Flow angle and flow magnitude factorization breaking

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with: W. Broniowski arXiv: 1711.03325
and H. Mehrabpour *in preparation*

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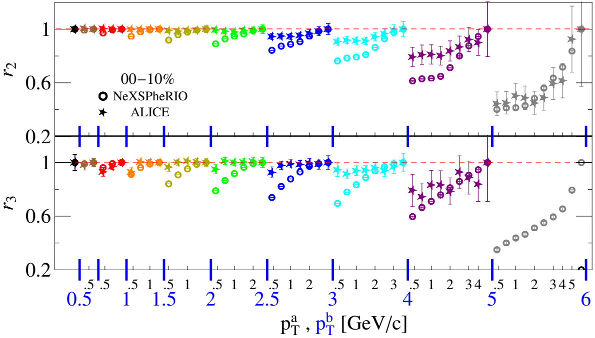
Flow factorization breaking

$$r_n(p_a, p_b) = \frac{< v_n(p_a) v_n^\star(p_b) >}{\sqrt{< v_n^2(p_a) >}\sqrt{< v_n^2(p_b) >}}$$



Gardim, Grassi, Luzum, Ollitrault: 1211.0989

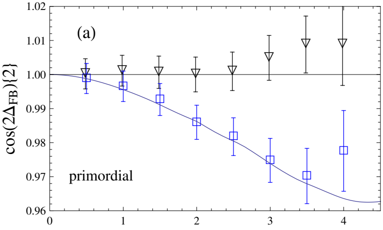
small decorrelation of flow vectors due to fluctuations

Flow factorization breaking in rapidity
forward-backward decorrelation

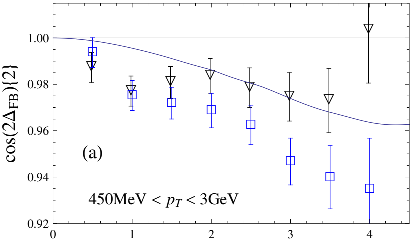
$$\frac{< v_2(F) v_2^{\star}(B) >}{\sqrt{< v_2^2(F) >}\sqrt{< v_2^2(B) >}}$$

PB, Broniowski, Moreira 1011.3354

events with decorrelation versus events without decorrelation



non-flow + flow decorrelation

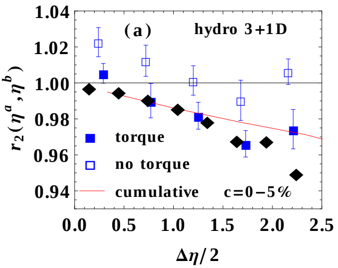


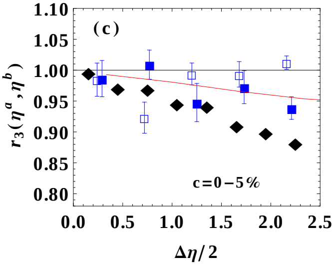
strong non-flow effects

3-bin measure of event-plane decorrelation (CMS)

$$r_n(\eta) = \frac{< q_n(-\eta) q_n^\star(\eta_{ref} >}{< q_n(\eta) q_n^\star(\eta_{ref}) >}$$

only pairs with large rapidity gap $\Delta\eta = \pm\eta - \eta_{ref}$





- nonflow under control

- torque effect seen in the CMS data

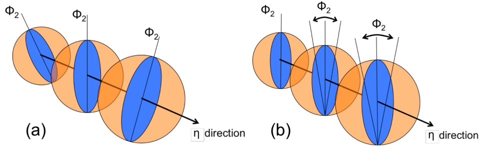
- semiquantitative agreement

- small factorization breaking observed

F-slope $\quad r_n(\eta) \simeq 1 - 2F_n^\eta \eta$

Flow magnitude decorrelation + Twist angle

$$r_2(\eta) = 1 - 2F_n\eta = 1 - 2F_n^{asy}\eta - 2F_n^{twi}\eta$$



Jia, Huo 1402.6680, 1403.6077

the two can be separated using

3-bin and 4-bin correlators **ATLAS** 1709.02301

$$R_n(\eta) = \frac{< q_n(-\eta_{ref})q_n^\star(\eta)q_n(-\eta)q_n^\star(\eta_{ref}) >}{< q_n(-\eta_{ref})q_n^\star(-\eta)q_n(\eta)q_n^\star(\eta_{ref}) >} \simeq 1 - 2F_{n,2}^{twi}\eta$$

