Linear and Non-linear Flow Mode in 5TeV Pb–Pb

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ALICE

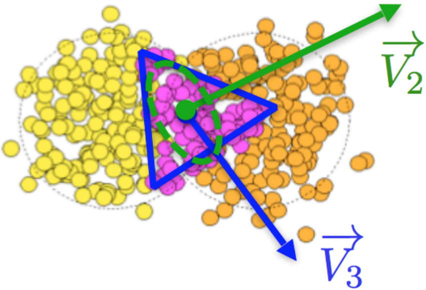
Initial and final state anisotropy in heavy-ion collisions

Initial (coordinate space) anisotropy (example definition):

$$\varepsilon_n \mathrm{e}^{in\Phi_n} \equiv -\frac{\langle r^n \mathrm{e}^{in(\phi-\Phi_n)}\rangle}{\langle r^n \rangle}. \qquad (1)$$

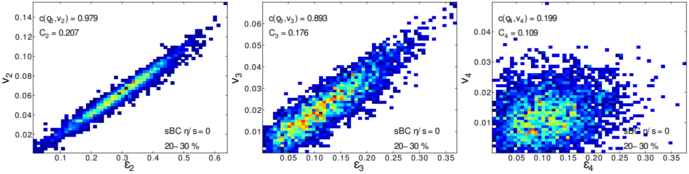
Final (momentum space) anisotropy:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto \frac{1}{2\pi}\sum_{n=-\infty}^{\infty} \underbrace{\langle \mathrm{e}^{in\phi}\rangle}_{V_n} \mathrm{e}^{-in\phi}, \qquad (2)$$



where $V_n \equiv \langle \mathrm{e}^{in\phi}\rangle = v_n \mathrm{e}^{in\psi_n}$.

A linear relation $v_n \mathrm{e}^{in\psi_n} = k\varepsilon_n \mathrm{e}^{in\Phi_n}$ is sufficient in case of $n = 2, 3$:

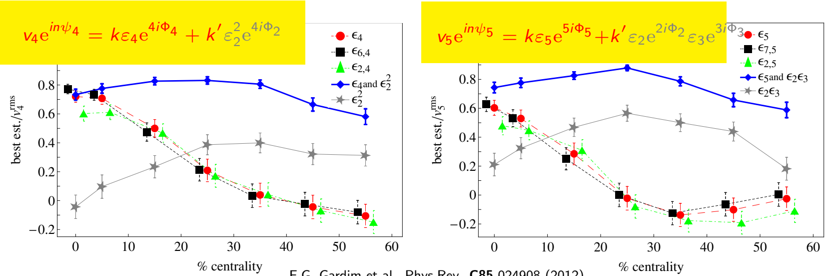


H. Niemi, G. S. Denicol, H. Holopainen, P. Huovinen, Phys.Rev. **C87** 054901 (2013)

Low harmonic relations inadequate as a constraint for QGP η/s

Non-linear decomposition

The higher order $n \geq 4$ requires a non-linear term:



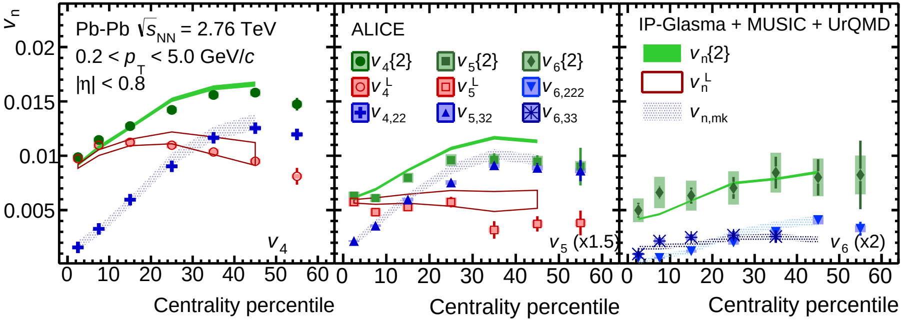
F.G. Gardim et al., Phys.Rev. **C85** 024908 (2012)

Combining the low and high order relations, one can write

$$
\begin{aligned}
V_4 &= V_{4L} + \chi_{4,22} V_2^2 \\
V_5 &= V_{5L} + \chi_{5,32} V_2 V_3 \\
V_6 &= V_{6L} + \chi_{6,222} V_2^3 + \chi_{6,33} V_3^2 + \chi_{6,2\hat{4}} V_2 V_{4L} \\
&\dots
\end{aligned} \tag{3}
$$

where χ_n are the non-linear flow mode coefficients. The magnitudes of the response are measurable ($\rightarrow$backup).

