Molecular structure hadron in coalescence model

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SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

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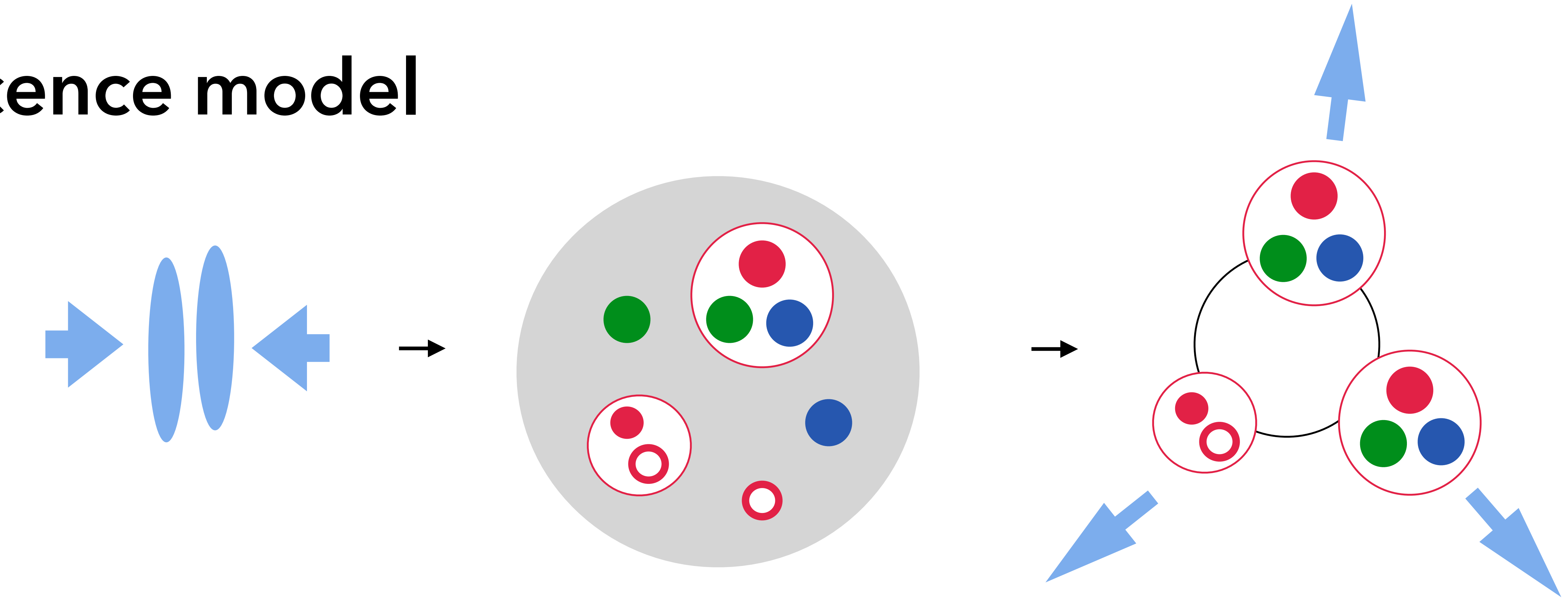
3. Summary

Coalescence model

2-dimension coalescence model



- The yields of produced hadron in transverse plane

$$N_h = g_h \int \prod_{i=1}^{N} d^2x_i d^2p_i \ f_i(x_i, p_i) W(r_1, \cdots r_{N-1}, k_1, \cdots, k_{N-1})$$

- Hadron transverse momentum distribution

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

- Normalization condition

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

Coalescence model

2-body coalescence

$d \;:\; p+n$

$X(3872) \;:\; D+\bar{D}^*$

S. Cho, K. J. Sun, C. M. Ko, S. H. Lee, Y. Oh, Phys. Rev. C 101, 024909 (2020)

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

$\vec{r}'$ ($\vec{k}'$) : relative distance (momentum) of constituent in center of mass frame of produced hadron

·Constituent distribution : $f(x_i, p_i) = \frac{d^2N_i}{A_L d^2p_{iT}}$

Lorentz transformation

$$\Delta t' = \gamma(\Delta t - \beta r_x), \quad r'_x = \gamma(r_x - \beta\Delta t)$$
$$\Delta E' = \gamma(\Delta E - \beta k_x), \quad k'_x = \gamma(k_x - \beta\Delta E)$$

·Coordinate :

$$R^\mu = \frac{x_1^\mu + x_2^\mu}{2}, \quad r^\mu = x_1^\mu - x_2^\mu,$$
$$P^\mu = p_1^\mu + p_2^\mu, \quad k^\mu = \frac{p_1^\mu - p_2^\mu}{2}$$

$$\frac{d^2N_h}{d^2P_T} = \frac{g_h}{g_1g_2}(2\sqrt{\pi})^2\sigma^2\frac{1}{A}\int d^2p_1^2p_2\ \frac{d^2N_1}{d^2p_{1T}}\frac{d^2N_2}{d^2p_{2T}}\exp\left[-\sigma^2(k')^2\right]\delta^{(2)}(P_T - p_{1T} - p_{2T}), \quad (\sigma = 2r)$$

- In $\sigma \to \infty$ limit, Wigner function : $W(\vec{r}, \vec{k}) = 4\left(\frac{\pi}{\sigma^2}\right)e^{-\frac{r'^2}{\sigma^2}} \times \delta^{(2)}(\vec{k}')$

$$\frac{d^2N_h}{d^2P_T} = \frac{g_h}{g_1g_2}(2\pi)^2\left(\frac{\gamma}{A}\right)\frac{d^2N_1}{d^2p_{1T}}\Big|_{\vec{p}_{1T}=\frac{\vec{P}_T}{2}}\frac{d^2N_2}{d^2p_{2T}}\Big|_{\vec{p}_{2T}=\frac{\vec{P}_T}{2}}$$

