Probing strongly interacting matter with heavy resonances in Pb+Pb collisions at LHC energies

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Abstract.
With the recent Pb+Pb collisions experiments at LHC, a new era has began in the field of heavy ion collisions. The heavy hadronic resonances such as J/ψ, Υ and their states are produced in plenty at LHC and can be tackled in perturbative QCD. These resonances along with other low mass resonances can be very well reconstructed with advanced detector technologies and are used to study the detailed tomography of the matter which would not have been possible at lower energies. In addition to the hot matter effects one also has to address the questions such as modification of parton distributions of protons when placed inside a nucleus. This is known as initial state effect and can be well addressed at LHC by measuring the Z boson. In addition, there are (cold) nuclear matter effects which can modify the probes and are planned to be studied in future p+Pb collisions. In this paper, we review the recent LHC results with emphasis on quarkonia. We devote a section on modeling of quarkonia suppression. The new calculation done in the case of Υ and its states are given.

1. Introduction
The heavy ion collisions are performed to study the interaction of matter at extreme temperatures and densities where it is expected to be in the form of Quark Gluon Plasma (QGP), in which the quarks and gluons can move far beyond the size of a nucleon making color degrees of freedom dominant in the medium. The experimental effort in this direction started with low energy CERN accelerator SPS and evolved through voluminous results [1] from heavy ion collision at Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Lab in recent years. The RHIC experiments at the energy $\sqrt{s_{NN}} = 200$ GeV indicate that such matter is strongly coupled and can consist of bound states which carry net color.

One of the most striking QGP signals is quarkonium suppression [2]. Quarkonia are identified by their reconstructed mass peaks in the dilepton invariant mass distribution. At both SPS and RHIC energies, the suppression of the J/ψ resonance suggests that a very high temperature system was created [3, 4]. With the start of Pb+Pb collisions at per nucleon center of mass energy $\sqrt{s_{NN}} = 2.76$ TeV at LHC, there is renewed excitement in this field. There are number of light and heavy resonances measured appear in dilepton invariant mass distribution. Below ~ 12 GeV/$c^2$, it includes a number of resonance peaks: $\rho$, $\omega$ and $\phi$ at low masses and the $\psi$ and $\Upsilon$ states at higher masses. At 91 GeV/$c^2$, the $Z^0 \rightarrow l^+l^-$ peak appears. The first measurements of the dilepton spectra at the LHC have recently been reported [5, 6, 7]. The CMS experiment reported the first measurements of the $Z^0$ mass region in Pb+Pb collisions [5].
as well as measurements of the full dimuon distribution, including quarkonia [6]. ATLAS has also reported $J/\psi$ and $Z^0$ measurements in the dimuon channel [7]. The second LHC Pb+Pb run, at much higher luminosity, will provide higher statistics measurements of the dilepton spectra over the full available phase space.

In this paper, we review the results from LHC starting with some global features then quarkonia and heavy flavour. We devote a section on modeling of quarkonia suppression. The new calculation done in the case of $\Upsilon$ states and their ratios as a function of transverse momentum are given.

2. Global features of heavy ion collisions at LHC as compared to RHIC

   The multiplicity of produced particles is probably the most basic of observables. It provides information on the energy density achieved in the collisions and constitutes a primary input for most model calculations. For central Pb-Pb collisions at the LHC (at $\sqrt{s_{NN}} = 2.76$ TeV), the produced multiplicity is about twice as at RHIC [8, 9, 10]. As function of collision energy the charged particle multiplicity measured in central collisions at LHC [11] is larger than most of the predictions and about 50 % more than expected from simple phenomenological extrapolations from RHIC energy. The centrality dependence of the charged particle multiplicity is rather mild, favouring models incorporating some mechanism (such as parton saturation) moderating the increase with centrality of the average multiplicity per participant pair [12, 13]. Once the multiplicities are rescaled to account for the difference in the central values, the centrality dependences at the LHC and at RHIC are remarkably similar.

