Reproduction of charmed mesons at 2.76 and 5.02 TeV

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I. BACKGROUND

Previously, we reproduce charmed meson ($J/\psi, D^0, D_s$) successfully in the Au Au collision at 200 GeV in the Recombination Model framework, seen in Figs.1, 2, 3. Thus, they are anticipated to be reproduced in the Pb Pb collisionat 2.76 TeV and 5.02 TeV.

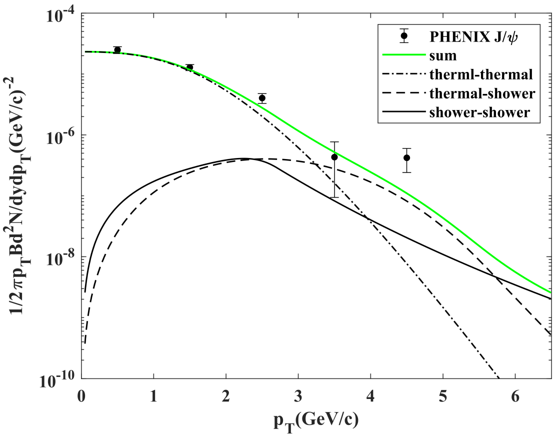

FIG. 1: Transverse momentum spectra of J/ψ at 200 GeV.

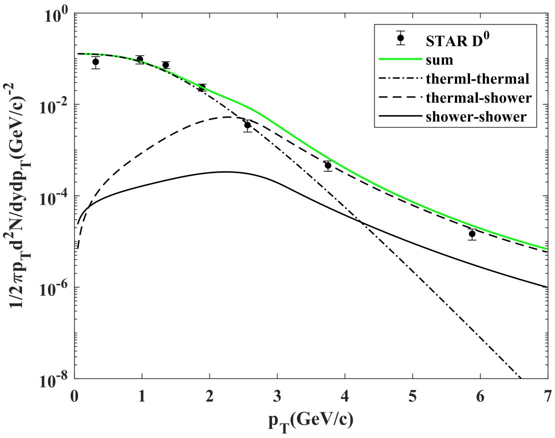

FIG. 2: Transverse momentum spectra of D^0 at 200 GeV.

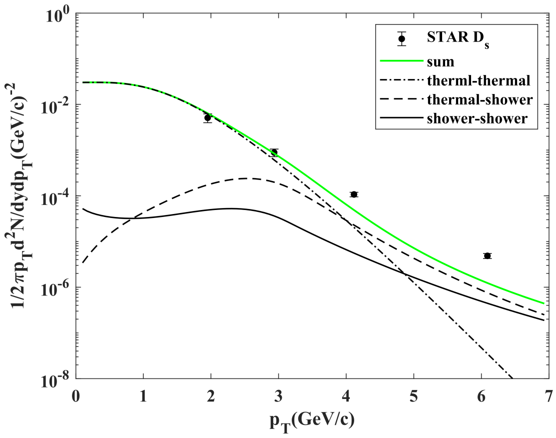

FIG. 3: Transverse momentum spectra of D_s at 200 GeV.

II. URGENT QUESTIONS

Data for $J/\psi, D^0, D_s$ at $\sqrt{s_{NN}}$=2.76/5.02 TeV are found in the form of dN/dp_T [4–9], which need to be multiplied by $1/2\pi p_T$. Change of energy only leads to the various coefficients in $f_i(k)$, which has impact on TT and TS terms. Moreover, some parameters, e.g. $\gamma, v_T, \beta L, ect$, may need to be reoptimized.

As for $f_i(k)$, parameters for the initial hard parton distribution at $\sqrt{s_{NN}}$=200 GeV (RHIC) and 5.5 TeV (LHC) are available in [1, 2], which are not certainly reliable at $\sqrt{s_{NN}}$=2.76/5.02 TeV.

$$f_i(p_T) = \frac{dN^{jet}}{d^2p_T dy} = K\frac{C}{(1+p_T/B)^{\beta}} \tag{1}$$

For $u, \bar{u}, d, \bar{d}, g, s, \bar{s}$ quark, we can obtain parameters at 2.76 and 5.02 TeV by logarithmic interpolations between 200 GeV and 5.5 TeV for lnA, B, β [3], whereas parameters for $c/\bar{c}$ are still not known. Following the notion in [3], we get the parameters in Eq.1 at 2.76 and 5.02 TeV.

