Phenomenology of exotic hadron and heavy quarkonium in heavy-ion collisions

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Outline

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

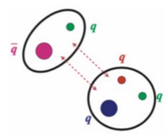
D meson spectrum $(c-\bar{q})$

J/ψ spectrum $(c-\bar{c})$

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



2. Heavy flavor spin dynamics

3. Summary

Heavy quark dynamical evolution

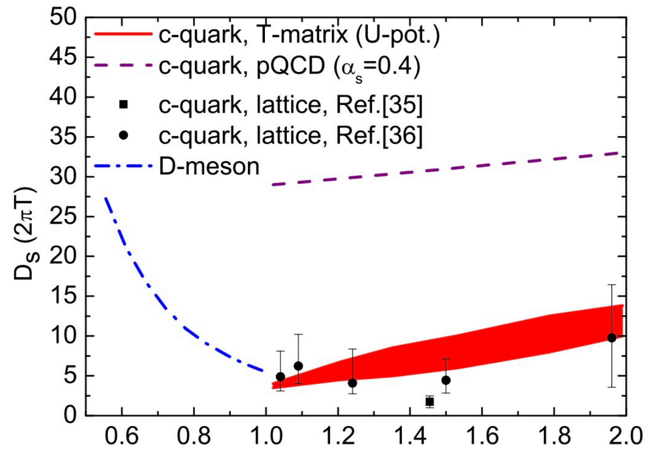
$$\frac{d\vec{p}}{dt} = -\eta\vec{p} + \vec{\xi} + f_g$$

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

$D_s(2\pi T) = 5$

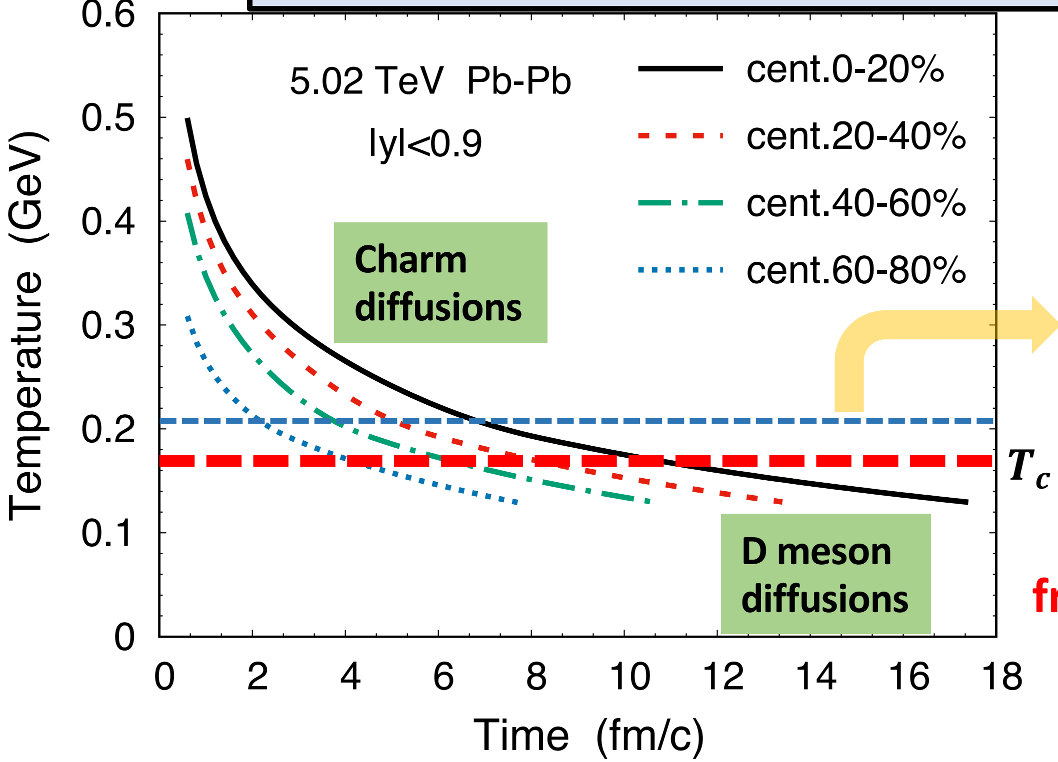
D_s, κ:

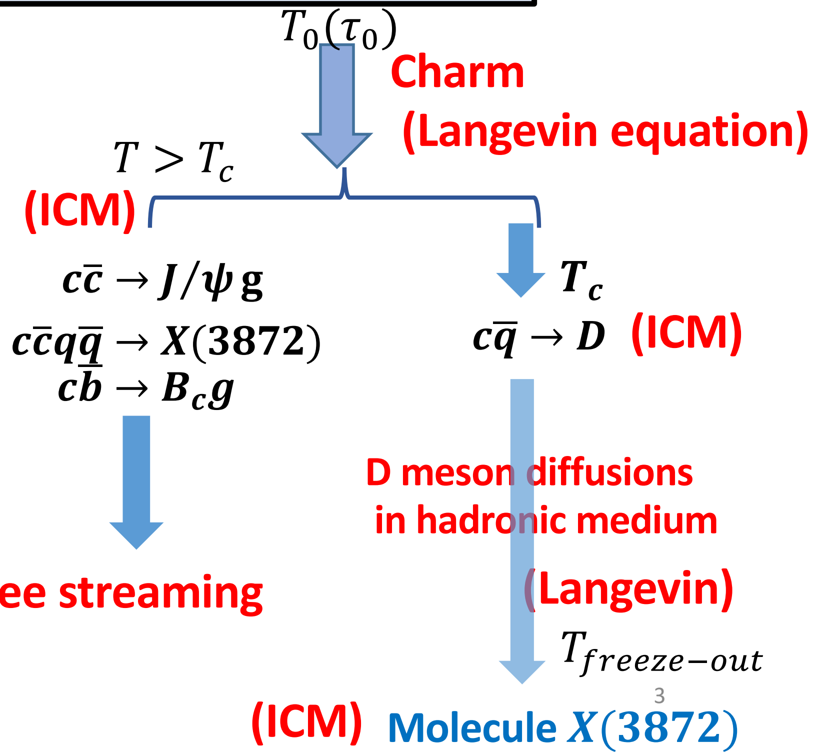
Spatial and Momentum Diffusion coefficients



t al PRL 2012

Langevin + Instantaneous coalescence model (LICM)





Heavy quark dynamical evolution

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D_s, κ:

