Summary of flow and its correlation in ALICE

Myunggeun Song

Yonsei Univ.

November 23, 2016

HIM 2016 @ iBS

Based on PRL

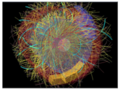
This Presentation based on

PHYSICAL REVIEW LETTERS

moving physics forward

Dear Sir or Madam,

We are pleased to inform you that the Letter



Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

J. Adam *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **117**, 182301 (2016)

Published 28 October 2016

has been highlighted by the editors as an Editors' Suggestion. Publication of a Letter is already a considerable achievement, as *Physical Review Letters* accepts fewer than 1/4 of submissions, and is ranked first among physics and mathematics journals by the Google Scholar five-year h-index. A highlighted Letter has additional significance, because only about

one Letter in six is highlighted as a Suggestion due to its particular importance, innovation, and broad appeal

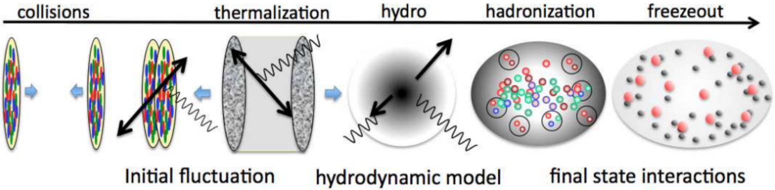
Reports from referee

- The first and only observables for measure correlation between "magnitudes" of flow harmonics
- It was demonstrated that this method has a good potential to validate different heavy-ion models and has high chances to be used in new measurements at the LHC energies, in particular in 5 TeV PbPb collisions and possibly in small systems like pPb collisions.
- The results are of significant importance for the field and without doubt worth to be published in PRL.

And also contains follow up paper (ongoing, IRC round 2 stage)

Introduction - Heavy ion collision

- At RHIC(200GeV) and LHC(2.76TeV) energies, lattice calculation of QCD predicts a transition to new state of matter, the so-called quark-gluon Plasma (QGP)
- These QCD state are thought to consist of asymptotically free quarks and gluons, and expected to occur around T = 150∼200MeV
- Hydrodynamics is consider as the most successful approach to describe QGP state

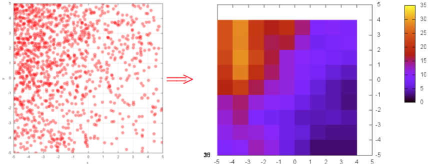


Introduction - Hydrodynamics

- In spite of its simple-looking Lagrangean of QCD

$$\mathcal{L} = \bar{\psi}_i(i\gamma_\mu D^\mu_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}F_{\mu\nu\alpha}F^{\mu\nu\alpha} \quad (1)$$

- It is very difficult to make *any* predictions directly from QCD [1]
  (due to its complexity which mainly arises from the interactions of the gluons, the strong coupling...)
  - → Need "coarse-grained" theory
  - If one is only interested in macroscopic properties, degree of freedom and their interactions are not necessary



new equation of states(EoS) from Hydrodynamics

$$P = P(\epsilon, n)$$

with additional parameter "the transport coefficient" such as η, ζ, λ

One of the most important observables supporting to the discovery of the QGP and validation of hydrodynamic is the high values of elliptic flow

[1] Quantum Chromodynamics, W. Greiner et al., Springer

Introduction - Flow

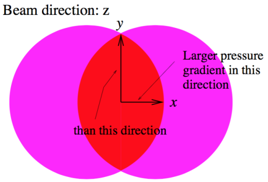
Large elliptic flow v_2 in Heavy-ion collisions

- Fourier decomposition is used to quantify the anisotropic distribution of produced particles

$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{1}{2\pi}\sum_{n=1}(2v_n \cos n(\varphi - \psi_n))$$

The large elliptic flow discovered at RHIC energies, and continues to increase also at LHC energies.

Hydrodynamic response of the system to the initial spatial anisotropy



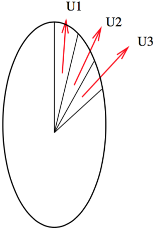
Large elliptic flow(v_2) has indicated fluid behavior of matter created

- Particles are more boosted in higher pressure gradient direction
- (for High p_T, energy lose of jet)

Share viscosity (η) plays a key role during

"coordinate space anisotropy" $\rightarrow$ **"momentum space anisotropy"**

- The large share viscosity is related to the large mean free path (λ_{mfp})
- The large mean free path → weakly coupled → long distance until next collision → "easy mixing"
- The short mean free path → mixing takes long time
- Share viscosity smears out flow difference (diffusion)
- Share viscosity reduces non-sphericity



- Since, $\eta/s \propto \frac{1}{\alpha_s 2ln(1/\alpha_s)}$
- QCD coupling α_s decreases as temperature → η/s must increase as T increasases
- Low temperature hadron gas is known to have large viscosity
  P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005)

→ η/s must have a minimum near T_c

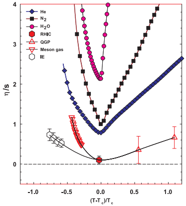
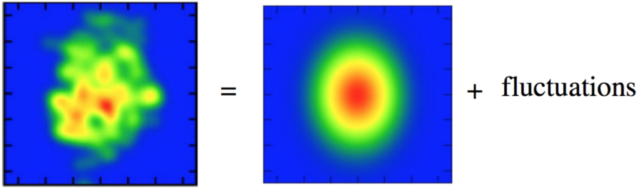


