STUDY OF $\Upsilon(1S)$ COLLECTIVITY IN pPb COLLISIONS WITH THE CMS DETECTOR*

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The creation of fluid-like quark–gluon plasma in small collision systems has been investigated via elliptical azimuthal anisotropy of emitted particles in these interactions. We report on the first measurement of the azimuthal anisotropy for the $\Upsilon(1S)$ meson in pPb collisions at 8.16 TeV. The dimuons used to reconstruct the $\Upsilon(1S)$ meson are coupled with charged hadrons using the long-range two-particle correlation method. The results are discussed in terms of collectivity of bottom quarks.

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1. Introduction

Strong azimuthal correlations in heavy-ion nucleus–nucleus collisions are observed at the BNL RHIC [1, 2] and the CERN LHC facilities [3–5]. These correlations are understood to arise from the creation of a strongly interacting quark–gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [6–8]. Similar long-range correlations are also observed in high particle multiplicity events in smaller collision systems, such as the proton–lead (pPb) [9–12] system.

Heavy-flavor quarks (charm and bottom) are useful probes as they are produced in the early stages of heavy-ion collisions and experience the entire evolution [13]. Significant elliptic flow v_2 signals of D^0 mesons (open charm) and prompt J/ψ mesons (closed charm) have been observed at the RHIC [14] and at the LHC [15–18] in several collision systems, indicating that charm quarks are also influenced by the collective flow behavior. However, a significant collective flow behavior is not seen for $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons (closed bottom) in PbPb collisions at the CMS [19].

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This contribution reports on a measurement of the elliptic anisotropy v_2 value for $\Upsilon(1S)$ mesons based on long-range, two-particle correlations in high-multiplicity pPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 8.16$ TeV [20]. This result complements the comprehensive study of collective flow of heavy-flavor quarks and study of small system.

2. Event selection

This analysis uses pPb collision data collected with the CMS detector in 2016, with an integrated luminosity of 186 nb^{-1} [21]. The detailed description of the CMS detector can be found in Ref. [22].

The azimuthal anisotropy results are reported for high-multiplicity events ($70 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 300$), where $N_{\mathrm{trk}}^{\mathrm{offline}}$ is the number of primary charged particle tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c. Events with $N_{\mathrm{trk}}^{\mathrm{offline}} < 50$ are also used to estimate the possible contribution of residual back-to-back jet-like correlations.

In this analysis, muons are reconstructed by extrapolating tracks from the silicon tracker to match a hit on at least one segment of the muon detectors. The kinematic range of the muons is $p_{\mathrm{T}}^{\mu} > 3.5$ GeV/c and $|\eta^{\mu}| < 2.4$ to ensure high efficiency for $\Upsilon(1S)$ meson reconstruction.

3. Analysis

The v_n harmonics for Υ particles are measured using the long-range ($|\Delta\eta| > 1$) two-particle correlation technique [9, 23]. The Υ candidates are used as the "trigger" particles, and are matched with "associated" charged particles with $|\eta| < 2.4$ and $0.3 < p_{\mathrm{T}} < 3$ GeV/c.

The per-trigger particle-associated yield distribution is then defined by

$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta\, \mathrm{d}\Delta\phi \Delta m_{\mu^+\mu^-} \Delta p_{\mathrm{T}}} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi, \Delta m_{\mu^+\mu^-}, \Delta p_{\mathrm{T}})}{B(\Delta\eta, \Delta\phi, \Delta m_{\mu^+\mu^-}, \Delta p_{\mathrm{T}})}\,, \quad (1)$$

where $\Delta\eta$ and $\Delta\phi$ are differences in η and in the azimuthal angle ϕ of the pair, N_{trig} and N^{pair} are the number of trigger particles in the event and the number of the trigger-associated pairs in the event, respectively. $S(\Delta\eta, \Delta\phi)$ represents the yield of particle pairs and $B(\Delta\eta, \Delta\phi)$ represents the mixed-event pair yield which is constructed by pairing the Υ candidates with charged particle tracks from ten random different events.

