\textbf{J/ψ with large }p_T\textbf{ probing the early stage of relativistic heavy ion collisions}

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We study the charmonium suppression in different evolutions of quark gluon plasma (QGP) based on the transport model. In the colliding energies of Large Hadron Collider, charmonium final yields are dominated by the recombination of charm and anti-charm quarks in the deconfined phase. Heavy quark diffusions depend less on the shear viscosity of the bulk medium, which makes the J/ψ nuclear modification factor in the entire }p_T\text{ bin shows weak dependence on the shear viscosity of QGP. However, charmonium with high transverse momentum }p_T\text{, can only be produced in the early stage of nuclear collisions, and is sensitive to the initial energy density (or temperature) of QGP, and can be a probe of the initial dynamical evolutions of quark gluon plasma.

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\textit{J/ψ} is a tightly bound state of charm quarks }c\text{ and }\bar{c}\text{, its dissociation temperature }T_d\text{ is much higher than the critical temperature }T_c\text{ of the phase transition between confined and deconfined matters. This means }J/ψ\text{ may survive in the early time of the hot medium and carry information of the medium. Therefore, the measured }J/ψ\text{ in nuclear collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) has been considered as not only a signature of the new state of matter, the so-called quark-gluon plasma (QGP) [1], but also a good probe to detect the early information of the medium [2,3]. In the ultra-peripheral and semi-central collisions, charmonium can be produced from the interactions between strong electromagnetic fields and the target nucleus [4] in the small transverse momentum }p_T\text{. In the middle and high }p_T\text{ bin, charmonium production is dominated by the initial production [12,13] and regeneration [14,15] in the deconfined phase. The QGP produced at RHIC and LHC turns out to be a strong coupling system, hydrodynamic models [17,18] have been widely used to simulate the collective expansion of the hot medium. Different hydrodynamic models have been developed with different approximations. The main constraints on those hydrodynamic models are the collective flows and transverse momentum spectra of light hadrons, which is mainly developed in the later time of medium expansion. This makes the observables of light hadrons less sensitive to the early information of hot medium. However, charmonium with large transverse momentum is produced in the initial stage of heavy ion collisions and may survive from the hot medium due to its large binding energy [19]. This inspires us to use charmonium as a probe of the early information of the QGP. With access to many hydrodynamic models, we can use charmonium as a good probe to detect the early information of different hydrodynamics, and check the charmonium sensitivity to the different hydrodynamics, hoping to give more constraints on QGP initial evolutions.}

Charmonium has a large mass, and its motion in the QGP can be described by a Boltzmann type transport approach [20,21],

\begin{equation}
\frac{\partial f_\Psi}{\partial t} + \mathbf{v_\Psi} \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi,
\end{equation}

\(\Psi\) stands for \((J/\psi, \chi_c, \psi')\). They contribute around \((60\%, 30\%, 10\%)\) of the final total }J/ψ\text{ yield respectively. The first term at L.H.S of Eq. (1) describe the evolution of charmonium distribution with time, }\nabla\text{ is the derivative in coordinate space, the second term represents the “leakage effect”, which means charmonium with large velocity }v_\Psi\text{ may escape from QGP and survive before medium reaching local thermal equilibrium. The final charmonium may come from two sources: the initial production, which is produced at the beginning of nuclear collisions, the other is called regeneration from }c\text{ and }\bar{c}\text{ (or }D\text{ and }\bar{D}\text{ in hadron phase) recombination during the evolution of the hot medium, represented by the gain term }\beta_\Psi\text{. Both initially produced and regenerated charmonium suffers the gluon dissociation, represented by the loss term }\alpha_\Psi\text{,}

\begin{equation}
\alpha_\Psi(p_t, x_t, \tau | b) = \frac{1}{2E_\Psi} \int \frac{d^3p_g}{(2\pi)^32E_g} W^{c\bar{c}}_{g\Psi} (s) f_g(p_g, x_t, \tau) \times \Theta (T(x_t, \tau | b) - T_c)
\end{equation}

