# Investigating the X(3872) as $D\bar{D}$ molecular state

## via coalescence model

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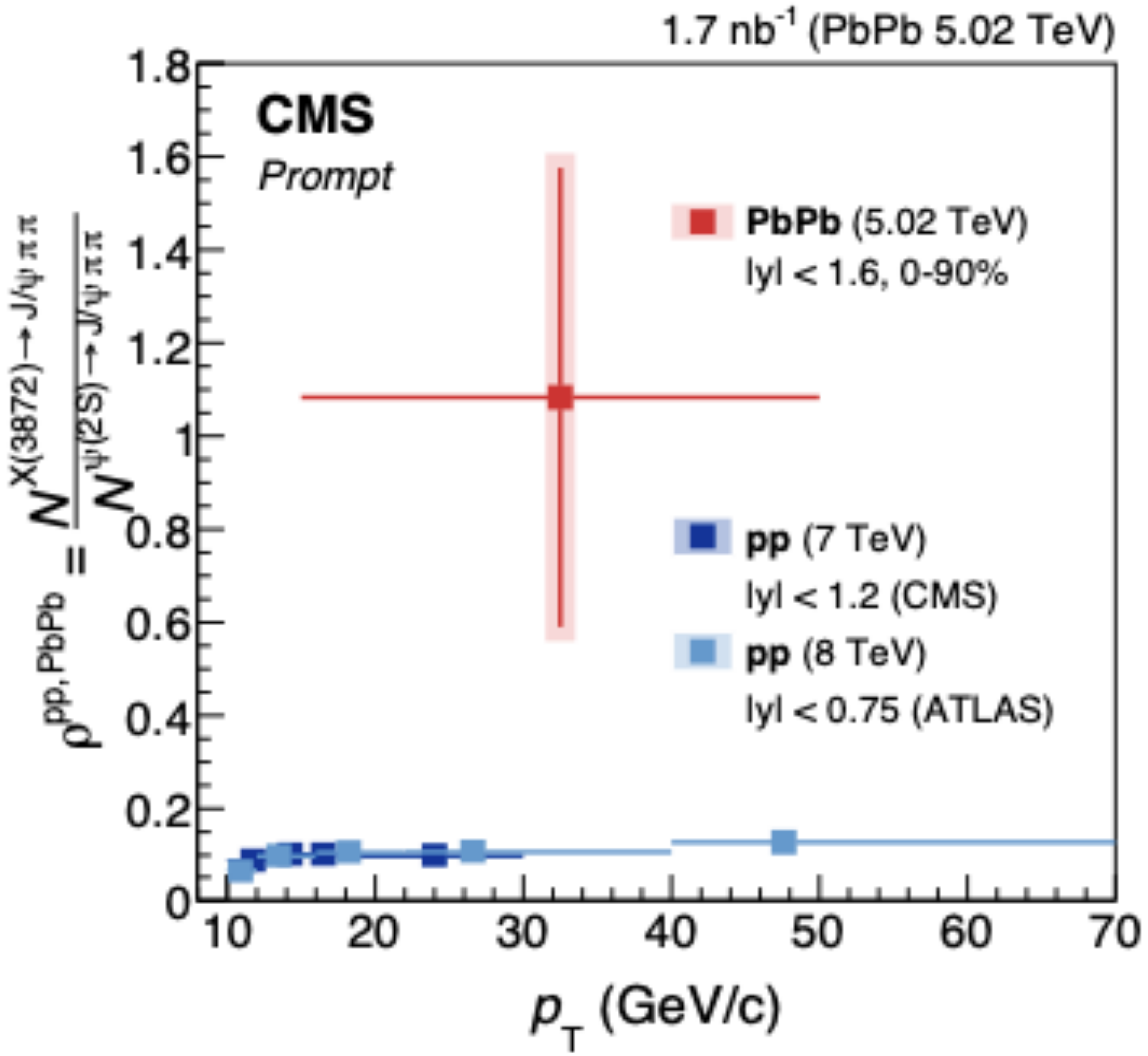
# $X(3872)/\psi(2S)$ ratio

## PbPb collision




HyeongOck Yun *at al* . Phys.Rev.C 107 (2023)

- Structure of X(3872) :

  Quark model - $D\bar{D}$ molecule

  QCD sum rule - $c\bar{c}g$ hybrid

Wei chen *at al*. Phys.Rev.D 88, 045027 (2013)

We now investigate how each scenario influences the production mechanism, using the coalescence model.

# X(3872) structure

## $\mathrm{D}-\bar{\mathrm{D}}^*$ molecular structure

- Quark color-spin wave function of X(3872)

