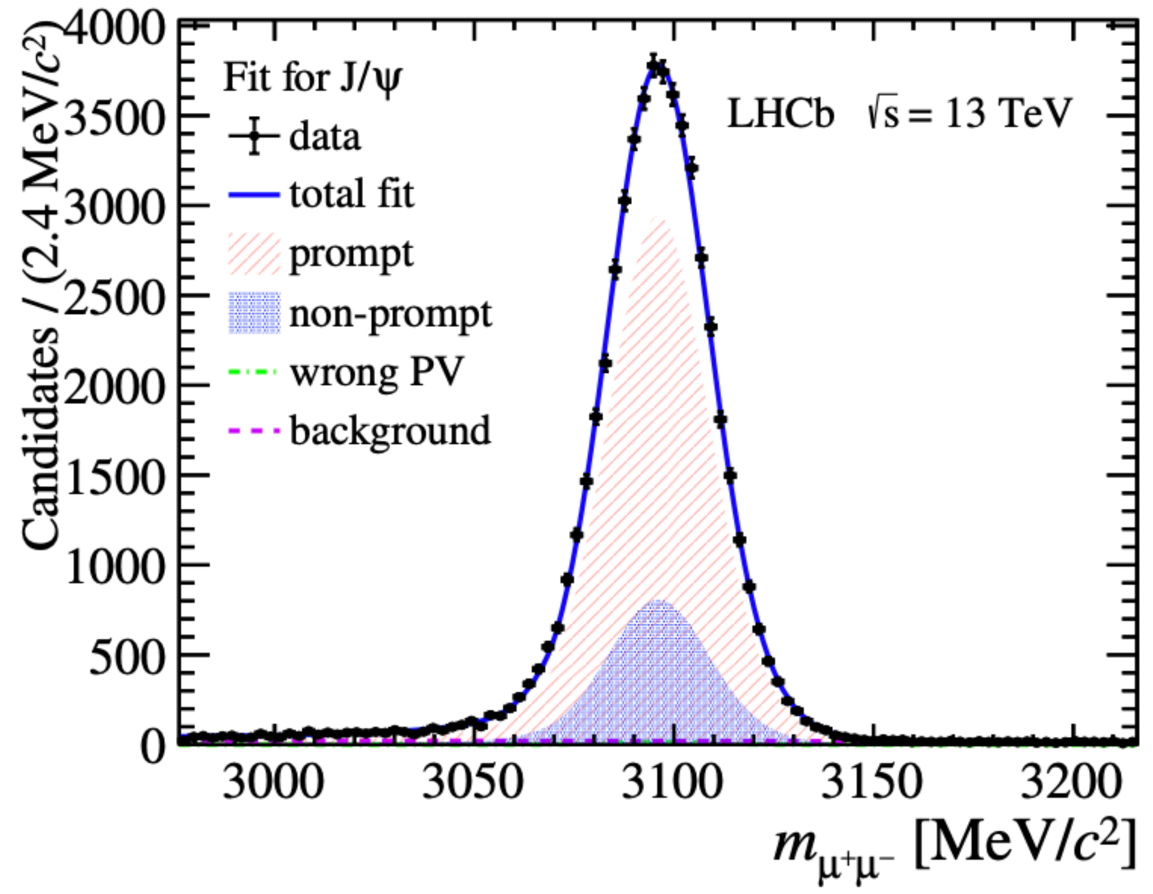
More details in the backup

✴ $\psi(2S)$-to-J/ψ **cross-section ratio** ⟶

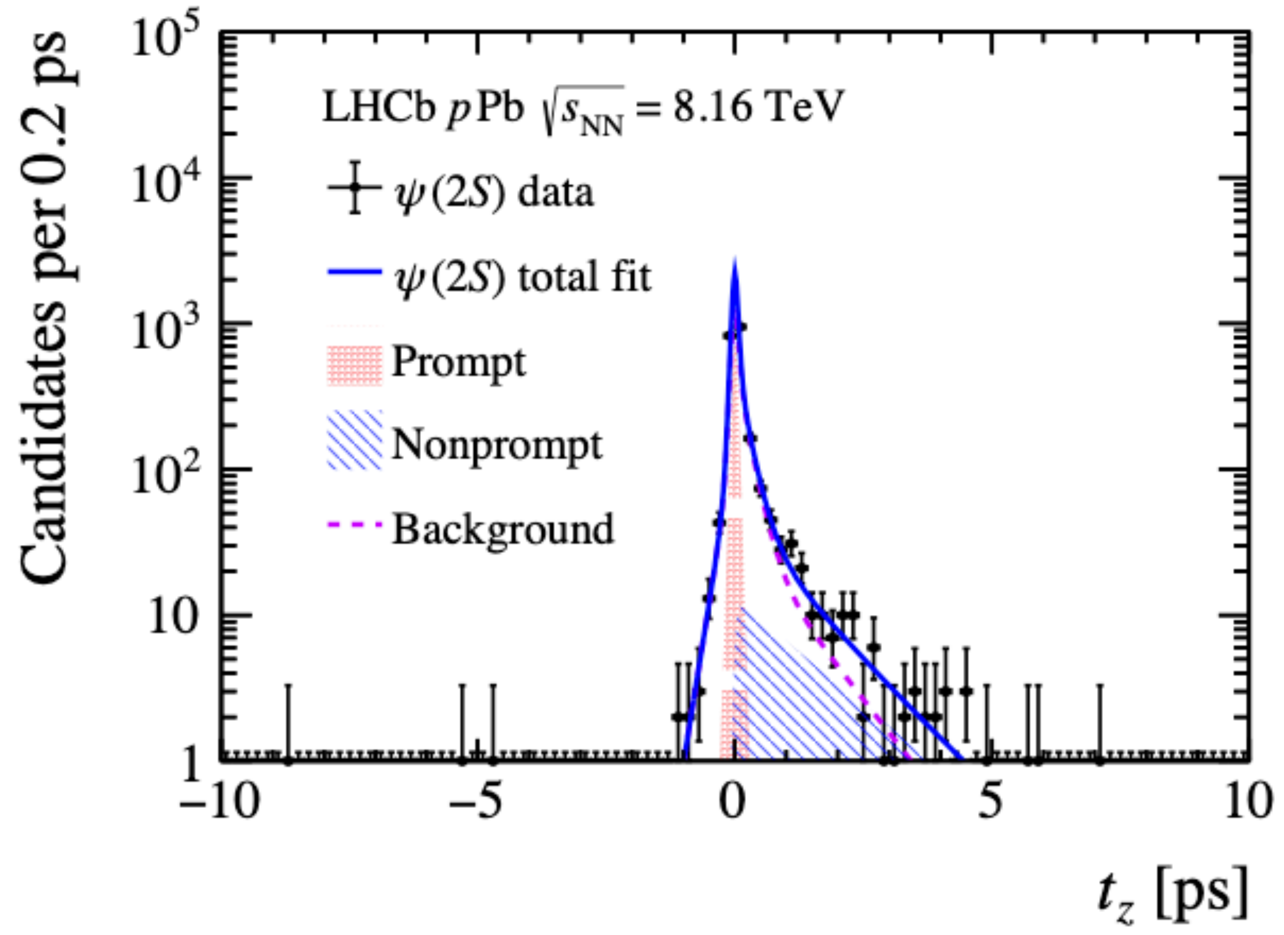
$$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = \underbrace{\frac{N_{\psi(2S)}}{N_{J/\psi}}}_{\text{Yields}} \times \underbrace{\frac{\varepsilon_{tot,J/\psi}}{\varepsilon_{tot,\psi(2S)}}}_{\text{Efficiencies}} \times \frac{\mathscr{B}_{J/\psi}}{\mathscr{B}_{\psi(2S)}}$$

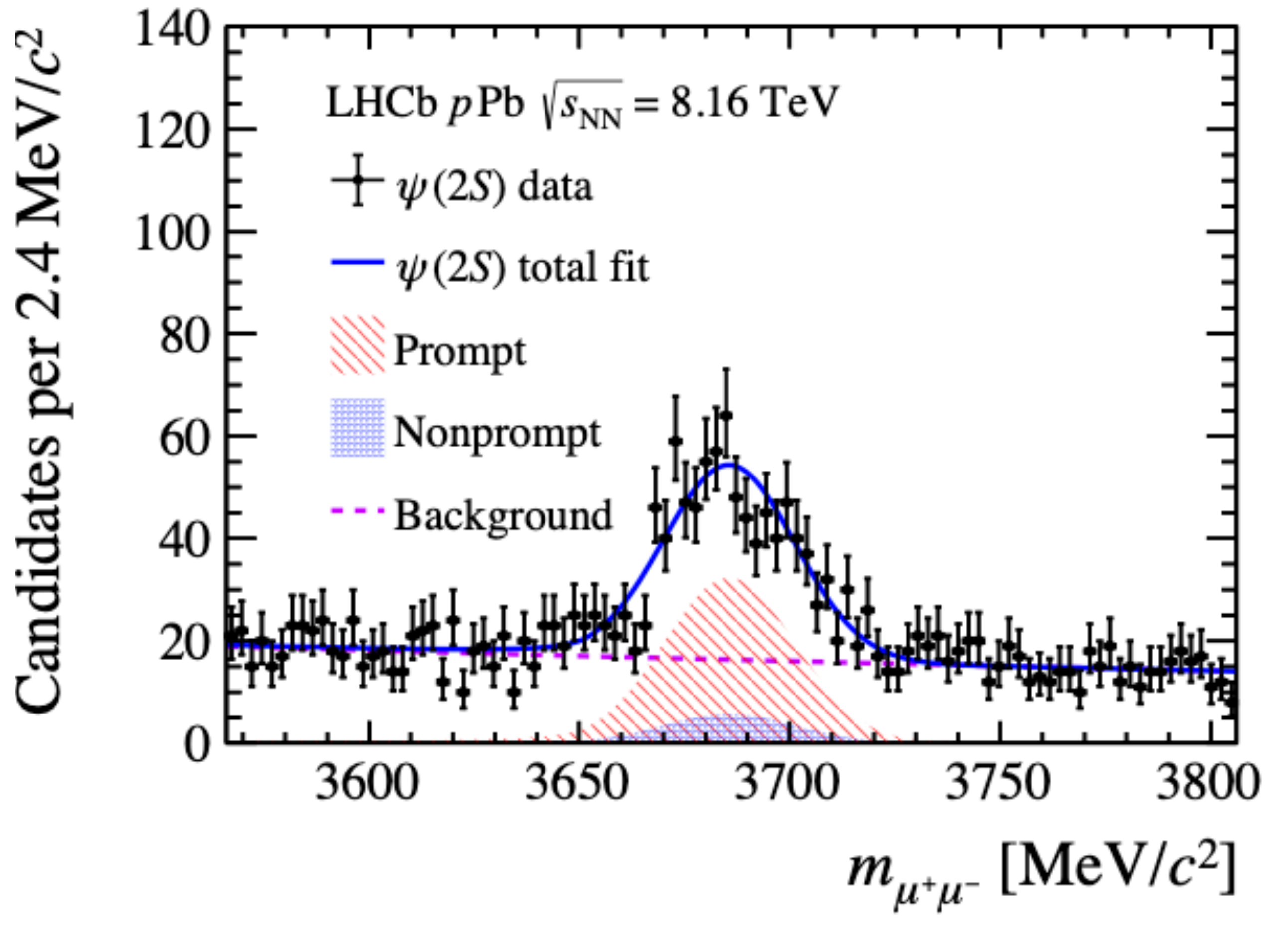
J/ψ fit example from pp [JHEP05(2024)243]





$\psi(2S)$ fit example from pPb [arXiv:2506.08624]





✴ As a function of multiplicity ⟶ N^{PV}_{tracks} ≡ number of VELO tracks used to reconstruct the PV

Primary Vertex

Quarkonium production
⇨ Observable in pp and pPb

More details in the backup

✴ $\psi(2S)$-to-J/ψ **cross-section ratio** → $$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{tot,J/\psi}}{\varepsilon_{tot,\psi(2S)}} \times \frac{\mathcal{B}_{J/\psi}}{\mathcal{B}_{\psi(2S)}}$$

