Scaling of anisotropic flow in the picture of quark coalescence

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Abstract. Measurements of anisotropic flow at low ($p_T < 1.5 \text{ GeV}/c$) and intermediate ($1.5 < p_T < 5 \text{ GeV}/c$) transverse momentum from the STAR collaboration are reviewed. While at low $p_T$ an ordering of elliptic flow strength with particle mass is observed, the measured signals appear to follow number-of-constituent quark scaling at intermediate $p_T$. The observations of higher harmonics support this picture qualitatively, and are sensitive to specific model assumptions.

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1. Introduction

The azimuthal anisotropy of particles created in ultra-relativistic heavy-ion collisions is commonly measured by expanding the particle’s azimuthal momentum distribution with respect to the reaction plane in terms of a Fourier series [1]. The obtained coefficients $v_n$ for increasing order $n$ characterize the distribution in more and more detail. In non-central collisions sufficient rescattering will drive the initial spatial anisotropy of the system into a state where this spatial anisotropy is diminished. During this evolution an azimuthal anisotropy in momentum space is built up. Due to the self-quenching nature of this process the signal of anisotropic flow is sensitive to an early stage in the evolution of the system. This picture holds for all different harmonics, even though flow of different order might test different time scales.

The second Fourier coefficient $v_2$, so-called elliptic flow, is studied in detail at RHIC [2]. This is mainly due to its large magnitude, which allows for a precise measurement of the reaction plane. It was realized that this high resolution of the second order reaction plane allowed for the measurement of higher order anisotropies as well [3].

While the qualitative agreement of hydrodynamical model predictions with anisotropic flow measurements below transverse momentum of about $p_T = 1.5 \text{ GeV}/c$ [4] is good, at higher momenta this picture breaks down. Instead, quark coalescence models provide a very intriguing explanation of the observed particle species dependence in the intermediate $p_T$-region up to $p_T \approx 5 \text{ GeV}/c$ [6].

‡ For the full author list and acknowledgments see Appendix “Collaboration” in this volume.
In this article the measurements of elliptic flow $v_2$ and higher order flow by the STAR experiment at RHIC will be reviewed. The data presented come from Au+Au collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$. About two millions events in the STAR main time projection chamber (TPC) with a pseudorapidity coverage of $-1.2 < \eta < 1.2$ were analyzed.

2. Mass ordering of elliptic flow $v_2$ at low $p_T$

In the low-$p_T$ region up to $p_T \approx 1.5\,\text{GeV}/c$ elliptic flow shows an almost linear increase with transverse momentum. This feature is present for all measured particle species, as can be seen in Fig. 1: charged pions, charged and neutral kaons, protons and lambdas and their anti-particles – all follow this general behavior. A clear mass ordering effect is visible: particles with a higher mass show a smaller $v_2$ at a given $p_T$ than particles with lower mass.

![Figure 1](image.png)

**Figure 1.** Elliptic flow $v_2$ for different particle species measured by STAR and PHENIX [5, 6] compared to hydrodynamic model predictions [8]. The data indicates the expected mass ordering in this low $p_T$ region.

Hydrodynamical model calculations [7, 8] can successfully describe these observations in this $p_T$-region to a level of 20 – 30 %, attributing the mass ordering to an underlying common transverse velocity field. These models assume a local thermal equilibrium of the particle source. Since the mechanism of generating anisotropic flow...
is self-quenching, the development of local thermal equilibrium at an early stage is supported. Nevertheless, since these calculations can’t predict the full shape of the event, neither the observed anisotropies at forward/backward rapidities nor other harmonics than $v_2$, the conclusion of thermal equilibrium is not at all solid.

It is important to note that the aforementioned hydrodynamical models fail to describe the mass and momentum dependence of elliptic flow as long as they don’t invoke a phase transition from partonic to hadronic degrees of freedom [10]. This sensitivity to the equation of state justifies the importance of elliptic flow for the understanding of hot and dense nuclear matter, including the possible creation of a quark-gluon plasma (QGP).

3. Meson-baryon ordering at intermediate $p_T$

At transverse momentum $1.5 < p_T < 5 \text{ GeV/c}$ the elliptic flow of different particle species starts to deviate significantly from the mass ordering schematics discussed above, see Fig. 2. Interestingly, different particle species seem to exhibit a different value of saturation for $v_2$, while they fall on top of each other if grouped into mesons and baryons. While at low $p_T$ the lighter mesons have a larger $v_2$ for a given $p_T$, at intermediate $p_T$ the elliptic flow of mesons is smaller than that of baryons.

