Towards a deeper understanding of heavy-ion collisions with flow harmonics in LHC

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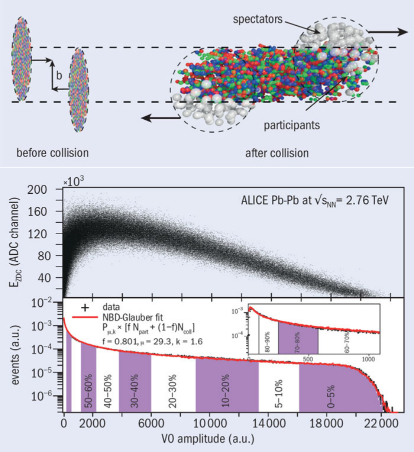
XIV Workshop on Particle Correlations and Femtoscopy, Dubna, Russian Federation

UNIVERSITY OF JYVÄSKYLÄ

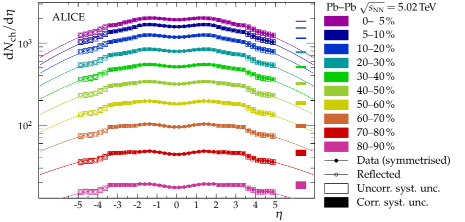
HELSINKI INSTITUTE OF PHYSICS

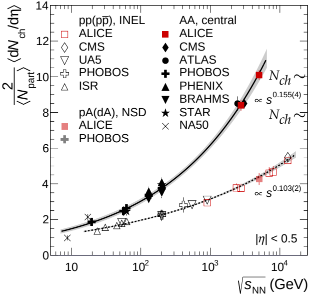
Heavy-ion Collisions, Centrality and Particle productions



b=11.4-12.5fm
$N_{part} \sim 53$
$N_{coll} \sim 100$

b=0-3.5fm
$N_{part} \sim 382$
$N_{coll} \sim 1685$



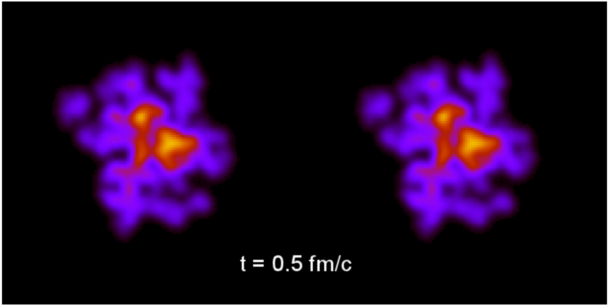


0–5%
$N_{ch} \sim$ 1943 at 5.02TeV
$N_{ch} \sim$ 1584 at 2.76TeV

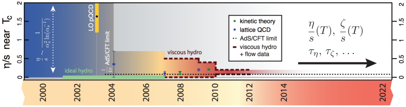
ALICE, Phys. Rev. Lett. 116 (2016) 222302

Space-time history of Heavy-Ion Collisions

Initial geometry fluctuations $\rightarrow$ Transport $\delta_\mu T^{\mu\nu} = 0$ (η/s) $\rightarrow$ final-state particles



Ideal hydrodynamics — Viscous hydrodynamics(η/s=0.16)



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

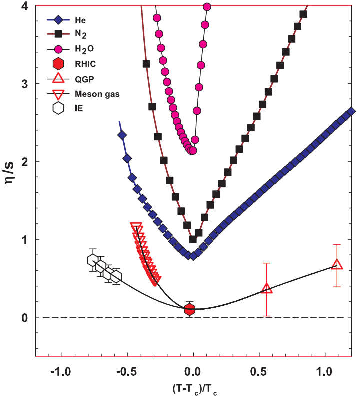
Figure: courtesy of Bjorn Schenke

> "String theory (AdS/CFT correspondence) finds $\eta/s \sim 1/4\pi(0.08)$ a strongly coupled conformal theory $\rightarrow$ hints at a lower bound of that order(KSS bound, 2005)."

using kinetic theory and quantum mechanical considerations, $\eta/s \sim 0.1$:
P. Danielewicz,
M. Gyulassy(PhysRevD.31.53 (1985))

CAN WE MEASURE OR ESTIMATE TRANSPORT PROPERTY OF QGP?

