Determining the initial conditions and transport properties of quark-gluon plasma by flow measurements at the LHC

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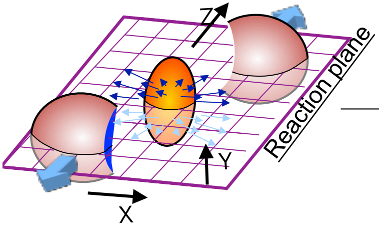
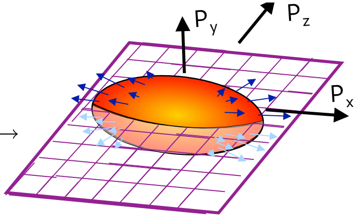
Anisotropic Flow

Initial geometry fluctuations $\rightarrow$ **Transport** $\delta_\mu T^{\mu\nu} = 0$ $\rightarrow$ final-state particles





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

$$\varepsilon_n \mathrm{e}^{in\Phi_n} \equiv -\frac{\langle r^n \mathrm{e}^{in(\phi-\Phi_n)} \rangle}{\langle r^n \rangle}, n \geq 2. \tag{1}$$

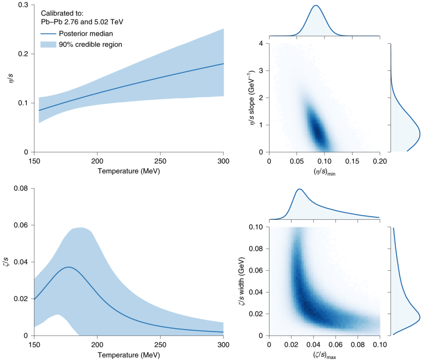
(theory only - Initial State models)

where $V_n \equiv \langle \mathrm{e}^{in\phi} \rangle = v_n \mathrm{e}^{in\psi_n}$. (experiments, theory - hydro+hadronization models with $\eta/s(T)$, $\zeta/s(T)$)

- Collectivity as a probe to the properties of the medium – transport properties such as $\eta/s(T)$, $\zeta/s(T)$, IS

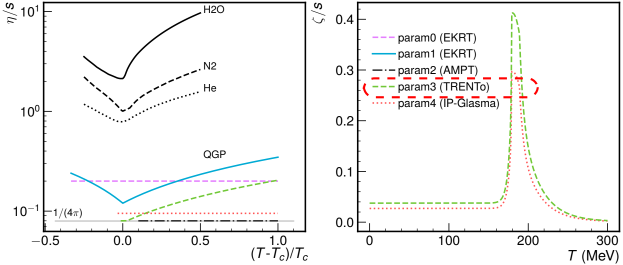
Current understanding of the medium properties

Steffen A. Bass *et. al*, Nature Physics (2019)



Bayesian Analysis (2017)

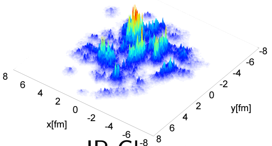
Various parameterizations used in latest hydrodynamic calculations



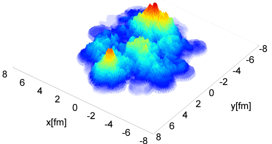
- ALICE data on multiplicity, spectra and flow are key inputs to estimate the properties of the QGP (including p–Pb data), i.e Global Bayesian Analysis and other theory groups.
- Best fit seems to indicate $\eta/s \approx 0.12$ around $T_c \approx 150\,\mathrm{MeV}$, very close to $1/4\pi$ (≈ 0.08) from string theory[1] (AdS/CFT correspondence).
- $\eta/s(T)$ and $\zeta/s(T)$ should be constrained further (larger uncertainties) by separating the effects from the initial conditions.