   The average amount of transverse energy produced per unit of pseudorapidity per participant pair in central collisions is about 9 GeV, or about a factor 2.7 larger than at RHIC (the larger multiplicity at LHC being accompanied by an increase in the average transverse momentum of the produced particles), corresponding to an energy density of about 16 GeV/fm$^3$ (taking the conventional value of 1 fm/c for the plasma formation time). Hanbury Brown – Twiss (HBT) interferometry [14, 15] exploits the quantum interference between identical bosons (e.g. charged pions) to evaluate the size of the system at the time of decoupling. Compared to RHIC, the ALICE experiment finds an increase in the dimensions of the system in all three components [16, 17] (including, finally, also the sidewards component $R_{\text{side}}$). The system expands significantly more than at RHIC, with an estimated increase by about a factor 2 of the homogeneity volume for central collisions.

3. Quarkonia as probes of QGP

   One of the most talked about signal of QGP is the suppression of quarkonium states, both of the charmonium ($J/\psi$, $\psi'$, $\chi_c$, etc) and the bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, $\chi_b$, etc) families. This is thought to be a direct effect of deconfinement, when the binding potential between the constituents of a quarkonium state, a heavy quark and its antiquark, is screened by the colour charges of the surrounding light quarks and gluons. The melting temperature depends on the binding energy of the quarkonium state. The ground states, $J/\psi$ and $\Upsilon(1S)$ are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. The masses and the radii of quarkonia states are given in Table 1 [18]. Since the $\Upsilon(1S)$ is the most tightly bound state among all quarkonia, it is expected to be the one with the highest dissociation temperature. Examples of dissociation temperatures are $T_{\text{diss}} \sim 1T_c$, 1.2$T_c$, and 2$T_c$ for the $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$ respectively. Similarly, in the charmonium family the dissociation temperatures are $\leq 1T_c$ and 1.2$T_c$ for the $\psi'$ and $J/\psi$ respectively [6].

   However, there are other possibilities that would affect the quarkonium production in heavy-ion collisions. The modifications to the parton distribution functions inside the nucleus (shadowing) and other cold-nuclear-matter effects can reduce the production of quarkonia without the presence of a QGP [9, 10]. Also, the large number of heavy quarks produced
in heavy-ion collisions, in particular at the energies accessible by the Large Hadron Collider (LHC), could lead to an increased production of quarkonia via statistical recombination.

Charmonium studies in heavy-ion collisions have been carried out first at the Super Proton Synchrotron (SPS) by fixed-target experiments at 17.3-19.3 GeV centre-of-mass energy per nucleon pair, then at the RHIC experiment and now at LHC with higher energy and luminosity. In all cases, $J/\psi$ suppression was observed in the most central collisions[6]. At the SPS, the suppression of the $\psi'$ meson was also measured. At RHIC, the reference was provided by the properly scaled yield measured in pp collisions. The PHENIX collaboration has updated the results on $J/\psi$ suppression using the 2007 data sample [19, 20]. The previous results, and in particular the stronger suppression at forward than at central rapidity, are confirmed, with reduced statistical and systematic uncertainties.

The CMS collaboration obtained production rates of $J/\psi$ mesons and of the $\Upsilon$ family in dimuon channel [6, 21]. Figure 1 shows the dimuon mass reconstructed in PbPb collisions at $\sqrt{s_{NN}} = 2.76$. Non-prompt $J/\psi$s (those produced from B-meson decays) could be identified by their displaced decay vertex. The suppressions of prompt and non-prompt $J/\psi$ particles were measured separately. Figure 2 gives an idea of $R_{AA}$ of prompt $J/\psi$ as function of centrality measured by CMS. The suppression pattern with CMS is very similar to PHENIX. One can easily see that a suppression of $\sim 5$ is observed in the 10% most central PbPb collisions with respect to pp. This suppression is reduced in more peripheral collisions, reaching a factor of $\sim 1.6$ in the 50-100% centrality bin. The $R_{AA}$ as function of the number of participants $N_{\text{part}}$ indicates that high $p_T$ $J/\psi$s are strongly suppressed as low as 0.2 for central collisions as shown in Fig. 2.