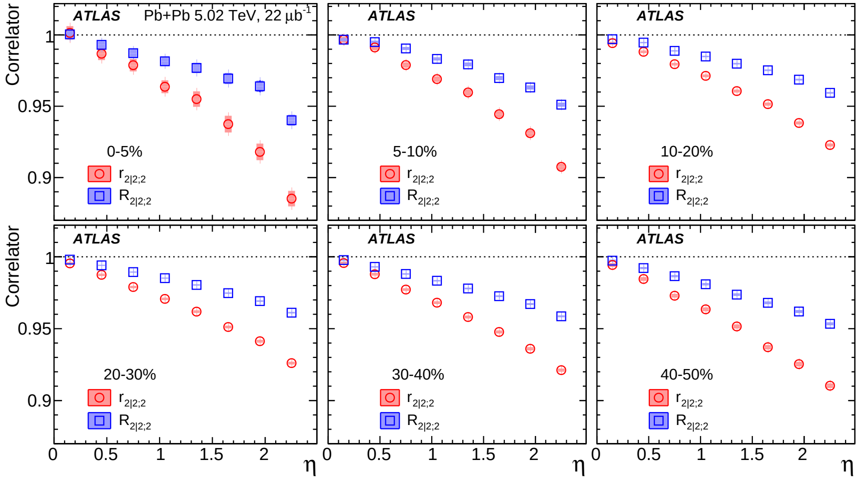
flow angle decorrelation

$$r_{n,2}(\eta) = \frac{< q(-\eta)^2 q^\star(\eta_{ref})^2 >}{< q(\eta)^2 q^\star(\eta_{ref})^2 >} \simeq 1 - 2F_{n,2}^{asy}\eta - 2F_{n,2}^{twi}\eta$$

flow angle+flow magnitude decorrelation

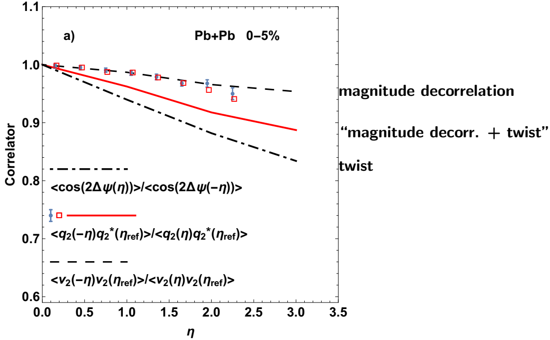
($r_{n,1}(\eta)$ first measured by CMS 1503.01692)

Observation of separate flow magnitude decorrelation and twist angle



$$r_2 \simeq 1 - 2F_2^{asy}\eta - 2F_2^{twi}\eta \qquad R_2 \simeq 1 - 2F_2^{twi}\eta$$

twist angle and flow magnitude decorrelation
3+1D hydro model

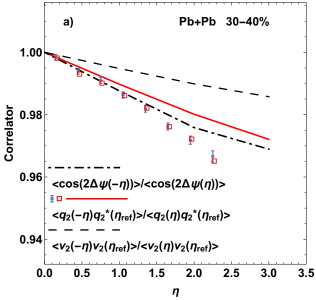


surprising result: “inverted hierarchy”

