Production of charmed hadrons in heavy-ion collisions

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Outline

1. Introduction

heavy ion collisions & charmed hadrons

2. Production of charmed hadrons: D, X(3872), B_c, J/ψ

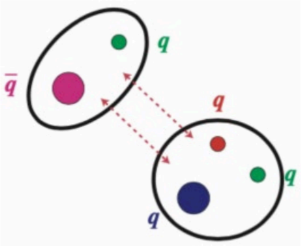
D meson spectrum $(\mathrm{c} - \bar{q})$

J/ψ **spectrum** $(\mathrm{c} - \bar{c})$ **flows** $\boldsymbol{v}_{\mathbf{1,2,3}}$

B_c **production** $(\mathrm{c} - \bar{b})$

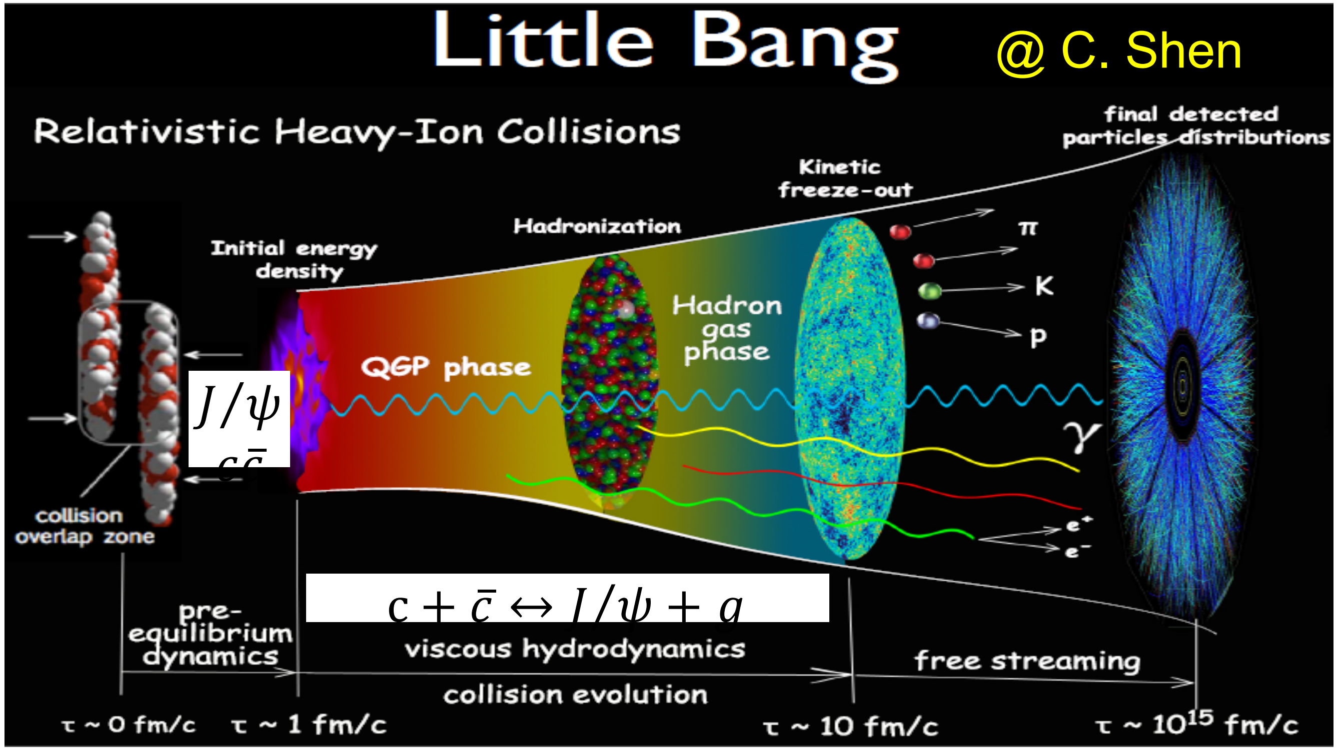
X(3872) as a tetraquark: $\mathrm{c} + \bar{c} + q + \bar{q} \rightarrow X(3872)$ **in QGP**

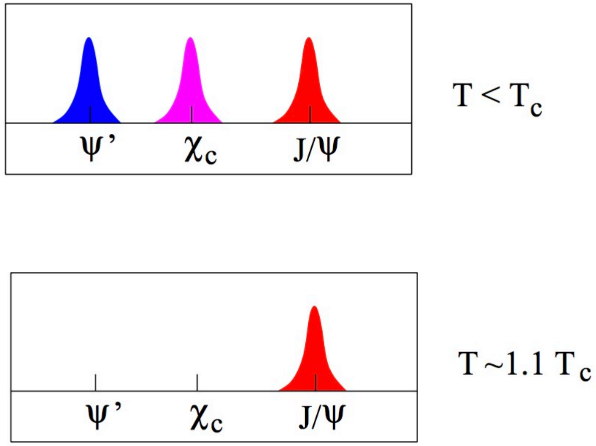
as a meson molecule: $\mathrm{c} + \bar{q} \rightarrow D,\ D^0 + \bar{D}^{*0} \rightarrow X(3872)$ **in hadronic gas**



3. Summary

1. introduction





Satz. 2005

- Different from pp collisions, AA collisions produce **an extremely hot de-confined medium**:

  significant **color screening + parton inelastic scatterings**

  Light hadrons: produced at the boundaries of QGP phase transition T=Tc

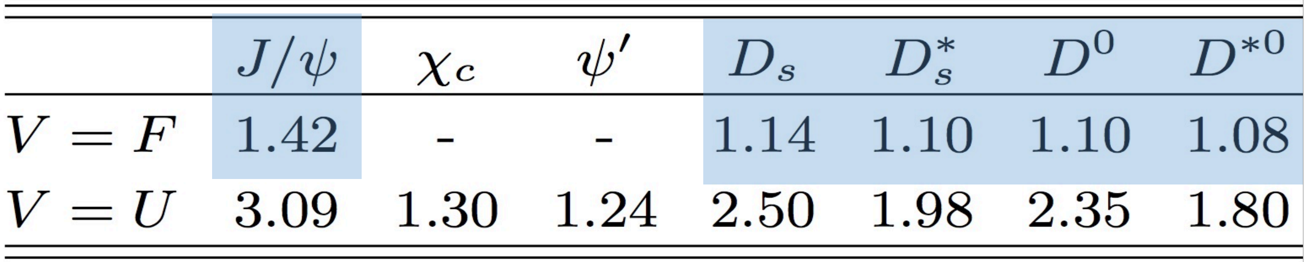
  Charmonium/bottomonium: primordial production + coalescence inside QGP (T>Tc)

1. Properties of charmed mesons

(1) For D mesons, **produced at $T = T_c$**

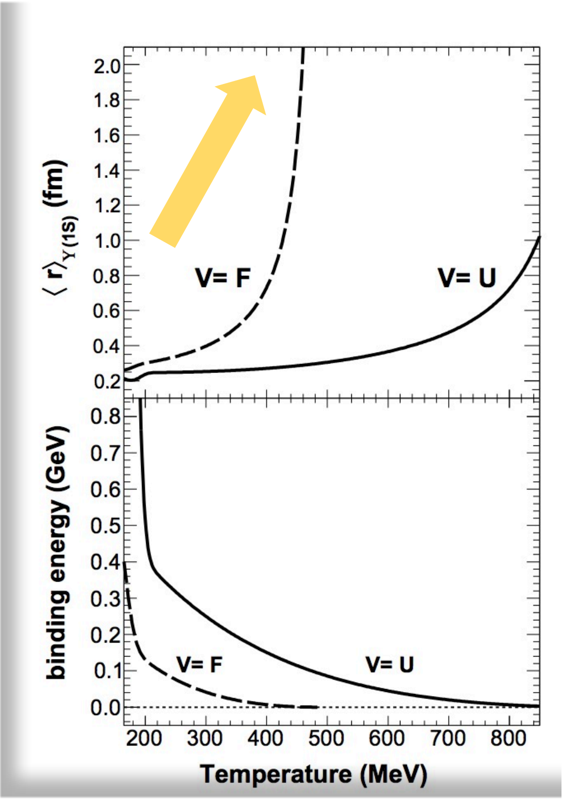
(2) For J/ψ or bottomonium,

they can be produced inside QGP with $\mathrm{T} > \mathrm{T_c}$ due to larger binding energies



