The elliptic flow of multi-strange hadrons in $\sqrt{s}_{NN} = 200$ GeV Au + Au collisions at STAR

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Abstract

The measurement of the elliptic flow, $v_2$, provides a powerful tool for studying the properties of hot and dense medium created in high-energy nuclear collisions. We present the measurement of $v_2$ of multi-strange hadrons ($\phi$, $\Xi$ and $\Omega$) in $\sqrt{s}_{NN} = 200$ GeV Au + Au collisions at STAR. In minimum-bias Au + Au collisions at $\sqrt{s}_{NN} = 200$ GeV, a significant amount of elliptic flow, almost identical to other mesons and baryons, is observed for multi-strange hadrons. Experimental observations of $p_T$ dependence of $v_2$ of identified particles at RHIC support partonic collectivity. We also discuss the possible breaking of mass ordering of the $\phi$ mesons in the low $p_T$ region.

Key words: elliptic flow, multi-strange hadrons, partonic collectivity
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In the non-central nucleus nucleus collisions, the overlapping region of the reaction zone is not spherical. There is a short axis which is parallel to the impact parameter and a long axis which is perpendicular to it. The initial geometrical anisotropy in the coordinated space will be translated to the final anisotropy in the momentum space by the interactions of constituents. This effect is characterized by the elliptic flow, $v_2$, which is the second order harmonic of the Fourier expansion of particle's azimuthal distribution with respect to the reaction plane, defined as

$$v_2 = \langle \cos 2(\phi - \Psi_R) \rangle$$

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where $\phi$ is azimuthal angle of an outgoing particle, $\Psi_R$ is the azimuthal angle of the impact parameter, and angular brackets denote an average over many particles and events. As the system expands it becomes more spherical, thus the driving force quenches itself. Therefore the elliptic flow is sensitive to the collision dynamics in the early stages. It has been proved that the elliptic flow is one of the most sensitive probes of the dynamics at the Relativistic Heavy Ion Collider (RHIC) [1–4], also see recent review in [5–7]. However, early dynamic information might be masked by later hadronic rescatterings. Multi-strange hadrons ($\phi$, $\Xi$ and $\Omega$) with their large mass and presumably small hadronic cross sections [8,9] should be less sensitive to hadronic rescattering in the later stage of the collisions and therefore a good probe of the early stage of the collision.

In this paper, we present $v_2$ measurements of multi-strange hadrons by the STAR experiment from $\sqrt{s_{NN}} = 200$ GeV Au + Au. Data were taken from the seventh RHIC run in 2007. About 63 million minimum bias events (0–80% most central) were analyzed. STAR’s Time Projection Chamber (TPC) [10] is used as the main detector for particle identification (PID) and event plane determination. The centrality was determined by the number of tracks from the pseudorapidity region $|\eta| \leq 0.5$. The PID is achieved via $dE/dx$ in TPC and topologically reconstructed hadrons: $K^0_S \rightarrow \pi^+ + \pi^-$, $\phi \rightarrow K^+ + K^-$, $\Lambda \rightarrow p + \pi^-$ ($\bar{\Lambda} \rightarrow \bar{p} + \pi^+$), $\Xi^- \rightarrow \Lambda + \pi^-$ ($\Xi^+ \rightarrow \bar{\Lambda} + \pi^+$) and $\Omega^- \rightarrow \Lambda + K^-$ ($\Omega^+ \rightarrow \bar{\Lambda} + K^+$). The detailed description of the procedure can be found in Refs. [11–13]. The event plane method [14,15] is used for the $v_2$ measurement.

![Fig. 1](image_url)

**Fig. 1.** The centrality dependence of $v_2$ as a function of $p_T$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for (a) $\phi$, (b) $\Xi$ and (c) $\Omega$. The error bars are shown only for the statistical uncertainties.