Figure: R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007)

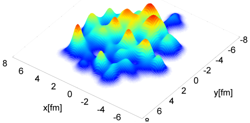
Not only almomd shape geometry but also its fluctuation formed anisotropic distribution of produced particles



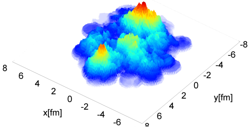
Currently, anisotropic ditribution is understood as the result of

- Initial density profile which is fluctuate event-by-event
- Hydrodynamic response (both linear and non-linear) which is related to transport coefficient

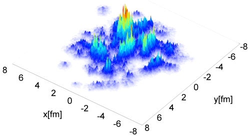
MC-Glauber



MC-KLN

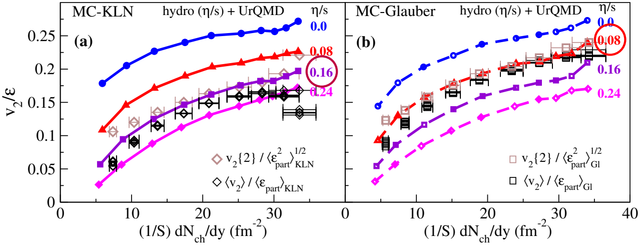


IP-Glasma



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)

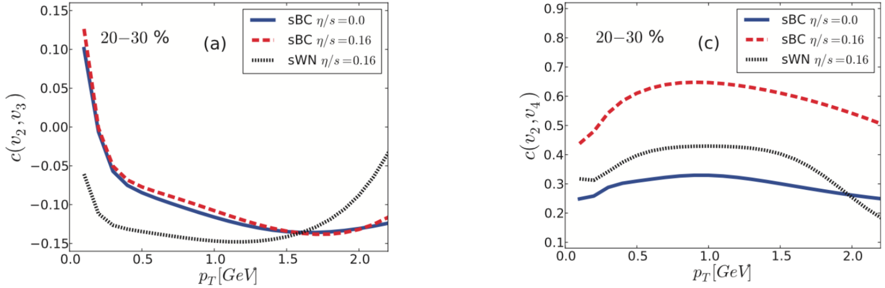
MC-KLN : T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys. Lett. B636, 299 (2006); A. Adil, H.J. Drescher, A. Dumitru, A. Hayashigaki, Y. Nara Phys. Rev. C, 74 (2006), p. 044905
MC-Glauber : Z. Qiu and U. W. Heinz, Phys. Rev. C84, 024911 (2011);Z. Qiu, C. Shen, and U. W. Heinz, Phys. Lett. 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

→ need better observable than single flow, more sensitive to initial conditions and η/s

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) [2]

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

- By construction, not sensitive to
  - non-flow effects
  - inter-correlations of various event-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.

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

Analysis details

Event selection and track selection are just followed as like ALICE SC short paper[3]

- Dataset : LHC10h, HIJING(Hijing_PbPb_LHC10h), AMPT [4]

Set	String Melting	Rescattering	Denote as
AMPT LHC13f3b	OFF	ON	AMPT, default
AMPT LHC13f3c	ON	ON	AMPT, String melting
AMPT LHC13f3a	ON	OFF	AMPT, String melting w/o hadronic rescattering

- Event selection : $|zvtx| < 10cm$, cut on outliers
- Trackcut condition :

$$|\eta| < 0.8, \quad 0.2 < p_T < 5.0 \text{ GeV}/c \text{ TPC Only tracks}$$

1. SC(m,n) with various model comparison (AMPT, Hydro simulation..)
2. SC(3,2), SC(4,2) + higher harmonics SC(5,2), SC(5,3), SC(4,3) (+ normalized)
3. p_T dependence SC(3,2) and SC(4,2) (+ normalized)
4. Paper preparation group twiki page [5]
    1. PC (Ante Bilandzic, DongJo Kim(Rep.), Myunggeun Song, You Zhou)
    2. Proposed IRC (Sergei Voloshin, Sudhir Raniwala, Peter Christiansen, Shinichi Esumi)
    3. list of the PAG presentations and analysis notes

[3] arXiv:1604.07663, submitted to PRL

[4] Thanks to the production team for x4 stat., https://alice.its.cern.ch/jira/browse/ALIROOT-6701

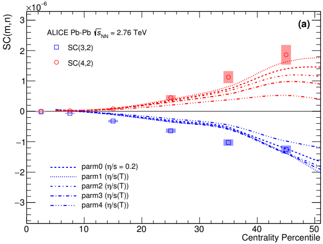
[5] https://twiki.cern.ch/twiki/bin/view/ALICE/PtDependentStandardCandles

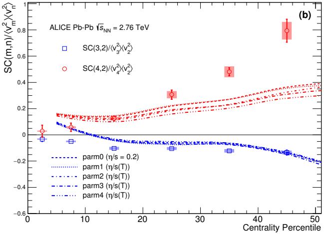
List of works

- Measure $SC(3,2)$ and $SC(4,2)$ (and also normalized $SC(3,2)$ and $SC(4,2)$)
- Compare with HIJING simulation to check the effect of Non-flow
- Measure $SC(m,n)$ with higher order flow harmonics (up to 5th order)
- Evaluate with various Hydrodynamic simulation (pQCD + viscous, AMPT, VISH2+1(iEbE)....) with various initial conditions and η/s
- Check the p_T dependence
- Cross-check with Scalar Product method
- ToyMC simulation (+ PYTHIA jet)
- Systematic uncertainty estimation

