Systematic studies of correlations between different order flow harmonics in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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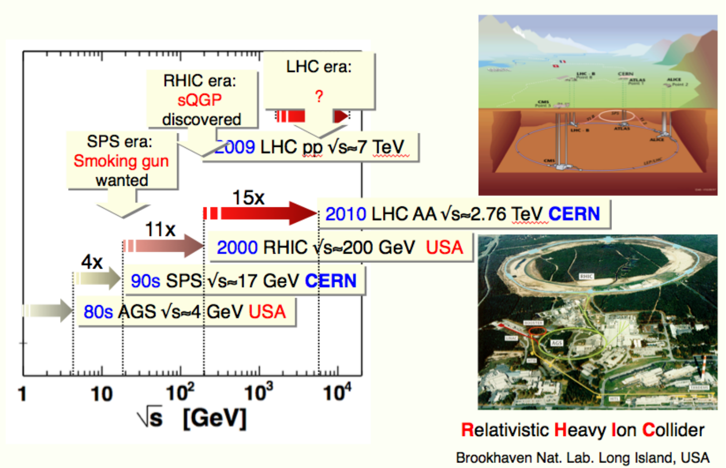
HIM 2016 05

based on arXiv:1604.07663

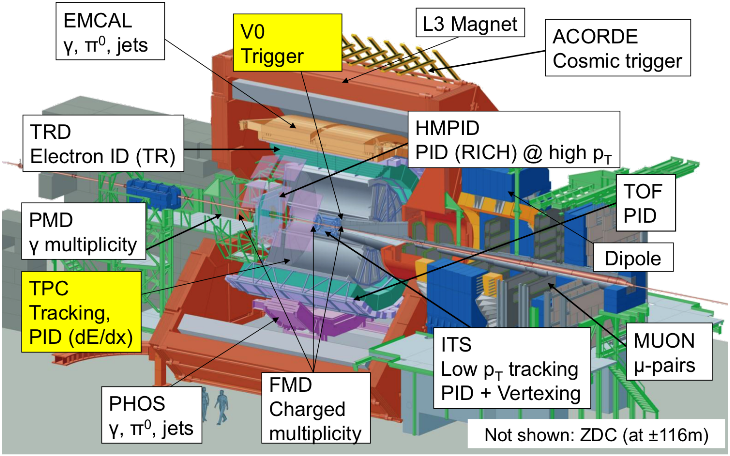
ALICE @ CERN

- LHC(Large Hadron Collider), SPS, PS
- 4 major experiments
- p+p collisions(as reference), Pb+Pb collisions