[1] D. T. Son et. al. Phys. Rev. Lett. 94 (2005) 111601

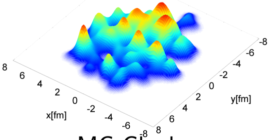
Model summary and parameterizations



IP-Glasma



MC-KLN

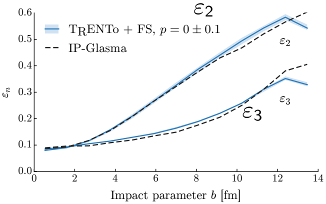


MC-Glauber

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

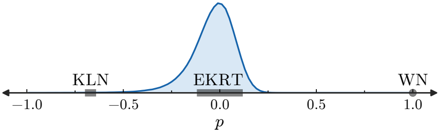
Model	Hydrodynamic code	Initial conditions	η/s	ζ/s
EKRT+param0	EbyE	EKRT	0.20	0
EKRT+param1	EbyE	EKRT	$\eta/s(T)$	0
AMPT[1]+param2	iEBE-VISHNU	AMPT	0.08	0
TRENTo+param3	iEBE-VISHNU	TRENTo($p=0$)	$\eta/s(T)$	$\zeta/s(T)$
IP-Glasma+param4	MUSIC	IP-Glasma	0.095	$\zeta/s(T)$

- State of the art models compared to latest measurements
- Many models calibrated to reproduce lower order harmonic observables



$$\epsilon \sim f(T_{\mathrm{A}}, T_{\mathrm{B}})$$

$$\varepsilon_n e^{in\Phi_n} = -\{r^n e^{in\varphi}\}/\{r^n\}$$

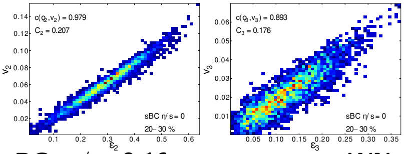


Phys.Rev. **C94**, 024907 (2016)

[1]HIJING with AMPT for initial thermalization

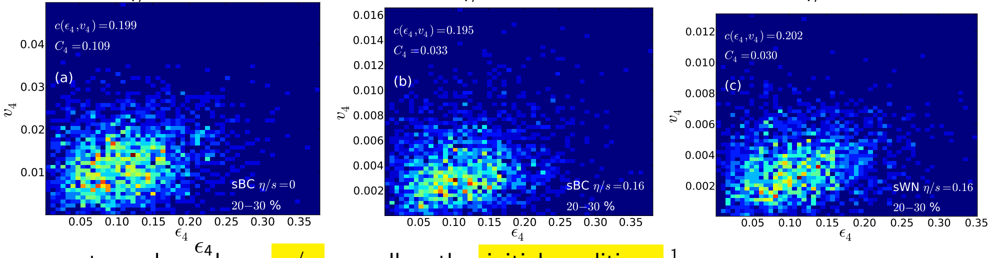
Non-linearity of the higher order flow, $\varepsilon_n \propto v_n$ holds only for $n = 2, 3$

$n = 2, 3$ $(v_n \propto \varepsilon_n)$



sBC, η/s=0. **sBC, η/s=0.16** **sWN, η/s=0.16**

$n = 4$



$20 - 30\%$

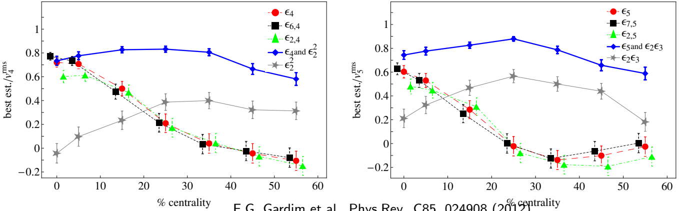
- v_4 response to ε_4 depends on η/s as well as the initial conditions.[1]
- For a rather minimal value of $\eta/s = 1/4\pi$, larger contributions from non-linear corrections.[2]

[1] H. Niemi et al.,Phys. Rev. C 87, 054901 (2013)
[2] D.Teaney, L Yan Phys.Rev. C86 (2012) 044908

Non-linearity of the higher order flow and cross-harmonic decomposition

- Decomposition into linear and non-linear contributions

$$v_4 e^{in\psi_4} = k\varepsilon_4 e^{4i\Phi_4} + k'\varepsilon_2^2 e^{4i\Phi_2} \qquad v_5 e^{in\psi_5} = k\varepsilon_5 e^{5i\Phi_5} + k'\varepsilon_2 e^{2i\Phi_2}\varepsilon_3 e^{3i\Phi_3}$$



