The production of exotic hadrons T_{cc} and $X_{cs\bar{c}\bar{s}}$ in heavy ion collisions

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Y.Hu, H.Zhang, Chin.Phys.C.47, No.5(2023) 051001

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Outline

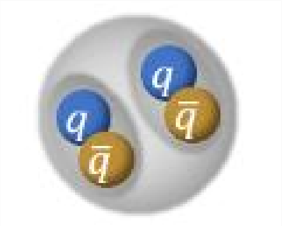
- Introduction
- Framework-AMPT
- Production of doubly charmed exotic hadrons in heavy ion collision
- Production of $X_{cs\overline{cs}}$ in heavy ion collision
- Summary and outlook

Introduction

Exotic Hadron States

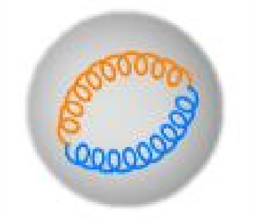
- Hadrons are mostly found in two modes:
  - Mesons ($q\bar{q}$)
  - Baryons (qqq)
- Many other types of color singlet compound hadrons, the so-called exotics, could exist:

Compact tetraquark



Molecular tetraquark

Pentaquark



Glueball

Hybrid

X: unknown

Y: the vector exotic states 1^{--}

Z: charged quarkoniumlike states

Introduction

Charmed hadrons

- Charmed mesons: D , D_s …
- Singly charmed baryons: Λ_c , Σ_c , Ξ_c , Ω_c …
- Doubly and triply charmed hadrons: Ξ_{cc} , Ω_{ccc} …

Multiquark state

Table: Tetraquark and pentaquark candidates: Nature Commun. 13(2022)1, 3351

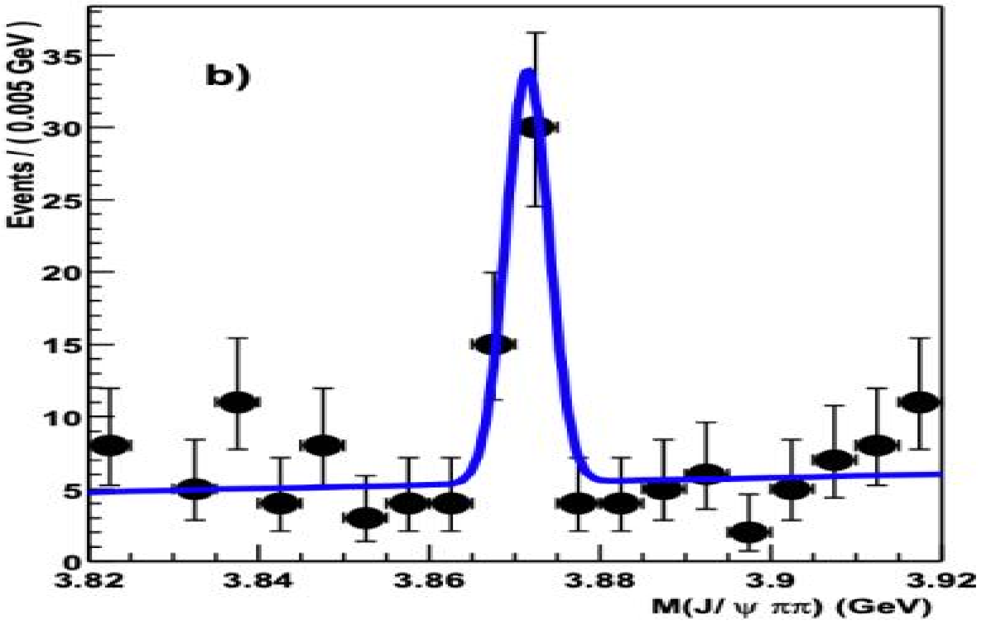
Table: Tetra- & pentaquark candidates Nature Commun. 13 (2022) 1, 3351

States	Quark content
$X_0(2900)$, $X_1(2900)$	$\bar{c}d\bar{u}\bar{s}$
$\chi_{c1}(3872)$	$c\bar{c}q\bar{q}$
$Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$, $X(4100)$, $Z_c(4200)$, $Z_c(4430)$, $R_{c0}(4240)$	$c\bar{c}u\bar{d}$
$Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$	$c\bar{c}u\bar{s}$
$\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$, $X(4630)$, $X(4685)$, $X(4740)$	$c\bar{c}s\bar{s}$
$X(6900)$	$c\bar{c}c\bar{c}$
$Z_b(10610)$, $Z_b(10650)$	$b\bar{b}u\bar{d}$
$P_c(4312)$, $P_c(4380)$, $P_c(4440)$, $P_c(4457)$, $P_c(4357)$	$c\bar{c}uud$
$P_{cs}(4459)$	$c\bar{c}uds$

Introduction

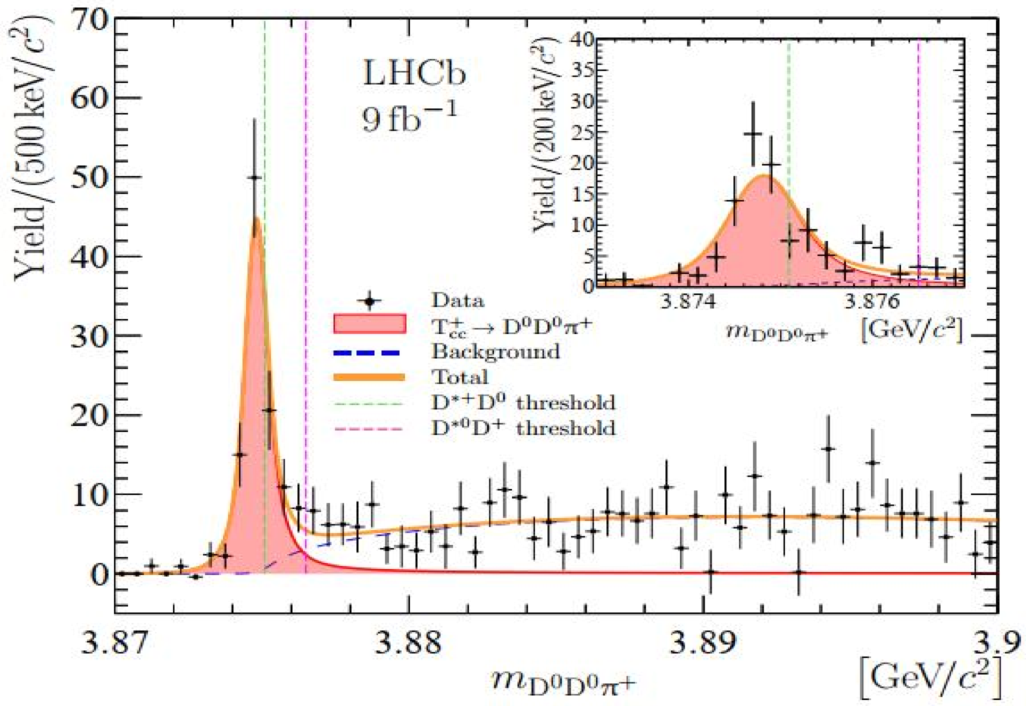
- X (3872) $J^{PC} = 1^{++}$ $(c\bar{c}q\bar{q})$
  - Bell collaboration(2003)
    $B \to J/\Psi\pi^+\pi^- K$
  - $M_X = 3871.69 \pm 0.17\text{MeV}$
  - Decay pattern:

$J/\Psi\rho(\pi^+\pi^-)$, $J/\Psi\omega(\pi^+\pi^-\pi^0), D^0\bar{D}^{0*}/\overline{D^0}D^{0*}/D\bar{D}\pi, J/\Psi\gamma$



X(3872) —Belle Collaboration, PRL 91.262001(2003)

