$J/\psi$ production and the elliptic flow parameter $v_2$ at LHC energy

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Abstract

We apply the recombination model to study $J/\psi$ production and its elliptic flow in the momentum region of $10 < p_T < 20\text{ GeV}/c$ at LHC energy. We show the distribution of $J/\psi$ as a function of the transverse momentum $p_T$ and the azimuthal angle $\phi$. If the contribution due to the recombination of shower partons from two neighboring jets cannot be ignored at the LHC, the elliptic flow parameter $v_2$ of $J/\psi$ is predicted to decrease with $p_T$.

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(Some figures in this article are in colour only in the electronic version.)

Experiments on heavy ion collisions provide us with very rich information on hadron production. The theoretical description of hadron production with large transverse momentum $p_T$ at high-energy collisions is traditionally framed by introducing fragmentation functions (FF) $D_i^h(x)$, which correspond to the probability that a parton $i$ fragments into a hadron $h$ carrying a momentum fraction $x$ of $i$. However, such a fragmentation mechanism has been found inadequate for the production of particles in the intermediate $p_T$ region because of the experimental discovery of anomaly $p/\pi \sim 1$ at $3 < p_T < 4\text{ GeV}/c$ at the Relativistic Heavy Ion Collider (RHIC) [1]. The quark recombination is expressed as the mechanism that a meson with momentum $p = p_1 + p_2$ is formed by a quark with momentum $p_1$ and an antiquark with $p_2$. This mechanism is shown to be more appropriate for describing the hadronization process in the intermediate $p_T$ region [2, 3].

In the two recombination models studied in [2] and [3], particle production is treated as recombination in the small $p_T$ region and fragmentation at high $p_T$. In order to propose a universal description that can be applied to any $p_T$ region, the fragmentation process is also treated as the result of the recombination of shower partons in a jet [4].

The distribution of the shower partons which are the evolution products of hard partons produced in the initial hard partonic interactions has been achieved by studying the FFs in the framework of the recombination model [4, 5]. Therefore, there are two sources of partons in heavy-ion collisions, shower ($S$) partons initiated from the evolution of the hard partons with high $p_T$ and low $p_T$ soft or thermal ($T$) partons from soft nearest neighbor (NN) collisions. The hadronization of the partonic matter produced in the collisions is described as several recombination modes from the thermal and shower partons. In particular, meson production is expressed as the sum of $TT$ (thermal–thermal), $TS$ (thermal–shower) and $SS$ (shower–shower) terms. With the shower parton distributions (SPD) the model has given good agreement with the experimental data of the hadron production at the RHIC energies [5–7]. A fundamental concept of the recombination model is that the recombination process involves quarks and antiquarks, while gluons are assumed being converted to quark–antiquark pairs before hadronization [8].

