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Letter

Study of azimuthal anisotropy of $\Upsilon(1S)$ mesons in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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ABSTRACT

The azimuthal anisotropy of $\Upsilon(1S)$ mesons in high-multiplicity proton-lead collisions is studied using data collected by the CMS experiment at a nucleon-nucleon center-of-mass energy of 8.16 TeV. The $\Upsilon(1S)$ mesons are reconstructed using their dimuon decay channel. The anisotropy is characterized by the second Fourier harmonic coefficients, found using a two-particle correlation technique, in which the $\Upsilon(1S)$ mesons are correlated with charged hadrons. A large pseudorapidity gap is used to suppress short-range correlations. Nonflow contamination from the dijet background is removed using a low-multiplicity subtraction method, and the results are presented as a function of $\Upsilon(1S)$ transverse momentum. The azimuthal anisotropies are smaller than those found for charmonia in proton-lead collisions at the same collision energy, but are consistent with values found for $\Upsilon(1S)$ mesons in lead-lead interactions at a nucleon-nucleon center-of-mass energy of 5.02 TeV.

1. Introduction

Substantial azimuthal (ϕ) correlations are observed among particles emitted over a wide pseudorapidity (η) range in heavy ion collisions at the BNL RHIC [1–5] and the CERN LHC [6–11]. These correlations are understood to arise from a nearly ideal hydrodynamic behavior of the strongly interacting quark-gluon plasma (QGP) created in such collisions [12–14]. Similar long-range correlations are also observed in high particle multiplicity events in smaller colliding systems, such as proton-proton (pp) [15–18], proton-lead (pPb) [19–27], proton-gold [28], deuteron-gold [29], and ^{3}He–gold [30,31]. The origin of the observed correlations in light systems is still under active investigation [32–35].

Heavy-flavor quarks (charm and bottom) are produced in the early stages of heavy ion collisions via hard scattering processes. Therefore, they experience the entire evolution of the produced medium [36], making them useful probes to study the properties of the created matter. The effect of the QGP medium on the propagating heavy-flavor quarks can be studied using the anisotropic azimuthal distribution of the emitted particles, which is experimentally characterized by its Fourier components. The second order coefficient, elliptic flow (v_2), reflects the anisotropy of the initial collision geometry [37]. Positive v_2 values have been reported for charmed mesons like D^0 (open charm) [38–42] at RHIC and LHC, in gold-gold and lead-lead (PbPb) collisions, respectively, indicating the presence of collective flow for charm quarks. The situation for J/ψ mesons (hidden charm) is less clear. In this case, the LHC results also support the presence of collective flow [43,44], but similar non-zero values were not observed at RHIC [45].

Positive v_2 values have also been found in high-multiplicity pPb collisions for D^0 and J/ψ mesons by the CMS Collaboration [46,47]. Measurements by the ATLAS [48] and CMS Collaborations [34] show indication of positive v_2 signals for charm quarks in high-multiplicity pp collisions. Also, muons for heavy-flavor hadron decays in high-multiplicity pPb collisions have positive v_2 values, as reported by the ALICE Collaboration [49]. These results suggest the possibility of collective flow for charm quarks in pp and pPb collisions. Bottom quarks, on the other hand, show little, if any, sign of collective flow in either heavy or light collision systems. Both ALICE [50] and CMS [51] have found v_2 values for the bottom quark $\Upsilon(1S)$ meson in PbPb collisions which are consistent with zero. Also, a dissociation transport model calculation predicts zero v_2 for $\Upsilon(1S)$ in pPb collisions [52]. Measurements by CMS of D^0 mesons arising from b hadron decays [34] in pp and pPb collisions, and by ATLAS of the azimuthal anisotropy of muons from bottom hadron decays in pp collisions [48], have also failed to find significant evidence of bottom quark flow. In order to further clarify the situation for heavy-quark flow in large and small systems, a measurement of the v_2 value for $\Upsilon(1S)$ mesons in pPb collisions will allow a more direct comparison of the flow of hidden charm and hidden bottom mesons in pPb. These measurements are particularly important in light of the uncertainty still remaining regarding the origin of collective behavior in lighter systems.

