Measurement of azimuthal anisotropy of hadrons in Au+Au collisions from the beam energy scan program by the PHENIX experiment at RHIC.

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Abstract.
The elliptic flow as given by the second term of the Fourier series for the azimuthal distribution of particles with respect to the event plane is believed to carry information on the initial geometrical anisotropy. The large azimuthal anisotropy of the particle emission was observed in heavy ion collisions at RHIC in 2001. In Au+Au $\sqrt{s_{NN}} = 200$ GeV collisions, the elliptic flow of identified charged hadrons was found to scale with the number of constituent quarks, which may be an indication of the flow of constituent quarks in the QGP phase. An event plane detector, RxPN, was installed in the PHENIX experiment in 2007, in order to improve the resolution of the event plane determination. The RxPN detector was also used to make accurate measurements of the elliptic flow at lower collision energies, where the transition of the QGP might be explored. The latest elliptic flow measurement for identified hadrons in Au+Au collisions from the beam energy scan program at the PHENIX will be presented and discussed.

1. Introduction
Quarks and gluons are expected to be deconfined in a high temperature or high density. This is called Quark Gluon Plasma (QGP)[1, 2]. The QGP may have existed in the early universe according to the big bang theory or in the core of the neutron star[3, 4]. Experimentally, it is formed with a relativistic heavy ion collider. The system geometry is elliptical at the first stage of a non-central heavy ion collision which generates the asymmetry in the yield of particles as a function of azimuthal angle with respect to the event plane of an event. The magnitude of the azimuthal anisotropy of particle emission is measured as the second term of Fourier series ($v_2$),

$$\frac{dN}{d(\phi - \Psi)} \propto 1 + 2v_2 \cos 2 (\phi - \Psi),$$

where $\phi$ is the particle emission angle and $\Psi$ is the event plane angle of the heavy ion collision which is the direction of the short axis of the oval region of the participants. The $v_2$ gives information about the initial state and its expansion, possibly through the QGP phase. The measured $v_2$ increases with $p_T$ at the low momentum range ($p_T < 3$ GeV/c). The rise of $v_2$ shifts towards higher $p_T$ for heavier particles. A hydrodynamic model with a low viscosity reproduces the collective behavior for the particles [5]. The $v_2$ reaches a constant value at $p_T = 2 - 3$ GeV/c where the value scales with the constituent quark number and independent...
of the particle mass [6]. It indicates that the flow of hadrons is built up by the flow of quarks in QGP according to the quark coalescence model [7, 8]. The study of the \( v_2 \) of rare particles, with high resolution event plane measurement provides further information about the quark number dependence and quark flow. \( \phi \)-meson is important because it is not only a heavy mass meson (the mass is similar to \( p \) even through it consists of two quarks), but also the hadronic re-scattering cross-section is different from that of baryons [9]. \( \Lambda \) \( v_2 \) should be similar to \( p \) \( v_2 \) because they are baryons and have similar mass. Deuteron \( v_2 \) should be larger than baryon \( v_2 \) if the quark coalescence model holds at the high \( p_T \) range. The \( v_2 \) may show a threshold behavior as a function of colliding energies if the quark number scaling of hadron \( v_2 \) is an indicator of a QGP phase. The resolution of \( v_2 \) measurement for the low energy collisions is reduced because the multiplicity is smaller than that of \( \sqrt{s_{NN}} = 200 \) GeV collision.

2. \( v_2 \) measurement and reaction plane resolution

When measuring the azimuthal anisotropy, particles must not be shared between reaction plane and \( v_2 \) measurement. Auto correlation effects will manifest themselves in this case, which create a large bias on \( v_2 \) measurement. Therefore, detectors which measure the event plane and \( v_2 \) should be separated in acceptance (the identified hadron \( v_2 \) is measured at a central rapidity range and the reaction plane is measured at forward rapidity range in PHENIX). Measurements of the \( v_2 \) of rare particles are limited by statistics of the identified particles and the reaction plane resolution. The reaction plane resolution is estimated with a distribution of \( \Delta \Phi \) which is the difference between the measured event plane \( \Phi \) and the reaction plane \( \Psi \) of each event \( (\Delta \Phi = \Phi - \Psi) \). The observed \( v_2 \) is reduced by the intrinsic event plane resolution of a detector. The relation between the observed \( v_2^{\text{observe}} \) and the corrected \( v_2^{\text{real}} \) is as follows,

\[
v_2^{\text{observe}} = v_2^{\text{real}} \times \langle \cos(2\Delta \Phi) \rangle,
\]