  - In $(q\bar{c})$, $(c\bar{q})$ basis

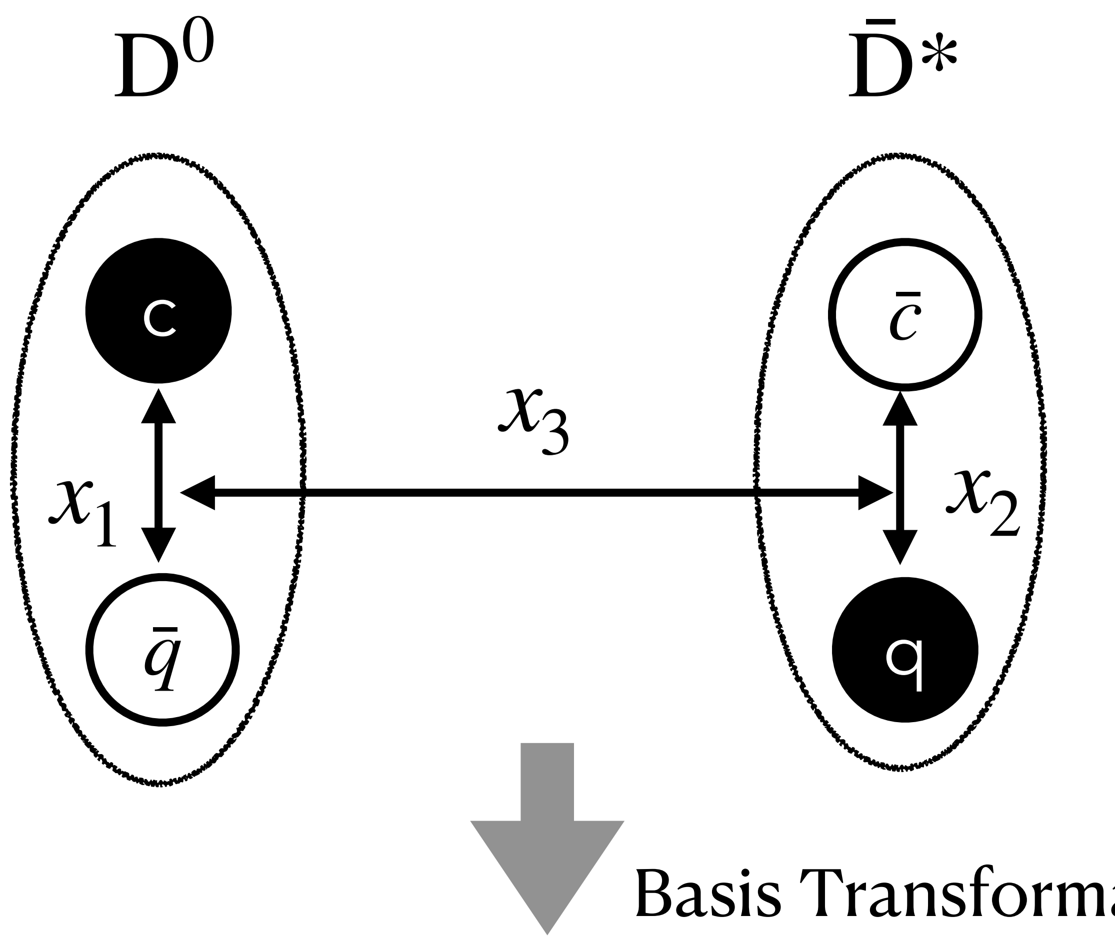
$$|1'\rangle = (q\bar{c})^{C=1}_{S=0} \otimes (c\bar{q})^{C=1}_{S=1} \longleftarrow \mathbf{D}-\bar{\mathbf{D}}^*$$

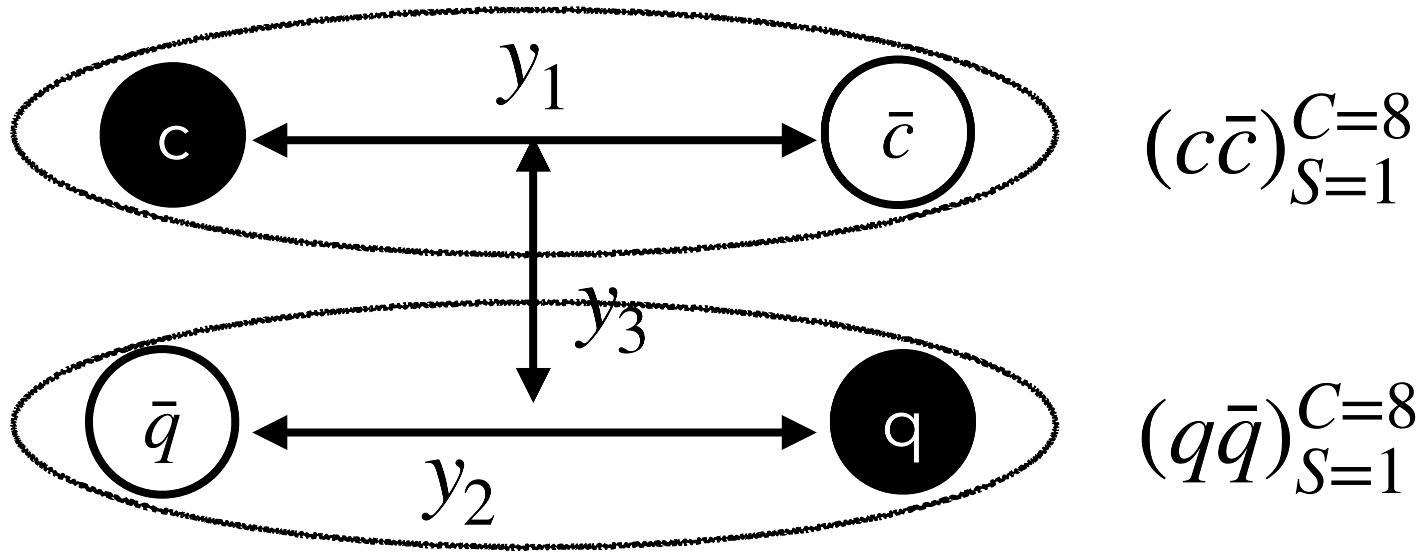
$$|2'\rangle = (q\bar{c})^{C=8}_{S=0} \otimes (c\bar{q})^{C=8}_{S=1}$$

  - Transformation into $(c\bar{c})$, $(q\bar{q})$ basis

$$|1\rangle = (c\bar{c})^{C=8}_{S=1} \otimes (q\bar{q})^{C=8}_{S=1}$$

$$|2\rangle = (c\bar{c})^{C=1}_{S=1} \otimes (c\bar{q})^{C=1}_{S=1}$$




$$|1'\rangle = \frac{2\sqrt{2}}{3}|1\rangle + \frac{1}{3}|2\rangle,$$ **$\mathrm{D}^0\ \bar{\mathrm{D}}^*$ is mostly composed of $(c\bar{c})^{C=8}_{S=1} \otimes (q\bar{q})^{C=8}_{S=1}$ (~90%)**

$$|2'\rangle = -\frac{1}{3}|1\rangle + \frac{2\sqrt{2}}{3}|2\rangle$$

# Coalescence model

## 2-dimension coalescence model

- Hadron transverse momentum distribution

$$\frac{d^2N_h}{d^2P_T} = g_h \int \prod_{i=1}^{N} d^2x_i d^2p_i \; f_i(x_i, p_i) W(r_1, \cdots r_{N-1}, k_1, \cdots, k_{N-1}) \delta^{(2)}\left(P_T - \sum_{j=1}^{N} p_j\right)$$

