

# Azimuthal Anisotropy of Identified Hadrons in 200 GeV Au+Au Collisions

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The azimuthal anisotropy parameter  $v_2$  has been measured with high statistics for identified hadrons in  $\sqrt{s_{NN}} = 200$  GeV Au+Au collisions with the STAR experiment. At high transverse momentum ( $p_T$ ) a strong  $v_2$  for  $\pi^+ + \pi^-$  and  $p + \bar{p}$  is observed. In the intermediate  $p_T$  region, number-of-constituent-quark scaling was tested to high precision. A detailed comparison of  $v_2$  for the multi-strange hadrons  $\phi$ ,  $\Xi^- + \bar{\Xi}^+$ , and  $\Omega^- + \bar{\Omega}^+$  with other particle species substantiates the development of collectivity among partons in the early phase of the collisions at RHIC.

## 1. Introduction

The study of ultra-relativistic heavy-ion collisions provides insight into properties of very high density nuclear matter. Since the observed particle distributions to first order only reflect the conditions in the final state of the system, signatures originating from the early stage are needed to conclude whether the system passes through a partonic phase. This is one necessary step to identify the predicted state of matter called the quark-gluon plasma; the other one being the proof that the system is thermalized.

One observable which is sensitive to the early stage of the collision is the second harmonic coefficient,  $v_2$ , of the Fourier expansion of the azimuthal momentum distribution, called elliptic flow [1]. In non-central collisions the initial spatial anisotropy is transformed into an anisotropy in momentum-space if sufficient interactions occur among the constituents within the system. Once the system has expanded enough to quench the spatial anisotropy, further development of momentum anisotropy ceases.

In the following we will discuss results on  $v_2$  for identified hadrons measured in  $\sqrt{s_{NN}} = 200$  GeV minimum bias Au+Au collisions from the STAR experiment at RHIC.

## 2. $v_2$ of identified hadrons at high $p_T$

With the high statistics available from RHIC's run IV the coverage for identified hadron  $v_2$  was extended up to  $p_T = 9$  GeV/ $c$  by disentangling the different contributions to the overall  $v_2^{\text{tot}}(dE/dx)$ , as shown in Fig. 1. To suppress non-flow effects, particles were correlated to the reaction plane determined in the opposite  $\eta$ -subevent. The difference of this  $v_2$ -measurement from the results of the method where the event plane is measured over the full acceptance, is an estimate of one of the contributions to the systematic error;

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another factor in the systematic error is based on the estimated level of contamination of protons by kaons. The systematic errors are shown as bands in Fig. 1, while the error bars include statistical uncertainties only. At low  $p_T$  the systematic errors were estimated to be less than 10% [3].

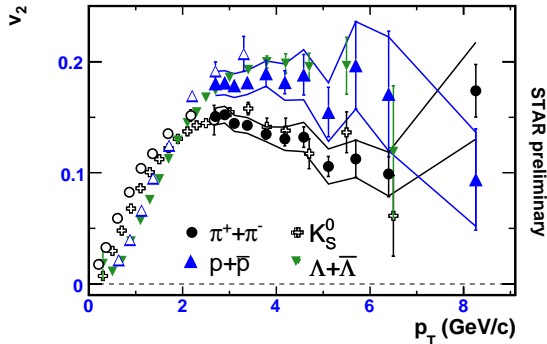


Figure 1. (left) Azimuthal anisotropy  $v_2$  for  $\pi^+ + \pi^-$  and  $p + \bar{p}$  in 200 GeV minimum bias Au+Au collisions.  $K_S^0$  and  $\Lambda + \bar{\Lambda}$   $v_2$  are shown for comparison.

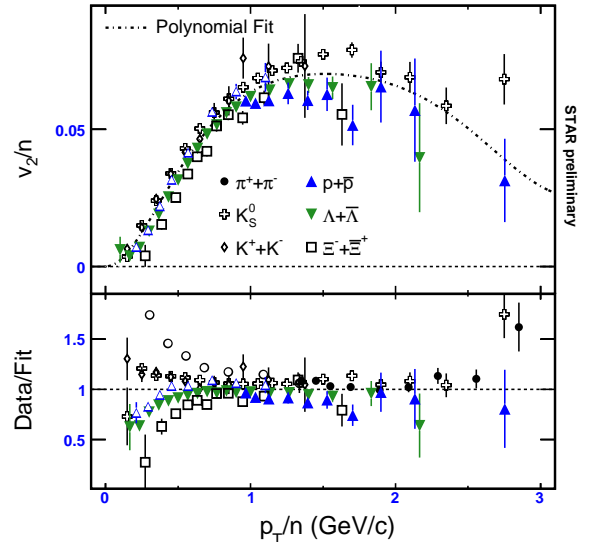


Figure 2. (right) Measurements of scaled  $v_2(p_T/n)/n$  for identified hadrons (upper panel) and ratio (lower panel) between the measurements and a polynomial fit through all data points except pions for 200 GeV minimum bias Au+Au collisions.

For both figures the open symbols for  $\pi^+ + \pi^-$  and  $p + \bar{p}$  were taken from [2].

While the proton  $v_2$  saturates at  $p_T \sim 3 \text{ GeV}/c$  the measurements for  $\pi^+ + \pi^-$  show a decline starting from their maximum at about  $p_T = 3 \text{ GeV}/c$ . The flow of these non-strange hadrons is strikingly similar to that of the strange particles  $K_S^0$  and  $\Lambda + \bar{\Lambda}$ . The mesons and baryons fall into separate groups and this behavior seems to extend out to rather high transverse momentum. Most surprisingly, even at the highest  $p_T$  measured a large  $v_2$  is still observed. This appears to be in contradiction to parton energy loss models [4] and multi-component calculations [5], which both predict a smaller  $v_2$  at and above  $p_T \sim 6 \text{ GeV}/c$ . At these high momenta the remaining  $v_2$  value should be essentially driven by the path-length dependence of jet quenching only [6].

### 3. Number-of-constituent-quark scaling of $v_2$

To further study the observed grouping into mesons vs. baryons, the top of Fig. 2 shows the scaled  $v_2/n$  for identified hadrons over a broad range of scaled transverse momentum  $p_T/n$ . Here  $n$  is the number of constituent quarks (NCQ) of a given hadron. Figure 2, bottom displays the ratio between the measurements and a polynomial fit to all data. At low  $p_T/n$  ( $< 0.75 \text{ GeV}/c$ ) the observed deviations from the fit follow a mass-ordering which is expected from hydrodynamic flow. At higher  $p_T$ , all  $v_2/n$  measurements are very

close to the common ‘mean value’. While the shown errors include statistical uncertainties only, it is still striking to see that the similarity of the scaled  $v_2$  extends out to  $p_T/n$  as high as 2 GeV/ $c$ . It seems that all mesons fall above the fit while all baryons fall below.

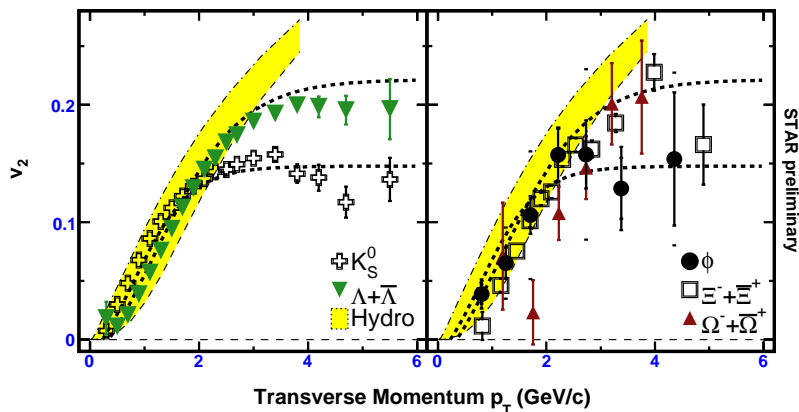
The observation that the  $v_2(p_T/n)/n$  is similar for all the different particle species, strongly supports quark coalescence (see for example [7]) as the dominant process of hadronization in the intermediate  $p_T$  region. With the available statistics small deviations from exact NCQ-scaling are now detectable, which were expected even for simple recombination models [7].

#### 4. $v_2$ of multi-strange hadrons

Compared to  $\pi^+ + \pi^-$ ,  $K^+ + K^-$ , and  $p + \bar{p}$  [8], measurements of particle spectra at RHIC have shown that the multi-strange hadrons  $\phi$  and  $\Omega$  are less affected by the hadronic phase [9] than by the partonic phase. It has been demonstrated [10] that the  $\Xi^- + \bar{\Xi}^+$  and  $\Omega^- + \bar{\Omega}^+$  baryons possess a significant amount of  $v_2$ , which suggests that this azimuthal anisotropy is generated at an early and partonic stage of the system’s evolution.

For the  $\phi$  meson, earlier measurements disfavored kaon coalescence as the dominant channel for  $\phi$  production at RHIC energies [11]. Also its lifetime is long compared to the lifetime of the fireball. Hence the  $\phi$  is a useful probe of the early stage of the system as well. The  $v_2$  of the  $\phi$  is particularly interesting, since the  $\phi$ -mass of 1019.5 MeV/ $c^2$  is similar to the mass of the proton (938.3 MeV/ $c^2$ ).

Figure 3. Azimuthal anisotropy  $v_2$  for strange hadrons (left) and multi-strange hadrons (right) in 200 GeV minimum bias Au+Au collisions. The dashed lines show a common fit [12] to the  $K_S^0$  and  $\Lambda + \bar{\Lambda}$  data. Hydrodynamic model calculations [13] are shown as shaded areas.



The new high statistics measurements of azimuthal anisotropy  $v_2$  of multi-strange hadrons show strong elliptic flow for all studied particles:  $\Xi^- + \bar{\Xi}^+$ ,  $\Omega^- + \bar{\Omega}^+$ , and  $\phi$  (see Fig.3, right). The error bars contain statistical uncertainties only. For the  $\phi$ -measurement systematic errors obtained by the comparison of two different methods are also shown. A common fit to the results obtained for  $K_S^0$  and  $\Lambda + \bar{\Lambda}$ , as depicted in Fig. 3, left and motivated by number-of-constituent-quark scaling [12], was used to compare the  $v_2$ -data of multi-strange hadrons to those of the other particles. A detailed comparison, carried out by calculating  $\chi^2/n. d. f.$  for the difference between the measurements and the fit function (see Tab.1), suggests that  $\Xi^- + \bar{\Xi}^+$  and  $\Omega^- + \bar{\Omega}^+$  indeed flow as strongly

as the other baryons, while the  $\phi$  favors the similarity to other mesons. Note that the fit function does not reproduce the data perfectly due to small deviations from the exact number-of-constituent-quark scaling, as discussed in Sec. 3.

Table 1

Comparison of  $v_2(p_T)$  measurements for multi-strange hadrons to a common fit [12] to  $v_2(p_T)$  of  $K_S^0$  and  $\Lambda + \bar{\Lambda}$ .

$p_T/n$	$\chi^2/\text{n. d. f.}$	$\chi^2/\text{n. d. f.}$
$> 0.75 \text{ GeV}/c$	for NCQ = 2	for NCQ = 3
$\Xi^- + \bar{\Xi}^+$	82.7/6	<b>27.4/6</b>
$\Omega^- + \bar{\Omega}^+$	4.1/3	<b>2.1/3</b>
$\phi$	<b>2.0/5</b>	7.4/5

Since the  $\phi$  flows like a meson and not as strongly as baryons, e.g. the proton with its similar mass, it is found that the observed scaling is a meson-baryon effect and not a mass effect. The observed strong flow of multi-strange hadrons substantiates the development of collectivity among partons at RHIC.

## 5. Summary

We have presented the azimuthal anisotropy parameter  $v_2$  for identified particles in 200 GeV minimum bias Au+Au collisions. Elliptic flow of  $p + \bar{p}$  and  $\pi^+ + \pi^-$  was measured up to  $p_T = 9 \text{ GeV}/c$ , where these particles still show a strong  $v_2$  signal. The observed meson-baryon grouping at intermediate  $p_T$  suggests parton coalescence to be the dominant process of hadronization in that region, even though small deviations from ideal number-of-constituent-quark scaling are observed. This scaling is a meson-baryon effect and not a mass effect. Finally, the multi-strange hadrons  $\phi$ ,  $\Xi^- + \bar{\Xi}^+$ , and  $\Omega^- + \bar{\Omega}^+$  flow as strongly as the other mesons and baryons, which confirms partonic collectivity at RHIC. The remaining item to address for the discovery of a quark-gluon plasma is the thermalization of the system.

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