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Measurement of $\Upsilon(1S)$ Elliptic Flow at Forward Rapidity in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The first measurement of the $\Upsilon(1S)$ elliptic flow coefficient ($v_2$) is performed at forward rapidity ($2.5 < y < 4$) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector at the LHC. The results are obtained with the scalar product method and are reported as a function of transverse momentum ($p_T$) up to 15 GeV/$c$ in the 5%–60% centrality interval. The measured $\Upsilon(1S)v_2$ is consistent with 0 and with the small positive values predicted by transport models within uncertainties. The $v_2$ coefficient in $2 < p_T < 15$ GeV/$c$ is lower than that of inclusive $J/\psi$ mesons in the same $p_T$ interval by 2.6 standard deviations. These results, combined with earlier suppression measurements, are in agreement with a scenario in which the $\Upsilon(1S)$ production in Pb–Pb collisions at LHC energies is dominated by dissociation limited to the early stage of the collision, whereas in the $J/\psi$ case there is substantial experimental evidence of an additional regeneration component.

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At the extreme energy densities and temperatures produced in ultrarelativistic collisions of heavy nuclei, hadronic matter undergoes a transition into a state of deconfined quarks and gluons, known as quark-gluon plasma (QGP). The created QGP medium is characterized as a strongly coupled system, which behaves as an almost perfect fluid in the sense that its shear viscosity to entropy density ratio approaches the smallest possible values [1–3]. Spatial initial state anisotropy of the overlap region of the two colliding nuclei is transformed by the fluid pressure gradients into a momentum anisotropy of the produced final-state particles. This effect is known as hydrodynamic anisotropic flow [4] and is usually quantified in terms of the harmonic coefficients of the Fourier decomposition of the azimuthal particle distribution [5]. The dominant coefficient in noncentral collisions is the second harmonic, denoted by $v_2$ and known as elliptic flow, since this coefficient directly arises from the almond-shaped interaction region between the colliding nuclei. It is approximately proportional to the eccentricity $e_2$ of the initial collision geometry [6]. The proportionality coefficient reflects the response of the QGP medium to the initial anisotropy and depends on the particle type, mass, and kinematics [7].

Charm and beauty quarks are important probes of the QGP. They are created predominantly in hard-scattering processes at the early collision stage and therefore experience the entire evolution of the QGP. The observed significant $D$ meson $v_2$ in nucleus-nucleus collisions suggests that the charm quarks participate in the collective anisotropic flow of the QGP fluid [8–10]. Nevertheless, since the light-flavor quarks also contribute to the $D$-meson flow, detailed comparisons with theoretical models are necessary to draw firm conclusions about the charm-quark flow. Quarkonia, which are bound states of heavy-flavor quark-antiquark pairs, offer a complementary way to study the interaction of the heavy-flavor quarks with the medium and thus to independently shed light on the properties of the QGP [11]. In a simplified picture, quarkonium production is suppressed by color screening inside the QGP medium created in nucleus-nucleus collisions [12]. The level of suppression depends on the heavy-quark interaction and the temperature of the surrounding medium [13,14]. The azimuthal asymmetry of the overlap region of the two colliding nuclei and the dependence of the suppression on the path length traversed by the quark-antiquark pair inside the medium lead to positive $v_2$ values increasing as a function of transverse momentum ($p_T$). At LHC energies, there is evidence for a competing effect that enhances the production of charmonia (bound states of charm quark-antiquark pairs) [15–17]. This effect originates from regeneration of charmonia via recombination of (partially) thermalized charm quarks either during the QGP evolution [18,19] or at the QGP phase boundary [20,21]. It becomes significant at LHC energies due to the large charm-quark production cross section, which implies that a sufficiently

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high number of charm quarks traveling inside the QGP are
available for recombination. Within the regeneration
scenario, the elliptic flow of charmonia is directly inherited from
the velocity field of the individual charm quarks within the
medium and results in a positive $v_2$ coefficient, mainly at low
$p_T$. Measurements of significant $J/\psi$-meson $v_2$ coefficient
in Pb-Pb collisions at LHC energies clearly speak in favor of
charm-quark flow and the regeneration scenario [22–25].
Despite this, the phenomenological models that incorporate
transport of heavy-flavor quark-antiquark pairs inside the
QGP are not yet able to provide a fully satisfactory
description of the $p_T$ dependence of the measured $J/\psi$
elliptic flow [19,26]. Moreover, recent results in high-
multiplicity $p$-Pb collisions also indicate a significant
$J/\psi v_2$ [27,28], which is unexpected within the present
transport models due to the small collision-system size and
low number of available charm quarks [29]. Recent calcu-
lations within the color-glass condensate framework attribute
this significant $v_2$ to initial-state effects [30].

