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Azimuthal anisotropy and nuclear modification of Upsilon states in heavy-ion collisions with the CMS detector

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Abstract

Bottomonia are produced by hard scattering in the early times of a relativistic heavy-ion collision, so they serve as excellent probes of the quark-gluon plasma (QGP). Early CMS data showed that the yields of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons are suppressed in PbPb relative to those in pp. In order to interpret the results in PbPb collision unambiguously, the cold nuclear matter effects need to be quantitatively estimated using pPb collisions data. Additionally, the measurement of the elliptic azimuthal anisotropy of bottomonium states have been suggested as a powerful tool to study the different in-medium effects such as dissociation and regeneration. In these proceedings, the new bottomonium results are reported for pPb and PbPb collisions data at 5.02 TeV with the CMS detector. First, the nuclear modification factors of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons are presented in pPb collisions as functions of the transverse momentum and rapidity. Then, the new measurements of the azimuthal anisotropy (v_2) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons are reported using PbPb collisions data at 5.02 TeV taken in 2018.

Keywords:

1. Introduction

Quarkonia in relativistic heavy-ion collisions have been considered as golden probes for the study of strongly interacting matter of deconfined quarks and gluons, the quark-gluon plasma (QGP), at high energy-density and temperature [1]. Among various quarkonium states, bottomonia have short formation times in their rest frames [2] and are produced in the early stage of collisions via hard scattering. The yields are modified inside the QGP as a consequence of color-screening [3] and dissociation from inelastic parton scattering [4]. The LHC experiments CMS, ALICE, and ATLAS reported a significant suppression of the bottomonium states in lead-lead (PbPb) collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [5, 6, 7]. In addition, the suppression of different bottomonium states has been observed in the ordering of their binding energy, which is consistent with the sequential melting picture of quarkonium suppression in the QGP [8]. In contrast to the Debye screening and dissociation, quarkonium yield can increase in the presence of QGP, by coalescence of uncorrelated quarks or recombination of heavy-quark pairs from an original dissociated quarkonium [9]. Since the number of heavy-quark pairs is much smaller for beauty than charm, compared to J/ψ studies the recombination processes is much smaller for Υ mesons.

In addition to the in-medium QGP effects, the modification of the bottomonium production in PbPb collisions involves also the effects of the Pb nucleus itself, the so-called cold nuclear matter (CNM) effects. In order to separate the color screening effect alone, pPb collisions are performed in which the modification of the measured bottomonium yields is expected to be dominated by CNM effects. To estimate the CNM effects quantitatively, the nuclear modification factors R_{pPb} are measured defined as the ratios of bottomonium production cross sections in pPb collisions to that in pp collisions scaled by the number of nucleons in the Pb ion.

On the other hand, it has been suggested that the study of the azimuthal dependence of quarkonium states develops a more comprehensive understanding of the dynamics of quarkonia. The spatial anisotropy of the overlap region of the colliding nuclei in mid-central collisions is transformed into momentum anisotropy. This leads to a hydrodynamical anisotropic flow, which can be characterized as the second-order Fourier coefficients (v_2) of the azimuthal particle distribution, known as the elliptic flow. A positive finite v_2 has been observed for J/ψ mesons at LHC in both PbPb and pPb collisions [10, 11]. The v_2 of the Υ(1S) meson has been reported by ALICE Collaboration at forward rapidity in PbPb collisions.

In this conference proceedings, new results of R_{pPb} are described for Υ(1S), Υ(2S), and Υ(3S) mesons measured in pPb and pp collisions at 5.02 TeV. Also the v_2 measurement of Υ(1S) and Υ(2S) mesons are reported in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