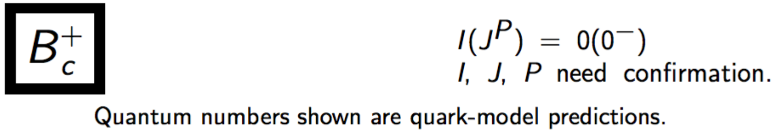
	J/ψ	χ_c	ψ'	D_s	D_s^*	D^0	D^{*0}
$V = F$	1.42	-	-	1.14	1.10	1.10	1.08
$V = U$	3.09	1.30	1.24	2.50	1.98	2.35	1.80

Tsinghua Group, Chin.Phys.C **44 (2020) 8, 084101**



BYC, Zhao,
Phys.Lett.B 772 (2017) 819-824

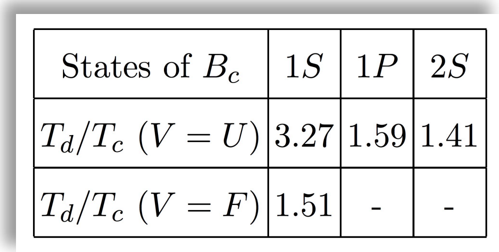
(3) For B_c



B_c^+

$I(J^P) = 0(0^-)$
I, J, P need confirmation.

Quantum numbers shown are quark-model predictions.



States of B_c	$1S$	$1P$	$2S$
$T_d/T_c\ (V = U)$	3.27	1.59	1.41
$T_d/T_c\ (V = F)$	1.51	-	-

Liu, Carsten, etal, Phys.Rev.C 87 (2013) 1, 014910

(4) For X(3872)

tightly bound tetraquark/charmonium-like(2P) states ? **Molecular states?**

2. Heavy quark dynamical evolution

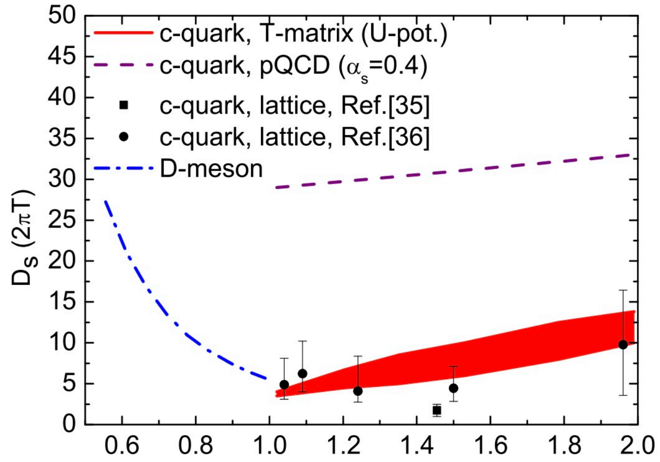
$$\frac{d\vec{p}}{dt} = -\eta\vec{p} + \vec{\xi}$$

$$\boxed{D_s(2\pi T) = 5}$$

$\eta = \kappa/(2TE) \quad \kappa D_s = 2T^2$

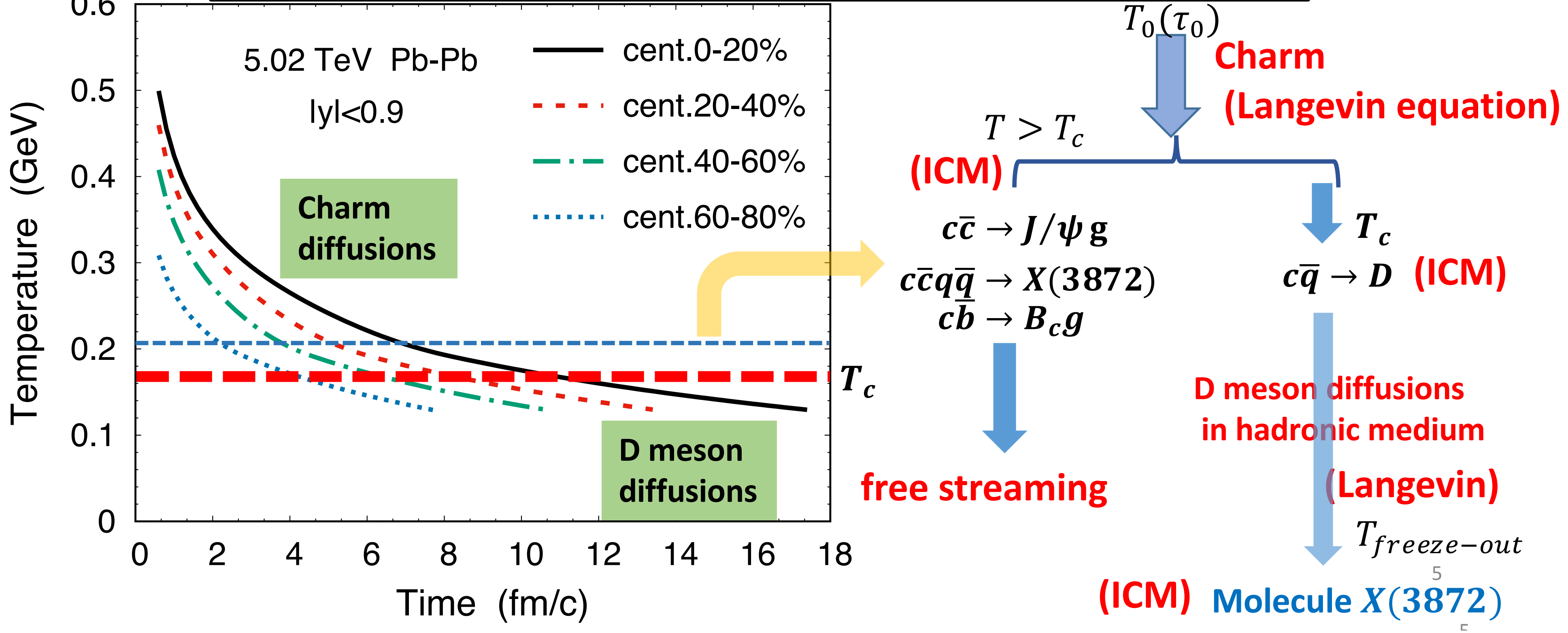
D_s, κ:

Spatial and Momentum Diffusion coefficients



Langevin + Instantaneous coalescence model (LICM)

et al PRL 2012



$T_0(\tau_0)$

Charm

(Langevin equation)

$T > T_c$

(ICM)

