Double ratio of charmonia in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV

To cite this article: Yunpeng Liu et al 2014 J. Phys.: Conf. Ser. 535 012011

View the article online for updates and enhancements.
Double ratio of charmonia in $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Yunpeng Liu$^1$, Che Ming Ko$^{1,2}$, Taesoo Song$^{1,3}$

$^1$ Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
$^2$ Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
$^3$ Frankfurt Institute for Advanced Studies, J. W. Goethe University, 60438 Frankfurt am Main, Germany

E-mail: yliu@comp.tamu.edu

Abstract. Based on a kinetic description of $J/\psi$ dissociation and production in an expanding quark-gluon plasma that is described by a 2+1 dimensional ideal hydrodynamics, we have studied the double ratio $R_{p+\text{Pb}}(\psi')/R_{p+\text{Pb}}(J/\psi)$ of charmonia in $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by including not only the cold nuclear matter effects but also the hot nuclear matter effects. We find that the double ratio of prompt charmonia is significantly suppressed in the most central collisions as a result of the hot nuclear matter effects.

Charmonia suppression in heavy ion collisions was first suggested in Ref. [1] based on the consideration of color screening in quark-gluon plasma (QGP). The anomalous suppression of $J/\psi$ production, besides the normal suppression due to the cold nuclear matter effects, observed in Pb+Pb collisions at the Super Proton Synchrotron (SPS) seemed to confirm this prediction and thus suggested that a QGP was produced in these collisions [2]. Since then, there have been extensive experimental and theoretical studies on $J/\psi$ production and suppression in both elementary and nuclear collisions. In particular,

- Baseline study of charmonia production in $p + p$ collisions has been carried out using the color singlet model (CSM) [3] and/or the color octet model (COM) [4].
- Cold nuclear matter effects, including the shadowing effect, the Cronin effect and the nuclear absorption, have been studied in $p + A$ and $d + A$ collisions.
- Hot medium effects, including the color screening, gluon dissociation, quasi-free scattering dissociation, regeneration and so forth, have been studied in $A + A$ collisions.

However, with the high beam energy at the LHC, the initial energy density in $p + \text{Pb}$ collisions can be sufficient large for the formation of a QGP. It is then of interest to study the hot medium effects on quarkonia production in these collisions and compare them to those due to the cold nuclear matter [5, 6, 7, 8, 9, 10, 11, 12].

In Ref. [13], we have carried out such a study by using a 2+1 dimensional ideal hydrodynamic model to describe the bulk dynamics of $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, i.e., based on the equation

$$\partial_{\mu}T^{\mu\nu} = 0$$  \hspace{1cm} (1)
with the boost invariant condition. In the above, $T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} p$ is the energy-momentum tensor in terms of the energy density $\epsilon$, pressure $p$, and four velocity $u$. For the equation of state $\epsilon(p)$, we have used that of Ref. [14] based on an ideal gas of massless partons for the QGP and massive hadrons for the hadronic matter, together with a bag constant which leads to a critical temperature $T_c = 165$ MeV [15, 16, 17] at zero baryon chemical potential.

For the initial energy density at time $\tau_0 = 0.6$ fm/c and its rapidity dependence, it is obtained from a multiple phase transport (AMPT) model [18]. Selecting the most central 10% collisions according to the yield of partons in AMPT, the maximum initial energy density is found at rapidity $y = -2$.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (Color online) Energy density $\epsilon$ at rapidity $y = -2$ in the most central 10% $p +$ Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of the transverse coordinate $x$ and $y$ relative to the center of the proton at different proper time $\tau$.

In Fig. 1, we show the energy density distribution in the transverse plane at rapidity $y = -2$ for different proper time $\tau$. The origin of the coordinates is located at the center of the proton, and the center of the lead lies on the negative x-axis. The initial energy density is roughly isotropic in the transverse plane with a slightly larger value on the lead side. The maximum value is $\epsilon_0 \approx 15$ GeV/fm$^3$, which corresponds to a temperature $T_0 \approx 290$ MeV.

Since the energy density is large and the volume is small compared with those in A+A collisions at lower energies, the system expands fast, leading to a quick decrease of the energy density at the center. At time $\tau = 2.0$ fm/c, the energy density at the center is even smaller than that in the peripheral region, and the maximum energy density is at the radius $r \approx 1.5$ fm. The value of the energy density on the positive axis is slightly larger than that at the negative axis. Since the center of the QGP produced in $p+$Pb collisions hadronizes earlier, its spacial topology differs from that in Pb+Pb collisions.

