Mapping of longitudinal correlations through collective expansion

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Longitudinal dynamics is important

- Initial stage
  - what is the initial density distribution
  - what is the initial energy density
  - what is the nature of thermalization mechanism
  - fluctuations
- Early dynamics
  - what is the pressure asymmetry
  - from initial fluctuations to final correlations

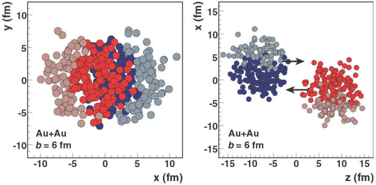
two unknowns

- pressure asymmetry

- initial distribution $\longleftarrow$ **this talk**

study of longitudinal dynamics $\longrightarrow$ to get **experimental** insight

Hydrodynamics - forward and backward assymetry in initial state

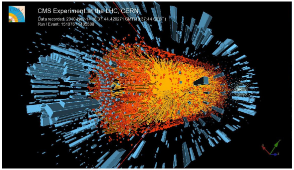


Ann.Rev.Nucl.Part.Sci. 57 (2007) 205

- Glauber Monte Carlo model $\longrightarrow$ different forward and backward distributions

- different fireball shape at forward and backward rapidities

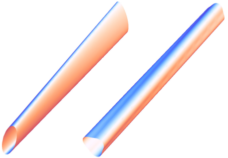
multiplicity-multiplicity correlations



dozens of years, hundreds of papers

many effects sum up ...

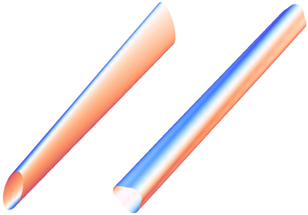
flow angle-flow angle correlations

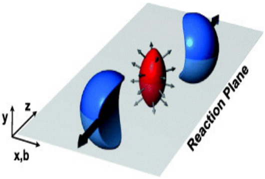


PB, W. Broniowski, J.Moreira : 1011.3354

experiment and theory picks up momentum

Twisted event-plane angles - torque effect

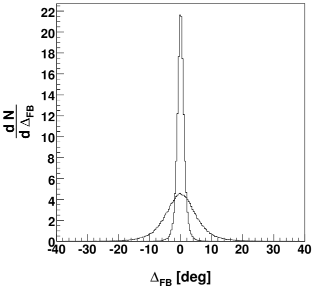




- due to fluctuations
- left-right orientation and magnitude are fluctuating
- only "smooth" long range twist
- random decorrelations on small scale, difficult to observe

Twist angle distribution - Glauber model

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

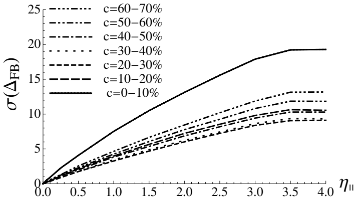


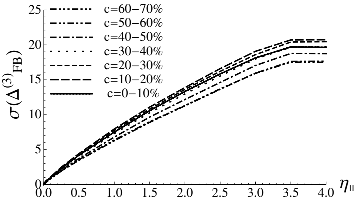
- very forward (backward), maximal decorrelation

- in between, intermediate

- linear around $\eta = 0$

width of the twist angle distribution



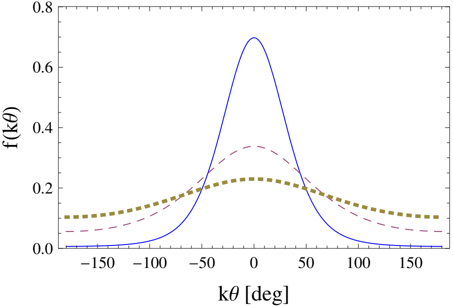


- $n = 2$, largest decorrelation for central collisions

- $n = 3$, similar decorrelation for all centralities

Event-plane resolution at finite multiplicity

event-plane distribution $N = 20, 100, 60,\ v_2 = 0.05$



- event-plane resolution much worse than signal
- $\Delta\Psi$ cannot be measured directly