Compare with other experiments

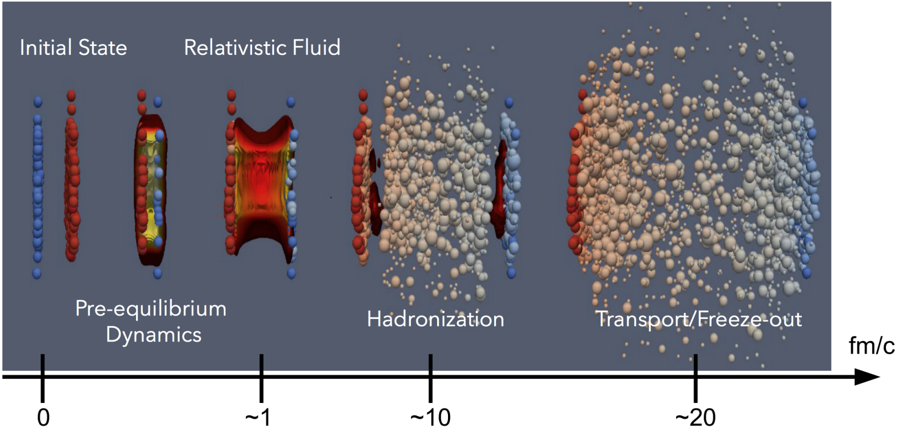


ALICE Detectors



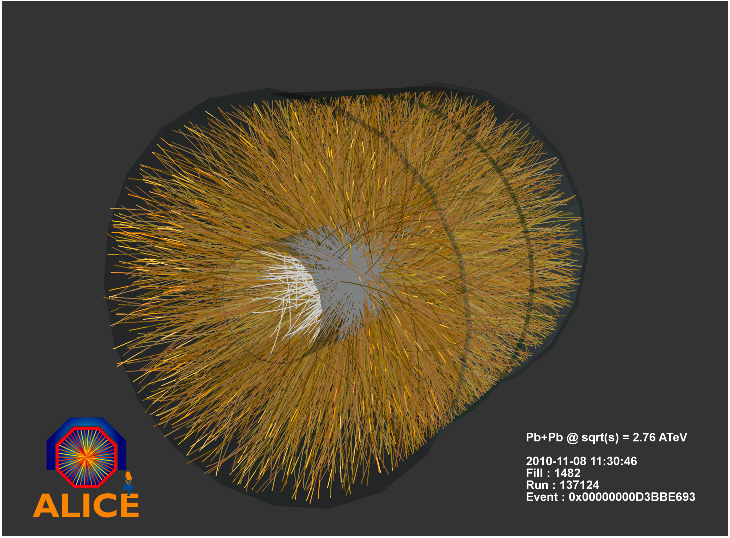
- Centrality determination by V0(N_{ch} with scintillators in $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV $\approx$ 20M events.
- Tracking - TPC tracks constrained to the primary vertex and full azimuthal acceptance (Unidentified charged particles $|\eta|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

Evlolution of heavy ion collision



Visualization: madai.us

And it's results



First event from ALICE experiments in 2010

Flow analysis

As $\frac{dN}{d\phi}$ is a periodic function($0\sim 2\pi$), it can be expressed with Fourier transformation.

$$\frac{dN}{d\phi} = \frac{x_0}{2\pi} + \frac{1}{\pi}\sum_{n=1}(A_n \cos n\phi + B_n \sin n\phi) \tag{1}$$

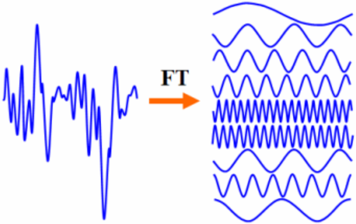
If we define v_n and ψ_n such as,

$$v_n^2 = A_n^2 + B_n^2, \; 0 \le \psi_n \le \frac{2\pi}{n} \tag{2}$$

Then we can express A_n and B_n with v_n and ψ_n. if we put back these into original equation (1) then

$$\frac{dN}{d\phi} = \frac{x_0}{2\pi} + \frac{1}{2\pi}\sum_{n=1}(2v_n \cos n(\phi - \psi_n)) \tag{3}$$

And, we called v_n as flow constant, and ψ_n as event plane angle.



How to measure flow?

(P. Danielewicz, G. Odyniec, Phys. Lett. 157B, 146 (1985))

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

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

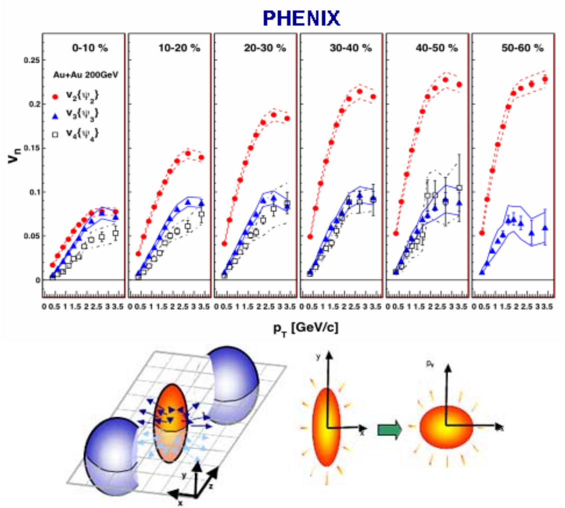
- Flow magnitude v_n can be estimated with Event Plane method

$$v_n\{EP\} = \langle \cos n(\varphi - \psi_n) \rangle$$

- or by measuring multi-particle correlation(Cumulant method)

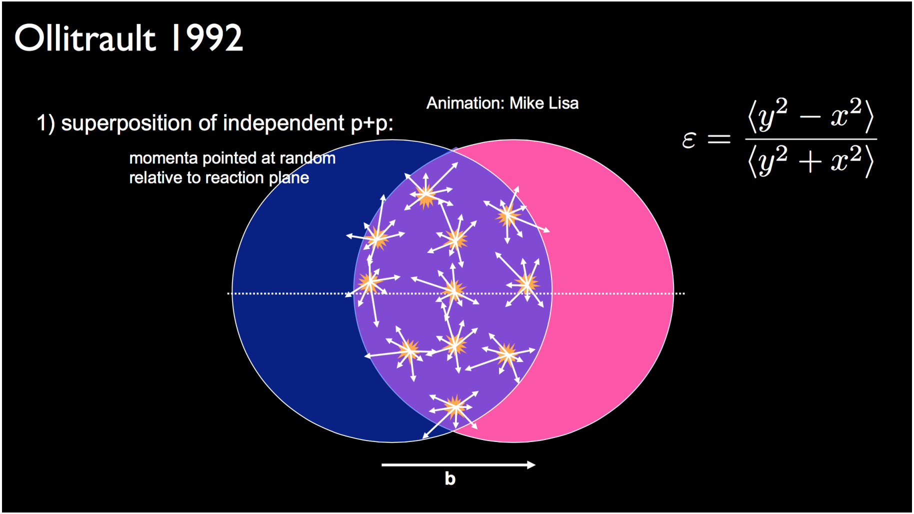
$$v_n\{2\} = \sqrt{\langle \cos n(\varphi_1 - \varphi_2) \rangle}$$