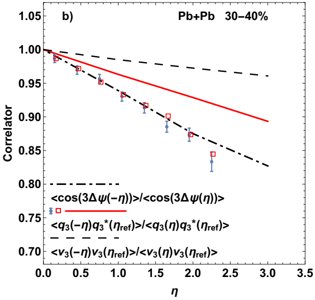
magnitude decorr. < “magnitude decorrelation + twist” < twist

elliptic versus triangular

v_2



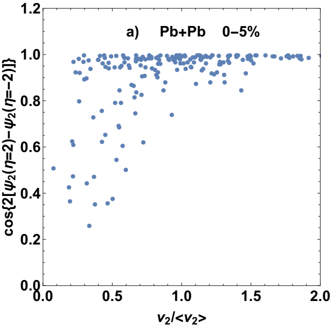
v_3



the "inverted hierarchy" effect is stronger for v_3

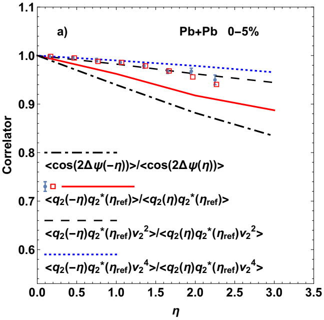
triangular flow - fluctuation dominated

Correlation between flow magnitude and twist angle



- **strong** correlation between flow magnitude and twist angle
- events with large flow have smaller twist angle
- twist angle measure $< cos(\Delta\Psi_2) > \propto (v_2)^{0}$
  "magnitude decorr.+twist" $< q_2(\eta) q_2^{\star}(\eta_{ref}) > \propto (v_2)^{2}$
- different weighting by (v_2) powers explains "inverted hierarchy"

Correlators weighted by powers of v_n

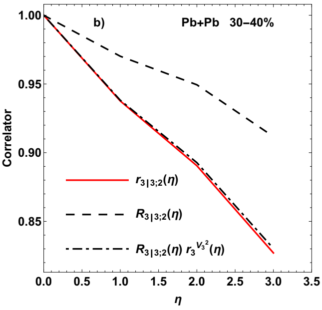


- hierarchy of correlators consistent with expectations

$$\frac{\langle q_n(-\eta) q_n^\star(\eta_{ref})\rangle}{\langle q_n(\eta) q_n^\star(\eta_{ref})\rangle} < \frac{\langle q_n(-\eta) q_n^\star(\eta_{ref}) v_n^2\rangle}{\langle q_n(\eta) q_n^\star(\eta_{ref}) v_n^2\rangle} < \frac{\langle q_n(-\eta) q_n^\star(\eta_{ref}) v_n^4\rangle}{\langle q_n(\eta) q_n^\star(\eta_{ref}) v_n^4\rangle}$$

- the correlation between flow magnitude and twist can be measured experimentally

Factorization of factorization breaking



- flow magnitude factorization breaking (square)

$$r_n^{v_n^2}(\eta) = \frac{\langle v_n^2(-\eta) v_n^2(\eta_{ref})\rangle}{\langle v_n^2(\eta) v_n^2(\eta_{ref})\rangle}$$

- twist angle factorization breaking (weighted with v_n^4)

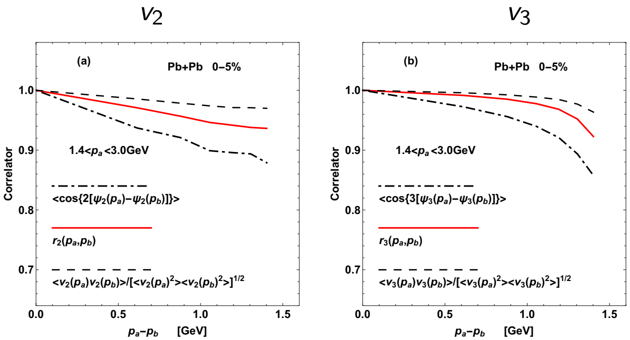
$$R_{n|n;2}(\eta) = \frac{< q_n(-\eta_{ref}) q_n^\star(\eta) q_n(-\eta) q_n^\star(\eta_{ref}) >}{< q_n(-\eta_{ref}) q_n^\star(-\eta) q_n(\eta) q_n^\star(\eta_{ref}) >}$$

