Azimuthal Asymmetries From Jets Quenched In Fluctuating Backgrounds

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Abstract. High momentum jets and hadrons are important probes for the quark gluon plasma (QGP) formed in nuclear collisions at high energies. We investigate how fluctuations in the background density of the QGP and fluctuations in the spatial distribution of the hard process create azimuthal asymmetries of the high momentum hadron spectrum, described by the Fourier coefficients v_n, $n > 0$. We estimate the coefficients up to v_6 in a simple energy loss model tuned to single inclusive hadron suppression.

With the study of the QGP created in collisions of relativistic heavy ions moving into an increasingly accurate quantitative phase it has been found important to include fluctuations in the space-time structure of the fireball into calculations of bulk quantities [1, 2]. These can emerge from fluctuations in the initial energy density $\epsilon(x, y)$ in the plane transverse to the beam axis and leave signature effects on bulk quantities like the azimuthal asymmetry coefficients v_n. For example fluctuations can lead to a sizeable triangular flow v_3 which would be vanishing in an averaged fireball due to the overall geometry of the nuclear overlap. [2]. At large transverse momentum p_T fluctuations in the position of the hard process can also affect observables accessible in current heavy ion experiments.

Here we have explored the role of such fluctuations on the suppression of high-p_T hadrons and their generalized azimuthal asymmetry coefficients v_n. The v_n are defined as a Fourier decomposition of the azimuthal angle dependent spectrum

$$\frac{dN}{dp_T^2 d\Phi} = \frac{dN}{2\pi p_T dp_T} \left[1 + 2 \sum_{n>0} v_n(p_T) \cos(n\Phi + \delta_n) \right] \quad (1)$$

where the angle Φ is measured with respect to the reaction plane defined below and the δ_n are phases that encode a misalignment with the reaction plane. We note that for smooth, non-fluctuating fireballs we expect all odd coefficients v_1, v_3 etc. at midrapidity to vanish for symmetry reasons.

However, in any given single event the initial energy density will typically exhibit a non-vanishing triangular eccentricity ϵ_3 which could in turn lead to a non-vanishing v_3. The event-by-event fluctuations in initial energy density are driven by fluctuations of the positions of nucleons in the initial nuclei and in the amount of energy deposited around midrapidity for every nucleon-nucleon collision [3]. We also expect that the triangular eccentricity is not correlated with the

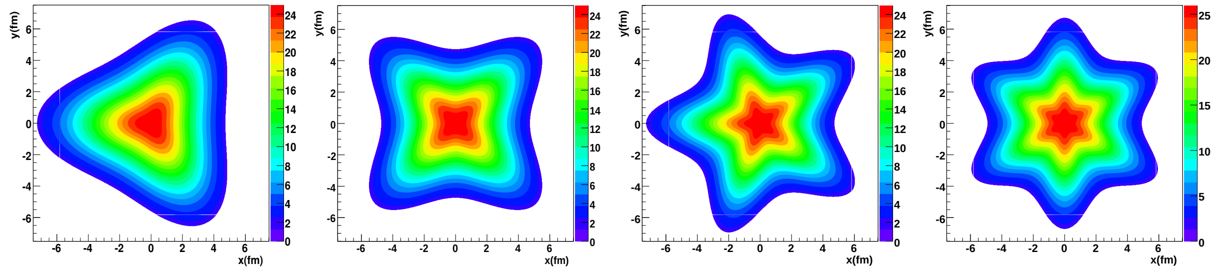


Figure 1. Engineered events with $n = 3, 4, 5, 6$

reaction plane, i.e. δ_3 should appear random. Similar arguments can be made for other $n > 0$ and we expect all odd v_n to acquire non-vanishing values with realistic fluctuations. While all of this has first been discussed for the bulk of the fireball [3] these statements easily transfer to hard probes. Fluctuations in the energy density lead to fluctuations in energy loss. In addition, the position of a hard process which creates a hard probe is subject to fluctuations.

Systematic measurements of v_n at large momentum could lead to further constraints on the type of energy loss prevalent in QGP, and on the size of the transport coefficient $\hat{q}$. It can also give an independent handle on the size and granularity of initial state fluctuations. Here we report on a quantitative study of high momentum azimuthal coefficients using a simple energy loss model with realistic fluctuations.

We calculate high momentum hadron spectra using our simulation package PPM [4, 5]. It samples initial momentum distributions of quark and gluon jets from a perturbative calculation and propagates leading partons through a given background fireball. Different energy loss models can be employed. Here we will show results from a simple LPM-inspired (sLPM) deterministic energy loss model $dE/dx \sim \hat{q}x$ where $\hat{q}$ scales with the 3/4th power of the local energy density [4]. As a cross check we will sometimes also use the non-deterministic Armesto-Salgado-Wiedemann (ASW) model [6, 7]. Fitted to the same experimental data on single hadron suppression these models cover a wide range of values for $\hat{q}$. PPM will eventually fragment leading partons into hadrons and all results here will be shown for pions.