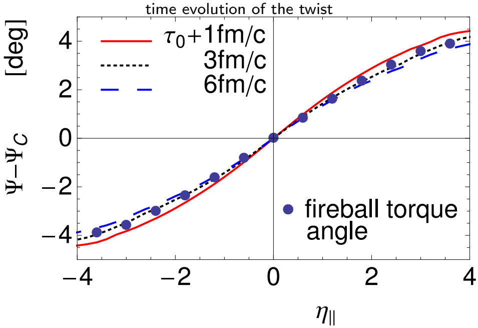
- observables must be quadratic in $\Delta\Psi$

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

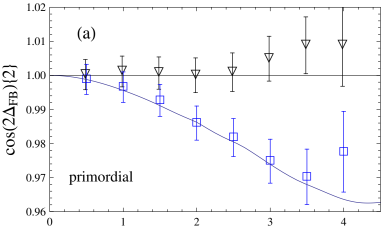


- the twist survives the hydrodynamic evolution

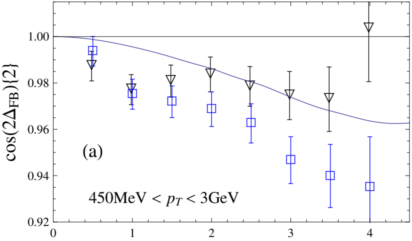
2-bin observable

$$cos(2\Delta\Psi) = \frac{<< cos[2(\phi_i(F) - \phi_j(B))] >>}{\sqrt{< v_2^2(F) >}\sqrt{< v_2^2(B) >}}$$

primordial particles, torque events + notorque events



charged particles, torque events + notorque events

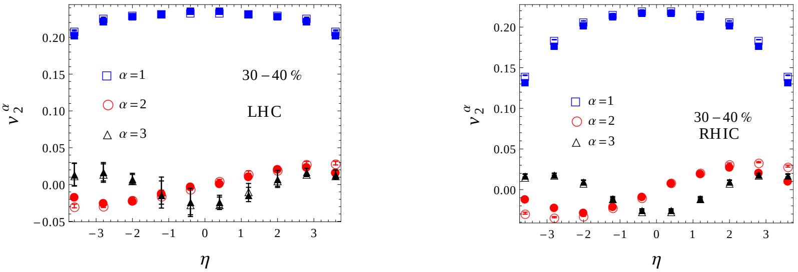


substantial nonflow contribution

2-bin observables in η dominated by nonflow!

PCA - nonflow strikes again

Principal Component Analysis (Bhalerao et al. PRL 114 (2015) 152301)



torque (full symbols), notorque (open symbols)

or was it the other way round?

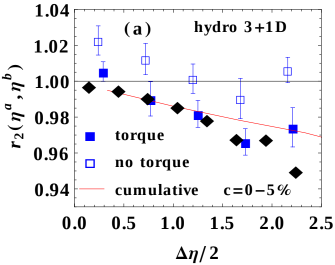
PCA in η dominated by nonflow!

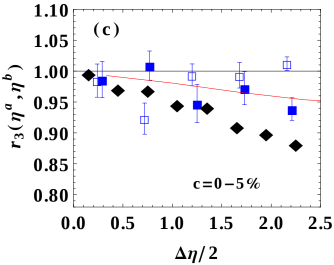
PCA works for oversampled events

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

$$r_2(\eta_a,\eta_b) = \frac{<< cos[n(\phi_i(-\eta_a) - \phi_j(\eta_b))] >>}{<< cos[n(\phi_i(\eta_a) - \phi_j(\eta_b))] >>} \simeq \frac{cos[n(\Psi(-\eta_a) - \Psi(\eta_b)]}{cos[n(\Psi(\eta_a) - \Psi(\eta_b)]}$$

only pairs with large rapidity gap $\eta_a - \eta_b$

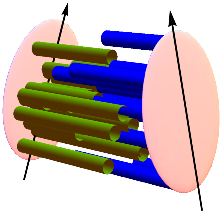




- nonflow under control
- torque effect seen in the CMS data
- semiquantitative agreement

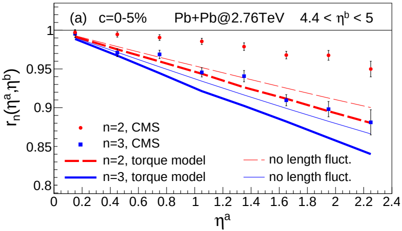
- does not work for p-Pb !

