Open Charm Production Based on QM2022

Ziyang Li

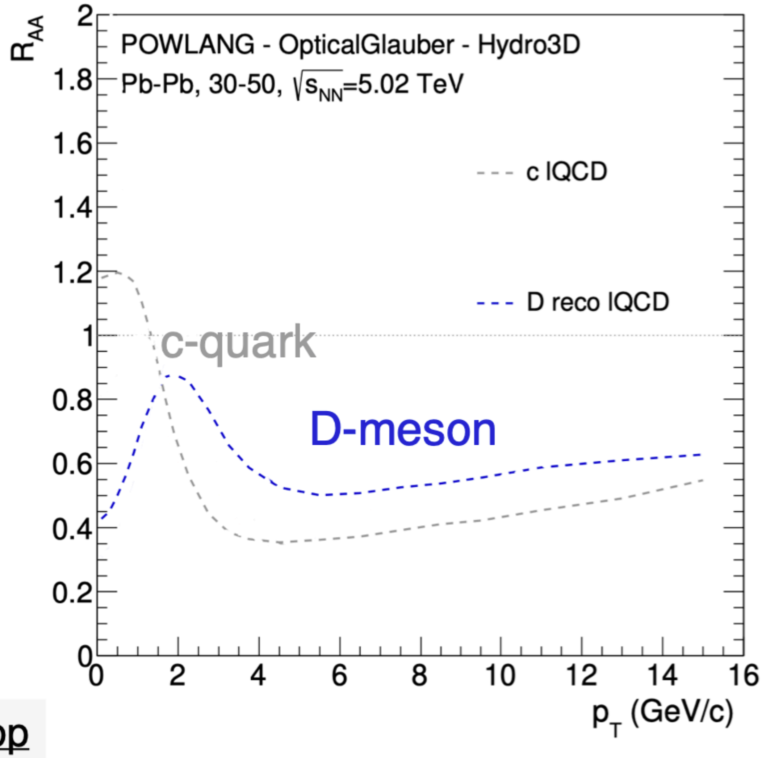
2022.5.6

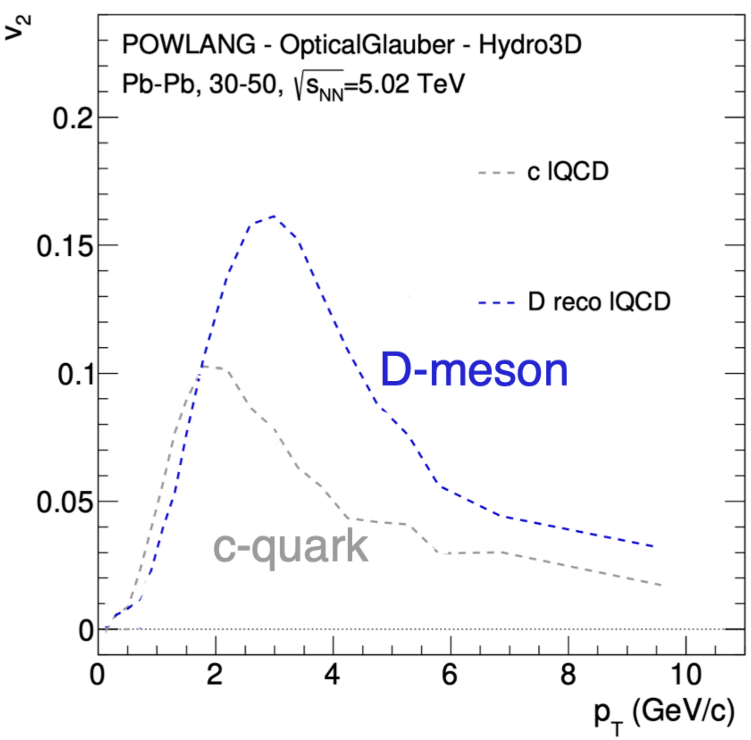
In-medium Hadronization is Important

From quarks to hadrons

- Hadronization: Important ingredient to the phenomenology of the observed R_{AA}, v_2
- Heavy quarks: flavor conservation in QGP ($m_Q \gg T_{QGP}$)

➜ Ideal probe of the in-medium hadronization mechanism





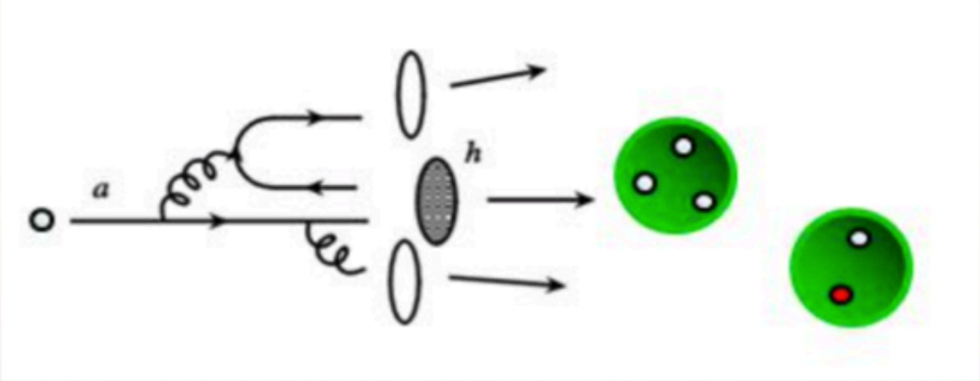
2021 ECT* HF workshop

Two major hadronization mechanisms

Two major hadronization mechanisms

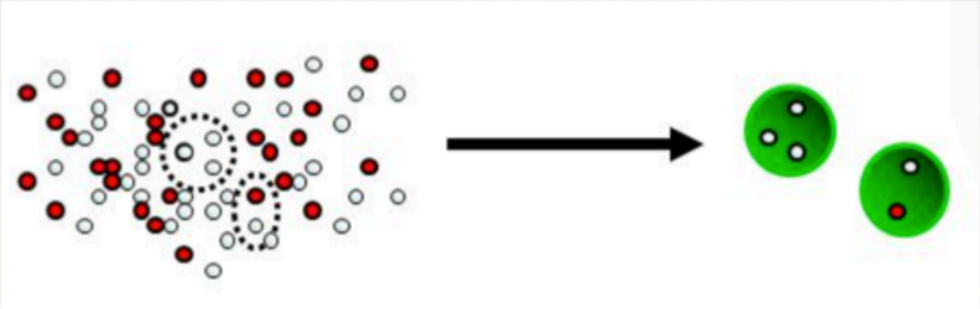
***Fragmentation*:**

High momentum heavy quarks are more likely to fragment into hadrons
[Peterson, FONLL, Pythia, etc.]



***Coalescence* (*recombination*):**

Low momentum heavy quarks are more likely to combine with thermal partons into hadrons

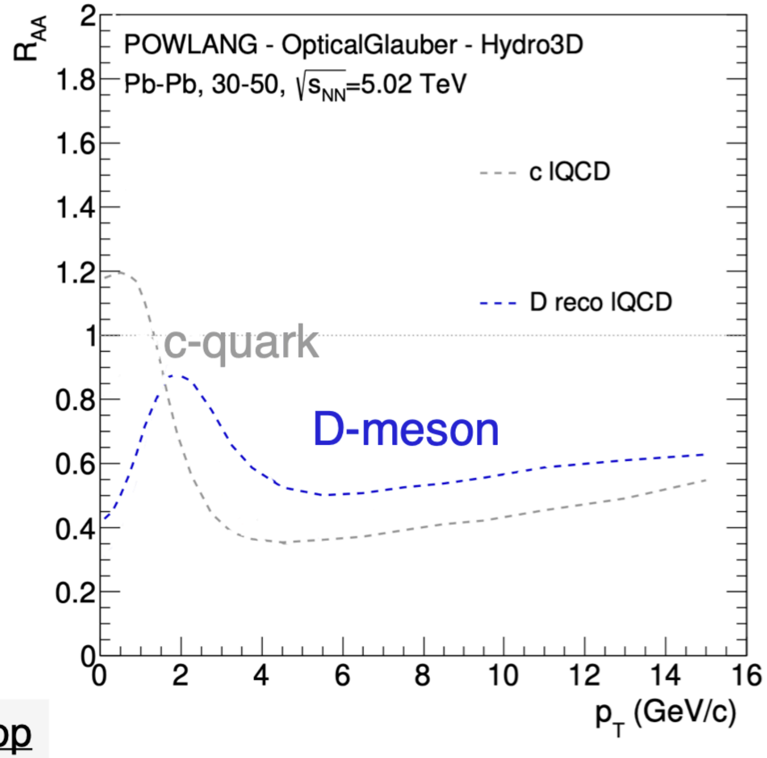


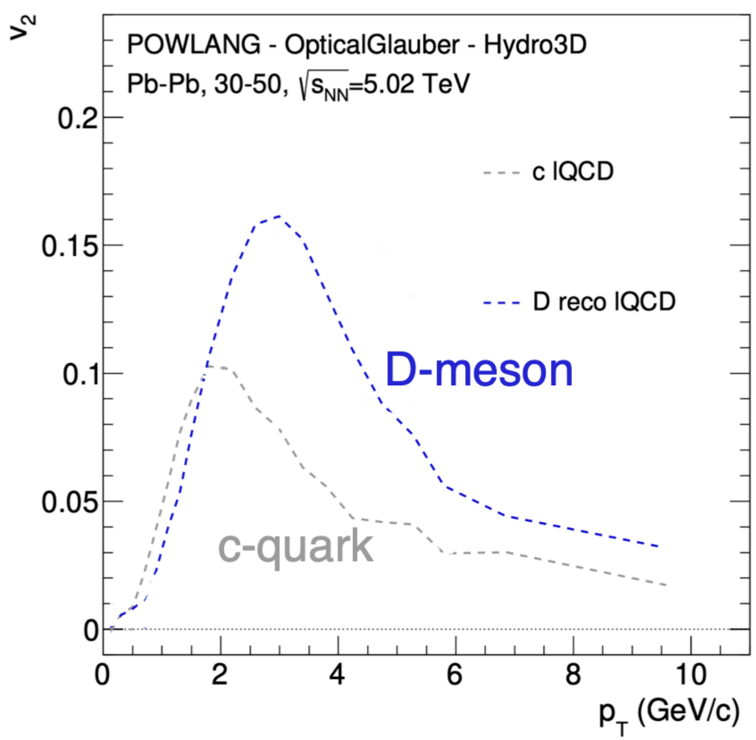
Oh, Ko, Lee and Yasui, PRC 79 (2019)
Plumari, Minissale, Das, Coci and Greco, EPJC 98 (2018)
Cho, Sun, Ko, Lee and Oh, PRC 101 (2020)
SC, Sun, Li, Liu, Xing, Qin and Ko, arXiv:1911.00456

In-medium Hadronization is Important

Hadronization via in-medium recombination + string-fragmentation:

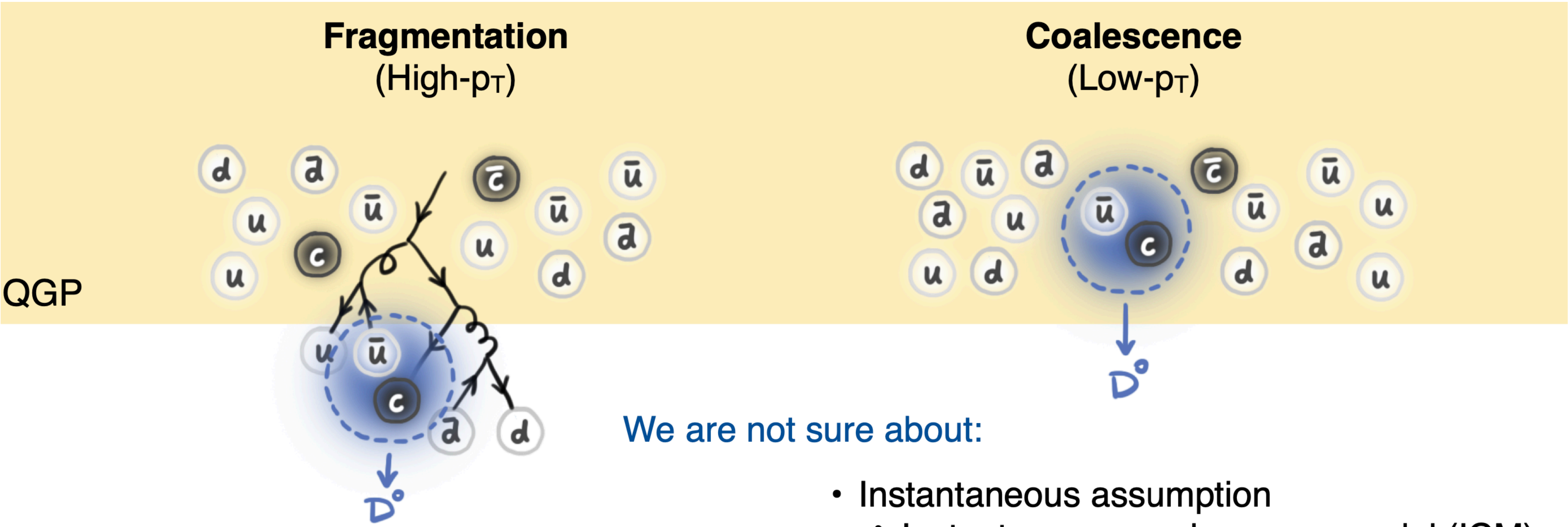
- Strong impact at low-intermediate p_T, HF hadrons inheriting part of the radial and elliptic flow of the light thermal parton;
- Naturally approaches the result of independent fragmentation at high-p_T, without having to switch scheme





2021 ECT* HF workshop

In-medium Hadronization is Complicated

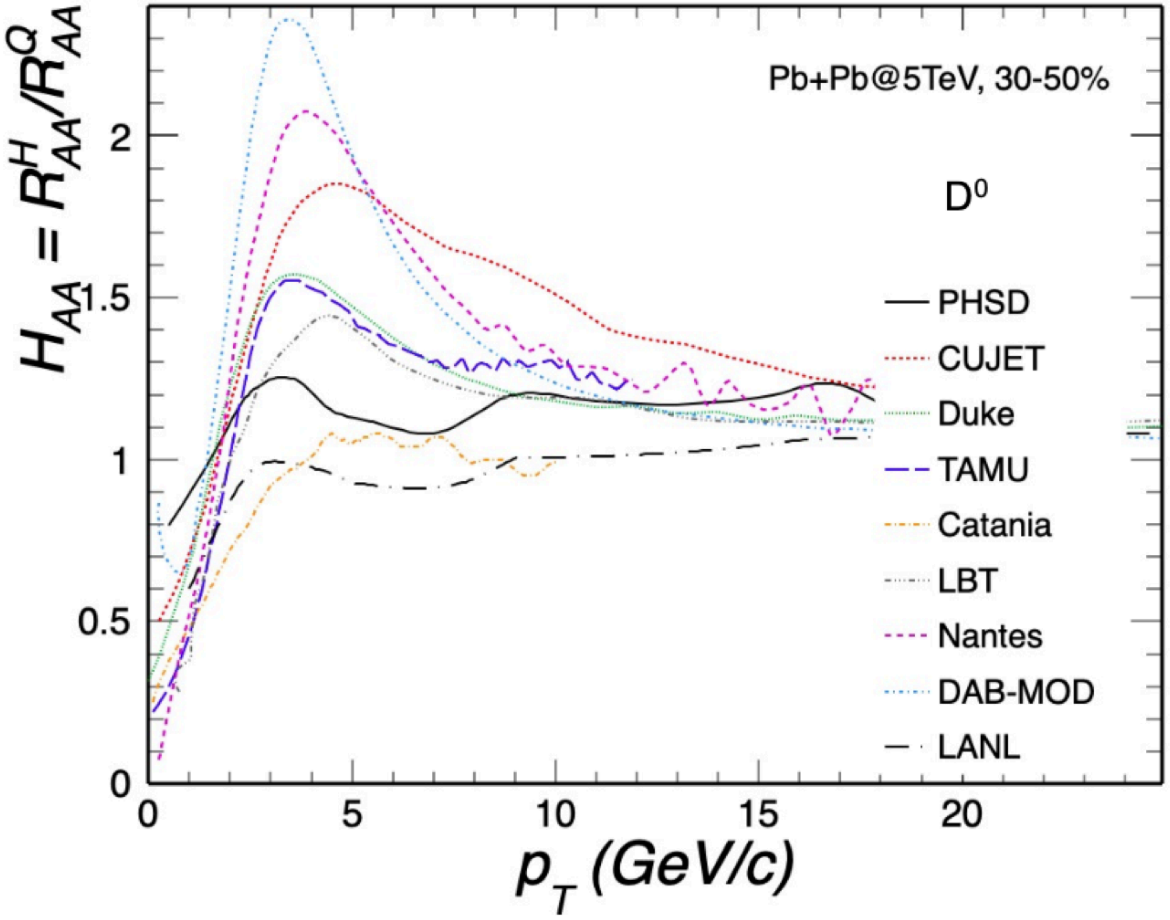


We are not sure about:

- Universality of fragmentation

- Instantaneous assumption
  ➜ Instantaneous coalescence model (ICM)
  ➜ Resonance recombination model (RRM)
- Parameters (thermal quark m_q, width parameter, global normalization, …)

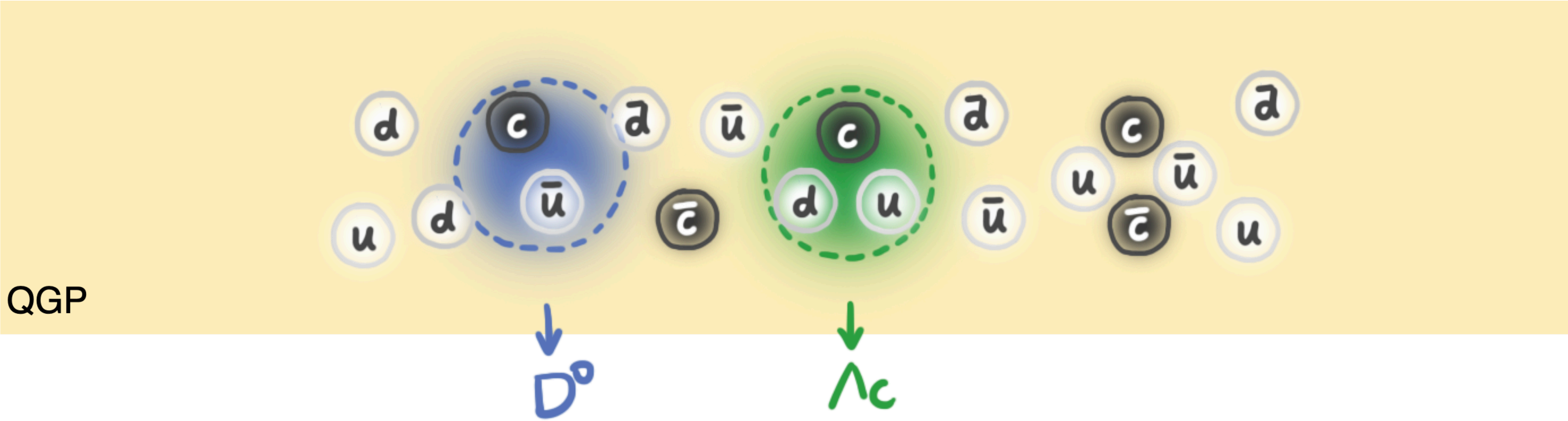
In-medium Hadronization is Complicated



- $H_{AA} = R_{AA}$ (D-meson) / R_{AA} (c-quark) directly exhibits hadronization effects
- Dramatically different hadronization effects in the models using different mechanisms and ways of implementing coalescence
- Lead to poor constraints on hot medium interaction effects