Coalescence model

3-body coalescence

$^3He \ : \ p+p+n$

$\cdot$Wigner function : $W(\vec{r}, \vec{k}) = 4^2 \exp\left[-\frac{(r_1')^2}{\sigma_1^2} - \sigma_1^2 (k_1')^2\right] \exp\left[-\frac{(r_2')^2}{\sigma_2^2} - \sigma_2^2 (k_2')^2\right]$

$\cdot$ Coordinate : $R^\mu = \frac{x_1^\mu + x_2^\mu + x_3^\mu}{3}, \quad r_1^\mu = x_1^\mu - x_2^\mu, \quad r_2^\mu = \frac{x_1^\mu + x_2^\mu}{2} - x_3^\mu$

$P^\mu = p_1^\mu + p_2^\mu, \quad k_1^\mu = \frac{p_1^\mu - p_2^\mu}{2}, \quad k_2^\mu = \frac{p_1^\mu + p_2^\mu - 2p_3^\mu}{3}$

Lorentz transformation : $\begin{matrix} \Delta t'_{1,2} = \gamma(\Delta t_{1,2} - \beta r_{1,2}) \\ r'_{1,2} = \gamma(r_{1,2} - \beta \Delta t_{1,2}) \end{matrix}, \quad \begin{matrix} \Delta E'_{1,2} = \gamma(\Delta E_{1,2} - \beta k_{1,2}) \\ k'_{1,2} = \gamma(k_{1,2} - \beta \Delta E_{1,2}) \end{matrix}.$

$$\frac{d^2N_h}{d^2P_T} = \frac{g_h}{g_1 g_2 g_3}(2\sqrt{\pi})^4(\sigma_1\sigma_2)^2 \frac{1}{A^2} \int d^2p_1^2 p_2 d^2 p_3 \ \frac{d^2N_1}{d^2p_{1T}} \frac{d^2N_2}{d^2p_{2T}} \frac{d^2N_3}{d^2p_{3T}} \exp\left[-\sigma_1^2(k_1')^2 - \sigma_2^2(k_2')^2\right] \delta^{(2)}(P_T - p_{1T} - p_{2T} - p_{3T})$$

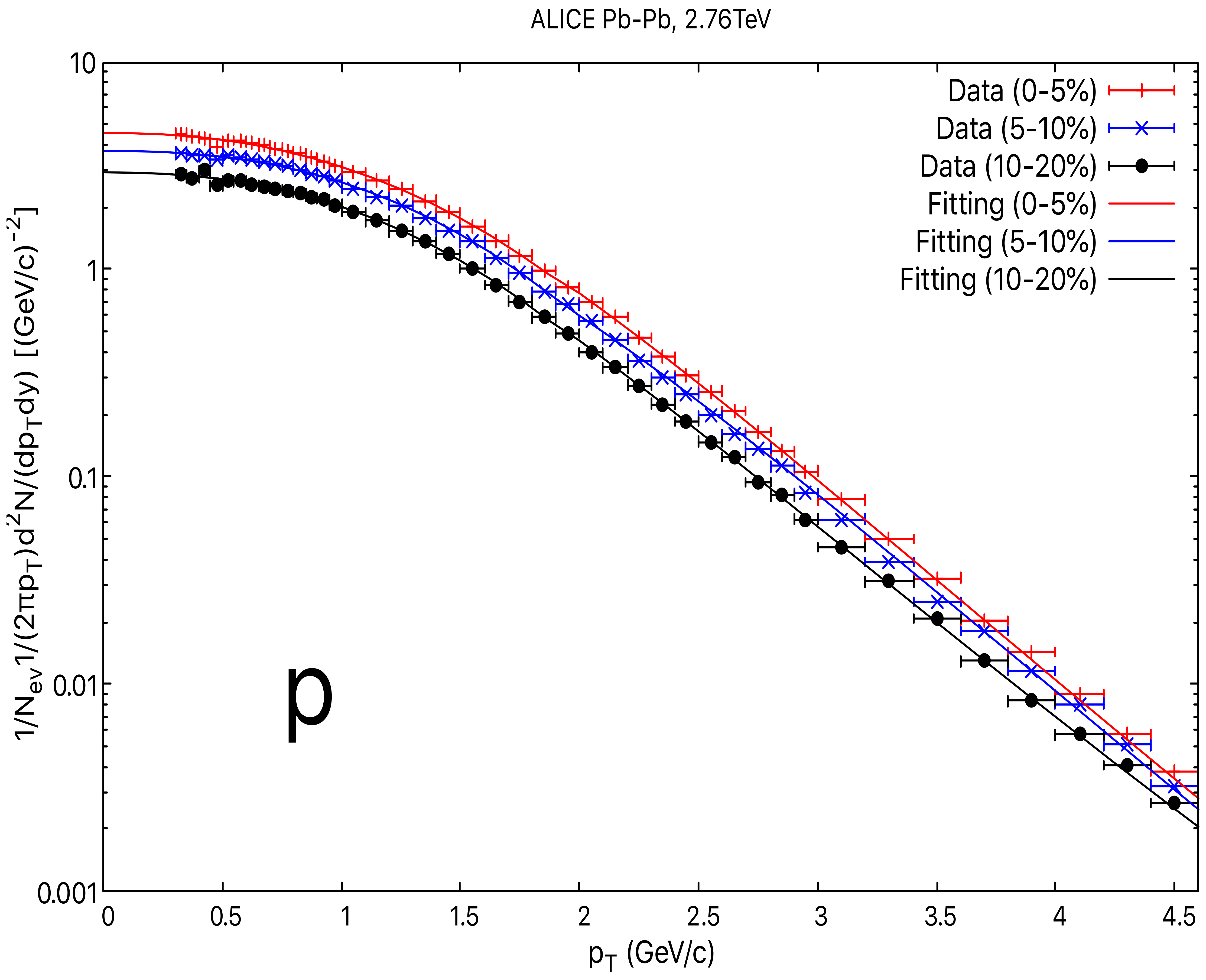
In $\sigma \to \infty$ limit, $\quad \frac{d^2N_h}{d^2P_T} = \frac{g_h}{g_1 g_2 g_3}(2\pi)^4 \left(\frac{\gamma}{A}\right)^2 \frac{d^2N_1}{d^2p_{1T}}\Big|_{\vec{p}_{1T}=\frac{\vec{P}_T}{3}} \frac{d^2N_2}{d^2p_{2T}}\Big|_{\vec{p}_{2T}=\frac{\vec{P}_T}{3}} \frac{d^2N_3}{d^2p_{3T}}\Big|_{\vec{p}_{3T}=\frac{\vec{P}_T}{3}}$

