

# Can baryon stopping explain the breakdown of constituent quark scaling and proposed signals of chiral magnetic waves at RHIC?

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**Abstract.** Azimuthal emission spectra of various hadron species in ultra-relativistic heavy ion collisions at  $\sqrt{s_{NN}} \approx 200$  GeV exhibit a curious hierarchy at intermediate  $p_t$  ( $\approx 2 - 3$  GeV). Rather than being ordered by mass, the spectra seem to be ordered by whether the species is a baryon or meson. It is seen that when the elliptic flow  $\nu_2$  and transverse momentum  $p_T$  are both scaled by the number of quarks in each hadron, the spectra fall in line with each other. This number of constituent quark (NCQ) scaling suggests a system where the relevant degrees of freedom are colored partons as opposed to hadrons: the quark-gluon plasma (QGP). Thus, a break down of this scaling as beam energy is reduced could be indicative of the QGP threshold. However, at lower energies, there is also an increase in the number of entrance-channel partons transported to mid-rapidity due to baryon stopping, which can violate NCQ scaling even above the QGP threshold. We describe a specific pattern for the break down of the scaling that includes the observed difference in elliptic flow for positive and negative pions. We also contrast baryon stopping with the Chiral Magnetic Effect (CME)—an alternative model for  $\pi_+/\pi_-$  flow difference—and discuss results from tests that can distinguish between them.

## 1. Introduction

In non-central heavy ion collisions the azimuthal momentum distribution is anisotropic. This anisotropy is typically characterized in terms of Fourier components:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos(n\phi) \quad (1)$$

The second component  $\nu_2$ —the elliptic flow parameter—is perhaps one of the most extensively analyzed quantities in the field. An important observation is the species dependence of  $\nu_2$  at top RHIC energies. At low  $p_T$ ,  $\nu_2$  displays a simple mass ordering, and agrees well with hydrodynamic predictions, with lighter particles exhibiting a larger  $\nu_2$  at a given  $p_T$ . But at  $p_T \geq 2$  GeV this ordering is broken, and mesons all begin to follow one common curve and baryons another, with baryons exhibiting a larger  $\nu_2$  than mesons. Intriguingly, scaling both  $\nu_2$  and  $p_T$  by the number of constituent quarks (NCQ) for each hadron—2 for mesons, 3 for baryons—causes  $\nu_2(p_T)$  for all particle species to follow a common curve.

This result suggests that the relevant degrees of freedom in the collision system are quarks, not hadrons [1]. Once the flow field has been established, the system cools and the constituent

quarks “coalesce” into the observed hadrons. This simple interpretation lends credence to claims that a new state of QCD matter—the quark-gluon plasma (QGP)—has been produced at RHIC.

If NCQ scaling is to be taken as a hallmark of QGP, it is compelling to search for the conditions under which it appears. A major thrust of the heavy ion community is an extensive beam energy scan program at RHIC [2], in which observables sensitive to the state of QCD matter are precisely measured as the collision energy  $\sqrt{s_{NN}}$  is measured in small steps. The *breakdown* of NCQ scaling as  $\sqrt{s_{NN}}$  is reduced may indicate the QGP threshold energy.

However, it is important to investigate less exciting phenomena that could bring about NCQ scaling violations. Two proposed mechanisms are baryon stopping [3] and chiral magnetic waves (CMW) [4].

## 2. Baryon stopping and Multi-component coalescence

In a recent publication [3], Dunlop *et al.* show that baryon stopping alone—with no change in the phase of matter—may lead to a characteristic pattern of NCQ-scaling breakdown. This is based on the speculation that entrance channel quarks must suffer many collisions to be *transported* to mid-rapidity. These collisions should give them higher elliptic flow profiles than the *produced* quarks ( $\nu_2^T > \nu_2^P$ ) which are created pairwise *at* mid-rapidity. The observed hadrons, however, will coalesce out of the combined quark population. We shall call this the multi-component coalescence (MCC) scenario.

If the data from the RHIC energy scan program show a breakdown of NCQ scaling at low energy, then comparing the measured species-dependent pattern of the breakdown with theoretical expectations may help distinguish the mechanism behind the breaking. Presumably, if the mechanism is a change of phase from partonic to hadronic matter, the observed  $\nu_2$  should be ordered according to hadron cross-section, rather than the pattern predicted [3] in the MCC scenario.