$c\bar{c} \to J/\psi\, g$

$c\bar{c}q\bar{q} \to X(3872)$

$c\bar{b} \to B_c g$

free streaming

T_c

$c\bar{q} \to D$ **(ICM)**

D meson diffusions in hadronic medium

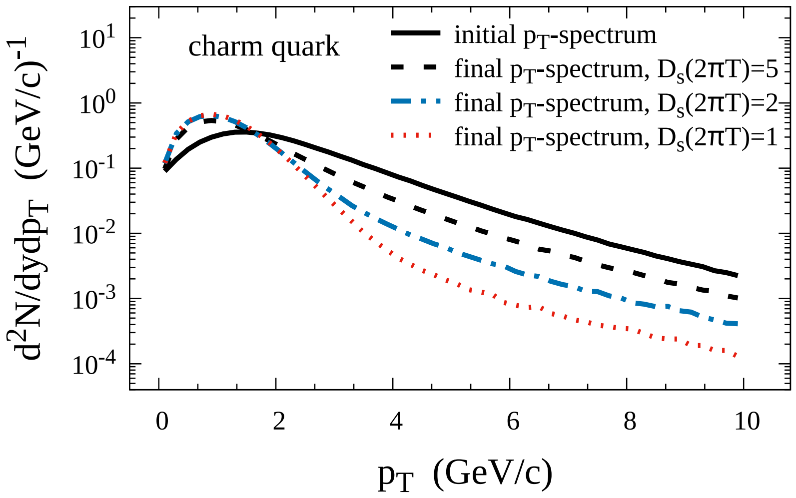
(Langevin)

$T_{freeze-out}$

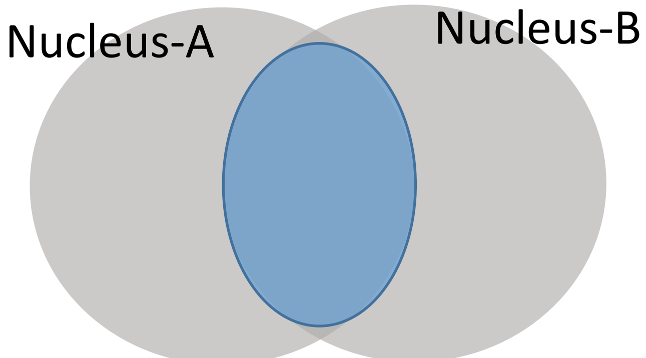
(ICM) **Molecule $X(3872)$**

2. Heavy quark dynamical evolution

（1）initial distribution



charm initial spectrum： FONLL model



$$\frac{dN^{test}}{d\vec{x}_T} \propto T_A(\vec{x}_T - \frac{\vec{b}}{2})T_B(\vec{x}_T + \frac{\vec{b}}{2})$$

Charm initial positions:

Proportional to the $N_{coll}(\vec{x}_T)$,

Corrected by shadowing effect (EPS09)

(2) Charmonium coalescence at the hadronization temperature

$$\mathrm{P}_{c+\bar{c}\to\psi}(\vec{x}_M,\vec{p}_M) = g_M \int d\vec{x}_1 d\vec{x}_2 \frac{d\vec{p}_1}{(2\pi)^3}\frac{d\vec{p}_2}{(2\pi)^3}\frac{d^2N_1}{d\vec{x}_1 d\vec{p}_1}\frac{d^2N_2}{d\vec{x}_2 d\vec{p}_2} f_M^W(\vec{x}_r,\vec{q}_r)$$

$$\times\delta^{(3)}(\vec{p}_M - \vec{p}_1 - \vec{p}_2)\delta^{(3)}(\vec{x}_M - \frac{\vec{x}_1+\vec{x}_2}{2})$$

- ➢ $g_M = 1/12$ Vector meson degeneracy factor from color and spin
- ➢ $f_M^W(\vec{x}_r,\vec{q}_r)$: Wigner function. $(\vec{x}_r,\vec{q}_r)$ in the center of mass frame of $c-\bar{c}$

3. charmed hadron production

Wigner function: encodes the information of formed states

$$f^{W}_{J/\psi}(\vec{x}_r,\vec{q}_r) = 8\exp[-\frac{x_r^2}{\sigma^2} - \sigma^2 q_r^2]$$

$$\vec{x}_r = \vec{x}_1^{\mathrm{cm}} - \vec{x}_2^{\mathrm{cm}}$$

$$\vec{q}_r = \frac{E_1^{cm}\vec{p}_1^{cm} - E_2^{cm}\vec{p}_2^{cm}}{E_1^{cm} + E_1^{cm}}$$

$$\sigma^2 = \frac{4}{3}\frac{(m_1+m_2)^2}{m_1^2+m_2^2} < r^2 >_M$$

$$< r^2 >_{J/\psi} = 0.54\, fm^2$$

Give **consistent formation conditions** on the relative distance and relative momentum of two particles.

The width σ in the Wigner function

is connected with the internal structure of the formed state

Hadron Spectrum in heavy-ion collisions

$$\frac{d^2N_\psi}{dy_M d\vec{p}_T} = \int d\vec{x}_M \frac{dp_z}{2\pi} < \mathrm{P}_{c+\bar{c}\to\psi}(\vec{x}_M,\vec{p}_M) >_{events} \times \frac{(\Delta N_{c\bar{c}}^{AA})^2}{\Delta y_M}$$

$$\Delta N_{c\bar{c}}^{AA} = \int d\vec{x}_T T_A(\vec{x}_T - \frac{\vec{b}}{2}) T_B(\vec{x}_T + \frac{\vec{b}}{2}) \frac{d\sigma_{pp}^{c\bar{c}}}{dy} R_S(\vec{b},\vec{x}_T)\Delta y_{c\bar{c}}$$

Shadowing factor

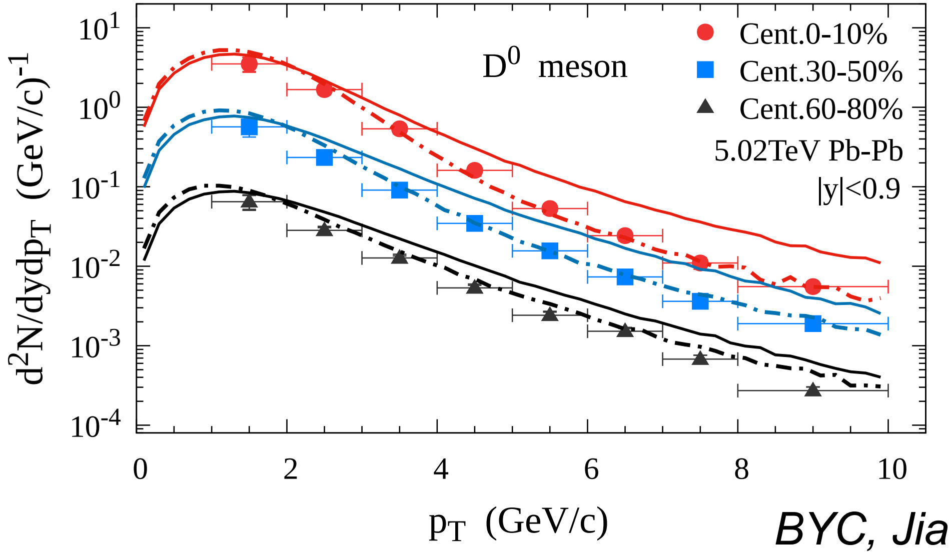
3. charmed hadron production: D meson

- **D meson coalescence**

$$P_{c\bar{q}\to D^0}(\vec{p}_M) = H_{c\to D^0}\int \frac{d\vec{p}_1}{(2\pi)^3}\frac{d\vec{p}_2}{(2\pi)^3}\frac{dN_1}{d\vec{p}_1}\frac{dN_2}{d\vec{p}_2} f_D^W(\vec{q}_r)\times\delta^{(3)}(\vec{p}_M-\vec{p}_1-\vec{p}_2)$$

$$\frac{d^2N_D}{dy_M d\vec{p}_T} = \int \frac{dp_z}{2\pi} < P_{c\bar{q}\to D^0}(\vec{p}_M) >_{events} \times \frac{\Delta N_{c\bar{c}}^{AA}}{\Delta y_M}$$