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

$$
\begin{aligned}
V_4 &= V_{4\mathrm{L}} + \chi_{4,22} V_2^2 \rightarrow v_{4,22} = \chi_{4,22} \langle |V_2|^4 \rangle^{\frac{1}{2}} \\
V_5 &= V_{5\mathrm{L}} + \chi_{5,32} V_2 V_3 \rightarrow \ldots \\
V_6 &= V_{6\mathrm{L}} + \chi_{6,222} V_2^3 + \chi_{6,33} V_3^2 + \chi_{6,24} V_2 V_{4\mathrm{L}} \\
&\ldots
\end{aligned} \tag{3}
$$

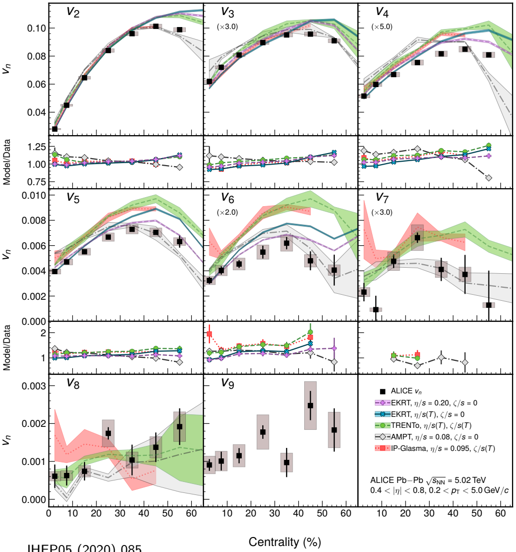
The magnitude of the non-linear contribution and non-linear flow mode coefficients:

$$
\begin{aligned}
v_{4,22} &= \frac{\Re\langle V_4 (V_2^*)^2 \rangle}{\sqrt{\langle |V_2|^4 \rangle}} \\
&\approx \langle v_4 \cos(4\psi_4 - 4\psi_2) \rangle, \\
\chi_{4,22} &= \frac{v_{4,22}}{\sqrt{\langle v_2^4 \rangle}}.
\end{aligned} \tag{4}
$$

Linear part is extracted from the total and non-linear contributions:

$$\underbrace{\langle |V_{4\mathrm{L}}|^2 \rangle^{\frac{1}{2}}}_{v_{4\mathrm{L}}} = \big(\underbrace{\langle |V_4|^2 \rangle}_{v_4^2} - \underbrace{\chi_{4,22}^2 \langle |V_2|^4 \rangle}_{v_{4,\mathrm{NL}}^2}\big)^{\frac{1}{2}}. \tag{5}$$

Anisotropic flow in heavy-ion collisions



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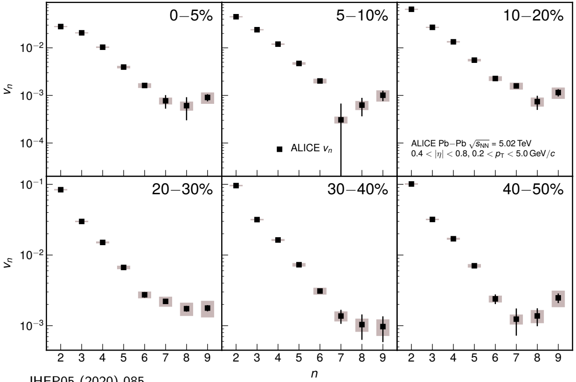
- Hydrodynamic calculations agree well with the data up to v_3.
- AMPT ($\eta/s = 0.08$) describes the data best in mid-peripheral collisions, but fails to describe the central collisions for $n = 4, 5$
- IP-Glasma, TRENTo: good description for $n = 2, 3$, overestimations at $n \geq 4$
- EKRT ($\eta/s = 0.20$): best agreement among all model configurations at $n \geq 4$
- EKRT ($\eta/s(T)$): comparable up to mid-central collisions, but overestimate the data for peripheral collisions for $n = 4, 5$

