Observation of an Energy-Dependent Difference in Elliptic Flow between Particles and Antiparticles in Relativistic Heavy Ion Collisions


(STAR Collaboration)

1AGH University of Science and Technology, Cracow, Poland
2Argonne National Laboratory, Argonne, Illinois 60439, USA
3University of Birmingham, Birmingham, United Kingdom
4Brookhaven National Laboratory, Upton, New York 11973, USA
5University of California, Berkeley, California 94720, USA
6University of California, Davis, California 95616, USA
7University of California, Los Angeles, California 90095, USA
8Universidad Estadual de Campinas, Sao Paulo, Brazil
9Central China Normal University (HZNU), Wuhan 430079, China
10University of Illinois at Chicago, Chicago, Illinois 60607, USA
11Creighton University, Omaha, Nebraska 68178, USA
12Czech Technical University in Prague, FNSPE, Prague, 115 19, Czech Republic
13Nuclear Physics Institute AS CR, 250 68 Rez/Prague, Czech Republic
14University of Frankfurt, Frankfurt, Germany
15Institute of Physics, Bhubaneswar 751005, India
16Indian Institute of Technology, Mumbai, India
17Indiana University, Bloomington, Indiana 47408, USA
18Alikhanov Institute for Theoretical and Experimental Physics, Moscow, Russia
19Joint Institute for Nuclear Research, Dubna 141 980, Russia
20University of Illinois, Urbana-Champaign, Illinois 61801, USA
21Kent State University, Kent, Ohio 44242, USA
22University of Kentucky, Lexington, Kentucky 40506-0055, USA
23Institute of Modern Physics, Lanzhou, China
24Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
25University of Kansas, Lawrence, Kansas 66045, USA
26Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA
27Max-Planck-Institut für Physik, Munich, Germany
28Michigan State University, East Lansing, Michigan 48824, USA
29Moscow Engineering Physics Institute, Moscow, Russia
30National Institute of Science Education and Research, Pashan, India
31The Ohio State University, Columbus, Ohio 43210, USA
32Old Dominion University, Norfolk, Virginia 23529, USA
33Institute of Nuclear Physics PAN, Cracow, Poland
34Panjab University, Chandigarh 160014, India
35Pennsylvania State University, University Park, Pennsylvania 16802, USA
36Institute of High Energy Physics, Protvino, Russia
37Purdue University, West Lafayette, Indiana 47907, USA
38Pusan National University, Pusan, Republic of Korea
39University of Rajasthan, Jaipur 302004, India
40Rice University, Houston, Texas 77251, USA
41Universidade de Sao Paulo, Sao Paulo, Brazil
42University of Science & Technology of China, Hefei 230026, China
43Shandong University, Jinan, Shandong 250100, China
44Shanghai Institute of Applied Physics, Shanghai 201800, China
45SUBATECH, Nantes, France
46Temple University, Philadelphia, Pennsylvania 19122, USA
47Texas A&M University, College Station, Texas 77843, USA
48University of Texas, Austin, Texas 78712, USA
49University of Houston, Houston, Texas 77204, USA
50Tsinghua University, Beijing 100084, China
51United States Naval Academy, Annapolis, Maryland 21402, USA
52Valparaiso University, Valparaiso, Indiana 46383, USA
53Variable Energy Cyclotron Centre, Kolkata 700064, India
54Warsaw University of Technology, Warsaw, Poland
55University of Washington, Seattle, Washington 98195, USA
Elliptic flow \( (v_2) \) values for identified particles at midrapidity in Au + Au collisions, measured by the STAR experiment in the beam energy scan at RHIC at \( \sqrt{s_{NN}} = 7.7-62.4 \text{ GeV} \), are presented. A beam-energy-dependent difference of the values of \( v_2 \) between particles and corresponding antiparticles was observed. The difference increases with decreasing beam energy and is larger for baryons compared to mesons. This implies that, at lower energies, particles and antiparticles are not consistent with the universal number-of-constituent-quark scaling of \( v_2 \) that was observed at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

Lattice quantum chromodynamics (QCD) predicts that, at sufficiently high temperatures \( T \) and/or high baryonic chemical potentials \( \mu_B \), normal nuclear matter will undergo a phase transition to a state of matter where quarks and gluons are deconfined, called the quark-gluon plasma (QGP) [1]. This transition is important for understanding the early evolution of the Universe [2]. A beam energy scan (BES) program [3] has been carried out at the Relativistic Heavy Ion Collider (RHIC) facility to study the QCD phase structure over a large range in \( T \) and \( \mu_B \).