In $\text{Pb+Pb}$ collisions at $\sqrt{s_{NN}} = 5.5\text{ TeV}$ at the Large Hadron Collider (LHC), the initial temperature and energy density are much higher than those at the RHIC, and therefore the LHC offers a new domain for the study of the physics of quark gluon plasma (QGP). The recombination model has also been applied to a large $p_T$ range of $10 < p_T < 20\text{ GeV}/c$ at the LHC and a novel prediction has been made that the proton-to-pion ratio can be as high as 20, much higher than that at the RHIC [9].
Charm quark, probably abundantly produced at the LHC, has been one of the main observables which can trace the initial phase of the collisions and provide information on the possible formation of QGP from the Super Proton Synchrotron (SPS) to the RHIC. Charm quark production at the SPS is expected to be small, but there are more than 10 \( \sigma \pi \) pairs produced in central Au+Au collisions at the RHIC and probably more than 200 pairs at the LHC [10]. About 25 years ago, it was predicted that \( J/\psi \) yield is suppressed by \( \sigma \pi \) dissociation due to the color screening of the produced hot partonic matter [11]. SPS experiment confirmed this prediction [12]. Since then \( J/\psi \) has been regarded as a key probe for the formation of QGP. At the RHIC, the initial energy density of the produced partonic matter is much higher than at the SPS, so that the \( \sigma \pi \) pairs produced in the initial hard gluon processes are dissociated much rapidly. On the other hand, when the density of charm quarks is high enough, hard gluon processes are dissociated much more rapidly. On the other hand, when the density of charm quarks is high enough, the regeneration of \( \sigma \pi \) must be included in order to explain the RHIC data [13]. In [5, 14, 15], we have studied the spectra and elliptic flow of mesons with open charm. The quark coalescence model has also been applied to describe \( J/\psi \) flow of mesons with open charms. The quark coalescence model has also been applied to describe \( J/\psi \) production in ultrarelativistic heavy-ion collisions \([14]\) results from the perturbative calculation in [23] multiplied by the corresponding number of binary collisions in the collisions \((N_{\text{coll}}) \approx 1700 [24]\) for most central 10% Pb+Pb collisions. In terms of \( \xi \), \( G(k, q, \xi) \) was assumed as a simple exponential form \( G(k, q, \xi) = q \delta (q - k e^{-\xi}) \) [17]. This expression was originally used for the photon production. Considering the fact that RHIC data showed almost the same amount of energy loss for heavy and light with \( F(p_1, p_2) \) being the joint distribution for the quark and antiquark having momentum \( p_1 \) and \( p_2 \), respectively. The recombination function \( R_{\Delta M}(p_1, p_2, p) \), which is determined by the wave function of the meson \([6]\), gives the probability for the two constituent quarks with momentum \( p_1 \) and \( p_2 \) to form a meson with \( p = p_1 + p_2 \).

In [5, 14] we have calculated \( J/\psi \) transverse momentum spectra for different centralities in Au+Au collisions at \( \sqrt{s_{NN}} = 200\text{ GeV} \) at the RHIC and the results fit the experimental data well. The contributions of \( TT \) and \( TS \) are lower than that from \( SS \) for \( p_T > 5.8\text{ GeV}/c \) [5]. The details of calculating \( TT \) and \( TS \) terms are given in [5, 14] where the thermal parton distribution is determined by fitting the low-\( p_T \) data of \( J/\psi \). There are two parameters in fitting the experimental data at the RHIC: fugacity of charm quark \( \gamma_c = 0.26 \) and the flow velocity \( v_T = 0.3 \). Since there has not been information on \( J/\psi \) production at the LHC so far, we will still use the same values for these two parameters, and we hope that at the moment of hadronization, the final state equilibrated system does not show too strong a difference from that at RHIC energy. In the \( p_T \) range considered in this paper, the medium properties do not matter too much, since \( TT \) and \( TS \) can both be neglected. The only influence on the medium is from the energy loss effect of the hard partons. Now we focus our attention on the \( SS \) component, which is the dominant contribution to the charmed meson production in the region of \( 10 < p_T < 20\text{ GeV}/c \) discussed in this paper.

From [4] the recombination of two shower partons from one jet \( SS(1) \) is related to FF \( D^M \). With the abbreviation \( p \) for the meson transverse momentum, the corresponding one-jet contribution to the inclusive distribution is [17]

\[
\frac{dN_{\Delta M}^{SS(1)}}{dp dp} = \frac{1}{p^9 p} \sum_q \int \frac{dq}{q} F_I(q, \phi, c) \frac{p}{q} D^M \left( \frac{p}{q} \right). \tag{3}
\]