The two-dimensional (2-D) distributions are projected onto one-dimensional (1-D) distributions in $\Delta\phi$. Then the azimuthal anisotropy harmonics are determined from a Fourier decomposition

$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta\, \mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi} \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right\}, \quad (2)$$

where $V_{n\Delta}$ are the Fourier coefficients and $N_{\rm assoc}$ represents the total number of pairs per-trigger particle for a given $(p_{\rm T}^{\rm trig}, p_{\rm T}^{\rm assoc})$ bin.

The signals and combinatorial backgrounds of the Υ mesons for the selected dimuon pairs are separated using fits to the dimuon invariant mass $(m_{\mu^+\mu^-})$ distribution as follows. First, the fraction α for $\Upsilon(1S)$ particles, as a function of $m_{\mu^+\mu^-}$, is defined as

$$\alpha(m_{\mu^+\mu^-}) = \frac{\mathrm{Sig}(m_{\mu^+\mu^-})}{\mathrm{Sig}(m_{\mu^+\mu^-}) + \mathrm{Bkg}(m_{\mu^+\mu^-})}\,. \tag{3}$$

We use a double Crystal Ball function for the Υ signals $(\mathrm{Sig}(m_{\mu^+\mu^-}))$ and a product of an exponential function and an error function for the background $(\mathrm{Bkg}(m_{\mu^+\mu^-}))$. The shape of V_2 distribution for Υ candidates as a function of the invariant mass $V_2^{\rm Sig+Bkg}(m_{\mu^+\mu^-})$ is fitted using

$$V_2^{\rm Sig+Bkg}\left(m_{\mu^+\mu^-}\right) = \alpha(m_{\mu^+\mu^-})V_2^{\rm Sig} + (1-\alpha(m_{\mu^+\mu^-}))V_2^{\rm Bkg}(m_{\mu^+\mu^-})\,. \tag{4}$$

Here, the signal $(V_2^{\rm Sig})$ is the V_2 of each $\Upsilon(nS)$ resonance. The V_2 of background $V_2^{\rm Bkg}(m_{\mu^+\mu^-})$ is described by a second-order polynomial function.

The back-to-back nature of dijets can be subtracted using the low-multiplicity subtraction method developed in Ref. [24]. The $V_n^{\rm Sig}$ values for $N_{\rm trk}^{\rm offline} < 50$ are subtracted from the higher multiplicity region, with

$$\begin{aligned} V_2^{\rm sub} &= V_2^{\rm Sig}\left(70 \le N_{\rm trk}^{\rm offline} < 300\right) - V_2^{\rm Sig}\left(N_{\rm trk}^{\rm offline} < 50\right) \\ &\quad \times \frac{N_{\rm assoc}\left(N_{\rm trk}^{\rm offline} < 50\right)}{N_{\rm assoc}\left(70 \le N_{\rm trk}^{\rm offline} < 300\right)} \times \frac{J_{\rm jet}\left(70 \le N_{\rm trk}^{\rm offline} < 300\right)}{J_{\rm jet}\left(N_{\rm trk}^{\rm offline} < 50\right)}\,, \end{aligned} \tag{5}$$

where $J_{\rm jet}$ represents the near-side jet yield, which is defined as the integral in the short-range region $(|\Delta\eta| < 1)$. The associated ratio, $N_{\rm assoc}(N_{\rm trk}^{\rm offline} < 50)/N_{\rm assoc}(70 \le N_{\rm trk}^{\rm offline} < 300)$, is introduced to account for the enhanced jet yield due to the difference of the associated track yield regardless of the $\Delta\eta$ gap. The ratio, $J_{\rm jet}(70 \le N_{\rm trk}^{\rm offline} < 300)/J_{\rm jet}(N_{\rm trk}^{\rm offline} < 50)$, is introduced to account for the enhanced jet correlations resulting from the selection of higher multiplicity events.