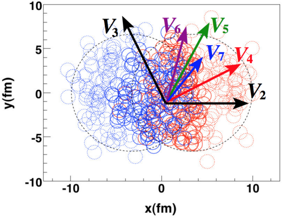
Initial geometry fluctuations $\rightarrow$ Transport $\delta_\mu T^{\mu\nu} = 0$ ($\eta/s(T)$) $\rightarrow$ final-state particles

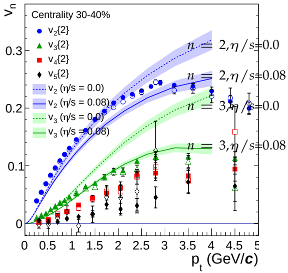


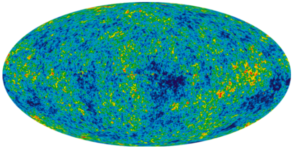
- He, N_2 and H_2O : taken from L. P. Csernai, J. I. Kapusta, and L. D. McLerran, Phys.Rev.Lett. 97, 152303 (2006)
- T$<T_c$: chiral perturbation theory with free cross sections, J.-W. Chen and E. Nakano, Phys.Lett.B647:371-375,2007
- T$>T_c$ and $T_c \approx$ 170 MeV : lattice QCD simulations, A. Nakamura and S. Sakai, Phys.Rev.Lett. 94, 072305(2005)

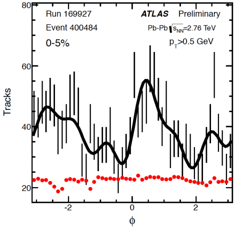
"It is argued that such a low value is indicative of thermodynamic trajectories for the decaying matter which lie close to the QCD critical end point.", R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007).

Higher Flow Harmonics Seen by All Experiments





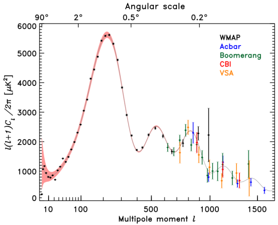




$$P(\varphi) \propto \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

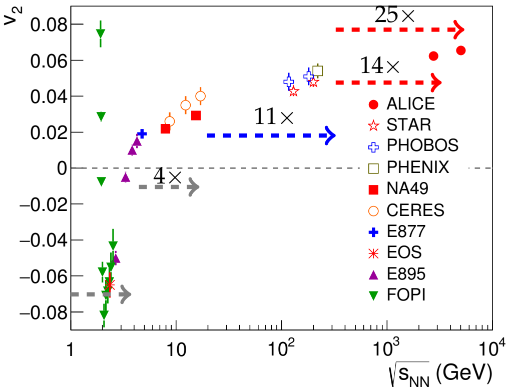
$$V_n \equiv v_n\{\psi_n\} e^{in(\psi_n - \phi)}$$

$$v_n \equiv v_n\{\psi_n\} = \sqrt{\langle |V_n|^2 \rangle}$$



- Fourier and Real Taylor series are particular cases of complex Taylor series.
- Like measurements of early universe sound harmonics
- Sensitive to initial state geometry and properties of the expanding QGP (viscosity(η/s), equation of state)

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



2015 LHC 5.02TeV CERN

2010 LHC 2.76TeV CERN

2000 RHIC 200GeV USA

90s SPS 17GeV CERN

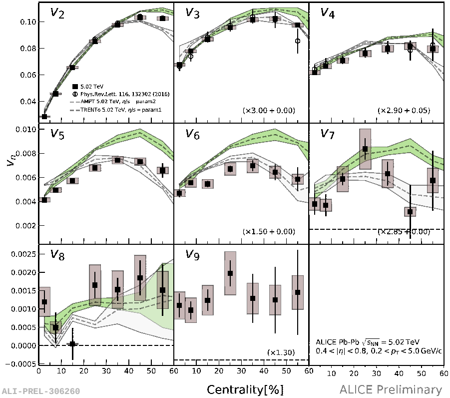
80s AGS 4GeV USA

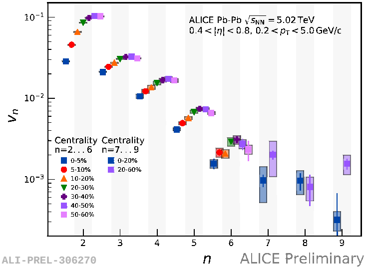
- The results of 5.02TeV shown here are based on small statistics from a low intensity run.
- Many flow analyses with Run2 Pb-Pb data with the full statistics($\approx$ x 100 Minimum bias data).

ALICE has measured the largest flow so far!!!

Higher order v_n

Jasper Parkilla (Jyvaskyla Univ.)