Spatial and Momentum Diffusion c

$D_s(2\pi T) = 5$

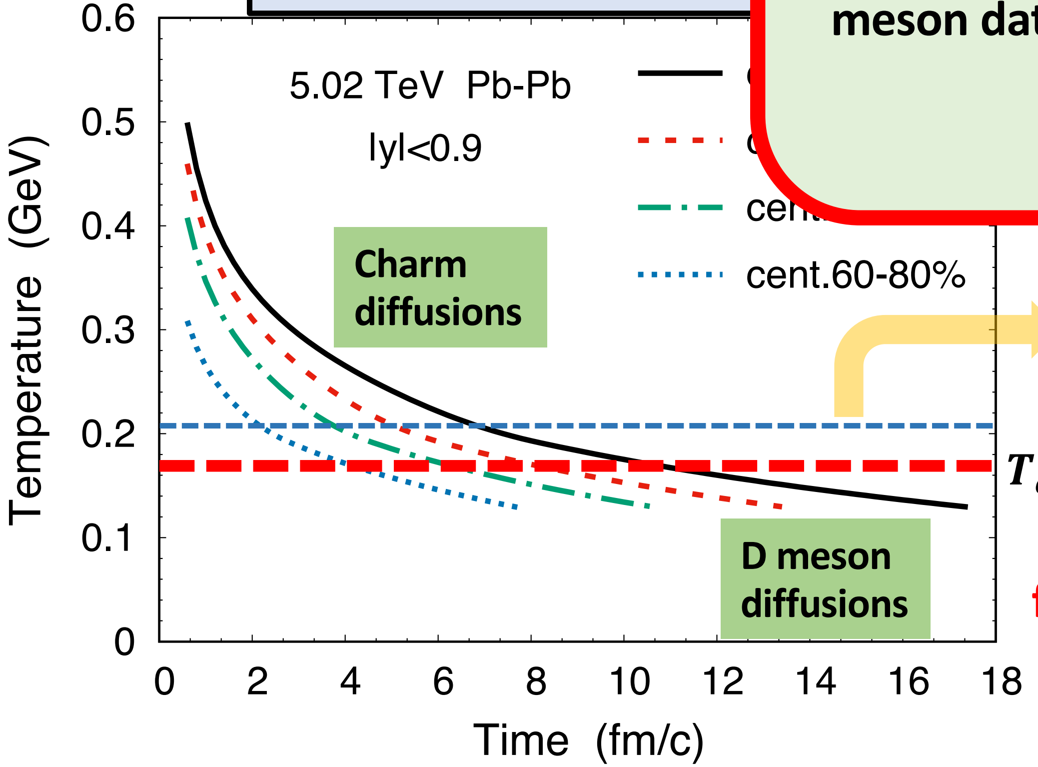
Spatial diffusion coefficient (T, p_T)-dependence

→刘佳敏的海报

Use Deep neural network to quantify the spatial diffusion coefficient with (RAA, v2) of D meson data at (5.02, 2.76, 0.2) TeV

collaborate with Kai Zhou

Langevin + Instantan



(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

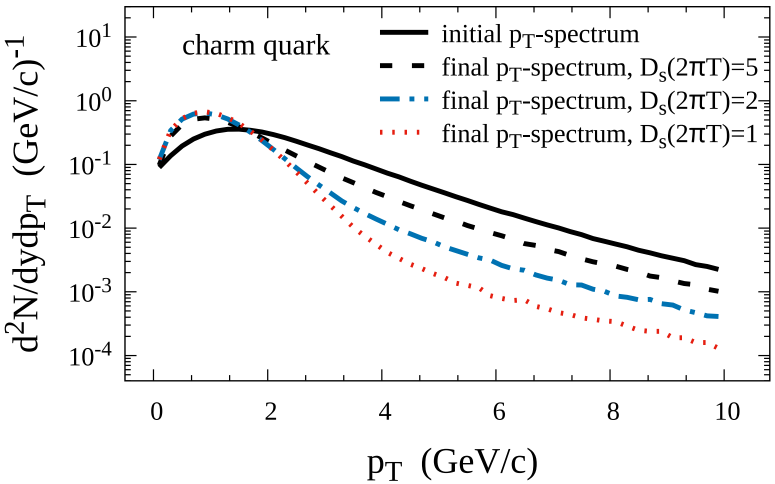
(Langevin)

$T_{freeze-out}$

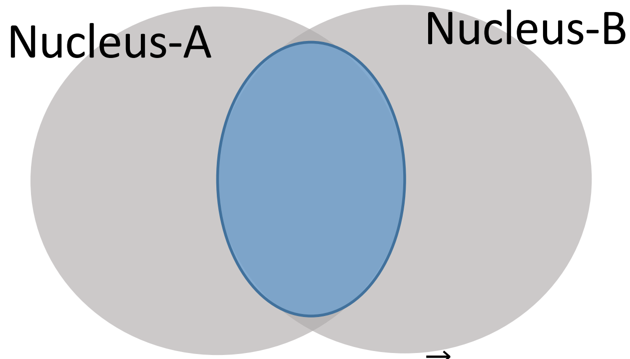
(ICM) Molecule $X(3872)$

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 $c - \bar{c}$

charmed hadron production

Wigner function: encodes the information of formed states

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

$$W(\mathbf{r},\mathbf{p}) = \int d^3\mathbf{y} e^{-i\mathbf{p}\cdot\mathbf{y}} \psi\left(\mathbf{r}+\frac{\mathbf{y}}{2}\right)\psi^*\left(\mathbf{r}-\frac{\mathbf{y}}{2}\right)$$

