X(3872) production in heavy-ion collisions

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arXiv: 2107.00969

Outline

1. Introduction

heavy ion collisions & coalescence model

2. Calculations of coalescence model

D meson spectrum (charm-light quarks)

J/psi spectrum (charm- anticharm quarks)

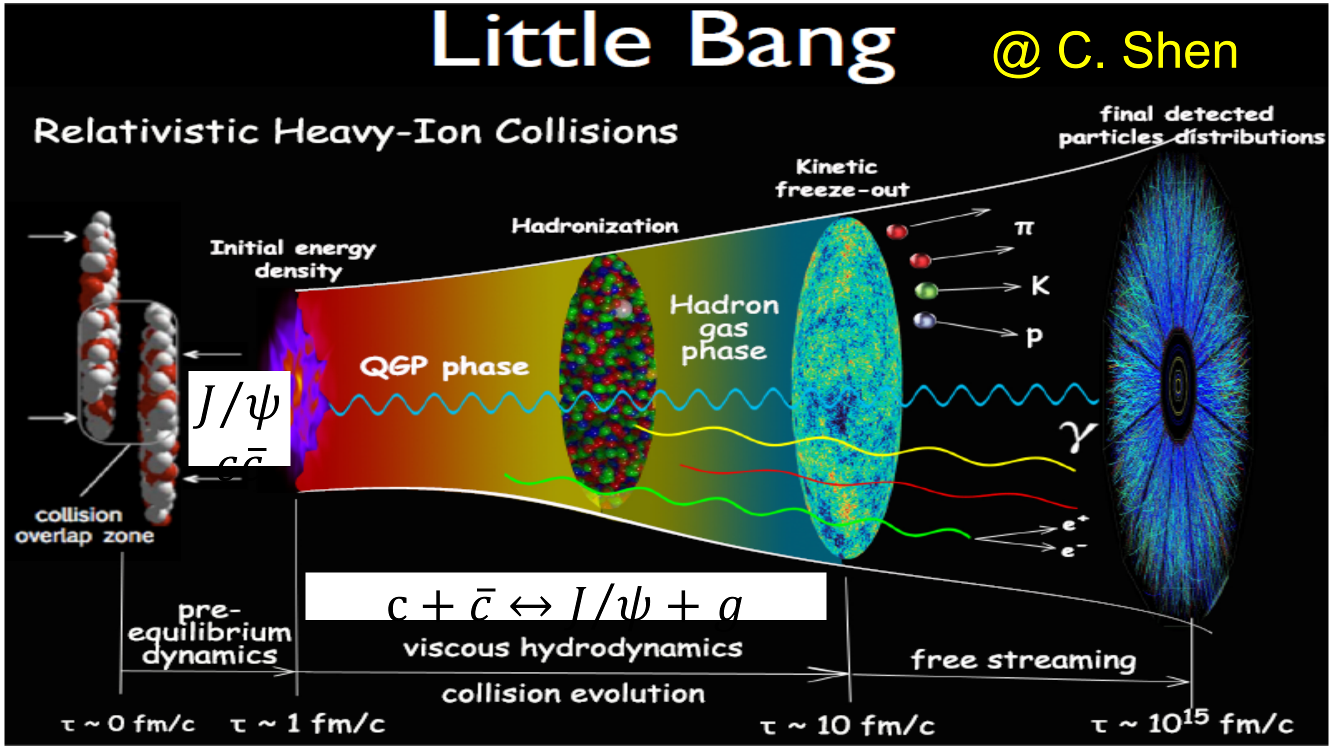
X(3872) as a tetraquark: $c+\bar{c}+q+\bar{q}\rightarrow X(3872)$ **in QGP**

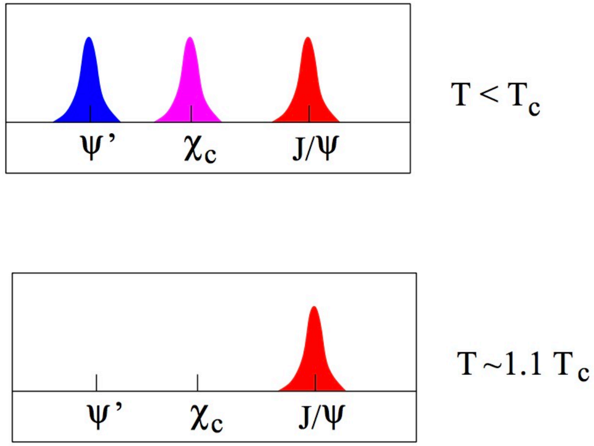
as a meson molecule: $c+\bar{q}\rightarrow D,\ D^0+\bar{D}^{*0}\rightarrow X(3872)$ **in hadronic medium**

3. Results in heavy ion collisions

4. Summary

Heavy ion collisions and heavy flavors





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)

Coalescence of **open-** and **hidden-** charm

- When the **local temperatures of QGP** drops down to a certain value, **heavy quark potential** is partially restored.

(1) For D mesons,

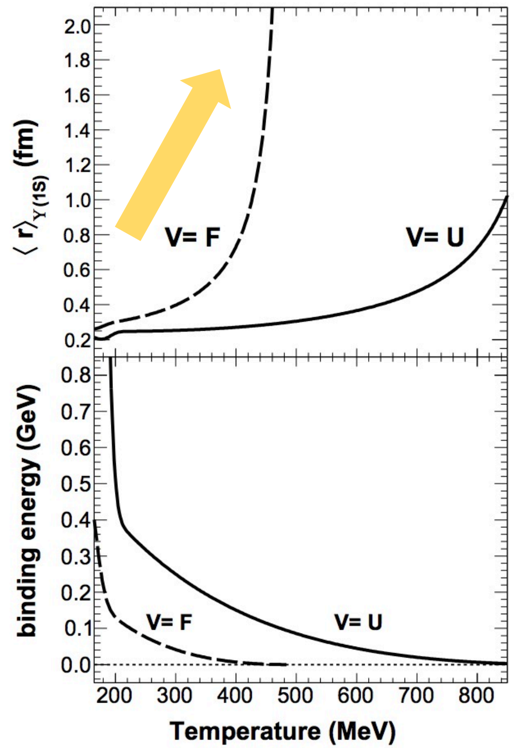
mainly produced close to the QGP phase boundaries with $T = T_c$

(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**



Bottomonium (BC, Zhao, PLB 2017)