- T_{cc} $J^{PC} = 1^+$ $(cc\bar{q}\bar{q})$
  - LHCb collaboration(2021)
    $T_{cc}^+ \to D^0D^0\pi^+$
  - $M_{T_{cc}^+} = 3875 \pm 0.41\text{MeV}$



T_{cc}^+—LHCb Collaboration, Nature Commun. 13(2022) 1,3351; Nature Phys. (2022)

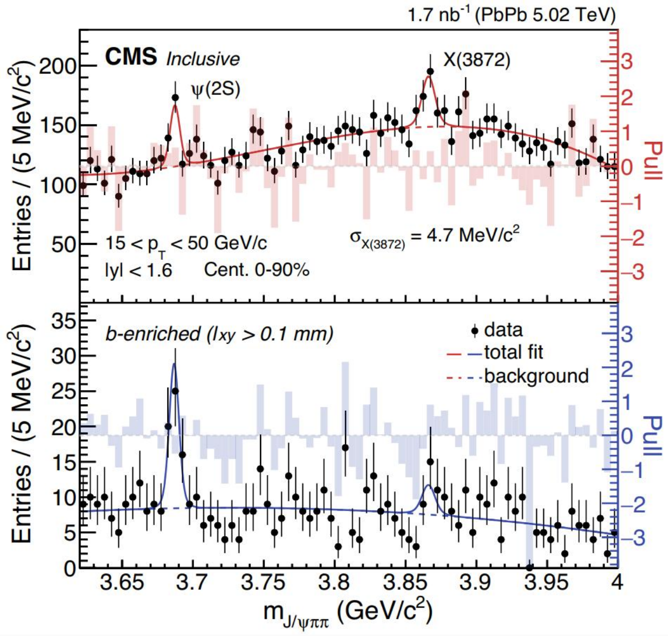
Introduction

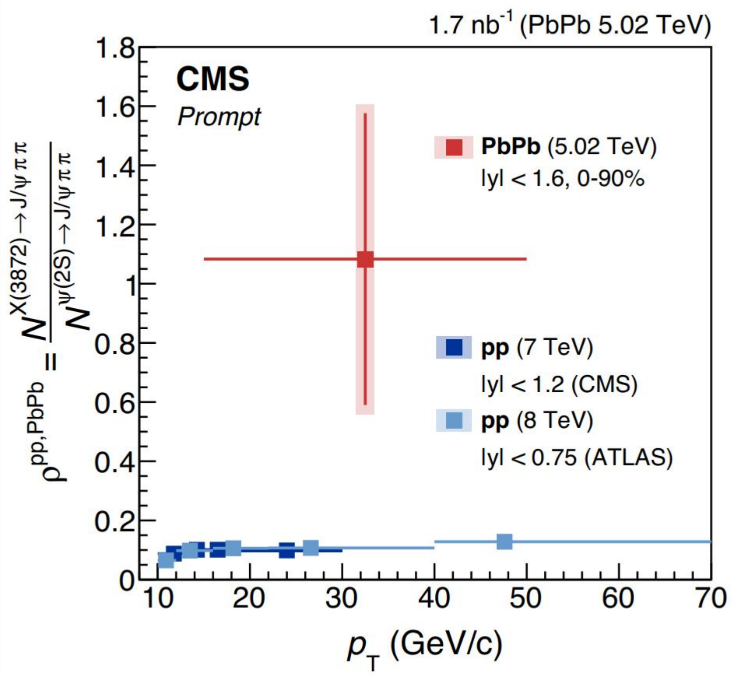
□ Estimated yields of X(3872) and T_{cc}

S.Cho et al. (ExHIC Coll.), PRC84(2011)064910

	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
T_{cc}^{1} [a]	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}

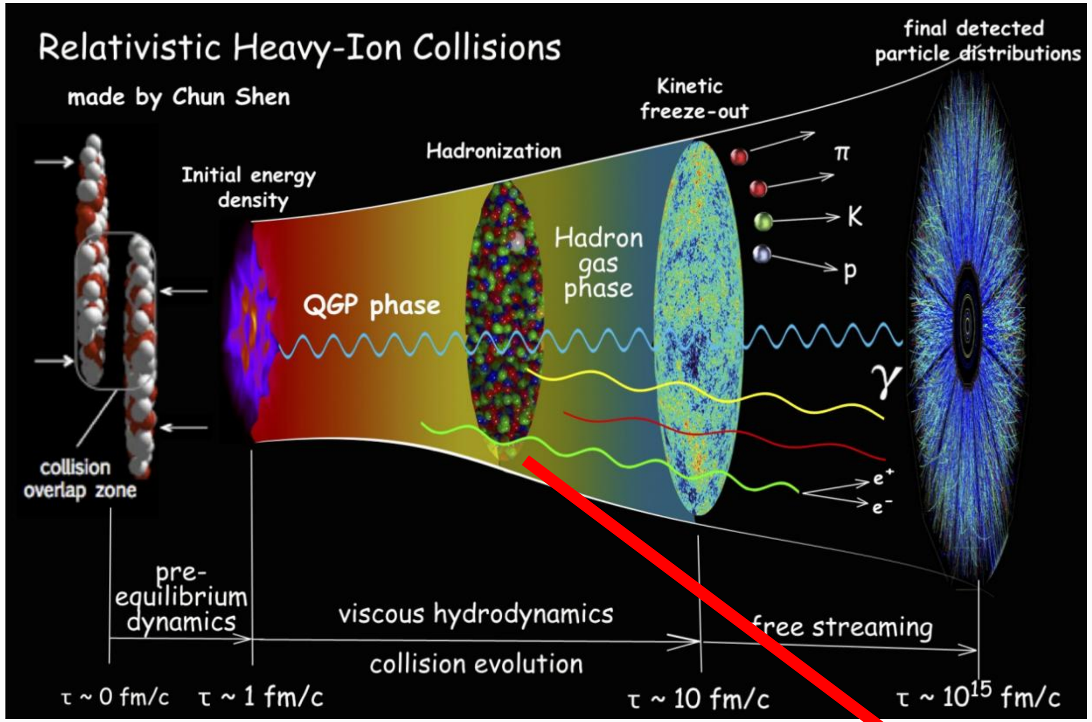
[a]Particles that are newly predicted by theoretical models.



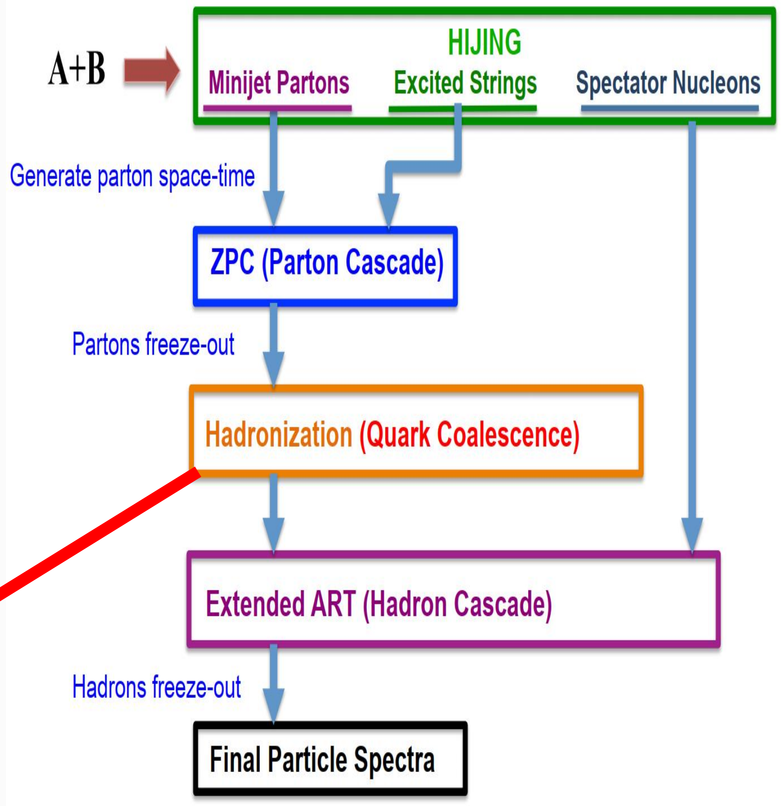


CMS, PRL128(2022)032001

Heavy Ion Collision & AMPT



Structure of AMPT (String Melting version)



