

Review Article

An Experimental Review on Elliptic Flow of Strange and Multistrange Hadrons in Relativistic Heavy Ion Collisions

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Strange hadrons, especially multistrange hadrons, are good probes for the early partonic stage of heavy ion collisions due to their small hadronic cross sections. In this paper, I give a brief review on the elliptic flow measurements of strange and multistrange hadrons in relativistic heavy ion collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC).

1. Introduction

At the early stage of high energy relativistic heavy ion collisions, a hot and dense, strongly interacting medium named Quark Gluon Plasma (QGP) is created [1, 2]. The subsequent system evolution is determined by the nature of the medium. Experimentally, the dynamics of the system evolution has been studied by measuring the azimuthal anisotropy of the particle production relative to the reaction plane [3–5]. The centrality of the collision, defined by the transverse distance between the centers of the colliding nuclei called the impact parameter, results in an “almond-shaped” overlap region that is spatially azimuthal anisotropic. It is generally assumed that the initial spatial anisotropy in the system is converted into momentum-space anisotropy through rescatterings [6]. The elliptic flow, v_2 , which is the second Fourier coefficient of the azimuthal distribution of produced particles with respect to the reaction plane, is defined as $v_2 = \langle \cos 2(\varphi - \Psi) \rangle$, where φ is the azimuthal angle of produced particle and Ψ is the azimuthal angle of the reaction plane. The initial anisotropy in the coordinate space diminishes rapidly as the system expands. Thus, the driving force of v_2 quenches itself. Due to the self-quenching effect, the elliptic flow provides information about the dynamics at the early stage of the collisions [7–9]. Elliptic flow can provide information about the pressure gradients, the effective degrees of freedom, the degree of thermalization, and equation of state of the matter created at the

early stage [5]. However, early dynamic information might be obscured by later hadronic rescatterings [10, 11]. Strange hadrons, especially multistrange hadrons, and the ϕ meson are believed to be less sensitive to hadronic rescatterings in the late stage of collisions, as their freeze-out temperatures are close to the phase transition temperature and their hadronic interaction cross sections are expected to be small [12, 13]. In this paper, I am going to review the elliptic flow results of strange and multistrange hadron in relativistic heavy ion collisions from RHIC to LHC energies.

2. Discussions

2.1. Centrality and System Size Dependence. The values of v_2 are usually divided by the initial spatial anisotropy, eccentricity, to remove the geometric effect in order to study the centrality and system size dependence of v_2 . The participant eccentricity is the initial configuration space eccentricity of the participants which is defined by [14, 15]

$$\varepsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2) + 4(\sigma_{xy}^2)}}{\sigma_y^2 + \sigma_x^2}, \quad (1)$$

where $\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2$, $\sigma_y^2 = \langle y^2 \rangle - \langle y \rangle^2$, and $\sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle$, with x , y being the position of the participating

