Phenomenology of exotic hadron and heavy quark polarization

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Collaborators:

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X(3872): 2107.00969 Bc: 2111.08490

Outline

1. **Introduction**

   heavy ion collisions & charmed hadrons

2. **Heavy quark polarization**

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

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

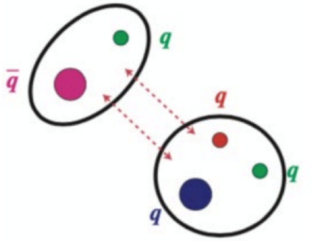
   J/ψ spectrum $(\mathrm{c}-\bar{c})$

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

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

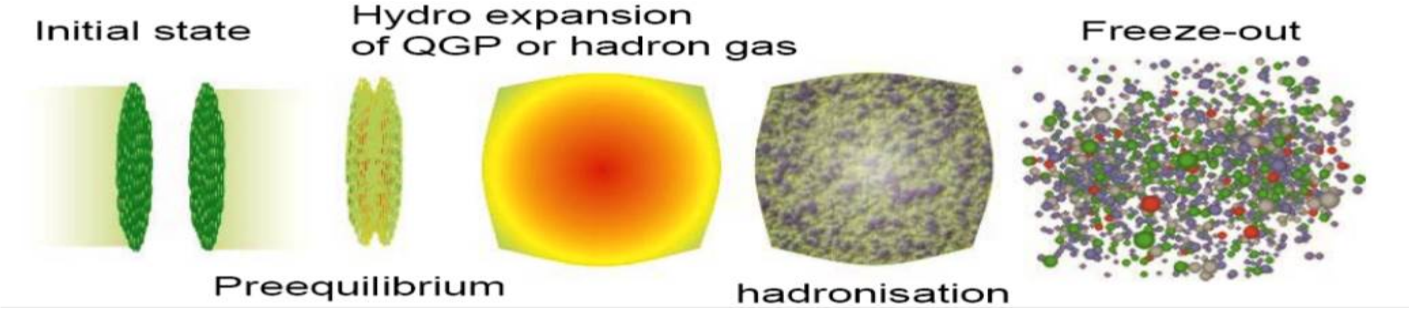
   as a meson molecule: $\mathrm{c}+\bar{q}\rightarrow D,\ D^0+\bar{D}^{*0}\rightarrow X(3872)$ **in hadronic gas**

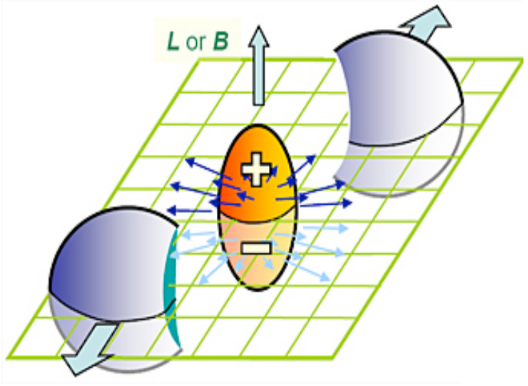
   T_{cc} as a meson molecule D^0D^{*0}, D^0D^{*+}, D^+D^{*0}

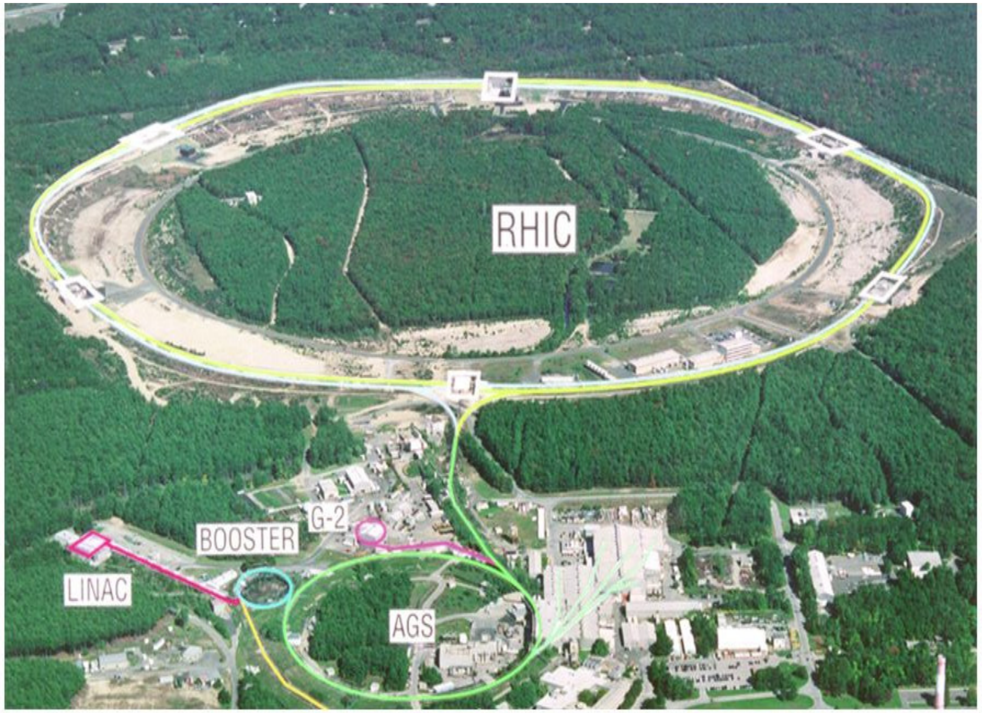


4. **Summary**

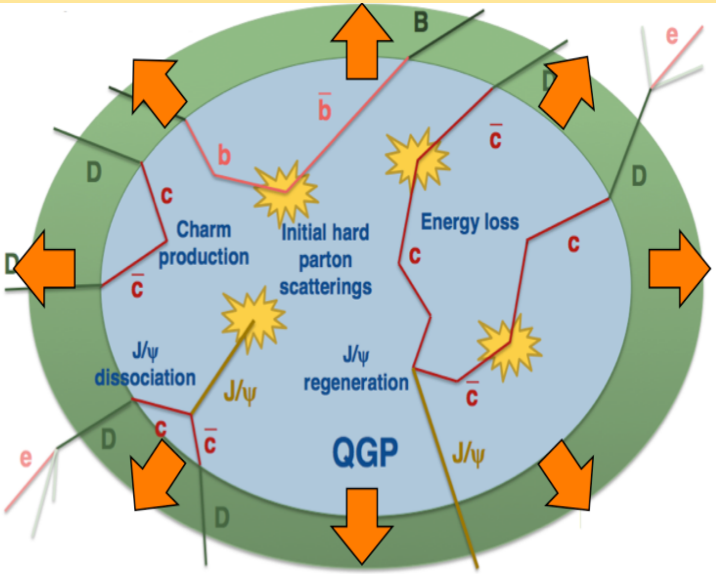
1. introduction







Expansion of Quark-Gluon Plasma



RHIC energy:
~ 100 GeV

nucleus velo.
$v \sim 0.9999c$

$$c + \bar{c} \leftrightarrow J/\psi + g$$

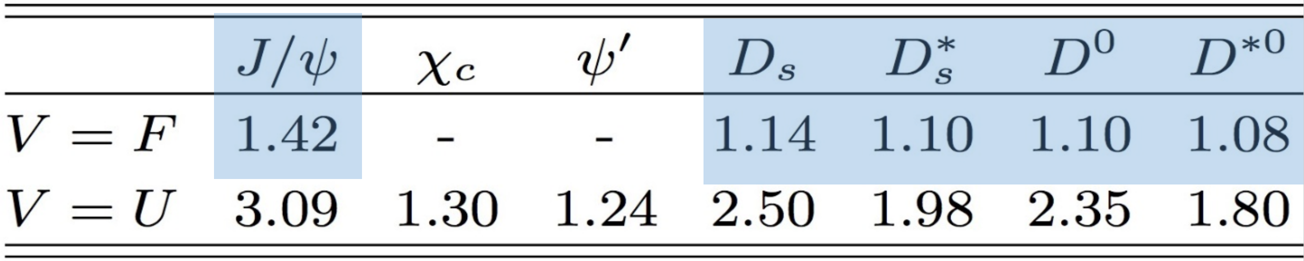
Hot medium effects:
screening + inelastic coll.