\(\alpha_\Psi\) is the charmonium loss term, connected with the gain term }\beta_\Psi\text{ by the detailed balance of the reaction }\Psi + g \leftrightarrow c + \bar{c}\text{. }W^{c\bar{c}}_{g\Psi}\text{ is the probability }\Psi\text{ dissolved by gluons. }b\text{ is the impact parameter. }f_g\text{ is the gluon density, which we take as Bose distribution. }\Theta\text{ function ensures that this process only happens in QGP and effects of hadron gas are neglected at LHC energies. Lattice calculations indicate a certain temperature }T_d\text{, above which the heavy quark potential is totally screened, and no charmonium can survive [22]. Taking the potential of heavy quarkonium to be its internal energy }V = U\text{, one can obtain the charmonium dissociation temperature }T_d = (2.3, 1.1, 1.1) T_c\text{ for }\Psi(J/\psi, \chi_c, \psi')\text{ by solving Schrödinger equation [2]. For elastic collisions between }J/\psi\text{ and the hot medium, it has already been checked, and can be neglected [19].}
The cold nuclear matter effects which happen before the formation of hot medium, including nuclear absorption, Cronin effect, and shadowing effect, can be included in the initial distribution of charmonium. At LHC colliding energies, the nucleons already leave the colliding region before charmonium is formed from \(\bar{c}c\) dipoles, and therefore charmonium normal dissociation by nucleons can be safely neglected. The averaged transverse momentum square of charmonium produced in pA collision is larger than the value in pp collisions, due to the multi-scatterings between gluons and nucleons. This effect can be included by modifying the charmonium averaged transverse momentum square, \(\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + a_g N(l)\) with \(a_g N = 0.15 \text{ GeV}^2/\text{fm. l}\) is the average length gluons pass through before fusing into \(\bar{c}c\) dipoles. Shadowing effect is important at high colliding energy, and is included by employing EKS98 package. It reduces yields of charmonium and charm pairs by around \((10 - 20)\%\). The momentum distribution of charm quark is taken as thermal distribution in QGP, and its distribution in coordinate space can be obtained by the law of conservation (assume the conservation of charm quark number during the QGP expansion), \(\partial_t n_c(u^\mu) = 0\). \(u^\mu\) is the four-velocity of QGP fluids. The charmonium density at \(\tau = \tau_0\) is initialized by

\[
\rho_c(x,y,\tau_0|\mathbf{b}) = \frac{d\sigma_N^c}{dy^{rap}} T_A(x - \frac{b}{2}, y) T_B(x + \frac{b}{2}, y) \quad (3)
\]

\[
T_{A(B)}(x,y) = \int \rho_{A(B)}(x,y,z) dz \quad (4)
\]

To avoid confusions in this work, rapidity is labeled as \(y^{rap}\), and \(x_T = (x,y)\) represents the coordinates in transverse plane. \(T_{A(B)}(x,y)\) is thickness functions of colliding nuclei. \(\rho_{A(B)}\) is the nucleon density taken as Woods-Saxon distribution.

Based on different hydrodynamic models, we get different evolutions of temperature and fluid velocities of the medium, and calculate charmonium nuclear modification factor \(R_{AA}\), defined as

\[
R_{AA} = \frac{N^\Psi_{AA}}{N^\Psi_{pp,N_{coll}}} \quad (5)
\]

Here, \(N^\Psi_{AA}\) is charmonium production in nucleus-nucleus collisions with both cold and hot medium modifications, including primordial production and regeneration of \(c + \bar{c} \rightarrow J/\psi + g\). \(N_{pp}\) and \(N_{coll}\) are charmonium production in proton-proton collisions and number of binary collisions respectively. Considering that QGP can only be produced in nucleus-nucleus collisions and absent in pp collisions, the value of \(R_{AA}\) indicates the magnitude of QGP suppression on charmonium final yields.

We use the viscous hydrodynamic model to simulate the hot medium evolution at LHC Pb+Pb \(\sqrt{s_{NN}} = 2.76\) TeV. By fitting the transverse momentum spectra and collective flows of light hadrons, viscous hydrodynamic models extract the properties of the bulk medium such as initial thermalization time \(\tau_0\) and shear viscosity over entropy density \(\eta/s\). Here, we show the difference of temperature from different hydrodynamic evolutions (with different values of parameters: initial thermalization time \(\tau_0\), initial entropy density distribution, shear viscosity \(\eta\)).