Flow modes (2.76 TeV, 2016)



Phys.Lett.**B773** 68-80 (2017)

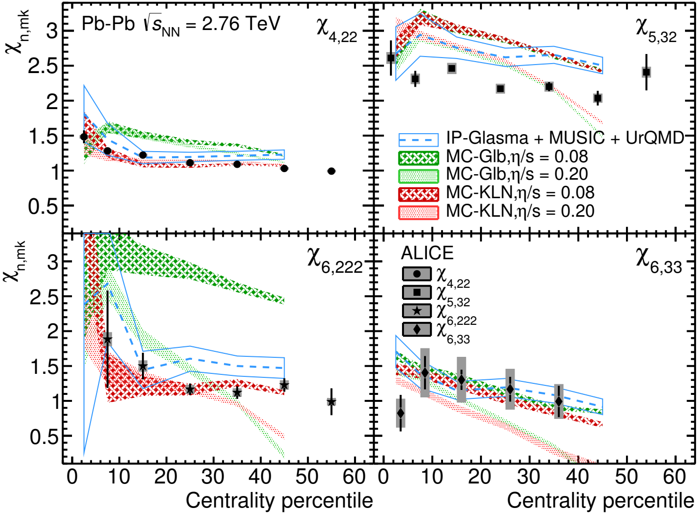
- Linear component dominant in central collisions
- Non-linear component increasing to dominant for more peripheral collisions

Non-linear flow mode coefficients (2.76 TeV, 2016)

Four coefficients have been measured by ALICE. Of these

- $\chi_{5,32}$, $\chi_{6,33}$ are insensitive to initial state
- $\chi_{4,22}$, $\chi_{6,222}$ are insensitive to η/s
- all have a centrality dependence

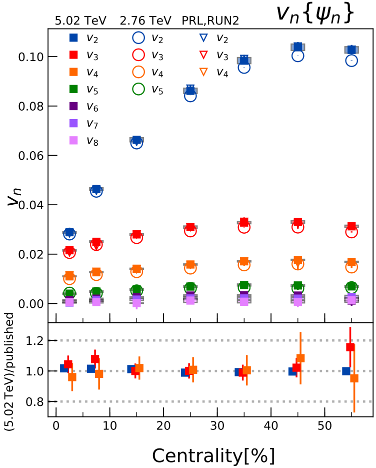
Hydrodynamic calculations mostly agree, except for $\chi_{5,32}$.

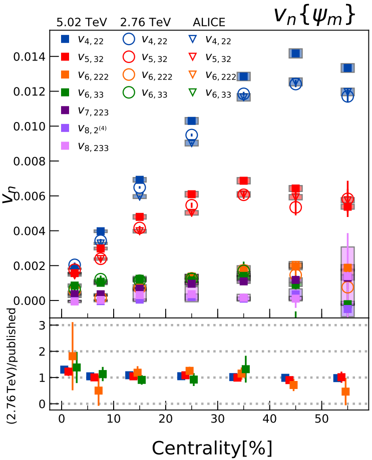


Phys.Lett.**B773** 68-80 (2017)

Flow harmonics (5.02 TeV)

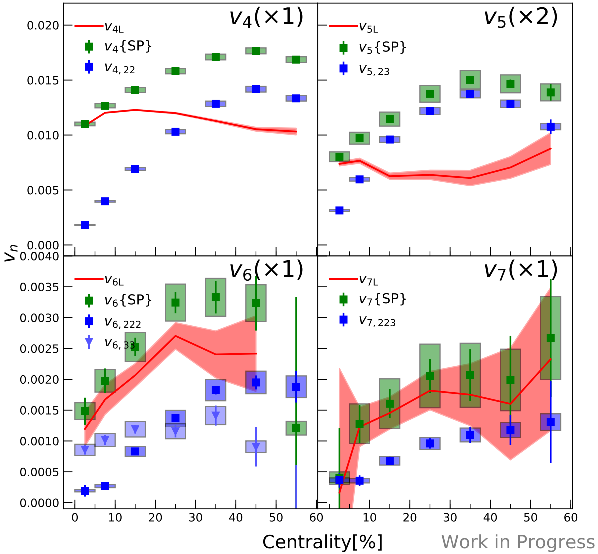
Improved statistics (13M→35M min. bias Pb–Pb) allow the measurement of the flow and its projections up to the 8^{th} harmonic order.





