J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration∗

Abstract

We report on the first measurement of inclusive J/ψ elliptic flow, $v_2$, in heavy-ion collisions at the LHC. The measurement is performed by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the rapidity range $2.5 < y < 4.0$. The dependence of the J/ψ $v_2$ on the collision centrality and on the J/ψ transverse momentum is studied in the range $0 \leq p_T < 10$ GeV/c. For semi-central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, an indication of non-zero $v_2$ is observed with a maximum value of $v_2 = 0.116 \pm 0.046$ (stat.) $\pm 0.029$ (syst.) for J/ψ in the transverse momentum range $2 \leq p_T < 4$ GeV/c. The elliptic flow measurement complements the previously reported ALICE results on the inclusive J/ψ nuclear modification factor and favors the scenario of a significant fraction of J/ψ production from charm quarks in a deconfined partonic phase.

∗See Appendix A for the list of collaboration members
The aim of ultra-relativistic heavy nuclei collisions is the study of nuclear matter at high temperature and pressure where Quantum Chromodynamics predicts the existence of a deconfined state of partonic matter, the Quark-Gluon Plasma (QGP). Heavy quarks are expected to be produced in the primary partonic scatterings and to interact with this partonic medium making them ideal probes of the QGP. The measurement of quarkonium states and hadrons with open heavy flavor is therefore expected to provide essential information on the properties of the strongly-interacting system formed in the early stages of heavy-ion collisions [1]. According to the color-screening model [2], quarkonium states will be suppressed in the medium with different dissociation probabilities for the various states. Recently, the CMS Collaboration at the Large Hadron Collider (LHC) claimed the observation of the sequential suppression in the Υ sector [3]. The ALICE Collaboration published the inclusive J/ψ nuclear modification factor $R_{AA}$ down to zero transverse momentum ($p_T$) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [4]. The $R_{AA}$ compares the yields in Pb-Pb to those in pp collisions scaled by the number of binary nucleon-nucleon collisions. The inclusive J/ψ nuclear modification factor reported is larger than that measured at the SPS [5] and at RHIC [6, 7] for central collisions and does not exhibit a significant centrality dependence. Complementarily, the CMS Collaboration measures the high $p_T$ ($6.5 \leq p_T < 30$ GeV/$c$) prompt J/ψ $R_{AA}$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the rapidity range $|y| < 2.4$ [8]. The data of CMS shows that high $p_T$ J/ψ are found to be more suppressed than low $p_T$ J/ψ and that this suppression does exhibit a strong centrality dependence.

The centrality dependence of the J/ψ $R_{AA}$ at low transverse momentum can be qualitatively understood with models including full [9,10] or partial [11,12] regeneration of J/ψ from deconfined charm quarks in the medium. The J/ψ regeneration mechanism was first proposed by the Statistical Hadronization Model (SHM), which assumes deconfinement and thermal equilibrium of the bulk of $c\bar{c}$ pairs to produce J/ψ at the phase boundary by statistical hadronization only [2]. Later, the transport models proposed a dynamical competition between the J/ψ suppression by the QGP and the regeneration mechanism, which enables them to describe also the $p_T$ dependence of the J/ψ $R_{AA}$ [11,12]. These models have in common the assumption of deconfinement and some degree of charm quark thermalization. More differential studies, like the J/ψ elliptic flow, could help to assess the charm quark thermalization in the medium.

The azimuthal distribution of particles in the plane perpendicular to the beam direction is an experimental observable also sensitive to the dynamics of the early stages of heavy-ion collisions. When nuclei collide at finite impact parameter (non-central collisions), the geometrical overlap region and, therefore, the initial matter distribution is anisotropic (almond-shaped). If the matter is strongly interacting, this spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution [13]. The second coefficient of the Fourier expansion describing the final state particle azimuthal distribution with respect to the reaction plane, $v_2$, is called elliptic flow. The reaction plane is defined by the beam axis and the impact parameter vector of the colliding nuclei.