ATLAS also observes strong centrality dependence in the central-to-peripheral nuclear modification factor $R_{CP}^{J/\psi}$ at high $p_T$ [7]. For $p_T > 0$ and $2.5 < y < 4$, ALICE observes a $J/\psi$ nuclear modification factor $R_{AA}^{J/\psi}$ of about 0.5, practically independent of centrality [22].

CMS reported suppression for the $\Upsilon(1S)$ (around 0.6, with a weak energy dependence) and further suppression by about a factor 3 relative to the $\Upsilon(1S)$ for the excited states $\Upsilon(2S+3S)$.
Figure 2. Measured $R_{AA}$ as a function of centrality, for prompt $J/\psi$.

Figure 3. The upsilon states measured in dimuon invariant mass distribution.

[21]. Fig. 3 shows that the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are suppressed as compared to the $\Upsilon(1S)$. This is compatible with differential melting of quarkonia states in the high temperatures produced by PbPb collisions.

The detailed pattern of quarkonia suppression will emerge with high statistics measurements. Establishing a good pA reference will also be essential in order to disentangle the contributions from cold nuclear effects.

4. Z boson in heavy ion collisions
To study QGP effects the measurements in heavy-ion (AA) collisions are compared to scaled measurements in proton-proton (pp) collisions. But scaling pp to PbPb is not sufficient as the production of particles is different due to effects such as shadowing (initial state effects). So we use the baseline, $Z^0$ to compare in the same AA sample the yields of particles that are modified by the QGP to those of unmodified reference particles.

In AA collisions, Z boson production can be affected by various initial-state effects, though predictions indicate that these contributions are rather small [5]. Firstly, the mix of protons and neutrons in AA collisions (the so-called isospin effect) is estimated to modify the Z yield by less than 3% compared to pp collisions. Secondly, energy loss and multiple scattering of the initial partons can also alter the Z production, by about 3%. The parton distributions functions (PDFs) however are modified in nuclei and a depletion (shadowing) is expected for Z bosons at the LHC, modifying their yield by as much as 20%. Precise measurements of Z production in heavy-ion collisions can therefore help to constrain nuclear PDFs. The Z bosons are therefore ideally suited to serve as a standard candle of the initial state in PbPb collisions at the LHC energies. CMS [5] has shown that Z yield does not vary in different centrality giving an impression that no centrality dependence of the binary-scaled Z yields is observed in data.

5. Open charm and beauty mesons
The heavy flavour such as D and B probe the medium properties. At RHIC it has been observed that heavy quarks loose substantial energy in the medium. Both STAR and PHENIX are planning to upgrade the apparatus with the addition of vertex detectors, which should allow them to separate the vertices of the weak decays of heavy flavour particles from the primary vertex. Heavy flavour vertexing is already available in the LHC experiments. Reconstructed $D^0$
and D\textsuperscript{+} signals have been presented by ALICE [24, 25], who observe substantial suppression of the production of D mesons over the currently available transverse momentum range (out to 12 GeV/c) in both central (0-20%) and peripheral (40-80%) Pb–Pb collisions. In BDMPS energy loss calculations for LHC, D are expected to be suppressed about a factor 2 less than pions for $p_T \sim 8$ GeV/c [26]). Could charm quarks be essentially thermalized in the QGP, and thereby ”lose memory” of their energy loss history? CMS have presented results on the nuclear modification factor of J/ψ originating in the decay of B mesons for $p_T^{(J/\psi)} > 6.5$ GeV/c [21]. The suppression is again about a factor 3, with very little – if any – centrality dependence.

