X(3872), B_c and charmonium production in heavy-ion collisions

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Exotics and Exotic Phenomena in Heavy Ion Collisions, Sep.29-Oct.1, 2022

Collaborators:

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Outline

1. Introduction

heavy ion collisions & charmed hadrons

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

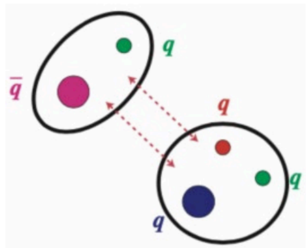
D meson spectrum $(c - \bar{q})$

J/ψ spectrum $(c - \bar{c})$ flows $v_{1,2,3}$

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

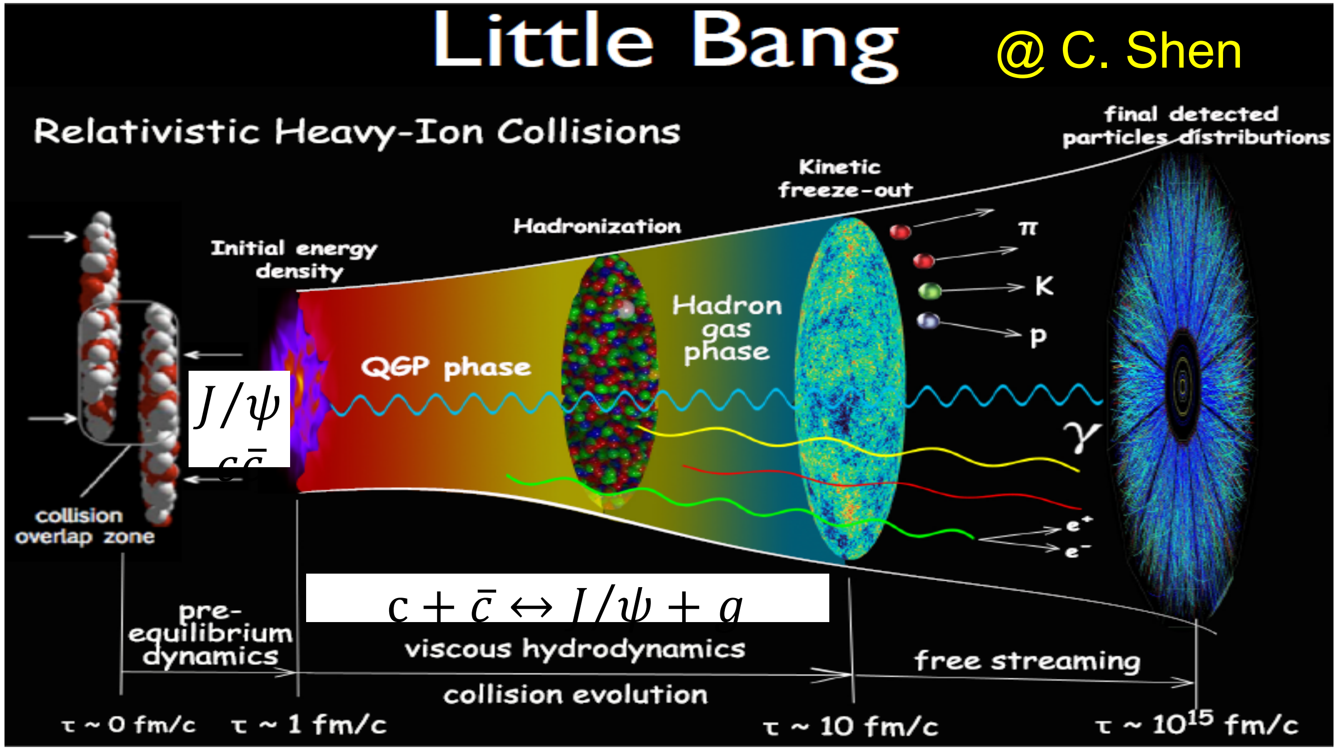
X(3872) as a tetraquark: $c + \bar{c} + q + \bar{q} \to X(3872)$ in QGP

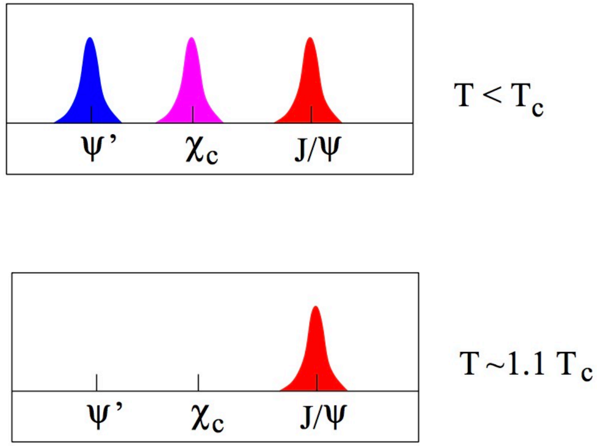
as a meson molecule: $c + \bar{q} \to D,\ D^0 + \bar{D}^{*0} \to X(3872)$ in hadronic gas



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

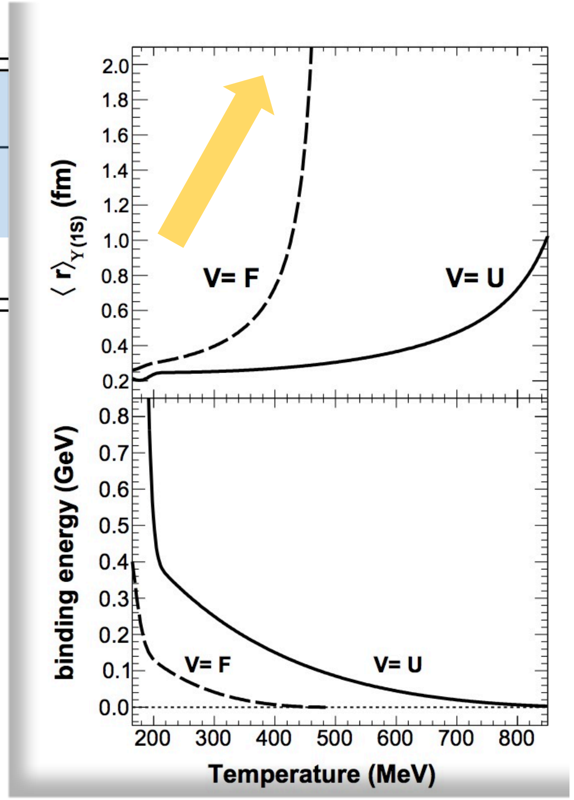
(1) For D mesons, **produced at $T = T_c$**

(2) For J/ψ or bottomonium,

they can be produced inside QGP with $T > T_c$ 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?