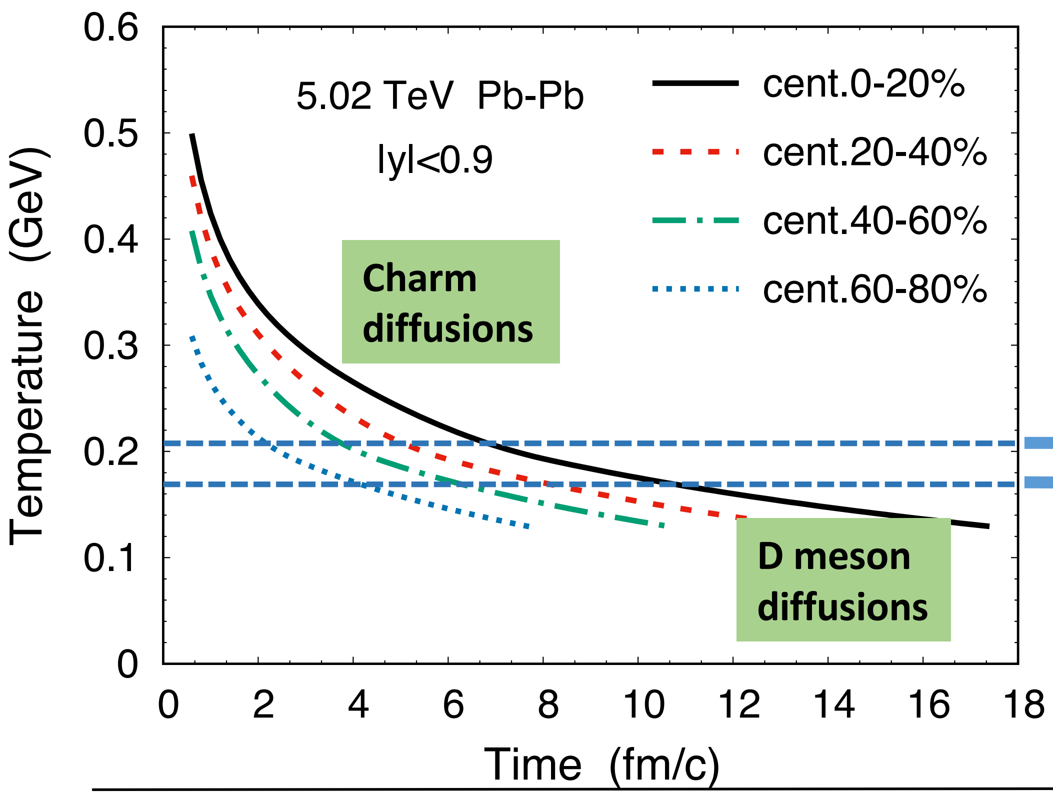
Bulk medium evolutions

5.02 TeV Pb-Pb collisions,

MUSIC hydro model is employed (crossover phase transition)

EoS:
- QGP EoS is from Lattice QCD results
- Hadron phase is treated as an ideal gas

At the center of the fireball (r=0) , its local temperature evolution is plotted:



Sequentially regenerated

$T = 1.2T_c$ → $c+\bar{c} \to J/\psi$, etc
Tightly bound charmonium

$T = T_c$ (170 MeV) → $c+\bar{q} \to D$, etc
D mesons

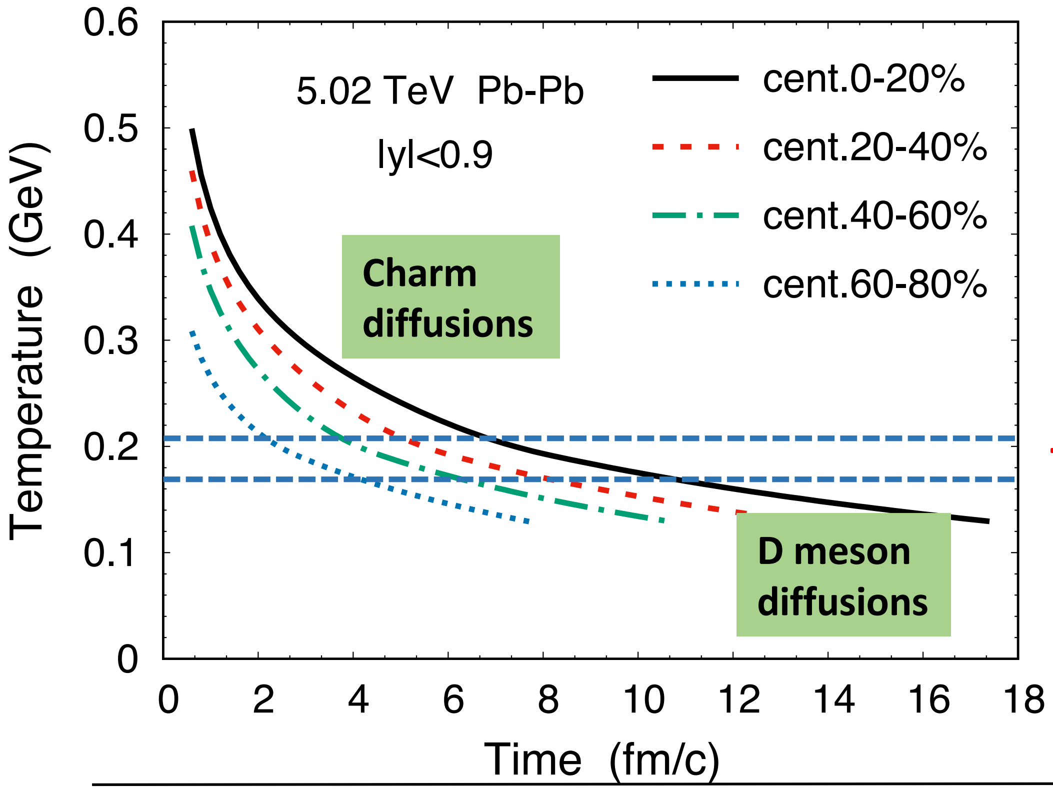
Bulk medium evolutions

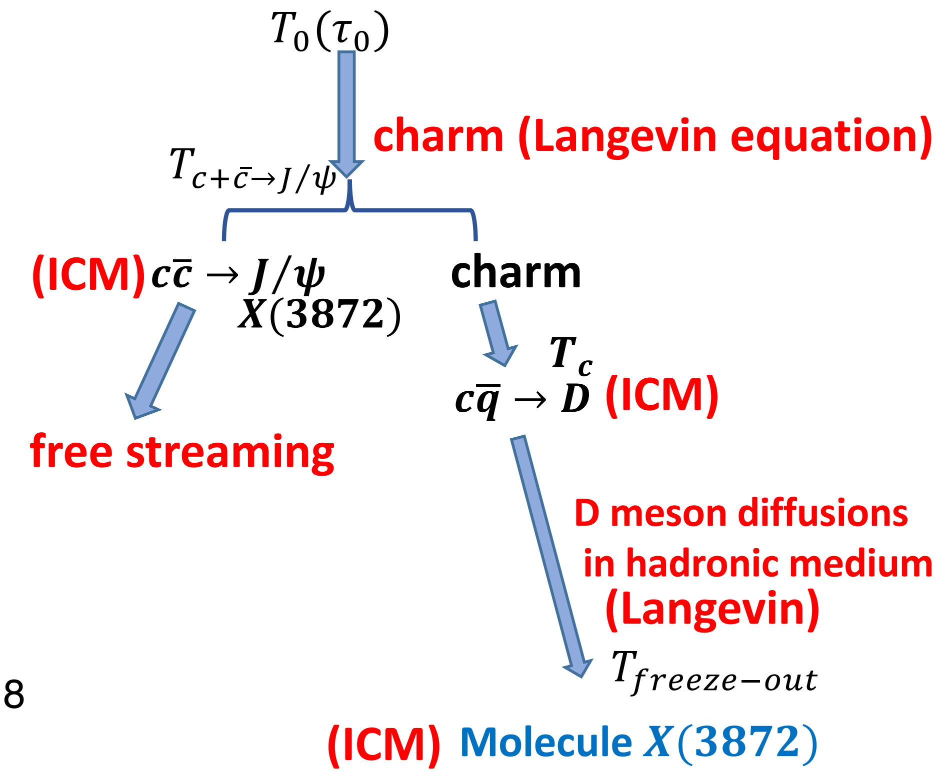
5.02 TeV Pb-Pb collisions,

MUSIC hydro model is employed with crossover phase transition

EoS:
- QGP EoS is from Lattice QCD results
- Hadron phase is treated with an ideal gas