First results from PHENIX



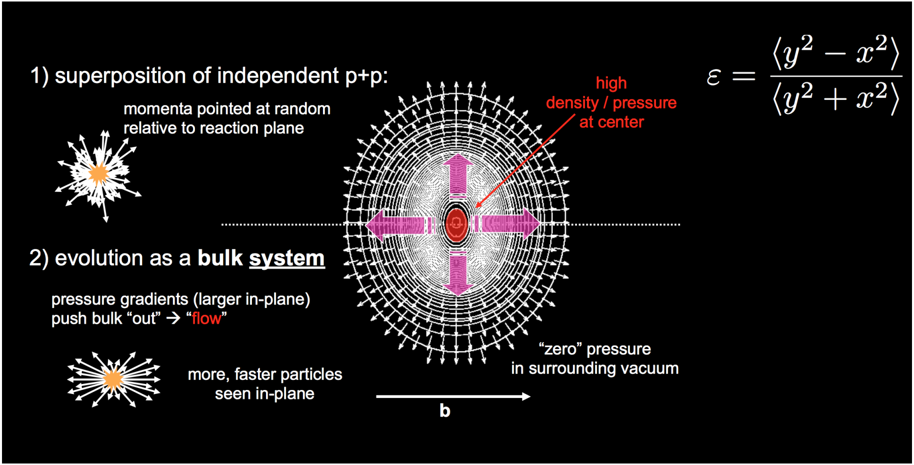
- The second coefficient of Fourier's harmonics(v_2) is significantly larger then any other harmonics
- This v_2 values are grow as function of p_T and Centrality
- This phenomenon was unique in heavy-ion collisions

Elliptic Flow



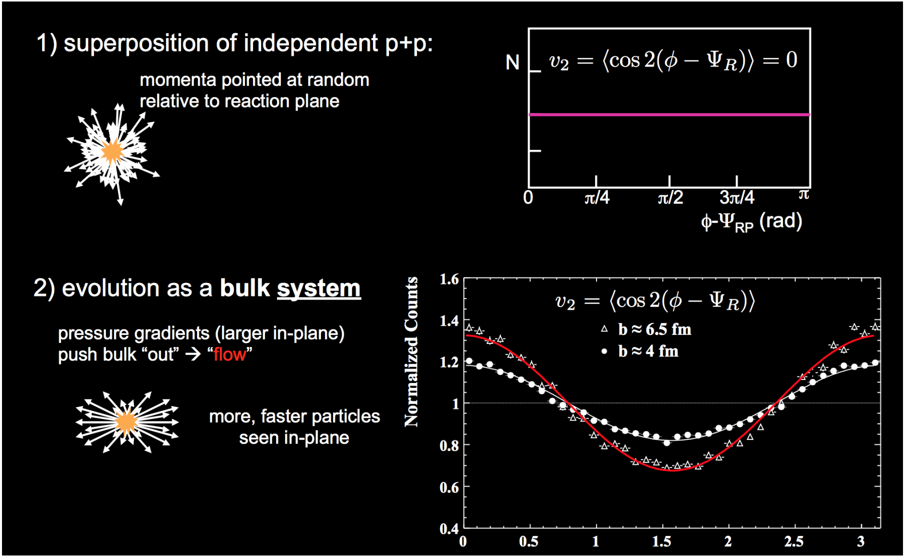
courtesy of Raimond Snellings (New J.Phys. 13 (2011) 055008)

Elliptic Flow



courtesy of Raimond Snellings (New J.Phys. 13 (2011) 055008)

Elliptic Flow

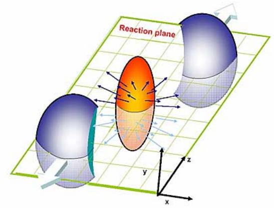


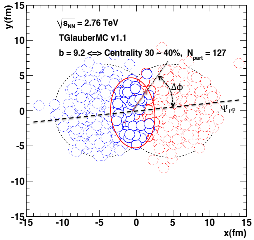
courtesy of Raimond Snellings (New J.Phys. 13 (2011) 055008)

