Testing the flow harmonic formalism for heavy-ion collisions with toy Monte-Carlo simulation

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1 Introduction

In the ultra-relativistic heavy ion physics course (FYSS4551) we learn about the extremely hot and dense medium called Quark Gluon Plasma (QGP) and some of its properties and signatures. One physics concept of QGP is the flow of the medium. An important factor of flow is the collision geometry which affects the momentum anisotropy. The momentum anisotropy can be expressed with a Fourier decomposition of the azimuthal particle distribution with respect to the reaction plane,

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n cos\left(n(\phi - \psi_n)\right). \tag{1}$$

In Eq. (??) v_n is the flow coefficient, i.e. the magnitude of the n-th order flow, and the ψ_n the symmetry plane.

The goal for this part of the course was to learn and get a deeper understanding of the different methods on how to calculate the flow coefficients and about the the QGP in general, e.g. are there fluctuations in the azimuthal distribution? or when do we get the largest flow? For this specific task we calculated the 2nd to 7th order flow. This was done with a programming exercise and the results will be presented in this report.

The two main methods used for calculating the flow coefficients are the event plane method and two particle cumulant method. For the Event plane method v_n is calculated as

$$v_n = \langle cos[n(\phi_i - \psi_n)]\rangle , \tag{2}$$

averaged over number of events. The symmetry plane ψ_n was calculated first analytically, meaning that ψ_n was sampled from a uniform distribution for $-\pi/n < \psi_n < \pi/n$. However, a more realistic way, and how it is done in experiments, of calculating v_n using the event plane method is using Q-vectors,

$$Q_{n,x} = \sum_i w_i cos(n\phi_i), Q_{n,y} = \sum_i w_i sin(n\phi_i). \tag{3}$$

where w_i is the weight for a particle i and in this study put to 1. The ϕ_i is still the azimuthal angle of particle i. The Q-vectors are then used to get the event plane angle,

$$\psi_{EP} = \frac{1}{n} arctan\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \tag{4}$$

Putting ψ_{EP} into Eq. (??) gives the observed flow coefficients, v_n^{obs}. In order to get the "true" value of the flow coefficient, one has to correct for the resolution by

$$v_n = \frac{v_n^{obs}}{R}, \tag{5}$$

where R is given by $R = \langle cos\left[n(\psi_n - \psi_{EP})\right]\rangle$.

The two particle cumulant method uses the correlation of azimuthal angles of two particles, ϕ_1 and ϕ_2. After a few steps of calculations, details shown in lecture notes [1], it is shown that the single particle flow coefficient, v_n, is the square root of the pair flow coefficient, $v_{n\Delta}$,

$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n^2 cos\left(n\Delta\phi\right), \tag{6}$$

and the coefficients are calculated as an average over all pairs of particles

$$v_{n\Delta} = v_n^2 = \langle cos[n(\phi_i - \phi_j)]\rangle\,. \tag{7}$$

The code written for this project can be found in GitHub at `https://github.com/aonnerst/ToyMCFlowAO`.

2 Results

The first part of this study was to check the ϕ-distribution for different events and centralities. In the main macro 10 events are checked for three different centralities, however, in Fig. 1 only three events are shown, one from each centrality bin. This was done in order to check whether the ϕ-distribution fluctuates or not. What can be seen in Fig. 1 is that it indeed does fluctuate for each event, both in amplitude and shape.