→ Contribution on $SC(m,n)$ paper arXiv:1604.07663 (Phys.Rev.Lett.)
→ Follow up paper (long SC paper) is being preparing (IRC review round 2 ongoing)

Result :SC(m,n) and Comparison to Hydrodynamics prediction

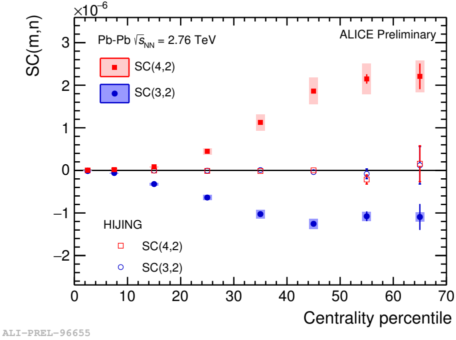




- SC(m,n) results shows that the correlation between v_2 and v_4 is positive, and v_2 and v_3 is negative
    - indicates finding $v_2 > \langle v_2 \rangle$ in an event enhances the probability of finding $v_4 > \langle v_4 \rangle$ and finding $v_3 < \langle v_3 \rangle$ in that event.
- These trends are also shown in hydro prediction [6] too
- But, none of η/s parametrization can reproduce exactly same result as data for both of SC(3,2) and SC(4,2) at the same time
- The differences between data and hydrodynamic predictions become worse in normalized SC

[6] Phys. Rev. C 93, 024907 (2016), H.Niemi et al

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

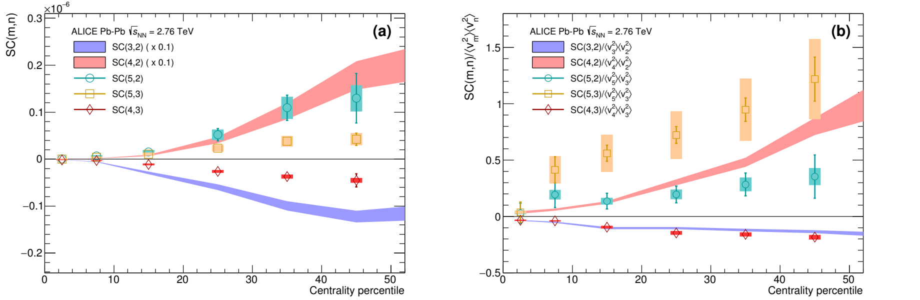


$$\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c$$
$$= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle - \langle\langle \cos[m(\varphi_1 - \varphi_2)]\rangle\rangle \langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle$$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

- 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
- Moreover, the results from like-sign method which is another approach to estimate non-flow effects, show only few % differences (See Backup)

$\rightarrow$ suggests SC measurements are not coming from non-flow constirbution

Result 2 : SC with higher order harmonics



- SC(4,3) is negative(anti-correlated), while SC(5,2) and SC(5,3) are positive(correlated).
- The strength of correlation between v_5 and v_2 is stronger than v_5 and v_3 in SC(m,n) however in NSC(m,n), the strength of correlation become weaker than v_5 and v_3

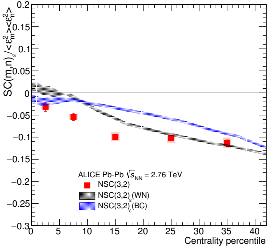
$\rightarrow$ the strength of higher order $SC(m, n)$ is weaker than lower order correlations not because correlation is weak, but because its single flow is weak.

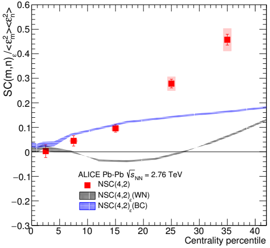
Results : Comparison with the Correlation from the Eccentricity

- If there is only linear response ($v_n \propto \epsilon_n$), then *NSC*(m, n) in coordinate space are able to capture $NSC(m, n)$ in the momentum space

$$SC(m,n)_\epsilon/\langle\epsilon_n^2\rangle\langle\epsilon_m^2\rangle \equiv (\langle\epsilon_n^2\epsilon_m^2\rangle - \langle\epsilon_n^2\rangle\langle\epsilon_m^2\rangle)/\langle\epsilon_n^2\rangle\langle\epsilon_m^2\rangle \quad (2)$$

Where the ϵ_n is the nth order coordinate space anisotropy[7]

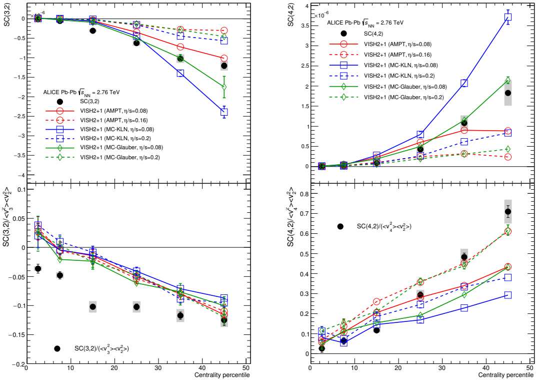




- A large deviation of $NSC(4, 2)$ indicates the contribution of the non-linear response of initial condition though hydrodynamic evolution
- $NSC(3, 2)$ describes the data better than $NSC(4, 2)$, because the $NSC(3, 2)$ appears to be sensitive only to initial conditions and not sensitive to hydrodynamic properties.