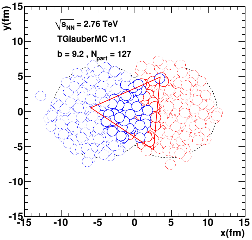
Note

For better understanding, I'd like to make it sure that

- Reaction plane (RP) : Plane which is defined by IP and z-axis(beam direction)
- Participant plane (PP) : Effective RP affected by non-perfect isotropic shape
- (n-th order) Event plane (EP) : Mathmaticaly defined by above equation







Note

For better understanding, I'd like to make it sure that

- Reaction plane (RP) : Plane which is defined by IP and z-axis(beam direction)
- Participant plane (PP) : Effective RP affected by non-perfect isotropic shape
- (n-th order) Event plane (EP) : Mathmaticaly defined by above equation

Note!

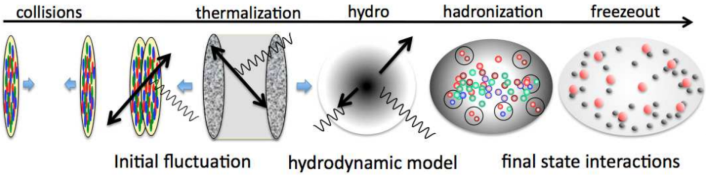
$$\Psi_{RP} \neq \Psi_{PP} \neq \Psi_{EP}$$

Also,

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

is not hold when we consider non-flow effects and non-ideal case

Schematics of Heavy ion collision



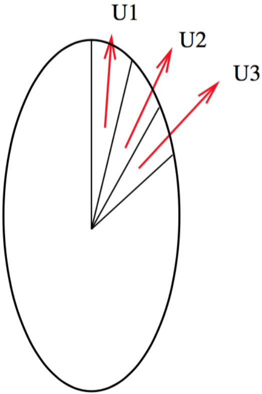
Schematic sketch of relativistic heavy ion collisions arXiv:1204.4795

A heavy ion collision can be divided into several stages,

- Pre-equilibrium : Immediately after collision
- Deconfined state : QGP is formed and starts expanding
- Hadron gas : Quarks and gluons are bound into hadrons when temperature is sufficiently low
- Free streaming : Hadrons stop interacting and fly to the detector

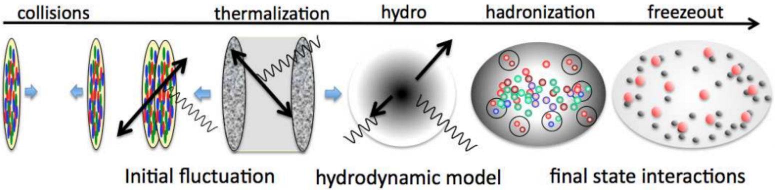
Flow in Heavy-ion collisions

Correlation between "Flow" and "System properties"

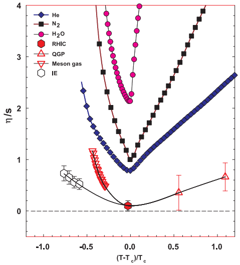


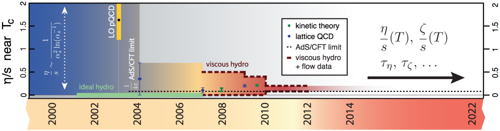
- Weakly coupled → Long distance until next collision → easy mixing
- Strongly coupled → Short distance until next collision → mixing take long time
- $\eta \propto l_{mfp} \propto 1/n_\sigma$
- The larger the corss-section, the smaller η, large v_2
- Stronger interaction → Less viscous fluid
- Shear viscosity smears out flow differences (it's a diffusion)
- Shear viscosity reduces non-sphericity

Result : Large v_2 means, low η/s



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



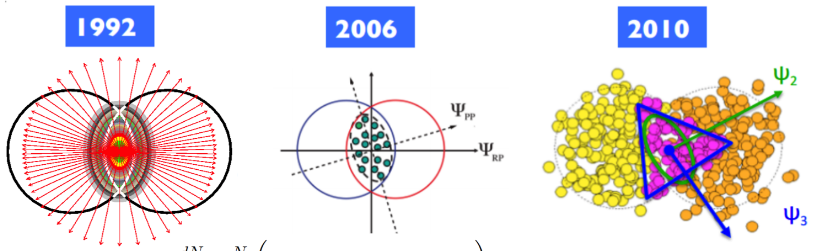


LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: 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