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

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

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

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

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

R_S: Shadowing factor

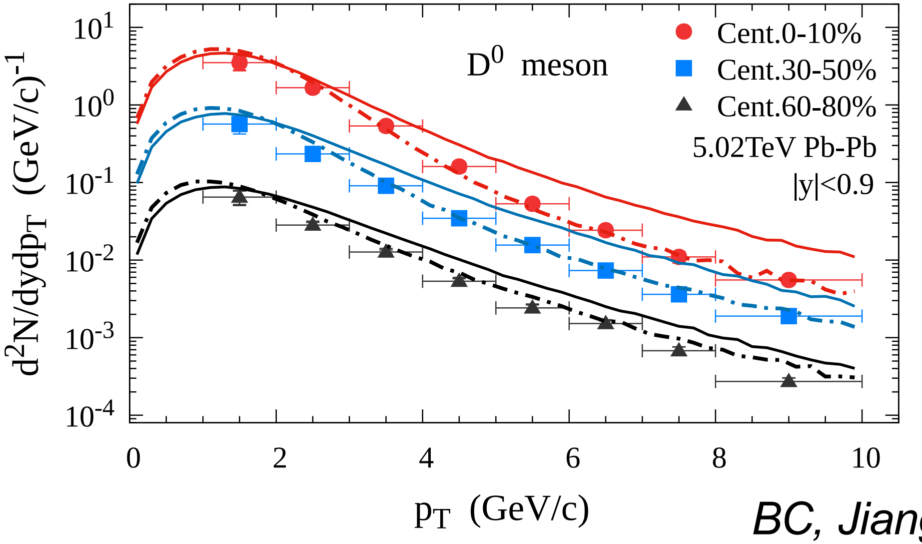
charmed hadron production: D meson

- **D meson coalescence**

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

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

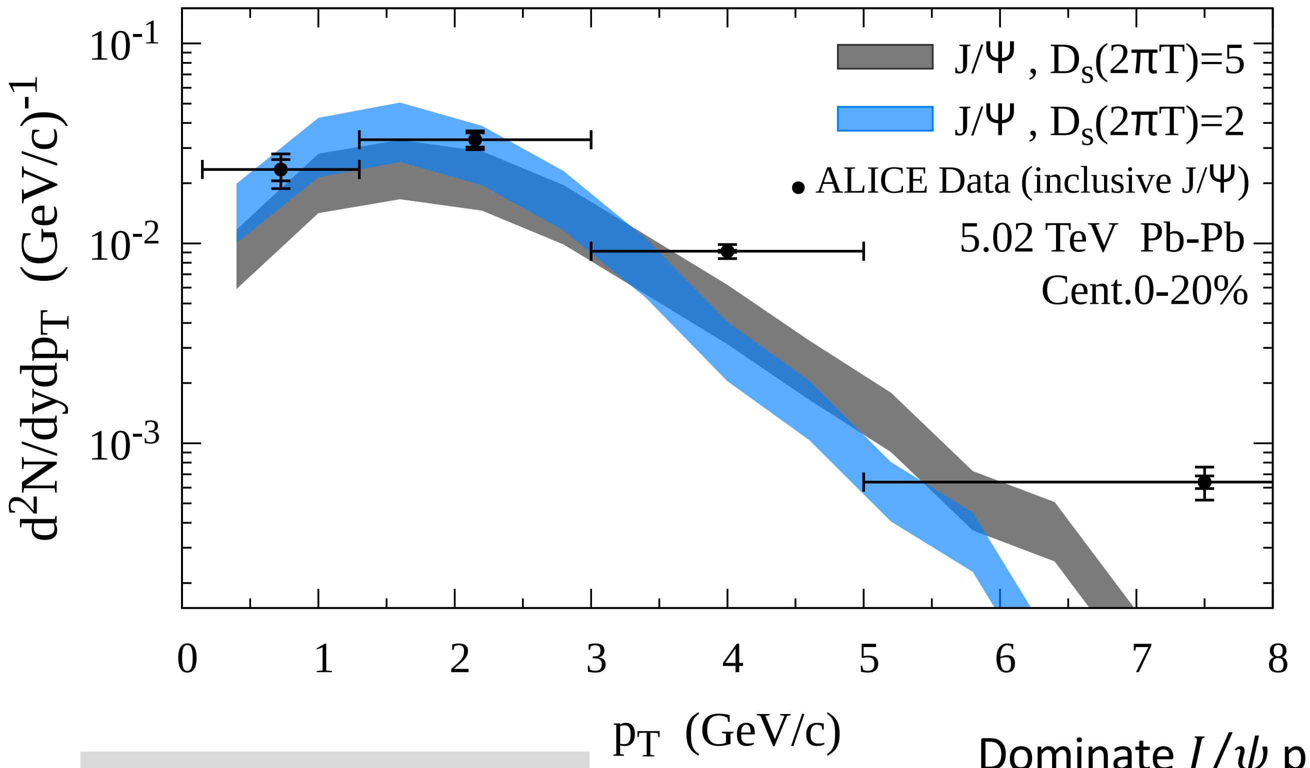
- $H_{c\to D^0} = 9.5\%$ (20%) : Charm turning into **direct** D^0 (D^{*0}) at Tc
- $\frac{dN_1}{d\vec{p}_1}$: **charm** momentum distribution
- $\frac{dN_2}{d\vec{p}_2}$: **light quark** momentum distribution: Fermi.



- 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)

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

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

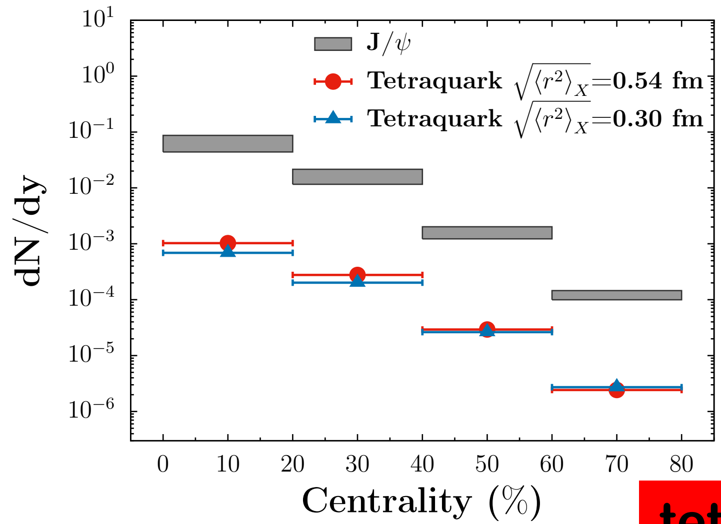
Dominate at low pT and **total yield**

Theoretical calculation:

$c - \bar{c}$ coalescence

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 firstly, then two diquarks form a tetraquark state.



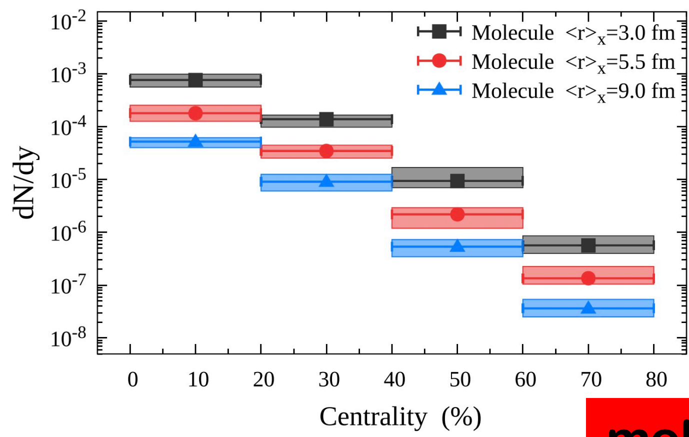
tetraquark

- 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

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

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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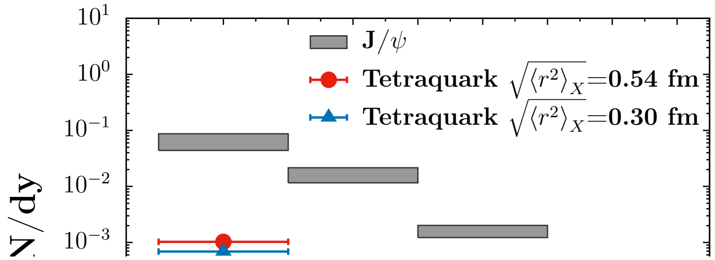

