Linear and non-linear flow modes in Pb–Pb at $\sqrt{s_{NN}}$=5.02 TeV

Jasper Parkkila for the ALICE Collaboration University of Jyväskylä

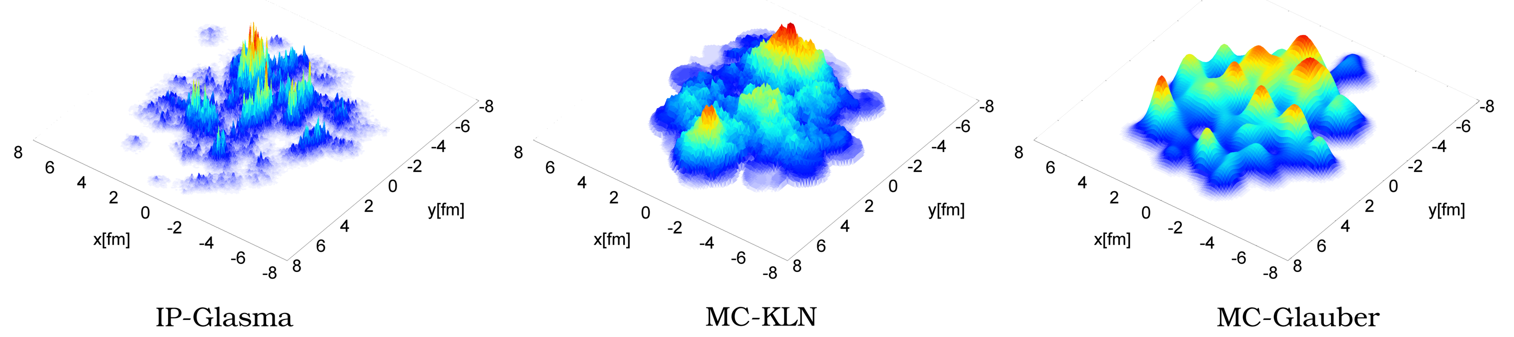
UNIVERSITY OF JYVÄSKYLÄ HELSINKI INSTITUTE OF PHYSICS ALICE

Motivation

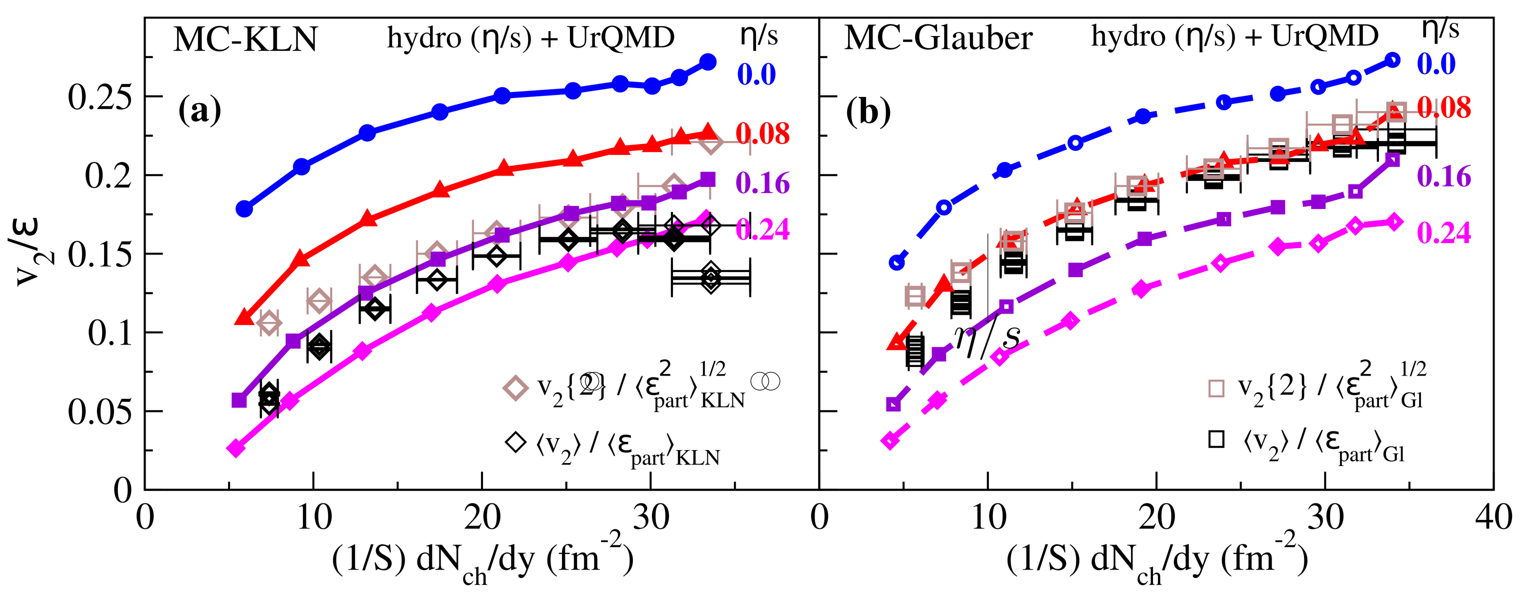
- Properties of Quark-Gluon Plasma (QGP): determination of the transport properties through the shear and bulk viscosity to entropy ratio η/s and ζ/s, respectively.