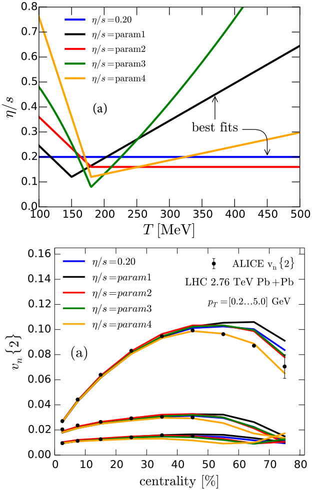


- Up to n=8, nonlinear hydrodynamic response($n > 3$) and searches for acoustic peak(E.Shuryak(arXiv:1710.03776), P. Sorensen et. al(arXiv:1008.3381)).
- $v_n(n > 3)$ are quantified as nonlinear flow mode.

- better constraints on hydrodynamic models, i.e. $\eta/s(T)$ and initial conditions.

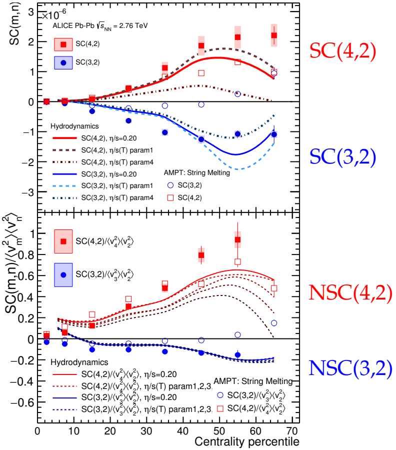
CORRELATIONS OF v_m AND v_n, $\mathrm{SC}(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$

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



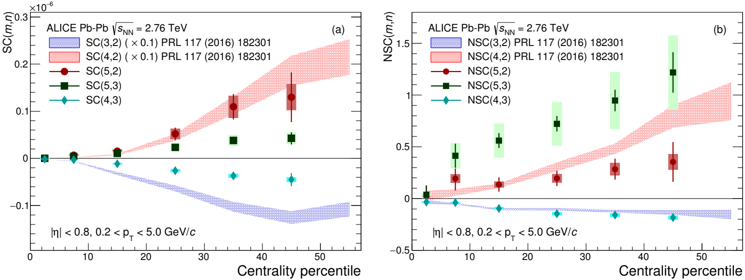
ALICE Phys. Rev. Lett. 117, 182301 (2016)

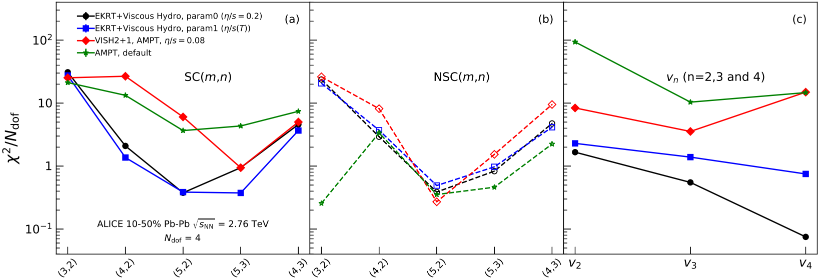
$\mathrm{NSC}(m,n) = \mathrm{SC}(m,n) / \langle v_m^2 \rangle \langle v_n^2 \rangle$



- Strong constraint on the $\eta/s(T)$ in hydrodynamic models.

Strong Constraints for $\eta/s(T)$ and the initial conditions.

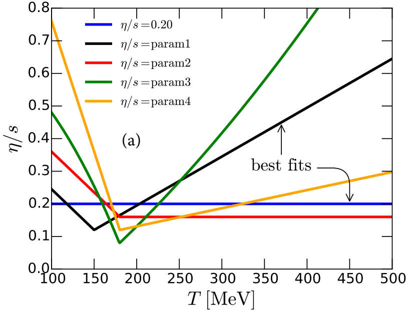




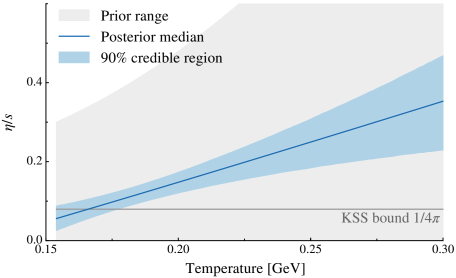
ALICE, Phys. Rev. C 97 (2018) 024906

Implications of the flow and spectra measurements

H. Niemi, K.J. Eskola, R.Paatelainen
(Phys. Rev. C 93, 024907 (2016), arXiv:1505.02677)



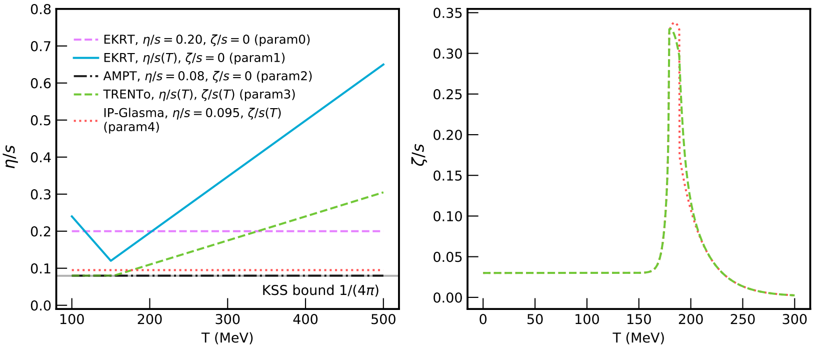
Steffen A. Bass et. al, Global Bayesian Analysis
(Nucl.Phys. A967 (2017) 67-73 , arXiv:1704.07671)



- ALICE data on multiplicity, spectra and flow are key inputs to estimate the properties of the QGP, i.e Global Bayesian Analysis and other theory groups.
- Best fit seems to indicate $\eta/s \approx 0.12$ around $T_c \approx 150$ MeV, very close to $1/4\pi (\approx 0.08)$ from string theory [1](AdS/CFT correspondence).
- η/s(T) can be constrained further, new observables(SC and flow modes) with v_n : separate the effects of $\eta/s(T)$ from the initial conditions.

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

However...

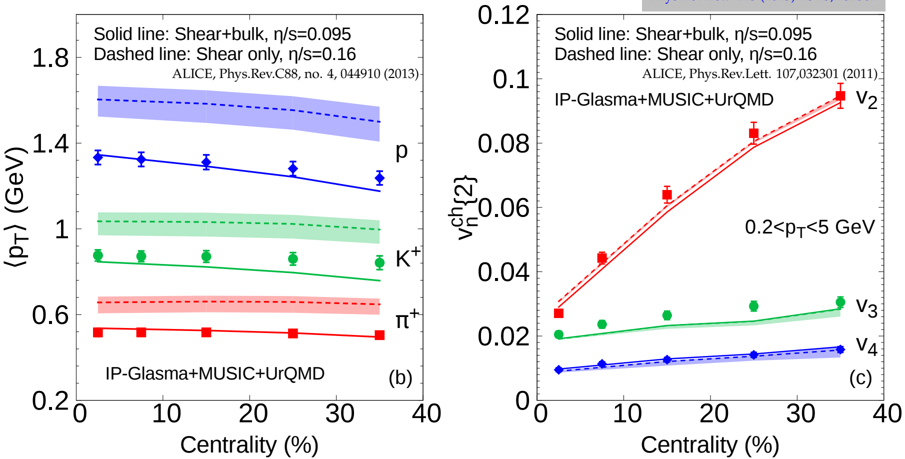


$$T^{hyd}_{\mu\nu} = T^{ideal}_{\mu\nu} - \eta\sigma_{\mu\nu} - \zeta\Pi\Delta_{\mu\nu} + \Pi^{(2)}_{\mu\nu}$$

- Initial conditions ?
- There is also a contribution from $\zeta/s(\mathrm{T})$.
- Relative contribitions from the initial conditions, $\eta/s(\mathrm{T})$ and $\zeta/s(\mathrm{T})$?

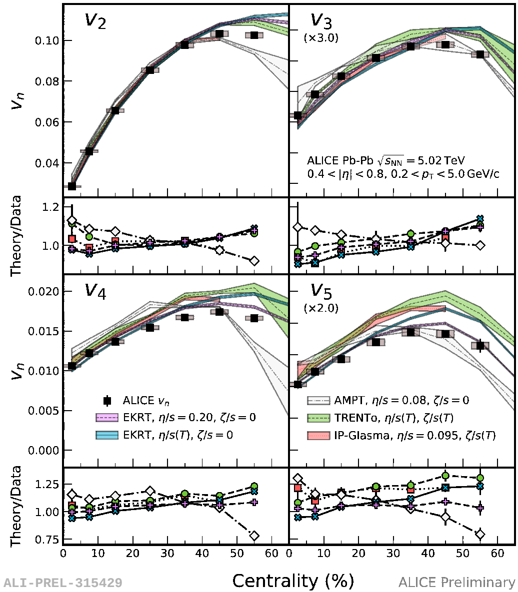
Effects of bulk viscosity

Phys.Rev.Lett. 115 (2015) no.13, 132301



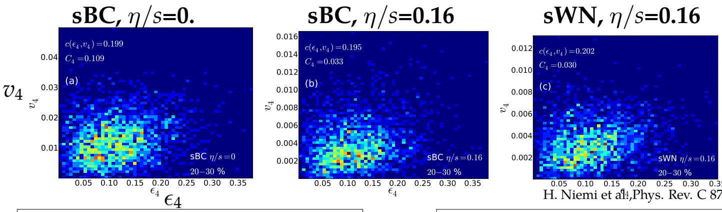
- There is also a contribution from $\zeta/s(T)$(S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol (McGill U.), B. Schenke (Brookhaven), S. Jeon, C. Gale (McGill U.).
- Relative contribitions from the initial conditions, η/s(T) and $\zeta/s(T)$?

However model parameters need to be better constrained



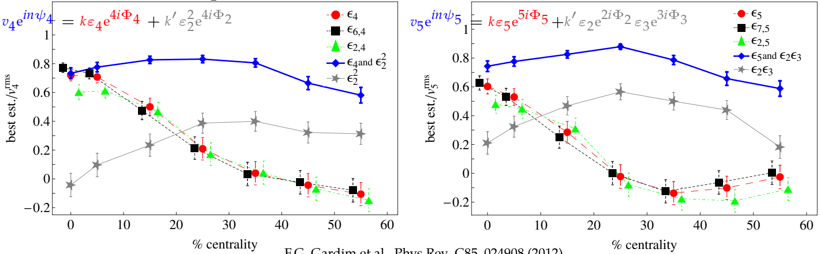
- Hydrodynamic calculations show the sensitivity to various parameters
- Theory/Data ratio gets larger for high harmonics.

$v_n \propto \varepsilon_n$ FOR $n = 2, 3$, NONLINEARITY FOR $n \geq 4$



20 – 30%

H. Niemi et al., Phys. Rev. C 87, 054901 (2013)



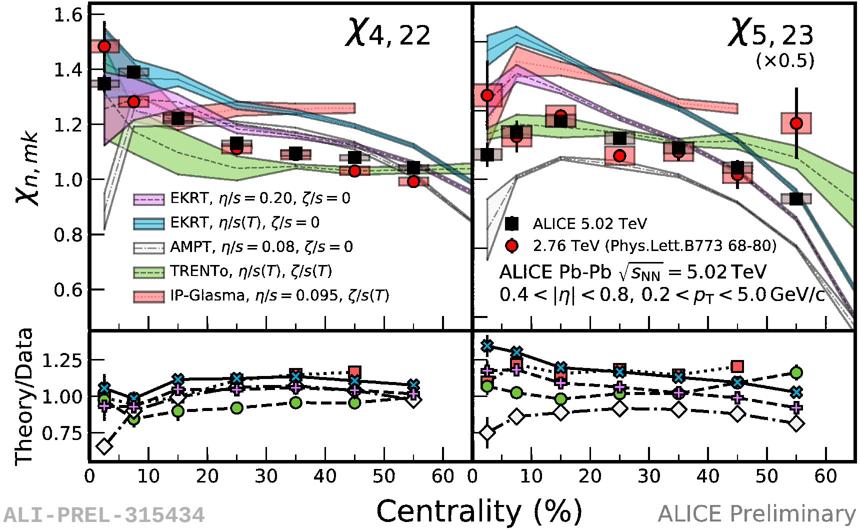
F.G. Gardim et al., Phys.Rev. C85, 024908 (2012)

The relative importance depends significantly on the properties of the medium.

- For increasing η/s, the linear response is more dominant and the relative weight of higher non-linear orders decreases.
- For a rather minimal value of $\eta/s = 1/4\pi$, larger contributions from non-linear corrections. D.Teaney, L Yan Phys.Rev. C86 (2012) 044908

Nonlinear response of high order harmonics ($n > 3$)

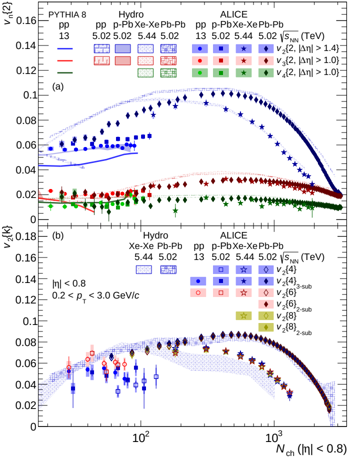
$$V_4 = V_4^L + \chi_{4,22}(V_2)^2 \qquad V_5 = V_5^L + \chi_{5,32}V_2V_3$$



- Clear seperation of the model calculations.
- $\chi_{n,mk}$ should be less sensitive to the detailed information of initial state.