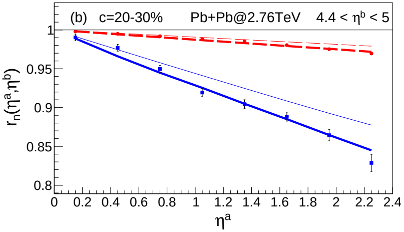
Fluctuations in energy deposition from each source

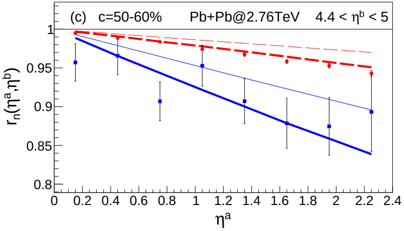


- the position (in rapidity) of string ends is random
- long range fluctuations
- each source fluctuates differently $\longrightarrow$ event-plan decorrelation in p-Pb
- short range fluctuations possible, but irrelevant for the CMS r_2
- average deposition same as in old model (linear in η)

Fluctuating strings $r_n(\eta_a, \eta_b)$ (initial state only)



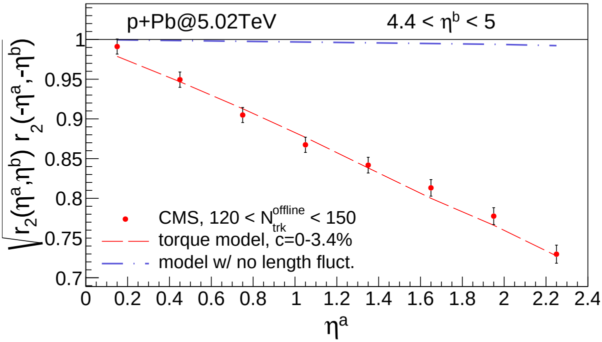




fluctuations improve description of r_2 in Pb-Pb

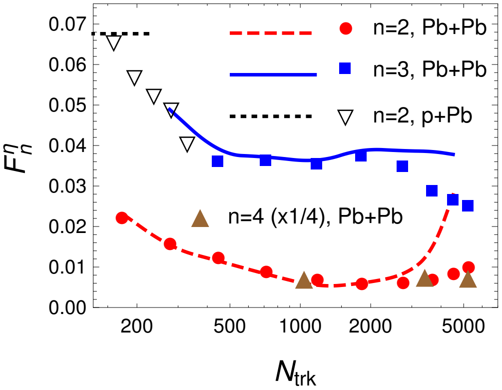
except for r_2 in central collisions

Fluctuating strings p-Pb



- fluctuations **essential** to describe event-plane decorrelation in p-Pb

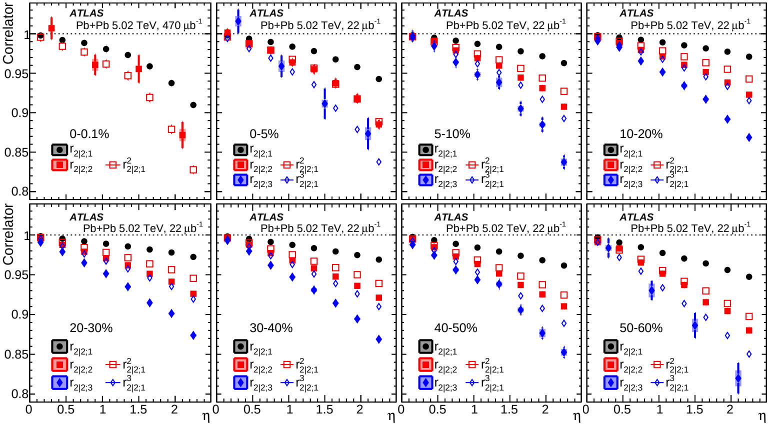
F slope



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

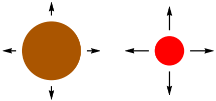
higher order correlators (ATLAS 1709.02301)

