

Measurements of Correlations between different order flow harmonics in Pb–Pb collisions with the ALICE experiment at the LHC

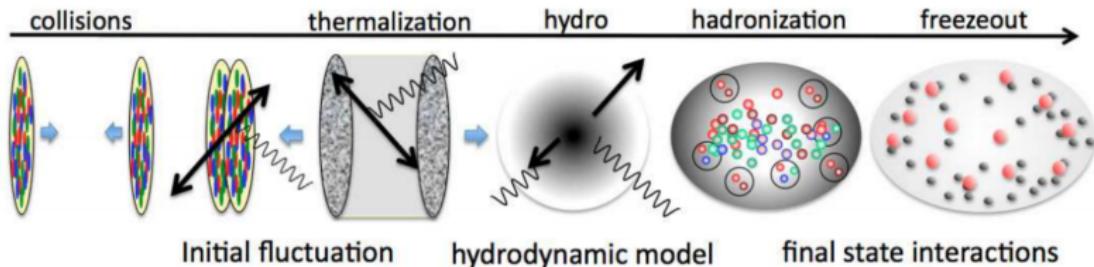
Dong Jo Kim ¹

¹University of Jyväskylä & Helsinki Institute of Physics, Finland

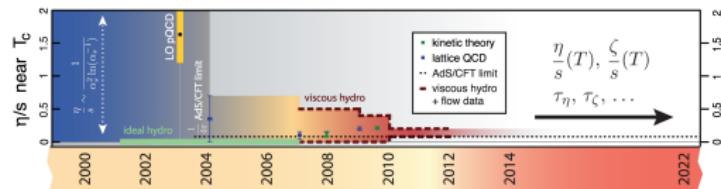
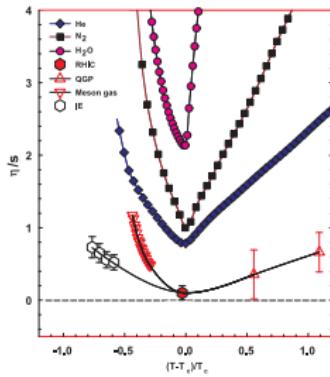
October 30, 2015

Particle Physics Day 2015, Helsinki, Finland

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

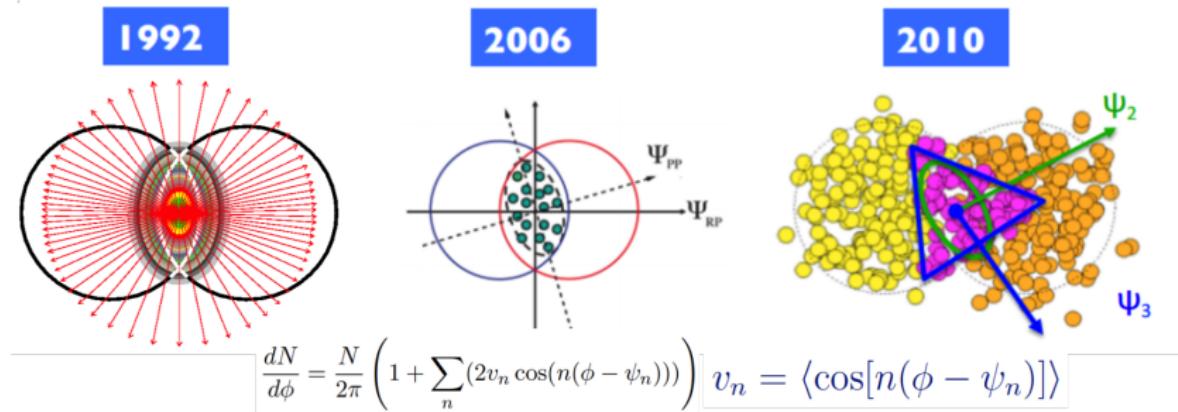
H. Song, U. W. Heinz, J. Phys. G36 (2009) 064033

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."

