Heavy-ion physics at LHCb

Focus on the most recent results

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On behalf of LHCb collaboration

ÉCOLE POLYTECHNIQUE
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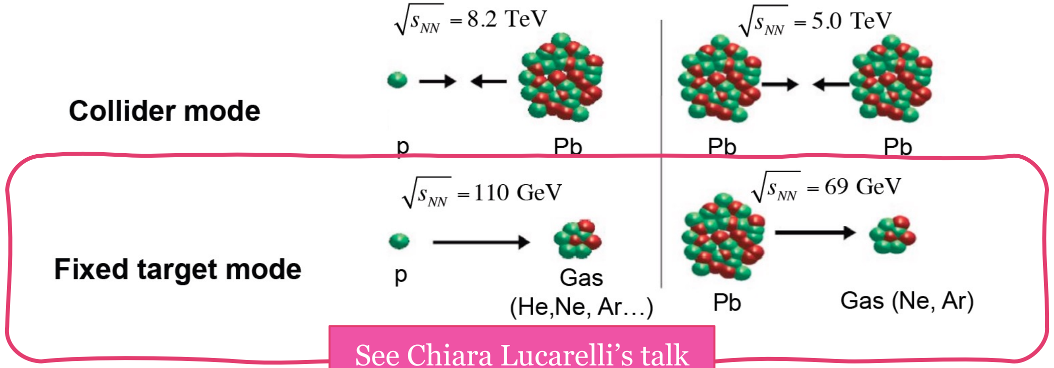
Heavy-ion physics at LHC*b* detector

- Excellent for measurements of quarkonia, heavy flavors and exotica states, etc
- Unique capability in different running modes

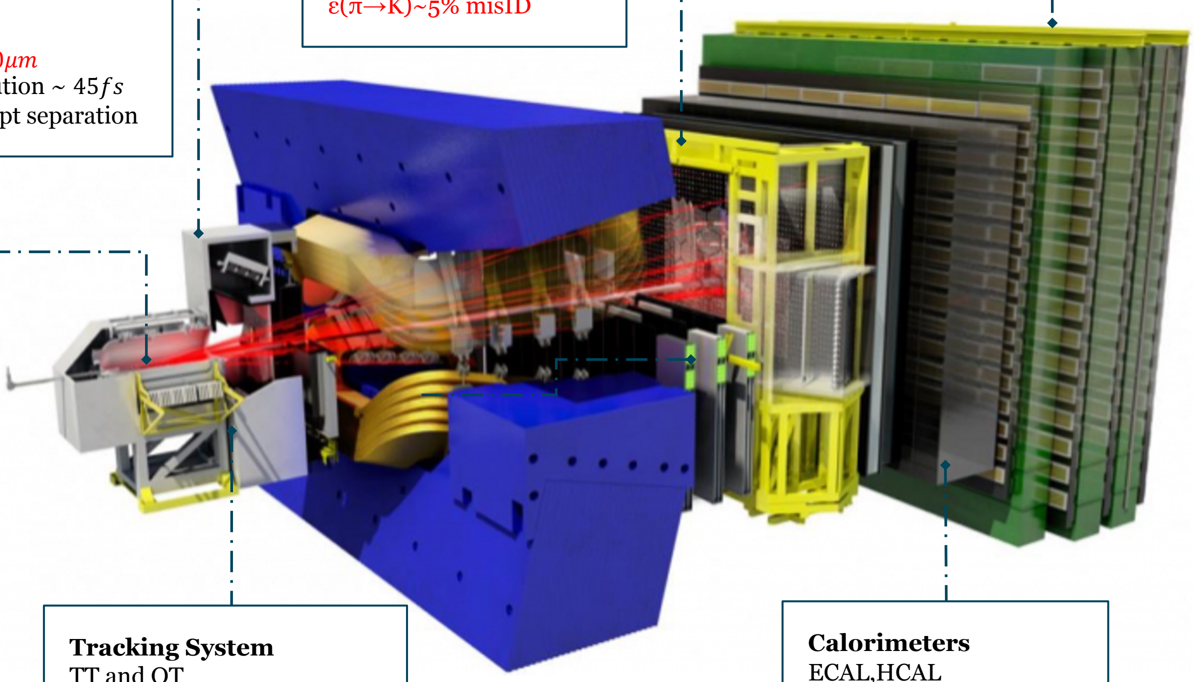


See Chiara Lucarelli's talk

- Large forward momentum boost
  - ✓ Precise measurements down to low-p_T
  - ✓ Clear separation for prompt and non-prompt
- Unique forward rapidity coverage
  - ✓ Crucial to constrain **nPDFs**
  - ✓ Study **QGP effects** at forward rapidity
  - ✓ Probing **saturation (low-x)** and **shadowing (high-x)**
- Major Upgrades completed

[JINST 3 (2008) S08005]

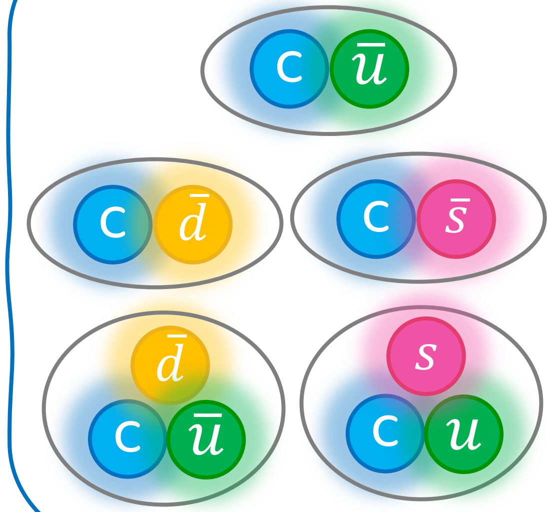
$2 < \eta < 5$



Hard Probes: **Heavy flavors** measurements

- Why **heavy flavors**?
  - Heavy quarks(charm, beauty) have large mass, strong interaction with QGP differently from light quarks
  - Initial production calculable with pQCD even at low-p_T
- Heavy flavors measurements at LHCb:

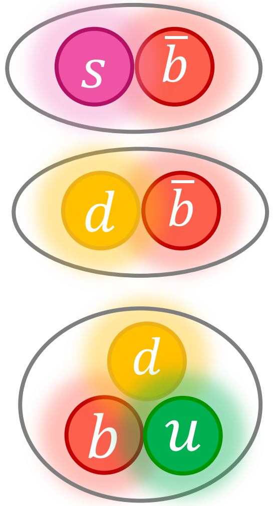
Open Charm



Lots of open-charm results(D^0, Λ_c^+/D^0, Ξ_c^+ ...) in pPb/PbPb collisions at LHCb

D^+, D_s^+ in pPb at 8.16 TeV
[arXiv: 2311.08490]

Open Beauty



B_s^+/B^0 in pp at 13 TeV
[Phys. Rev. Lett. 131 (2023) 061901]

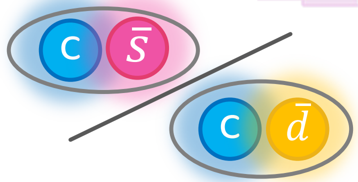
Λ_b^0/B^0 in pp at 13 TeV
[Phys. Rev. Lett. 132 (2024) 081901]

- Study the **nuclear modification factor**: get information of medium by measuring how they are modified in heavy-ion collisions, compared to pp collisions(no medium) as reference

Prompt D_s^+, D^+ production in pPb at 8.16 TeV

Why study strange hadrons:

- Offering unique probes of the hadronization mechanism: **Fragmentation or Coalescence?**



[2311.08490]

pPb: a good system for multiplicity interpretation

- Low multiplicity: resemble those of pp collisions
- High multiplicity: occupancy similar to PbPb

Common: increasing trend with $dN_{ch}/d\eta$ occurs

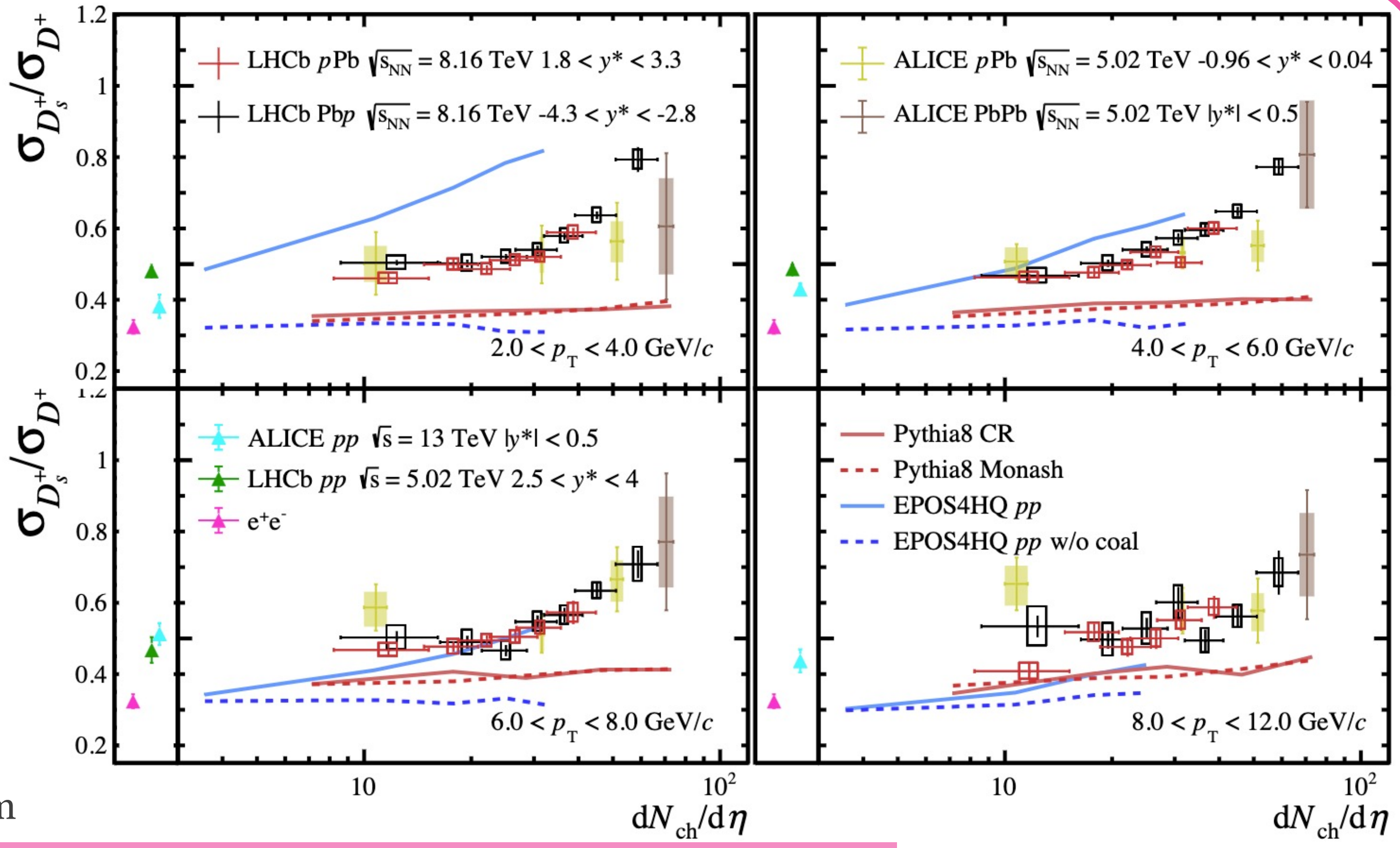
- For all p_T intervals
- For both forward and backward regions

Discrepancies: comparing data and predictions

- Pythia8 model under-estimates the data
- EPOS4HQ+coalescence depicts the increasing trend across all p_T intervals

Strangeness enhancement:

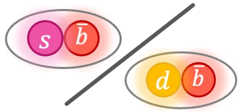
- More pronounced at low-p_T
- Qualitatively compatible with coalescence mechanism



Conclusion: First observation of strangeness enhancement in charm quark hadronization in high-multiplicity small systems

