Production of molecular structure hadron

in Pb-Pb collisions

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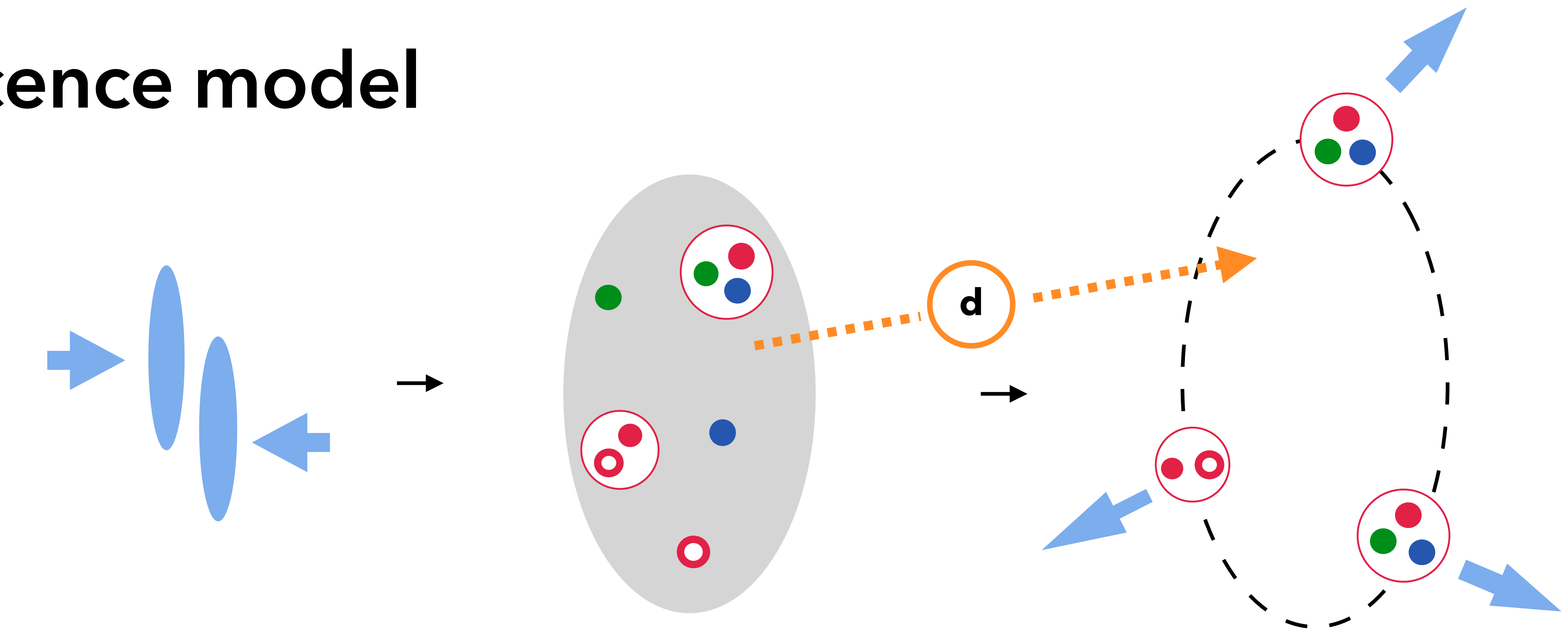
3. Summary

Coalescence model

2-dimension coalescence model



- The yields of produced hadron

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

- 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

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

Coalescence model

2-body coalescence

$d \ : \ p + n$

$X(3872) \ : \ D^* + \bar{D}^0$

$T_{cc} \ : \ D + D^*$

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

A_L : Coalescence area at kinetic freeze-out point in Lab frame

Lorentz transformation

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

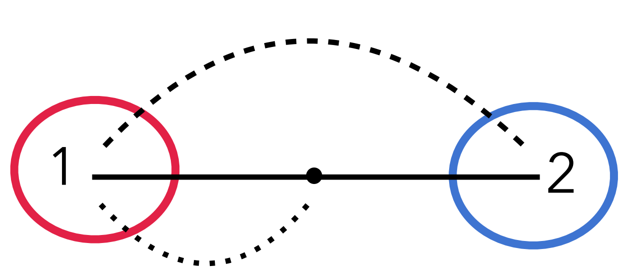
$$\Delta E' = \gamma(\Delta E - \beta k_x), \quad k'_x = \gamma(k_x - \beta \Delta E)$$

·Coordinate : $R^\mu = \frac{x_1^\mu + x_2^\mu}{2}, \quad r^\mu = x_1^\mu - x_2^\mu,$

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

$$\frac{d^2 N_h}{d^2 P_T} = \frac{g_h}{g_1 g_2} (2\sqrt{\pi})^2 \sigma^2 \frac{1}{A} \int d^2 p_1^2 p_2 \frac{d^2 N_1}{d^2 p_{1T}} \frac{d^2 N_2}{d^2 p_{2T}} \exp\left[-\sigma^2 (k')^2\right] \delta^{(2)}(P_T - p_{1T} - p_{2T}), \quad \langle r^2 \rangle = \frac{3}{2}\sigma^2 \rightarrow \langle r_h^2 \rangle = \frac{3}{8}\sigma^2$$

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



$$\frac{d^2 N_h}{d^2 P_T} = \frac{g_h}{g_1 g_2} (2\pi)^2 \left(\frac{\gamma}{A}\right) \frac{d^2 N_1}{d^2 p_{1T}} \Big|_{\vec{p}_{1T} = \frac{\vec{P}_T}{2}} \frac{d^2 N_2}{d^2 p_{2T}} \Big|_{\vec{p}_{2T} = \frac{\vec{P}_T}{2}}$$