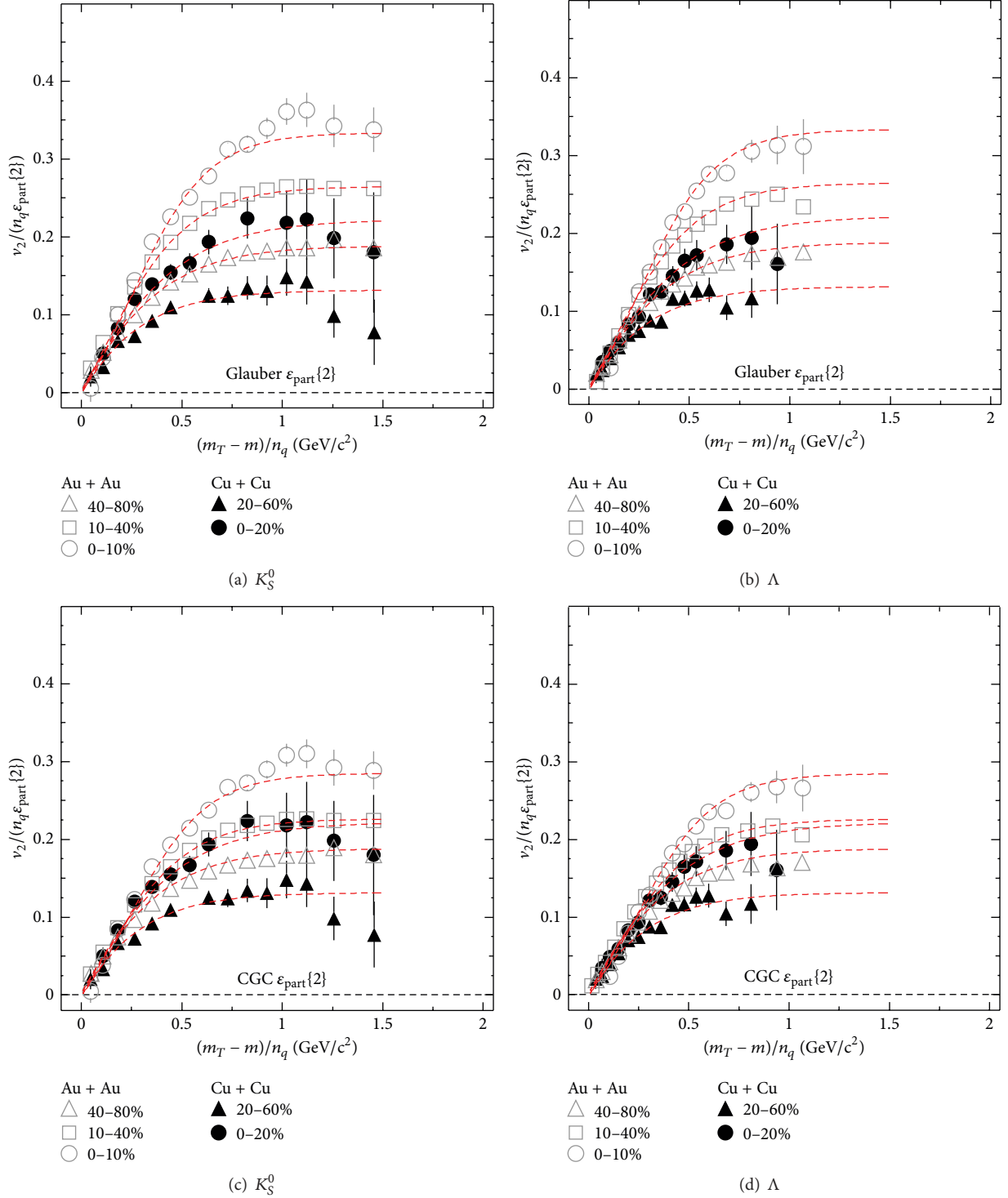


FIGURE 1: Centrality dependence of v_2 scaled by number of quarks and participant eccentricity ($v_2/(n_q \epsilon_{\text{part}}\{2\})$) for K_S^0 and Λ as a function of $(m_T - m)/n_q$ in 0-10%, 10-40%, and 40-80% Au + Au collisions and 0-20% and 20-60% Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV [14].

nucleons in the transverse plane. The root mean square of the participant eccentricity,

$$\epsilon_{\text{part}}\{2\} = \sqrt{\langle \epsilon_{\text{part}}^2 \rangle}, \quad (2)$$

is calculated from the Monte Carlo Glauber model [16] and Color Glass Condensate (CGC) model [17].

Figure 1 shows the centrality and system size dependence of K_S^0 and Λ v_2 in $\sqrt{s_{NN}} = 200$ GeV heavy ion collisions [14]. The eccentricity scaled v_2 has been further normalized

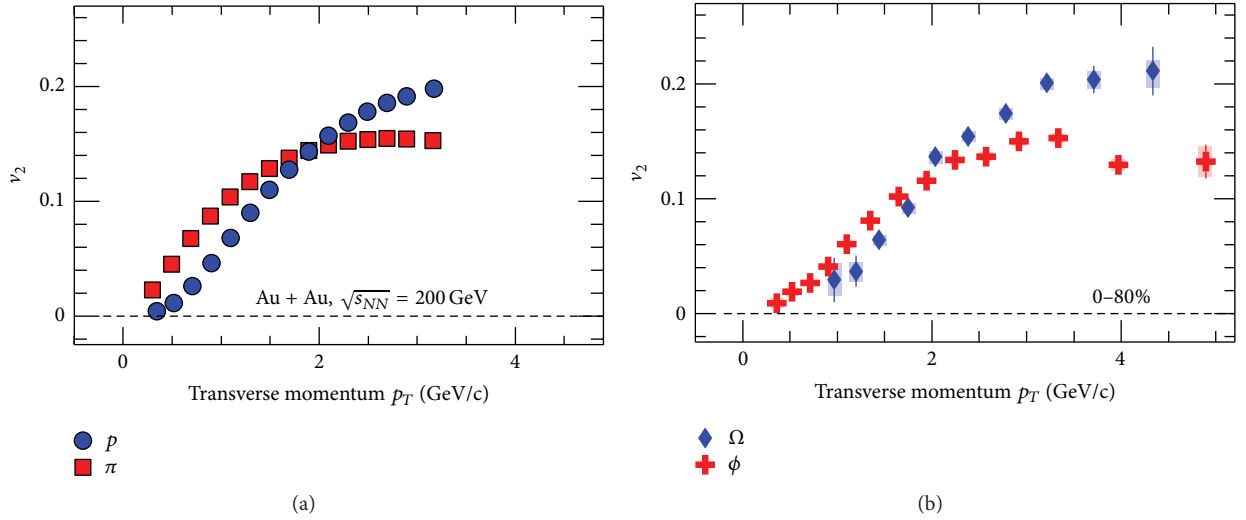


FIGURE 2: The v_2 as function of p_T for (a) π and proton and (b) ϕ , Ω in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for 0–80% centrality [19].

by number of constituent quarks (n_q) to make K_S^0 and Λ results follow the same curve. The results from 0–20% and 20–60% central Cu + Cu collisions and from 0–10%, 10–40%, and 40–80% central Au + Au collisions are presented. For a given collision system, stronger collectivity flow is apparent as higher scaled v_2 values in more central collisions. For both Au + Au and Cu + Cu collisions, larger collective flow is observed in larger system size which could be characterized by number of participants. Namely, the collisions with larger number of participants generate larger collective flow.