$g_h$ : statistical factor, $f_i(x_i, p_i)$ : $p_{\mathrm{T}}$ distribution of constituent , $W(r, k)$ : Wigner function

- Normalization condition

$$\int d^2x_i d^2p_i \; f_i(\vec{x}_i, \vec{p}_i) = N_i, \quad \int \prod_{i=1}^{N-1} d^2r_i d^2k_i W_H(\vec{r}_1, \cdots, \vec{r}_{N-1}, \vec{k}_1, \cdots, \vec{k}_{N-1}) = (2\pi)^{2(N-1)}$$

$$f(x_i, p_i) = \frac{d^2N_i}{Ad^2p_{iT}}$$

# Coalescence model

## Wigner function

- Wigner function

: Gaussian type Wigner function - $W(\vec{r},\vec{k}) = 4\exp\left[-\frac{(r)^2}{\sigma^2} - \sigma^2(k)^2\right]$

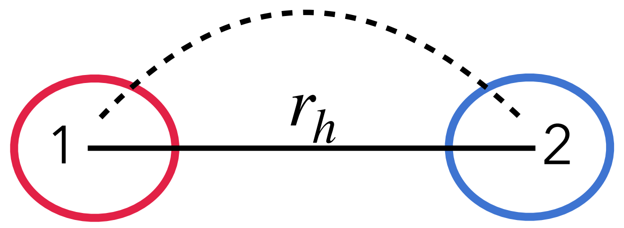
- Coordinate :

$$R^\mu = \frac{m_1 x_1^\mu + m_2 x_2^\mu}{m_1 + m_2}, \quad r^\mu = x_1^\mu - x_2^\mu,$$

$$P^\mu = p_1^\mu + p_2^\mu, \quad k^\mu = \frac{m_2 p_1^\mu - m_1 p_2^\mu}{m_1 + m_2}$$

At $k^2 = 0$, the Wigner function becomes maximal

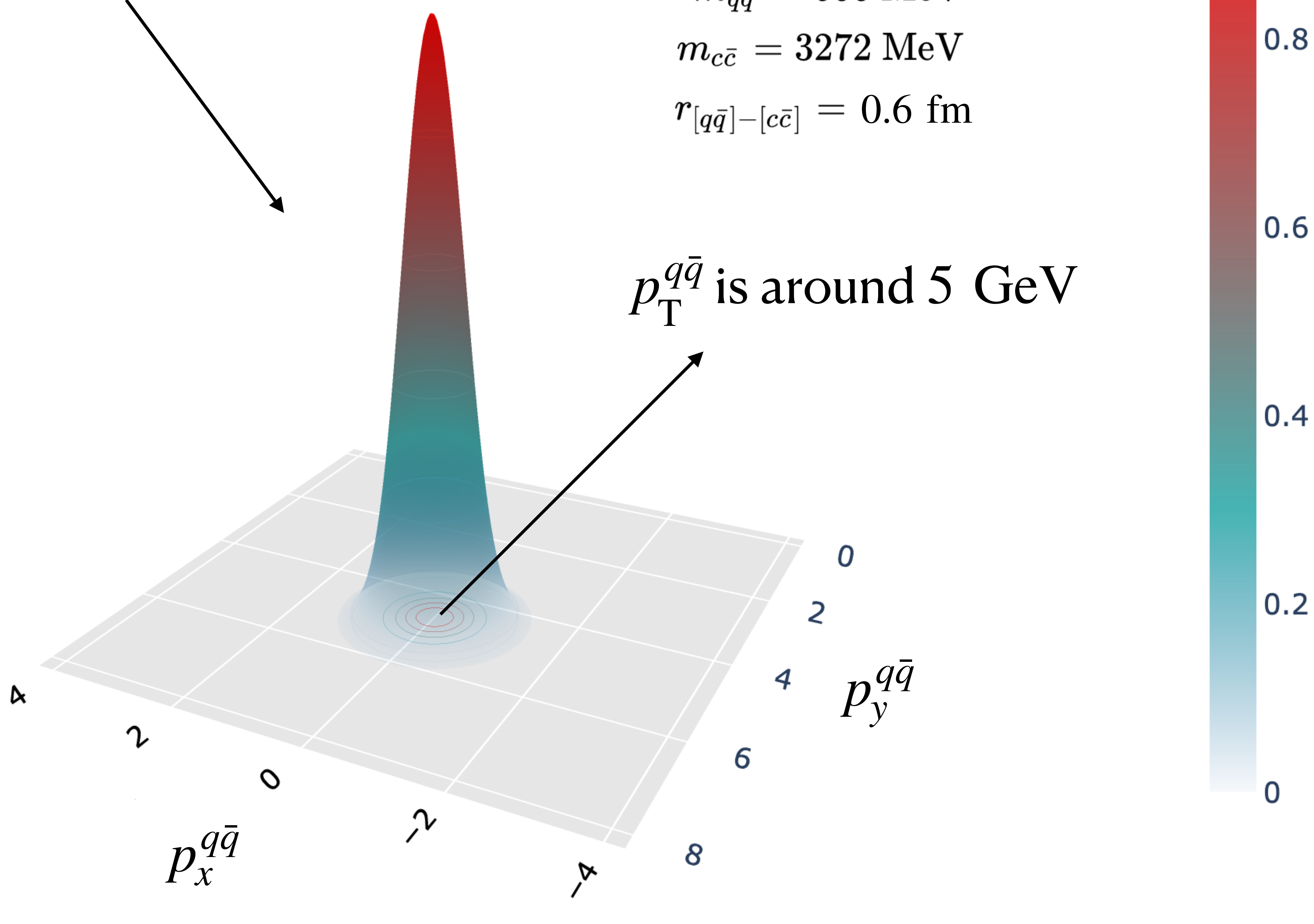
Due to the large mass difference between $c\bar{c}$ and $q\bar{q}$, high-$p_T$ $c\bar{c}$ can coalesce with low- $p_T$ $q\bar{q}$




$\langle r_h^2 \rangle = \frac{3}{2}\sigma^2$

$\exp(-\sigma^2 k^2)$,
$P_T^{X(3872)} = (0,30\ \text{GeV})$

$m_{q\bar{q}} = 600$ MeV
$m_{c\bar{c}} = 3272$ MeV
$r_{[q\bar{q}]-[c\bar{c}]} = 0.6$ fm