Coalescence model

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

3-body coalescence

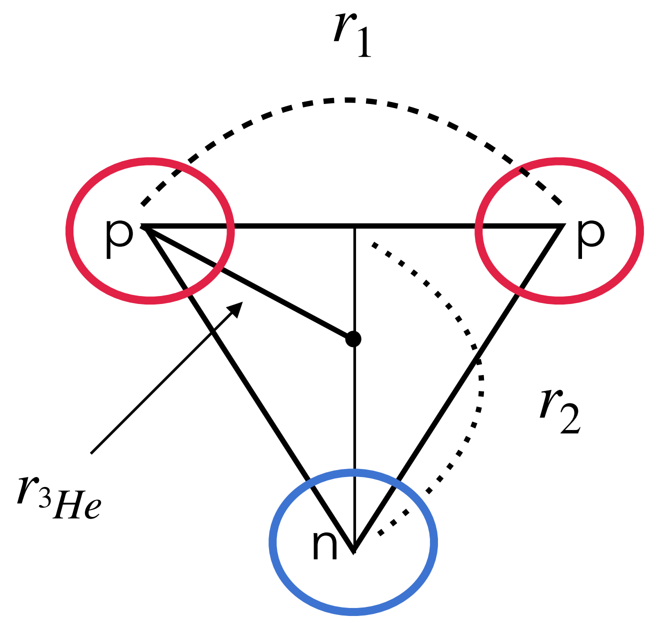
·Wigner function : $W(\vec{r}, \vec{k}) = 4^2 \exp\left[-\frac{(r_1')^2}{\sigma_1^2} - \sigma_1^2 (k_1')^2\right] \exp\left[-\frac{(r_2')^2}{\sigma_2^2} - \sigma_2^2 (k_2')^2\right]$

· 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 :
$$\Delta t_{1,2}' = \gamma(\Delta t_{1,2} - \beta r_{1,2}) \quad \Delta E_{1,2}' = \gamma(\Delta E_{1,2} - \beta k_{1,2})$$
$$r_{1,2}' = \gamma(r_{1,2} - \beta \Delta t_{1,2})' \quad k_{1,2}' = \gamma(k_{1,2} - \beta \Delta E_{1,2}).$$

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

$$\langle r_i^2 \rangle = \frac{3}{2}\sigma_i^2$$



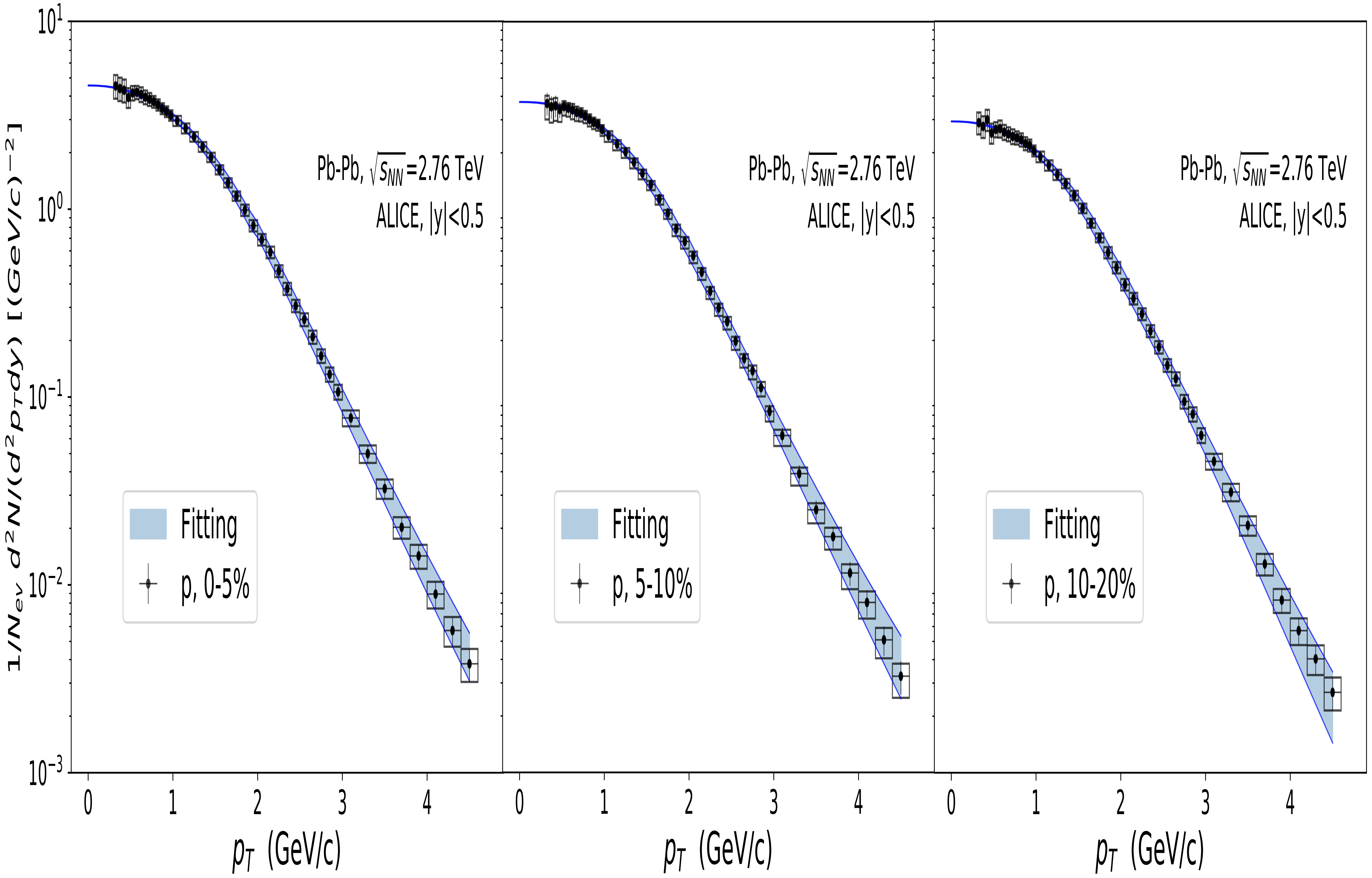
In $\sigma \to \infty$ limit, $\frac{d^2N_h}{d^2P_T} = \frac{g_h}{g_1 g_2 g_3}(2\pi)^4 \left(\frac{\gamma}{A}\right)^2 \frac{d^2N_1}{d^2p_{1T}}\Big|_{\vec{p}_{1T}=\frac{\vec{P}_T}{3}} \frac{d^2N_2}{d^2p_{2T}}\Big|_{\vec{p}_{2T}=\frac{\vec{P}_T}{3}} \frac{d^2N_3}{d^2p_{3T}}\Big|_{\vec{p}_{3T}=\frac{\vec{P}_T}{3}}$