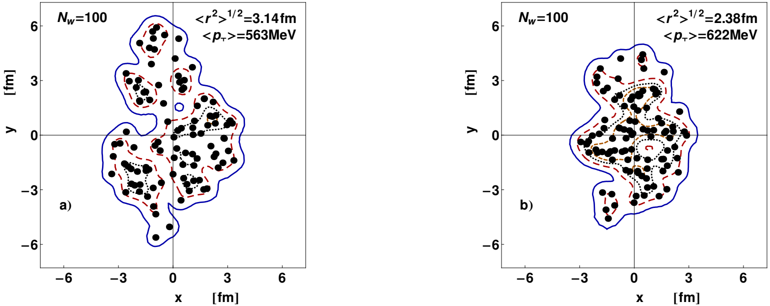
$$r_{2|2,k} = \frac{\langle (v_2(\eta_1) v_2(\eta_2))^k \cos(2k\Delta\Phi(\eta_1+\eta_2))\rangle}{\langle (v_2(\eta_1) v_2(-\eta_2))^k \cos(2k\Delta\Phi(\eta_1-\eta_2))\rangle}$$



Size fluctuations $\leftrightarrow$ $p_\perp$ fluctuations

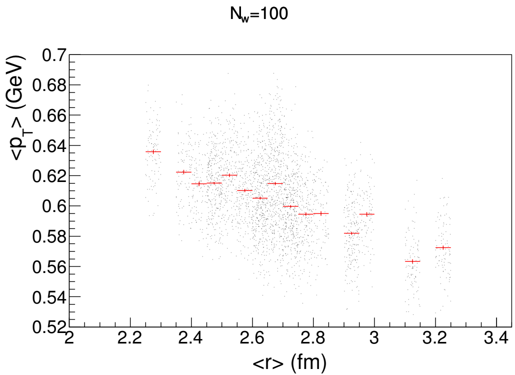
another manifestation of collective flow





proposed by Broniowski et al. Phys.Rev. C80 (2009) 051902 : two-shots calculation

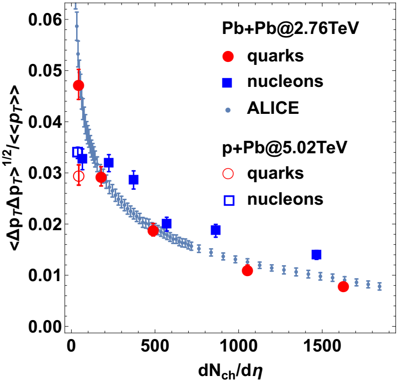
Physical and statistical fluctuations



$$C_{p_\perp} = \frac{\frac{1}{N(N-1)} \sum_{i \neq j} \langle (p_i - \langle\langle p \rangle\rangle)(p_j - \langle\langle p \rangle\rangle) \rangle}{\langle\langle p_\perp \rangle\rangle^2}$$

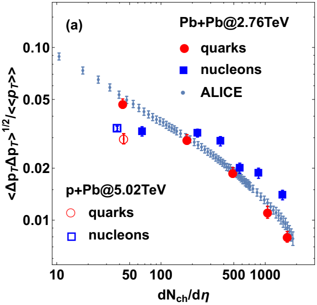
PB, Broniowski 1203.810

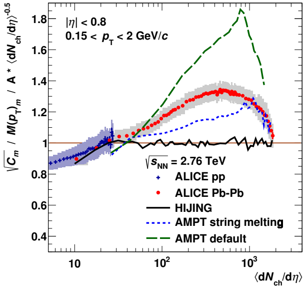
$p_\perp$ fluctuation quark Glauber model initial conditions