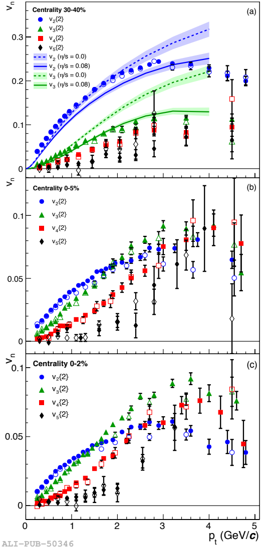


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n (2v_n \cos(n(\phi - \psi_n)))\right) \quad v_n = \langle \cos[n(\phi - \psi_n)] \rangle$$

- 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

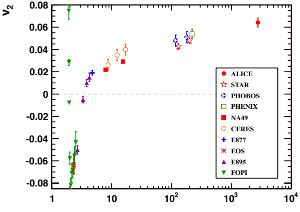
Selected flow measurements at LHC in one slide

Higher Harmonics

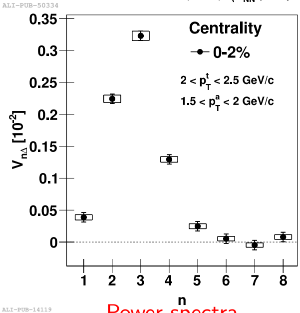


ALICE, Phys. Rev. Lett. 107, 032301(2011)

$\sqrt{s}$ dependence elliptic flow



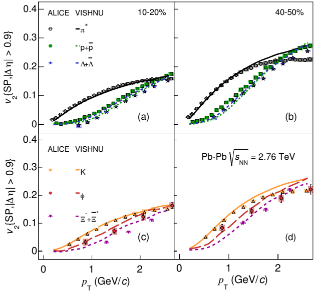
Phys. Rev. Lett. 105, 252302(2010)



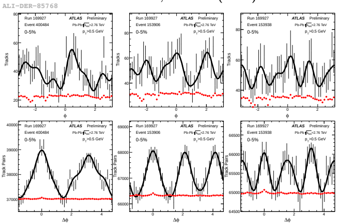
Power spectra

ALICE, Phys. Lett. B708(2012)249 — 264

PID elliptic flow



ALICE, JHEP06(2015)190

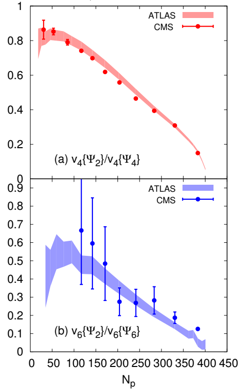


Event-by-event flow harmonics

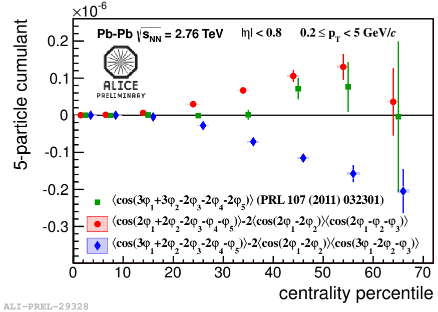
ATLAS, JHEP1311(2013)183

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



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



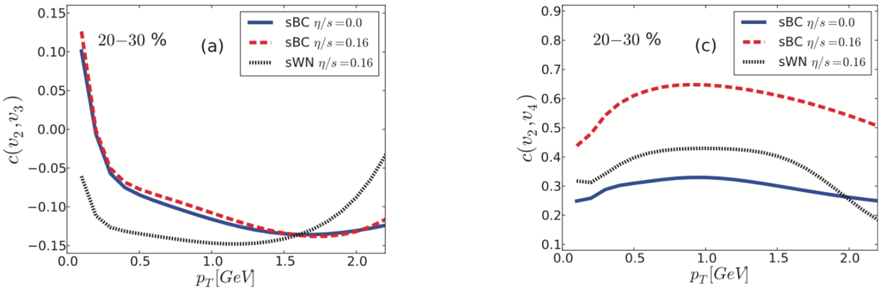
$\frac{v_4\{\Psi_2\}}{v_4\{\Psi_4\}}$, $\frac{v_6\{\Psi_2\}}{v_6\{\Psi_6\}}$ from ATLAS(arXiv:1403.0489), CMS (arXiv:1310.8651))

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

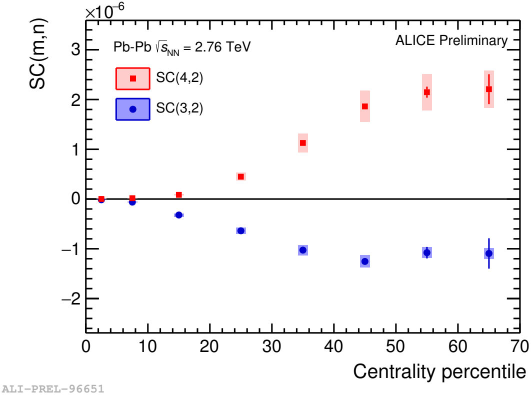
New Observable : Symmetric 2-harmonic 4-particle Cumulants (SC) [1]

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

- 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.