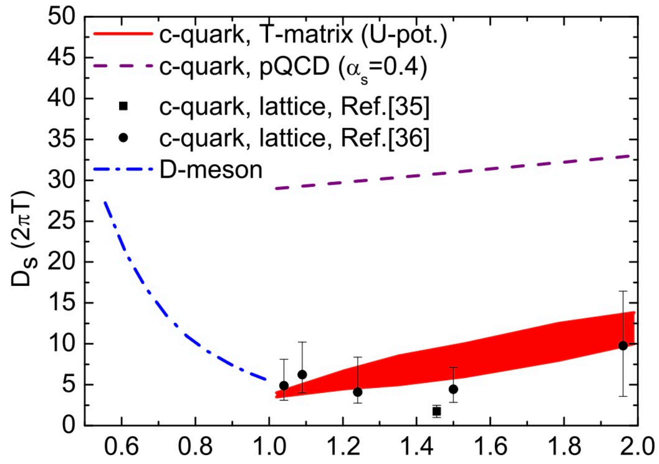
2. Heavy quark dynamical evolution

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

$$D_s(2\pi T) = 5$$

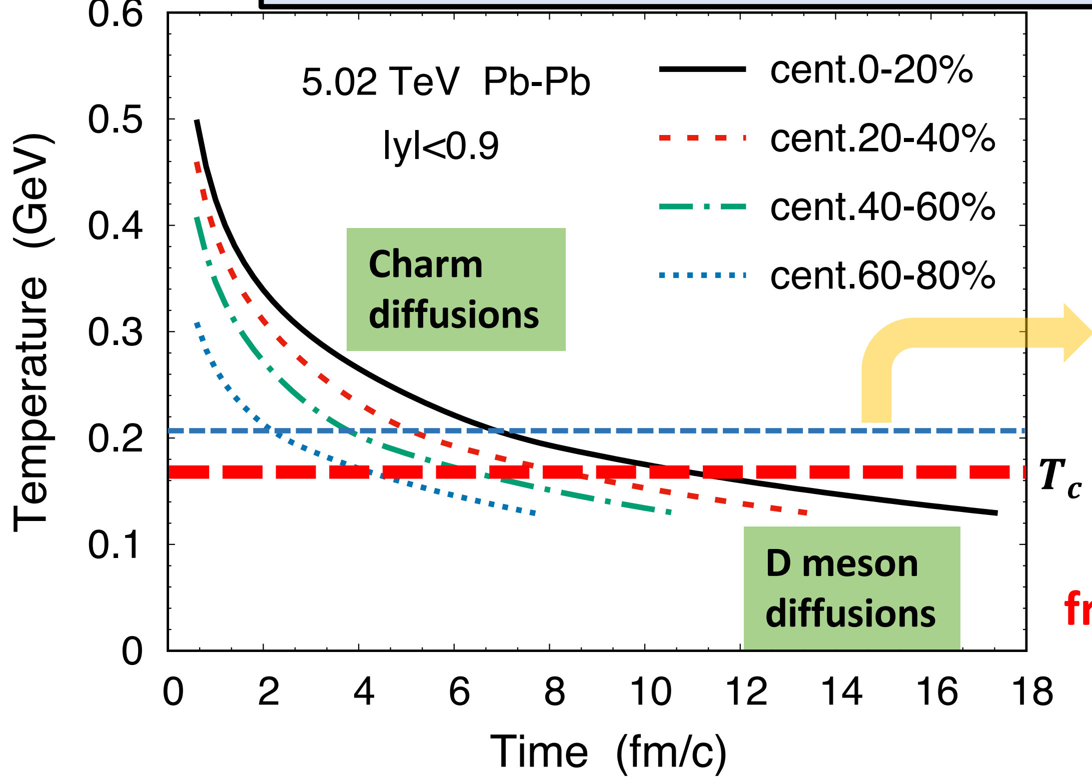
$\eta = \kappa/(2TE) \quad \kappa D_s = 2T^2$

D_s, κ:
Spatial and Momentum Diffusion coefficients



et al PRL 2012

Langevin + Instantaneous coalescence model (LICM)



$T_0(\tau_0)$

Charm (Langevin equation)

$T > T_c$

(ICM)

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

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

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

free streaming

T_c

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

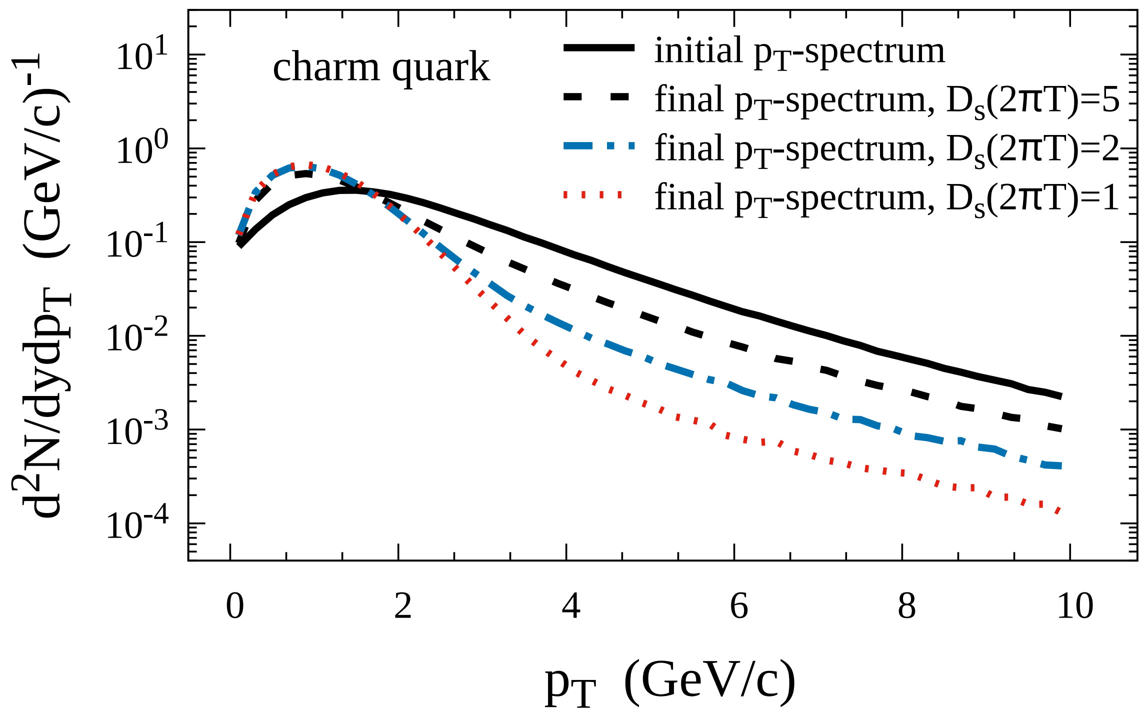
D meson diffusions in hadronic medium (Langevin)