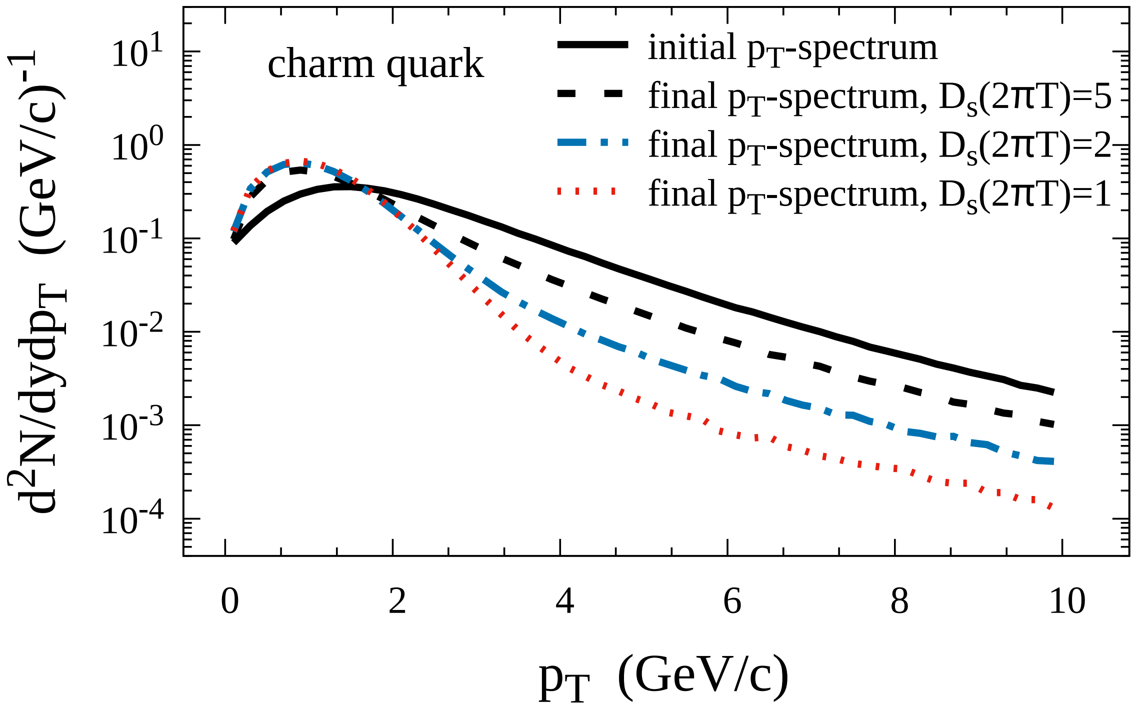
Langevin + Instantaneous coalescence model (LICM)

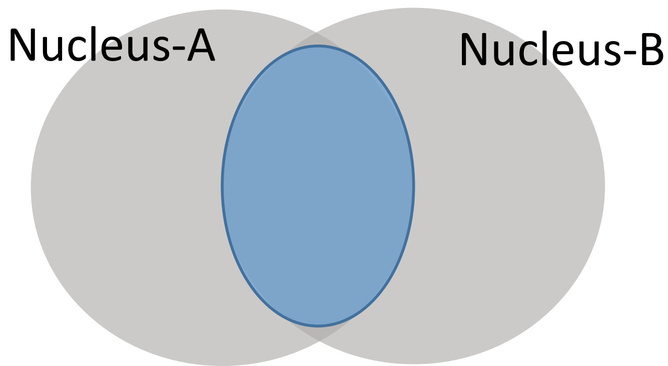




Coalescence of **open-** and **hidden-** charm

（1）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 $N_{coll}(\vec{x}_T)$

Coalescence of **open-** and **hidden-** charm

（2） Charm diffusions in QGP (Classical Langevin equation)

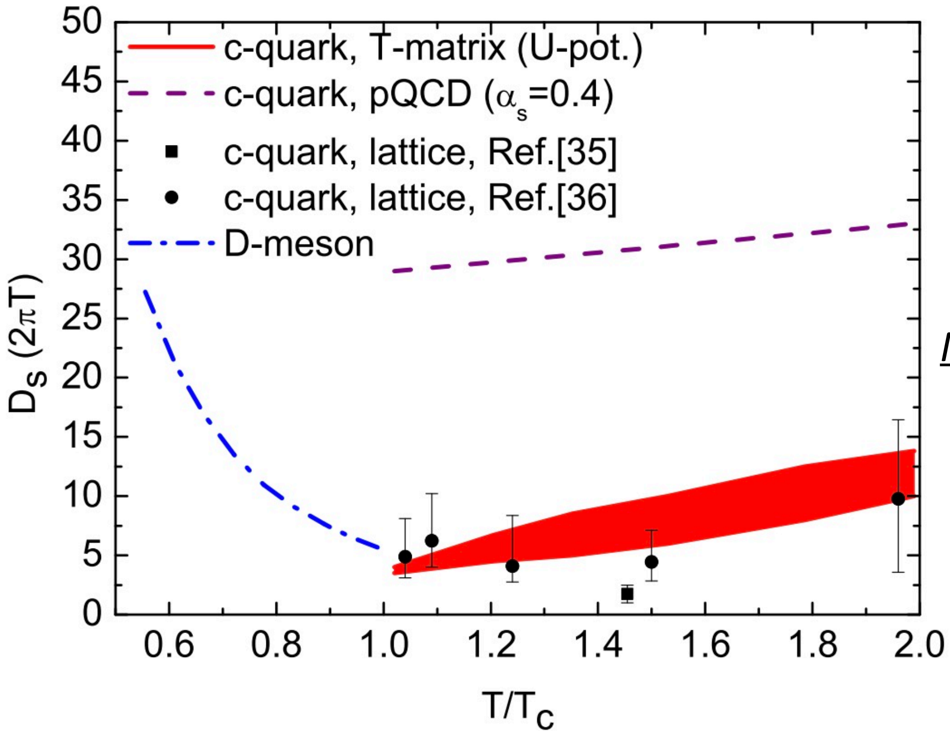
$$\frac{d\vec{p}}{dt} = -\eta\vec{p} + \vec{\xi}$$

$\eta = \kappa/(2TE)$

$\kappa D_s = 2T^2$

$D_s(2\pi T) = 5$

D_s, κ: Spatial and Momentum Diffusion coefficients



Diffusion coefficients' Ref:
ShanShan Cao et al, PRC 92 ,024907(2015)

Min He, Ralf Rapp, et al PRL 2012c

$$\mathbf{p}(t+\Delta t) = \mathbf{p}(t) - \eta(p)\mathbf{p}(t)\Delta t + \xi\Delta t$$

$$\mathbf{x}(t+\Delta t) = \mathbf{x}(t) + \frac{\mathbf{p}(t)}{E}\Delta t$$

$$\langle \xi^i(t)\xi^j(t-n\Delta t)\rangle = \frac{\kappa}{\Delta t}\delta^{ij}\delta^{0n}$$

Test particle Monte Carlo method is used.

Coalescence of **open-** and **hidden-** charm

（3） coalescence via ICM model

- **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
- $\frac{d^2N_1}{d\vec{x}_1 d\vec{p}_1}$: 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 charmonium wave function

Coalescence of **open-** and **hidden-** charm

（3） coalescence via ICM model

- **Wigner function:** take charmonium wave function to be the eigenstates of the harmonic oscillators

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

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

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

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

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

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

Determined by the **geometry size** of the formed state

Coalescence of **open-** and **hidden-** charm

（4）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:
from EPS09 model
It reduce around **30%**
of charm pairs at 5.02
TeV Pb-Pb collisions

Rapidity range of
charm pairs

After the formation of charmonium via the coalescence process ,
Neglect the following suppressions from the hot medium,
do free streaming

Coalescence of **open-** and **hidden-** charm

- **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
(local rest frame)
$m_l = 0.3\ GeV$

$$f(p) = \frac{N_0}{e^{\sqrt{m_l^2+p^2}/T}+1}$$

In event-by-event Simulations:
Randomly generate a light quark at the hadronization of charm quark