Particle production in heavy ion collisions with respect to the event plane (EP) can be characterized by the following Fourier expansion:

\[
\frac{dN}{d(\phi - \Psi)} \propto 1 + 2 \sum_{n=1} v_n^{\text{obs}} \cos \left[ n(\phi - \Psi) \right],
\]

where \( \phi \) is the azimuthal angle of the particles, \( n \) the harmonic number, \( v_n^{\text{obs}} \) the observed Fourier coefficient that has to be corrected for the EP resolution to get \( v_n \), and \( \Psi \) the reconstructed EP azimuthal angle [4,5]. The second harmonic coefficient is denoted as elliptic flow \( v_2 \) [4].

Elliptic flow measurements have been used to conclude that strongly interacting partonic matter is produced in Au + Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) and that \( v_2 \) develops in the early, partonic, stage. This conclusion is based in part on the observed scaling of \( v_2 \) versus the transverse momentum \( p_T \), with the number of constituent quarks (NCQ) [6–9] for hadrons at intermediate \( p_T \) (2 to 5 \text{ GeV/c}) deviations from such a scaling for identified hadron \( v_2(p_T) \) at lower beam energies is thus an indication for the absence of a deconfined phase [3].

In a hydrodynamic picture, \( v_2 \) arises in noncentral heavy ion collisions due to an initial pressure gradient, which is directly connected to the eccentricity. This leads to particle emission predominantly in the direction of the maximum of the pressure gradient. During the expansion of the system the pressure gradient decreases, which means that elliptic flow primarily probes the early stage of a heavy ion collision.

For Au + Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \), a mass ordering in \( v_2(p_T) \) between the different particle species was observed at low transverse momenta (\( p_T < 2 \text{ GeV/c} \)) [6,10,11]. This behavior can be described by nonviscous hydrodynamic calculations [12–17]. The relative mass ordering can be suppressed by using the reduced transverse kinetic energy (\( m_T - m_0 \)) instead of \( p_T \), with \( m_T = \sqrt{p_T^2 + m_0^2} \) and \( m_0 \) being the mass of the particle. At large (\( m_T - m_0 \)), a splitting in \( v_2(m_T - m_0) \) between baryons and mesons was observed that cannot be described by hydrodynamic calculations. This splitting can be explained, in part, by assuming that the particle production occurs via coalescence of constituent quarks [18].

The \( v_2 \) values for \( \pi^\pm, K^\pm, K^0_S, p, \bar{p}, \phi, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^-, \Omega^- \) measured at midrapidity in minimum bias Au + Au collisions will be reported. The data were recorded by STAR, the Solenoidal Tracker at RHIC, for \( \sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, \) and 62.4 \text{ GeV} \) in the years 2010 and 2011 as part of the BES program [3].

STAR is a multipurpose experiment at RHIC with a complete azimuthal coverage. The main detectors used for the data analysis were the time-projection chamber (TPC) [19] for tracking and particle identification at pseudorapidities \( \eta < 1.0 \), and the time-of-flight (TOF) detector, which was especially important to identify charged particles at intermediate momenta. A minimum bias trigger was defined using a coincidence of hits in the zero degree calorimeters, vertex position detectors, or beam-beam counters [20,21]. To suppress events from collisions with the beam pipe (radius 3.95 cm), an upper limit cut on the radial position of the reconstructed primary vertex of 2 cm was applied. In addition, the \( z \) position of the vertices was limited to values less than \( \pm 70 \) cm. Collisions within a 0%–80% centrality range of the total reaction cross section were selected for the analysis. The centrality definition is based on a comparison between the measured track multiplicity within \( \eta < 0.5 \) and a Glauber Monte Carlo simulation [20].