Deuteron and helium-3

Proton distribution and Feed-down

Pb-Pb collisions at 2.76TeV

- Fitting (ALICE Collaboration, Phys. Rev. C 88, 044910)



- Feed-down (Pb-Pb collisions, 2.76TeV)

  - Experimental data : $dN^{p}_{0-10\%}/dy = 31 \pm 1.8$

  - Statistical hadronization model,

    $N,\ \Delta\ \rightarrow\ p$ contribution

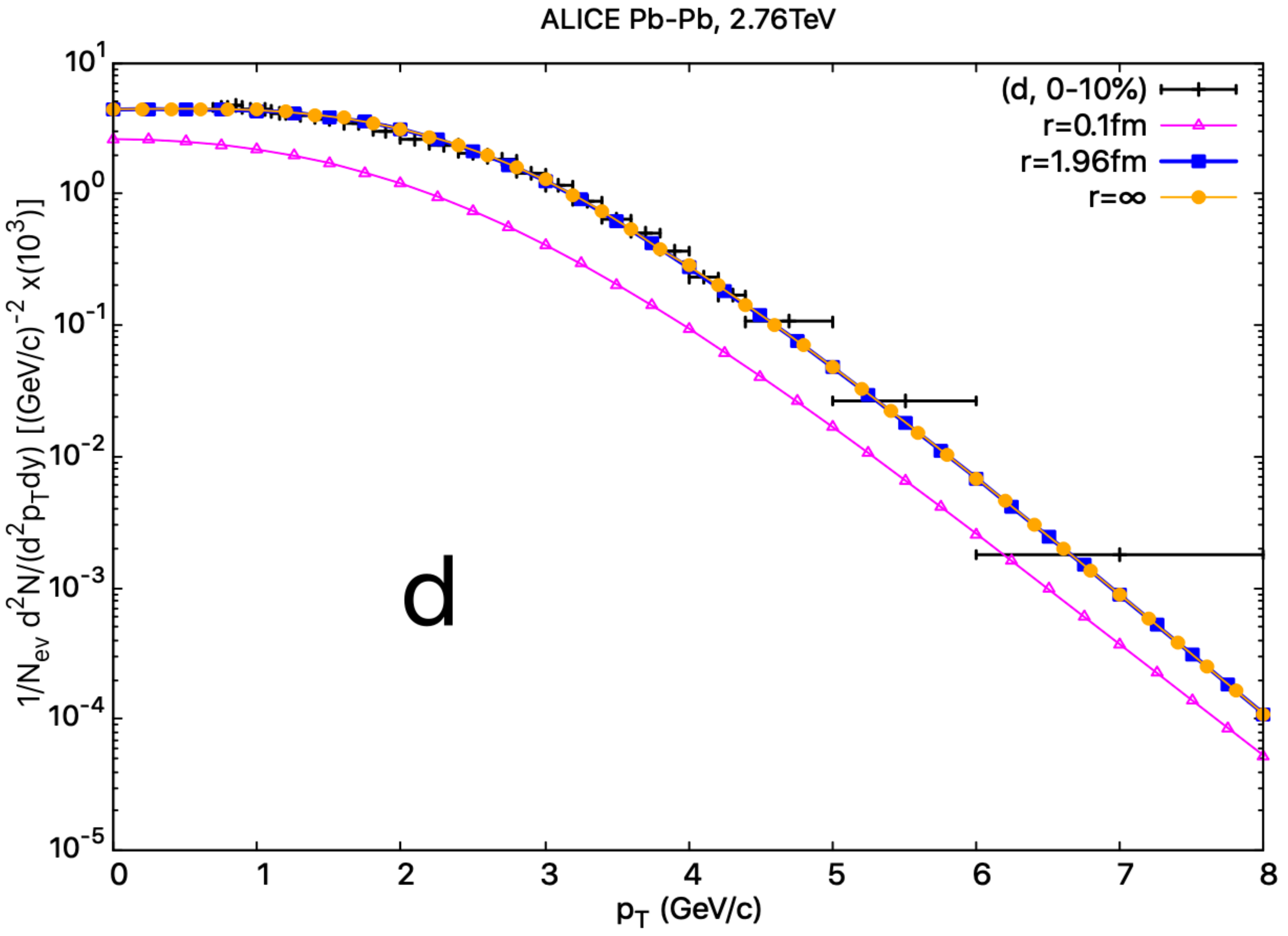
    $N^{p}_{stat} = 11.42,\ N^{N}_{stat} = 10.56,\ N^{\Delta}_{stat} = 28.66,\ \frac{10.56 + 28.66}{2} + 11.42 = 31$

  - 36.8% protons participate in coalescence at kinetic freeze-out

Deuteron and helium-3 p_T distribution

Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76TeV

- Experimental Data - ALICE Collaboration, Eur. Phys. J. C (2017) 77:658



- 2-body formula

1. $$\frac{d^2N_d}{d^2P_T} = \frac{g_d}{g_p g_n}(2\sqrt{\pi})^2\sigma^2\frac{1}{A}\int d^2p_p d^2p_n \frac{d^2N_p}{d^2p_{pT}}\frac{d^2N_n}{d^2p_{nT}}\exp\left[-\sigma^2(k')^2\right] \times \delta^{(2)}(P_T - p_{pT} - p_{nT})$$