# Freeze out condition

## Wigner function and Lorentz boost effect

Lorentz transformation :

$$\Delta t' = \gamma(\Delta t - \beta r_x), \quad r_x' = \gamma(r_x - \beta \Delta t)$$

$$\Delta E' = \gamma(\Delta E - \beta k_x), \quad k_x' = \gamma(k_x - \beta \Delta E)$$

- Wigner function - $W(\vec{r},\vec{k}) = 4\exp\left[-\frac{r^2}{\sigma^2} - \sigma^2 k^2\right] \rightarrow 4\exp\left[-\frac{(r')^2}{\sigma^2} - \sigma^2 (k')^2\right]$

  Primed frame : CM frame

- Color octet formation time is longer than color singlet

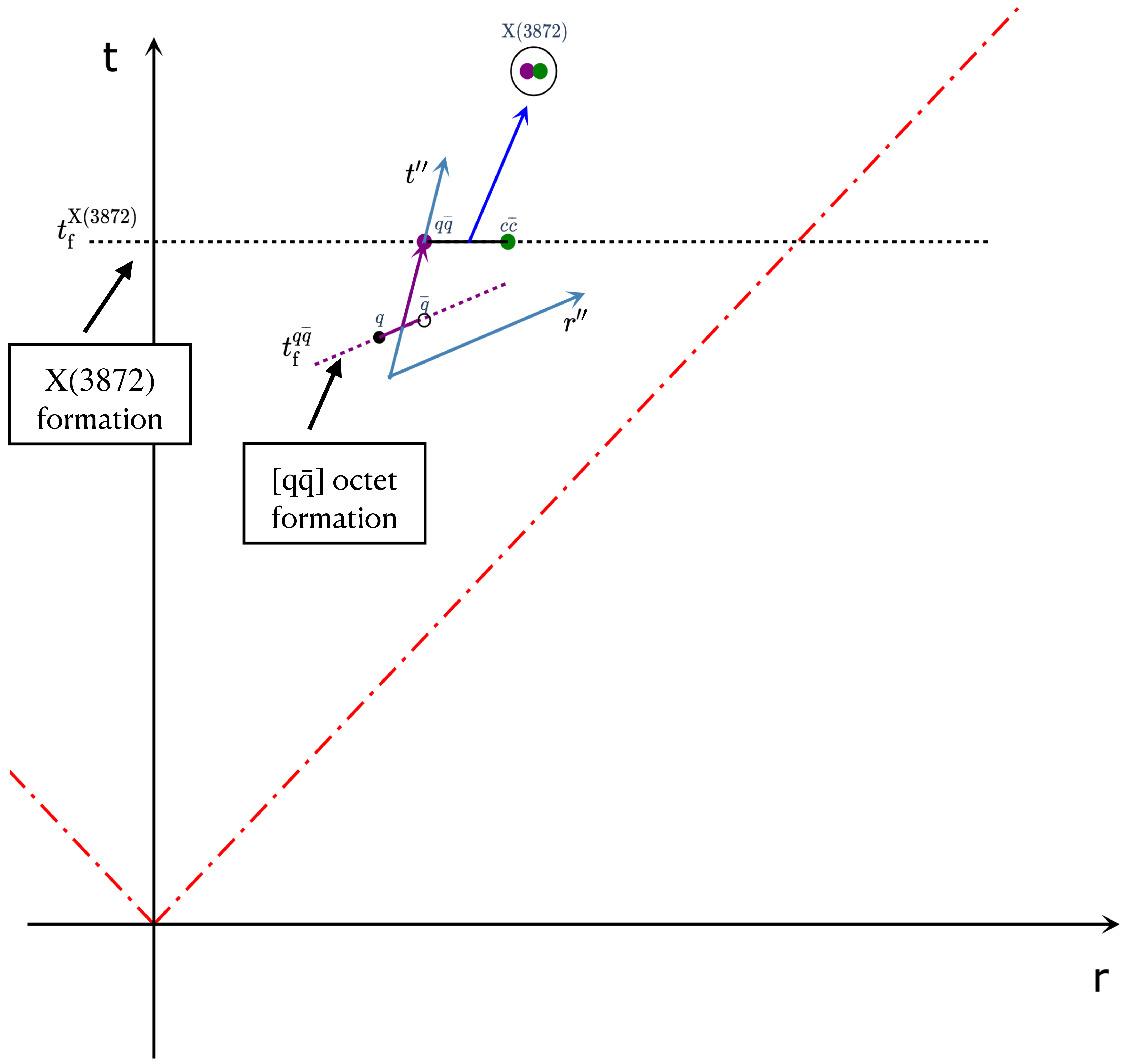
  Taesoo song, Che Ming Ko, Su Houng Lee, Phys.Rev.C 87, 034910 (2013),
  Jasmine Brewer, Wilke van der Schee, Ure Wiedemann, arXiv:2503.11764

  Color singlet hadron (short formation time)

  $$: W(\vec{r},\vec{k})_{X(3872)} = 4\exp\left[-\frac{\gamma^2 r^2}{\sigma^2} - \frac{\sigma^2 k^2}{\gamma^2}\right]$$

  Color octet state (with longer formation time than singlet)

  $$: W(\vec{r},\vec{k})_{[q\bar{q}]} = 4\exp\left[-\frac{r^2}{\gamma^2\sigma^2} - \frac{\sigma^2 k^2}{\gamma^2}\right]$$



# Parton and $q\bar{q}$ $p_T$ distribution

- Parton distribution at low $p_T$ ($p_T < 2.0$)

: Blast-wave model + Thermal model

- Blast-wave model - $p_T$ shape of parton

$$\frac{1}{p_T}\frac{dN}{dp_T} \sim m_T \int_0^R I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right) rdr,$$

$I_0(x),\ K_1(x)$ : Bessel function

$\rho = \tanh^{-1}\beta_r,\quad \beta_r = \left(\frac{r}{R}\right)^n \beta_s$

Parameter of blast-wave model
: ALICE Collaboration, Eur. Phys. J. C 80 (2020) 693

| Collision system | $T_k$ | $\langle\beta\rangle$ | $n$ |
|---|---|---|---|
| PbPb, 5.02 TeV | 113 MeV | 0.659 | 0.650 |