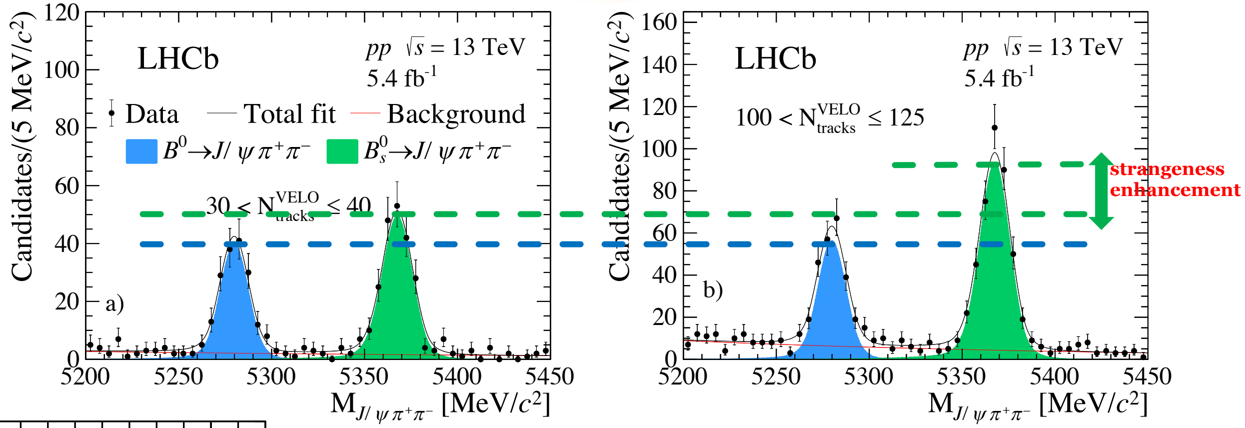
B_s^0/B^0, Λ_b^0/B^0 production in pp at 13 TeV

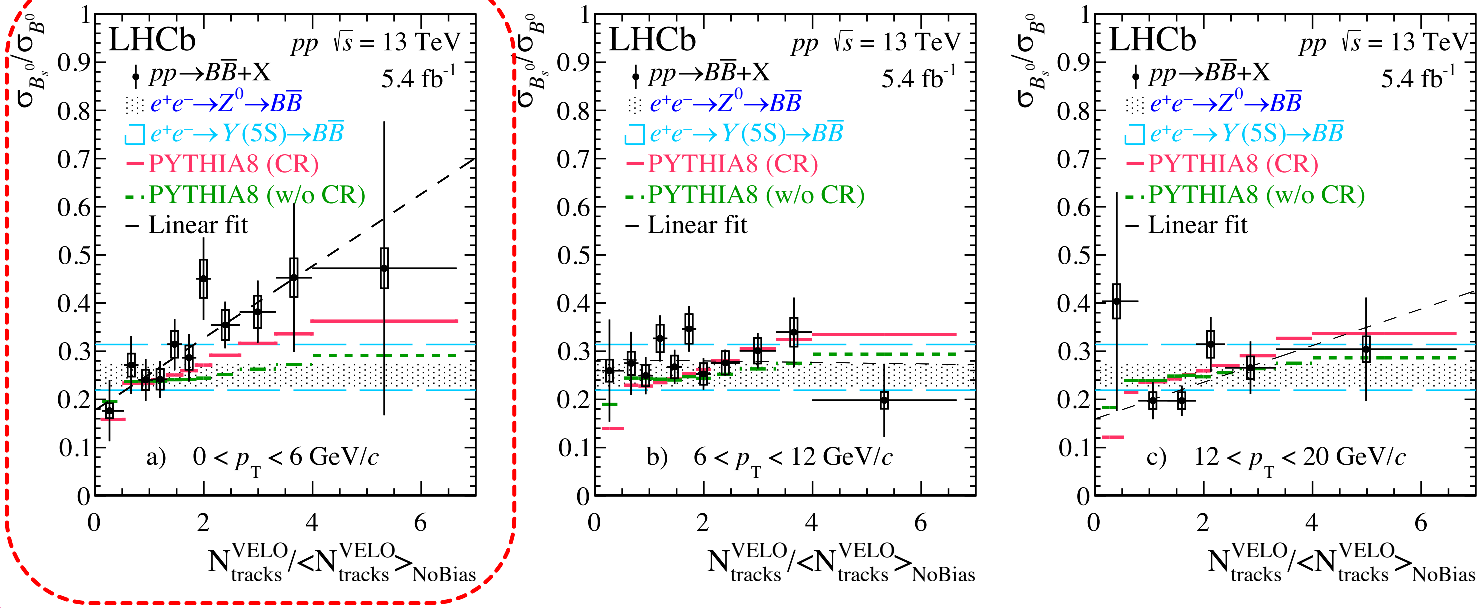
Could we see strangeness enhancement in open beauty?

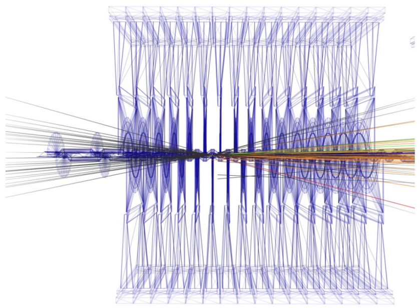


[Phys. Rev. Lett. 131 (2023) 061901]

- ✓ Apparent increase of B_s^0 yield compared to B^0 as a function of multiplicity
- ✓ Enhancement more notable at $p_T < 6\ GeV/c$







N_{tracks}^{VELO} = Number of tacks in VELO

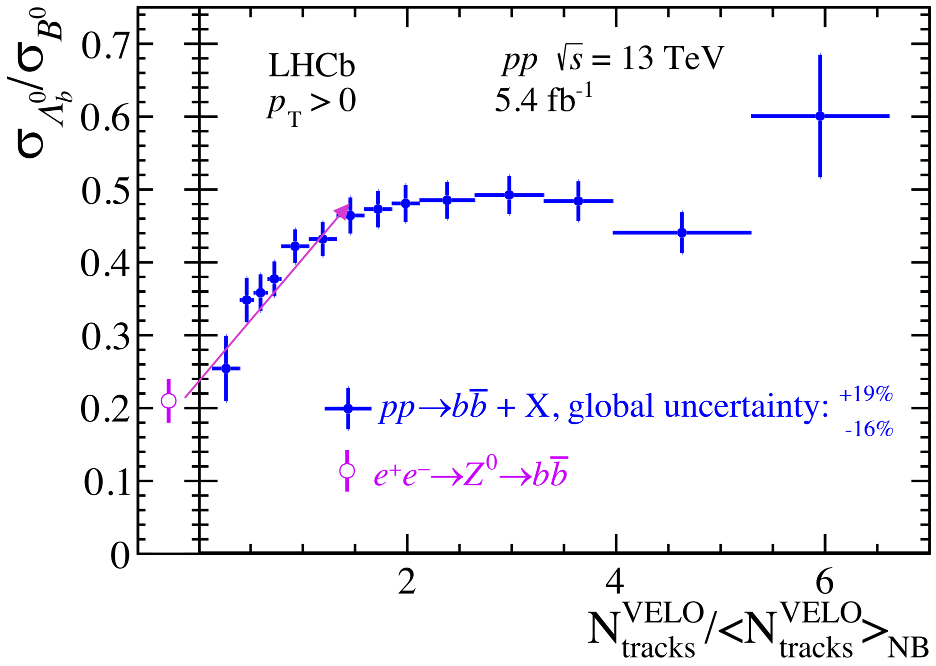
Conclusion: Yes!

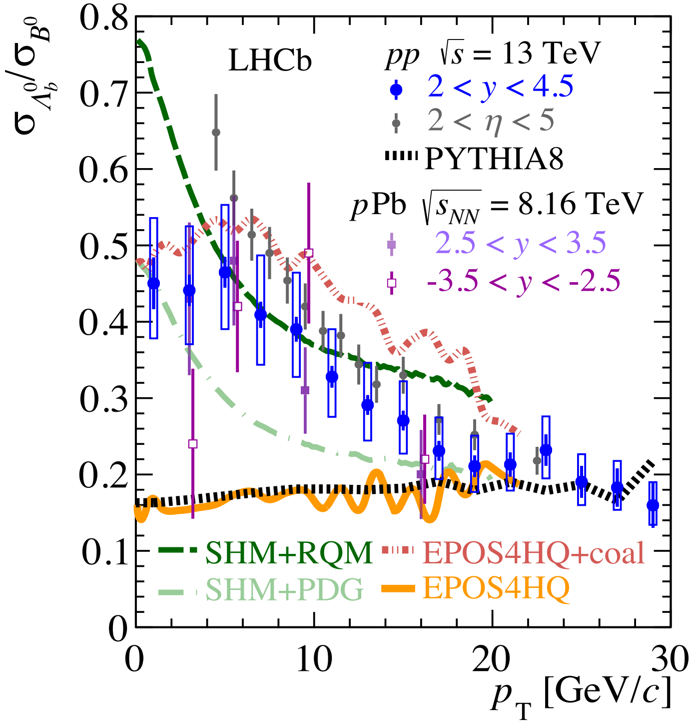
B_s^0/B^0, Λ_b^0/B^0 production in pp at 13 TeV

Study hadronization mechanism with open beauty (Λ_b^0/B^0):

[Phys. Rev. Lett. 132 (2024) 081901]

- Observed a strong baryon enhancement with multiplicity
- Reproduce result of e^+e^-(QCD vacuum) as multiplicity approaches zero
- p_T trend compatible with measurement in pPb collisions



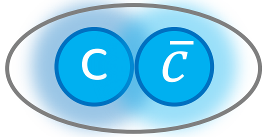


Conclusion:
Better agreement with the coalescence picture being dominant at low p_T

Hard Probes: **Quarkonia** measurements

- Due to color charge screening, charmonia **dissociated** in QGP:
  - **Sequential suppression**:
    - Quarkonium productions are “melted” at dissociation temperature
    - Weaker the bound state, easier to be dissociated
- Charmonia **regeneration**:
  - Quark meets the other anti-quark
  - Bound state recovered in final state
- **Cold nuclear matter effects(Non-QGP effect)**:
  - Co-mover, energy loss, nuclear absorption, etc..
  - Quantify in small systems (pp,pA..)

Charmonia



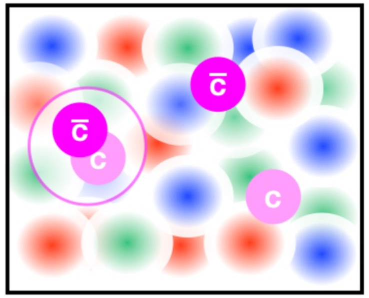
ψ(2S)/J/ψ in pp at 13 TeV
[JHEP 05 (2024) 243]

ψ(2S)/J/ψ in pPb at 8.16 TeV
[JHEP 04 (2024) 111]

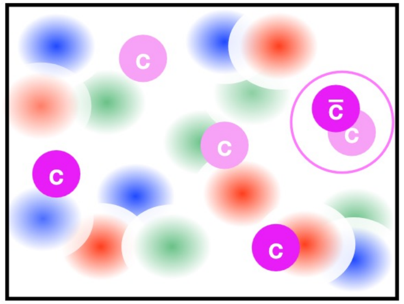
$\chi_c(3872)/\psi(2S)$ in pp at 8 TeV
[Phys. Rev. Lett. 126 (2021) 092001]

$\chi_c(3872)/\psi(2S)$ in pPb at 8.16 TeV
[Phys. Rev. Lett. 132 (2024) 242301]

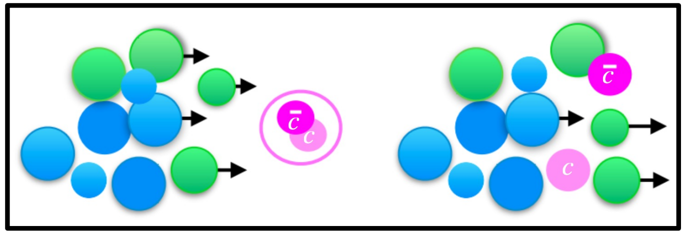
Fraction of χ_c in prompt J/ψ in pPb at 8.16 TeV
[Phys. Rev. Lett. 132 (2024) 102302]



