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CHARMONIUM PRODUCTION AT THE LHC*

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We summarise the perspectives on quarkonium, in particular charmonium, detection at the LHC, both for proton–proton and heavy-ion collisions. We give a review of the experimental capabilities of the four LHC detectors: ALICE, ATLAS, CMS and LHCb.

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1. Introduction

The measurement of the charmonium (J/ψ, $\psi^{'}$) resonances in nucleus–nucleus collisions is considered to be one of the most powerful methods to probe the nature of the high density QCD matter. First, the in-medium behaviour of quarkonium is supposed to be one of the most direct probes of the Quark Gluon Plasma (QGP) formation [1]. It was predicted that in a deconfined medium, the Debye screening of the colour potential leads to the melting of quarkonium states and thus provides an estimate of the medium temperature. Second, at LHC energies heavy quarks are produced mainly through gluon–gluon fusion process thus they are significantly affected by parton dynamics in the low-x regime. Therefore, they can be used as a tool to probe the saturation of the gluon density at low-x in the nucleus and the Colour Glass Condensate formation [2].

The LHC (Large Hadron Collider) will provide, at nominal operating conditions, Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5\,\mathrm{TeV}$ allowing the study of the quarkonium production in an unprecedented energy regime. The LHC will deliver $p+p$ and p+Pb collisions at $\sqrt{s_{NN}} = 14$ and $8.8\,\mathrm{TeV}$ respectively, providing a solid baseline for the Pb+Pb system.

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2. From SPS to RHIC

2.1. Normal and anomalous suppression at SPS

The J/ψ yields (normalised to the Drell–Yan process) were measured at the CERN SPS for different colliding systems and energies: from $p+p$ to various p+nucleus (p+A) with proton energy of 450 GeV. Moreover, nucleus–nucleus ($A+A$) collisions, from O+U and S+U (NA38) with a projectile energy of 200 GeV per nucleon to Pb+Pb and In+In (NA50 and NA60) with a projectile energy of 158 GeV per nucleon have been studied.

It was observed that $p+p$, $p+A$ and peripheral $A+A$ data show an exponential suppression of the J/ψ to Drell–Yan ratio when plotted as a function of the average length of nuclear matter traversed by the $c\bar{c}$ pair. This behaviour was interpreted in terms of the normal nuclear absorption (normal suppression) of the $c\bar{c}$ pair prior to the J/ψ formation with a corresponding absorption cross section of 4.18 ± 0.35 mb [3]. For more central $A+A$ collisions (In+In and Pb+Pb) an additional suppression (anomalous suppression) was seen [4]. This result was interpreted as a consequence of the creation of the deconfined medium.

One can thus think that the J/ψ behaves as a predicted golden signature of the QGP formation.

2.2. The RHIC anomalies

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) measured the J/ψ production in $A+A$ (Au+Au) collisions at $\sqrt{s_{NN}} =$ 200 GeV. The J/ψ behaviour was studied via the nuclear modification factor R_{AA} defined as following:

$$R_{AA} = \frac{d^2 N^{AA}_{J/\psi}/dp_{\mathrm{T}}dy}{N_{\mathrm{coll}} d^2 N^{pp}_{J/\psi}/dp_{\mathrm{T}}dy}\,,$$

where $d^2 N^{AA}_{J/\psi}/dp_{\mathrm{T}}dy$ is the J/ψ yield in Au+Au collisions, N_{coll} the corresponding mean number of binary collisions and $d^2 N^{pp}_{J/\psi}/dp_{\mathrm{T}}dy$ the yield in $p+p$ collisions. The PHENIX results brought up two surprises [5]:

- if plotted R_{AA} as a function of the number of participants N_{part}: at mid rapidity the amount of suppression at RHIC is similar to the suppression observed at SPS. J/ψ were expected, as predicted in the colour screening mechanism, to be more suppressed at RHIC because of the higher energy density reached at collider energies.
- if plotted R_{AA} as a function of the number of participants N_{part} for different rapidity domains: J/ψ are more suppressed at forward rapidity where the energy density is lower than at mid rapidity.