Λ_c -- CMS

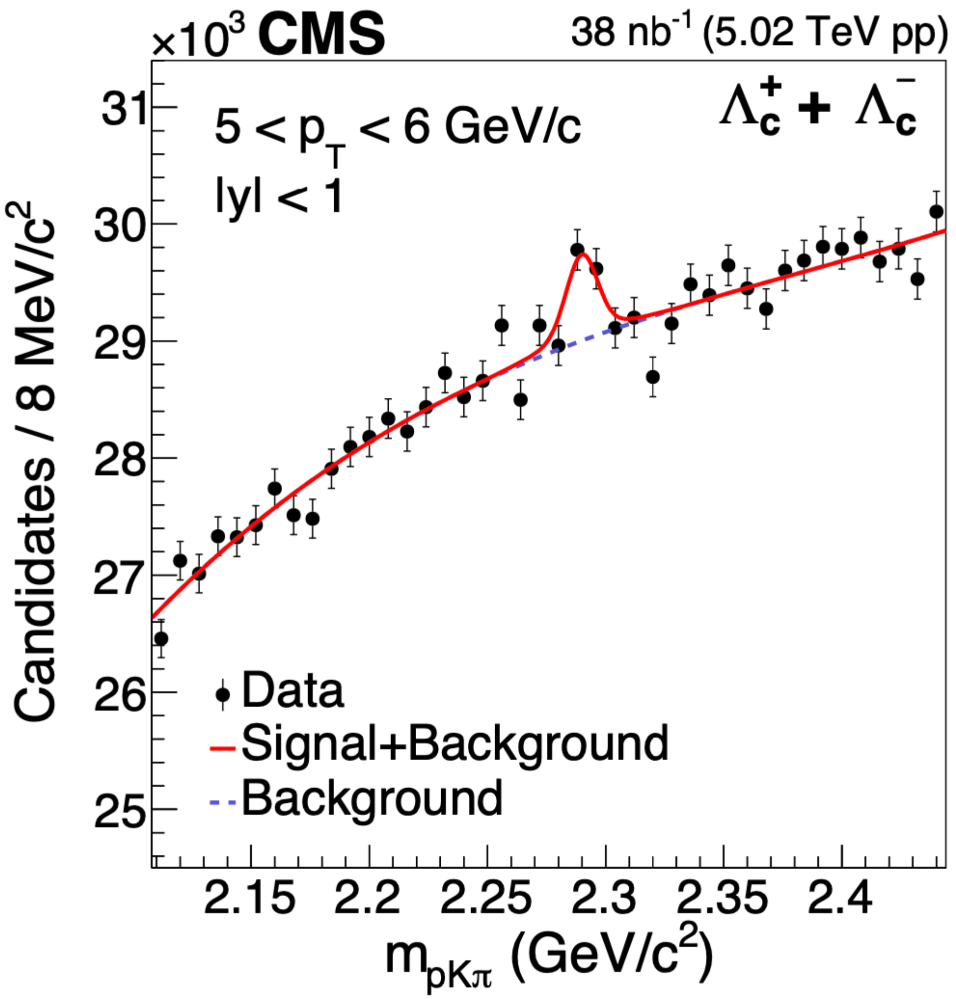
Study Coalescence with Baryons



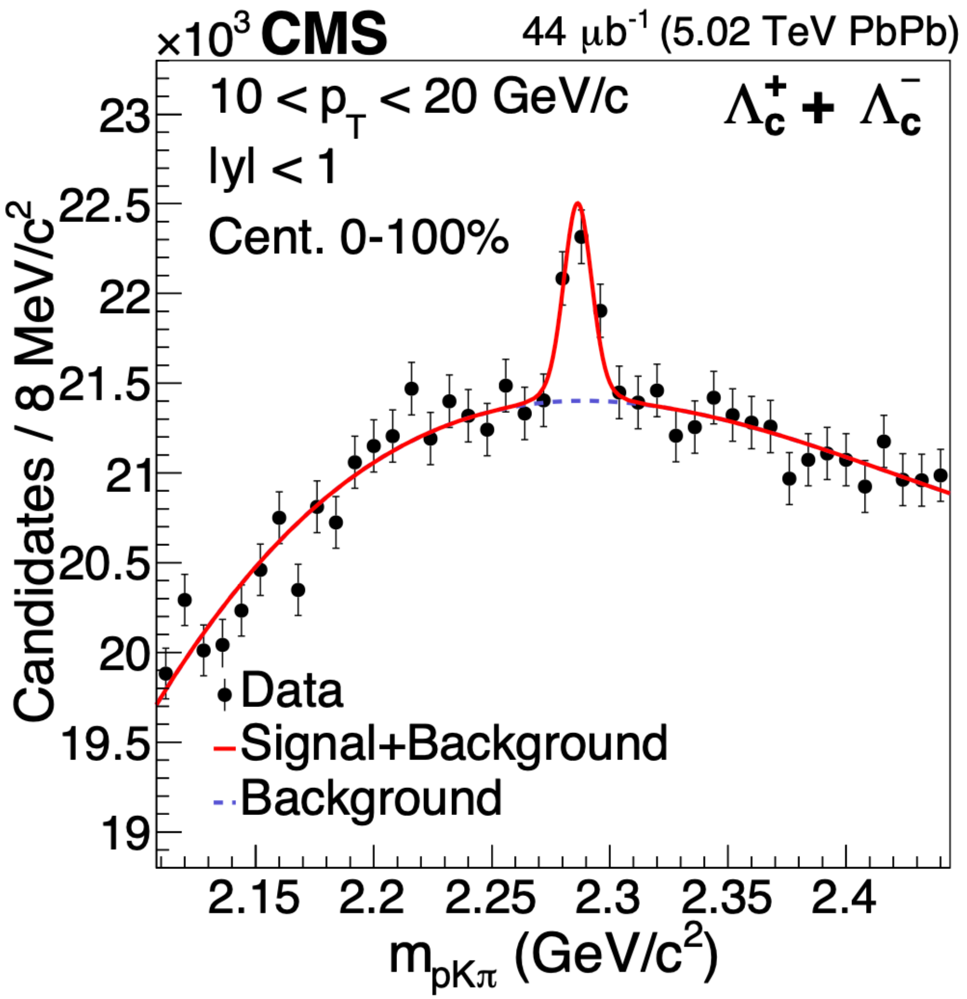
- Coalescence more significant for baryons with 3 valence quarks
- Baryon to meson ratio Λ_c/D is essential to study hadronization
- Λ_c Reconstruction: $\Lambda_c \rightarrow pK\pi$ (Branching ratio ~ 6.2%)

Λ_c Signals

pp



PbPb



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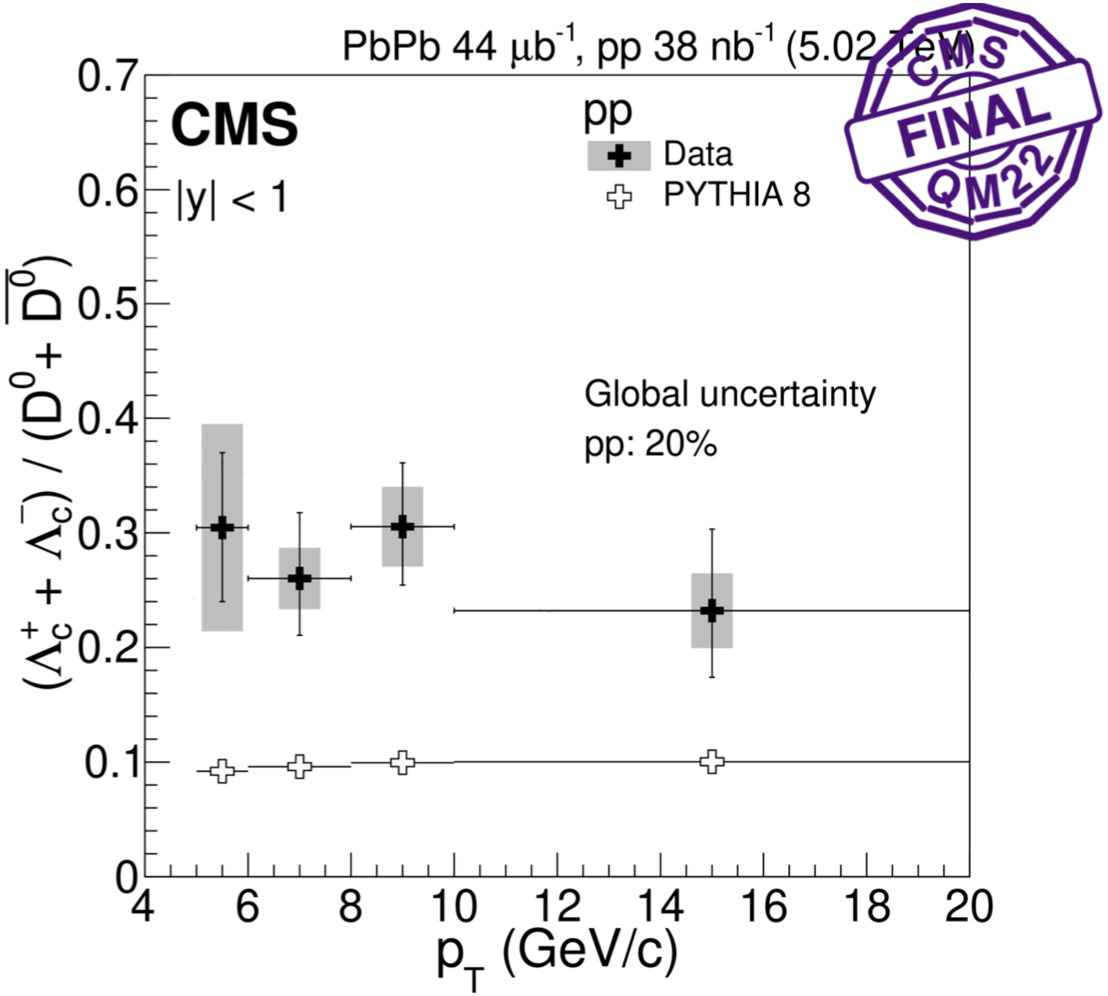
Λ_c in pp Collisions (1/4)



- PYTHIA8 underestimates Λ_c/D^0 in 5-20 GeV

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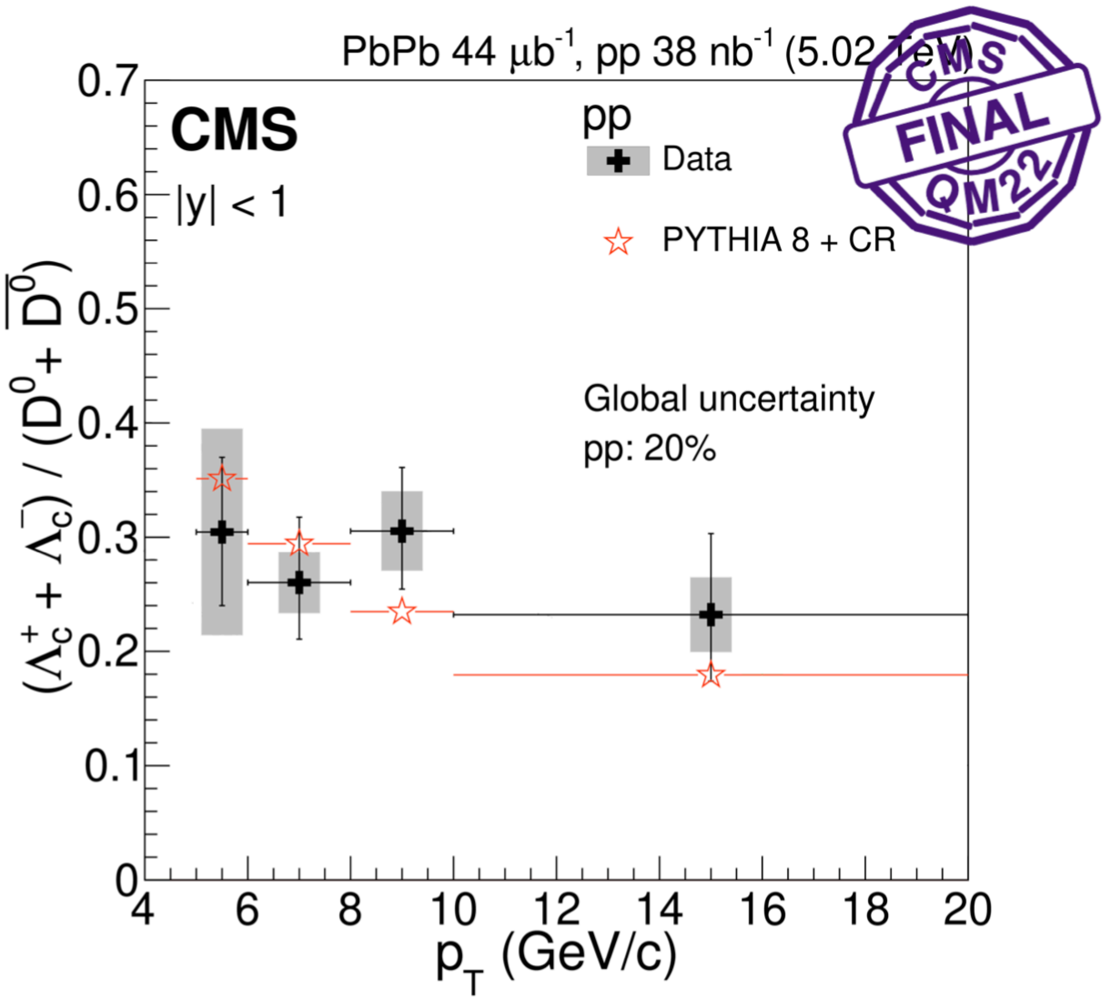
Λ_c in pp Collisions (2/4)



- PYTHIA8 underestimates Λ_c/D^0 in 5-20 GeV
- Color reconnection enhances the ratio
  ➜ String formation between other partons than leading color
  ➜ Significant in pp due to MPI

MPI: multiple parton interactions

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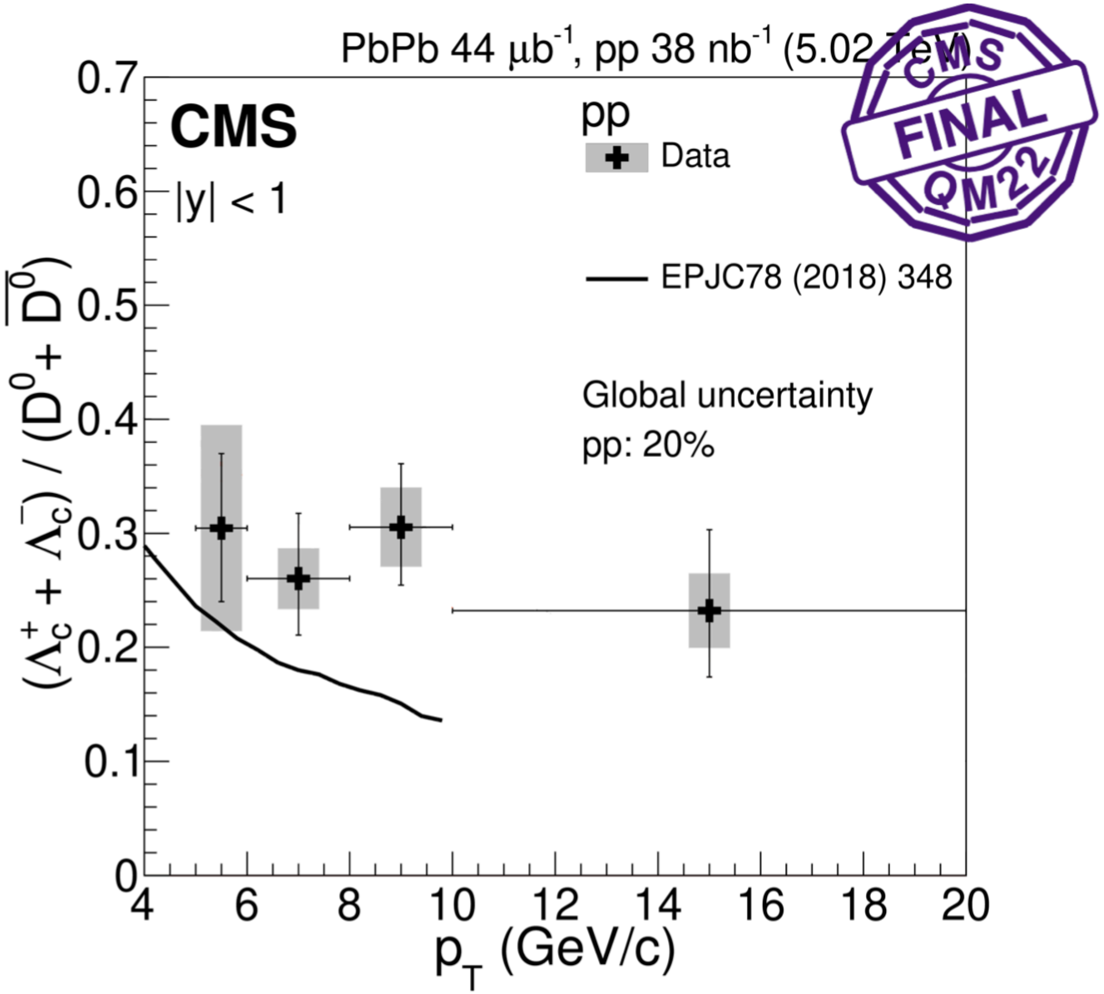
Λ_c in pp Collisions (3/4)



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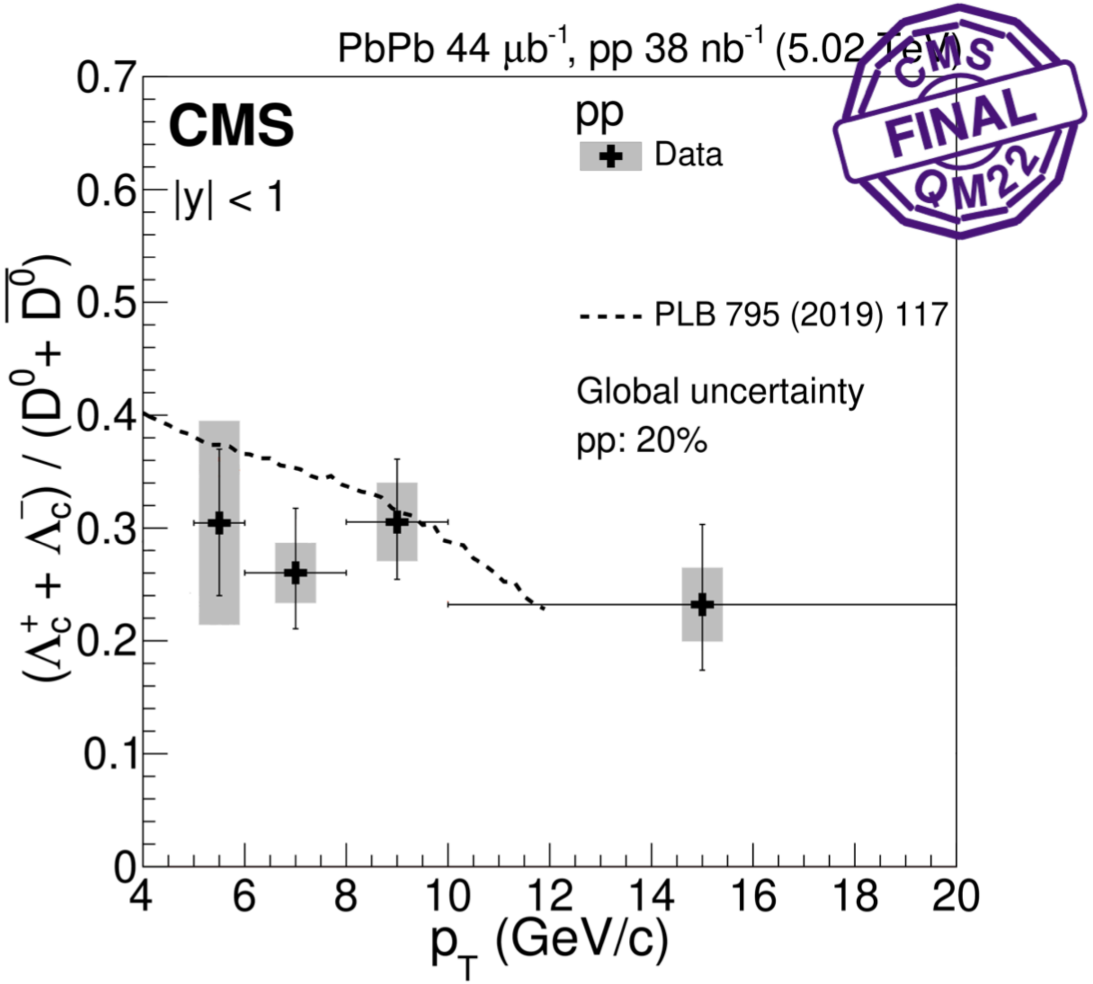
- PYTHIA8 underestimates Λ_c/D^0 in 5-20 GeV
- Color reconnection enhances the ratio
  ➜ String formation between other partons than leading color
  ➜ Significant in pp due to MPI
- Solid line: Partonic coalescence in pp as well

Why coalescence in pp?