2. $$\frac{d^2N_d}{d^2P_T}\ (\sigma \to \infty) = \frac{g_d}{g_p g_n}(2\pi)^2\left(\frac{\gamma}{A}\right)\frac{d^2N_p}{d^2p_{pT}}\Big|_{\vec{p}_{pT}=\frac{\vec{P}_T}{2}}\frac{d^2N_n}{d^2p_{nT}}\Big|_{\vec{p}_{nT}=\frac{\vec{P}_T}{2}}$$

- Parameter

$$\sigma = 2r, \quad r = 1.96fm, \quad A_{0-10\%} = 608fm^2$$

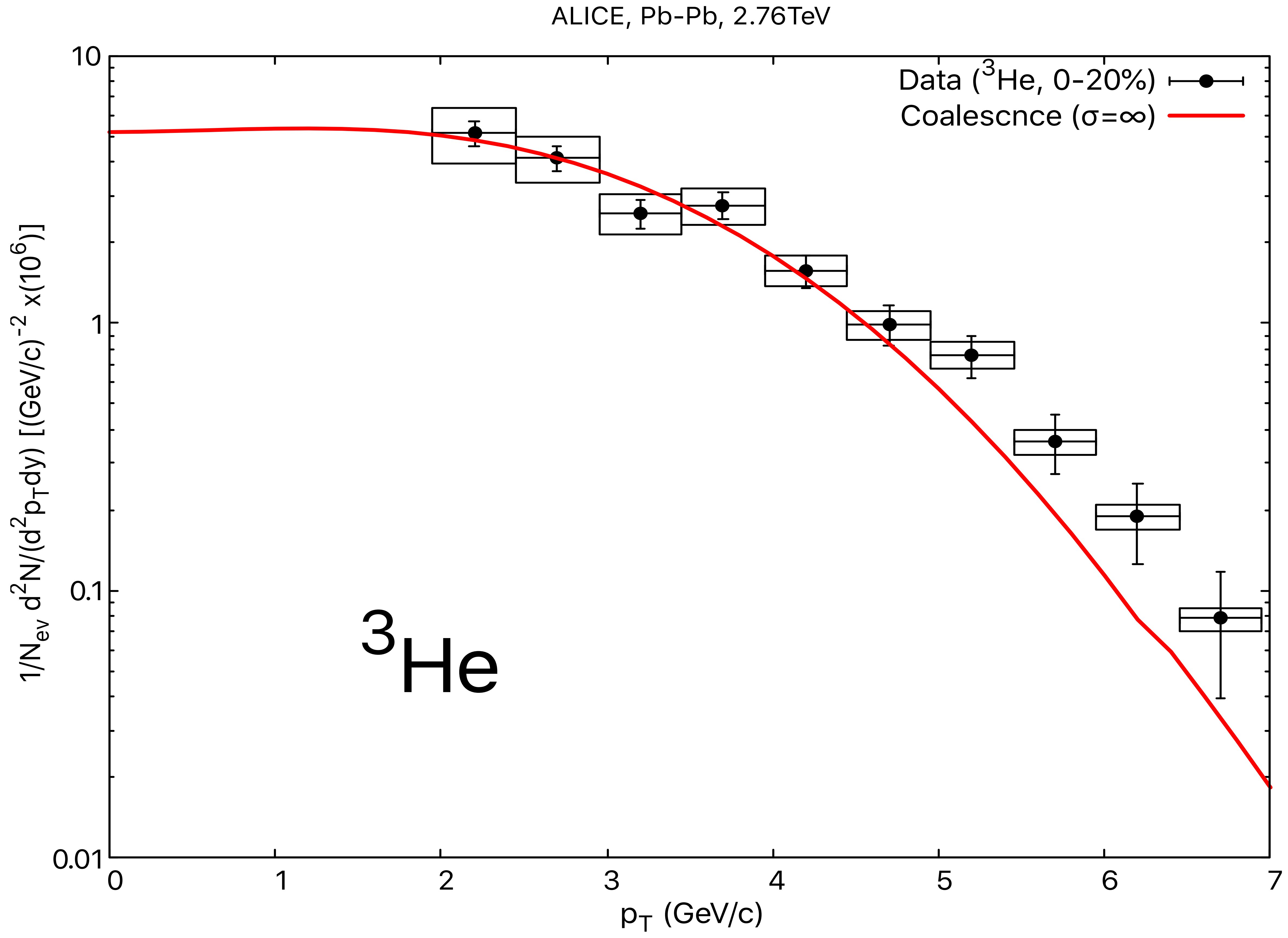
- Yield

$$\frac{N^{coal}_{d,\ 0-10\%}}{N^{stat}_{d,\ 0-10\%}} = 0.971$$

Deuteron and helium-3 p_T distribution

Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76TeV

- Experimental Data - ALICE Collaboration, Phys. Rev. C 93, 024917 (2016)



- 3-body formula

$$\frac{d^2N_{^3He}}{d^2P_T} = \frac{g_{^3He}}{g_p g_p g_n}(2\pi)^4\left(\frac{\gamma}{A}\right)^2 \frac{d^2N_p}{d^2p_{pT}}\Big|_{\vec{p}_{pT}=\frac{\vec{P}_T}{3}} \frac{d^2N_p}{d^2p_{pT}}\Big|_{\vec{p}_{pT}=\frac{\vec{P}_T}{3}} \frac{d^2N_n}{d^2p_{nT}}\Big|_{\vec{p}_{nT}=\frac{\vec{P}_T}{3}}$$