Coalescence

Z.W.Lin et al.,PRC 65, 034904(2002)
Z.W.Lin et al.,PRL 89, 152301(2002)

T_{cc} Molecule: $D + D^*$

X(3872) Molecule and Tereaquark : $D + \bar{D}^*$, $cq + \bar{c}\bar{q}$

$X_{cs\bar{c}\bar{s}}$ Molecule : $D_s^+ D_s^{-*}$ and $D_s^{+*} D_s^-$

Tetraquark: $[cs]_1 + [\bar{c}\bar{s}]_0$ and $[cs]_0 + [\bar{c}\bar{s}]_1$

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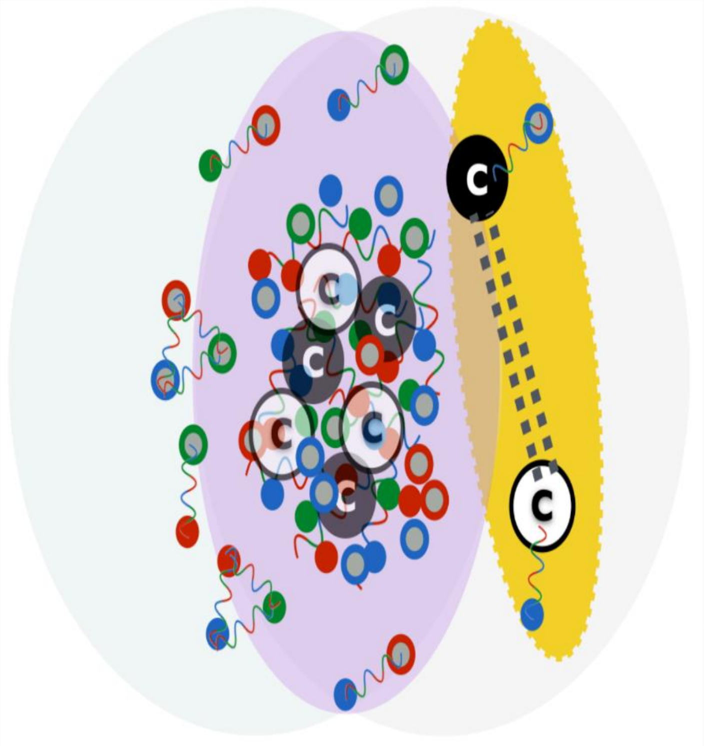
Molecule (X(3872) and T_{cc}) in heavy ion collisions

☐ Molecule states



- Coalescence of D mesons
- The relative distance between D meson pairs:

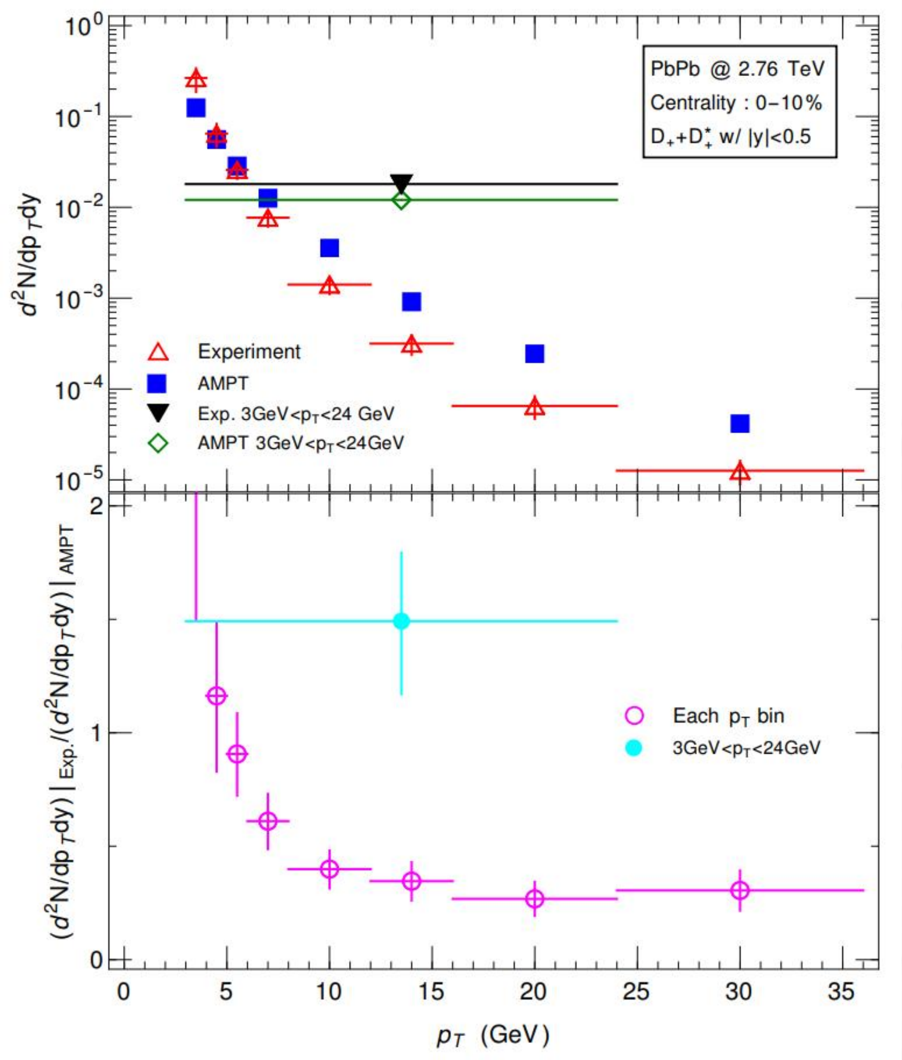
$$R_{D\bar{D}^*} \sim 5 - 7 fm$$

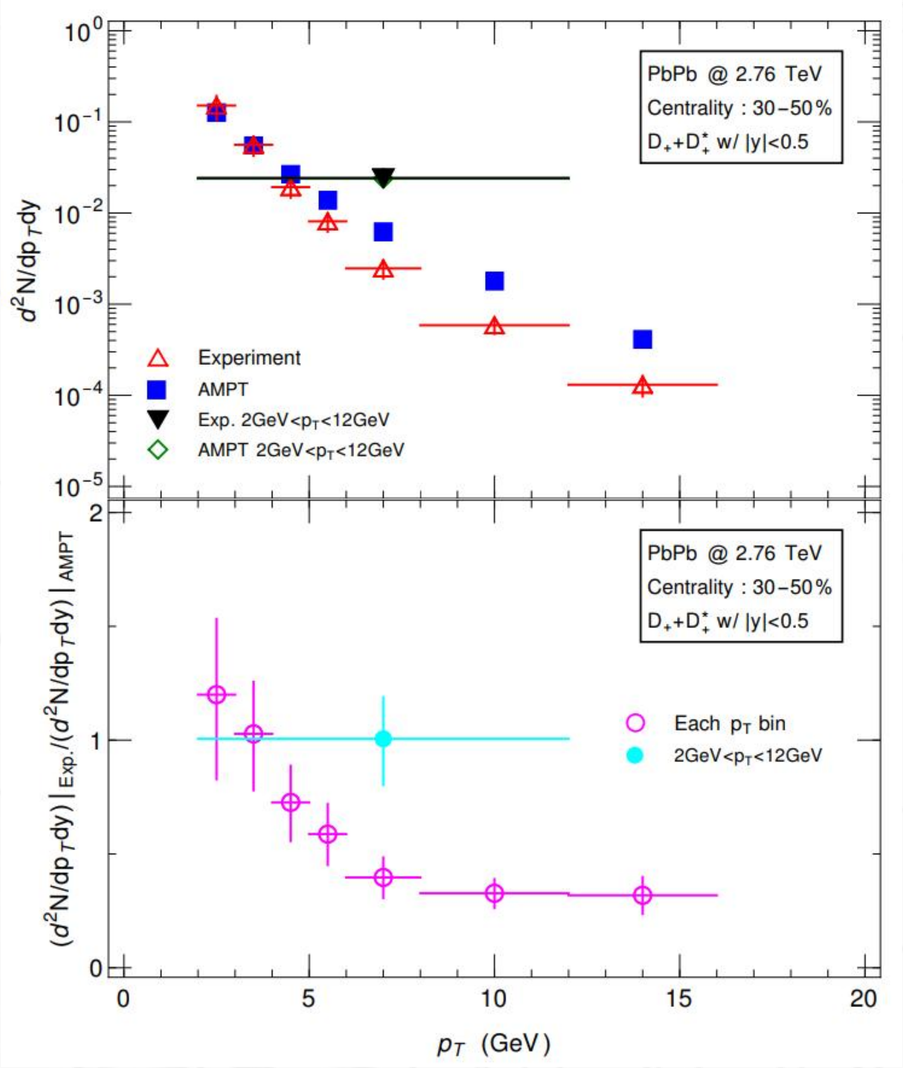
$$R_{DD^*} \sim 5 - 7 fm$$

- Mass: $2M_D < M_X < 2M_{D^*}$

Compared with experiment

- Compared with the experiment, the amount produced by charm quark



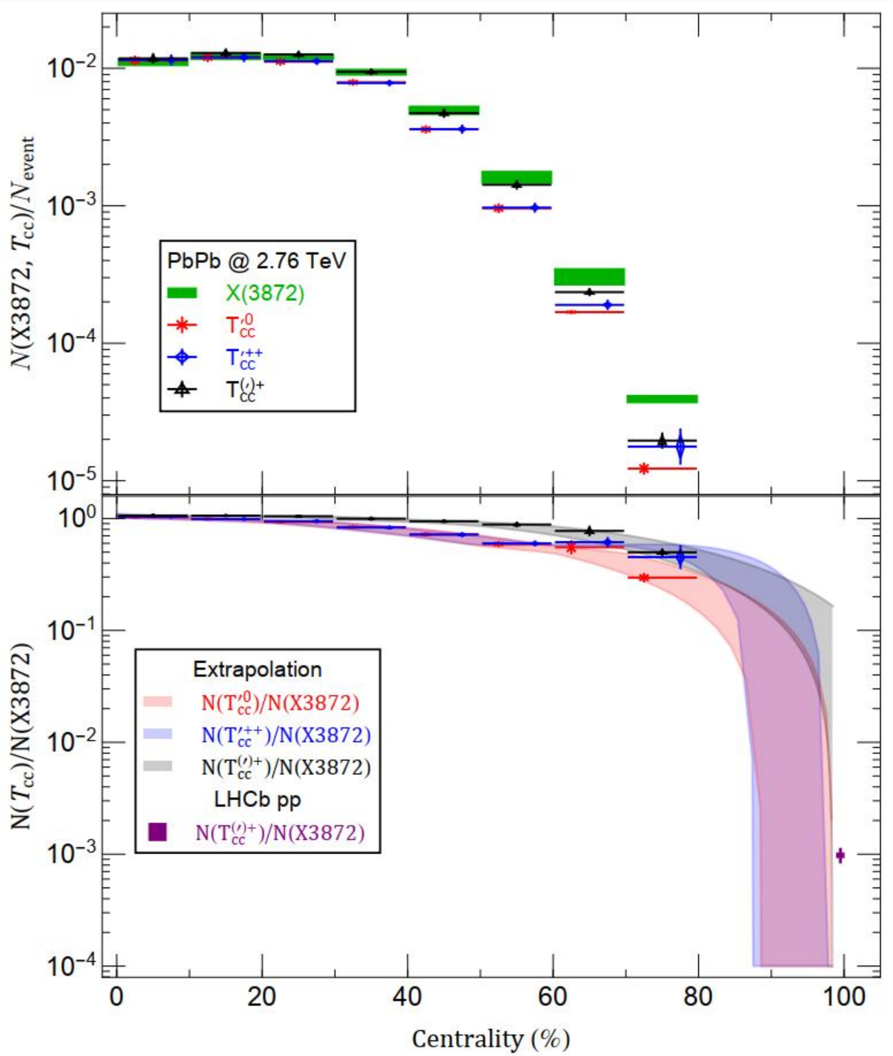


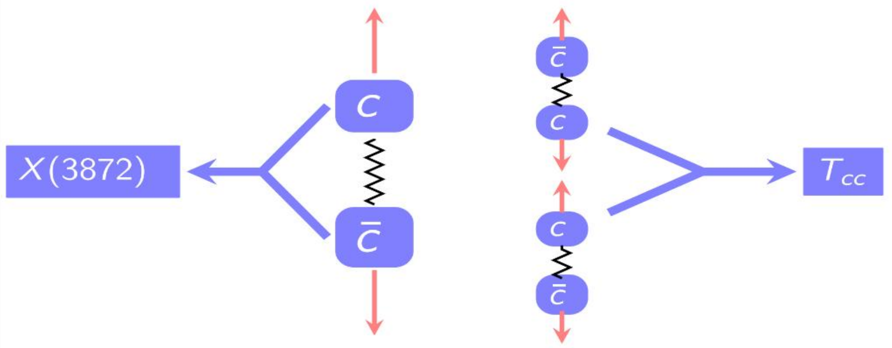
The experimental data comes from ALICE Collaboration, JHEP03(2016)081