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This Letter reports measurements of v_2 values for Υ(1S) mesons based on long-range, two-particle correlations in high-multiplicity pPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{_{\mathrm{NN}}}}$ = 8.16 TeV. The v_2 coefficient for the Υ(1S) meson is determined over a wide transverse momentum (p_{T}) range. To correct for the residual contribution from nonflow effects, such as back-to-back jet-like correlations, the v_2 results are presented after subtracting correlations obtained from low-multiplicity pPb events. The results for this analysis are tabulated in the HEPData record [53].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, as well as a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The hadron forward (HF) calorimeters, located at $3 < |\eta| < 5$, extend the η coverage provided by the barrel and endcap detectors. The HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form 0.175×0.175 radians ($\Delta\eta\times\Delta\phi$) towers. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid within the coverage of $|\eta| < 2.4$. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of about 100 kHz within a fixed latency of about 4 μs [54]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. The HLT reduces the event rate to about 1 kHz before data storage [55]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [56].

3. Event selection

This analysis uses pPb collision data collected with the CMS detector in 2016, corresponding to an integrated luminosity of 186 nb^{-1} [57,58]. Events are selected by the Level-1 trigger requiring two muon candidates reconstructed in the muon detectors using the loosest possible selection criteria to maximize detection efficiency. Additional event selection criteria are applied to remove beam-gas interaction as discussed in [59]. Also, at least one HF tower on each side is required to have transverse energy $E_{\mathrm{T}} > 3$ GeV in order to reject non-hadronic collisions. Pileup events, where multiple overlapping collisions occur in a single bunch crossing, are rejected by requiring that only one primary vertex be found within 15 cm from the nominal interaction point along the beam axis and within 0.2 cm of the beam axis in the transverse direction.

The azimuthal anisotropy results are reported for high-multiplicity events in the range $70 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 300$, where $N_{\mathrm{trk}}^{\mathrm{offline}}$ is the number of reconstructed primary charged-particle tracks [60] with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c. This range corresponds to the 25% of minimum bias events with the highest particle multiplicities. Events with $N_{\mathrm{trk}}^{\mathrm{offline}} < 50$ (corresponding to the 40% of events with the lowest particle multiplicities) are also used to estimate the possible contribution of residual back-to-back jet-like correlations. Similar selection criteria and background corrections have been used in previous pp and pPb analyses [32,61,62].

To keep only high-quality muons, a set of offline selection criteria are applied to select "soft" muons [63,64]. A soft muon is required to have a matched reconstructed track in the inner tracking system. This track must have at least six silicon tracker (pixel+strip) hits, with at least one of these hits occurring in the silicon pixel tracker. In addition, the distance of the closest approach of a muon track to the primary vertex must be less than 0.3 cm and 20 cm in the transverse and longitudinal directions, respectively. Also, the pairs of oppositely charged muons are fitted with a common vertex constraint, and the χ^2 probability calculated by a Kalman vertex filter fit [65] is required to be greater than 1%. Lastly, the muons are selected in the kinematic range $p_{\mathrm{T}}^{\mu} > 3.5$ GeV/c and $|\eta^{\mu}| < 2.4$ to ensure high efficiency for the Υ(1S) meson reconstruction. The $|\eta^{\mu}| < 2.4$ range corresponds to the center-of-mass pseudorapidity range of $-2.87 < \eta^{\mu}_{CM} < 1.93$.

4. Analysis

4.1. Two-particle correlation technique

The Υ signals are reconstructed using their dimuon decay channel. The invariant mass of the selected dimuons is studied in the range 8–14 GeV/c^2, which covers the Υ(1S), Υ(2S), and Υ(3S) resonance peaks, and which is sufficient to ensure the stability of the description of the background dimuon distribution in the high-mass region [66].