Within the transport model scenario [11,12] the observed J/ψ have two origins. First, primordial J/ψ, which are produced in the initial hard scatterings, traverse and interact with the created medium. During this process they may be dissociated. Second, J/ψ could be regenerated from deconfined charm quarks and anti-quarks in the QGP. Primordial J/ψ emitted in-plane traverse a shorter path through the medium than those emitted out-of-plane resulting in a small azimuthal anisotropy for the surviving J/ψ. Regenerated J/ψ inherit the elliptic flow of the charm quarks in the QGP. If charm quarks do thermalize in the QGP then J/ψ formed there can exhibit a significant elliptic flow.

At RHIC energies, the (preliminary) measurements by the (PHENIX) STAR Collaboration of the J/ψ elliptic flow in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14,15] are consistent with zero albeit with large uncertainties in the $p_T$ and centrality ranges (0–5 GeV/$c$) 2–10 GeV/$c$ and (20%–60%) 10%–50%. The measurement of quarkonium elliptic flow is especially promising at the LHC where the high energy density of the medium and the large number of $c\bar{c}$ pairs produced in Pb-Pb collisions should favor the development
of flow and the regeneration mechanisms.

In this Letter, we report ALICE results on inclusive $J/\psi$ elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at forward rapidity, measured via the $\mu^+\mu^-$ decay channel. The $J/\psi$ elliptic flow is presented as a function of transverse momentum and collision centrality.

The ALICE detector is described in [16]. At forward rapidity ($2.5 < y < 4$) the production of quarkonium states is measured via the decay channel $\mu^+\mu^-$ in the muon spectrometer down to $p_T = 0$. The spectrometer consists of a ten interaction length thick absorber stopping the hadrons in front of five tracking stations comprising two planes of cathode pad chambers each, with the third station inside a dipole magnet delivering a 3 Tm field integral. The tracking apparatus is completed by a triggering system made of four planes of resistive plate chambers downstream of a 1.2 m thick iron wall, which absorbs secondary hadrons escaping from the front absorber and low momentum muons coming mainly from $\pi$ and K decays. In addition, the silicon pixel detector (SPD) and scintillator arrays (VZERO) were used in this analysis. The VZERO counters consist of two arrays of 32 scintillator sectors each distributed in four rings covering $2.8 \leq \eta \leq 5.1$ (VZERO-A) and $-3.7 \leq \eta \leq -1.7$ (VZERO-C). The SPD, used to determine the location of the interaction point, consists of two cylindrical layers covering $|\eta| \leq 2.0$ and $|\eta| \leq 1.4$ for the inner and outer layers, respectively. All of these detectors have full azimuthal coverage. The data sample used for this analysis, collected in 2011, amounts to $17 \times 10^6$ dimuon unlike sign (MU) triggered Pb-Pb collisions and corresponds to an integrated luminosity $L_{int} \approx 70 \mu b^{-1}$. In addition to a minimum bias (MB) trigger, the MU trigger requires at least a pair of opposite sign track segments, each with a $p_T$ above the threshold of the on-line trigger algorithm. The $p_T$ threshold of the trigger algorithm was set to provide 50% efficiency for muon tracks with $p_T = 1$ GeV/$c$. The MB trigger requires a signal in VZERO-A and a signal in VZERO-C. The beam induced background was further reduced offline using the VZERO and the zero degree calorimeter (ZDC) timing information. The contribution from electromagnetic processes was removed by requiring a minimum energy deposited in the neutron ZDCs [17]. The centrality determination is based on a fit of the VZERO amplitude distribution as described in [18]. A cut corresponding to the most central 90% of the nuclear cross section was applied; for these events the MB trigger is fully efficient and the contribution from electromagnetic processes is negligible.

$J/\psi$ candidates are formed by combining pairs of opposite-sign (OS) tracks reconstructed in the geometrical acceptance of the muon spectrometer. To improve the muon identification, the reconstructed tracks in the muon tracking chambers are required to match a track segment in the muon trigger system above the $p_T$ threshold of the on-line trigger algorithm.

