

Phenomenology of exotic hadron and heavy quark polarization

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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 ($c - \bar{q}$)

J/ψ spectrum ($c - \bar{c}$)

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

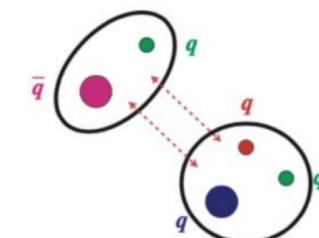
X(3872) as a tetraquark: $c + \bar{c} + q + \bar{q} \rightarrow X(3872)$ in QGP



Tetraquark

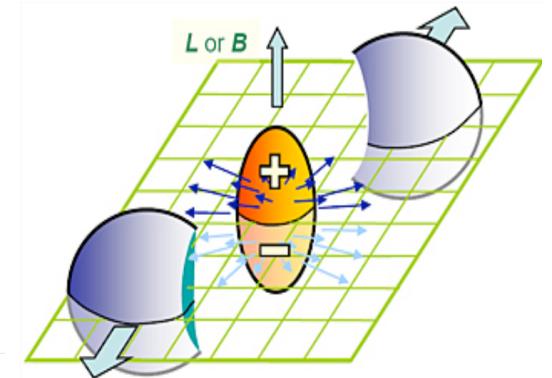
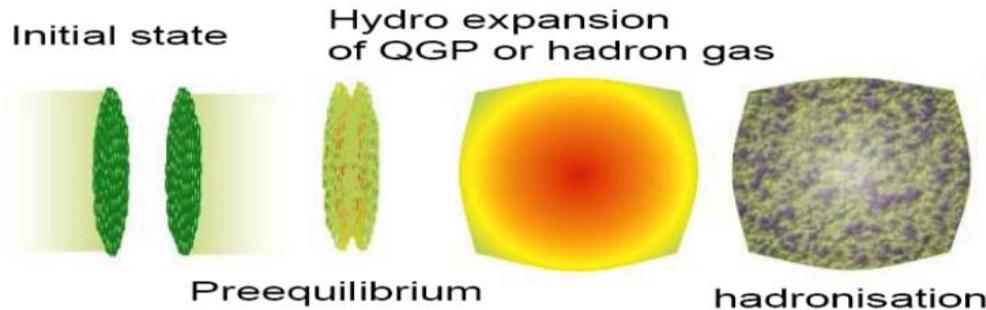
as a meson molecule: $c + \bar{q} \rightarrow D$, $D^0 + \bar{D}^{*0} \rightarrow X(3872)$ in hadronic gas

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



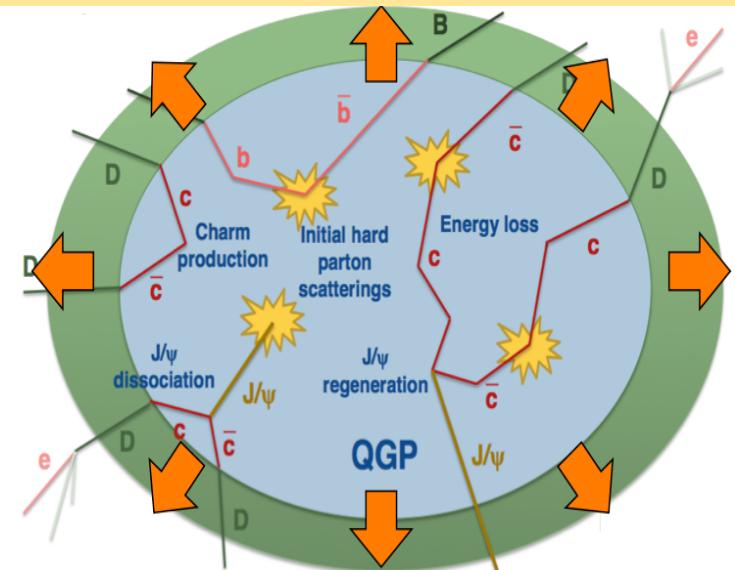
4. Summary

1. introduction



RHIC energy: nucleus velo.
 $\sim 100 \text{ GeV}$ $v \sim 0.9999c$

Expansion of Quark-Gluon Plasma



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

Hot medium effects:
screening + inelastic coll.

1. introduction:Properties of charmed mesons

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

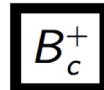
(2) For J/ψ or bottomonium,

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

(3) For B_c



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

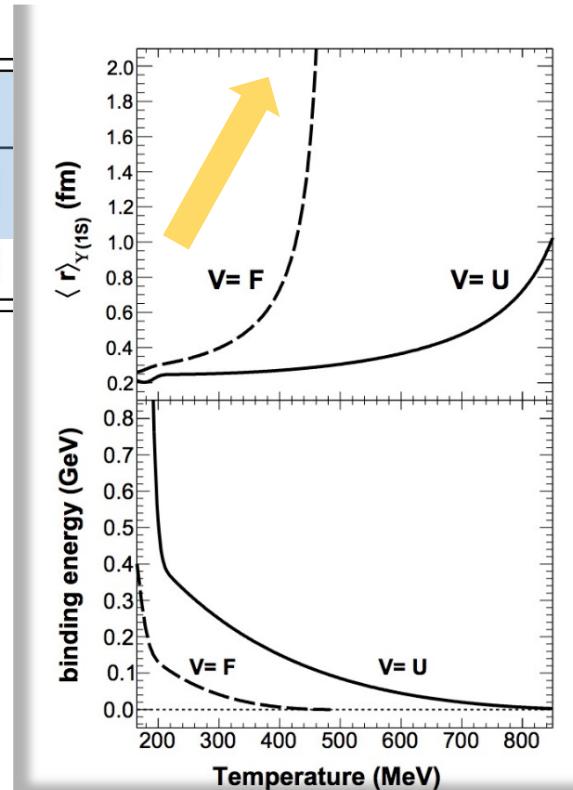
Quantum numbers shown are quark-model predictions.

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, et al, Phys.Rev.C 87 (2013) 1, 014910

(4) For X(3872)

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



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

2. Heavy quark dynamical evolution

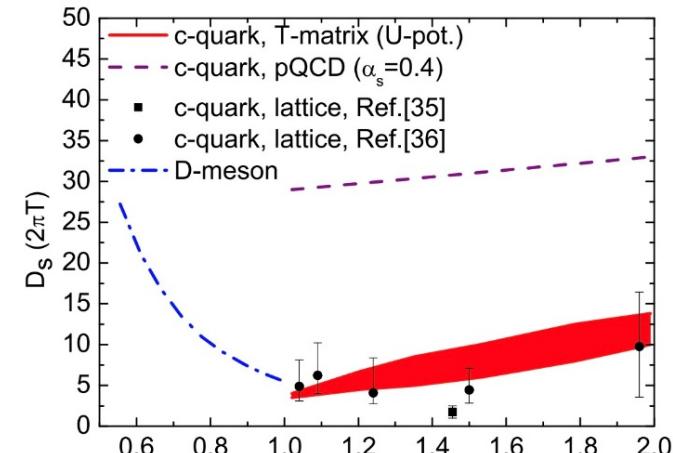
$$\frac{d\vec{p}}{dt} = -\eta \vec{p} + \vec{\xi} + f_g$$

$D_s(2\pi T) = 5$

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

D_s, κ :

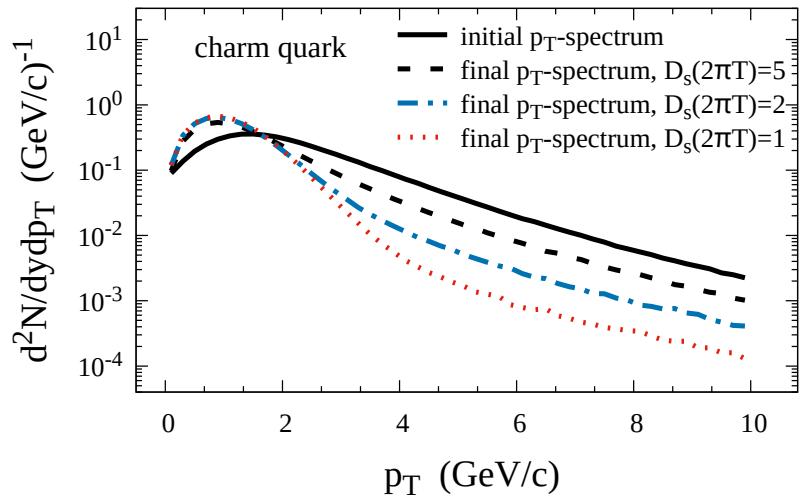
Spatial and Momentum Diffusion coefficients