Yields Efficiencies

↳ Normalised ratio for multiplicity bin n → Normalised $$\frac{\sigma_{\psi(2S),n}}{\sigma_{J/\psi,n}} = \frac{\sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n}/\sum_n \sigma_{J/\psi,n}}$$

Ratio of integrated cross section

✴ As a function of multiplicity → N^{PV}_{tracks} ≡ number of VELO tracks used to reconstruct the PV

Primary Vertex

↳ Non-dimensional multiplicity → $N^{PV}_{tracks} / < N^{PV}_{tracks} >_{NB}$

Un-biased reference

Quarkonium production
➯ Observable in PbPb

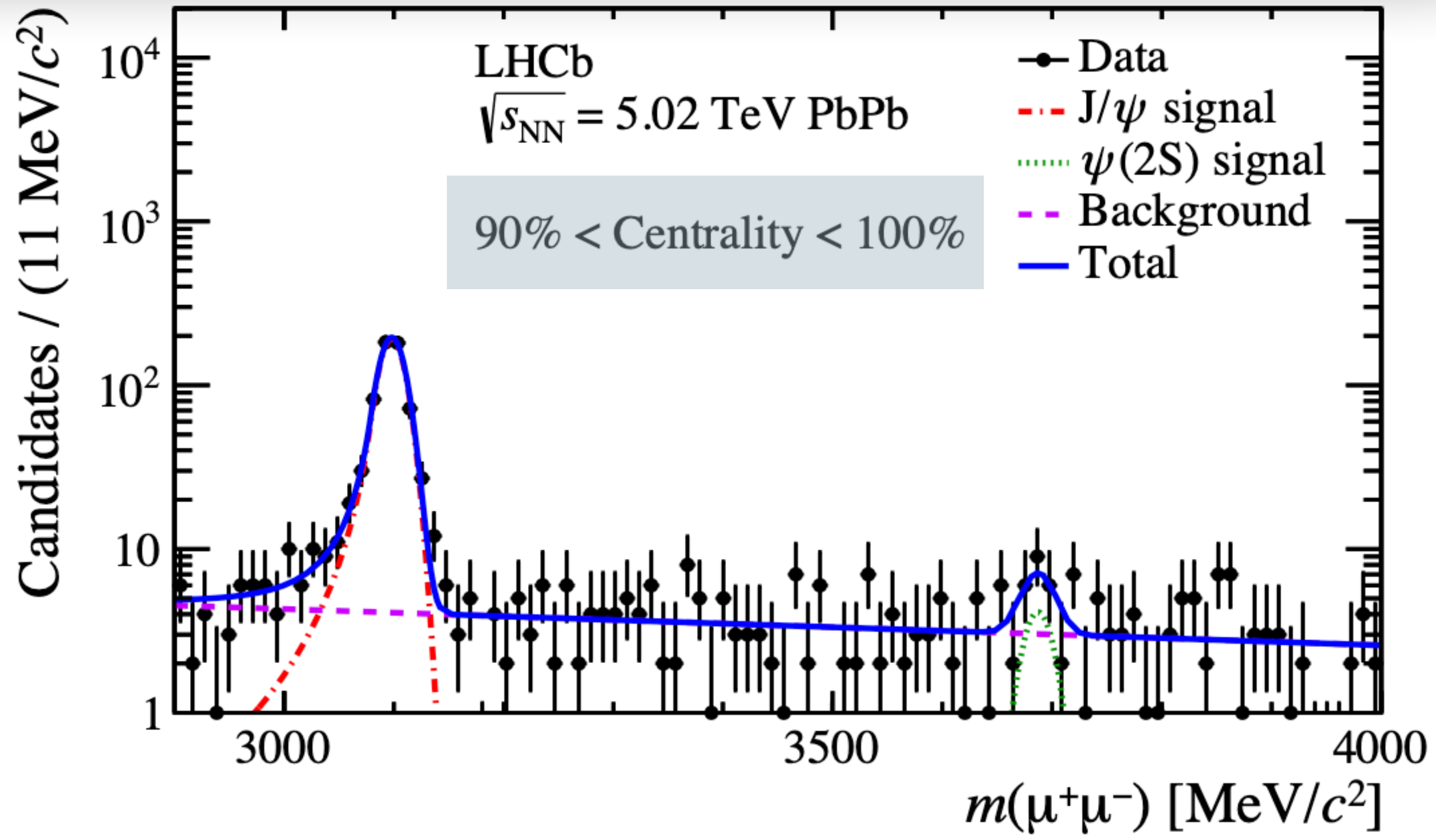
More details in the backup

- ✶ $\psi(2S)$-to-J/ψ **cross-section ratio**

To compare across different collision systems

$$\frac{\mathcal{B}_{J/\psi}}{\mathcal{B}_{\psi(2S)}} \times \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{tot,J/\psi}}{\varepsilon_{tot,\psi(2S)}}$$

Yields Efficiencies

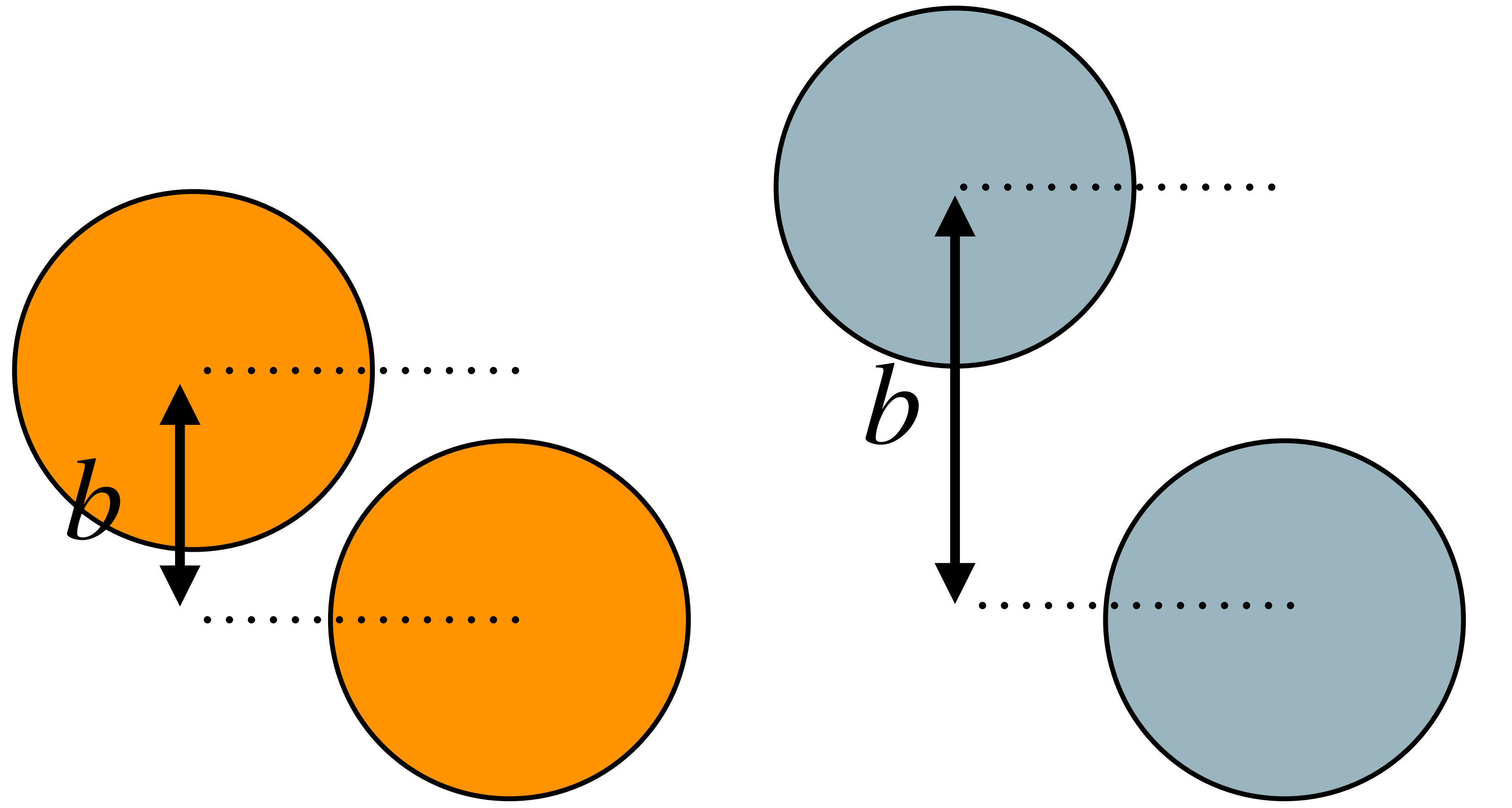


Fit at highest centrality from PbPb [arXiv:2411.05669]

- ✶ As a function of centrality

Percentile label that informs us how **central** or **peripheral** a heavy-ion collision is

  - Associated with the impact parameter, b, and with the mean number of participating nucleons, $< N_{part} >$
  - Obtained from Glauber Monte Carlo (GMC) model [arXiv:2111.01607]



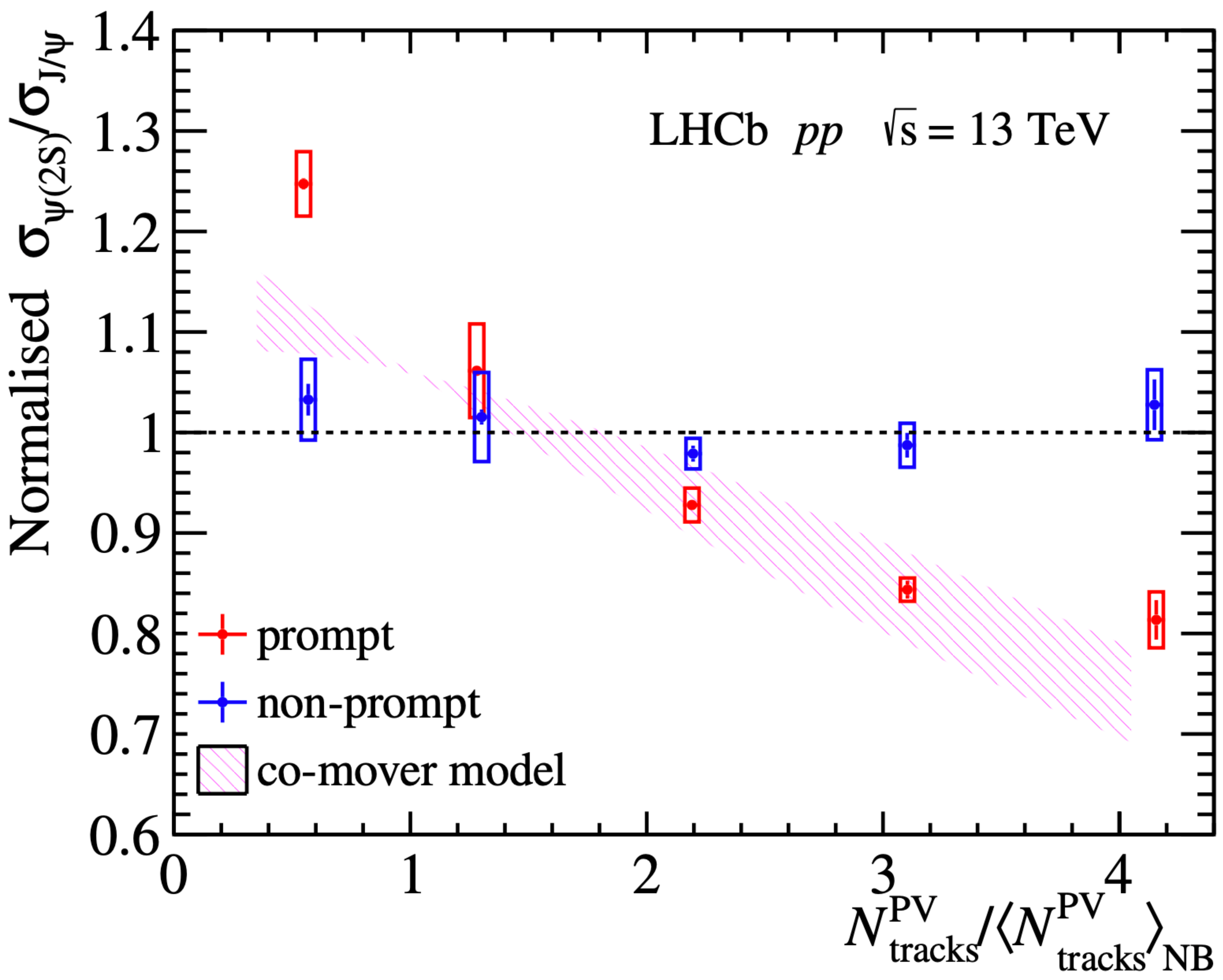
Low centrality *High centrality*

Centrality classes
100 - 90
90 - 80
80 - 70
70 - 60

PROTON - PROTON

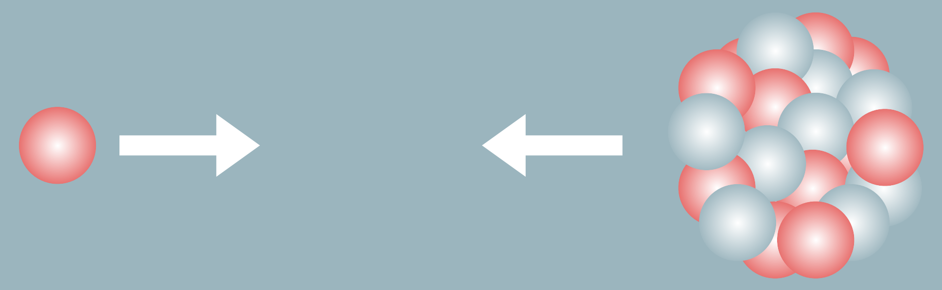
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in *pp* collisions at $\sqrt{s} = 13$ TeV