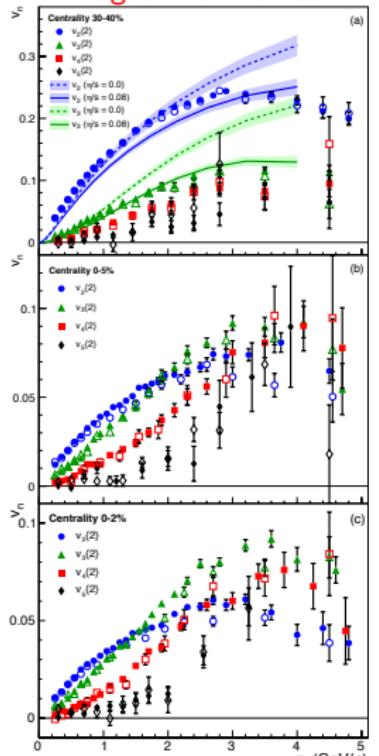
Flow measurements in Heavy-Ion Collisions



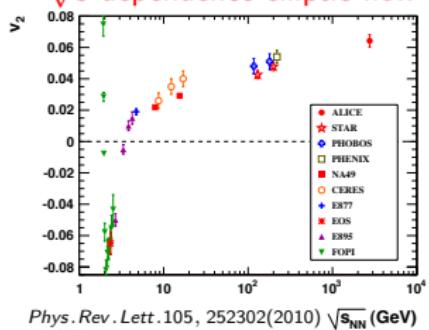
- The magnitudes of Flow-vector, anisotropic flow harmonics v_n , have been measured in great details (centrality, p_T , η , PID)
 - Large elliptic flow has indicated **fluid behavior of matter created at RHIC** in early 2000's (BNL announces perfect liquid in 2005 press release)
 - The importance of fluctuations was realized later and **analysis of odd flow harmonics** began in 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

Selected flow measurements at LHC in one slide

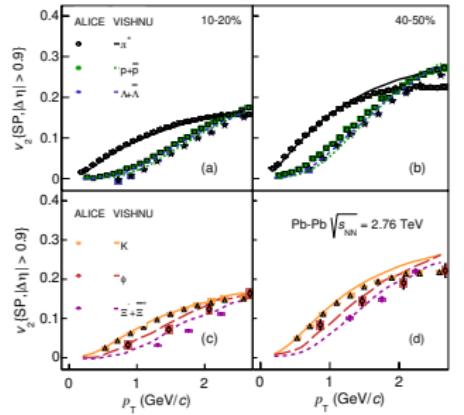
Higher Harmonics



\sqrt{s} dependence elliptic flow



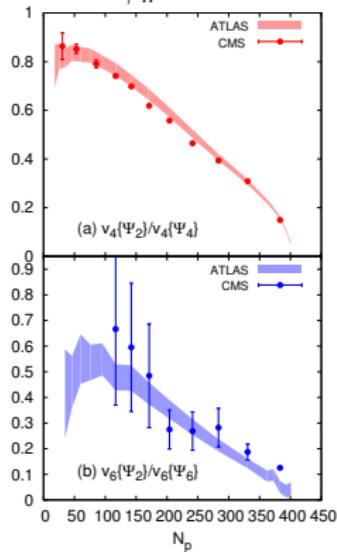
PID elliptic flow



Event-by-event flow harmonics
ATLAS, JHEP1311(2013)183

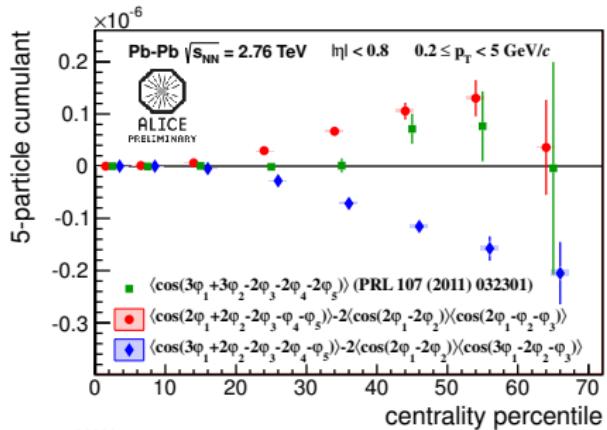
Correlation between flow-vectors

- Flow direction correlations: ψ_n and ψ_m correlations
- Flow magnitude correlations: v_m and v_n correlations
 - Are v_n and v_m correlated? anti-correlated? or not correlated?
 - How can we investigate the relationship between v_n and v_m without contribution of ψ_m and ψ_n



$\frac{v_4\{\Psi_2\}}{v_4\{\Psi_4\}}$, $\frac{v_6\{\Psi_2\}}{v_6\{\Psi_6\}}$ from ATLAS(arXiv:1403.0489), CMS (arXiv:1310.8651))