The $J/\psi$ $v_2$ is calculated using event plane (EP) based methods. The azimuthal angle $\Psi$ of the second harmonic event plane is used as an estimate of the reaction plane angle [19]. $\Psi$ is determined from the azimuthal distribution of the VZERO amplitude. The VZERO-C has a common acceptance region with the muon spectrometer. Therefore, only the VZERO-A was used for the event plane determination to avoid autocorrelations. The $J/\psi$ $v_2$ results were obtained determining $v_2 = \langle \cos 2(\phi - \Psi) \rangle$ versus invariant mass ($m_{\mu\mu}$) [20], where $\phi$ is the dimuon azimuthal angle. In this method, $v_2$ of the OS dimuons is calculated as a function of $m_{\mu\mu}$ and then the resulting $v_2(m_{\mu\mu})$ distribution is fitted using:

$$v_2(m_{\mu\mu}) = v_2^{sig}\alpha(m_{\mu\mu}) + v_2^{bkg}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})],$$

(1)

where $v_2^{sig}$ and $v_2^{bkg}$ correspond to the $v_2$ of the $J/\psi$ signal and of the background, respectively. $v_2^{bkg}$ was parametrized using a second order polynomial (see Fig.1(b)). Here, $\alpha(m_{\mu\mu}) = S/(S + B)$ is the ratio of the signal over the sum of the signal plus background of the $m_{\mu\mu}$ distributions. It is extracted from fits to the OS invariant mass distribution (see Fig.1(a)) in each $p_T$ and centrality class. The OS dimuon invariant mass distribution was fitted with a Crystal Ball (CB) function to reproduce the $J/\psi$ line shape,
J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration

Fig. 1: (Color online) Invariant mass spectrum (a) and $\langle \cos 2(\phi - \Psi) \rangle$ (b) as a function of the invariant mass of $\mu^+\mu^-$ pairs (fitted with Eq. 1) with $2 \leq p_T < 4$ GeV/c and $2.5 < y < 4$ in the 20%–40% semi-central Pb-Pb collisions.

and either a third order polynomial or a gaussian with a width linearly varying with mass to describe the underlying continuum. The CB function connects a Gaussian core with a power-law tail [21] at low mass to account for energy loss fluctuations and radiative decays. An extended CB function with an additional power-law tail at high mass, to account for alignment and calibration biases, was also used. The combination of several CB and underlying continuum parametrizations described before were tested to assess the signal and the related systematic uncertainties. The $J/\psi \nu^2$ and its statistical uncertainty in each $p_T$ and centrality class were determined as the average of the $\nu^2_{\text{sig}}$ obtained by fitting $\nu^2_{\text{bkg}}(m_{\mu\mu})$ using Eq. 1 with the various $\alpha(m_{\mu\mu})$, while the corresponding systematic uncertainties were defined as the RMS of these results. Figure 1 shows typical fits of the OS invariant mass distribution (a) and of the $\langle \cos 2(\phi - \Psi) \rangle$ as a function of $m_{\mu\mu}$ (b) in the 20%–40% centrality class. The systematic uncertainty related to the unknown shape of the $\nu^2_{\text{bkg}}(m_{\mu\mu})$ was evaluated by repeating the procedure above using either a first order polynomial or its inverse as $\nu^2_{\text{bkg}}$ parametrization. The largest deviation of the results obtained with the three different $\nu^2_{\text{bkg}}$ parametrizations was conservatively adopted as the systematic uncertainty. A similar method is used to extract the uncorrected (for detector acceptance and efficiency) average transverse momentum ($\langle p_T \rangle_{\text{uncor}}$) of the reconstructed $J/\psi$ in each centrality and $p_T$ class. The $\langle p_T \rangle_{\text{uncor}}$ is used to locate the data points when plotted as a function of transverse momentum. Consistent $\nu^2$ values were obtained using an alternative method [19] in which the $J/\psi$ raw yield is extracted, as described before, in bins of $(\phi - \Psi)$ and the $\nu^2$ values are evaluated using a fit to the data with the function $\frac{dN}{d(\phi - \Psi)} = A[1 + 2\nu^2 \cos 2(\phi - \Psi)]$, where $A$ is a normalization constant.

The finite resolution in the event plane determination smears out the azimuthal distributions and leads to a lower value for the measured anisotropy [19]. The VZERO-A event plane resolution as a function of the centrality was determined using MB events and the 3 sub-event method [19]. To estimate the systematic uncertainty from the event plane determination two sets of 3 sub-events were used: first, VZERO-A,
Table 1: VZERO-A event plane resolution for the centrality classes expressed in percentages of the nuclear cross section [18].

