Mapping initial state correlations in rapidity using collective flow

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Fireball at different rapidities

is the shape similar at different rapidities
- same event-planes
often assumed (even for event-by-event simulations)
Twisted event-plane angles - torque effect

- due to fluctuations
- left-right orientation and angle magnitude are random
- only “smooth” long range twist
- random decorrelations on small scale, difficult to observe
Twist angle distribution - Glauber model

\[ \psi_2(\eta) - \psi_2(-\eta), \quad \Delta \eta = 1, 5 \]

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

- \( n = 2 \), largest decorrelation for central collisions
- \( n = 3 \), similar decorrelation for all centralities
Event-plane resolution at finite multiplicity

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

**Event-plane distribution $N = 20, 100, 60, \nu_2 = 0.05$**
One-shot 3+1D hydro evolution (2010)

initial density with a twist

\[ s(x, y, \eta) \propto \rho_+(R_x, R_y)f_+(\eta) + \rho_-(R^T_x, R^T_y)f_-(\eta) \]

forward (backward) participants rotated in the transverse plane

- the twist survives the hydrodynamic evolution
2-bin observable

\[ \cos(2\Delta\psi) = \frac{\langle\langle \cos[2(\phi_i(F) - \phi_j(B))] \rangle\rangle}{\sqrt{\langle \nu_2^2(F) \rangle} \sqrt{\langle \nu_2^2(B) \rangle}} \]

primordial particles, torque events + notorque events

charged particles, torque events + notorque events

substantial nonflow contribution

2-bin observables in \( \eta \) dominated by nonflow!
3-bin measure of event-plane decorrelation (CMS)

\[ r_2(\eta_a, \eta_b) = \frac{\langle < \cos[n(\phi_i(-\eta_a) - \phi_j(\eta_b))] \rangle}{\langle < \cos[n(\phi_i(\eta_a) - \phi_j(\eta_b))] \rangle} \approx \frac{\cos[n(\Psi(-\eta_a) - \Psi(\eta_b))]}{\cos[n(\Psi(\eta_a) - \Psi(\eta_b))]} \]

only pairs with large rapidity gap \( \eta_a - \eta_b \)

- nonflow under control
- torque effect seen in the CMS data
- semiquantitative agreement, but need more fluctuations

- other calculation (hybrid hydro, AMPT) reproduce the data) see talk by L.-G. Pang on Thursday
\( r_n(\eta_a, \eta_b) \)  Au-Au at 200GeV

predictions \((3 < \eta_b < 4.5)\)

- larger twist angle at RHIC energies
Fluctuations in energy deposition from each source

- the position (in rapidity) of string ends is random
- long range fluctuations
- each source fluctuates differently $\rightarrow$ 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 $\eta$)
fluctuations improve description of $r_2$ in Pb-Pb
except for $r_2$ in central collisions
- fluctuations essential to describe event-plane decorrelation in p-Pb
- fair description of mid-central collisions
- overestimates decorrelation in central collisions
- $F_4 \approx 4F_2$
Higher cumulants for correlations in rapidity

- we want to measure event by event fluctuations of particle density $\rho(y, \phi, p_{\perp})$
- fluctuations from left and right going participants (Bzdak, Teaney, 2012)

$$\rho(y) = \rho_0(1 + a_1 y + \ldots) = \rho_0(1 + d(N_+ - N_-)y + \ldots)$$

- two particle correlations measure $< a_1 a_1 >$, with strong nonflow!

- Solution!
  Measure higher cumulants of $a_n$ coefficients (Bzdak, Bozek, 1509.02967)
  $$< a_1 a_1 a_1 a_1 > = -3 < a_1 a_1 > < a_1 a_1 >$$
  $$< a_1 a_1 a_1 a_1 a_1 > = -15 < a_1 a_1 a_1 a_1 > < a_1 a_1 > + 30 < a_1 a_1 >^3$$
  and many other cumulants for different $a_n$ combinations
higher cumulants of $a_n$ coefficients are different than $v_2$ cumulants

for density fluctuations from forward-backward asymmetry

$$\rho(y) = \rho_0(1 + a_1 y + \ldots) = \rho_0(1 + d(N_+ - N_-)y + \ldots)$$

we measure cumulants of the participant asymmetry

$$\langle a_1 a_1 a_1 a_1 \rangle_c = d^4 \langle (N_+ - N_-)^4 \rangle_c$$

but cumulants of $N_+ - N_-$ are close to zero (Glauber model)

So what can be measured with cumulants?

long range sources of 4, 6, \ldots particles

cumulants can be defined also for rapidity correlations of $v_n v_p \ldots v_m$

$$\langle a_{i_1}[m_1]\ldots a_{i_n}[m_n] \rangle_c = \left\langle \sum_{a_1,\ldots,a_n} \frac{T_{i_1}}{Y \langle N(\eta_{a_1}) \rangle} e^{im_1\phi_{a_1}} \ldots \frac{T_{i_n}}{Y \langle N(\eta_{a_n}) \rangle} e^{im_n\phi_{a_n}} \right\rangle_c$$

( for details see Bozek. Broniowski, Olszewski 1509.04362)
Collective flow enables a mapping of the initial longitudinal profile and its fluctuations to some observables.

Torque effect observed by CMS

\[ r_2(\eta_a, \eta_b) \text{ in p-Pb requires additional long range fluctuations in the energy deposition} \]

The observed relation \( F_4 \approx 4F_2 \) consistent with flow with dominant \( v_2 \)

Nonflow is a serious issue

Measure higher cumulants of multiplicity or flow correlations in rapidity!

Studies of rapidity correlations give insight into (largely inexplored) mechanism of energy deposition in the longitudinal direction.
Fluctuating strings $r_n(\eta_a, \eta_b)$ RHIC energies

longitudinal fluctuations can be seen at RHIC
PCA - nonflow strikes again

Principal Component Analysis (PRL 114 (2015) 152301)

PCA in $\eta$ dominated by nonflow!
PCA works for oversampled events
The factorization breaking ratio $r_n(\eta_a, \eta_b)$ is given by:

\[ r_n(\eta_a, \eta_b) \approx 1 - 2n^2 \langle (\Psi_n(0) - \Psi_n(\eta_b)) \frac{d\psi_n(0)}{d\eta} \rangle \eta_a \]

It is linear in $\eta_a$:

\[ r_n(\eta_a, \eta_b) \approx 1 - 2f_n \eta_a \approx \exp(-2F_n \eta_a) \]

If $\Psi_4 \approx \Psi_2$,

\[ F_4 \approx 4F_2 \]

$F_n$ is an estimate of the decorrelation angle variance:

\[ F_n \approx 2n^2 A \frac{\langle (\psi_n(0) - \psi_n(\eta_b))^2 \rangle}{\eta_{\text{range}}} \]
Forward and backward going participants

- Glauber Monte Carlo model $\rightarrow$ different distributions for forward and backward going participants
- different event-planes at forward and backward rapidities
Asymmetric emission


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