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),

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

where ϕ is the particle emission angle and Ψ 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. *ϕ-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]. Λ 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 Φ and the reaction plane Ψ 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 $v_2^{observe}$ and the corrected v_2^{real} is as follows,

$$v_2^{observe} = v_2^{real} \times \langle \cos(2\Delta\Phi) \rangle, \tag{2}$$

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 $(\frac{1}{\cos 2\Delta\Phi})^2$ 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 π, K, *(anti-)p*, *(anti-)d*, *(anti-)*Λ and ϕ 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 *π-meson* and *ϕ-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 π, K and ϕ (mesons) or p and Λ (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

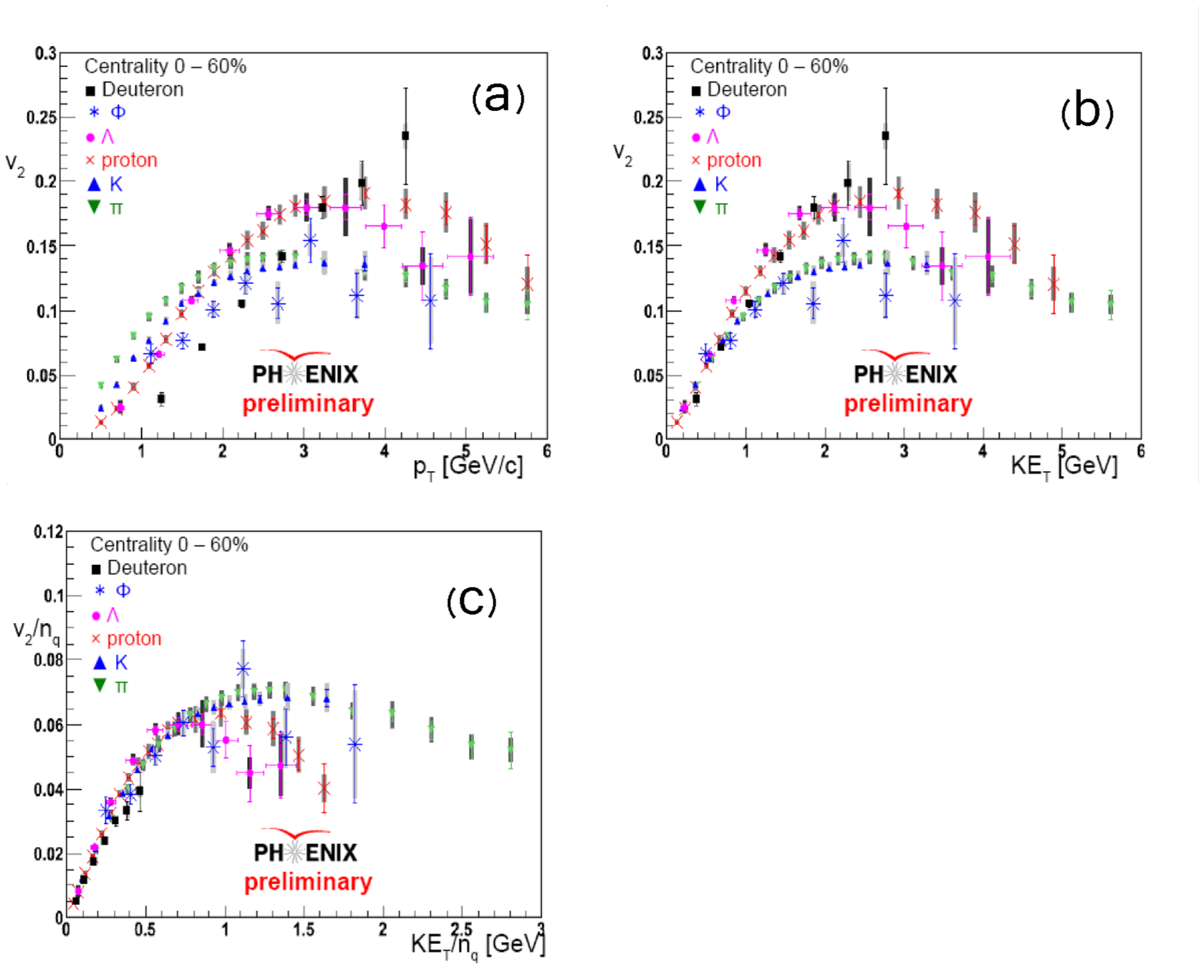

Figure 1. v_2 of identified particles (π, K, *(anti-)p*, *(anti-)*Λ, ϕ and *(anti-)d)* in Au+Au $\sqrt{s_{NN}}$ = 200 GeV. (a) shows v_2 as a function of transverse momentum p_T. (b) shows v_2 as a function of KE_T. (c) shows the v_2 with the number of constituent quarks and KE_T scaling.