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

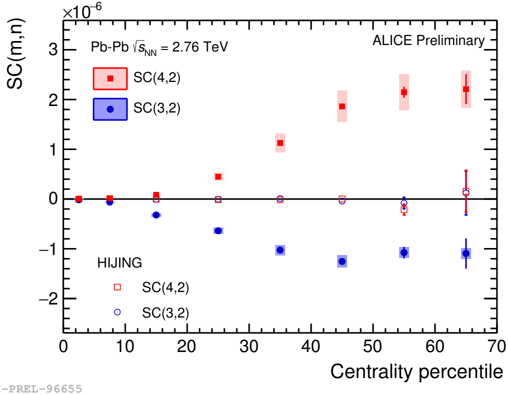
SC(m, n) results



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

- 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?

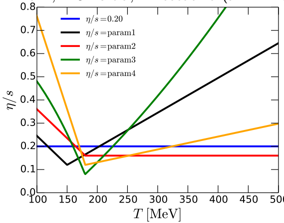


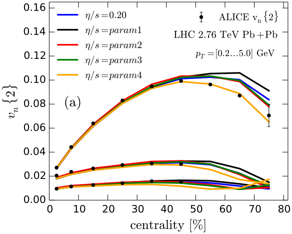
$$\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c = \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle$$

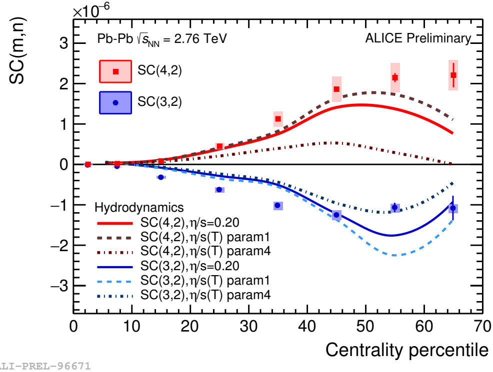
- It is found that both $\langle v_m^2 v_n^2\rangle$ and $\langle v_m^2\rangle\langle v_n^2\rangle$ are non-zero in HIJING, but calculation of SC(m,n) from HIJING are compatible with zero
    - suggests SC measurements are nearly insensitive to non-flow correlations
- non-zero values of SC measurements 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)







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

- 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 constrains on the η/s in hydro in combination with standard v_n measurements

Working on progress : Symmetric 2-harmonic 4-particle Cumulants

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

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

- 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)

Measuring correlation with moments

This SC(m,n) can be calculated with multi-particle cumulants(QC) but also can be calculated with Scalar Product method(SP) by using Moments[3]

$$\mathcal{M} \equiv \left\langle \prod_n (V_n)^{k_n} (V_n^*)^{l_n} \right\rangle = \left\langle \prod_n (Q_{nA})^{k_n} (Q_{nB}^*)^{l_n} \right\rangle \quad (4)$$

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 is normalized flow Q-vector ($\frac{1}{M} \sum_{i=1}^{M} e^{in\phi_i}$), and A, B denotes sub event groups which are divided with η gap

  Auto(self) correlation term in red part with 4p correlation between $Q_{An} - Q_{Am}$ and $Q_{Bn} - Q_{Bm}$, theses could be corrected by correction term
  (credit : Ante and Sergei)