Here \( F_I(q, \phi, c) \) is the probability of a hard parton \( i \) with momentum \( q \) at azimuthal angle \( \phi \) in a heavy-ion collision with centrality \( c \). FFs for \( J/\psi \) and other D mesons from various hard partons can be found in [18, 19] and [5, 14, 20], including \( D^0_{\pi}, D^0_{\pi}, D^+_{\pi}, D^0_{s}, D^0_{s}, D^0_{c}, D^+_{c} \). In this paper, the azimuthal angle \( \phi \) of a particle is relative to the reaction plane. Because of the energy loss the initial hard parton momentum \( k \) is reduced to \( q \) after traversing an absorptive distance \( \xi \). The resultant distribution of hard partons is expressed from the initial distribution \( f_i(k) \) by the momentum degradation factor \( G(k, q, \xi) \)

\[
f_i(q, \xi) = \int dkkf_i(k)G(k, q, \xi). \tag{4}
\]

The initial transverse momentum \( k \) distributions \( f_i(k) \) for hard parton \( i \) (u, d, s and gluon) at the creation point can be found in [21]. For the c quark its initial transverse momentum spectra [22] have been obtained from the perturbative calculation in [23] multiplied by the corresponding number of binary collisions in the collisions \((N_{\text{coll}}) \approx 1700 [24]\) for most central 10% Pb+Pb collisions.
quarks, the same form of function $G$ will be used for $J/\psi$ production here. If $P(\xi, \phi, c)$ is the probability of having a dynamical path length $\xi$ for a parton directed at $\phi$, after carrying out the integration over $\xi$, the degraded hard parton distribution in equation (3) can be rewritten as

$$F_i(q, \phi, c) = \int d\xi P(\xi, \phi, c) F_i(q, \xi).$$

(5)

In [17], a scaling behavior of $P(\xi, \phi, c)$ is found for the dependences on $\phi$ and $c$ for pion production. $P(\xi, \phi, c)$ can be written as a universal function in terms of a scaling variable $z = \xi/\bar{\xi}(\phi, c)$:

$$P(\xi, \phi, c) = \psi(z)/\bar{\psi}(\phi, c),$$

(6)

where $\bar{\xi}$ is the mean dynamical length and the scaling function $\psi(z)$ has been given in [17], which will be used in our calculations.

The two-jet contribution $SS(2)$ can be given as

$$\frac{dN_{SS(2)}}{dp_T d\phi} = \frac{1}{p^2} \sum_{i,j} \int \frac{dq}{q} \frac{dq'}{q'} F_i(q, \phi, c) F_j(q', \phi, c) \Gamma(q, q') \times \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} F_{ii'}(q, q'; p_1, p_2) R_M(p_1, p_2, p).$$

(7)

In the above expression, $F_{ii'}$ is the distribution of shower parton pairs related to the two jets and can be written as

$$F_{ii'}(q, q'; p_1, p_2) = S_i' \left( \frac{p_1}{q} \right) S_j' \left( \frac{p_2}{q} \right),$$

(8)

with $S_i'(z)$ being the momentum fraction $z$-distribution for shower parton $j$ in a jet initiated by hard parton $i$. The parameterized results of the SPDs and RFs for the charmed mesons have been discussed in [5, 14]. The only quantity we need to know now is the overlap probability $\Gamma(q, q')$ between the two neighboring jets. This probability depends on the jet density, which is a function of the colliding energy $\sqrt{s_N}$, the momentum vectors $\vec{q}$ and $\vec{q}'$ of the hard partons, and the width of the jet cone, and therefore $\Gamma(q, q')$ should be determined in some dynamical way. Since we do not have sufficient information on such dependences for collisions at the LHC, the overlap probability is approximated by an average number $\Gamma$. In this paper, we use $\Gamma$ with a value in the range $\Gamma = 10^{-n}$, where $n = 1, 2, 3, 4$, a range estimated in [9]. As can be seen from equations (5) and (6), the quenched hard parton distributions depend on the direction $\phi$ in their traversing the medium, because the average path length the parton travels is different for different $\phi$. Therefore, one may expect an azimuthal dependence in the spectrum of the final state hadrons, even for large $p_T$.