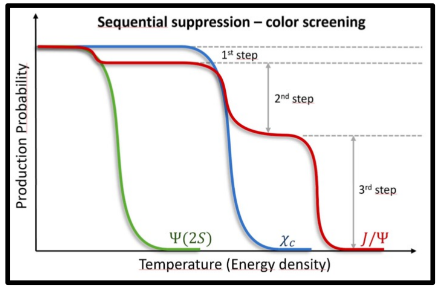
Dissociation in QGP



Regeneration in QGP



Co-mover in non-QGP

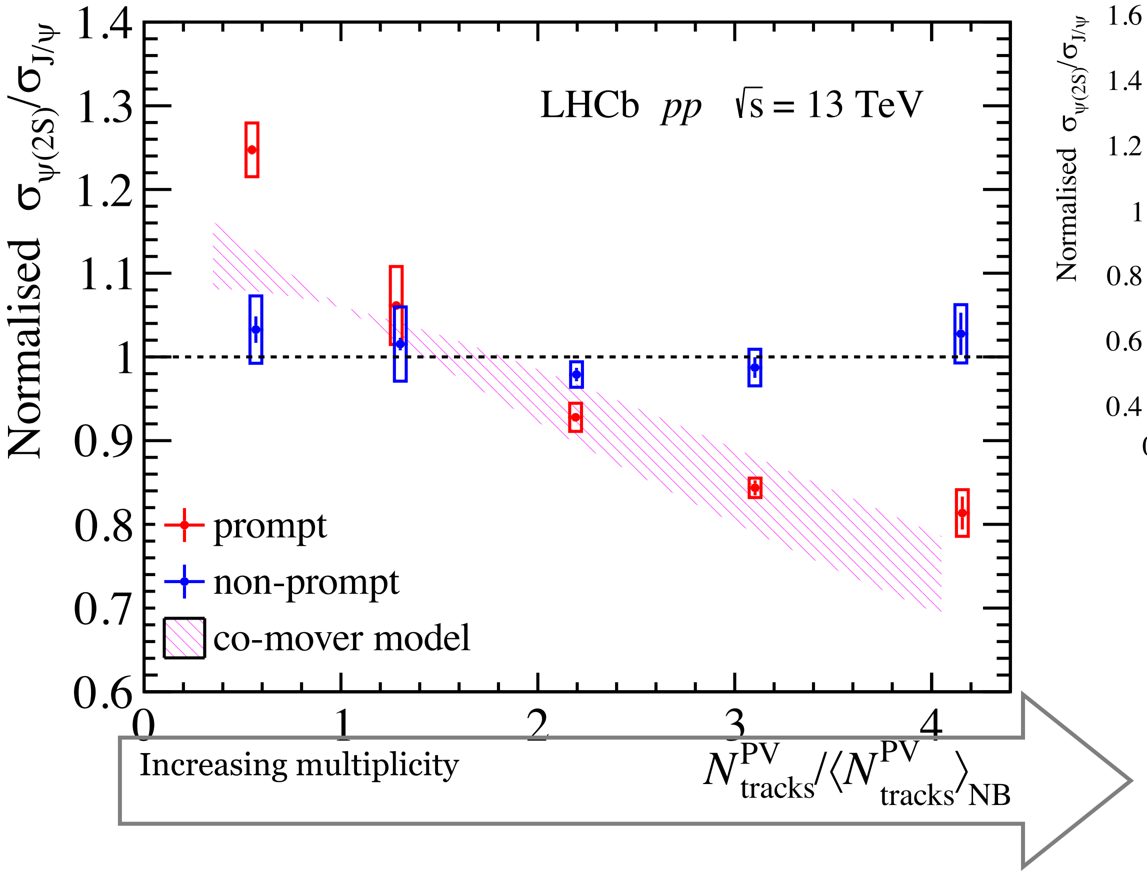


Sequential suppression

$\psi(2S)/J/\psi$ in pp collisions at 13 TeV

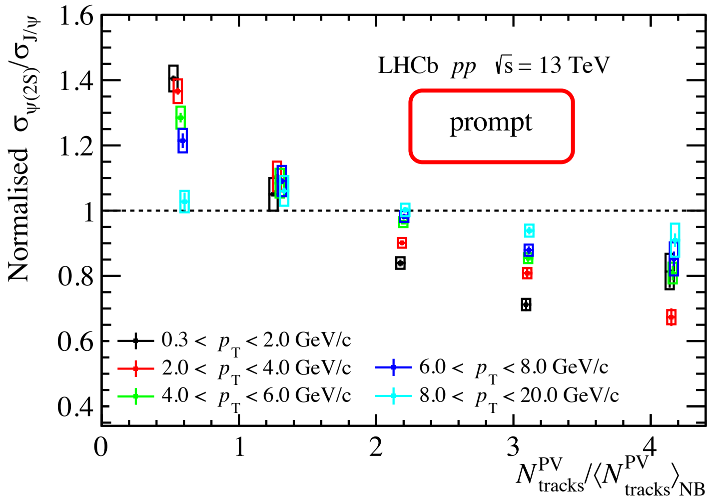
NEW

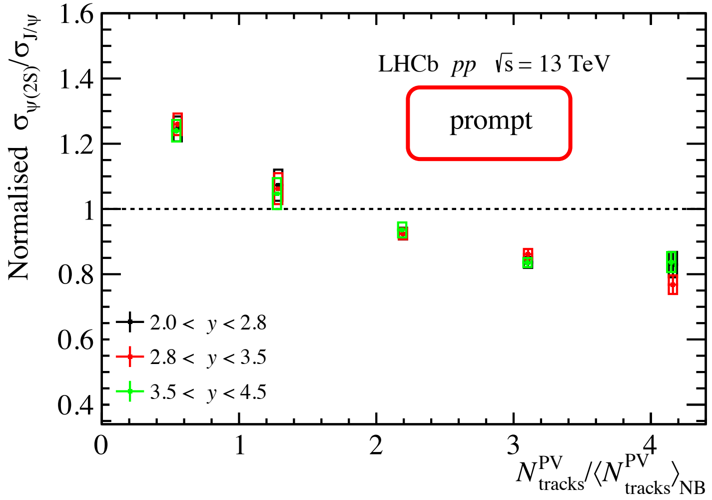
pp collisions as a starting point



Initial-state effects cancelled

[JHEP 05 (2024) 243]





Non-prompt production: no multiplicity dependence

Prompt production:

- Decreases as a function of multiplicity, describe well by co-mover model
- Stronger dependence with the multiplicity as a function of p_T
- Similar dependence with the multiplicity as a function of rapidity

Conclusion:
Very precise measurement of (non-)prompt charmonium in pp collision as a function of multiplicity.
Testing production mechanism as a baseline for the studies in pPb collisisons.

$\psi(2S)/J/\psi$ in pPb collisions at 8.16 TeV

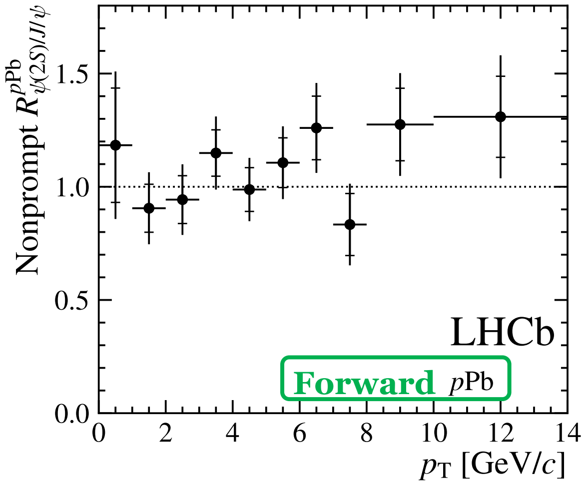
NEW

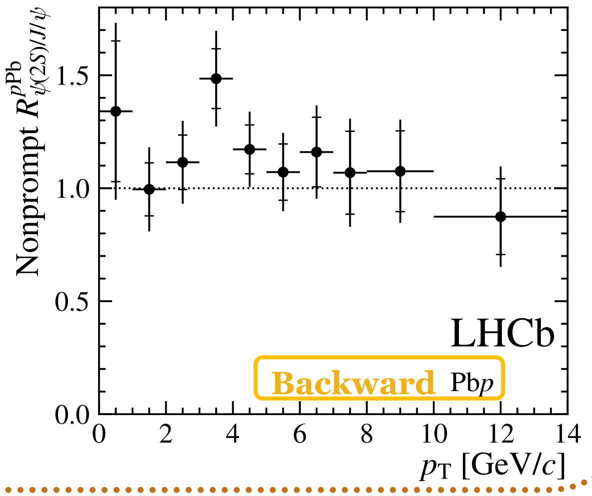
[JHEP 04 (2024) 111]

How about in pPb collisions? **Initial-state effects cancelled**

$$R^{pPb}_{\psi(2S)/J/\psi} = \frac{R^{pPb}_{\psi(2S)}}{R^{pPb}_{J/\psi}} = \frac{[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}]_{pPb}}{[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}]_{pp}}$$

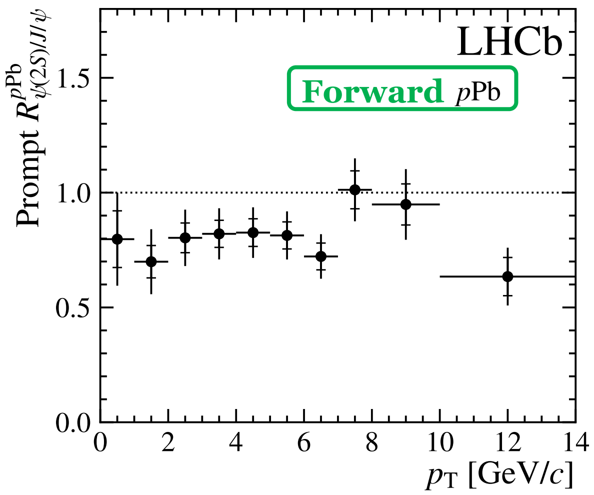
of **non-prompt productions** are compatible with unity as expected, with larger uncertainties due to the smaller statistics. Nuclear effects affect **b-hadron production** rather than their decays.

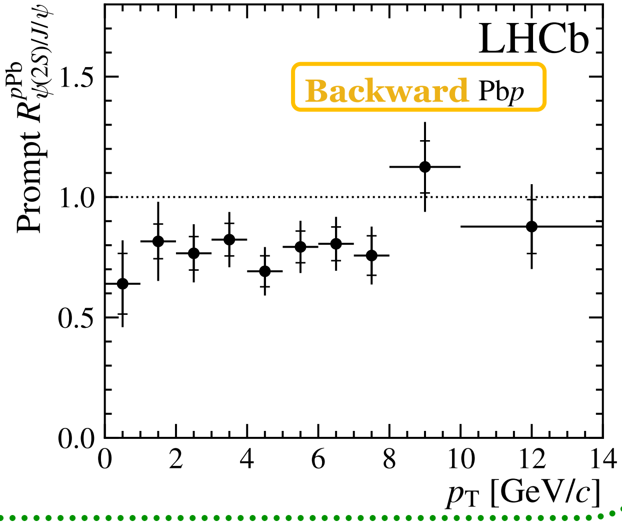




$R^{pPb}_{\psi(2S)/J/\psi}$ of **Prompt production** is suppressed in pPb compared to pp.

$\psi(2S)$ and J/ψ are both affected by initial-state effects, but **$\psi(2S)$** is also more affected by final-state effects.