$\langle \cos 4(\Phi_2 - \Phi_4) \rangle_w \equiv \frac{v_4\{\Psi_2\}}{v_4\{\Psi_4\}}$, which includes not only event plane angle correlations but also it's magnitude
(J.Y.Ollitrault et. al., Phys.Lett. B744 (2015) 82-87)

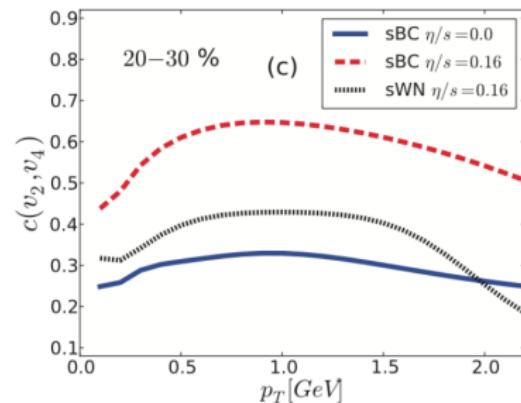
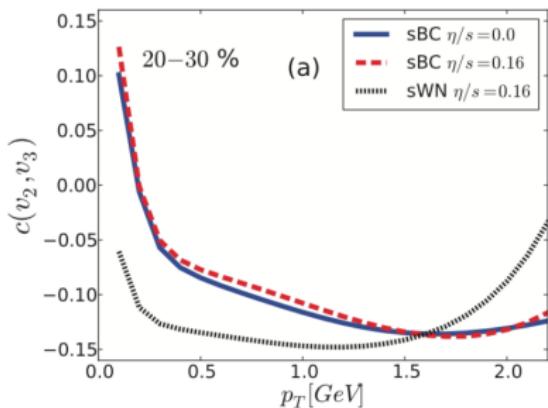


multi-particle cumulant from ALICE (PRL 107 (2011) 032301)

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

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



- $c(v_2, v_3)$ 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

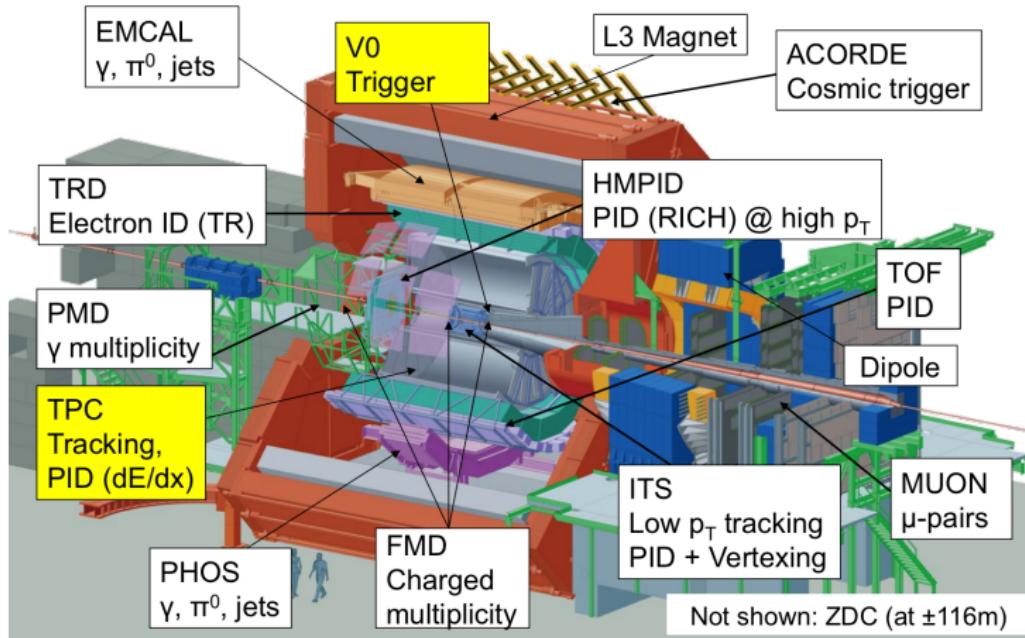
New Observable : Symmetric 2-harmonic 4-particle Cumulants (SC) ¹

$$\begin{aligned}\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c &= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle \\ &\quad - \langle\langle \cos[m(\varphi_1 - \varphi_2)] \rangle\rangle \langle\langle \cos[n(\varphi_1 - \varphi_2)] \rangle\rangle \\ &= \left\langle v_m^2 v_n^2 \right\rangle - \left\langle v_m^2 \right\rangle \left\langle v_n^2 \right\rangle\end{aligned}$$

- 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.