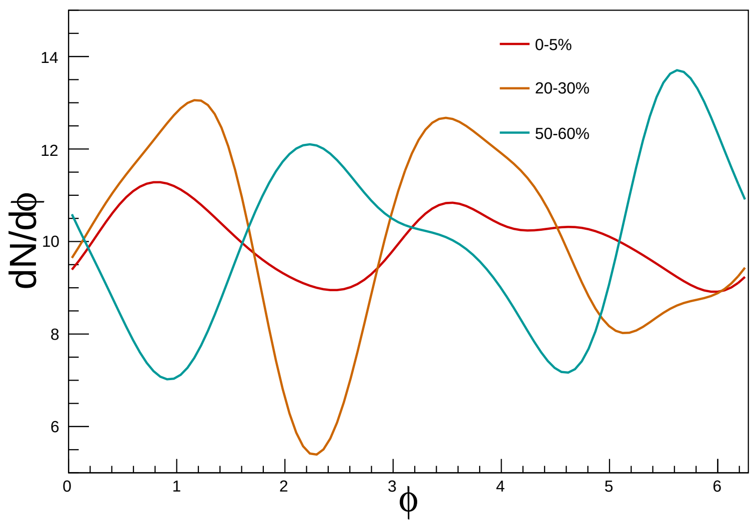

Figure 1: Phi distribution for three different events and three different centrality classes.

The second part of this study was to calculate the flow coefficients using the event plane method and to plot the $\Delta\phi = \phi - \psi_n$ distribution. The $\Delta\phi = \phi - \psi_n$ distribution for centrality class $20 - 30\%$ is presented in Fig. 2. The different harmonics are clearly seen and the values for v_n agrees well with the input values. The results for the other centrality classes are found in appendix.

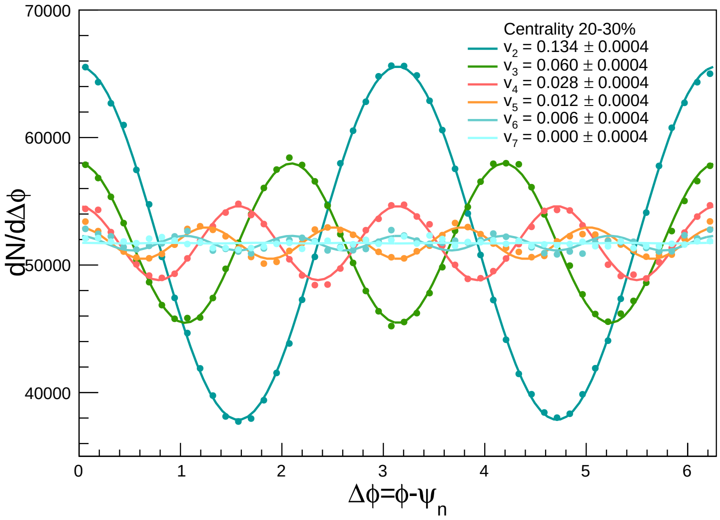

Figure 2: This figure was produced using the event plane method and what is seen is the $\Delta\phi = \phi - \psi_n$ distribution for the second to seventh order flow for the $20-30\%$ centrality class.

In Fig. 3, the results from the two particle method is presented for the $20 - 30\%$ centrality class. Here the $\Delta\phi$ is calculated as $\phi_1 - \phi_2$ and the sum of all harmonics are shown (black dots). This summed distribution was fitted with eq 6 and from the fit one gets the different harmonics that are shown in colored lines. Once again, centrality class $20 - 30\%$ produces values of v_n closest to input values.

Fig. 4 shows the centrality dependence for the different harmonics and using the different methods to extract the value for v_n are shown. The different methods presented here is the Single Plane method (SP), the Two Particle cumulant method (TP), and the v_n value extracted from the single particle angle distribution and from the two particle angle distribution. It is clearly seen that the uncertainty increases with increasing harmonics. Another observation is that the $20-30\%$ centrality class gives the highest flow coefficient value up until n=5.