Hydrodynamic models demonstrate a linear dependency between the second and third order flow and eccentricity $v_n \propto \varepsilon_n$. Given the effect of η/s on hydrodynamic evolution, measurements of the second and third harmonic flow may be used to extract the η/s and ζ/s of QGP. However, it turns out that

- the initial state uncertainty complicates the extraction of η/s
- relative contribution from initial conditions and η/s and ζ/s should be better understood.



B. Schenke, P. Tribedy and R. Venugopalan, *Phys.Rev.Lett.* **108** 252301 (2012)



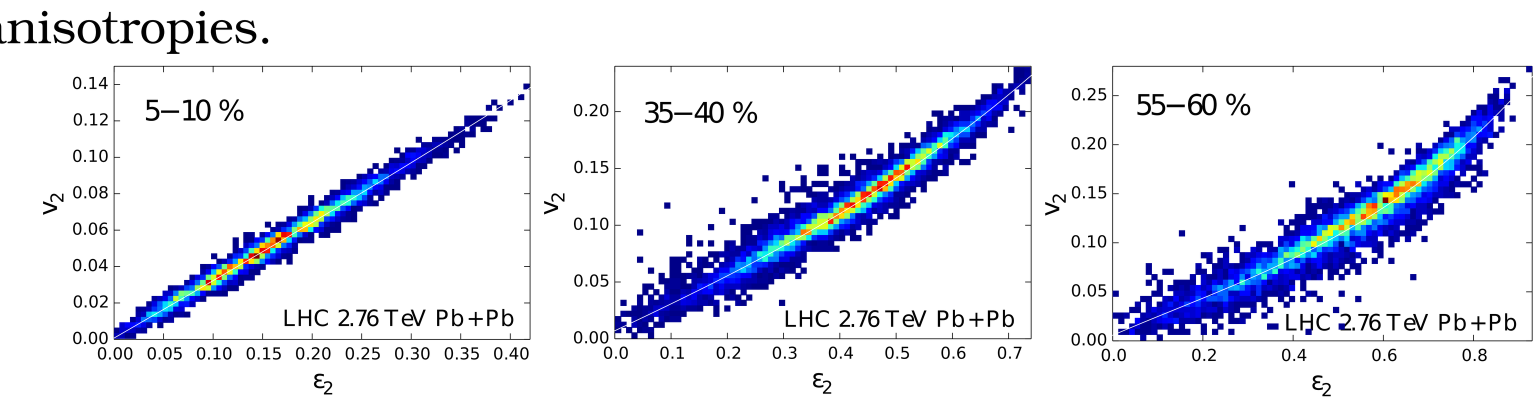
C. Shen et al., *J.Phys.* **G38** 124045 (2011)

Different energy density profiles yield incompatible results on η/s.