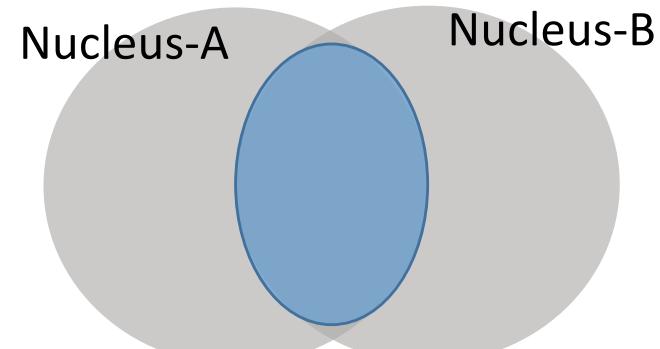
Langevin + Instantaneous coalescence model (LICM) [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56] [57] [58] [59] [60] [61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74] [75] [76] [77] [78] [79] [80] [81] [82] [83] [84] [85] [86] [87] [88] [89] [90] [91] [92] [93] [94] [95] [96] [97] [98] [99] [100] [101] [102] [103] [104] [105] [106] [107] [108] [109] [110] [111] [112] [113] [114] [115] [116] [117] [118] [119] [120] [121] [122] [123] [124] [125] [126] [127] [128] [129] [130] [131] [132] [133] [134] [135] [136] [137] [138] [139] [140] [141] [142] [143] [144] [145] [146] [147] [148] [149] [150] [151] [152] [153] [154] [155] [156] [157] [158] [159] [160] [161] [162] [163] [164] [165] [166] [167] [168] [169] [170] [171] [172] [173] [174] [175] [176] [177] [178] [179] [180] [181] [182] [183] [184] [185] [186] [187] [188] [189] [190] [191] [192] [193] [194] [195] [196] [197] [198] [199] [200] [201] [202] [203] [204] [205] [206] [207] [208] [209] [210] [211] [212] [213] [214] [215] [216] [217] [218] [219] [220] [221] [222] [223] [224] [225] [226] [227] [228] [229] [230] [231] [232] [233] [234] [235] [236] [237] [238] [239] [240] [241] [242] [243] [244] [245] [246] [247] [248] [249] [250] [251] [252] [253] [254] [255] [256] [257] [258] [259] [260] [261] [262] [263] [264] [265] [266] [267] [268] [269] [270] [271] [272] [273] [274] [275] [276] [277] [278] [279] [280] [281] [282] [283] [284] [285] [286] [287] [288] [289] [290] [291] [292] [293] [294] [295] [296] [297] [298] [299] [300] [301] [302] [303] [304] [305] [306] [307] [308] [309] [310] [311] [312] [313] [314] [315] [316] [317] [318] [319] [320] [321] [322] [323] [324] [325] [326] [327] [328] [329] [330] [331] [332] [333] [334] [335] [336] [337] [338] [339] [340] [341] [342] [343] [344] [345] [346] [347] [348] [349] [350] [351] [352] [353] [354] [355] [356] [357] [358] [359] [360] [361] [362] [363] [364] [365] [366] [367] [368] [369] [370] [371] [372] [373] [374] [375] [376] [377] [378] [379] [380] [381] [382] [383] [384] [385] [386] [387] [388] [389] [390] [391] [392] [393] [394] [395] [396] [397] [398] [399] [400] [401] [402] [403] [404] [405] [406] [407] [408] [409] [410] [411] [412] [413] [414] [415] [416] [417] [418] [419] [420] [421] [422] [423] [424] [425] [426] [427] [428] [429] [430] [431] [432] [433] [434] [435] [436] [437] [438] [439] [440] [441] [442] [443] [444] [445] [446] [447] [448] [449] [450] [451] [452] [453] [454] [455] [456] [457] [458] [459] [460] [461] [462] [463] [464] [465] [466] [467] [468] [469] [470] [471] [472] [473] [474] [475] [476] [477] [478] [479] [480] [481] [482] [483] [484] [485] [486] [487] [488] [489] [490] [491] [492] [493] [494] [495] [496] [497] [498] [499] [500] [501] [502] [503] [504] [505] [506] [507] [508] [509] [510] [511] [512] [513] [514] [515] [516] [517] [518] [519] [520] [521] [522] [523] [524] [525] [526] [527] [528] [529] [530] [531] [532] [533] [534] [535] [536] [537] [538] [539] [540] [541] [542] [543] [544] [545] [546] [547] [548] [549] [550] [551] [552] [553] [554] [555] [556] [557] [558] [559] [560] [561] [562] [563] [564] [565] [566] [567] [568] [569] [570] [571] [572] [573] [574] [575] [576] [577] [578] [579] [580] [581] [582] [583] [584] [585] [586] [587] [588] [589] [590] [591] [592] [593] [594] [595] [596] [597] [598] [599] [600] [601] [602] [603] [604] [605] [606] [607] [608] [609] [610] [611] [612] [613] [614] [615] [616] [617] [618] [619] [620] [621] [622] [623] [624] [625] [626] [627] [628] [629] [630] [631] [632] [633] [634] [635] [636] [637] [638] [639] [640] [641] [642] [643] [644] [645] [646] [647] [648] [649] [650] [651] [652] [653] [654] [655] [656] [657] [658] [659] [660] [661] [662] [663] [664] [665] [666] [667] [668] [669] [670] [671] [672] [673] [674] [675] [676] [677] [678] [679] [680] [681] [682] [683] [684] [685] [686] [687] [688] [689] [690] [691] [692] [693] [694] [695] [696] [697] [698] [699] [700] [701] [702] [703] [704] [705] [706] [707] [708] [709] [710] [711] [712] [713] [714] [715] [716] [717] [718] [719] [720] [721]</span

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

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

- $g_M = 1/12$ 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

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

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

$$\sigma^2 = \frac{4}{3} \frac{(m_1 + m_2)^2}{m_1^2 + m_2^2} \langle r^2 \rangle_M$$
$$\sqrt{\langle r^2 \rangle_{J/\psi}} = 0.54 \text{ fm}$$

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

$$\frac{d^2N_\psi}{dy_M d\vec{p}_T} = \int d\vec{x}_M \frac{dp_z}{2\pi} \langle P_{c+\bar{c} \rightarrow \psi}(\vec{x}_M, \vec{p}_M) \rangle_{events} \times \frac{(\Delta N_{c\bar{c}}^{AA})^2}{\Delta y_M}$$

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

Shadowing factor

3. Heavy quark polarization in magnetic field

- Landau-Lifshitz-Gilbert (LLG) equation

[arXiv:1805.01776 \(2018\)](https://arxiv.org/abs/1805.01776)

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

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

Unit vector

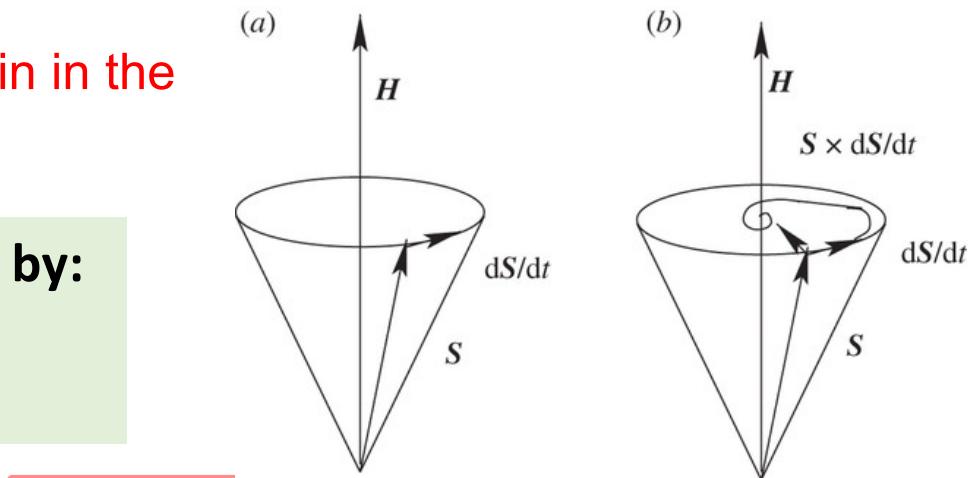
stochastic dynamics of a spin in the medium with magnetic field