$\psi(2S)/J/\psi$ in pPb collisions at 8.16 TeV

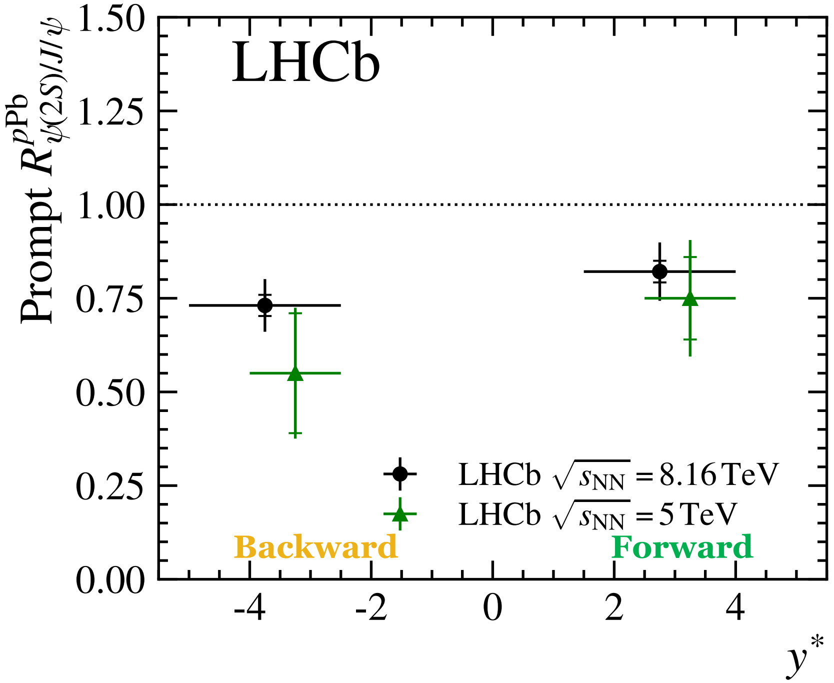
NEW

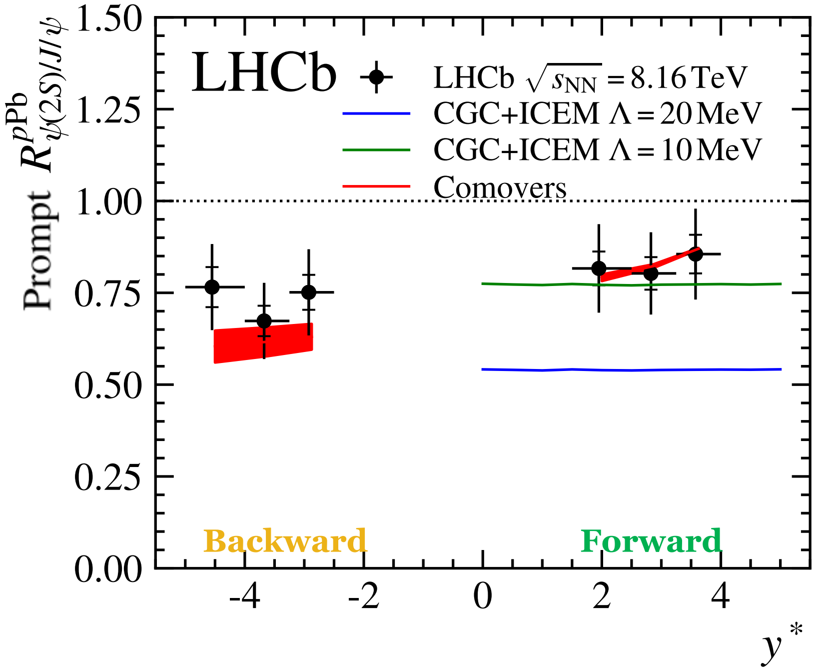
Charmonium suppression in pPb? **Initial-state effects cancelled**

[JHEP 04 (2024) 111]

$$R^{pPb}_{\psi(2S)/J/\psi} = \frac{R^{pPb}_{\psi(2S)}}{R^{pPb}_{J/\psi}} = \frac{[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}]_{pPb}}{[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}]_{pp}}$$

- The additional suppression seen in prompt ψ(2S) production is **compatible** between the forward (pPb collisions) and backward (Pbp collisions).
- Consistent with **5TeV** results with much higher precision.
- Results can be described by **models** (CGC+ICEM, co-mover).





Conclusion:
Precise measurement of (non-)prompt charmonium in pPb collision.
Important to constrain factorization breaking with respect to the final state in nuclear collisions, in order to interpret quarkonium data in heavy-ion collisions.

Fraction of χ_c in prompt J/ψ in pPb at 8.16 TeV

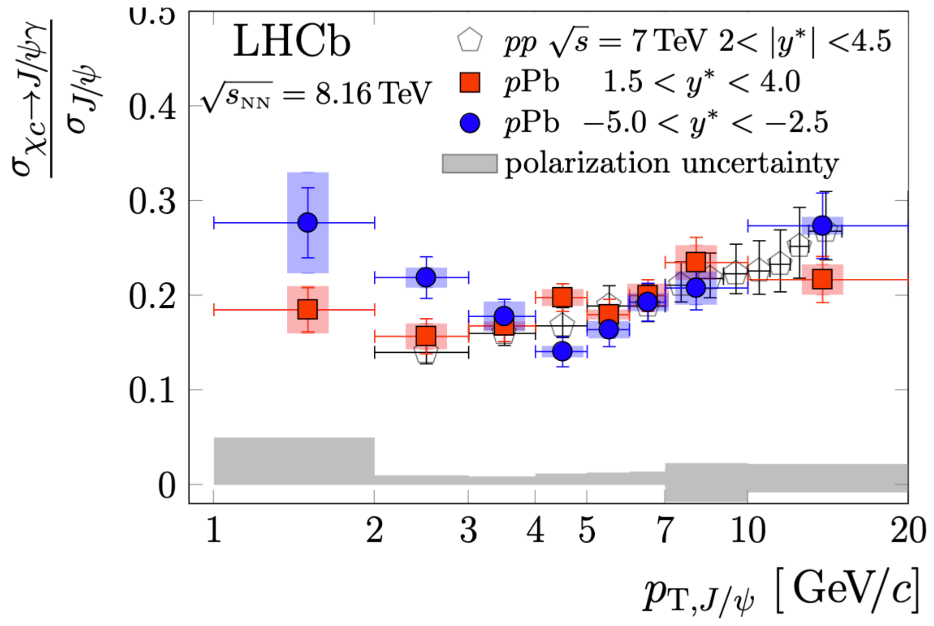
NEW

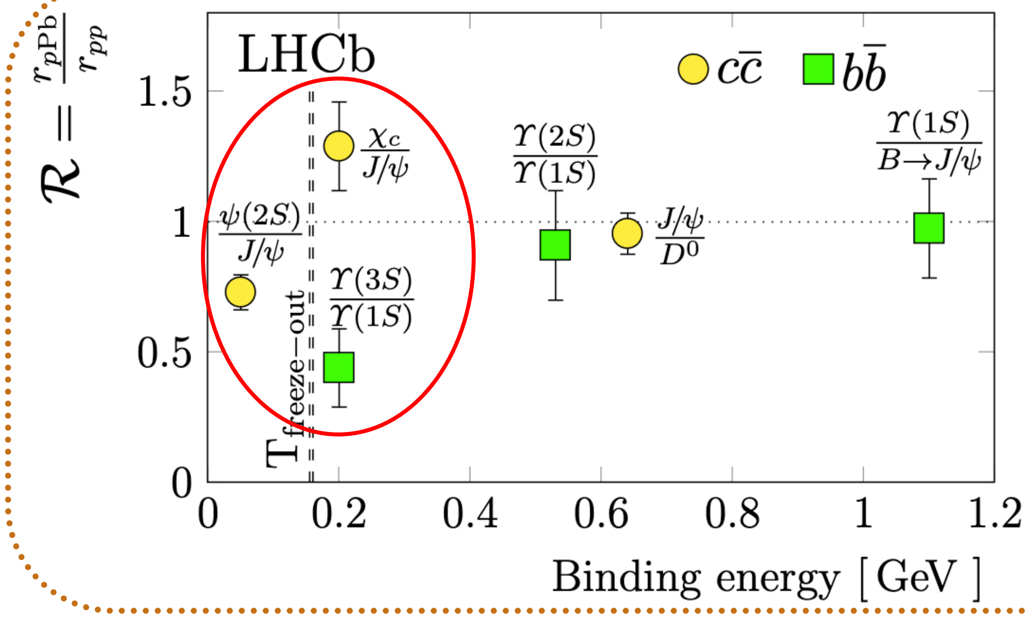
$$F_{\chi_c \to J/\psi} \equiv \frac{\sigma_{\chi_c \to J/\psi \gamma}}{\sigma_{J/\psi}} = \frac{N_{\chi_c \to J/\psi \gamma}}{N_{J/\psi}\ \varepsilon_{\chi_c/J/\psi}}$$

$N_{\chi_c \to J/\psi \gamma}$: Direct J/ψ from χ_c decay

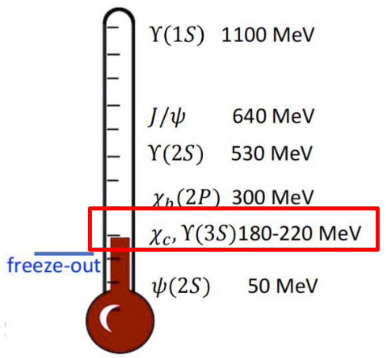
$N_{J/\psi}$: Direct J/ψ + contributions from feed-down from $\psi(2S)$ and χ_c decay

[Phys. Rev. Lett. 132 (2024) 102302]





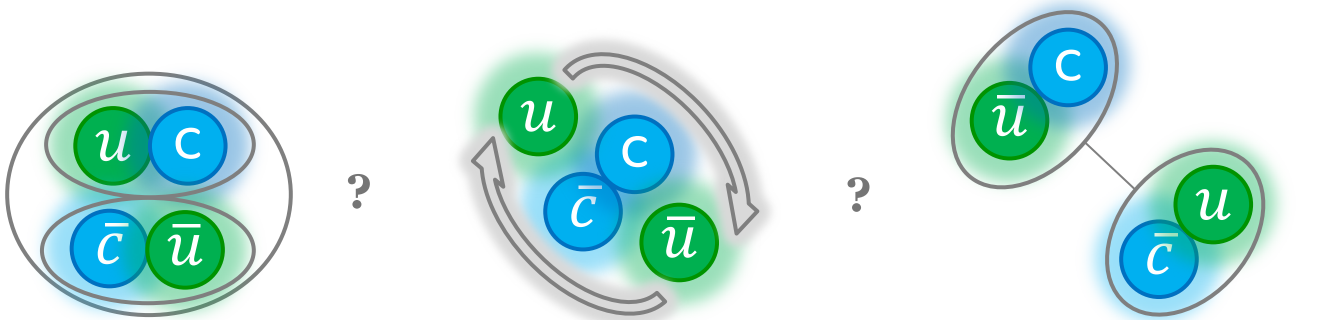
The first measurement for the fraction of χ_c in prompt J/ψ yield in heavy-ion collisions at the LHC!