The initial p_T spectra of charm quarks at midrapidity at 200 GeV is taken to be

$$f_c(p_T) = \frac{dN_c}{d^2p_T} = \frac{19.2\left[1+(p_T/6)^2\right]}{(1+p_T/3.7)^{12}\left[1+\exp(0.9-2p_T)\right]} \tag{2}$$

which is obtained by multiplying the heavy quark p_T spectra from p+p collisions at same energy by the number of binary collisions (~960) in Au+Au collisions [2].

For LHC energies (5.5 TeV) we take the initial p_T spectra of charm quark at midrapidity from the perturbative

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calculation multiplied by the number of binary collisions (~1700) [10].

$$f_c(p_T) = \frac{dN_c}{d^2p_T} = 2497(1+\frac{p_T}{1.95})^{-5.5}\left(p_T\left[1+\left(\frac{4}{0.1+p_T}\right)^2\right]\right)^{-1} \quad (3)$$

Thus, we now just use the formula at 5.5 TeV for 2.76/5.02 TeV, as it is rough to generalize them to 2.76/5.02 TeV.

Besides, while it is negligible at $\sqrt{s_{NN}}$=200 GeV, the new component of the two-jet contribution $SS(2)$ should be taken into account at $\sqrt{s_{NN}}$=2.76/5.02 TeV, which is given by [11]

$$\frac{dN^{SS(2)}}{pdp} = \frac{1}{p^0p}\sum_{i,i'}\int\frac{dq}{q}\frac{dq'}{q'}F_i(q)F_{i'}(q')\Gamma(q,q') \times \int\frac{dp_1}{p_1}\frac{dp_2}{p_2}F_{ii'}(q,q';p_1,p_2)R_M(p_1,p_2,p). \quad (4)$$

More details are shown in the next section. Then, the first results are shown in Figs.4, 5, 6.

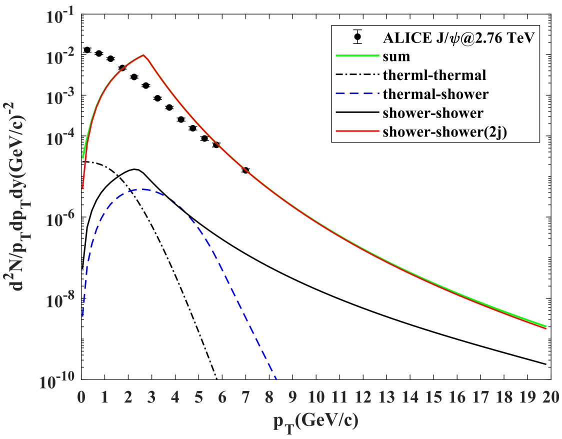

FIG. 4: Transverse momentum spectra of J/ψ at 2.76 TeV with $\Gamma = 10^{-3}$.

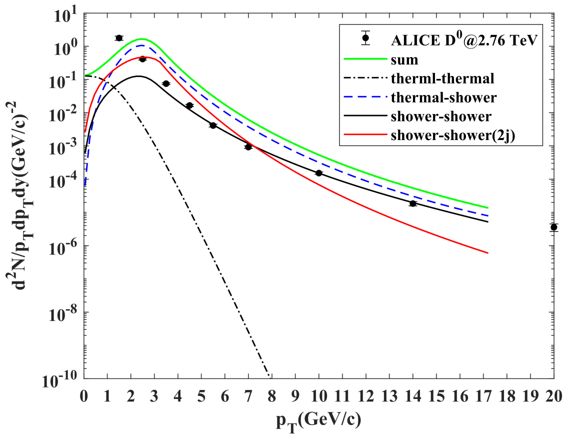

FIG. 5: Transverse momentum spectra of D^0 at 2.76 TeV with $\Gamma = 10^{-3}$.

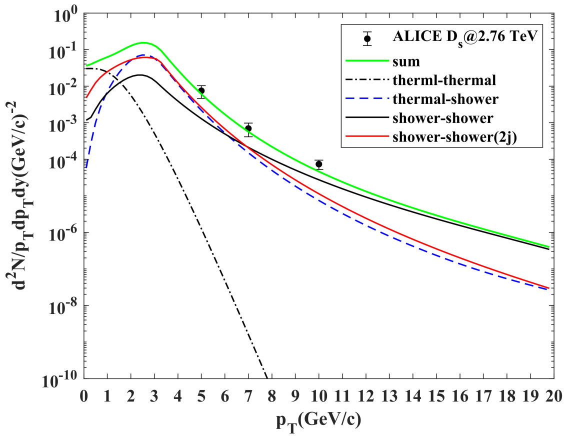

FIG. 6: Transverse momentum spectra of D_s at 2.76 TeV with $\Gamma = 10^{-3}$.