<table>
<thead>
<tr>
<th>Centrality</th>
<th>\langle N_{\text{part}} \rangle</th>
<th>EP resolution ± (stat.) ± (syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%–20%</td>
<td>283 ± 4</td>
<td>0.548 ± 0.003 ± 0.009</td>
</tr>
<tr>
<td>20%–40%</td>
<td>157 ± 3</td>
<td>0.610 ± 0.002 ± 0.008</td>
</tr>
<tr>
<td>40%–60%</td>
<td>69 ± 2</td>
<td>0.451 ± 0.003 ± 0.008</td>
</tr>
<tr>
<td>60%–90%</td>
<td>15 ± 1</td>
<td>0.185 ± 0.005 ± 0.013</td>
</tr>
<tr>
<td>20%–60%</td>
<td>113 ± 3</td>
<td>0.576 ± 0.002 ± 0.008</td>
</tr>
</tbody>
</table>

Fig. 2: (Color online) Inclusive \( J/\psi \) \( v_2(p_T) \) for semi-central (20%–40%) Pb-Pb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \). The \( v_2 \) was measured in the \( p_T \) ranges: 0–2, 2–4, 4–6 and 6–10 GeV/c and the points are located at the measured \( \langle p_T \rangle_{\text{uncor}} \).

VZERO-C and the Time Projection Chamber (TPC), with pseudo-rapidity gaps \( \Delta \eta_{\text{V0A-TPC}}=1.9 \) and \( \Delta \eta_{\text{TPC-V0C}}=0.8 \); second, VZERO-A, VZERO-C-1st ring and VZERO-C-4th ring, with pseudo-rapidity gaps \( \Delta \eta_{\text{V0A-V0C1}}=4.5 \) and \( \Delta \eta_{\text{V0C1-V0C4}}=1.1 \). The differences between the event plane resolution for VZERO-A obtained from these two sets of sub-events are taken as systematic uncertainties. Since \( v_2 \) is measured here in a wide centrality class, the resolution must reflect the distribution of events with a \( J/\psi \) within the class. Therefore, the event plane resolution for each wide class was calculated as the average of the values obtained in finer centrality classes weighted by the number of reconstructed \( J/\psi \). Table I shows the corresponding resolution for each centrality class which is applied to the results reported in this Letter.

The \( J/\psi \) reconstruction efficiency depends on the detector occupancy which could result in a bias of the \( v_2 \) measurement. This effect was evaluated by embedding azimuthally isotropic simulated \( J/\psi \rightarrow \mu^+\mu^- \) decays into real events. The measured \( v_2 \) of those embedded \( J/\psi \) was found not to deviate from zero by more than 0.015 in all the centrality and \( p_T \) classes considered in this Letter. This value is used as a conservative systematic uncertainty on all measured \( v_2 \) values.
Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration

Figure 2 shows the transverse momentum dependence of the inclusive $J/\psi$ $v_2$ for semi-central (20%–40%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which include the uncertainties from the signal extraction, the $v_2^{bkg}$ shape and from the reconstruction efficiency. The global correlated relative systematic uncertainty on the event plane resolution is 1.3%. A non-zero $v_2$ is observed in the intermediate transverse momentum range $2 \leq p_T < 6$ GeV/$c$. Taking into account statistical and systematic uncertainties the combined significance of a non-zero $v_2$ in this $p_T$ range is $2.7\sigma$. At lower and higher transverse momentum the inclusive $J/\psi v_2$ is compatible with zero within uncertainties.