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

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

Electric charge
gyromagnetic ratio

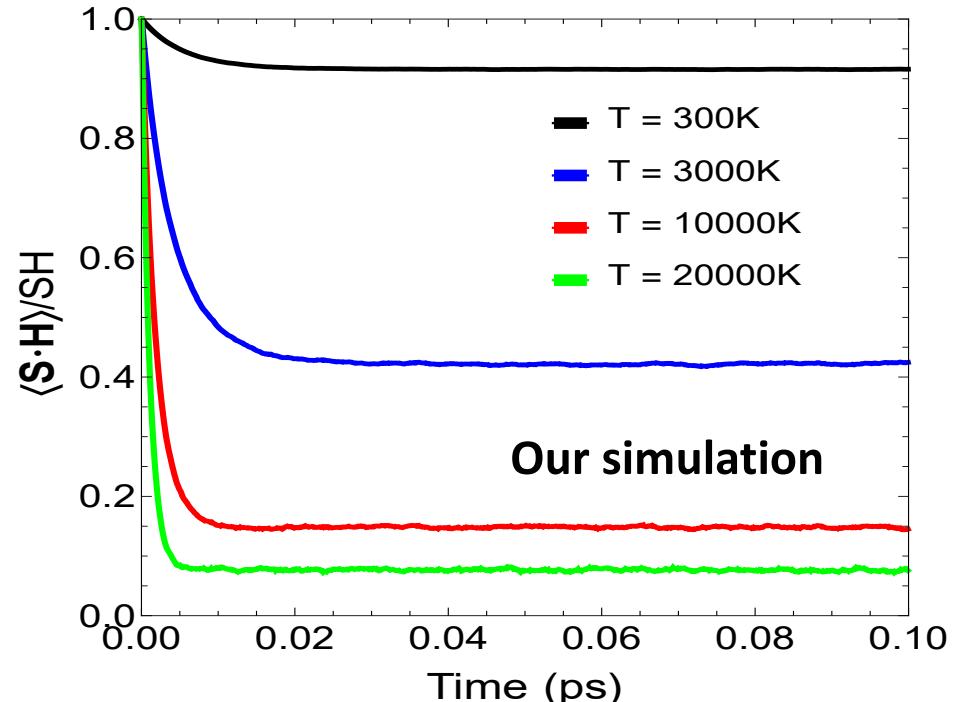
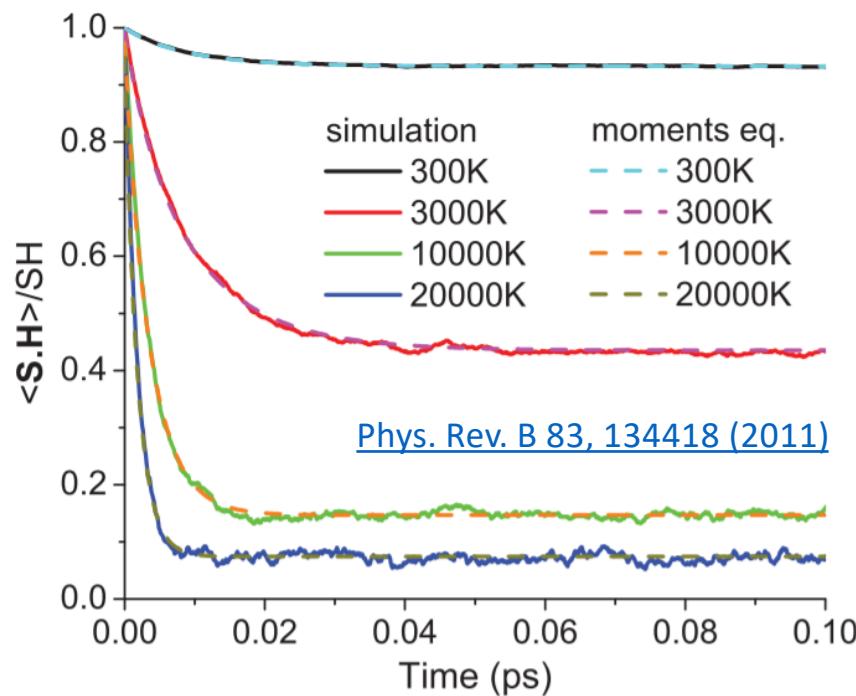
Damping factor
(to be determined later)



noise term

$$\begin{aligned}\langle \overrightarrow{H_{th}}(t) \rangle &= 0 \\ \langle H_{th,i}(t) H_{th,j}(t') \rangle &= \frac{4\alpha T}{\gamma^2} \delta_{i,j} \delta(t - t')\end{aligned}$$

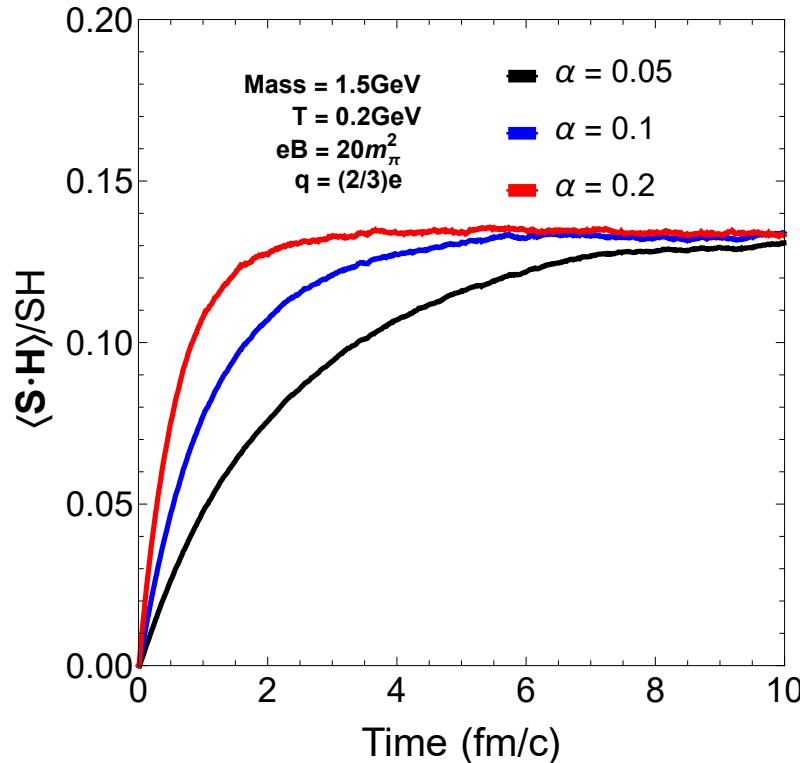
3. Heavy quark polarization in magnetic field



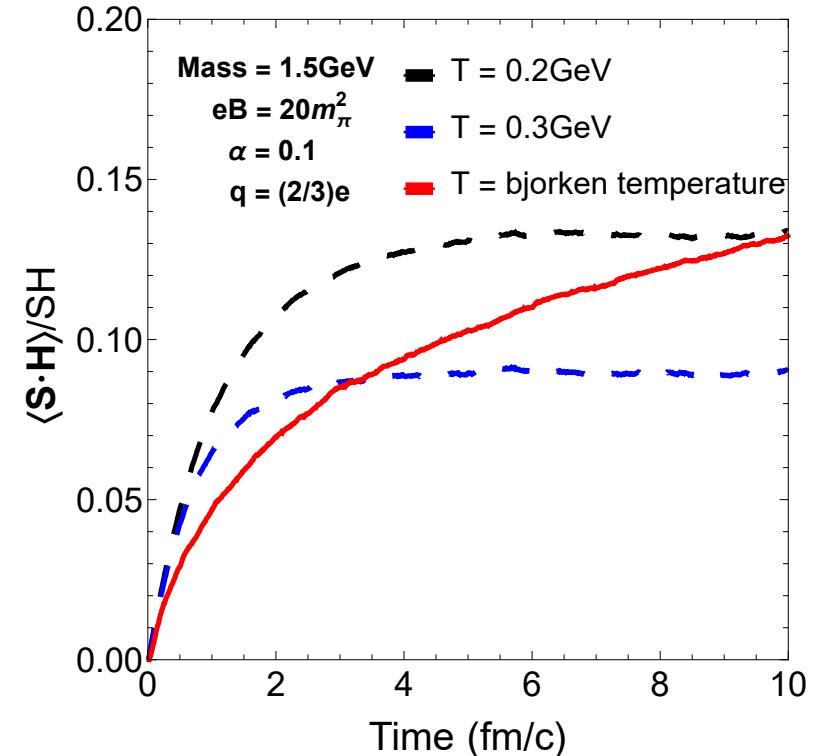
Compare with the reference (PRB 83, 134418, 2011)

3. Heavy quark polarization in magnetic field

Polarization rate:



T dependence:

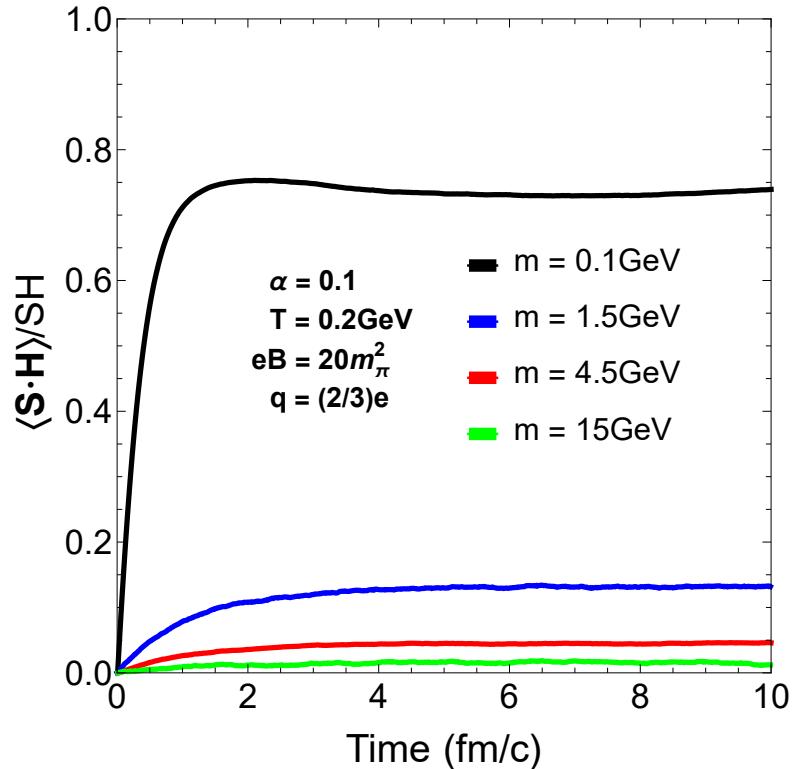


Zhiwei, Anping, Baoyi, in progress

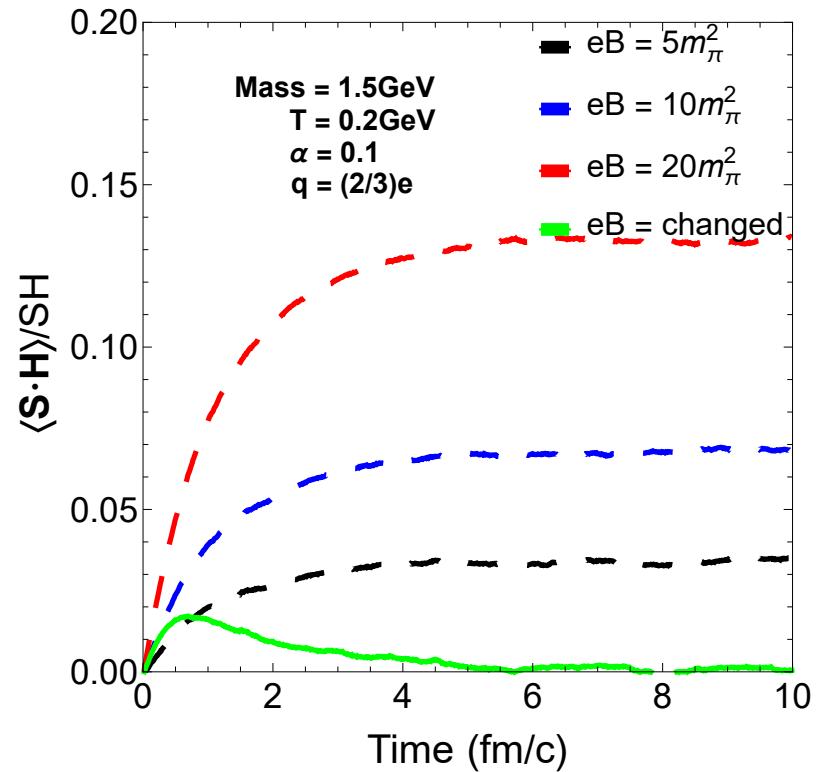
- Damping factor alpha do not affect the equilibrium value, only affect the rate.
- Higher temperature → smaller polarization

3. Heavy quark polarization in magnetic field

Mass dependence:



B dependence:



Zhiwei, Anping, Baoyi, in progress

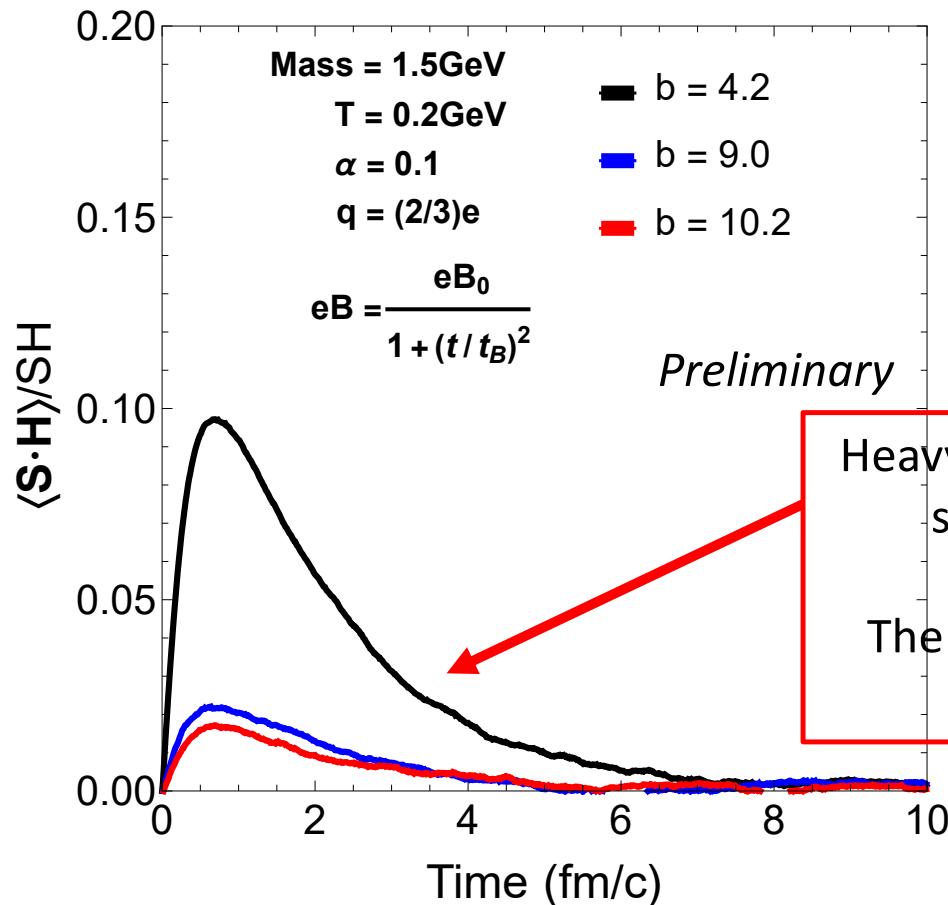
$$eB = \frac{eB_0}{1 + (t/t_B)^2}, \text{ where } t_B = 0.6 \text{ fm/c}, B_0 = \frac{2\gamma Ze}{\pi b^2}$$

- 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:



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

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

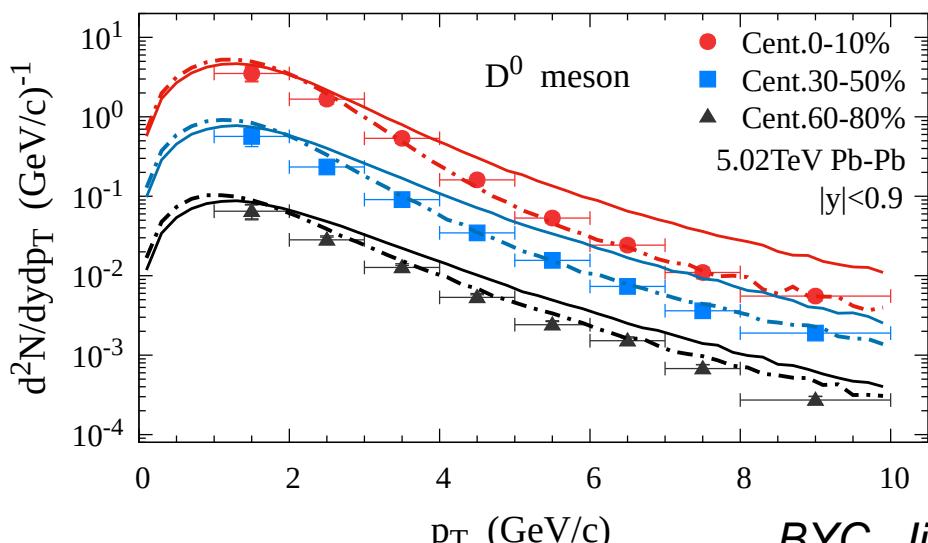
4. charmed hadron production: D meson

- **D meson coalescence**

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

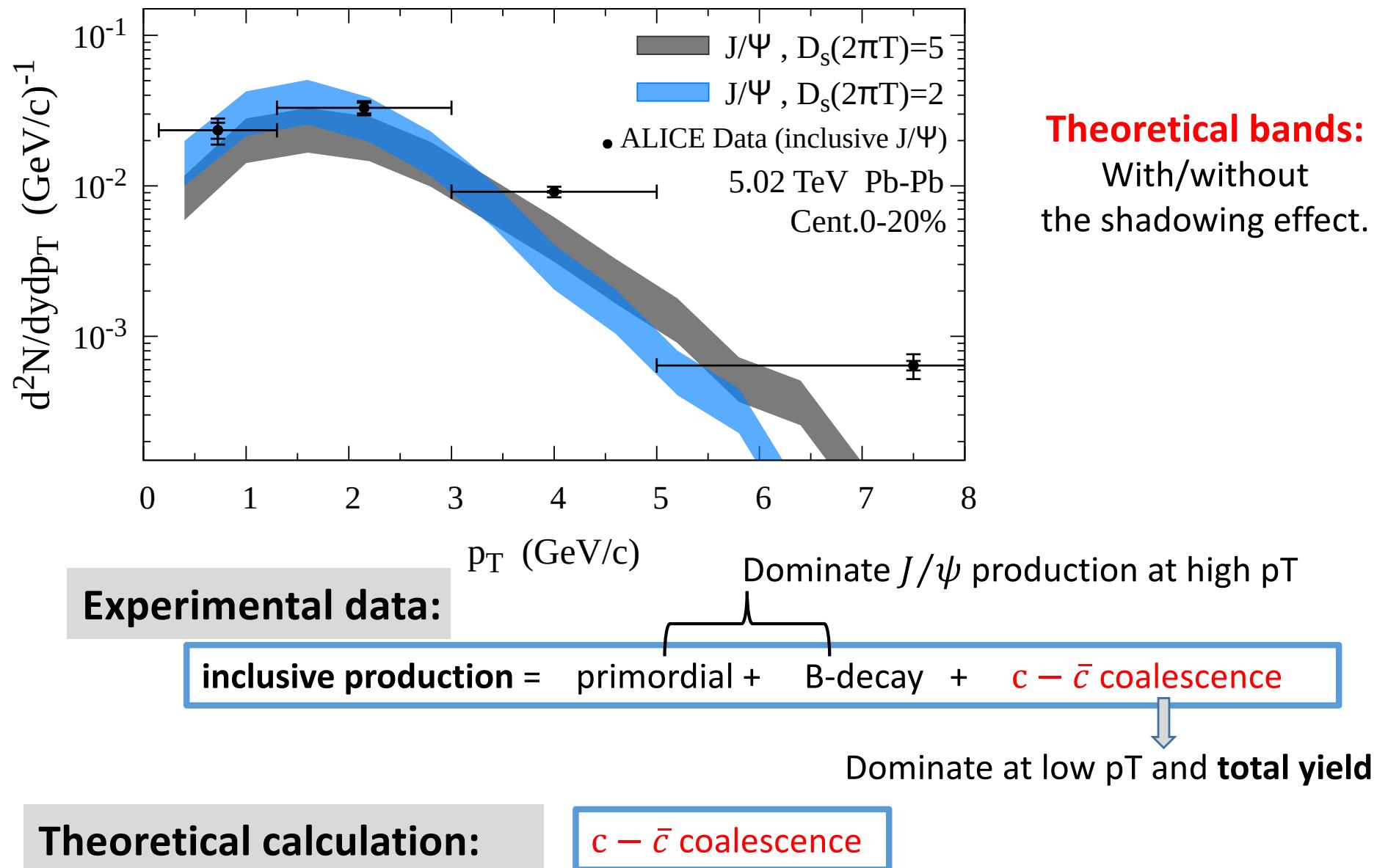
$$\frac{d^2 N_D}{dy_M d\vec{p}_T} = \int \frac{dp_z}{2\pi} < P_{c\bar{q} \rightarrow D^0}(\vec{p}_M) >_{events} \times \frac{\Delta N_{c\bar{c}}^{AA}}{\Delta y_M}$$

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



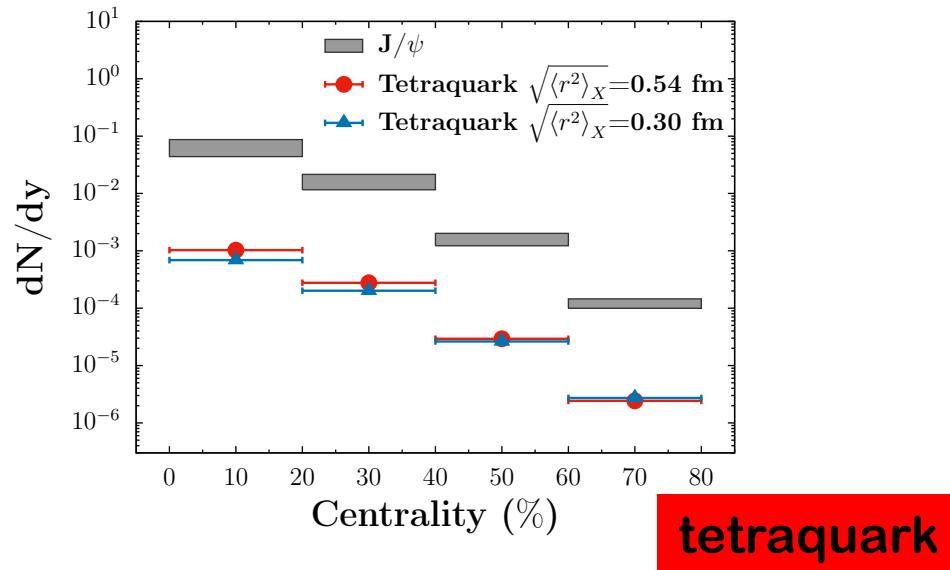
- We take the ratio of prompt D^0 over charm:
 $N(D^0)/N_{c\bar{c}} = 39\%$
ALICE pp, arXiv:2105.06335
- Different thermalization: $D_s(2\pi T) = 5$ (solid line) and $D_s(2\pi T) = 2$ (dotted-dashed line)

4. charmed hadron production: J/ψ



4. charmed hadron production: X(3872)

- $g_{X(3872)} = 1/432$ with X(3872) spin J=1
- Root-mean-square radius of tetraquark: $\langle r^2 \rangle_X = 0.30 - 0.54 \text{ fm}^2$
- diquark ($c\bar{q}$) is formed firstly, then two diquarks form a tetraquark state.

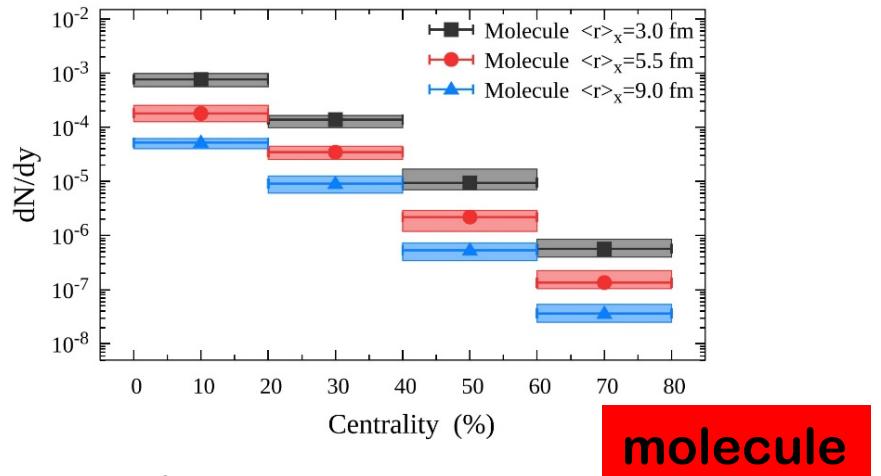


- Tetraquark yield is around **40 times** smaller than J/ψ
- Tetraquark yield is controlled by both **spatial** and **momentum** part of the Wigner function

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
$\langle r \rangle (\text{fm})$	2.47	2.85	3.41	4.31	6.01	10.52	22.60
$\sqrt{\langle r^2 \rangle} (\text{fm})$	3.08	3.59	4.36	5.61	8.00	14.33	28.94