III. FIT AND OPTIMIZATION

Since last meeting, two ideas are put forward. First, the contribution TT should be optimized by fitting η_T. Second, $f_i(k)$ in Pb+Pb at 2.76 and 5.02 TeV should be given, which cannot be replaced by that at 5.5 TeV.

As a result, we find that the change of v_T can effect only one order of magnitude of TT. But the running mass of charm does matter in T composition. The change m_c from 1.5 to 1.2 can fit the data at least in TT, although $v_T = 0.1c$ and $\gamma_c = 1.1$ can also fit the data. Consequently, we fix $\gamma_c = 0.26$, $v_T = 0.25c$, temperature $T = 0.185$ GeV and $m_c = 1.28$, fitted by thermal parton distribution at low p_T.

Here, we give the four contributions again as follows.

A. TT term

$$\frac{dN_M^{TT}}{d^2p} = C_M M_T \frac{\tau A_T}{(2\pi)^3} 2\gamma_a\gamma_b I_0 \left[\frac{psinh\eta_T}{T}\right] \times \int_0^1 dx|\phi_M(x)|^2 k_M(x,p), \quad (5)$$

where

$$k_M(x,p) = K_1\left[\frac{cosh\eta_T}{T}(\sqrt{m_a^2+p_1^2}+\sqrt{m_b^2+p_2^2})\right] \quad (6)$$

$$|\phi_M(x)|^2 = \frac{1}{B(a,b)}x^{a-1}(1-x)^{b-1} \quad (7)$$

and $p_1 = xp, p_2 = (1-x)p, A_T = \rho_0^2\pi$ with the radius $\rho_0 = 9$ fm, the meson degeneracy factor $C_M = (2\times 3)^2$. It was assumed that hadronization occurs at $\tau = 5$ fm with temperature $T = 0.175$ GeV in the parton phase. I_0 and K_1 are the modified Bessel functions. Moreover, the fugacities of light quarks are $\gamma_u = \gamma_d = 1$ and for the strange quarks $\gamma_s = 0.8$. The free parameters are fugacity $\gamma_c = 0.26$(fixed) and transverse flow rapidity η_T defined by a flow velocity with $v_T = tanh\eta_T$. Fitted by experimental data in Au+Au collision at RHIC energy, we have obtained $v_T = 0.3c(J/\psi)$ and $v_T = 0.42c(D^0)$.

B. TS term

$$\frac{dN_M^{TS}}{d^2p} = C_M\int_0^1 dx|\phi_M(x)|^2 \times \left[\frac{T_a(p_1)S_b(p_2)}{g\gamma_a x}+\frac{S_a(p_1)T_b(p_2)}{g\gamma_b(1-x)}\right] \quad (8)$$

with $g = 6$ coming from the color and spin degeneracy of a quark. And the thermal parton spectrum

$$T_a(p) = \frac{2g\gamma_a m_T}{(2\pi)^3} I_0\left[\frac{psinh\eta_T}{T}\right] K_1\left[\frac{m_T cosh\eta_T}{T}\right]. \quad (9)$$

Then, the the distribution of shower parton j

$$S_j(p) = \sum_i \int \frac{dq}{q} F_i(q) S_i^j(p/q), \quad (10)$$

where

$$F_i(q) = \frac{1}{\beta L}\int_q^{qe^{\beta L}} \frac{dk}{k} f_i'(k), \quad (11)$$

with $f_i'(k) = f_i(k)\dot{(}2\pi)^3/E$.

C. $SS(1j)$ term

$$\frac{dN_M^{SS(1)}}{pdp} = \frac{1}{p^0 p}\sum_i \int \frac{dq}{q} F_i'(q)\frac{p}{q} D_i^M(\frac{p}{q}), \quad (12)$$

where

$$F_i'(q) = \frac{1}{\beta L}\int_q^{qe^{\beta L}} dkkf_i(k), \quad (13)$$

and D_i^M is the FF of quark i splitting into meson M.