d and ^{3}He in Pb-Pb at $\sqrt{s_{NN}}$=2.76TeV

Proton p_T distribution

Pb-Pb collisions at 2.76TeV

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



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

Measured proton data includes the feed-down contribution (N, Δ, $etc.$)

- $\frac{d^2N_p}{d^2p_T}|_{t=t_k} = R_b \frac{d^2N_p}{d^2p_T}|_{Exp}$

$$\left(R_b = \frac{\text{the number of proton at formation point}}{\text{the number of final proton}}\right)$$

R_b can be determined using deuteron and helium-3 data ($R_b = 0.368$)

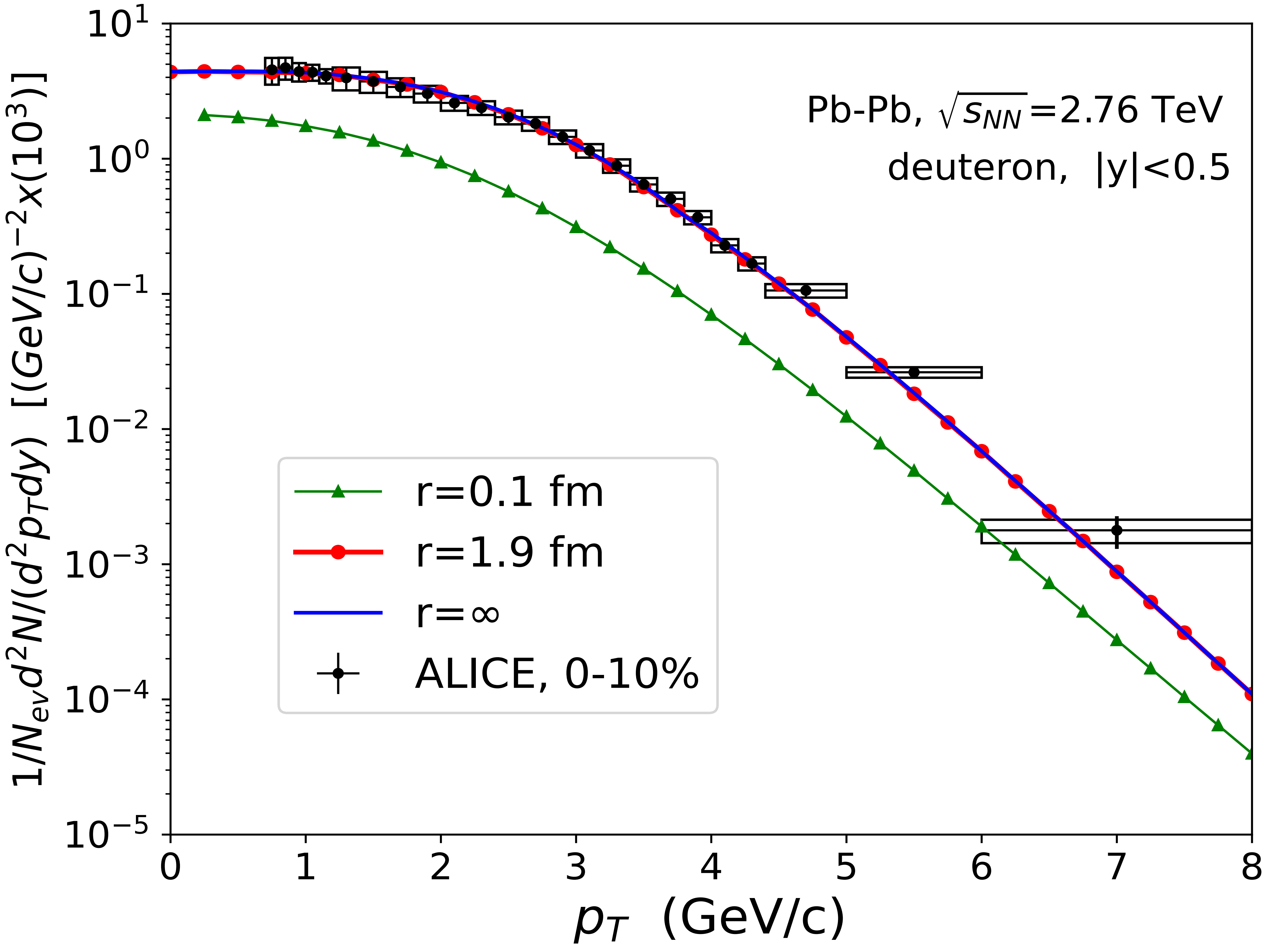
→ 36.8% of the measured p participate in coalescence