No feed-down $\rightarrow$ $$\frac{d^2N_{^3He}}{d^2p_T dy} = 0.368 \times \frac{g_{^3He}}{g_p g_p g_n}(2\pi)^4\left(\frac{\gamma}{A}\right)^2 \frac{d^2N_p}{d^2p_T dy}\frac{d^2N_p}{d^2p_T dy}\frac{d^2N_n}{d^2p_T dy}$$

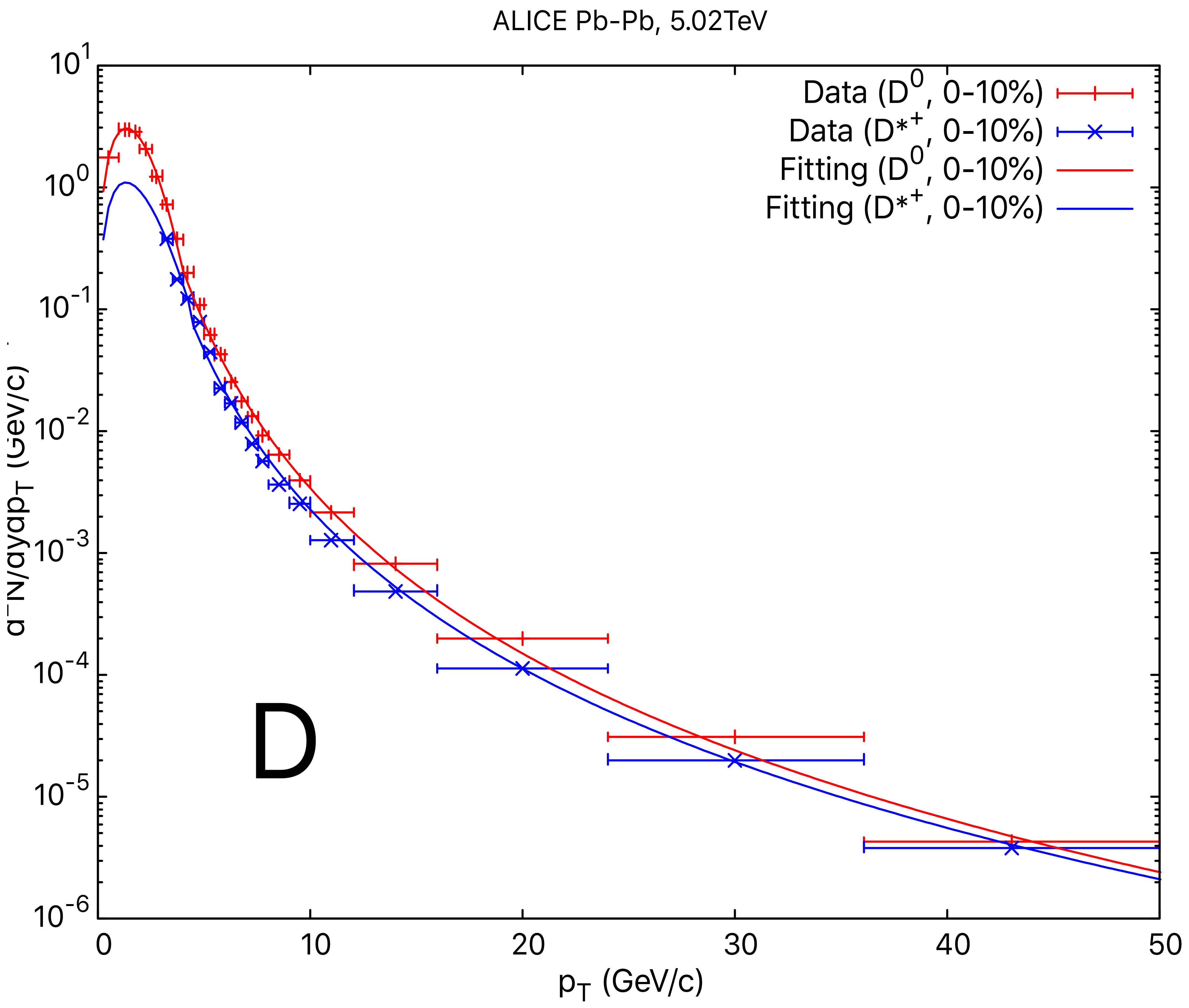
Can not explain the experiment result

X(3872) and T_{cc}

D meson distribution and Feed-down

Pb-Pb collisions at 5.02TeV

- Fitting (ALICE Collaboration, JHEP 01 (2022) 174)



- Feed-down (Pb-Pb collisions, 5.02TeV)
  - Experimental data : $dN^{D^0}_{0-10\%}/dy = 6.819 \pm 0.457(stat.)^{+0.912}_{-0.936}(syst.)$
  - Decay channel