Λ_c in pp Collisions (4/4)



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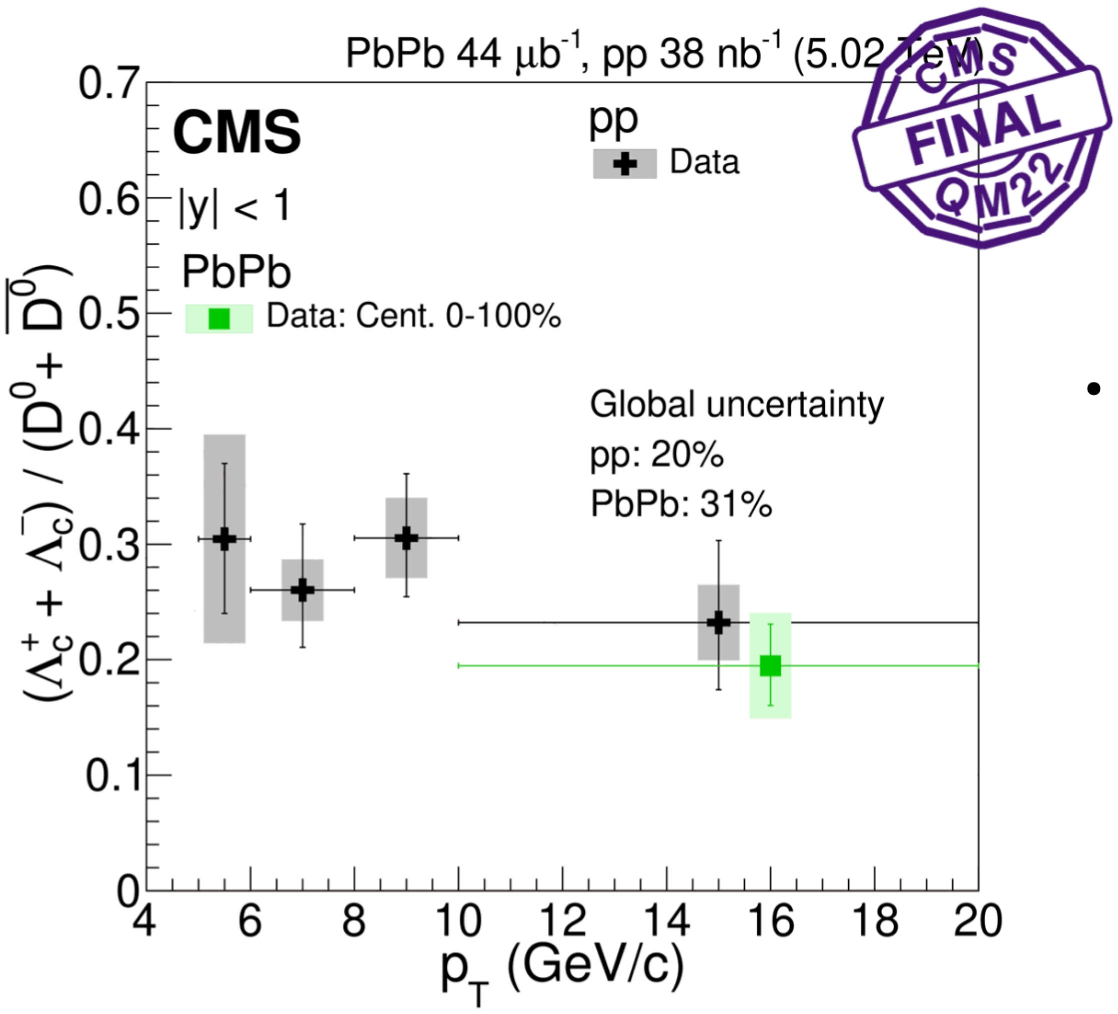
- PYTHIA8 underestimates Λ_c/D^0 in 5-20 GeV
- Color reconnection enhances the ratio
  ➜ String formation between other partons than leading color
  ➜ Significant in pp due to MPI
- Solid line: Partonic coalescence in pp as well
- Dashed line: SHM + Feed-down from more excited charm baryon states than PDG list predicted by Relativistic Quark Model (RQM)

SHM: statistical hadronization model

Λ_c in PbPb Collisions (1/2)



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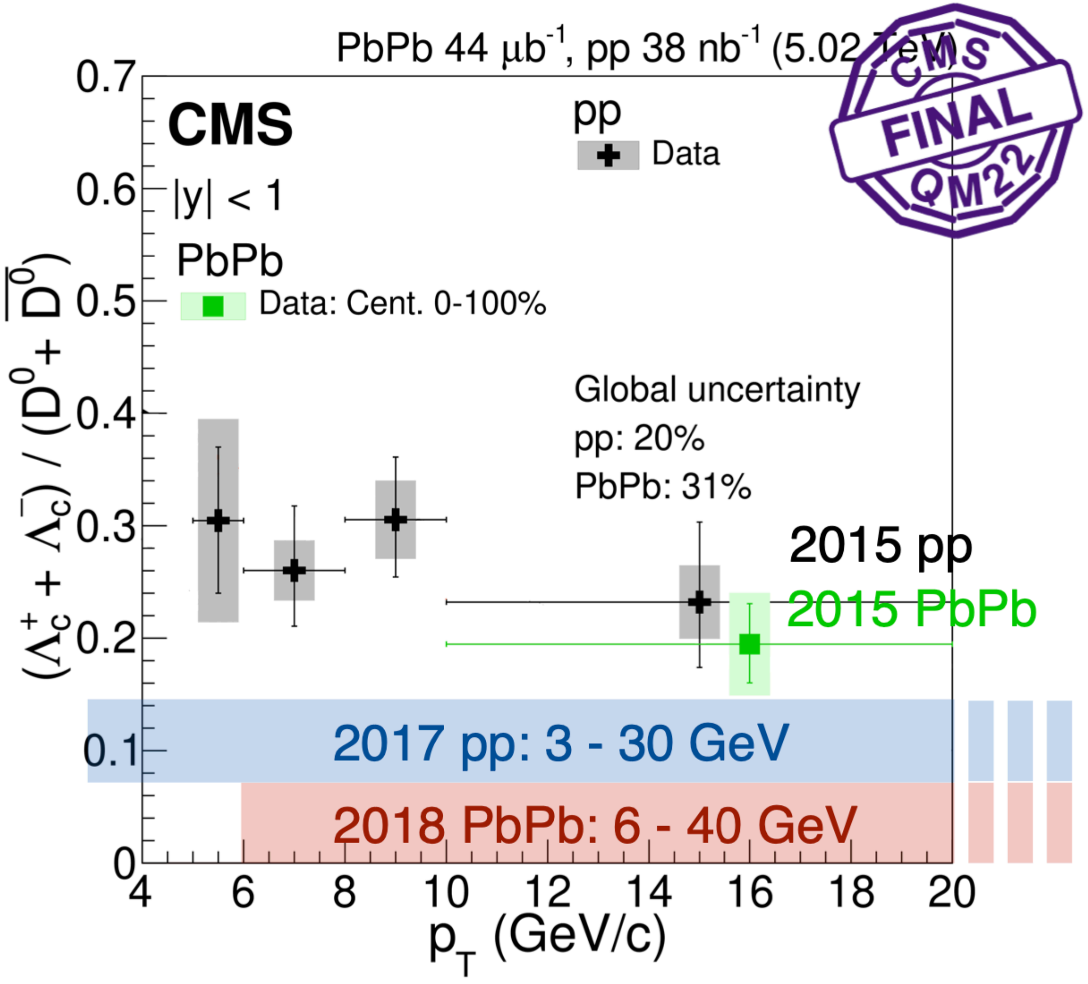
- Comparable Λ_c/D^0 in PbPb and pp collisions in $10 < p_T < 20$ GeV



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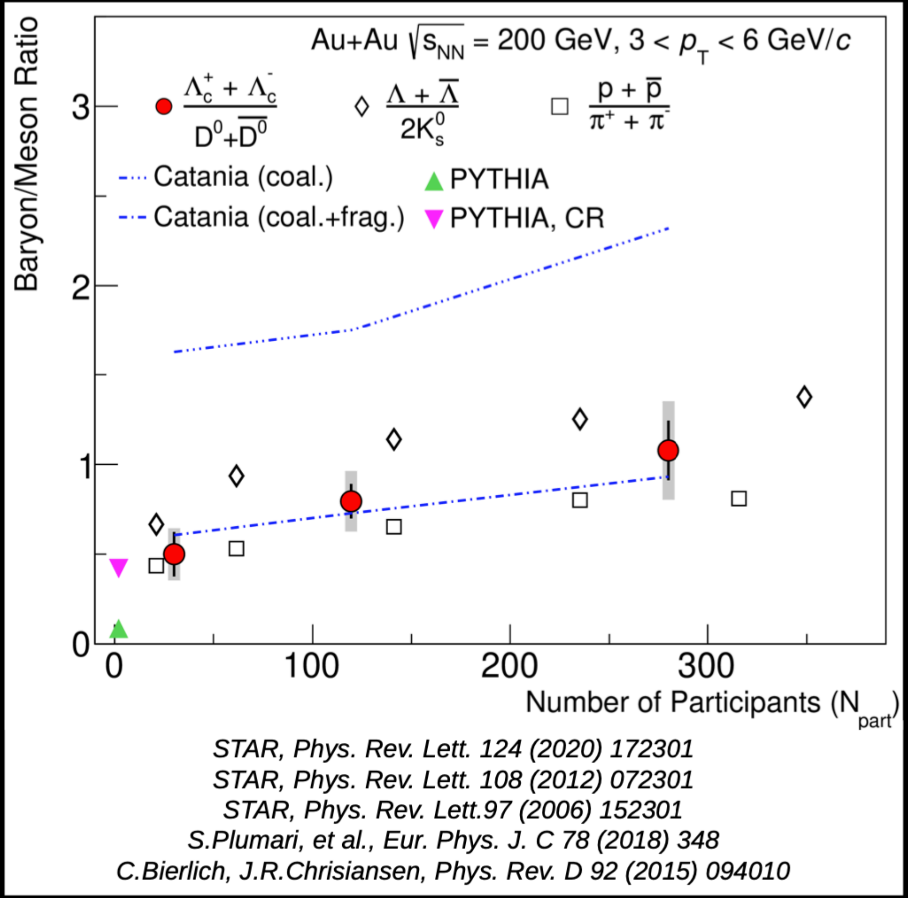
- Higher precision and wider kinematic analysis is ongoing with latest dataset
  ➜ 2017 pp: $3 < p_T < 30$ GeV
  ➜ 2018 PbPb: $6 < p_T < 40$ GeV

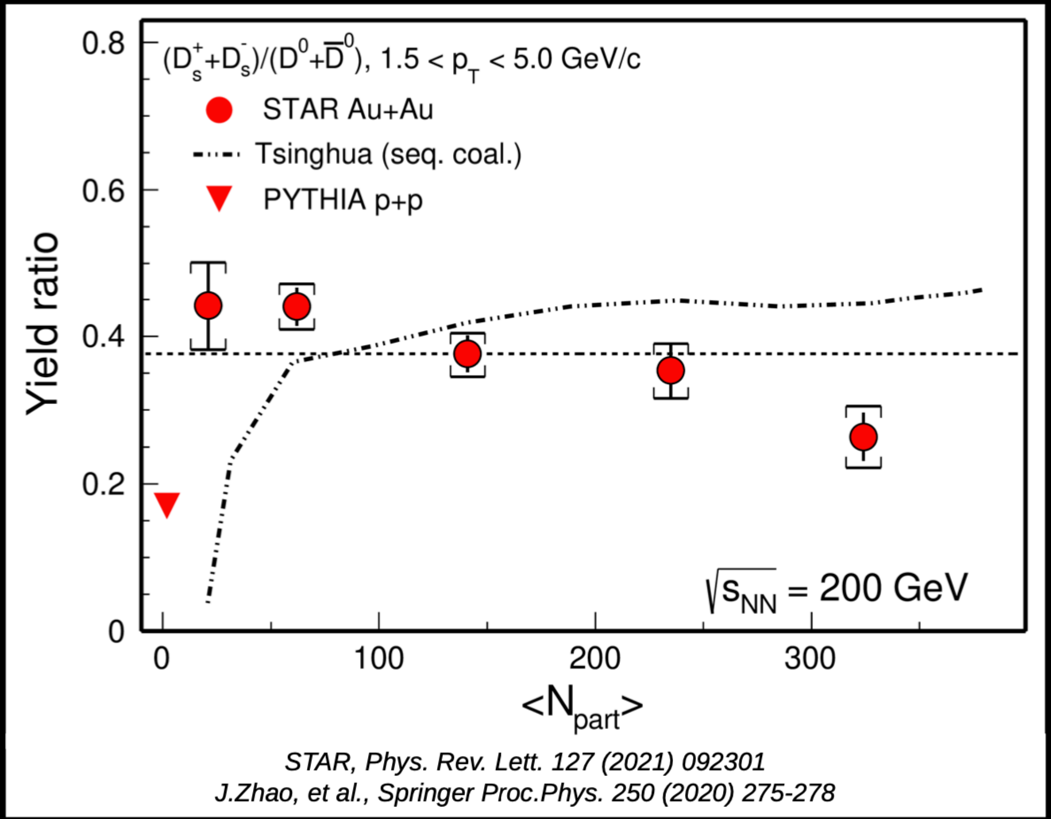
Summary of Λ_c in CMS

- Λ_c measured in pp and PbPb collisions
  ➜ PYTHIA8 underestimates Λ_c/D^0 in pp
  ➜ CR, coalescence and feed-down from more excited baryons can enhance Λ_c/D^0 in pp
  ➜ Analysis using larger dataset is ongoing

STAR – AuAu

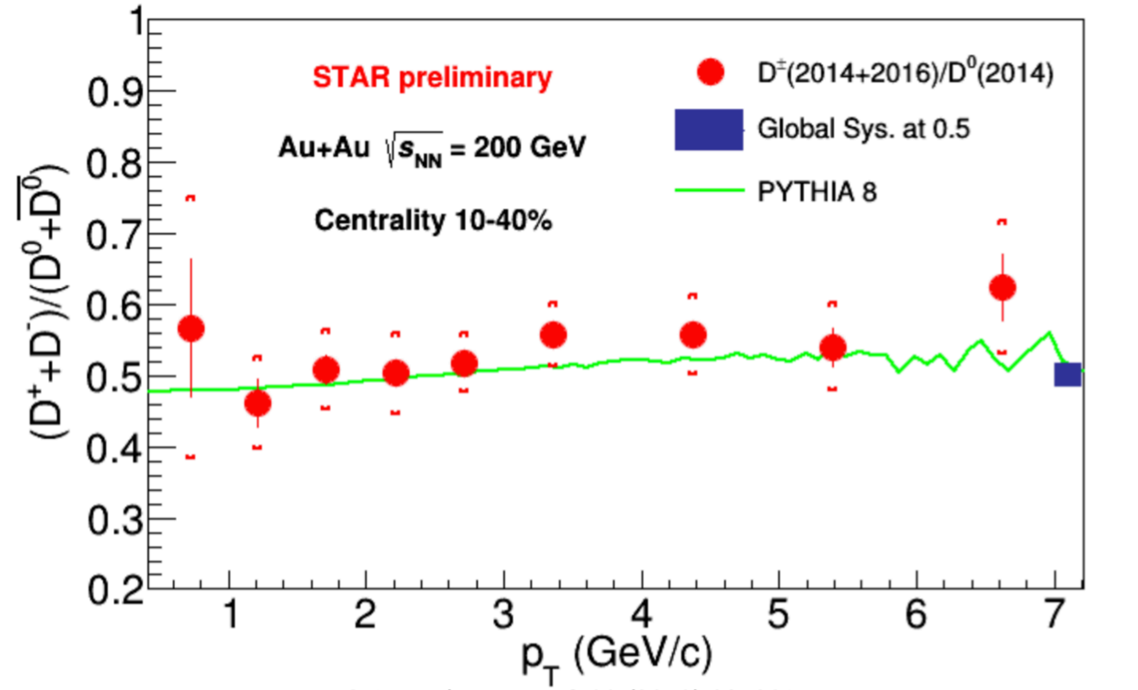
Open Heavy Flavor Production in 200 GeV Au+Au Collisions





- Enhancements compared to PYTHIA for both Λ_c and D_s
- Λ_c and D_s significantly contribute to the total charm production
- Coalescence plays an important role in hadronization

Open Heavy Flavor Production in 200 GeV Au+Au Collisions



STAR, Phys. Rev. C 99 (2019) 034908
STAR, Phys. Rev. D 86 (2012) 072013

Similar level of suppression is observed for $D^{\pm}$ and D^0

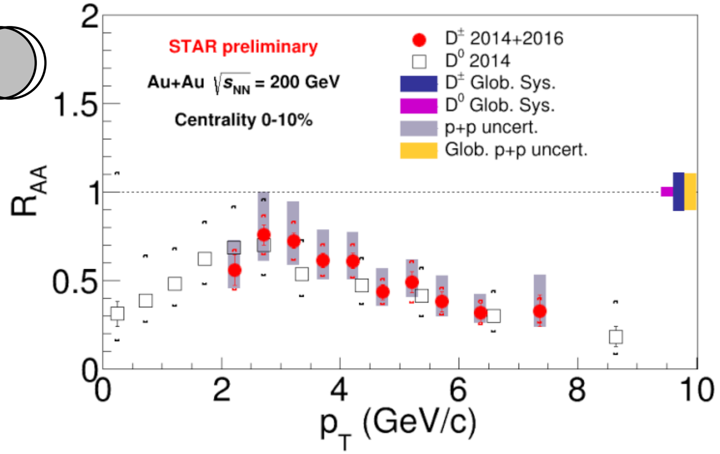
Jan Vaněk, Apr 8, 2022
Poster Session 3 T11_3

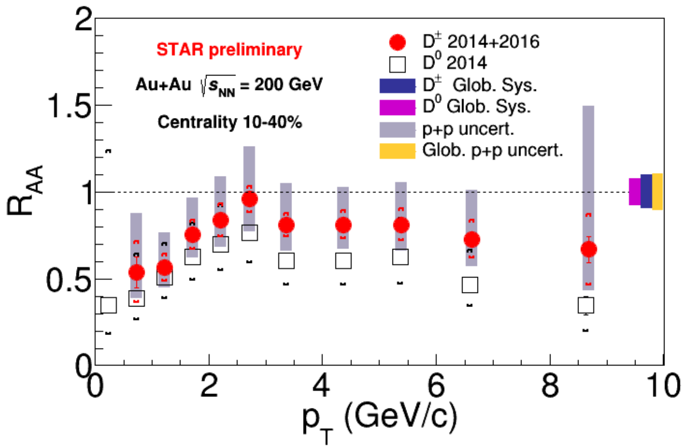
Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

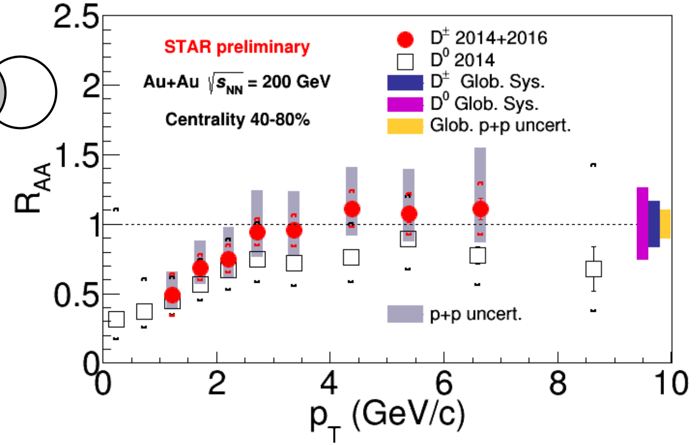
D^0 [1] STAR, Phys. Rev. C 99 (2019) 034908
D_s [2] STAR, Phys. Rev. Lett. 127 (2021) 092301
Λ_c [3]STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p [4] STAR, Phys. Rev. D 86 (2012) 072013

*$D^{\pm}$ calculated from preliminary invariant yields
**Cross section of Λ_c is calculated based on Λ_c/D^0 yield ratio

D^0 AND $D^{\pm}$ NUCLEAR MODIFICATION FACTOR







- Nuclear modification factor:

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T}$$

  - Systematic uncertainty of p+p reference plotted separately for $D^{\pm}$ (grey band), for D^0 included in brackets
- High-p_T $D^{\pm}$ and D^0 suppressed in central Au+Au collisions
- Similar level of suppression and centrality dependence for $D^{\pm}$ and D^0
- **Strong interactions between charm quarks and the medium**

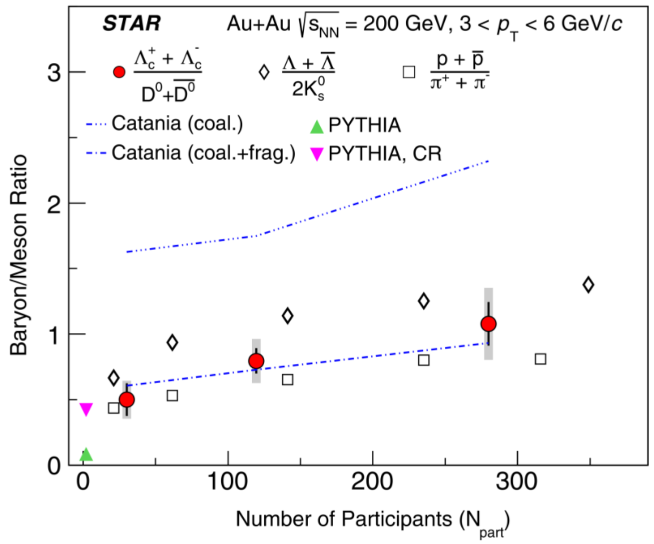
p+p reference (STAR): Phys. Rev. D 86, 072013, (2012)
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).