The observed \( v_2 \) is corrected for the correction factor \( \langle \cos 2\Delta \Phi \rangle \). This correction factor is called the reaction plane resolution. The value will be 1 if the detector has perfect event plane resolution. The statistical value of the measurement is reduced by a factor of \( \left( \frac{1}{\cos 2\Delta \Phi} \right)^2 \) due to the reaction plane resolution.

In 2007, a new reaction plane detector RxPN was installed and \( v_2 \) was measured with two times better resolution compared to the ones measured before in \( \sqrt{s_{NN}} = 200 \) GeV Au+Au collisions at RHIC-PHENIX [10, 11]. It allows us to study \( v_2 \) of the rare particles or at low collision energy. In 2010, the identified hadron \( v_2 \) was measured in \( \sqrt{s_{NN}} = 39 \) and 62 GeV Au+Au collisions at RHIC-PHENIX. The higher event plane resolution obtained from RxNP detector compensates for the lower statistics in lower energy collisions.

3. Results

The \( v_2 \) of \( \pi, K, (\text{anti-})p, (\text{anti-})d, (\text{anti-})\Lambda \) and \( \phi \) are measured in \( \sqrt{s_{NN}} = 200 \) GeV Au+Au collisions and shown in figure 1. The \( v_2 \) increases with \( p_T \) in the low momentum range \( (p_T < 2 \) GeV/c). Heavier particles have smaller values of \( v_2 \) than lighter particles in this \( p_T \) range. \( K \)-meson has smaller \( v_2 \) than \( \pi \)-meson and \( \phi \)-meson has smaller \( v_2 \) than \( K \)-meson at \( p_T < 2 \) GeV/c. Alternately, one can say that the \( v_2 \) is shifted towards higher \( p_T \) for heavier particles. It is an indication of collective flow of the particles. \( v_2 \) of \( \pi, K \) and \( \phi \) (mesons) or \( p \) and \( \Lambda \) (baryons) are consistent separately with \( KE_T = m_T - m_0 \) (see panel (b) of Fig.1). The \( v_2 \) of the particles depends on the number of constituent quarks. It was found that the \( v_2 \) of mesons and baryons saturate at \( p_T > 2 \) GeV/c. The saturated values for baryons are higher than those of mesons. The \( d \) \( v_2 \) is higher than that of baryons at \( p_T > 3 \) GeV/c. The \( v_2 \) of the particles divided by the number of constituent quarks were plotted as a function of \( KE_T/n_q \) (see panel (c) of Fig.1). These particles are almost consistent with each other at \( KE_T/n_q < 0.7 \) GeV. This
Figure 1. $v_2$ of identified particles ($\pi$, $K$, (anti-)p, (anti-)\Lambda, \phi$ and (anti-)d) in Au+Au $\sqrt{s_{NN}} = 200$ GeV. (a) shows $v_2$ as a function of transverse momentum $p_T$. (b) shows $v_2$ as a function of $KE_T$. (c) shows the $v_2$ with the number of constituent quarks and $KE_T$ scaling. $v_2$ dependence on the number of constituent quarks of the particle suggests the collective flow of quarks and the quark coalescence of u, d and s quarks. The $v_2$ scaling of the quark number and $KE_T$ is broken at $KE_T/n_q > 0.7$ GeV. $v_2$ of $\pi$ and $p$ are approaching each other at the high $p_T$ range (6 GeV/c). There could be another process generates $v_2$, such as jet production from hard processes and jet quenching from energy loss. In this case, the $v_2$ of the high $p_T$ particle is expected to be given by the path length dependence of the jet quenching coming from the partonic energy loss.