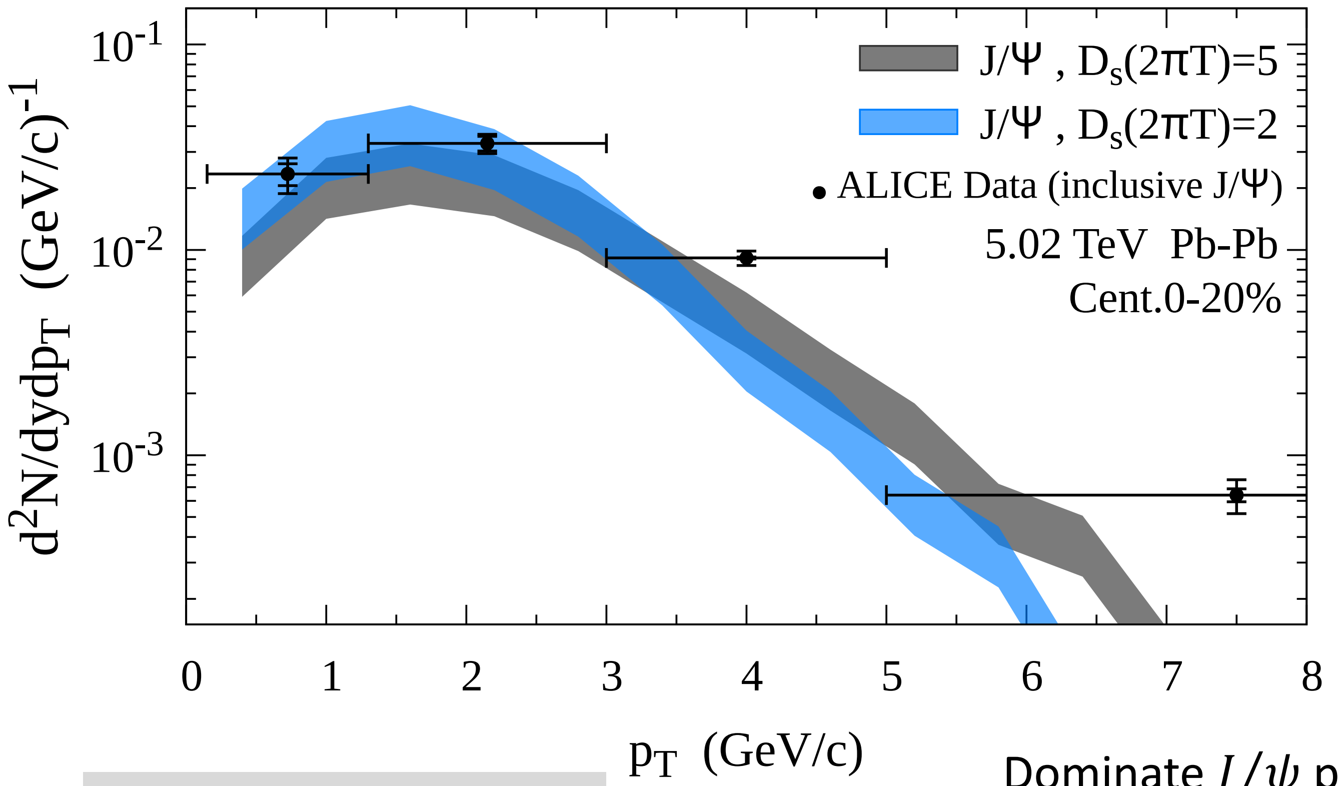
- $H_{c\to D^0} = 9.5\%$ (20%) : Charm turning into **direct** D^0 (D^{*0}) at Tc
- $\frac{dN_1}{d\vec{p}_1}$: charm momentum distribution
- $\frac{dN_2}{d\vec{p}_2}$: light quark momentum distribution: Fermi.



- We take the ratio of prompt D^0 over charm:
  $N(D^0)/N_{c\bar{c}} = 39\%$
  ALICE pp, arXiv:2105.06335
- Different thermalization: $D_s(2\pi T) = 5$ (solid line) and $D_s(2\pi T) = 2$ (dotted-dashed line)

BYC, Jiang,Liu,Liu, Zhao, **Phys. Rev. C 105, 054901 (2022)**

3. charmed hadron production: J/ψ



Theoretical bands:

With/without the shadowing effect.

Experimental data:

Dominate J/ψ production at high pT

inclusive production = primordial + B-decay + c $-$ $\bar{c}$ coalescence

Dominate at low pT and **total yield**

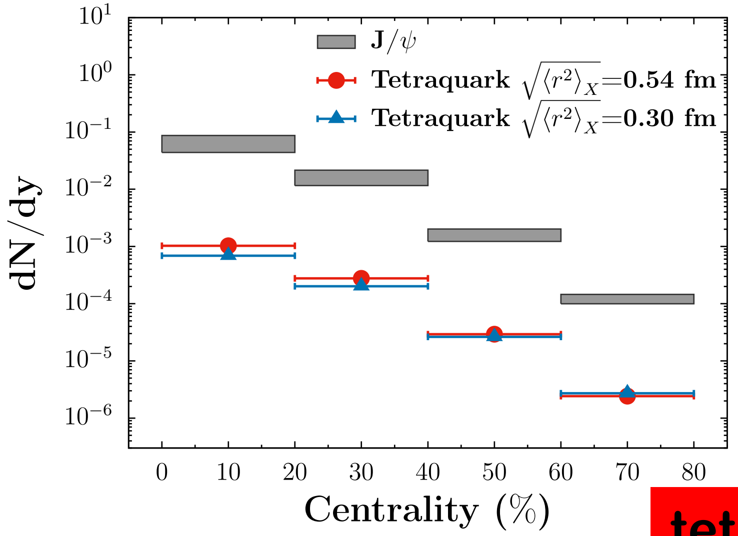
Theoretical calculation:

c $-$ $\bar{c}$ coalescence

3. charmed hadron production: **X(3872)**

- ➢ $g_{X(3872)} = 1/432$ with X(3872) spin J=1
- ➢ Root-mean-square radius of tetraquark: $< r^2 \ >_X = 0.30 - 0.54\ fm^2$

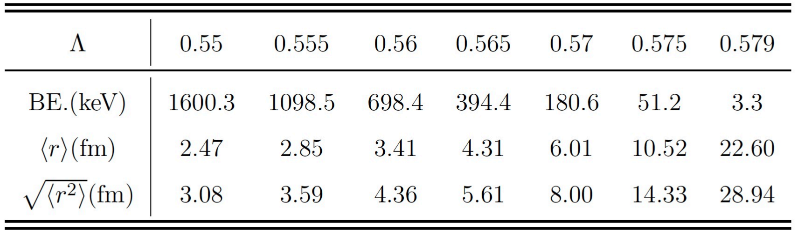
- diquark (cq) is formed at first, then two diquarks form a tetraquark state.