2.2. Multistrange Hadron and ϕ Meson v_2 . STAR experiment presented the first v_2 results of multistrange hadrons based on 2×10^6 events collected in the year of 2001–2002 [18]. Significant v_2 signals of Ξ baryons which are similar to results for Λ baryons are observed in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. At low p_T (< 2 GeV/c), the mass ordering is observed for Ξ v_2 which is in agreement with the hydrodynamic model calculations. Due to limited statistics, the v_2 of Ω baryons have large statistical uncertainties, and it is not clear whether Ω v_2 follows baryon or meson band at the intermediate p_T range (2–5 GeV/c). But nonzero value of v_2 was clearly observed at that time. These results suggest that collective motion has been developed at parton phase in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Later, in the RHIC runs of the year 2010–2011, about 730 million minimum bias events were recorded by STAR. Sufficient statistics of multistrange hadrons and ϕ mesons support the precise measurements on v_2 . The multistrange hadrons and the ϕ meson were reconstructed despite the following decay channels: $\phi \rightarrow K^+ + K^-$, $\Xi^- \rightarrow \Lambda + \pi^-$ ($\Xi^+ \rightarrow \bar{\Lambda} + \pi^+$), and $\Omega^- \rightarrow \Lambda + K^-$ ($\Omega^+ \rightarrow \bar{\Lambda} + K^+$). Figure 2 shows the v_2 as a function of p_T for (a) π and protons and (b) ϕ , Ω in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for 0–80% centrality [19]. A comparison between v_2 of π and protons, consisting of up (u) and down (d) light constituent quarks, is shown in panel (a). Correspondingly, panel (b) shows a

comparison of v_2 of ϕ and Ω containing s constituent quarks. This is the first time that high precision measurement of Ω baryon v_2 up to 4.5 GeV/c is available in experiments of heavy ion collisions. In the low p_T region ($p_T < 2.0$ GeV/c), the v_2 of ϕ and Ω follows mass ordering. At intermediate p_T ($2.0 < p_T < 5.0$ GeV/c), a baryon-meson separation is observed. The v_2 results of ϕ mesons are consistent in two independent measurements at RHIC, PHENIX [20], and STAR. It is evident that the $v_2(p_T)$ of hadrons consisting only of strange constituent quarks (ϕ and Ω) is similar to that of light hadrons, π and protons. However the ϕ and Ω do not participate strongly in the hadronic interactions, because of the smaller hadronic cross sections compared to π and protons. It suggests the major part of the collectivity is developed during the partonic phase in high energy heavy ion collisions. ALICE experiment recently published multistrange hadron and ϕ meson v_2 measurements in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [21]. Also significant v_2 values for these particles are observed. Experimental measurements at RHIC and LHC indicate partonic collectivity has been built up in high energy heavy ion collisions.

2.3. Comparison of ϕ Meson and Proton v_2 . The ϕ meson and proton show different sensitivity on the hadronic rescatterings. As discussed previously, the ϕ meson is less sensitive to the late hadron-hadron interactions than light hadrons due to the smaller hadronic cross section. It means light hadrons (e.g., protons) would gain larger additional radial flow which modifies the $v_2(p_T)$ shape during final hadronic rescatterings. Hydrodynamical model calculations predict that v_2 as a function of p_T for different particle species follows mass ordering, where the v_2 of heavier hadrons is lower than that of lighter hadrons [22]. The identified hadron v_2 measured in experiment indeed proves the mass ordering in the low p_T region ($p_T < 2.0$ GeV/c). Hirano et al. predict that the mass ordering of v_2 could be broken between ϕ mesons and protons at low p_T ($p_T < 1.5$ GeV/c) based on a