- Thermal model - Parton yield determination ($T_c = 156$ MeV)

$$N^{q \text{ or } \bar{q}}_{\text{PbPb}} = 616,\quad N^{g}_{\text{PbPb}} = 924$$

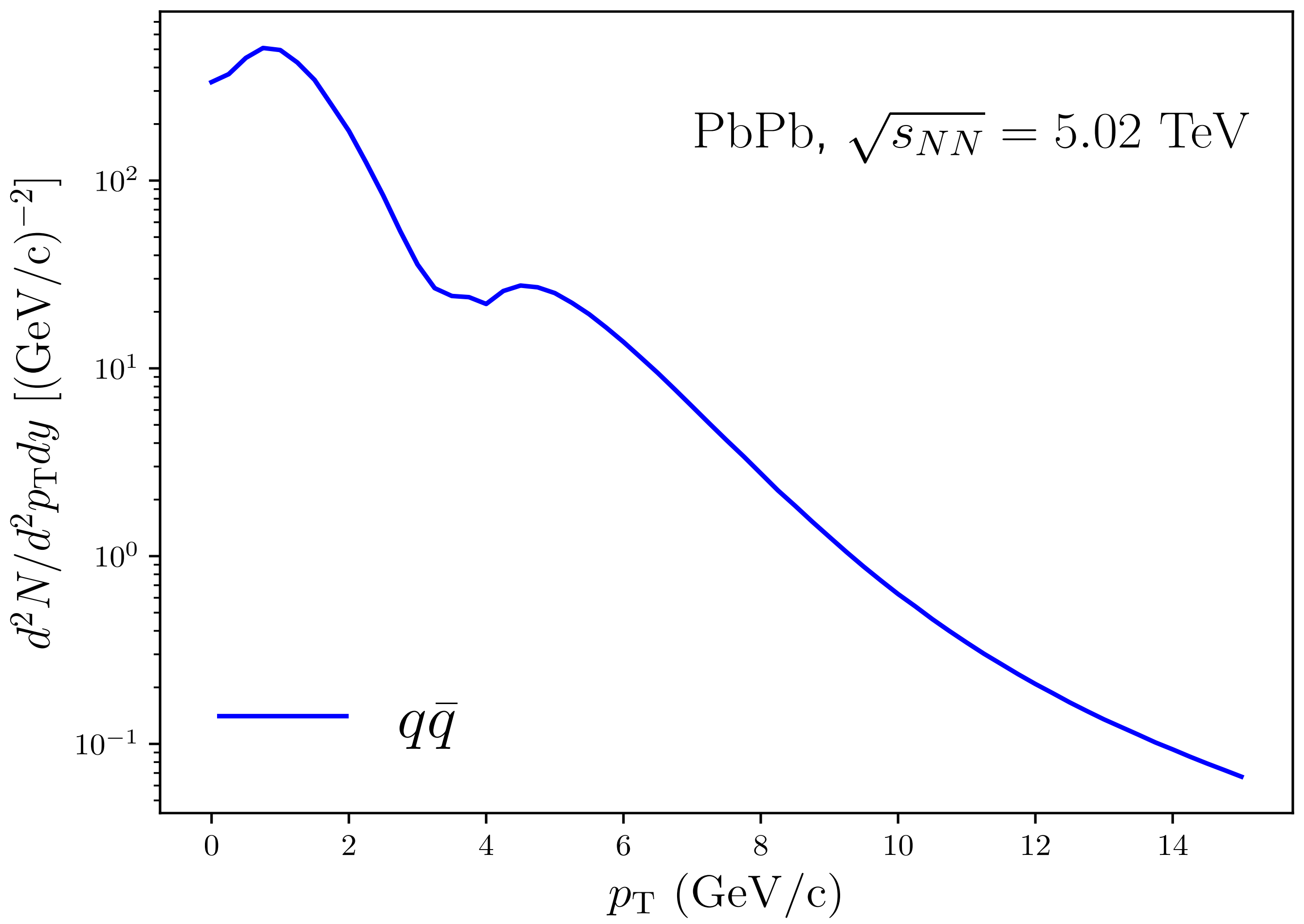
- Parton minijet ($p_T > 2.0$)

: pQCD + Glauber model (Eur. Phys. J.C (2018) 78:340)

$$\frac{dN^{u,d}_{jet}}{d^2p_T} = 24.68\left[1+\left(\frac{p_T}{5.11}\right)^2\right]^{-8.01} + 0.55\left[1+\left(\frac{p_T}{5.65}\right)^2\right]^{-2.56}$$

$$\frac{dN^{g}_{jet}}{d^2p_T} = 23.46\left[1+\left(\frac{p_T}{4.84}\right)^2\right]^{-8.08} + 2.78\left[1+\left(\frac{p_T}{2.79}\right)^2\right]^{-2.31}$$