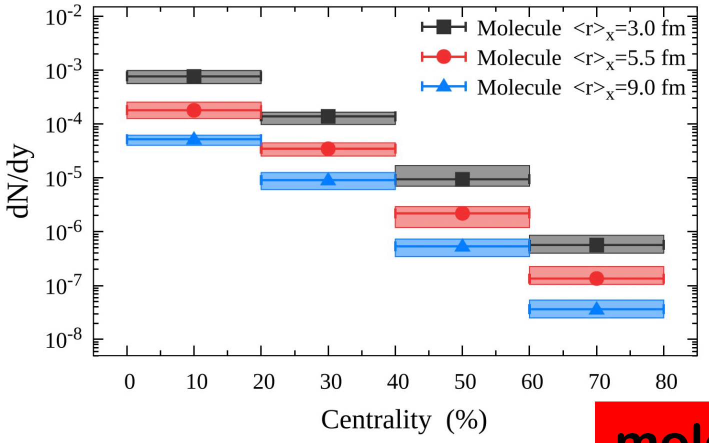
tetraquark

- ➢ Tetraquark yield is around 40 times smaller than J/ψ
- ➢ Tetraquark yield is controlled by both **spatial** and **momentum** part of the Wigner function

Molecule state with potential model



Λ	0.55	0.555	0.56	0.565	0.57	0.575	0.579
BE.(keV)	1600.3	1098.5	698.4	394.4	180.6	51.2	3.3
$\langle r\rangle$(fm)	2.47	2.85	3.41	4.31	6.01	10.52	22.60
$\sqrt{\langle r^2\rangle}$(fm)	3.08	3.59	4.36	5.61	8.00	14.33	28.94



molecule

Bands:

Volume dependence in freeze-out

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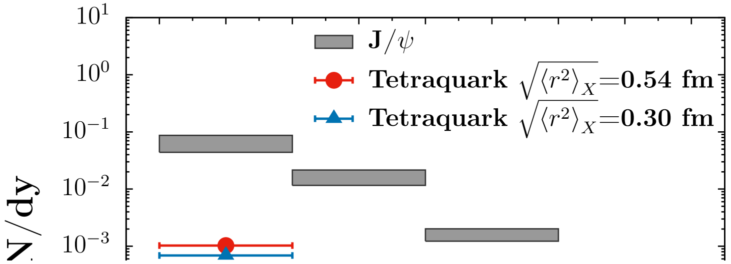

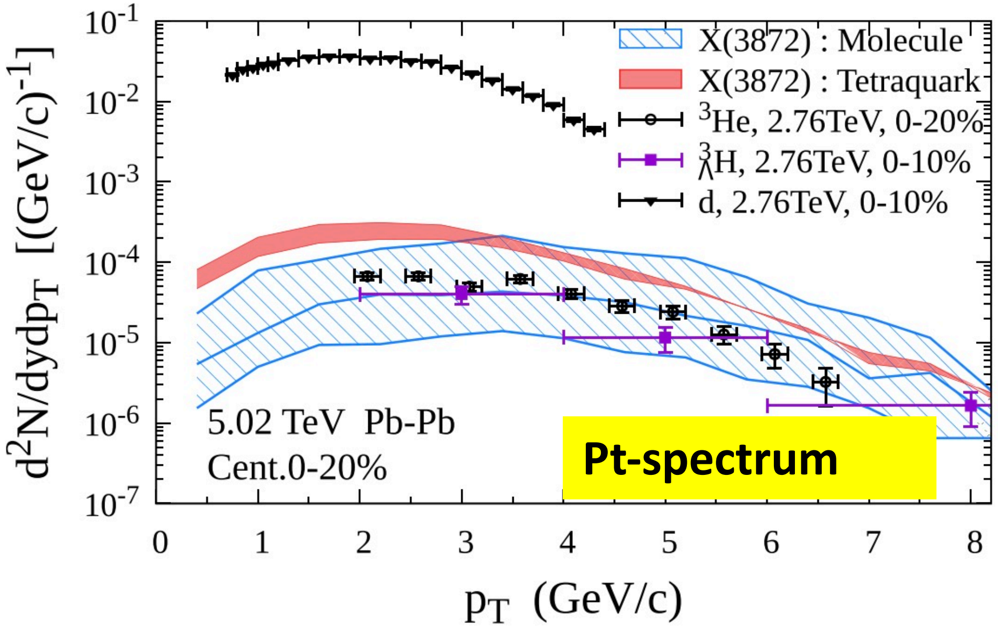

Pt-spectrum

Molecule state with potential model

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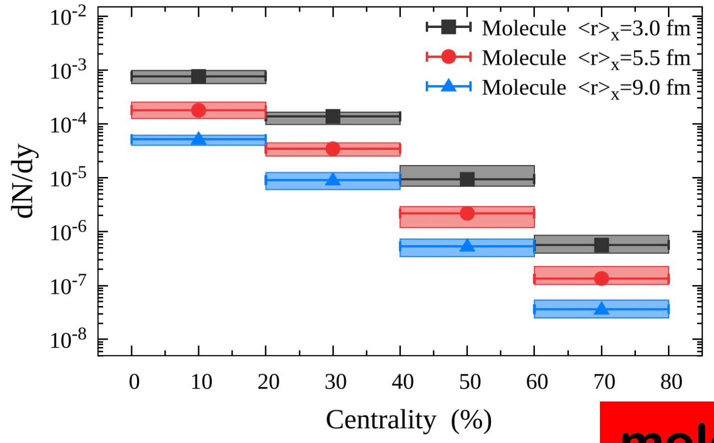

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BYC, Jiang,Liu,Liu, Zhao,
Phys. Rev. C 105, 054901 (2022)

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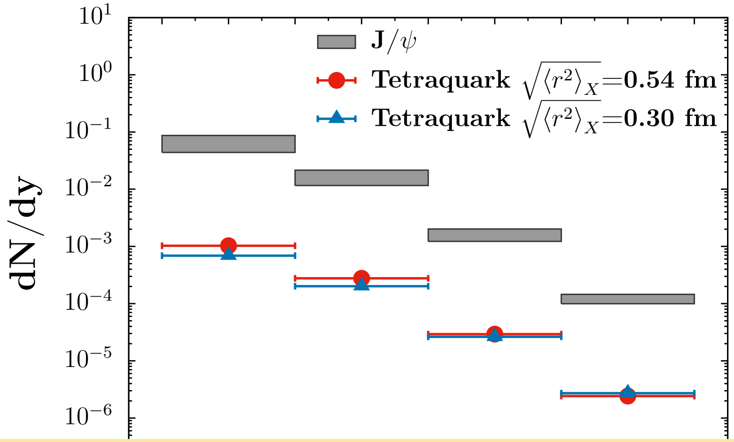

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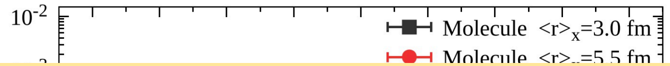


- Our tetraquark yield $\sim 10^{-3}$ is consistent with ***Cho. Prog.Part.Nucl.Phys. 95,279-322 (2017);*** our molecule production is **a few times smaller** than this.