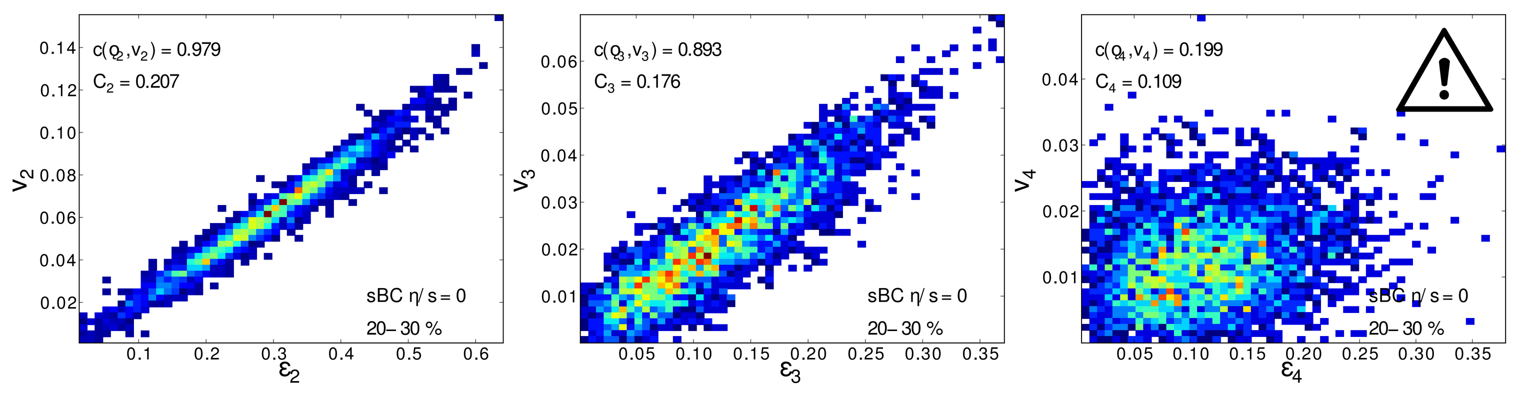
In the light of these limitations, more sensitive observables are required.

Non-linear response

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



H. Niemi, K. J. Eskola, R. Paatelainen, *Phys.Rev.* **C93** 024907 (2016)



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

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 $V_n \equiv \langle e^{in\phi} \rangle = v_n e^{in\psi_n}$ this is