The particle identification and yield extraction for long-lived charged hadrons (\( p, \bar{p}, \pi^\pm, K^\pm \)) was based on a combination of the ionization energy loss \( dE/dx \) in the TPC, the reconstructed momentum (\( p \)), and the squared mass \( m^2 \) from the TOF detector [21]. Short-lived particles
that decay within the detector acceptance, such as \( \phi \), \( \Lambda \), \( \bar{\Lambda} \), \( \Xi^- \), \( \Xi^+ \), \( \Omega^- \), \( \Omega^+ \), and \( K^0 \), were identified using the invariant mass technique. The combinatorial background to the weakly decaying particles like \( \Lambda \) and \( \Xi \) was reduced by topological reconstruction. The remaining combinatorial background was fit and subtracted with the mixed event technique [21].

The event plane was reconstructed using the procedure described in Ref. [4]. In order to reduce the effects of nonflow contributions arising mainly from Hanbury-Brown Twiss correlations and Coulomb interactions, the event plane angles were estimated for two subevents separated by an additional \( \eta \) gap instead of using the full TPC event plane method [21]. For such an “\( \eta \)-sub-EP” reconstruction, one uses only the particles from the opposite \( \eta \) hemisphere with respect to the particle of interest and outside of an additional \( \eta \) gap of \( |\eta| > 0.05 \). The nonflow contributions were studied for the six beam energies by comparing different methods of extracting \( v_2 \) for inclusive charged hadrons [20]. The four particle cumulant \( v_2(4) \) strongly suppresses nonflow contributions. It has been shown that the difference between \( v_2(\eta\text{-sub}) \) and \( v_2(4) \) is 10%–20% for 19.2, 27, and 39 GeV and decreases with decreasing energy. All observed values (\( v_2^{\text{obs}} \)) were corrected on an event-by-event basis using the EP resolution [22] that was calculated by comparing the two \( \eta \)-sub-EP angles [20].

For each particle species, the cuts used for particle identification and background suppression were varied to estimate the systematic uncertainties. The errors were also estimated by varying the methods used to flatten the EP, to obtain the yields, and to extract the \( v_2 \) values. A more detailed description of the detector setup and the analysis can be found in Ref. [21].

In Fig. 1, the \( p_T \) dependence of the proton and antiproton \( v_2 \) is shown for \( \text{Au + Au} \) collisions at \( \sqrt{s_{\text{NN}}} = 7.7 \), 11.5, 27, and 39 GeV. At all energies, the \( v_2 \) values increase with increasing \( p_T \). At \( p_T = 2 \) GeV/c, the magnitude of \( v_2 \) for protons increases with energy from about 0.10 at 7.7 GeV to 0.15 at 39 GeV. Lower values of \( v_2(p_T) \) are observed for antiprotons compared to protons at all energies. The difference in the \( v_2 \) values for protons and antiprotons increases with decreasing beam energy. The lower panels of Fig. 1 show the \( p_T \) dependence of the difference in \( v_2 \) for protons and antiprotons. No significant \( p_T \) dependence is observed, as characterized by the horizontal line fits. The negative values of the antiproton \( v_2 \) at low \( p_T \) at \( \sqrt{s_{\text{NN}}} = 11.5 \) GeV could be influenced by absorption in the medium [23]. Suppressed or negative \( v_2 \) values are also observed at \( \sqrt{s_{\text{NN}}} = 7.7 \) GeV for different centralities [21].