D. $SS(2j)$ term

Besides, while it is negligible at $\sqrt{s_{NN}}$=200 GeV, the new component of the two-jet contribution $SS(2)$ should be taken into account at $\sqrt{s_{NN}}$=2.76/5.02 TeV, which is given by [11]

$$\frac{dN^{SS(2)}}{pdp} = \frac{1}{p^0 p}\sum_{i,i'}\int \frac{dq}{q}\frac{dq'}{q'} F_i'(q)F_{i'}'(q')\Gamma(q,q') \times \int \frac{dp_1}{p_1}\frac{dp_2}{p_2} F_{ii'}(q,q';p_1,p_2) R_M(p_1,p_2,p). \quad (14)$$

In the above expression, F_{ii} is the distribution of shower partons related to the two jets and for a meson it is written as

$$F_{ii'}(q,q';p_1,p_2) = S_i^j(\frac{p_1}{q}) S_{i'}^{j'}(\frac{p_2}{q'}), \quad (15)$$

and since we have not sufficient information of such dependencies for collisions at LHC, the overlap function is approximated by an average quantity Γ which varies over a wide range $\Gamma = 10^{-n}$ with $n = 1, 2, 3$ and 4.

Specifically, we simply the formulae of 3 mesons respectively for numerical computing as follows:

$$\frac{dN_{J/\psi}^{SS(2)}}{pdp} = \frac{10^{-n}}{p^0 p}\sum_{\substack{i=g,c\\ i'=g,c}}\int \frac{dq}{q}\frac{dq'}{q'} F_i'(q)F_{i'}'(q') \times S_i^c(\frac{p}{2q}) S_{i'}^{\bar{c}}(\frac{p}{2q'}), \quad (16)$$

$$\frac{dN_{D^0}^{SS(2)}}{pdp} = \frac{5*10^{-n}}{p^0 p^6}\sum_{\substack{i=q,\bar{q},g\\ i'=g,c}}\int \frac{dq}{q}\frac{dq'}{q'} F_i'(q)F_{i'}'(q') \times \int_0^p dp_2 S_i^{\bar{u}}(\frac{p-p_2}{q}) S_{i'}^c(\frac{p_2}{q'}) p_2^4, \quad (17)$$

$$\frac{dN_{D_s}^{SS(2)}}{pdp} = \frac{660*10^{-n}}{p^0 p^{13}}\sum_{\substack{i=q,\bar{q},g,s,\bar{s}\\ i'=g,c}}\int \frac{dq}{q}\frac{dq'}{q'} F_i'(q)F_{i'}'(q') \times \int_0^p dp_2 S_i^{\bar{s}}(\frac{p-p_2}{q}) S_{i'}^c(\frac{p_2}{q'}) p_2^9 (p-p_2)^2. \quad (18)$$

To testify the accuracy of calculations, we reproduce the results (transverse momentum spectra for J/ψ at 5.5 TeV) in Ref.[11], shown in Fig.7, which has a good agreement with the reference.

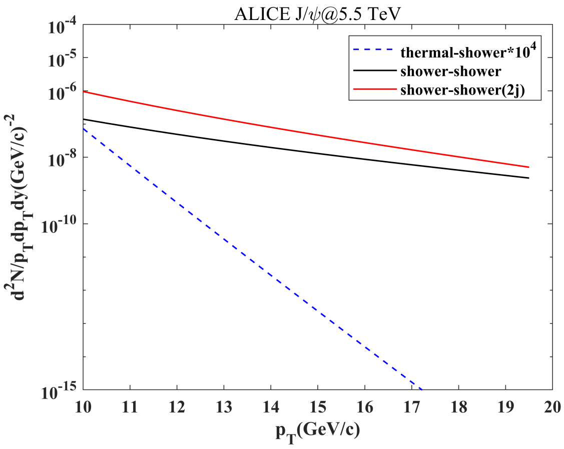

FIG. 7: The comparison of three terms for J/ψ at 5.5 TeV with $\Gamma = 10^{-2}$.

IV. SOLUTION OF HARD PARTON DISTRIBUTIONS FOR CHARM

After search and contacting some professors, it seems no one had studied parameterized initial charm quark distribution. Thus, we attempt to figure out interpolated functions at 2.76/5.5 TeV between 200 GeV and 5.5 TeV to solve it.