In calculating the invariant mass distribution and in determining the anisotropy of the detected particles, acceptance and efficiency corrections are applied event-by-event. Acceptance is defined as the probability for both decay muons originating from an Υ meson to have $p_{\mathrm{T}}^{\mu} > 3.5$ GeV/c and $|\eta^{\mu}| < 2.4$. The efficiency correction is determined as a function of p_{T} using the PYTHIA 8.212 [67] Monte Carlo (MC) generator with tune CUETP8M1 [68] and its range is 0.74–0.98. The PYTHIA MC samples are embedded in pPb MC events generated by EPOS LHC [69] that simulate underlying background events. The MC events are reweighted such that the p_{T} spectra of Υ(1S) mesons match the ones in pPb data. The efficiency values are found to not significantly depend on multiplicity, as also found in previous bottomonium and charmonium studies for pPb collisions [70,71]. The efficiency, calculated using a full simulation of the CMS detector based on GEANT4 [72], gives the fraction of dimuons within the acceptance that are reconstructed, satisfy the trigger selection, and pass the analysis selection criteria described in Section 3. An additional correction to the dimuon efficiency is applied to take into account possible differences between data and MC simulation using the "tag-and-probe" method with muon pairs from J/ψ meson decays [63]. This technique calculates the single-muon efficiency in both data and simulation by requiring a tight selection on one muon (the "tag" muon), which is then paired with the other muon that has looser selection criteria (the "probe" muon). The ratio of the single-muon efficiency in data to that in simulation is applied as an event-by-event weight to the dimuon efficiency in simulation. The systematic uncertainty originating from the scale factor is calculated by varying its value by its uncertainty.

The v_n harmonics for the Υ particles are measured using the long-range ($|\Delta\eta| > 1$) two-particle correlation technique previously discussed in Refs. [6,7,19]. The Υ candidates (trigger particles) with transverse momentum $p_{\mathrm{T}}^{\mathrm{trig}}$ in the ranges [0, 3], [3, 6], [6, 10], [10, 30] GeV/c are coupled with the charged tracks (associated particles) with transverse momentum $0.3 < p_{\mathrm{T}}^{\mathrm{assoc}} < 3$ GeV/c and pseudorapidity $|\eta^{\mathrm{assoc}}| < 2.4$. The associated particle yields are corrected for the detector acceptance, reconstruction efficiency, and fractions of misidentified tracks [18].

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

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi} = B(0,0)\,\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}, \tag{1}$$

where $\Delta\eta$ and $\Delta\phi$ are differences in η and ϕ of the pair, N_{trig} and N_{pair} are the numbers of trigger particles and trigger-associated pairs, respectively, in the event. This analysis procedure is repeated for each $m_{\mu^+\mu^-}$ and p_{T} interval. The S($\Delta\eta$, $\Delta\phi$) distribution represents the per-trigger particle yield of trigger-associated pairs from the same event ($m_{\mu^+\mu^-}$, p_{T}) range. A mixed-event pair yield distribution, B($\Delta\eta$, $\Delta\phi$), is constructed by pairing the Υ candidates with charged-particle tracks from different events to account for the combinatorial background and pair-acceptance effects. The normalization factor, B(0, 0), is the mixed-events yield for both particles of the pair going in the same direction, corresponding to the maximum pair-acceptance. The sample of mixed events is formed by randomly selecting ten events from the same multiplicity ($N_{\text{trk}}^{\text{offline}}$) and p_{T} ranges that fall within the same 2 cm wide longitudinal primary vertex range as the Υ candidate event. The specific multiplicity range limits for the mixed events are [70, 80], [80, 90], [90, 110], [110, 150], [150, 300] and [0, 35], [35, 50] for high- and low-multiplicity events, respectively. The ranges are combined for the final reported results. These multiplicity ranges are selected to have similar Υ candidate yields. We also report a result for the extended p_{T} range of 0–30 GeV/c, by combining the per-trigger-particle associated yield distribution from individual p_{T} intervals.

Both signal and background distributions are normalized by N_{trig} after summing up the pair density distributions and the total number of the trigger particles for all events. To quantify the correlation structure, the two-dimensional (2D) distributions are projected onto 1D distributions in $\Delta\phi$ by averaging over the $\Delta\eta$ range.

