Quarkonia Measurements with ALICE

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Abstract.

ALICE is the dedicated heavy-ion physics experiment at LHC. It is designed to provide excellent means to study the quark-gluon plasma, a deconfined state of matter assumed to be created under extreme conditions of temperature and/or baryonic density. A very promising observable is the measurement of quarkonia, including all the \textit{J/ψ}, \textit{ψ'} and Υ states. We will review the capabilities of ALICE to measure quarkonia and it’s associated physics program. Furthermore we will present the current status of the analysis techniques and the results which can be obtained with the data collected during the first year of running.

1. Introduction

Bound hadronic states made of heavy quark-anti-quark pairs are called quarkonia. Due to their high masses, heavy quark pairs are expected to be created predominantly in the early stage of the collision of two heavy nuclei. Thus, quarkonia can be utilized as a very interesting probe to study the quark-gluon plasma (QGP).

The evolution of this state of matter is expected to take place in later stages of the collision and is therefore believed to modify the measured rates of quarkonia. Before being able to carry out such measurements in A-A, the elementary production processes have to be understood.

1.1. Elementary Reactions

Various theoretical models are supposed to describe the production of quarkonia in elementary reactions such as proton-proton collisions. Three of the most popular ones are the Colour Singlet Model (CSM), the Colour Octet Model (COM) and the Colour Evaporation Model (CEM). One of the main difference between the models is the way the necessity of coulor-neutrality of the final state is dealt with. This is also reflected by the models’ names: In the CSM for example the bound state has the same quantum numbers as the initial $Q\bar{Q}$ pair; hence, only pairs that lead to a colour singlet state are allowed to bind \cite{1,2}. So far the theoretical predictions do not yet fully reproduce the experimental observations such as differential cross sections or polarization, or many free parameters limit their predictive power. The latter is the case e.g. for the CEM \cite{2}. The fact that the CSM strongly underpredicts the measured yields, especially for the $\psi'$\cite{3,4} (see fig. \ref{fig:1}), seem to indicate that colour octet states cannot be neglected \cite{5}.

Precise measurements at a new energy regime will give important constraints for predictions. ALICE \cite{6} at LHC will contribute to such measurements.
The above mentioned models describe the direct production of quarkonia. However, there are further sources for bound $Q\bar{Q}$ states and especially the $J/\psi$:

- Feed-down from higher mass quarkonium states, such as $\chi_c \to J/\psi + \gamma$
- $b$-hadron decays such as $B \to J/\psi + X$ or $\psi' + X$

For the understanding of quarkonia production these sources have to be taken into account. This subject will be addressed in §3.

1.2. Heavy Ions
In the collision of two heavy ions two further groups of effects might influence the measured rates of quarkonia and have to be taken into account: Cold nuclear matter effects (CNM) and QGP induced effects. The first group includes nuclear absorption, i.e. the breakup of pre-resonant $Q\bar{Q}$-pairs due to multiple scattering with nuclear matter surrounding the hot core of the collision scene at SPS energies.

The parton distribution function (PDF) of a free nucleon differs from the one of a nucleon bound in a nucleus. Depending on whether the PDF is suppressed or enhanced inside the nucleus at a given $x$ this effect is called shadowing or anti-shadowing. Since the cross sections of quarkonia production directly depend on these distributions these modifications have to accounted for when comparing different collision systems as p-p and A-A. Such cold nuclear matter effects can be unveiled by measuring collisions in which no hot matter is created, such as p-A collisions.