2. Data and Event selection

The datasets used to obtained the R_{pPb} values are for pp and pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The v_2 of Υ(1S) and Υ(2S) mesons are measured using the data in PbPb collisions taken in late 2018. The detailed description of the CMS detector can be found in Ref. [12]. For both analyses, the Υ mesons are reconstructed using the dimuon decay channel with single muons detected in the pseudorapidity interval of $|\eta| < 2.4$. The dimuon events are selected by a fast hardware-based trigger system, which requires two muon candidates based on the information from the muon detectors. No explicit momentum is required for the muons in pp and pPb collisions. The event selection trigger recorded an integrated luminosity of 28 pb^{-1} and 34.6 nb^{-1} in pp and pPb collisions, respectively. On the other hand, in the v_2 analysis, the two muon candidates require track fits in the outer muon spectrometer with applying a transverse momentum cut on one of the muon to be larger than 2 GeV/c. In addition, the other muon is reconstructed using full tracks from tracks in the outer muon spectrometer and the inner tracker information, with a minimum of 10 high-quality hits in the inner tracker and a minimum p_{T} threshold at 2 GeV/c. Finally, the events are selected with the invariant mass of the those two muons being larger than 7 GeV/c^2. The recorded integrated luminosity of the trigger used for the v_2 analysis is 1.7 nb $^{-1}$. Muons used in pp and pPb collisions are selected in the kinematic range of $p_{\mathrm{T}} > 4$ GeV/c and $|\eta| < 2.4$, and the dimuons are studied in $p_{\mathrm{T}} < 30$ GeV/c and $|y^{\mu^+\mu^-}| < 2.4$. In PbPb collisions, the single muon p_{T} cut is loosened to 3.5 GeV/c and the dimuon p_{T} range is increased up to 50 GeV, while the η and y selection is kept the same.

3. Analysis procedure

The yields of the Υ states in pp and pPb collisions are extracted using an unbinned maximum-likelihood fit to the invariant mass spectra within 8–14 GeV/c^2 with a signal PDF and background PDF. The sum of two Crystal Ball (CB) functions is used for the signal PDF and an error function multiplied by an exponential function for the background PDF. The elliptic flow signal v_2 values of the Υ candidates in PbPb collisions are obtained using the scalar product (SP) method [13]. The event plane angles in this method are characterized by Q–vectors that are determined in different pseudorapidity ranges using the tracks in mid–rapidity region or the HF calorimeters located in $3 < |\eta| < 5$. In order to separate the signal and background in the v_2 distribution, the invariant mass and v_2 spectrum of Υ candidates are fitted simultaneously. The same signal and background functions are used to describe the mass distribution as in pp and pPb collisions. The dependence of the v_2 profile on the dimuon mass (m_{inv}) is taken as

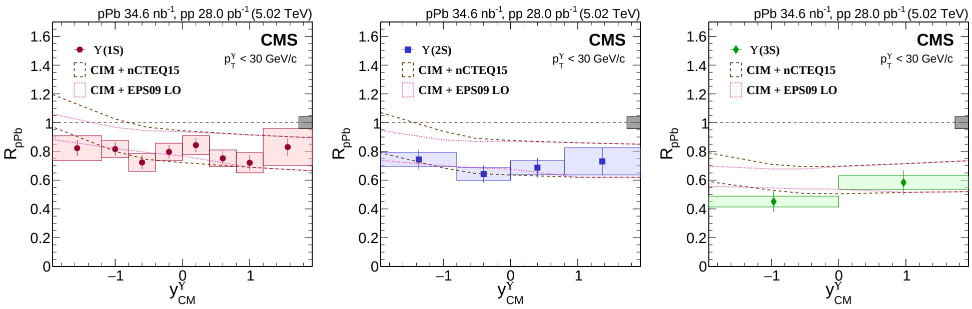

Fig. 1. $R_{\rm pPb}$ versus $y_{\rm CM}$ [17] with comover effect predictions from E. Ferreiro and J. Lansberg [14] with shadowing corrections using nCTEQ15 and EPS09 for ϒ(1S) (left), ϒ(2S) (middle) and ϒ(3S) (right). The final-state comover effect is seen to modify the ϒ states sequentially. Error bars on the points represent statistical and fit uncertainties and filled boxes represent systematic uncertainties. The gray box around the line at unity represents the global uncertainty due to luminosity normalization.

$$v_2(m_{inv}) = \alpha_1(m_{\rm inv})v_2^{\Upsilon(1S)} + \alpha_2(m_{\rm inv})v_2^{\Upsilon(2S)} + \alpha_3(m_{\rm inv})v_2^{\Upsilon(3S)} + [1-\alpha_1(m_{\rm inv})-\alpha_2(m_{\rm inv})-\alpha_3(m_{\rm inv})]v_2^{Bkg}(m_{\rm inv}), \quad (1)$$

where

$$\alpha_n(m_{inv}) = \ [Sig_{\Upsilon(\rm nS)}]\,/\,[Sig_{\Upsilon(1S)}(m_{\rm inv}) + Sig_{\Upsilon(2S)}(m_{\rm inv}) + Sig_{\Upsilon(3S)}(m_{\rm inv}) + Bkg(m_{\rm inv})]\ ({\rm n} = 1,2,3). \quad (2)$$