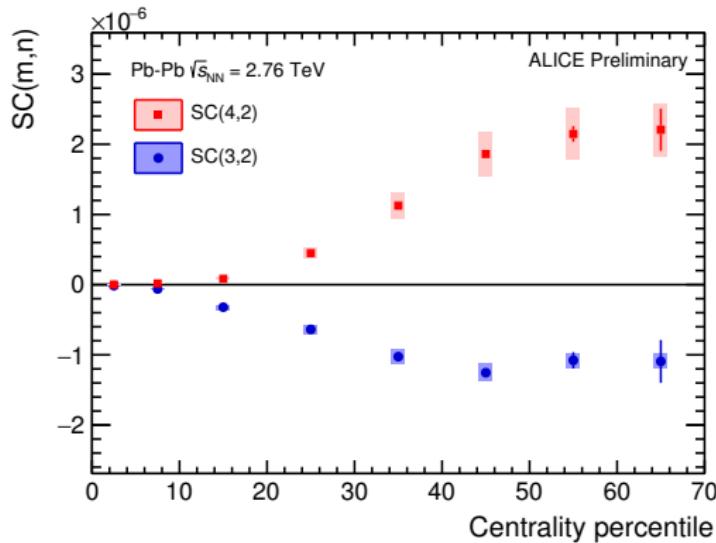
¹Ante Bilandzic et al., Phys. Rev. C 89, 064904 (2014)

ALICE Detectors



- Centrality determination by V0(N_{ch}) with scintillators in $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV $\approx 20M$ events.
- Tracking - TPC tracks constrained to the primary vertex and **full azimuthal acceptance** (Unidentified charged particles $|\eta| < 0.8$, $0.2 < p_T < 5.0$ GeV/c)

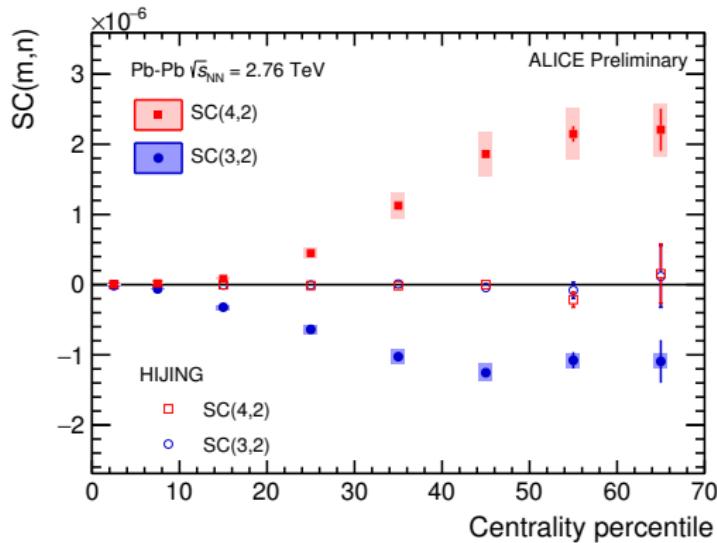
SC(m, n) results



$$\begin{aligned} \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c \\ = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle \end{aligned}$$

- The positive values of $SC(4,2)$ and negative $SC(3,2)$ are observed for all centralities.
 - suggests a correlation between v_2 and v_4 , and an anti-correlations between v_2 and v_3 .
 - indicates finding $v_2 > \langle v_2 \rangle$ in an event enhances the probability of finding $v_4 > \langle v_4 \rangle$ and finding $v_3 < \langle v_3 \rangle$ in that event.

SC(m, n) results with HIJING: is Non-flow contribution?