Among other consequences of multi-component coalescence, the elliptic flow of negative pions should be larger than that of positive pions:  $\Delta\nu_2^\pi \equiv \nu_2^{\pi^-} - \nu_2^{\pi^+} > 0$ . This is due to the relative number of entrance channel quarks that will coalesce into exit channel negative pions versus positive pions. More specifically, in the MCC scenario, the resulting baryon (meson)  $\nu_2$  is given by adding the flow profiles of the three (two) quark species that make it up. In pions, for example:

$$\begin{aligned}\nu_2^{\pi^-} [d\bar{u}] &= X_{d^T} \nu_2^{d^T} + (1 - X_{d^T}) \nu_2^{d^P} + \nu_2^{\bar{u}^P} \\ \nu_2^{\pi^+} [u\bar{d}] &= X_{u^T} \nu_2^{u^T} + (1 - X_{u^T}) \nu_2^{u^P} + \nu_2^{\bar{d}^P}\end{aligned}\quad (2)$$

where the  $\nu_2$  values on the right side of the equations represent quark (or anti-quark) flow strengths. Superscripts  $T$  and  $P$  denote transported and produced quarks, respectively. The quantity  $X_{d^T}$  ( $X_{u^T}$ ) represents the fraction of all  $d$  ( $u$ ) quarks at mid-rapidity that arise from transport from the entrance channel:

$$X_{d^T} \equiv \frac{N_{d^T}}{N_{d^T} + N_{d^P}}, \quad X_{u^T} \equiv \frac{N_{u^T}}{N_{u^T} + N_{u^P}} \quad (3)$$

Because coalescence and MCC only consider valence quarks, the incoming nuclei have no anti-quarks or strange quarks to transport:  $X_{s^T} = X_{\bar{u}^T} = X_{\bar{d}^T} = X_{\bar{s}^T} = 0$ .

Let us consider the simple case where all produced quarks have the same flow strength, and all transported quarks have the same flow strength. Then,

$$\begin{aligned}\nu_2^P &\equiv \nu_2^{u^P} = \nu_2^{d^P} = \nu_2^{s^P} = \nu_2^{\bar{u}^P} = \nu_2^{\bar{d}^P} = \nu_2^{\bar{s}^P} \\ \nu_2^T &\equiv \nu_2^{d^T} = \nu_2^{u^T}\end{aligned}\quad (4)$$

Combining equations (2) and (4) yields:

$$\Delta\nu_2^\pi = \Delta X_T(\nu_2^T - \nu_2^P) \quad (5)$$

where  $\Delta X_T \equiv (X_{dT} - X_{uT})$ . Since the quantity  $\nu_2^T - \nu_2^P$  is assumed to be positive, equation (5) implies a *positive correlation* between  $\Delta\nu_2^\pi$  and  $\Delta X_T$ .

### 3. Pion elliptic flow and chiral magnetic waves

Burnier *et al.* [4] have proposed an explanation for non-zero  $\Delta\nu_2^\pi$  that arises from chiral magnetic waves (CMW). The CMW induce an electric quadrupole moment in the QGP, which is predicted to lead to more elliptic flow for negative pions than for positive pions. The magnitude of this difference is predicted to be proportional to the charge asymmetry:

$$\Delta\nu_2^\pi \approx rA_\pm \quad (6)$$

where  $A_\pm \equiv (N_+ - N_-)/(N_+ + N_-)$  is the charge asymmetry of the plasma,  $N_+$  ( $N_-$ ) is the number of positively (negatively) charged particles in the plasma, and  $r$  is the (positive) normalized electric quadrupole moment of the system. This relation is derived in the small  $A_\pm$  limit.

Direct measurement of the electric quadrupole moment is impossible, but one may, for a given centrality selection, measure  $\Delta\nu_2^\pi$  as a function of  $A_\pm$ . A direct proportionality would be consistent with the chiral magnetic wave prediction [4].

We would like to compare the predictions of the CMW and baryon stopping hypotheses by finding some meaningful way to compare equations (5) and (6). That is, what is the relation between  $\Delta X_T$  and  $A_\pm$ ?

To see how these quantities *might* be correlated, consider event by event fluctuations of both the number of stopped baryons and of isospin. Increasing the number of stopped baryons will inject net charge to mid-rapidity (by stopping more protons), thereby increasing  $A_\pm$ . It will also enrich the down quark population preferentially more than up quarks (since there are more down quarks in the entrance channel), thereby increasing  $\Delta X_T$ : a *positive* correlation.