- As n increases, the sensitivity to model parameterizations gets larger

Flow power spectrum



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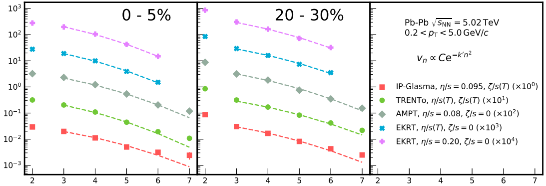
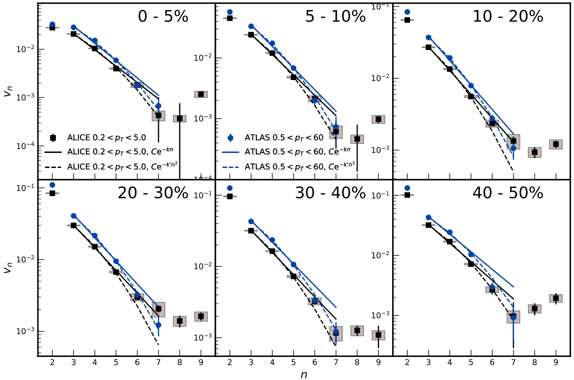


- Power spectra is measured up to v_9 in various centrality bins.
- Clear decrease in magnitude $v_n \propto e^{-k'n^2}$ (viscous damping[1]) is observed as n increases
  - Clear damping also observed in hydrodynamical calculations
  - Slope of the calculations is dependent on the model parameterizations
- Interesting feature predicted in acoustic model[2] for $n \geq 7$ can be further investigated with 2018 data

[1] E. Shuryak, PRC84,044912 (2011), R. Lacey et. al. arXiv:1301.0165
[2] E. Shuryak, PRC84,044912 (2011), Universe 3 (2017) no.4, 75

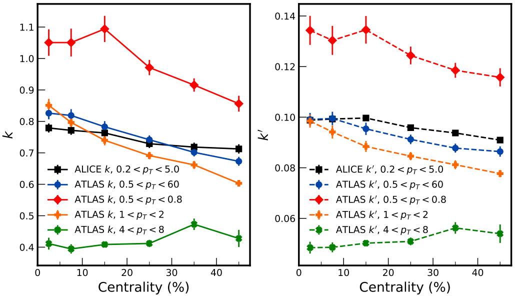
Damping depends on p_{T}



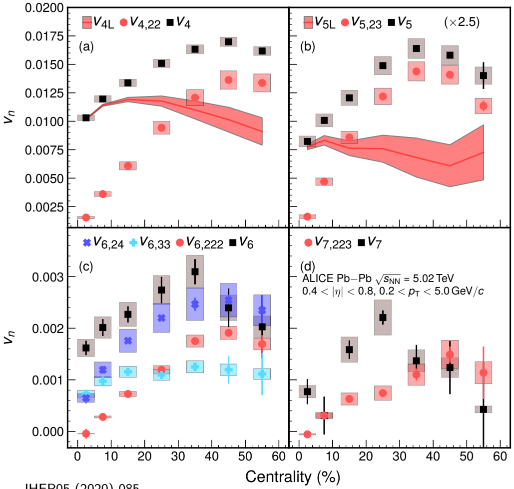
$v_n \propto e^{-kn}$ $v_n \propto e^{-k'n^2}$

ATLAS, Eur. Phys. J. C 78 (2018) 997

- Both functions work well for $3 \leq n \leq 5$. Note that p_T ranges are different.
  1. $0.2 < p_{\mathrm{T}} < 5.0\,\mathrm{GeV}/c$
  2. $0.5 < p_{\mathrm{T}} < 60.0\,\mathrm{GeV}/c$
- $e^{-k'n^2}$ works better for $n > 5$
- For $n > 7$, clear deviation from both fits.