    $Br(D*(2007)^0 \to D^0\pi^0) = (64.7 \pm 0.9)\,\%$

    $Br(D*(2007)^0 \to D^0\gamma) = (35.3 \pm 0.9)\,\%$

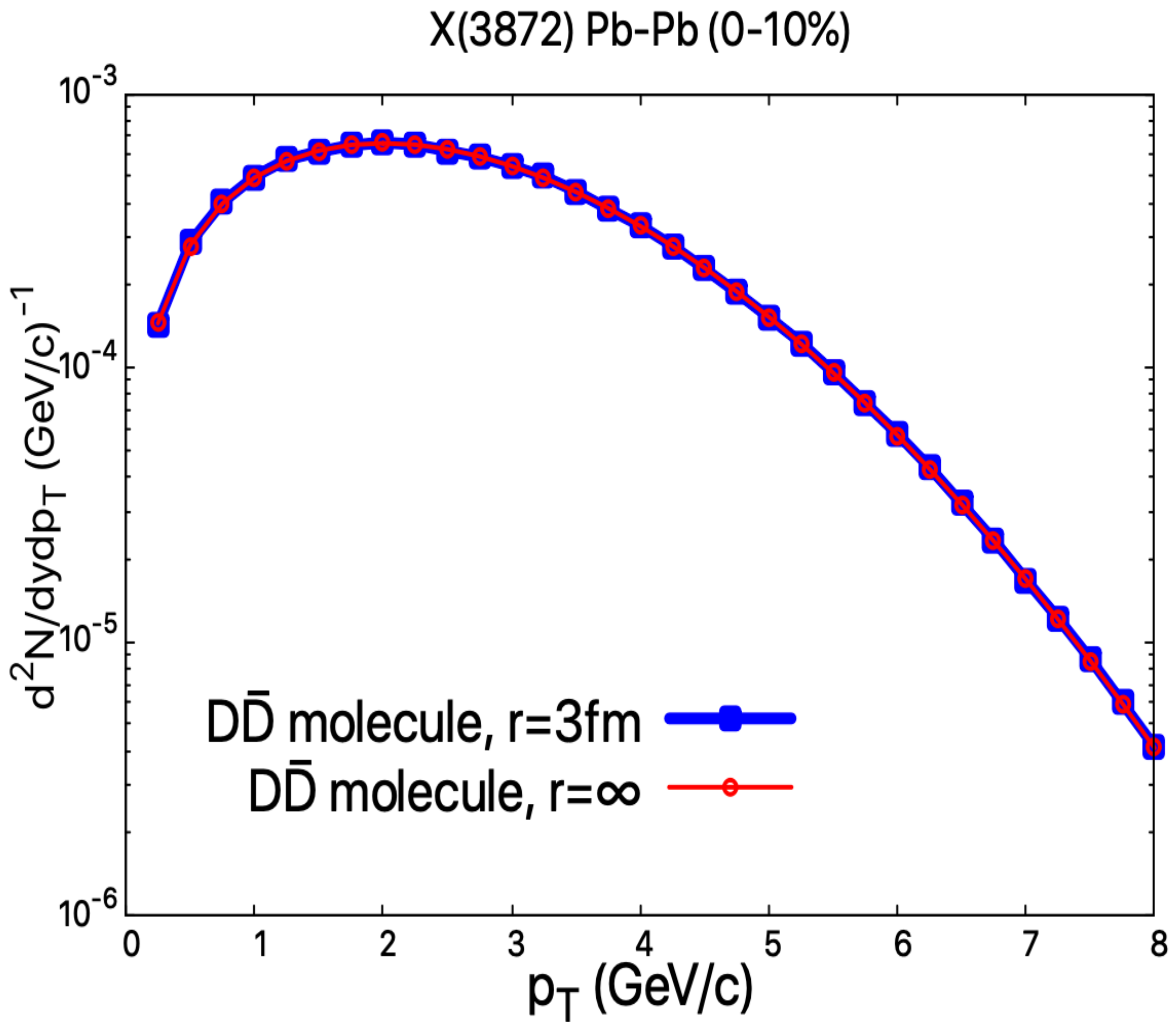
    $Br(D*(2010)^+ \to D^0\pi^+) = (67.7 \pm 0.5)\,\%$

  - From Statistical model, 31% D^0 participate in coalescence at kinetic freeze-out

X(3872) p_T distribution

$X(3872)\ :\ D + \bar{D}^*$

Pb-Pb collisions at 5.02TeV



- $$\frac{d^2N_{X(3872)}}{d^2P_T} = \frac{g_X}{g_{D^0}g_{\bar{D}^*}}(2\sqrt{\pi})^2\sigma^2\frac{1}{A}\int d^2p_{D^0}d^2p_{\bar{D}^*}\,\frac{d^2N_{D^0}}{d^2p_{D^0T}}\frac{d^2N_{\bar{D}^*}}{d^2p_{\bar{D}^*T}}\exp\left[-\sigma^2(k')^2\right] \times \delta^{(2)}(P_T - p_{D^0T} - p_{\bar{D}^*T})$$
- $$\frac{d^2N_{X(3872)}}{d^2P_T}\ (\sigma \to \infty)\ = \frac{g_X}{g_{D^0}g_{\bar{D}^*}}(2\pi)^2\left(\frac{\gamma}{A}\right)\frac{d^2N_{D^0}}{d^2p_{D^0T}}\Big|_{\vec{p}_{D^0T}=\frac{\vec{P}_T}{2}}\frac{d^2N_{\bar{D}^*}}{d^2p_{\bar{D}^*T}}\Big|_{\vec{p}_{\bar{D}^*T}=\frac{\vec{P}_T}{2}}$$