4.2. Elliptic flow extraction

The dimuon invariant mass spectrum for the Υ candidates is fitted using a signal function, $\text{Sig}(m_{\mu^+\mu^-})$, and a background function, $\text{Bkg}(m_{\mu^+\mu^-})$, to describe the Υ signals and background dimuons, respectively. To take into account the different momentum resolutions of the muons in the endcap and barrel sections, a sum of two Crystal Ball (CB) functions [73] is used to model each Υ state. The width parameters for the two CB functions are allowed to vary independently, while the mean and radiative-tail parameters are set to be equal. All parameters are kept to be the same among the three Υ states except for the mean and width parameters, which have values for the excited states, Υ(2S) and Υ(3S), that are equal to those for the Υ(1S) state multiplied by the PDG [74] mass ratios to the Υ(1S) state. The $\text{Bkg}(m_{\mu^+\mu^-})$ is formed by taking the product of an exponential function, which models the combinatorial mass distribution in the high-mass region, and an error function, which models the saturation that occurs because of the muon p_{T} cutoff. The yield parameters for the Υ signals $N_{1\text{S}}$, $N_{2\text{S}}$, and $N_{3\text{S}}$, and the background dimuons N_{Bkg} are left free in the fit. More details about the fitting procedure can be found in Ref. [51].

For the elliptic flow extraction, the azimuthal anisotropy harmonics are determined from a Fourier decomposition,

$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}N_{\text{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left\{1+\sum_{n} 2V_n\cos(n\Delta\phi)\right\}, \quad (2)$$

where V_n are the Fourier coefficients and N_{assoc} represents the total number of pairs per trigger particle for a given ($p_{\text{T}}^{\text{trig}}, p_{\text{T}}^{\text{assoc}}$) range; V_n is assumed to be the product of single-particle anisotropies of Υ(1S) mesons and reference charged particles [62]. The Fourier coefficients are studied across the dimuons invariant mass range, by dividing it into 23 intervals. The number of intervals is chosen to ensure similar yield in each $m_{\mu^+\mu^-}$ interval. The number of intervals was varied and found to have little effect on the final results. The first three terms of the Fourier series $V_n^{\text{Sig+Bkg}}$, with n = 1, 2, and 3, capture the most significant components and are determined for each $m_{\mu^+\mu^-}$ interval using a binned χ^2 fit. Fig. 1 shows a typical $\Delta\phi$ projection fit.

The signal component of the V_2 coefficient is found using a simultaneous binned χ^2 fit of the invariant mass and V_2 distribution, with

$$\begin{aligned}V_2^{\text{Sig+Bkg}}(m_{\mu^+\mu^-}) &= \alpha_1(m_{\mu^+\mu^-})V_2^{\Upsilon(1\text{S})} + \alpha_2(m_{\mu^+\mu^-})V_2^{\Upsilon(2\text{S})} \\ &+ \alpha_3(m_{\mu^+\mu^-})V_2^{\Upsilon(3\text{S})} + [1-\alpha_1(m_{\mu^+\mu^-}) \\ &- \alpha_2(m_{\mu^+\mu^-}) - \alpha_3(m_{\mu^+\mu^-})]v_2^{\text{Bkg}}(m_{\mu^+\mu^-}), \end{aligned} \quad (3)$$

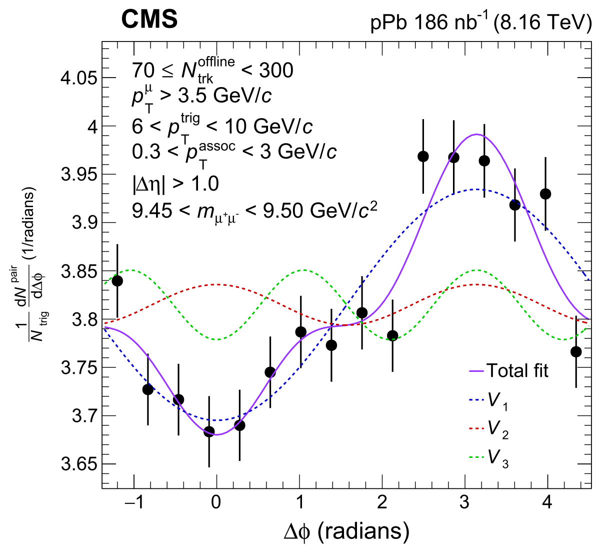

Fig. 1. The $\Delta\phi$ projection of the Υ(1S)-track correlation function for the long-range correlation region ($|\Delta\eta| > 1$) in high-multiplicity events ($70 \leq N_{\text{trk}}^{\text{offline}} < 300$). The three dashed lines represent the first three Fourier coefficients V_1 (blue), V_2 (red), V_3 (green); the magenta solid line corresponds to the total fit.