In Fig. 5 the power spectra is reconstructed from the event plane method, using the symmetry plane angle, in red, and the two particle cumulant method in yellow. The green line corresponds to to the input values of the flow coefficients. The best agreement between the input values and the two different methods is for centrality class $20 - 30\%$ where they agree up n=6. For the more central events $(0 - 5\%)$ and the peripheral events $(50 - 60\%)$ there is a good agreement up until n=4 for both methods, however, the event plane method deviates from n=5 and up. The two particle cumulant method seems to agree better than the event plane method

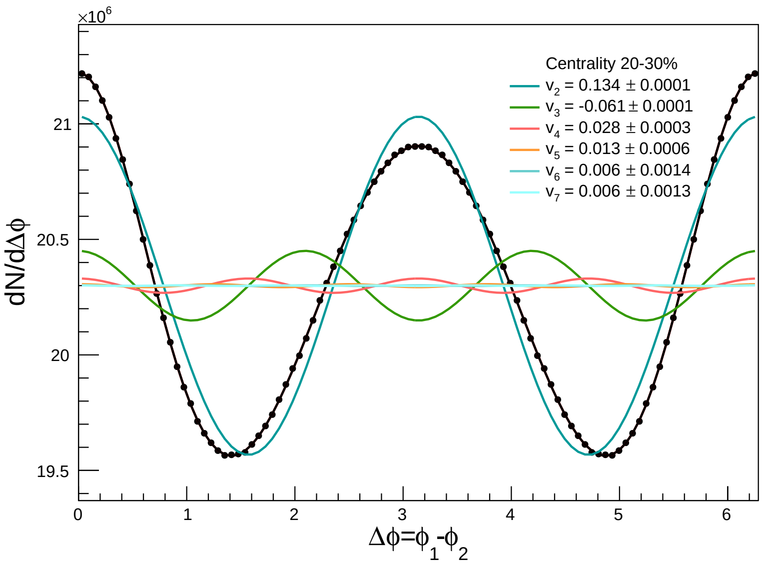

Figure 3: This figure was produced using the two particle cumulant method and what is shown is the $\Delta\phi = \phi_1 - \phi_2$ distribution for the second to seventh order flow for the $20-30\%$ centrality class. The black dots represents the sum of the $\Delta\phi$ values for all harmonics and the lines represents the fits.

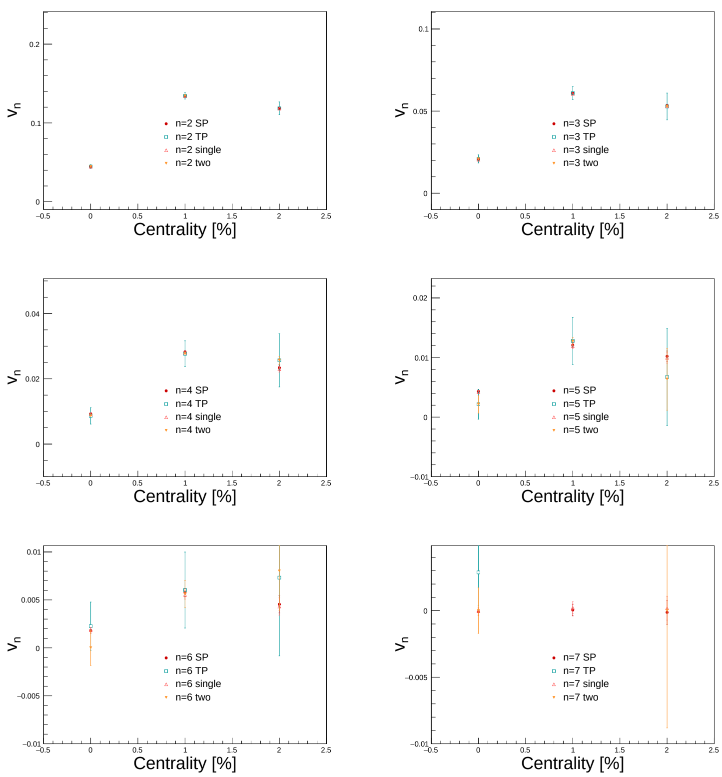

Figure 4: The flow coefficient values as a function of the three different centrality classes is here shown for each flow harmonic from n=2 to n=7.

for these two centrality classes, this method agrees well up to n=6 for $0-5\%$ but starts do deviate from n=5 for $50-60\%$, however the deviation is not as large as for the event plane method.