The centrality dependence of charged and strange hadron $v_2$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been well studied in Ref [3]. The large statistics from run 7 of RHIC make the study on the centrality dependence of $v_2$ for multi-strange hadrons possible. The results are shown in Fig. 1. Panel (a) and (b) show the $v_2$ as a function of $p_T$ in 0 – 10%, 10 – 40% and 40 – 80% most central events for $\phi$ and $\Xi$. Due to the limited statistics, the $v_2(p_T)$ of $\Omega$ are shown in two centrality bins, 0 – 20% and 20 – 80%, in panel (c). The estimated systematic error based on the background evaluation and track selection criteria is around 10%. The larger $v_2$ values could be observed in the more peripheral collisions. It is because the final anisotropy in the momentum space is...
converted by the initial anisotropy of the collision geometry. The larger eccentricity in the more peripheral collision drives the larger magnitude of $v_2$.

$$v_2 = \frac{q}{n^2} \frac{200 \text{ GeV}}{NN}$$

**Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV**

Fig. 2. The $v_2$ scaled by number of constituent quarks ($n_q$) as a function of (a) $p_T/n_q$ and (b) $(m_T - \text{mass})/n_q$ for identified particles in minimum bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. PHENIX data are from [16]. The error bars are shown only for the statistical uncertainties.

The Number of Quark (NQ) scaling on $v_2$ in the intermediate $p_T$ range ($2 \text{ GeV}/c < p_T < 1.5 \text{ GeV}/c$) could be reproduced by the quark coalescence [17] or recombination [18] mechanisms in particle production. Thus, the NQ scaling indicates the deconfinement has been achieved in the heavy ion collisions at RHIC. With the $v_2$ results from multi-strange hadrons, we could test whether the scaling works for them. Multi-strange hadrons are regarded as good probes to the early partonic stage of collision dynamics, because of their larger mass and smaller hadronic cross section compared to the light-quark (u, d) hadrons. Figure 2 shows the constituent-quark scaled $v_2$ as a function of $p_T/n_q$ and $(m_T - \text{mass})/n_q$ in panel (a) and (b), respectively. It is known the NQ scaling works for identified charged hadrons ($\pi$, K and p) and strange hadrons ($K^0_S$ and $\Lambda$) [4,12]. The important information is that multi-strange hadrons, especially $\phi$ and $\Omega$ which are pure s constituent quark contained hadrons, follow the NQ scaling up to $p_T/n_q \sim 1.5 \text{ GeV}/c$ or $(m_T - \text{mass})/n_q \sim 1 \text{ GeV}/c^2$. This indicates that the major part of the $v_2$ has been built up at the partonic stage. Hence, the partonic collectivity has been established at RHIC.

The mass ordering in data [3,4], which is qualitatively consistent with ideal hydrodynamics, works well for $\pi$, K, p, $K^0_S$, $\Lambda$ and $\Xi$. Namely, the hadron with heavier mass shows the smaller $v_2$ in a given $p_T$ bin. Recently, the calculations based on ideal hydrodynamical model together with the hadron cascade [19] suggest that the mass ordering of $v_2$ at low $p_T$ ($p_T < 1.5 \sim 2.0 \text{ GeV}/c$) could be broken for $\phi$ mesons due to the small hadronic cross section at late hadronic stage within their model. Figure 3 shows the comparison in $10 - 40\%$ centrality bins. The mass ordering could be observed for $\pi$, $K^0_S$ and p clearly. For clarity, in the lower panel, we show the ratio of $\phi$ meson $v_2$ to that of protons. Within errors, they are consistent in the low $p_T$ region ($p_T < 1 \text{ GeV}/c$). Data with higher precision are needed for the final conclusion.

In summary, we present the $v_2$ for multi-strange hadrons in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions at STAR. The centrality dependence of $v_2$ shows larger $v_2$ value in more peripheral collisions. This is because of the larger initial anisotropy in the coordinate
space. The NQ scaling works for multi-strange hadrons in the intermediate $p_T$ range, it indicates the partonic collectivity has been built up at RHIC. In order to the study the late hadronic effect on $v_2$, the comparison of $\phi$ meson $v_2$ to proton $v_2$ has been made in the low $p_T$ region. They are consistent within errors. In the future, the performance of Time-Of-Flight detector in the tenth RHIC run at STAR will help us on the further investigation.

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