With any chosen $\Gamma$, the spectrum of $J/\psi$ can be calculated without new parameters for any $p_T$, azimuthal $\phi$ and centrality. In figure 1, we show the $\phi$ dependence of the contributions from $TS$, $SS(1)$ and $SS(2)$ terms to the transverse momentum distribution at given $p_T = 15$ GeV/c for arbitrary chosen $\Gamma = 10^{-2}$. At this $p_T$ the dependence of the $SS(2)$ term on $\phi$ is stronger than those of $TS$ and $SS(1)$. Experimentally, the spectrum is usually given for $\phi = \pi/24, 3\pi/24, \ldots, 11\pi/24$. Also, we can show our calculated $p_T$ dependence of the inclusive $J/\psi$ distribution at a given azimuthal angle $\phi = 5\pi/24$ for the above four values of $\Gamma$ as shown in figure 2. A very strong dependence of the spectrum on $\Gamma$ can be seen in the figure, as expected from our discussion. In order to take a clear comparison of the contributions from every term we show them (with $\Gamma = 10^{-2}$ for $SS(2)$) in figure 3, where the $TT$ term is too small to be shown in the figure. In the $p_T$ range shown, the $TT$ term is about four orders of magnitude lower than $SS(1)$ and $SS(2)$ because of the rapidly decreasing thermal parton distribution. The contribution from $SS(2)$ decreases with $p_T$ faster than that from $SS(1)$. Our numerical results show that $SS(1)$ exceeds $SS(2)$ when $\Gamma$ is smaller than $10^{-3}$.

We have calculated the elliptic flow $v_2$ for the produced $J/\psi$. One can obtain the elliptic flow $v_2$ for different values of $\Gamma$ from the $\phi$ dependence of the spectrum through

$$\frac{dN}{p_T dp_T d\phi} = A(p_T) [1 + 2v_2(p_T) \cos(2\phi) + \cdots].$$

(9)

Shown in figure 4 is the predicted $v_2$ of $J/\psi$ as a function of $p_T$ for different $\Gamma$. The $v_2$ value increases with $\Gamma$. The values of $v_2$ for $\Gamma$ from $10^{-3}$ to $10^{-1}$ are larger than that at the

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**Figure 1.** The azimuthal dependence of distributions of $TS$, $SS(1)$ and $SS(2)$ terms at $p_T = 15$ GeV/c.

**Figure 2.** The distribution of $J/\psi$ as a function of the transverse momentum $p_T$ at a given azimuthal angle $\phi = 5\pi/24$ for four different values of $\Gamma$. 

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RHIC calculated in [15], where \(v_2\) increases monotonically till \(p_T \approx 4\) GeV/c and then saturates at 0.04 for 0–10% centrality. If \(\Gamma\) is small enough (\(\Gamma = 10^{-4}\)) such that the impact of \(SS(2)\) can be ignored, the value of \(v_2\) remains constant at about 0.04, which is almost the same as the saturated constant calculated at the RHIC [15]. When \(\Gamma = 10^{-1}\) is used, the obtained \(SS(2)\) term becomes so large that the other three terms are negligible and \(v_2\) also almost remains constant at 0.07.

The values of \(v_2\) for \(\Gamma = 10^{-3}\) and \(\Gamma = 10^{-2}\) decrease with increasing \(p_T\). In fact, the trend that \(v_2\) decreases with \(p_T\) has been probed in heavy-ion collisions at the RHIC at \(p_T > 3\) GeV/c [25, 26] (reviewed in [27]). The STAR Collaboration presented the \(v_2\) results for Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV with \(p_T\) up to 12 GeV/c [28] from the reaction plane method and four-particle cumulant method. The results show that \(v_2\) is maximum at \(p_T \sim 3\) GeV/c, saturates at \(3 < p_T < 6\) GeV/c and then decreases slowly up to the highest momentum measured. Thus, a reliable discussion of the trends in the region of \(p_T > 6\) GeV/c requires multi-particle correlation measurements [29]. The eventual decrease of \(v_2\) at high \(p_T\) has been demonstrated as a consequence of finite inelastic jet energy loss by the perturbative quantum chromodynamics (QCD) theory [30].