![Figure 2. Identified particle $v_2$, hydrodynamic predictions, and elliptic flow of quarks derived from number-of-constituent quark scaling. Figure taken from [9].](image)

Quark coalescence models provide an elegant explanation for this observed feature. These models assume that in this $p_T$ range particle production is dominated by...
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coalescing quarks: Two quarks moving with the same momentum make up a meson with twice the momentum of the original quarks, three quarks coalesce into a baryon with three times the quark momentum. Therefore, by scaling the observed $v_2$ signal and the transverse momentum by the number of constituent quarks $n$ one obtains the underlying quark flow.

![Figure 3](image-url)

**Figure 3.** Elliptic flow for different particle species scaled according to the number of constituent quarks of the hadrons. The lower plot shows the ratio of the data to the dashed-dotted fit to the data in the upper plot. Pions were not included in this fit and are only shown in the lower panel. This figure combines data from [12] and [13].

The results, as shown in Fig. 3, are very intriguing. In the region $0.6 < p_T/n < 2\text{ GeV}/c$ of scaled particle momentum, elliptic flow for different particles is literally the same. Only the pions deviate from the universal curve, which can be explained by feed-down from resonances [14].

The success of these quark coalescence models in describing the measured $v_2$ is a strong hint that the observed large anisotropic flow builds up at the partonic stage of the system’s evolution already. On one hand this suggests that the system evolves through a state of partonic degrees of freedom, which – on the other hand – suffer a lot of rescattering and therefore should be close to local thermal equilibrium.
4. Higher order anisotropies

In order to measure harmonics higher than \( n = 2 \) we use the knowledge of the very well determined second order reaction plane\(^\S\) \cite{1}. As shown in Fig. 4 the coefficient for the fourth harmonic is significantly lower than that for the second harmonic, but is non-zero for all \( p_T \). Within errors \( v_6 \) is equal to zero.

![Figure 4. Minimum bias measurements of anisotropic flow of charged hadrons for different harmonics. The dashed lines show \( 1.2 \cdot v_2^2 \) and \( 1.2 \cdot v_2^3 \), respectively. Figure taken from \cite{15}.](image)

It was suggested that \( v_n \) could be proportional to \( v_2^{n/2} \), as long as the \( \phi \) distribution is a smooth, slowly varying function of \( \cos(2\phi) \) \cite{16}. The ratio of \( v_4 \) over \( v_2^2 \) is shown in Fig. 5 and is close to 1.2. Even though a straight line might not be the best fit, the ratio is clearly larger than 1. According to this mean ratio the two dashed lines in Fig. 4 were drawn.

This very good agreement between the scaled \( v_2 \) and the measurements of higher order can be also seen in the picture of parton coalescence. Assuming a simple model \cite{18} one obtains for the ratio \( v_4/v_2^2 \approx 1/4 + 1/2 \cdot (v_4^2/(v_2^2)^2) \) for mesons and \( v_4/v_2^2 \approx 1/3 + 1/3 \cdot (v_4^2/(v_2^2)^2) \) for baryons. As shown, this ratio is experimentally determined to be 1.2, which means that the fourth-harmonic flow of quarks \( v_4^q \) must be greater than zero. One can go one step further and assume that the observed scaling of the hadronic \( v_2 \) actually results from a similar scaling occurring at the partonic level \cite{19}. In this case \( v_4^q = (v_2^q)^2 \) and the hadronic ratio \( v_4/v_2^2 \) then equals \( 1/4 + 1/2 = 3/4 \)

\(^\S\) In this framework only harmonics which are multiples of \( n = 2 \) – like \( v_4, v_6, ..., v_{2k} \), ... – are accessible.
for mesons and $1/3 + 1/3 = 2/3$ for baryons, respectively. Again, since this value is measured to be 1.2, even the partonic $v_4^q$ must be greater than simple scaling and quark coalescence models predict.

5. Summary and outlook

Elliptic flow of identified particles was shown to exhibit a constituent-quark-number dependence at intermediate transverse momentum $1.5 < p_T < 5 \text{ GeV/c}$. The quantitative measurements of $v_2$ support model predictions for quark-number scaling which imply hadronization by coalescing partons. Within statistical uncertainties observations of higher order momentum anisotropies for charged hadrons support these model predictions. The quantitative deviations of only about 20% compared to model assumptions can be easily explained in the light of simplifications in the models while going from hadronic to partonic scaling of $v_4$ vs. $v_2$.

It has to be stressed that the observed mass ordering of elliptic flow measurements at low $p_T$ is nevertheless present and stands in no contradiction to the described behavior at intermediate transverse momentum.

With the large data set taken during RHIC run IV the STAR experiment will greatly enhance the statistical significance of the presented measurements. We will be able to test constituent-quark-number scaling with much higher precision. It will be interesting to see the outcome of these new measurements compared to recent developments in the theoretical understanding of the underlying process of hadronization.
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