Quarkonium and $B_c$ mesons from Pb + Pb at LHC energies

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Abstract. The $b\bar{b}$ ($\Upsilon$) mesons appear to be produced in the initial PbPb collision at 2.76 TeV per nucleon pair followed by partial melting in the hot quark-gluon plasma. In sharp contrast, the $c\bar{c}$ ($J/\psi$) mesons seem more likely to be formed by recombination at the hadronization stage. The $B_c$ mesons, with one quark of each kind are seldom seen in pp collisions because a particle-antiparticle pair requires the simultaneous production of four heavy quarks. Although a family of $B_c$ mesons have been predicted, only the ground state has been seen. If the $c\bar{c}$ mesons are produced by recombination, it could be expected that $B_c$ mesons would be abundant with PbPb. Because the quark and antiquark have different flavor, the $B_c$ are relatively long lived, 0.45 ps (to be compared with about 1.5 ps for the lighter $B$ mesons). They would be seen with PbPb reactions by $J/\psi(\mu^+\mu^-)\pi^\pm$ looking at muons and pions from displaced vertices.

1. Introduction

Quarkonium is a meson made of a quark-antiquark pair, analogous to positronium. The term is usually applied to the heaviest quarks, $c$ and $b$. (The top quark is too short-lived to combine with anything.) Quarkonia can self annihilate. Of particular interest here is the decay into a $\mu^+\mu^-$ pair. The mass and kinetic energy of a quarkonium can be determined from the direction and energy of the two muons. The $\mu^+\mu^-$ derived mass spectrum, measured with CMS [1], is shown in figure 1. This figure is for $\sqrt{s} = 7$ TeV protons. The corresponding figure for PbPb at $\sqrt{s_{NN}} = 2.76$ TeV/nucleon pair is similar but with poorer statistics. The behavior of $c\bar{c}$ ($J/\psi$) and $b\bar{b}$ ($\Upsilon$) in the quark-gluon plasma of PbPb reactions are strikingly different. $b\bar{b}$ and $b\bar{c}$ mesons, $B_c^\pm$, are of mass between $J/\psi$ and $\Upsilon$ with a decay mode to $J/\psi \pi^\pm$, seen as $\mu^+\mu^- \pi^\pm$. If the $c\bar{c}$ mesons are formed by recombination in PbPb reactions, it could be expected that the $B_c^\pm$ are abundantly produced in PbPb collisions by recombination.

![Figure 1. Invariant-mass spectrum from $\mu^+\mu^-$ measured with CMS.](image-url)
2. Upsilon Y(1S), Y(2S), Y(3S)

Melting of the excited states of quarkonia, \(c\bar{c} (J/\psi)\) and \(b\bar{b} (\Upsilon)\), in the QGP is thought to provide a measure of the temperature in the region where they are formed [2]. They are formed early and provide a measurement of the maximum QGP temperature. A detailed discussion of suppression by color screening and enhancement by regeneration is given in [3]. The \(\Upsilon(1S)\) is the most tightly bound quarkonium state, and so is the one with the highest dissociation temperature. As of this writing, the calculation of the temperature from the latest data has not been published. Figure 2 provides a visualization of these effects.

The prediction of the suppression pattern is complicated by various factors. These include feeddown contributions from higher-mass resonances into the observed quarkonium yields, as well as several competing nuclear and medium effects including recombination. These factors have played an important role in the interpretation of the charmonium measurements [4]. However, measurements of the excited state of the \(J/\psi\), the \(\psi(2S)\), may require reconsideration of this analysis. The \(\Upsilon\) states provide additional and theoretically cleaner probes of the QGP. The three \(\Upsilon(nS)\) states are characterized by similar decay kinematics but distinct binding energies. They are useful for the measurement of relative state suppression because common experimental and theoretical factors cancel. The CMS detector clearly resolves the three \(\Upsilon\) states below the open bottom threshold by their decay into muons making use of the excellent muon energy resolution of CMS [5]. The ratios of the observed yields, figure 3, not corrected for differences in acceptance and efficiency, of the \(\Upsilon(2S)\) and \(\Upsilon(3S)\) states to the \(\Upsilon(1S)\) state, in the \(\text{PbPb}\) and \(\text{pp}\) data, are [5]

\[
\begin{align*}
\Upsilon(2S) / \Upsilon(1S) |_{\text{pp}} &= 0.56 \pm 0.13 \text{ (stat.)} \pm 0.02 \text{ (syst.)}, \\
\Upsilon(2S) / \Upsilon(1S) |_{\text{PbPb}} &= 0.12 \pm 0.03 \text{ (stat.)} \pm 0.02 \text{ (syst.)}, \\
\Upsilon(3S) / \Upsilon(1S) |_{\text{pp}} &= 0.41 \pm 0.11 \text{ (stat.)} \pm 0.04 \text{ (syst.)}, \\
\Upsilon(3S) / \Upsilon(1S) |_{\text{PbPb}} &= 0.02 \pm 0.02 \text{ (stat.)} \pm 0.02 \text{ (syst.)} < 0.07 \text{ at 95\% confidence level},
\end{align*}
\]

