Particle dependence of elliptic flow in Au + Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV

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Abstract. The elliptic flow parameter ($v_2$) for $K^0_S$ and $\Lambda + \bar{\Lambda}$ has been measured at mid-rapidity in Au + Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV by the STAR collaboration. The $v_2$ values for both $K^0_S$ and $\Lambda + \bar{\Lambda}$ saturate at moderate $p_T$, deviating from the hydrodynamic behavior observed in the lower $p_T$ region. The saturated $v_2$ values and the $p_T$ scales where the deviation begins are particle dependent. The particle-type dependence of $v_2$ shows features expected from the hadronization of a partonic ellipsoid by coalescence of co-moving quarks. These results will be discussed in relation to the nuclear modification factor ($R_{CP}$) which has also been measured for $K^0_S$ and $\Lambda + \bar{\Lambda}$ by the STAR collaboration.

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1. Introduction

The elliptic component of the event-wise azimuthal anisotropy of particle production (i.e. elliptic flow or $v_2$) is thought to probe the early stages of relativistic heavy ion collisions [2]. Measurements of $v_2$ for identified particles [3, 4] and charged hadrons [5, 6] at the Relativistic Heavy Ion Collider (RHIC) indicate a conversion of spatial anisotropy to momentum anisotropy near the hydrodynamical limit [2, 7, 8]. For $p_T$ greater than 2 GeV/c, however, the charged hadron $v_2$ deviates from hydrodynamical calculations and saturates at a large value approximately independent of $p_T$ up to 6 GeV/c [6]. The measurements of $v_2$ for $K^0_S$ and $\Lambda + \bar{\Lambda}$ also indicate a saturation at moderate $p_T$. Models using large parton energy loss [9, 10] and transport opacity [11] have been discussed in relation to the saturation and centrality dependence of charged hadron $v_2$ at large $p_T$. A saturated $v_2$ could also arise if the extent of the $p_T$ region where soft processes dominate the spectrum is particle dependent [12]. In this case the hyperon $v_2$ may continue to rise at intermediate $p_T$ (perhaps following hydrodynamic model calculations) while $v_2$ of the less massive meson decreases. It has also been suggested that if a partonic state

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exists prior to hadronization, the process of particle formation at moderately high $p_T$, by string fragmentation, parton fragmentation [13] or quark coalescence [14, 15, 16, 17], may lead to a dependence of $v_2$ and $R_{AA}$ on particle type. As such, it’s possible that these measurements will provide information on the existence and nature of an early partonic state.

In this Letter, we report the measurement of $v_2$ at mid-rapidity, $|y| \leq 1.0$, for $K^0_S$ and lambda ($\Lambda$) + antilambda ($\bar{\Lambda}$) with $0.4 < p_T < 6.0$ GeV/$c$ and $0.6 < p_T < 6.0$ GeV/$c$ respectively in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

2. Analysis and Results

This analysis uses $1.6 \times 10^6$ minimum–bias trigger events and $1.5 \times 10^6$ central trigger events detected in the STAR detector system [18]. The particles, $K^0_S$, $\Lambda$ and $\bar{\Lambda}$, were identified from the charged daughter tracks produced in the decays $K^0_S \rightarrow \pi^+ + \pi^-$, $\Lambda \rightarrow p + \pi^-$ and $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$. A detailed description of the analysis, such as track finding, decay vertex topology cuts, and the estimation of detection efficiency, is given in Refs. [4, 19].

We use the yield as a function of $(\phi_{ij} - \Psi^R_j)$ to calculate $v_2 = \langle \cos [2(\phi_{ij} - \Psi^R_j)] \rangle$, where $\phi_{ij}$ is the azimuthal emission angle of particle $i$ in event $j$ and $\Psi^R_j$ is the reaction plane angle for event $j$, where, to remove autocorrelations, the decay daughter tracks associated with particle $i$ are excluded from its calculation. Within statistical errors, the $\Lambda$ $v_2$ is the same as $\bar{\Lambda}$ $v_2$, so they are summed together.

| $p_T$ (GeV/$c$) | $K^0_S$            | $\Lambda + \bar{\Lambda}$ |
|---------------|---------------------|-----------------------------|
| 1.0           | $+0.000$ $-0.001$   | $+0.001$ $-0.007$           |
| 2.5           | $+0.001$ $-0.007$   | $+0.003$ $-0.018$           |
| 4.0           | $+0.001$ $-0.007$   | $+0.005$ $-0.001$           |

Table 1. The systematic errors for minimum bias $v_2$ from non-flow effects (n-f) and background contamination (bkg). The values represent the absolute errors. The $p_T$ resolution, $\delta p_T/p_T$ is also listed.

Possible sources of systematic error in the calculation of $v_2$ are correlations unrelated to the reaction plane (non-flow effects), uncertainties in the extraction of yields from the invariant mass distributions, the particle momentum resolution ($\delta p_T/p_T$), and biases introduced by the cuts used in the analysis. Table 1 lists the dominant systematic errors for three transverse momenta. The non-flow systematic error is dominant. The non-flow effects for charged particle $v_2$ are discussed in Refs. [6, 5] but, the particle dependence of these effects has not been measured. We assume a similar magnitude of non-flow contribution to $\Lambda + \bar{\Lambda}$ and $K^0_S$ $v_2$. A 4-particle cumulant analysis of $\Lambda + \bar{\Lambda}$ and $K^0_S$ $v_2$ will be less sensitive to non-flow effects but, to be conclusive, will require a larger data sample than is currently available.
Fig. 1 shows $v_2$ of $K_S^0$ and $\Lambda + \bar{\Lambda}$ as a function of $p_T$ for the centrality intervals, 30–70% (a), 5–30% (b), 0–5% (c), and 0–80% (d) of the geometrical cross section. The $p_T$ dependence of the $v_2$ for all the centrality bins has a similar trend. There is a saturation and particle dependence at moderate $p_T$ for each of the centrality intervals and, as such, the saturation for the minimum-bias $v_2$ (0–80%) cannot be due to the superposition of drastically different $p_T$ dependencies in various centrality bins. This measurement establishes the saturation and particle dependence of $v_2$ at the moderate to high $p_T$ region.

Fig. 2 and Fig. 3 show the same data as Fig. 1 but plotted versus $m_T - m_0$ which is
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Anisotropy Parameter $v_2$

Hydro calculations

The elliptic flow of $K_S^0$ and $\Lambda + \bar{\Lambda}$ as a function of $p_T$ (top panel) and $m_T - m_0$ (bottom panel) for 0–80% of the collision cross section. The error bars shown are statistical errors only.

approximately the kinetic energy of the hadron. In the low momentum region the $K_S^0$ and $\Lambda + \bar{\Lambda}$ $v_2$ appears to fall on a single straight line. The hydrodynamic calculations in Fig. 3 seem to capture this trend. In the bottom panels of Fig. 2 we've scaled the $v_2$ values by the eccentricity of the overlap region for the various centralities. Hydrodynamic models predict that $v_2$ should scale with this initial eccentricity.

In In Fig. 4 (top) we show $v_2(p_T)$ for $K_S^0$, $\Lambda + \bar{\Lambda}$, and charged hadrons [20] along with hydrodynamic model calculations of $v_2$ for identified particles [7]. Below $p_T \sim 1.2$ GeV/c $v_2$ is consistent with the calculations and in agreement with the previous results for $K_S^0$ and $\Lambda + \bar{\Lambda}$ at $\sqrt{s_{NN}} = 130$ GeV [4]. Contrary, however, to hydrodynamical calculations, where at a given $p_T$ heavier particles will have smaller $v_2$ values, the measured $v_2$ of the heavier hyperon saturates at a value significantly larger than the $v_2$ of the lighter $K_S^0$ meson. The $p_T$ scale where the measured $v_2$ deviates from the hydrodynamical prediction is particle dependent with the hyperon $v_2$ following the prediction up to $p_T \sim 2.0$ GeV/c while the $K_S^0$ $v_2$ deviates much sooner.

The ratio ($R_{CP}$) of the yields in central and peripheral collisions scaled by the number of binary nucleon-nucleon collisions ($N_{binary}$), may also be sensitive to the effects of energy loss and hadronization via parton coalescence [16, 9]. In Fig. 4 (bottom) we show $R_{CP}$ for $K_S^0$, $\Lambda + \bar{\Lambda}$ and charged hadrons using the centrality intervals 0–5% (central) and 60–80% (peripheral) [21, 22]. The charged hadron spectrum at $p_T > 2$ GeV/c for the 60–80% centrality bin approximately follows binary collision scaling without medium modification [22]. As such, when this bin is used, $R_{CP}$ approximates $R_{AA}$. The bands in Fig. 4 represent the expected values of $R_{CP}$ for $N_{binary}$ and $N_{part}$ scaling including systematic variations within the calculation [22].

For $p_T < 5$ GeV/c, the $K_S^0$ and $\Lambda + \bar{\Lambda}$ yields are suppressed (relative to $N_{binary}$ scaling) by different magnitudes. In addition, the $p_T$ scale associated with the onset suppression has a dependence on particle-type that is similar to the dependence in $v_2$ for the onset of saturation. At $p_T \sim 5.0$ GeV/c, $R_{CP}$ values for $K_S^0$ and $\Lambda + \bar{\Lambda}$ are both approaching the value of the charged hadron $R_{CP}$. 
Figure 4. Minimum-bias $v_2$ (top panel) and $R_{CP}$ (bottom panel) for $K_S^0$ and $\Lambda + \bar{\Lambda}$. The $v_2$ errors are statistical only. The widths of the gray bands represent uncertainties in the model calculation of $N_{\text{binary}}$ and $N_{\text{part}}$. Charged hadron $v_2$ and $R_{CP}$ are also shown.

3. Discussion

Although $R_{CP}$ depends only on the yield in the central and peripheral bins, and the $v_2$ in Fig. 4 is from a minimum-bias centrality interval, the two parameters may be intimately related. The differential elliptic flow ($v_2(p_T)$) measures the ratio of the $p_T$ spectrum of particles emitted in the direction of the reaction plane (in-plane) to that of particles emitted perpendicular to the reaction plane (out-of-plane). In hydrodynamic models, we expect the pressure gradient to be larger in the in-plane direction than the out-of-plane direction. In this case, $v_2$ will be the ratio of a $p_T$ spectrum with more hydrodynamic flow to one with less flow. As such, taking the ratio ($R_{CP}$) of a $p_T$ spectrum that exhibits large flow (central) and one exhibiting less flow (peripheral) should lead to a very similar $p_T$ and particle-type dependence. A detailed study of $v_2$ and $R_{CP}$ for identified particles should reveal the extent (in $p_T$ and centrality) to which hydrodynamical models are valid.

A surface emission scenario, where partons traversing a dense medium experience large energy losses, has been discussed in relation to the large, $p_T$ independent $v_2$ measured for charged hadrons [10]. This mechanism should also lead to a suppression of particle production in central Au+Au collisions. This scenario, however, is inconsistent with STAR measurements of $v_2$ and $R_{CP}$ for $K_S^0$ and $\Lambda + \bar{\Lambda}$. The smaller suppression manifested in the $\Lambda + \bar{\Lambda}$ $R_{CP}$ contradicts the larger azimuthal anisotropies manifested
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in $\Lambda + \bar{\Lambda}$ $v_2$ values. In addition, calculations based on a surface emission model \[10\] cannot produce $v_2$ values as large as those measured.

The absence of a net suppression of $\Lambda + \bar{\Lambda}$ for $p_T$ from 1.8–3.5 GeV/c in central Au+Au collisions could also indicate the presence of dynamics beyond the framework of parton energy loss followed by fragmentation. The stronger dependence on centrality (and thus parton density) for baryon production indicated by the larger $R_{CP}$ would naturally be expected from multi-parton mechanisms such as gluon junctions \[23\], quark coalescence \[14\], or recombination \[16\]. Within the framework of these models, the measured $v_2$ and $R_{CP}$ features may reflect the anisotropy and hadronization properties of the bulk quark matter. Fig. 5 shows $v_2$ of $K^0_S$ and $\Lambda + \bar{\Lambda}$ as a function of $p_T$ where the $v_2$ and $p_T$ values have been scaled by the number of constituent quarks ($n$). Above $p_T/n \sim 0.8$ GeV/c, the $v_2/n$ vs $p_T/n$ is the same, within errors, for both species. In a scenario where hadrons at intermediate $p_T$ ($\sim 1 - 5$ GeV/c) are predominantly formed from bulk partonic matter by quark coalescence, e.g. Ref. \[14\], $v_2/n$ should reveal the $v_2$ developed by partons prior to the hadronic phase. The verification of this scenario, to the exclusion of other possible explanations, would be strong evidence for the formation of a quark-gluon plasma at RHIC.

The scenario discussed in Ref. \[12\], where soft processes dominate the hyperon $v_2$ up to a higher $p_T$ than mesons, could also lead to a particle dependence for $R_{CP}$ that is qualitatively consistent with these measurements. Quantitative calculations of $v_2$ and predictions for $R_{CP}$ from this scenario, however, are still needed. Up-coming measurements of $R_{CP}$ for identified particles in d + Au collisions at RHIC will also make it possible to study the effect of initial state interactions on $R_{CP}$.

**Figure 5.** The $v_2$ parameter for $K^0_S$ and $\Lambda + \bar{\Lambda}$ scaled by the number of constituent quarks ($n$) and plotted verses $p_T/n$.\[200 GeV; |y|<1.0\]
4. Summary

We have reported the measurement of $v_2$ for $p_T$ up to $\sim 6.0$ GeV/c for $K_S^0$ and $\Lambda + \bar{\Lambda}$ from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. For $p_T < 1.2$ GeV/c, hydrodynamic model calculations agree well with the $p_T$ and mass dependence of the measured $v_2$. At this low momentum region $K_S^0$ and $\Lambda + \bar{\Lambda}$ $v_2$ lie on a single straight line when plotted versus $m_T - m_0$. In the moderate $p_T$ region, however, the particle type and $p_T$ dependence of $v_2$ suggests hydrodynamics no longer describes the collision dynamics. The value of $v_2$ for $K_S^0$ saturates earlier and at a lower value than the $\Lambda + \bar{\Lambda}$ $v_2$. Measurements of $R_{CP}$ show that the suppression of particle production in central collisions depends on particle-type in a similar way. The measurement of the particle-type and $p_T$ dependence of $v_2$ and $R_{CP}$ at moderate $p_T$ may provide a unique means to establish the existence (and study the properties) of a quark-gluon plasma that may be formed in collisions at RHIC.

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5. References

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