Quark Glauber model gives better description of initial volume fluctuations

Same in log scale



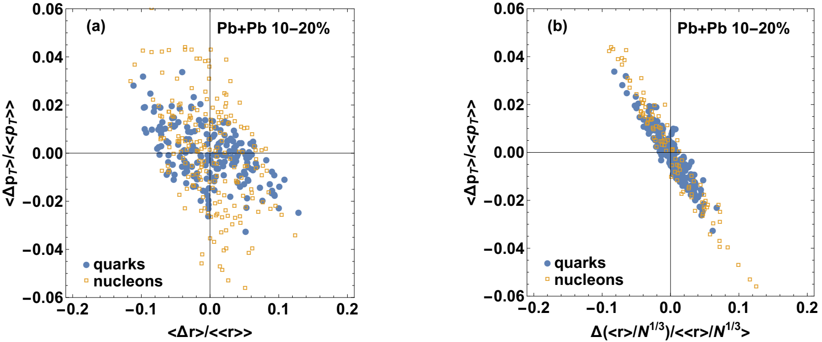


ALICE 1407.5530

more than simple $N^{-1/2}$ scaling

both experiment and theory $\longrightarrow$ not minijets

Size - $p_\perp$ correlation

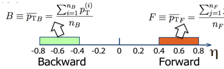


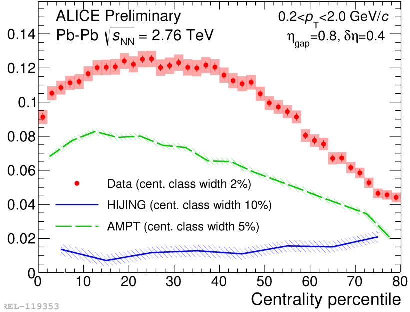
$\frac{N_q^\alpha}{<r>}$ - predictor of the final $p_\perp$ $\quad(\alpha \simeq 0.3 - 0.4)$

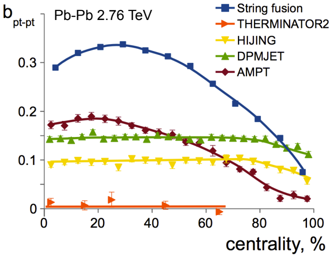
consistent with predcitor of Mazellauskas-Teaney, PRC 2016

$p_\perp - p_\perp$ correlation in rapidity - ALICE preliminary

$$b_{\rm corr} = \frac{\langle FB\rangle - \langle F\rangle\langle B\rangle}{\langle F^2\rangle - \langle F\rangle^2}$$



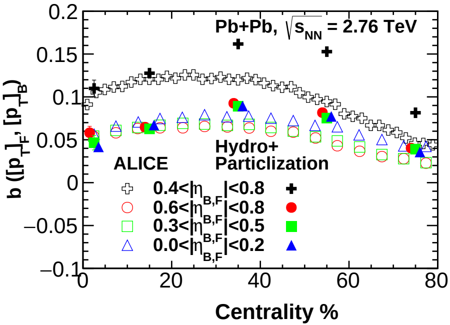




QM poster I. Altsybeev for ALICE

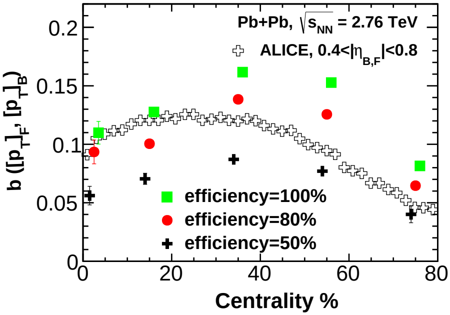
event generators have problems to reproduce data

$p_\perp - p_\perp$ correlation in rapidity - hydro



reasonable description of the data does the model correctly describe rapidity correlations?

$p_\perp - p_\perp$ correlation coefficient - statistical fluct.



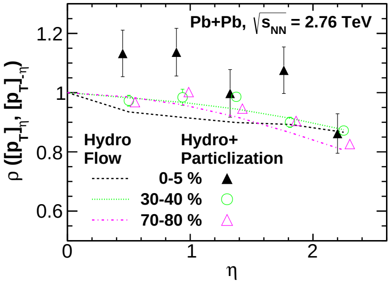
$$b = \frac{Cov([p]_F,[p]_B)}{\sqrt{Var([p]_F)Var([p]_B)}} \simeq \frac{Cov([p]_F,[p]_B)}{\sqrt{\left(C^F_{p_T} + \frac{1}{N_F}\int dp(p-<[p]>)^2 <f(p)>\right)(\dots)}}$$

sensitive to accepteance, particle multiplicity

dominated by statistical fluctuations!

$[p_\perp] - [p_\perp]$ correlation coefficient

$$\frac{Cov(\int dpf(p)_F, \int dpf(p)_B)}{\sqrt{Var(\int dpf(p)_F) Var(\int dpf(p)_B)}} = \frac{Cov([p]_F, [p]_B)}{\sqrt{C^F_{p_\perp} C^B_{p_\perp}}} = \frac{\dots}{\sqrt{\frac{1}{n_F(n_F-1)} \sum_{i\neq j} p^F_i p^F_j \ .}}$$

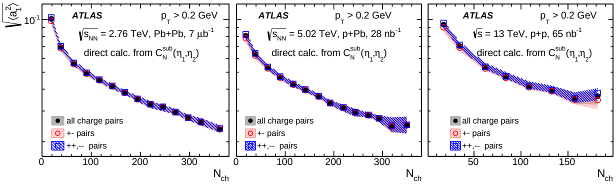


$$\rho([p_T],[p_T]) \simeq 1$$

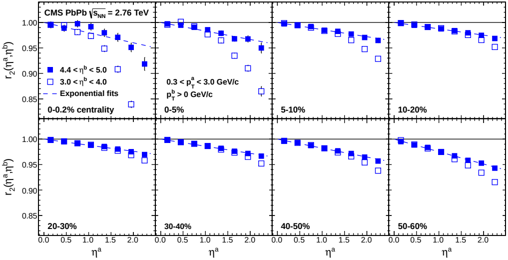
in the current model - strong correlations

Small decorrelation expected!

FB multiplicity fluctuations $\rho_2(\eta_1,\eta_2) \simeq <\rho(\eta_1)><\rho(\eta_2)>(1+a_1 a_1 \frac{\eta_1}{Y}\frac{\eta_2}{Y})$

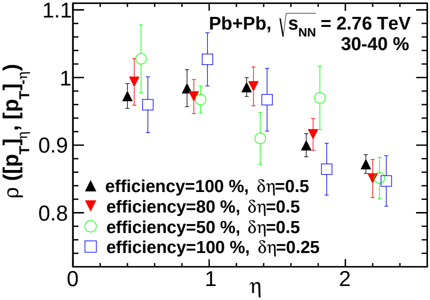


Azimuthal flow decorrelations (3-bin measure)



small decorrelation of flow and multiplicity in pseudorapidity

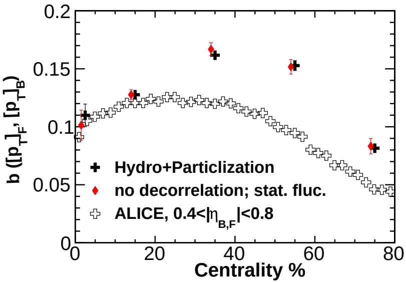
$[p_\perp] - [p_\perp]$ correlation coefficient