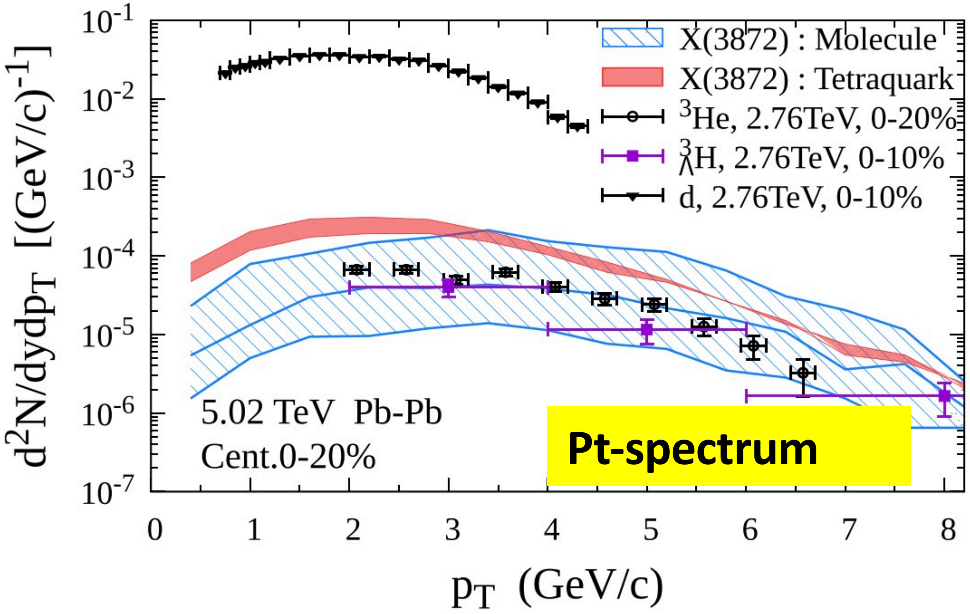

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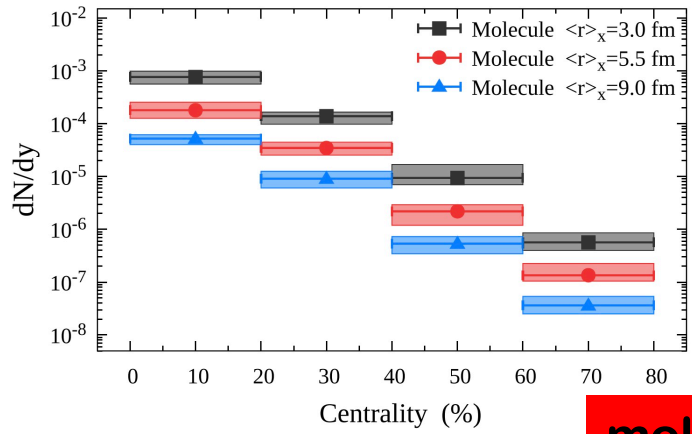

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BC, Jiang, Liu, Liu, Zhao,
Phys. Rev. C 105, 054901 (2022)

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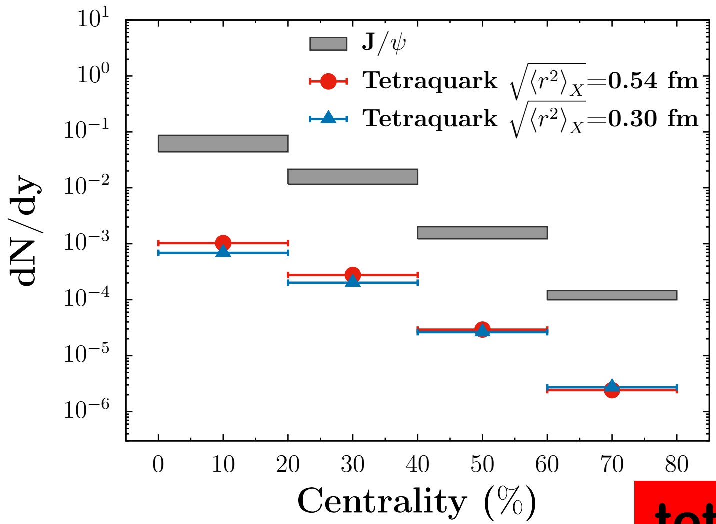

tetraquark

- Tetraquark yield is around

Molecule state with potential model

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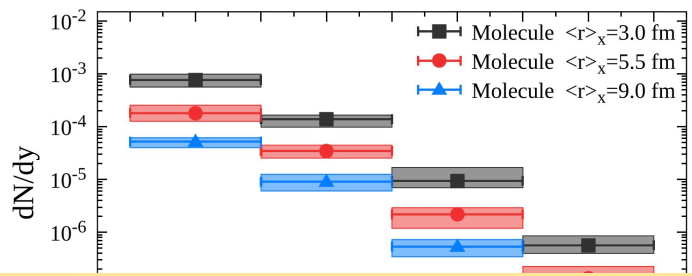
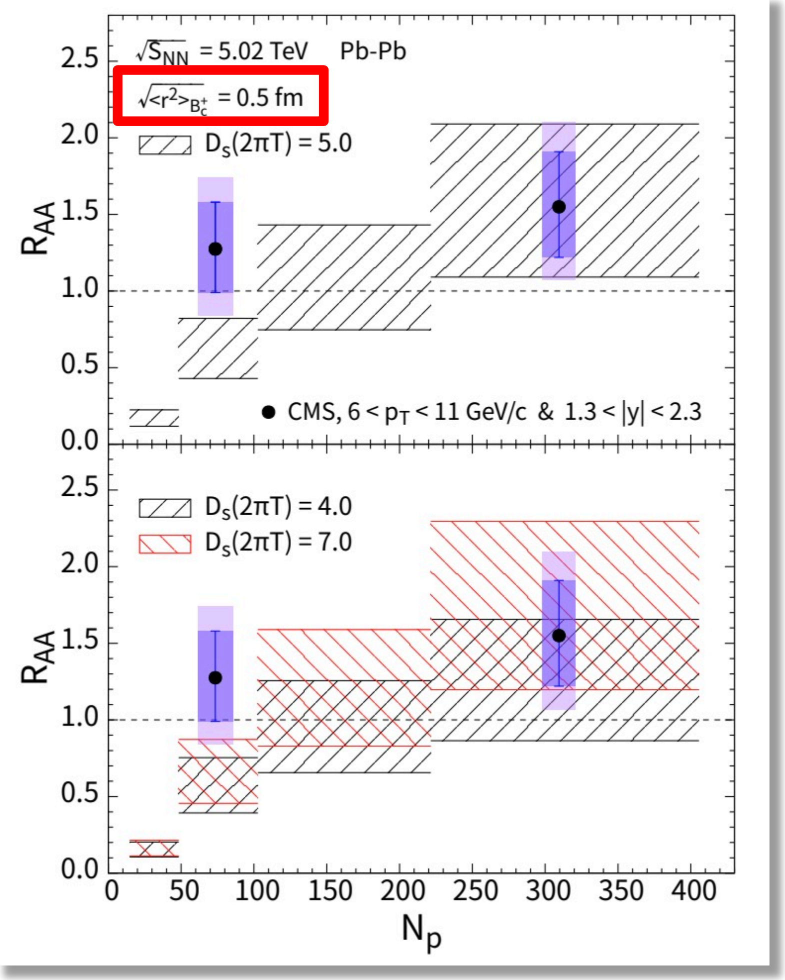