1. introduction:Properties of charmed mesons

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

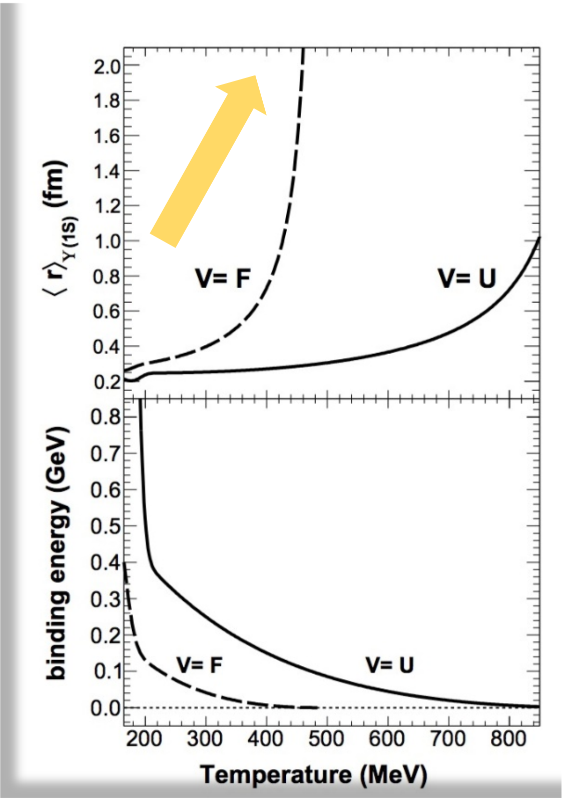
(2) For J/ψ or bottomonium,

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

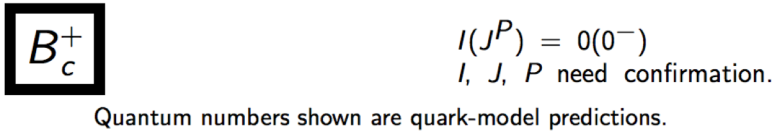
Tsinghua Group, Chin.Phys.C **44 (2020) 8, 084101**



BYC, Zhao,

Phys.Lett.B 772 (2017) 819-824

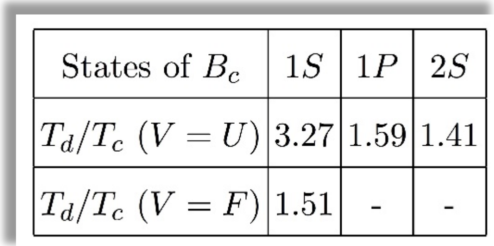
(3) For B_c



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

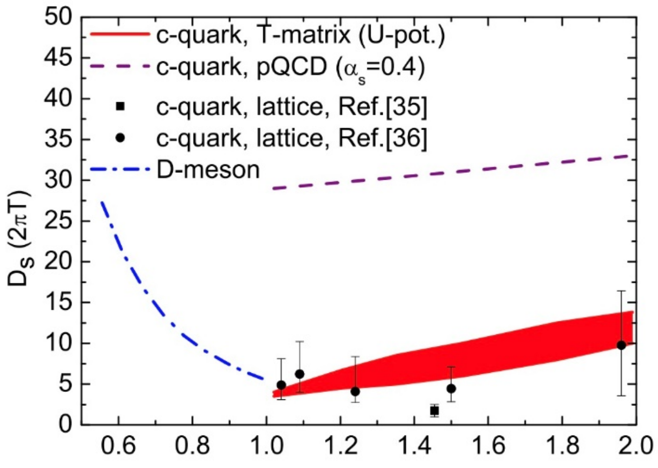
$$\frac{d\vec{p}}{dt} = -\eta\vec{p} + \vec{\xi} + f_g$$

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

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

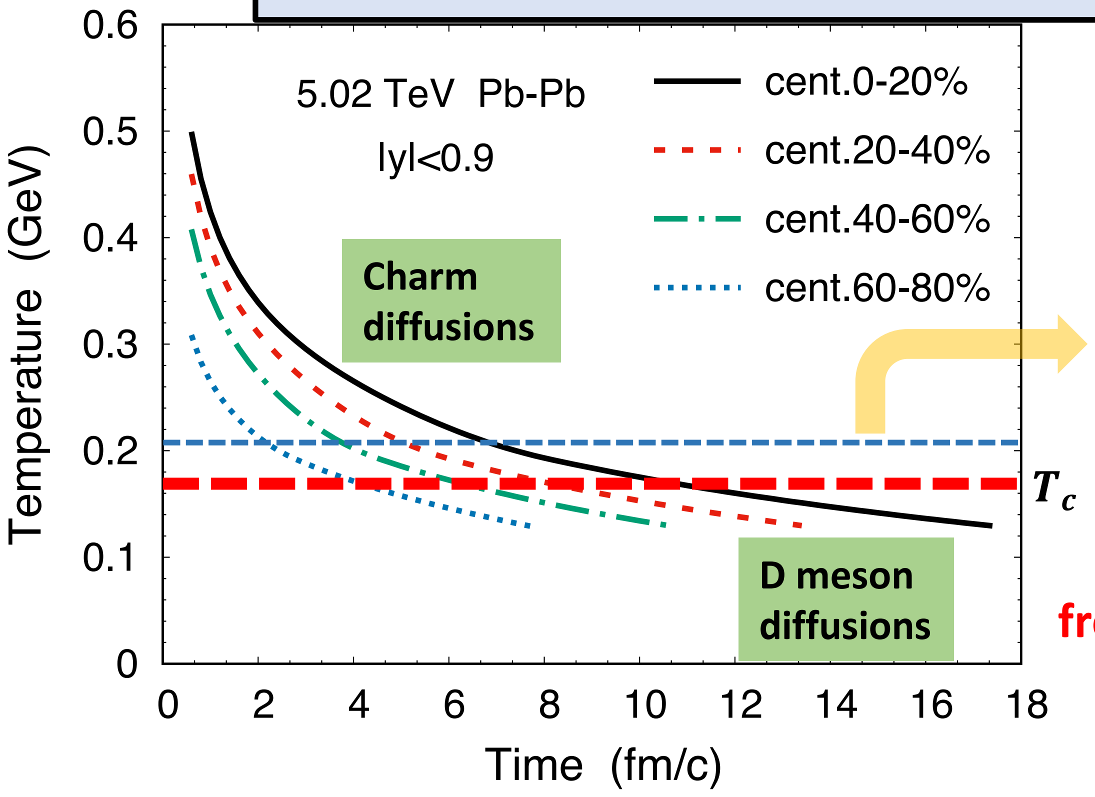
D_s, κ:

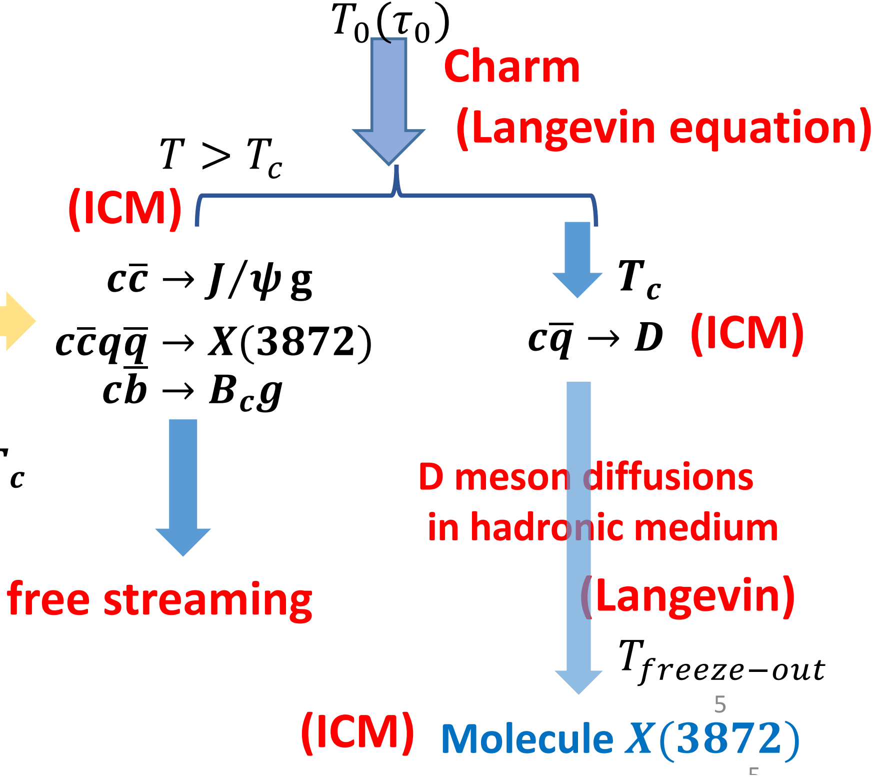
Spatial and Momentum Diffusion coefficients



t al PRL 2012

Langevin + Instantaneous coalescence model (LICM)





$T_0(\tau_0)$

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)**

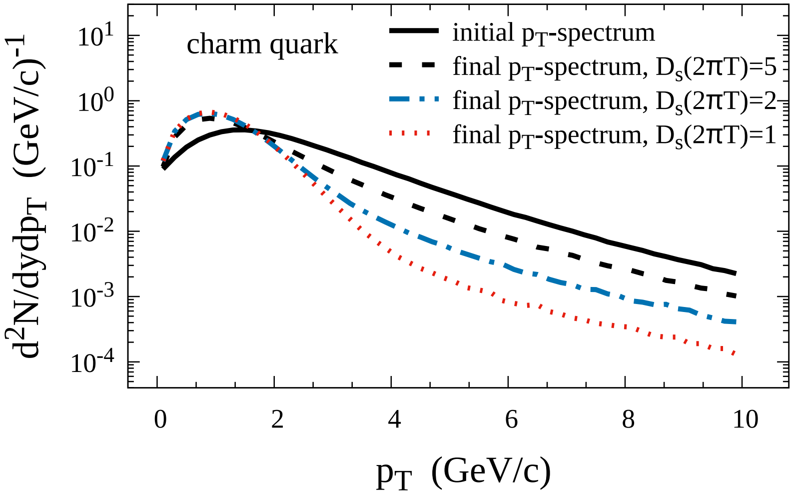
D meson diffusions in hadronic medium (Langevin)