Production of doubly charmed exotic hadrons in HIC

☐ Total yields in 1M events

➢ Centrality dependence



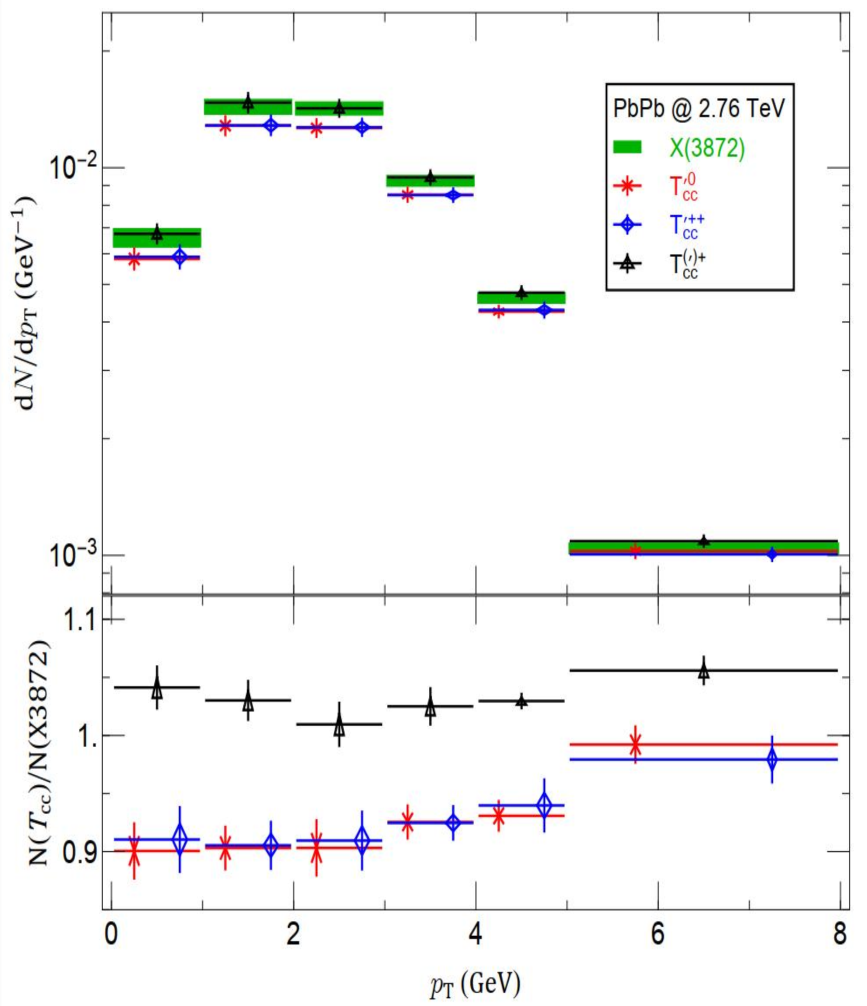


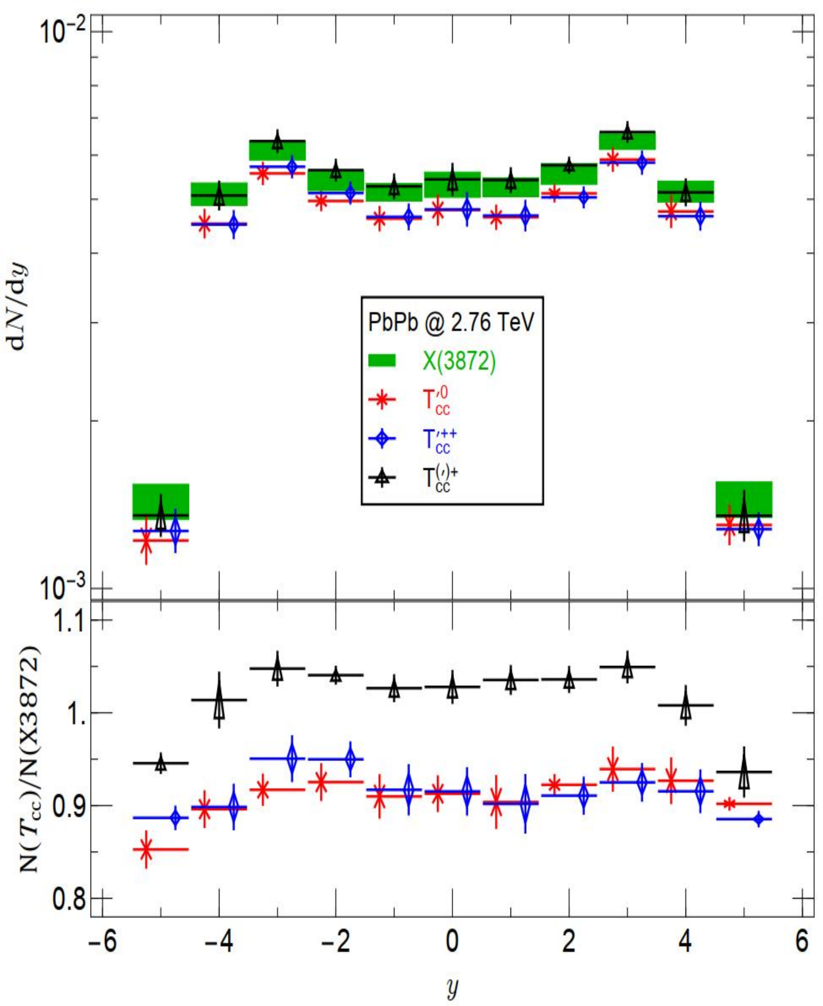
- When the centrality is large, T_{cc} is smaller than X(3872) .
- Isotriplet partners is even smaller than that of T^+_{cc}
- Pb-Pb collisions can provide us with an environment rich in charm quarks.

Y. Hu, J. Liao, E. Wang, Q. Wang, H. Xing and H. Zhang, Phys. Rev. D. 104. L111502 (2021);

Production of doubly charmed exotic hadrons in HIC

- Transverse momentum distribution and rapidity distribution in X(3872) and T_{cc}



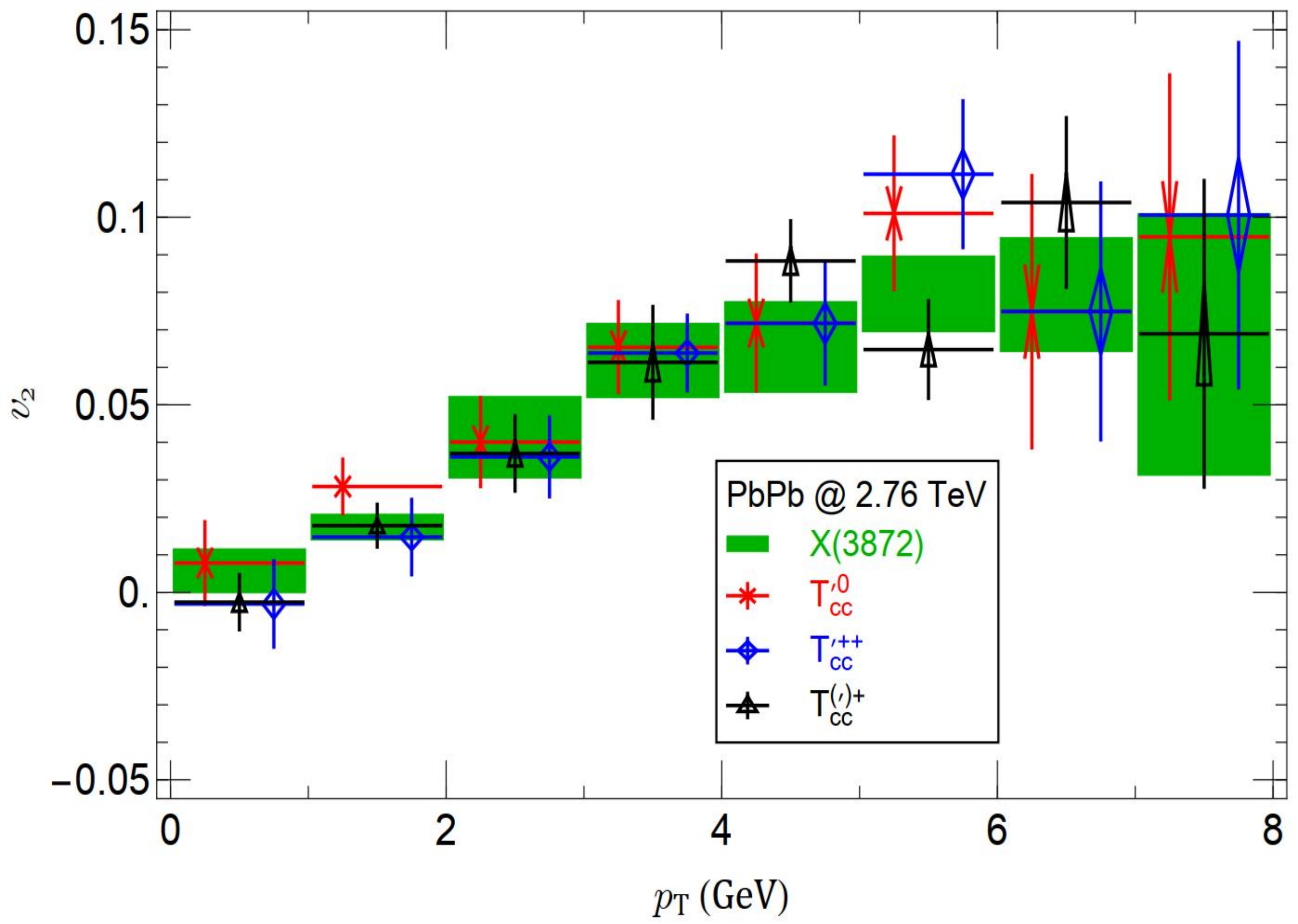


- Similar to normal hadrons.
- The overall trends of X(3872) and T_{cc} of the two graphs are similar.
- X(3872) is similar to T^{+}_{cc}, T^{0}_{cc} and T^{++}_{cc} are both smaller than X(3872).