Of most interest are the effects induced by the creation of a quark-gluon plasma. The first prediction of a modification of $J/\psi$ yields in heavy ion collisions was put forward by T. Matsui and H. Satz [7]. The basic idea is the breakup of $Q\bar{Q}$ pairs in the hot environment of a quark-gluon plasma via Debye screening by free color charges, analogous to the well-known QED process. This effect would depend on the distance of the $Q$ and the $\bar{Q}$ in the bound state which can be calculated from the binding energy of that particle. Depending on the temperature of the quark-gluon plasma and the corresponding Debye length the formation of such a state of matter would lead to a suppression of quarkonia rates in heavy ion collisions. By this the different quarkonia states can reflect the temperature of the quark-gluon plasma [8].
Figure 2. Sketch of the dissociation of correlated $c\bar{c}$ pairs (A), their diffusion (B) and the statistical production (C) of uncorrelated $c\bar{c}$ pairs in the quark-gluon plasma in heavy ion collisions.

| $\sqrt{s_{NN}}$ (GeV) | $N_{c\bar{c}}$/ev. cent. AA |
|------------------------|-----------------------------|
| SPS 17.3               | 0.2                         |
| RHIC 200               | 10                          |
| LHC 5500               | 115                         |

Table 1. Average numbers of produced $c\bar{c}$ pairs per central A-A collision for different accelerator energies (centre of mass)

A suppression of $J/\psi$ yields has indeed been found at SPS and RHIC. But so far the interpretation of the results is not as unambiguous as theoretically predicted, mainly because the CNM effects have not been fully understood yet [9].

Moreover, when going to higher accelerator energies, an additional effect may set in. The more $c\bar{c}$ pairs are created in one collision (see average values in table 1), after their dissociation, depicted in panel A of figure 2, and diffusion through the medium, panel B, the higher the probability for statistical production of uncorrelated $c$ and $\bar{c}$ becomes. This effect might lead to an enhancement of the yields, especially of the $J/\psi$ as depicted in panel C, fig. 2 [10, 11].

1.3. LHC - New Perspectives

The design values of the LHC collision energies are $\sqrt{s} = 14$ TeV for proton-proton collisions and $\sqrt{s_{NN}} = 5.5$ TeV for Pb-Pb, respectively. One nominal year of LHC data taking comprises approx. $10^7$ s of proton-proton and $10^9$ s of Pb-Pb running time. The maximum luminosities of the proton and the Pb beams in the ALICE experiment of $\mathcal{L}_{pp} \approx 5 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ and $\mathcal{L}_{pbpb} \approx 5 \cdot 10^{26}$ cm$^{-2}$s$^{-1}$, $10^9$ p-p and $2 \cdot 10^8$ Pb-Pb minimum bias events correspond to one nominal LHC running year at ALICE.

The LHC experiments will highly benefit from the dependence of the $Q\bar{Q}$ production cross sections on the collision energy. NLO calculations [12] as shown in fig. 3 predict a strong increase with the energy. Average expected numbers of produced $c\bar{c}$ pairs in central nucleus-nucleus collisions are summarized in table 1. Compared to the top RHIC energy for Au-Au, an order of magnitude higher rates are expected at the nominal LHC Pb-Pb collision energy. An even stronger increase with the energy is expected for $b\bar{b}$ production, see the right panel of fig. 3. Thus, the LHC will deliver excellent conditions for quarkonia measurements.
Figure 3. Extrapolations of the NLO total $c\bar{c}$ (left panel) and $b\bar{b}$ (right panel) production cross sections versus the collision energy in proton-proton collisions compared to measured data \cite{12}. The solid curve is the central result, the dashed curves represent the uncertainty band. The dotted curve on the left panel is a calculation with different input parameters.

2. The Experiment

2.1. ALICE

ALICE is the dedicated heavy ion experiment at LHC \cite{6}. Its general setup can be divided into two parts: The central barrel and the forward muon spectrometer. The latter consists of a 10 plane tracking system with high granularity, partially inside a large area dipole magnet for momentum determination. Four planes of trigger chambers behind a filter wall provide a fast trigger decision on events with one or more opposite sign muon pairs with high $p_t$. The muon system is protected from hadrons and photons by a large front absorber and a beam shield. \cite{13,14} The muon system will measure $J/\psi$, $\psi'$, $\Upsilon$, $\Upsilon'$ and $\Upsilon''$ in their dimuon decay channel. The longitudinal acceptance of the system is $-4.0 < \eta < -2.4$. Quarkonia will be measured over the whole range of transverse momenta down to $p_t = 0$.

The various detectors of the central barrel part are placed inside the L3 solenoidal magnet. In the following only the systems of importance for quarkonia measurements are discussed. All these cover the full azimuth and the longitudinal range of $|\eta| < 0.9$. Starting from the interaction vertex, the innermost detector is the Inner Tracking System (ITS). Consisting of two layers each of silicon pixel, silicon strip and silicon drift detectors it provides high precision primary and secondary vertex reconstruction, tracking and particle identification (PID). Surrounding the ITS, the cylindrical Time Projection Chamber (TPC) serves as the main tracking and particle identification detector. The Transition Radiation Detector (TRD) is the next subdetector which embraces the TPC. One of its main purposes is the identification of electron tracks. Since this is of main importance for the measurement of quarkonia the TRD will be introduced in more detail in the following.

2.2. Transition Radiation Detector

The two main purposes of the TRD \cite{15} are PID in terms of electron-pion separation and triggering on high momentum electrons or electron pairs. The TRD will also be incorporated in the ALICE High Level Trigger which will allow full online data analysis, event selection and data compression. Therein complex trigger scenarios such as a trigger on a given $e^+e^-$ invariant...
mass will be implemented.

The TRD is segmented in 18 super modules out of which seven are currently installed and operational. Each supermodule is further divided into five stacks with six layers. The left panel of fig. 4 shows a side view on one layer with a pion and an electron track and illustrates the working principle of the TRD. The particles have to traverse a radiator. Therein, particles with $\gamma$ factors $> 1000$ are likely to emit transition radiation (TR). Electrons are fast enough already around 1 GeV/$c$ whereas the pions, which are the main source of background, do not emit TR at momenta around a few GeV/$c$. The TR photon is absorbed in the Xe detector gas mixture and leads to an enhanced signal at late drift times in the drift chamber of the TRD module (see right panel of fig. 4). By this the TRD reaches a factor of 100 in pion rejection (above $p > 1$ GeV/$c$) leading to an enormous reduction of the background in quarkonia measurements.

3. Performance Studies

3.1. Direct Quarkonia

ALICE will measure all quarkonia with the quantum numbers of the photon and mass below the $D\bar{D}/B\bar{B}$ thresholds by their dileptonic decay.

The main advantages of the muon system are the low background since only few other species than muons punch through the absorber. Further, the tracking and triggering stations are very fast detectors that can operate at high rates, triggered by dimuon pairs above a given momentum. Fig. 5 shows the expected invariant mass distribution of opposite sign muon pairs in one nominal year of p-p data taking at 14 TeV. In this simulation only the combinatorial background has been investigated. Very high signal rates bring along small statistical errors, the little combinatorial

Figure 4. Left panel: setup and working principle of a ALICE TRD readout chamber. Traversing charged particles ionize the detector gas. Electrons create additional ionization clusters by transition radiation produced inside the radiator. After the drift of the electrons to the cathode wires, signals are created by their amplification at the anode wire plane [15]. Right panel: TRD signal (average pulse height) vs. drift time. This very first sample from 900 GeV p-p collisions contains mostly electrons (red) around 1 GeV/$c$ which emit only little TR. However, a clear rise at late drift times can already be seen.
Figure 5. Simulated unlike-sign dimuon mass spectra for one nominal LHC p-p year at 14 TeV. The dashed lines represent the correlated background. The $J/\psi$ and $\Upsilon$ mass regions are shown on the left and right panels, respectively [6].

Figure 6. Simulated unlike-sign dimuon mass spectra of central events for one nominal LHC Pb-Pb year at 5.5 A·TeV. Points represent the total number of dimuons, the lines disentangle the different sources to the spectrum. The $J/\psi$ and $\Upsilon$ mass regions are shown on the left and right panels, respectively [6].

background in p-p events result in good signal to background ratios. This holds for all analyzed quarkonia species, the numbers are summarized for $J/\psi$ and $\Upsilon$ in table 2.