The future will bring high statistics D and B measurements, allowing us to establish the mass and colour change dependence of the parton energy loss.

6. Ratios of upsilon states as probe of QGP

The ratio of upsilon states has been measured in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [23] which looks a more promising signal of QGP as the nuclear matter effects cancel out in the ratio. It was shown many years back [27, 28] that the $p_T$ dependence of such ratio would show large variation and would be a direct probe of the QGP. In this work, we calculate the ratios of upsilon states using essentially same model with the parameters relevant for LHC.

6.1. Radius and formation time of quarkonia

Radius and formation time of quarkonia are calculated in potential models which are based on the assumption that the interaction between the heavy quark and its antiquark inside the quarkonium can be described by a potential. Due to the largeness of the heavy quark mass and the smallness of the heavy quark velocity, $v<<1$, one can treat the quark-antiquark system nonrelativistically and solve the Schrodinger equation to obtain the bound state properties. Following Ref [29, 30], the interquark potential for non-relativistically bound quarkonium at zero temperature is

$$V(r,0) = \sigma r - \frac{\alpha}{r},$$

where $r$ is the separation between Q and $\overline{Q}$ with $\sigma=0.192$ GeV$^2$ and $\alpha=0.471$. At a finite temperature $T$, the quark binding is modified by the color screening and the potential becomes

$$V(r,T) = \frac{\sigma}{\mu(T)}(1 - e^{-\mu(T)r}) - \frac{\alpha}{r} e^{-\mu(T)r},$$

where $\mu(T)$ is called screening mass. For $\mu=0$, we get the confining potential equation (1). Since the range of the binding force decreases exponentially with the screening mass, $\mu(T)$ the temperature dependence of the potential can be included in $\mu$ [29]. Screening effect can be evaluated with the semi-classical approximation,

$$E(r,\mu) = 2m + \frac{c}{mr^2} + V(r,\mu).$$

where $m$ is mass of quark and $c$ is obtained from the uncertainty relation $c = <p^2> <r^2 >$. Minimizing the $E(r,\mu)$ with respect to $r$ gives us the temperature dependence of the lowest bound state radius. Each bound state has definite formation time $\tau_F$, the time needed to form a bound state after the production of heavy quarks

$$\tau_F = m r/p,$$

where $p$ is the momentum of each quark inside the states. The values obtained from the non-relativistic Schrodinger equation [29] are given in Table 2. In the rest-frame of medium, the time $\tau_F$ is obtained by
\[ t_F = \tau_F \left( 1 + \frac{P^2}{M^2} \right)^{1/2}. \]  

with \( P \) and \( M \) denoting the momentum and mass of the pairs respectively.

6.2. Dissociation temperature

In order to get quantitative idea about how the bound state properties change with temperature one should derive this directly from QCD as in zero temperature potential [31]. One of the common features of potential models is that there is strong decrease of binding energy with increasing temperature. The binding energy is defined as the distance between the peak position and the continuum threshold [32]

\[ E_{\text{bin}} = 2m + V_\infty - M, \]  

where \( V_\infty = \sigma/\mu \) in the case of screened Cornell potential [30]. When the binding energy of a resonance drops below a particular temperature called dissociation temperature \( T_D \), the state is weakly bound, and thermal fluctuation can destroy it by transferring energy and exciting the quark anti-quark pair into the continuum. Above this temperature no resonance structure can be seen. The rate of this excitation or the width of the states is determined by the binding energy. Due to the uncertainty in potential one cannot determine the binding energy exactly but set an upper limit for it.