To study the centrality dependence of the $v_2$ we select $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ for which the signal to background ratio as well as the observed $v_2$ are maximized. Since the initial spatial anisotropy for head-on collisions is small, the expected elliptic flow is also small. Therefore, we do not consider the 0%–5% centrality range. Figure 3 (a) shows $v_2$ for inclusive $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ as a function of the number of participating nucleons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The average number of participant nucleons $\langle N_{\text{part}} \rangle$ for the centrality classes used in this analysis are derived from a Glauber model calculation [18]. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which in addition to those discussed above also include the uncertainty from event plane resolution determination. The measured $v_2$ depends on the $p_T$ distribution of the reconstructed $J/\psi$, which could vary with the centrality of the collision. Therefore, $\langle p_T \rangle_{\text{uncor}}$ of the reconstructed $J/\psi$ is also shown in Fig. 3 (b) as a function of $\langle N_{\text{part}} \rangle$. For the most central collisions, 5%–20% and 20%–40% the inclusive $J/\psi v_2$ for $1.5 \leq p_T < 10$ GeV/$c$ are $0.101 \pm 0.044$(stat.) $\pm 0.032$(syst.) and $0.116 \pm 0.045$(stat.) $\pm 0.041$(syst.), respectively. The combined significance of a non-zero $v_2$ measurement is $2.9\sigma$. For most peripheral Pb-Pb collisions, i.e. the two classes with low $\langle N_{\text{part}} \rangle$ values, the $v_2$ is consistent with zero within uncertainties. Although there is a small variation with centrality, the $\langle p_T \rangle_{\text{uncor}}$ stays in the range 3.0–3.3 GeV/$c$ indicating that the bulk of the reconstructed $J/\psi$ are in the same $p_T$ range for all centralities. Thus, the observed centrality

![Diagram](image-url)
dependence of the $v_2$ for inclusive $J/\psi$ with $1.5 \leq p_T < 10$ GeV/$c$ does not result from any bias in the sampled $p_T$ distributions. For $J/\psi$ with $p_T < 1.5$ GeV/$c$ (not shown) the $v_2$ was found to be compatible with zero within one standard deviation for the four centrality classes. The $\langle p_T \rangle_{uncor}$ ranges from about 0.75 to 0.9 GeV/$c$.

To allow a direct comparison with current model calculations, the inclusive $J/\psi v_2(p_T)$ was also calculated in a broader centrality range, namely 20%–60%. Figure 4 shows the inclusive $J/\psi v_2(p_T)$ for non-central (20%–60%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In this broader centrality range, the measured $v_2$ signal in the $p_T$ range 2–4 GeV/$c$ deviates from zero by 2$\sigma$. The same trend of $v_2(p_T)$ is observed in the 20%–60% and in the 20%–40% centrality classes. This trend is different from the STAR measurement [15] at lower collision energy, which is compatible with zero for $p_T \geq 2$ GeV/$c$ albeit in somewhat different (10%–50% and 0%–80%) centrality ranges. Also shown in Fig. 4 are two transport model calculations that include a $J/\psi$ regeneration component from deconfined charm quarks in the medium [22, 23]. In both models about 30% of the measured $J/\psi$ in the 20%–60% centrality range are regenerated. On the one hand, thermalized charm quarks in the medium transfer a significant elliptic flow to regenerated $J/\psi$. On the other hand, initial $J/\psi$ emitted out-of-plane traverse a longer path through the medium than those emitted in-plane resulting in a small apparent $v_2$. The predicted maximum $v_2$ at $p_T \sim 2.5$ GeV/$c$ results from an interplay between the regeneration component, dominant at lower $p_T$, and the initial $J/\psi$ component which takes over at higher $p_T$. The first model [22] is shown for the hypothesis of thermalization (full line) and non-thermalization (dashed line) of $b$ quarks. The LHCb Collaboration measured the fraction of $J/\psi$ from $B$ hadron decays in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV [24, 25] in the rapidity acceptance used for this measurement. At 7 TeV this fraction increases from about 7% at $p_T \sim 0$ to 15% at $p_T \sim 7$ GeV/$c$, while at 2.76 TeV it is about 7% for $p_T < 12$ GeV/$c$. In Pb-Pb collisions this fraction could increase to a maximum of 11% if the $B$ hadron $R_{AA} = 1$. If $b$ quarks
do thermalize then their elliptic flow will be transferred to B mesons at hadronization and to the J/ψ at the B meson decay. In the second model [23] (dash-dotted line) only the case assuming thermalization of the b quark is shown. Both models are able to qualitatively describe the \( p_T \) dependence of the \( v_2 \) and the nuclear modification factor of inclusive J/ψ [4].