Y. Hu, J. Liao, E. Wang, Q. Wang, H. Xing and H. Zhang, Phys. Rev. D. 104. L111502 (2021);

Production of doubly charmed exotic hadrons in HIC

➢ Elliptic flow



- Elliptic flow: $v_2 \equiv \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$ p_x, p_y, p_z is the three momentum of the produced hadron, with z-axis beam direction.
- Elliptic flow is the key observable for collective property of bulk medium.
- v_2 can be used as a QGP probe, can describe the geometry of the fireball at the beginning of the collision, and can be used to understand the generation of particles.
- The properties of T_{cc} and X(3872) are almost the same, both have anisotropic flow.

Y. Hu, J. Liao, E. Wang, Q. Wang, H. Xing and H. Zhang, Phys. Rev. D. 104. L111502 (2021);

Production of doubly charmed exotic hadrons in HIC

- Estimate the production rate of the T_{cc} and X(3872) in the molecular picture.
- Centrality, rapidity, p_T distribution and Elliptic flow of T_{cc}.
- Fireball effect of T_{cc} is more significant than that of X(3872).
- The yield of T_{cc} is almost the same as that of the X(3872) in HIC.
- Explain why the $T_{cc}'^{++}$ is not observed by LHCb and the relative small production rate $T_{cc}'^{0}$/X(3872).

Part Ⅲ

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$X_{cs\overline{cs}}$ in AMPT

Molecule states

- Coalescence of D_s^+ mesons.
- The relative distance between D_s^+ meson pairs:

$$5fm < \text{relative distance} < 7fm$$

- Mass: $2M_{D_s^+} < M_X < 2M_{D_s^{+*}}$

Tetraquark:

- coalescence of diquark and anti-diquark
- The relative distance between diquark pairs $R_{[cs][\bar{c}\bar{s}]} < 1fm$
- Mass: $2M_{[cs]_1} < M_X < 2M_{[\overline{cs}]_0}$
   - Maiani, et. al., PRD89(2014)114010

Calibration of the baseline

- $X_{cs\overline{cs}}$ simulation by AMPT

- Calibration of the baseline

  - AMPT does not have spin degrees of freedom, we distribute the yield into different spin state according to thermal model approximation

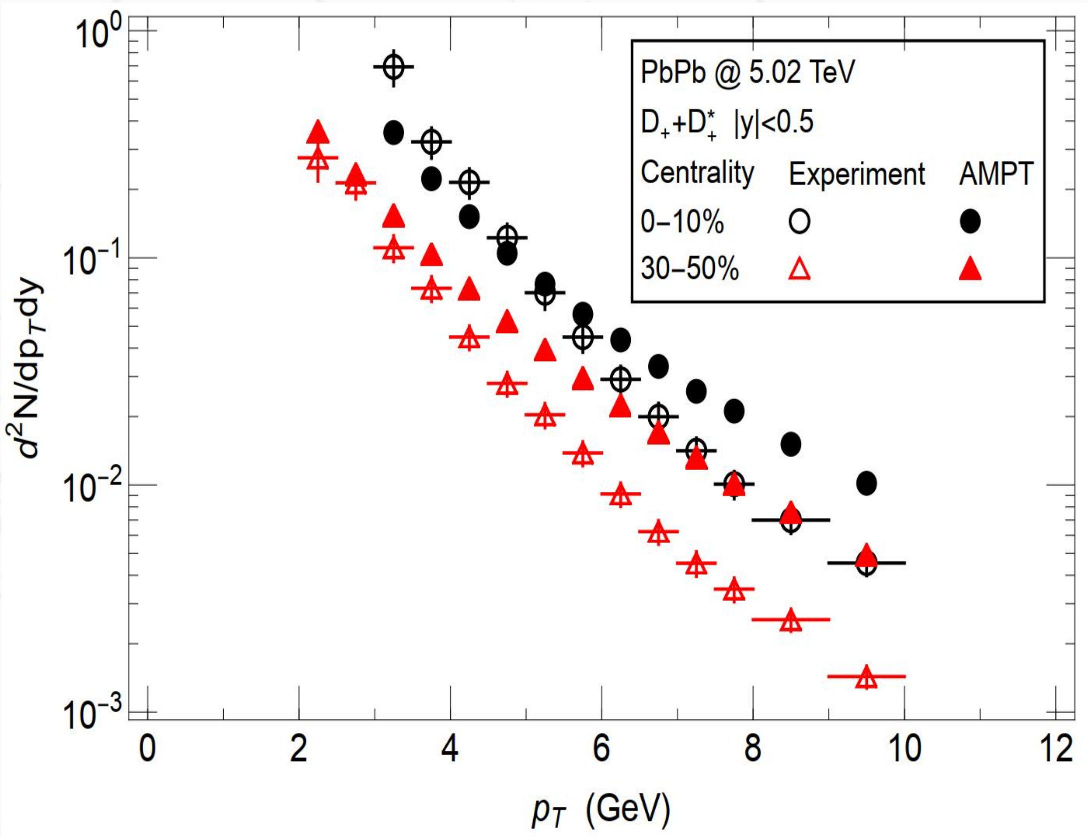
$$R\left(\frac{A}{B}\right) = \frac{Yield(A)}{Yield(B)} = e^{-(m_A - m_B)/T_{freezeout}}$$

  - $T_{freezaout}$ = 160MeV

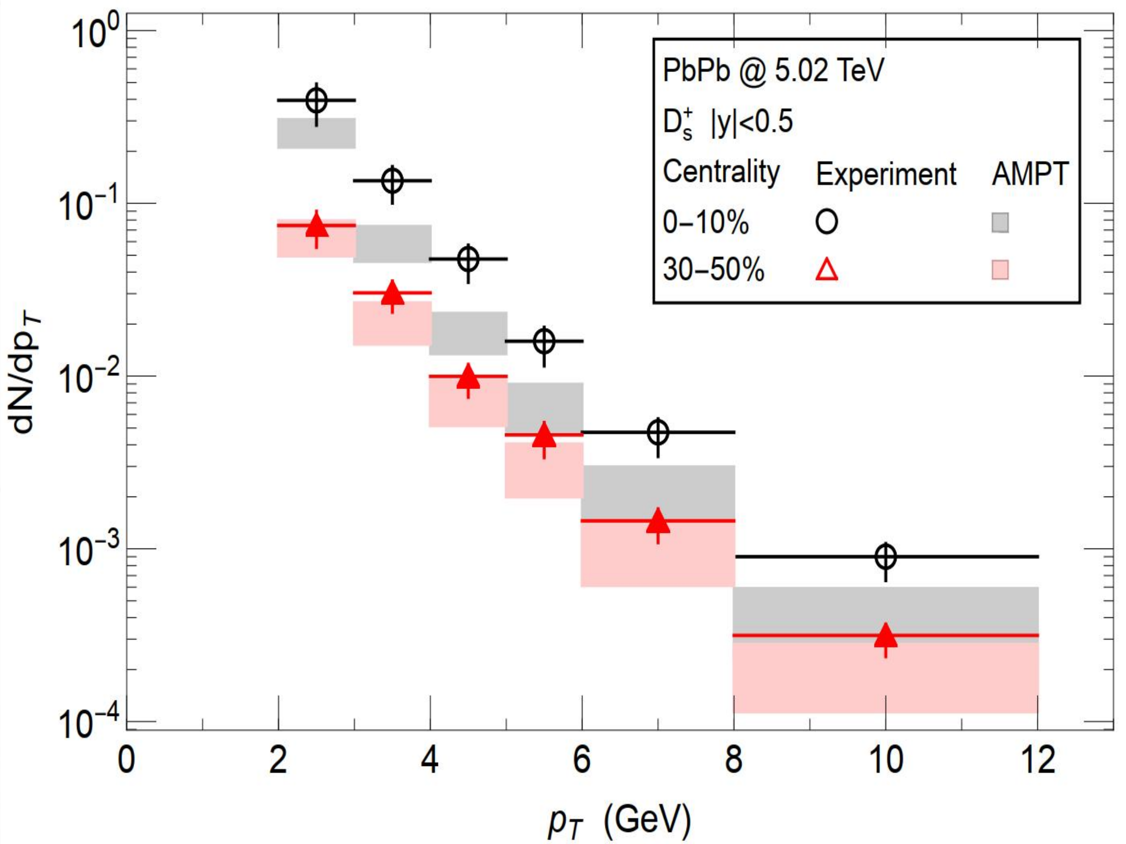
  - The invariant mass is less than 70% is D_s^+, 10% up and down as the theoretical error , the rest is D_s^{+*}

Compared with experiment

- Compared with the experiment, the amount produced by charm quark and strange quark



The experimental data of $D^+ + D^{+*}$ from the ALICE Collaboration, JHEP01, 174 (2022) .