**$q\bar{q}$ $p_T$ distribution (2 body coalescence)**



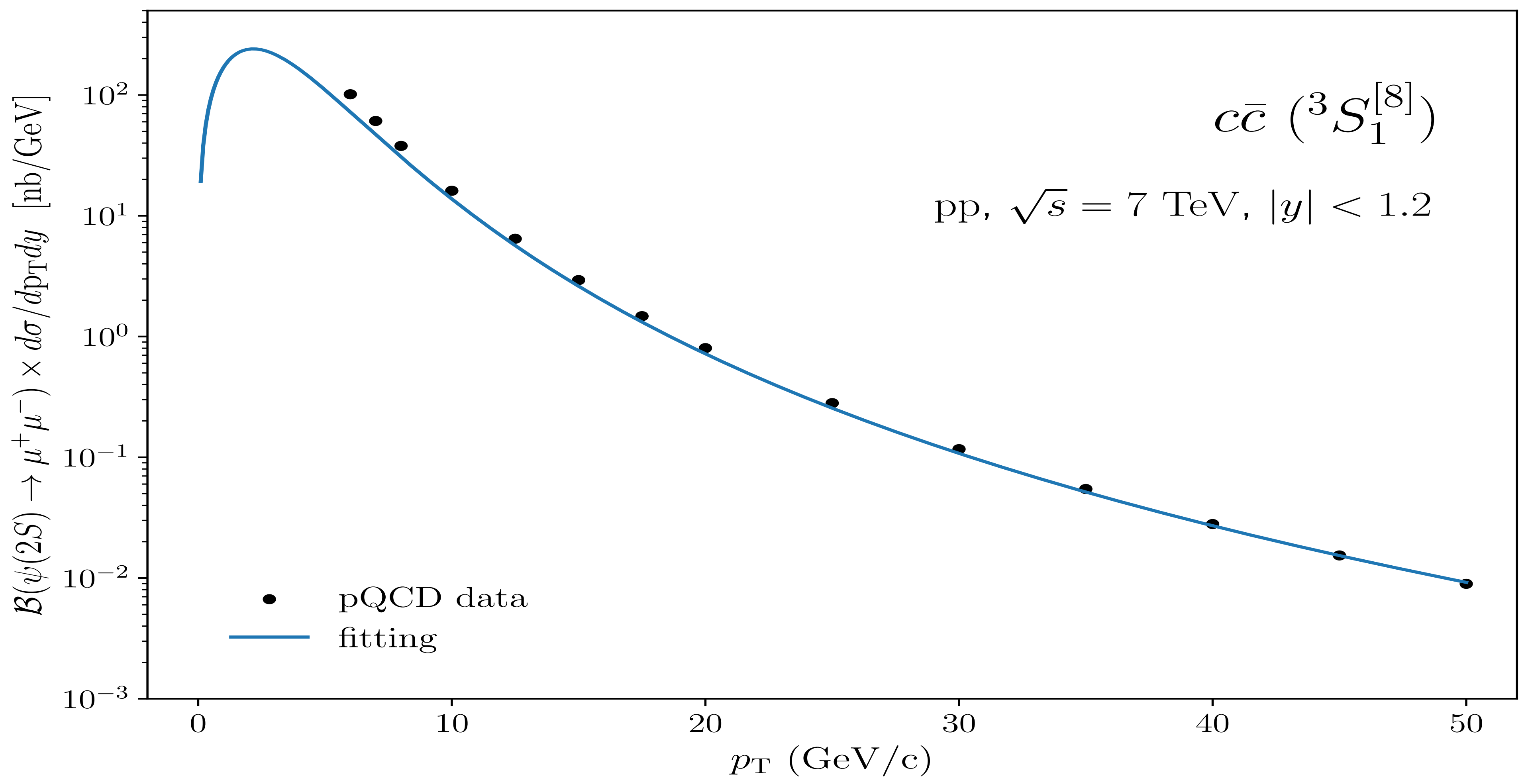
# $c\bar{c}$ octet $p_T$ distribution

## perturbative QCD

- $c\bar{c}$ octet cross section in pp collision (*JHEP* 03 (2023) 242 )

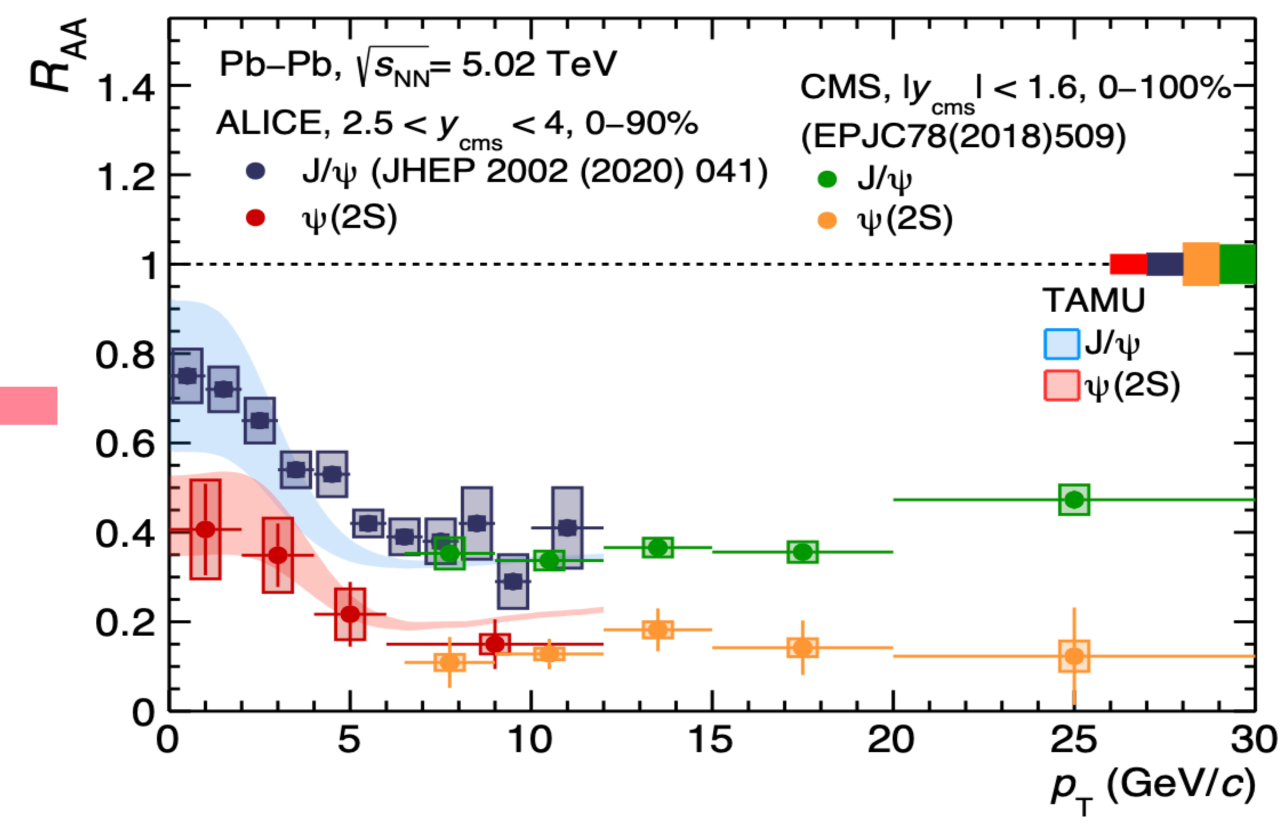
$$\frac{d\sigma^{[c\bar{c}(^3S_1^{[8]})]}}{dp_T dy} = \frac{1}{\langle \mathcal{O}^{\psi(2S)}_{[c\bar{c}(^3S_1^{[8]})]}\rangle} \frac{d\sigma^{[c\bar{c}(^3S_1^{[8]})] \to \psi(2S)}}{dp_T dy},$$