- Forward rapidity consistent with pp results, backward largely consistent with pp at higher p_T.
- Looking at $\psi(2S)$, with binding energy below freeze-out temperature, $\psi(2S)$ shows significant suppression.
- Compared to $\Upsilon(3S)$, similar binding energy as χ_c, $\Upsilon(3S)$ breaks up while χ_c does not.
  - (non-relativistic potential theory): $\Upsilon(3S)$ is 2.9 times heavier, traveling the medium slowly than the χ_c
  - Favoring its dissociation by its interaction with co-moving particles

Hard Probes: **Exotica** measurements

- 20-year debate of $\boldsymbol{\chi_{c1}(3872)}$ structure:

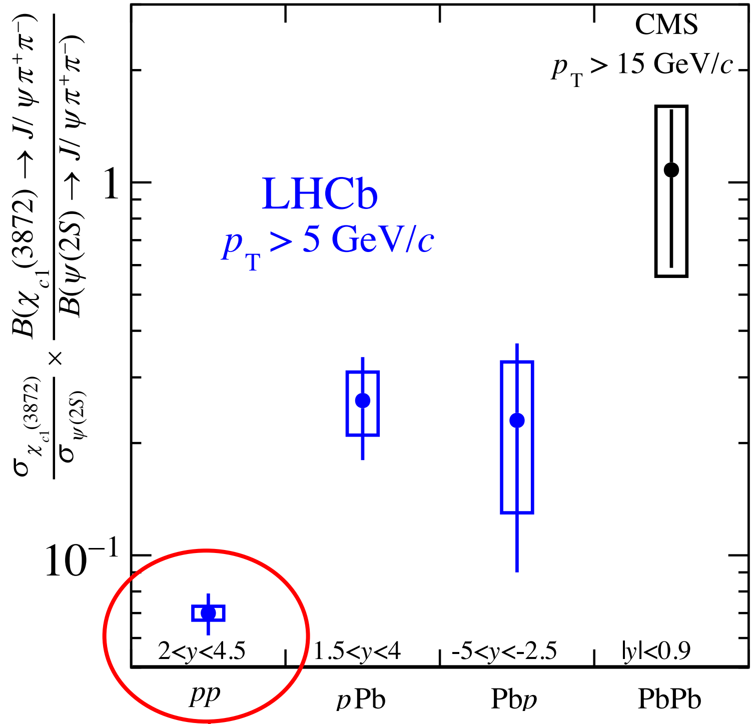


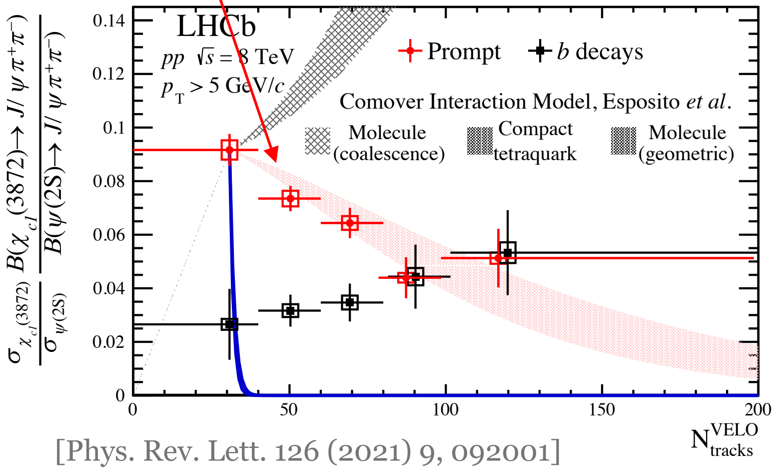
Compact tetraquark **Hadrocharmonium** **Hadronic molecules**

- $\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}}$ increases as the system size increases, while decreases as multiplicity increases inside pp collisions.

Conclusion:
The first measurement of exotic hadron $\chi_{c1}(3872)$ in proton-nucleus collisions!
Supports the idea that the exotic hadron experiences different dynamics in the nuclear medium than conventional hadrons.

[Phys. Rev. Lett. 132 (2024) 242301]





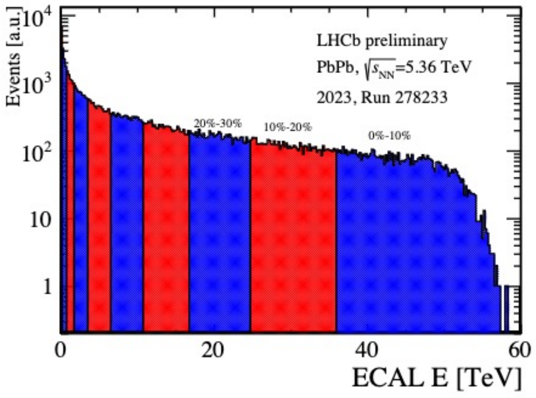
[Phys. Rev. Lett. 126 (2021) 9, 092001]

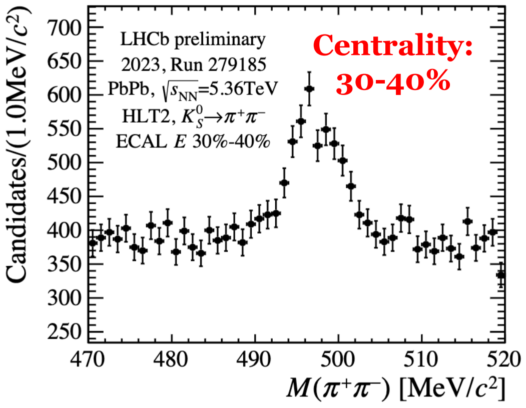
Take away message

- **LHCb** provides an unique and excellent way to study heavy-ion physics:
  - Accessible in large range of Bjorken-x, crucial to constrain nPDFs as well as cold and hot nuclear matter effects
  - Providing new and precise measurements of heavy flavors, quarkonia, exotica in different collision systems

- Still **plenty of results** coming out from Run2 data-taking:
  - Most precise open heavy flavor measurements in pPb collisions
  - Most precise quarkonium measurements in pp and pPb collisions
  - Last but not least: **Ultra-peripheral Collisions(coherent quarkonia)** and **light flavors(flow, $\pi^0, \eta, \eta', \pi^{\pm}, K^{\pm}, p, \bar{p}..\, in\ pPb$)** haven't discussed in this talk but also excellent measurements!

- Ambitious **upgrade** plan on heavy-ion physics program is well underway:
  - UpgradeI: LHCb already reconstructed PbPb collisions down to **30%** centrality - big milestone for heavy-ion program
  - UpgradeII: aiming to achieve the whole centrality region(**0-100%**) dedicated detectors for UPC to be installed





[LHCb-FIGURE-2023-030]

Back Ups

Prompt D^0 production in pPb at 8.16 TeV

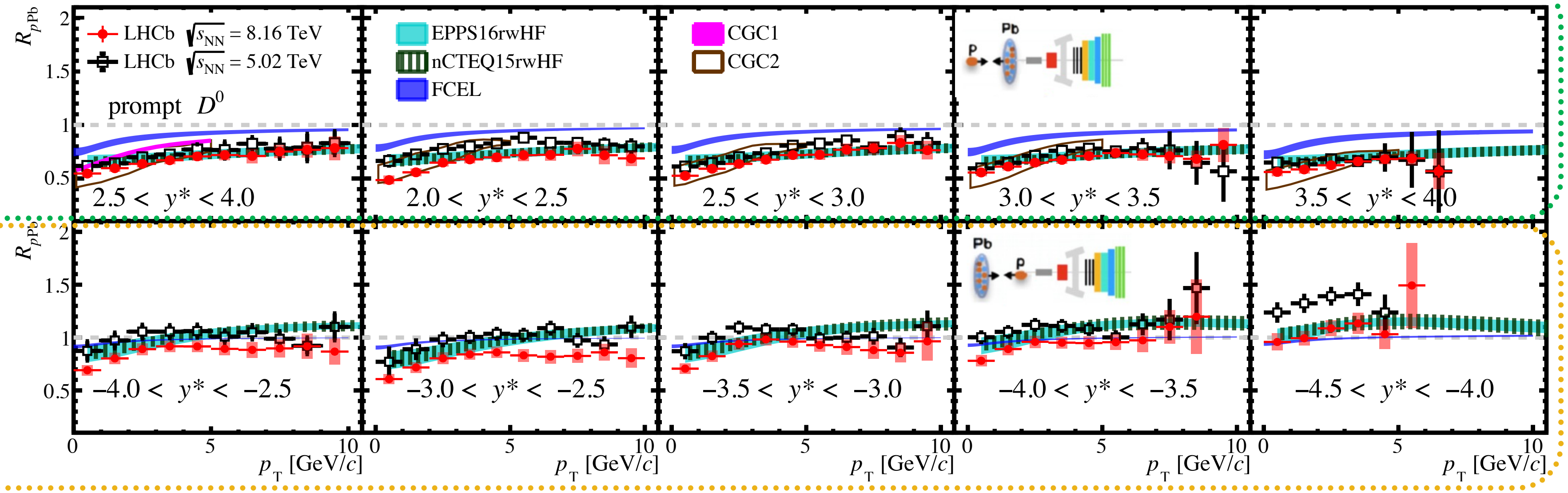
Studying cold nuclear matter effect:

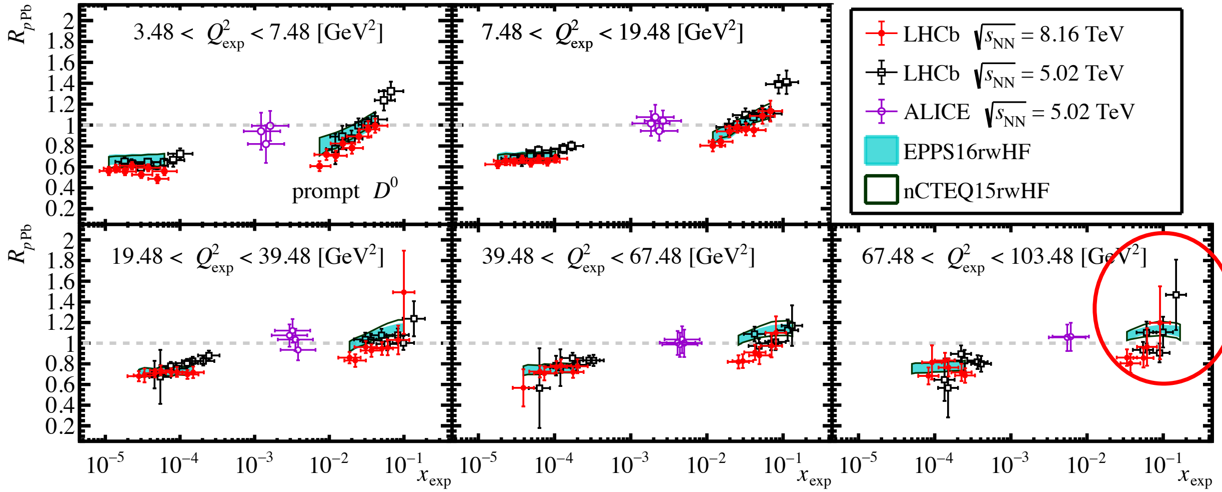
$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

[Phys. Rev. Lett. 131 (2023) 102301]

Forward: stronger suppression for $R_{pPb}(D^0)$ than nPDF at low-p_T, possibly due to the fully coherent energy loss (FCEL) effects besides nuclear shadowing.

Backward: more suppression for $R_{pPb}(D^0)$ than nPDF at low- p_T, indicating additional initial or final state effects.





$$x_\mathrm{exp} \equiv 2\frac{\sqrt{{p_\mathrm{T}}^2(D^0)+M^2(D^0)}}{\sqrt{s_\mathrm{NN}}}e^{-y^*} \text{ and } Q^2_\mathrm{exp} \equiv {p_\mathrm{T}}^2(D^0)+M^2(D^0)$$

Stronger suppression than nPDF calculations in $x\sim0.01$ at larger Q^2.

Conclusion:

The most precise measurement of prompt $\boldsymbol{D^0}$ production in pPb collisions, constraining nPDF parametrization down to $x\sim10^{-5}$.