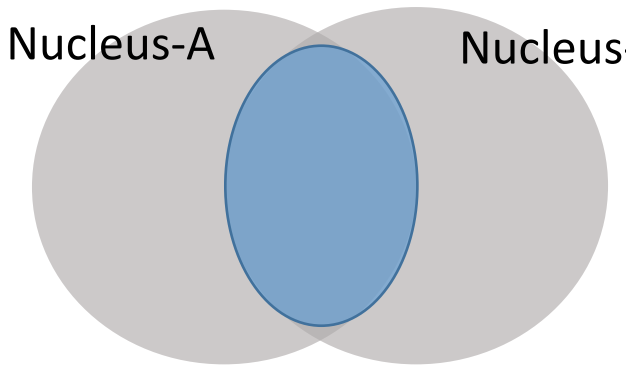
$T_{freeze-out}$

(ICM) Molecule $X(3872)$

2. Heavy quark dynamical evolution

randomly generate heavy quarks in Pb-Pb collisions





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

charm **initial** spectrum: 5.02 TeV pp collisions in central rapidity |y|<0.9 via FONLL model

Final spectrum: obtained via Langevin equations in Pb-Pb collisions

Charm initial positions:
produced in parton hard scatterings,
Proportional to the $N_{coll}(\vec{x}_T)$

2. Heavy quark dynamical evolution

coalescence via ICM model

- **Charmonium coalescence at the hadronization temperature**

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

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

- $g_M = 1/12$ Vector meson degeneracy factor from color and spin
- $\frac{d^2N_1}{d\vec{x}_1 d\vec{p}_1}$: one test particle distribution (represent charm); $\frac{d^2N_2}{d\vec{x}_2 d\vec{p}_2}$: anti-charm
- $c+\bar{c}\to\psi$+g, the gluon momentum has been neglected to get the relation $\vec{p}_M=\vec{p}_1+\vec{p}_2$
- $f_M^W(\vec{x}_r,\vec{q}_r)$: Wigner function. $(\vec{x}_r,\vec{q}_r)$ in the center of mass frame of $c-\bar{c}$
- **Wigner function:** the Weyl transform of the hadron **wave function**

3. charmed hadron production

Wigner function: encodes the information of formed states

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

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

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

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

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

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

The width σ in the Wigner function determined by the wave function

Wave function plays a crucial role.

Hadron Spectrum in heavy-ion collisions

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

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

5.02 TeV: $\frac{d\sigma_{pp}^{cc}}{\mathrm{dy}} = 1.165\, mb$

Shadowing factor. It reduce around **30%** of charm pairs at 5.02 TeV Pb-Pb collisions