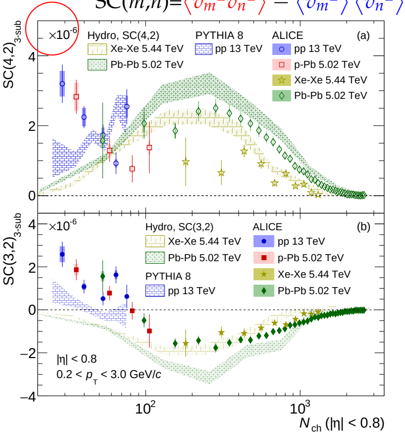
v_n AND FLOW CORRELATIONS IN SMALL AND LARGE SYSTEMS

arXiv:1903.01790, submitted to PRL



- Higher harmonics, mostly due to fluctuations in the initial geometry, show weak multiplicity dependence.
- The origin of the flow in small system, initial conditions, collectivity or non-flow?

$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

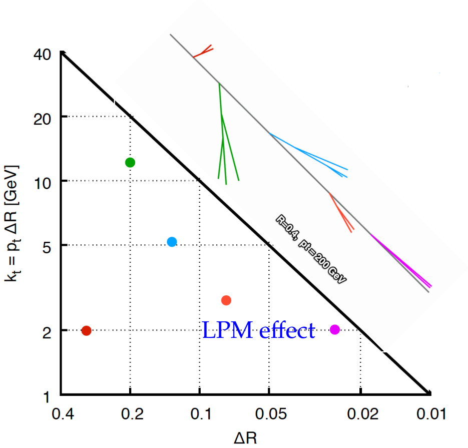


- Extensive studies on Symmetric cumulant up to n=5.
  - Phys. Rev. Lett. 117, 182301 (2016)(arXiv:1604.07663)
  - Phys. Rev. C 97 (2018) 024906(arXiv:1709.01127)
- Measured now in small systems.

Summary

- Precision measurements on soft observables
  - Higher precision data on $\langle dN_{ch}/d\eta \rangle$, spectra and v_n become "Run"-ly routine.
  - $\langle v_m v_n \rangle$ correlations and the nonlinear response of v_n(n>3) $\rightarrow$ Strong constraint on the η/s(T) and ζ/s(T)
  - IP-Glasma/EKRT/AMPT Iintial Condition based hydrodynamic models are favored by the data.
  - ζ/s(T) should be better constrainted with new observables.

Relating η/s and Jet quenching($\hat{q}$)

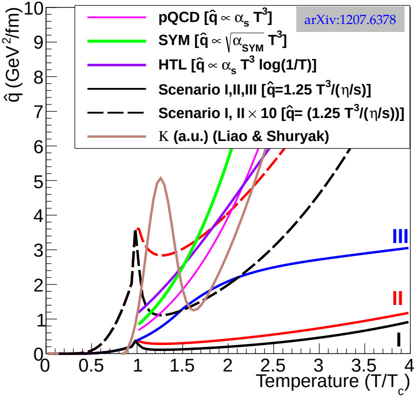


Gavin P. Salam, Dreyer, Soyez, GPS, in progress

$$< p_\perp{}^2 >= \hat{q}L,$$

$$\Delta E \sim \alpha_s\, C_F\, \hat{q}\, L^2.$$

$C_F = 3$(gluon) and $4/3$(quark)

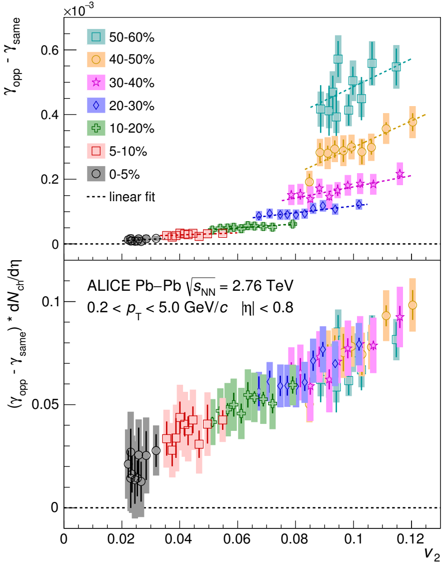


- How do T or scale dependent features translate to final state ?
- An unambiguous determination of both sides of [the equation] from experimental data ? (Phys. Rev. Lett., 99:192301, 2007)