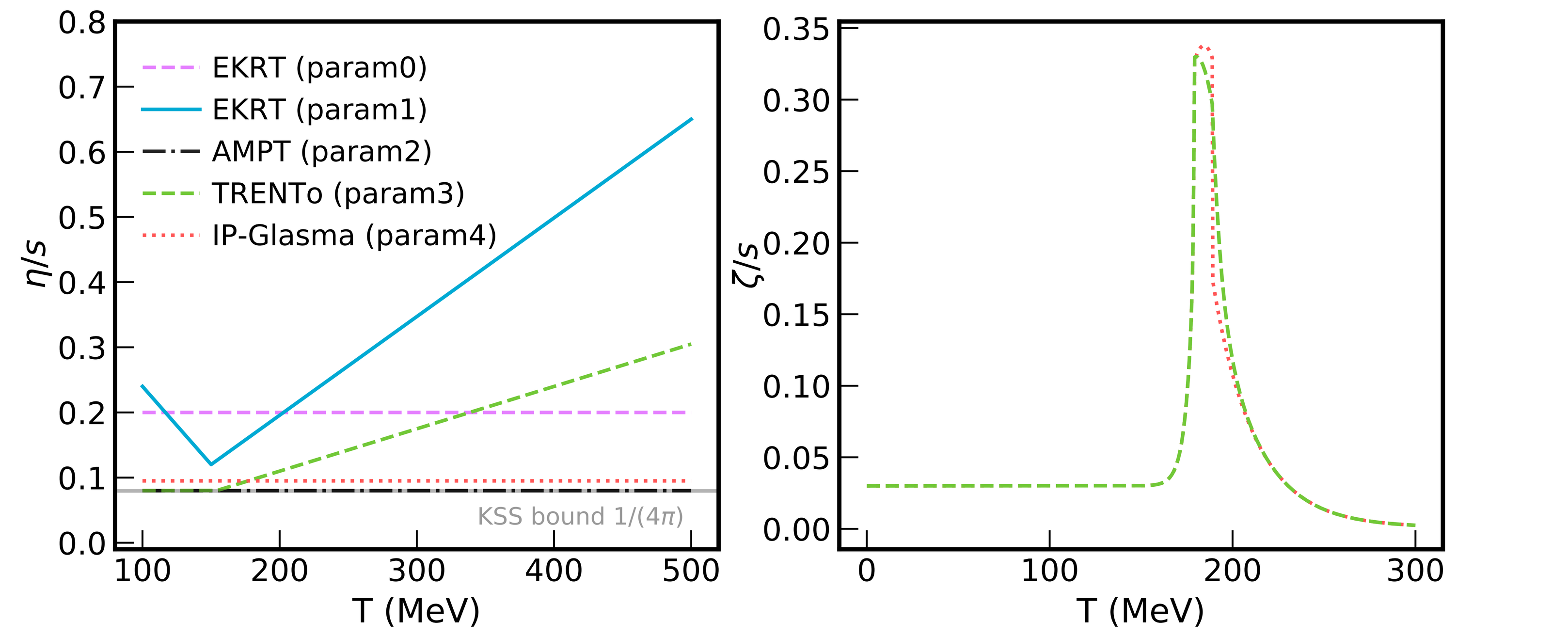
$$\begin{aligned} V_4 &= V_{4L} + \chi_{4,22} V_2^2 \\ V_5 &= V_{5L} + \chi_{5,32} V_2 V_3 \\ V_6 &= V_{6L} + \chi_{6,222} V_2^3 + \chi_{6,33} V_3^2 + \chi_{6,24} V_2 V_{4L} \\ &\dots \end{aligned} \quad (1)$$

where χ_n are the non-linear mode coefficients.

Conclusions

- Cross harmonic decomposition: access to higher order relations $\varepsilon_n \propto v_n$ for more sensitive η/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 η/s.