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 π 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 π, K and *(anti-)p* in Au+Au lower energy collisions. The p includes not only direct p but also p from p-π decay of Λ. It is expected that v_2 of p from Λ decay is similar to v_2 of Λ because p is considerably heavier than π. Λ 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 Λ 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 π and K in Au+Au $\sqrt{s_{NN}} = 39$ GeV which

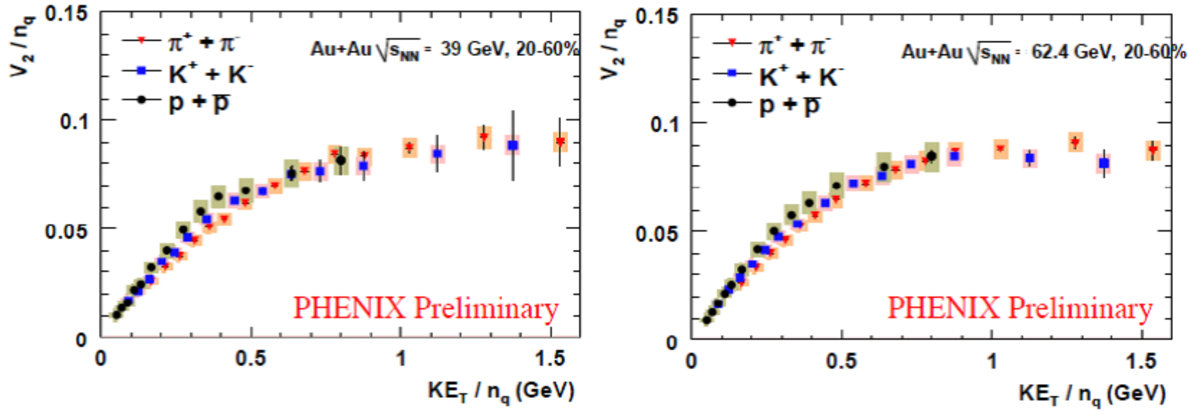

Figure 2. v_2 with the number of constituent quarks scaling of π, K and *(anti-)p* in low energy Au+Au collisions. Left picture shows those for Au+Au $\sqrt{s_{NN}} = 39$ GeV. Right picture shows those for Au+Au $\sqrt{s_{NN}} = 62$ GeV.[12]

indicates that QGP is generated already at this energy.

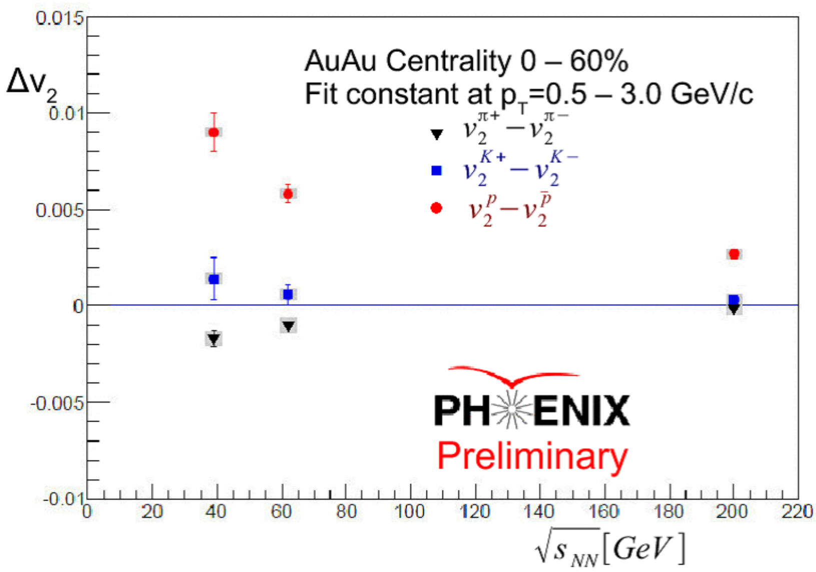

Figure 3. The difference v_2 of π, K and *(anti-)p* between positive charged hadron and negative charged hadron as a function of the collision energy at $p_T = 0 - 3.0$ GeV/c.

Figure 3 shows the difference of v_2 of π, 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, π, K, *(anti-)p*, *(anti-)d*, *(anti-)*Λ and ϕ in Au+Au $\sqrt{s_{NN}} = 200$ GeV and π, 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 π, 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 π, 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 π, 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.

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