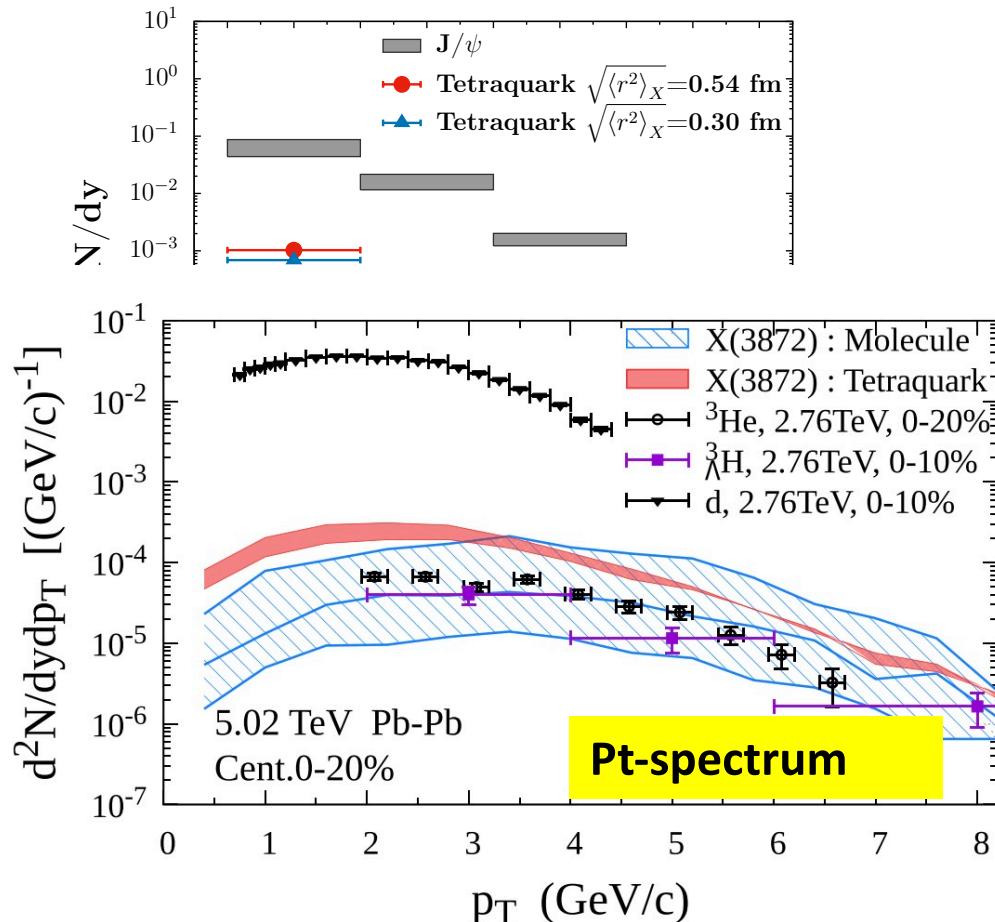


Bands:

Volume dependence in freeze-out

4. charmed hadron production: X(3872)

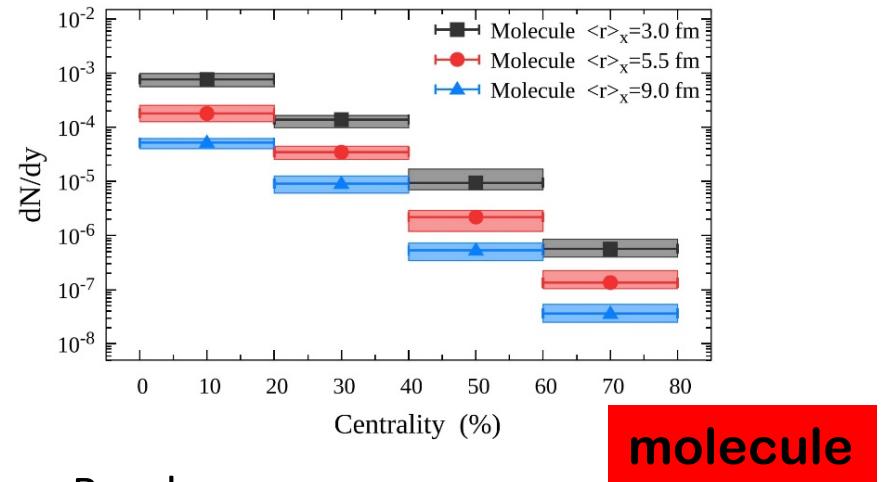
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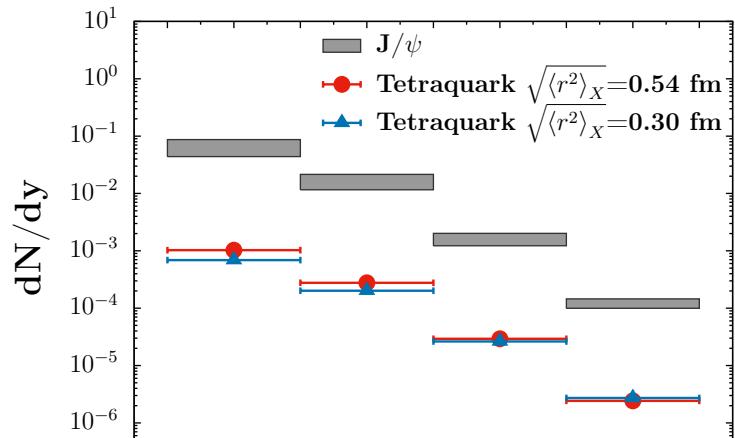


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Molecule state with potential model

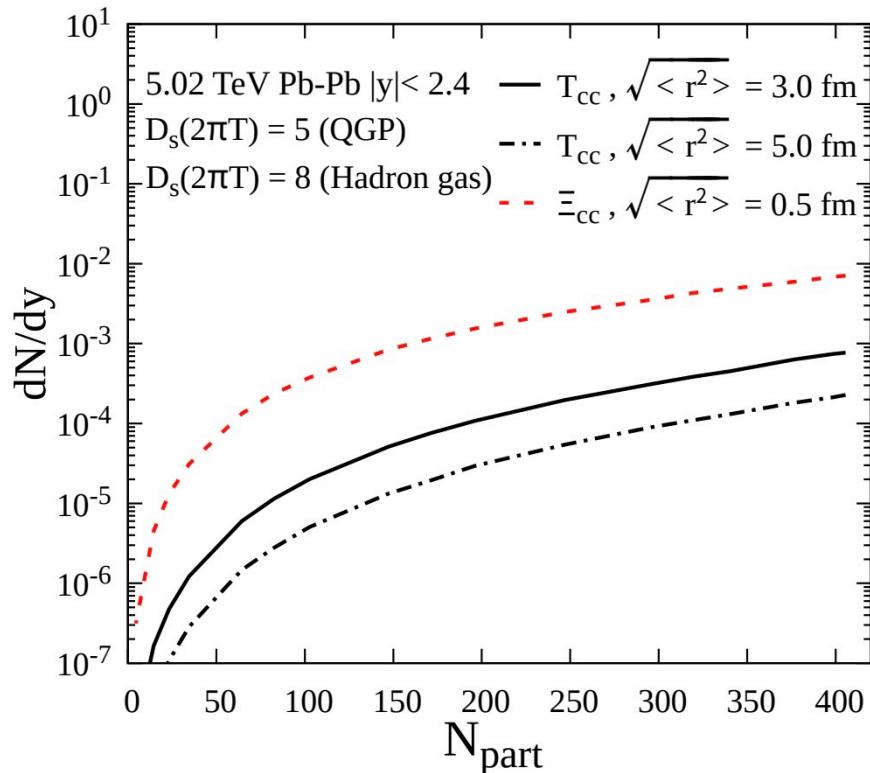
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- Our tetraquark yield $\sim 10^{-3}$ is consistent with [Cho. Prog.Part.Nucl.Phys. 95,279-322 \(2017\); when taking same coalescence temperature](#)
- **Relations** between **tetraquark** and **molecule** production:
ours is consistent with rate equation model [Rapp EPJA 57, 122 \(2021\)](#);
different from AMPT model: [Zhang PRL 126, 012301 \(2021\)](#);
- maybe due to its different formation conditions. $\left\{ \begin{array}{l} 5\text{fm} < \text{relative distance} < 7\text{fm} \\ 2M_D < \text{pair mass} < 2M_{D^*} \end{array} \right.$

4. Mesonic molecule production: T_{cc}

- T_{cc} includes $T_{cc}^0, T_{cc}^+, T_{cc}^{++}, D^0 - D^{*0}, D^{0/+} - D^{*+/0}, D^+ - D^{*+}$
- Wigner function is determined by the $\langle r^2 \rangle_T$



in preparation...