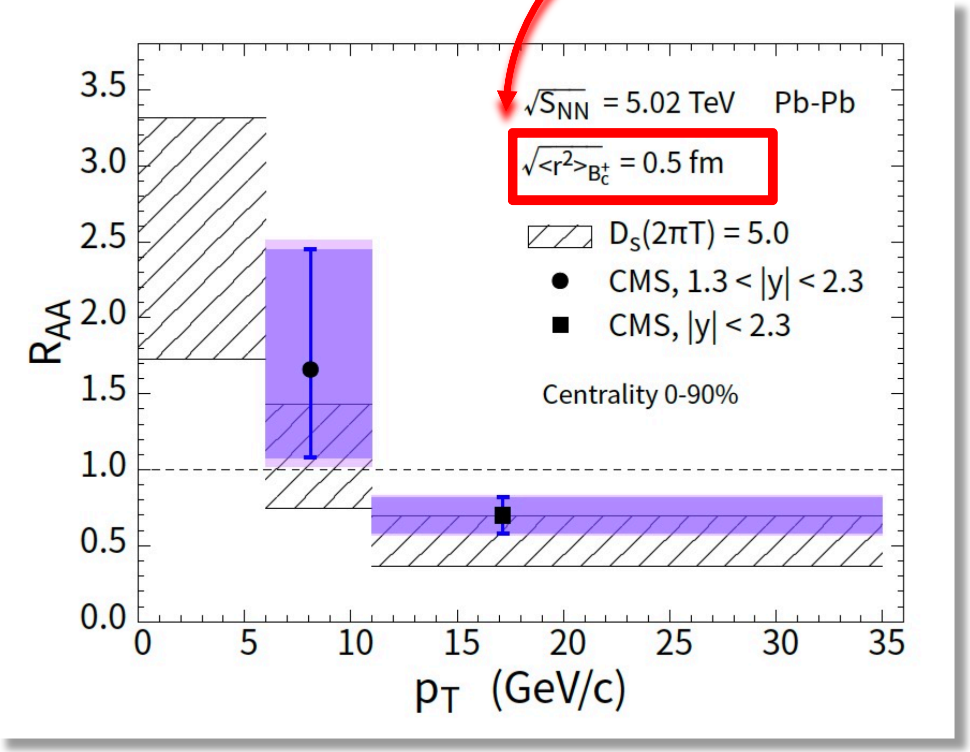
- Our tetraquark yield $\sim 10^{-3}$ is consistent with ***Cho. Prog.Part.Nucl.Phys. 95,279-322 (2017);*** ***when taking same coalescence temperature***

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

charmed hadron production: B_c

Geometry size





BC, Wen, Liu, *Phys.Lett.B* **834 (2022) 137448**

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

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

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

$\boldsymbol{B_c}$: spin 0
fig: $\boldsymbol{B_c}$(1s)+ $\boldsymbol{B_c}$(2s->1s)

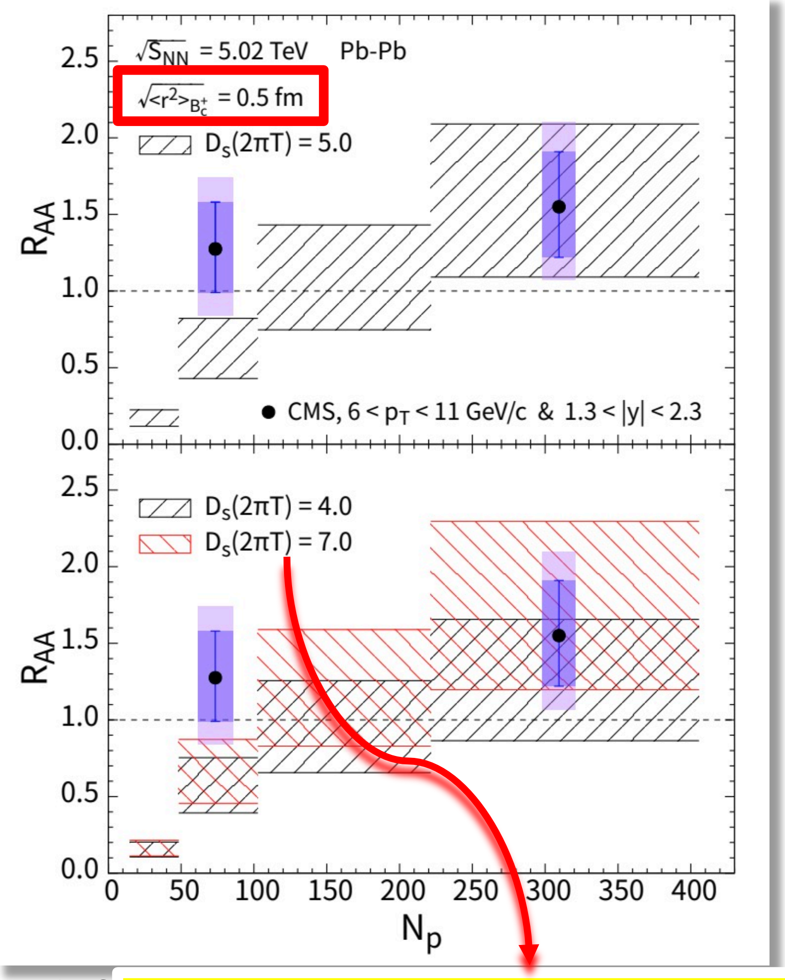
1) **Bc final production is evidently enhanced,** due to **a large number of** c and b quarks in QGP.

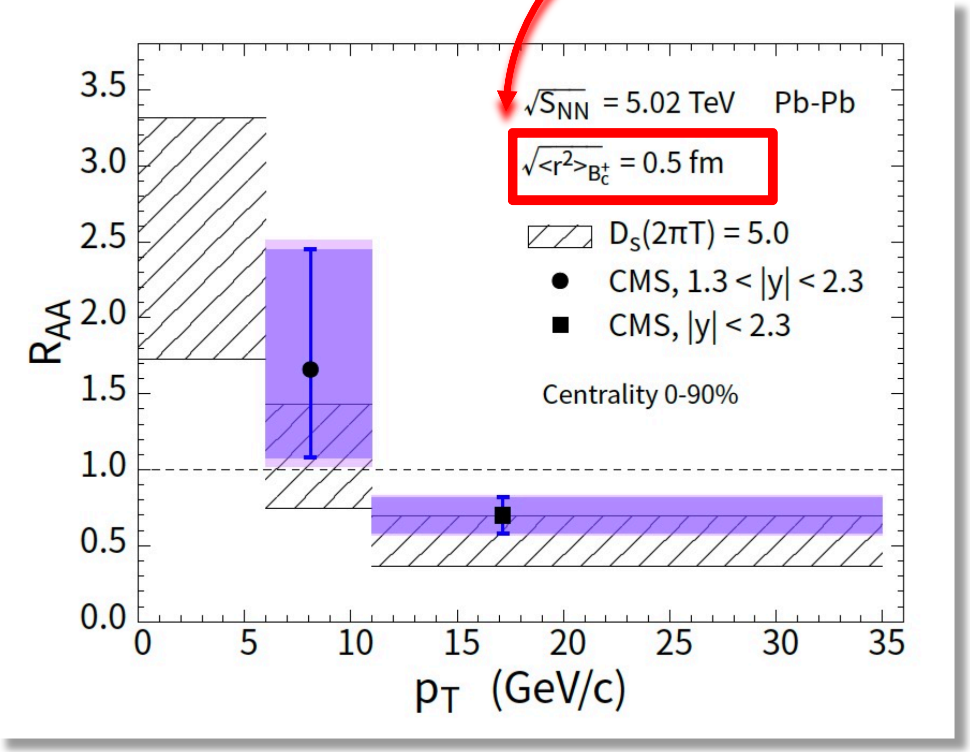
$$\boldsymbol{c + \bar{b} \rightarrow B_c + g}$$