Models in review

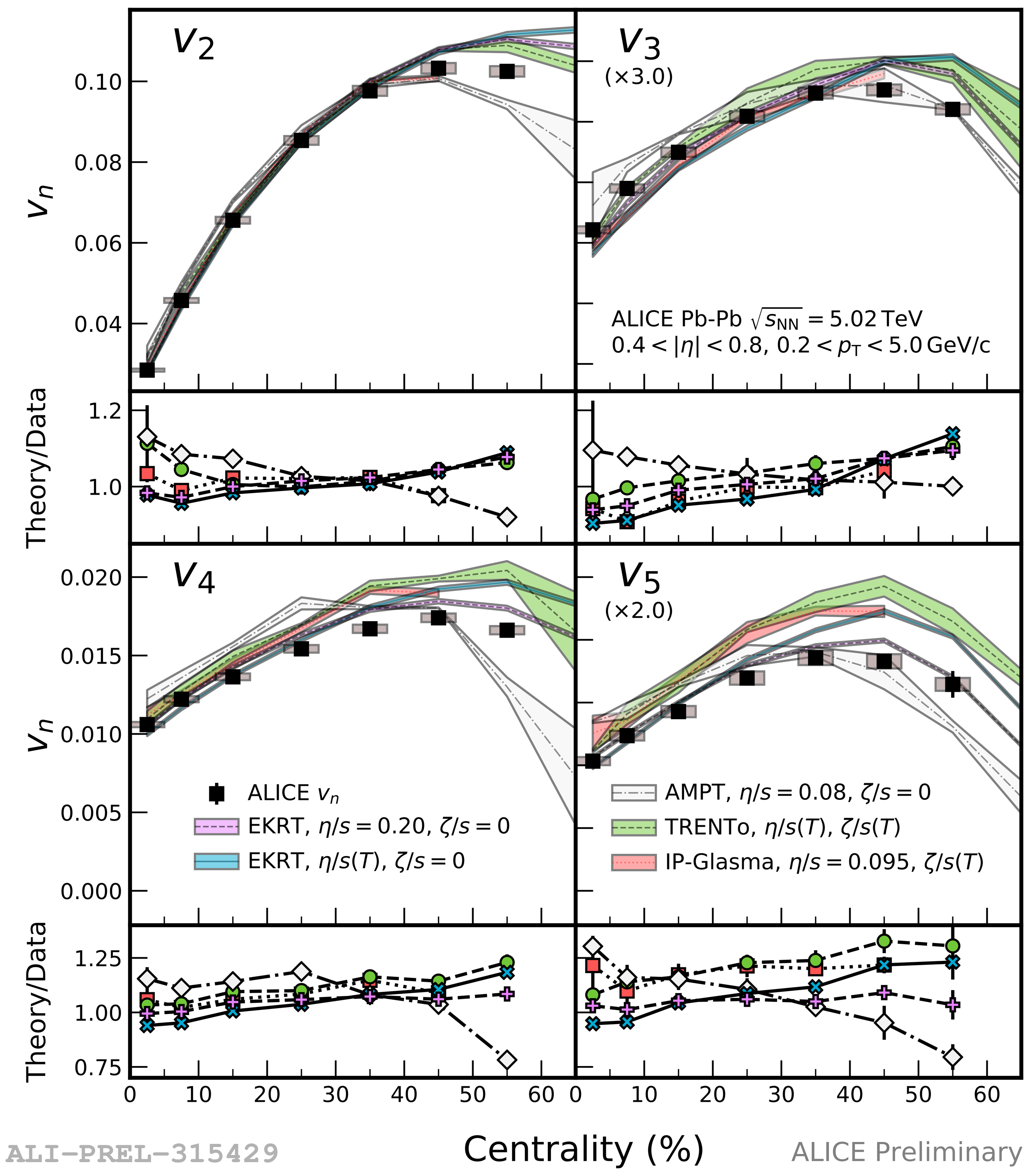


Five different parameterizations of η/s (ζ/s) used for the hydrodynamic model calculations are shown in the left (right) panel.