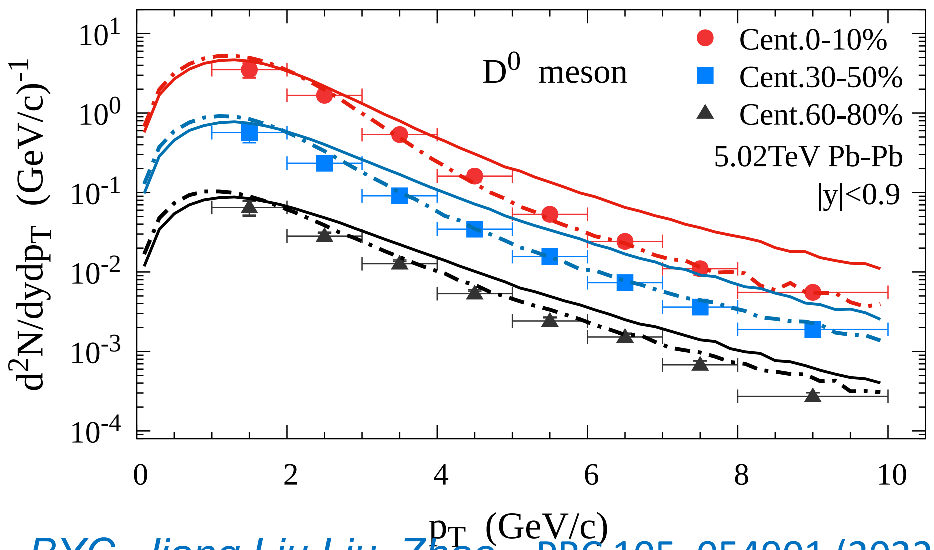
3. charmed hadron production: D meson

- **D meson coalescence**

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

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

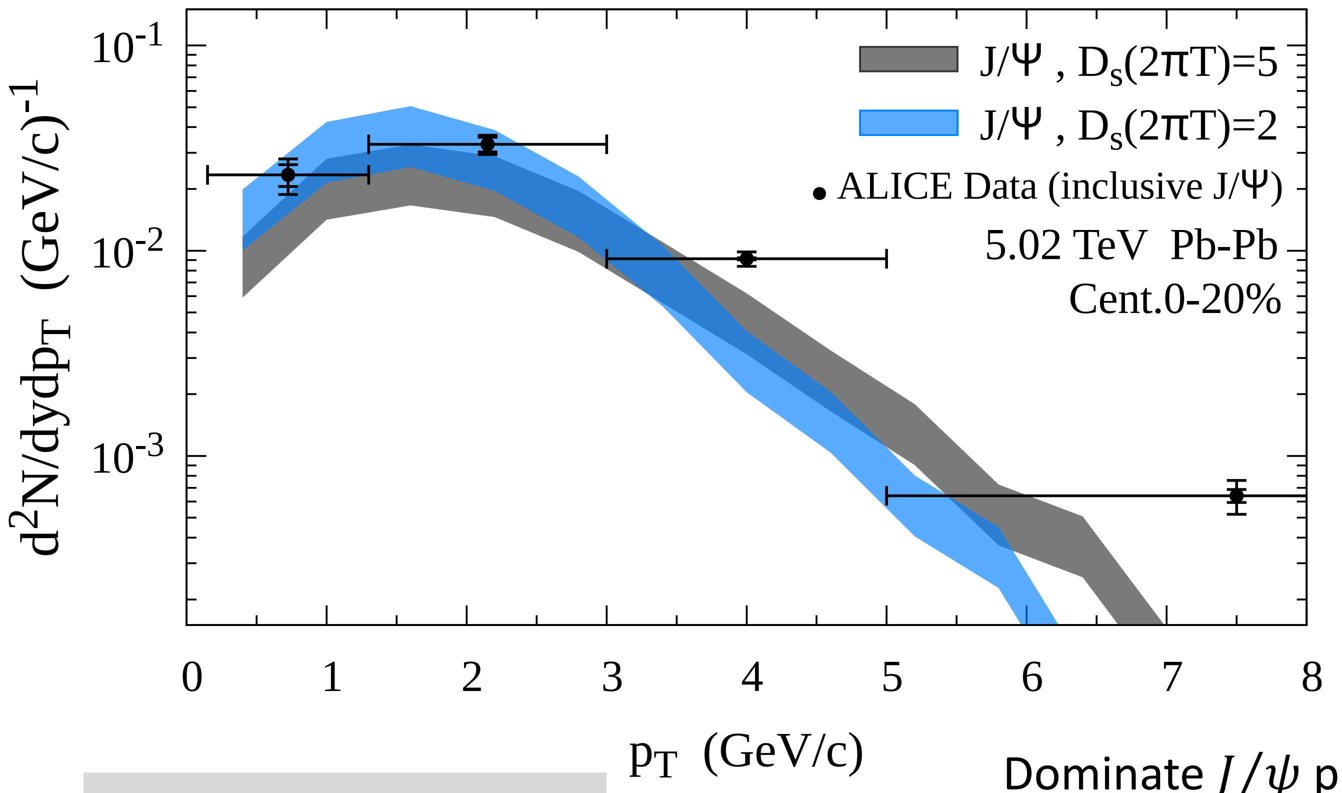
- $H_{c\to D^0} = 9.5\%$ (20%) : Charm turning into **direct** D^0 (D^{*0}) at Tc
- $\frac{dN_1}{d\vec{p}_1}$: charm momentum distribution
- $\frac{dN_2}{d\vec{p}_2}$: light quark momentum distribution: Fermi.



BYC, Jiang,Liu,Liu, Zhao, PRC 105, 054901 (2022)

- 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)

3. charmed hadron production: J/ψ



Theoretical bands:
With/without the shadowing effect.

Dominate J/ψ production at high pT

Experimental data:

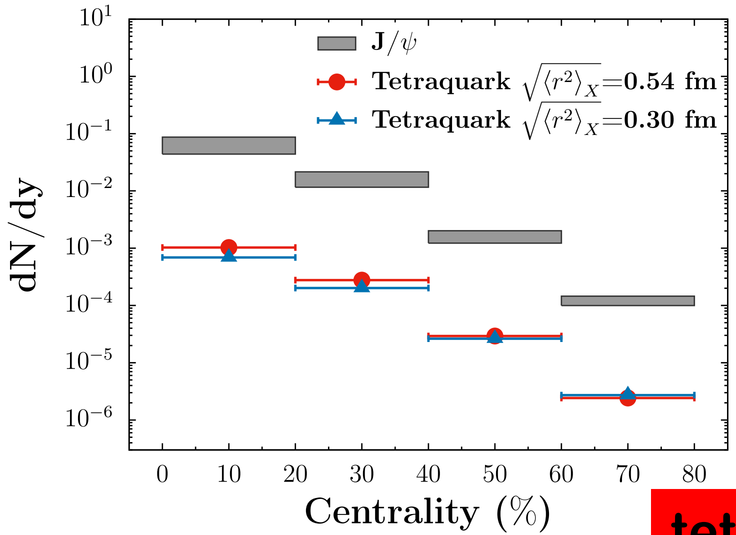
inclusive production = primordial + B-decay + $c-\bar{c}$ coalescence

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: $< r^2 >_X = 0.30 - 0.54\ fm^2$

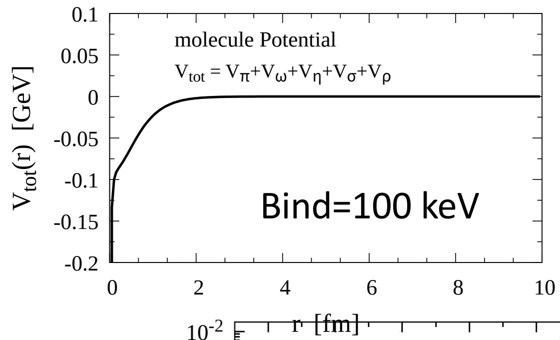


tetraquark

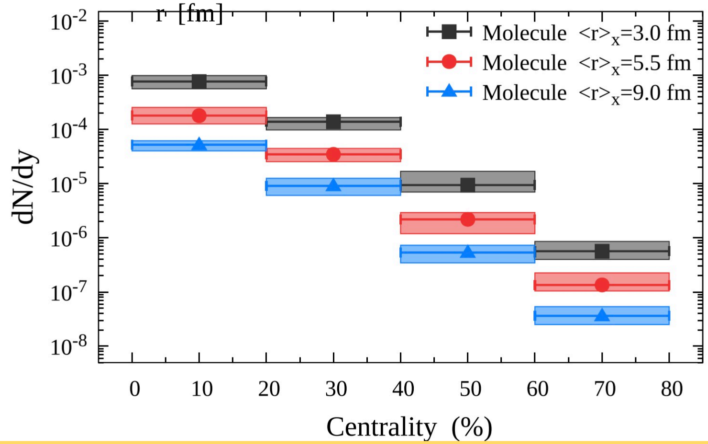
- Tetraquark yield is around 40 times smaller than J/ψ
- Tetraquark yield is controlled by both **spatial** and **momentum** part of the Wigner function