Because of known formula of u quark, we compare the parameterized results at various energy, shown in Fig. 8. Obviously, $\ln(f_i(k))$ is not linear with $\sqrt{s_{NN}}$, otherwise the curve of 2.76 TeV should be almost at the position where two curves of 5.5 TeV and 0.2 TeV are bisected. For simplicity, it is assumed that $\ln(f_i^{\sqrt{s}}(k))$ is linear with $\ln(\sqrt{s_{NN}})$(in TeV), i.e. $f_i^{\sqrt{s}}(k)$ increases linearly with $\sqrt{s_{NN}}$. Therefore, hard parton distribution at any energy can be expressed:

$$\frac{f_i^{\sqrt{s}} - f_i^{5.5}}{\sqrt{s} - 5.5} = \frac{f_i^{0.2} - f_i^{5.5}}{0.2 - 5.5} \tag{19}$$

Then, we give the deviation between our linear evaluation and parameterized values in Fig.9, from which it is reasonable to accept the linear assumption. So we generalize this simple relation to initial charm quark distribution and get the distributions at 2.76 and 5.02 TeV successfully by linear combination of distributions at 0.2 and 5.5 TeV, shown in Fig.10. We also give another results assuming $\ln(f_i(k))$ is linear with $\sqrt{s_{NN}}$ to trial, shown in Fig.11.

Subsequently, we test the two $f_i(k)$, which is linear or exponential with $\sqrt{s_{NN}}$ respectively, by calculating the momentum spectra for J/ψ at 2.76 TeV shown in Fig.12 and 13. Unfortunately, the former result, which should be logically compelling, is even worse than the latter, and both of all cannot fit the experiment data. But the latter conveys that the dominant components $SS(1j)$ and $SS(2j)$ in high transverse momentum determine the accuracy of fitting. And next step should be to determine further the shape of $f_i(k)$ for charm.

After that, from the high contribution of SS, it is reasonable to decrease $f_i(k)$ of charm. Therefore, we adjust the weight of $f_c(k)$ at 200 GeV from about 0.51, according to Eq.19, to 0.6, improving the calculated p_T distribution for J/ψ at 2.76 TeV shown in Fig.14.

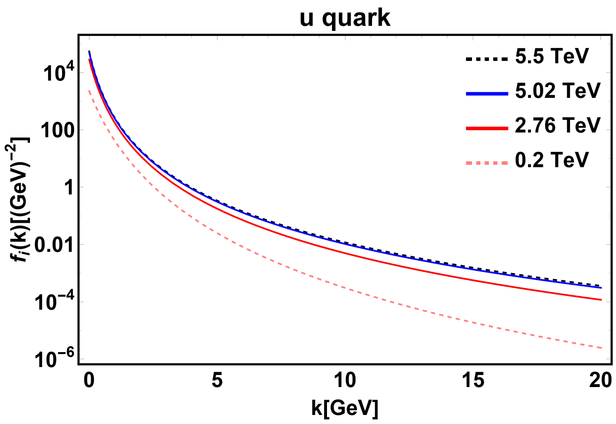

FIG. 8: Hard parton distribution of u quark at various energy.

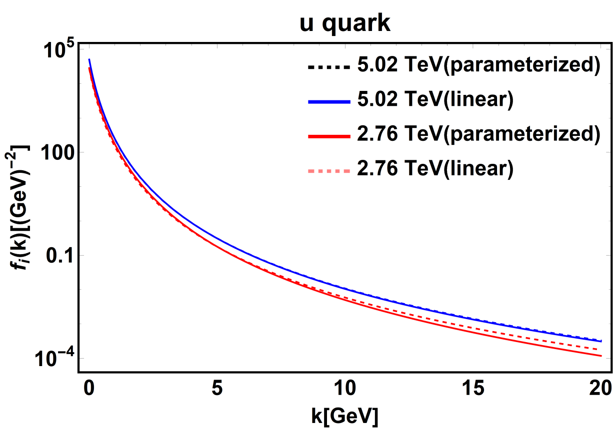

FIG. 9: Deviation between linear evaluation and parameterized values for u quark at 2.76 and 5.02 TeV.

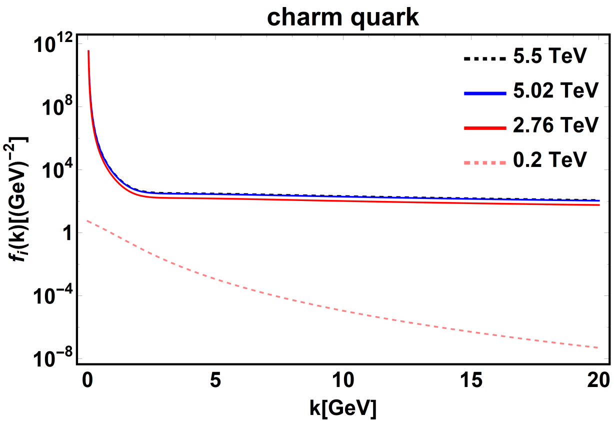

FIG. 10: Hard parton distribution of charm quark at various energy assuming $f_i(k)$ is linear with $\sqrt{s_{NN}}$.