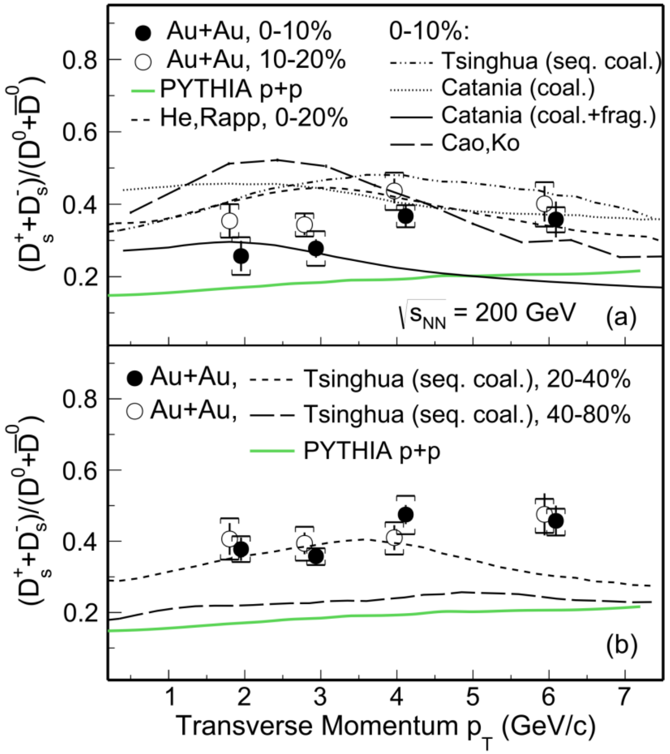
Jan Vanek, QM 2022

08. 04. 2022 3

Λ_c/D^0 and D_s/D^0 yield ratio enhancement

- Λ_c/D^0 and D_s/D^0 yield ratios enhanced in Au+Au collisions with respect to PYTHA calculations
- **Enhancement consistent with coalescence hadronization of charm quarks in QGP**





Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020)
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)
Λ /K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Catania: Eur. Phys. J. C 78, 348, (2018)

D_s (STAR): Phys. Rev. Lett. 127, 092301 (2021).
Catania: Eur. Phys. J. C 78, 348, (2018).
Tsinghua: arXiv1805.10858, (2018).
He, Rapp, Phys. Rev. Lett. 124, 042301 (2020)
Cao, Ko *et al.*: Phys. Lett. B 807, 135561 (2020).

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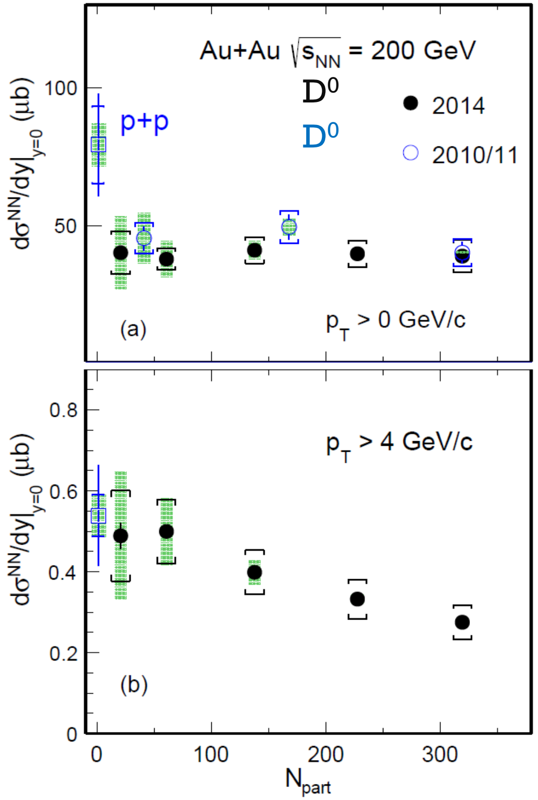
TOTAL CHARM PRODUCTION CROSS SECTION

- Total charm production **cross section per binary collision** in Au+Au extracted from the measurements of open-charm hadrons
- The Au+Au result is consistent with that measured in p+p collisions within the uncertainties
- **Redistribution of charm quarks among open – charm hadron species in Au+Au collisions compared to p+p collisions**

Coll. system	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3
	D_s	15 ± 2 ± 4
	Λ_c	40 ± 6 ± 27*
	Total:	**112 ± 6 ± 27**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

*The Λ_c cross section is derived using the Λ_c/D^0 yield ratio
$D^{\pm}$ cross section calculated using preliminary invariant yields
Remaining cross sections calculated using published results



D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. Lett. 113, 142301 (2014), erratum: Phys. Rev. Lett. 121, 229901 (2018).
p+p (STAR): Phys. Rev. D 86 072013, (2012).
D_s (STAR): Phys. Rev. Lett. 127, 092301 (2021).
Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020).

Acknowledgement: This research is funded by the project LTT18002 of the Ministry of Education, Youth, and Sport of the Czech Republic

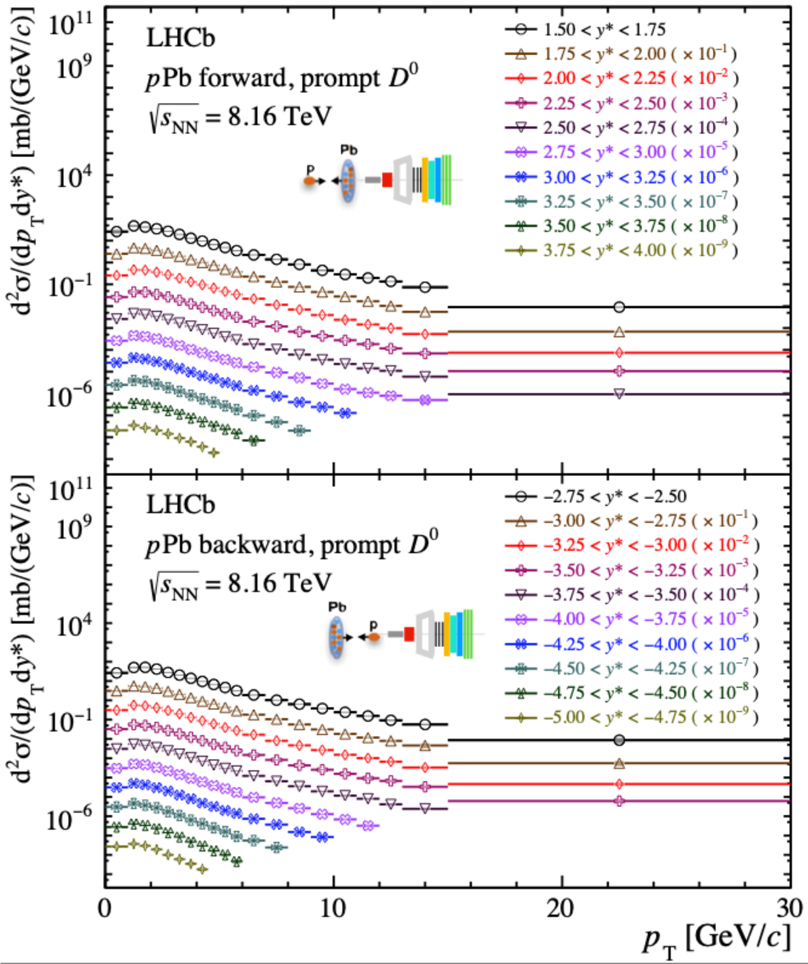
Summay of STAR

- Open heavy flavor production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - Coalescence plays an important role in hadronization
  - Total charm production cross section per binary nucleon-nucleon collision in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is consistent with that in p+p collisions with a hint of suppression

LHCb – pPb and peripheral PbPb

New # Open-charm production in pPb collisions

LHCb-PAPER-2022-007

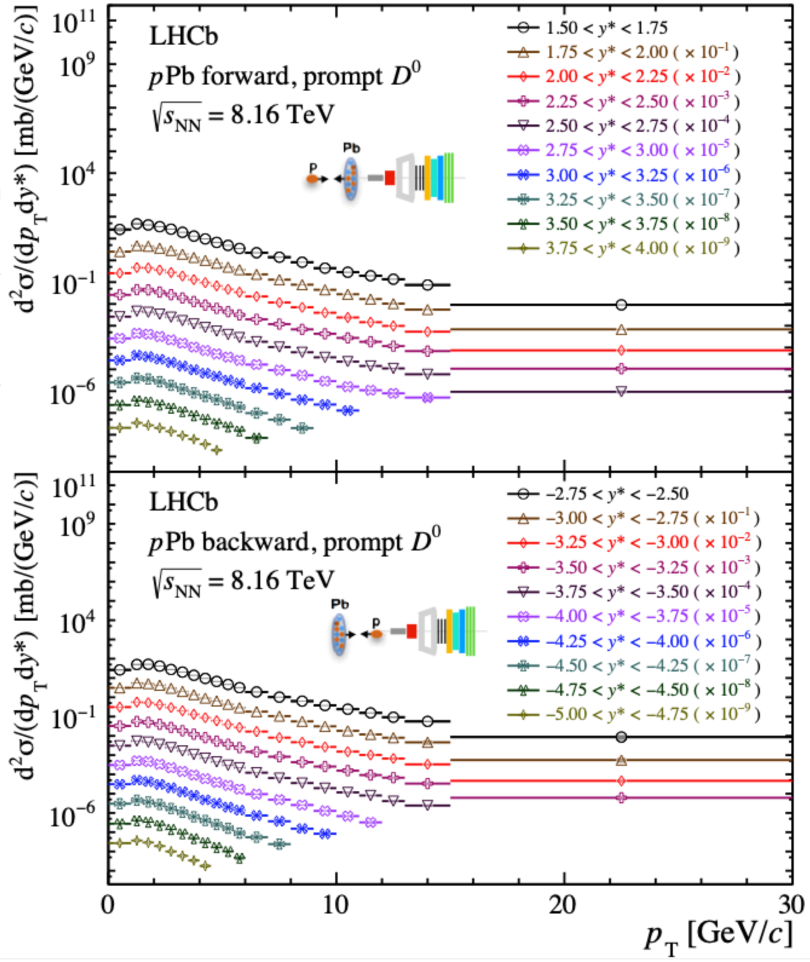


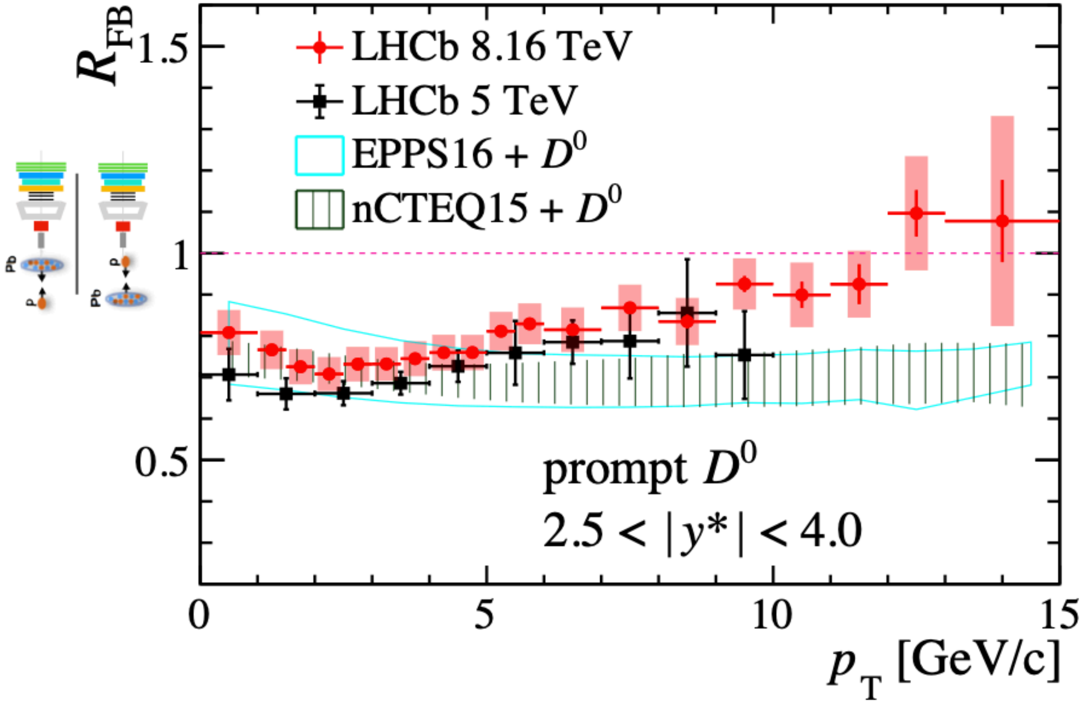
- **New results for D^0 cross-section** in *p*Pb / Pb*p* collisions at $\sqrt{s_{NN}} = 8$ TeV **up to $p_T = 30$ GeV/c**.
- **Improved statistics** by factor 20 compared to previous LHCb results.

8

New Open-charm production in pPb collisions

LHCb-PAPER-2022-007





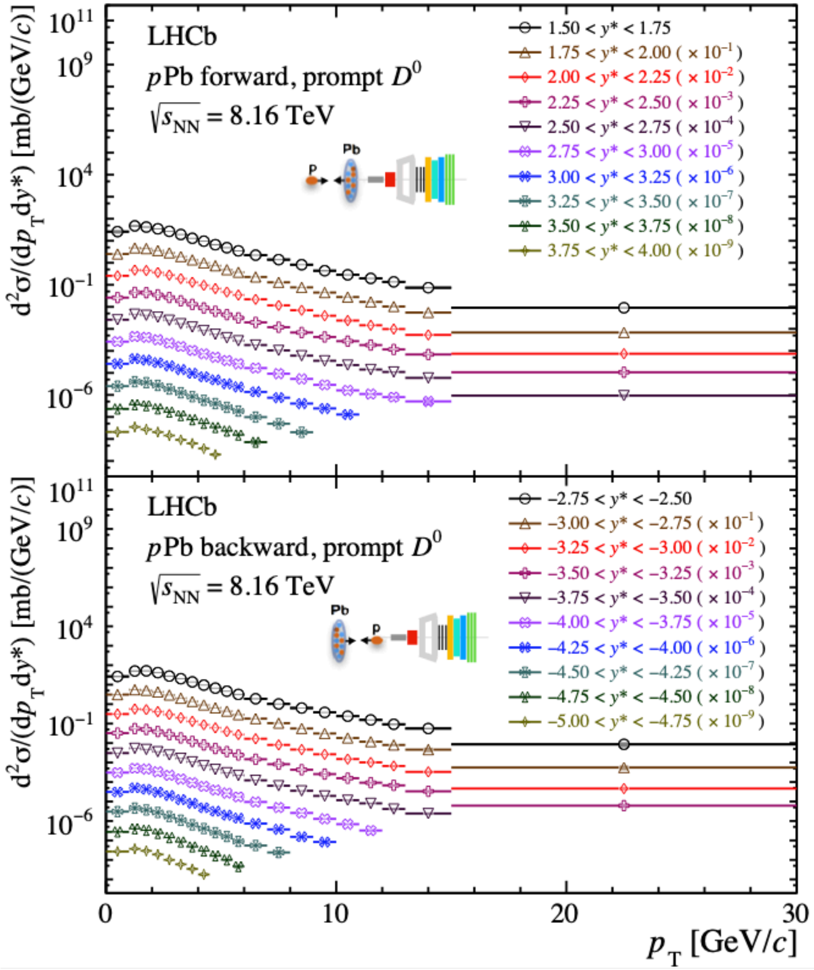
- Tension between data and theory predictions at high p_T.
- Additional effect required?

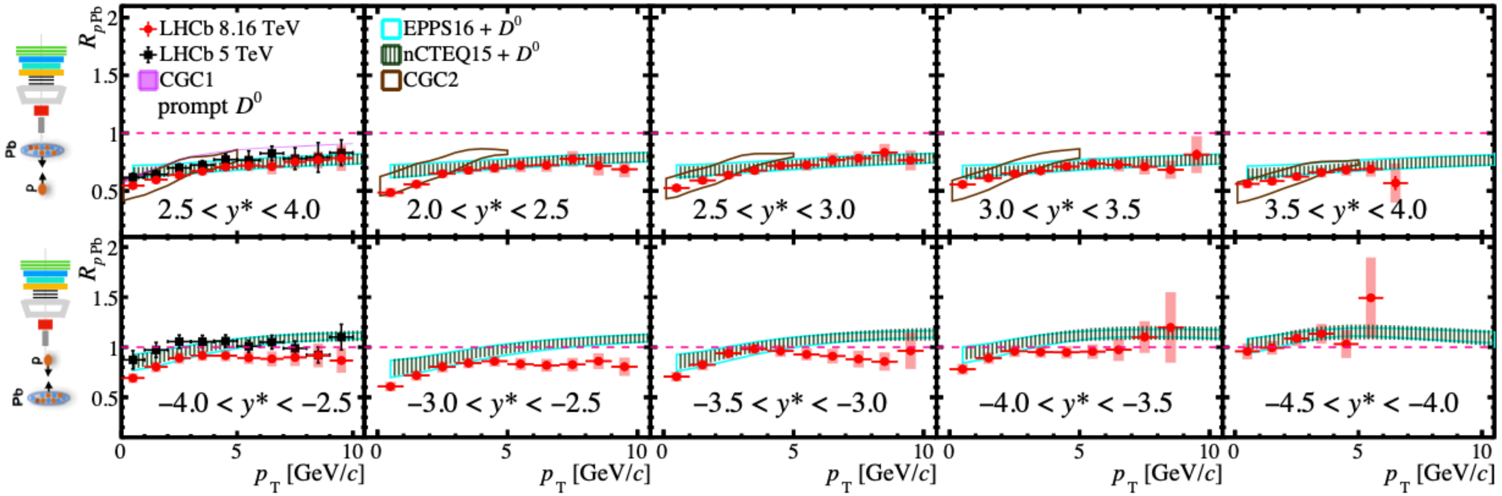
8

New

Open-charm production in pPb collisions

LHCb-PAPER-2022-007

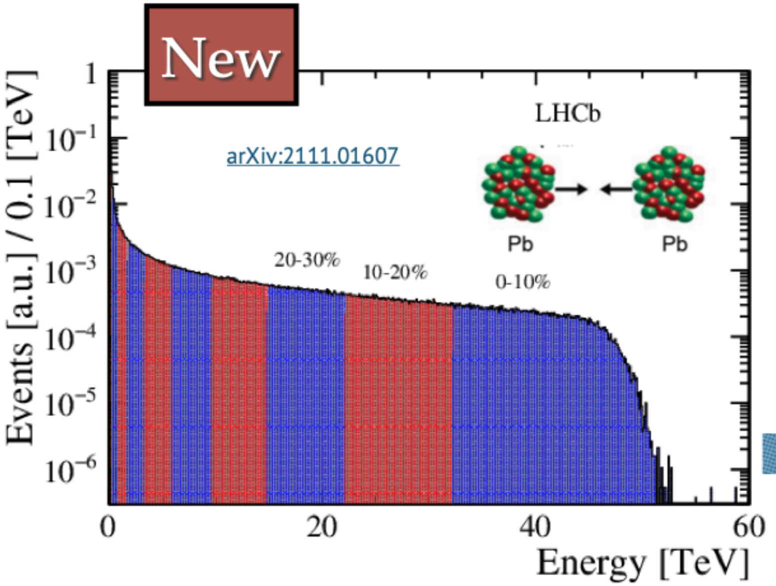




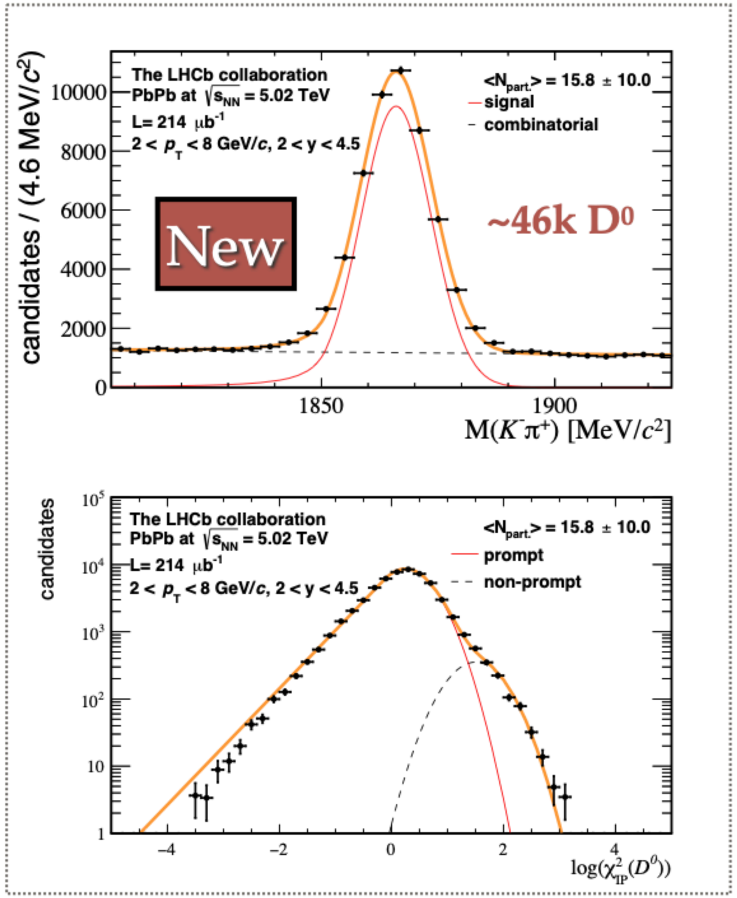
- Tension between data and theory predictions at high p_T.
- Additional effect required?