Bottomonia, bound states of bottom quark-antiquark
pairs, are also expected to be suppressed inside the QGP
by the color-screening effect [11,13,31]. Indeed, mea-
surements in Pb-Pb collisions at the LHC demonstrate a
significant suppression of inclusive $\Upsilon(1S)$ production
[32–35]. In recent calculations the $v_2$ coefficient of
inclusive $\Upsilon(1S)$ is predicted to be significantly smaller
when compared to that of inclusive $J/\psi$ [36]. The reason
is that the $\Upsilon(1S)$ dissociation happens at higher temper-
atures due to its greater binding energy. The dissociation
is therefore limited to the earlier stage of the collision,
when the path-length differences are less influential. In
addition, the recombination of (partially) thermalized
down quarks gives a negligible contribution to the $v_2$
coefficient due to the small number of available bottom
quarks [36]. As a result, the predicted values of $\Upsilon(1S) v_2$
coefficient are small in contrast to the charmonium case.
It is worth noting that even though the $v_2$ coefficient of
the excited bottomonium state $\Upsilon(2S)$ is currently beyond
experimental reach, it is expected to be significantly
higher than that of $\Upsilon(1S)$. Because of its lower binding
energy and other bound-state characteristic differences,
the suppression and regeneration occur up to a later stage
of the collision. Hence, the path-length dependent sup-
pression induces a larger $v_2$, the fraction of regenerated
$\Upsilon(2S)$ is higher, and the inherited $v_2$ is larger [36].
Consequently, the measurement of the bottomonium
elliptic flow is a crucial ingredient in the study of
heavy-flavor interactions with the QGP, not only to
complement the corresponding charmonium measure-
ments, but also in the search for any sizable $v_2$ beyond
the theoretical expectations.

In this Letter, we present the first measurement of $\Upsilon(1S)$
elliptic flow in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}=5.02$ TeV at
forward rapidity ($2.5 < y < 4$). The $\Upsilon$ mesons are recon-
structed via their $\mu^+\mu^-$ decay channel. The results are
obtained in the momentum interval $0 < p_T < 15$ GeV/c
and the 5%–60% collision centrality interval.

General information on the ALICE apparatus and its
performance can be found in Refs. [37,38]. The muon
spectrometer, which covers the pseudorapidity range
$-4 < \eta < -2.5$, is used to reconstruct muon tracks. (In
the ALICE reference frame, the muon spectrometer covers
a negative $\eta$ range and consequently a negative $y$ range.
The results were chosen to be presented with a positive $y$
notation, due to the symmetry of the collision system.) It
consists of a front absorber followed by five tracking
stations with the third station placed inside a dipole magnet.
Two trigger stations located downstream of an iron wall
complete the spectrometer. The silicon pixel detector (SPD)
[39,40] consists of two cylindrical layers covering the full
azimuthal angle and $|\eta| < 2.0$ and $|\eta| < 1.4$, respectively.
The SPD is employed to determine the position of the
primary vertex and to reconstruct tracklets, track segments
formed by the clusters in the two SPD layers and the
primary vertex [41]. Two arrays of 32 scintillator counters
each [42], covering $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta <$
$-1.7$ (V0C), are used for triggering, the event selection,
and the determination of the collision centrality and the
event flow vector. In addition, two neutron zero degree
calorimeters [43], installed 112.5 m from the interaction
point along the beam line on each side, are employed for
the event selection.

The data samples recorded by ALICE during the 2015
and 2018 LHC Pb-Pb runs at $\sqrt{s_{\mathrm{NN}}}=5.02$ TeV are used
for this analysis. The trigger conditions and the event
selection criteria are described in Ref. [24]. The primary
vertex position is required to be within $\pm 14$ cm from the
nominal interaction point along the beam direction. The
data are split in intervals of collision centrality, which is
obtained based on the total signal in the V0A and V0C
detectors [44]. The integrated luminosity of the analyzed
data sample is about 750 $\mu$b$^{-1}$.

The muon selection is identical to that used in
Refs. [24,27]. The dimuons are reconstructed in the
acceptance of the muon spectrometer ($2.5 < y < 4.0$)
and are required to have a transverse momentum between
0 and 15 GeV/c. The alignment of the muon spectrometer
is performed based on the MILLEPEDE package [45] and
using Pb-Pb data taken with the nominal dipole magnetic
field [38]. The presence of the magnetic field limits the
precision of the alignment procedure in the track
bending direction. Indeed, a study of the reconstructed
$\Upsilon$ mass as a function of the momentum of muon tracks ($p_{\mu}$)
reveals a residual misalignment leading to a systematic
shift in the measured muon track momentum $\Delta(1/p_{\mu}) \approx$
$2.5 \times 10^{-4}$ (GeV/c)$^{-1}$, where the sign of the shift
depends on the muon charge and the magnetic field polarity.
A correction of this misalignment effect is obtained via
a high-statistics sample of reconstructed $J/\psi \to \mu^+\mu^-$
decays and the spectra of high-momentum muon tracks.
The correction is then applied to the reconstructed muon track momentum, resulting in up to 25% improvement of the $\Upsilon(1S)$ mass resolution for $p_T > 6$ GeV/c.