Linear and non-linear decomposition up to 7^{th} order



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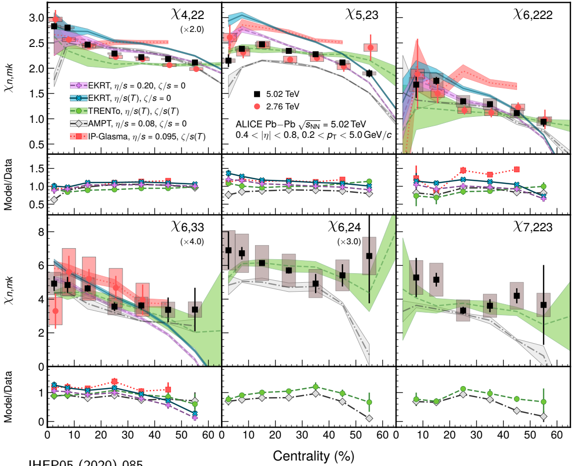
- Linear component dominant in central collisions
- Non-linear component increasingly dominant in mid-central to peripheral collisions
- Strength of the non-linear flow mode depends on the harmonic order.

Measured quantities v_n and $v_{n,m}$, from which the linear component is derived.

Non-linear flow mode cofficients, hydrodynamic predictions



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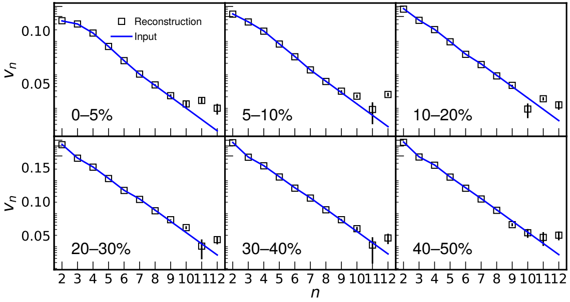
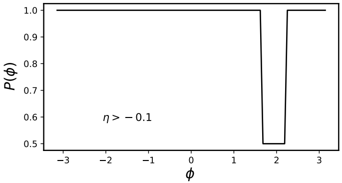
- Clear centrality dependence for all harmonics
- Non-linear response at high harmonics larger
- Large disagreements between the data and the models for $\chi_{5,23}$.

- Model parameterizations need further tuning to capture the magnitude and the centrality dependence.

Toward measurement of ultra-high harmonics

ToyMC:





1. Damped input according to $v_n \propto e^{-k' n^2}$, $n \geq 7$
2. ϕ-gap modulation
3. Measured multiplicity

- Plausibility of ultra-high harmonic results. Reconstruction to be verified with ToyMC simulations.
- 35M event ToyMC closure test, converged up to v_{11}
- $n > 11$ needs further investigation

Summary

General:

- The flow coefficients, flow modes and non-linear flow mode coefficients of the charged hadrons are measured up to the 9^{th} and 7^{th} harmonic, respectively.
- Cross harmonic decomposition: higher order harmonic non-linear flow mode is more sensitive η/s, ζ/s parameterizations.
- Better constraints on initial conditions and $\eta/s(T)$, $\zeta/s(T)$ with improved precision and extended harmonic orders.

Hydrodynamic models:

- Good agreement for low order harmonic v_n. However, higher orders are not well reproduced.
- Set for the future Bayesian analysis

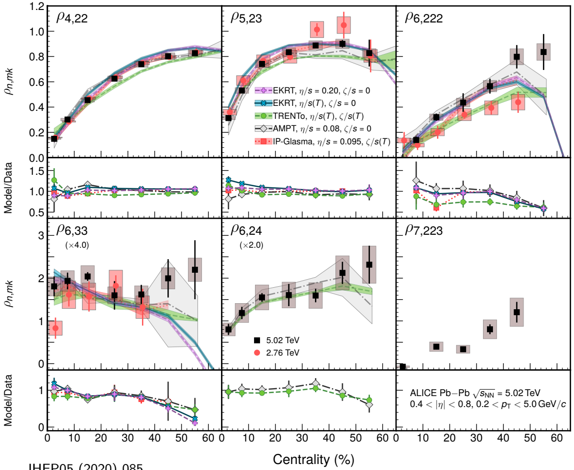
Our data can help to further constrain η/s and ζ/s in model calculations.

Related:

- E-b-E two or three harmonic flow magnitude correlations [A. Bilandzic, today]
- What can we learn from small systems? [Y. Zhou, today]

Thank you!

Symmetry-plane correlations, hydrodynamic predictions



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- Clear centrality dependence for all harmonics
- Good agreement between the data and the models