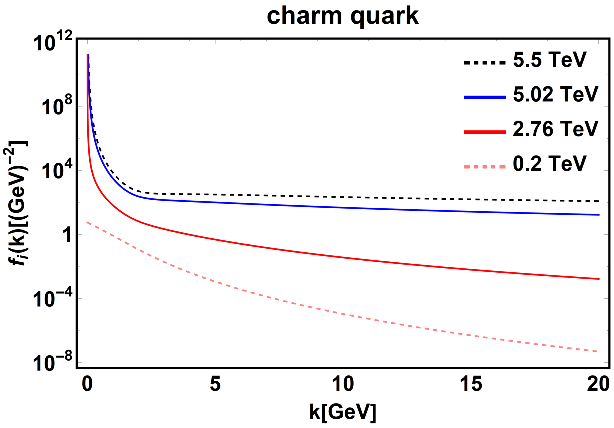

FIG. 11: Hard parton distribution of charm quark at various energy assuming $\ln(f_i(k))$ is linear with $\sqrt{s_{NN}}$.

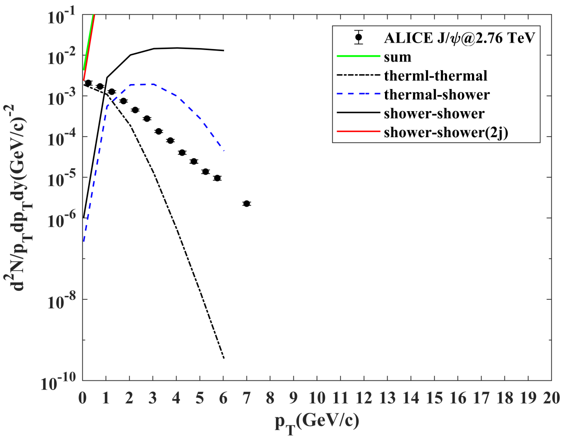

FIG. 12: J/ψ distribution at 2.76 TeV assuming $f_c(k)$ is linear with $\sqrt{s_{NN}}$.

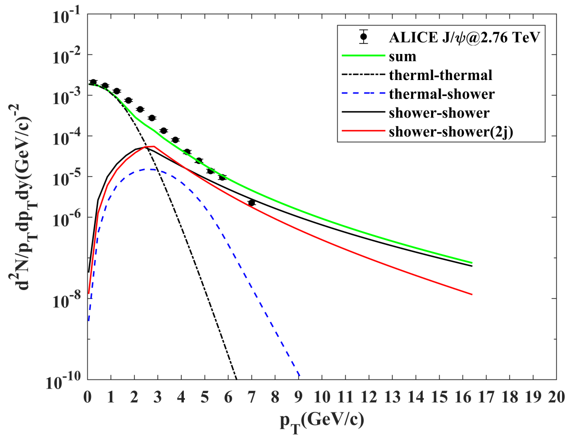

FIG. 13: J/ψ distribution at 2.76 TeV assuming $f_c(k)$ is exponential with $\sqrt{s_{NN}}$.

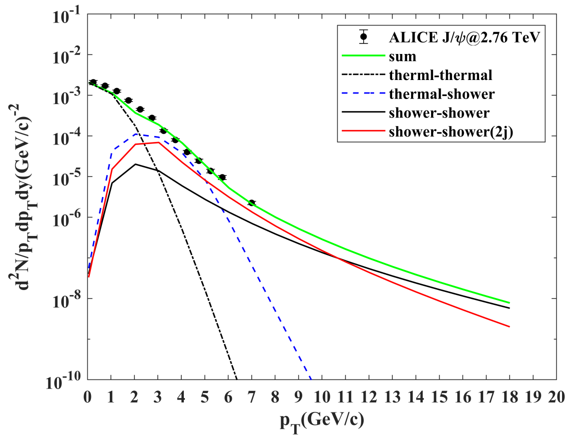

FIG. 14: J/ψ distribution at 2.76 TeV applying improved $f_c(k)$.

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