where the systematic uncertainty arises from the fitting procedure. For the \(\Upsilon(3S)\) to \(\Upsilon(1S)\) ratio in PbPb, a 95% confidence level (CL) limit is set, based on the Feldman–Cousins statistical method [6]. There was a special \(\text{pp}\) run at \(\sqrt{s} = 2.76\) TeV to allow a comparison of PbPb and \(\text{pp}\) cross sections. The shapes of the pp \(\Upsilon\) spectra are essentially the same as at \(\sqrt{s} = 7\) and 8 TeV.

The total \(\Upsilon(nS)\) yields in PbPb and pp collisions can be compared after suitable corrections [5]. The corrected ratios, \(R_{AA}\), for PbPb/pp are:

\[
\begin{align*}
R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08 \text{ (stat.)} \pm 0.07 \text{ (syst.)}, \\
R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (syst.)}, \\
R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)} < 0.10 \text{ at 95\% CL}.
\end{align*}
\]

As the \(\Upsilon(3S)\) peak is not observed above the dimuon continuum (significance less than one standard deviation), only an upper limit is given. There is still no clear dependence on centrality for the \(\Upsilon\) states in these data. The lifetimes of the three \(\Upsilon\) states are long enough (of the order 5000 fm/c) that they get out of the collision region before they decay, but still so short that the decay products appear to come from the primary interaction region.
Figure 3. Dimuon invariant-mass distributions in PbPb (left) and pp (right) data at $\sqrt{s_{\text{NN}}} = 2.76$ TeV.

The same reconstruction algorithm and analysis selection are applied to both datasets, including a transverse momentum requirement on single muons of $p_T > 4$ GeV/c. The solid (signal + background) and dashed (background-only) curves show the results of the simultaneous fit to the two data sets [5].

3. $J/\psi$ and $\psi(2S)$

Prompt and non-prompt $J/\psi$ $R_{AA}$ have been measured with CMS for both the 2010 and 2011 runs at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [7]. The non-prompt $J/\psi$ are from various B hadrons with lifetimes sufficient for the vertex of the $\mu^+\mu^-$ from the $J/\psi$ decay to be separated from the PbPb reaction vertex. About a quarter of the $J/\psi$ were found to be non-prompt. The non-prompt fraction is found to vary slowly with $p_T$. Measurements have been made of the non-prompt fraction from pp at $\sqrt{s} = 7$ TeV in the four LHC experiments with results varying from 10% to 60% depending on the $J/\psi$ $p_T$ [8-11]. Many more PbPb measurements, covering the complete range of $p_T$, will be needed before the results can be used as a measure of the relative attenuation of $J/\psi$ and B mesons.

The $\psi(2S)$, 3.683 GeV/c$^2$, is an excited state of the $J/\psi$, 3.097 GeV/c$^2$. It might be expected that the relative $R_{AA}$ for the two states would provide a measure of the temperature, but there are complicating factors. The quantity of interest is the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}$. The extent to which this ratio is less than one is a measure of the melting of the excited state, relative to the ground state, and is, therefore, a measure of the temperature. The instrumental effects cancel when all the measurements are made with the same detector. Measurements of the ratio were made with CMS using data from the 2011 PbPb run [12]. The results, figure 4, are considered preliminary because of uncertainties in the pp data.

One scenario is that the heavy-quark mesons are produced early by hard parton-parton collisions and that they then move through the nuclear medium. The attenuation in their number, given by $R_{AA}$, is caused by interactions in the medium. In this case $R_{AA}$ would be less than one with the attenuation increasing as the size of the interaction region increases. The size of the interaction region is specified by $N_{\text{part}}$, the number of nucleons in the overlap region of the colliding nuclei. This can be related to the impact parameter, which is zero for the most central collisions. The less bound excited state would be attenuated more rapidly than the ground state, so that the ratio shown in figure 4 should decrease with $N_{\text{part}}$. Such predictions are in sharp disagreement with the data in figure 4. A different model assumes that the heavy quarks are produced early in primary hard collisions and do not combine into mesons until the system cools and hadronization occurs. With the large number of charm quarks and
antiquarks produced in PbPb collisions (O(100)) at \( \sqrt{s_{NN}} = 2.76 \) TeV, charmonia is produced at the hadronization stage of the PbPb collisions from initially uncorrelated c and \( \bar{c} \) quarks produced in the initial inelastic collisions [13]. While no precise prediction of the relative probabilities to form a \( J/\psi \) or \( \psi(2S) \) state are provided, this mechanism could explain why \( \psi(2S) \) mesons were less suppressed than \( J/\psi \) in PbPb collisions. Such recombination effects would be contributing mostly at low charmonium \( p_T \) because the quarks are thermalized. The inclusive \( \psi(2S) \) yield is comprised of non-prompt \( \psi(2S) \) from b-hadron decays and directly produced \( \psi(2S) \). In contrast to prompt \( J/\psi \), there is no significant feed down from heavier charmonium states. CMS has measured non-prompt contributions to the \( J/\psi \) and \( \psi(2S) \) inclusive yields in pp collisions at \( \sqrt{s} = 7 \) TeV [14] that, in the forward region, are relatively similar and of the order of 20\% for \( p_T \) around 6.5 GeV/c, increasing with \( p_T \). For the data in figure 4, prompt and non-prompt \( J/\psi \) or \( \psi(2S) \) are not separated because of the limited \( \psi(2S) \) yield.