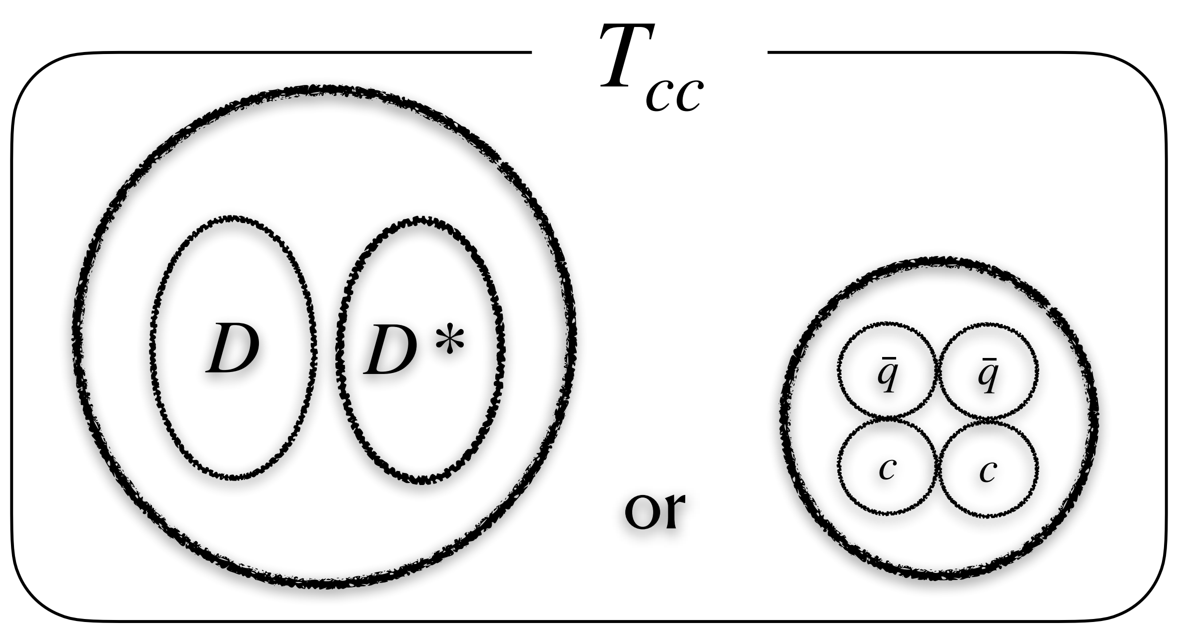
$$N^{coal}_{X-D\bar{D}} = 1.794 \times 10^{-3}$$

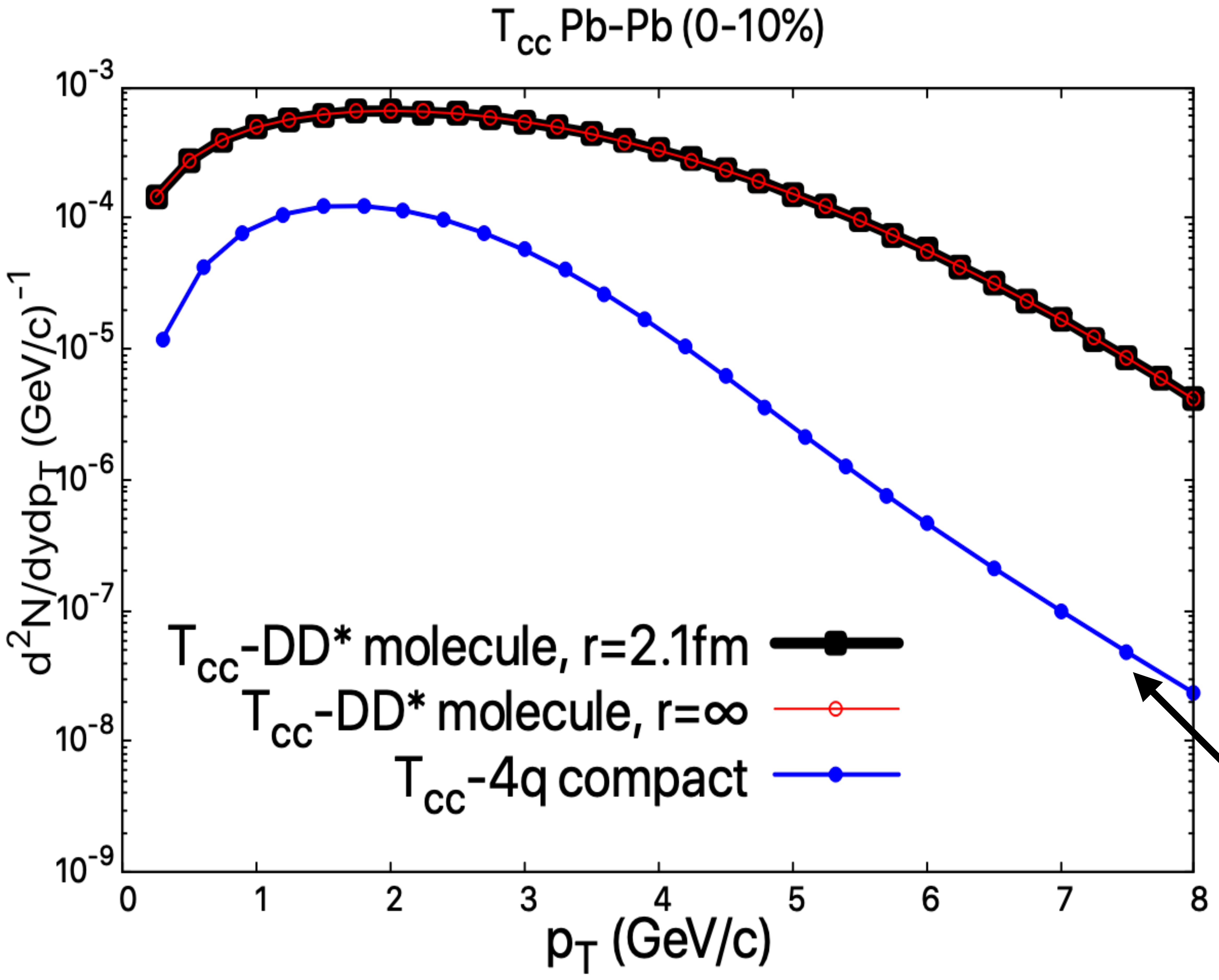
D. Park, A. Park, S. Noh and S. H. Lee, in preparation