The \( v_2(p_T) \) behavior for \( \Lambda(uds), \bar{\Lambda} \bar{\bar{d}} \bar{s} \) and \( \Xi^- (dss) \), \( \Xi^+ (\bar{d} \bar{s} \bar{s}) \) is similar to that for protons (\( uud \)) and antiprotons (\( \bar{u} \bar{u} \bar{d} \)). In all cases, the baryon antiparticle \( v_2 \) is lower than the corresponding particle \( v_2 \). The \( v_2(p_T) \) difference for \( \Lambda \) and \( \bar{\Lambda} \) in agreement with previous STAR results at \( \sqrt{s_{\text{NN}}} = 62.4 \) GeV [7]. For the mesons \( \pi^+(u\bar{u}), \pi^- (\bar{u}d), \) and \( K^+(u\bar{s}), K^- (\bar{u}d) \), the differences are smaller than those for the baryons (the antiparticle convention from Ref. [24] is used for mesons). At \( \sqrt{s_{\text{NN}}} = 7.7 \) GeV, the \( v_2(p_T) \) difference between \( K^+ \) and \( K^- \) is about 5–6 smaller as compared to the baryons, with \( K^+ \) having a systematically larger \( v_2(p_T) \) than \( K^- \). On the other hand, the \( v_2(p_T) \) of the \( \pi^- \) is larger than the \( v_2(p_T) \) of the \( \pi^+ \). However, the magnitude of the difference for pions as a function of energy is similar to that for the kaons. The details of the \( p_T \) dependence of the difference in \( v_2 \) between particles and corresponding antiparticles can be found in Ref. [21].

Figure 2 summarizes the variation of the \( p_T \) independent difference in \( v_2 \) between particles and corresponding antiparticles with \( \sqrt{s_{\text{NN}}} \). Here, \( v_2(X) - v_2(\bar{X}) \) denotes the horizontal line fit values of the difference in \( v_2(p_T) \) between particles \( X (p, \Lambda, \Xi^-, \pi^+, K^+) \) and corresponding antiparticles \( \bar{X} (\bar{p}, \bar{\Lambda}, \Xi^+, \pi^-, K^-) \). Larger \( v_2 \) values are found for particles than for antiparticles, except for pions, for which the opposite ordering is observed. A monotonic increase of the magnitude of \( \Delta v_2 = v_2(X) - v_2(\bar{X}) \) with decreasing beam energy is observed. The data can be described by a power-law function.

![FIG. 1 (color online). The elliptic flow \( v_2 \) of protons and antiprotons as a function of the transverse momentum \( p_T \) for 0%–80% central \( \text{Au + Au} \) collisions. The lower panels show the difference in \( v_2(p_T) \) between the particles and antiparticles. The solid curves are fits with a horizontal line. The shaded areas depict the magnitude of the systematic errors.](142301-4)
While in Au + Au collisions at √sNN = 200 GeV a single NCQ scaling can be observed for particles and antiparticles, the observed difference in v2 at lower beam energies demonstrates that this common NCQ scaling of particles and antiparticles splits. Such a breaking of the NCQ scaling could indicate increased contributions from hadronic interactions in the system evolution with decreasing beam energy. The energy dependence of v2(X) − v2(̅X) could also be accounted for by considering an increase in nuclear stopping power with decreasing √sNN if the v2 of transported quarks (quarks coming from the incident nucleons) is larger than the v2 of produced quarks [25,26]. Theoretical calculations [27] suggest that the difference between particles and antiparticles could be accounted for by mean field potentials where the K − and ̅p feel an attractive force while the K + and p feel a repulsive force.

Most of the published theoretical calculations can reproduce the basic pattern but fail to quantitatively reproduce the measured v2 difference [25–28]. So far, none of the theory calculations describes the observed ordering of the particles. Therefore, more accurate calculations from theory are needed to distinguish between the different possibilities. Other possible reasons for the observation that the π− v2(pT) is larger than the π+ v2(pT) is the Coulomb repulsion of π+ by the midrapidity net protons (only at low pT) and the chiral magnetic effect in finite baryon-density matter [29]. Simulations have to be carried out to quantify if those effects can explain our observations.

In Ref. [21], the study of the centrality dependence of Δv2 for protons and antiprotons is extended to investigate if different production rates for protons and antiprotons as a function of centrality could cause the observed differences. It was observed that the differences, Δv2, are significant at all centralities.