- angle+magnitude factorization breaking

$$r_{n|n;2}(\eta) = \frac{\langle q_n(-\eta)^2 q_n^\star(\eta_{ref})^2\rangle}{\langle q_n(\eta)^2 q_n^\star(\eta_{ref})^2\rangle}$$

(angle+magnitude f. b.) $\simeq$ (twist angle f. b.)(flow magnitude f. b.)
measured by ATLAS

flow magnitude and flow angle decorrelation p_T factorization breaking

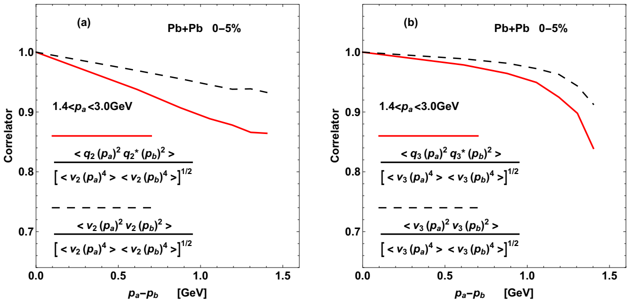


PB : 1808.09840

Similar effect for p_T and rapidity factorization breaking

Measuring flow magnitude and flow angle decorrelation p_T factorization breaking

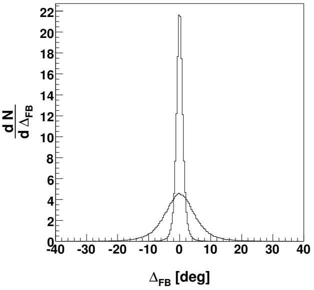
v_2 v_3



Flow magnitude and flow angle decorrelation in p_T
can be separately measured in experiment

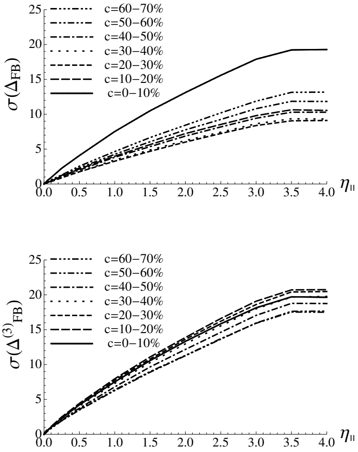
Twist angle distribution - Glauber model

$\Psi_2(\eta) - \Psi_2(-\eta), \qquad \Delta\eta = 1, 5$



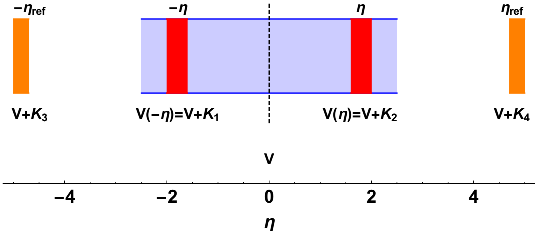
- very forward (backward), maximal decorrelation
- in between, intermediate
- linear around $\eta = 0$

width of the twist angle distribution



- $n = 2$, largest decorrelation for central collisions
- $n = 3$, similar decorrelation for all centralities

Simple model of flow factorization breaking



flow vector in a small bin

$$Q_i = V_i + K_i$$

has a random component + global flow

random components correlated (depending on bin separation)

random component independent from global flow constraints on global flow, flow moments in small bins

PB, H. Mehrabpour

Predicts flow angle, flow magnitude, and flow vector decorrelation

decorrelation of flow vectors

$$\frac{\langle q_n^m(\eta) q_n^{m\ \star}(-\eta)\rangle}{\sqrt{\langle q_n^m(\eta) q_n^{m\ \star}(\eta)\rangle \langle q_n^m(-\eta) q_n^{m\ \star}(-\eta)\rangle}} \simeq 1 - 2m\frac{\langle \delta^2\rangle}{\langle v_n^2\rangle}$$