In summary, we reported the ALICE measurement of inclusive J/ψ elliptic flow in the range \( 0 \leq p_T < 10 \) GeV/c at forward rapidity in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. For semi-central collisions indications of a non-zero J/ψ \( v_2 \) are observed in the intermediate \( p_T \) range. This measurement complements the results on the J/ψ nuclear modification factor, where a smaller suppression was seen at low transverse momentum at the LHC compared to RHIC. These results suggest that a significant fraction of the observed J/ψ is produced from deconfined charm quarks in the QGP phase.

References

J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration

1203.2436.


1 Acknowledgements

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex.

The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector:

State Committee of Science, World Federation of Scientists (WFS) and Swiss Fonds Kidagan, Armenia, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP);
National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC);
Ministry of Education and Youth of the Czech Republic;
Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation;
The European Research Council under the European Community’s Seventh Framework Programme;
Helsinki Institute of Physics and the Academy of Finland;
French CNRS-IN2P3, the ‘Region Pays de Loire’, ‘Region Alsace’, ‘Region Auvergne’ and CEA, France;
German BMBF and the Helmholtz Association;
General Secretariat for Research and Technology, Ministry of Development, Greece;
Hungarian OTKA and National Office for Research and Technology (NKTH);
Department of Atomic Energy and Department of Science and Technology of the Government of India;
Istituto Nazionale di Fisica Nucleare (INFN) and Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Italy;
MEXT Grant-in-Aid for Specially Promoted Research, Japan;
Joint Institute for Nuclear Research, Dubna;
National Research Foundation of Korea (NRF);
CONACYT, DGAPA, México, ALFA-EC and the EPLANET Program (European Particle Physics Latin American Network)
Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor
M. LeRoy et al.

J/ψ Elliptic Flow in Pb-Pb Collisions at √s_{NN} = 2.76 TeV

The ALICE Collaboration

Wetenschappelijk Onderzoek (NWO), Netherlands;
Research Council of Norway (NFR);
Polish Ministry of Science and Higher Education;
National Authority for Scientific Research - NASR (Autoritatea Națională pentru Cercetare Științifică - ANCS);
Ministry of Education of Slovakia;
Department of Science and Technology, South Africa;
CIEMAT, EELA, Ministerio de Economía y Competitividad (MINECO) of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency);
Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW);
Ukraine Ministry of Education and Science;
United Kingdom Science and Technology Facilities Council (STFC);
The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.
A  The ALICE Collaboration


The ALICE Collaboration

J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

11
Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration

Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

Also at: Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
√

Also at: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

Also at: Academy of Scientific Research and Technology (ASRT), Cairo, Egypt

Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

Also at: University of Belgrade, Faculty of Physics and Vinvca Institute of Nuclear Sciences, Belgrade, Serbia

Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

Also at: Budker Institute for Nuclear Physics, Novosibirsk, Russia

Also at: California Institute of Technology, Pasadena, California, United States

Also at: Centre de Calcul de l’IN2P3, Villeurbanne, France

Also at: Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

Affiliation Notes

1 Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

2 Also at: University of Belgrade, Faculty of Physics and Vinvca Institute of Nuclear Sciences, Belgrade, Serbia

3 Also at: Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland

Collaboration Institutes

1 Academy of Scientific Research and Technology (ASRT), Cairo, Egypt

2 A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

3 Benemérita Universidad Autónoma de Puebla, Puebla, Mexico

4 Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

5 Bose Institute, Department of Physics and Centre for Astrophysics Physics and Space Science (CAPSS), Kolkata, India

6 Budker Institute for Nuclear Physics, Novosibirsk, Russia

7 California Institute of Technology, Pasadena, California, United States

8 Central China Normal University, Wuhan, China

9 Centre de Calcul de l’IN2P3, Villeurbanne, France

10 Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

The ALICE Collaboration

11 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
12 Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
13 Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Rome, Italy
14 Chicago State University, Chicago, United States
15 Commissariat à l’Energie Atomique, IRFU, Saclay, France
16 COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
17 Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
18 Department of Physics, Aligarh Muslim University, Aligarh, India
19 Department of Physics and Technology, University of Bergen, Bergen, Norway
20 Department of Physics, Ohio State University, Columbus, Ohio, United States
21 Department of Physics, Seoul National University, Seoul, South Korea
22 Department of Physics, University of Oslo, Oslo, Norway
23 Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
24 Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
25 Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy
26 Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN, Rome, Italy
27 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy
28 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy
29 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
30 Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
31 Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
32 Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
33 Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
34 European Organization for Nuclear Research (CERN), Geneva, Switzerland
35 Fachhochschule Köln, Köln, Germany
36 Faculty of Engineering, Bergen University College, Bergen, Norway
37 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
38 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
39 Faculty of Science, P.J. Šafárik University, Košice, Slovakia
40 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
41 Gangneung-Wonju National University, Gangneung, South Korea
42 Gauhati University, Department of Physics, Guwahati, India
43 Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland
44 Hiroshima University, Hiroshima, Japan
45 Indian Institute of Technology Bombay (IIT), Mumbai, India
46 Indian Institute of Technology Indore, Indore, India (IITI)
47 Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
48 Institute for High Energy Physics, Protvino, Russia
49 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
50 Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
51 Institute for Theoretical and Experimental Physics, Moscow, Russia
52 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
53 Institute of Physics, Bhubaneswar, India
54 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
55 Institute of Space Sciences (ISS), Bucharest, Romania
56 Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
57 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
58 Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
59 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
60 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
61 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
Joint Institute for Nuclear Research (JINR), Dubna, Russia
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Korea Institute of Science and Technology Information, Daejeon, South Korea
KTO Karatay University, Konya, Turkey
Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
Laboratori Nazionali di Frascati, INFN, Frascati, Italy
Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
Lawrence Berkeley National Laboratory, Berkeley, California, United States
Lawrence Livermore National Laboratory, Livermore, California, United States
Moscow Engineering Physics Institute, Moscow, Russia
National Centre for Nuclear Studies, Warsaw, Poland
National Institute for Physics and Nuclear Engineering, Bucharest, Romania
National Institute of Science Education and Research, Bhubaneswar, India
Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rež u Prahy, Czech Republic
Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
Petersburg Nuclear Physics Institute, Gatchina, Russia
Physics Department, Creighton University, Omaha, Nebraska, United States
Physics Department, Panjab University, Chandigarh, India
Physics Department, University of Athens, Athens, Greece
Physics Department, University of Cape Town and iThemba LABS, National Research Foundation, Somerset West, South Africa
Physics Department, University of Jammu, Jammu, India
Physics Department, University of Rajasthan, Jaipur, India
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Politecnico di Torino, Turin, Italy
Purdue University, West Lafayette, Indiana, United States
Pusan National University, Pusan, South Korea
Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
Rudjer Bošković Institute, Zagreb, Croatia
Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
Russian Research Centre Kurchatov Institute, Moscow, Russia
Saha Institute of Nuclear Physics, Kolkata, India
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
Sezione INFN, Catania, Italy
Sezione INFN, Turin, Italy
Sezione INFN, Padova, Italy
Sezione INFN, Bologna, Italy
Sezione INFN, Cagliari, Italy
Sezione INFN, Trieste, Italy
Sezione INFN, Bari, Italy
Sezione INFN, Rome, Italy
Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
Suranaree University of Technology, Nakhon Ratchasima, Thailand
Technical University of Split FESB, Split, Croatia
Technische Universität München, Munich, Germany
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
J/$\psi$ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The ALICE Collaboration

The University of Texas at Austin, Physics Department, Austin, TX, United States
Universidad Autónoma de Sinaloa, Culiacán, Mexico
Universidade de São Paulo (USP), São Paulo, Brazil
Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
University of Houston, Houston, Texas, United States
University of Tennessee, Knoxville, Tennessee, United States
University of Tokyo, Tokyo, Japan
University of Tsukuba, Tsukuba, Japan
Eberhard Karls Universität Tübingen, Tübingen, Germany
Variable Energy Cyclotron Centre, Kolkata, India
Vestfold University College, Tonsberg, Norway
V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
Warwick University of Technology, Warsaw, Poland
Wayne State University, Detroit, Michigan, United States
Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
Yale University, New Haven, Connecticut, United States
Yıldız Technical University, Istanbul, Turkey
Yonsei University, Seoul, South Korea
Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany