Success and challenges of flow harmonic analysis in LHC heavy-ion physics

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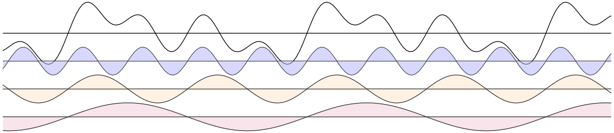

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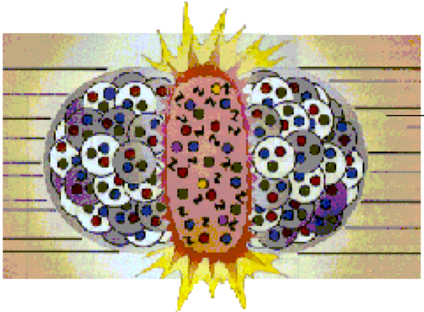
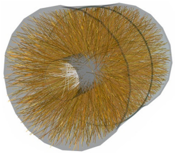
Understanding Heavy-ion collisions with the collective flow

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



Creating Quark Gluon Plasma(QGP) in a high energy collision



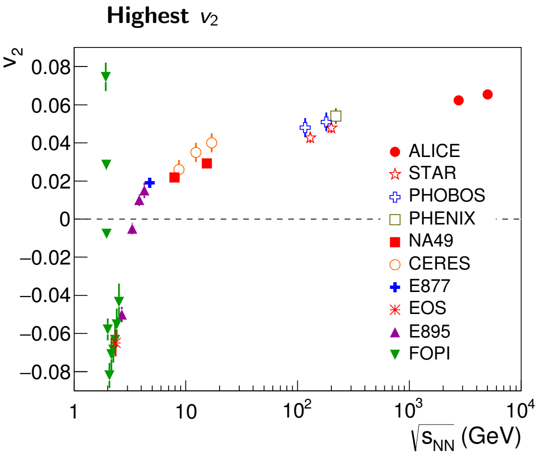
$N_{ch} \approx 1000$

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

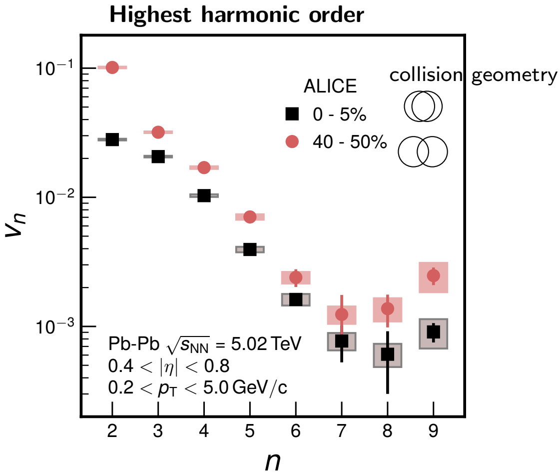
where $V_n \equiv \langle e^{in\phi} \rangle = v_n e^{in\psi_n}$. (experiments, theory - hydrodynamic models with η/s, ζ/s)

- Collectivity as a probe to the properties of the medium – transport properties such as η/s, ζ/s

Highest v_2(n=2) and highest harmonic v_n(n=9) are measured in LHC

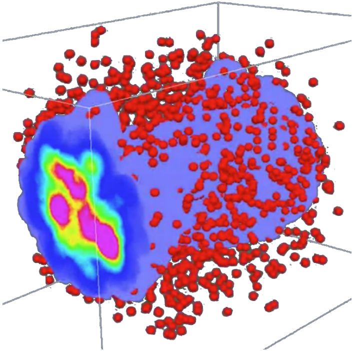


Phys.Rev.Lett. **105** 252302 (2010)



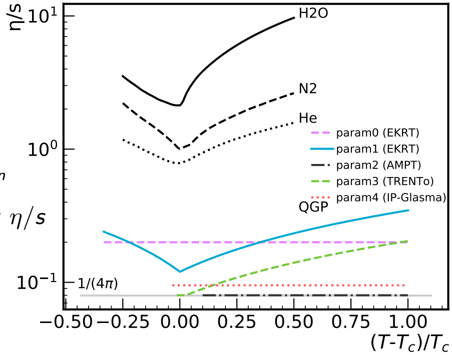
JHEP05 085 (2020)

Perfect quark-gluon fluid, lowest η/s in nature($\approx 1/4\pi$)



$\uparrow$ *large* v_n

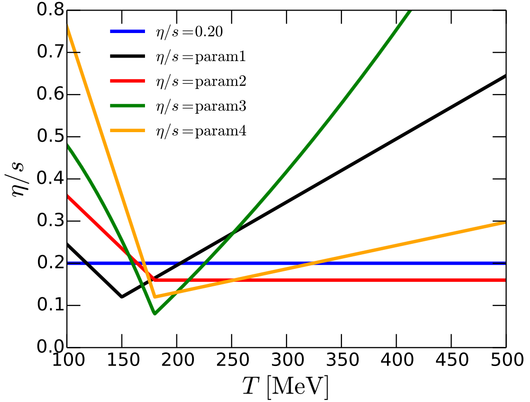
$\downarrow$ *smaller* η/s

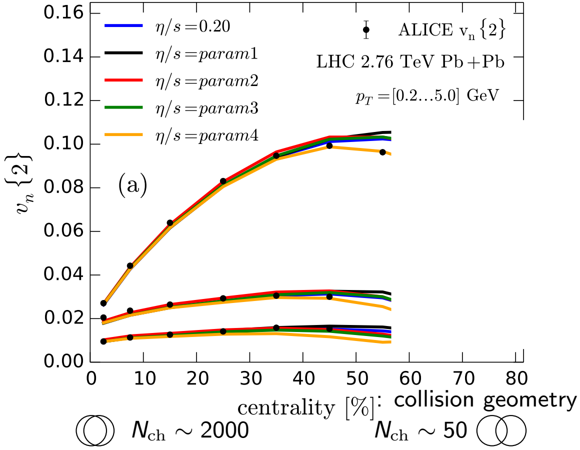


- Lower bound of the η/s – D. T. Son *et al.* *Phys.Rev.Lett* **94** (2005) 111601

How to constrain temperature dependence of the $\eta/s(T)$?

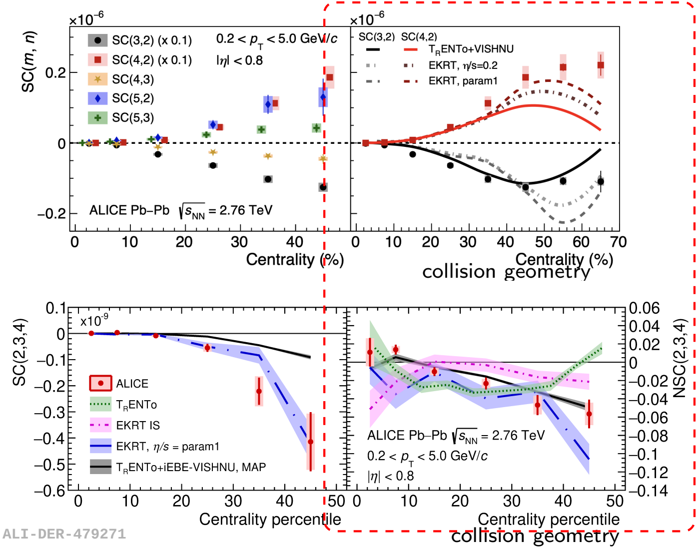
Temperature dependent $\eta/s(T)$ vs. v_n by H. Niemi, K.J. Eskola, R. Paatelainen, *Phys.Rev* **C93** 024907 (2016)





- v_n not sufficiently sensitive to temperature dependence.

Measuring inner correlations of QGP, two or three harmonic correlations



$$\langle v_m v_n \rangle$$

Phys. Rev. Lett. 117 (2016) 182301

Phys. Rev. C 97 no. 2, (2018) 024906

- Temperature dependence, $\eta/s(T)$ can be explored!
- Bonus $\zeta/s(T)$.

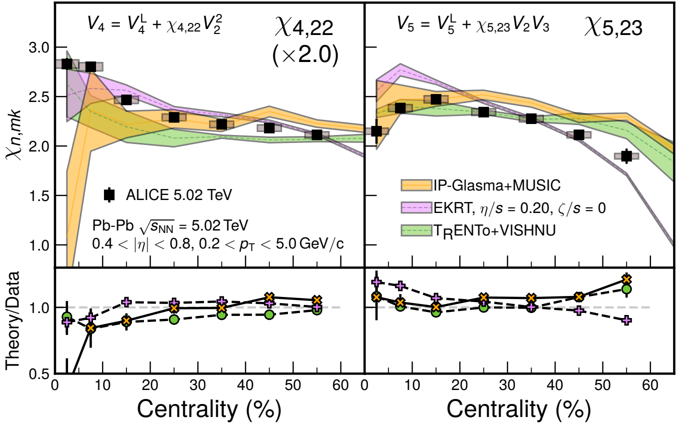
$$\langle v_k v_l v_m \rangle$$

arXiv:2101.02579, submitted to PRL

Credits to D. J Kim(Exp.) and H. Niemi(Theory)

Non-linear flow modes are measured!

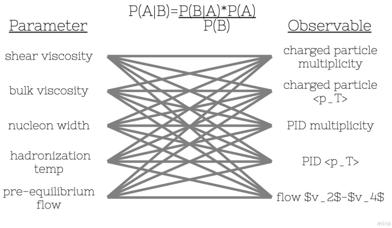
Non-linear flow mode coefficients, *JHEP05* 085 (2020), PhD thesis work



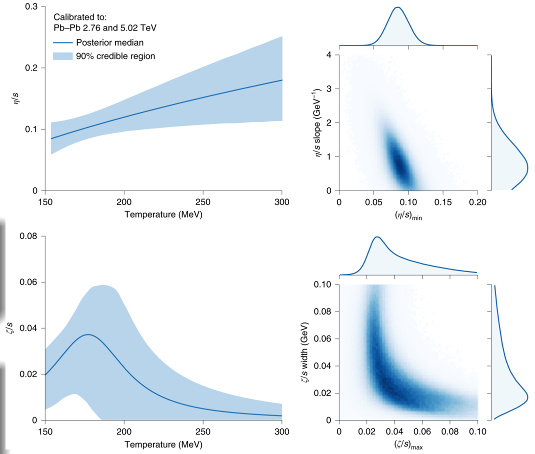
collision geometry

- higher order v_n's are better understood!
- better sensitivity to $\eta/s(T)$.

Current understanding of the medium properties



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



- Only low order harmonic v_n used, limited set of observables and mostly with 2.76TeV data.
- Uncertainties need to be improved further.

Testing a single set of parameters requires $\mathcal{O}(10^4)$ hydro events, and evaluating eight different parameters five times each requires $5^8 \times 10^4 \approx 10^9$ hydro events.
That's roughly 10^5 computer years!

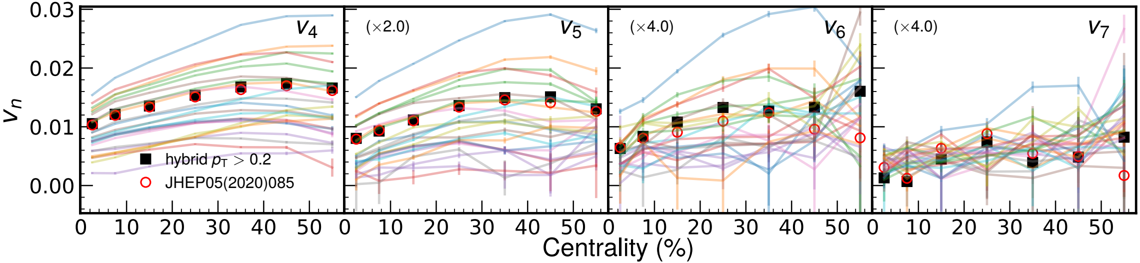
Bayesian analysis with advanced observables

Used observables:
only with the high precision 5.02 TeV data

- Charged particle multiplicity N_{ch}
- PID multiplicity (pion, Kaon and proton)
- PID $\langle p_{\mathrm{T}} \rangle$
- v_2 to v_7 (up to v_9 available)
- $\chi_{4,22}$, $\chi_{5,23}$ and $\chi_{6,m}$ (up to $\chi_{7,223}$ available)

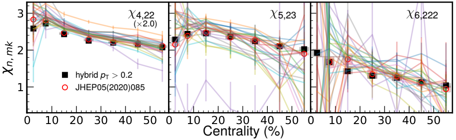
Details on productions

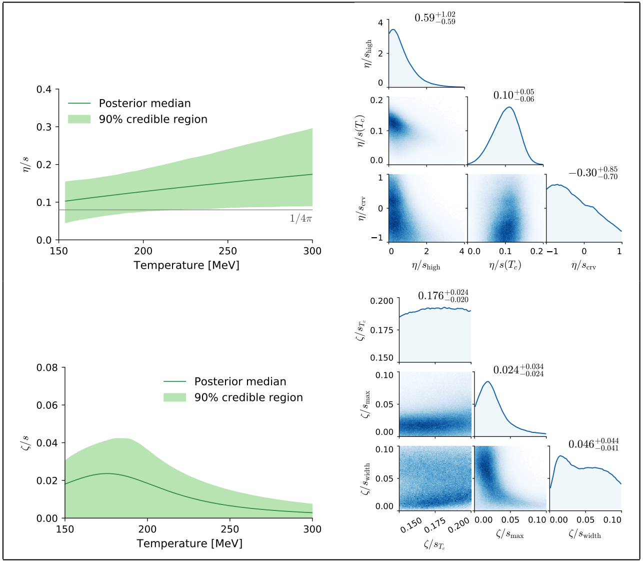
- CSC project 2003154 at Mahti, thanks to much improved performance.
- $\mathcal{O}(10^6)$ hydro events per one parameter point, x 100 than the previous studies.
- 900 h in 500 parameter points.