Analogous distributions for the most central ($0 < b < 3$ fm) Pb-Pb events (one nominal year of data taking) are shown in fig. 6. Less events will be recorded in comparison to proton-proton. Still, large signal rates are expected. Combinatorics and the larger underlying heavy ion event multiplicity lead to much more prominent background compared to p-p. Also, in this study more background sources have been taken into account and are represented by the dashed lines in fig. 6. Good measurements of the both ground states $J/\psi$ and $\Upsilon$ will be possible already in one
Figure 7. The efficiencies of \( J/\psi \) reconstruction of various reconstruction steps versus \( p_t \) (left panel) and \( y \) (right panel).

Data taking period, with significances of around 150 and 30 respectively. Two or three data taking periods lead to comparable significances of the higher \( \Upsilon \) states. For the \( \psi' \) the situation is worse, the signal is of the same order of magnitude as the the one of the \( \Upsilon \) but the background is expected to be only a factor of two smaller compared to the \( J/\psi \).

Since the detector does not cover the whole phase space and each step of the reconstruction performs only with a certain efficiency, simulations have to be carried out to correct for losses due to acceptance and reconstruction efficiency. Fig. 7 shows an example of the efficiency maps of various different reconstruction steps. Red stars represent the efficiency of measuring both \( J/\psi \) daughter tracks within the acceptance \(|\eta| < 0.9\). For the distribution of the green circles the daughters also have to pass track quality cuts. The blue squares correspond to the additional requirement that both daughters hit the TRD. Since the TRD is not completely installed yet the efficiency drops about one order of magnitude when giving this requirement. Such maps are later applied to the measured yields. Signal to background ratios are under investigation both with TPC and TRD alone as well as both detectors combined.

In Pb-Pb collisions the situation in the dielectron channel is comparable to the one in the dimuon channel. The results of the simulation corresponding to \( 2 \cdot 10^8 \) central events are shown in fig. 8 and summarized in table 2. In contrast to that study in the first year of Pb-Pb data taking the TRD will not be fully installed yet (see 2.2). Assuming that further the nominal luminosity will not be reached in the first running year the expected statistics therein are expected to be at least one order of magnitude lower than for one year at nominal conditions discussed here. Due to the very little material budget of the central barrel detectors the mass resolution is even better, especially in the \( J/\psi \) mass region. On the other hand, the distributions have a long tail towards low masses due bremsstrahlung. The TRD drastically reduces the number of misidentified pions and with this the background of the measurement. The main source of the remaining background are semi-electronic decays of open charm and beauty particles.

3.2. Secondary \( J/\psi \)

As mentioned already in 1.1 a detailed investigation of all sources for quarkonia has to be carried out. Two substantial contributions for the total \( J/\psi \) yield are the radiative decay of \( \chi_c \) and the
Figure 8. Simulated dielectron mass spectrum of 10% most central events for one nominal LHC Pb-Pb year at 5.5 A·TeV. The bold line represents the total number of opposite-sign dielectrons, the dashed lines disentangle the different sources to the spectrum, the thin line shows the distribution of the like-sign spectrum [10].

Table 2. Summary of the expected signals, signal to background ratios, significances and mass resolutions for $J/\psi$ and $\Upsilon$ in both dileptonic channels at top LHC energies with a fully installed TRD weak decay of $B$ mesons. Due to the excellent momentum resolution of the ALICE central barrel detectors and their acceptance down to very low $p_t$, a total signal of around 7400 $\chi_c$ are assumed to be measurable in one nominal year of LHC p-p data taking [17]. Note that this estimation still assumes a perfect trigger, the real value will be reduced by the efficiency of that trigger. As depicted in the event display in fig. 9 the decay photon will be reconstructed by its conversion into an electron-positron pair in the detector material (mostly ITS). The probability of this process is expected in the order of 8.3%. The $J/\psi$ is as well reconstructed by its dielectronic decay, the $\chi_c$ are finally identified in the resulting invariant mass spectrum. However, the difference in invariant mass $\Delta M = M(e^+e^-) - M(e^+e^-)$ provides a better resolution since the uncertainty of $M(e^+e^-)$ cancels out. As can be seen in fig. 9 the precision of the measurement is expected to be high enough to clearly separate the $\chi_{c1}$ and $\chi_{c2}$ states.
Measurements of the fraction of $J/\psi$ coming from $b$ hadron decay will exploit the time scale of its weak decay process: With a $c\tau$ of 491.1 µm of the $B^\pm$, for example, the daughter $J/\psi$ is likely to have a vertex displaced from the primary one. The measurement of that displaced vertex is carried out via the pseudo proper decay time $x = L_{xy} \frac{M_{J/\psi}}{p_t}$, where $L_{xy} = \frac{\vec{L} \cdot \vec{p}_t}{|\vec{p}_t|}$, the projection of the flight distance of the $J/\psi$, $\vec{L}$, on its transverse momentum [18, 19]. Secondary $J/\psi$ lead to an asymmetric distribution of $x$ as can be seen in fig. 10. The B fraction is then deduced from a simultaneous fit of the invariant mass and the pseudo proper decay time.