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 temperature

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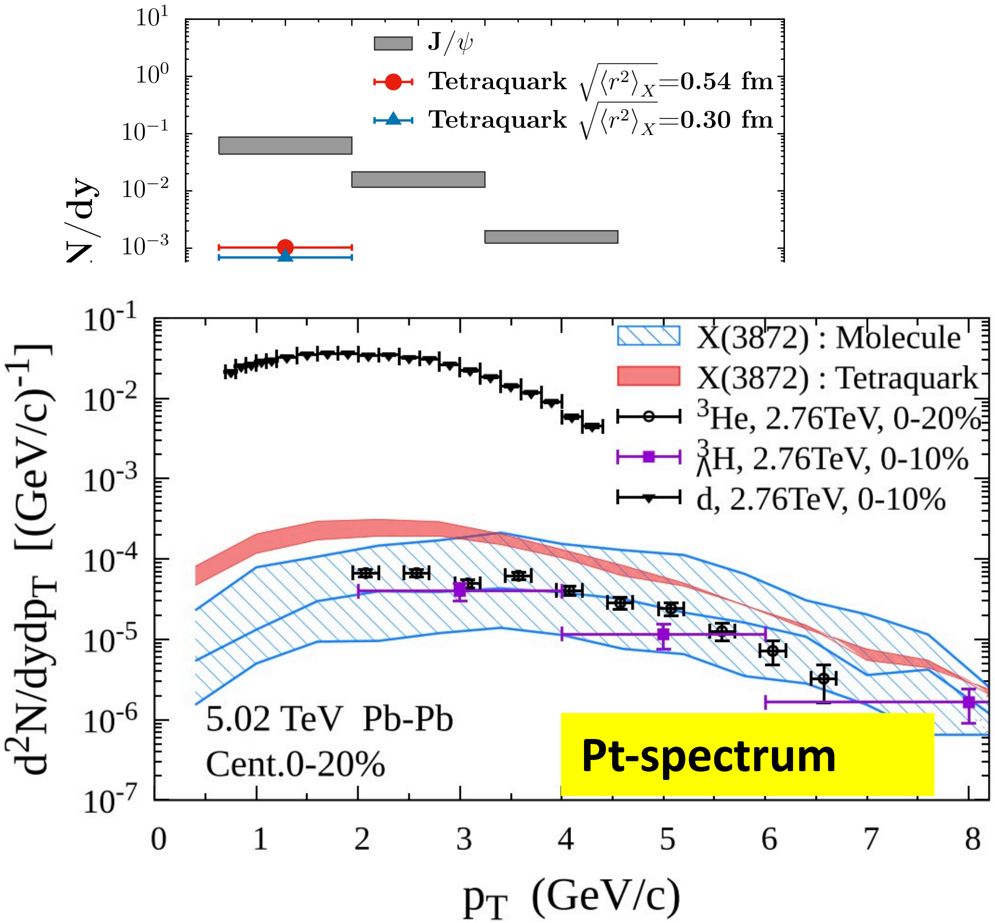

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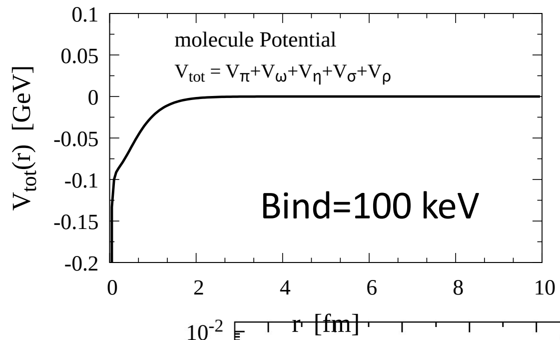

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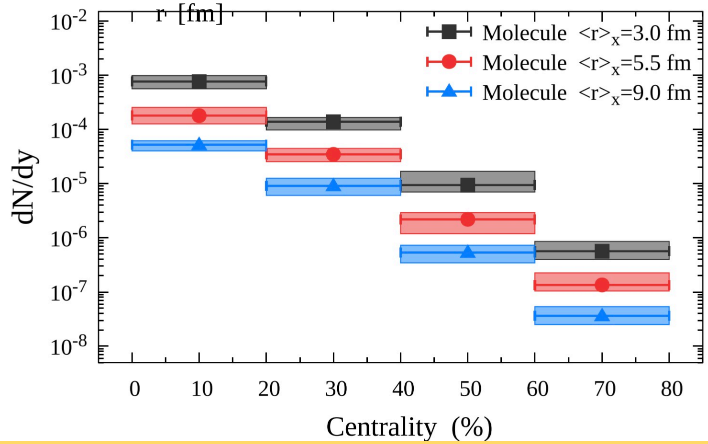

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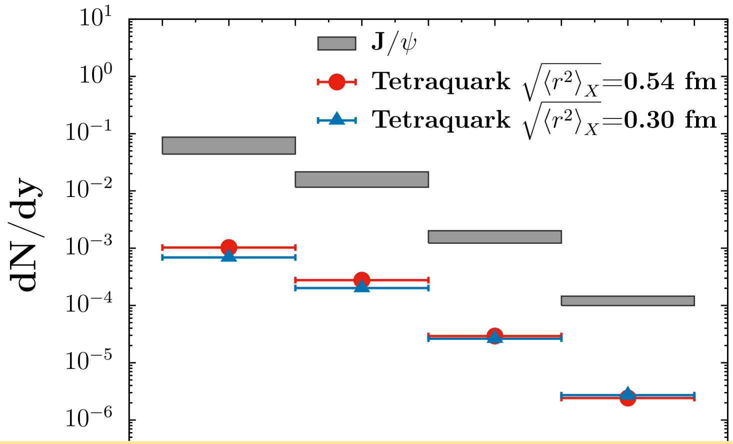

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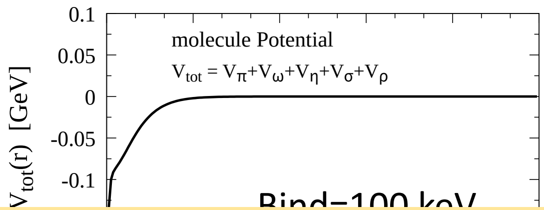


- Our tetraquark yield $\sim 10^{-3}$ is qualitatively consistent with ***Cho. Prog.Part.Nucl.Phys. 95,279-322 (2017);*** our molecule production is **a few times smaller**.