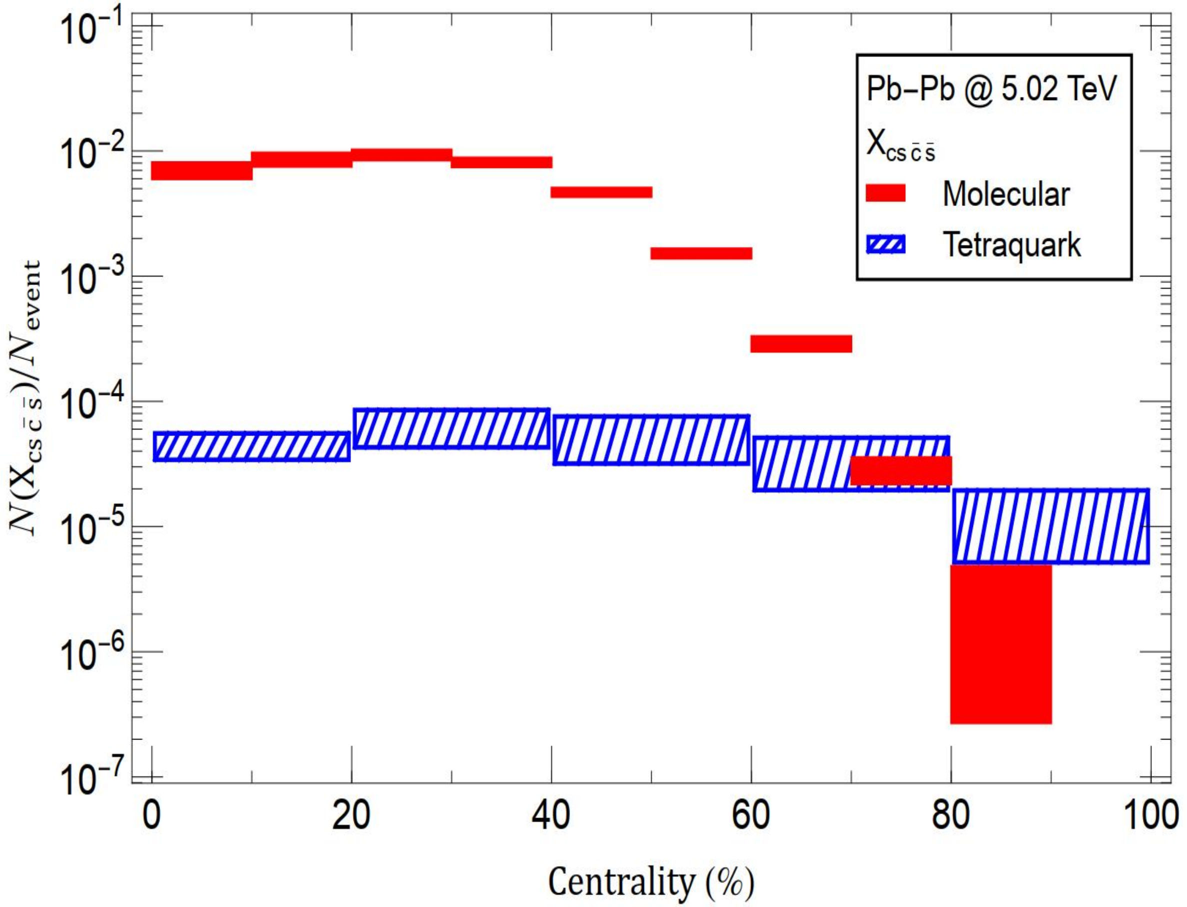


The experimental data of D_s^+ from the ALICE Collaboration, Phys. Lett. B 827, 136986 (2022).

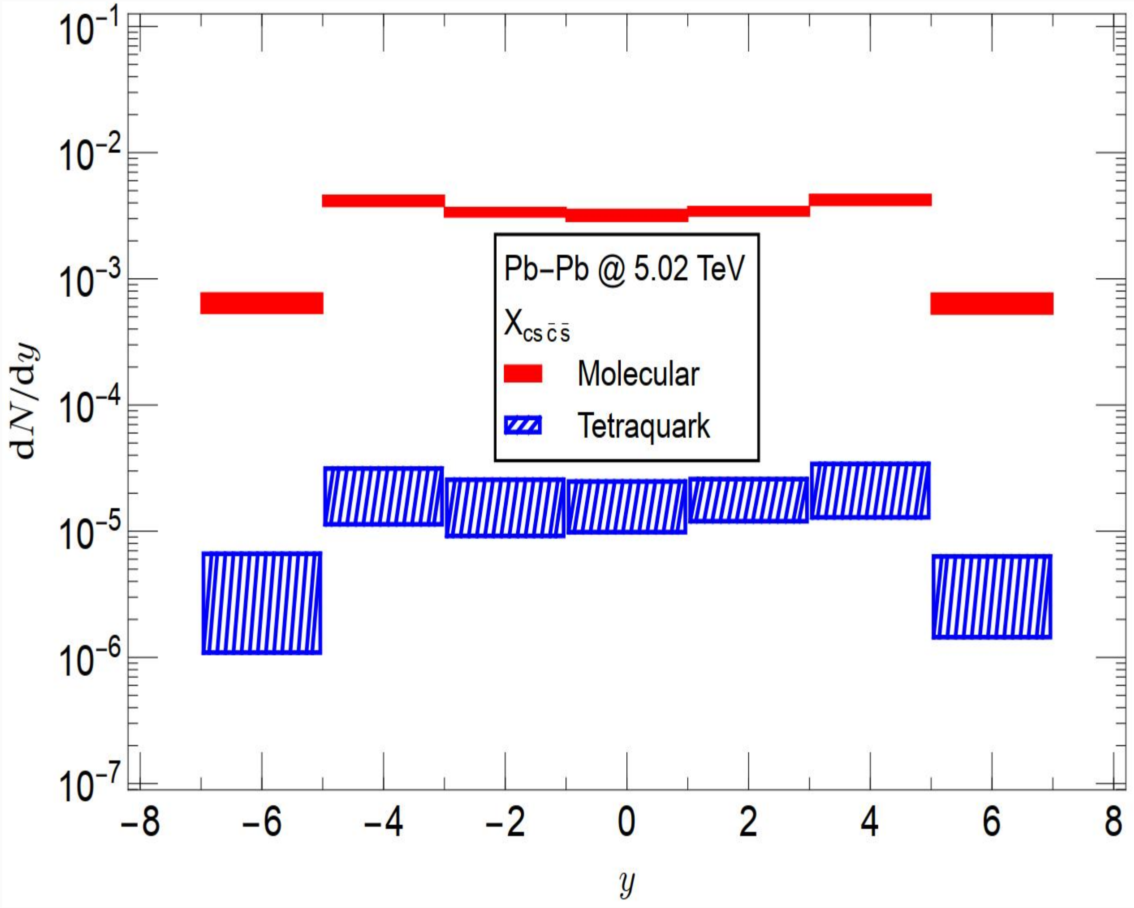
Production of $X_{cs\bar{c}\bar{s}}$ in HIC