insensitive to acceptance, efficiency, mulitplicity

robust measure of flow-flow correlations

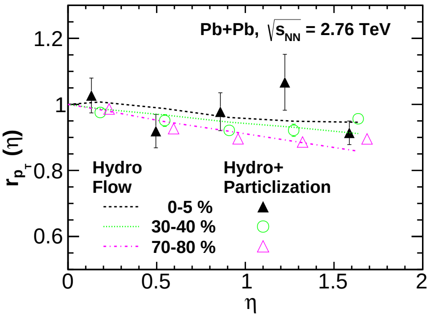
Statistical fluctuations



in our cacluation $b([p_T]_F, [p_T]_B)$ dominated by stat. fluct.
$\rho = 1$ or $\rho < 1$ makes almost no difference
(even if fireball is FB symmetric in each event $b \simeq 0.1 - 0.15$)

3-bin measure of $[p_\perp]$ decorrelation

$$r_{p_T}(\Delta\eta) = \frac{Cov([p_T],[p_T])(\eta_{ref}+\eta)}{Cov([p_T],[p_T])(\eta_{ref}-\eta)}$$



Measure of $[p_T]$ decorrelation in pseudorapidity

expect small decorrelation

less sensitive to non flow, no need to define $[p_T]$ variance

Correlations and fluctuations - flow dominated dynamics

moments and correlations of flow observables

- azimuthal flow coefficients
  $v_n 2, \ldots$, flow decorrelations in p_T or pseudorapidity
- $[p]_T$ fluctuations and decorrelations
  - $[p]_T$ fluctuations $C_{p_T} = \frac{1}{N(N-1)} \sum_{i \neq j} (p_i - < [p] >)(p_j - < [p] >)$
  - correlations with $[p_T]$, e.g. (1601.04513)

$$\rho([p_T], v_2^2) = \frac{Cov([p_T], v_2^2)}{\sqrt{\frac{1}{N(N-1)} \sum_{i \neq j} (p_i - < [p] >)(p_j - < [p] >) Var(v_2^2)}}$$

- multiplicity (density) fluctuations
  - moments of the density (Bialas, Zalewski 1101.5706)
  $< s > \propto < N >, < s^2 > \propto < N^2 > - < N >, \ldots$
  - correlations with density, e.g.

$$\rho(s, v_2^2) = \frac{Cov(N, v_2^2)}{\sqrt{(< N^2 > - < N > - < N >^2) Var(v_2^2)}}$$

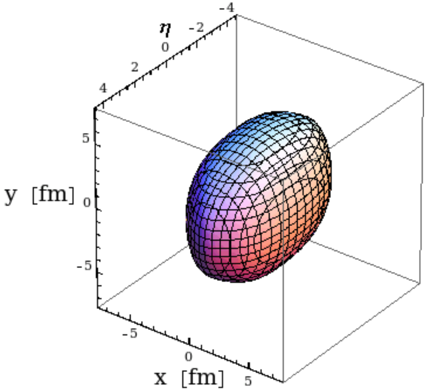
- **Correlations in rapidity**
  - flow-flow correlations
  - p_T-p_T correlations
  - multiplicity correlations
  - ... any combination
- **Methods**
  - factorization breaking coefficient
  - correlation coefficient
  - expansion in orthogonal polynomials
  - principal component analysis
- **Observations**
  - longitudinal decorrelation expected due to flucuations
  - longitudinal sdecorrelation observed
  - could test scenarios of initial sttae
  - p-Pb system more sensitive

Studies of rapidity correlations give insight into (largely inexplored) mechanism of energy deposition in the longitudinal direction

factorization breaking ratio $r_n(\eta_a, \eta_b)$

- $r_n(\eta_a, \eta_b) \simeq 1 - 2n^2 \langle (\Psi_n(0) - \Psi_n(\eta_b)) \frac{d\Psi_n(0)}{d\eta} \rangle \eta_a$
- linear in η_a $\quad r_n(\eta_a, \eta_b) \simeq 1 - 2f_n\eta_a \simeq exp(-2F_n\eta_a)$
- if $\Psi_4 \simeq \Psi_2$
  $F_4 \simeq 4F_2$
- F_n is an estimate of the decorrelation angle variance
  $F_n \simeq 2n^2 A \frac{(\Psi_n(0) - \Psi_n(\eta_b))^2 \rangle}{\eta_{range}}$