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

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

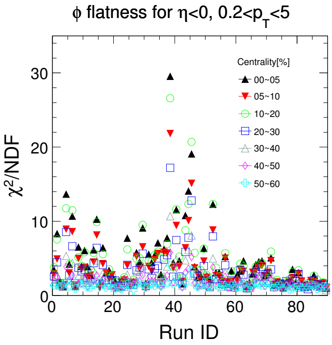
Summary

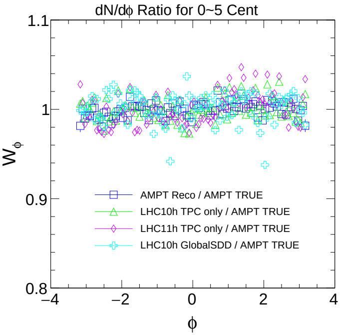
- Moments of the distribution of V_n provide a complete set of multiparticle correlation , which can be used to probe the physics of flow fluctuations.
- Flow fluctuations have been measured as SC and Normalized SC
  - SC(m,n) results with Q-Cumulants and Scalar Product are consistant within errors up to 40% centrality bins
  - SC results($v_n^2 - v_m^2$ correlation) and normalized SC(scaled with $\langle v_n^2 \rangle \langle v_m^2 \rangle$) results shows similar trends with Hydrodynamics and AMPT simulation
  - Higher order SC correlations(SC(5,2), SC(5,3), SC(4,3)) are smaller then lower order SC correlation(SC(3,2), SC(4,2))
  - But in normalized results, correlation between higher order flow harmonics are stronger than lower order flow correlations
- p_T dependence of SC(m,n)
  - p_T dependence of SC(3,2) and SC(4,2) are checked both in Data and AMPT simulation but, no p_T dependence for normalized SC(m,n) results up to 1.0GeV/c
  - we go to more higher pT cuts ¿ 1GeV /c, we start to see a clear pT dependence of normalized SC, which might indicate the pT dependent flow angle fluctuations.

Backup Slides

Backup

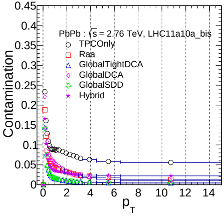
How to estimate the systematics from the non-uniform ϕ efficiency ?

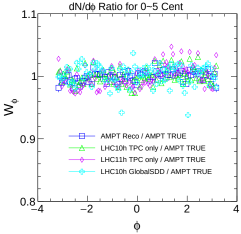


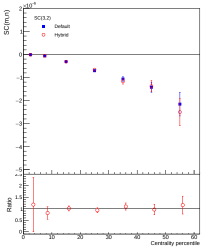


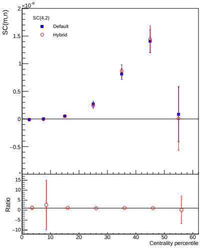
1. Check the deviations of the observables with 3 different group of runs based on χ^2/NDF cuts.
2. Check the deviations between track selection cuts (TPCOnly:FilterBit128, GlobalSDD:96..).
3. MC method using the large statistics AMPT sets (LHC13f3c,b,a)
   - Physical Primary particle only + imposing non-uniform ϕ distribution
   - ϕ distribution taken from the data

SC(m,n) results with different TrackFilter bit





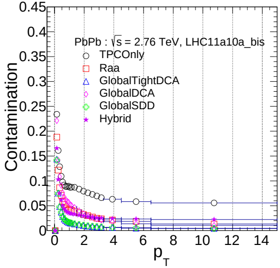


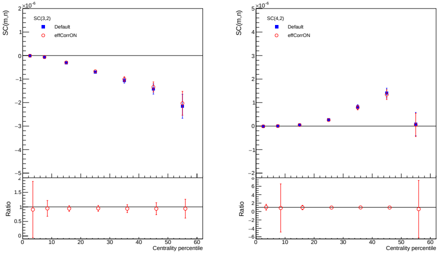


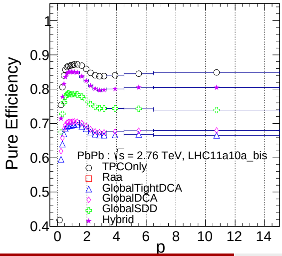
cut	filter bit	comments
TPCOnly	128 (7)	GetStandardTPCOnlyTrackCuts() + SetMinNClustersTPC(70)
GlobalSDD	96 (5|6)	GetStandardITSTPCTrackCuts2010() with requiring the first SDD cluster instead of an SPD cluster

- more fake and secondary tracks for TPCOnly track cut
- two track cuts give relatively good uniform ϕ distribution

Systematics of SC(m,n) with Efficiency correction







correction to p_T dependent efficiency

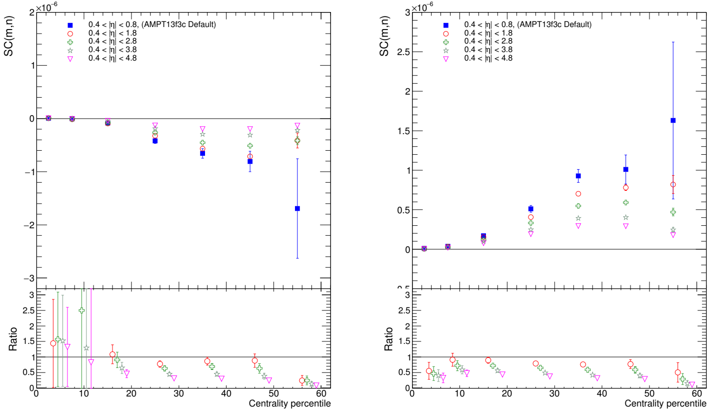
In following equations G_{trigvtx} stands for the number of true charged physical primaries emitted to $|\eta| < 0.8$ in triggered events where an event vertex was reconstructed. $C(p_T)$,