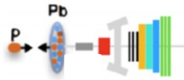
Prompt charged particle production in pPb and pp at 5TeV

Studying cold nuclear matter effect: $R_{pPb}(\eta, p_T) \equiv \frac{1}{A} \frac{d^2\sigma^{ch}_{pPb}(\eta, p_T)/dp_T d\eta}{d^2\sigma^{ch}_{pp}(\eta, p_T)/dp_T d\eta}$

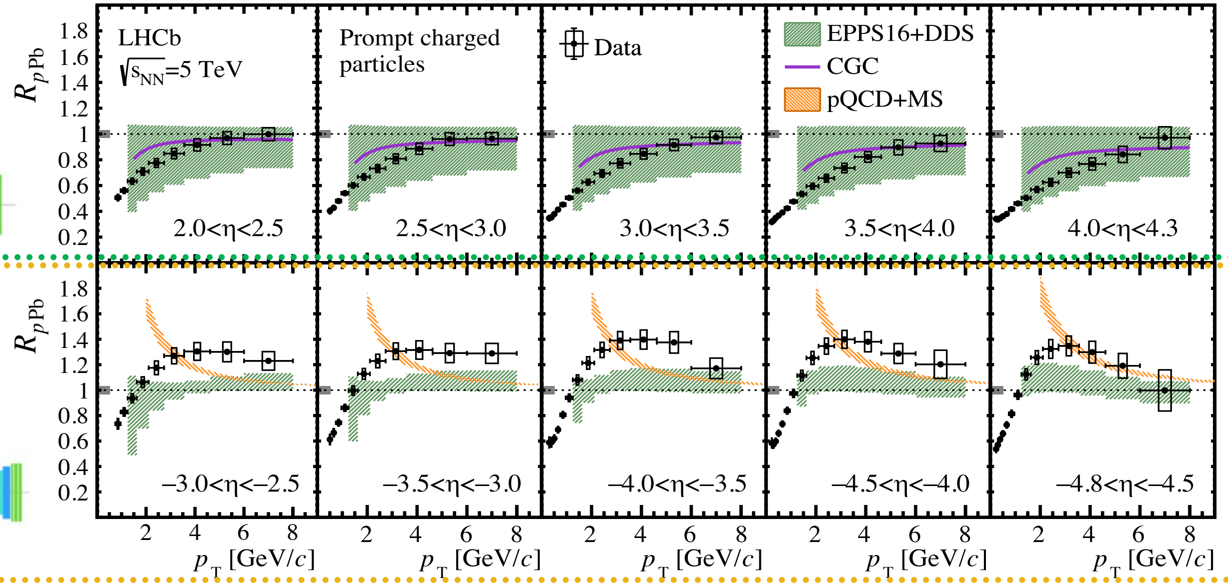
unidentified charged particles: $\pi^{\pm}, K^{\pm}, p, \bar{p}, \ldots$

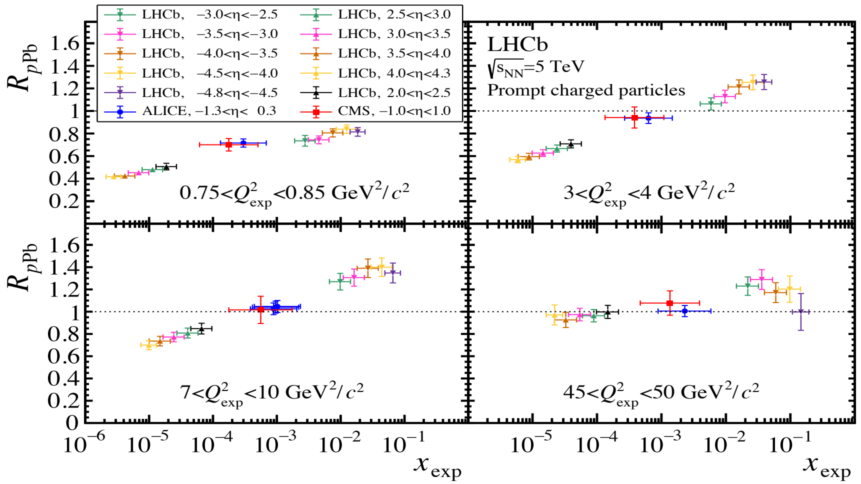
[Phys. Rev. Lett. 128 (2022) 142004]

Forward: strong **suppression** of charged particle production in pPb collisions relative to in pp. Well described by the models(nPDFs, NLO CGC).



Backward: more suppression at low- $p_T(< 1.5GeV)$,while enhancement at high- $p_T(> 1.5GeV)$. Inconsistent with theoretical models(nPDFs, pQCD+MS).





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

A consistent trend between LHCb measurements (forward&backward) and ALICE and CMS(mid-rapidity) is observed.

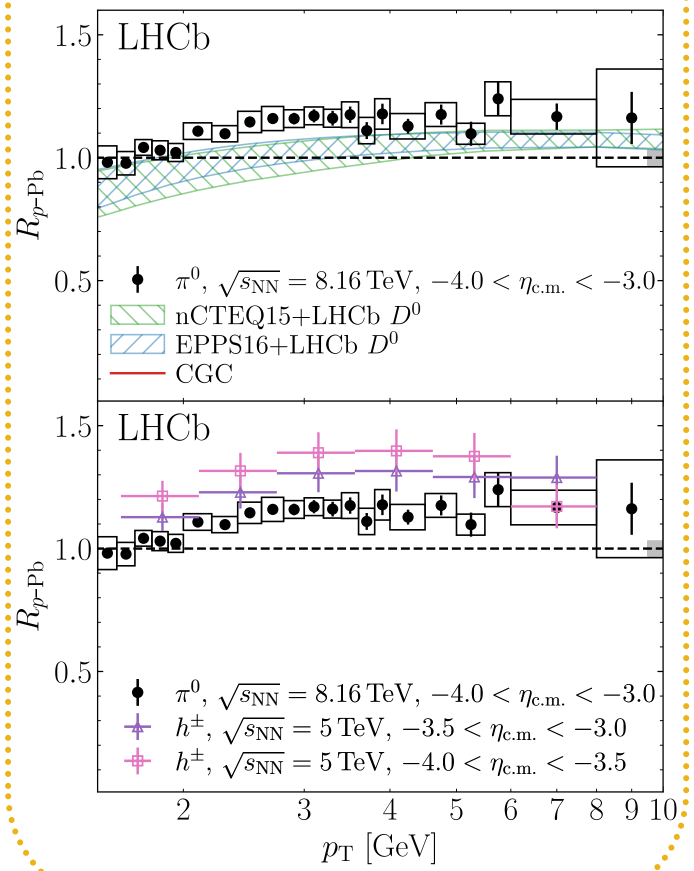
Conclusion:
The first measurement of determination of such cross-section in pPb at the LHC, and the first measurement in pp collisions at 5TeV.

π^0 production in pPb and pp at 5TeV

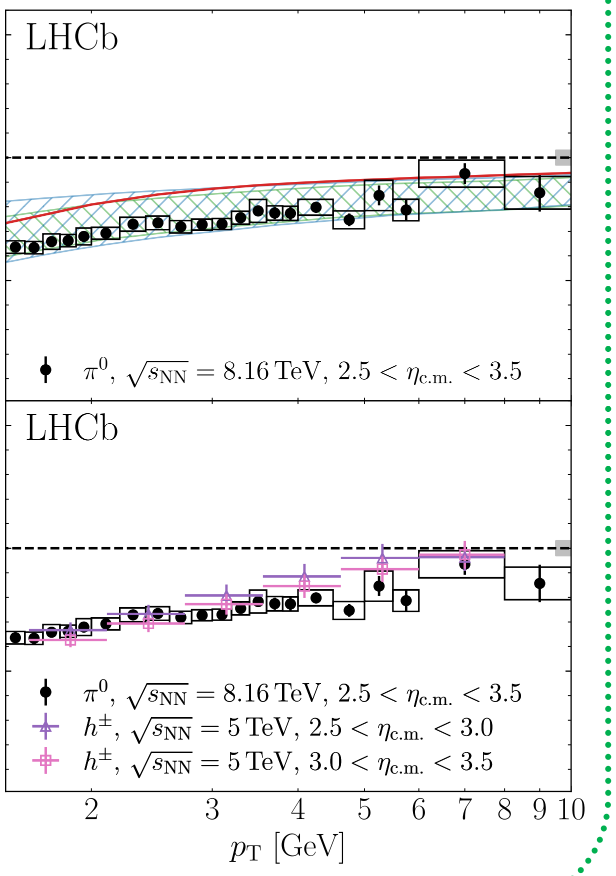
Identified light mesons: π^0

[Phys. Rev. Lett. 131 (2023) 042302]

Backward



Forward



Forward: Agreement with nPDFs predictions and charged hardon data, sensitive to low-$x \sim 10^{-6}$.

Backward: Enhancement below the charged hadron data, but above the nPDFs predictions.

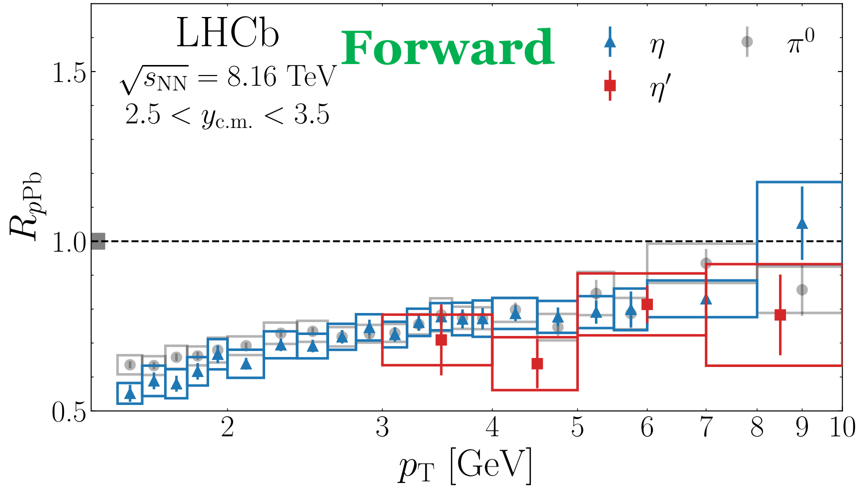
Potential explanations:

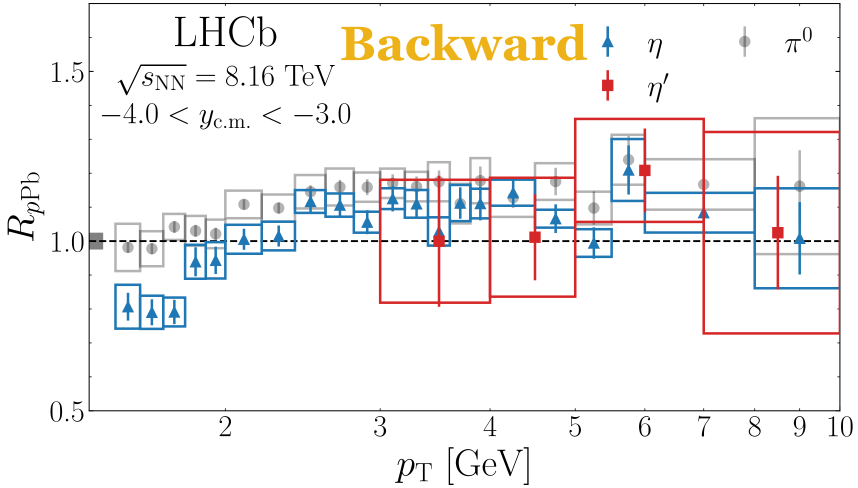
- Mass-dependent enhancement from radial flow
- Baryon enhancement inal-state recombination

Conclusion:
Very precise measurements of nuclear modification factor, with $\delta_{total} < 6\%$ in almost p_T intervals.
Constraining nPDFs in small collisions systems.