The v2(mT − m0) and possible NCQ scaling was also investigated for particles and antiparticles separately. Figure 3 shows v2 as a function of the reduced transverse mass, (mT − m0), for various particles and antiparticles at √sNN = 11.5 and 62.4 GeV. The baryons and mesons are clearly separated for √sNN = 62.4 GeV at (mT − m0) > 1 GeV/c2. While the effect is present for particles at √sNN = 11.5 GeV, no such separation is observed for the antiparticles at this energy in the measured (mT − m0) range up to 2 GeV/c2. The lower panels of Fig. 3 depict the difference of the baryon v2 relative to a fit to the meson v2 data with the pions excluded from the fit. The antiparticles at √sNN = 11.5 GeV show a smaller difference compared to the particles. At √sNN = 11.5 GeV the difference becomes negative for the antiparticles at (mT − m0) < 1 GeV/c2 but the overall trend is still similar to the one of the particles and to √sNN = 62.4 GeV.
In Fig. 4, the $v_2(m_T - m_0)$ values scaled on both axes with the number of constituent quarks are presented for $\sqrt{s_{NN}} = 11.5$ and 62.4 GeV. A simultaneous fit [30] to $p$, $\bar{p}$, $\Lambda$, and $\bar{\Lambda}$ at a given energy is shown as the dashed line. The differences between data and corresponding fits are shown in the lower panels. The general scaling holds, except for the $\phi$ mesons, for the various particles, as shown in Figs. 4(a) and 4(b) with deviations of $\sim 10\%$ at a $(m_T - m_0)/n_q$ value of 0.7 GeV/$c^2$. A significant change in the scaling behavior can be observed between baryon and antibaryon $v_2$ from $\sqrt{s_{NN}} = 62.4$ to 11.5 GeV, as shown in Figs. 4(c) and 4(d). The $\phi$ mesons are also an exception to the trend of other hadrons. At the highest $(m_T - m_0)/n_q$ values, the $\phi$ meson data point for $\sqrt{s_{NN}} = 11.5$ GeV ($p_T = 1.9$ GeV/$c$) is $2.3\sigma$ lower than those of the other hadrons. This is comparable to the observed deviation at $\sqrt{s_{NN}} = 7.7$ GeV ($p_T = 1.7$ GeV/$c$) by $1.8\sigma$ [21]. The smaller $v_2$ values of the $\phi(\bar{s}\bar{s})$ meson, which has a smaller hadronic interaction cross section [31], may indicate that hadronic interactions become more important than partonic effects for the systems formed at collision energies $\leq 11.5$ GeV [32,33].

In summary, the first observation of a beam-energy-dependent difference in $v_2(p_T)$ between particles and corresponding antiparticles for minimum bias $\sqrt{s_{NN}} = 7.7$–62.4 GeV Au + Au collisions at midrapidity is reported. The difference increases with decreasing beam energy. Baryons show a larger difference compared to mesons. The relative values of $v_2$ for charged pions have the opposite trend to the values of charged kaons. It is concluded that, at the lower energies, particles and antiparticles are no longer consistent with the single NCQ scaling that was observed for $\sqrt{s_{NN}} = 200$ GeV. However, for the group of particles the NCQ scaling holds within $\pm 10\%$ while for the group of antiparticles the difference between baryon and meson $v_2$ continues to decrease to lower energies. We further observed that the $\phi$ meson $v_2$ at the highest measured $m_T - m_0$ value is low compared to other hadrons at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV with $1.8\sigma$ and $2.3\sigma$, respectively.

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the offices of NP and HEP within the U.S. DOE Office of Science, the U.S. NSF, the Sloan Foundation, CNRS/IN2P3, FAPESP CNPq of Brazil, Ministry of Ed. and Sci. of the Russian Federation, NNSFC, CAS, MoST, and MoE of China, GA and MSMT of the Czech Republic, FOM and NWO of the Netherlands, DAE, DST, and CSIR of India, Polish Ministry of Sci. and Higher Ed., Korea Research Foundation, Ministry of Sci., Ed. and Sports of the Rep. of Croatia, and RosAtom of Russia, and VEGA of Slovakia.