$T_{freeze-out}$

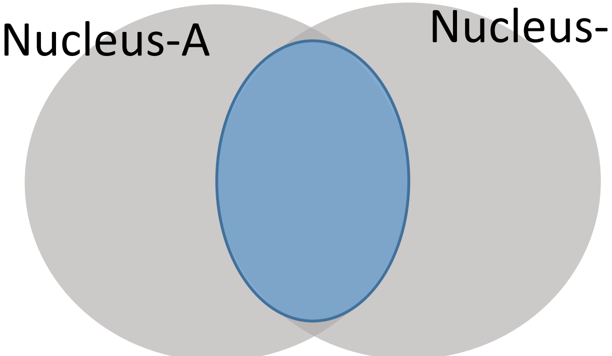
(ICM) **Molecule $X(3872)$**

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

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

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

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

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

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

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

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

Shadowing factor

3. Heavy quark polarization in magnetic field

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

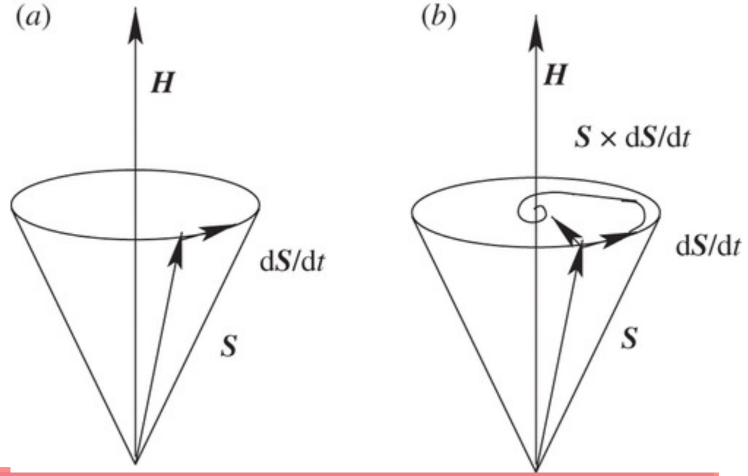
arXiv:1805.01776 (2018)

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

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

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

Electric charge

$\gamma = \frac{g|Q|}{2m_Q}$ **gyromagnetic ratio**

α= 0.1 **Damping factor**

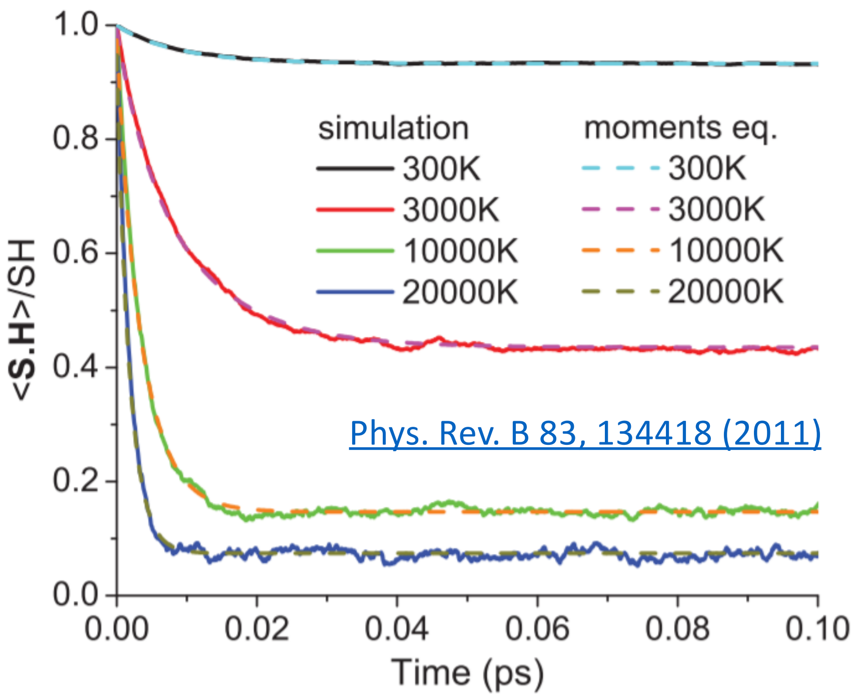
(to be determined later)

noise term

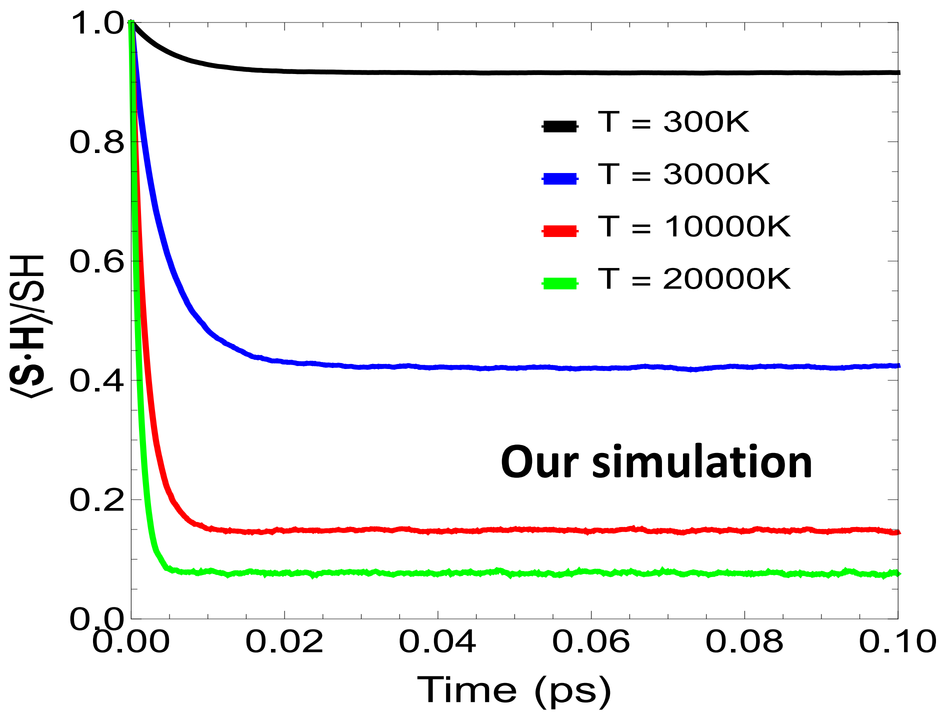
$$<\overrightarrow{H_{th}}(t)> = 0$$

$$<H_{th,i}(t)H_{th,j}(t')> = \frac{4\alpha T}{\gamma^2}\delta_{i,j}\delta(t-t')$$

3. Heavy quark polarization in magnetic field



Phys. Rev. B 83, 134418 (2011)

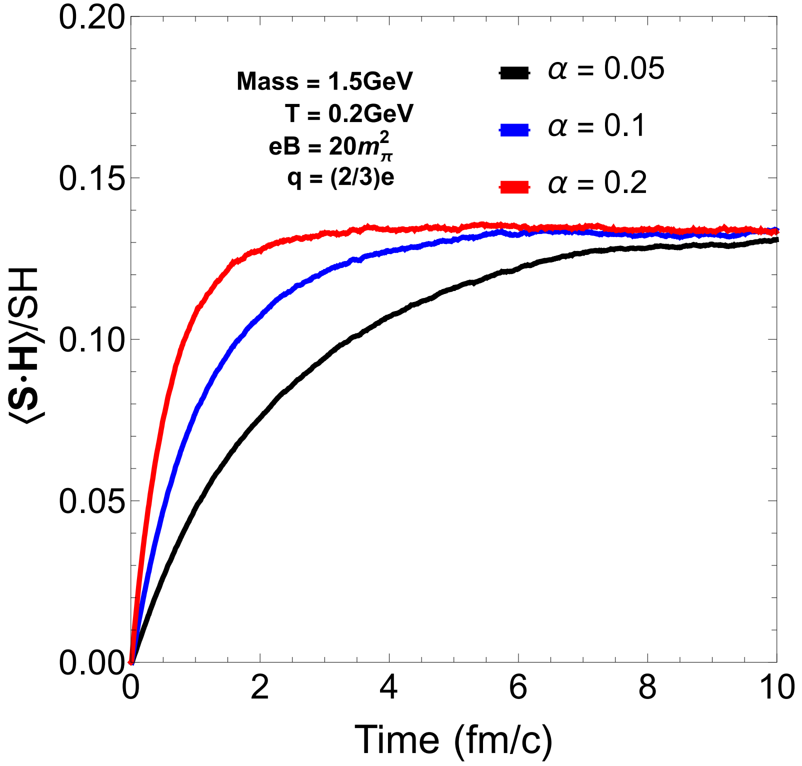


Our simulation

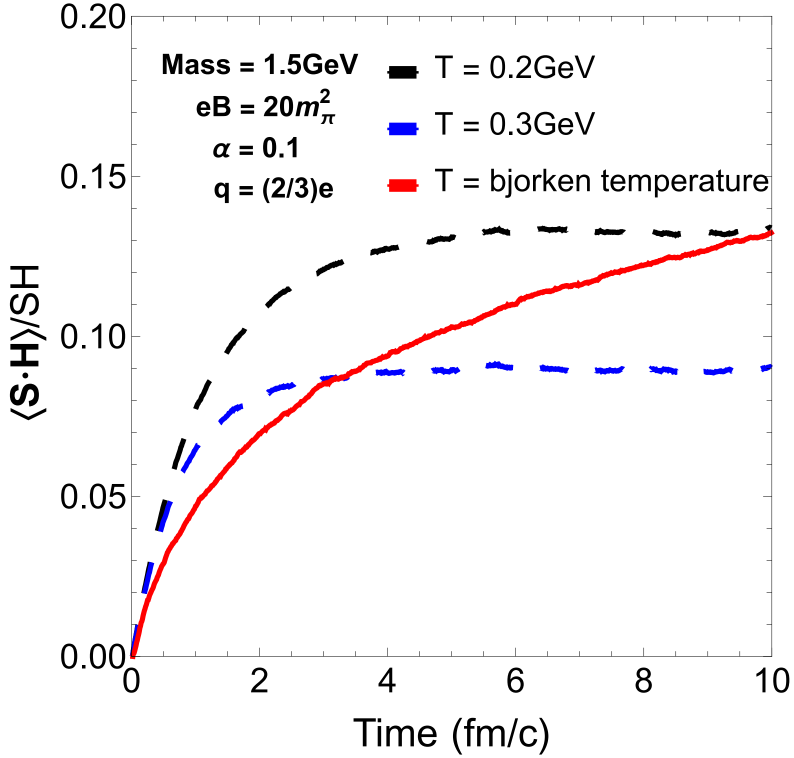
Compare with the reference (PRB 83, 134418, 2011)

3. Heavy quark polarization in magnetic field

Polarization rate:



T dependence:

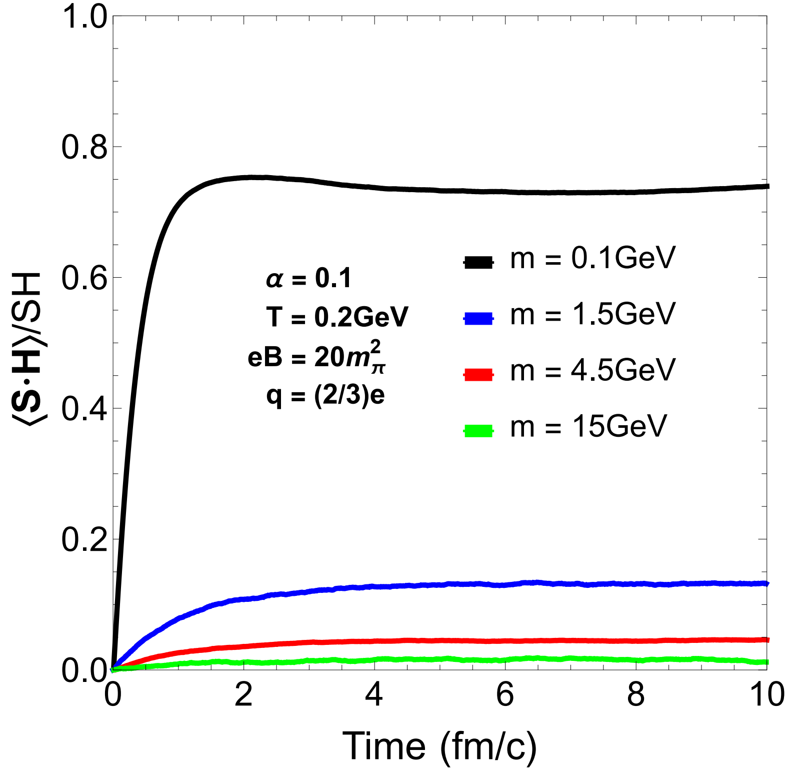


Zhiwei, Anping, Baoyi, in progress

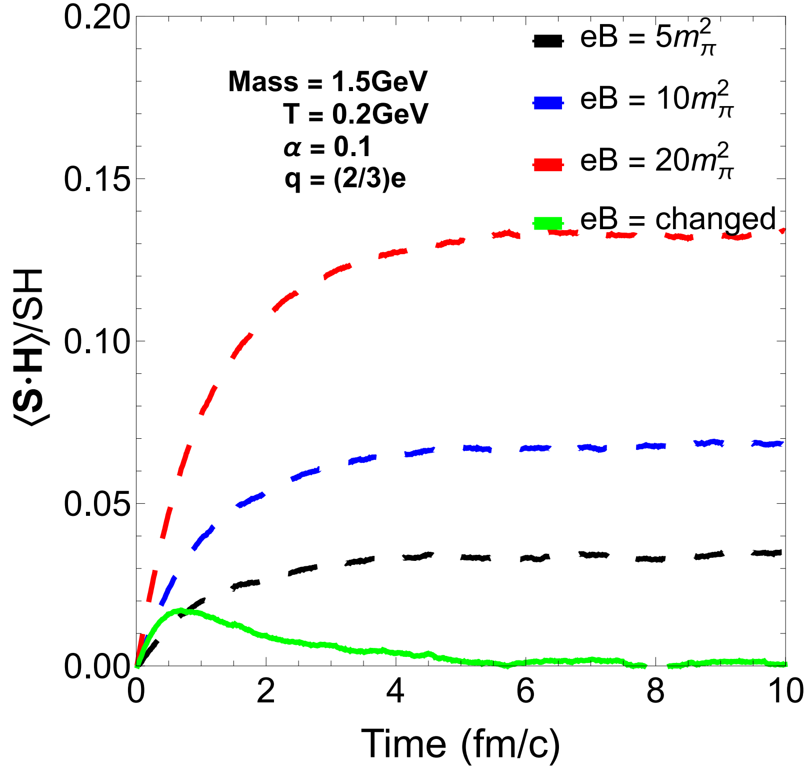
- ➢ Damping factor alpha do not affect the equilibrium value, only affect the rate.
- ➢ Higher temperature → smaller polarization

3. Heavy quark polarization in magnetic field

Mass dependence:



B dependence:



Zhiwei, Anping, Baoyi, in progress

$$eB = \frac{eB_0}{1+(t/t_B)^2}\ \text{,where } t_B = 0.6\ \text{fm/c},\ B_0 = \frac{2\gamma Ze}{\pi b^2}$$

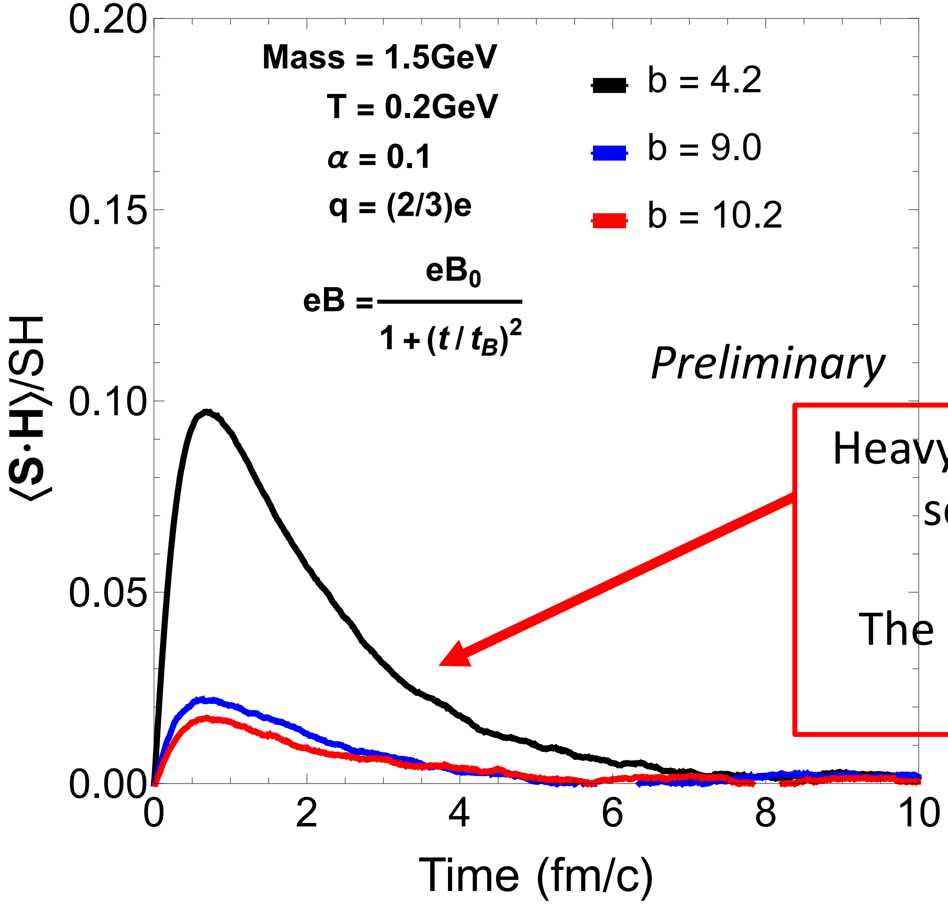
- ➢ Larger Quark mass → smaller polarization
- ➢ Higher B field → larger polarization

PRB Volume 737, 7 October 2014, Pages 262-266

3. Heavy quark polarization in magnetic field

In the changing systems:

$$B_0 = \frac{2\gamma Z e}{\pi b^2}$$



Further improvement:
LLG + Spin-coalescence-model

Heavy quarks may hadronized in this time scale (where LLG equation stops)

The polarization of HQ may be partially preserved in charmed hadron.

Magnetic field induced polarization & thermal particle random collisions

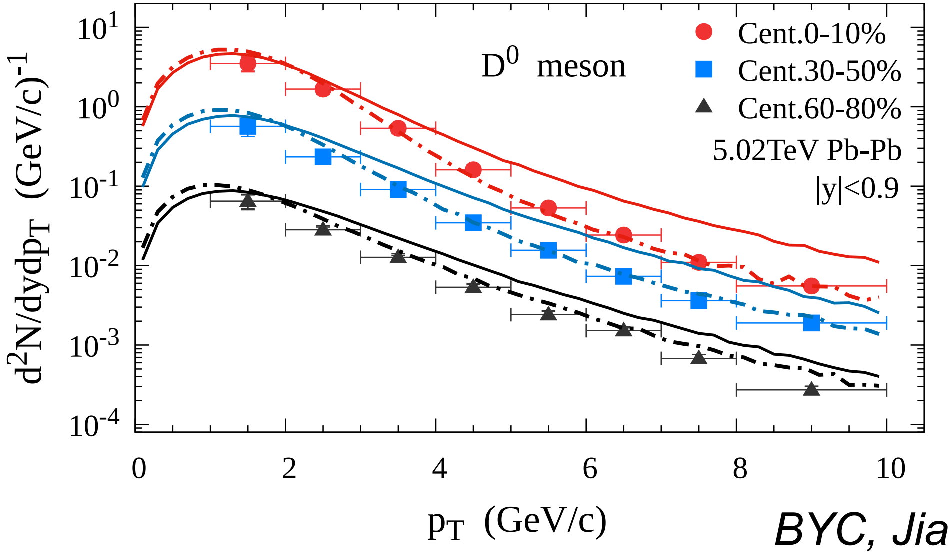
4. charmed hadron production: D meson

- **D meson coalescence**

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

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

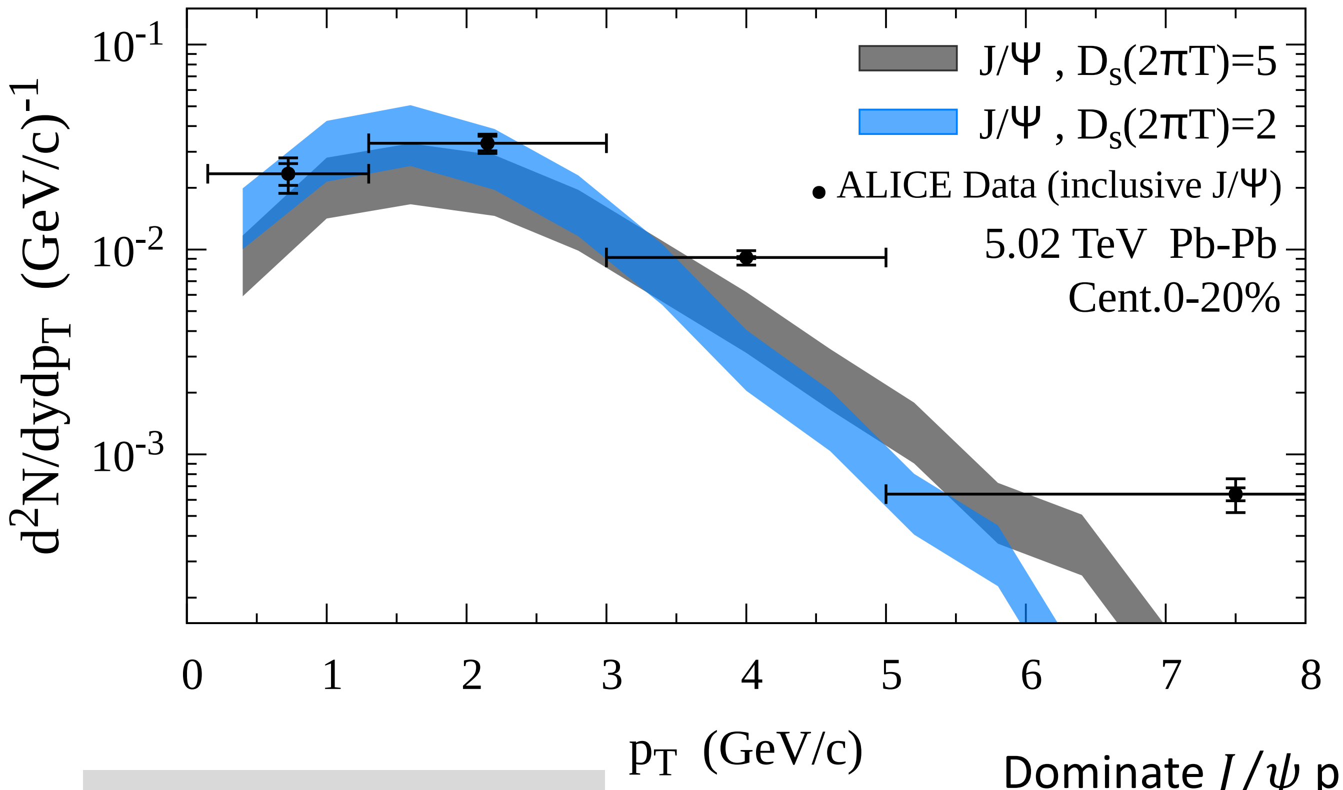
- ➢ $H_{c\to D^0} = 9.5\%$ (20%) : Charm turning into **direct** D^0 (D^{*0}) at Tc
- ➢ $\frac{dN_1}{d\vec{p}_1}$: charm momentum distribution
- ➢ $\frac{dN_2}{d\vec{p}_2}$: light quark momentum distribution: Fermi.



- 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)**

4. 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

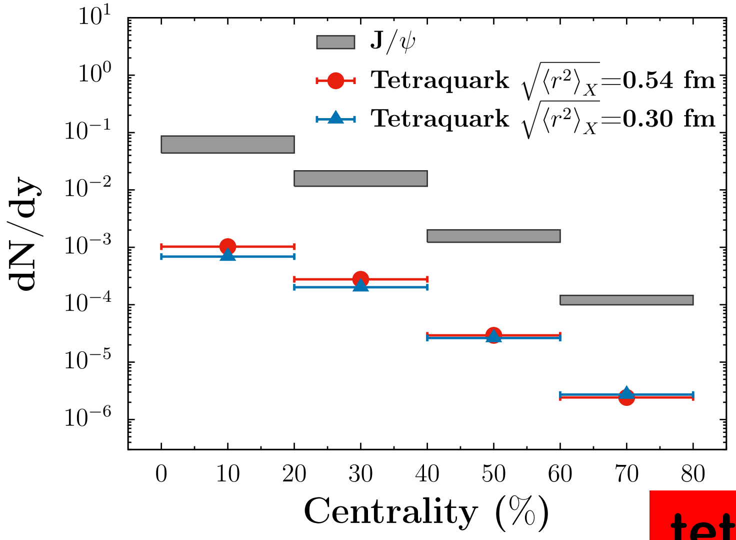
Dominate at low pT and **total yield**

Theoretical calculation:

$c-\bar{c}$ coalescence

4. 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.



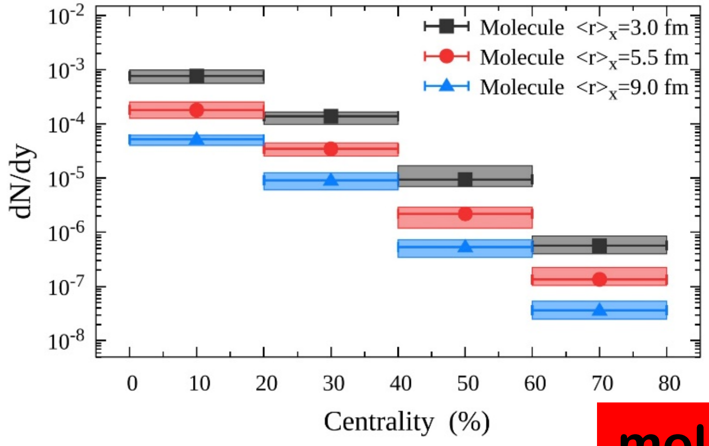
tetraquark

- ➢ 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

4. charmed hadron production: X(3872)

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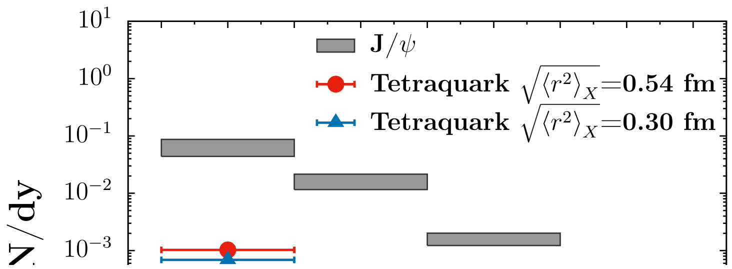

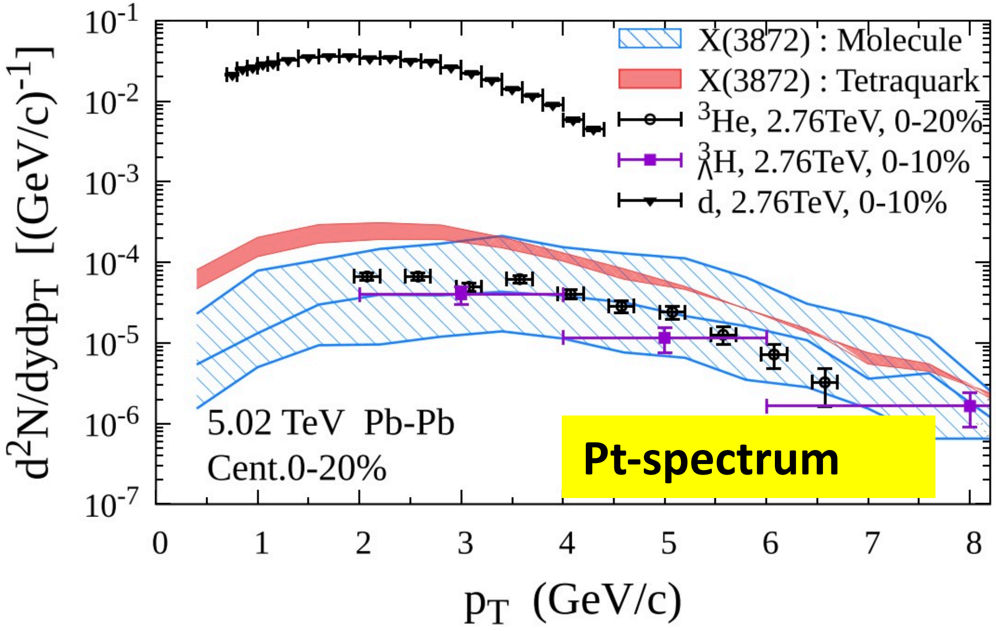

Pt-spectrum

Molecule state with potential model

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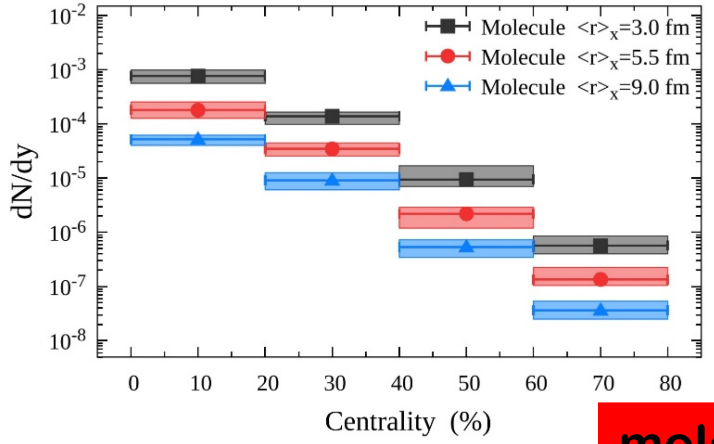

molecule

Bands:

Volume dependence in freeze-out

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Phys. Rev. C 105, 054901 (2022)

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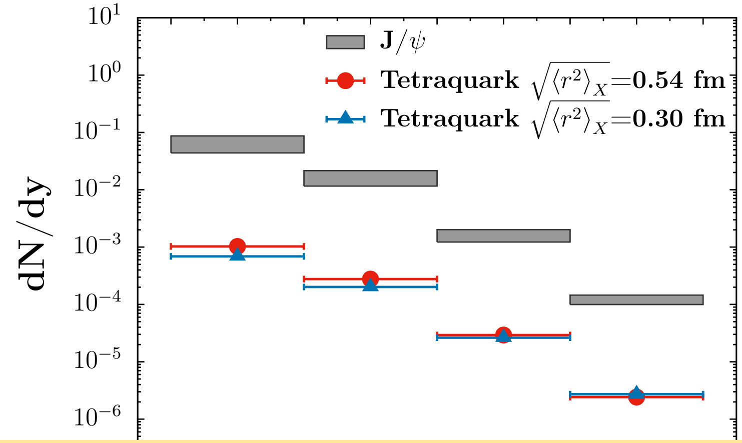

Molecule state with potential model

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$\sqrt{\langle r^2\rangle}$(fm)	3.08	3.59	4.36	5.61	8.00	14.33	28.94

- 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) ;***

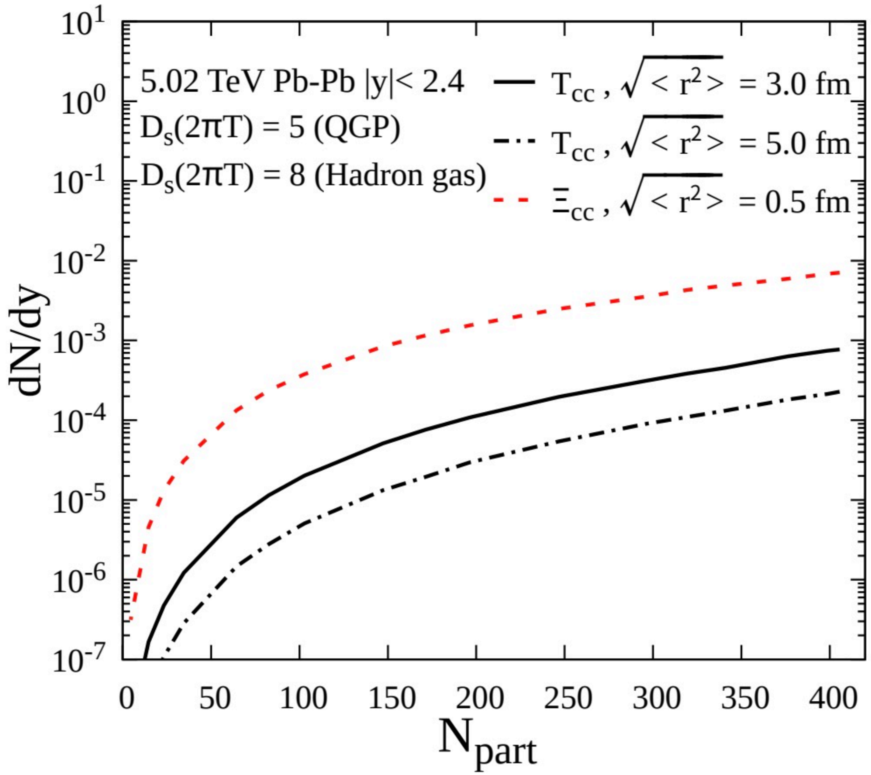
  different from AMPT model: ***Zhang PRL 126, 012301 (2021) ;***

→ maybe due to its different formation conditions. $\left\{ \begin{array}{l} \textbf{5fm < relative distance < 7fm} \\ 2M_D < pair\ mass < 2M_{D^*} \end{array} \right.$

Phys. Rev. C 105, 054901 (2022)

4. Mesonic molecule production: T_{cc}

- ➢ T_{cc} includes T^0_{cc}, T^+_{cc}, T^{++}_{cc} $D^0 - D^{*0}$, $D^{0/+} - D^{*+/0}$, $D^+ - D^{*+}$
- ➢ Wigner function is determined by the $< r^2 >_T$



in preparation…

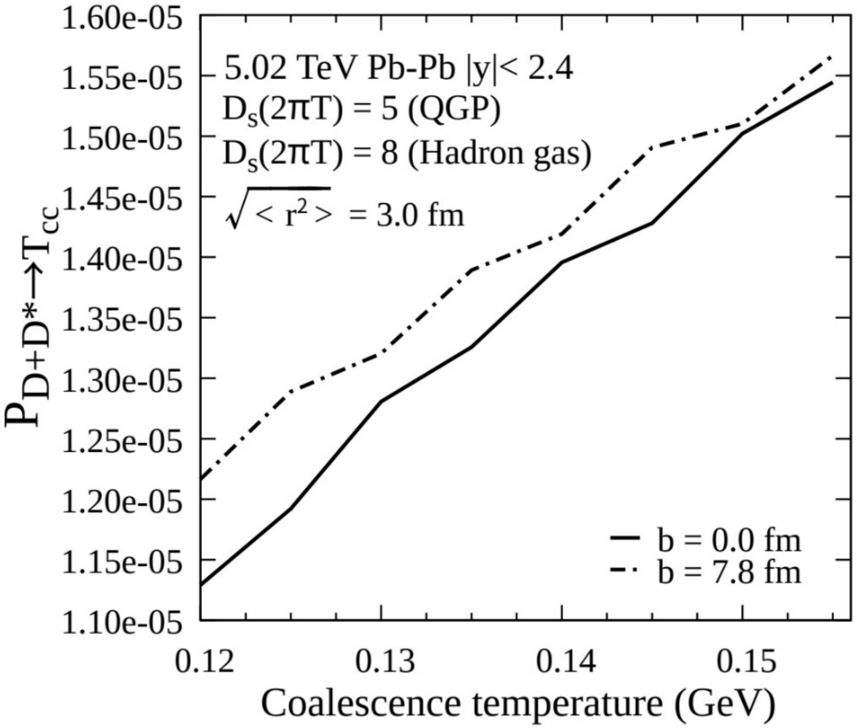
- ● $c \rightarrow (D^0, D^{*0})$
- ● Shadow factor =0.65
- ● Molecules are produced at T=0.12 GeV

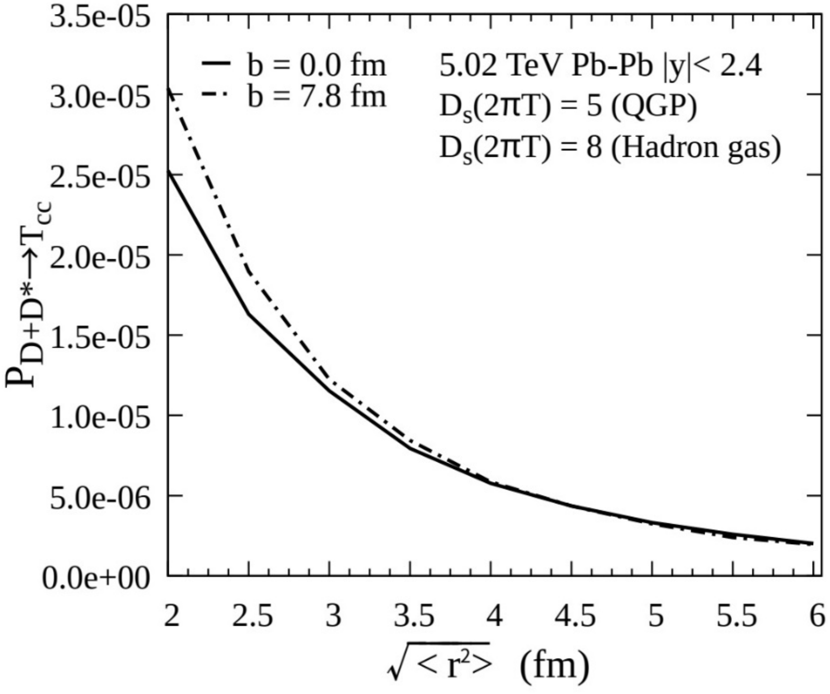
Three states are included in the results.

- ● N_{cc} **large:** $N_{cc}(b = 0) \sim 35$ per rapidity at 5.02 TeV Pb-Pb, $(N_{c\bar{c}})^2$ & $N_{c\bar{c}}(N_{c\bar{c}}$-1)/2
- ● N_{cc} **small:** T_{cc} is more suppressed than X(3872), like at peripheral collisions.

4. Mesonic molecule production: T_{cc}

- ➢ T_{cc}: $D^0 - D^{*0}$, $D^0 - D^{*+}$, $D^+ - D^{*0}$
- ➢ Wigner function is determined by the $< r^2 >_T$





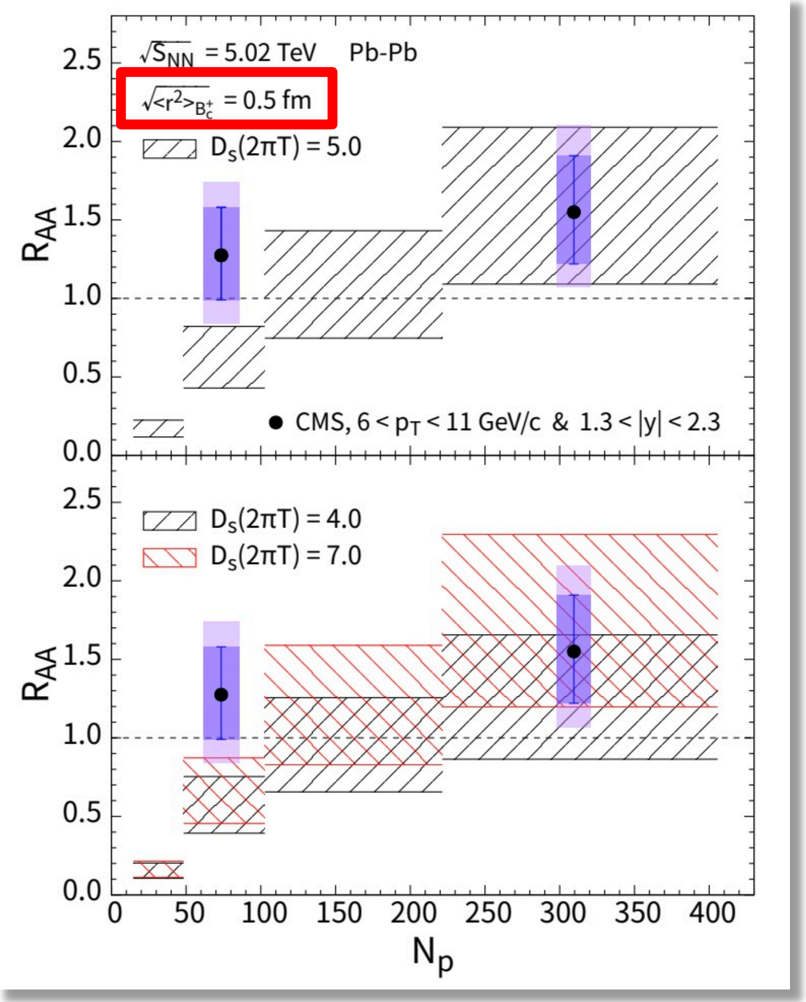
2309.02987

Coalescence probability per one D and D^*

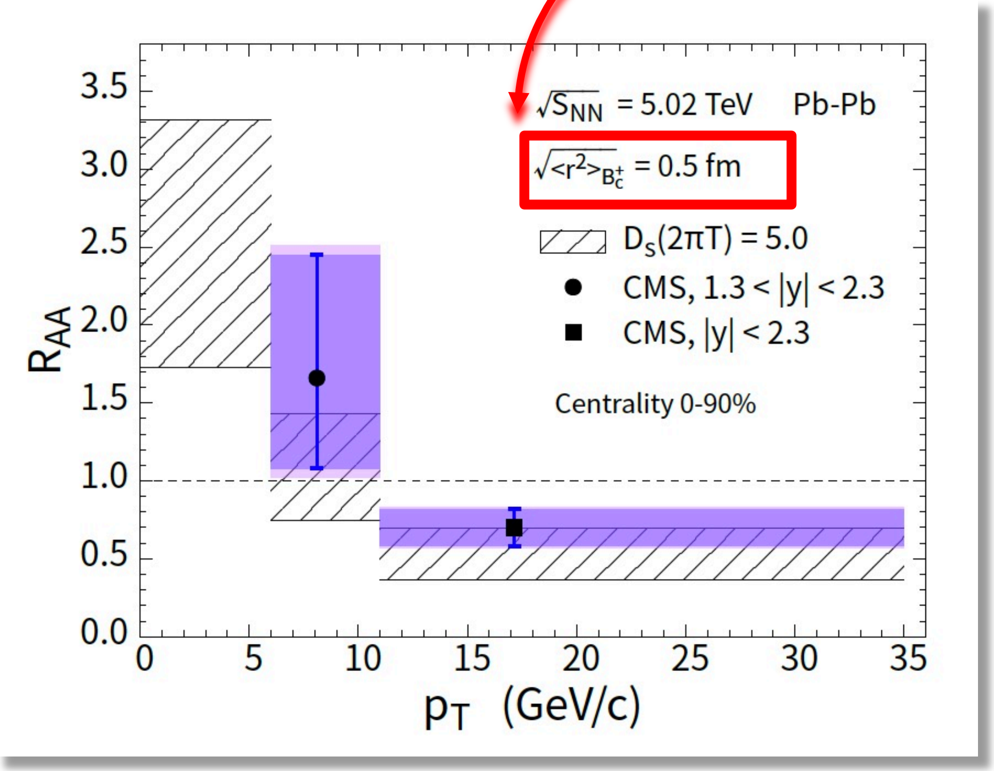
$$f^W(\vec{x}_r, \vec{q}_r) = 8\exp[-\frac{x_r^2}{\sigma^2} - \sigma^2 q_r^2]$$

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

4. charmed hadron production: B_c



Geometry size



BYC, Wen, Liu, arXiv: 2111.08490

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

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

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

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.

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

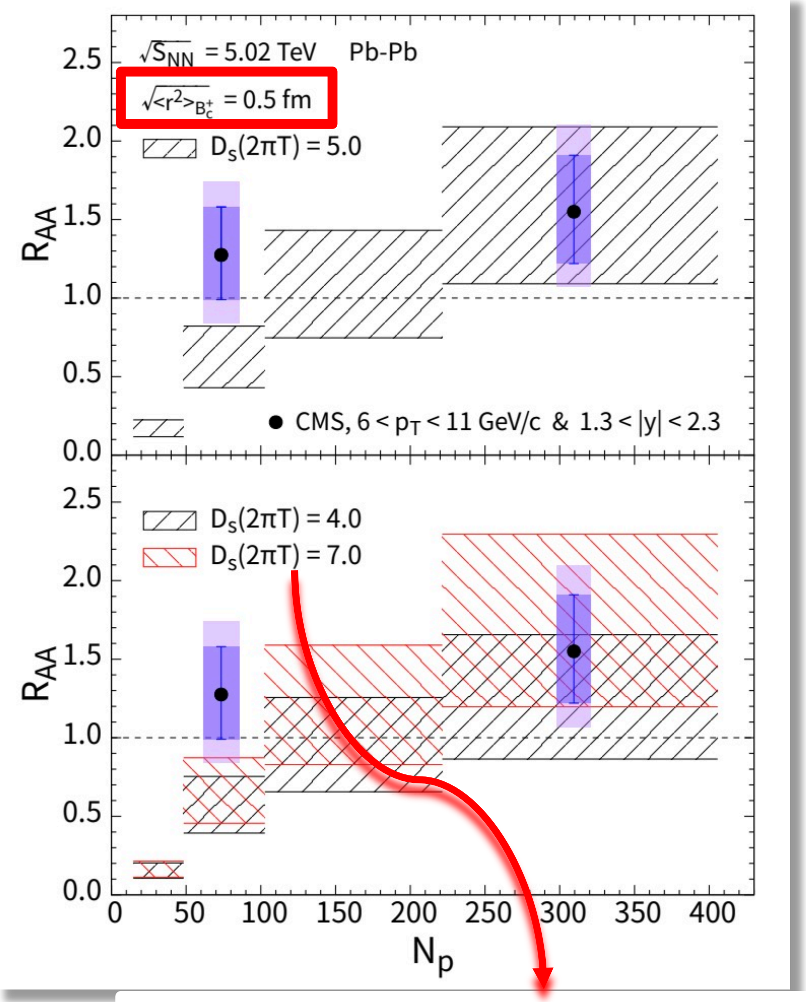
2) RAA>1 at central collisions:

QGP signal

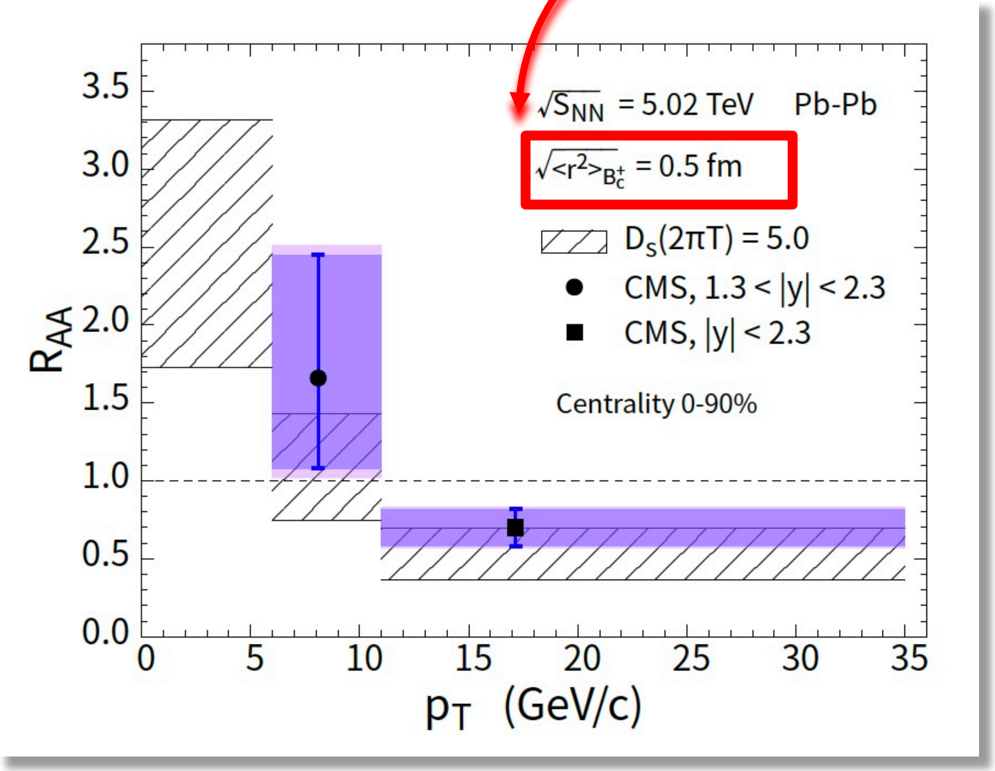
RAA<1 at peripheral collisions:

absence of initial production

4. charmed hadron production: B_c



Geometry size



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

5. Summary

- We study the heavy quark polarization in magnetic field.

- 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), and Tcc

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

5. Summary

- We study the heavy quark polarization in magnetic field.

- 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).

Thank you'very much for your attention!

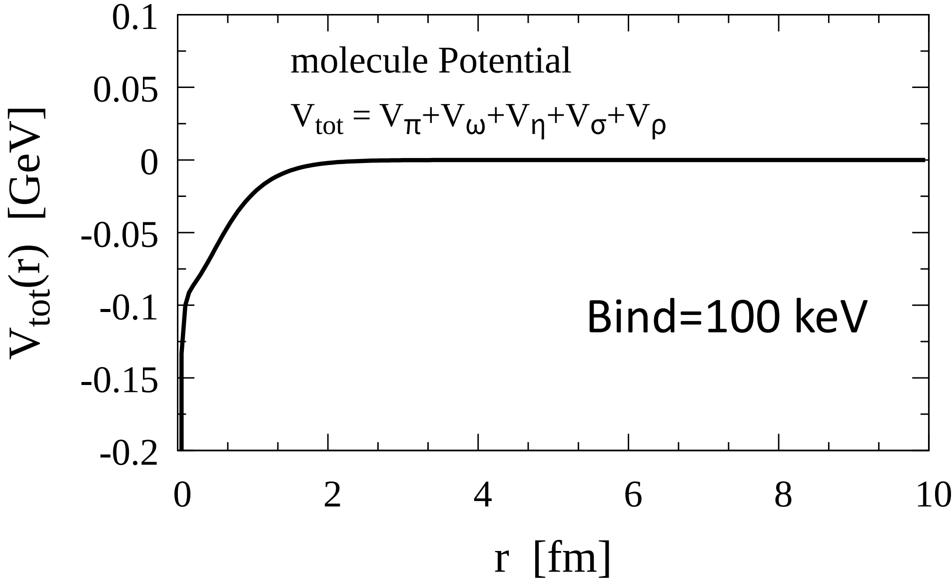
Binding energy of X(3872)

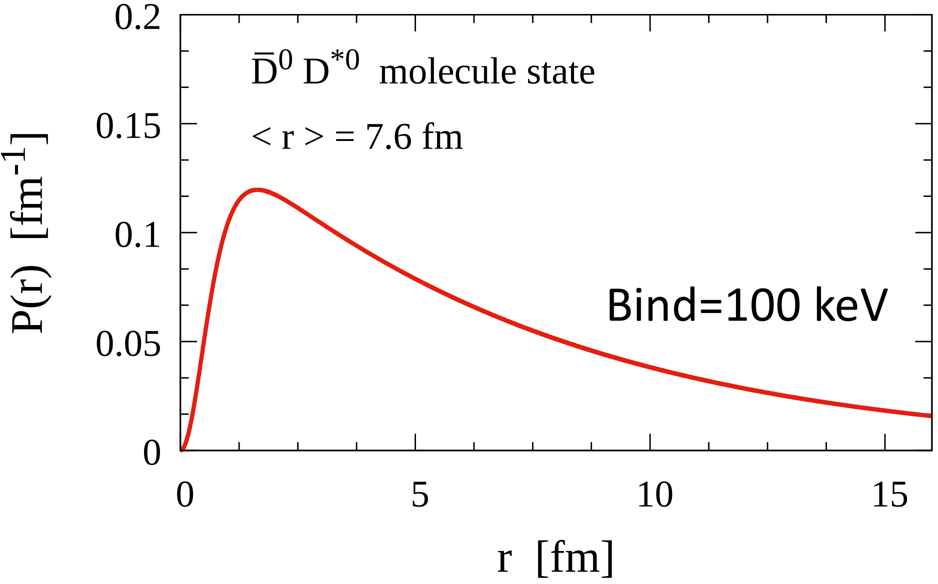
➢ Molecule state based on potential model

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

arXiv: 2107.00969

Λ	0.55	0.555	0.56	0.565	0.57	0.575	0.579
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





1. Properties of charmed mesons

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

3. Heavy quark polarization in magnetic field

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

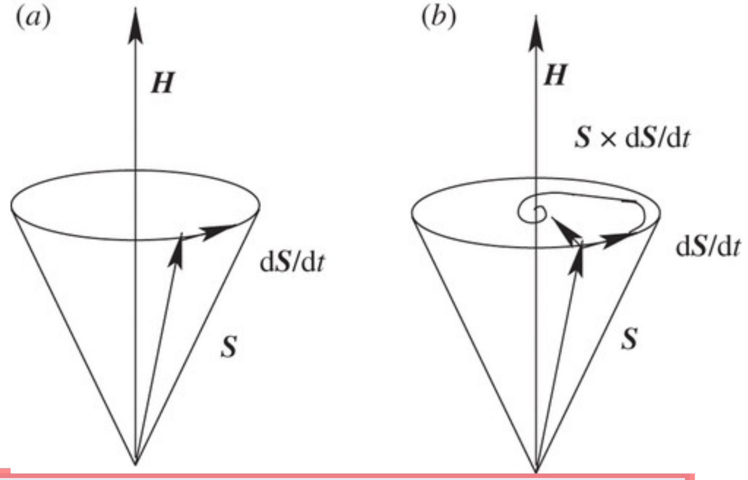
PRB 83, 134418 (2011)

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

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

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

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

α= 0.1 **Damping factor**
(to be determined later)

noise term

$$< \overrightarrow{H_{th}}(t) > = 0$$

$$< H_{th,i}(t) H_{th,j}(t') > = 2\gamma T\, \delta_{i,j}\delta(t-t')$$

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 quark momentum N

(loca k

m_l = uark

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