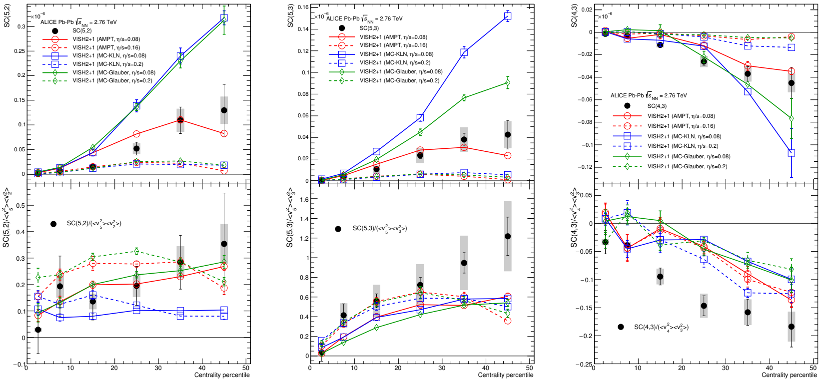
[7] defined in Phys. Rev. C 82 (2010) 039903

Lower order SC : Comparison with Hydrodynamic calculation



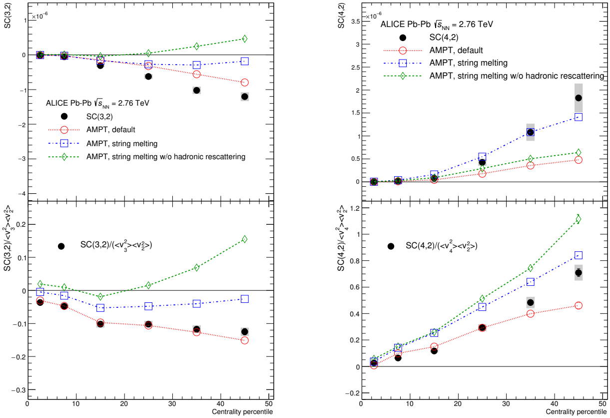
- Hydro calculation with VISH2+1 with two different share viscosity (large η/s : dashed line, small η/s : solid line), and three initial conditions
- Prediction with large share viscosity all failed to capture the SC(m,n).
- The sign of the NSC(3,2) is opposite to the data in most central range(where the fluctuation dominant region)
- NSC(3,2) does not show sensitivity to initial conditions or η/s parametrizations, while NSC(4,2) is sensitive to both

Higher order SC : Comparison with Hydrodynamic calculation



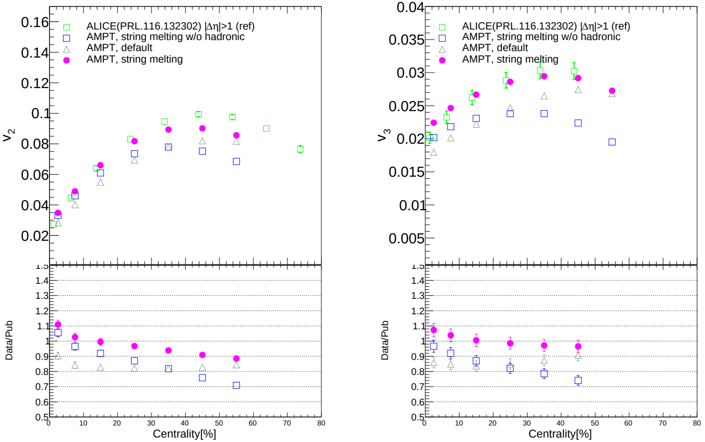
- Prediction with large share viscosity all failed to capture the SC(m,n).
- Among the models with small η/s, data was well described by one from AMPT initial condition.
- But still cannot capture the data quantitively for most of centrality ranges

Comparison with various AMPT simulations



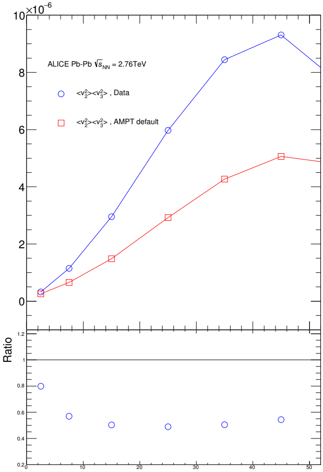
- AMPT default (without string melting) describes better than other configurations
- For $NSC(3,2)$(left, bottom), the AMPT default settings(red, open circle) describe the data up to 50% centralities in good agreements
- However, for the original $SC(3,2)$(top), AMPT does not described data well.
- It might come from the difference of single v_n of AMPT and data, not comes from correlation

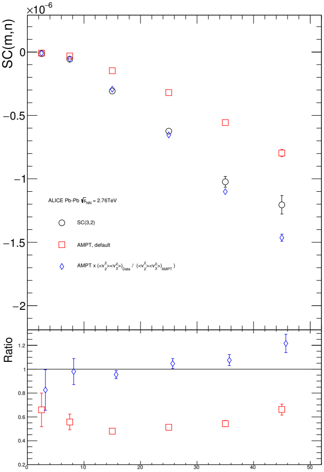
Single v_n measurment with data, and AMPT



- indeed the signel v_n from AMPT, default (gray triangle) are relatively smaller than v_n from data (2p cumulants method with $\eta > 1.0$)