[JHEP05(2024)243]



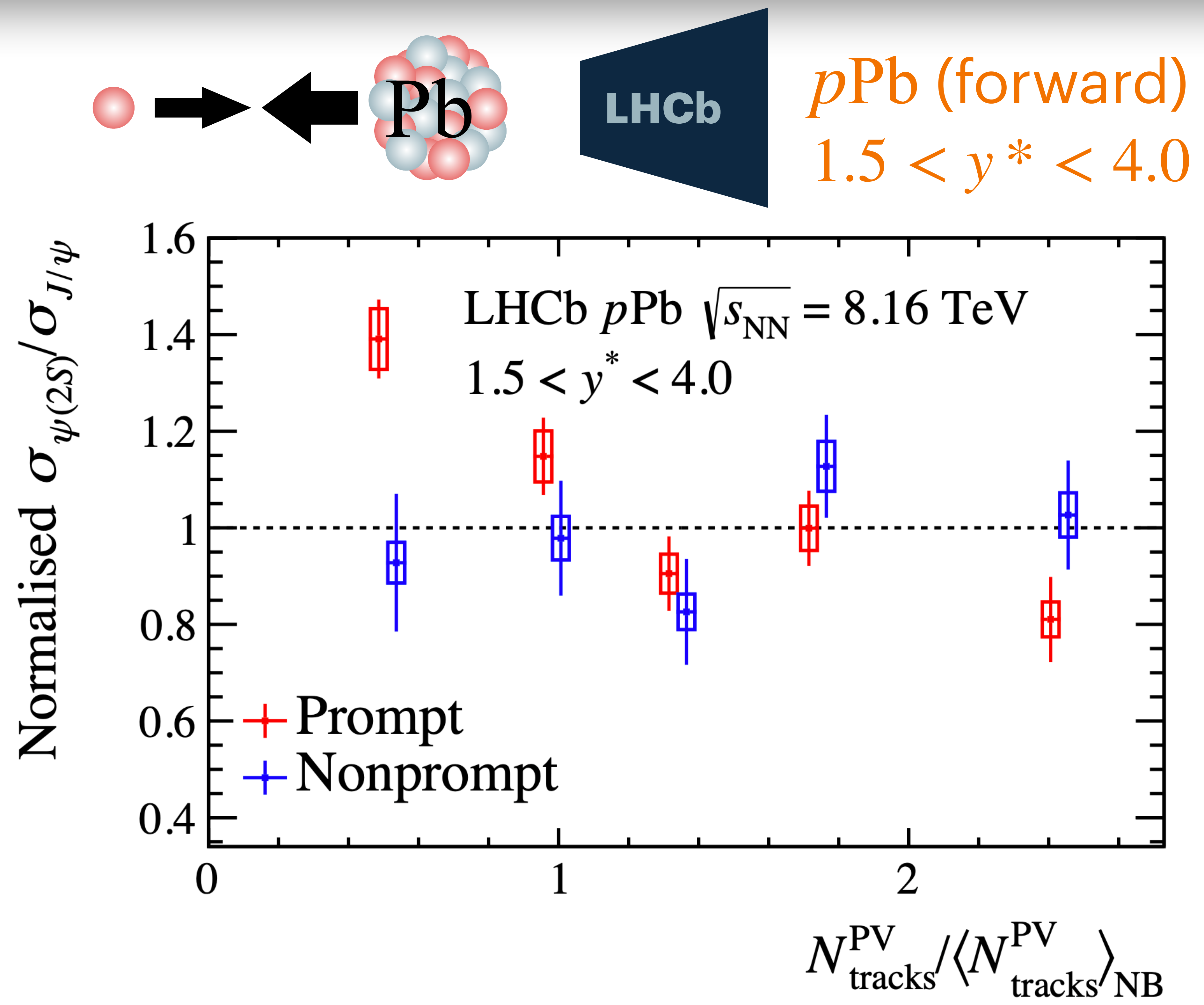
- ✳ Normalised ratio of $\psi(2S)$-to-J/ψ integrated over $2.0 < y < 4.5$ and $0.3 < p_T < 20$ GeV/c versus non-dimensional multiplicity
- ✓ Non-prompt (from $b-$hadrons) ratio:
  - No dependence on multiplicity
- ✓ Prompt (from the PV) ratio:
  - Evident decrease with multiplicity
  - Agreement with co-mover predictions except at low multiplicities
- ✳ Comparison with previous measurements shows compatibility between results (backup)

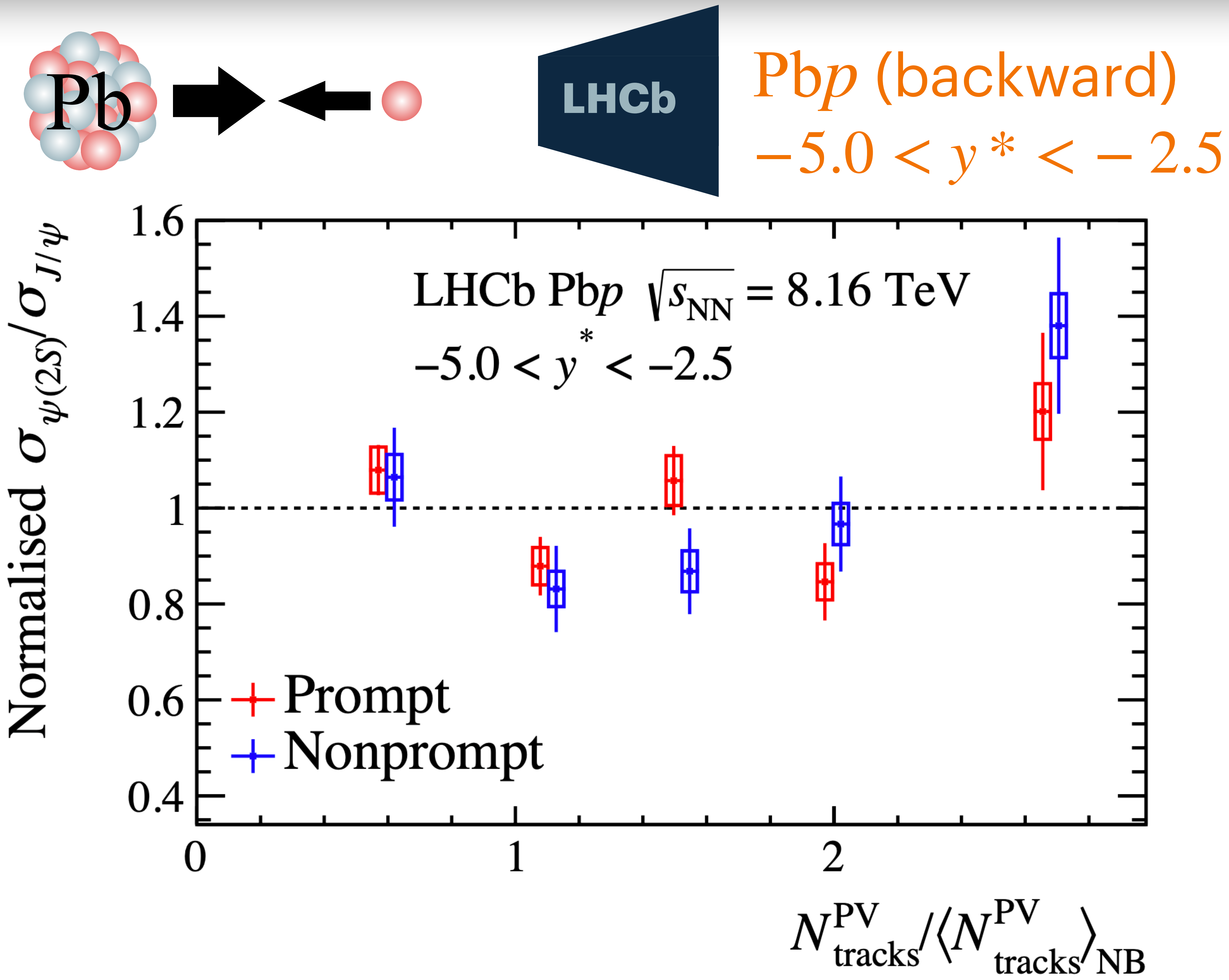
PROTON - LEAD



$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in pPb collisions at $\sqrt{s} = 8.16$ TeV

[arXiv:2506.08624], submitted to JHEP





pPb (forward):

✓ Non-prompt ratio:
- No dependence on multiplicity

✓ Prompt ratio:
- Decrease of ratio with multiplicity

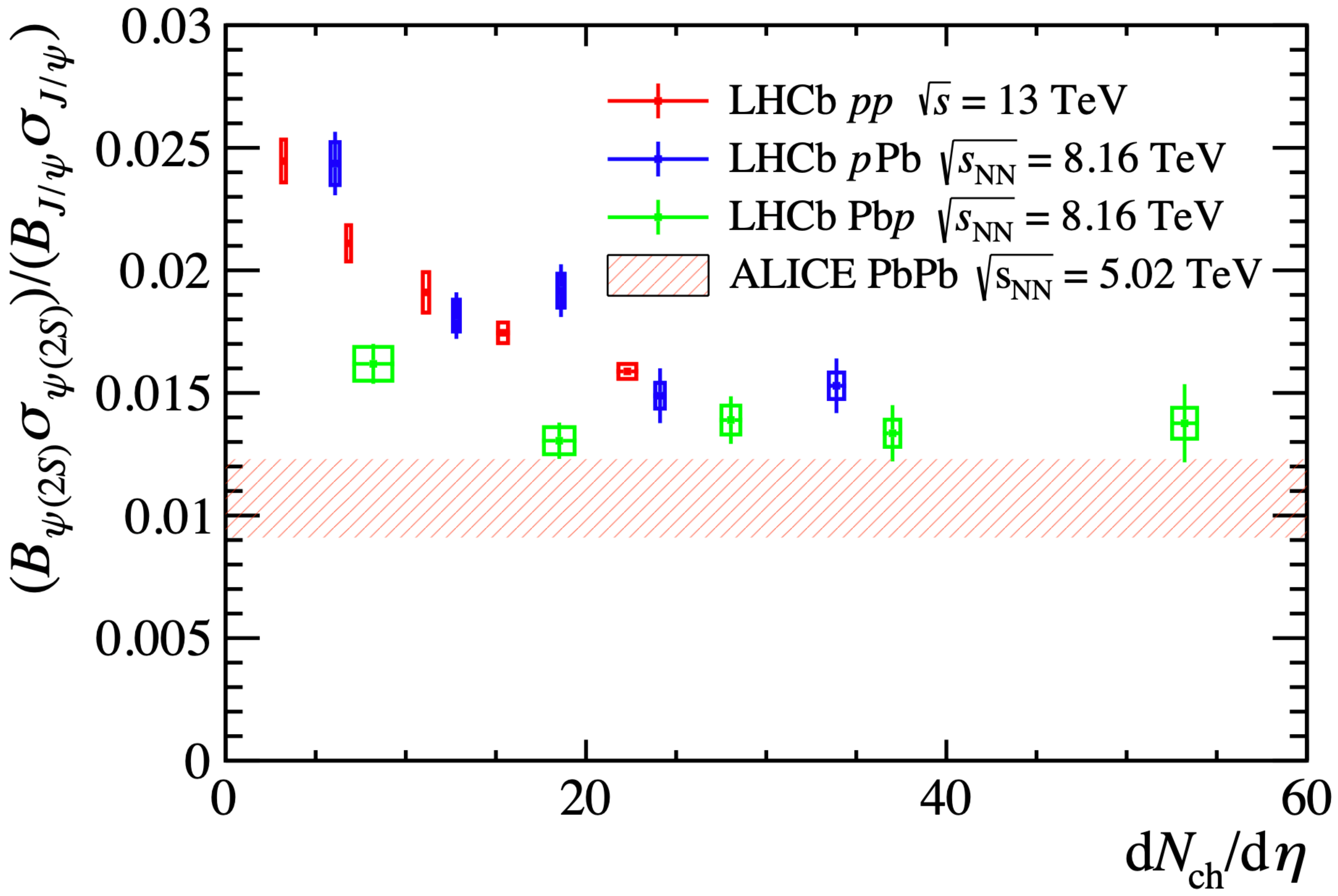
Pbp (backward):