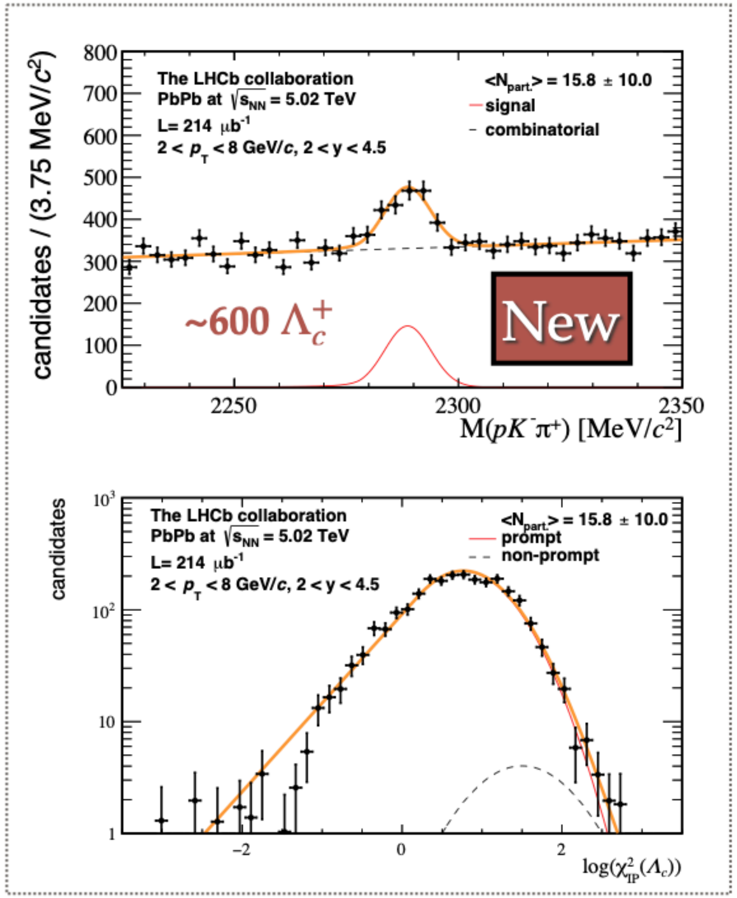
8

Λ_c^+-to-D^0 ratio in peripheral PbPb collisions



Simultaneous fit



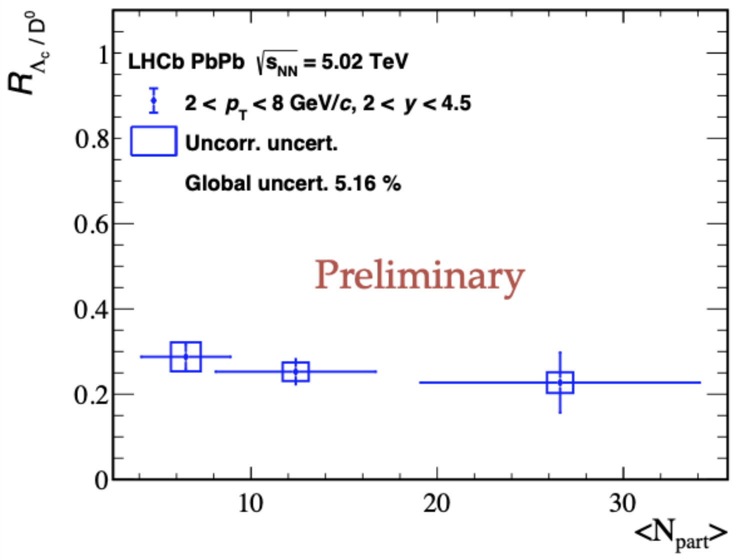


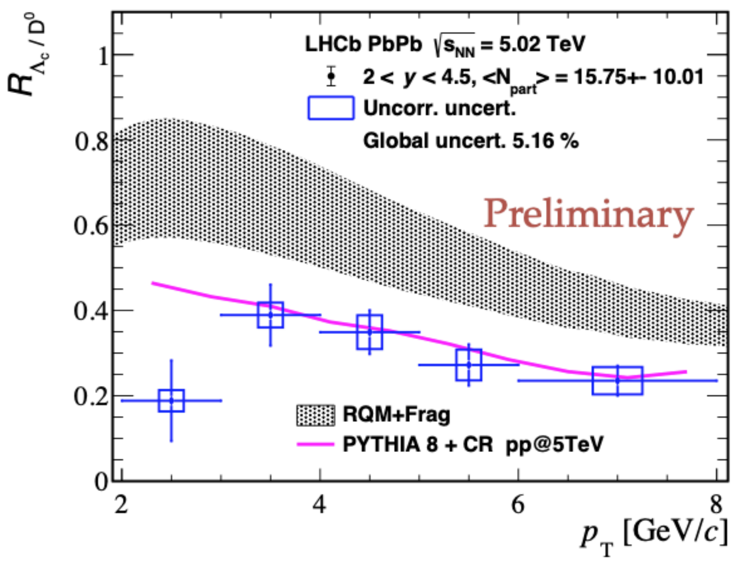
- Centrality measured in 2018 PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.
- Up to 60% centrality reached in hadronic collisions !

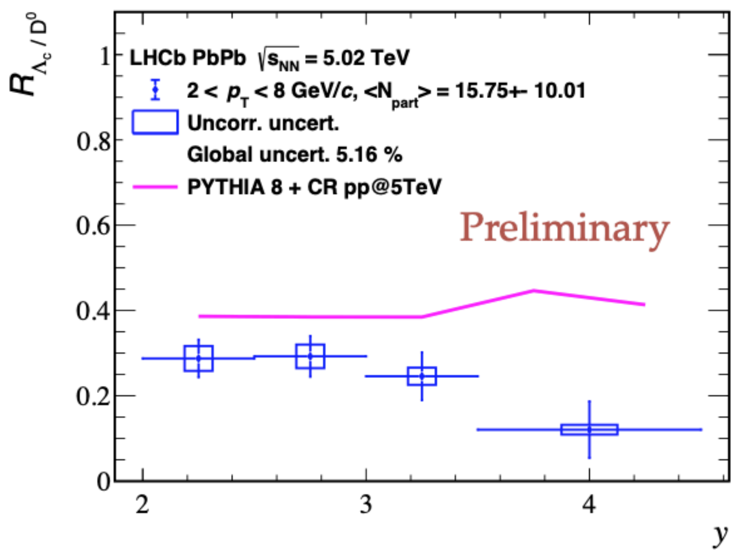
New Λ_c^+-to-D^0 ratio in peripheral PbPb collisions

LHCB-PAPER-2021-046

First Λ_c^+-to-D^0 production ratio measured in peripheral PbPb collisions at forward rapidity.







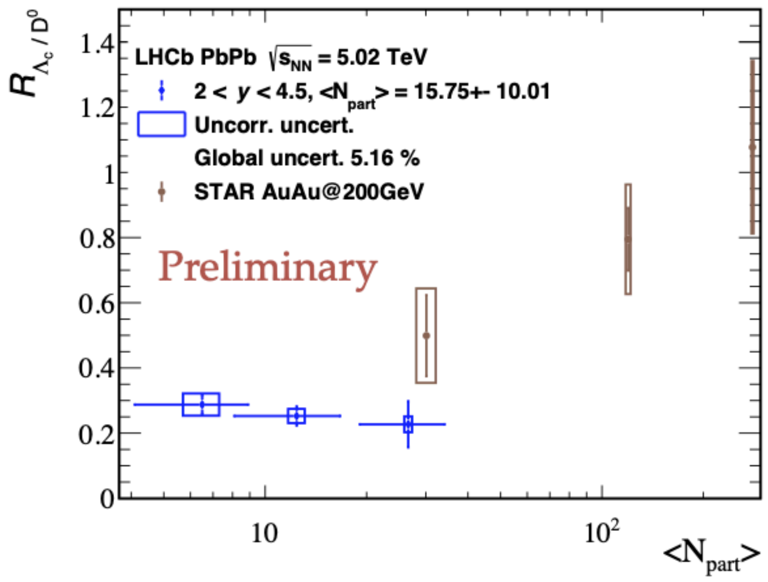
- Flat dependence versus $\langle N_{part} \rangle$.
- $\langle R_{\Lambda_c/D^0} \rangle \sim 0.27$

- p_T dependance compatible with a relative enhancement at intermediate p_T.
- Compatible with flat rapidity dependence.
- Comparison to theory predictions:
  - PYTHIA 8 + Colour Reconnection: compatible with data within 3σ.
  - Standard Hadronization Model do not reproduce the data.

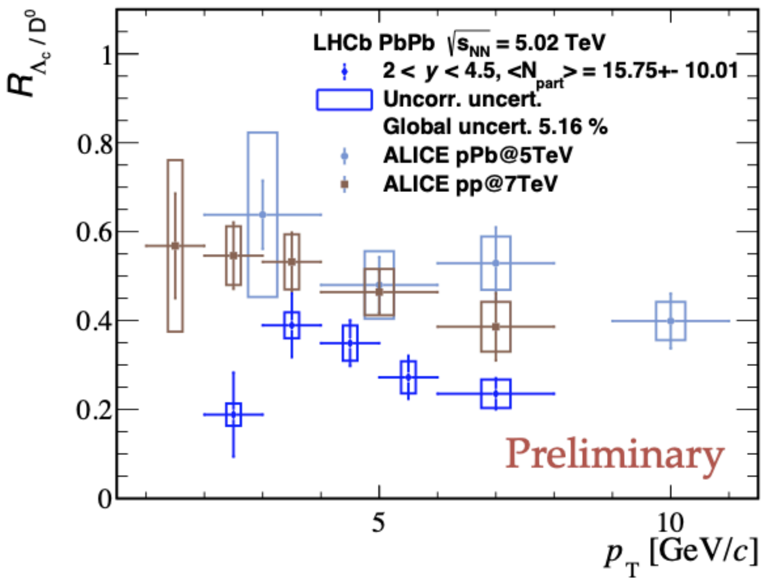
New Λ_c^+-to-D^0 ratio in peripheral PbPb collisions

LHCB-PAPER-2021-046

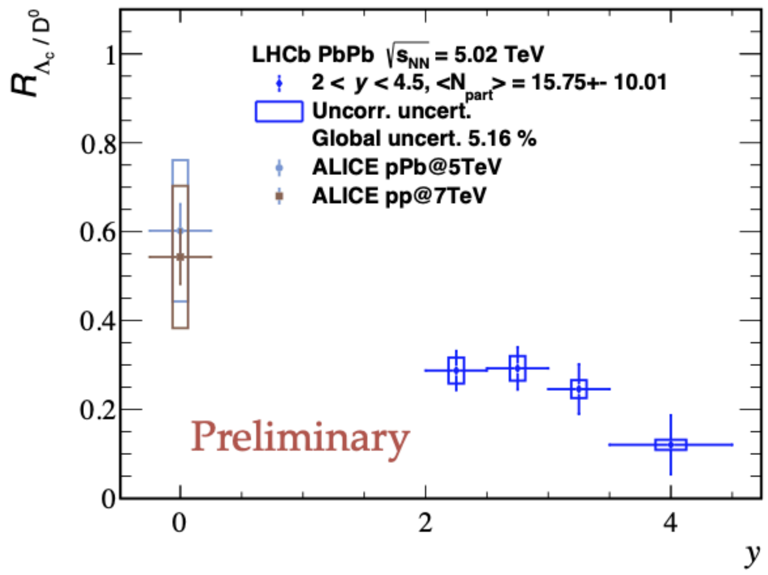
First Λ_c^+-to-D^0 production ratio measured in peripheral PbPb collisions at forward rapidity.



- Most central point compatible with STAR measurements.
- Rising trend ?



- Similar p_T trend between ALICE and LHCb for $p_T > 4$ GeV/c.



- Difference between LHCb and ALICE data versus rapidity.

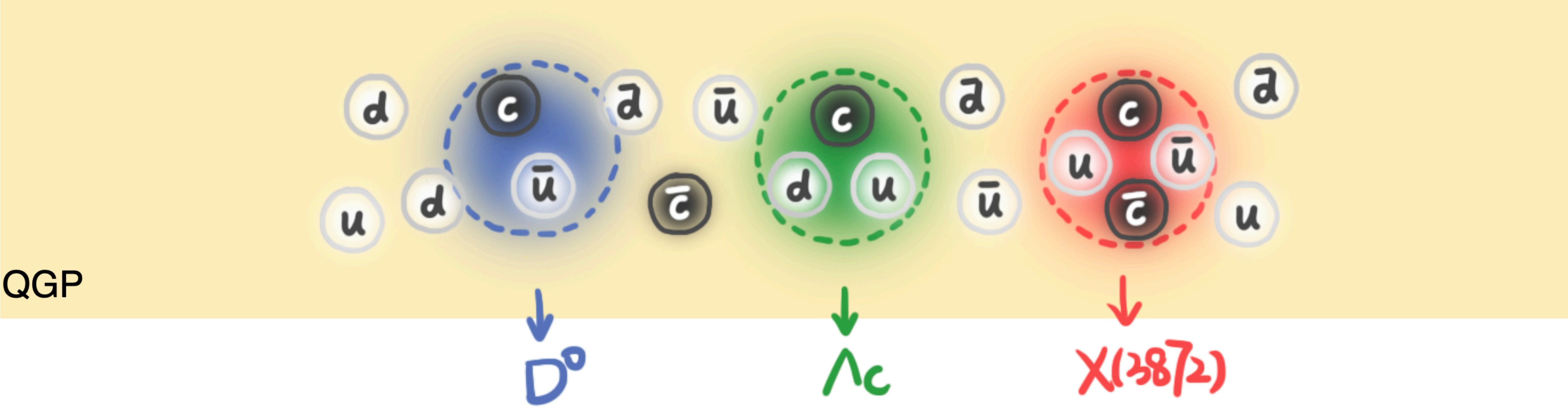
Systematically lower Λ_c^+-to-D^0 ratio in LHCb compared to ALICE due to different rapidity range confirmed?

Summary of LHCb

- Tension between data and theory predictions at high p_T for D0 production in *p*Pb collisions.
- Λ_c^+-to-D^0 ratio in peripheral PbPb collisions compatible to similar measurement in *p*Pb collisions made by LHCb → **difference with ALICE remains.**

X(3872) -- CMS

Study Coalescence with Exotic Hadrons



How about one more quark? ➜ X(3872)

X(3872) in Heavy-ion Collisions

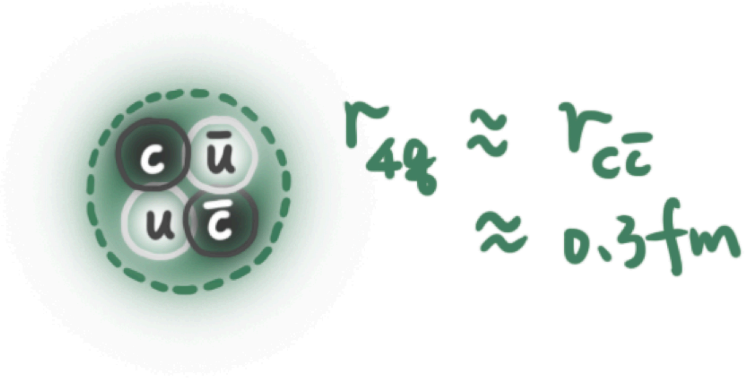
Not that simple: the inner structure of X(3872) affects its production in HIC

Tetraquark

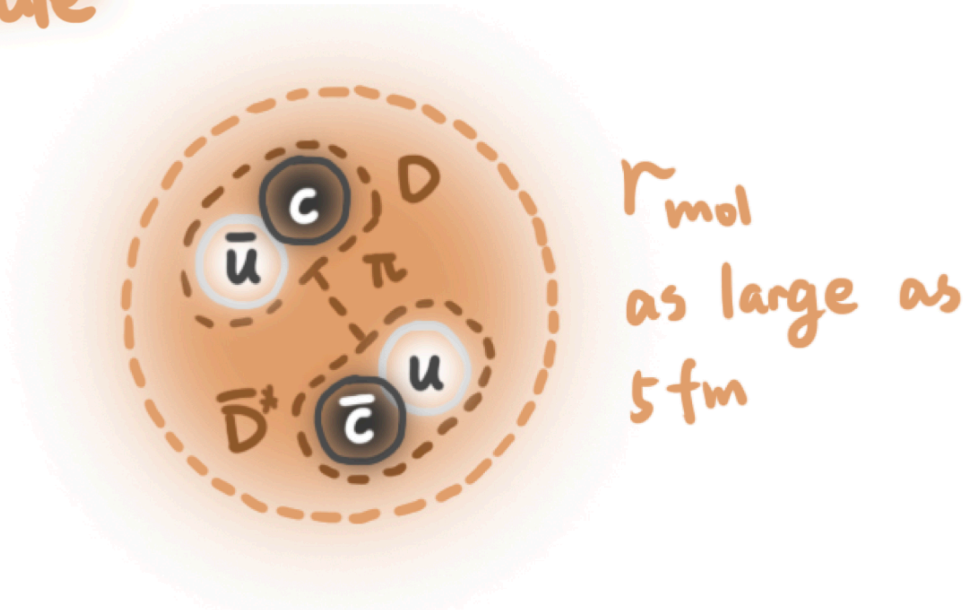
Tightly bound
Small radius

Hadron molecule

Loosely bound
Large radius



Compact four quark state



D-D̄* hadron molecule

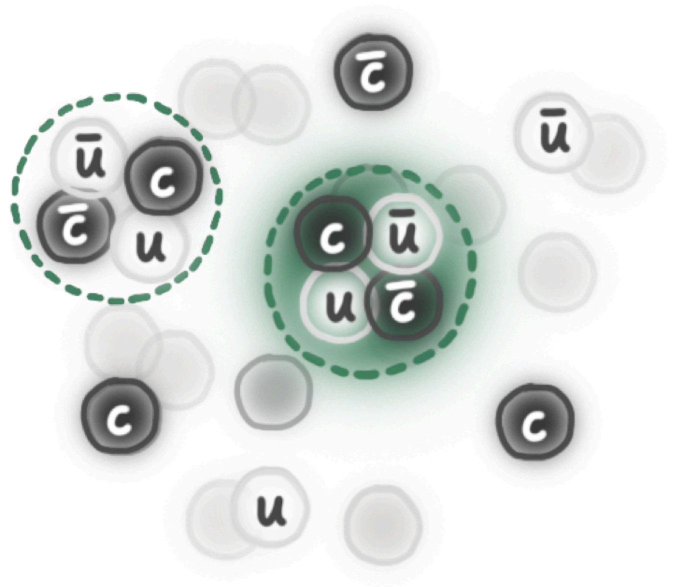
X(3872) in HIC (1/2): Coalescence

- Coalescence with particles in HIC ➜ Enhance X(3872)