Two possible reasons for theses results are explored and discussed. Firstly, the abundant production of c and $\bar{c}$ quarks at mid rapidity domain can lead to their recombination [6] and J/ψ creation from initially uncorrelated quarks. Secondly, the nuclear effects like standard gluon shadowing that are important at forward rapidity domain have to be taken into account. Also the saturation effects (Colour Glass Condensate) could lead to the observed J/ψ behaviour.

For the moment, both interpretations are possible. There is not enough experimental data to exclude one of them and to draw a definite conclusion.

3. LHC

The LHC collider will open up new perspectives in the study of the quarkonium of QCD. One can ask what is different at the LHC in comparison with RHIC or SPS. First of all, an unprecedented collision energy will be reached ($\sim$ 28 times bigger than at RHIC). Secondly, the LHC will allow to access an unexplored Bjorken-x region and thus probe the low-x QCD phenomena ($x = (M_{Q\overline{Q}}/\sqrt{s_{NN}})\exp(\pm y_{Q\overline{Q}})$). Finally, the expected copious production of heavy quarks should help us to bring down the curtain on the different predicted J/ψ behaviours (suppression, regeneration or both simultaneously).

There are several experimental challenges for quarkonium measurements at the LHC: (a) the choice of the reference production process for the normalisation; (b) estimation of the J/ψ contribution originated from B-meson decays; (c) understanding the complex combinatorial background very well and (d) taking into account possible heavy quark energy loss.

These topics are under investigation as they are crucial points needed to understand quarkonium production at the LHC.

3.1. ALICE

ALICE (A Large Ion Collider Experiment) [7–9] experiment is dedicated to the study of heavy ion collisions. Its goal is to study the properties of deconfined matter: the Quark Gluon Plasma (QGP). The ALICE detector is composed of a central barrel system ($|\eta| < 0.9$), a muon spectrometer ($-4.0 < \eta < -2.5$) and several small additional detectors. Quarkonium will be measured in ALICE via two channels: the dielectron channel at mid rapidity and the dimuon channel at forward rapidity.

The measurement via dielectron channel is provided by the combination of several detectors that are here described, as seen by a particle travelling out from the interaction point:

- Inner Tracking System (ITS) [10] allows the reconstruction of the primary vertex, secondary vertex finding, and particle identification via dE/dx. This detector is composed of three subsystems of two layers each: the Silicon Pixel Detector, the Silicon Drift Detector and the Silicon Strip Detector.

- Time Projection Chamber (TPC) [11] allows track finding, momentum measurement, and charged hadron identification via dE/dx. TPC has an inner radius of 0.9 m, an outer radius of 2.5 m and a length of 5.1 m. The momentum resolution for the track reconstruction, including TPC and ITS information, is expected to be better than 2% for $p_{\mathrm{t}} < 20\,\mathrm{GeV}/c$.

- Transition Radiation Detector (TRD) [12] allows electron identification and also provides fast triggering. Electron identification is provided by the TRD for momenta larger than 1 GeV$/c$. This detector is made of 18 longitudinal supermodules, 6 radial layers, and 5 stacks along the beam axis.

The invariant mass resolution for the quarkonium was studied in the full simulation for Pb+Pb collisions. The reconstructed peaks were fitted by a Gaussian and the invariant mass resolution for the J/ψ is found to be 30 MeV$/c^2$. The analysis showed that the J/ψ signal can be reconstructed up to $p_{\mathrm{t}} = 10\,\mathrm{GeV}/c$.

The detection via dimuon channel in the forward rapidity region is provided by the muon spectrometer [13]. This detector is composed of a set of absorbers: a front absorber, a muon filter, a beam shielding and an absorber against the LHC background. The goal of these absorbers is to suppress hadron and electron background. The tracking system allowing the muon trajectory reconstruction contains five tracking stations. The dipole magnet with a field integral of 3 Tm along the beam axis provides the bending power to measure the momenta of the muons. Two trigger stations provide a fast electronic signal for the trigger selection of muon events. The p_{t} cut of 1 GeV$/c$ applied to single muons allows charmonia detection down to zero transverse momenta. The invariant mass resolution for the J/ψ in Pb+Pb collisions is expected to be around $70\,\mathrm{MeV}/c^2$. The high-p_{t} reach for the J/ψ is expected to be around $20\,\mathrm{GeV}/c$.