✓ Non-prompt ratio:
- No dependence on multiplicity

✓ Prompt ratio:
- No dependence on multiplicity

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in pPb collisions at $\sqrt{s} = 8.16$ TeV

[arXiv:2506.08624], submitted to JHEP



forward

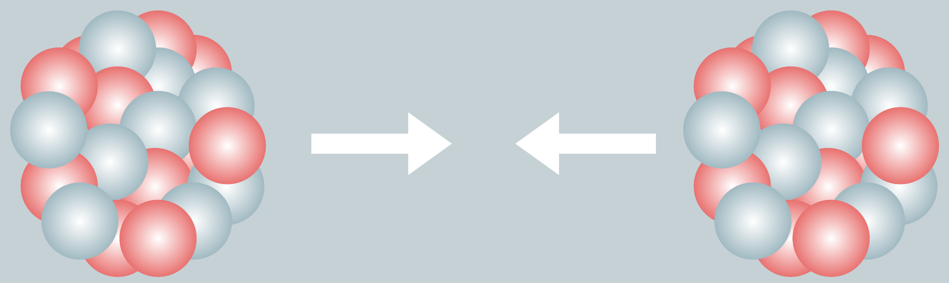
✓ pPb ratio consistent with pp ratio
Suggests that a similar environment is created in the final states of both systems, where the suppression is dominated by co-movers

backward

[PRL 132 (2024) 042301]

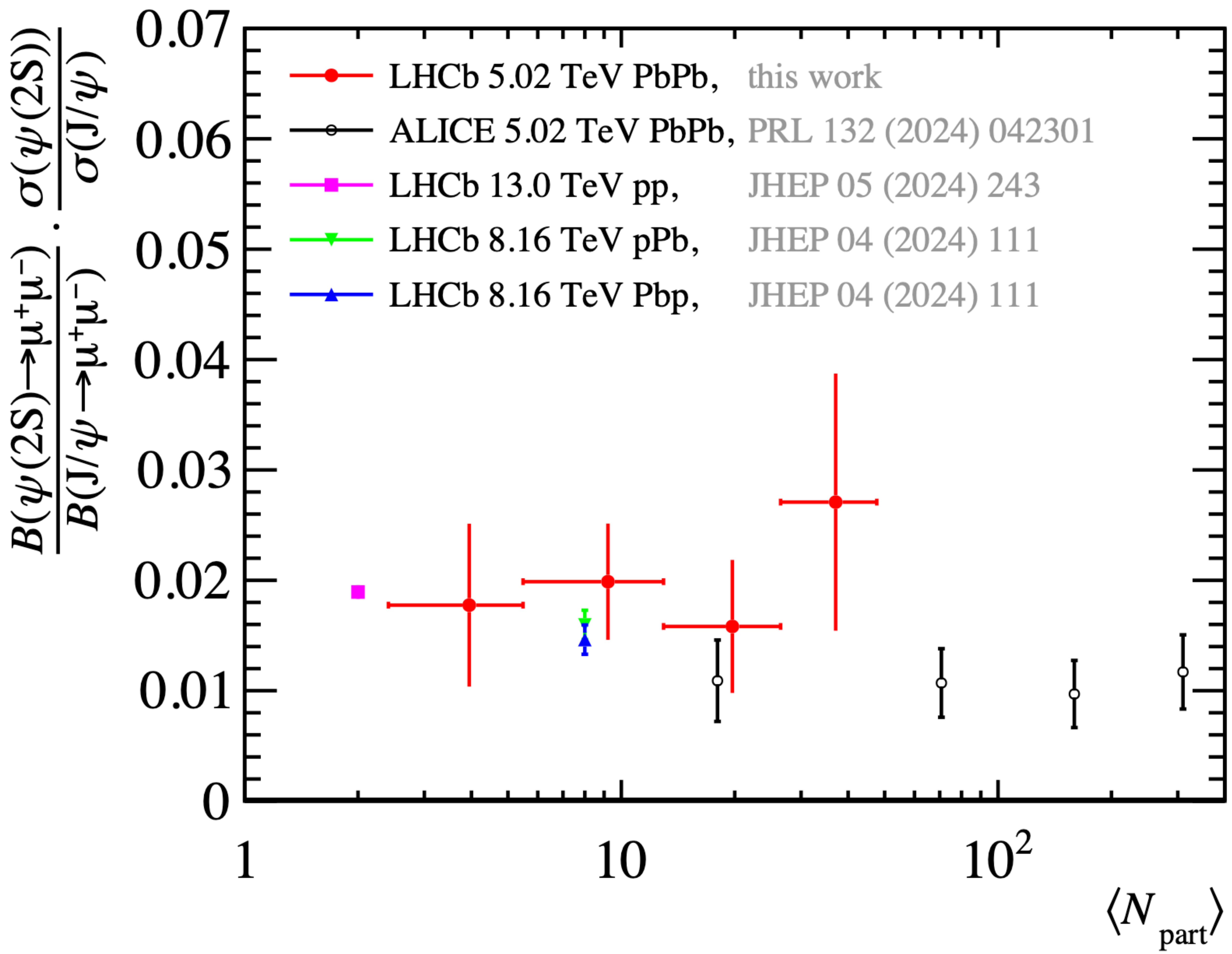
✓ Pbp ratio compatible with PbPb ratio
Suggests that a similar physical effect is present in both systems, where additional suppression mechanisms such as QGP could exist

LEAD - LEAD



$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs centrality in PbPb collisions at $\sqrt{s} = 5.02$ TeV

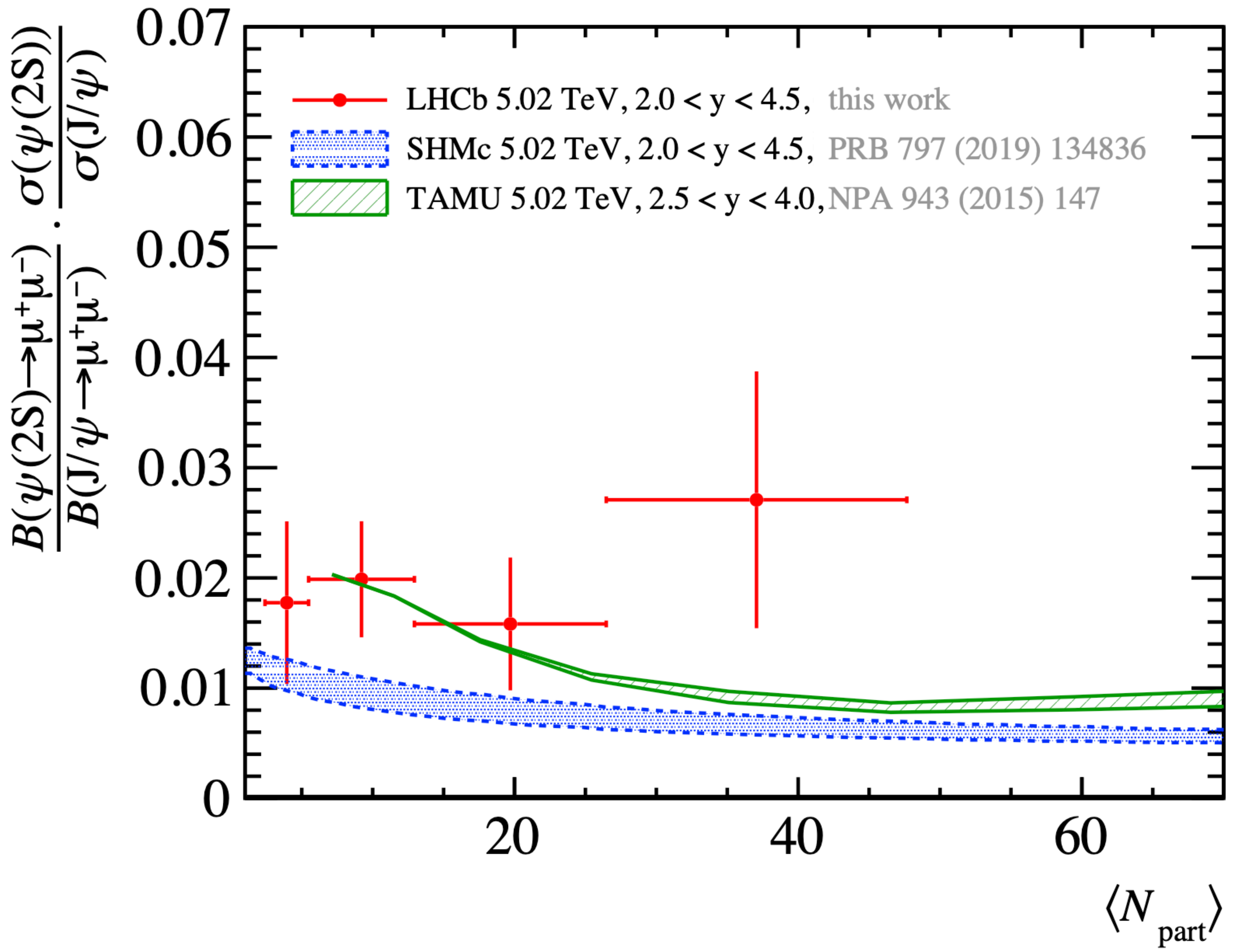
[arXiv:2411.05669], accepted in JHEP



- ✳ Cross section ratio of $\psi(2S)$-to-J/ψ as a function of the mean number of participating nucleons, $< N_{part} >$
- ✳ Comparison with other collision systems:
  - ✓ This work's results show no dependency on $< N_{part} >$ [PRL 132 (2024) 042301]
  - ✓ Agreement with ALICE PbPb result within uncertainties
  - ✓ Agreement with LHCb pp and pPb / Pbp results ($< N_{part} > = 2$ and 8, respectively)