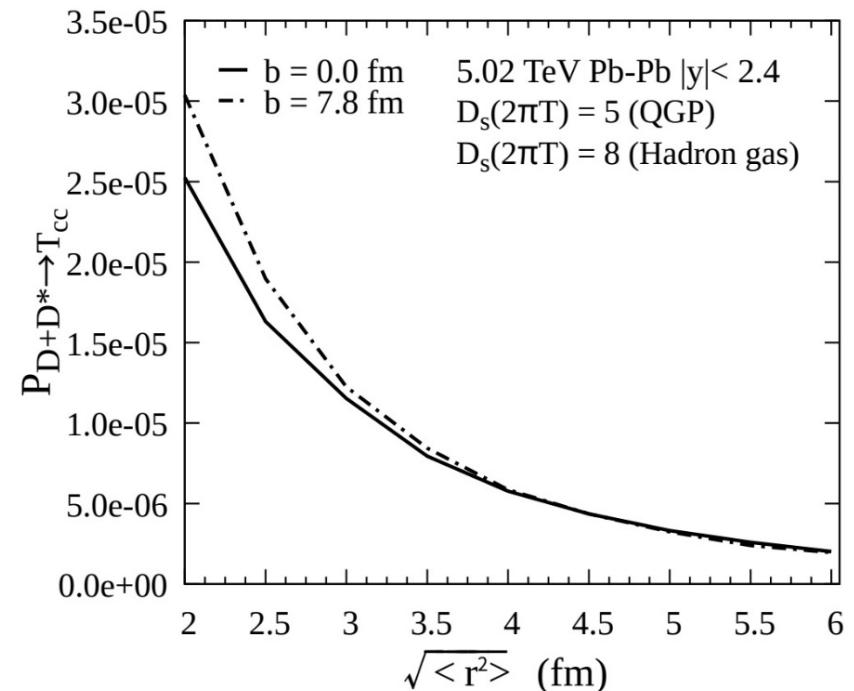
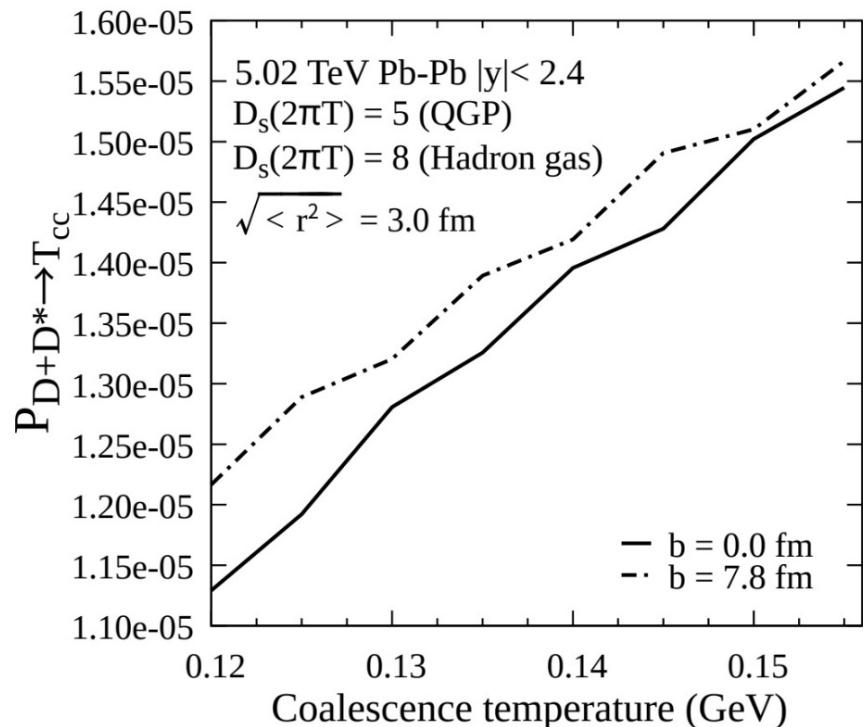
- $c \rightarrow (D^0, D^{*0})$
- Shadow factor = 0.65
- Molecules are produced at $T=0.12 \text{ GeV}$

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 $\langle r^2 \rangle_T$



[2309.02987](#)

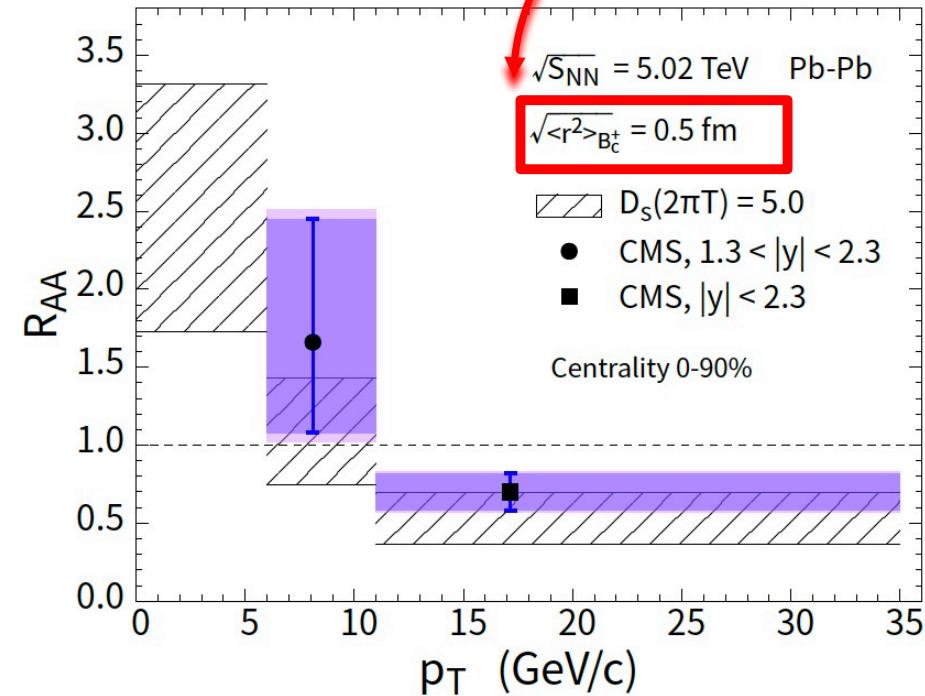
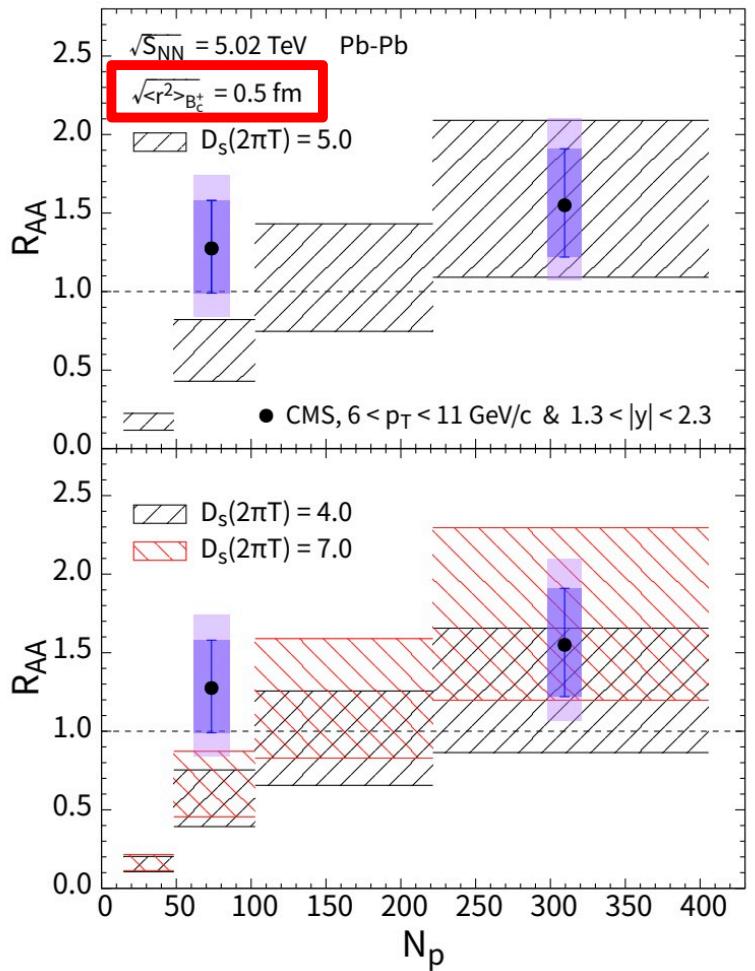
Coalescence probability per one D and D^*

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

$$\sigma^2 = \frac{4}{3} \frac{(m_1 + m_2)^2}{m_1^2 + m_2^2} \langle r^2 \rangle_{M_{19}}$$

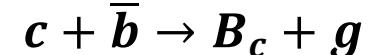
4. charmed hadron production: B_c

Geometry size



BYC, Wen, Liu, arXiv: 2111.08490

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



2) RAA>1 at central collisions:

QGP signal

RAA<1 at peripheral collisions:

absence of initial production

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

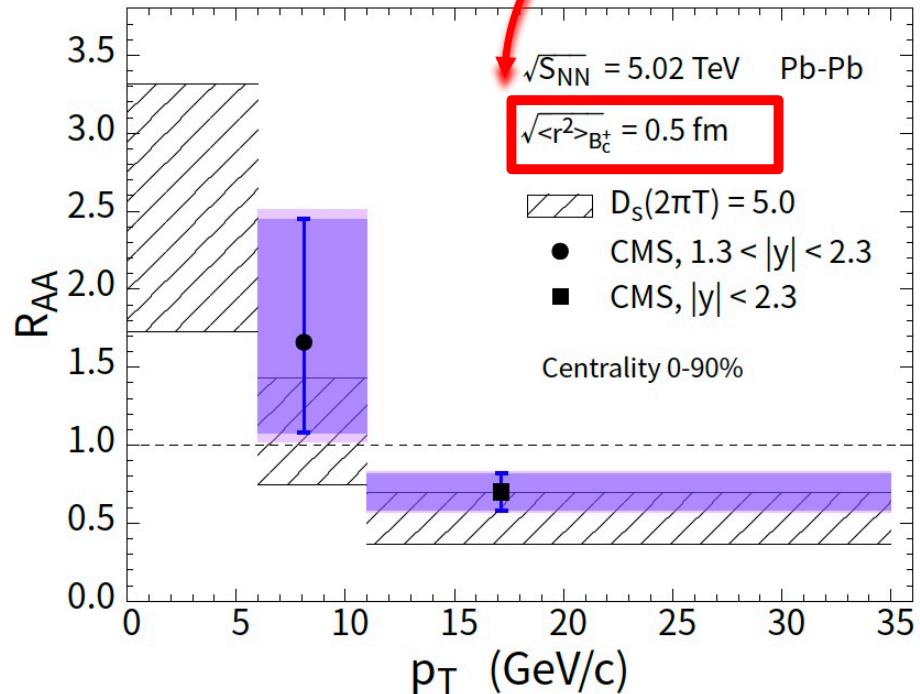
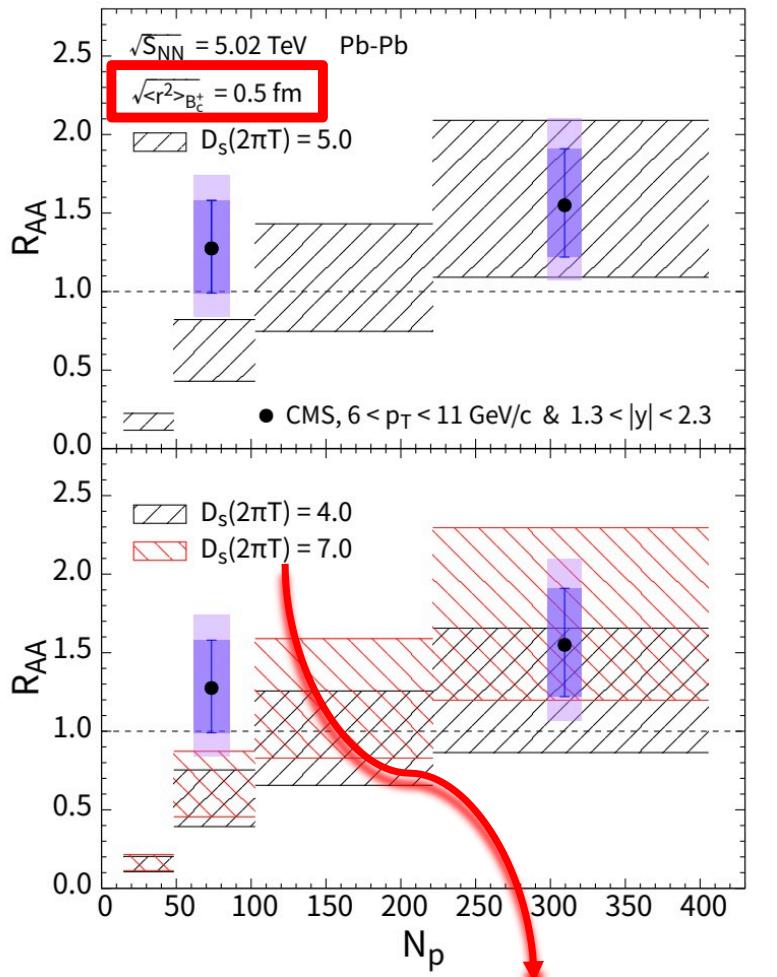
B_c : spin 0
fig: $B_c(1s) + B_c(2s \rightarrow 1s)$

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

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

4. charmed hadron production: B_c

Geometry size



BYC, Wen, Liu, arXiv: 2111.08490

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

$\frac{d\sigma_{p_1}^c}{dy}$

$\frac{d\sigma_t}{dy}$

$+ g$

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!

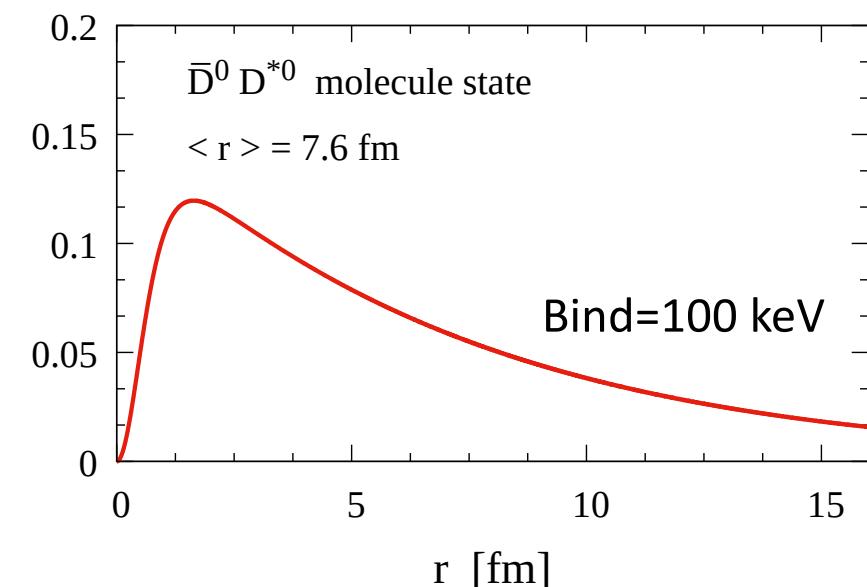
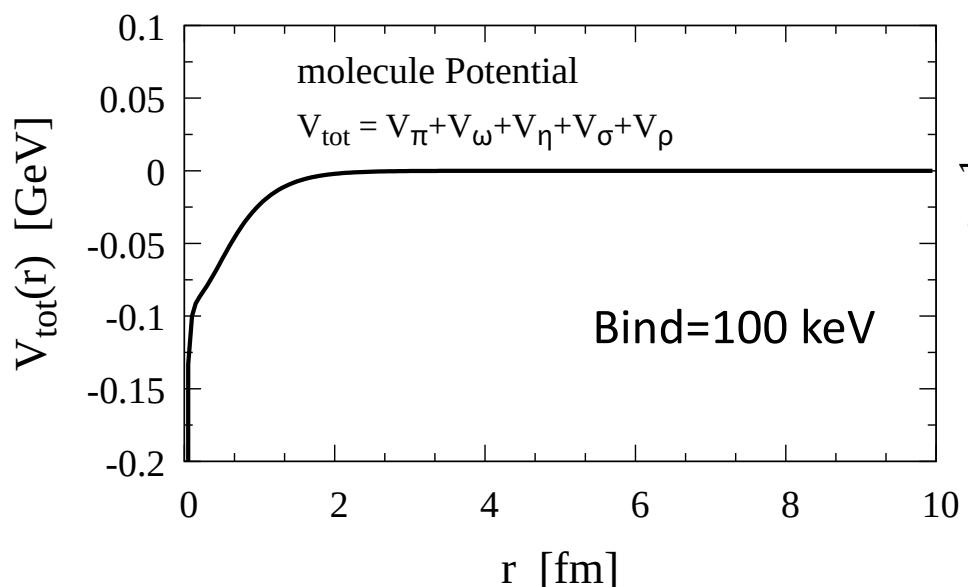
Binding energy of X(3872)

➤ 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

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

3. Heavy quark polarization in magnetic field

- Landau-Lifshitz-Gilbert (LLG) equation

PRB 83, 134418 (2011)

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

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

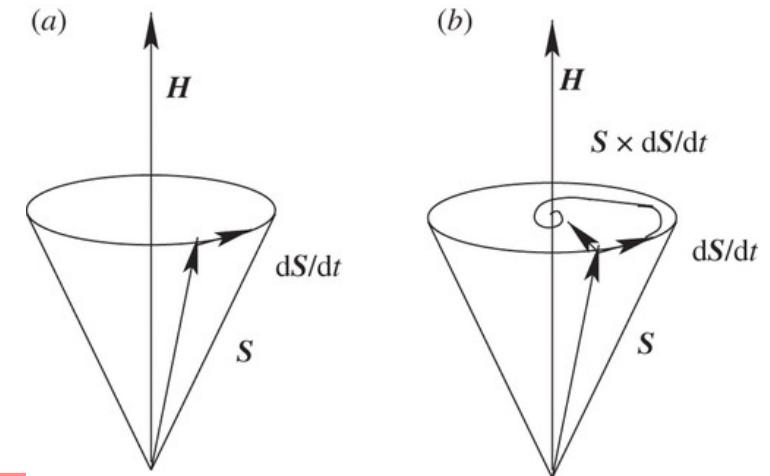
Unit vector

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

$$\gamma = \frac{Q}{2m} \dots$$

$\alpha = 0.1$ Damping factor
(to be determined later)



noise term

$$\begin{aligned} < \overrightarrow{H_{th}}(t) > &= 0 \\ < H_{th,i}(t) H_{th,j}(t') > &= 2\gamma T \delta_{ij} \delta(t - t') \end{aligned}$$

● D meson coalescence

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

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

- $H_{c \rightarrow D^0} = 9.5\%$: 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 $c \rightarrow D^0$ via the **coalescence process**, neglect the fragmentation. This simplification works well in low or moderate p_T region.

Light quark momentum

(local)

m_l :

After coalescence at T_c ,

D meson continues diffusion in hadronic medium via Langevin,
(with $D_s(2\pi T) = 8$)

Until kinetic freeze-out $T=0.14$ GeV