Radius	X(3872)
Molecule	3fm
Compact 4-quark	Not possible

T_{cc} p_T distribution

Pb-Pb collisions at 5.02TeV





T_{cc} : Molecule or Compact 4-quark

D. Park, A. Park, S. Noh and S. H. Lee, in preparation

Radius	Tcc
Molecule	2.1fm
Compact 4-quark	0.433fm

S. Noh, W. Park and S.H. Lee, Phys.Rev. D 103, 114009 (2021)

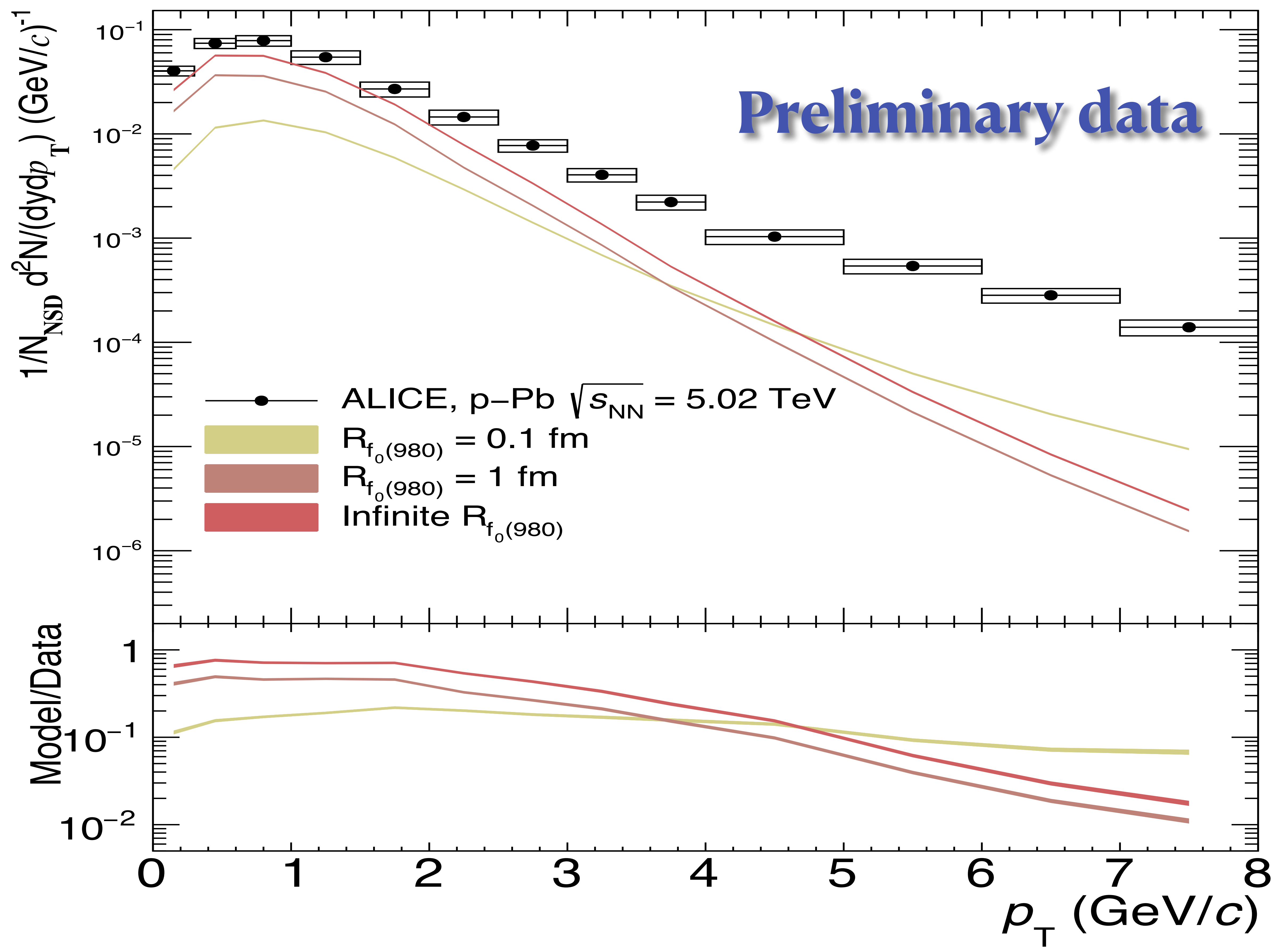
S. H. Lee and S. Cho, Phys. Rev. C 101, 024902
+ in preparation

f_0(980) p_T distribution

p-Pb collisions at 5.02TeV (NSD event)

$f_0(980) \;:\; K^+ + K^-$

- ALICE preliminary data (S.H. Lim, E.J. Kim, B.K. kim and J. Kim)



$$\frac{d^2N_{f_0(980)}}{d^2P_T} = \frac{g_{f_0(980)}}{g_{K^+}g_{K^-}}(2\sqrt{\pi})^2\sigma^2\frac{1}{A}\int d^2p_{K^+}d^2p_{K^-}\,\frac{d^2N_{K^+}}{d^2p_{K^+T}}\frac{d^2N_{K^-}}{d^2p_{K^-T}}\exp\left[-\sigma^2(k')^2\right] \times \delta^{(2)}(P_T - p_{K^+T} - p_{K^-T})$$

$$\frac{d^2N_{f_0(980)}}{d^2P_T}(\sigma\to\infty) = \frac{g_{f_0(980)}}{g_{K^+}g_{K^-}}(2\pi)^2\left(\frac{\gamma}{A}\right)\frac{d^2N_{K^+}}{d^2p_{K^+T}}\Big|_{\vec{p}_{K^+T}=\frac{\vec{P}_T}{2}}\frac{d^2N_{K^-}}{d^2p_{K^-T}}\Big|_{\vec{p}_{K^-T}=\frac{\vec{P}_T}{2}}$$

f_0(980) is not $K\bar{K}$ molecular structure

or

System is too small

Summary

- We study the transverse momentum distribution of loosely-bound molecular configuration hadron.
- The $\sigma \to \infty$ limit coalescence model explained deuteron and helium-3 distribution well.
- We assume that $X(3872)$ is $D\bar{D}*$ molecular structures and estimate the transverse momentum distributions using the same formula as deuteron.
- T_{cc} - compact 4-quark state or $DD*$ molecule. By measuring p_T distribution from heavy ion collisions, the structure of T_{cc} could be known.