At a temperature where the width \( \Gamma(T) \) is greater than the binding energy the state will likely to be dissociated. The upper limit for the dissociation temperatures of the quarkonium states is determined by the applying conservative quantitative condition \( \Gamma(T) \geq 2E_{\text{bin}}(T) \). The corresponding dissociation temperatures are given in Table 2 [32].

| \( \Upsilon \) | \( \Upsilon' \) | \( \chi_b \) |
| --- | --- | --- |
| \( \tau_F \) [fm] | 0.76 | 1.9 | 2.6 |
| \( T_D \) [GeV] | \( 2T_c \) | \( 1.2T_c \) | \( 1.3T_c \) |

6.3. Quarkonia suppression model

For a screening mass \( \mu(T) \) above a certain critical value, the resonance no longer forms in the plasma. The temperature \( T_D \) at which this happens is break up temperature for each bound state. The essential of this model can be found in Ref. [33]. The time at which the temperature drops to \( T_D \) can be obtained using Bjorken scenario [34] as

\[ t_D = t_0 \left( \frac{T_0}{T_D} \right)^3, \]  

where \( t_0 \) is formation time and \( T_0 \) is initial temperature of the QGP.

The \( p_T \) suppression pattern of a resonance is the consequence of the competition between the resonance formation time, \( \tau_F \) and temperature, lifetime and spatial extent of the QGP. As long as \( t_D/\tau_F > 1 \), quarkonium formation will be suppressed. The maximum \( p_T \) below which suppression occurs is

\[ p_{(T,\text{max})} = M \sqrt{\frac{t_D}{\tau_F}} - 1. \]  

(8)
At any time $t$, during the evolution of the QGP, the spatial boundary of the screening region is located at the transverse radius $r_S$ given by
\[
    r_S = R \left( 1 - \left( \frac{\gamma \tau_F}{t_D(0)} \right)^{1/\beta} \right)^{1/2},
\]  
where $t_D(0)$ is the value of $t_D$ calculated by equation (7) for resonances produced in the center of the system and $\gamma = \sqrt{1 + (p_T/M)^2}$. The $Q\bar{Q}$ can escape the QGP before the $\tau_F$ for a range of angles between $r$ and $p_T$ provided $(r + \tau_F p_T/M) > r_S$.

The probability $S(p_T)$ that the $Q\bar{Q}$ pair survives and is able to form an onium state is the ratio of the number of bound states produced by those pairs that escape the plasma to the maximum possible number of onium bound states that would be formed at the given $p_T$ in the absence of the QGP:
\[
    S(p_T) = \frac{\int_0^R drr\rho(r)\theta(r,p_T)}{\pi \int_0^R drr\rho(r)},
\]
where $\rho(r)$ and $\theta(r,p_T)$ are
\[
    \rho(r) = \left( 1 - \left( \frac{r}{R} \right)^2 \right)^\alpha
\]
and
\[
    \theta(r,p_T) = \begin{cases} 
    \pi & z \leq -1 \\
    \cos^{-1}z & |z| < 1 \\
    0 & z \geq 1,
\end{cases}
\]
where $z$
\[
    z = \frac{r_S^2 - r^2 - (\tau_F p_T/M)^2}{2r\tau_F p_T/M}.
\]
The parameters $\beta = 1/3$ and $\alpha = 1/2$.

| Table 3. | Screening temperature, screening time and $p(T_{\text{max}})$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Set 1 | | | | |
| $T_D$ (GeV) | $2T_c$ | $1.2T_c$ | $1T_c$ | $1.3T_c$ |
| $t_D$ (fm/$c$) | 0.785 | 3.63 | 6.28 | 2.85 |
| $p(T_{\text{max}})$ | 2.45 | 16.3 | 25.05 | 4.50 |
| Set 2 | | | | |
| $T_D$ (GeV) | $1.7T_c$ | $1.1T_c$ | $0.9T_c$ | $1T_c$ |
| $t_D$ (fm/$c$) | 1.28 | 4.72 | 8.62 | 6.28 |
| $p(T_{\text{max}})$ | 12.79 | 22.78 | 35.72 | 21.68 |
Figure 4. Survival probability for different bottomonium states versus $p_T$ for two sets of dissociation temperatures.