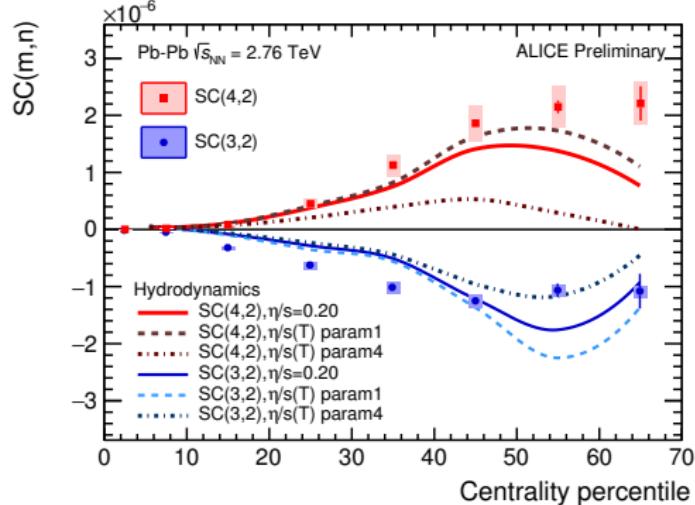
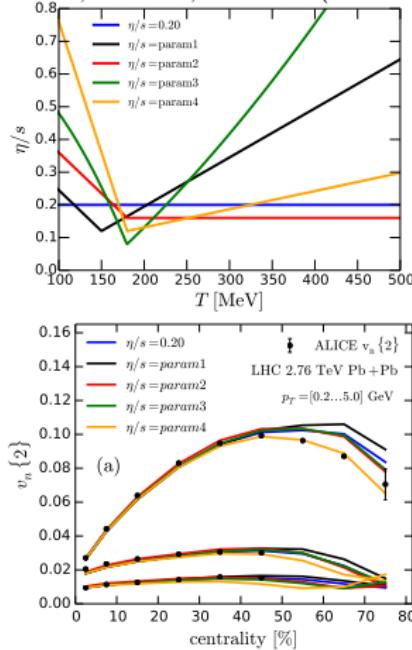
$$\begin{aligned}\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c \\ = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle\end{aligned}$$

ALI-PREL-96655

- SC(m,n) calculations from HIJING
- It is found that both $\langle v_m^2 v_n^2 \rangle$ and $\langle v_m^2 \rangle \langle v_n^2 \rangle$ are non-zero in HIJING, but calculation of SC(m,n) from HIJING are compatible with zero
 - suggests SC measurements are nearly insensitive to non-flow correlations
- non-zero values of SC measurements cannot be explained by non-flow effects, thus confirms the existence of (anti-)correlations between v_n and v_m harmonics.

SC(m, n) results : Comparisons to hydrodynamics

H. Niemi, K. J. Eskola, R. Paatelainen (arXiv : 1505.02677)



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

Comparisons of SC measurements to hydrodynamic calculations

- 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)
- SC measurements provide stronger constraints on the η/s in hydro in combination with standard v_n measurements

Summary

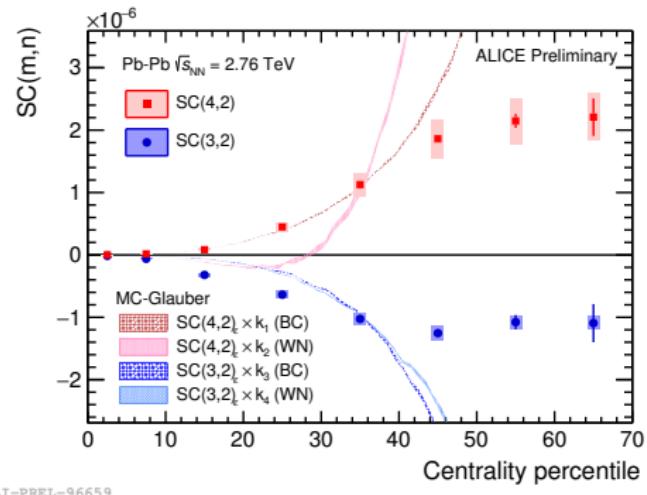
We have measured for the first time the new multi-particle observables $SC(m,n)$ which quantify the relationship between event-by-event fluctuations of two different flow harmonics.

- v_2 and v_4 are correlated, v_2 and v_3 are anti-correlated in all centralities, the centrality dependence can not be described quantitatively by any existing calculations.
- $SC(m,n)$ measurements provide strong constraints on the η/s in hydro in combination with the individual flow harmonics, discriminating the inputs to hydro model with different parameterizations of η/s .
- In fluctuation-dominated regime (very central region 0-10%) the MC-Glauber initial conditions with binary collisions weights are favored over wounded nucleon weights by $SC(m,n)$ data.