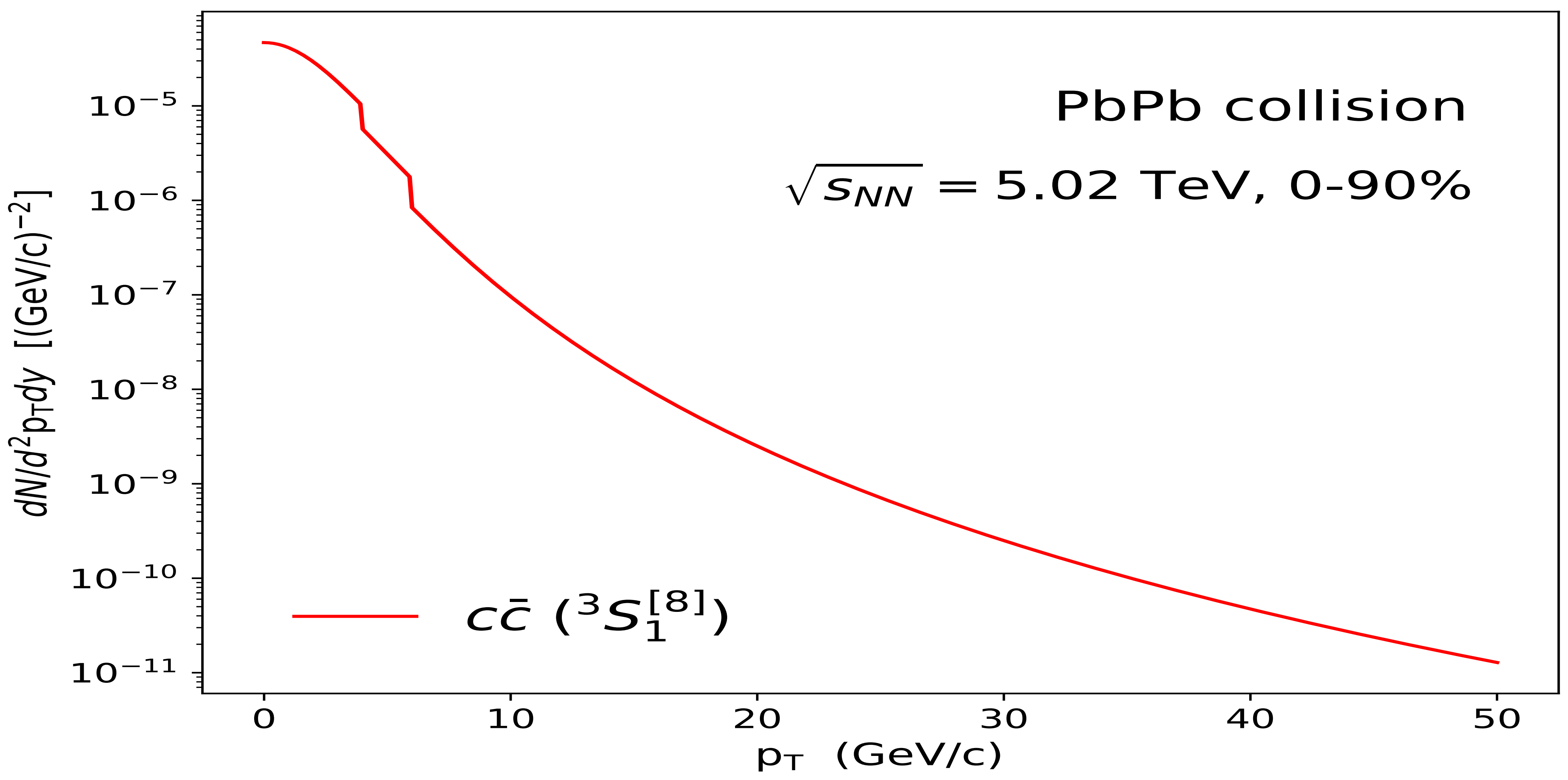
$$\langle \mathcal{O}^{\psi(2S)}_{[c\bar{c}(^3S_1^{[8]})]}\rangle = 0.96 \times 10^{-2}\ \mathrm{GeV}^3$$




- Nuclear modification factor (ALICE Collaboration, Phys. Rev. Lett. 132 (2024) 042301)