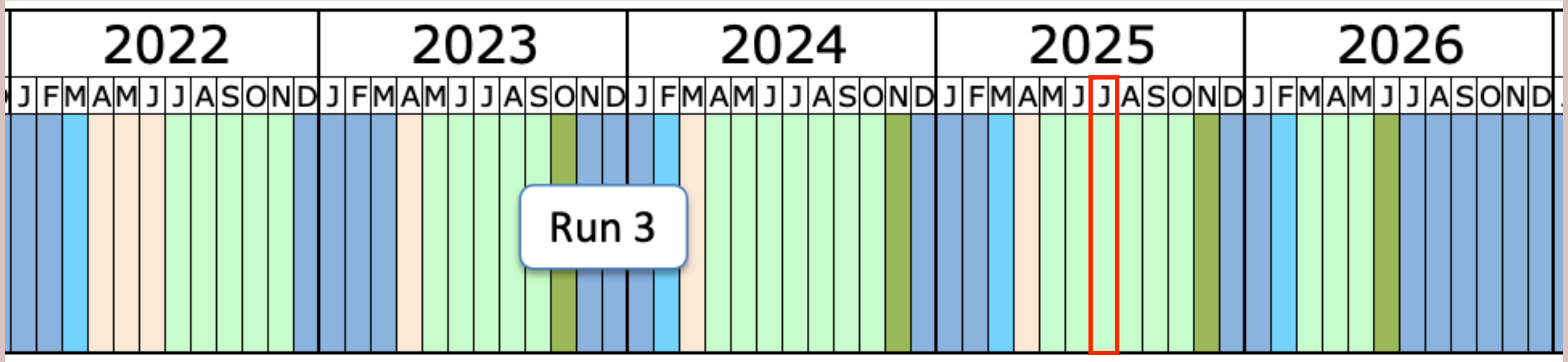
$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs centrality in PbPb collisions at $\sqrt{s} = 5.02$ TeV

[arXiv:2411.05669], accepted in JHEP

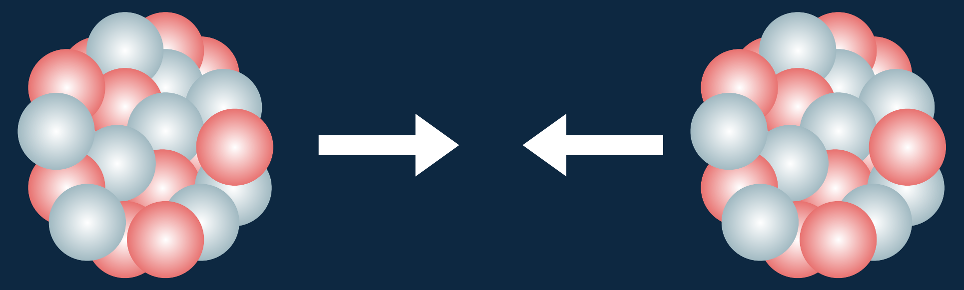


- ✳ Cross section ratio of $\psi(2S)$-to-J/ψ as a function of the mean number of participating nucleons, $< N_{part} >$
- ✳ Comparison with theory predictions:
  - ✓ SHMc model underestimates data, although showing a flat trend
    SHMc assumes that c quarks are produced in the collision, conserved throughout the QGP, thermalised in the medium, and then hadronised at the phase boundary
  - ✓ TAMU model is in better agreement with data
    TAMU is a transport model that respects detailed balance and simulates the gradual dissociation and regeneration of charmonia

RUN 3 OUTLOOK



Run 3 outlook
⇨ Lead-lead sample



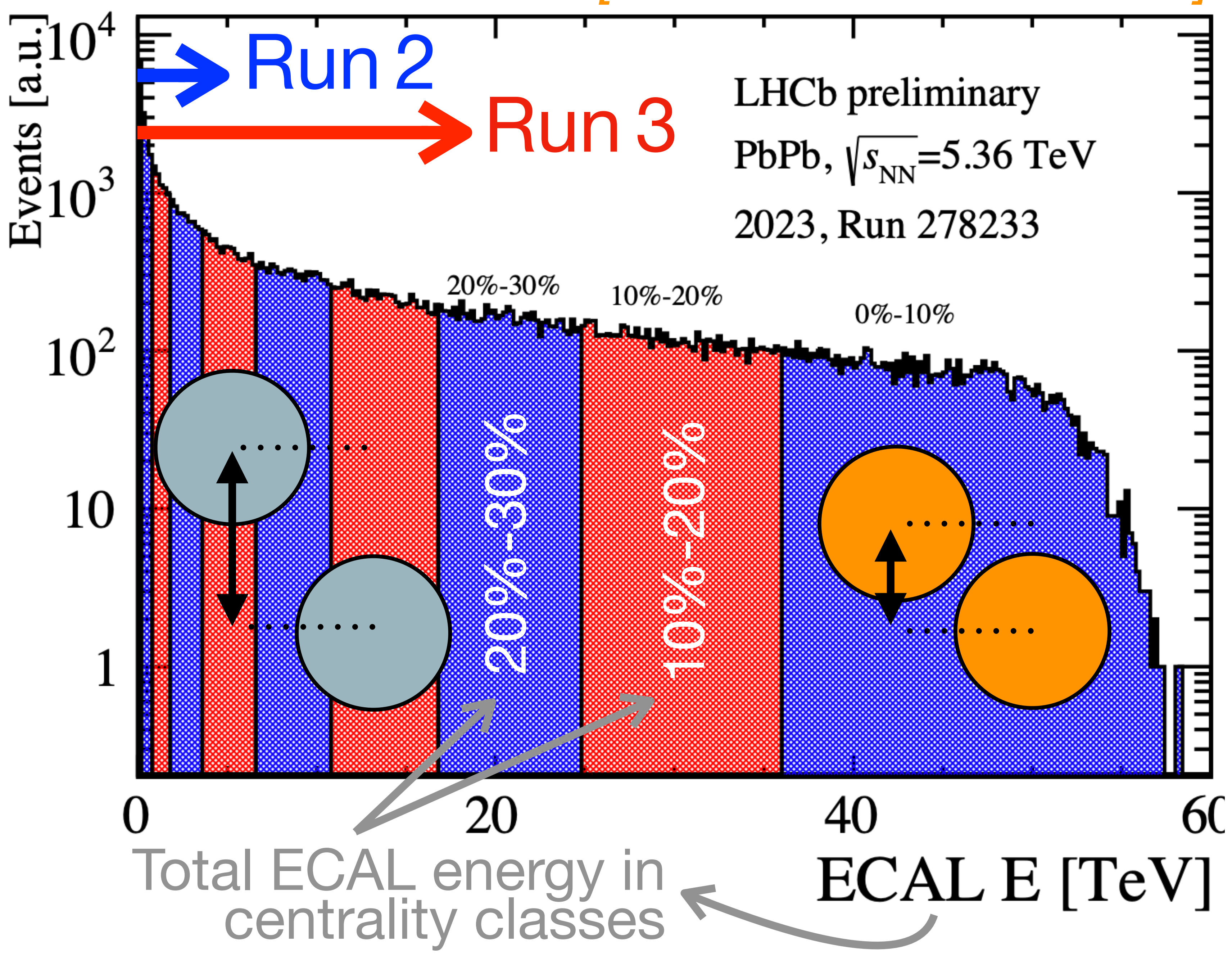
✳ **LHCb has recorded an unprecedented sample of PbPb collisions ($\mathscr{L} \sim 0.43$ nb^{-1})!**

✳ Down to a centrality never achieved before due to the power of the newly upgraded detectors

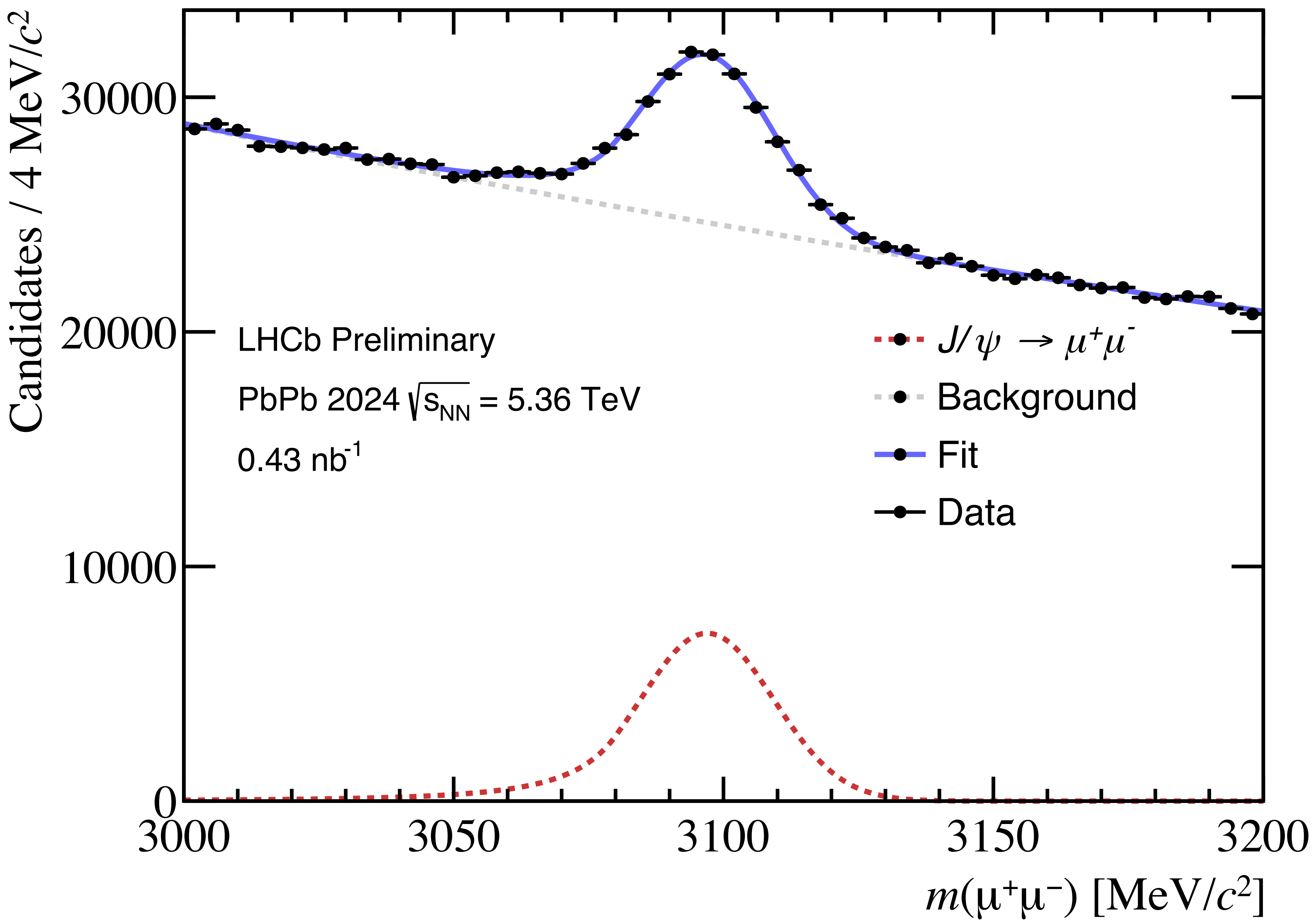
✳ Increased luminosity might allow to observe more quarkonium states in PbPb