We have used the Glauber Monte Carlo generator GLISSANDO [8] to produce an ensemble of Au+Au events at top RHIC energy using the three different centralities $b = 3.2,\ 7.4$ and 11 fm. However, first we check the general relation between the spatial eccentricities ϵ_n [9]

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle} \tag{2}$$

and the azimuthal asymmetry coefficients v_m using "engineered" events with particular fixed eccentricities. These are created with the energy density modeled as simple Gaussians in the transverse plane with a $\cos n\phi$ modulation of the mean square radius, as shown in the examples in Fig.1. Observe that r is the distance to the origin of the participant plane.

First we scanned the space (v_n, ϵ_m), $n, m = 1, 6$ in search of correlations. As expected we find non-zero v_n for a given ϵ_m only if $n = im$ where $i > 0$ is an integer. Next we explored the scaling of v_n with the size of the eccentricity ϵ_n. We expected a monotonically increasing function $v_n(\epsilon_n)$ which can be seen confirmed in Fig. 2. Deviations from monotonic behavior only occur for unrealistically large eccentricities. These basic results should hold if realistic fluctuations are considered. Fig. 3 shows the correlation between v_2 and ϵ_2 for our ensemble of GLISSANDO events for all 3 impact parameters for Au+Au collisions at top RHIC energies. The basic linear correlation persists for $n = 2$ but is washed out. Correlations for $n > 2$, not shown here, are much

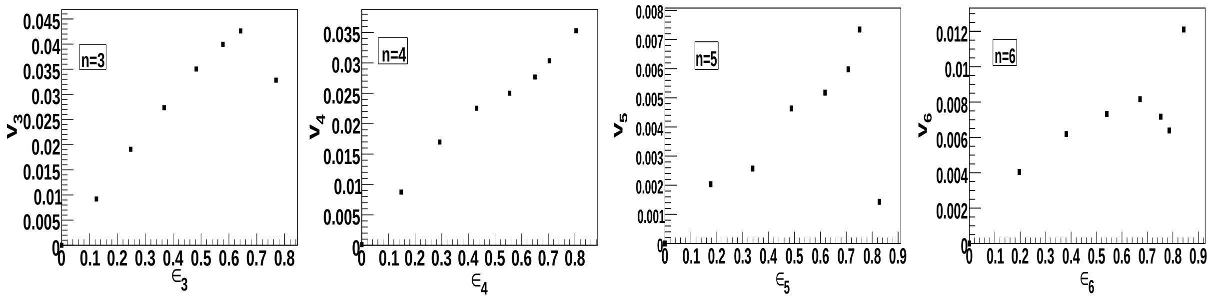


Figure 2. Azimuthal asymmetry v_n vs eccentricity ϵ_n in engineered events for $n = 3, 4, 5, 6$.

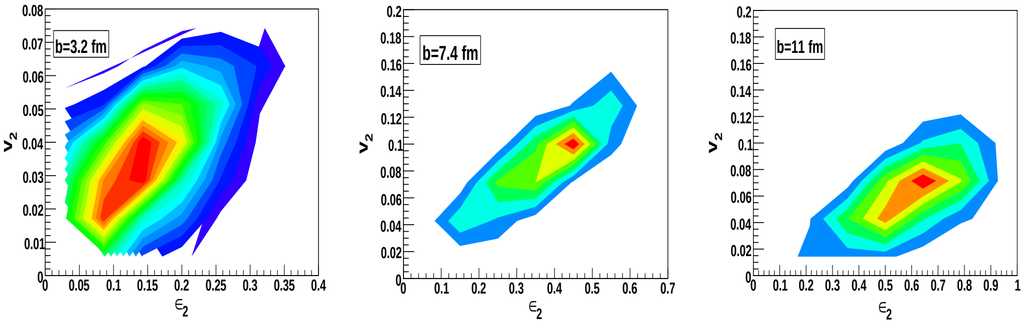


Figure 3. Correlation between v_2 and ϵ_2 for an ensemble of Au+Au collisions at top RHIC energy in GLISSANDO for three impact parameters 3.2, 7.4 and 11 fm.

more weakened to a point that makes it hard to predict v_n for a known ϵ_n. All results shown are for sLPM energy loss but the corresponding result for ASW show no noticable difference, making the conclusions rather robust against large variations in the microscopic origin of energy loss.

We determined the phases δ_n for high momentum pions in our ensemble of GLISSANDO events for three different impact parameters. In Fig. 4 we plot those phases relative to the reaction plane determined by the eccentricity ϵ_2. In other words our definition of a reaction plane is given by the fundamental initial ellipticity, which in general deviates from the plane defined by beam axis and impact vector. We observe that δ_3 and δ_5 are randomly distributed, so there is no correlation between the reaction plane and the fluctuations which create ϵ_3 or ϵ_5. This had also been found for the bulk azimuthal asymmetries before [9]. δ_4 and δ_6 on the other hand show a correlation with the reaction plane which is consistent with v_4 and v_6 receiving contributions from ϵ_2.