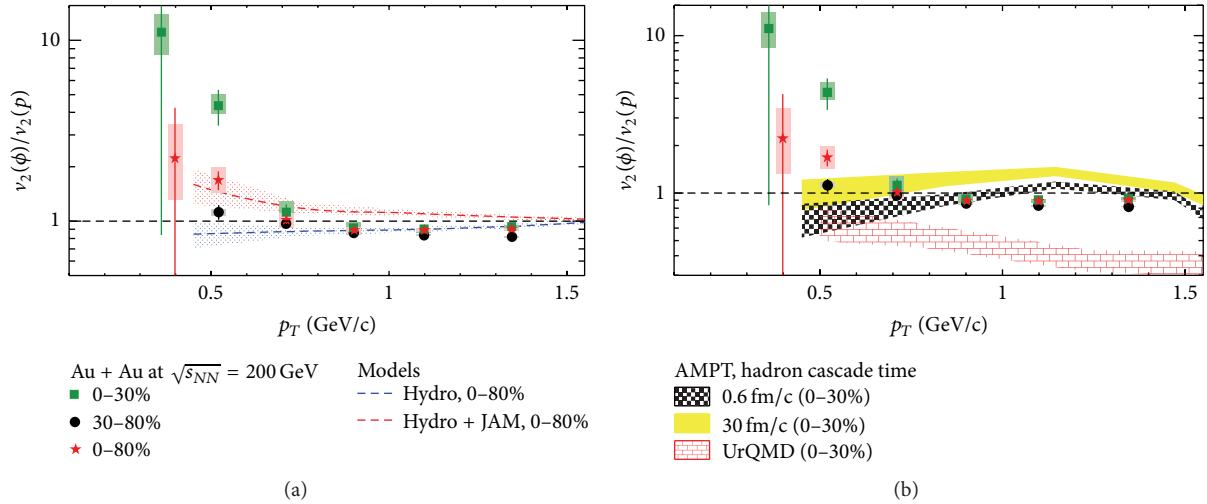


FIGURE 3: The ratio of $v_2(\phi)$ to $v_2(p)$ as function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for two centralities, 0–30% and 30–80%. The bands in panels (a) and (b) represent the hydro and transport model calculations for $v_2(\phi)/v_2(p)$, respectively [19].

model with ideal hydrodynamics plus hadron cascade process [10, 11]. Here ϕ mesons and protons are chosen for the study, as their rest masses are quite close to each other. As the model calculations assign a smaller hadronic cross section for ϕ mesons compared to protons, the broken mass ordering is regarded as the different hadronic rescattering contributions on the ϕ meson and proton v_2 .

Figure 3 shows the ratios of ϕv_2 to proton v_2 from model calculations and experimental data [19]. This ratio is larger than unity at $p_T \sim 0.5$ GeV/c for 0–30% centrality. It indicates breakdown of the expected mass ordering in that momentum range. This could be due to a large effect of hadronic rescatterings on the proton v_2 . The data of 0–80% centrality around 0.5 GeV/c quantitatively agrees with hydro + hadron cascade calculations indicated by the shaded red band in panel (a) of Figure 3, even though there is a deviation in higher p_T bins. A centrality dependence of $v_2(\phi)$ to $v_2(p)$ ratio is observed in the experimental data. Namely, the breakdown of mass ordering of v_2 is more pronounced in 0–30% central collisions than in 30–80% peripheral collisions. In the central events, both hadronic and partonic interactions are stronger than in peripheral events. Therefore, the larger effect of late stage hadronic interactions relative to the partonic collectivity produces a greater breakdown of mass ordering in the 0–30% centrality data than in the 30–80%. This observation indirectly supports the idea that the ϕ meson has a smaller hadronic interaction cross section. The ratio of ϕv_2 to proton v_2 was also studied by using the transport models AMPT [23] and UrQMD [24]. Panel (b) of Figure 3 shows the $v_2(\phi)$ to $v_2(p)$ ratio for 0–30% centrality from AMPT and UrQMD models. The black shaded band is from AMPT with a hadronic cascade time of 0.6 fm/c while the yellow band is for a hadronic cascade time of 30 fm/c. Larger hadronic cascade time is equivalent to stronger hadronic interactions. It is clear that the $v_2(\phi)/v_2(p)$ ratio increases with increasing hadronic cascade time. This is attributed to a decrease in the proton v_2 due to an increase in hadronic rescattering

while the ϕ meson v_2 is less affected. The ratios from the UrQMD model are much smaller than unity (shown as a brown shaded band in panel (b) of Figure 3). The UrQMD model lacks partonic collectivity; thus the ϕ meson v_2 is not fully developed. None of these models could describe the detailed shape of the p_T dependence. In $\sqrt{s_{NN}} = 2.76$ TeV Pb + Pb collisions at LHC, there is an indication that the ϕ meson v_2 is larger than the proton v_2 for the lowest p_T bin [21, 25]. Unfortunately, currently the uncertainties on the ALICE ϕ meson v_2 measurements are too large to conclude.