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

charmed hadron production: B_c

Geometry size





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1) **Bc final production is evidently enhanced,**
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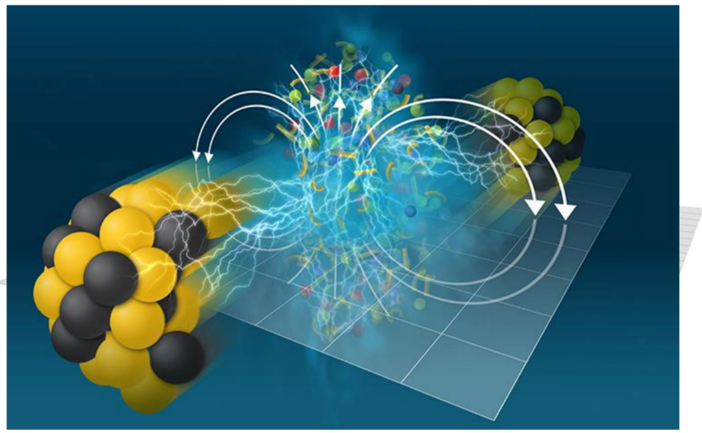
$+ g$

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

$\frac{d\sigma}{dy}$

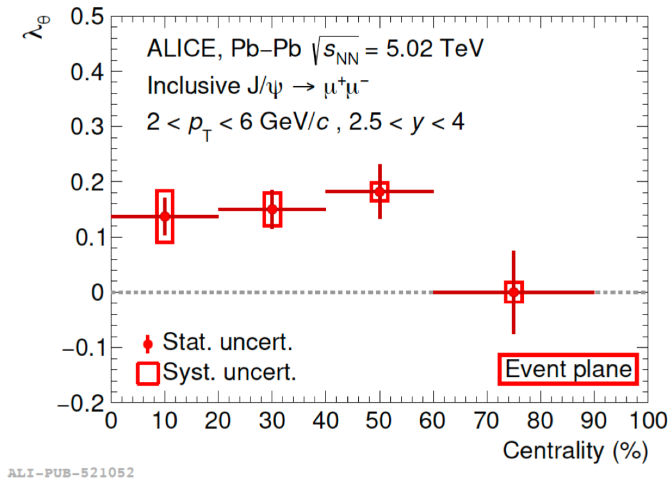
Different thermalization
of charm and bottom quarks on B_c production,
By taking spatial diffusion coefficient $D_s(2\pi T) = 4$ and 7

Can heavy quark be polarized in the rotating QGP and strong B-field ?

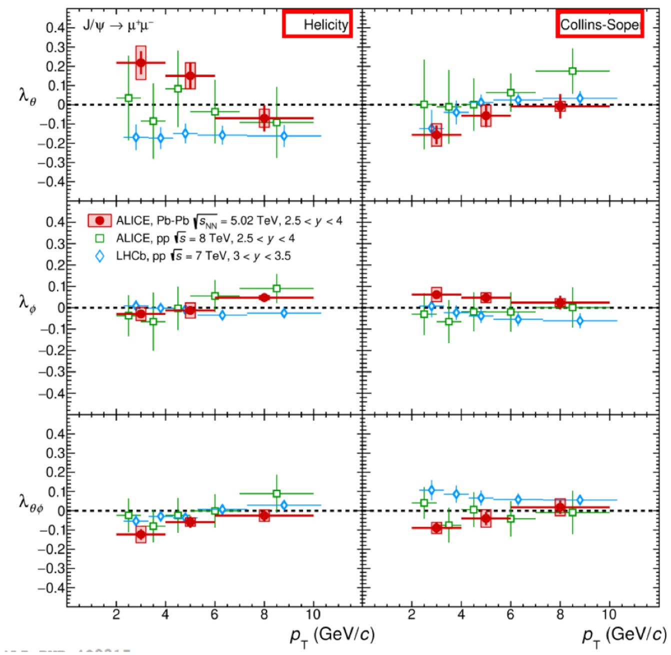


[T. Bowman and J. Abramowitz/Brookhaven National Laboratory]

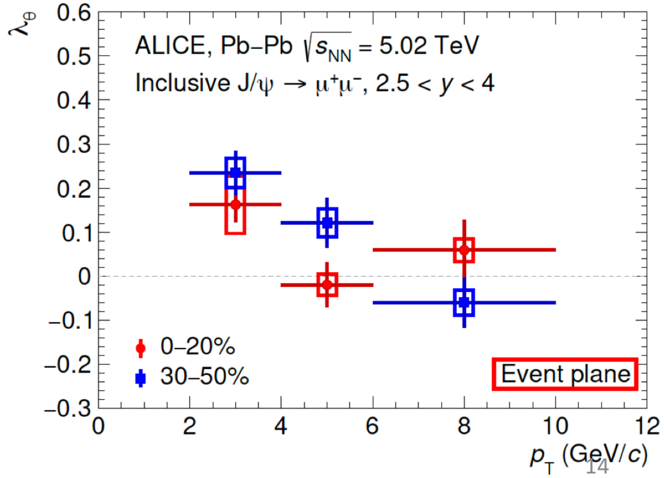
Recent polarization data-points:



PLB 815 (2021) 136146



ALICE: *PRL* 131 (2023) 042303



Can heavy quarks be polarized ?

By magnetic field or vorticity ?

Dynamical process:
simulating Heavy quark polarization in B-field

- **Landau-Lifshitz-Gilbert (LLG) equation**

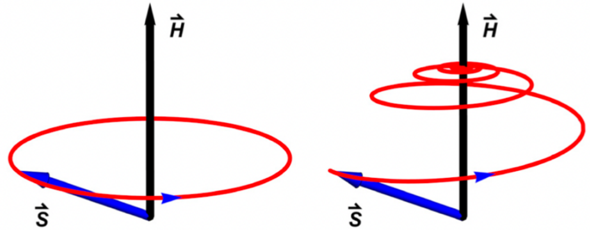
PRB 83, 134418 (2011)

$$\frac{d\vec{S}}{dt} = -\frac{\gamma}{1+\alpha^2}[\vec{S}\times(\vec{H}+\overrightarrow{H_{th}})] - \frac{\alpha\gamma}{1+\alpha^2}\vec{S}\times[\vec{S}\times(\vec{H}+\overrightarrow{H_{th}})]$$

$\vec{S} = \vec{s}/|\vec{s}|$

Unit vector

stochastic dynamics of a spin in the medium with magnetic field



Polarization of heavy quark is induced by:
spin-magnetic field interaction
+ particle-particle interaction

$\gamma = g\frac{Q}{2m}$ → Electric charge

α= 0.1 **Gilbert damping factor**
(to be determined later)

noise term

$$\langle H_{th,i}(t)\rangle = 0,$$

$$\langle H_{th,i}(t)H_{th,j}(t')\rangle = \frac{2\alpha T}{|\mu|\gamma}\delta_{ij}\delta(t-t').$$