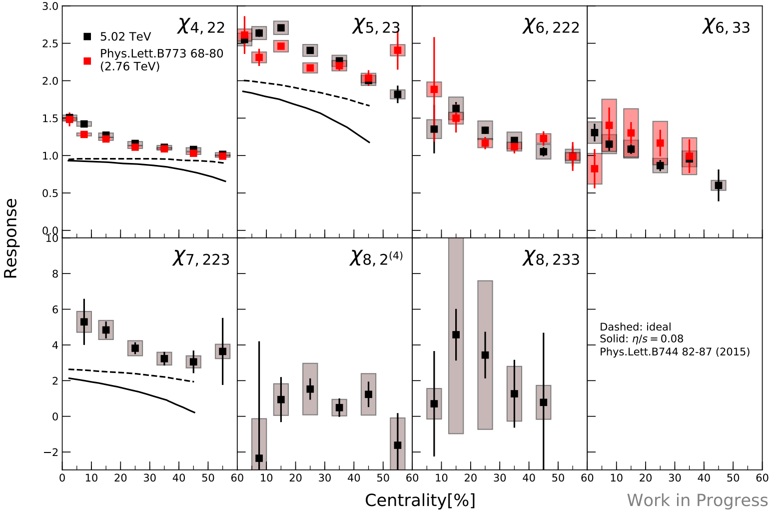
- **PRL,RUN2**: PRL.116.132302 (v_n 5.02 TeV)
- **ALICE** arXiv:1705.04377 ($v_n\{\psi_m\}$ 2.76 TeV)

Flow modes (5.02 TeV)



- High energy measurements follow the trend of the previous results
- $n = 6, 7$: Linear component dominant in the whole centrality range
- Good v_6 precision!
- Tracking systematics large, will be resolved. . .

Non-linear flow mode coefficients (5.02 TeV)



New measurements agree with the low energy results ($\chi_{5,23}$?). $\chi_{7,223}$ is now measurable with good precision. The hydro predicts a significant η/s dependency for the seventh coefficient.

Summary

- The outcome of the linear–non-linear decomposition provides improved constraints for the QGP η/s
- Following the previous low energy measurements, the non-linear flow mode coefficients have been measured up to the eighth order at $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$
- Larger statistics provide better precision over previous measurements. Higher harmonics can be measured.
- Various other correlations not shown here also measured
- Result finalizing in progress (reduction of uncertainty, etc.)

Backup

Linear mode

Mean-squaring Eq. (3) and assuming non-correlation* between terms

$$\langle |V_4|^2 \rangle = \langle |V_{4L}|^2 \rangle + \chi_4^2 \langle |V_2|^2 \rangle^2 + 2\chi_4 \underbrace{\langle (V_2^*)^2 V_{4L} \rangle}_{\simeq 0} \quad (4)$$

the magnitude of the linear part is acquired:

$$\underbrace{\langle |V_{4L}|^2 \rangle^{\frac{1}{2}}}_{v_{4L}} = \Big(\underbrace{\langle |V_4|^2 \rangle}_{(v_4\{\psi_4\})^2} - \underbrace{\chi_4^2 \langle |V_2|^2 \rangle^2}_{v_{4,NL}^2} \Big)^{\frac{1}{2}}. \quad (5)$$

*** The assumption has been tested in**
Phys.Lett.B742 94-98 (2015) and Phys.Lett.B773 68-80 (2017)

Non-linear mode

The non-linear part is obtained by projecting Eq. (3) onto lower harmonics. The harmonic projections

$$v_4\{\psi_2\} = \frac{\Re\langle V_4(V_2^*)^2\rangle}{\sqrt{\langle|V_2|^4\rangle}}, \quad v_5\{\psi_{23}\} = \frac{\Re\langle V_5 V_2^* V_3^*\rangle}{\sqrt{\langle|V_2|^2|V_3|^2\rangle}}, \quad \cdots \tag{6}$$

are constructed to be symmetrically valid. Using the projections on Eq. (3), for V_4:

$$\underbrace{\frac{\Re\langle V_4(V_2^*)^2\rangle}{\sqrt{\langle|V_2|^4\rangle}}}_{v_4\{\psi_2\}} = \underbrace{\frac{\Re\langle V_{4L}(V_2^*)^2\rangle}{\sqrt{\langle|V_2|^4\rangle}}}_{\simeq 0} + \frac{\Re\langle\chi_{4,22}\overbrace{V_2^2(V_2^*)^2}^{|V_2|^4}\rangle}{\sqrt{\langle|V_2|^4\rangle}} \rightarrow \chi_{4,22} = \frac{\Re\langle V_4(V_2^*)^2\rangle}{\langle|V_2|^4\rangle}, \tag{7}$$

from which also $v_{4,NL} = v_4\{\psi_2\}$ for Eq. (5). Similarly,

$$\chi_{5,23} = \frac{\Re\langle V_5 V_2^* V_3^*\rangle}{\langle|V_2|^2|V_3^2|\rangle}, \quad \chi_{6,222} = \frac{\Re\langle V_6(V_2^*)^3\rangle}{\langle|V_2|^6\rangle}, \quad \chi_{6,33} = \frac{\Re\langle V_6(V_3^*)^2\rangle}{\langle|V_3|^4\rangle}, \quad \cdots \tag{8}$$

for each harmonic and its one or more non-linear modes.