Motivation

- Properties of Quark-Gluon Plasma (QGP): determination of the transport properties through the shear and bulk viscosity to entropy ratio $\eta/s$ and $\zeta/s$, respectively.

Hydrodynamic models demonstrate a linear dependency between the second and third order flow and eccentricity $v_2 \propto \varepsilon_{2}$. Given the effect of $\eta/s$ on hydrodynamic evolution, measurements of the second and third harmonic flow may be used to extract the $\eta/s$ and $\zeta/s$ of QGP. However, it turns out that:

- the initial state uncertainty complicates the extraction of $\eta/s$.
- relative contribution from initial conditions and $\eta/s$ and $\zeta/s$ should be better understood.

Models in review

Five different parameterizations of $\eta/s$, $\zeta/s$ used for the hydrodynamic model calculations are shown in the right panel.

A comparison to 5 different hydrodynamic configurations is provided.

Non-linear response

Higher harmonics are inherently more sensitive to $\eta/s$. These higher harmonics ($n \geq 4$) on the other hand, exhibit no linear relation to initial state anisotropies.

Assumption of the linear relation breaks as soon as $n \geq 4$.

It has been demonstrated, that the higher order harmonics are partly induced by the initial state anisotropy of the lower orders. This has led to an understanding, that the high order flow can be decomposed as a superposition of linear and non-linear response, where the latter originates from the lower order harmonics. In terms of flow vectors $V_n \equiv \langle v^{\text{nonlin}} \rangle \propto v^{\text{nonlin}}$, this is

$$\begin{align*}
V_1 &= V_L + \chi_2 v_2^2 \\
V_2 &= \chi_2 v_2^2 + \chi_3 v_3 V_1 \\
V_3 &= \chi_2 v_2^2 + \chi_3 v_3 V_1 + \chi_4 v_4 V_2 \\
\vdots
\end{align*}$$

(1)

where $\chi_n$ are the non-linear mode coefficients.

Conclusions

- Cross harmonic decomposition: access to higher order relations $v_n \propto \varepsilon_n$ for more sensitive $\eta/s$ response.
- Better constraints on initial conditions and $\eta/s(T)$, $\zeta/s(T)$ with improved precision and extended harmonic orders.
- Further tuning required to accurately constrain $\eta/s$.

For preliminary measurements of higher order harmonics, see https://indico.cern.ch/event/703015/contributions/3095151/.