- **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.** { **5fm < relative distance < 7fm**; $2M_D < pair\ mass < 2M_{D^*}$ }

3. charmed hadron production: X(3872)

- **Estimate the R_{AA} of $X(3872)$ at low p_T**

➢ In pp collisions: $N_{pp}^{X(3872)}/N_{pp}^{\psi(2s)} \approx 0.1$

at low multiplicity pp 8TeV collisions,
LHCb: PRL 126, 092001 (2021)

*With **tetraquark scenario** and $< r^2 >_X = 0.54\ fm$*

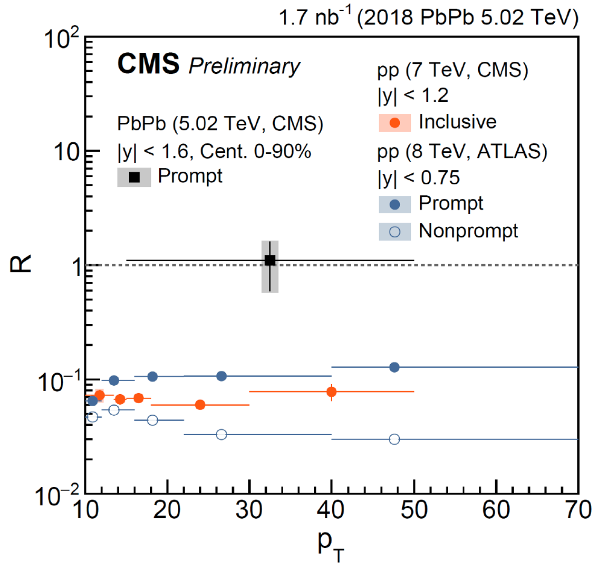
$N_{pp}^{X(3872)}/N_{pp}^{J/\psi} \approx 8\times10^{-3}$

$R_{AA}^{X(3872)}/R_{AA}^{J/\psi} \approx 2.8$
in central Pb-Pb 5.02 TeV

$N_{AA}^{X(3872)}/N_{AA}^{\psi(2s)} \approx 0.3$

Enhanced compared with pp

- **$X(3872)$ at high p_T**

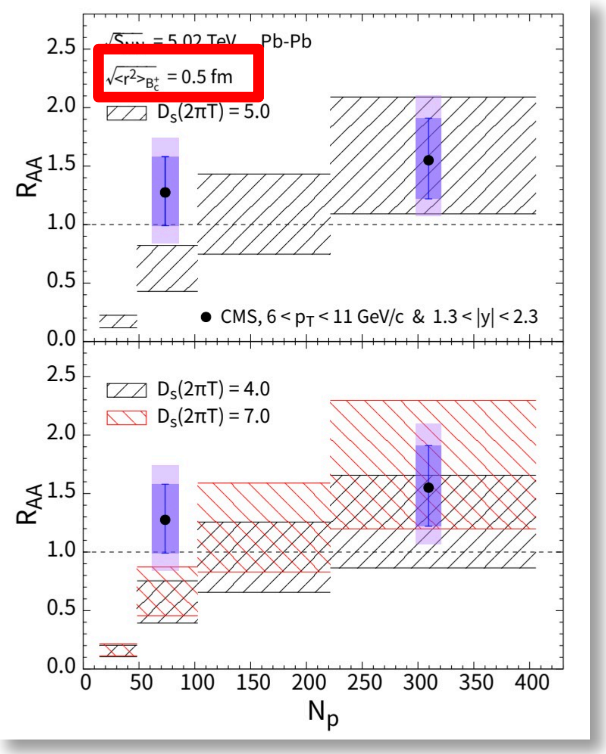


We can also extend above calculation to the T_{cc} production: in progress…

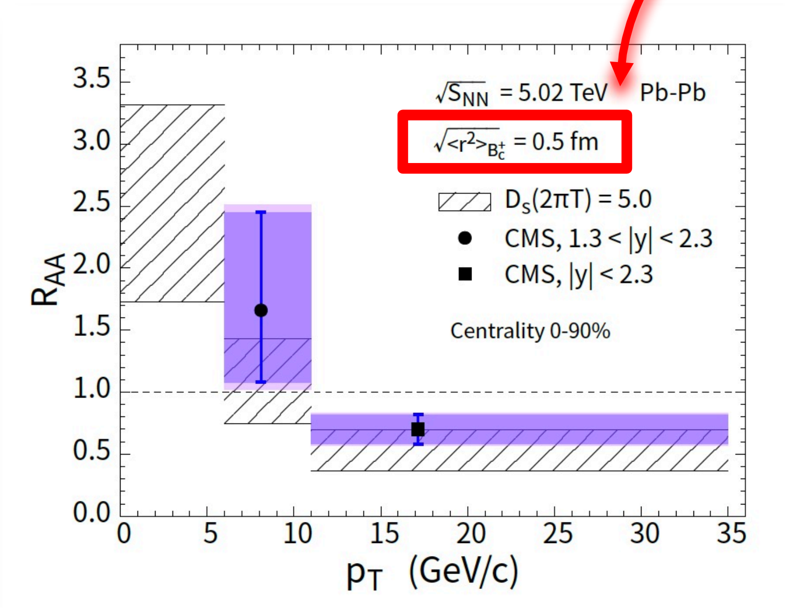
$$T_{cc}^0 : \quad D^0 D^{*0}$$

B.Chen@Exhic Sep.29-Oct.1, 2022, Korean

3. charmed hadron production: B_c



Geometry size



BYC, Wen, Liu, PLB 834, (2022) 137448

fig: B_c(1s)+ B_c(2s->1s) States;
all spin states are included

Event-by-event c(b) quark realistic Brownian motion + coalescence

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

$$\frac{d\sigma_{pp}^{bb}}{dv} = 47.5\, \mu b \qquad \frac{d\sigma_{pp}^{Bc}}{dy} = (151.9 - 79.3)\, nb$$

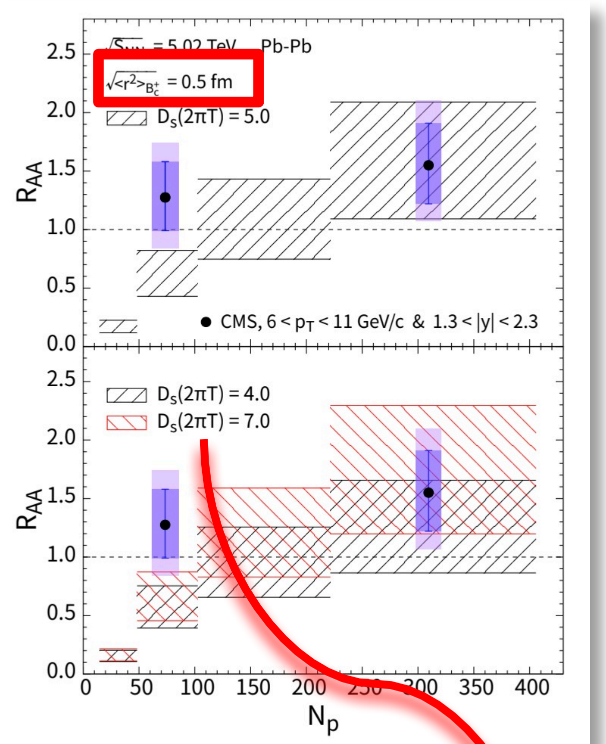
1) **Bc final production is evidently enhanced,** due to a large number of c and b quarks in QGP.