where $V_2^{\Upsilon(i\text{S})}$ ($i = 1,2,3$) is the V_2 value for the Υ(iS) mesons and is assumed to be independent of $m_{\mu^+\mu^-}$. The V_2 distribution of the background dimuons as a function of mass, $V_2^{\text{Bkg}}(m_{\mu^+\mu^-})$, is described by a second order polynomial function. The $\alpha_i(m_{\mu^+\mu^-})$ factors are the signal fractions for the Υ(iS) states as a function of $m_{\mu^+\mu^-}$, as given by

$$\begin{aligned}\alpha_i(m_{\mu^+\mu^-}) = \text{Sig}_{\Upsilon(i\text{S})}(m_{\mu^+\mu^-})/[&\text{Sig}_{\Upsilon(1\text{S})}(m_{\mu^+\mu^-}) \\ &+ \text{Sig}_{\Upsilon(2\text{S})}(m_{\mu^+\mu^-}) + \text{Sig}_{\Upsilon(3\text{S})}(m_{\mu^+\mu^-}) \\ &+ \text{Bkg}(m_{\mu^+\mu^-})].\end{aligned} \quad (4)$$

Fig. 2 shows the fit to the mass spectrum and $V_2^{\text{Sig+Bkg}}$ as a function of the invariant mass for dimuon pairs with $0 < p_{\text{T}}^{\text{trig}} < 3$ GeV/c (the lowest p_{T} range) and event multiplicities $70 \leq N_{\text{trk}}^{\text{offline}} < 300$.

4.3. Dijet subtraction

The back-to-back nature of dijets can result in a significant V_2 signal even if there is a large $\Delta\eta$ gap between the Υ(1S) trigger particles and the associated charged hadrons. This nonflow contribution is subtracted using the low-multiplicity subtraction method developed in Refs. [18,62]. The V_2^{Sig} values for $N_{\text{trk}}^{\text{offline}} < 50$ are subtracted from the corresponding values in the higher multiplicity region, with

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

where J_{jet} represents the near-side jet yield, which is defined as the integral in the short-range region ($|\Delta\eta| < 1$) of the 1D $\Delta\phi$ correlation functions. The associated ratio, $N_{\text{assoc}}(N_{\text{trk}}^{\text{offline}} < 50)/N_{\text{assoc}}(70 \leq N_{\text{trk}}^{\text{offline}} < 300)$, is introduced to account for the enhanced jet yield due to the difference in the associated track yield regardless of the $\Delta\eta$ gap. The ratio, $J_{\text{jet}}(70 \leq N_{\text{trk}}^{\text{offline}} < 300)/J_{\text{jet}}(N_{\text{trk}}^{\text{offline}} < 50)$, is introduced to