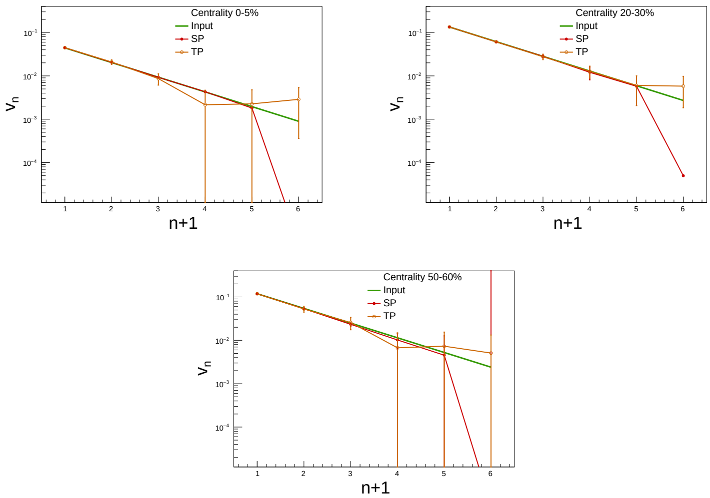

Figure 5: Power spectra reconstructed from the event plane method using the symmetry plane angle, and the two particle cumulant method.

3 Summary

In this report I have presented that the basic formalism for calculating the particle flow coefficients works well within uncertainties from lower to higher order harmonics. From the ϕ-distribution we learned that it fluctuates per event and for different centralities. We also learned that for both methods used the agreement between the input values and the calculated values for the flow coefficients was best for the mid-central centrality class. For the centrality dependent distributions it is shown that the mid-centrality class gives the largest flow coefficient value, which agrees with what has been previously observed. The power spectra makes it possible to see how well the different methods agrees, and it was observed that the mid-central collisions had the best agreements.