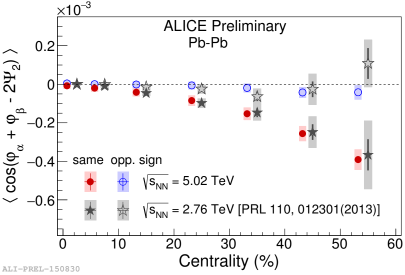
$$\frac{\eta}{s} \left\{ \begin{matrix} \approx \\ \gg \end{matrix} \right\} 1.25 \frac{T^3}{\hat{q}} \quad \left\{ \begin{matrix} \text{for weak coupling,} \\ \text{for strong coupling.} \end{matrix} \right.$$


Dziękuje
Obrigado
谢谢
Hvala
有り難う
Danke
Merci
תודה
Tack
Thank you
Gracias
Grazie
감사합니다
شكرا
謝謝
Спасибі
Спасибо
Mulţumesc
Asante

Extensive CME searches

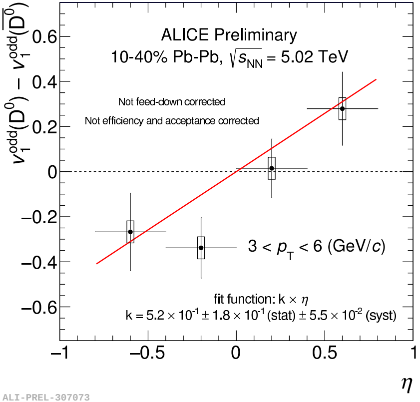


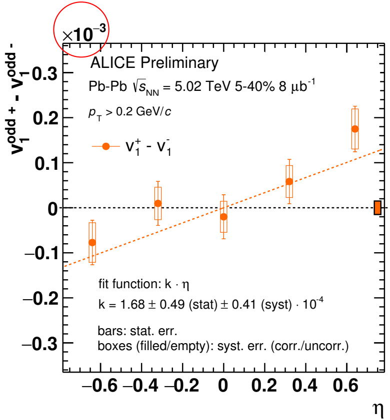
Phys. Lett. B 777 (2018) 151-162, arXiv:1709.04723



- Estimated CME fraction based on linear dependence of backgrounds to elliptic flow, the upper limit 16-33%,at 95% confidence level.
- 5TeV results in QM18.
- CME analyses in various collisions system XeXe, 5TeV PbPb and pPb are ongoing.

Heavy flavor and charged particle v_1

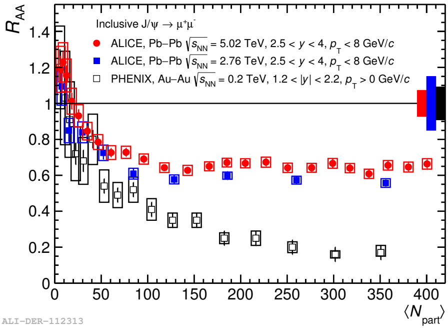


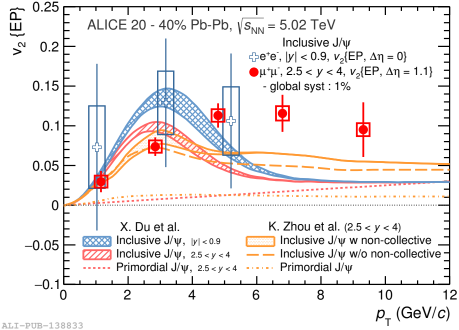


- Charge dependent directed flow is sensitive to the EM fields in the early stages of the collision.
- First measurement on D meson, hint of positive slope with a significance of 2.7σ(HP2018,talk).
- Similar trend observed for charged particles, but different magnitude.
- Large effect expected for heavy flavor due to the shorter formation time ≈ the time scale when B is maximum (K. Das et. al, Phys.Lett. B768 (2017) 260-264)

J/ψ Suppression and Regeneration

Bound states of $c\bar{c}$ and $b\bar{b}$ can be Debye color screened in the QGP as one increases the temperature (melting)

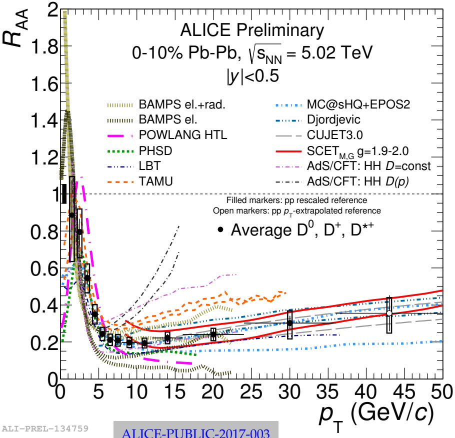




ALICE, Phys.Lett. B766 (2017) 212-224 ALICE, Phys. Rev. Lett. 119 (2017) 242301 arXiv:1709.05260

- Regeneration is more dominant in LHC energies.
- Regeneration gives rise a significant v_2 while primordial J/ψ give minimal effect(high p_T not explained by models).
- -Precision run 2 data allow us to measure v_3 and v_2 in fine centrality bins, submitted to JHEP, arXiv:1811.12727.
- -J/ψ v_2 in p-Pb, ALICE, Phys. Lett. B 780 (2018) 7-20 arXiv:1709.06807.