$$C^{-1}(p_T) = \frac{M_{\text{trigvtx}}(p_T) + B(p_T)}{G_{\text{trigvtx}}(p_T)}, \quad (5)$$

$$\text{true efficiency} = M_{\text{trigvtx}}(p_T) / G_{\text{trigvtx}}(p_T), \quad (6)$$

$$\text{contamination} = B(p_T) / \left[M_{\text{trigvtx}}(p_T) + B(p_T)\right] \quad (7)$$

SC(m,n) AMPT results with large η

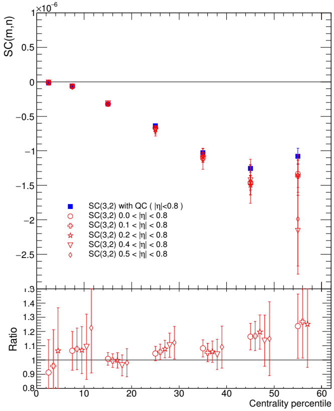


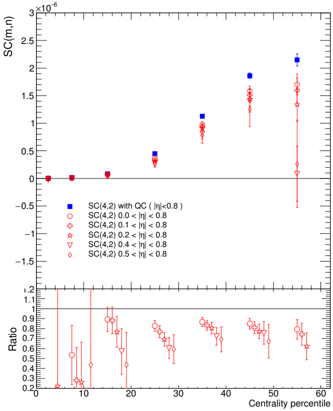
- When η region extend to large(forward) region, SC(m,n) values getting smaller
- SC(m,n) with $0.4 < |\eta| < 0.8$ have 5 times larger then SC(m,n) with $0.4 < |\eta| < 4.8$

Deviation of two different method comes from Non-flow effects?

Applying different $\Delta\eta$ for SP method. Generally we can easily expect that

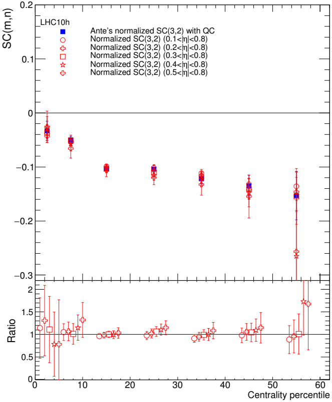
- Small η gap between subevent groups $\rightarrow$ big non-flow effect
- Large η gap between subevent groups $\rightarrow$ small non-flow effect

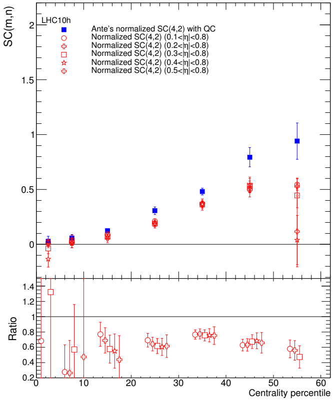


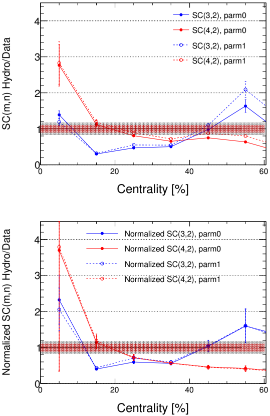


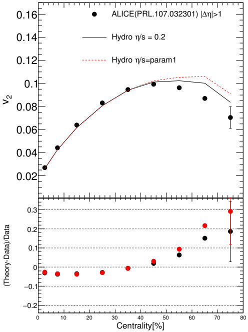
But, SP method with smaller $\Delta\eta$ results are more closes to QC method results.

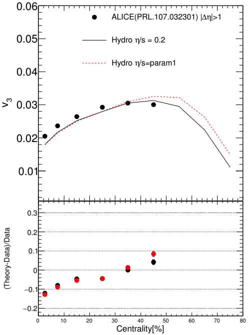
How about Normalized SC(m,n)?











- But the Hydrodynamic calculations cannot capture the data well, a significant deviation for SC(4,2) in 0-10%.
- Actually, this is similar for individual v_n's, better agreement but the centrality dependence doesn't look good either.