The dimuon invariant mass ($M_{\mu\mu}$) distribution is fitted with a combination of an extended crystal ball (CB2) function for the $\Upsilon(1S)$ signal and a variable-width Gaussian function with a quadratic dependence of the width on $M_{\mu\mu}$ for the background [46]. A binned maximum-likelihood fit is employed. The $\Upsilon(1S)$ peak position and width are left free, while the CB2 tail parameters are fixed to the values extracted from Monte Carlo simulations [35]. The $\Upsilon(2S)$ and $\Upsilon(3S)$ signals are included in the fit. Their peak positions and widths are fixed to those of the $\Upsilon(1S)$ scaled by the ratio of their nominal masses to the nominal mass of the $\Upsilon(1S)$. An example of the $M_{\mu\mu}$ fit is shown in the left panel of Fig. 1. It is worth noting that no statistically significant $\Upsilon(3S)$ is observed in any of the studied centrality and $p_T$ intervals, and thus it is not considered in the further analysis.

The dimuon $v_2$ is measured using the scalar product method [47,48], correlating the reconstructed dimuons with the second-order harmonic event flow vector $Q_{2,\text{SPD}}$ [5,49] calculated from the azimuthal distribution of the reconstructed SPD tracklets

$$v_2\{\text{SP}\} = \left\langle u_2 Q_{2,\text{SPD}}^\mu \right\rangle \cdot \left\langle \frac{Q_{2,\text{SPD}}^{\text{V0A}^\mu} Q_{2,\text{SPD}}^{\text{V0C}^\mu}}{Q_{2,\text{V0A}}^{\mu} Q_{2,\text{V0C}}^{\mu}} \right\rangle_{\mu\mu},$$

where $u_2 = \exp(i2\varphi)$ is the unit flow vector of the dimuon with azimuthal angle $\varphi$. The brackets $\left\langle \cdot \cdot \right\rangle_{\mu\mu}$ denote an average over all dimuons belonging to a given $p_T$, $M_{\mu\mu}$ and centrality interval. The $Q_{2,\text{V0A}}^\mu$ and $Q_{2,\text{V0C}}^\mu$ are the event flow vectors calculated from the azimuthal distribution of the energy deposition measured in the V0A and V0C detectors, respectively, and $^*$ is the complex conjugate. The brackets $\langle \cdot \cdot \rangle$ in the denominator denote an average over all events in a sufficiently narrow centrality class that encloses the event containing the dimuon. In order to account for a nonuniform detector response and efficiency, the components of all three event flow vectors are corrected using a recentering procedure [50]. The gaps in pseudorapidity between the muon spectrometer and SPD ($|\Delta\eta| > 1.0$) and between the SPD, V0A, and V0C remove autocorrelations and suppress short-range correlations unrelated to the azimuthal asymmetry in the initial geometry (“nonflow”), which largely come from jets and resonance decays. In the following, the $v_2\{\text{SP}\}$ coefficient is denoted as $v_2$.

The $\Upsilon(1S)v_2$ coefficient is obtained by a least squares fit of the superposition of the $\Upsilon(1S)$ signal and the background to the dimuon flow coefficient as a function of the dimuon invariant mass [51]

$$v_2(M_{\mu\mu}) = \alpha(M_{\mu\mu}) v_2^\Upsilon(1S) + (1 - \alpha(M_{\mu\mu})) v_2^B(M_{\mu\mu}),$$

where $v_2^\Upsilon(1S)$ is the flow coefficient of the signal, $v_2^B$ is the $M_{\mu\mu}$-dependent flow coefficient of the background, and $\alpha(M_{\mu\mu})$ is the signal fraction, obtained from the fit of the $M_{\mu\mu}$ distribution described above. The background $v_2^B$ is modeled as a second-order polynomial function of $M_{\mu\mu}$. For consistency, and despite its low yield, the $\Upsilon(2S)$ is included in the fit by restricting the value of its $v_2$ coefficient within the range between $-0.5$ and $0.5$. In practice, this inclusion has a negligible impact on the $\Upsilon(1S)$ fit results. An example of $v_2(M_{\mu\mu}$ fit is presented in the right panel of Fig. 1.