R_b is close to the result of statistical hadronization model

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

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

- Parameter

G. Röpke, Phys. Rev. C 79 (2009) 014002

$$\sigma = \sqrt{8/3}\,r_d,\ r_d \sim 1.9fm,\ R_b = 0.368,\ A_{0-10\%} = 608fm^2$$

- Yield

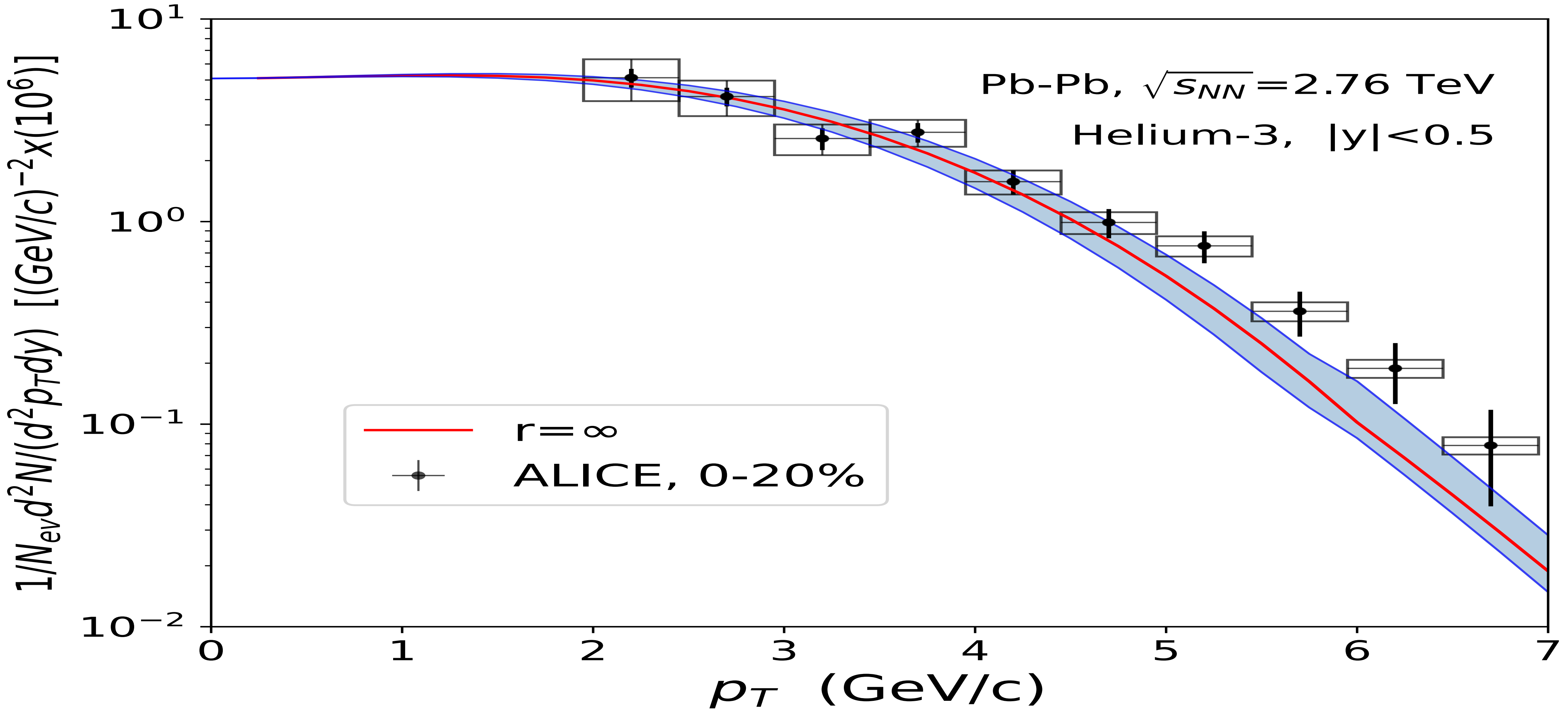
$$\frac{N^{coal}_{d,\,0-10\%}}{N^{stat}_{d,\,0-10\%}} = 0.97$$