4. Summary

The LHC provides a very good environment for quarkonia measurements. ALICE will measure quarkonia of the $J/\psi$ and the Υ family via their dielectron (around midrapidity) as well as dimuon (in forward direction) decay channel. It will be possible to analyze various different sources of secondary $J/\psi$. ALICE has a large acceptance in transverse momentum and will measure quarkonia down to $p_t = 0$. Dedicated triggers will significantly enhance the signals in proton-proton and especially the Υ states in Pb-Pb. The very good mass resolution of the ALICE detectors will allow to clearly separate all different $Q\bar{Q}$ states.

References

[1] Berger E L and Jones D 1981 Phys. Rev. D 23 1521–1530
[2] Lansberg J P 2006 Int. J. Mod. Phys. A21 3857–3916 (Preprint hep-ph/0602091)
[3] Lansberg J P 2009 Eur. Phys. J. C61 693–703 (Preprint 0811.4005)
[4] E Braaten, M A Doncheski, S Fleming and M L Mangano 1994 Phys. Lett. B333 548 (Preprint hep-ph/9405607)
[5] Cho P and Leibovich A K 1996 Phys. Rev. D 53 150–162
[6] The ALICE Collaboration 2005 Physics Performance Report Volume II CERN/LHCC 2005-030
[7] Matsui T and Satz H 1986 Phys. Lett. B 178 416
[8] Satz H 2006 (Preprint hep-ph/0602245)
[9] Arnaldi R (NA60) 2009 Nucl. Phys. A830 345c–352c (Preprint 0907.5004)
Figure 10. Distributions of the $x$ variable, scaled from a larger statistical sample to the number of events corresponding to one nominal year of LHC p-p data taking. The total sum (black line) is composed of the background (blue squares) and signal (red open triangles) contributions. The latter is further consisting of secondary (magenta triangles) and prompt $J/\psi$.

[10] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2003 Phys. Lett. B571 36–44 (Preprint nucl-th/0303036)
[11] Thews R L 2005 Eur. Phys. J. C43 97–102 (Preprint hep-ph/0504226)
[12] Vogt R 2008 Eur. Phys. J. ST 155 213–222 (Preprint 0709.2531)
[13] The ALICE Collaboration 1999 Dimuon Forward Spectrometer Technical Design Report CERN/LHCC 99-22
[14] The ALICE Collaboration 2000 Dimuon Forward Spectrometer Technical Design Report Addendum CERN/LHCC 2000-046
[15] The ALICE Collaboration 2001 TRD Technical Design Report CERN/LHCC 2001-021
[16] W Sommer, C Blume, F Kramer, J F Grosse-Oetringhaus 2007 IJMPE 16 2484–2490 (Preprint nucl-ex/0702045v1)
[17] Gonzalez P, Ladron de Guevara P, Lopez Torres E, Marin A and Serradilla E (ALICE Collaboration) 2009 Eur. Phys. J. C61 899–903 and Erratum 915 (Preprint 0811.1592)
[18] D Acosta et al (CDF Collaboration) 2005 Phys. Rev. D 71 032001
[19] Bruno G E (ALICE Collaboration) 2009 J. Phys. G: Nucl. Part. Phys. 36 064053