4. Results

The values of $R_{\rm pPb}$ in pPb collisions for ϒ(1S), ϒ(2S), and ϒ(3S) mesons are calculated using the ratio of mesured yields in pPb collisions to that in pp collisions scaled by the number of nucleons in the Pb ion. The normalized yields in pp and pPb collisions are obtained using the fit to the dimuon mass spectrum detailed in Sec. 3. Figure 1 shows the $R_{\rm pPb}$ values as a function of dimuon rapidity in the center-of-mass frame ($y_{\rm CM}$). ϒ(1S), ϒ(2S), and ϒ(3S) mesons are observed to be suppressed in pPb collisions compared to pp collisions in all studied rapidity ranges. Also, the amount of suppression is in the order of the binding energy of the ϒ states. Also, the results are compared with the predictions using the comover interaction model (CIM) [14] with two different leading-order nPDF calculations from EPS09 [15] and nCTEQ15 [16]. The CIM suggests stronger modification for the excited states due to their larger size which increases the cross section for comover interaction. The v_2 results of ϒ(1S) and ϒ(2S) mesons are shown in Fig. 2. The left panel shows the results in four centrality intervals for ϒ(1S) mesons and the values are found to be consistent with zero. The rightmost points are the average v_2 values in the 10–90% centrality interval for ϒ(1S) and ϒ(2S) mesons. Both values are consistent with zero and the v_2 value for ϒ(1S) meson in that bin is determined to be 0.007 ± 0.011 (stat) ± 0.005 (syst). The right panel of Fig. 2 shows the v_2 of ϒ(1S) mesons as a function of $p_{\rm T}$ in the centrality interval 10–90% the results are consistent with zero in all studied $p_{\rm T}$ bins. The 0–10% interval is excluded in this plot due to the small eccentricity by the circular shape of the collision geometry in the transverse plane. The plot is also compared to four different theory calculations with different ingredients such as in-medium effects like regeneration and initial temperature of the QGP.

5. Summary

The nuclear modification factors $R_{\rm pPb}$ are measured for ϒ(1S), ϒ(2S), and ϒ(3S) mesons. All three states are found to be suppressed in pPb collisions, sequentially in the ordering of their binding energy, which can be explained by final state effects such as dissociation from comover interactions. The modification of bottomonium states in pPb collisions is much smaller than that in PbPb collisions, indicating the suppression in PbPb collisions is dominated by the in-medium effects of the QGP. The v_2 of ϒ(1S) mesons is measured as

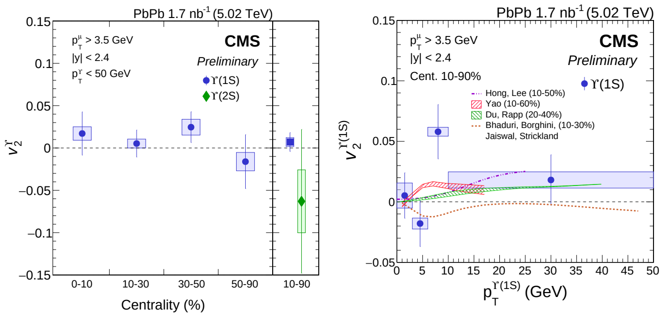

Fig. 2. (Left) p_T integrated v_2 values for Υ(1S) mesons measured in four centrality bins and for the Υ(2S) meson in the 10-90% centrality range [18]. (Right) v_2 as a function of p_T in the 10-90% centrality range compared with model calculations from Du and Rapp (Green shaded area) [9], from Hong and Lee (dashed violet line) [19], from Yao (red band) [20], and from Bhadury, Borghini, Jaiswal and Strickland (dashed brown line) [21]. All results are for the rapidity range of $|y| < 2.4$. The vertical bars denote statistical uncertainties, and the rectangular bands show the total systematic uncertainties.

a function of p_T and PbPb collision centrality. The v_2 values have been measured with the highest precision achieved to date. The observation that the v_2 of the Υ states are small and consistent with zero contrasts with the previously measured J/ψ v_2 results, suggesting different medium effects for charmonia and bottomonia. Recent calculations predict a larger v_2 value for Υ(2S) mesons compared to Υ(1S), resulting from differences in the degree to which regeneration processes contribute to their respective production.

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