News on collectivity in Pb-Pb collisions from the ALICE experiment

Dong Jo Kim [1] for the ALICE Collaboration

[1]University of Jyväskylä & Helsinki Institute of Physics, Finland

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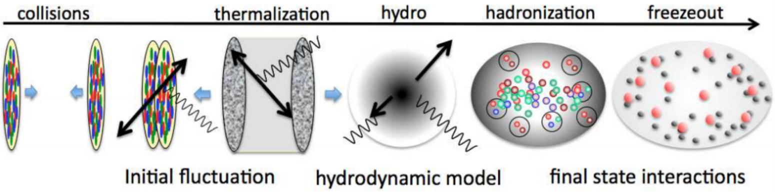
UNIVERSITY OF JYVÄSKYLÄ

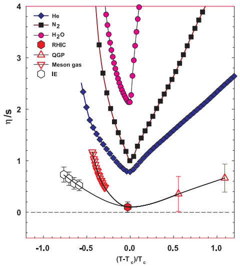
ALICE

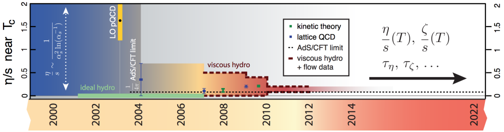
HELSINKI INSTITUTE OF PHYSICS

Space-time history of Heavy-Ion Collisions



Initial geometry and its fluctuations → Transport properties ($\eta/s(T)$) →final-state particles



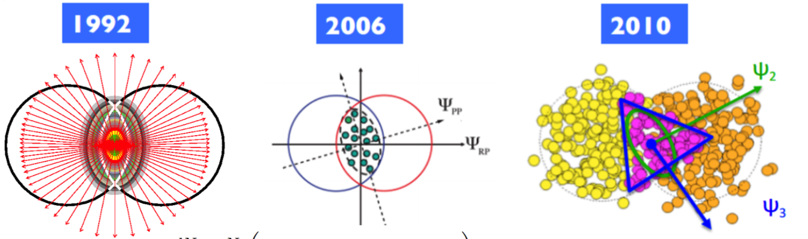


LO pQCD:	P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT:	P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD:	A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
	H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro:	P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
	P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
pQCD/kin. theory:	Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302
	J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro:	P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
	M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
	H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
	H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007), "It is argued that such a low value is indicative of thermodynamic trajectories for the decaying matter which lie close to the QCD critical end point."

courtesy of Bjorn Schenke, "String theory (AdS/CFT correspondence) finds η/s is $1/4\pi$ a strongly coupled conformal theory → hints at a lower bound of that order."

Flow measurements in Heavy-Ion Collisions



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n (2v_n \cos(n(\phi - \psi_n)))\right) \qquad v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

relative to it′s own plane

- The magnitudes of Flow-vector, anisotropic flow harmonics v_n, have been measured in great details (centrality, p_T, η, PID)
  - Large elliptic flow has indicated fluid behavior of matter created at RHIC in early 2000's (BNL announces perfect liquid in 2005 press release)
  - The importance of fluctuations was realized later and analysis of odd flow harmonics began around 2010 (since B. Alver, G. Roland, Phys.Rev. C81, 054905)
- The fluctuations of each individual flow harmonic have been investigated in great details in recent years

"Initial conditions" $\rightarrow$ "flow coefficients and correlations"

coordinate space anisotropy

momentum space anisotropic flow

$$\varepsilon_n e^{in\Psi_n} = -\{r^n e^{in\phi}\}/\{r^n\} \qquad (1)$$

$$v_n(p_T, y) e^{in\Psi_n(p_T, y)} = \langle e^{in\phi} \rangle_\phi \qquad (2)$$

$$v_n\{2\}^2 = \langle e^{in(\phi_1-\phi_2)} \rangle_\phi \equiv \frac{1}{N_2} \int d\phi_1 d\phi_2 \frac{dN_2}{d\phi_1 d\phi_2} e^{in(\phi_1-\phi_2)} \qquad (3)$$

$$v_n\{2\} = \langle v_n^2 + \delta_2 \rangle_{ev}^{1/2} \stackrel{\text{flow}}{=} \langle v_n^2 \rangle_{ev}^{1/2} \qquad (4)$$

$$v_n\{2\} \equiv \langle v_n^2 \rangle_{ev}^{1/2} \qquad (5)$$

$$v_n\{4\} \equiv \left(2\langle v_n^2 \rangle_{ev}^2 - \langle v_n^4 \rangle_{ev} \right)^{1/4}. \qquad (6)$$

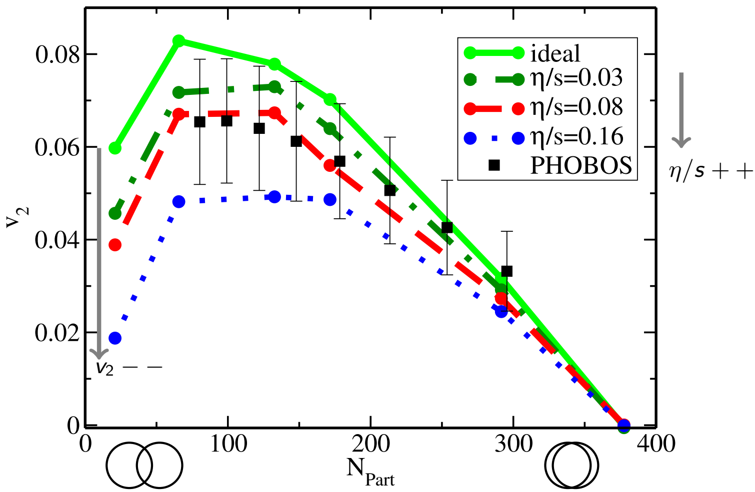
v_n values have not only distributions, but they can also have correlations [1]

$$\langle \cos(k_1\Psi_1 + \cdots + nk_n\Psi_n) \rangle_{\mathrm{SP}} \equiv \frac{\langle v_1^{|k_1|} \cdots v_n^{|k_n|} \cos(k_1\Psi_1 + \cdots + nk_n\Psi_n) \rangle_{ev}}{\sqrt{\langle v_1^{2|k_1|} \rangle_{ev} \cdots \langle v_n^{2|k_n|} \rangle_{ev}}}, \qquad (7)$$

where the k_n's are integers with the property $\sum_n nk_n = 0$.

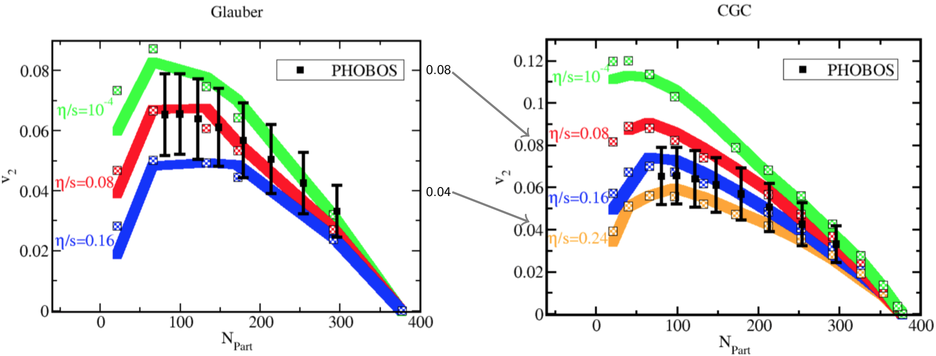
[1] Luzum and Ollitrault, used at Phys. Rev. C90, 024905 (2014), Phys. Rev. C 93, 024907 (2016)

Shear viscosity over entropy density ratio is small



P. Romatschke and U. Romatschke, Phys.Rev.Lett. 99, 172301 (2007)

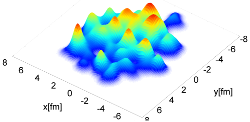
But the extracted value depends on the initial conditions



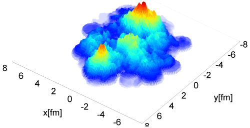
P. Romatschke and U. Romatschke, Phys.Rev.Lett. 99, 172301 (2007)

Extracting η/s from experimental data: Initial conditions

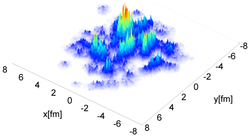
MC-Glauber



MC-KLN

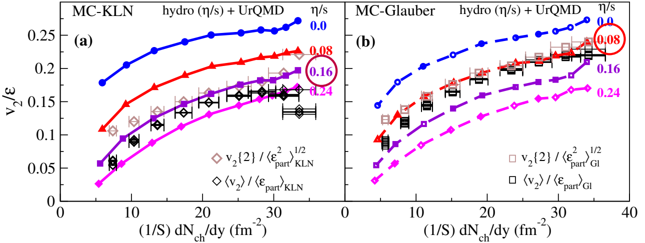


IP-Glasma



Initial energy density

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

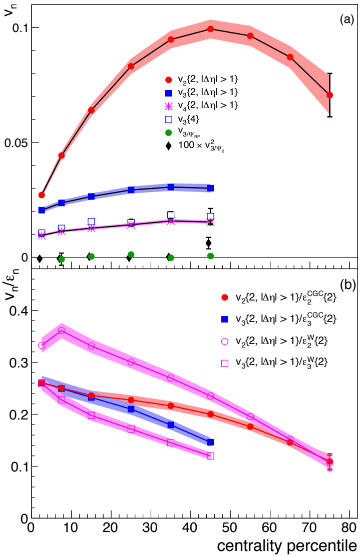


C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. Heinz
J. Phys. G 38, 124045 (2011) [arXiv:1106.6350[nucl-th]]

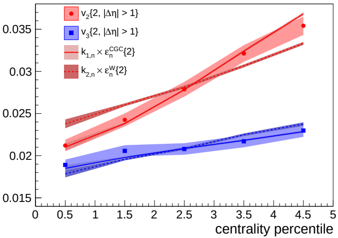
- $\eta/s \approx 0.08$ - 0.24
- Large uncertainty from the initial conditions (MC-Glauber vs. MC-KLN)

MC-KLN : T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys. Lett. B636, 299 (2006); A. Adil, H.J. Drescher, A. Dumitru, A. Hayashigaki, Y. Nara Phys. Rev. C, 74 (2006), p. 044905
MC-Glauber : Z. Qiu and U. W. Heinz, Phys. Rev. C84, 024911 (2011);Z. Qiu, C. Shen, and U. W. Heinz, Phys. Lett. B707,151 (2012);S. Esumi (PHENIX Collaboration), J.Phys.G G38,124010 (2011).
IP-Glasma : B. Schenke,P. Tribedy,R. Venugopalan Phys.Rev.Lett. 108 (2012) 252301

Extracting η/s from experimental data: Initial conditions, higher harmonics



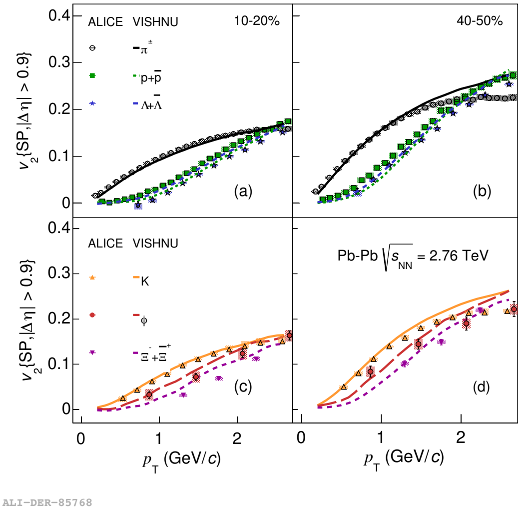
ALICE, Phys.Rev.Lett. 107 (2011) 032301



- For a Glauber model, v_3/ε_3 is smaller than v_2/ε_2, indicating significant viscous corrections.
- For MC-KLN CGC calculations, v_3/ε_3 $\approx$ v_2/ε_2 for the most central collisions, as expected for an almost ideal fluid [a].
- 0–5%, viscous effects do not change much and directly sensitive to the change in the initial spatial geometry.

[a] M. Luzum and J. Y. Ollitrault et al., Phys. Rev. C 82, 034913 (2010)

Extracting η/s from experimental data: identified hadrons



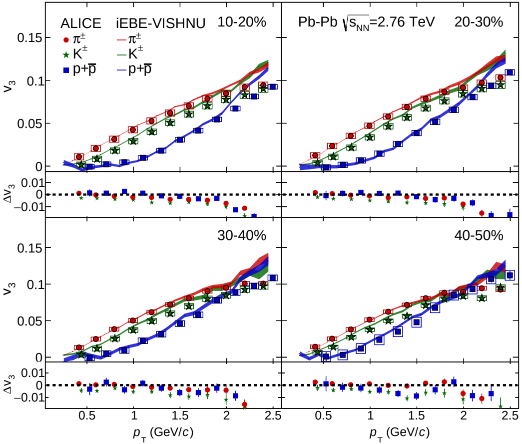
$\pi^{\pm}$, $K^{\pm}$, K^0_S, **p+$\overline{\text{p}}$**, ϕ, $\Lambda+\overline{\Lambda}$, $\Xi^-+\overline{\Xi}^+$ **and** $\Omega^-+\overline{\Omega}^+$

ALICE :
JHEP 1506 (2015) 190
(arXiv:1405.4632)

Hydrodynamics : VISHNU
H. Song, S. Bass and U. W. Heinz, Phys. Rev. C 89, 034919 (2014)
(2+1)-D viscous hydro + UrQMD (hybrid)

- Mass ordering of elliptic flow (definite prediction of hydrodynamics)
- Details of hadronic evolution matter

Extracting η/s from experimental data: identified hadrons



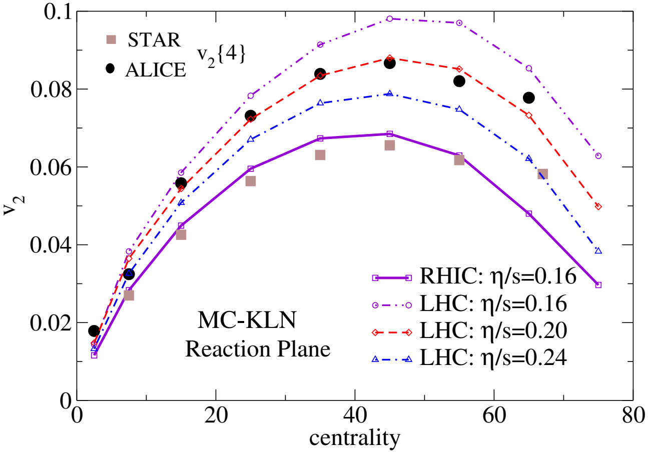
ALICE :
submitted to JHEP 2016.06.21(arXiv:1606.06057)
measured for v_2, v_3 and v_4
- better control on non-flow contribution based on pp or MC(HIJING)

$$v_n^{\mathrm{sub}}(p_{\mathrm{T}}) = v_n^{\mathrm{AA}}(p_{\mathrm{T}}) - \delta_n^{\mathrm{AA,pp}}(p_{\mathrm{T}})$$

Hydrodynamics : iEBE-VISHNU
Phys. Rev. C 93, 064905 (2016)
(2+1)-D viscous hydro + UrQMD with the fluctuating AMPT initial conditions

- In the low momentum region, hydrodynamic calculations based on iEBE-VISHNU describe v_2 for all three particle species and v_3 and v_4 of pions fairly well.
- For kaons and protons the model seems to overpredict v_3 and v_4 in almost all centrality intervals.

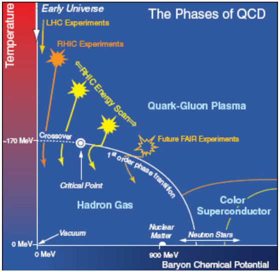
Extracting η/s from experimental data: RHIC vs LHC

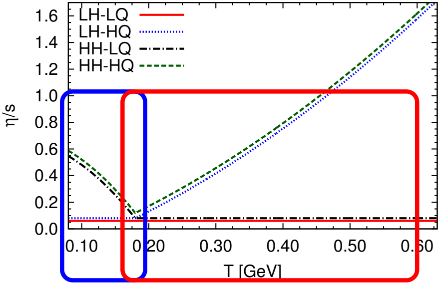


- $\eta/s \approx 0.16$ (RHIC) $= \eta/s \approx 0.20$ (LHC) ?
- Temperature dependent $\eta/s(T)$?

C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. Heinz, J. Phys. G 38, 124045 (2011) [arXiv:1106.6350 [nucl-th]]

How to constrain $\eta/s(T)$?





Phys.Rev.Lett. 106 (2011) 212302

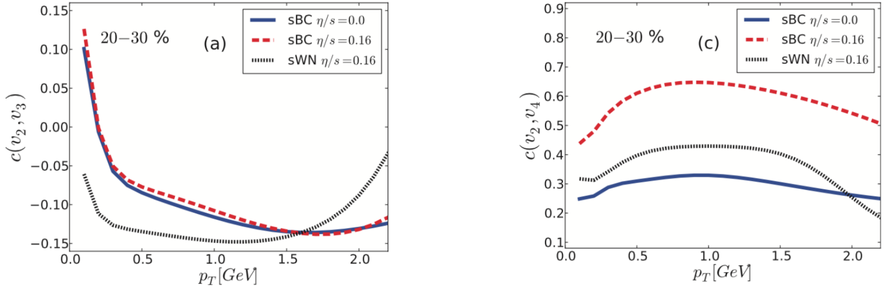
- Present understanding
  - RHIC : highly sensitive to the viscosity in hadronic matter and almost independent of the viscosity in the QGP phase [2] ?
  - LHC : almost independent of the hadronic viscosity, but depends strongly on the QGP viscosity[2] ?
- How to discriminate the contributions from the different stages of the collsions?
  - need more differential observables which might be more sensitive to **initial conditions, QGP phase or freeze-out**?

[2] H. Niemi, G.S. Denicol, P. Huovinen, E. Molnar, D.H. Rischke, Phys.Rev.Lett. 106 (2011) 212302

Correlations of v_m and v_n

A linear correlation coefficient c(v_n,v_m) was proposed (H. Niemi et al.,Phys. Rev. C 87, 054901 (2013)) to study the correlations between v_n and v_m

$$c(v_m, v_n) = \langle \frac{(v_m - \langle v_m \rangle_{ev})(v_n - \langle v_n \rangle_{ev})}{\sigma_{v_n}\sigma_{v_m}} \rangle_{ev}$$



- c(v_2, v_3) is sensitive to initial conditions and insensitive to η/s.
- c(v_2, v_4) is sensitive to both.
- However, this observable is not easily accessible in flow measurements which are relying on two- and multi-particle correlations.

Symmetric 2-harmonic 4-particle Cumulants

New Observable : Symmetric 2-harmonic 4-particle Cumulants (SC) [3]

$$\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c = \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle - \langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle = \left\langle v_m^2 v_n^2\right\rangle - \left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle$$

- By construction, not sensitive to
    - non flow effects
    - inter-correlations of various symmetry planes
- It is non-zero if the event-by-event amplitude fluctuations of v_n and v_m are (anti-)correlated.

Also SC(m,n) can be normalizable with $\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle$

$$SC(m,n)_{norm} = SC(m,n)/\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle$$

- Normalized SC(m,n) reflects the degree of the correlation.
- While SC(m,n) contains both the degree of the correlation and individual v_n.

[3] Ante Bilandzic et al., Phys. Rev. C 89, 064904 (2014)

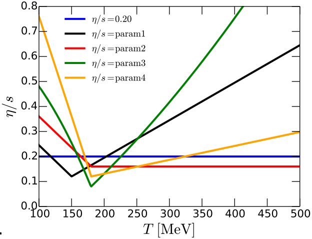
Correlations of v_m and v_n

$$\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

Hydrodynamics

H. Niemi, K.J. Eskola, R.Paatelainen

(Phys. Rev. C 93, 024907 (2016))



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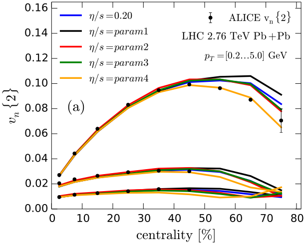
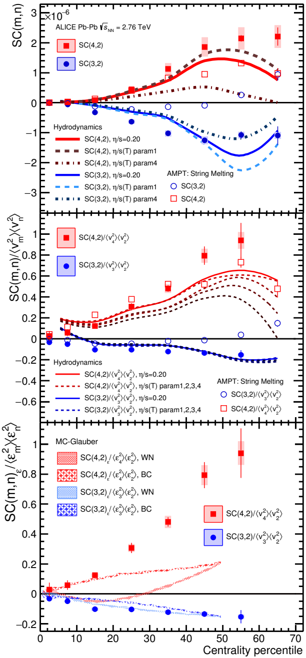


ALICE arXiv:1604.07663 submitted to Phys.Rev.Lett.

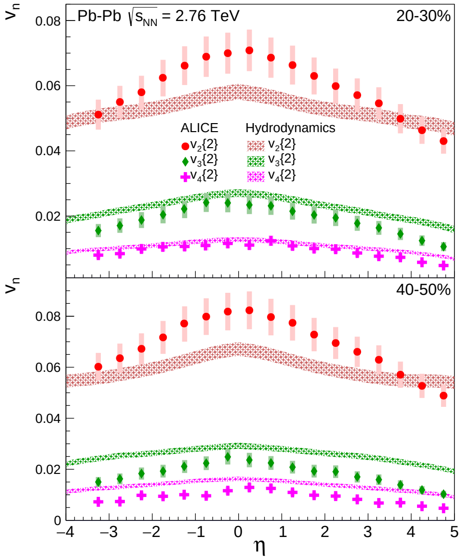


(4,2)

(3,2)

- Although Hydro describes the v_n fairly well, there is not a single centrality bin for which a given η/s parameterization describes simultaneously SC(4,2) and SC(3,2)
- provide stronger constrains on the $\eta/s(T)$ in hydro in combination with individual v_n.

Pseudorapidity dependence of v_n

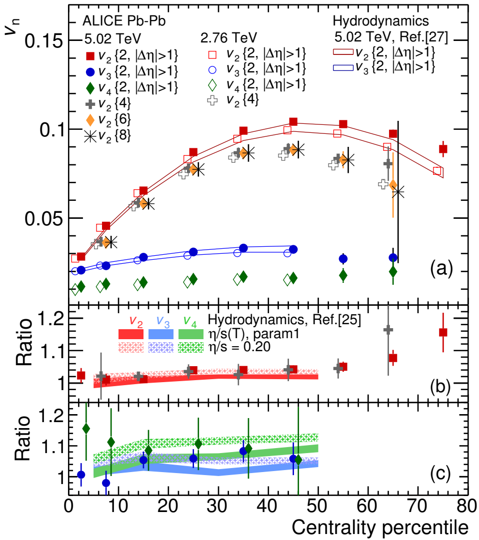


ALICE :
arXiv:1605.02035 submitted to PLB

Hydrodynamics :
G. Denicol, B. Schenke et al.
Phys.Rev.Lett. 116, 212301 (2016)

- The shape of $v_n(\eta)$ is largely independent of centrality n=2,3,4
- v_3 and v_4 have weaker dependence on η than v_2
- Hydro calculation is tuned $\eta/s(T)$ to fit $v_n(\eta)$ at RHIC but can't describe the data well, challenge to the theory community.
- However, better independent constraints for the initial state fluctuations in 3D and $\eta/s(T)$ even at a fixed collision energy.

Anisotropic flow from 2.76 to 5.02 TeV



ALICE,Phys.Rev.Lett. 116 (2016) no.13, 132302

- v_2, v_3 and v_4 are found to increase by (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, mainly due to the increase of $\langle p_T \rangle$.
- no strong centrality dependent increase of flow harmonics from 2.76 to 5.02 TeV.
- Changes of anisotropic flow are compatible with theoretical predictions.

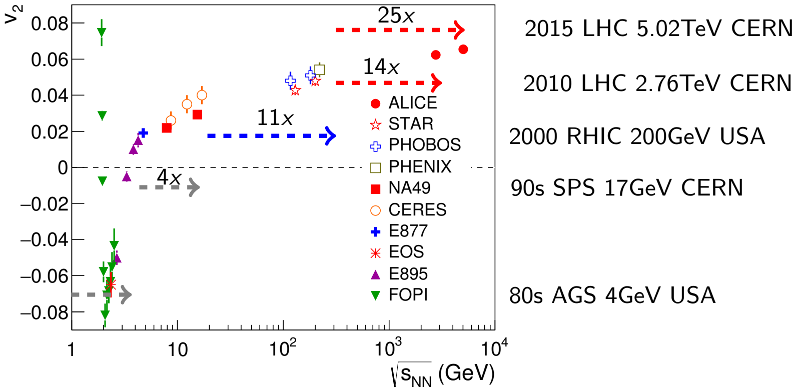
Hydrodynamics

(a) Ref [27]: J. Noronha-Hostler et al., PRC93 (2016) 034912

(b)(c) Ref [25]: H. Niemi et al, PRC 93, 014912 (2016)

Ratio = [v_n at 5.02]/ [v_n at 2.76]

v_2 vs $\sqrt{s_{NN}}$



- The results of 5.02TeV shown here are based on small statistics from a low intensity run.
- Many flow analyses with Run2 Pb-Pb data with the full statistics($\approx$ x 100 Minimum bias data) are underway.

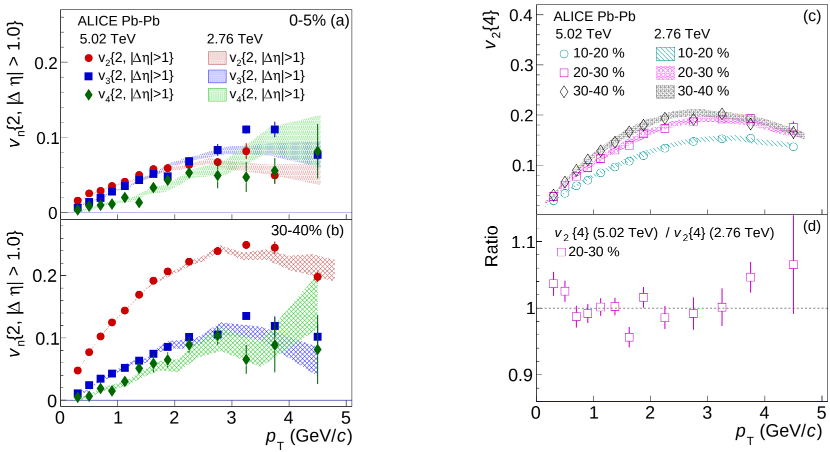
ALICE has measured the largest flow so far!!!

Summary

- The ALICE experiment has been leading important roles for completing the individual flow harmonic measurements(including pid flow) at the highest energies to date.
- We are improving flow harmonic correlation techniques to understand the properties of the QGP and the full evolution of the heavy-ion collisions i.e flow vector correlation and Event Shape Engineering(ESE)(see B.20).
- New SC(m,n) measurements provide strong constraints on the $\eta/s(T)$ in hydro in combination with the individual flow harmonics.
- Rapidity dependent $v_{2,3,4}$ results can provide access to a range of varying medium properties, even at a fixed collision energy.
- Many analyses with Run2 Pb-Pb data with the full statistics are underway, reducing the stat. and syst. errors in the future.

Thank You!

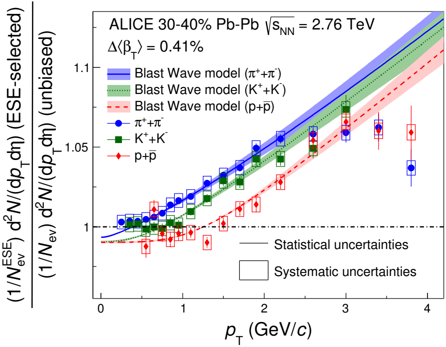
Run2 : p_T dependence

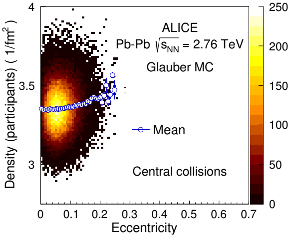


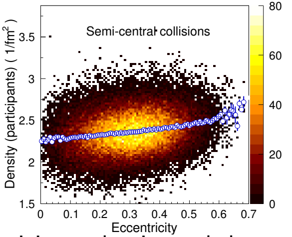
- ALICE, Phys.Rev.Lett. 116 (2016) no.13, 132302
- Comparable results to Run 1 results, increase in integrated flow can be attributed to the increase in mean transverse momentum.

Indicating an interplay between radial and elliptic flow

10% largest q_2, ALICE, Phys.Rev. C93 (2016) no.3, 034916



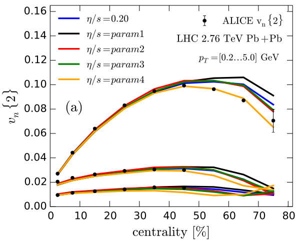


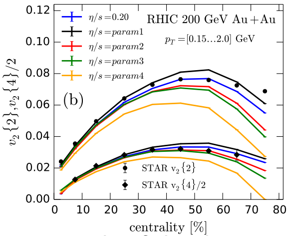


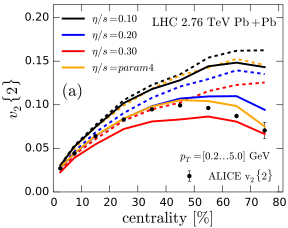
the spectra in the large $q_2(v_2)$ sample are affected by a larger radial flow push.

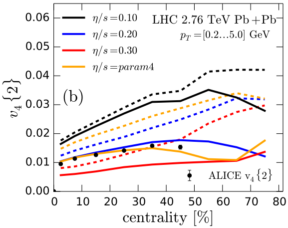
- MC Glauber : a correlation between the transverse participant density and the eccentricity which could be the origin of this effect
- A quantitative comparison would require a full hydrodynamic calculation to test sensitivity to η/s in the hydrodynamic evolution

Hydro results from RHIC to LHC, v_n vs $\eta/s(T)$, δf corrections?





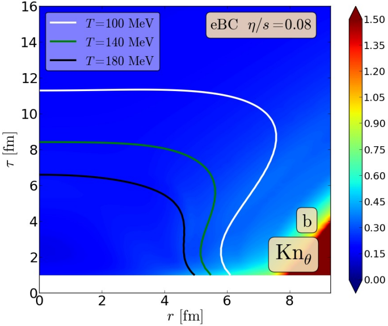


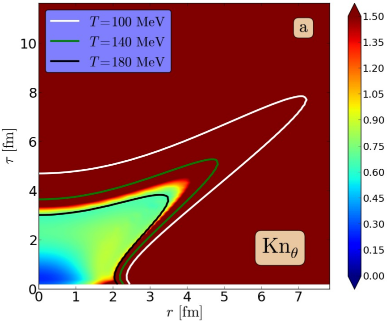


H. Niemi, K.J. Eskola, R.Paatelainen (Phys. Rev. C 93, 024907 (2016))

- the magnitude of the shear-stress tensor at the decoupling, i.e. the magnitude of the δf corrections to the equilibrium distributions
- Relative magnitude of δf depends on the η/s parametrization, it is larger at lower energy collisions.

Flow in small systems, Applicability of fluid dynamics ?





- H. Niemi and G. S. Denicol, arXiv:1404.7327
- AA collisions $\rightarrow$ pA collisions
- $Kn = \lambda/L << 1$ for AA but for pA, $Kn > 0.5$ almost everywhere even with small QGP $\eta/s = 0.08$
- Romatschke, Eur.Phys.J. C75 (2015) no.7, 305, which extent viscous hydrodynamics offers a reliable description?