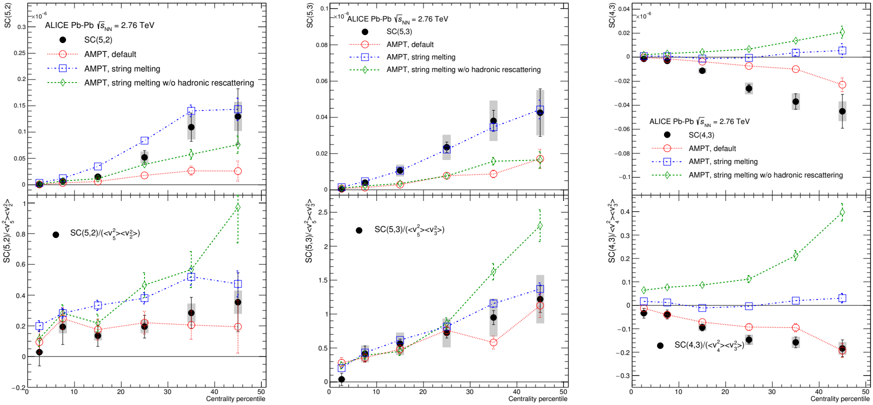
Correction AMPT's $SC(3,2)$ with single v_n from Data





- As the results, the normalize factor $\langle v_2^2\rangle\langle v_3^2\rangle$ of AMPT is always smaller than Data's
- When we correction single v_n differences of AMPT and Data, the original $SC(3,2)$ with AMPT, default come close to data

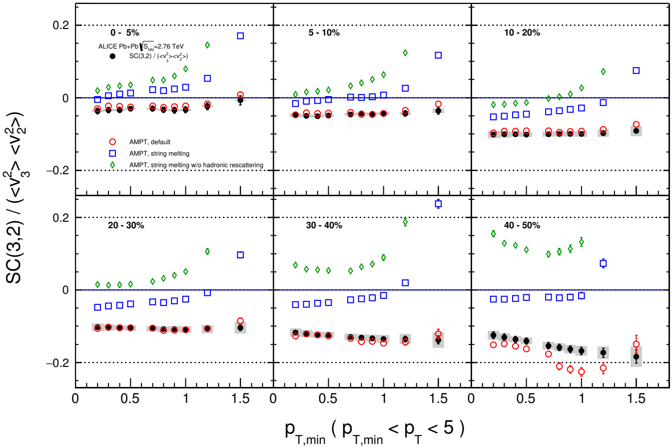
Higher order SC : Comparison with various AMPT simulations



- Normalized SC(m,n) were well described by AMPT default.
- Other settings are failed to reproduce the data, and even fail to predict negative correlation of $SC(4,3)$

Transvers momentum dependence of normalized SC(m,n)

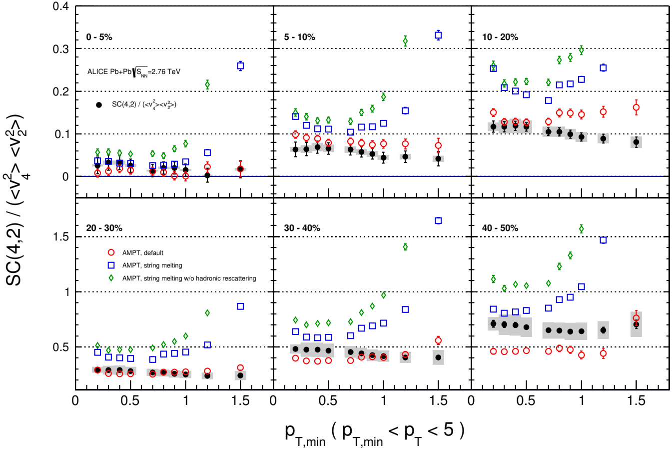
as function of $p_{T,min}(p_{T,min} < p_T < 5)$, and comparison to model



- No clear trends of p_T dependence for normalized SC(3,2)
- AMPT default (String melting OFF, Rescattering ON) describes better

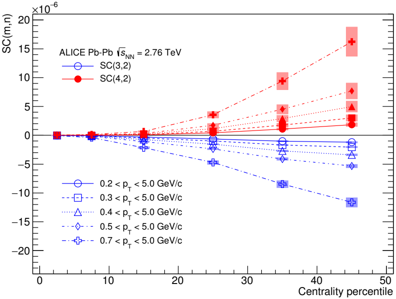
Transvers momentum dependence of normalized SC(m,n)

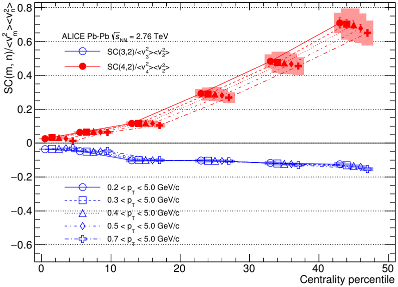
as function of $p_{T,min}(p_{T,min} < p_T < 5)$, and comparison to model



- No clear trends of p_T dependence for normalized SC(4,2)
- AMPT default (String melting OFF, Rescattering ON) describes better

