Centrality Dependence of Azimuthal Anisotropy of Strange Hadrons in 200 GeV Au+Au Collisions

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Abstract. Measurements of azimuthal anisotropy for strange and multi-strange hadrons are presented for the first time in their centrality dependence. The high statistics results of \( v_2(p_T) \) allow for a more detailed comparison to hydrodynamical model calculations. Number-of-constituent-quark scaling was tested for different centrality classes separately. Higher order anisotropies like \( v_4(p_T) \) are measured for multi-strange hadrons. While we observe agreement between measured data and models a deeper understanding and refinement of the models seem to be necessary in order to fully understand the details of the data.

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1. Introduction

The initial stage of high-energy heavy-ion collisions can be probed by measuring the azimuthal momentum anisotropies of the emitted particles [1]. In non-central collisions the initial spatial anisotropy of the reaction region is transformed into an collective anisotropic motion, given that the constituents of the hot and dense system interact with each other. Multi-strange hadrons give an additional insight into the early phase of the reaction. Measurements show [2] that these particles freeze out with a lower mean collective velocity \( \langle \beta_T \rangle \) and at a higher temperature \( T_{\text{kin}} \) compared to protons, pions, and kaons, suggesting that they decouple earlier from the strongly interacting system. The measured significant azimuthal momentum anisotropy in the final state must therefore be developed very early, presumably during a partonic stage of the system. This effect is called partonic collectivity.

To measure the final state momentum anisotropy the transverse momentum \( (p_T) \) distribution is expanded in terms of a Fourier decomposition. The different Fourier coefficients \( v_n = \langle \cos(n \cdot \phi) \rangle \) are called ‘flow of order \( n \)’. The second order coefficient \( v_2 \) is called ‘elliptic flow’.

The Au+Au data sample at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) used in this study contains 13.3 M minimum bias triggered events. This was subdivided into three different centrality

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classes: 40–80 % (peripheral) with 6.6 M events, 10–40 % (mid-central) with 5.0 M events, and 0–10 % (central). The number of events in the central bin was enhanced to a total of 19 M events by using our large data set of central triggered events. The average event plane resolutions for these three centrality regions were 66 % (peripheral), 82 % (mid-central), and 69 % (central). The average minimum bias event plane resolution was 76 %.

While a detailed study of the systematic errors is still under way, initial estimates have been obtained for $K^0_S$ and $\Lambda + \bar{\Lambda}$. The systematic errors are mainly influenced by so-called non-flow effects: two particle correlations not correlated with the event plane. Different analysis methods (e.g. the cumulant method or analyses with Lee-Yang-zeros) offer ways to reduce this non-flow contribution to the measured signal. By comparing our results for the aforementioned particles obtained with the ‘standard’ method with the measurements from the different methods it was established that at $p_T < 4 \text{ GeV}/c$ the systematic uncertainty due to non-flow effects is of the order of 5 %, rising to 25–30 % at $4 \text{ GeV}/c < p_T < 6 \text{ GeV}/c$. Above $p_T = 5 \text{ GeV}/c$ there is possibly a large non-flow contribution. However, limited statistics prevents us from being more quantitative. In view of these caveats only statistical uncertainties are shown in this publication.

2. Centrality dependence of $v_2(p_T)$

![Figure 1](image)

**Figure 1.** Centrality dependence of 2nd-order azimuthal anisotropy. The panels show $v_2(p_T)$ for (from left to right) $K^0_S$, $\Lambda + \bar{\Lambda}$, $\Xi^- + \Xi^+$, and $\Omega + \bar{\Omega}$. Different symbols represent different centrality classes: 40–80 % (squares), 10–40 % (triangles), 0–10 % (circles), and 10–80 % (upside down triangles, for $\Omega + \bar{\Omega}$ only). Hydrodynamical model calculations are also shown for the given particle species and the same centrality regions.

Measurements of minimum bias $v_2(p_T)$ showed [3] that in the low momentum region, where hydrodynamical effects dominate, the strange and multi-strange particles show...
the same mass ordering behavior as all the other particle species. In particular this mass dependence can be described reasonably well with hydro model calculations [4].