$SC(m, n)$ provides strong constraints to initial conditions and η/s .

Backup Slides

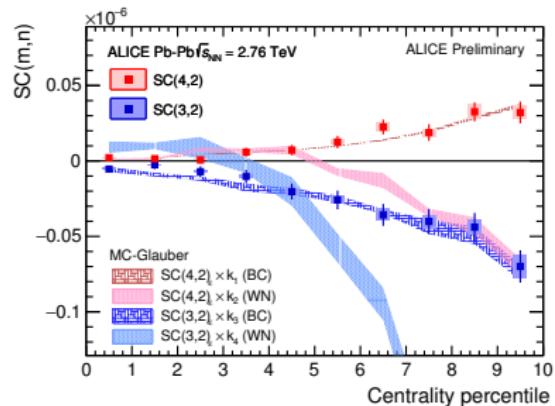
SC(m, n) results : comparison to MC-Glauber model



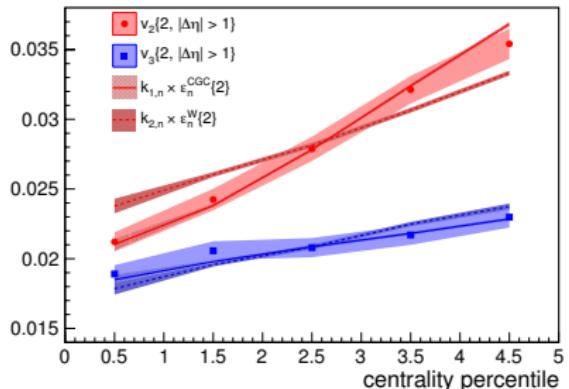
Comparisons to MC-Glauber model calculations

- SC(m,n) from MC-Glauber model using weights of wounded nucleon (WN) and binary collisions (BC) weights are scaled and compared to data.
- Increasing trend from central to peripheral collisions with different signature has been observed for SC(4, 2) and SC(3, 2), the centrality dependence of corresponding measurements cannot be captured well.
- correlations in the initial conditions is not the only contribution to SC measurements.