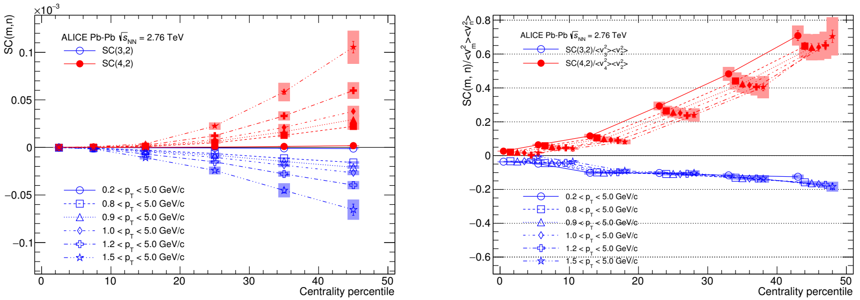
Transvers momentum dependence of SC(m,n) $0.2 < p_{T,min} < 0.7 GeV/c$





- SC results with various min p_T cuts (left) shows clear p_T dependence of SC.
- No significant difference in NSC (right) might indicate that p_T dependence of SC(m,n) mainly results from p_T dependence of v_n rather than p_T dependent correlation between flow harmonics

Transvers momentum dependence of SC(m,n) $0.7 < p_{T,min} < 1.5 GeV/c$



- When expand minimum p_T cut from 0.8 to 1.5 GeV$/c$
- SC results with various min p_T cuts shows clear p_T dependence of SC (as like previous page)
- NSC tends to decrease as the minimum p_T or the centrality increase. But it's not clearly seen in errors
- Hints of possible viscous correction for the equilbrium distribution at hadronic freeze-out?

Optional pages

Measuring SC(m,n) with Scalar Product method

Moments can be obtained with normalized Q-vector with 2 sub event groups which seperated η gap range [8]

$$\mathcal{M} \equiv \left\langle \prod_n (V_n)^{k_n} (V_n^*)^{l_n} \right\rangle = \left\langle \prod_n (Q_{nA})^{k_n} (Q_{nB}^*)^{l_n} \right\rangle \tag{3}$$

Then SC(m, n) can be expressed as

- $\langle (Q_{An} Q_{Bn}^* Q_{Am} Q_{Bm}^*) \rangle - \langle (Q_{An} Q_{Bn}^*) \rangle \langle (Q_{Am} Q_{Bm}^*) \rangle$

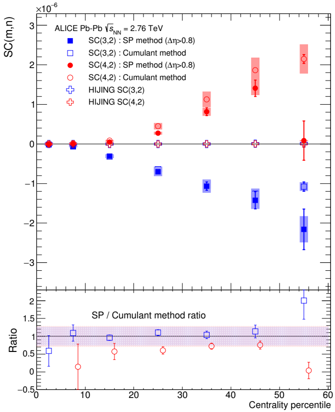
  where $Q_n = \frac{1}{M} \sum_{i=1}^{M} e^{in\phi_i}$, η gap between A, B subgroups

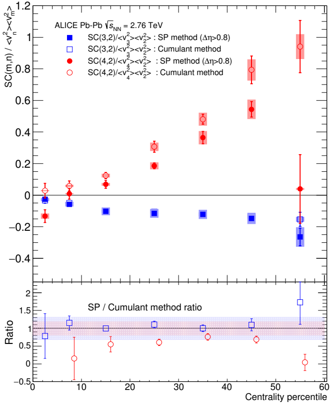
but In red part there are auto(self) correlation term between $Q_{An} - Q_{Am}$ and $Q_{Bn} - Q_{Bm}$, theses could be corrected by following terms

$$\frac{1}{M_B} Re(Q_{Bm+n}^* Q_{Am} Q_{An}) - \frac{1}{M_A} Re(Q_{Am+n} Q_{Bn}^* Q_{Bm}^*) + \frac{1}{M_A M_B} Re(Q_{Am+n} Q_{Bm+n}^*)))$$

[8] Rajeev S. Bhalerao et al, http://doi.org/10.1016/j.physletb.2015.01.019

Method comparison, QC vs SP



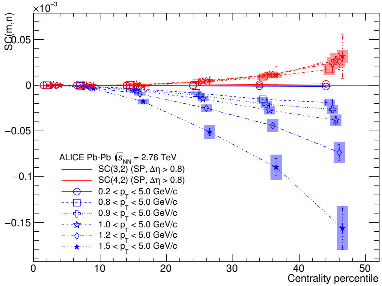


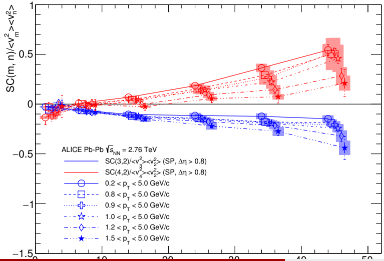
- SC(m,n) with HIJING are compatible with zero for both methods
- There are some systematic differences (especially for SC(4,2)) between two methods [9].
- We are not sure whether different methods respond differently to flow fluctuations or if we can rule out non-flow effects in the end

[9] different sensitivities to flow fluctuations and non-flow effects

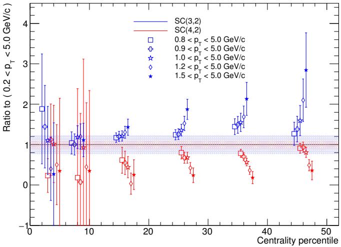
Transvers momentum dependence of SC(m,n) with SP method

Extend to hihger p_T bins up to minimum cut = 1.5GeV/c





- As same as QC results, clear p_T dependence for SC(m,n)
- Also p_T dependence of normalized SC(m,n) is shown



Summary

We have measured SC(m,n) which quantify the relationship between event-by-event fluctuations of two different flow harmonics.