In Fig. 1 the different initial distributions of temperature with x-coordinate at \(\tau = \tau_0\) and the time evolutions of temperature at central point \((x = 0, y = 0)\) are given. All lines are fixed by the initial charged multiplicity \(dN_{ch}/dy^{rap} = 1601\). Different initial distributions of entropy density will also result in different behaviors of final light hadrons and cause the uncertainties of extracting initial thermalization time and shear viscosity of the medium. We take the initial distributions of entropy density given in Glb model.
In this work, we don’t want to fit all the experimental charmonium data by adjusting parameters in our transport model. Instead, we focus on the sensitivity of charmonium observables to the different properties of the quark gluon plasma, and try to find out connections between them. In $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions, the final observable charmonium consists of initial production and regeneration. The initially produced charmonium are from the hard scatterings of partons, and usually carry relatively large transverse momentum. The regenerated charmonium is from recombination of thermalized charm quarks in the quark gluon plasma, and carry small transverse momentum. At high transverse momentum region in Fig. 2, the final yield is dominated by the initial production. With smaller initial thermalization time $\tau_0$, the temperature of the medium is larger, and it makes charmonium suffer stronger suppression due to color Debye-screening. We take the $\tau_0$ to be 0.6 fm/c (black solid line) and 1.0 fm/c (blue solid line). As one can see, $R_{AA}$ with different $\tau_0$ shows larger difference compared with the situations of different $\eta/s$ in central collisions ($N_p \sim 380$). The difference of $R_{AA}$ between three situations of $\eta/s = (0, 0.08, 0.2)$ (red solid line, black solid line, red dotted line) is much smaller. This is because their temperatures are much close to each other (see Fig. 1). $R_{AA}$ with (2+1)D ideal hydro (red solid line) and (3+1)D ideal hydro (black dotted line) are very close to each other at central and semi-central collisions, which is due to the boost invariance of the hot medium in central rapidity region. At peripheral collisions, The boost invariance may not be a good approximation anymore, and the difference between (2+1)D and (3+1)D hydro is larger. In (3+1)D ideal hydro, there is a larger acceleration in longitudinal expansion, and so the temperature of the medium drops faster, compared with (2+1)D ideal hydro. This results in weaker suppression of charmonium in (3+1)D ideal hydro and explain the experimental data better. So at central collisions, the initial time of medium reaches local thermalization plays important roles in charmonium suppression. At peripheral collisions, the full simulation of medium evolution in (3+1) dimension seems necessary and its effect on charmonium suppression helps to explain the experimental data.

Situations becomes more complicated when coming to the entire $p_T$-bin ($p_T > 0$) of charmonium production. The final charmonium consist of initial production and regeneration. When the temperature of the QGP is larger, the initially produced charmonium suffer stronger suppression. However, the longer lifetime of QGP makes regeneration becomes larger too. These two effects cancel with each other and the final total yield of charmonium is less changed by the difference of temperature in the hot medium.

Different initial thermalization time of the medium $\tau_0$ and shear viscosity over entropy density $\eta/s$ gives opposite effects on charmonium initial production and regen-

density from MC-Glb model and MC-KLN model respectively. QGP temperature evolutions are shown in upper sub-figure of Fig. 1. For the initial entropy density from MC-Glb model, the shear viscosity over entropy density is set as $\eta/s = 0.08$, initial time of the medium reaching local equilibrium is set as $\tau_0 = 0.6$ fm/c. For MC-KLN model, the relevant parameters are taken as $\eta/s = 0.2$ and $\tau_0 = 0.6$ fm/c to explain the final momentum spectra of light hadrons.

At the beginning of evolutions, the difference between temperatures with $\eta/s = 0.0$ and $\eta/s = 0.2$ in MC-Glb model is around 40 MeV. With different time $\tau_0$ of medium reaching local thermal equilibrium, the initial temperatures show relatively larger difference ($\sim 70$ MeV). Between MC-Glb and MC-KLN models, the maximum difference of temperatures is about 60 MeV at central point. However, the later evolutions of all situations are very close to each other at $\tau > 4$ fm/c, see Fig. 1. Charmonium suppression is mainly due to the gluon dissociation and color Debye-screening, which are sensitive to the density of partons and so the temperature of medium. The maximum difference of temperatures is at the initial time. It indicates that charmonium observables may be more sensitive to the initial thermalization time $\tau_0$, compared with other parameters of the bulk medium.

With these hydrodynamics and the transport model for charmonium evolution, we can calculate the nuclear modification factor, averaged transverse momentum square and collective flows of charmonium, and check their sensitivities to the properties of the hot medium.

**FIG. 2:** (Color Online) Nuclear modification factor of prompt charmonium $R_{AA}$ with number of participants $N_p$ in high $p_T$-bin ($6.5 < p_T < 30$ GeV/c) in central rapidity $|y^{na}| < 2.4$. Different lines represent hydrodynamics with different values of parameters in the viscous hydro. The calculations of charmonium with (3+1)D ideal hydrodynamics are also included. The experimental data is from CMS Collaboration [27].
eration. The total $R_{AA}$ almost keep unchanged in different situations. A new distribution of entropy density from MC-KLN model is also considered, and its effect is neglectable on charmonium nuclear modification factor $R_{AA}$.

With transport model and different hydrodynamic inputs, we study the $J/\psi$ suppression in different QGP evolutions. The competition between initial production and regeneration makes the total number of $J/\psi$ not sensitive to the QGP initial evolutions. However, $J/\psi$s with high $p_T$ can only be produced at the very beginning of nuclear collisions, which makes the nuclear modification factor $R_{AA}$ at high $p_T$s sensitive to the time $\tau_0$ of QGP reaching local equilibrium (also the time scale of charmonium suffering hot medium suppression).

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