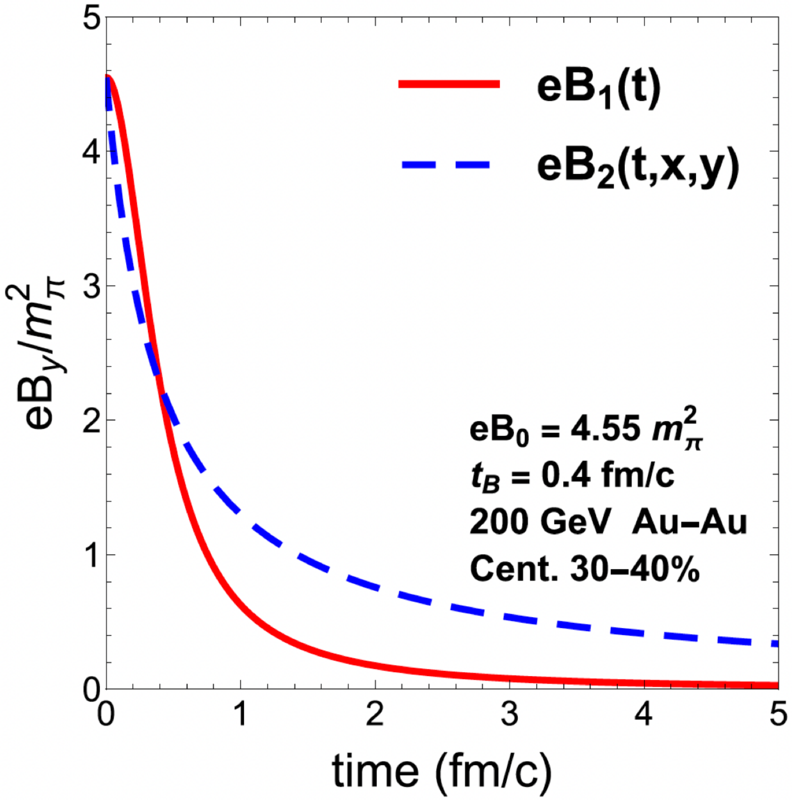
Heavy quark polarization in magnetic field

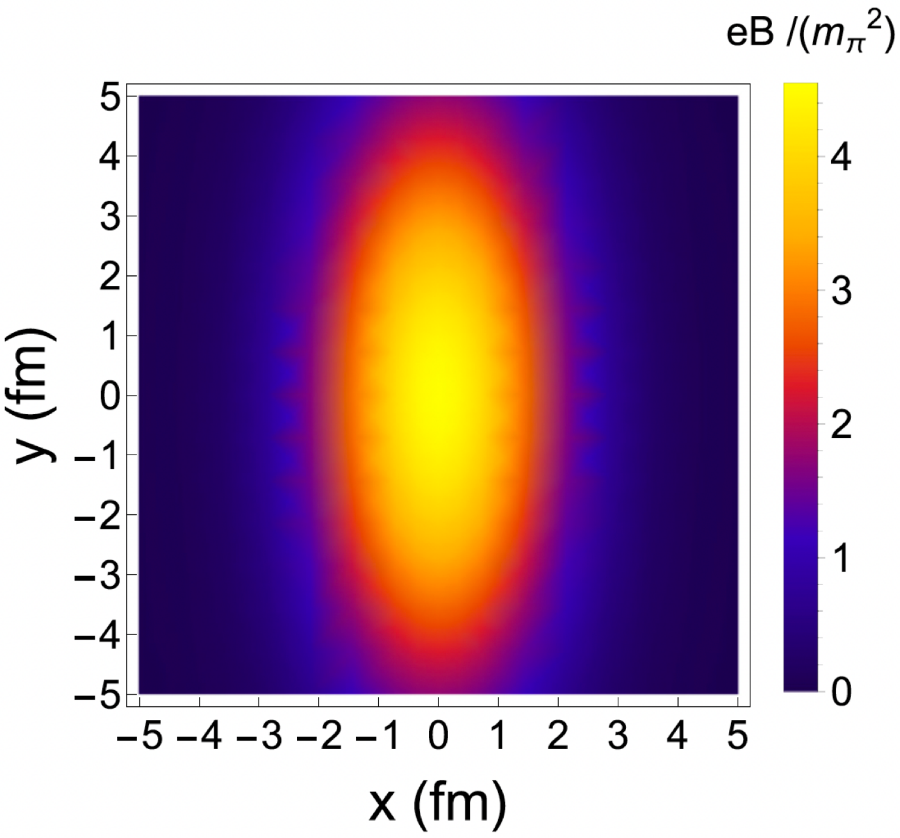
In-medium magnetic field
(two cases are considered)

Liu, Bai, Zheng, Huang, **BC**, PRC110, 034910 (2024)

$$eB_1(t) = \frac{eB_0}{1+\left(\frac{t}{t_B}\right)^2}$$

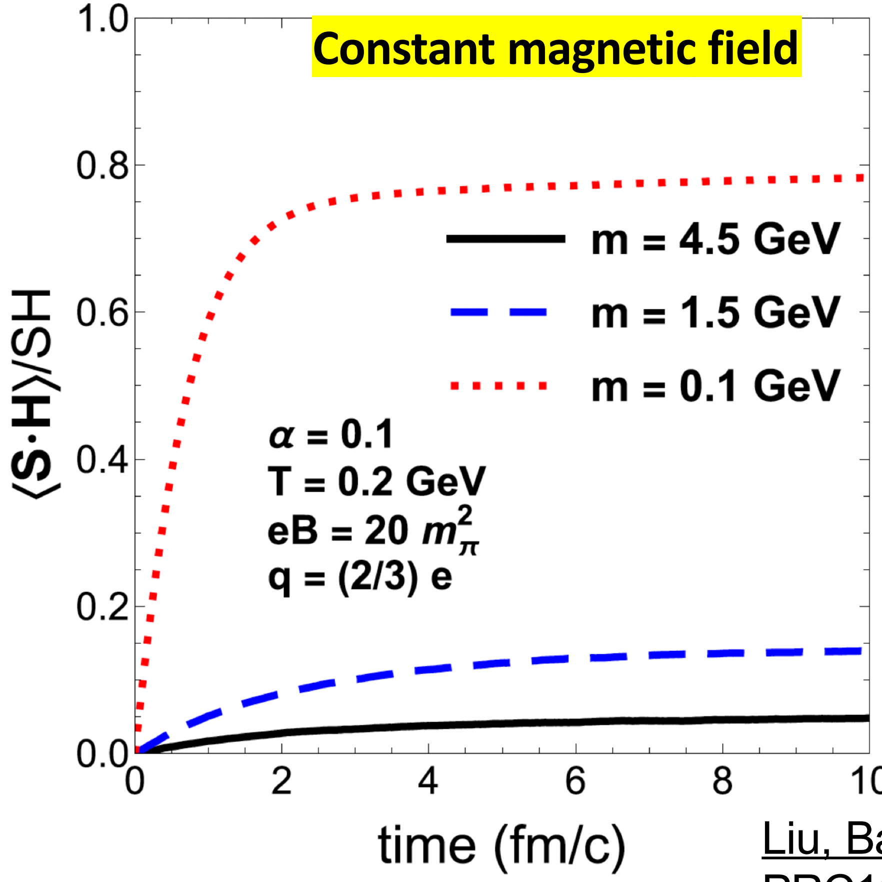
$$eB_2(t,x,y) = \frac{eB_0}{1+\left(\frac{t}{t_B}\right)} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)$$