Probing the initial conditions



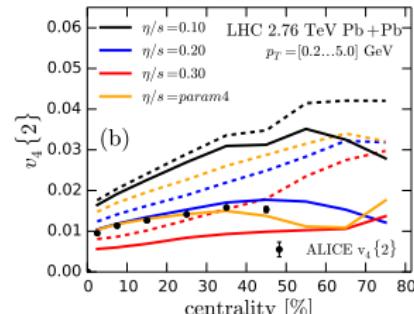
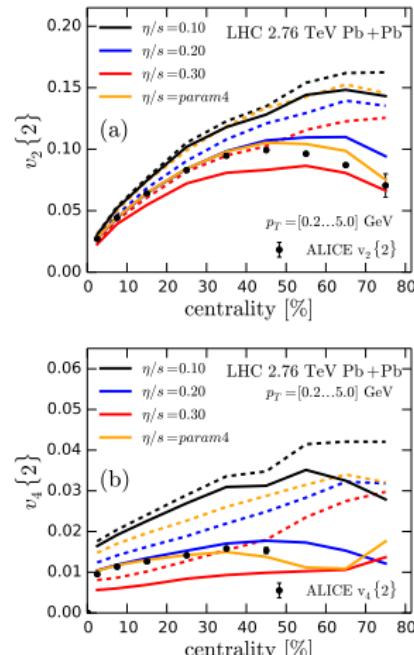
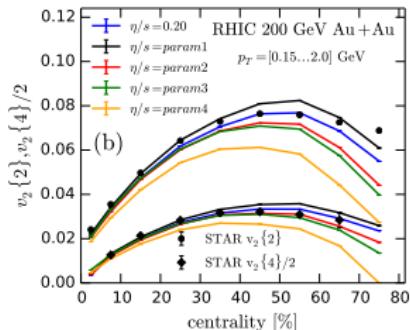
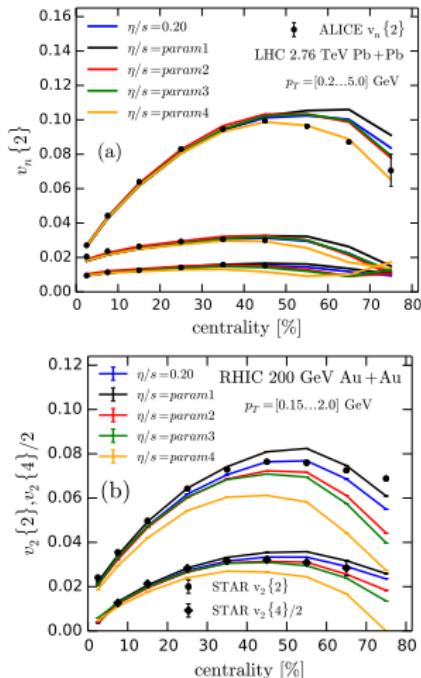
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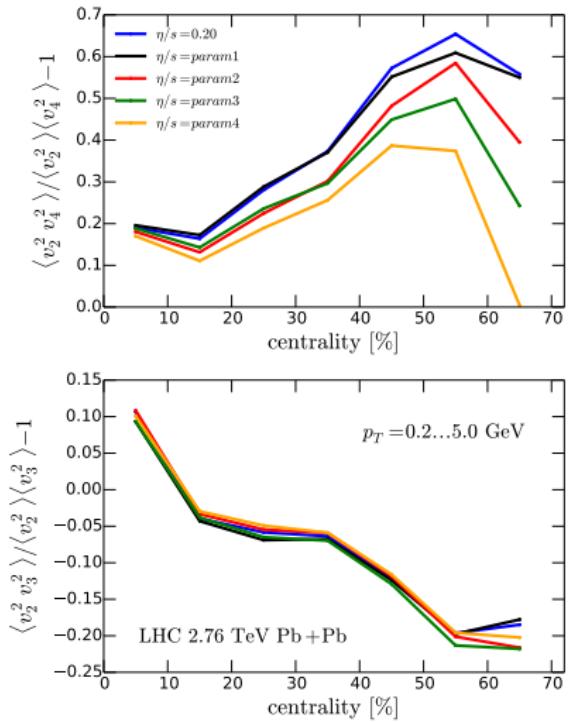
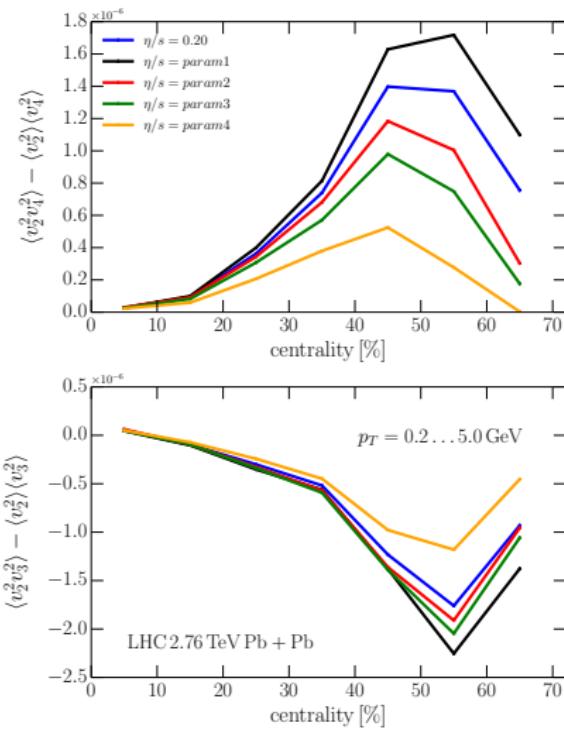
- $v_n \propto \epsilon_n$ for most central collisions discriminate the initial condition, Phys.Rev.Lett. 107:032301,2011(ALICE)
- Assuming $v_n \propto \epsilon_n$ in the very central collisions, the $SC(m, n)_\epsilon$ after scaling might be able to describe the measured $SC(m, n)$.
- Comparison to MC-Glauber calculations (initial conditions)
 - the one with Binary Collision weight (BC) quantitatively describes $SC(m,n)$ for 0-10%, while Wounded Nucleon (WN) fails.