4 Appendix

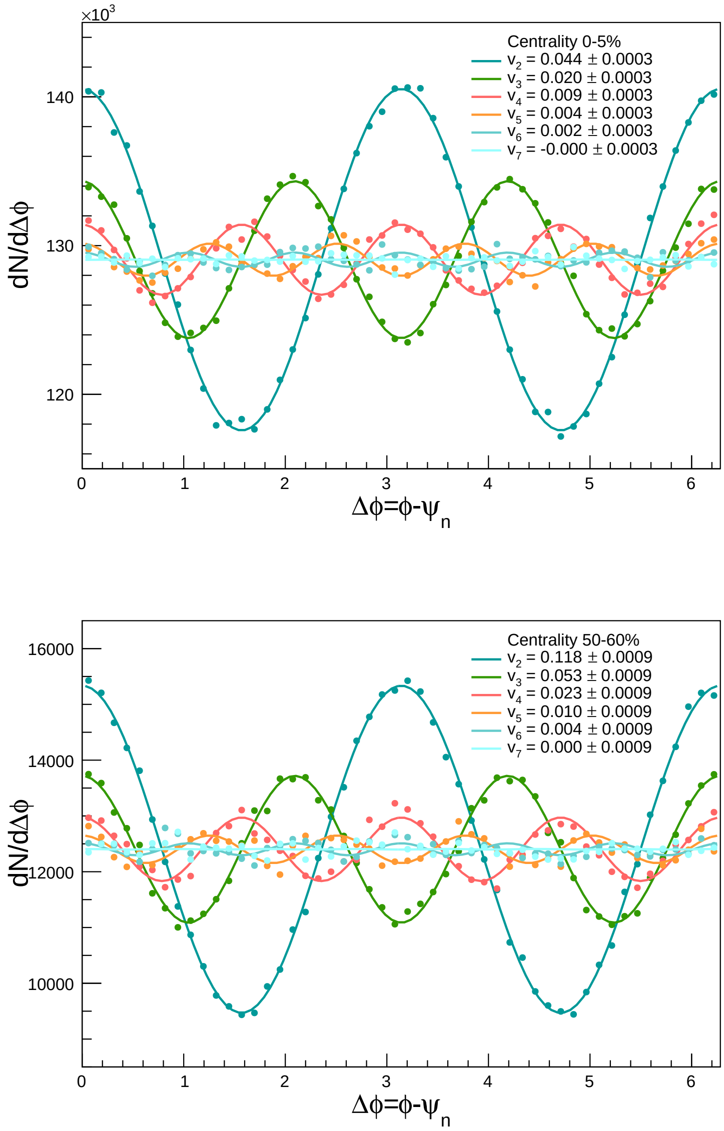

Figure 6: The $\Delta\phi = \phi - \psi_n$ (event plane method) distribution for the $0-5\%$ and $50-60\%$ centrality classes respectively.

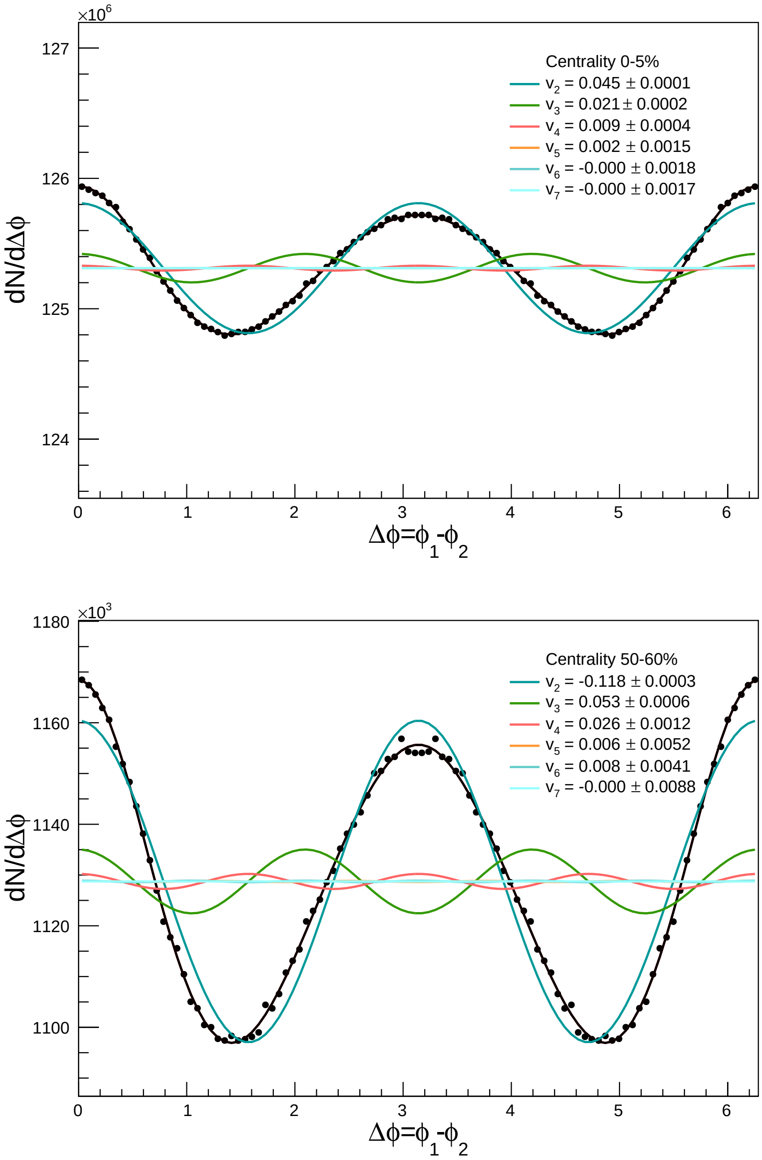

Figure 7: The $\Delta\phi = \phi_1 - \phi_2$ (two particle cumulant method) distribution for the $0 - 5\%$ and $50 - 60\%$ centrality classes respectively.

Bibliography

[1] Kim DJ. Flow measurement in Heavy-Ion Collisions;. https://moodle.jyu.fi/pluginfile.php/322393/mod_resource/content/1/flow.pdf.