In addition to direct J/ψ also those from B decays (secondary J/ψ) have to be taken into account. The contribution of secondary J/ψ to the total J/ψ yields is about 20%. To separate the prompt J/ψ's from the secondary ones, the measure of dielectron pairs with displaced vertex must be performed. In fact, the secondary J/ψ are produced at large distances (several hundred of microns) from the primary vertex. The ITS vertexing capabilities allow to perform this study in the central barrel. This analysis is not possible in the forward rapidity region because the muon spectrometer does not provide vertexing capabilities.

The suppression of J/ψ was studied in the dimuon channel. Two extreme suppression scenarios were considered. The first one characterised by a high critical deconfinement temperature at $T_{\mathrm{c}} = 270\,\mathrm{MeV}$ [14] and the second one using $T_{\mathrm{c}} = 190\,\mathrm{MeV}$ [15]. To check the detector capability for distinguishing between different suppression scenarios the ratios of the resonance rates over those for beauty as a function of the number of participants were studied. It was seen that the error bars for the J/ψ to open beauty ratio are small enough to distinguish between these two suppression scenarios.

To distinguish between different quarkonia production mechanisms the quarkonia polarisation study must be performed. The angular distribution of the decay products (dielectrons or dimuons) in the quarkonia rest frame allows to reconstruct the polarisation. It has been predicted that the QGP formation may change the quarkonia polarisation. In fact an increase of J/ψ polarisation is expected in this case [16].

3.2. ATLAS

The primary physics goal of the ATLAS experiment [17] is the search of the Higgs boson and SUSY particles (supersymmetry). Nevertheless, other physics sectors like CP violation and rare B decays, can be explored. ATLAS will be able to provide evidence of physics phenomena beyond the Standard Model (SM) in $p+p$ collisions at $\sqrt{s_{NN}} = 14\,\mathrm{TeV}$.

The ATLAS detector consists of four major components: inner tracking system ($|\eta| < 2.5$), calorimeters (electromagnetic: $|\eta| < 3.2$, hadronic barrel: $|\eta| < 1.7$, hadronic end-cap: $1.5 < |\eta| < 3.2$ and forward: $3.1 < |\eta| < 4.9$), muon spectrometer ($|\eta| < 2.5$) and forward detectors (LUCID: $5.3 < |\eta| < 6$, ZDC: $|\eta| < 8.3$ and ALFA).

ATLAS can detect the J/ψ in the dimuon channel using the muon spectrometer covering $|\eta| < 2.7$ and full azimuth. The track coordinates measurement is provided by Monitored Drift Tubes (barrel and end-cap regions) and by Cathode Strip Chambers (at large pseudorapidities and close to the interaction point). The trigger system covers the pseudorapidity range $|\eta| \leq 2.4$. Resistive Plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) in the end-cap regions. The magnetic bending is provided by the large barrel toroid with a magnetic field of 0.5–1 T. The strong magnetic field and the large material budget of the inner detector and calorimeters make difficult the reconstruction of the muons with a $p_{\mathrm{T}} < 3\,\mathrm{GeV}/c$. The minimum dimuon trigger threshold is around $4\,\mathrm{GeV}/c$. The invariant mass resolution for J/ψ is expected to be around $54\,\mathrm{MeV}/c^2$ and $68\,\mathrm{MeV}/c^2$, respectively in $p+p$ and Pb+Pb collisions.

3.3. CMS

The CMS experiment [18, 19] is dedicated to explore physics at the TeV scale. The prime goals of CMS are to study the mechanism of electroweak symmetry breaking and provide evidence of physics beyond SM. CMS will also study a large amount of signatures arising in the SM: QCD, B-physics, diffraction, top quark properties, and electroweak physics topics such as the W and Z boson properties.