2.4. Number-of-Constituent-Quark Scaling. The number-of-constituent-quark (NCQ) scaling in v_2 in the intermediate p_T range ($2 < p_T < 5$ GeV/c) could be well reproduced by the quark coalescence [26] or recombination [27] mechanisms in particle production. The NCQ scaling indicates that the collectivity in the parton level has been achieved in high energy heavy ion collisions at RHIC. Figure 4 shows number of constituent quarks (n_q) scaled v_2 as a function of transverse momentum scaled by n_q (p_T/n_q) and transverse mass minus rest mass scaled by n_q ($(m_T - m_0)/n_q$) for identified hadrons from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for two centralities, 0–30% and 30–80%. To investigate the possible system size dependence deviation from NCQ scaling, $K_S^0 v_2$ was fitted with a third-order polynomial function. Then the ratio to the K_S^0 fit was calculated. Figures 4(e)–4(h) show the results. Excluding pions, the scaling holds approximately within 10% for both 0–30% and 30–80% centralities. The pion is excluded as it is strongly affected by resonance decay process and nonflow correlations [28, 29]. Figure 5 shows NCQ scaling at LHC energy. The maximum deviation from NCQ scaling is $\sim 20\%$ at $\sqrt{s_{NN}} = 2.76$ TeV as observed by ALICE experiment [21]. Therefore, at top RHIC energy, NCQ scaling holds better than LHC energy.

Recently, CMS collaboration presented the v_2 results of strange hadrons (K_S^0 and Λ) in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV with event sample of large multiplicity [30, 31]. Nice

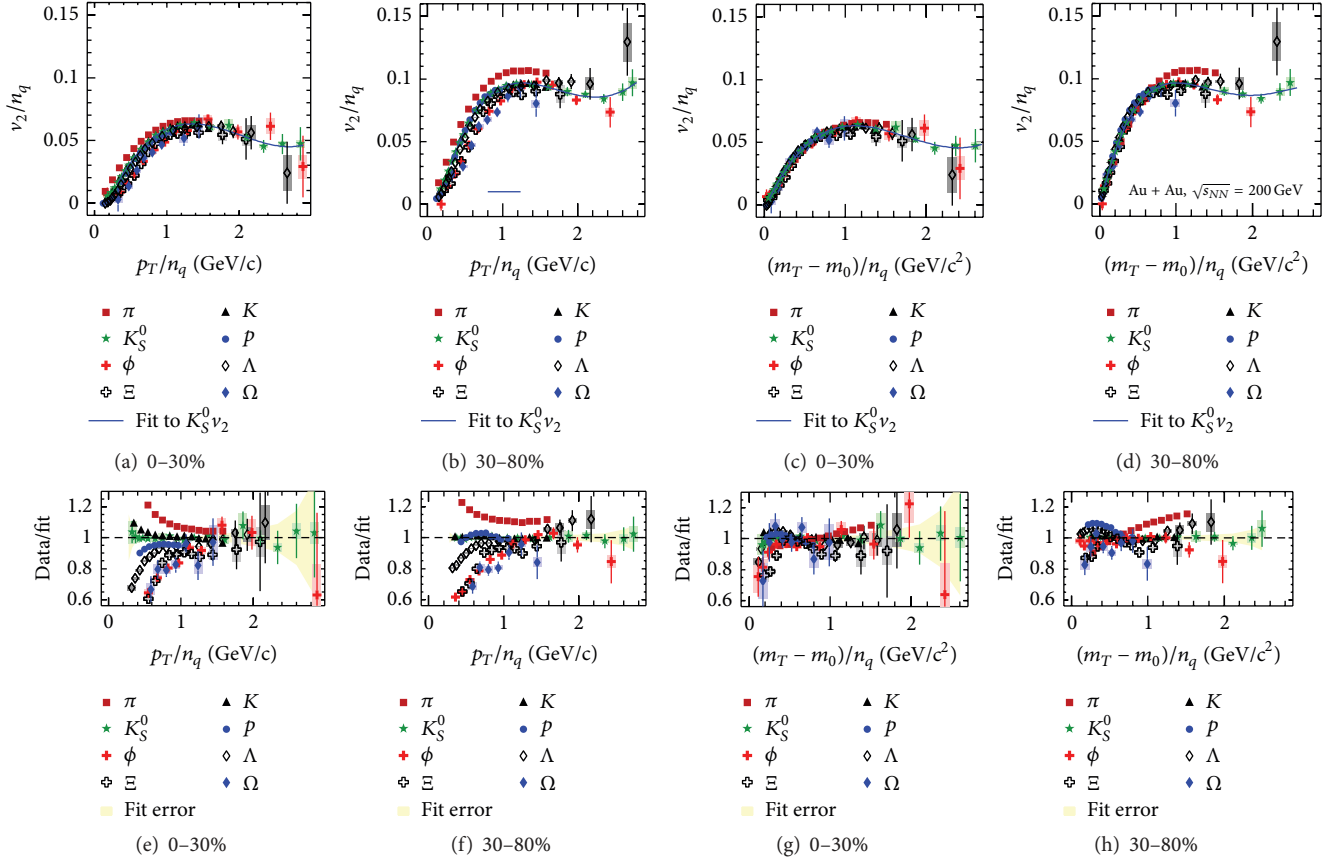


FIGURE 4: v_2 scaled by number of constituent quarks (n_q) as a function of p_T/n_q and $(m_T - m_0)/n_q$ for identified hadrons from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for two centralities, 0–30% and 30–80%. Ratios with respect to a polynomial fit to $K_S^0 v_2$ are shown in the corresponding panels (e–h) [19].