- **Total yields in 1M events**

  - Centrality distributions



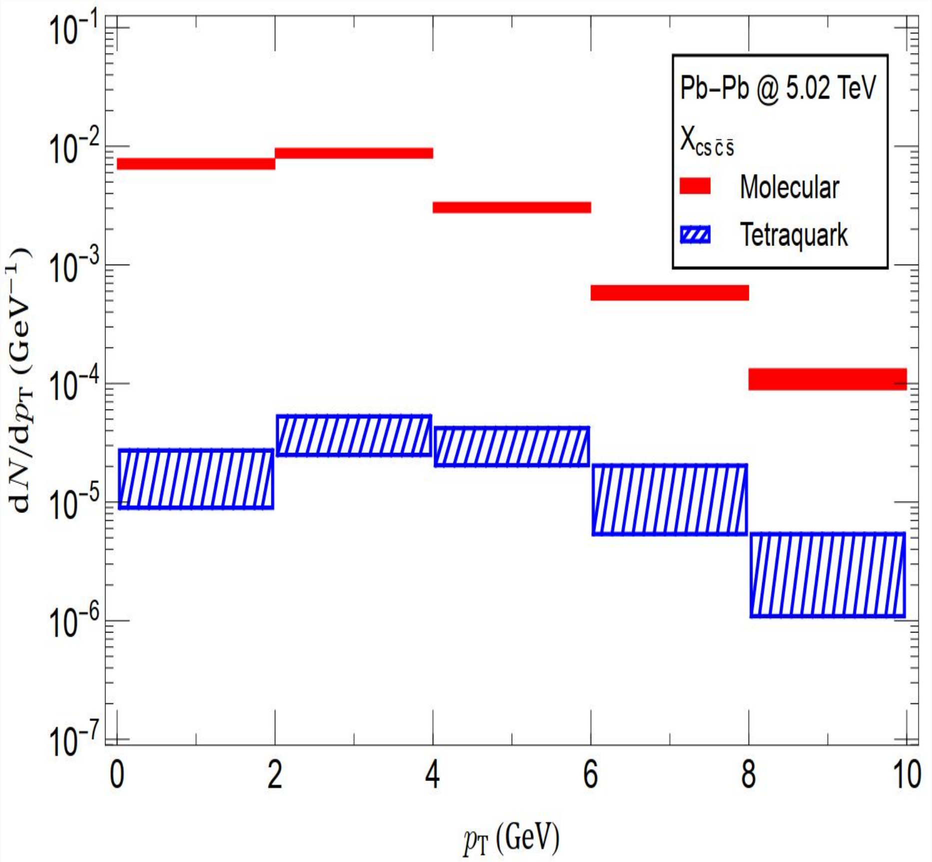
  - Rapidity distributions

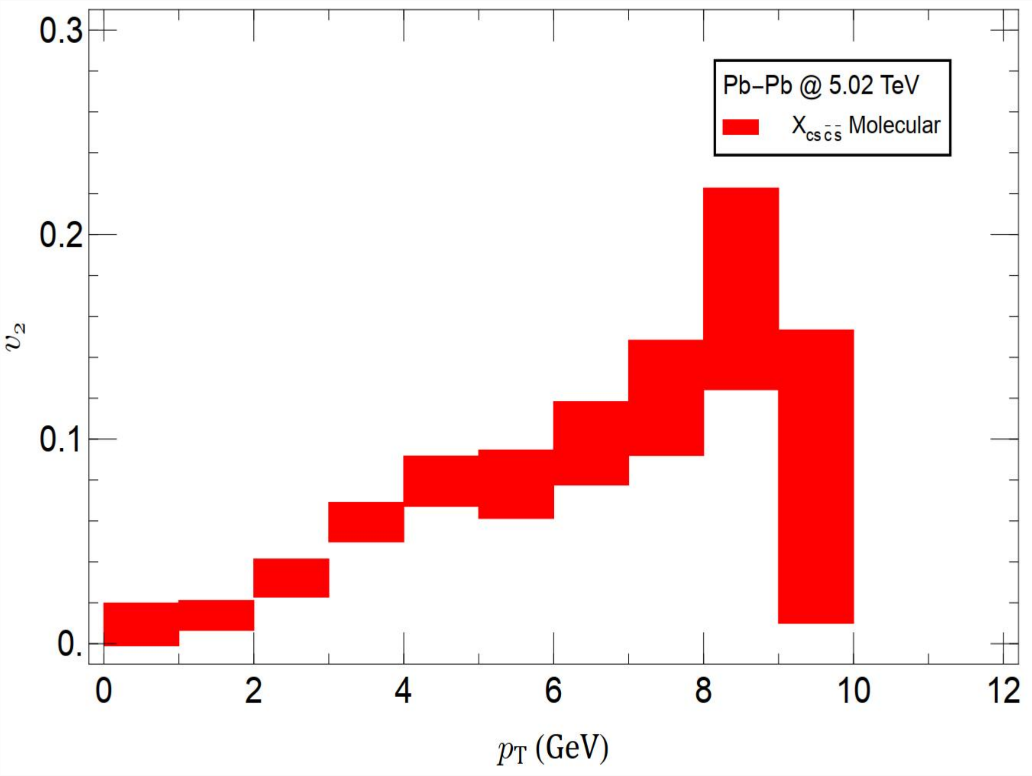


Y. Hu, H. Zhang, Chin. Phys. C. 47, No. 5 (2023) 051001

Production of $X_{cs\overline{cs}}$ and X(3872) in HIC

➢ Transverse momentum distributions and Elliptic flow





➢ Molecular and Tetraquark have a 2-order-of-magnitude.

➢ Similar to normal hadrons.

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Production of $X_{cs\overline{cs}}$ and X(3872) in HIC

- Estimate the production rate of the $X_{cs\overline{cs}}$ in the molecular picture and tetraquark picture .
- Centrality, rapidity, p_T distribution and Elliptic flow of $X_{cs\overline{cs}}$
- A volume effect is found from the centrality distribution of $X_{cs\overline{cs}}$, which could help us to distinguish the inner structure of $X_{cs\overline{cs}}$.
- The Pb-Pb collision process provides an environment rich in charm quarks and strange quarks.

Summary and outlook

Production of doubly charmed exotic hadrons in heavy ion collision

- Estimate the production rate of the T_{cc} in the molecular picture.
- Centrality, rapidity, p_T distribution of T_{cc} .
- Fireball effect of T_{cc} is more significant than that of X(3872).
- The yield of T_{cc} is almost the same as that of the X(3872) in HIC.
- Explain why the $T_{cc}^{++}$is not observed by LHCb and the relatively small production rate T_{cc}^{0}/X(3872).

The production of $X_{cs\bar{c}\bar{s}}$ and X(3872) in heavy ion collision

- Estimate the production rate of the $X_{cs\bar{c}\bar{s}}$ and in the molecular picture and tetraquark picture .
- Centrality, Rapidity, p_T distribution of $X_{cs\bar{c}\bar{s}}$.
- A volume effect is found from the centrality distribution of $X_{cs\bar{c}\bar{s}}$, which could help us to distinguish the inner structure of $X_{cs\bar{c}\bar{s}}$.
- The Pb-Pb collision process provides an environment rich in charm quarks and strange quarks.

Outlook

- This size effect could help to explore the internal structure of $X_{cs\bar{c}\bar{s}}$ through different collision systems, e.g. Pb-Pb, Au-Au, Xe-Xe, Cu-Cu, O-O, d-A/p-A, etc.
- Hadron Gas Phase: interact with other hadrons:production + absorption
- …

Thank you for your attention!

2023/12/18