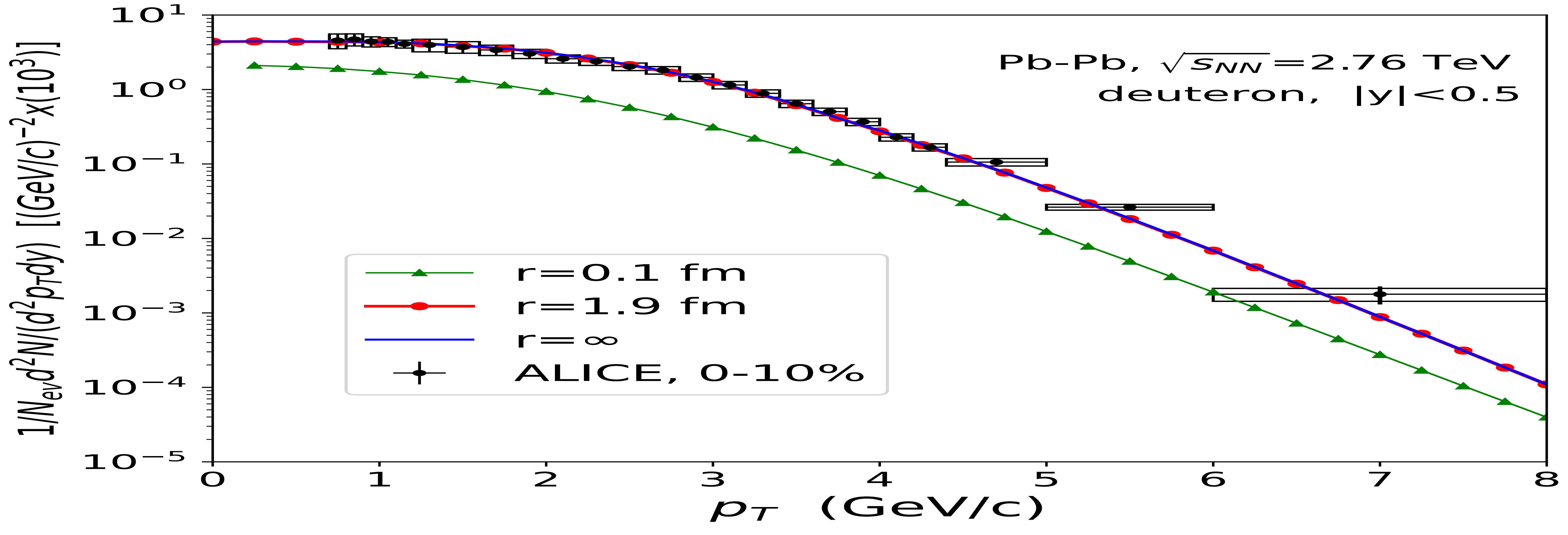
Helium-3 p_T distribution and consistency of the parameters (R_b, A)

$$\frac{d^2N}{d^2p_T}|_{t=t_k} = R_b \frac{d^2N}{d^2p_T}|_{Exp}$$

$$R_b = \frac{\textit{the number of proton at formation point}}{\textit{the number of final proton}}$$

- Phys. Rev. C 93, 024917 (2016)





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

When $R_b \rightarrow \alpha R_b$,

$$\frac{d^2N_d}{d^2p_T} \sim \frac{R_b^2}{A} \rightarrow \frac{\alpha^2R_b^2}{\alpha^2A}, \qquad \frac{d^2N_{^3He}}{d^2p_T} \sim \frac{R_b^3}{A^2} \rightarrow \frac{\alpha^3R_b^3}{\alpha^4A^2}$$

Determine A and R_b correctly
($R_b = 0.368$, $A_{0-10\%} = 608fm^2$)

→

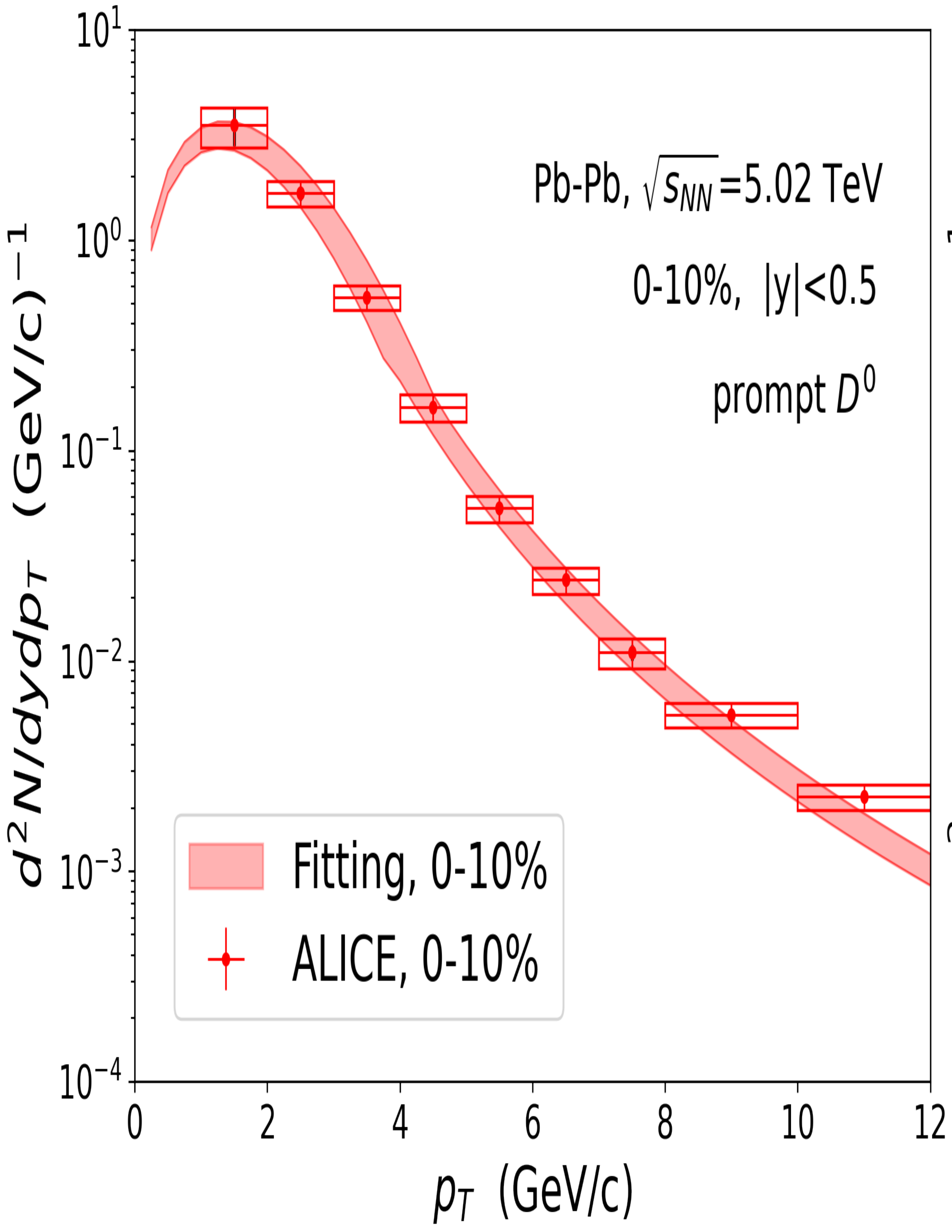
d and ^3He can be explained simultaneously