Coalescence of **open-** and **hidden-** charm

- **D meson coalescence**

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

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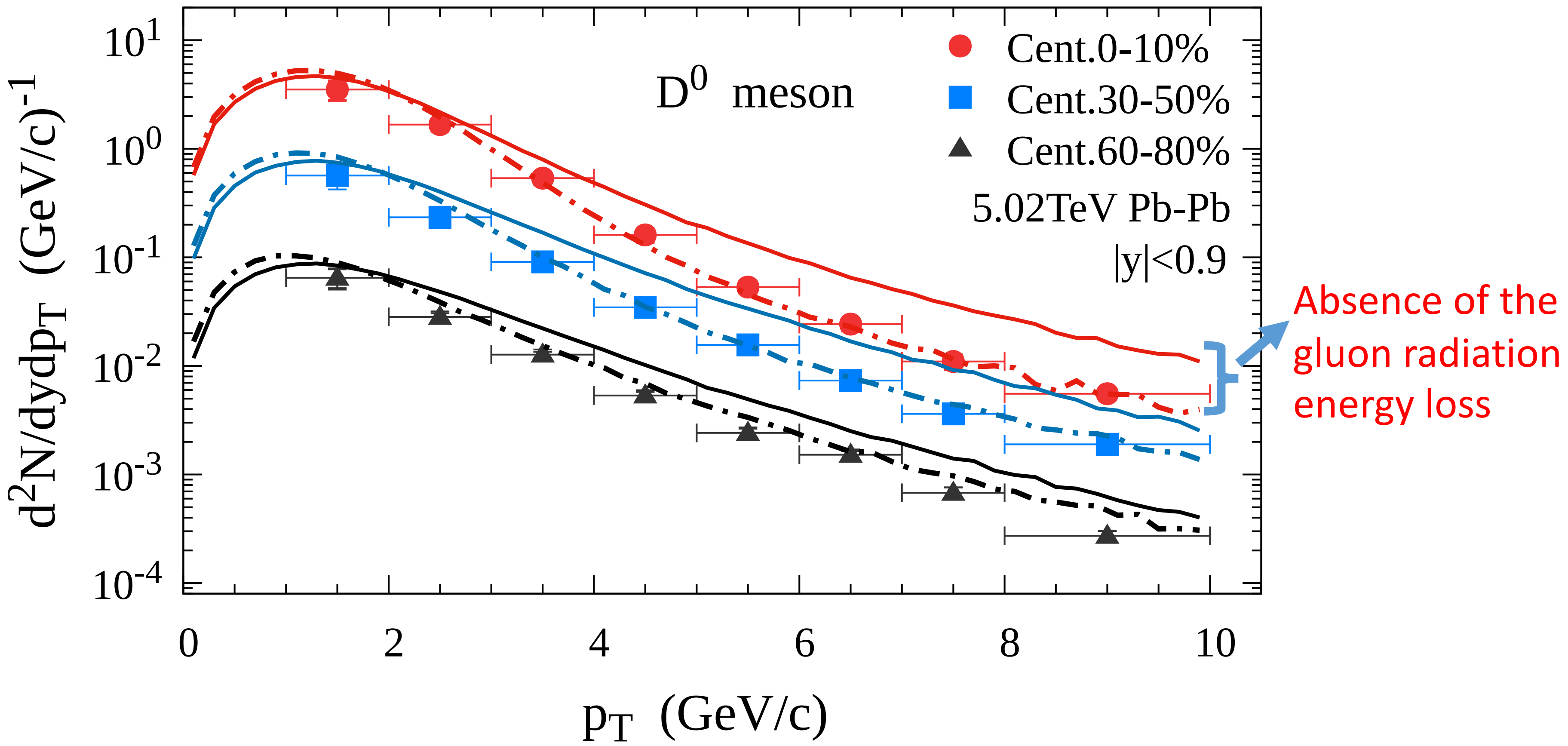
Light qu...

(loca...

m_l = ...

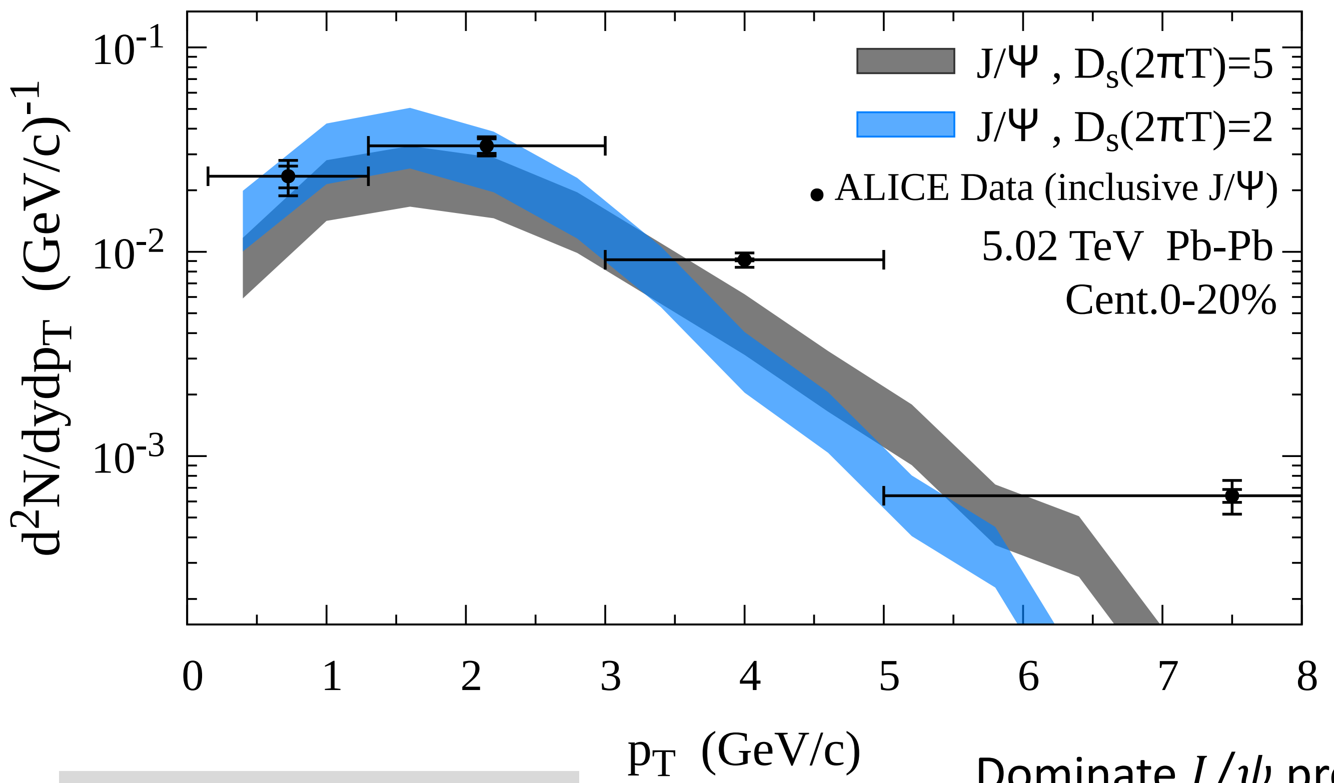
After coalescence at Tc,
D meson continues diffusion in hadronic medium via Langevin,
(with $D_s(2\pi T) = 8$)
Until kinetic freeze-out T=0.14 GeV

D meson spectrum



- We take the ratio of prompt D^0 over charm quark production:
  $\boldsymbol{N(D^0)/N_{c\bar{c}} = 39\%}$ ***ALICE pp, arXiv:2105.06335***
- In order to consider stronger energy loss at high p_T,
  Both $\boldsymbol{D_s(2\pi T) = 5}$ (solid line) and $\boldsymbol{D_s(2\pi T) = 2}$ (dotted-dashed line) are considered.