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

2) RAA>1 at central collisions:
QGP signal
RAA<1 at peripheral collisions:
absence of initial production

3. charmed hadron production: B_c

Geometry size



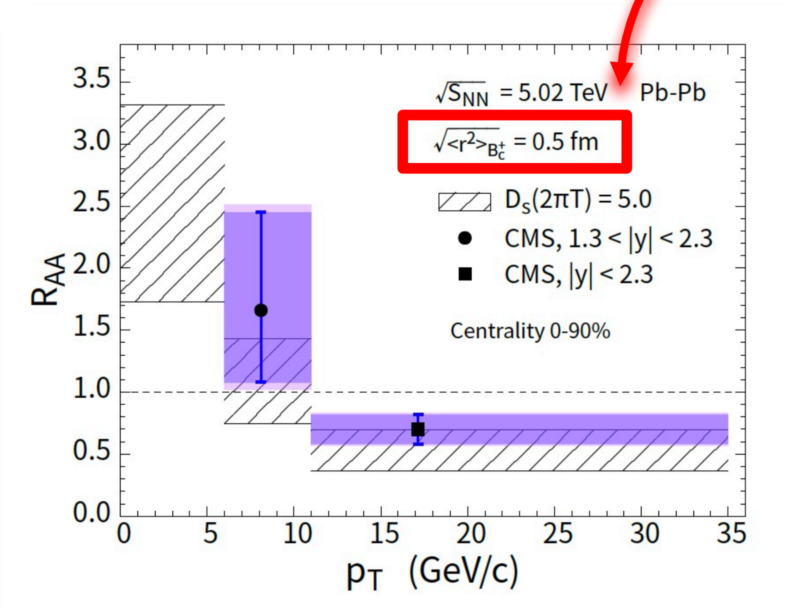


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fig: B_c(1s)+ B_c(2s->1s) States;
all spin states are included

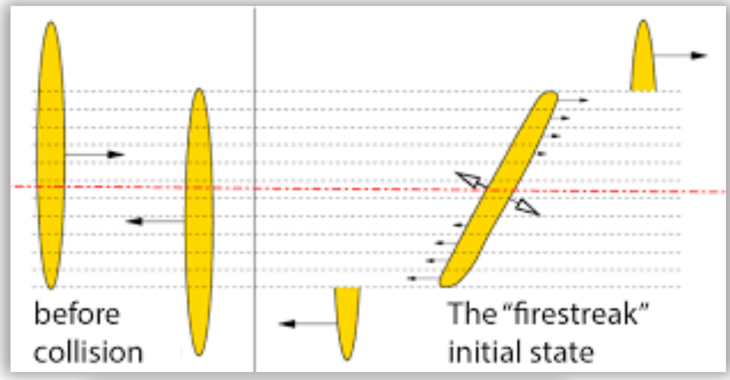
1) **Bc final production is evidently enhanced,** due to a large number of c and b quarks in QGP.

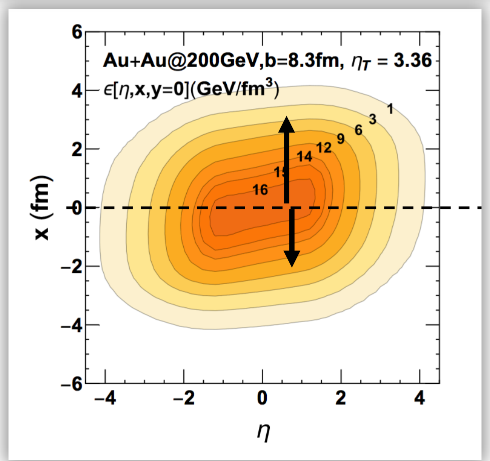
$\frac{d\sigma_{p}^{c}}{dy}$ ... $\frac{d\sigma}{dy}$ ... dy

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





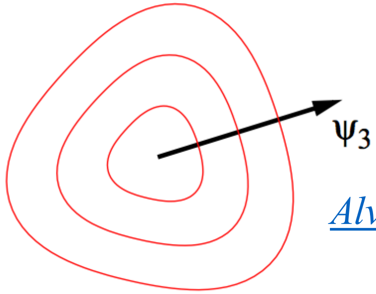
Longitudinal rotated medium

Rapidity-odd distribution

Due to the fluctuation of nucleon positions in event-by-event collisions,
Triangularity is include via a deformation factor

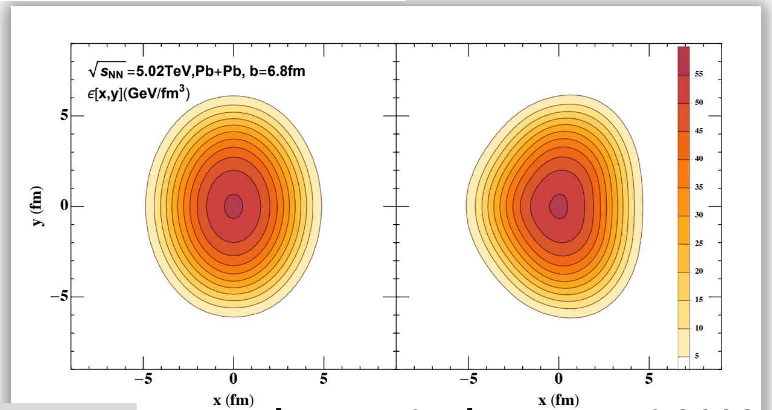
$$\epsilon(\boldsymbol{x}, \tau_0|\boldsymbol{b}) \rightarrow \epsilon(\tilde{\boldsymbol{x}}, \tau_0|\boldsymbol{b})$$