Tetraquark

Tightly bound

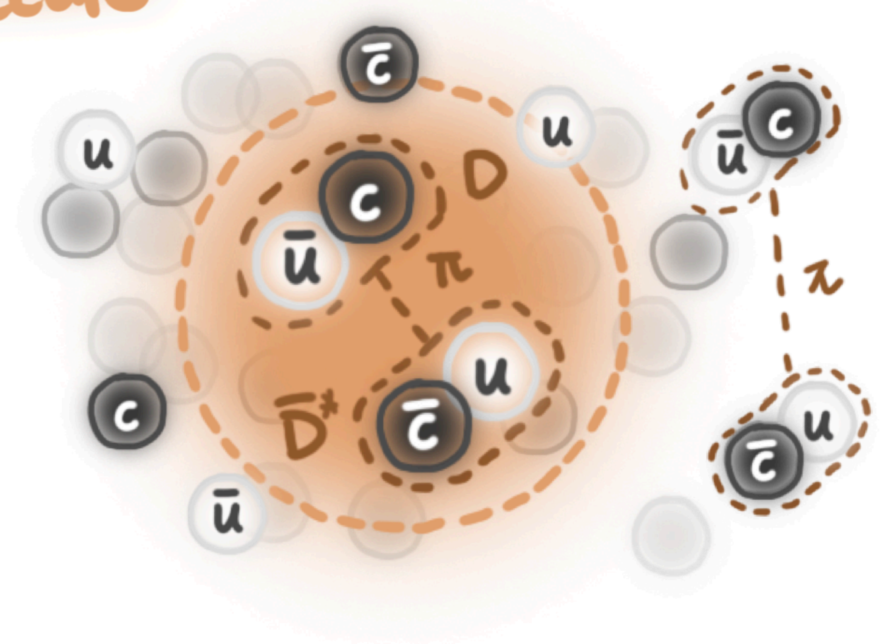
Small radius



Hadron molecule

Loosely bound

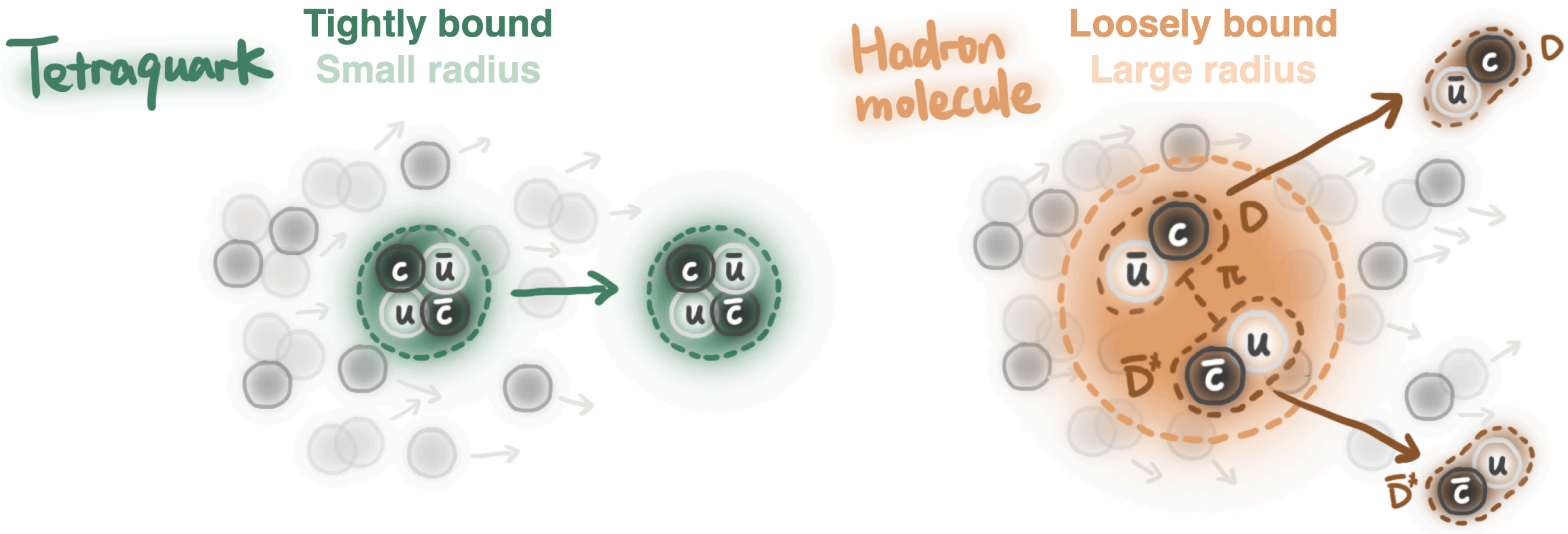
Large radius



Coalescence probability depends on X(3872) inner structure

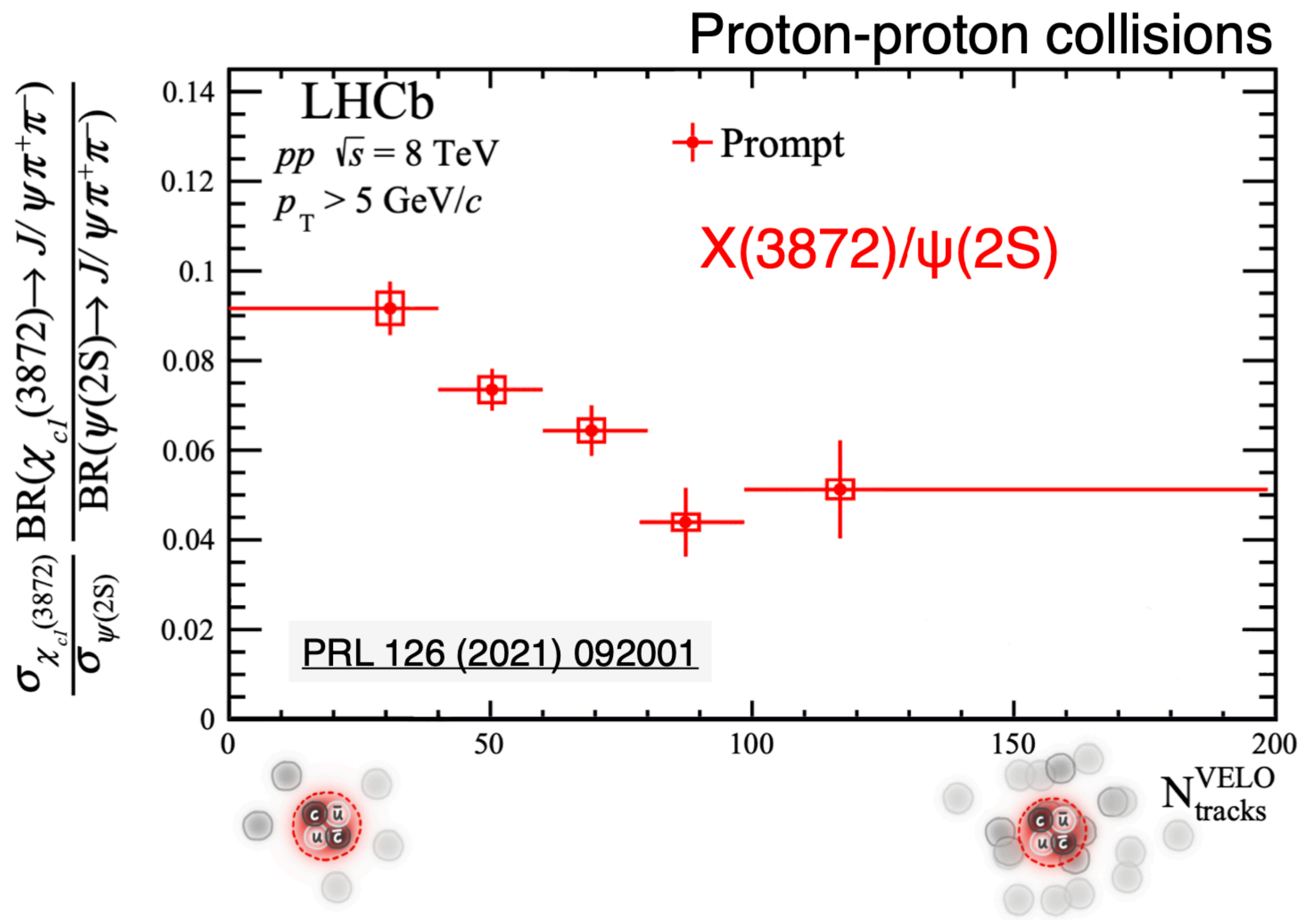
X(3872) in HIC (2/2): Breakup

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with particles in HIC ➜ Enhance X(3872)



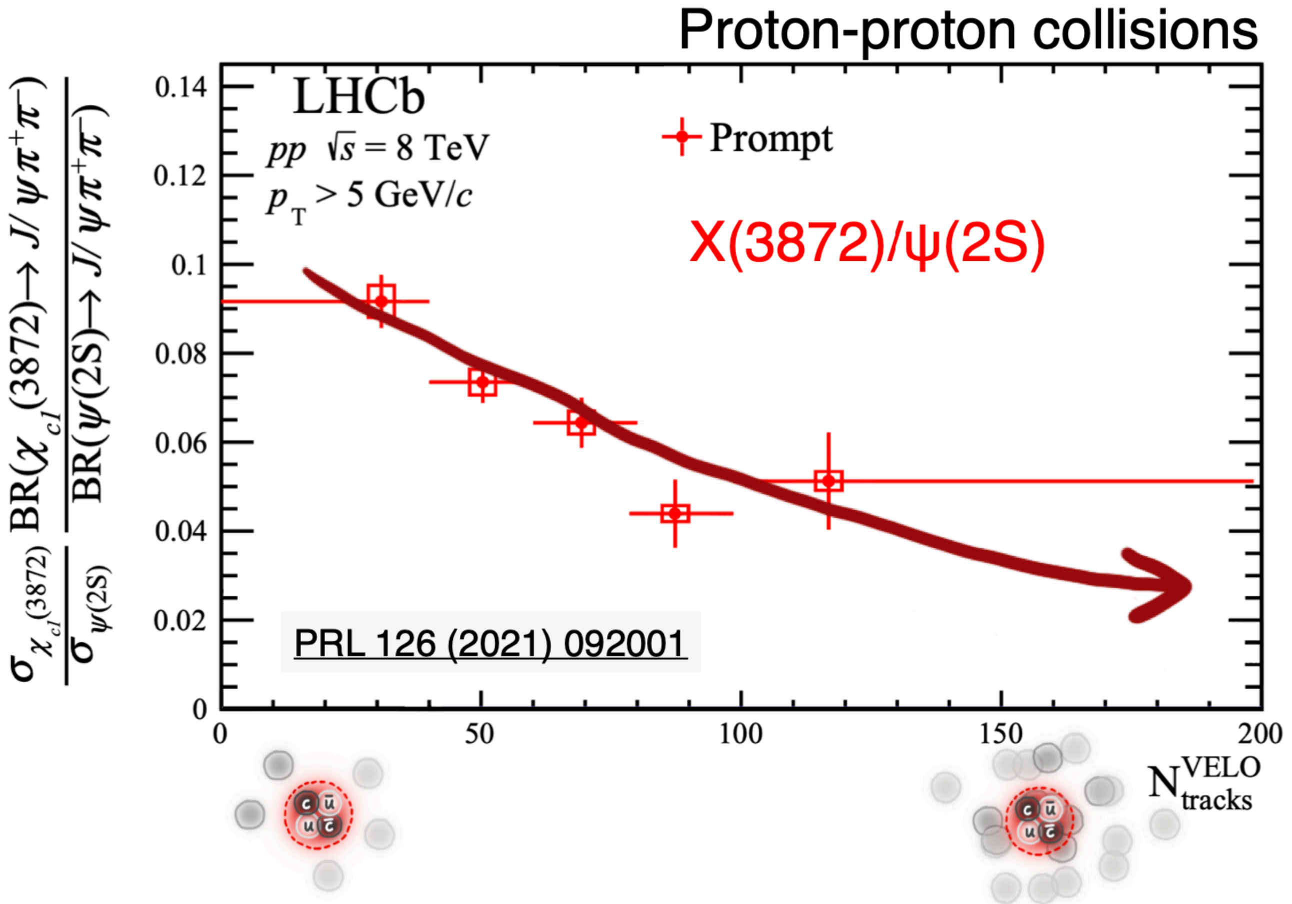
Dissociation probability depends on X(3872) inner structure

X(3872) in High-Multiplicity pp Collisions



X(3872) in High-Multiplicity pp Collisions

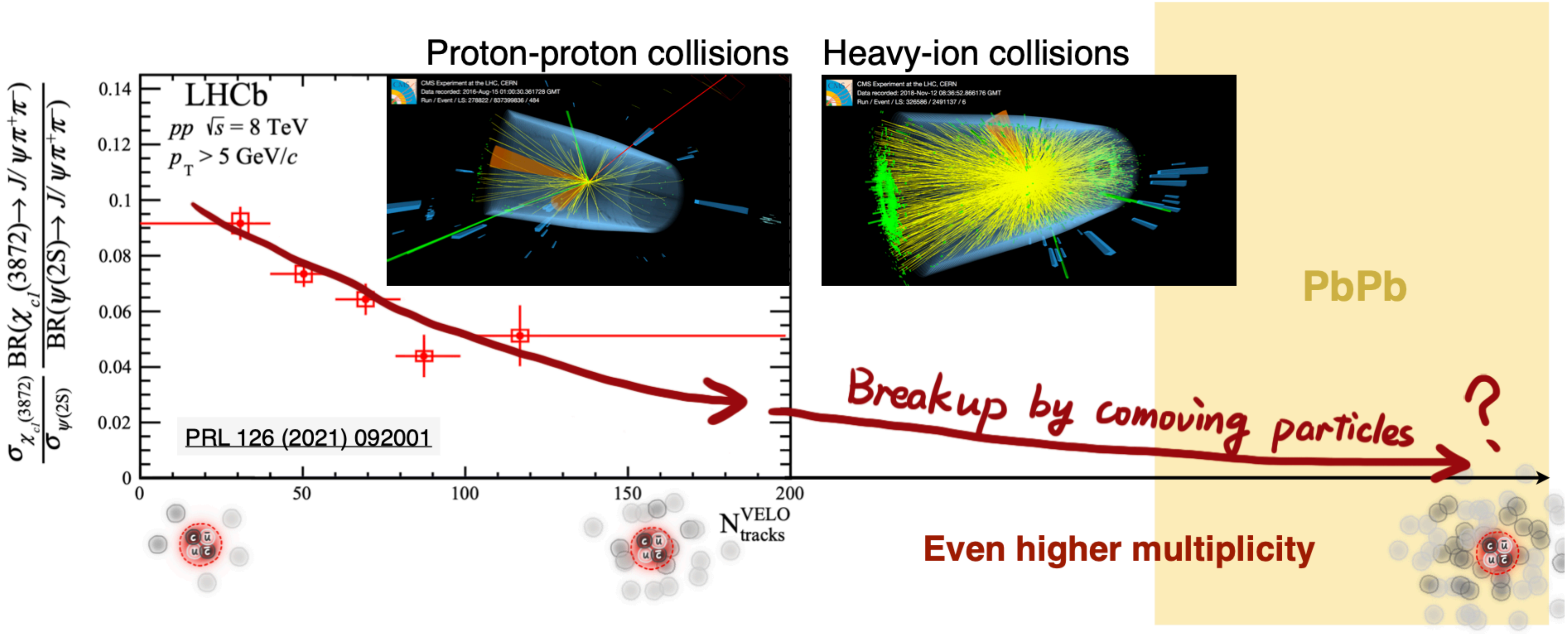
- Breakup by comoving particles ➜ Suppress X(3872)



- Destroyed by comoving particles due to smaller binding energy than ψ(2S)?

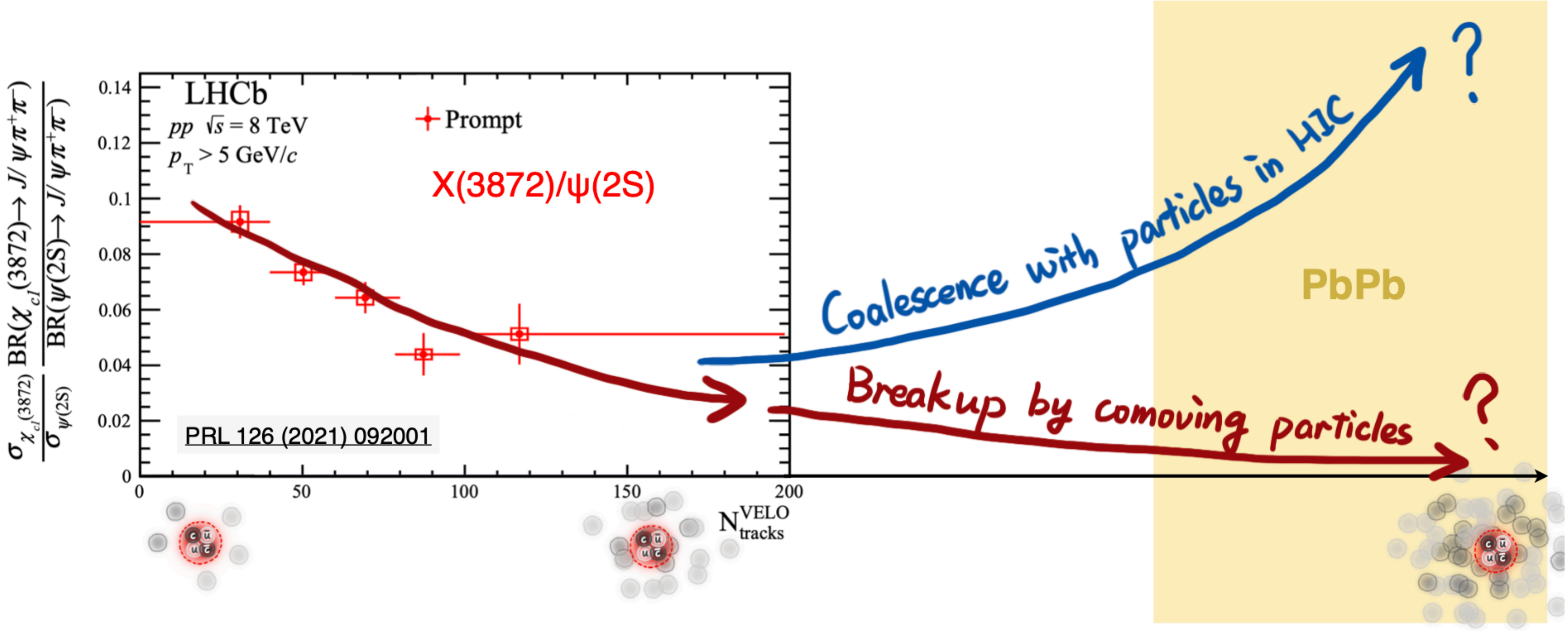
X(3872) in Heavy-ion Collisions

- Breakup by comoving particles ➜ Suppress X(3872)

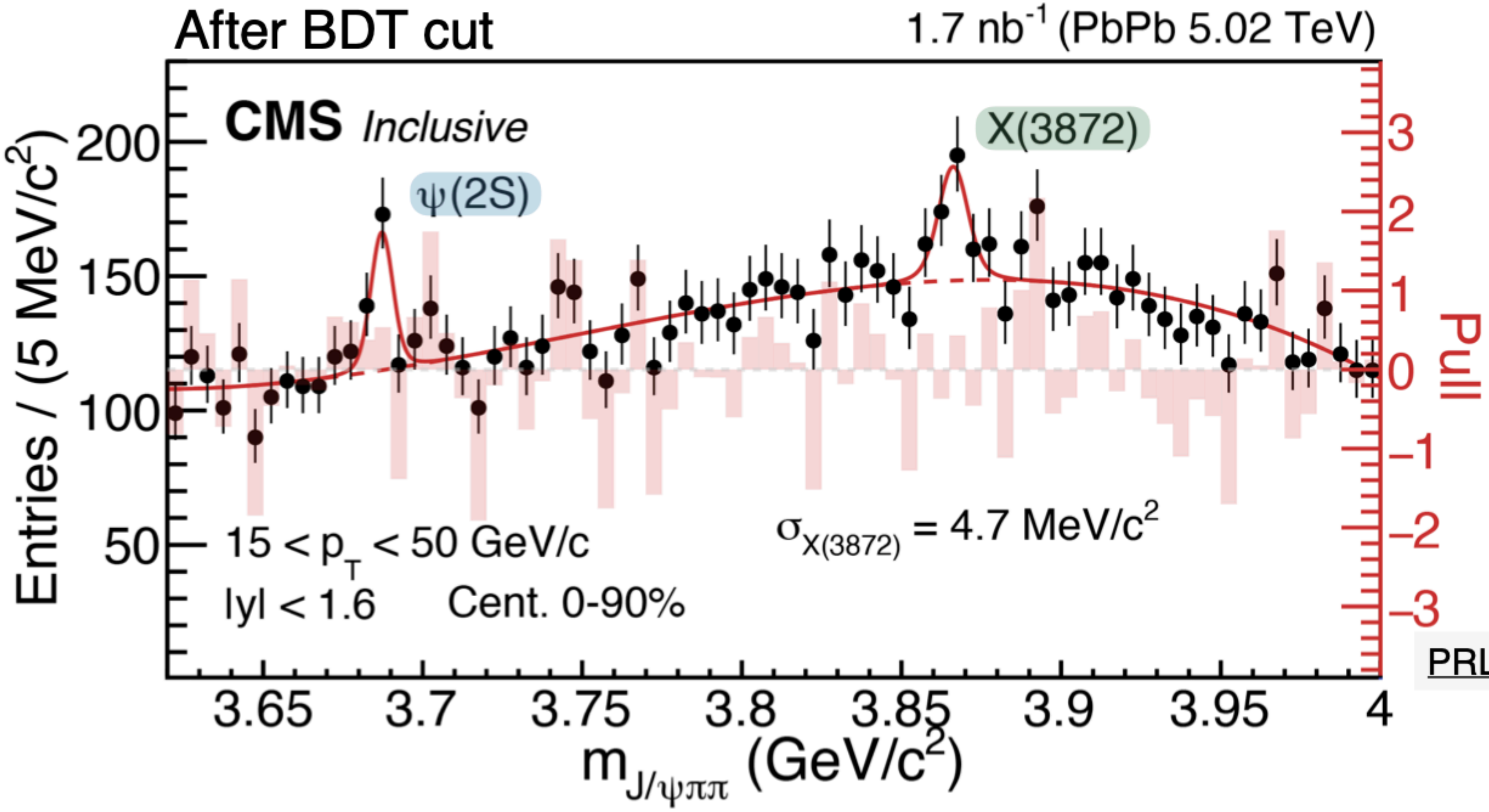


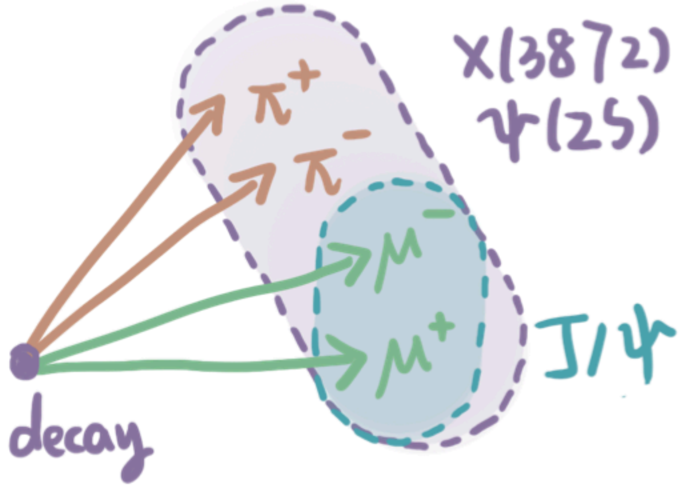
X(3872) in Heavy-ion Collisions

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with particles in HIC ➜ Enhance X(3872)