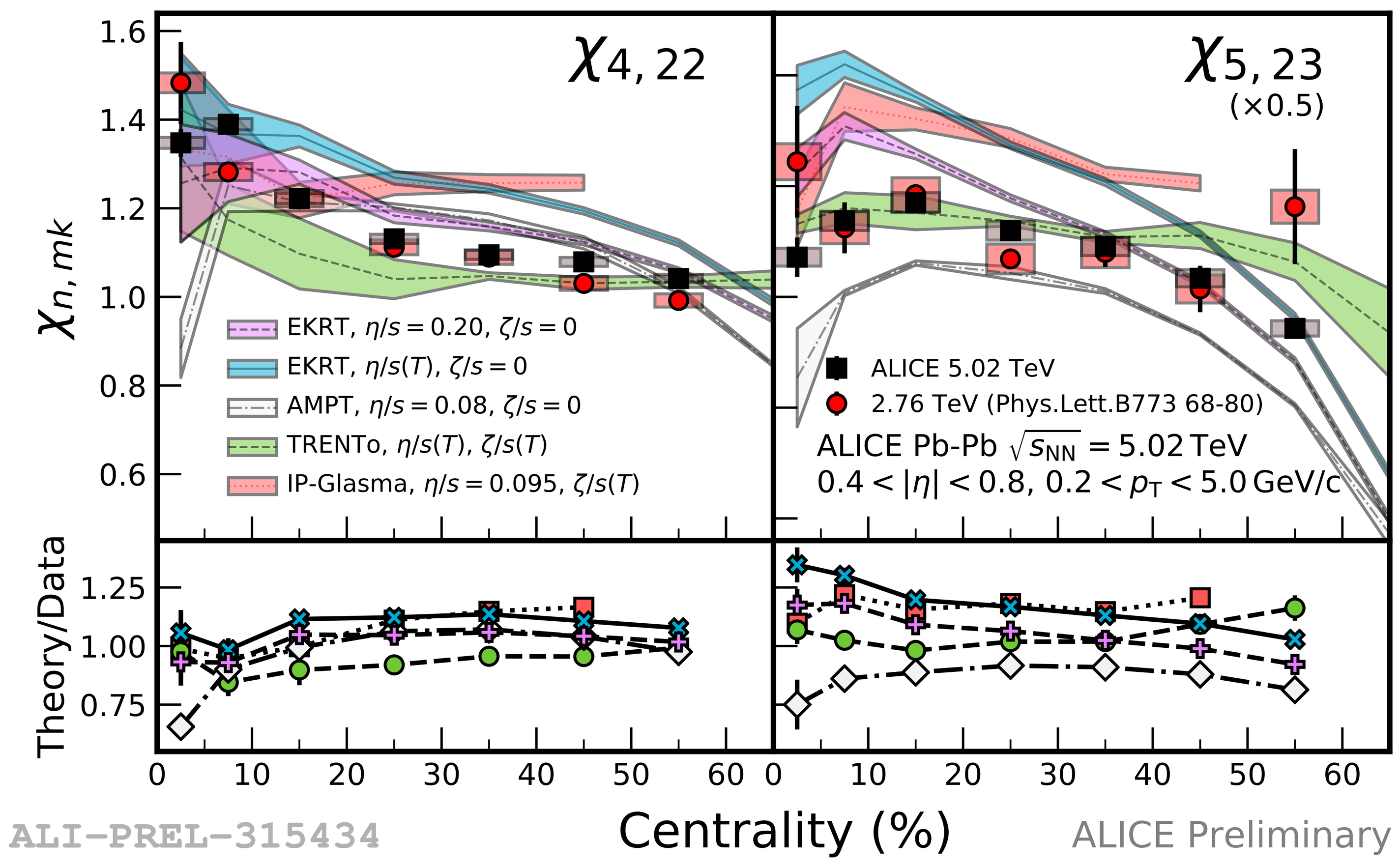
A comparison to 5 different hydrodynamic configurations is provided.

Model	Hydrodynamic code	Initial conditions	η/s	ζ/s
EKRT+EbyE+param0	EbyE	EKRT	0.20	0
EKRT+EbyE+param1	EbyE	EKRT	$\eta/s(T)$	0
AMPT+VISHNU+param2	iEBE-VISHNU	AMPT	0.08	0
TRENTo+VISHNU+param3	iEBE-VISHNU	TRENTo($p=0$)	$\eta/s(T)$	$\zeta/s(T)$
IP-Glasma+MUSIC+param4	MUSIC	IP-Glasma	0.095	$\zeta/s(T)$

Results



Discrepancies between data and models become clearly visible at $n=5$. EKRT describes the data for v_5 in peripheral collisions.



Model reproduction of non-linear mode cofficients at $n=5$ (right). In this case, TRENTo captures the data in central to mid-central collisions, while other models under- or overestimate.

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