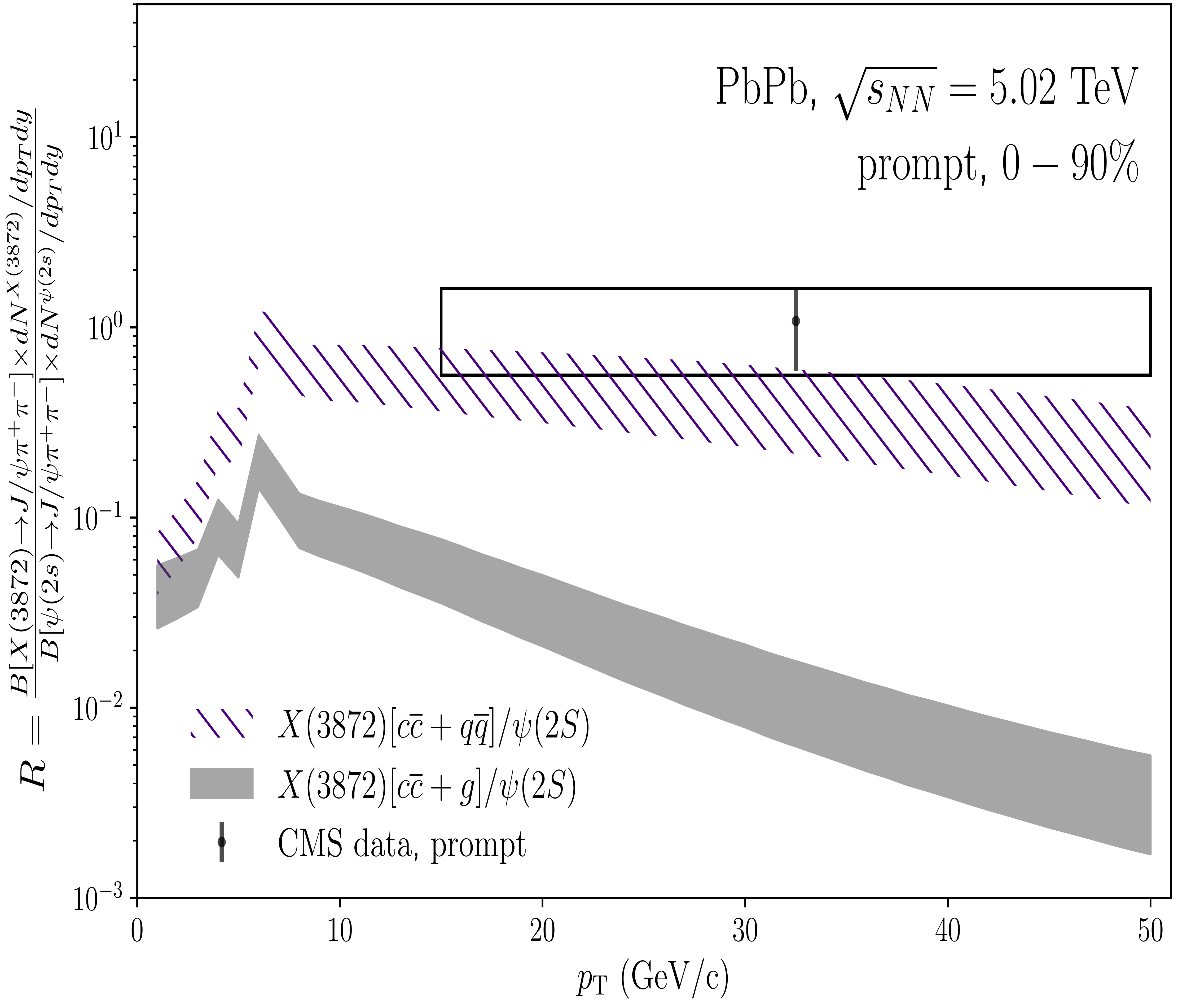
$$R_{AA} = \begin{cases} 0.35\ (p_T < 4) \\ 0.2\ \ (4 \le p_T < 6) \\ 0.1\ \ (6 \le p_T) \end{cases}$$



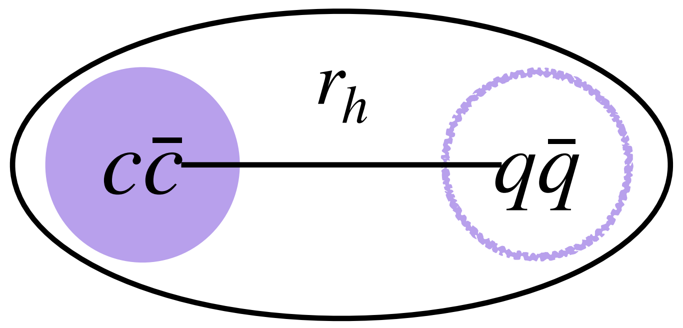



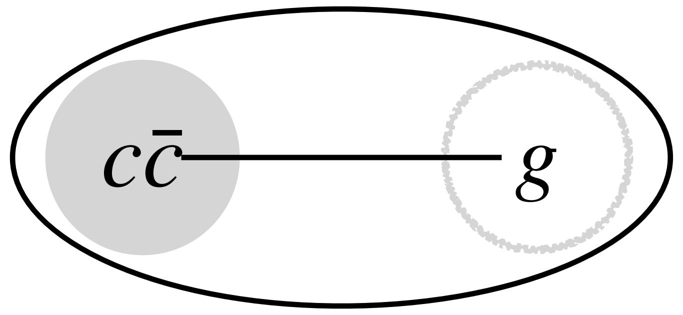
# X(3872)/$\psi$(2S) ratio

## PbPb collision




X(3872) — $([c\bar{c}]+[q\bar{q}])$ / $([c\bar{c}]+g)$




$$\frac{dN_{X(3872)}}{d^2P_T} = g_{X(3872)}(2\sqrt{\pi}\sigma)^2\frac{1}{A}\int d^2p_{q\bar{q}T}d^2p_{c\bar{c}T}\,\frac{dN_{q\bar{q}}}{d^2p_{q\bar{q}T}}\frac{dN_{c\bar{c}}}{d^2p_{c\bar{c}T}}$$
$$\times \exp\left(-\sigma^2|\mathbf{k}'|^2\right)\delta^{(2)}(\mathbf{P}_T-\mathbf{p}_{q\bar{q}T}-\mathbf{p}_{c\bar{c}T})$$

- Parameter

$m_{[c\bar{c}]} = 3272$ MeV, $m_{[q\bar{q}]} = 600$ MeV, $m_g = 600$ MeV

$r_h^{[q\bar{q}]} = 6$ fm, $r_h^{[q\bar{q}\text{ or }g]-[c\bar{c}]} = 0.6$ fm, $A = 565$ fm$^2$

| Scenario | Calculation result | Agreement with Data |
|---|---|---|
| Molecule | Similar pt dependence | ✓ |
| Hybrid | Underpredicts | ✗ |

# Summary

- We investigated the production of X(3872) in PbPb collisions using the coalescence model.
- Two scenarios of X(3872) were considered:

  - A loosely bound $D\bar{D}^*$ ([$q\bar{q}$] + [$c\bar{c}$]) molecular state

  - A hybrid state of $c\bar{c}$ and gluon
- Result:

  - Molecular scenario: consistent with experimental data

  - Hybrid scenario: underestimates the observed yield