Another recombination model [31] has also been applied to explain the elliptic flow of mesons and baryons at RHIC energies.

To understand the behavior of \(v_2\) in the \(J/\psi\) spectrum, we show the values of \(v_2\) in figure 5 from only one of the terms \(TS\), \(SS(1)\) and \(SS(2)\). The values of \(v_2\) from \(TS\) and \(SS(1)\) terms are almost constants at 0.041 and 0.038, respectively, in the \(p_T\) range shown. Normally the initial hard parton distribution \(f_i(k)\) can be regarded as a power of \(k\). When the energy loss is proportional to the initial momentum, one can expect that the \(k\) and \(\phi\) dependences can be factorized in \(f_i(q, \phi, c)\) for each hard parton \(i\). Therefore, one can obtain a constant value of \(v_2\) from contributions of \(TS\) and \(SS(1)\).

Of course, the two values of \(v_2\) thus obtained are different, as shown in our results. The \(v_2\) from \(SS(2)\) increases with \(p_T\) slightly and at the same time is much larger than those from \(TS\) and \(SS(1)\). It is reasonable. If the meson is formed by the recombination of thermal-shower partons or shower–shower partons from the same jet, the process is related to only one jet and the nonzero \(v_2\) comes from the \(\phi\) dependence of the energy loss of the single jet. While two different quenched jets need to be considered in the recombination of \(SS(2)\), shower partons from each jet may undergo a \(\phi\)-dependent energy loss. To form a meson, the two SPDs for the two quenched jets are multiplied in equation (7) and, as a result, a stronger \(\phi\) dependence can be expected, as shown in figure 1. Thus, the value of \(v_2\) associated with the \(SS(2)\) term is larger than that from the other terms. Also we find that the contribution from \(SS(2)\) to the spectrum decreases faster than that from \(SS(1)\) when \(p_T\) increases in the range shown in figure 3.

When the contributions to the observed flow from the terms \(SS(1)\) and \(SS(2)\) are comparable (\(\Gamma = 10^{-3}\) and \(10^{-2}\)), the \(\phi\) dependence of the distribution of \(J/\psi\) will decrease with increasing \(p_T\), as can be seen in figure 4.

Finally, we make a prediction for the spectra of the other two charmed mesons \(D^0\) and \(D_s\) as functions of the transverse momentum and the azimuthal angle. For definition, we choose \(\Gamma = 10^{-2}\). The obtained results are shown in figure 6. The spectrum of the \(D^0\) meson is an order of magnitude higher than that of \(D_s\) and three orders of magnitude higher than that of \(J/\psi\). This can be understood as follows: for the distribution of \(J/\psi\) the shower partons of both \(c\) and \(\bar{c}\) initiated from the
light quarks $u$, $d$ and $s$ are neglectable, whereas for $D^0$ or $D_s$ mesons, shower partons of $\pi$ or $\pi$ can come from $i = q, \bar{q}, g$ with $q = u, d, s, c$. In simple words, the higher spectrum of $D^0$ or $D_s$ results from the much higher contents of the light shower partons in jets. Also the hard parton distributions affect the $p_T$ trend of the meson spectra. It is shown in figure 6 that the momentum spectrum of $J/\psi$ decreases more rapidly than those for $D^0$ or $D_s$ when $p_T$ increases.

In summary, we have predicted the distribution of $J/\psi$ and its elliptic flow parameter $v_2$ at LHC energy in the framework of the recombination model. Because of the high hard parton density the recombination of shower partons from two neighboring jets may play an important role in meson production, and the influence to $v_2$ from such a novel recombination is discussed. The elliptic flow parameter $v_2$ of $J/\psi$ is predicted to decrease with $p_T$ if the contributions from the terms $SS(1)$ and $SS(2)$ are comparable.

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