Simultaneous fit of R_{AA} and v_2 for D-mesons : Constraining models



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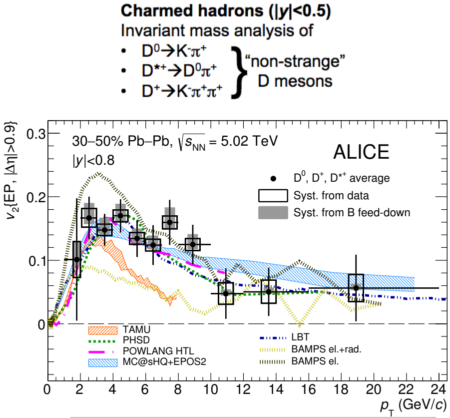
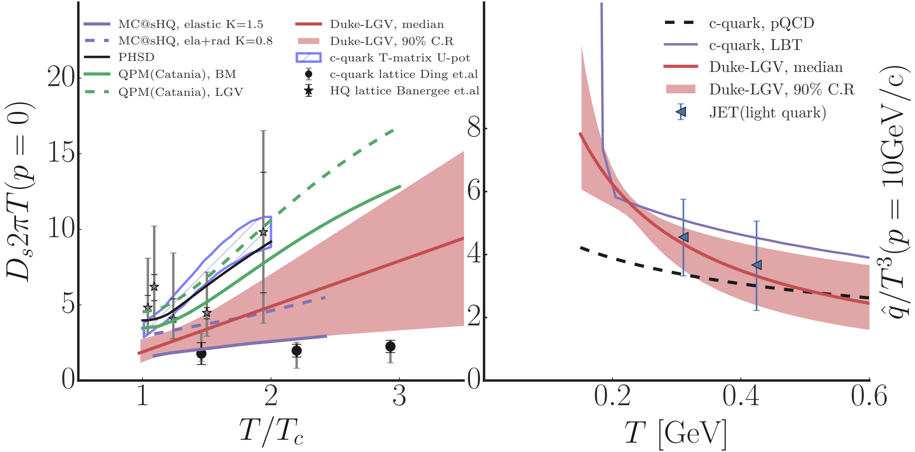


ALICE, Phys. Rev. Lett. 120 (2018) 102301, arXiv:1707.01005

- Strong suppression of high p_T D-meson production in central Pb-Pb collisions.
- Similar for 2.76 TeV and 5 TeV.
- Challenging models with simultaneous fit of R_{AA} and v_2.
- Run1 2.76 TeV data were used for a Bayesian model-to-data analysis.

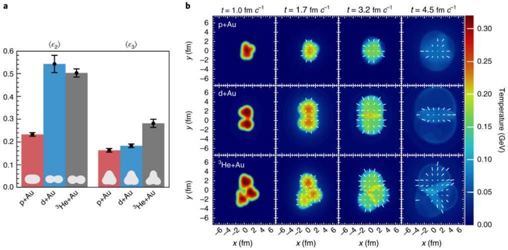
Global anaysis and Uncertainty in Theory, utilizing heavy flavor data

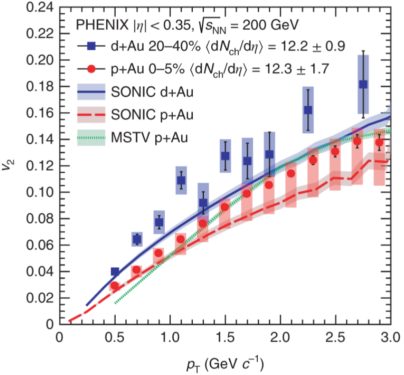


M. Nahrgang, S. A. Bass et. al., Phys. Rev. C 97, 014907 (2018)(arXiv:1710.00807)

Small system flow at RHIC

Nature Physics vol 15, 214-220(2019)





- n=2 and 3
- Creation of quark gluon plasma droplets with three distinct geometries?

- Hydro works better than MSTV.
- It doesn't mean that MSTV is wrong, need initial conditions(MSTV) + final state effects as same as larger systems.
- The relative contributions matter, initial state dominant in smaller system than larger systems.