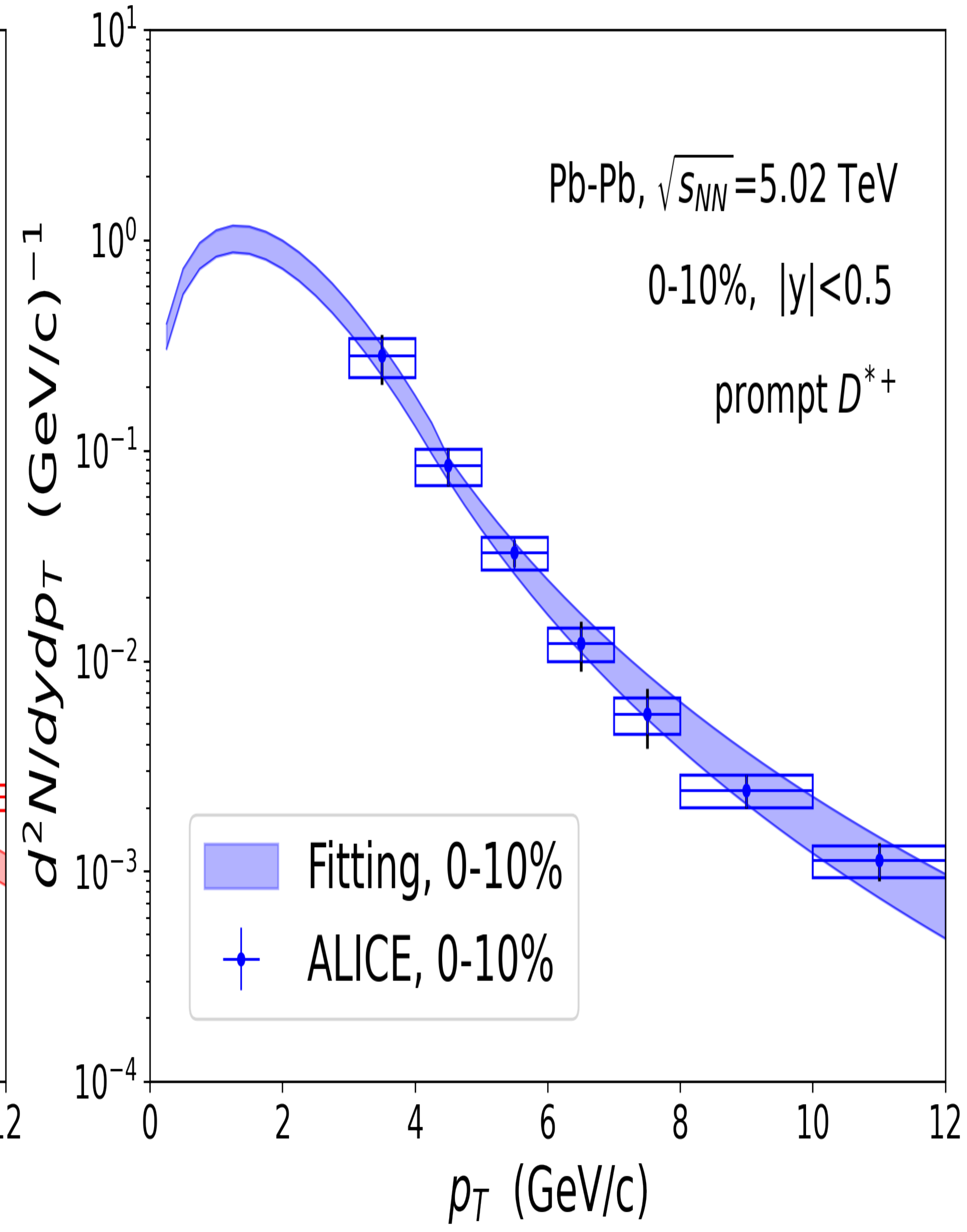
$X(3872)$ and T_{cc} in Pb-Pb at $\sqrt{s_{NN}}$=5.02TeV