Results with additional observables, Preliminary results

- Better constraints for η/s.
  - Strong correlation for higher order v_n and their non-linear response.
  - Reduced temperature dependence
- What about ζ/s?
  - Lower ζ/s maximum than previously ($\sim 30\%$)
- Preliminary results, need to look various combinations and other parameters in detail.





Summary

Successes:

- QGP is nearly perfect fluid $\eta/s \approx 1/4\pi$ based on the measurements.
- Collective flow measurements have been improved significantly in LHC, highest flow magnitude, highest harmonic orders and non-linear flow mode. $\rightarrow$ provide better constraints for the transport properties.

Challenges:

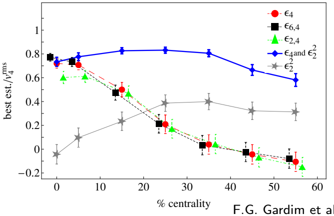
- Inclusion of High order harmonics and their non-linear responses in Bayesian analysis improved the result, showing weak temperature dependence of η/s and smaller ζ/s.
- going beyond $n > 9$ is very challenging due to high sensitivity to small data imperfections $\rightarrow$ needs further investigation for 2022- LHC runs.

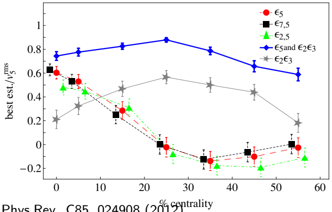
Thank you!

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)

$$V_4 = V_{4\mathrm{L}} + \chi_{4,22} V_2^2 \rightarrow v_{4,22} = \chi_{4,22}\langle |V_2|^4\rangle^{\frac{1}{2}}$$
$$V_5 = V_{5\mathrm{L}} + \chi_{5,32} V_2 V_3 \rightarrow \dots$$
$$V_6 = V_{6\mathrm{L}} + \chi_{6,222} V_2^3 + \chi_{6,33} V_3^2 + \chi_{6,24} V_2 V_{4\mathrm{L}}$$
$$\dots \qquad (2)$$

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

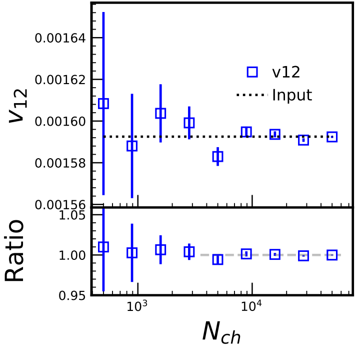
$$v_{4,22} = \frac{\Re\langle V_4 (V_2^*)^2\rangle}{\sqrt{\langle |V_2|^4\rangle}} \approx \langle v_4 \cos(4\psi_4 - 4\psi_2)\rangle, \qquad (3)$$
$$\chi_{4,22} = \frac{v_{4,22}}{\sqrt{\langle v_2^4\rangle}}.$$

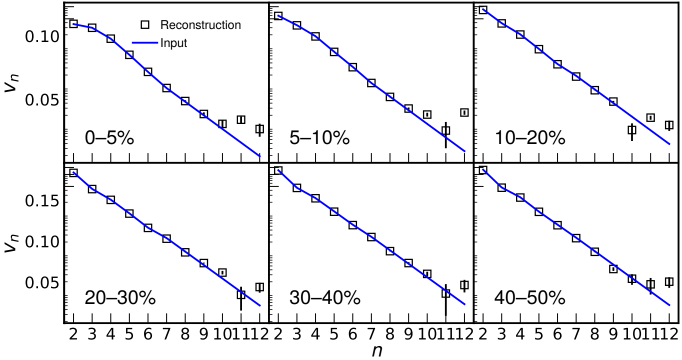
Linear part is extracted from the total and non-linear contributions:

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

Toward measurement of ultra-high harmonics

- Need for high precision reconstruction and correction of the ϕ fine-modulations.





- Plausibility of ultra-high harmonic results. Reconstruction to be verified with ToyMC simulations.

$0.8 < p_T < 5.0$ GeV, input $= 0.00159252$

- $n > 11$ needs further investigation