A positive fluctuation of isospin will also increase  $A_\pm$  by stopping more protons (increasing  $N_+ - N_-$ ) or fewer neutrons (decreasing  $N_+ + N_-$ ). However, this will also enrich the up quark population preferentially more than down quarks, decreasing  $\Delta X_T$ . Thus isospin fluctuations lead to a *negative* correlation.

Surely both types of fluctuations occur, but which one dominates?

### 4. UrQMD analysis

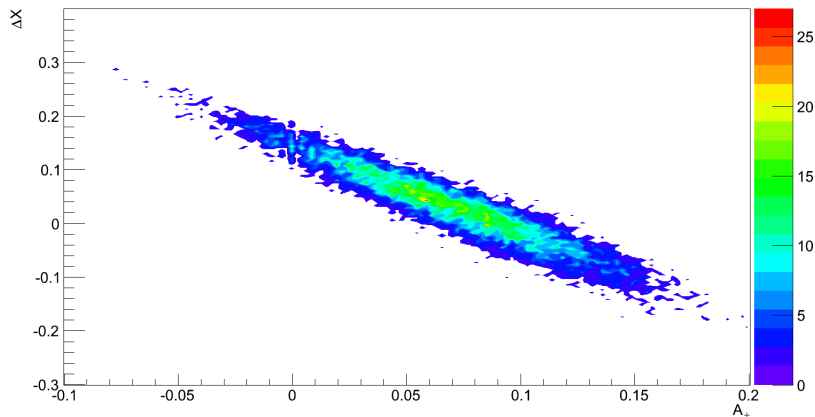
To determine the dominant source of fluctuations we seek to relate  $\Delta X_T$  and  $A_\pm$ . Here we present results from UrQMD simulations of Pb+Pb collisions at  $\sqrt{s_{NN}} = 17$  GeV. The distribution shown in figure 1 shows a strong linear relationship between  $\Delta X_T$  and  $A_\pm$ . We are therefore justified in writing:

$$\Delta X_T = mA_\pm + b \quad (7)$$

where  $m$  is the slope of the distribution and  $b$  is some intercept. The data shown in Figure 1 yield  $m = -1.64$  and  $b = 0.15$ . Combining this with equations (5) and (7) gives:

$$\Delta\nu_2^\pi = -1.64(\nu_T - \nu_P)A_\pm + 0.15(\nu_T - \nu_P) \quad (8)$$

We now have a prediction from the MCC scenario that is qualitatively different from the CMW prediction. From equation (6), CMW predicts a directly proportional, positive correlation between  $\Delta\nu_2^\pi$  and  $A_\pm$ . MCC predicts a *negative* correlation, with some non-zero offset.



**Figure 1.** 10,000 events of Pb+Pb collisions at  $\sqrt{s_{NN}} = 17$  GeV  $\cdot |\eta| \leq 0.5$ .

## 5. Summary

Measured  $\nu_2$  parameters of hadrons at top RHIC energies follow a simple pattern that strongly suggests that it is the constituent quarks, rather than the hadrons themselves, that are experiencing collective flow. Searches for a break-down of this pattern are under way in the beam energy scan program at RHIC. Mechanisms behind such a break down include a change in the fundamental dynamical degrees of freedom in hot QCD matter and chiral magnetic wave effects.

Rather than evoking such interesting mechanisms, the multi-component coalescence approach asks what would be the consequence of changing nothing about the system except what we already *know* changes as the collision energy is lowered: increased baryon number transport. This simplistic approach yields a characteristic pattern of hadron  $\nu_2$  that should be compared to data arising from the energy scan. Indeed, the measured pattern—for a wide range of hadron species—should be compared to predictions of any proposed mechanism such as chiral magnetic waves.

Here we have compared MCC- and CMW-based predictions of the difference between the elliptic flow strengths of negative and positive pions. UrQMD simulations suggest that the two hypotheses have qualitatively different implications. Namely, CMW predicts a directly proportional, positively correlated, relationship between  $\Delta\nu_2^\pi$  and  $A_\pm$ , whereas MCC predicts a negative correlation, with some positive  $\Delta\nu_2^\pi$  at zero charge asymmetry.

## 6. Acknowledgments

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