For the time evolution of the distribution function $f(x, p, t)$ of $J/\psi$ in the phase space of coordinate $x$ and momentum $p$, we use the transport equation

$$\partial_t f + v \cdot \nabla f = -\alpha f + \beta,$$

(2)

where $v$ is the velocity of the $J/\psi$, and $\alpha$ and $\beta$ are the dissociation and the regeneration rate, respectively. The dissociation rate

$$\alpha(T, u, p) = \frac{N_g}{E} \int \frac{d^3k}{(2\pi)^3 E_g} k \cdot p f_g(T, u, k) \sigma_D.$$

(3)

takes into account the gluon dissociation process $J/\psi + g \rightarrow c + \bar{c}$ with the cross section $\sigma_D$ [19, 20, 14]. The regeneration rate takes into account the inverse process $c + \bar{c} \rightarrow J/\psi + g$, whose cross section is related to that of the gluon dissociation process by the detailed balance

$^1$ The Euler characteristic $\chi$ changes from 2 to 4 in central $p+$Pb collisions.
relation, and can be calculated using the distribution functions of charm and anticharm quarks. For simplicity, we take the charm quark distribution to be in thermal equilibrium, i.e.,

\[ f_c(x, \mathbf{q}_c) = \rho_c(x) \frac{N}{e^{e_c u/T} + 1}, \]

where \( \rho_c \) is the number density of charm quarks and satisfies the conservation equation \( \partial_t \rho_c + \nabla \cdot (\rho_c \mathbf{v}_m) = 0 \) with \( \mathbf{v}_m \) being the velocity of the medium, and \( N \equiv \left[ \frac{(2\pi)^{-3}}{3} \int d\mathbf{q}_c \left( e^{e_c u/T} + 1 \right)^{-1} \right]^{-1} \) is the normalization factor for the Fermi distribution. For anticharm quarks, their distribution function \( f_{\bar{c}} \) has a similar form. We also include a velocity-dependent dissociation temperature \( T_d \) to describe the color screening effect [21].

Different from Pb+Pb collisions at the LHC, at most one pair of charm and anticharm quarks are produced in a \( p+p \) collision, and they are also not likely to reach thermal equilibrium. These effects are included via a canonical enhancement factor \( C_{ec} = 1 + 1/(dN_{\text{dir}}/dy) \) in the evaluation of the equilibrium number of \( J/\psi \), as in the statistical model [22, 23, 24], and the relaxation reduction factor \( r = 1 - \exp(-\tau_r/\tau_c) \) [25] with the charm quark relaxation time \( \tau_r = 7 \text{ fm}/c \) [26, 27]. More details can be found in Ref. [13]. We note that these effects can be more accurately studied in a transport model [28].

For the initial distribution of \( J/\psi \), it is obtained from the Glauber model with the inclusion of initial-state cold nuclear matter effects and a \( J/\psi \) production cross section of \( d\sigma_{pp}/dy = 5.68 \mu \text{b} \) for \( pp \) collisions at 5.02 TeV. The latter is obtained from interpolating the experimental results at lower (\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)) [29] and higher (\( \sqrt{s_{NN}} = 7 \text{ TeV} \)) [30] energies with a power-law form and an average transverse momentum square \( \left\langle p_T^2 \right\rangle = 9.5 \text{ GeV}^2 \) at middle rapidity. As to the rapidity distribution, it is assumed to be Gaussian with parameters taken from Refs. [31, 32]. The density distribution of initially produced \( J/\psi \) in space is assumed to be proportional to the thickness of a uniform solid sphere of radius \( r = 0.8 \text{ fm} \) as that for the proton.

For the cold nuclear matter effects on \( J/\psi \) and charm quarks, they are assumed to be the same and are taken from Refs. [33, 20], which then lead to a suppression in proton rapidity and an enhancement in Pb rapidity.

The above treatment for the ground state \( J/\psi \) is generalized to include its excited states \( \chi_c \) and \( \psi' \) with different dissociation temperatures \( T_D \) and cross sections [34, 35] as in Ref. [21]. For the initial abundance of these excited states, they are determined from that of \( J/\psi \) by using the empirically known feed-down contributions to \( J/\psi \) production in \( p+p \) collisions, i.e., using the proportion 6 : 3 : 1 for direct \( J/\psi \), feed-down from \( \chi_c \) and from \( \psi' \) [36]. They are further assumed to subject to the same cold nuclear matter effects as the \( J/\psi \).

For the contribution to \( J/\psi \) production from the decay of regenerated \( \chi_c \) and \( \psi' \), they are included with the branch ratios from Ref. [37].

In Fig. 2, we show the double ratio of prompt charmonia as a function of rapidity. It is seen that the double ratio at rapidity from −4 to 0 is smaller than unit due to stronger suppression of \( \psi' \) in the hot medium. In the most central 10% collisions, it is smaller than 0.1, while in collisions with centrality 40%-60%, it is between 0.3 and 0.4. Since the formation time of \( J/\psi \) and \( \psi' \) is much longer than that for the proton and Pb to pass through each other, the cold nuclear matter effects are not expected to differ much between the \( J/\psi \) and \( \psi' \).