Figure 5. The ratio $\Upsilon'/\Upsilon$ versus $p_T$ for two sets of dissociation temperatures.

The initial temperature $T_0$ for a given initial time $t_0$ is obtained by

$$T_0^3t_0 = \frac{3.6}{4a_q\pi R^2} \frac{dN}{dy}$$

$dN/dy = 1.5 \times 1600$, charge multiplicity measured in Pb+Pb collisions at 2.76 TeV and $a_q = 37\pi^2/90$ is the degrees of freedom in quark phase. $R$ is the radius of the nucleus.

Figure 4 shows the survival probability versus $p_T$ for $\Upsilon$, $\Upsilon'$, $\Upsilon''$, $\chi_b$ with initial conditions $T_0 = 0.636$ GeV, $t_0 = 0.1$ fm/$c$, $T_c = 0.160$ GeV. Taking $R = 7.1$ fm, equivalent to the radius of Pb nucleus we can produce medium effect in the calculation of survival probability. The two sets of dissociation temperatures used are shown in Table 3. One can observe that all resonance states are suppressed in the medium. At small $p_T$, $S(p_T) \sim 0$ corresponding to total suppression. The maximum transverse momentum $p_T, \max$ below which the upsilon is suppressed is different for different states. If the QGP is of smaller spatial extent, the survival probability can become unity even for a smaller $p_T$.

Figure 5 shows ratio $\Upsilon'/\Upsilon$ again for two sets of dissociation temperatures. We assumed that the $p_T$ distribution of the $\Upsilon$ states are similar and we have taken $\Upsilon'/\Upsilon = 0.53$ and $\Upsilon''/\Upsilon = 0.17$ corresponding to the measurement at Tevatron [35]. We used these values for calculating the ratio of different states. Only directly produced $\Upsilon'$ and $\Upsilon$ are included in the ratio. Due to
different suppression patterns of the states, the ratio is small at low $p_T$ with some fluctuating behavior and will become constant at high $p_T$.

7. Conclusions

With the start of LHC with its high tech detectors high energy nucleus-nucleus collisions are entering an era of precision measurements that should allow us to impose tight constraints on the properties of the medium. The multiplicity and transverse energy measured at LHC are larger than most of the predictions. With CMS, $J/\psi$ suppression of $\sim 5$ is observed in the $10\%$ most central PbPb collisions with respect to pp. This suppression is reduced in more peripheral collisions, reaching a factor of $\sim 1.6$ in the 50-100\% centrality bin. High $p_T$ $J/\psi$s are strongly suppressed as low as 0.2 for central collisions. CMS shows that the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are suppressed as compared to the $\Upsilon(1S)$. This is compatible with differential melting of quarkonia states in the high temperatures produced by PbPb collisions. The $Z$ boson yield in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV has been measured inclusively and as a function of rapidity, transverse momentum, and centrality. No centrality dependence of the binary-scaled $Z$ yields is observed in data. With higher luminosity data, the $Z$ boson can be a powerful reference tool for final-state heavy-ion related signatures as well as providing a means to study modifications of the parton distribution functions.

The ratio of upsilon states looks a more promising signal of QGP as the nuclear matter effects cancel out in the ratio. The $p_T$ dependence of such ratio would show large variation and would be a direct probe of the QGP. In this work, we calculate the ratios of upsilon states with the parameters relevant for LHC. One can observe that all resonance states are suppressed in the medium. At small $p_T$, $S(p_T) \sim 0$ corresponding to total suppression. The maximum transverse momentum $p(T_{\text{max}})$ below which the upsilon is suppressed is different for different states. Due to different suppression patterns of the states, the ratio is small at low $p_T$ with some fluctuating behavior and will become constant at high $p_T$.

With a high luminosity LHC Pb–Pb run in 2011 (20 times the 2010 luminosity) and possibly a p–Pb run as early as next year, we could be in for some paradigm shifting in this field.

8. References

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