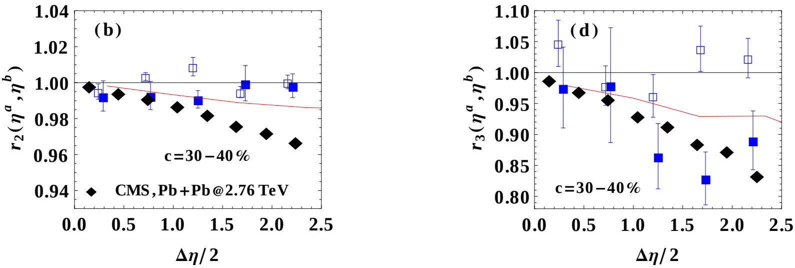
Fireball at different rapidities



is the shape similar at different rapidities
- same event-planes

often assumed (even for event-by-event simulations)

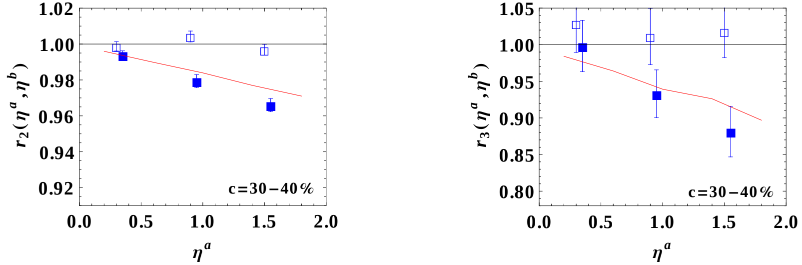
30-40%



(b)
$r_2(\eta^a,\eta^b)$
1.04
1.02
1.00
0.98
0.96
0.94
c=30−40%
CMS, Pb+Pb@2.76 TeV
0.0
0.5
1.0
1.5
2.0
2.5
$\Delta\eta/2$
(d)
$r_3(\eta^a,\eta^b)$
1.10
1.05
1.00
0.95
0.90
0.85
0.80
c=30−40%
0.0
0.5
1.0
1.5
2.0
2.5
$\Delta\eta/2$

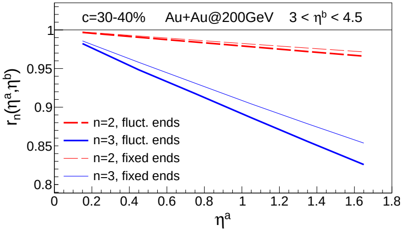
$r_n(\eta_a, \eta_b)$ **Au-Au at 200GeV**

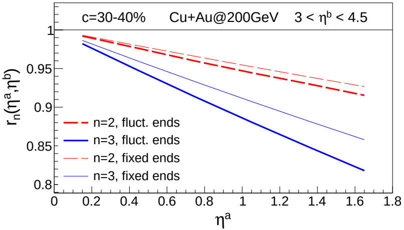
predictions $(3 < \eta_b < 4.5)$



- larger twist angle at RHIC energies

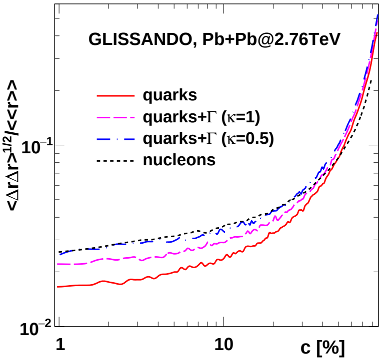
Fluctuating strings $r_n(\eta_a, \eta_b)$ RHIC energies





longitudinal fluctuations can be seen at RHIC
stronger decorrelation at lower energies

Caution - additional fluctuation may change the results



additional fluctuations of width Γ?

new constraint on the initial state