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

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

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

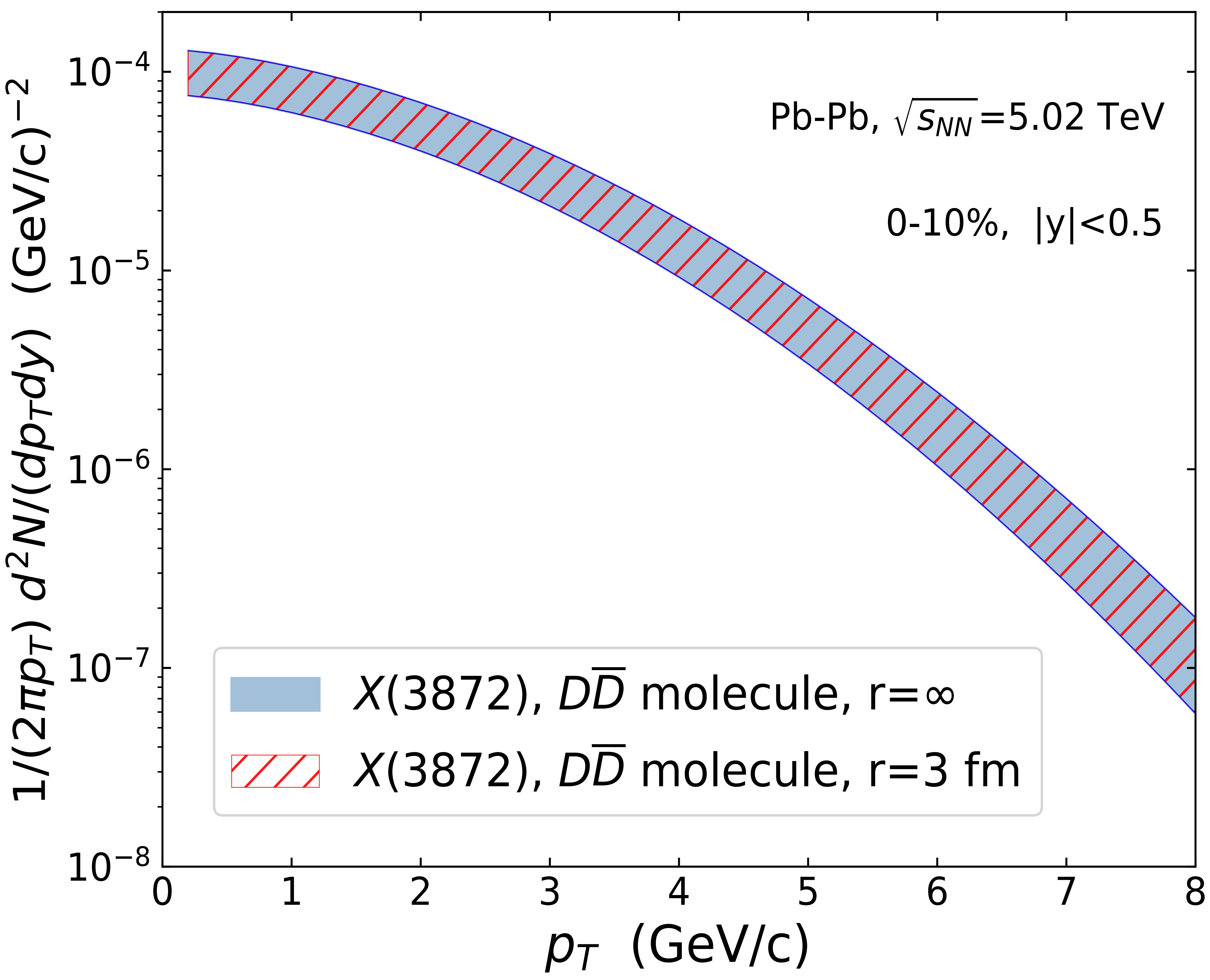
  $Br(D*(2010)^+ \rightarrow D^0\pi^+) = (67.7 \pm 0.5)\,\%$

- From Statistical hadronization model, 31% of measured D^0 participate in coalescence

X(3872) p_T distribution

Pb-Pb collisions at 5.02TeV

$X(3872)\ :\ D^* + \bar{D}^0$



$$\frac{d^2N_{X(3872)}}{d^2P_T} = g_X(2\sqrt{\pi})^2\sigma^2\left(\frac{R_b^2}{A}\right)\int d^2p_{D^0}d^2p_{\bar{D}^*}\ \frac{d^2N_{D^0}^{Exp}}{d^2p_{D^0T}}\frac{d^2N_{\bar{D}^*}^{Exp}}{d^2p_{\bar{D}^*T}}\exp\left[-\sigma^2(k')^2\right] \times \delta^{(2)}(P_T - p_{D^0T} - p_{\bar{D}^*T})$$

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

- Yields

$$\frac{N_{coal}^{X(3872)}}{N_{SHMc}^{X(3872)}} = 2.47 \pm 0.716\,,\quad \frac{N_{coal}^{X(3872)}}{N_{SHMc}^{\psi(2S)}} = 0.806 \pm 0.234$$

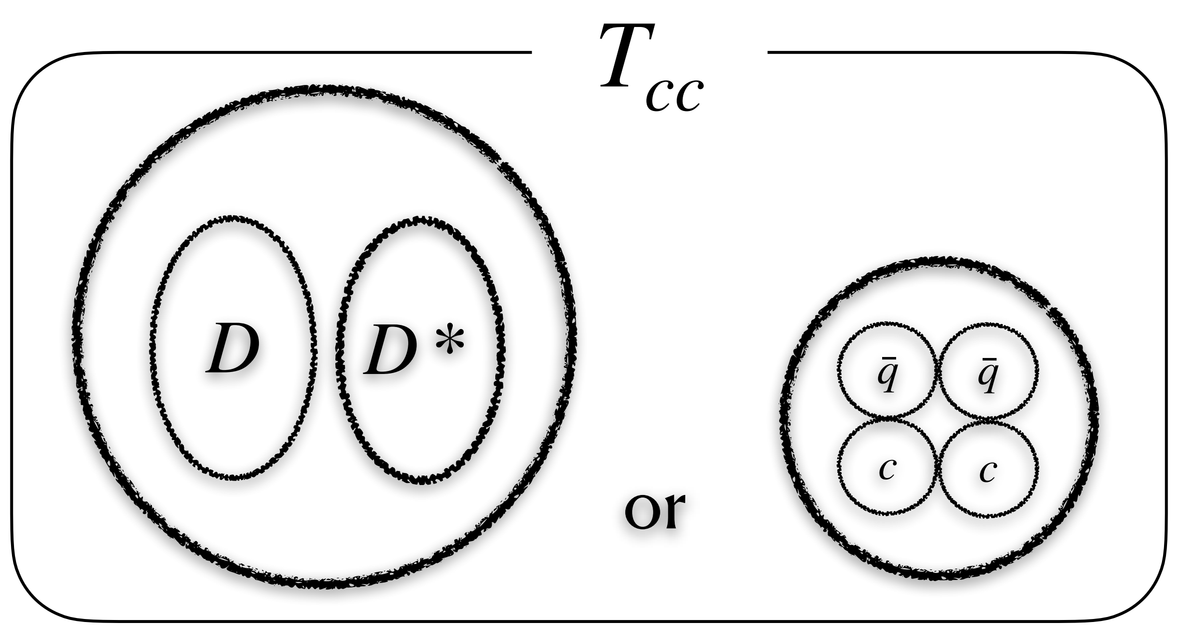
$$(\,dN_{SHMc}^{\psi(2S)}/dy = 3.04\times10^{-3},\quad N_{SHMc}^{X(3872)}/N_{SHMc}^{\psi(2S)} = 0.326\,)$$