✳ Possibility to separate prompt and non-prompt production

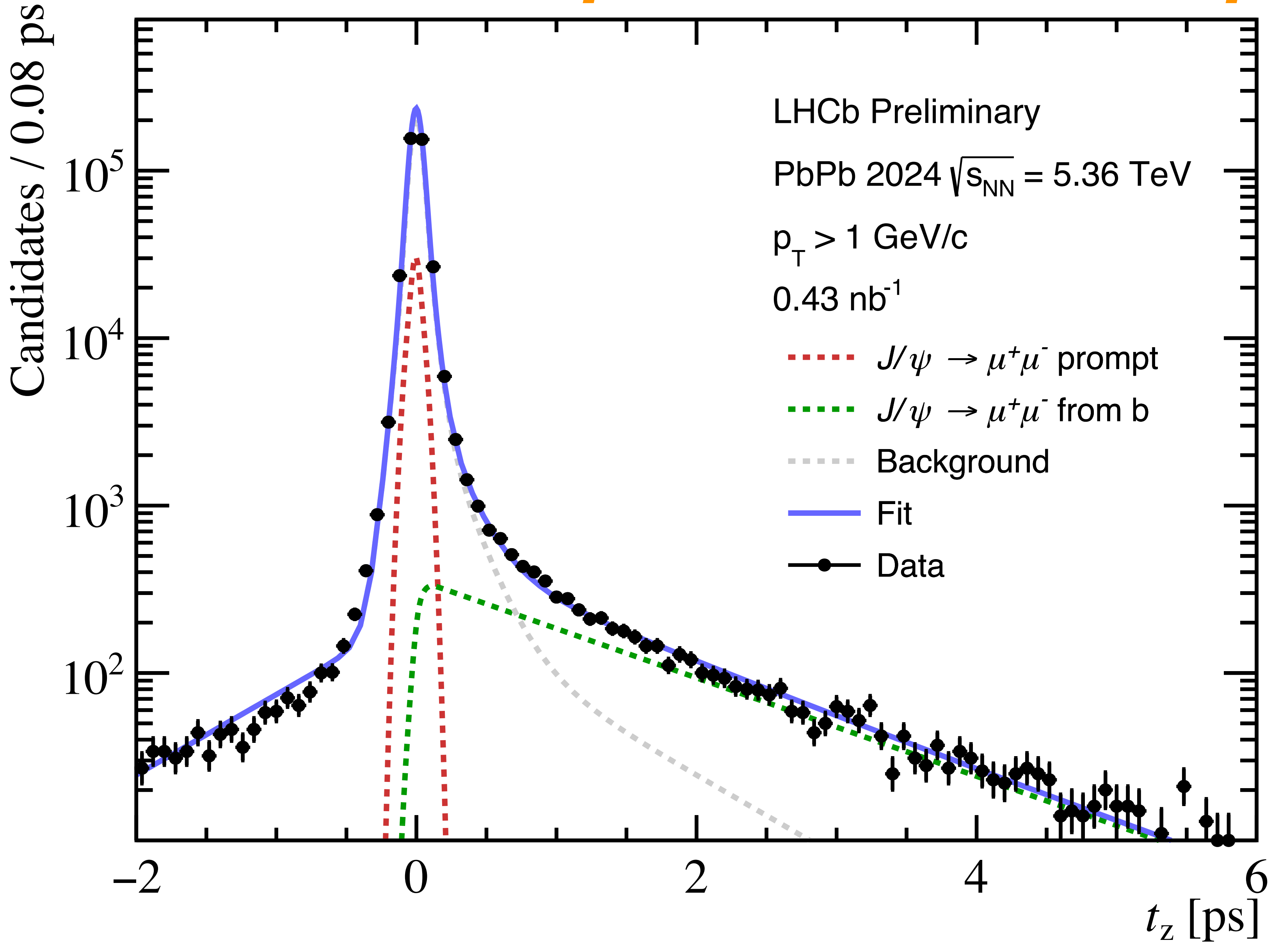
[LHCb-FIGURE-2023-030]



[LHCb-FIGURE-2025-004]

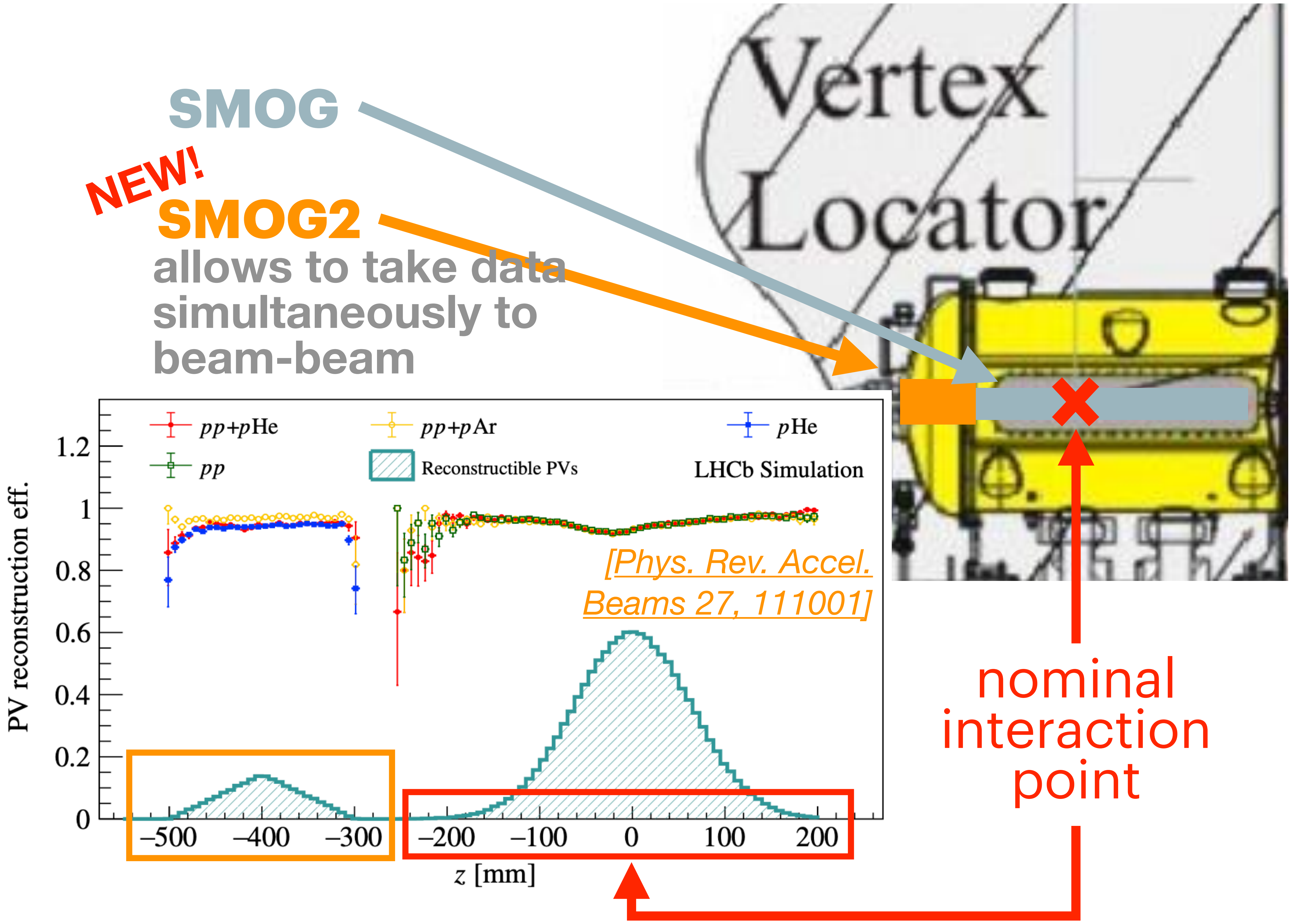


[LHCb-FIGURE-2025-012]

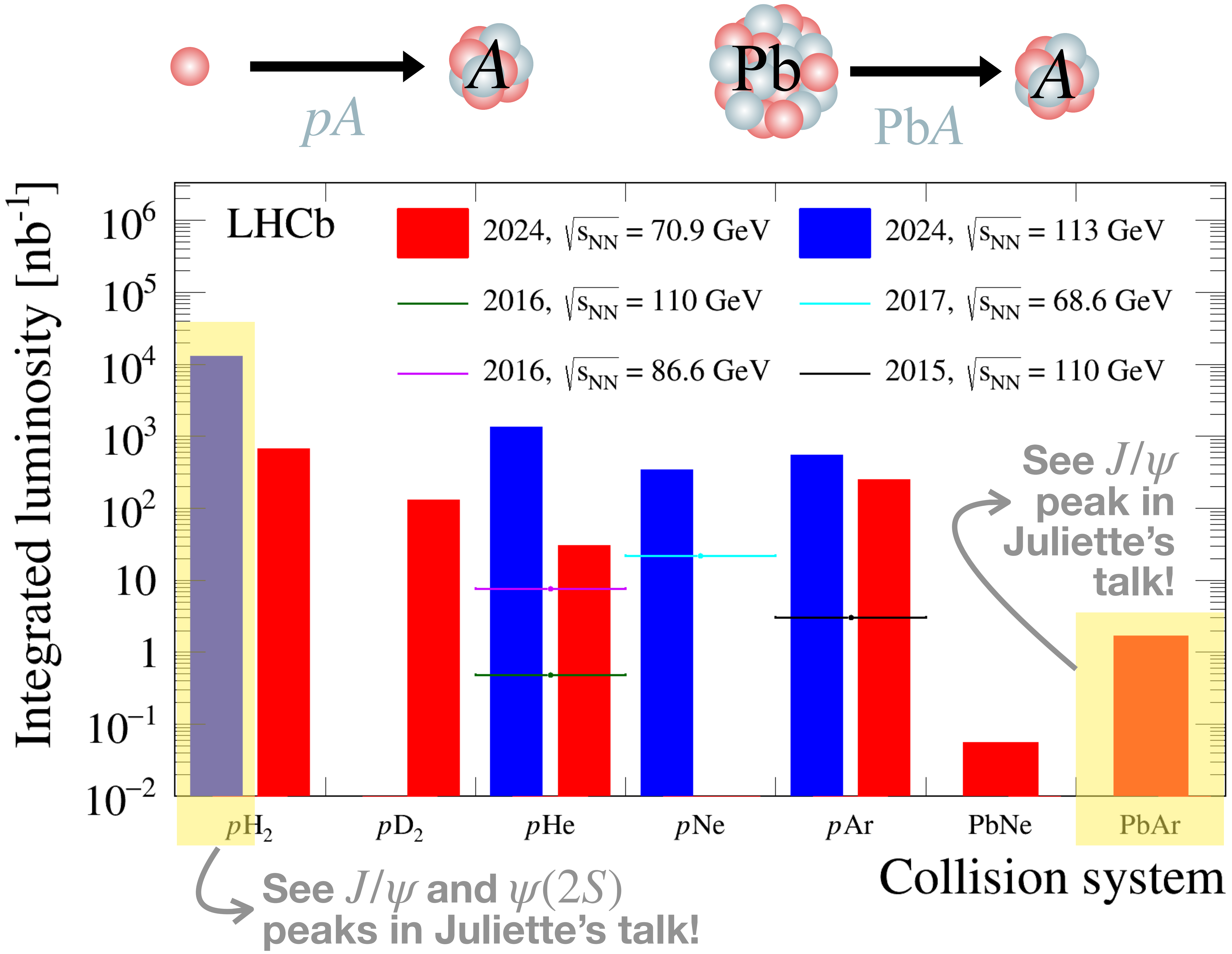


Run 3 outlook
➯ Fixed target mode

✴ LHCb has a unique system called **SMOG** to inject noble gases allowing to operate in **fixed-target** mode



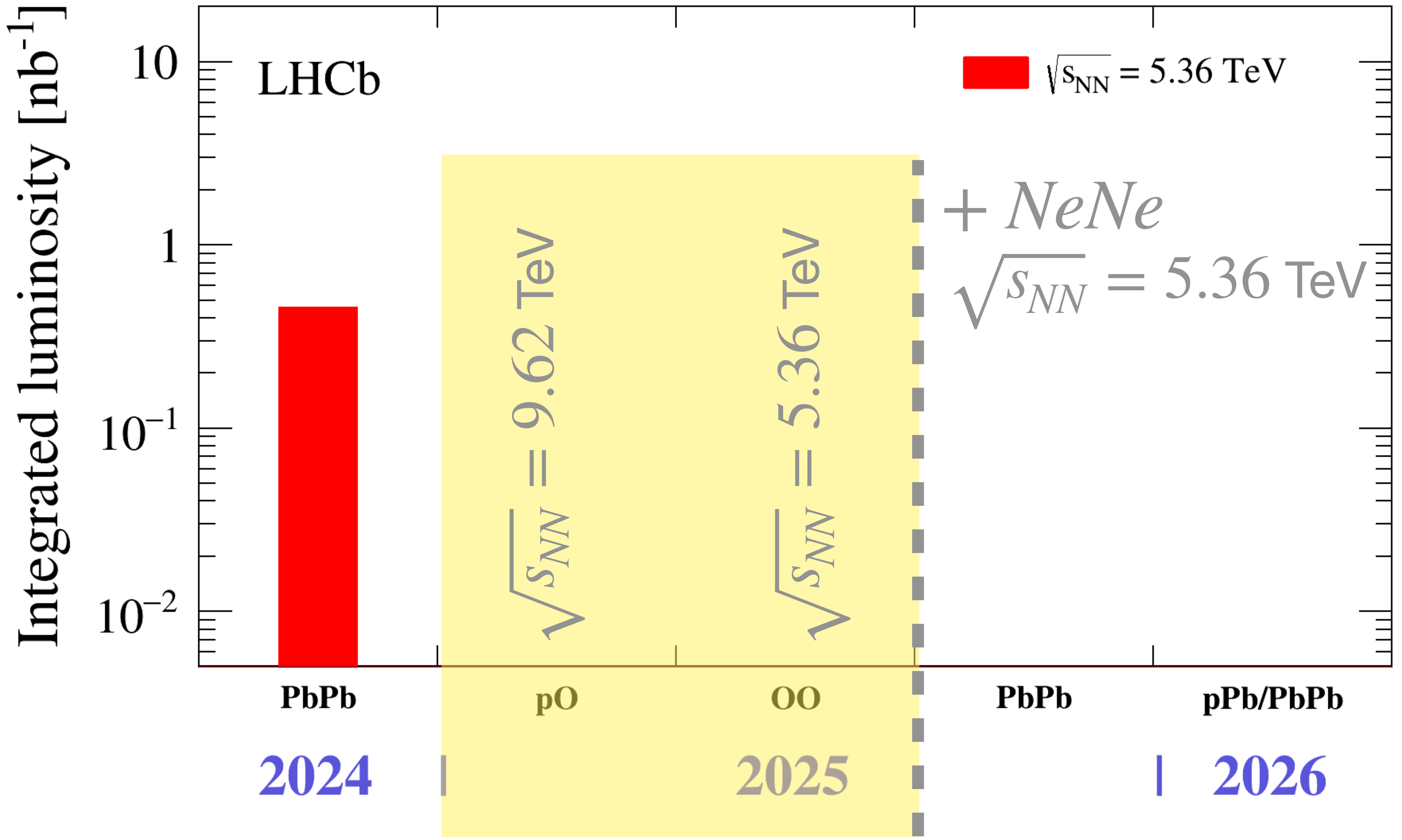
✴ Fixed-target **samples collected in 2024**:

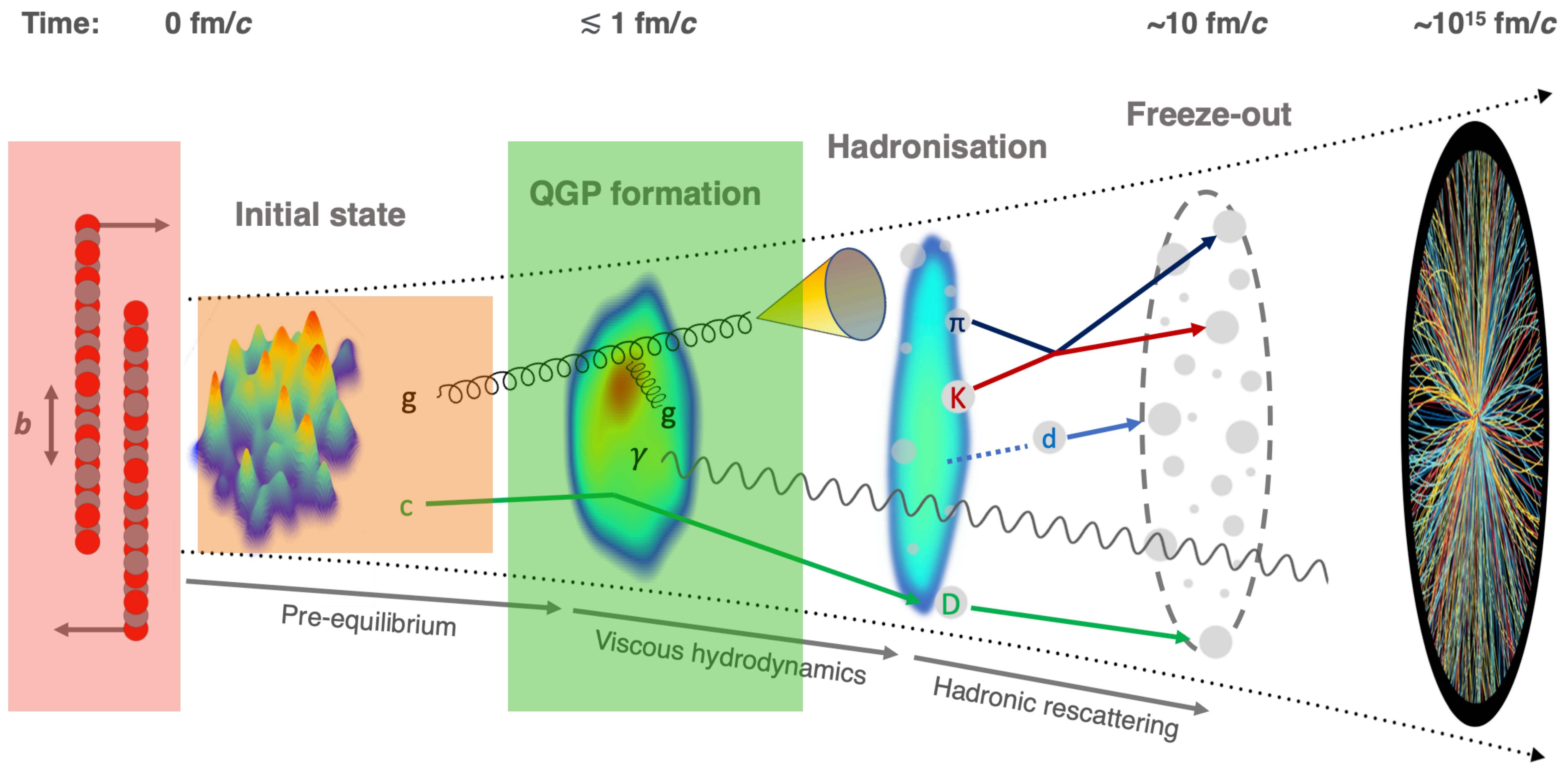


Run 3 outlook
➯ The light ion run

- The light ion run started last week! **Really important run for the heavy ion community!**
- LHCb plans to take fixed-target OH_2 and $NeNe$ at $\sqrt{s_{NN}} = 70.9$ GeV simultaneously to OO and $NeNe$ at $\sqrt{s_{NN}} = 5.36$ TeV, respectively

[Eur. Phys. J. C 84 (2024) 813]



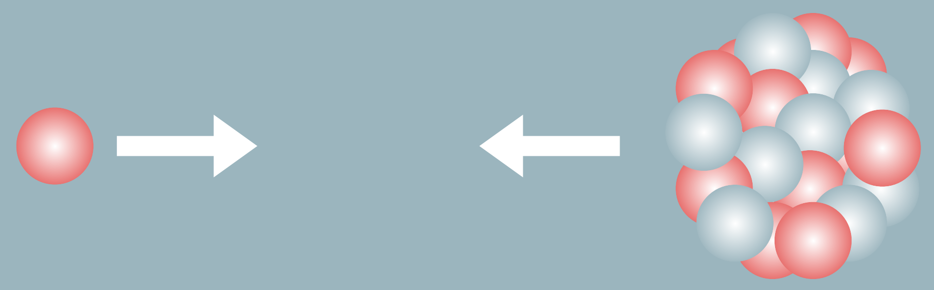


NeNe *pO* *OO, NeNe*

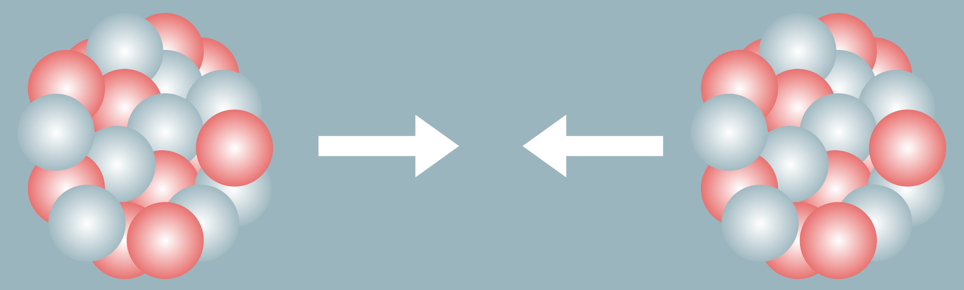
CONCLUSIONS

Run 2

- Dependence on multiplicity for prompt states consistent with co-movers.
- Non-prompt don't show multiplicity dependence.



- In pPb (forward) dependence on multiplicity compatible with pp.
- In Pbp (backward) flat behaviour compatible with PbPb ALICE results.



- First forward rapidity measurement of prompt charmonium production!
- Results compatible with other measurements.
- Comparison with theory shows better agreement with TAMU transport model.

Run 2

Run 3

Upgraded LHCb detector allows to

→ Further investigate quarkonium production in PbPb with higher precision, up to more central region and separating prompt/non-prompt.

→ Extend our knowledge to other collision systems thanks to the new SMOG2!

Stay tuned for future results!

Run 3

☺ ***Thank you for your attention!*** ☺

Backup

HEP2025

MARSEILLE

07

11

JULY

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in pp collisions at $\sqrt{s} = 13$ TeV

[JHEP05(2024)243]

- Fiducial region $2.0 < y < 4.5$ and $0.3 < p_T < 20$ GeV/c
- Double-differential cross-section for prompt and non-prompt J/ψ and $\psi(2S)$ production in a given (p_T, y) bin and multiplicity range:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}} = \frac{N(p_{\mathrm{T}}, y)}{\mathcal{L} \times \epsilon_{\mathrm{tot}}(p_{\mathrm{T}}, y) \times \mathcal{B} \times \Delta y \times \Delta p_{\mathrm{T}}}$$

- Double-differential ratio of prompt or non-prompt production in a certain multiplicity range:

$$\frac{\sigma_{\psi(2S)}(p_{\mathrm{T}}, y)}{\sigma_{J/\psi}(p_{\mathrm{T}}, y)} = \frac{N_{\psi(2S)}(p_{\mathrm{T}}, y)}{N_{J/\psi}(p_{\mathrm{T}}, y)} \times \frac{\epsilon_{\mathrm{tot,J/\psi}}(p_{\mathrm{T}}, y)}{\epsilon_{\mathrm{tot,\psi(2S)}}(p_{\mathrm{T}}, y)} \times \frac{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}{\mathcal{B}_{\psi(2S)\to e^+e^-}}$$

- Ratio of production over an integrated kinematics:

$$\frac{\sum_j \sigma_{\psi(2S),j}}{\sum_j \sigma_{J/\psi,j}}$$

where j run over all (p_T, y) bins

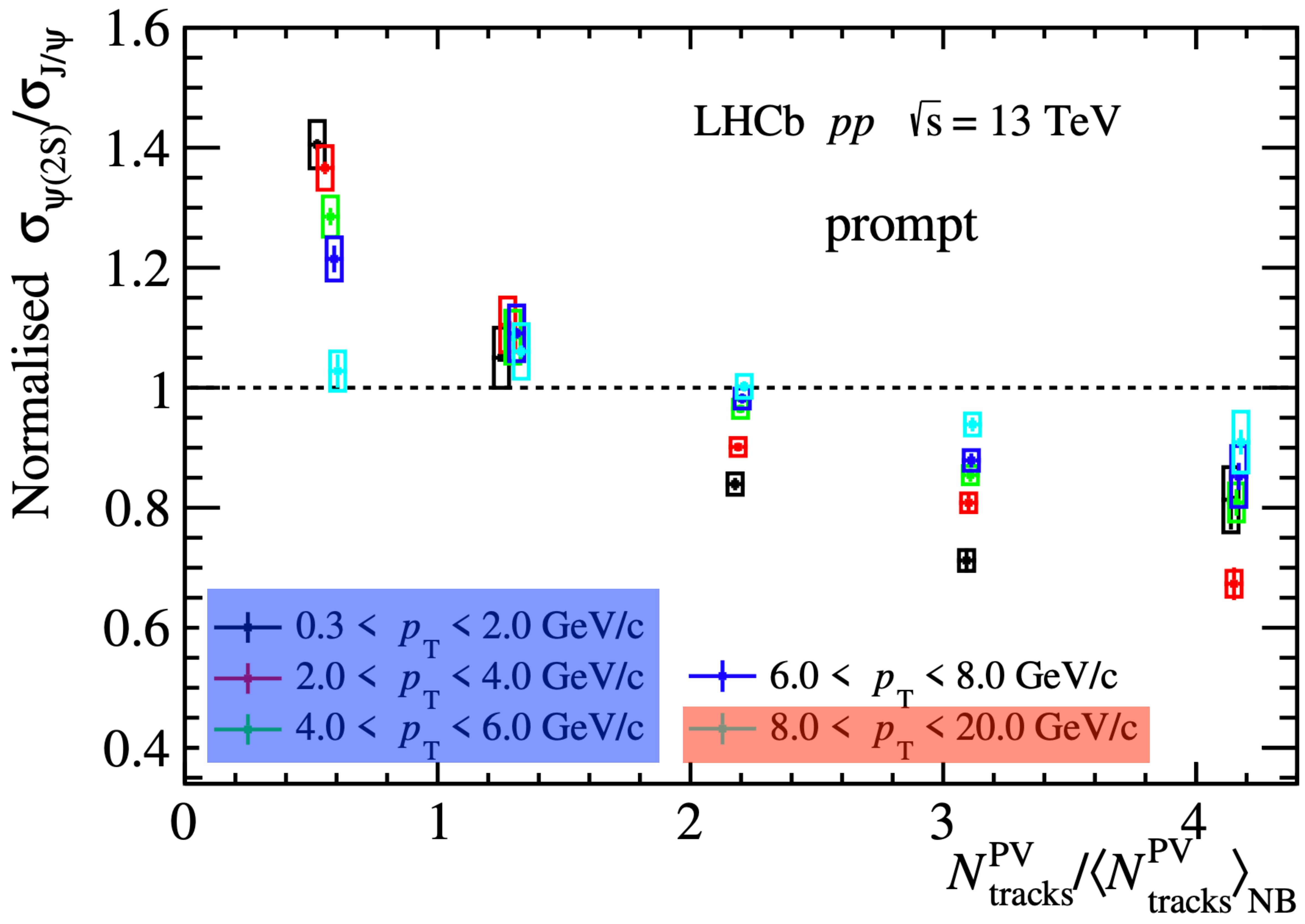
- Normalised cross-section ratio:

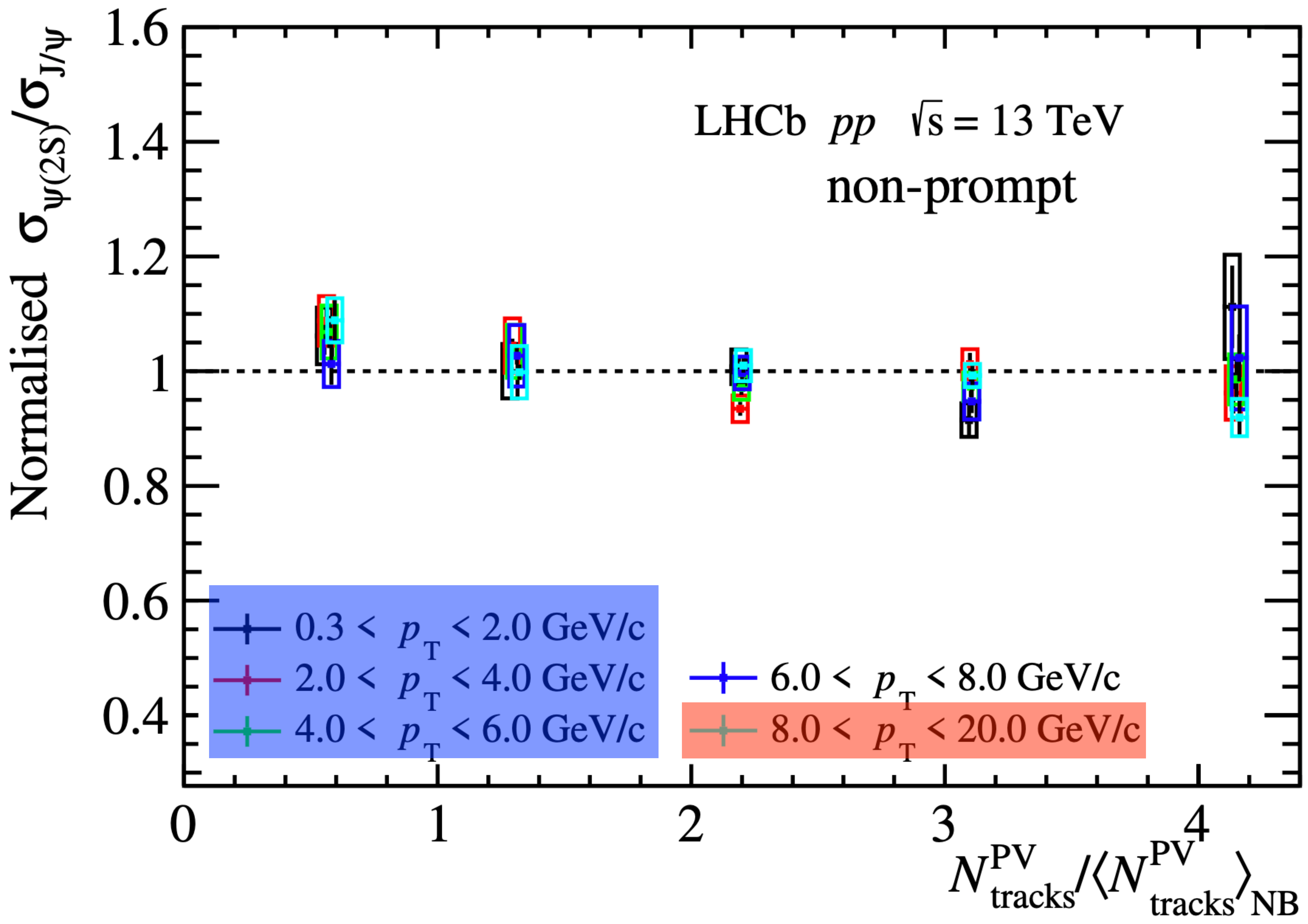
$$\text{Normalised } \frac{\sigma_{\psi(2S),n}}{\sigma_{J/\psi,n}} = \frac{\sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}$$

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in pp collisions at $\sqrt{s}$ = 13 TeV

[JHEP05(2024)243]

✴ Production of $\psi(2S)$ is suppressed at low p_T; almost independent of multiplicity at high p_T





$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs multiplicity in pPb collisions at $\sqrt{s} = 8.16$ TeV

[arXiv:2506.08624], submitted to JHEP

- Fiducial region: $1.5 < y^* < 4.0$ ($-5.0 < y^* < -2.5$) for pPb (Pbp) and $0.3 < p_T < 14$ GeV/c

- The cross-section ratio for a multiplicity bin i:

$$\frac{\sigma^i_{\psi(2S)}}{\sigma^i_{J/\psi}} = \frac{\mathcal{B}_{J/\psi\to\mu^+\mu^-}}{\mathcal{B}_{\psi(2S)\to\mu^+\mu^-}} \frac{Y^i_{\psi(2S)}}{Y^i_{J/\psi}}$$

- Multiplicity bins:

pPb $N^{\text{PV}}_{\text{tracks}}$	Pbp $N^{\text{PV}}_{\text{tracks}}$
4–45	4–60
45–70	60–90
70–90	90–120
90–120	120–160
120–270	160–330
4–270	4–330

$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ vs centrality in PbPb collisions at $\sqrt{s} = 5.02$ TeV

[arXiv:2411.05669], accepted in JHEP

- Centrality intervals (estimated using the total energy deposited in the ECAL), $< N_{part} >$, and signal yields:

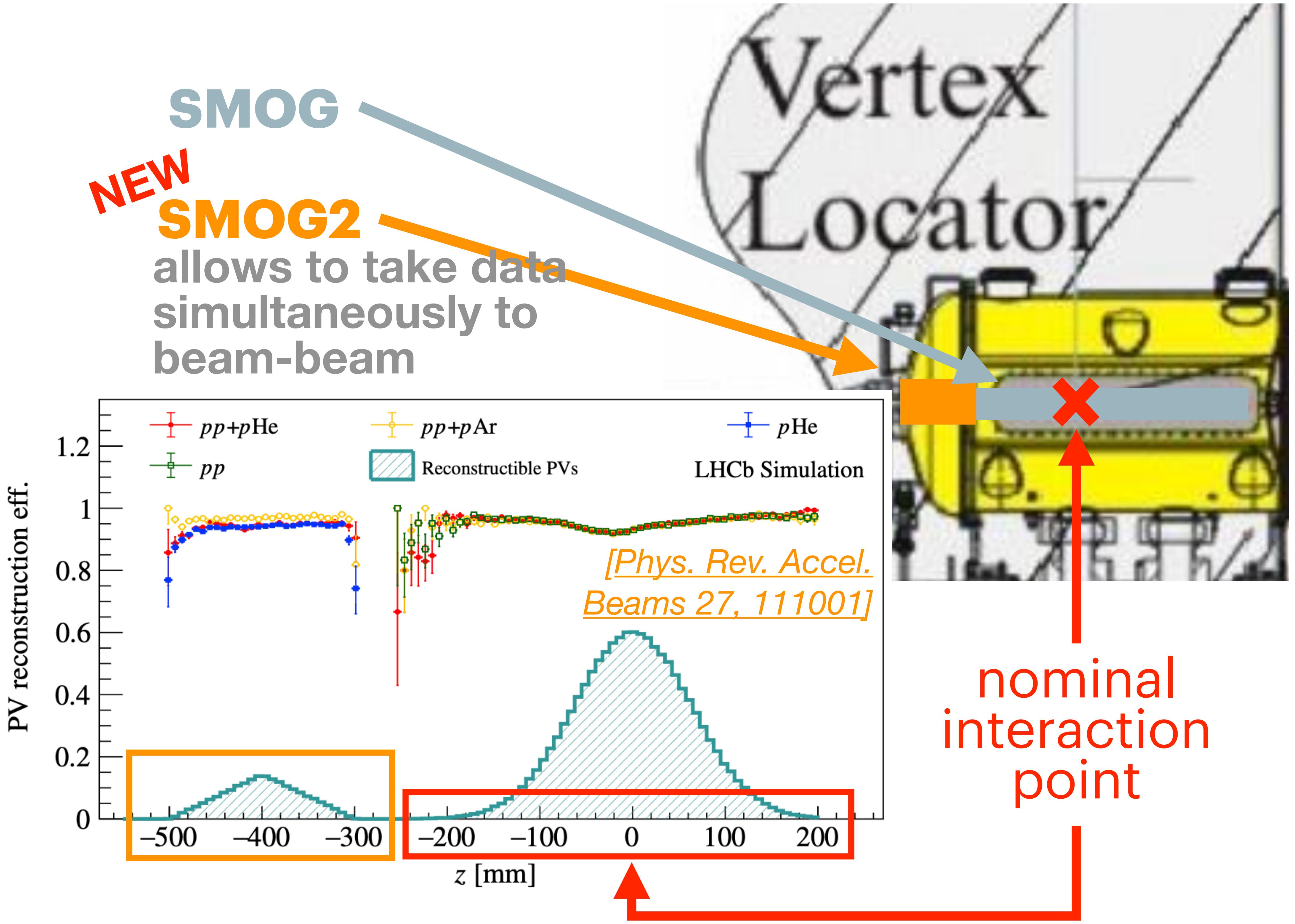
Centrality (%)	90–100	80–90	70–80	60–70
$\langle N_{\text{part}} \rangle$	2.4–5.5	5.5–13.0	13.0–26.5	26.5–48.0
$N(J/\psi)$	596 ± 28	2099 ± 52	3320 ± 74	2221 ± 77
$N(\psi(2S))$	13 ± 5	53 ± 14	68 ± 26	85 ± 36

- Ratio of cross-sections multiplied by their branching fractions:

$$\frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)} \cdot \frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = \frac{N(\psi(2S))}{N(J/\psi)} \cdot \frac{\varepsilon_{\text{tot}}(J/\psi)}{\varepsilon_{\text{tot}}(\psi(2S))}$$

Run 3 outlook
➩ Fixed target mode

✴ LHCb has a unique system called **SMOG** to inject noble gases allowing to operate in **fixed-target** mode



✴ **SMOG2 improvements** respect to SMOG:

✓ $\times 100$ more density that translates into a massive increase in luminosity

✓ Precise luminosity determination (<2% systematic uncertainty)

✓ Wider choice of target gases: $H_2, D_2, He, Ne, O_2, Ar$

✓ Clear separation between the beam-gas and nominal (beam-beam) interaction points that allows **simultaneous data taking with same physics performance**