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



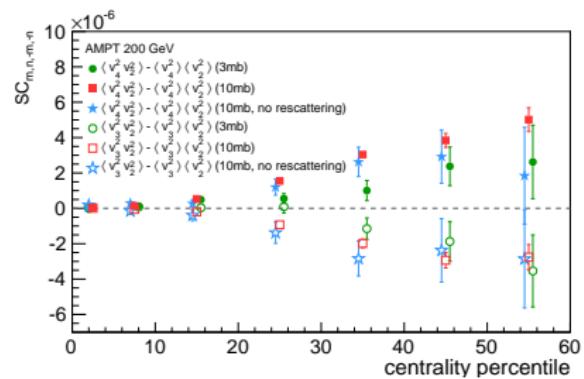
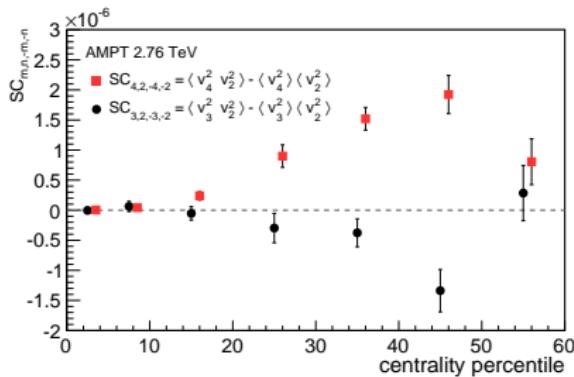
- H. Niemi, K.J. Eskola, R.Paatelainen (arXiv:1505.02677)

Hydro results from RHIC to LHC, SC(m,n) vs $\eta/s(T)$



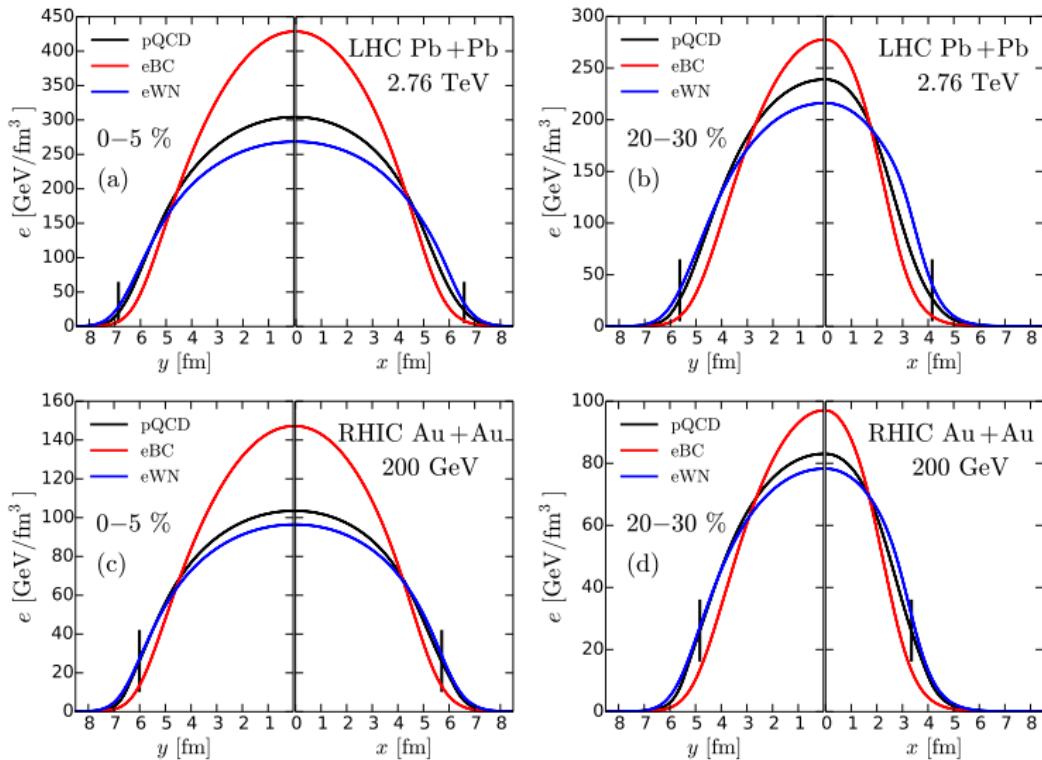
- H. Niemi, K.J. Eskola, R.Paatelainen (arXiv:1505.02677)

AMPT results from RHIC to LHC



- Ante Bilandzic et al., Phys. Rev. C 89, 064904 (2014)

initial energy density profile from RHIC to LHC



Energy density profiles, H. Niemi, K.J. Eskola, R.Paatelainen (arXiv:1505.02677)