Figure 2 shows the $v_2$ with the $KE_T$ and the quark number scaling for $\pi$, $K$ and (anti-)$p$ in Au+Au lower energy collisions. The $p$ includes not only direct $p$ but also $p$ from $p$-$\pi$ decay of $\Lambda$. It is expected that $v_2$ of $p$ from $\Lambda$ decay is similar to $v_2$ of $\Lambda$ because $p$ is considerably heavier than $\pi$. $\Lambda v_2$ as a function of $p_T$ is consistent with that of $p$ in Au+Au $\sqrt{s_{NN}} = 200$ GeV (see panel (a) of Fig.1). The $v_2$ of $p$ from $\Lambda$ decay may be slightly smaller than the $v_2$ of the direct $p$. Therefore, the direct $p$ $v_2$ may be slightly larger than the measured $p$ $v_2$. It is expected that the number of constituent quark dependence of hadron $v_2$ disappears and the scaled $v_2$ with the quark number of baryon will be smaller than that of meson without the QGP phase. The scaled $v_2$ of $p$ is not found to be smaller than that of $\pi$ and $K$ in Au+Au $\sqrt{s_{NN}} = 39$ GeV which
Figure 2. $v_2$ with the number of constituent quarks scaling of $\pi$, $K$ and (anti-)p in low energy Au+Au collisions. Left picture shows those for Au+Au $\sqrt{s_{NN}} = 39$ GeV. Right picture shows those for Au+Au $\sqrt{s_{NN}} = 62$ GeV.[12]

indicates that QGP is generated already at this energy.

Figure 3. The difference $v_2$ of $\pi$, $K$ and (anti-)p between positive charged hadron and negative charged hadron as a function of the collision energy at $p_T = 0 - 3.0$ GeV/c.

Figure 3 shows the difference of $v_2$ of $\pi$, $K$ and (anti-)p for positive charge and negative charge as a function of the collision energy at $p_T = 0 - 3.0$ GeV/c. The particle (especially p) $v_2$ differs from the anti-particle $v_2$ which could be given by annihilation within the high baryon density caused by the baryon stopping of the low beam energy.

4. Summary
The elliptic flow $v_2$ was measured for the identified hadrons, $\pi$, $K$, (anti-)p, (anti-)d, (anti-)Λ and $\phi$ in Au+Au $\sqrt{s_{NN}} = 200$ GeV and $\pi$, $K$, (anti-)p in Au+Au $\sqrt{s_{NN}} = 39$ and 62 GeV
with the help of the enhanced resolution obtained from the new reaction plane detector at RHIC-PHENIX. The measured $v_2$ of the particles are consistent with quark number scaling at $KE_T/n_q < 0.7$ GeV in Au+Au $\sqrt{s_{NN}} = 200$ GeV. This behavior is explained well by the quark coalescence mechanism for hadron production. The $v_2$ of $\pi$, $K$, (anti-)p are almost consistent with the quark number scaling at Au+Au $\sqrt{s_{NN}} = 39$ and 62 GeV. The measured $v_2$ indicates the QGP is already created at $\sqrt{s_{NN}} = 39$ GeV. Charged separated $v_2$ of $\pi$, $K$ and (anti-)p were measured at the three collision energies. The difference $v_2$ between positive charge and negative charge for the charged separated $v_2$ of $\pi$, $K$ and (anti-)p were shown as a function of the collision energy. The particle (especially p) $v_2$ deviates from the anti-particle $v_2$ in the lower energy collisions.

References
[1] Karsch F 2002 Lecture Notes in Physics 583 209
[2] Karsch F, Laermann E and Peikert A 2000 Phys. Lett. B 478 447
[3] Shuryak E V 1980 Phys. Rep. 61 71
[4] Collins J C and Perry M J 1975 Phys. Rev. Lett. 34 1353
[5] Houvinen P, Kolb P E, Heinz U W, Ruuskanen P V and Voloshin S A 2001 Phys. Lett. B 503 58
[6] Adler S S et al. 2003 Phys. Rev. Lett. 91 182301
[7] Fries R J, Muller B, Nonaka C and Bass S A 2003 Phys. Rev. Lett. 90 202303
[8] Fries R J, Muller B, Nonaka C and Bass S A 2003 Phys. Rev. C 68 044902
[9] Shor A 1985 Phys. Rev. Lett. 54 1122
[10] Richardson E et al. 2010 Nucl. Instr. And Mass. A 636 99
[11] Adare A et al. 2012 Phys. Rev. C 85 064914
[12] Huang S 2011 27th Winter Workshop on Nuclear Dynamics (Winter Park)