With $\tilde{x} = (x_T\sqrt{1+\epsilon_3\cos[3(\phi-\Psi_3)]}, \phi, \eta)$



The reference angle $\Psi_3 = 0$ is taken

Alver,et PRC 82 (2010) 034913



Zhao, BYC, Zhuang, PRC 2022

Transport model for charmonium + hydro for QGP

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

Boltzmann-type transport model from Tsinghua Group

Developed by :
Pengfei Zhuang, Xianglei Zhu, Li Yan, Kai Zhou, Yunpeng Liu, BYC, et al ....

$$\left[\cosh(y-\eta)\frac{\partial}{\partial\tau} + \frac{\sinh(y-\eta)}{\tau}\frac{\partial}{\partial\eta} + \mathbf{v}_T\cdot\nabla_T\right] f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi$$

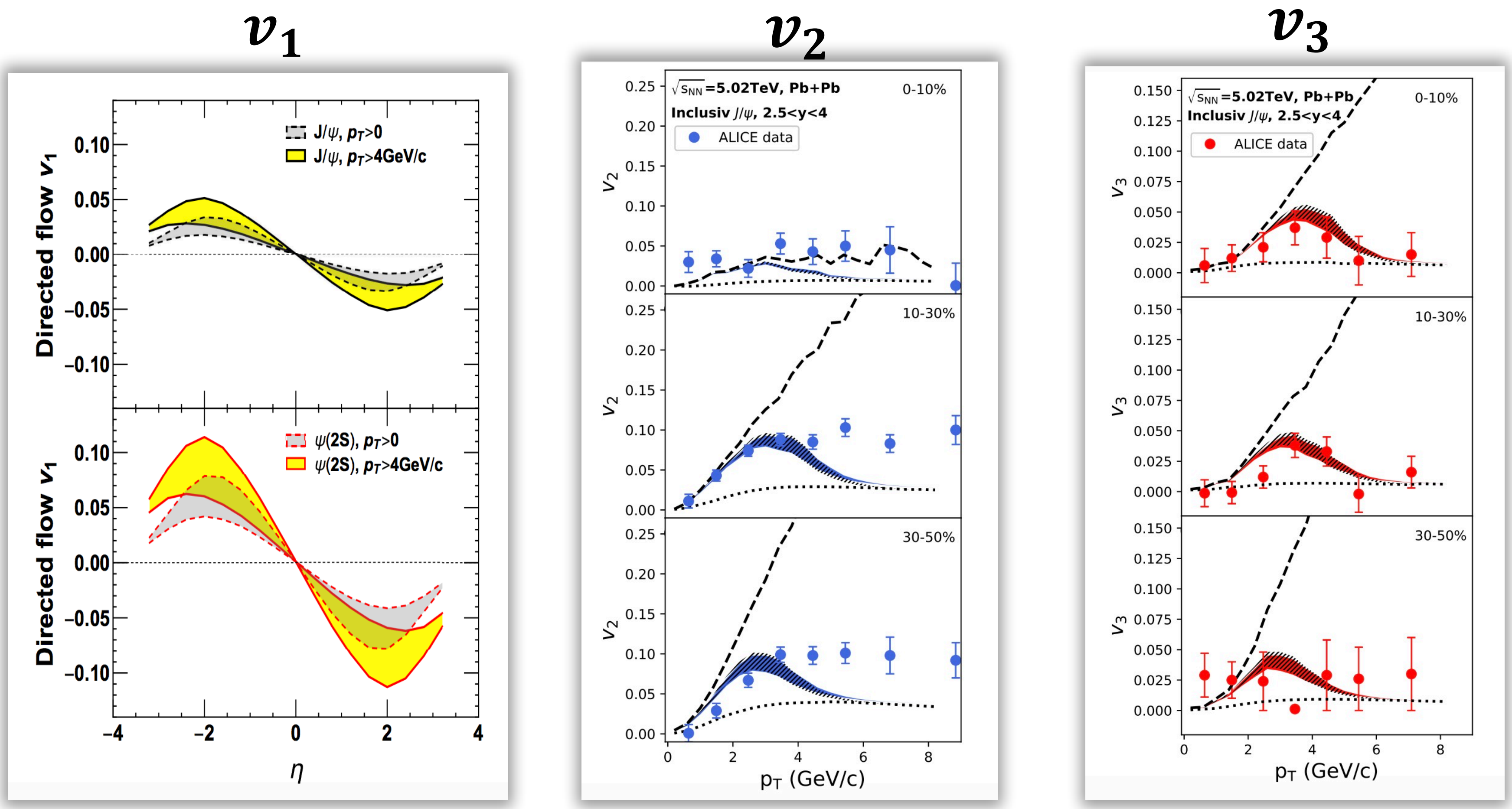
Color screeing
+ gluon dissociation

$$\alpha_\Psi(\boldsymbol{p},\boldsymbol{x},\tau|\mathbf{b}) = \frac{1}{2E_T}\int\frac{d^3\boldsymbol{p}_g}{(2\pi)^3 2E_g} W_{g\psi}^{c\bar{c}}(s) f_g(\boldsymbol{p}_g,\boldsymbol{x},\tau)\Theta(T(\boldsymbol{x},\tau|\boldsymbol{b})-T_c),$$

$$\beta_\Psi(\boldsymbol{p},\boldsymbol{x},\tau|\boldsymbol{b}) = \frac{1}{2E_T}\int\frac{d^3\boldsymbol{p}_g}{(2\pi)^3 2E_g}\frac{d^3\boldsymbol{p}_c}{(2\pi)^3 2E_c}\frac{d^3\boldsymbol{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} \times W_{c\bar{c}}^{g\psi}(s) f_c(\boldsymbol{p}_c,\boldsymbol{x},\tau|\boldsymbol{b}) f_{\bar{c}}(\boldsymbol{p}_{\bar{c}},\boldsymbol{x},\tau|\boldsymbol{b}) \times(2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}})\Theta(T(\boldsymbol{x},\tau|\boldsymbol{b})-T_c).$$

Charm dynamical evolution
in the anisotropic hot medium

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



Weak cent.-dependence

Directed flow: *PLB* 802 (2020) 135271

Elliptic flow and **triangular** flow: *PRC* 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.
  the wave function of X(3872) is crucial for the thermal production .
  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}.**
  Besides, collective flows of X(3872) and Bc are also expected.

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.
the wave function of X(3872) is crucial for the thermal production .
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}.**
Besides, collective flows of X(3872) and Bc are also expected.

Thank you very much for your attention!