The available much higher than previous statistics allows for measuring the centrality dependence of elliptic flow for strange and multi-strange particles, see Fig. 1. For \( K^0_S, \Lambda + \overline{\Lambda}, \) and \( \Xi + \overline{\Xi} \) three centrality classes are shown. The lower yield of \( \Omega + \overline{\Omega} \) limited the measurement to two centrality bins, only.

Even though the general trend of hydrodynamical model calculations carried out for the same centrality regions is similar to the data, we observe some significant deviations. Especially at low \( p_T \), where the biggest trust was put into these models, these differences show that the overall agreement of the minimum bias measurements to the model does not hold for this more detailed comparison. At higher \( p_T \) and for the peripheral bins the agreement breaks down completely. It is interesting to note that for different particles the agreement with the model is best for different centrality classes. For example, while for \( \Omega + \overline{\Omega} \) the most central bin (0–10%) shows the best agreement, the hydro calculations fail to explain the results of all the other shown particles at this centrality.

3. Centrality dependence of number-of-constituent-quark scaling of \( v_2(p_T) \)

![Figure 2](image-url)

**Figure 2.** Centrality dependence of 2nd-order azimuthal anisotropy, scaled by the number of constituent quarks for \( K^0_S, \Lambda + \overline{\Lambda}, \Xi + \overline{\Xi} \), and \( \Omega + \overline{\Omega} \). The different panels show different centrality classes: a) and d) 40–80%, b) and e) 10–40%, c) and f) 0–10%. In the upper panels a common polynomial fit to all data points is shown. For each centrality region the lower panels show the ratio of the measured data to this common fit.

The scaling of \( v_2(p_T) \) with the number of constituent quarks at intermediate \( p_T \) was established early on [5]. Recently these measurements included multi-strange baryons as
well, even though only for minimum bias collisions. Our latest measurements in Fig. 2, upper row show the results for $v_2(p_T)/n_q$ vs. $p_T/n_q$ for three different centrality classes. Here $n_q$ is the number of constituent quarks of the given particle, i.e. $n_q = 2$ for mesons and $n_q = 3$ for baryons. A common polynomial fit to all data points is shown for each centrality bin.

The lower panels of Fig. 2 show the ratio of the measured data points to the common fit for each centrality bin. While especially for the most central collisions the statistics is not sufficient the general trend is clearly visible: even in their centrality dependence the $v_2(p_T)$ for different strangeness containing particles seem to obey number-of-constituent-quark scaling at intermediate $p_T$.

4. Fourth order anisotropy $v_4(p_T)$

Higher statistics allows for measuring higher harmonics $v_n$, with $n > 2$, where the signal is usually smaller than $v_2$ and therefore more difficult to distinguish from zero. The first measurement of $v_4(p_T)$ for $\Xi + \Xi$ shows strong, almost linear $p_T$ dependence. While ideal fluid dynamics predicts the ratio of $v_4$ to $v_2^2$ to be $1/2$ [6], a simple comparison shows that the ratio we observe is much better described by $v_4/v_2^2 \sim 1.2$. This result is consistent with the earlier measurements [3] for charged hadrons.

Even though it was argued that this deviation from ideal fluid dynamics could be a hint of incomplete thermalization [7], these results have to be taken with caution, because the studies of the systematic errors and the contribution of non-flow effects for the higher harmonics are still under way.

5. Conclusions

We have shown the centrality dependence of $v_2(p_T)$ for strange and multi-strange hadrons. While the minimum bias measurement follows the hydro model calculations, we observe a deviation from the predictions for the different centrality classes. The high statistics allowed for a more detailed study of number-of-constituent-quark scaling, where at intermediate $p_T$ an indication of scaling even for different centrality regions was observed. Finally, the higher harmonic $v_4(p_T)$ was measured for $\Xi + \Xi$, showing similar scaling with $v_2^2$ as for the other charged hadrons.

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