The main systematic uncertainty of the measurement arises from the choice of the background fit function $v_2^B(M_{\mu\mu})$. In order to estimate this uncertainty, linear and constant functions are also used instead of the second-order
collision geometry is small for the former and the signal
variations are not considered as the eccentricity of the initial
The central (0%–0.0015 and is conservatively assumed to be
the same in all transverse momentum and centrality
intervals. The variations of the fit range and invariant-
to be at most 0.0015 and is conservatively assumed to be
the in transverse momentum in the 5%
while the magenta dashed line represents the BBJS model calculations.
the QGP medium [52]. The TAMU model incorporates in addition a regeneration component
originating from the recombination of (partially) thermalized bottom quarks [36]. Given that
component gives practically negligible contribution to the total \( \Upsilon(1S) v_2 \), the differences between the two models
are marginal. It is worth noting that although the quoted
model predictions are for midrapidity, they remain valid also for the rapidity range of the measurement within the
theoretical uncertainties. Indeed the fractions of regener-
ated and initially produced \( \Upsilon(1S) \) are very close at mid and forward rapidities [36]. In addition, the QGP medium
evolution is also similar between mid and forward rapidities, given the weak rapidity dependence of the charged-particle multiplicity density [53]. The presented \( \Upsilon(1S) v_2 \) result is coherent with the measured \( \Upsilon(1S) \) suppression in Pb-Pb collisions [35], as the level of suppression is also fairly well reproduced by the BBJS model and the TAMU model including or excluding a regeneration component. Therefore, the result is in agreement with a scenario in which the predominant mechanism affecting \( \Upsilon(1S) \) production in Pb-Pb collisions at the LHC energies is the dissociation limited to the early stage of the collision. It is interesting to note that the presented \( \Upsilon(1S) v_2 \) results are reminiscent of the corresponding charmonia measurements in Au-Au collisions at RHIC [54], where so far non-
observation of significant \( v_2 \) is commonly interpreted as a sign of a small regeneration component from recombination of thermalized charm quarks at lower RHIC energies.
The \( \Upsilon(1S) v_2 \) values in the three \( p_T \) intervals shown in Fig. 2 are found to be lower, albeit with large uncertainties, compared to those of the inclusive \( J/\psi \) measured in the same centrality and \( p_T \) intervals using the data sample and analysis procedure described in Ref. [24]. Given that any \( v_2 \) originating either from recombination or from path-length dependent dissociation vanishes at zero \( p_T \), the observed difference between \( \Upsilon(1S) \) and \( J/\psi \) \( v_2 \) is quantified by performing the \( p_T \)-integrated measurement excluding the low \( p_T \) range. Figure 3 presents the \( \Upsilon(1S) v_2 \) coefficient integrated over the transverse momentum range 2 < \( p_T < 15 \) GeV/c for three centrality intervals compared with that of the inclusive \( J/\psi \). The \( \Upsilon(1S) v_2 \) is found to be −0.003 ± 0.030(stat) ± 0.006(syst) in the 2 < \( p_T < 15 \) GeV/c and 5%–60% centrality interval. This value is lower than the corresponding \( J/\psi \) \( v_2 \) by 2.6σ. This observation, coupled to the different measured centrality and \( p_T \) dependence of the \( \Upsilon(1S) \) and \( J/\psi \) suppression in Pb-Pb collisions at the LHC [17,35], can be interpreted within the models used for comparison as a sign that unlike \( \Upsilon(1S) \), \( J/\psi \) production has a significant regeneration component.

**FIG. 2.** The \( \Upsilon(1S) v_2 \) coefficient as a function of \( p_T \) in the 5%–60% centrality interval compared to that of inclusive \( J/\psi \). The cyan dashed line represents the BBJS model calculations [52], while the magenta band denotes the TAMU model calculations [36]. Error bars (open boxes) represent the statistical (systematic) uncertainties.
FIG. 3. The $\Upsilon(1S)$ $v_2$ coefficient integrated over the transverse momentum range $2 < p_T < 15$ GeV/$c$ in three centrality intervals compared to that of inclusive $J/\psi$. Error bars (open boxes) represent the statistical (systematic) uncertainties.

Nevertheless, no firm conclusions can be drawn, given that currently the transport models cannot explain the significant $J/\psi v_2$ for $p_T > 4$–5 GeV/$c$ observed in the data [23].

In summary, the first measurement of the $\Upsilon(1S)$ $v_2$ coefficient in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented. The measurement is performed in the 5%–60% centrality interval within $0 < p_T < 15$ GeV/$c$ range at forward rapidity. The $v_2$ coefficient is compatible with 0 and with the model predictions within uncertainties. Excluding low $p_T$ ($0 < p_T < 2$ GeV/$c$), $\Upsilon(1S)$ $v_2$ is found to be $2.6\sigma$ lower with respect to that of inclusive $J/\psi$. The presented measurement opens the way for further studies of bottomonium flow using the future data samples from the LHC Runs 3 and 4 with an expected tenfold increase in the number of the $\Upsilon$ candidates [55,56].

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