![Figure 4](image.png)

Figure 4. Measured yield double ratio \( (N_{\psi(2S)/N_{J/\psi}}^{\text{PbPb}})/(N_{\psi(2S)/N_{J/\psi}}^{\text{pp}}) \) as a function of the size of the interaction region. The \( p_T \) and rapidity bins are \( 3.0 < p_T < 30 \) GeV/c and \( 1.6 < |y| < 2.4 \) (left), and \( 6.5 < p_T < 30 \) GeV/c and \( |y| < 1.6 \) (right). The error bars and boxes give the PbPb statistical and systematic uncertainties, respectively. The shaded band is the uncertainty on the pp measurement, common to all double-ratio points.

The increase in the \( (2S)/(1S) \) ratio with volume could be a reflection of the increase in the volume to surface ratio as the volume increases. If the hadronization occurs in a surface layer and the number of charmed quarks available for recombination is proportional to the volume, the concentration of charmed quarks at the surface would increase with volume thereby increasing the probability of recombination.

There is another possible explanation for the increase in the \( (2S)/(1S) \) ratio. A sufficiently energetic quark moving through the QGP is thought to produce a color charge analogue to Čerenkov radiation [15-16]. In this case the radiation is heavy quarkonium mesons rather than photons. This would provide a mechanism for the number of charmed quarks per unit volume to increase as the size of the reaction volume increases. The energetic light quarks that are producing the “radiation” have a larger distance available for travel.
4. $B_c$ mesons

The $B_c^{±}(1S)$ mesons have a mass of 6.273 GeV/c$^2$, intermediate between $J/\psi$ at 3.097 GeV/c$^2$ and $\Upsilon(1S)$ at 9.460 GeV/c$^2$ [17]. Because they cannot self annihilate, the life time is a relatively long 0.135 mm/c. The other B hadrons have even longer lifetimes of almost 500 mm/c. The $B_c$ have a shorter lifetime because the weak decay can occur with either the c quark or the b quark. The $B_c$ can be observed by the decay mode $B_c^{±} \rightarrow J/\psi + \pi^{±}$, with the $J/\psi$ going to a muon pair that diverges from a point separated from the primary interaction (displaced vertex). They are difficult to produce with pp reactions because making a $B_c$ pair requires the production of four heavy quarks. Of the positively charged B mesons from pp only 0.68% are $B_c^+$ [17]. The remaining 99.3% are $B_u$ with a mass of 5.279 GeV/c$^2$ and a lifetime of 0.492 mm/c.

$B_c$ mesons have not been identified in PbPb studies, but if $J/\psi$ is made primarily by recombination, it could be expected that recombination would also produce an abundance of $B_c$. The $B_c$ mesons from recombination of thermalized quarks would have small $p_T$ values. Prompt and non-prompt $J/\psi$ decays to muon pairs have been measured for PbPb at $= 2.76$ TeV by CMS, figure 5. The fit assumes that all of the non-prompt $J/\psi$ result from decays of the various B mesons and baryons, all of which have about the same lifetime except for the $B_c$. The change in the slope at about 0.2 mm suggests the presence of a short-lived component, but it would be difficult to prove the existence of the $B_c$ by decay rate vs. distance measurements alone, because of the large background that varies with distance.

If measurements of the invariant mass of $\mu\mu\pi$ events at small decay distances turned up even a few examples of masses close to that of the $B_c$, that would be sufficient to show that $B_c$ are more abundantly produced with PbPb than with pp. There is a whole family of $B_c$, but only the ground state lives long enough to appear as a displaced vertex [18]. The pions and less than 500 MeV photons coming from the excited state $B_c$ mesons, as they decay to the ground state, appear to come from the primary reaction vertex; for PbPb they would be buried in background.

The next PbPb run at the LHC will be at twice the energy. Because the production of heavy quarks increases faster than the background, the higher energy data should allow a more detailed study of the $B_c$ mesons.
5. Conclusions

It seems likely that PbPb reactions will make an abundance of $B_c$ mesons, which are difficult to make with pp reactions. Heavy ion reactions should be considered as a possible source of new particles, both conventional and exotic particles.

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