The transverse momentum dependence of the coefficients v_n for pions for our ensemble of GLISSANDO Au+Au events is shown in Fig. 5. We observe two hierarchies of coefficients, one being $v_2 > v_4 > v_6$ and the second one being $v_1 > v_3 > v_5$. v_2 is always the largest coefficient, even in the most central events. Interestingly v_1 is non-zero and the second largest coefficient, beating v_3 and v_4 by more than a factor 2. Momentum conservation dicatates a sum rule for v_1 integrated over p_T. The recoil of the medium in which energy is lost would lead to a negative v_1 at lower momentum. Such a back reaction is not included in this calculation. v_1 at intermediate and large p_T could be sensitive to the mechanism of medium recoil. Generally we point out that our results start to become unreliable below 4 to 6 GeV/c since transverse expansion was not included in the calculation. Fig. 5 shows the results for both sLPM and ASW energy

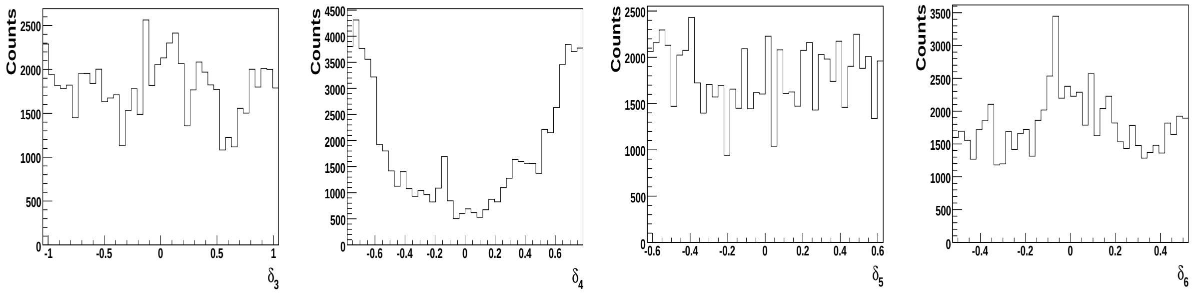
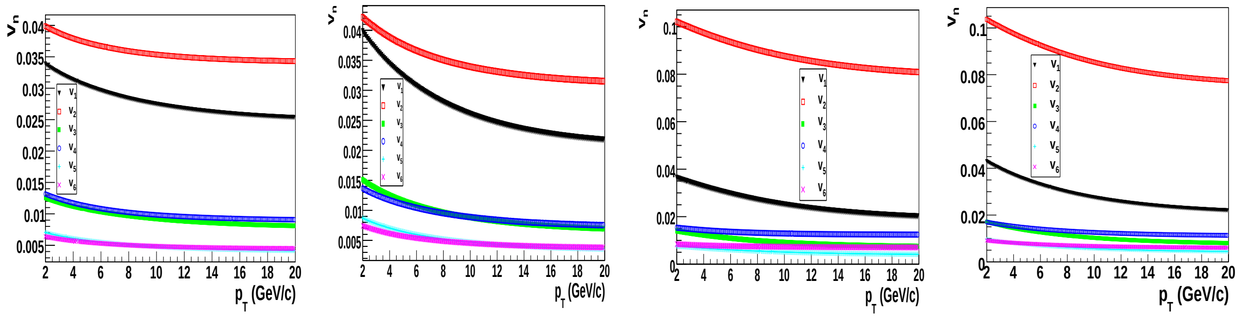


Figure 4. Distribution of the phases δ_n for $n = 3$, 4, 5, 6 in our ensemble of Au+Au events.



(a) sLPM, $b = 3.2\,\text{fm}$ (b) ASW, $b = 3.2\,\text{fm}$ (c) sLPM, $b = 7.4\,\text{fm}$ (d) ASW, $b = 7.4\,\text{fm}$

Figure 5. Pion v_n vs p_T for two impact parameters for Au+Au collisions at top RHIC energy, calculated with either sLPM or ASW energy loss.

loss. We have to conclude that azimuthal asymmetry coefficients are not particularly useful to discriminate between energy loss models. We also find that the p_T dependence of the coefficients becomes rather weak at large momenta.

To summarize, in this study we have explored higher order azimuthal asymmetry coefficients at large momentum in heavy ion collisions. We find that in general v_n rises with ϵ_n but this correlation weakens for larger n. We also find that there are only a few cross correlations between v_n and ϵ_m. We have also classified the preferred angular orientation of the azimuthal asymmetries as given by the phases δ_n with respect to the second order participant plane. We find a decorrelation with the reaction plane for all odd n. Finally we have made predictions for v_n as a function of p_T in two different energy loss models. We find mostly consistent results between those two models with v_2 being the largest coefficient followed by v_1. In general the v_n carry important geometrical information and measurements at large momentum can be complementary to those for bulk observables, but they seem less useful to distinguish different energy loss models.

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