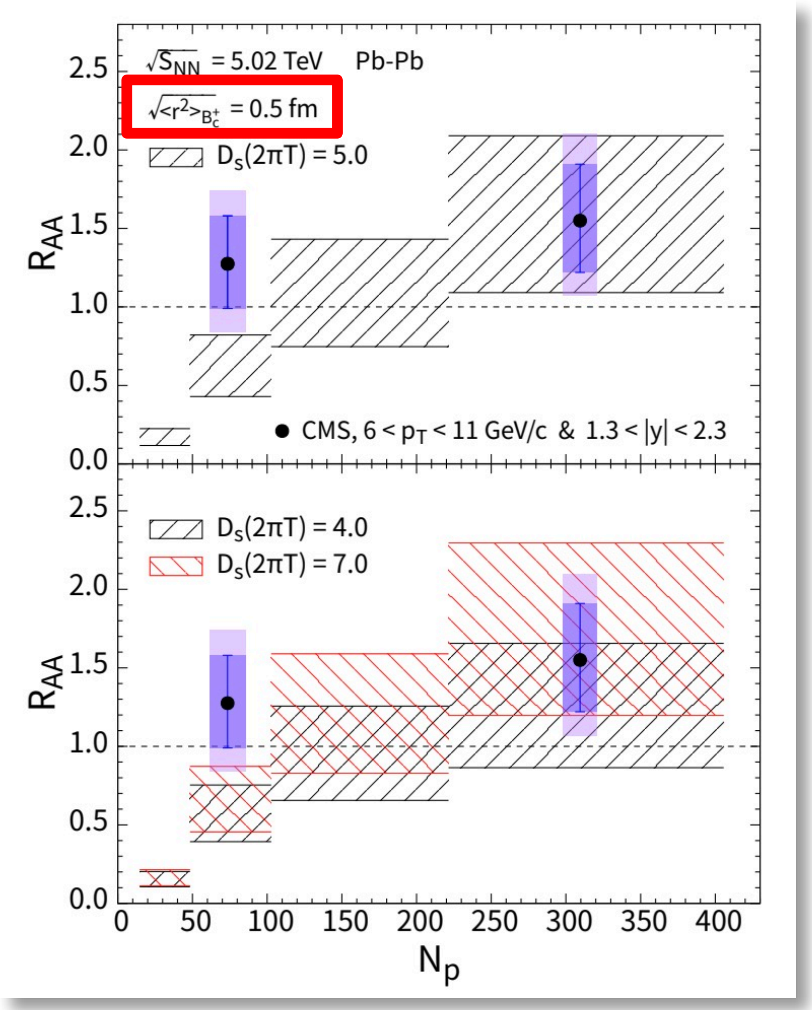
- **Relations** between **tetraquark** and **molecule** production:
  ours is consistent with rate equation model ***Rapp EPJA 57 , 122 (2021) ;***

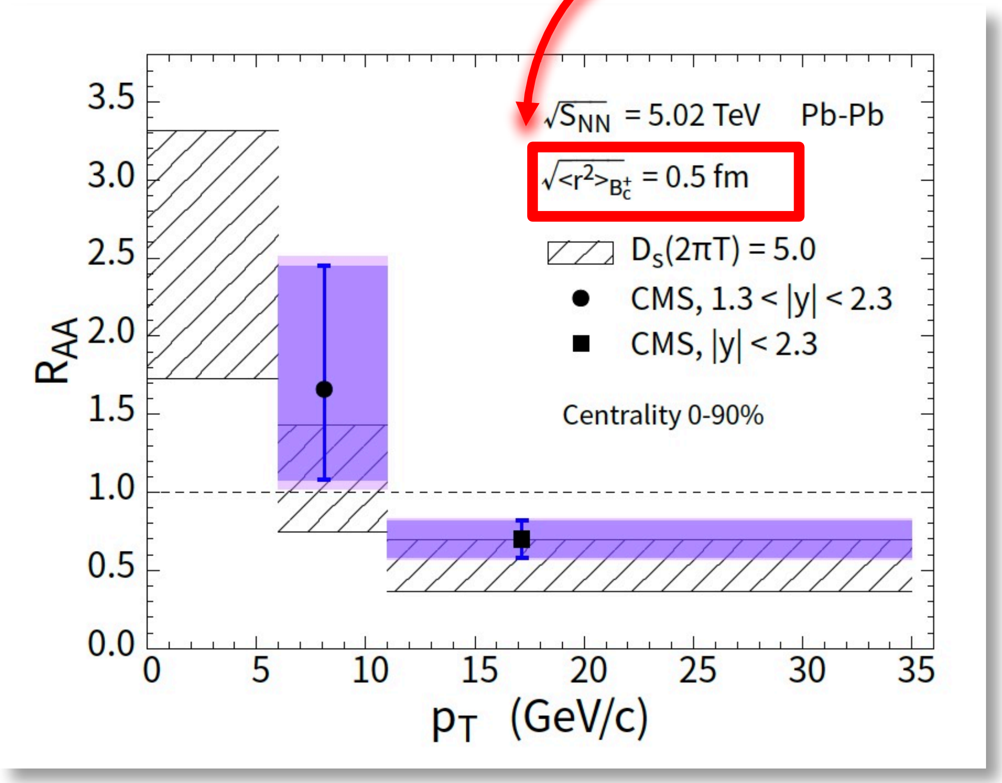
  different from AMPT model: ***Zhang PRL 126, 012301 (2021) ;***

  → maybe due to its different formation conditions.

$$\left\{ \begin{array}{c} \textbf{5fm < relative distance < 7fm} \\ 2M_D < pair\ mass < 2M_{D^*} \end{array} \right.$$

3. charmed hadron production: B_c





Geometry size

BYC, Wen, Liu, arXiv: 2111.08490

$$\frac{d\sigma_{pp}^{cc}}{\mathrm{dy}} = 1.165\ mb$$

$$\frac{d\sigma_{pp}^{bb}}{\mathrm{dy}} = 47.5\ \mu b$$

$$\frac{d\sigma_{pp}^{Bc}}{\mathrm{dy}} = (151.9 - 79.3)\ nb$$

B_c: spin 0

fig: B_c(1s)+ B_c(2s->1s)

1) **Bc final production is evidently enhanced,** due to a large number of c and b quarks in QGP.

$$c + \bar{b} \rightarrow B_c + g$$

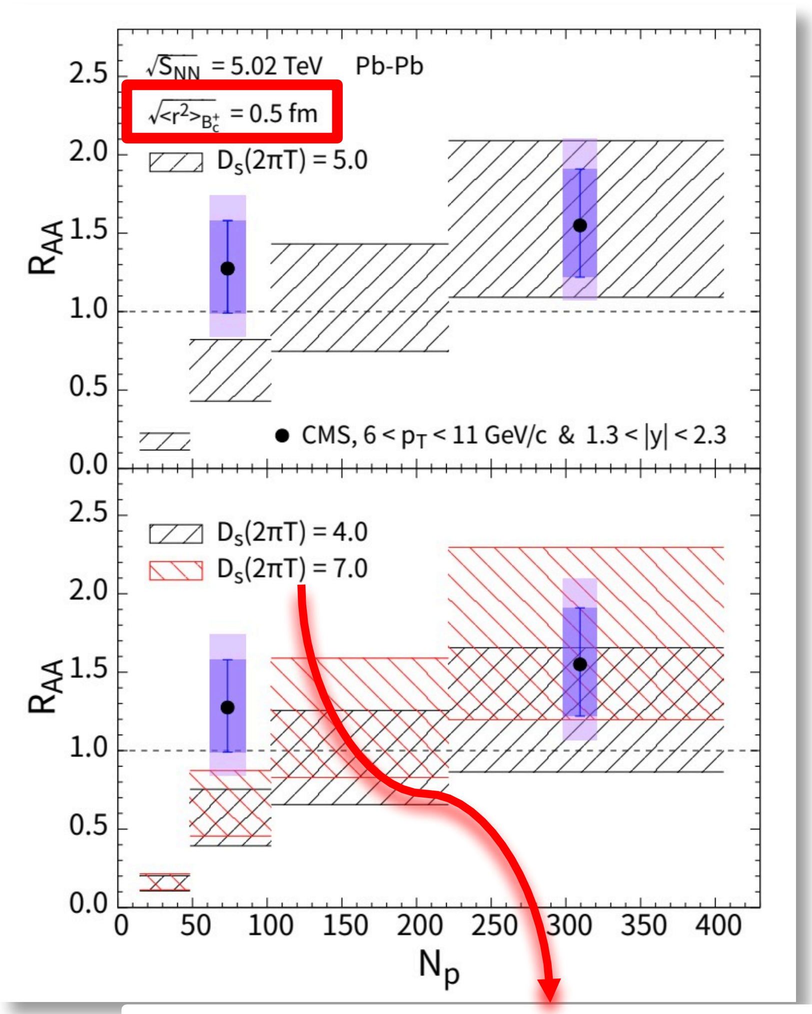
2) RAA>1 at central collisions:

QGP signal

RAA<1 at peripheral collisions:

absence of initial production

3. charmed hadron production: B_c



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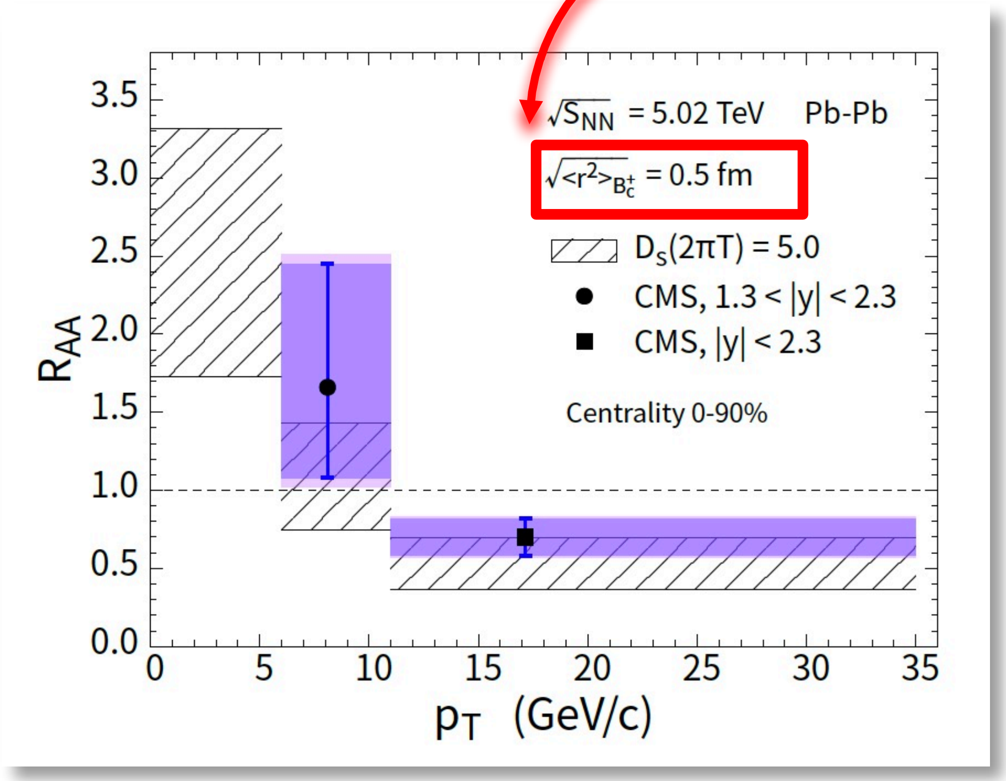


BYC, Wen, Liu, arXiv: 2111.08490

1) **Bc final production is evidently enhanced,** due to a large number of c and b quarks in QGP.

$+ g$

Different thermalization

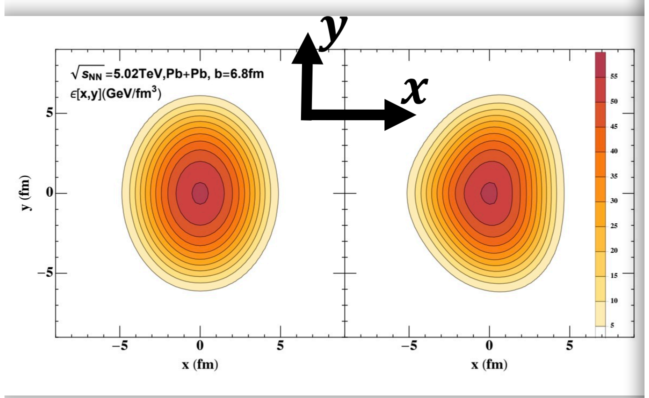
of charm and bottom quarks on B_c production,

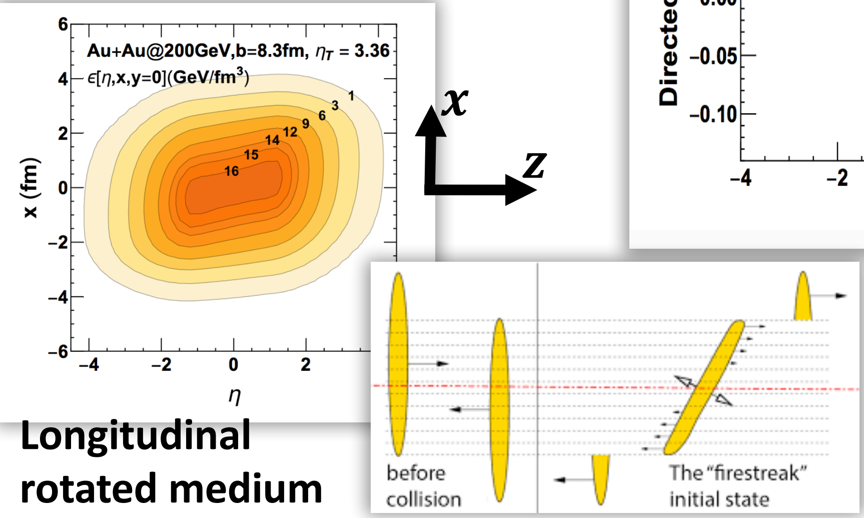
By taking spatial diffusion coefficient $D_s(2\pi T) = 4$ and 7

3. charmed hadron flows: J/ψ v_1 v_2 v_3

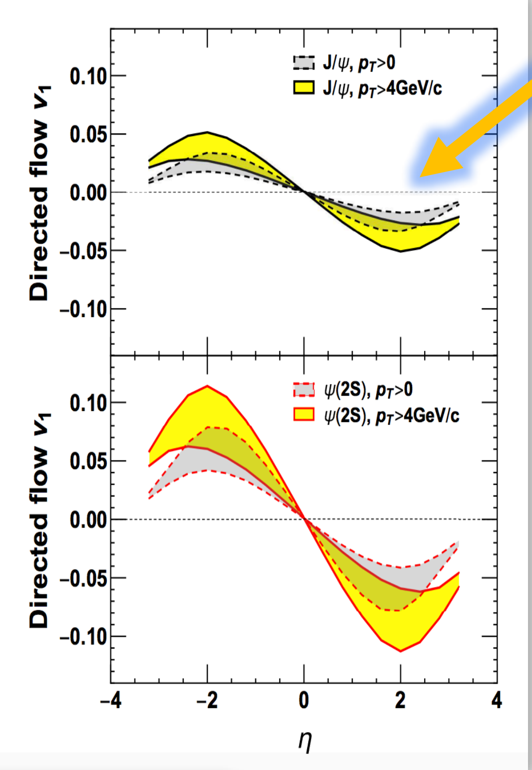
Input:

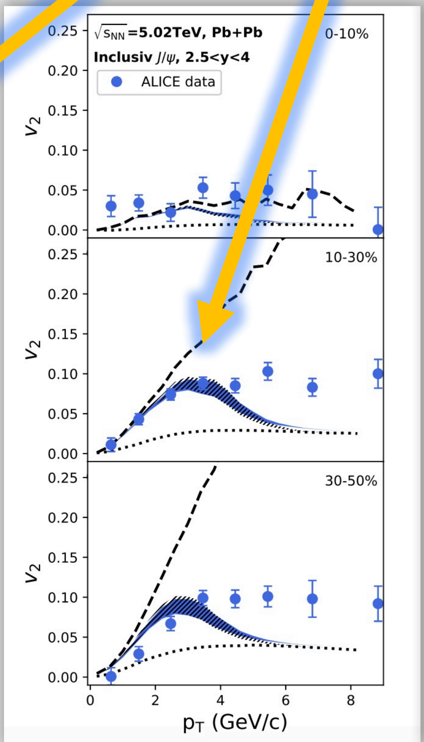
Different initial energy density

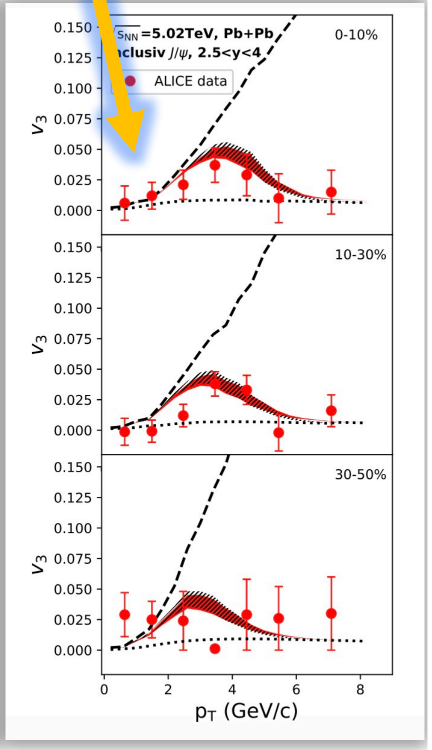




Longitudinal rotated medium







Weak cent.-dependence

Directed flow:

Phys.Lett.B 802 (2020) 135271

Elliptic flow and triangular flow:

Phys.Rev.C 105 (2022) , 034902

- **Longitudinal tilted distribution:** ***medium rotation***
- **Elliptic shape of** initial energy density: ***geometry overlap***
- **Triangular shape** of initial energy density: ***event-by-event fluctuations.***

4. Summary

- We study the formation of charmed hadrons in the QGP.

- X(3872) as a **tightly bound tetraquark** and **a hadronic molecule**, is formed via different processes.
  Their production depends on **the wave function of X(3872).**
  Therefore, heavy-ion collisions provide a new opportunity to study the nature of X(3872).

- B_c **meson is firstly observed in AA collisions,**
  evident enhancement of R_{AA}: a very clear signal of QGP

- **Charm quarks carry collective flows from QGP, inherited by the charmed hadrons.**

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  Their production depends on **the wave function of X(3872).**
  Therefore, heavy-ion collisions provide a new opportunity to study the nature of X(3872).

Thank you very much for your attention!

buckup

➢ Molecule state based on potential model

$$V_{mole} = V_{\pi} + V_{\omega} + V_{\eta} + V_{\rho}$$

arXiv: 2107.00969

Λ	0.55	0.555	0.56	0.565	0.57	0.575	0.579
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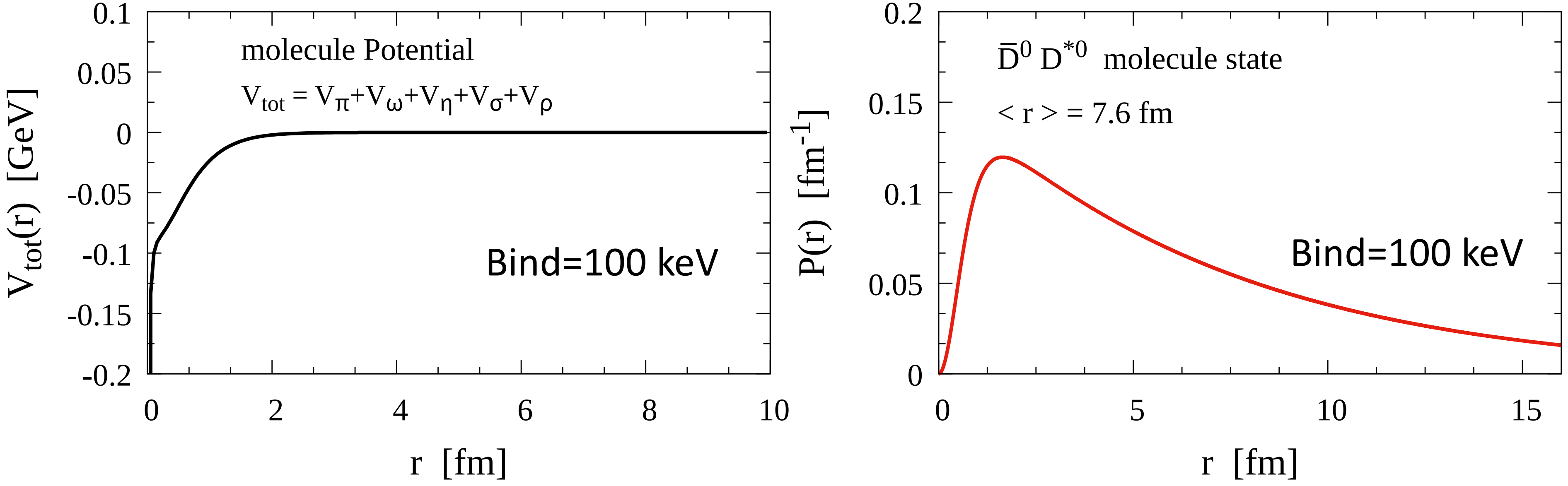

1. Properties of charmed mesons

$$B(B_c^+ \longrightarrow J/\psi\, \mu^+ \nu) = (2.37 - 4.54)\%$$

● D meson coalescence

$$P_{c\bar{q}\to D^0}(\vec{p}_M) = H_{c\to D^0}\int \frac{d\vec{p}_1}{(2\pi)^3}\frac{d\vec{p}_2}{(2\pi)^3}\frac{dN_1}{d\vec{p}_1}\frac{dN_2}{d\vec{p}_2} f_D^W(\vec{q}_r)\times\delta^{(3)}(\vec{p}_M-\vec{p}_1-\vec{p}_2)$$

$$\frac{d^2N_D}{dy_M d\vec{p}_T} = \int\frac{dp_z}{2\pi} < P_{c\bar{q}\to D^0}(\vec{p}_M) >_{events} \times \frac{\Delta N_{c\bar{c}}^{AA}}{\Delta y_M}$$

- ➢ $H_{c\to D^0} = 9.5\%$: Charm quarks turning into **direct** D^0 at the phase transition
- ➢ $\frac{dN_1}{d\vec{p}_1}$: **charm** momentum distribution
- ➢ $\frac{dN_2}{d\vec{p}_2}$: **light quark** momentum distribution. See below.
- ➢ Assume all $c \to D^0$ via the **coalescence process**, neglect the fragmentation. This simplification works well in low or moderate p_T region.

Light qu

(loca

m_l =

After coalescence at Tc,

D meson continues diffusion in hadronic medium via Langevin,

(with $D_s(2\pi T) = 8$)

Until kinetic freeze-out T=0.14 GeV

k

uark