Charmonium spectrum



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**

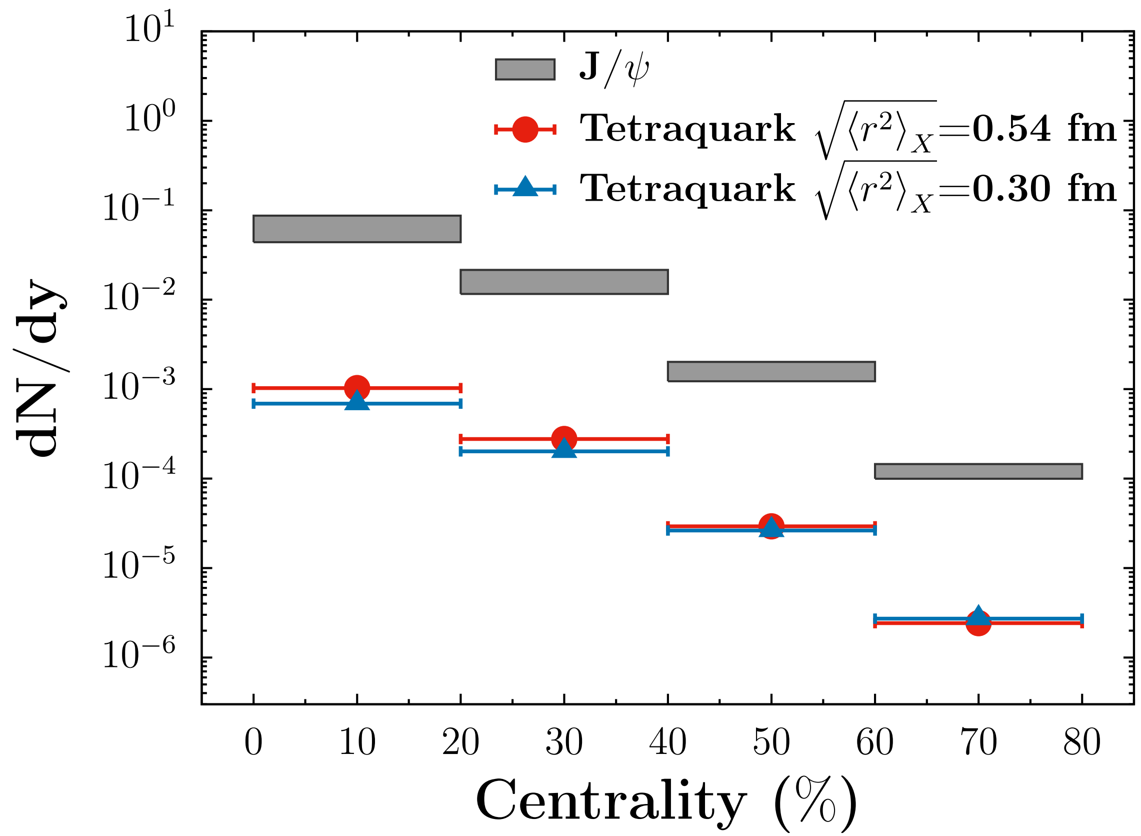
Theoretical calculation:

Only $c - \bar{c}$ coalescence

X(3872) as a tetraquark

- $g_{X(3872)} = 1/432$ 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 yield is around 40 times smaller than J/ψ
- Different geometry sizes of tetraquark are considered.
- Tetraquark yield is controlled by both **spatial** and **momentum** part of the Wigner function

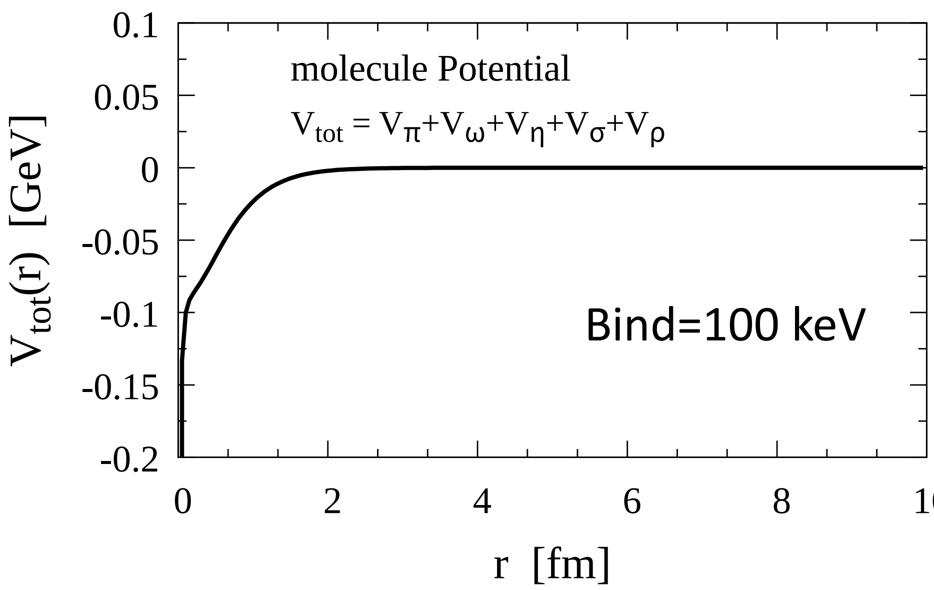
X(3872) as a molecule

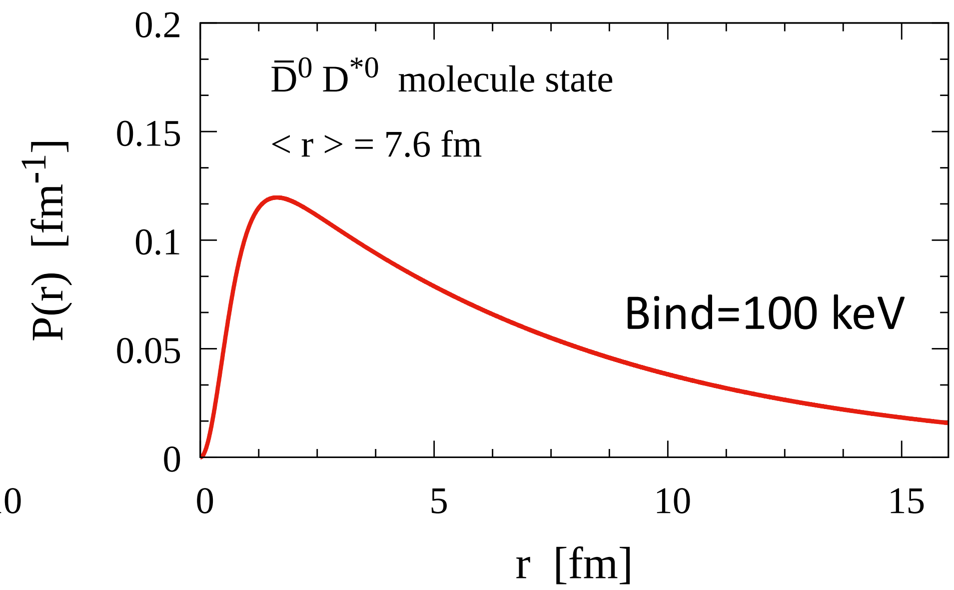
➢ Molecule state based on potential model