decorrelation of flow angles

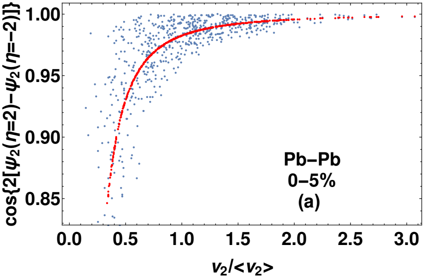
$$\frac{\langle v_n^{2m} \cos(mn(\Psi_n(\eta) - \Psi_n(-\eta)))\rangle}{\langle v_n^{2m}\rangle} \simeq 1 - m\frac{\langle \delta^2\rangle}{\langle v_n^2\rangle}$$

decorrelation of flow magnitudes

$$\frac{\langle v_n^m(\eta) v_n^m(-\eta)\rangle}{\sqrt{\langle v_n^{2m}(\eta)\rangle \langle q_n^{2m}(-\eta)\rangle}} \simeq 1 - m\frac{\langle \delta^2\rangle}{\langle v_n^2\rangle}$$

$\delta = K(\eta) - K(-\eta)$
increases with bin separation

global flow - twist angle anticorrelation



$$\cos\left(n(\Psi_n(\eta) - \Psi_n(-\eta))\right) \simeq 1 - \frac{\delta_n^2}{v_n^2}$$

explains the relation between twist angle and global flow magnitude

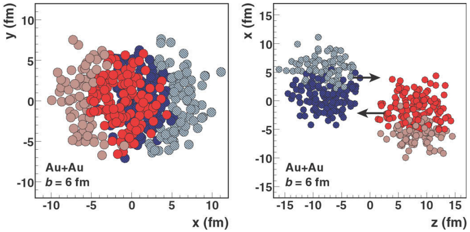
explains differences between v_2 and v_3 (smaller global flow)

also : explains qualitatively 3- and 4-bin correlators

explains relation between correlators of different powers of flow

- Longitudinal flow decorrelation - **angle+magnitude**
  has been measured by ATLAS
- Additional event-by-event correlations
  Large flow magnitude $\leftrightarrow$ Small twist angle
  Small flow magnitude $\leftrightarrow$ Large twist angle
  (cannot be easily separated)
- Factorization breaking in p_T - **flow+magnitude**
  can be measured
- simple random model of flow decorrelation
  explains qualitatively separate flow magnitude
  and flow angle decorrelation

Twisted event-plane angles - torque effect



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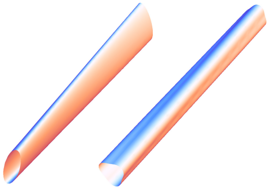
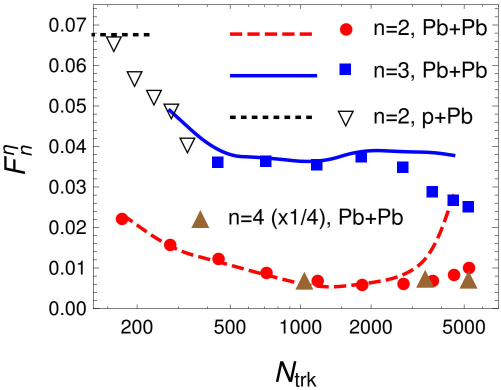


- due to fluctuations of F-B participants
- left-right orientation and angle magnitude are random
- only "smooth" long range twist
- random decorrelations on small scale, difficult to observe

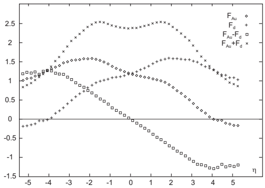
also other models of initial state: fluctuating strings, hybrid models . . . $\rightarrow$ additional fluctuations

F slope $\quad (r_n(\eta) \simeq 1 - 2F_n^\eta \eta)$



- fair description of mid-central collisions
- overestimates decorrelation in central collisions
- $F_4 \simeq 4F_2$

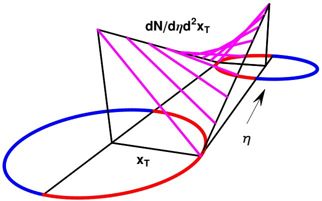
Matter distribution in space-time rapidity



Asymmetric emission functions

(Białas, Czyż, 2005

$$\rho(\eta, x, y) \propto f_+(\eta)N_+(x,y) + f_-(\eta)N_-(x,y)$$



bremsstrahlung Adil Gyulassy, 2005

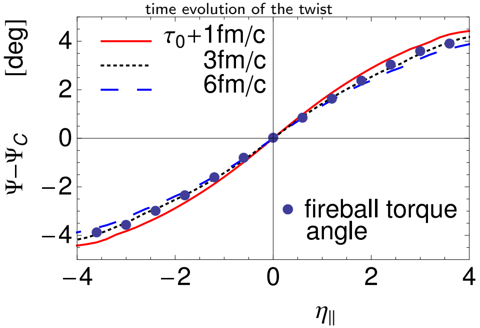
signatures of tilt:
charged particles v_1, tilted source HBT, D meson directed flow

One-shot 3+1D hydro evolution (2010)

initial density with a twist

$$s(x,y,\eta) \propto \rho_+(Rx,Ry)f_+(\eta) + \rho_-(R^T x, R^T y)f_-(\eta)$$

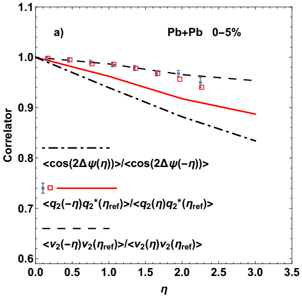
forward (backward) participants rotated in the transverse plane

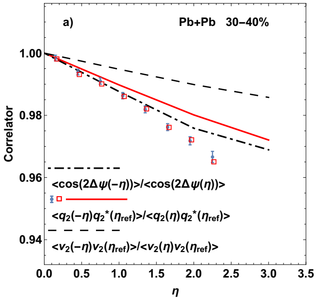


- the twist survives the hydrodynamic evolution

central versus peripheral

$0-5\%$ | $30-40\%$



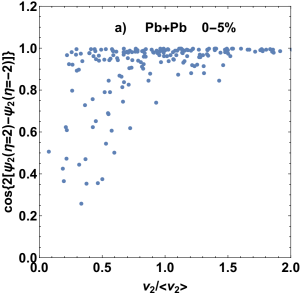


the "inverted hierarchy" effect is stronger in central collisions

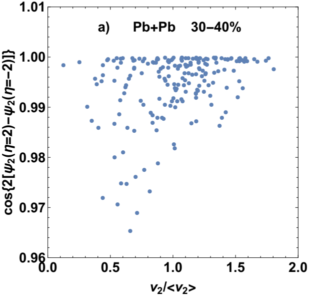
large elliptic flow in semi-central collisions $\rightarrow$ less fluctuations

central versus peripheral

$0-5\%$



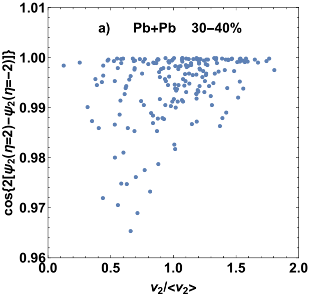
$30-40\%$

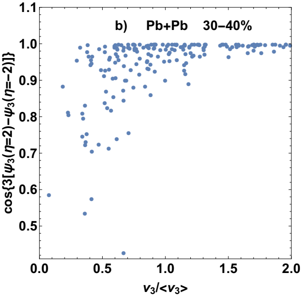


stronger correlation in central collisions

elliptic versus triangular

v_2 v_3

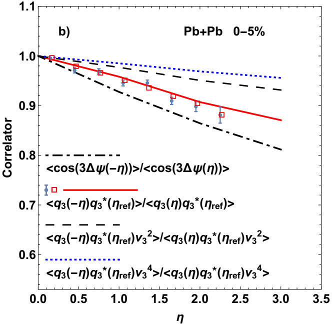




stronger correlation for v_3

similar for triangular flow

$0-5\%$



$30-40\%$