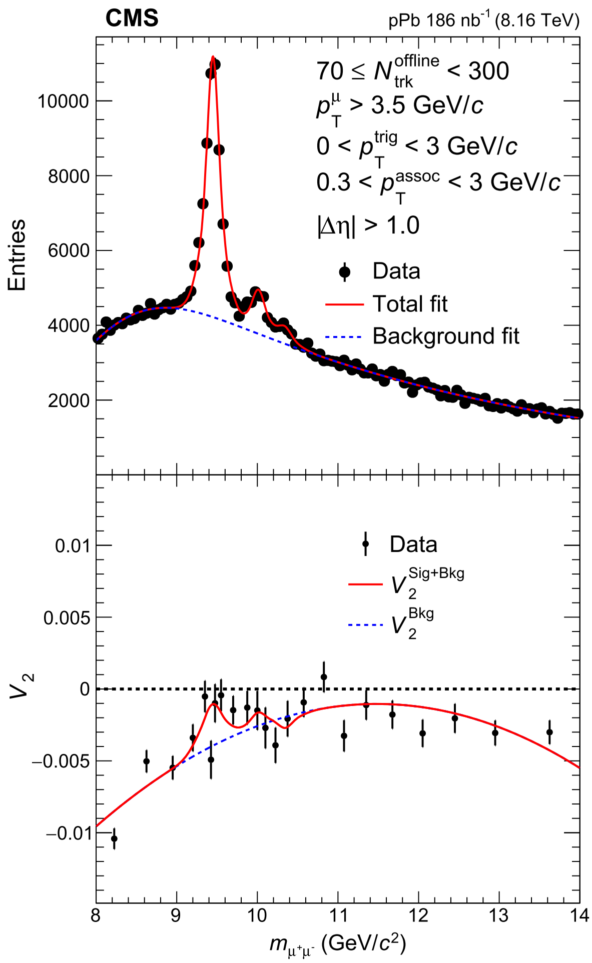

Fig. 2. Simultaneous fit of the $m_{\mu^+\mu^-}$ and V_2 distributions for high-multiplicity ($70 \leq N_{trk}^{offline} < 300$) pPb events. The symbols indicate the event yields in the upper plot and V_2 values from the Fourier component fit in the lower plot. The red solid (blue dash) lines correspond to the total (background) simultaneous fit to both distributions.

account for the enhanced jet correlations resulting from the selection of higher-multiplicity events. For $p_T < 10$ GeV/c, where the $\Upsilon(1S)$ candidates tend to have values of η outside the acceptance for charged particles (of $|\eta| < 2.4$), the jet yield ratio cannot be directly estimated from the two-particle azimuthal correlations. In this case, based on previous analyses in the charm sector where no p_T dependence was observed [46,47], the jet yield ratio value is assumed to be the same as that for the high-p_T region. The $\Upsilon(1S)$ V_2 results, after subtracting the correlations obtained from low-multiplicity events, are denoted as V_2^{sub}.

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 charged hadrons, with

$$v_2^{sub}(p_T^{trig}) = \frac{V_2^{sub}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_2^{sub}(p_T^{assoc}, p_T^{assoc})}}. \tag{6}$$

The quantity $V_2^{sub}(p_T^{assoc}, p_T^{assoc})$ represents the Fourier coefficients extracted by correlating two reference charged particles.

5. Systematic uncertainties

The systematic uncertainties from acceptance and efficiency corrections are estimated by comparing the v_2^{sub} values with and without applying the corrections. To account for the differences between MC simulation and data for the single-muon efficiency, an additional correction factor from the tag-and-probe technique is used. The difference between the resulting v_2^{sub} and the nominal v_2^{sub} value is taken as the systematic uncertainty for this source.

To estimate the systematic uncertainty for the fit procedure, alternative functions are used instead of the nominal functions. A sum of Crystal Ball and Gaussian functions is used as an alternative function for the signal mass distribution. For the background template, a fourth-order polynomial is used to replace the product of the error function and the exponential function. The background function in the $V_2^{Sig+Bkg}$ shape is also changed, from a second-order to a third-order polynomial.

In the simultaneous fitting step described in Section 4.2, all parameters for the Sig($m_{\mu^+\mu^-}$) and Bkg($m_{\mu^+\mu^-}$), except the yields for the Υ states and the background dimuons, are fixed to achieve fit stability. The uncertainties associated with holding these fit parameters fixed are studied by releasing them, one by one, and redoing the fit. The differences between the nominal v_2^{sub} values and those where a parameter is allowed to vary are determined, and the root-mean-square average value is taken as the fit uncertainty.

The final v_2^{sub} value can be affected by the amount of low-multiplicity subtraction. The systematic uncertainty associated with this effect is estimated by varying the jet ratio in Eq. (5) by $\pm 3\sigma$ for $p_T < 10$ GeV/c, and by $\pm 1\sigma$ for $p_T > 10$ GeV/c; here, σ is the standard deviation of the jet ratio, as obtained by fitting the $\Delta\phi$ distribution for $\Delta\eta < 1$. In this analysis, jets are mostly produced in the same direction as the $\Upsilon(1S)$ particles. As the geometrical acceptance in the CMS detector for charged particles is $|\eta| < 2.4$, we lose part of the jet tracks (the ones at $|\eta^{trk}| > 2.4$) when the $\Upsilon(1S)$ is in the high-$|\eta|$ region around 2.4. This leads to a truncation of jets in the $\Delta\eta\Delta\phi$ 2D distribution. Because such truncations are mostly found at low-p_T, the jet yield ratio is calculated from the fit using only the high-p_T region. Hence, a larger variation is considered for the p_T ranges below 10 GeV/c.