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

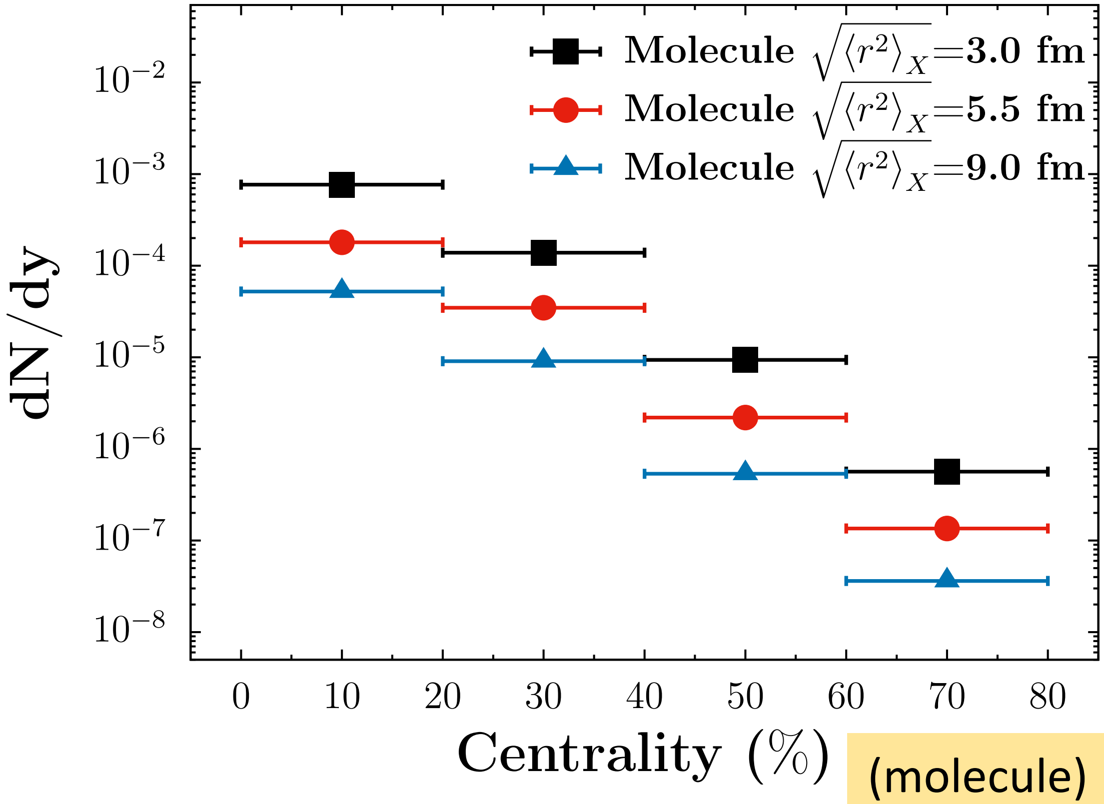
arXiv: 2107.00969

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

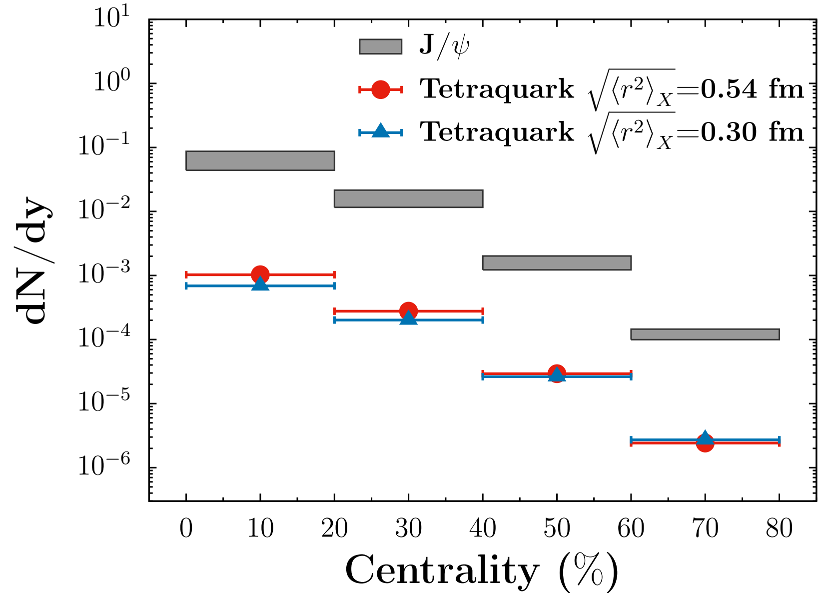




X(3872) as a molecule



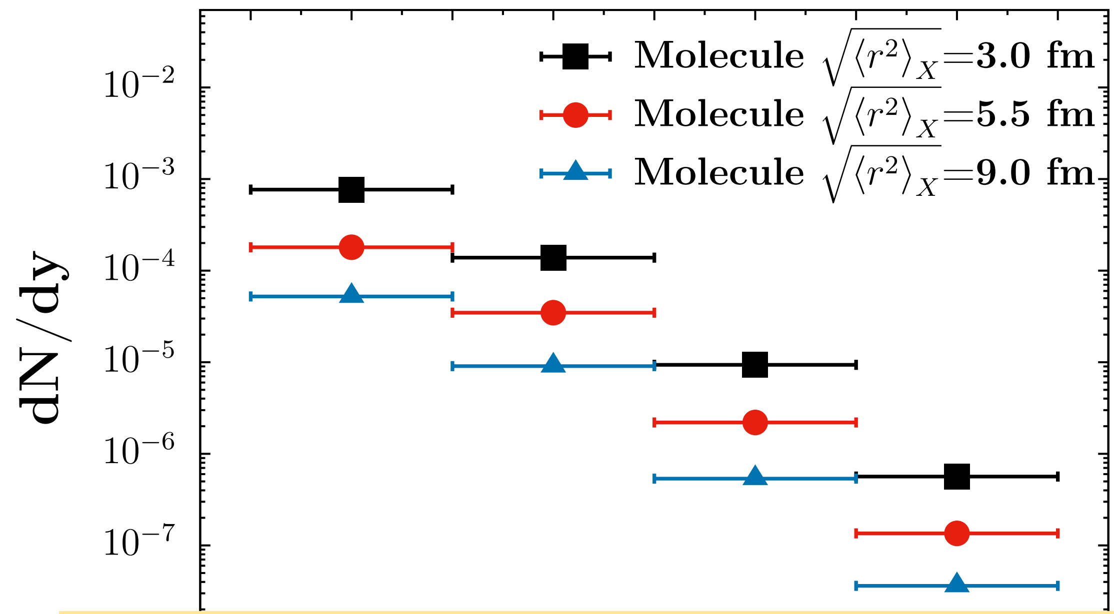
(molecule)

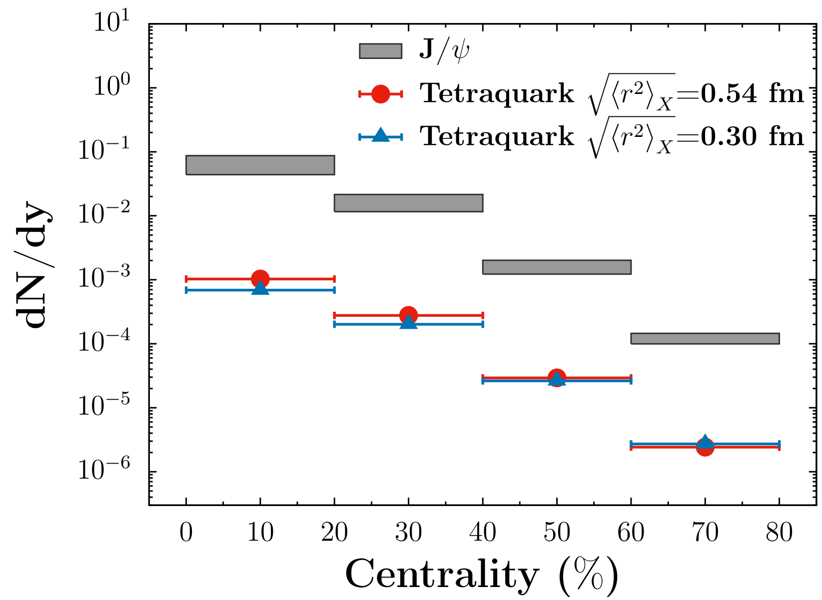


(tetraquark)