X(3872) Signals





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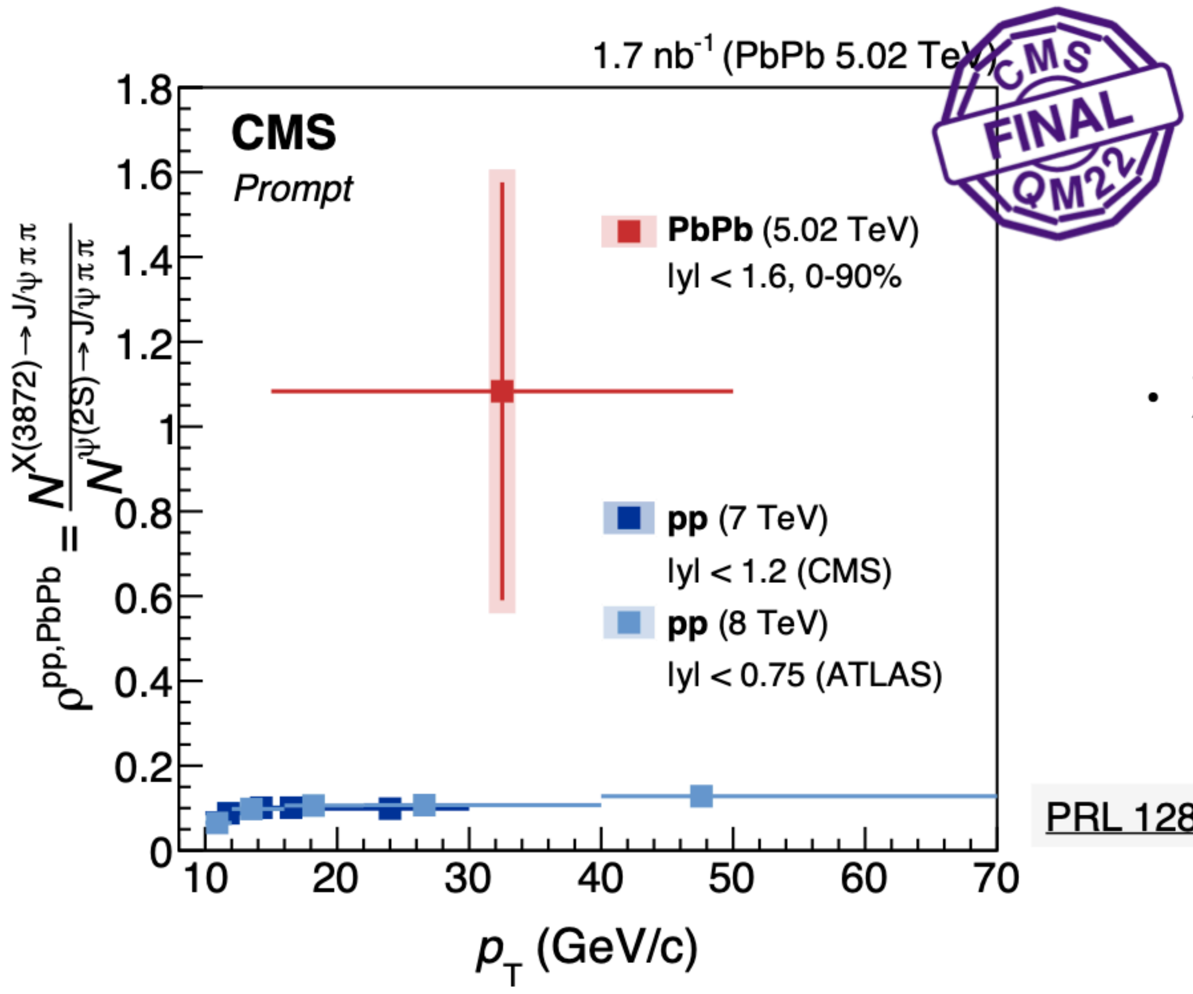
- First evidence of X(3872) production in heavy ion collisions!

  ➡ Statistical significance ~ 4.2σ

X(3872)/ψ(2S) Ratio in PbPb



- X(3872) to ψ(2S) ratio
  $\rho^{PbPb} = 1.08 \pm 0.49\ (\text{stat.}) \pm 0.52\ (\text{syst.})$

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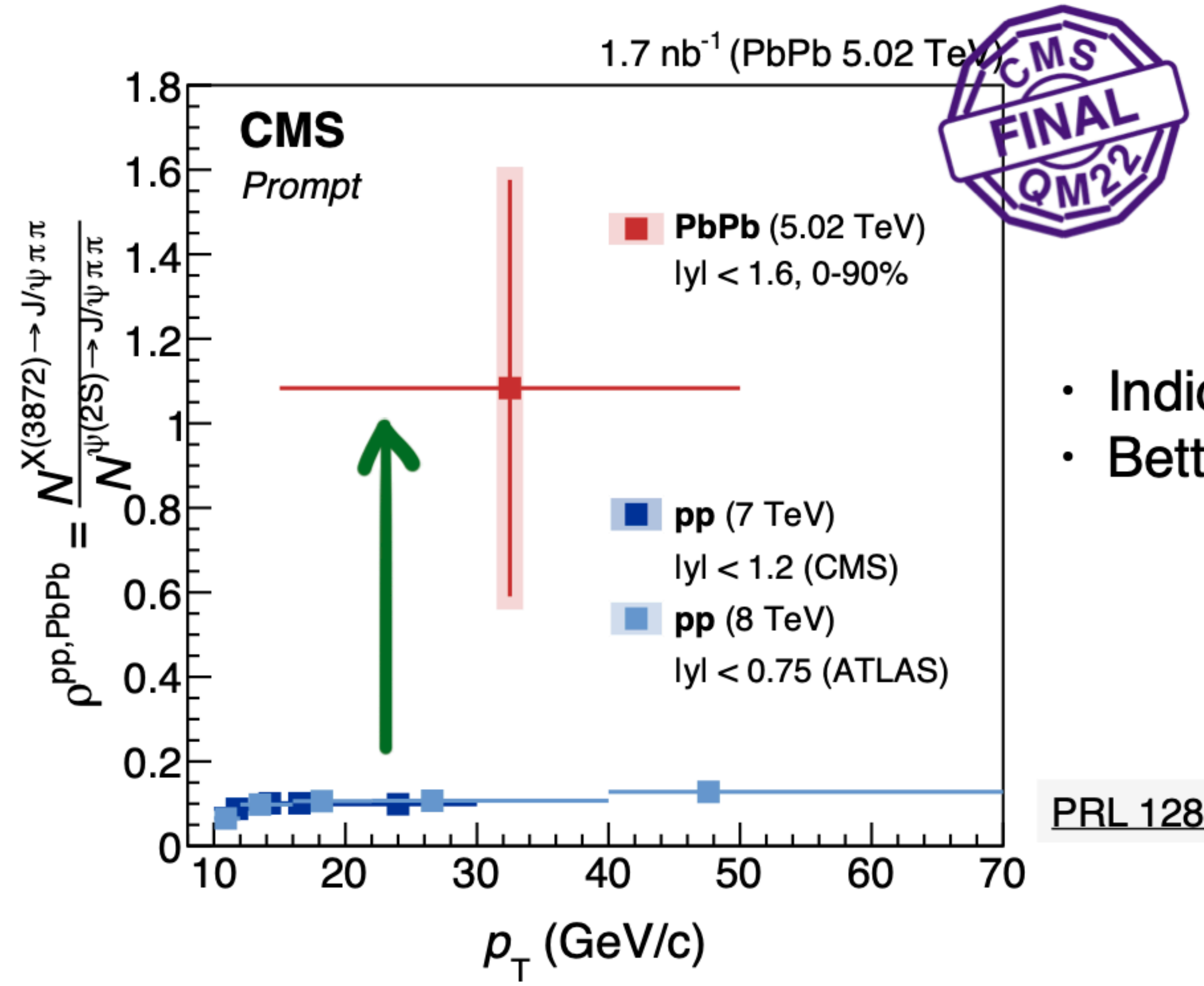
X(3872)/ψ(2S) Ratio in PbPb



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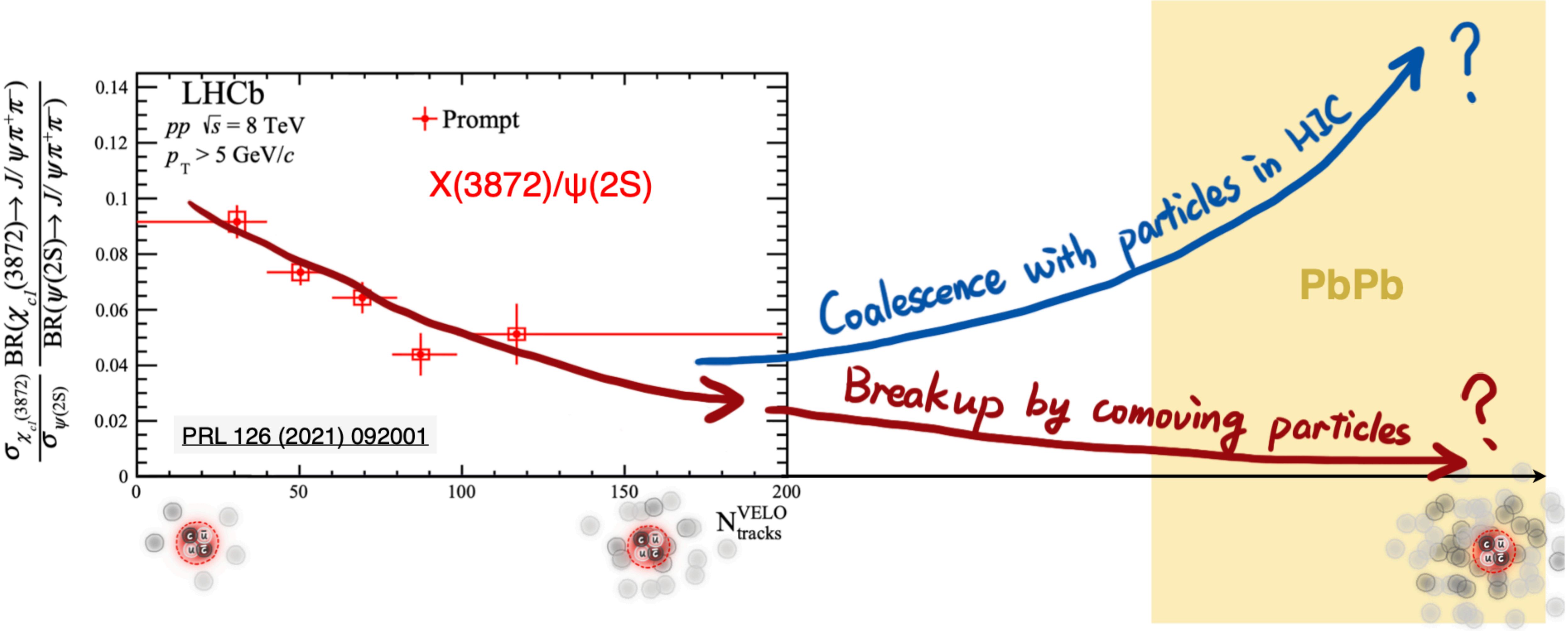
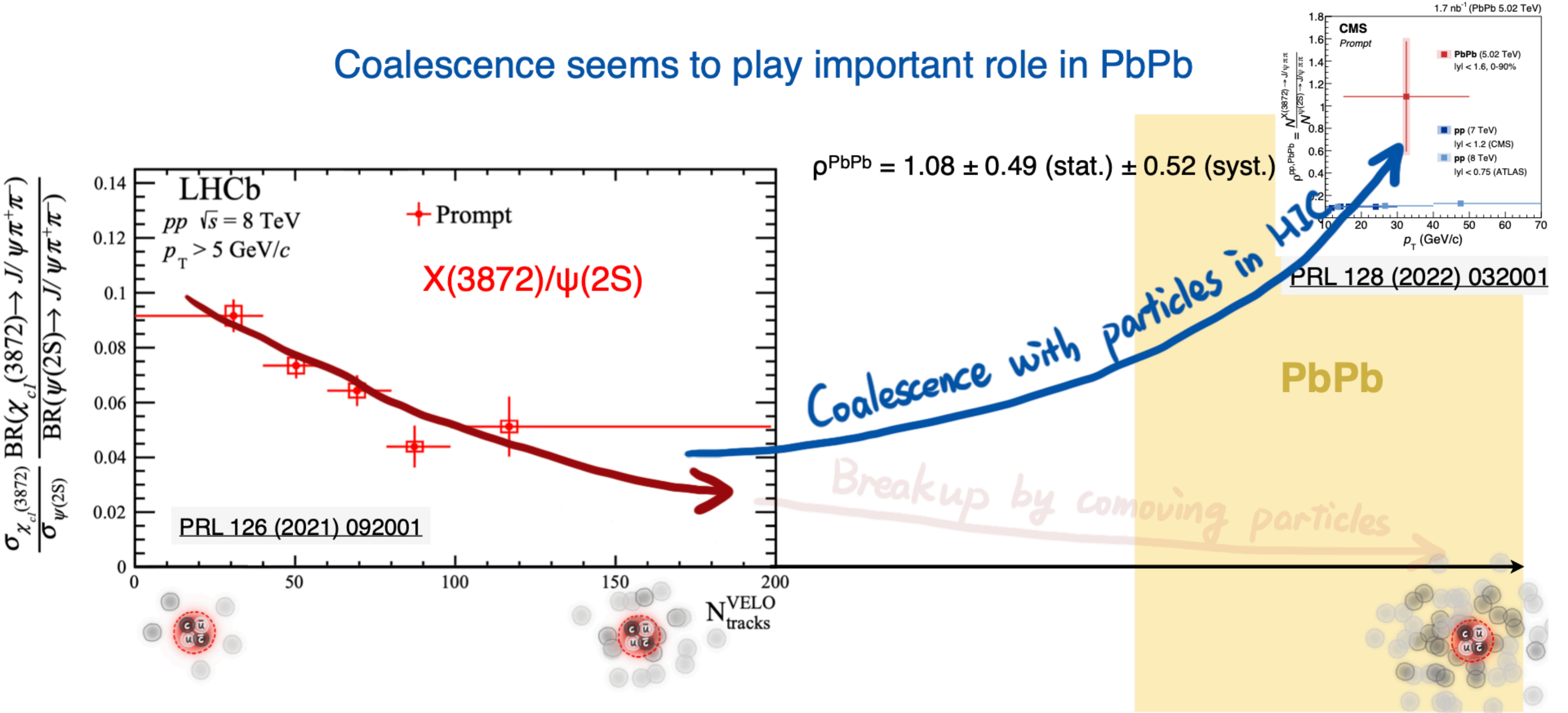
- Indication of ρ enhancement in PbPb w.r.t to pp
- Better precision needed to draw conclusion

- Breakup by comoving particles ➜ Suppress X(3872)
- Coalescence with particles in HIC ➜ Enhance X(3872)



X(3872)/ψ(2S) Ratio in PbPb

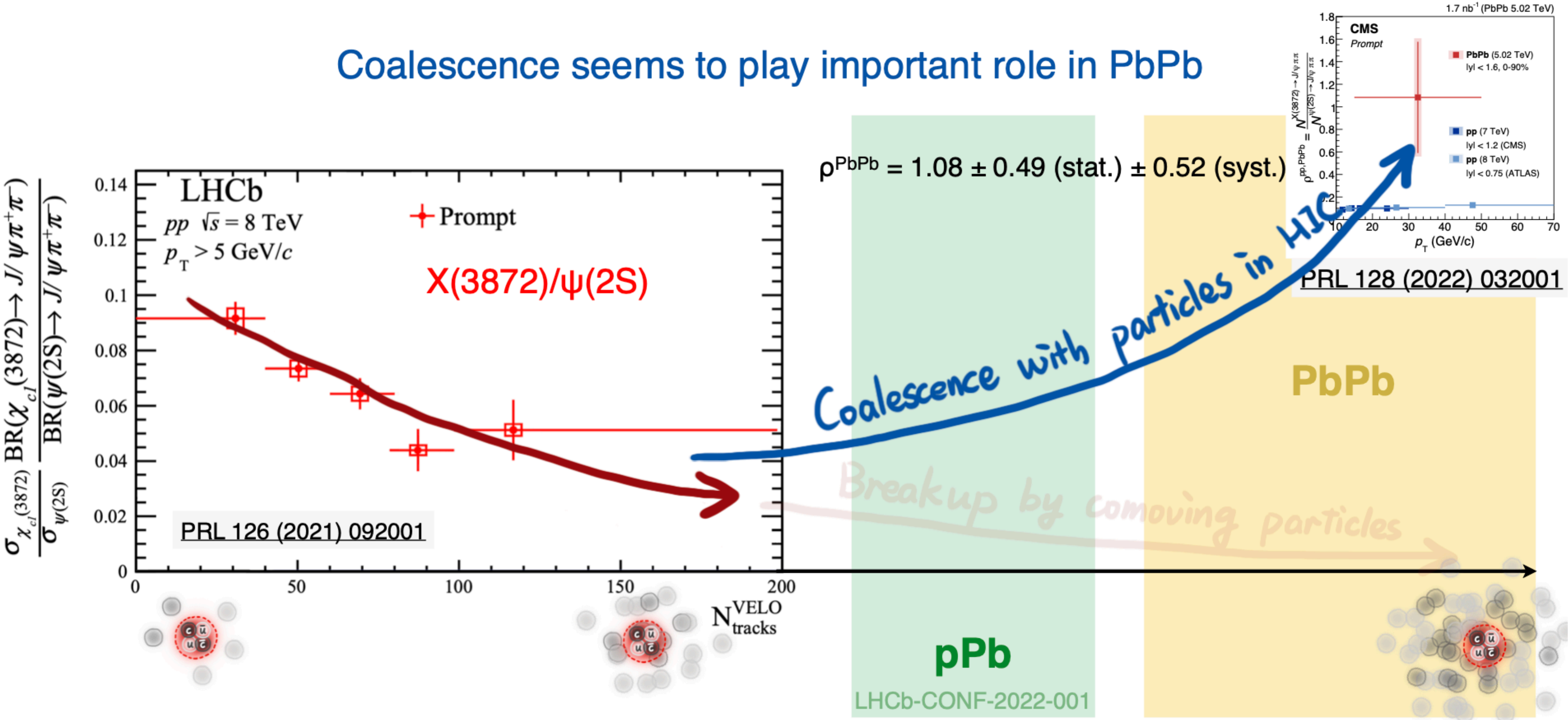
Coalescence seems to play important role in PbPb



X(3872)/ψ(2S) Ratio in Different Systems

Coalescence seems to play important role in PbPb

ρ^{PbPb} = 1.08 ± 0.49 (stat.) ± 0.52 (syst.)