NCQ scaling (less than 10% violation) is observed. It indicates that the partonic level collectivity has been built up even in small $p + \text{Pb}$ colliding system. It would be interesting to compare the NCQ scaling using event samples with large and small multiplicity in the future.

2.5. Beam Energy Dependence. STAR experiment has covered the beam energies of $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4,$ and 200 GeV. During 2010–2014, a Beam Energy Scan program (phase I) was carried out at RHIC. The main motivation is to explore the nuclear matter phase structure in the higher net-baryon region.

The most striking feature on the v_2 measurements is the observation of an energy dependent difference in v_2 between particles and their corresponding antiparticles [32, 33]. Figure 6 shows the difference in v_2 between particles and their corresponding antiparticles as a function of beam energy. The difference between baryon and antibaryon is much more pronounced than difference between mesons. Proton versus antiproton and Λ versus $\bar{\Lambda}$ show the same magnitude of difference. This difference naturally breaks the number-of-constituent-quark scaling (NCQ) in v_2 which is regarded as an evidence of partonic collectivity in the top energy heavy ion collisions at RHIC. It indicates that the

hadronic degrees of freedom play a more important role at lower collision energies. The data have also been compared to hydrodynamics + transport (UrQMD) hybrid model [34] and Nambu-Jona-Lasinio (NJL) model [35] which considers both partonic and hadronic potential. The hybrid model could reproduce the baryon (proton) data but fails to explain the mesons, whereas the NJL model could qualitatively reproduce the hadron splitting. However, even if one tunes the R_v parameter which is related to the partonic potential, NJL model fails to reproduce the magnitude for all hadron species simultaneously. Analytical hydrodynamic solution can reproduce the data within uncertainties [36]. It predicts $\Delta v_2^p > \Delta v_2^\Lambda > \Delta v_2^\Xi > \Delta v_2^\Omega$ for baryons. Future high precise data will clarify the validity of this description.

2.6. Comparison with Hydrodynamic Calculations. The p_T differential v_2 could be modified by an increase on both collective and radial flow with increasing of colliding energy. It is qualitatively described by hydrodynamic calculations [37]. The recent comparison between ALICE measurements and model calculations shows a nice agreement in 40–50% central collisions including strange baryon Λ and multi-strange baryon Ξ . However, for more central collisions (e.g.,