- Both of them show similar centrality dependence.
- Molecule production with $< r^2 >_X = 3.0\ fm^2$ is slightly below the tetraquark yield.
- But molecule yields with $< r^2 >_X = 5.5, 9\ fm^2$ is **5-20 times smaller** than the tetraquark

X(3872) as a molecule





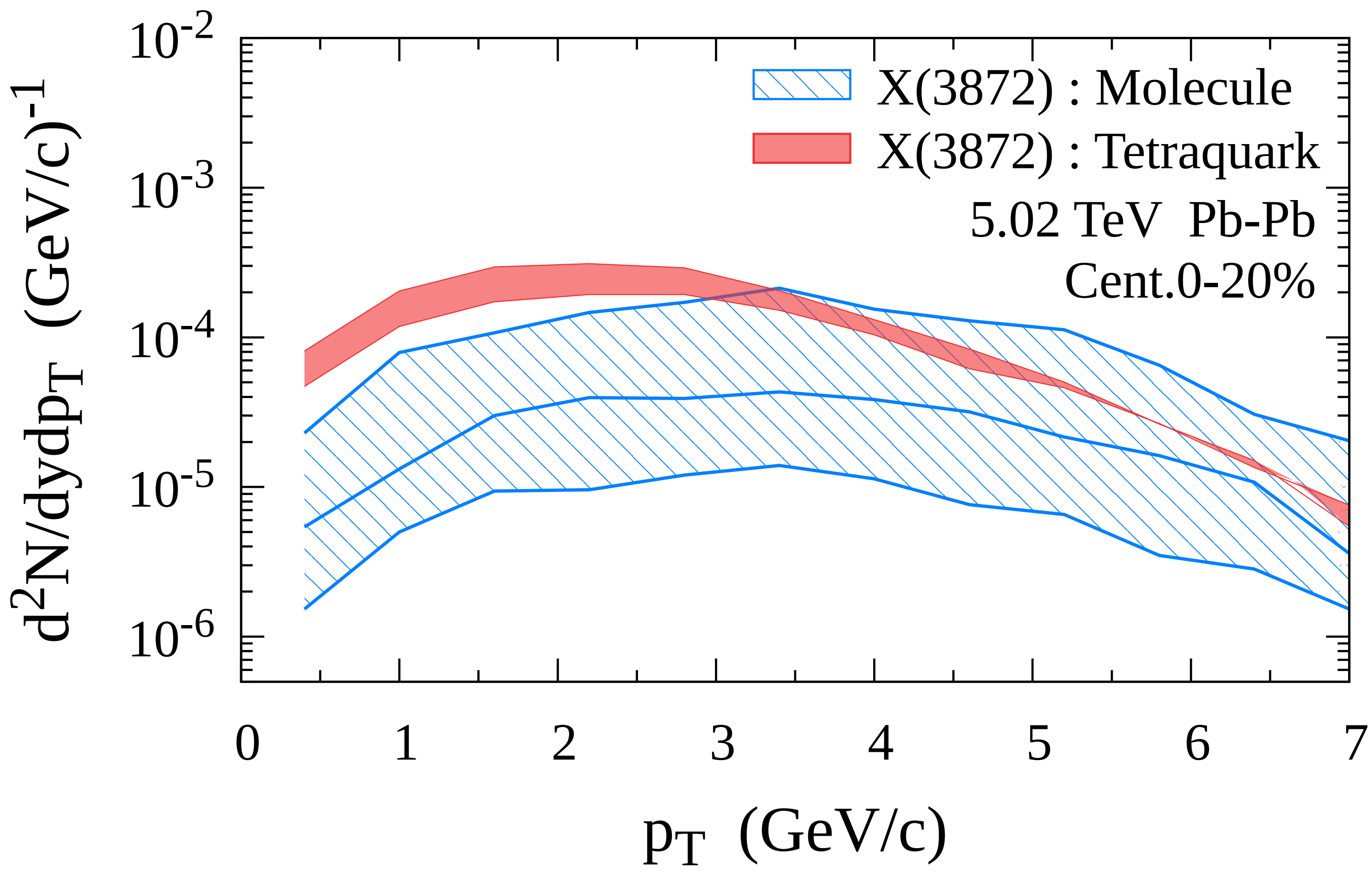
- Our tetraquark yield $\sim 10^{-3}$ is consistent with ***Cho. Prog.Part.Nucl.Phys. 95,279-322 (2017);*** our molecule production is **a few times smaller** than his.

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

  different from another coalescence model: ***Zhang PRL 126, 012301 (2021) ;***
  (Molecule yield is 200 times larger than the tetraquark)

→ maybe due to its different coalescence conditions: { **5fm < relative distance < 7fm**; $2M_D < pair\ mass < 2M_{D^*}$ }

Molecule production



- Molecule: via the coalescence of D mesons, at kinetic freeze-out (T=0.14 GeV)
- Tetraquark: in QGP via heavy-light quark coalescence.
- **The peak** of molecule pT-spectrum **is shifted to larger pT**, due to the **medium radial flows**

Summary

- We develop **Langevin + Instantaneous Coalescence Model (LICM)** to study the **realistic diffusions of charm quarks** in the hot medium.

- We calculated the production of **D meson, J/ψ**.
  The production of X(3872) treated as a compact hadron state or a loosely bound molecule are presented respectively.
  The **formation probability** between constituent particles in both **spatial** and **momentum** space are given consistently via the Wigner function.

The uncertainties of the model are also studied: charm quark non-thermalization and hadronization temperatures can change the final production of X(3872) by around 1-2 times.

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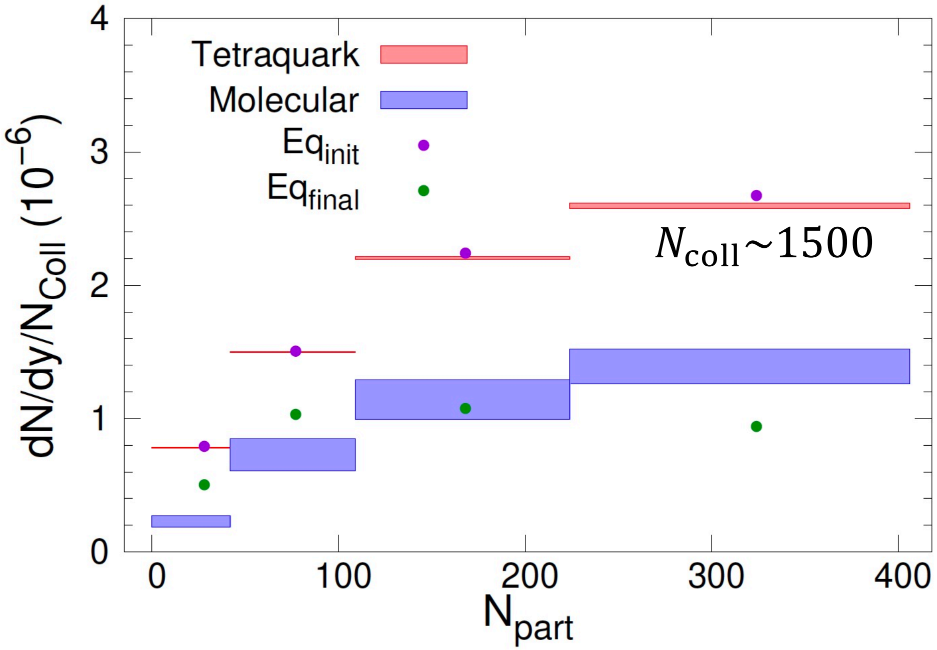
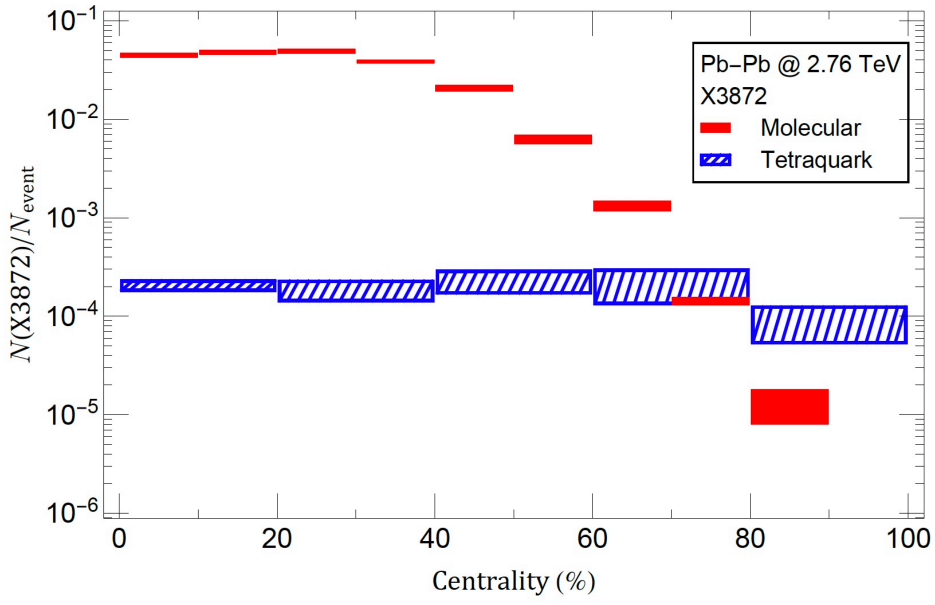
Thank you for your attention!