The response of the CMS detector to the MC generated particles was simulated using the GEANT4 toolkit. To check the robustness of the full simulation, a closure test is performed by comparing generator- and reconstruction-level results in the MC simulation. The uncertainty associated with this closure test is in the range 0.002–0.007.

Individual systematic uncertainties are expected to be uncorrelated, and are therefore added in quadrature to obtain the final quoted values. Systematic uncertainties from HLT trigger biases and pileup effects are assumed to be the same for $\Upsilon(1S)$ particles and charged particles and, consequently, they cancel in applying Eq. (6).

The systematic uncertainties for each source are listed in Table 1. The total systematic uncertainty for the measured v_2^{sub} values, taken as the sum in quadrature of all sources considered, is in the range 0.005–0.022, depending on the $\Upsilon(1S)$ meson p_T. Because of the low yield of dimuons in the highest p_T interval, the uncertainties for the signal extraction in the mass fit (signal function and background function) are found to be the largest for this interval. The uncertainty is

Table 1
Absolute systematic uncertainties (10^{-2}) included in the measurement of v_2^{sub} evaluated in different $p_T^{\Upsilon(1S)}$ ranges (in GeV/c).

Systematic source	$p_T^{\Upsilon(1S)}$ range in GeV/c.				
	[0-3]	[3-6]	[6-10]	[10-30]	[0-30]
Acceptance	0.04	0.05	0.10	0.26	0.07
Efficiency	0.01	0.01	0.02	0.05	0.05
Tag-and-probe technique	0.11	0.10	0.03	0.07	0.03
Signal function	0.06	0.03	0.02	0.21	0.10
Background function	0.03	0.01	0.13	0.59	0.12
V_2 background function	0.31	0.07	0.12	0.03	0.07
Parameter choice	0.06	0.01	0.04	0.07	0.01
Jet ratio	0.32	0.43	2.18	1.88	0.45
MC closure test	0.66	0.23	0.35	0.32	0.50
Total	0.81	0.51	2.22	2.03	0.70