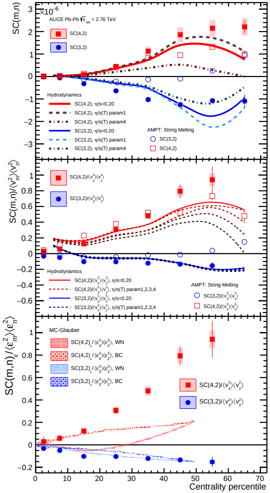
$$\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- Symmetric cumulants (SC) and normalized SC (NSC), which quantify the relationship between flow harmonics are measured and we found
  - SC(3,2) and SC(4,3) are negative(anti-correlated) and SC(4,2), SC(5,2) and SC(5,3) are positive(correlated) for all centralities.
  - Higher order SC (SC(5,2), SC(5,3), SC(4,3)) are smaller than lower order SC(SC(3,2), SC(4,2)), while NSC are comparable
- Also from model comparison
  - differenent order harmonic correltions have different sensitivities to the initial conditions and the system properties.
  - In most central collision region (0%-10% , where the fluctuation dominant), the sign of correlation is different between data and hydrodynamic model calculation
  - VISH2+1 with large η/s failed to cpature the centrality dependence of SC(m,n), espeically for higher orders
- From p_T dependence study
  - SC results with various min p_T cuts shows clear p_T dependence of SC.
  - No significant difference in Normalized SC up to $p_T = 0.7$ GeV/c might indicate that p_T dependence of SC(m,n) mainly comes from p_T dependence of v_n rather than p_T dependent correlation between flow harmonics within the errors.

Backup Slides

Backup pages

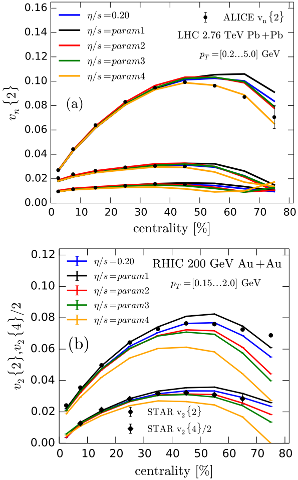
Results from short SC paper (arXiv:1604.07663)

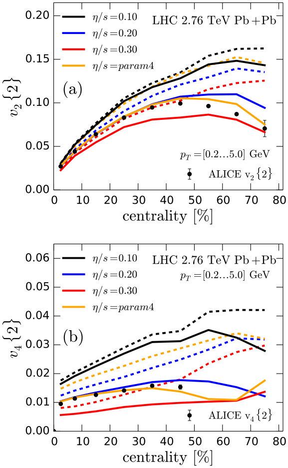


- v_2 and v_4 are correlated, v_2 and v_3 are anti-correlated in all centralities, the centrality dependence can not be described quantitively by any existing calculations.
- Normalized SC(3,2) is sensitive to initial conditions and insensitive to η/s, normalized SC(4,2) is sensitive to both
- SC(m,n) measurements provide strong constrains 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.

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

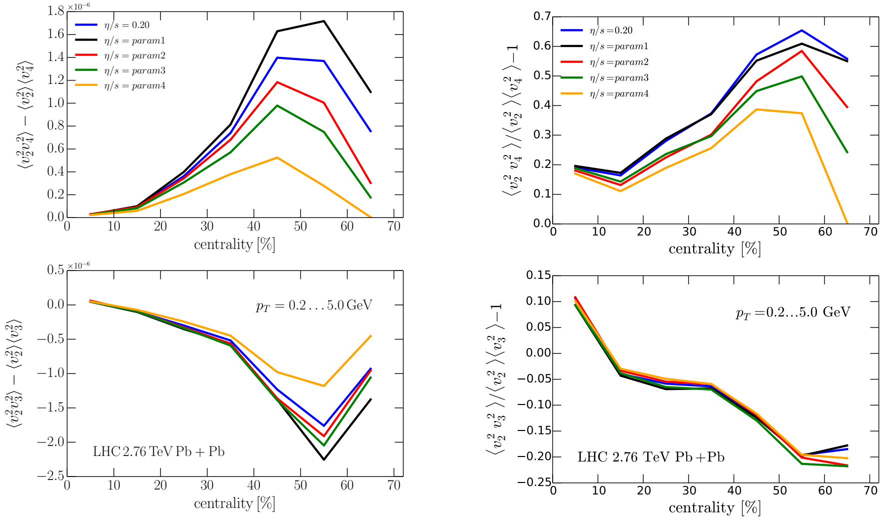
Hydro results from RHIC to LHC, v_n vs $\eta/s(T)$





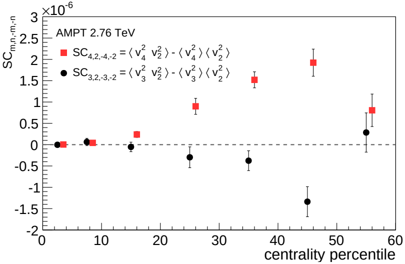
- H. Niemi, K.J. Eskola, R.Paatelainen (arXiv:1505.02677)

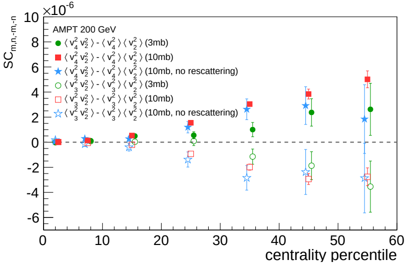
Hydro results from RHIC to LHC, SC(m,n) vs $\eta/s(T)$