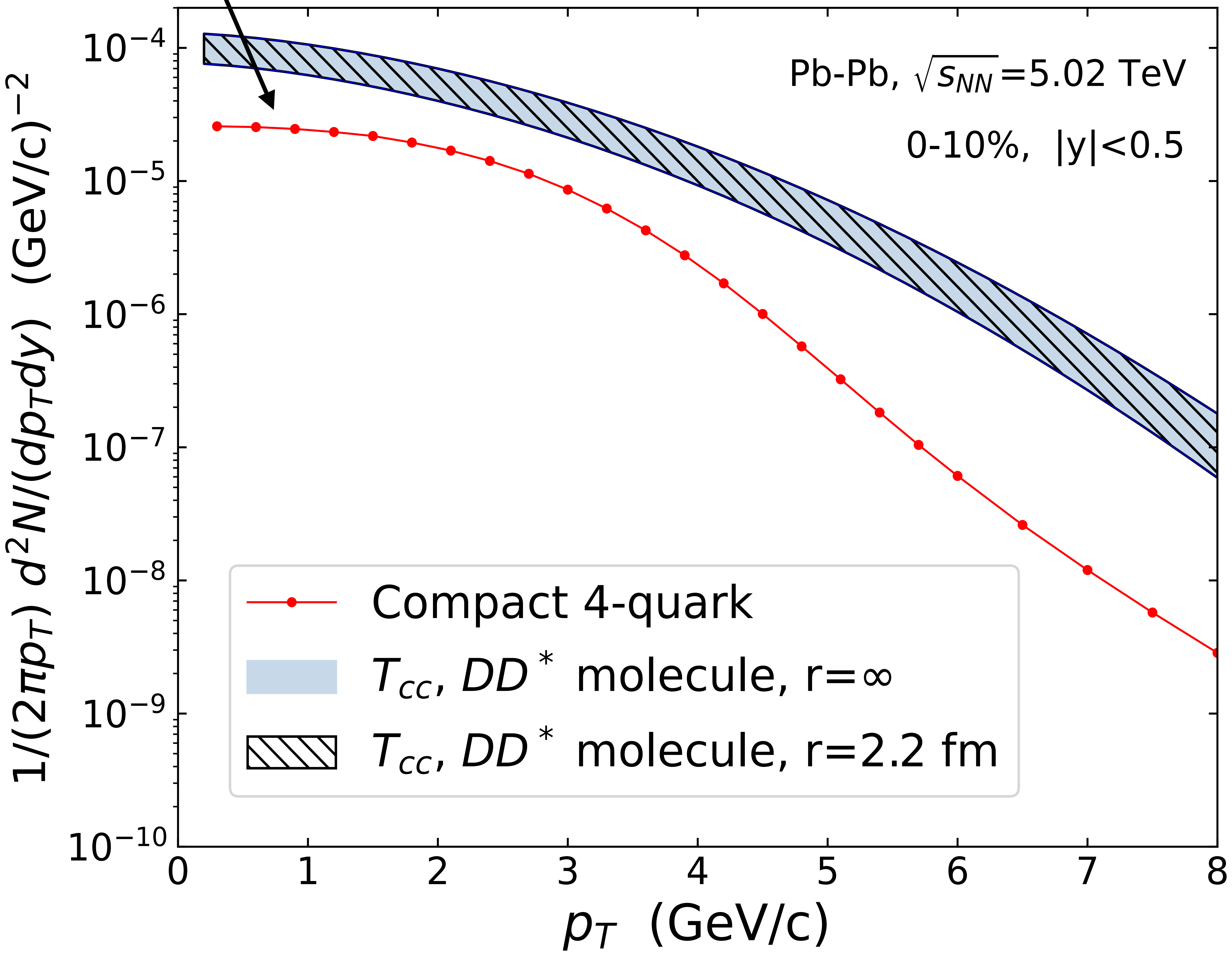
A. Andronic *et al*. JHEP 07, 035 (2021)

T_{cc} p_T distribution

Pb-Pb collisions at 5.02TeV

S. H. Lee and S. Cho, Phys. Rev. C 101, 024902
+ Scaling (× 1.63, 2.76TeV → 5.02TeV)





Radius	Tcc
Molecule	2.2fm
Compact 4-quark	0.433fm

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

- Yields

$$dN_{coal}^{DD^*}/dy = (2.47 \pm 0.71) \times 10^{-3}, \ \ dN_{coal}^{4q}/dy = 6.2 \times 10^{-4}$$

Two possible configurations of T_{cc} are markedly different

Measurement of the pt distribution of T_{cc} in heavy-ion collisions → Confirmation of the structure of T_{cc}

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} can be confirmed.