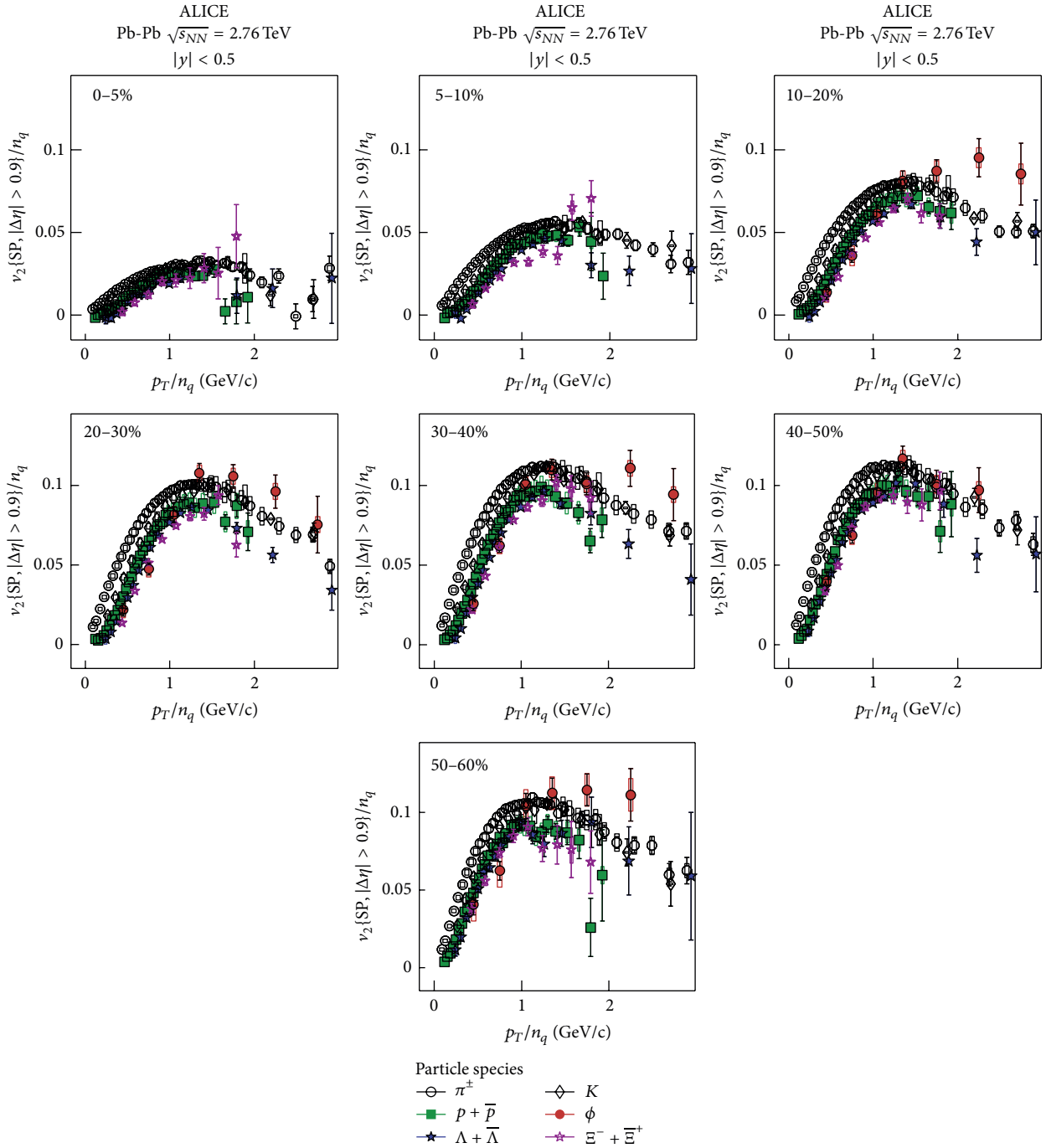


FIGURE 5: v_2 scaled by number of constituent quarks (n_q) as a function of p_T/n_q for identified hadrons from Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for various centrality intervals [21].

10–20%) a clear discrepancy is observed for protons, Λ , and Ξ [21].

Later, it was realized that the hadronic rescatterings are important to be included in the hydrodynamic calculations for a fair comparison between data and models [38]. In Figure 7, viscous hydrodynamical calculations with (VISHNU) and without (VISH2+1) a hadronic cascade afterburner are compared. The increase in mass splitting between identified particles for VISHNU (solid curves) compared to VISH2+1

(dashed curves) illustrates the larger radial flow in the VISHNU calculations due to the contribution of the hadronic cascade. The mass splitting between the pions and strange baryons (Λ)/multistrange baryons (Ξ) does not change much, as small hadronic rescattering cross sections are assigned to these particles. The mass ordering observed in pure viscous hydrodynamical calculations is not preserved anymore between protons and strange baryons (Λ)/multistrange baryons (Ξ) after including the hadronic interactions in

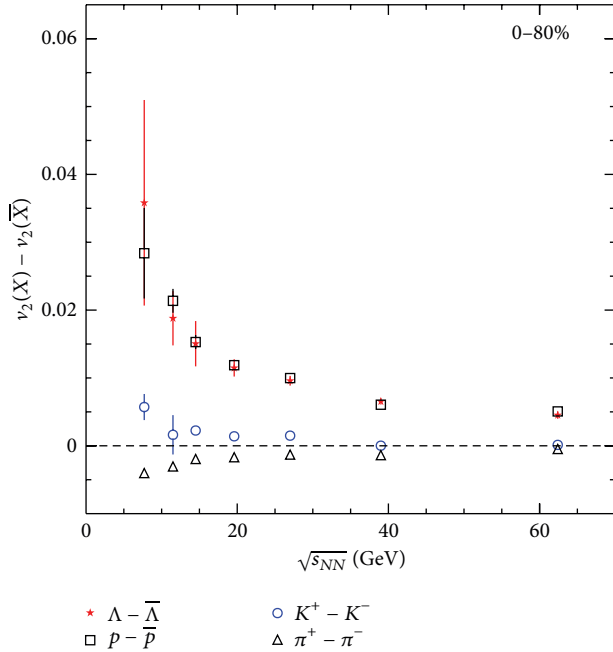


FIGURE 6: The difference in v_2 between particles (X) and their corresponding antiparticles (\bar{X}) as a function of beam energy for 0–80% central Au + Au collisions [32, 39].

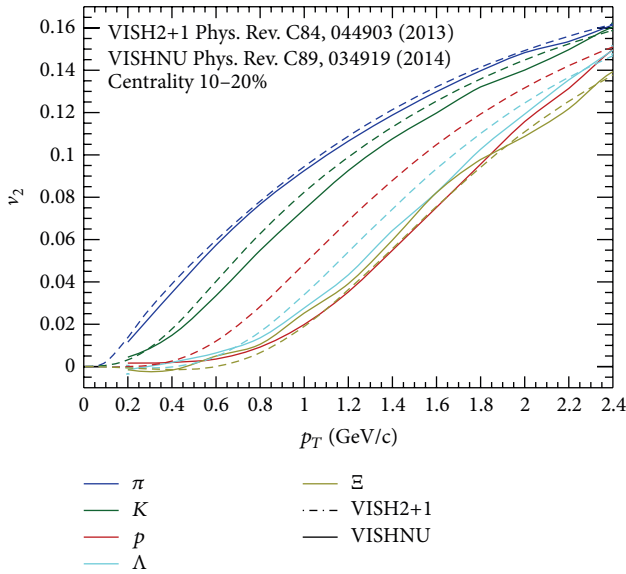


FIGURE 7: The viscous hydrodynamical calculations without a hadronic cascade afterburner (VISH2+1) and with a hadronic cascade afterburner (VISHNU) [25, 37, 38, 40].