Finally, to determine the $\Upsilon(1S)$ v_2 values, factorization is assumed where the two-particle V_2 value is taken as the product of single-particle v_2 values for the trigger $\Upsilon(1S)$ particle and the associated charge hadrons, with

$$v_2^{\rm sub}\left(p_{\rm T}^{\rm trig}\right) = \frac{V_2^{\rm sub}\left(p_{\rm T}^{\rm trig}, p_{\rm T}^{\rm assoc}\right)}{\sqrt{V_2^{\rm sub}\left(p_{\rm T}^{\rm assoc}, p_{\rm T}^{\rm assoc}\right)}}\,. \tag{6}$$

4. Results

The observed $v_2^{\rm sub}$ values are within one standard deviation of zero over the measured $p_{\rm T}$ range. The total systematic uncertainty for the measured $v_2^{\rm sub}$ values ranges from 0.004 to 0.028, depending on the $\Upsilon(1S)$ meson $p_{\rm T}$. These results are consistent with $\Upsilon(1S)$ $v_2^{\rm sub}$ values measured in PbPb data as shown in Fig. 1 (left). This suggests that the modification of the bottom quark does not significantly depend on the path length through the media. To see the effect of different quark, we also compare our result with those of J/ψ mesons in Fig. 1 (right), which exhibit a significant amount of flow. While the $v_2^{\rm sub}$ values of both quarkonia are similar, the J/ψ mesons with $3 < p_{\rm T} < 6$ GeV/c are found to demonstrate an azimuthal anisotropy. This indicates that bottom quarks experience less collective motion than charm quarks in pPb collisions.

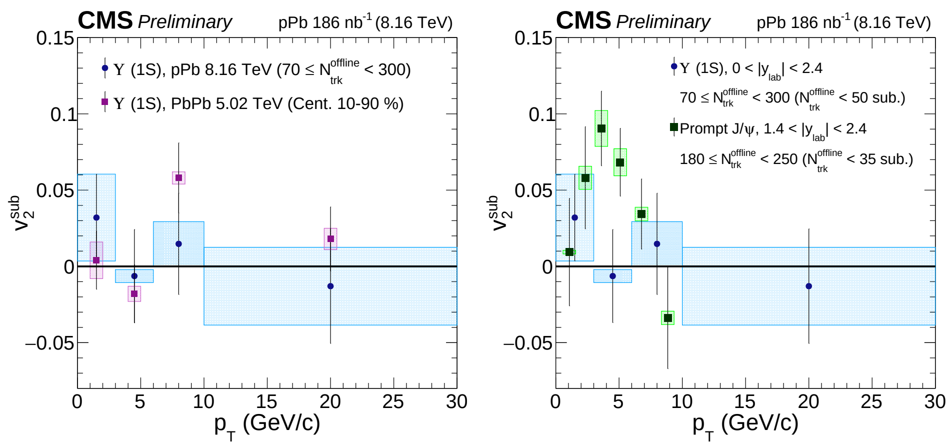

Fig. 1. (Left) The $p_{\rm T}$-dependent $v_2^{\rm sub}$ values for $\Upsilon(1S)$ mesons are compared to corresponding results from PbPb collisions at 5.02 TeV, measured within the 10–90% centrality range [19]. (Right) The same distribution is also compared with the $v_2^{\rm sub}$ values for prompt J/ψ mesons within $|y_{\rm lab}| < 1.4$ in pPb collisions at 8.16 TeV for $180 \le N_{\rm trk}^{\rm offline} < 250$, where a low-multiplicity range with $N_{\rm trk}^{\rm offline} < 35$ is used to estimate and correct for the dijet contribution [18]. The vertical bars denote statistical uncertainties and the rectangular boxes systematic uncertainties, while the widths of the boxes represent the $p_{\rm T}$ bin ranges [20].

5. Summary

The azimuthal anisotropy of $\Upsilon(1S)$ mesons, as expressed in terms of dijet corrected elliptic flow $v_2^{\rm sub}$ coefficients, is presented as a function of transverse momentum $p_{\rm T}$ in high-multiplicity proton–lead (pPb) collision events at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 8.16$ TeV. The $v_2^{\rm sub}$ values are reported for transverse momenta $0 < p_{\rm T} < 30$ GeV/c and observed to be consistent with zero within uncertainties. These results are consistent with those found previously for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Comparing the $v_2^{\rm sub}$ values of $\Upsilon(1S)$ and J/ψ mesons in the same collision system, the results suggest that any medium effect on bottomonia is similar or smaller than that of charmonia in pPb collisions. As this analysis presents the first measurement of the $\Upsilon(1S)$ meson azimuthal anisotropy in the pPb system, it provides an additional constraint on the study of bottomonia production in small systems.

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