In experiments, the inclusive double ratio is easier to measure. According to a recent study [38], the contribution of \( B \) meson decay increases the double ratio in heavy ion collisions. The corresponding result for \( p+p \) collisions is shown in Fig. 3. The qualitative effect of \( B \) meson decay is the same as that in Pb+Pb collisions [38], and the double ratio is above 0.4 in the whole rapidity range.

In summary, we have studied the double ratio of quarkonia in \( p+p \) collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) in a transport approach based on a 2+1 dimensional ideal hydrodynamic model and found
that both the prompt and inclusive double ratios are smaller than one, especially for the prompt one in the most central 10% collisions. This is not expected from the cold nuclear matter effects as they exist before $J/\psi$ and $\psi'$ are formed. Measuring the double ratio of charmonia thus provides the possibility to study the hot medium effects in $p+Pb$ collisions at the LHC.

**Acknowledgments**

This work was supported by the U.S. National Science Foundation under Grant No. PHY-1068572, the US Department of Energy under Contract No. DE-FG02-10ER41682, and the Welch Foundation under Grant No. A-1358.

**References**

[1] Matsui T and Satz H 1986 *Phys. Lett.* B178 416
[2] Gonin M et al. (NA50) 1996 *Nucl. Phys.* A610 404c–417c
[3] Chang C H 1980 *Nucl. Phys.* B172 425–434
[4] Bodwin G T, Braaten E and Lepage G P 1995 *Phys. Rev.* D51 1125–1171 (*Preprint* hep-ph/9407339)
[5] Gerschel C and Hufner J 1988 *Phys. Lett.* B207 253–256
[6] Gousset T and Pirner H 1996 *Phys. Lett.* **B375** 349–354 (*Preprint* hep-ph/9601242)
[7] McLerran L D and Venugopalan R 1999 *Phys. Rev.* **D59** 094002 (*Preprint* hep-ph/9809427)
[8] Kopeliovich B and Zakharov B 1991 *Phys. Rev.* **D44** 3466–3472
[9] Kopeliovich B, Nemchik J, Nikolaev N N and Zakharov B 1994 *Phys. Lett.* **B324** 469–476 (*Preprint* hep-ph/9311237)
[10] Kopeliovich B 2003 *Phys. Rev.* **C68** 044906 (*Preprint* nucl-th/0306044)
[11] Iancu E and Venugopalan R 2003 (*Preprint* hep-ph/0303204)
[12] Ferreiro E, Fleuret F, Lansberg J and Rakotozafindrabe A 2009 *Phys. Lett.* **B680** 50–55 (*Preprint* 0809.4684)
[13] Liu Y, Ko C M and Song T 2014 *Phys. Lett.* **B728** 437–442 (*Preprint* 1309.5113)
[14] Liu Y, Qu Z, Xu N and Zhuang P 2009 *Phys. Lett.* **B678** 72–76 (*Preprint* 0901.2757)
[15] Aoki Y, Fodor Z, Katz S and Szabo K 2006 *Nature* **443** 675–678 (*Preprint* hep-lat/0611014)
[16] Lin Z W, Ko C M, Li B A, Zhang B and Pal S 2005 *Phys. Rev.* **C72** 064901 (*Preprint* nucl-th/0411110)
[17] Liu Y, Ko C M and Zhuang P 2013 *Phys. Rev.* **C87** 014910 (*Preprint* 1207.2366)
[18] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2007 *Nucl. Phys.* **A789** 334–356 (*Preprint* nucl-th/0611023)
[19] Beringer J et al. (Particle Data Group) 2012 *Phys. Rev.* **D86** 010001
[20] Abelev B et al. (ALICE Collaboration) 2012 *Phys. Lett.* **B718** 295–306 (*Preprint* 1203.3641)
[21] Bossu F et al. (ALICE Collaboration) 2011 *Phys. Lett.* **B704** 442–455 (*Preprint* 1105.0380)
[22] Albacete J L et al. 2013 *Int. J. Mod. Phys. E* Vol. **22** 1330007 (*Preprint* 1301.3395)
[23] Wang X N and Yuan F 2002 *Phys. Lett.* **B540** 62–67 (*Preprint* nucl-th/0202005)
[24] Arleo F, Gossiaux P, Gousset T and Aichelin J 2002 *Phys. Rev.* **D65** 014005 (*Preprint* hep-ph/0102095)
[25] Zoccoli A et al. (HERA-B Collaboration) 2005 *Eur. Phys. J.* **C43** 179–186
[26] Beringer J et al. (Particle Data Group) 2012 *Phys. Rev.* **D86** 010001
[27] Chen B, Liu Y, Zhou K and Zhuang P 2013 *Phys. Lett.* **B726** 725–728 (*Preprint* 1306.5032)