VISHNU. Figure 8 shows the comparison between the p_T differential v_2 measured by ALICE and the VISHNU model. Even though VISHNU gives a very well description of kaons, clear discrepancy for protons, Λ and Ξ , is observed. The VISHNU calculations underpredict the v_2 of protons and overpredict the v_2 of Λ and Ξ . Obviously, the current theoretical framework of viscous hydrodynamics plus a hadron cascade afterburner does not describe the v_2 as a function of p_T

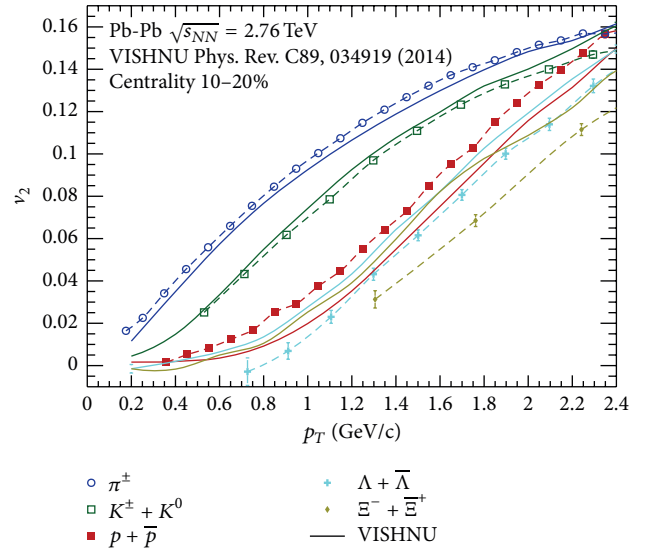


FIGURE 8: The comparison of ALICE measurements and VISHNU model calculations of v_2 as a function of p_T at $\sqrt{s_{NN}} = 2.76$ TeV for 10–20% central collisions [21, 25, 37, 38, 40].

for identified particles in more central collisions better. One of the possible reasons is that hadronic interaction process for some particle species might not be well understood.

3. Summary

In this paper, I review the elliptic flow results of strange and multistrange hadrons in relativistic heavy ion collision from RHIC to LHC energies. The centrality and system size dependence of v_2 could be described by number of participants in both Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. The precise measurements of multistrange hadron v_2 , especially for the Ω baryons, indicate that the collectivity has been built up in the early partonic stage of collisions. The comparison between the v_2 of ϕ mesons and protons shows a possible violation of hydrodynamics inspired mass ordering in 0–30% central collisions. It can be qualitatively explained by the different effects of late hadronic interactions on the ϕ meson and proton v_2 . The NCQ scaling of identified particles in top energy heavy ion collisions at RHIC is better than LHC energy suggesting that coalescence might be the dominant hadronization mechanism at RHIC in the intermediate transverse momentum region ($2 < p_T < 5$ GeV/c). Also, the NCQ scaling is observed in small colliding system, $p + \text{Pb}$, at $\sqrt{s_{NN}} = 5.02$ TeV. It indicates that the partonic level of collectivity has also been reached in high energy $p + \text{Pb}$ collisions. At lower beam energy ($< \sqrt{s_{NN}} = 39$ GeV), a difference is observed between v_2 values of particles and antiparticles. Currently there is no theoretical framework that can reproduce the data quantitatively. The recent comparison between viscous hydrodynamic calculations with a hadronic cascade afterburner and experimental data shows a discrepancy on the baryons which challenges the current knowledge on the hadronic interactions.

Competing Interests

There is no conflict of interests related to this paper.


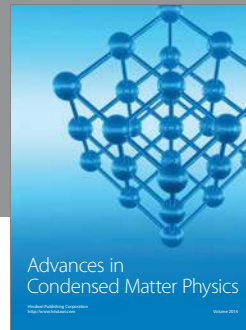
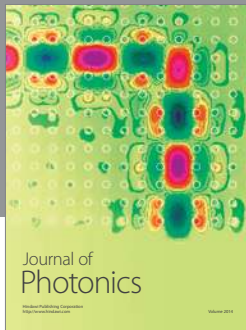
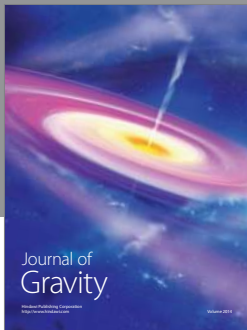
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