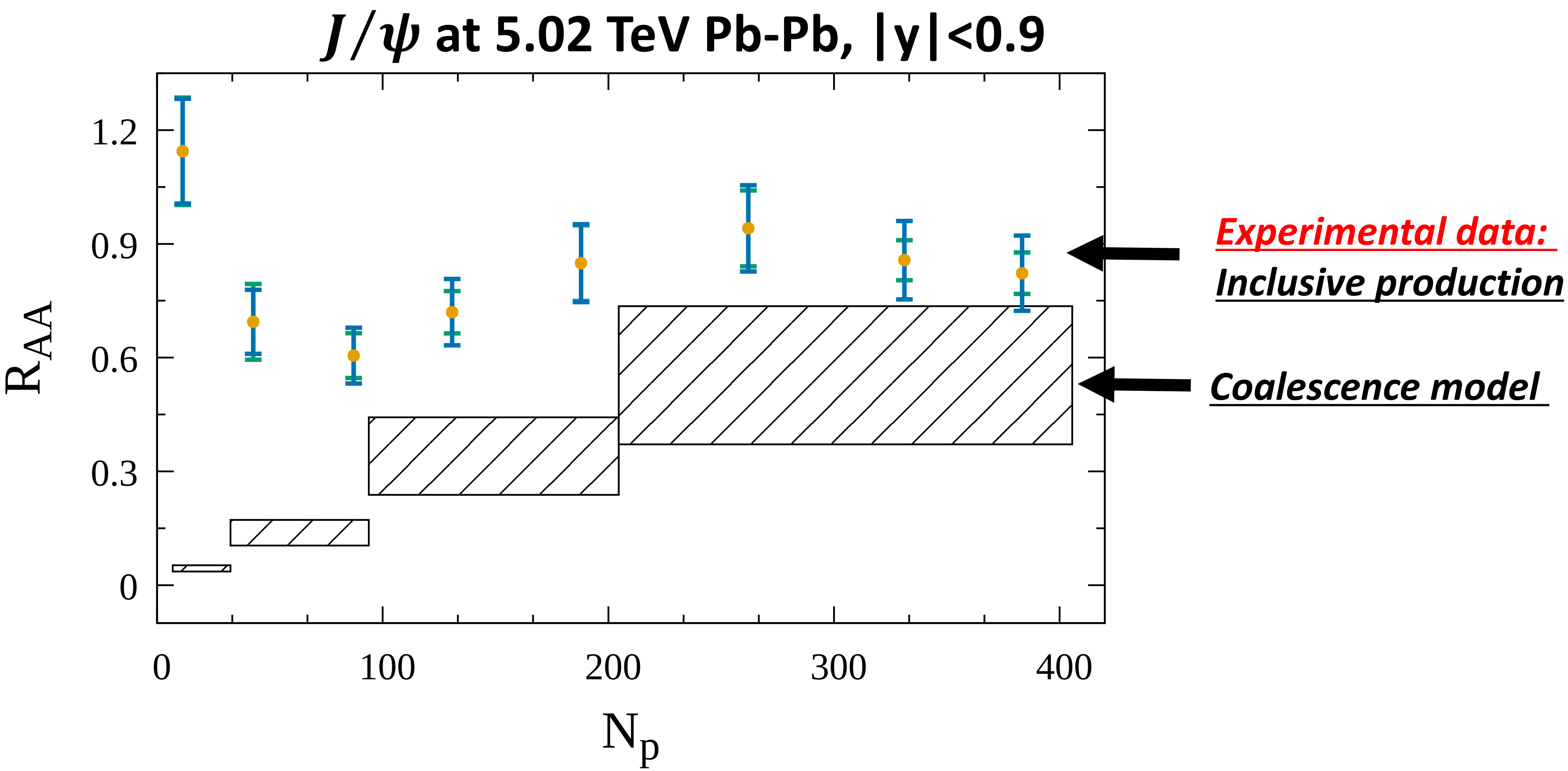
More slides: X(3872) from other models



Rate equation model from
from Zhang PRL 126, 012301 (2021) ;



Coalescence model
from Zhang PRL 126, 012301 (2021) ;



Inclusive production= primordial production + coalescence + B-decay (10%)

Coalescence of **open-** and **hidden-** charm

- When the **local temperatures of QGP** drops down to a certain value, **heavy quark potential** is partially restored.

(1) For D mesons,
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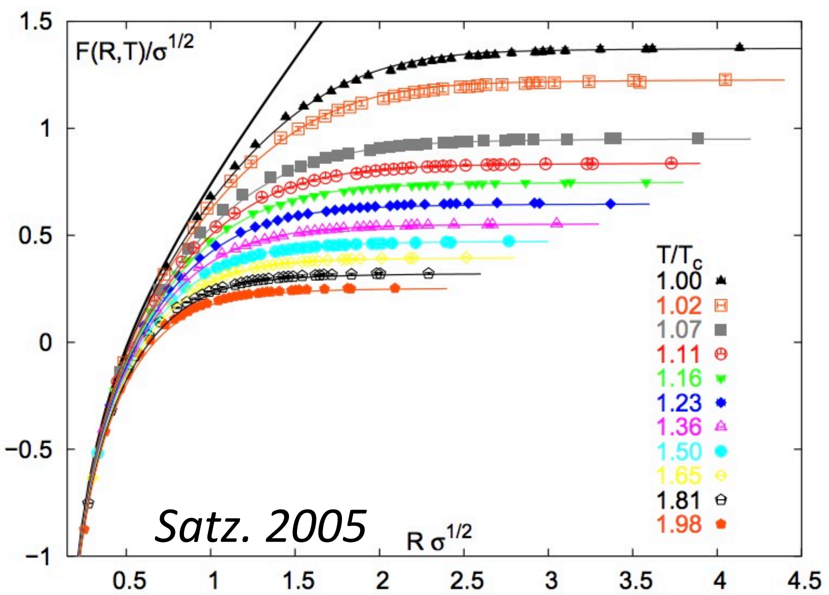

Free energy of heavy quarkonium
→ One limit of
in-medium heavy quark potential

Partially restored at T→ 1.2Tc
at the distance of J/ψ radius (~0.5fm)