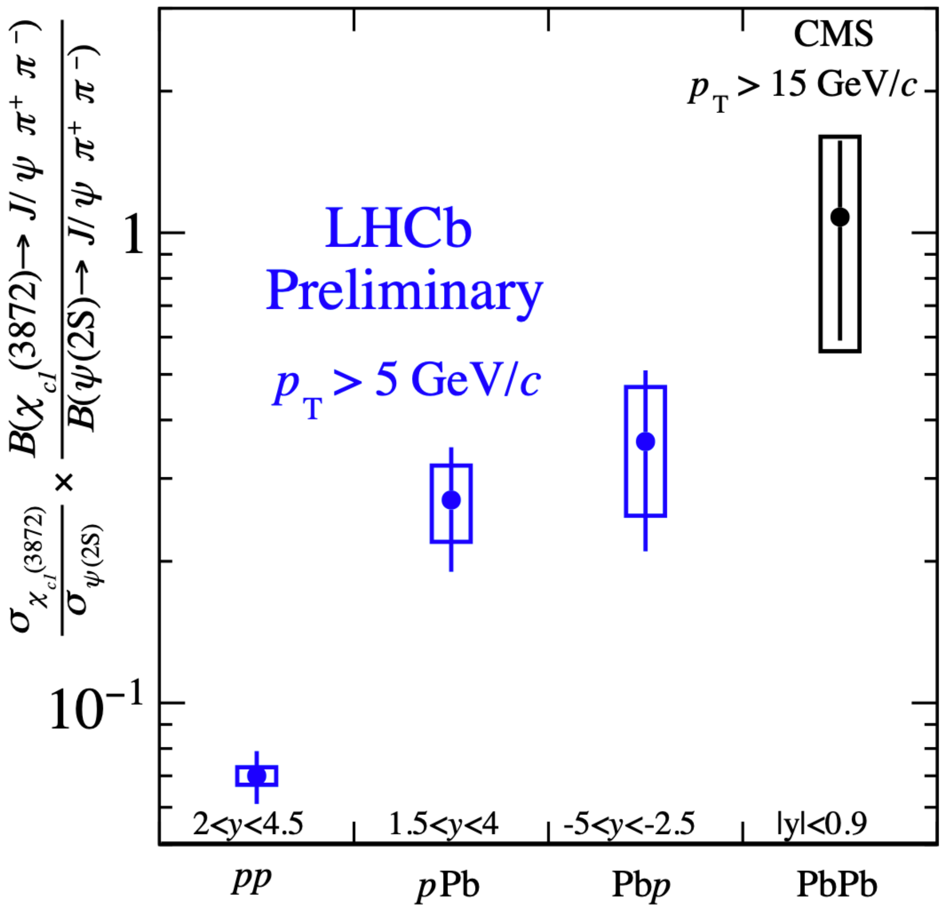
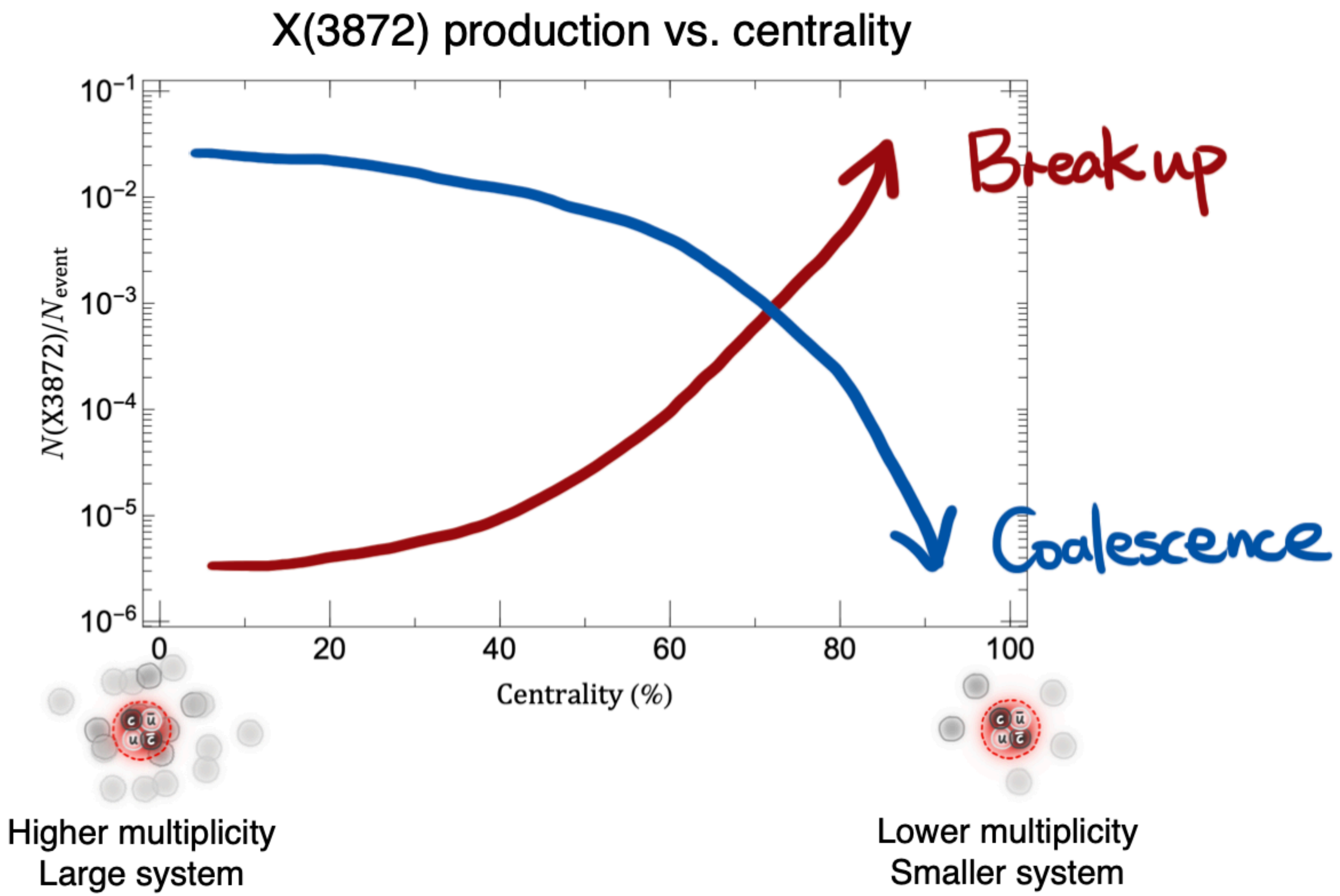
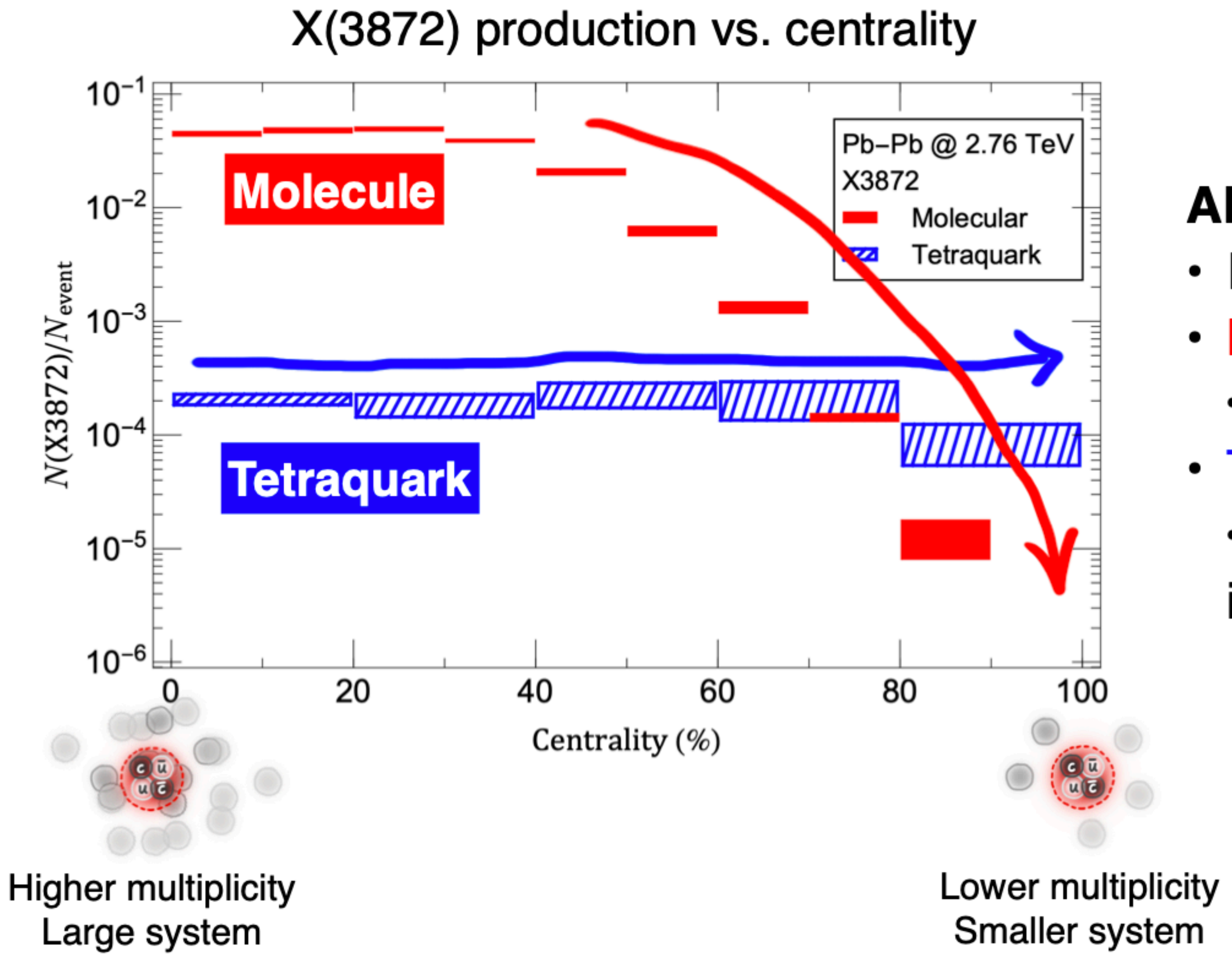


Figure 2: The ratio of $\chi_{c1}(3872)$ to $\psi(2S)$ cross-sections in the $J/\psi\pi^+\pi^-$ decay channel, measured in pp [2], pPb, Pbp, and PbPb [5] collisions. The error bars (boxes) represent the statistical (systematic) uncertainties on the ratio.

Theoretical calculation (1)



Theoretical calculation (2)

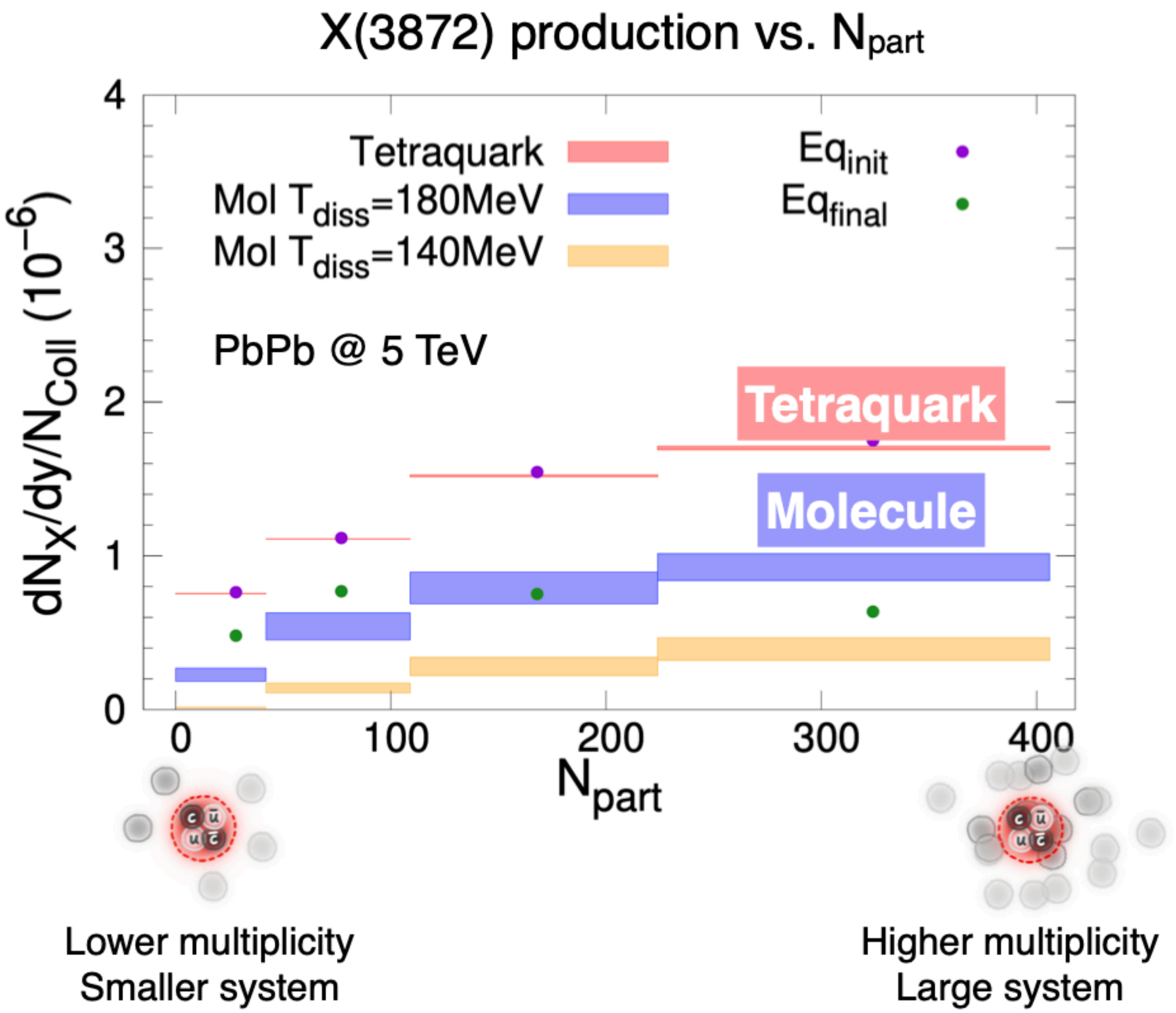


AMPT model PRL 126 (2021) 012301

- Instantaneous coalescence model (ICM)
- Molecule: decrease at peripheral
  ➜ Higher coalescence rate in large system
- Tetraquark: relatively flat vs. centrality
  ➜ Decreasing numbers of available $c\bar{c}$ vs. increasing chances of small spatial separation

TAMU model EPJA 57 (2021) 122

- Thermal-rate equation framework, focusing on hadronic phase
- Yield (molecule) < Yield (tetraquark)
  ➜ Tetraquark: Mostly produced in hadronization in QGP transition region
  ➜ Molecule: Regeneration in hadronic medium stage dominates
- Different from ICM

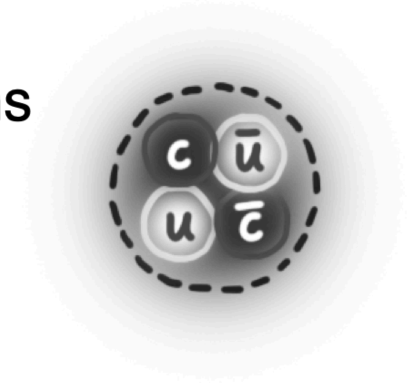


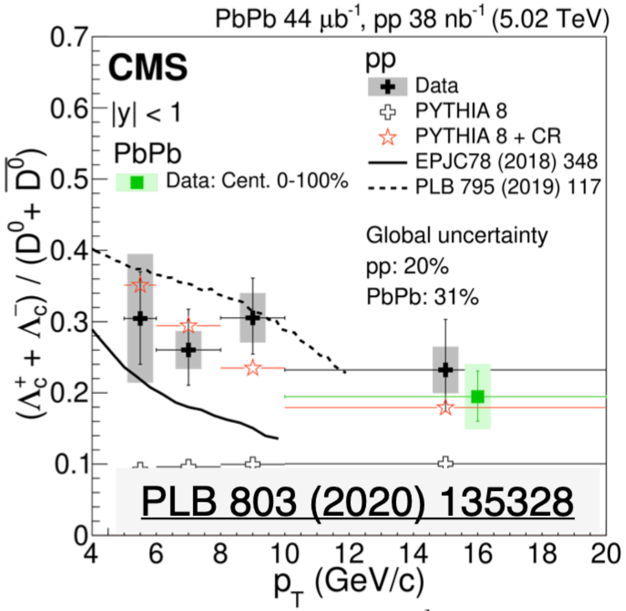
Summary of CMS

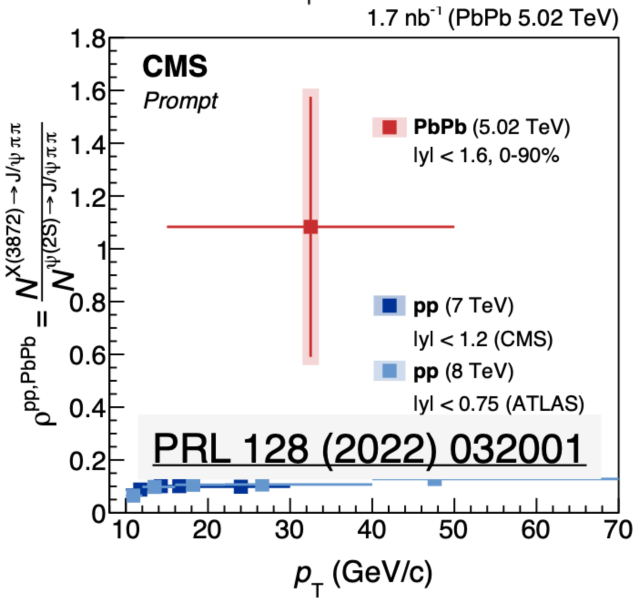
- Study charm in-medium hadronization by baryons and exotic hadrons in CMS

- Λ_c measured in pp and PbPb collisions
  ➜ PYTHIA8 underestimates Λ_c/D^0 in pp
  ➜ CR, coalescence and feed-down from more excited baryons can enhance Λ_c/D^0 in pp
  ➜ Analysis using larger dataset is ongoing

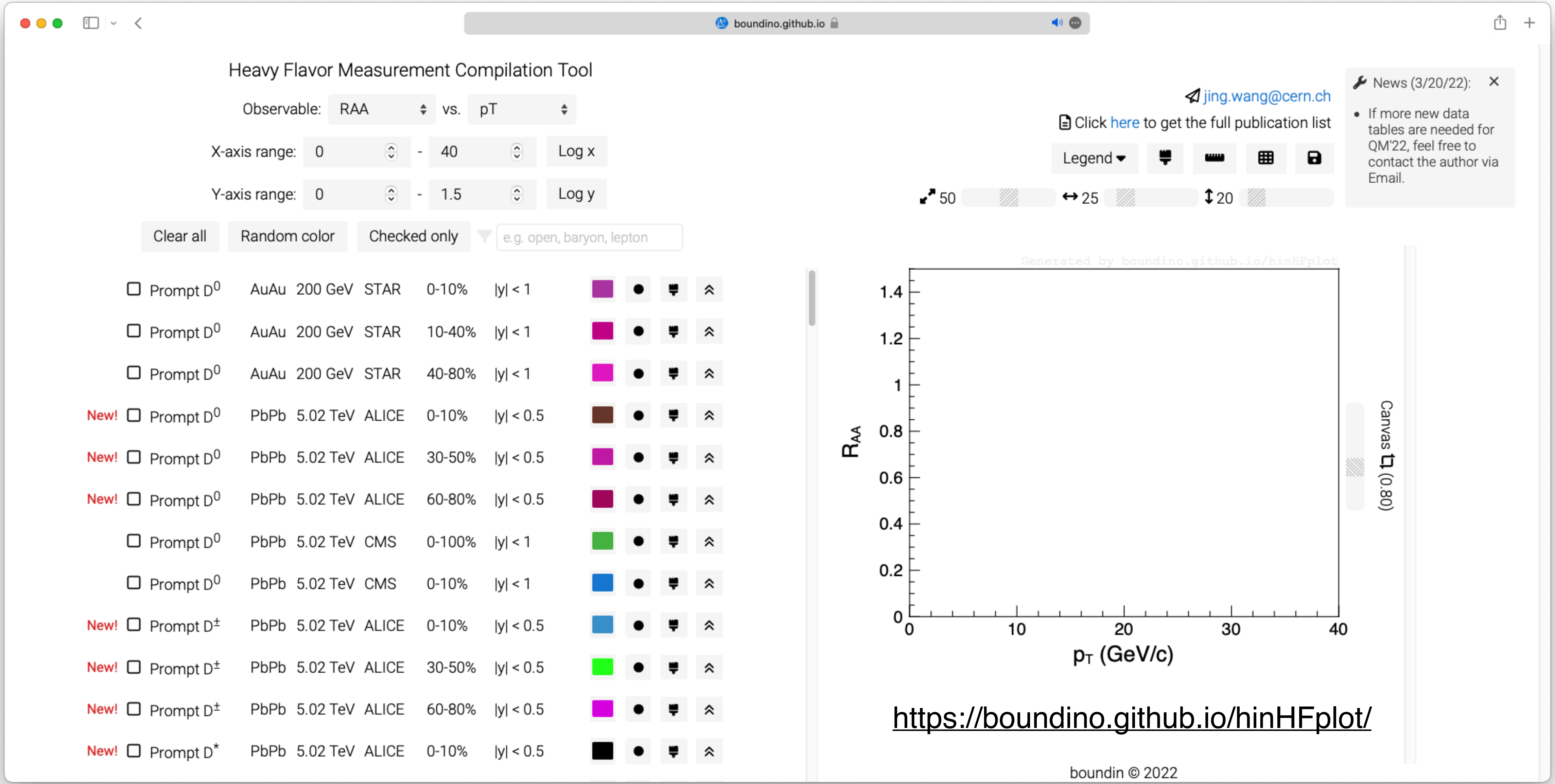
- First evidence of X(3872) In heavy-ion collisions
  ➜ Indication of strong coalescence in PbPb
  ➜ Discriminate nature of exotic hadrons







Have Some Fun with Heavy Flavors!



Summary

- CMS:
  - Λc measured in pp and PbPb collisions
  - First evidence of X(3872) In heavy-ion collisions
- STAR:
  - Open heavy flavor production in Au+Au collisions
- LHCb:
  - Open-charm production in *p*Pb collisions
  - Λ^{+}_{c} -to-D^0 ratio in peripheral PbPb collisions