η, η' production in pPb and pp at 5TeV

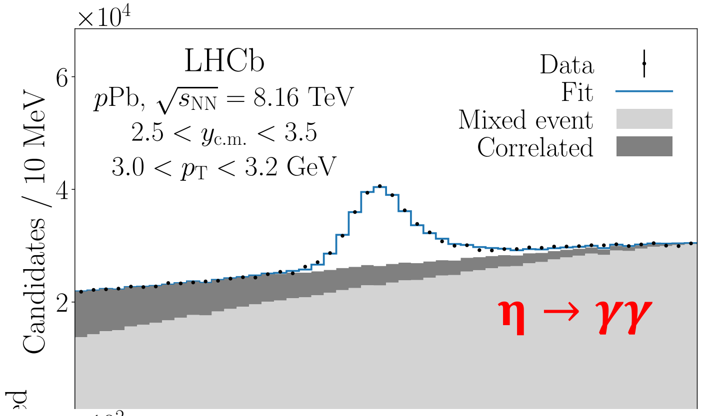
Studying mass-dependent nuclear effects :

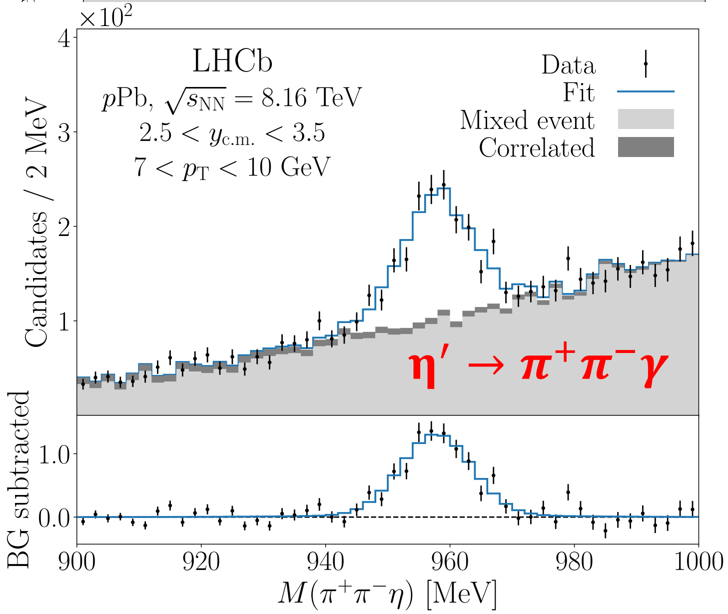




Identified light mesons: η, η'

[Phys. Rev. C 109 (2024) 024907]



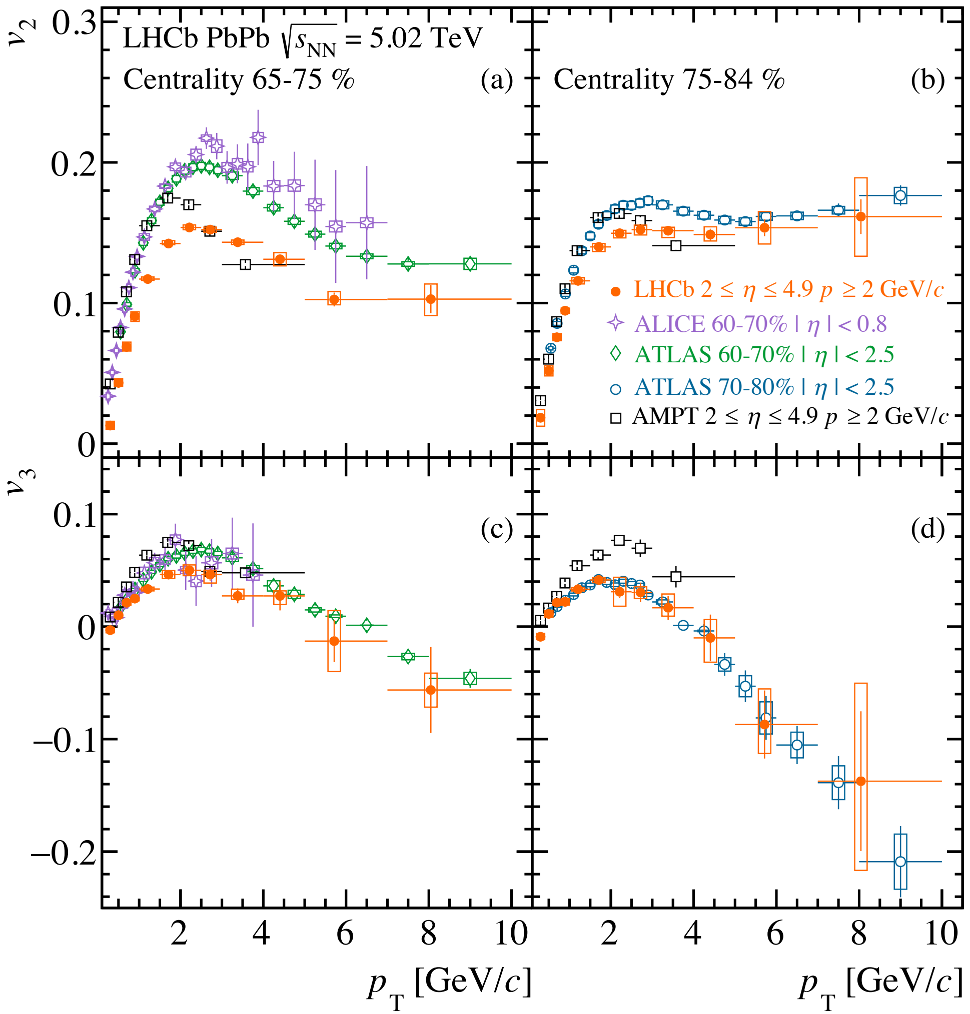


- ✓ The R_{pPb} of π^0, η, η' are in agreement.
- ✓ No clear indication for mass-dependent nuclear effects.
- ✓ Interpretation of baryon and strangeness enhancement studies in small collision systems.

Conclusion:
The first measurement of η meson at forward and backward rapidity at LHC.
The first measurement of η' meson in p-A collisisons.

Charged-hadron flow harmonics in PbPb

Studying hydrodynamics of QGP created in heavy-ion collisions:



$$v_n^b(\langle p_{Tb}\rangle) = \sqrt{V_n(\langle p_{Tb}\rangle, \langle p_{Tb}\rangle)}$$

v_2, v_3 measured at LHCb are smaller than those at ALICE and ATLAS at mid-rapidity, possibly due to the dominant freeze-out phase in forward region leading to a weaker flow.

Sharing same features of rising v_2 and v_3 at $p_T < 2.5\ ^{GeV}/_{c}$ and falling at high p_T.

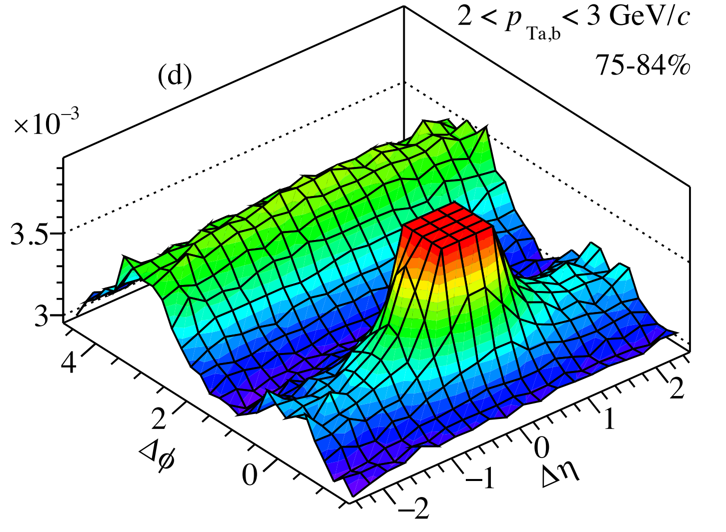
AMPT simulations overestimate both flows.

Forward rapidity coverage provides new constraints on flow models.

[Phys. Rev. C109 (2024), 054908]

2D angular correlation functions

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

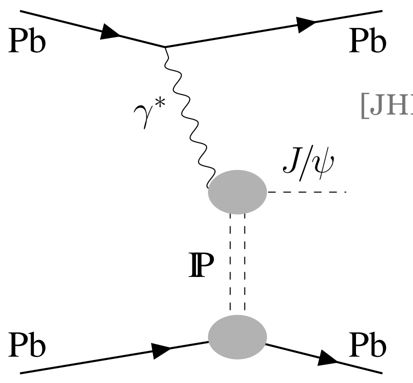


Stronger flow in PbPb than in pPb collisisons

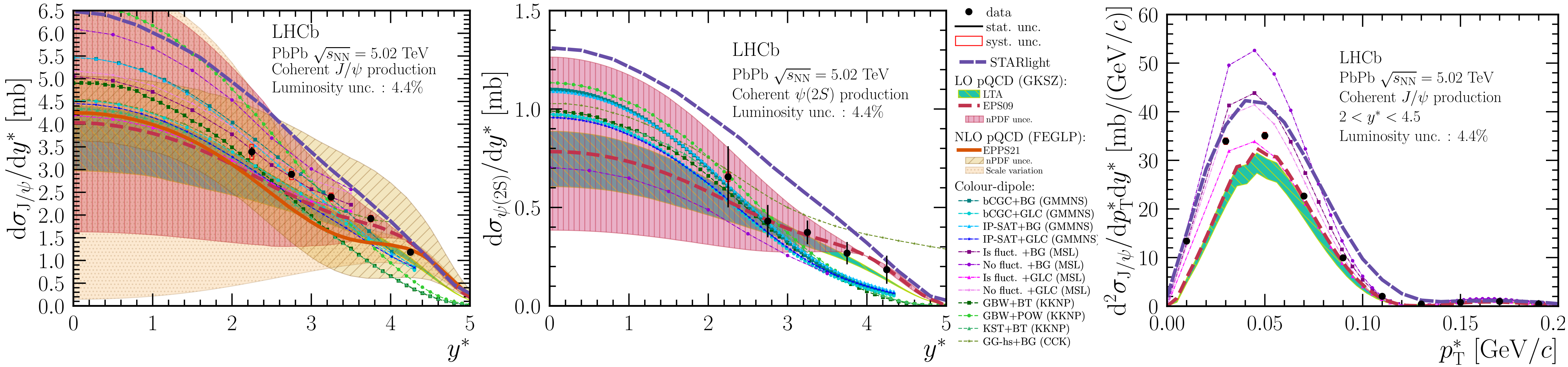
Conclusion:
The first flow harmonics measurement at LHCb!
More results are coming out!

Electromagnetic Probes: Ultra-peripheral Collisions (UPCs)

- Coherent photo-produced charmonia production in UPC with 2018 PbPb is studied
- Probing the nuclear gluon distribution functions at the scale of $Q^2 \sim m^2/4$
  - High precision J/ψ data at forward rapidity helps to constrain the theoretical models
  - First measurement of $\psi(2S)$ in UPC at LHC
  - High precision down to very low- p_T, better tuning the models as a function of p_T



[JHEP 06 (2023) 146]

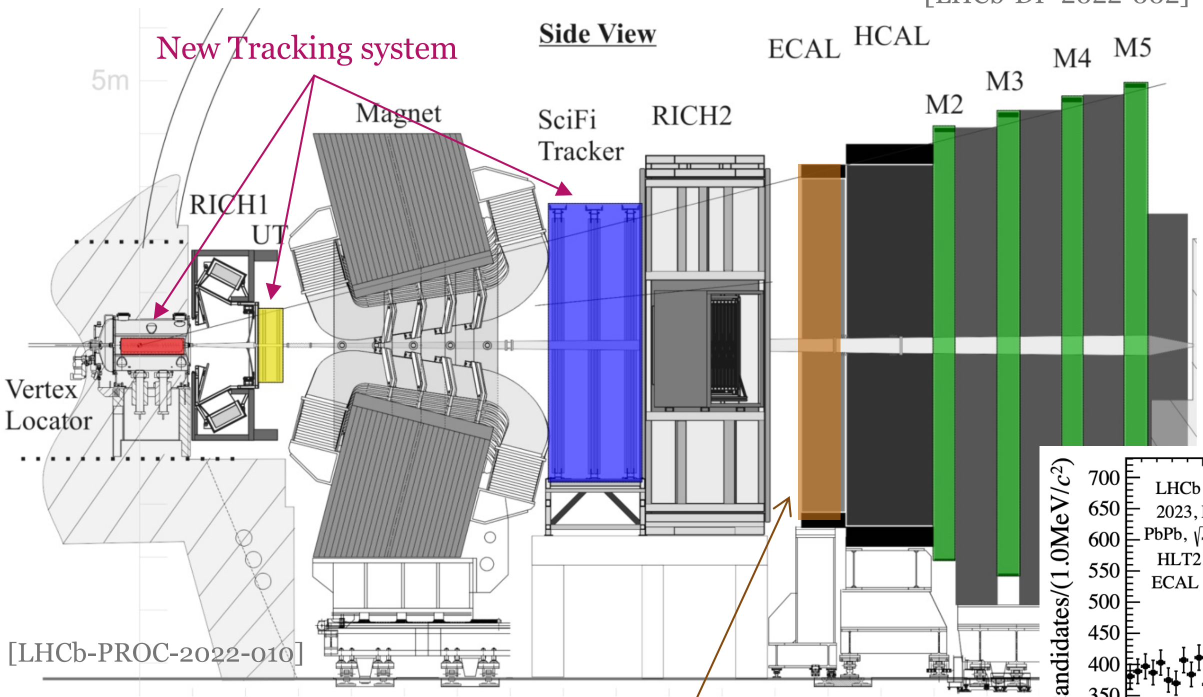


Conclusion:
LHCb is also an excellent photon collider (UPC) to study the nPDFs and gluon density functions at low-x region.
More new UPC measurements(ρ, ϕ, ALP, etc) underway.