The CMS detector is composed of: inner tracking system ($|\eta| < 2.5$), calorimeters (electromagnetic: $|\eta| < 3$, hadronic: $|\eta| < 5$), muon system and few forwards detectors (CASTOR: $5 < |\eta| < 6.6$ and ZDC: $|\eta| > 8.3$). In this experiment, the J/ψ are detected via their $\mu^+\mu^-$ decay by the muon system ($|\eta| < 2.4$) that is divided into a central part (Barrel Detector: $|\eta| < 1.2$) and forward parts (Endcap Detector: $|\eta| < 2.4$). The barrel detector comprises the Drift Tubes chambers and Resistive Plates Chambers. The forward parts are composed of a set of Cathode Strip Chambers in the 2 muon endcaps and a layers of Resistive Plates Chambers. The CMS superconducting solenoid has a large bending power and can generate the magnetic fields up to 4 T. The minimum muon momenta of 3.5 and 4 GeV/c, respectively for barrel and endcap region. The non-prompt fraction is estimated using the traditional method of the cut on pseudo proper decay length. The high-$p_{\rm t}$ reach for the J/ψ is expected to be around 40 GeV/c. The invariant mass resolution for the J/ψ is 35 MeV/c^2 in Pb+Pb collisions. The CMS will also perform the polarisation study of the quarkonium states.

3.4. LHCb

The main goal of the LHCb [20] experiment is to study CP violation in the B meson systems and to search for rare B decays. The LHCb apparatus is a single arm forward spectrometer with a polar angular coverage from 15 to 300 mrad in the horizontal and 250 mrad in the vertical plane. This corresponds to a pseudorapidity range $2 < \eta < 5$. The choice of the detector geometry is motivated by the fact that at high energies B hadrons are predominately produced in the forward region. This detector is composed of a vertex detector system (VELO), a tracking system, aerogel and gas RICH counters (Cherenkov detectors), an electromagnetic calorimeter with preshower detector, a hadron calorimeter and a muon detector.

The measurement of quarkonium will be performed in $p+p$ collisions via $J/\psi \to \mu^+\mu^-$. In fact, J/ψ candidates are reconstructed by combining pairs of oppositely charged tracks that originate from a common vertex. The muon trigger system requires a muon with a $p_{\rm t} > 1$ GeV/c and one of the tracks with $p_{\rm t} > 1.5$ GeV/c. Both tracks have to be identified as muons. In addition, one of the tracks is needed to be identified by cutting hard on likelihood of the muon hypothesis relative to the pion [21]. The expected mass resolution is around 11 MeV/c^2.

The LHCb detector will be able to separate prompt J/ψ's from those from b decays using the t variable defined as following:

$$t = \frac{dz}{p_z^{J/\psi}} \times m^{J/\psi} .$$

This variable is an approximation of the proper time of the b quark in the forward region. This distribution contains four components: a prompt component due to the J/ψ originating from the primary vertex (Gaussian distribution), an exponential component due to the J/ψ coming from b decays, a combinatorial component due to particles coming from the primary vertex and a long tail component due to the association of the J/ψ to the wrong primary vertex.

Moreover, the LHCb will measure the feed down from decays of $\chi_{c1,c2}$ to the prompt J/ψ and the J/ψ polarisation.

4. Conclusions

We presented an overview of perspectives of the four LHC experiments for quarkonium (charmonium) physics. To understand the quarkonium production picture different colliding systems have to be studied. The study of the $p+p$ system allows to test the pQCD calculations and learn more about the quarkonium production mechanisms. Additionally, the $p+p$ system is a reference for more complicated systems like p+Pb and Pb+Pb. The investigating of the p+Pb collisions allows us to evaluate the so-called Cold Nuclear Matter (shadowing, saturation, hadronic absorption) effects that can be very important at the LHC energies. Finally, the study of the J/ψ production in Pb+Pb collisions allows to probe the properties of the QGP formation and evolution. The LHC will deliver $p+p$, p+Pb and Pb+Pb collisions offering a new possibilities for the quarkonium study. The four LHC detectors (ALICE, ATLAS, CMS and LHCb) have excellent experimental capabilities for quarkonium detection. The large statistics of quarkonium expected at the LHC and performances of the LHC experiments will help to clarify the current knowledge of this topic.

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