- 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

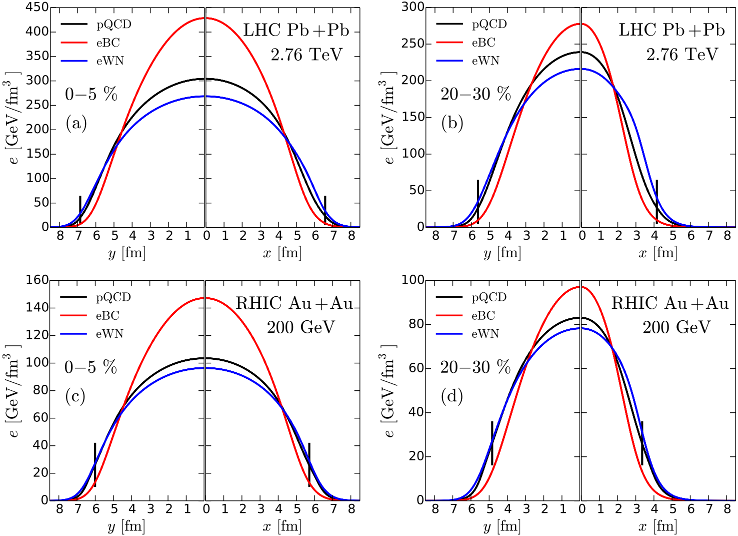
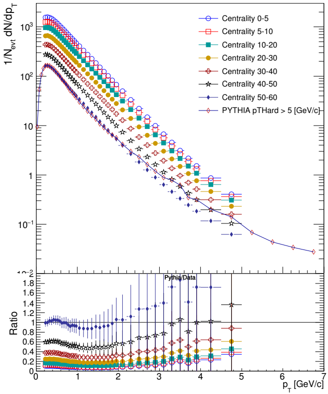


Figure: Energy density profiles, H. Niemi, K.J. Eskola, R.Paatelainen (arXiv:1505.02677)

Can we rule out non-flow effects?

- SC(m,n) results with HIJING are zeros for all centralities for both method, even with the high p_T bins (see B**??**).
- Those suggested that SC(m,n) is insensitive to non-flow effect.
- In additional to HIJING results, we now have studied it explicitly with PYTHIA jet particles on SC(m,n), this implies the largest effect from the particles which stem from jets in PYTHIA in mid central collisions.

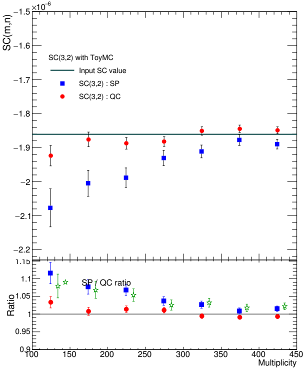


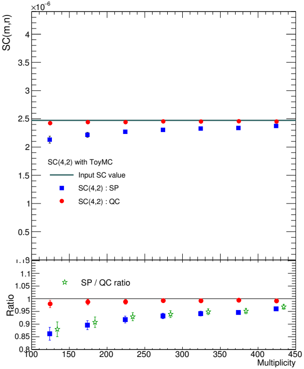
- Setup same ToyMC as previous slides.
- Use PYTHIA8 to impose jets into ToyMC.
- implement PYTHIA jet particles for every events.
    - $\sqrt{s} = 2.76 TeV$
    - $PhaseSpace : pTHatMin > 5\ GeV/c$

Comparison two method : SC(m,n) results with ToyMC

From low to high multiplicity

Calculate SC analytically based on MC study[10].

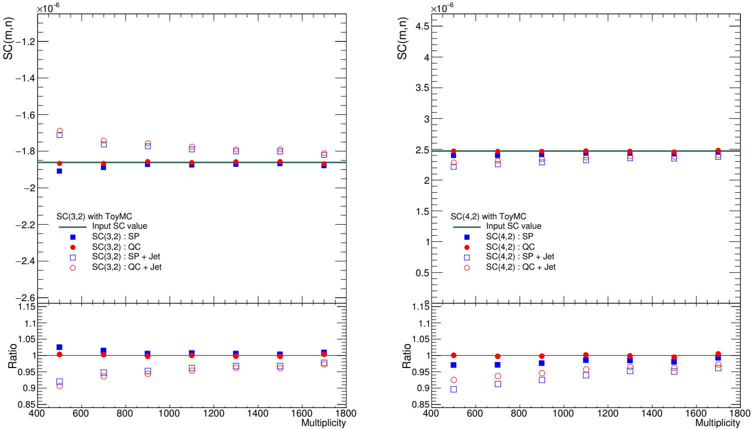




- we observe discrepancy between two methods. This effect is most pronounced in lowest multiplicity $\sim 10\%$
- QC method recover better the input value than SP method
- SP method results are always smaller than QC for all multiplicity bins.

[10] http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_A_Bilandzic.pdf p118

ToyMC + Jet results



- When we implement particles from jets in PYTHIA (Open markers), strengths of correlation from both SP and QC methods are getting smaller.
- The response to particles from jet are similar for both QC and SP methods.
- few % difference in central collisions and 10% effect in 50-60% centrality bin.
- These observations hold both for SC(3,2) and SC(4,2).