LHCb Upgrade

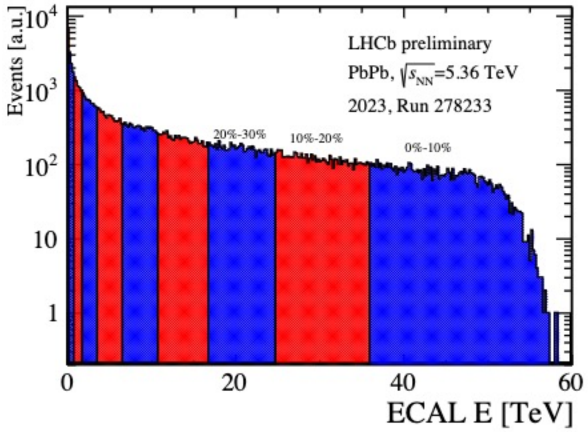
Challenges:
High luminosity, pile-up
High occupancy and radiation

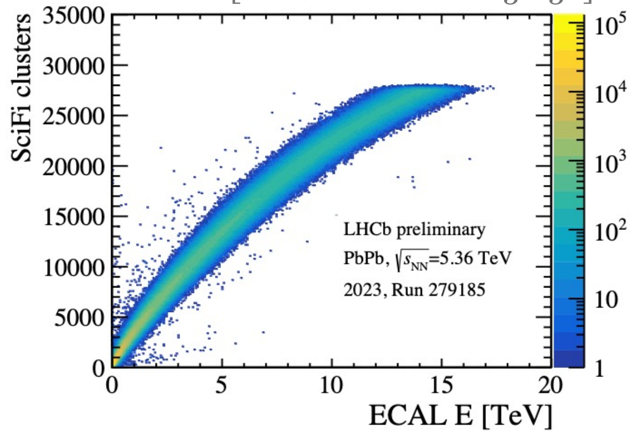
About Upgrade I

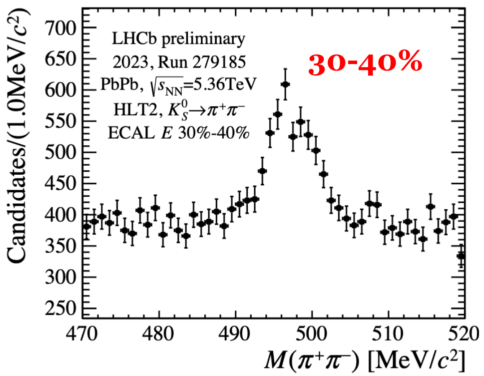


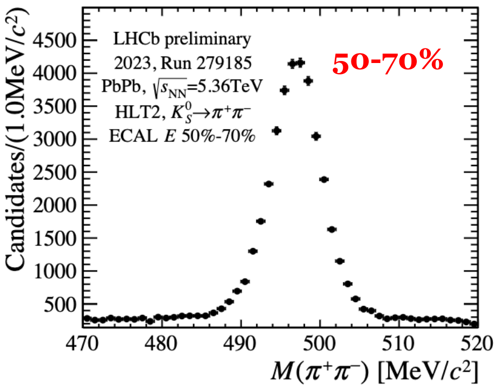
Removal of hardware trigger for a completely software-based trigger system

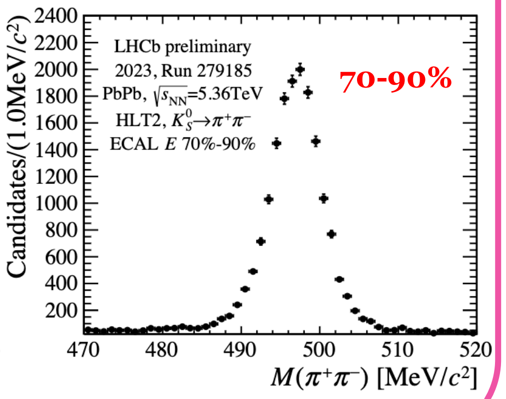
Upgraded readout electronics







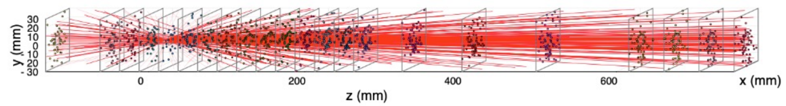




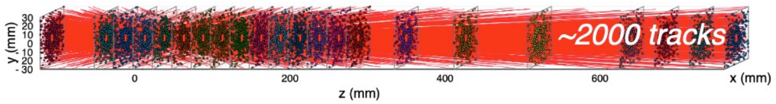
About Upgrade II:

- Reconstruct PbPb down to **~0%** centrality
- More precise measurements come at **low p_T** in **central** collisions

(UpgradeI) Run3&4: pile-up ~6

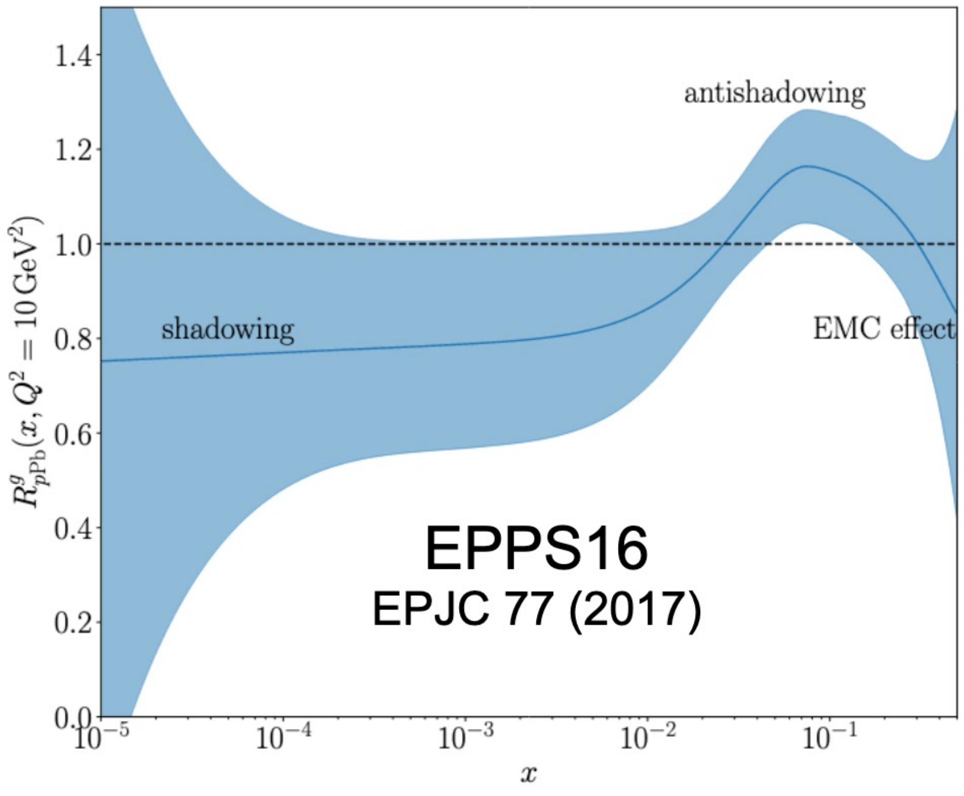


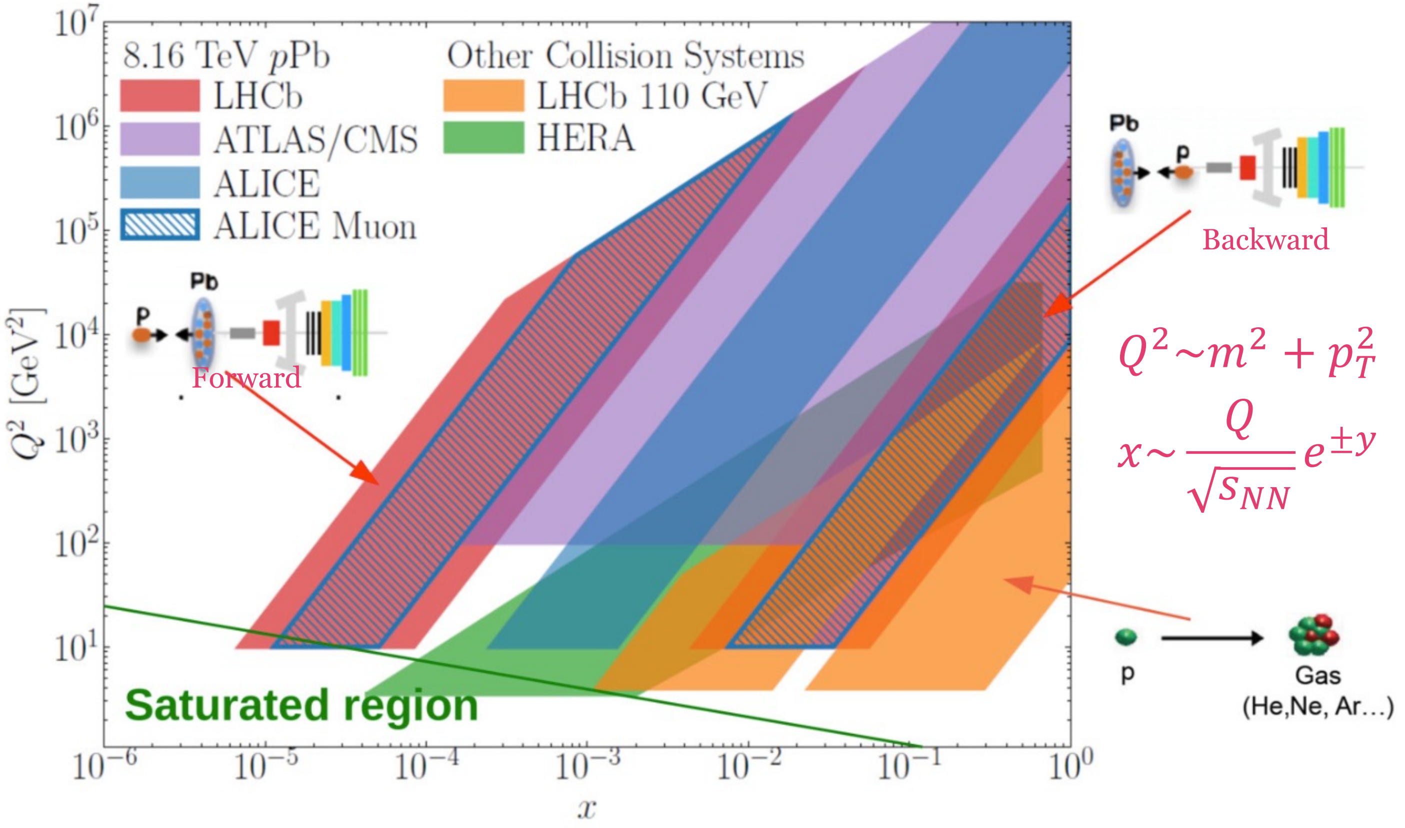
(UpgradeII) Run5&6: pile-up ~40



Heavy-ion studies at LHCb

- Unique forward rapidity coverage
  - ✓ Constrain nPDFs at small and large Bjorken-x
  - ✓ Probing gluon saturation in low-x and low Q2 region
  - ✓ Probing (anti-)shadowing in large-x region
  - ✓ Test hadronization mechanisms in medium
  - ✓ Studying final state effects in medium
  - ✓ Search for possible QGP formation in small systems





$$Q^2 \sim m^2 + p_T^2$$

$$x \sim \frac{Q}{\sqrt{s_{NN}}} e^{\pm y}$$