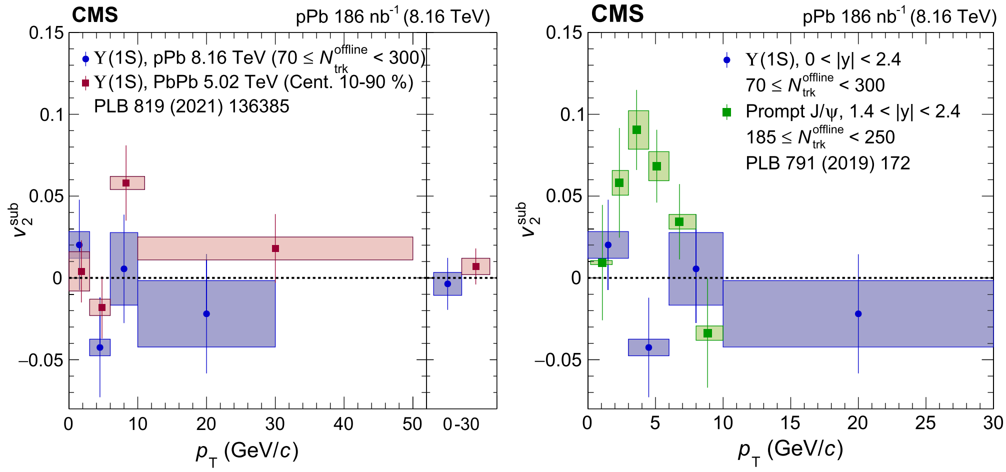

Fig. 3. The p_{T} dependent v_2^{sub} values of $\Upsilon(1\mathrm{S})$ mesons measured in the high-multiplicity region $70 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 300$, where a low-multiplicity region $N_{\mathrm{trk}}^{\mathrm{offline}} < 50$ is used to estimate and correct for the dijet contribution. (Left) The results are compared to the corresponding results from PbPb collisions at 5.02 Te V, measured within the 10–90% centrality range [51]. The integrated range is 0–50 Ge V / c for PbPb. (Right) The same distribution is also compared with the v_2^{sub} values for prompt J/ψ mesons within $1.4 < |y| < 2.4$ in pPb collisions at 8.16 Te V for $185 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 250$, where a low-multiplicity range with $N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ was used to estimate and correct for the dijet contribution [47]. The vertical bars denote statistical uncertainties and the shaded boxes represent systematic uncertainties, while the widths of the boxes represent the p_{T} ranges.

dominated by the MC closure test, the background function, the jet ratio, and the V_2 background function.

6. Results

Fig. 3 shows the comparison of the current v_2^{sub} results for $\Upsilon(1\mathrm{S})$ mesons in pPb collisions with those for $\Upsilon(1\mathrm{S})$ in PbPb (left panel) [51] and J/ψ in pPb (right panel) [47], as a function of the $\Upsilon(1\mathrm{S})$ meson p_{T}. The symbols are plotted at the center of each p_{T} range. The average p_{T} for the highest range is found to be around 15 GeV/c. The observed v_2^{sub} values for $\Upsilon(1\mathrm{S})$ in pPb are consistent with zero over the measured p_{T} range, as also found for centrality-integrated PbPb data. This suggests that the azimuthal anisotropy of $\Upsilon(1\mathrm{S})$ mesons does not significantly depend on the size of the system despite the different level of suppression in pPb and PbPb collisions [71]. Future v_2 measurements for the excited states with larger data sets would be an interesting subject to further study the medium response of bottomonia in small collision systems. In Fig. 3 (right), we also compare our results with those of J/ψ mesons, which exhibit significant flow-related correlations for the range of $0 < p_{\mathrm{T}} < 10$ GeV/c [47]. It should be noted that the $N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges are different for the J/ψ and $\Upsilon(1\mathrm{S})$ measurements. Restricting the $\Upsilon(1\mathrm{S})$ study to an $N_{\mathrm{trk}}^{\mathrm{offline}}$ range similar to that for the J/ψ analysis does not significantly change the observed $\Upsilon(1\mathrm{S})$ distribution, although it does increase the statistical uncertainties. In contrast to the $\Upsilon(1\mathrm{S})$ results, positive v_2^{sub} values are reported for J/ψ mesons in the range $2 < p_{\mathrm{T}} < 8$ GeV/c. To investigate the variation in v_2^{sub} for these two quarkonium species, a p-value comparison is employed. The p-value determined for each J/ψ v_2^{sub} value against the hypothesis of an equivalent v_2^{sub} value for $\Upsilon(1\mathrm{S})$ mesons in the p_{T} integrated range, taking into account the given uncertainties. Notably, in the range $2 < p_{\mathrm{T}} < 8$ GeV/c, p-values less than 0.05, indicating dissimilar results, are observed for the two J/ψ p_{T} intervals within the range $3 < p_{\mathrm{T}} < 6$ GeV/c, with p-values of 0.0035 and 0.0150, respectively. This indicates that bottom quarks experience less collective motion, if any, than charm quarks in pPb collisions.

7. Summary

The azimuthal anisotropy of $\Upsilon(1\mathrm{S})$ mesons, as quantified using the elliptic flow coefficients v_2^{sub}, is measured as a function of transverse momentum for the first time in high-multiplicity proton-lead (pPb) collision events at the center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. The measurement is corrected for dijet background using a low-multiplicity subtraction method. The v_2^{sub} values are observed to be consistent with zero. These results are also consistent with those found previously in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Comparing v_2^{sub} of $\Upsilon(1\mathrm{S})$ and those of J/ψ mesons, the results suggest that any collectivity of bottomonia is smaller than that of charmonia in pPb collisions. The direct comparison of $\Upsilon(1\mathrm{S})$ flow results for pPb and PbPb reinforces the conclusion that there is no evidence for collective flow of bottom quarks in systems of any size.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in "CMS data preservation, re-use and open access policy".

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