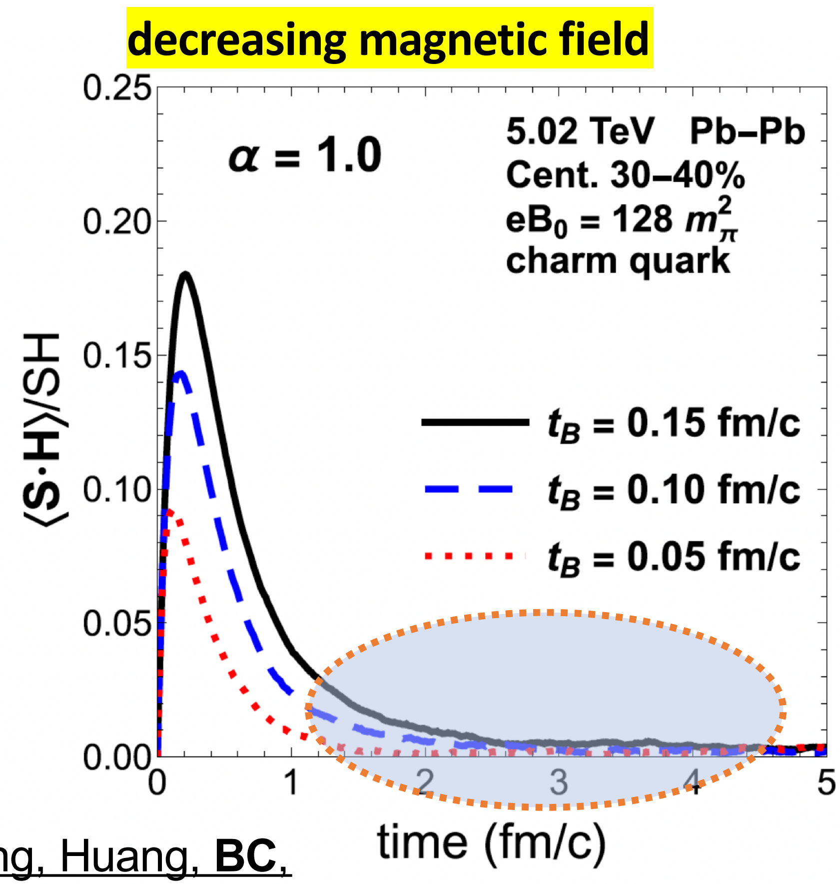


Heavy quark polarization in magnetic field

Mass dependence :



B dependence:



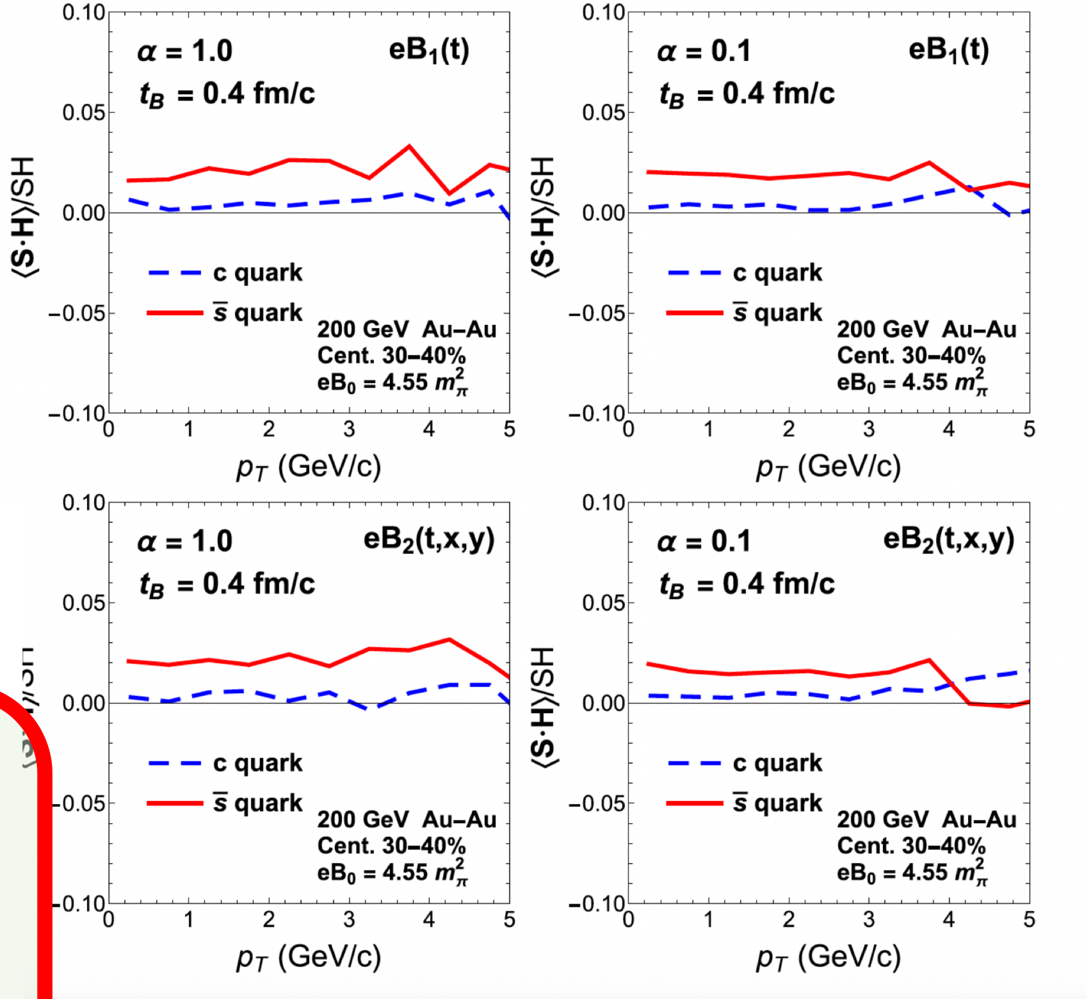
Liu, Bai, Zheng, Huang, **BC**, PRC110, 034910 (2024)

- Larger Quark mass → smaller polarization
- smaller B field → smaller polarization

Heavy quark polarization in magnetic field

In realistic heavy-ion collisions

Liu, Bai, Zheng, Huang, **BC**, PRC110, 034910 (2024)



Key parameter: α

Gilbert damping factor of HQ spin

It can be calculated with Linear Response Theory.

→ 李天阳的海报

(Gilbert damping factor of heavy quark spin)

Collaborate with Anping, paper in preparation

Magnetic field induced polarization & thermal particle **random collisions**

Summary

- 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

- **heavy quark spin dynamics**

Thank you very much for your attention!