Triangular Flow in Relativistic Heavy Ion Collisions in an Event-by-Event Hybrid Approach

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Outline

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  – Initial State Fluctuations & Triangular Flow
• The Hybrid Approach
  • Fluctuating Initial Conditions
  • Ideal Hydrodynamic Evolution
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• Constraining Granularity
  • Eccentricity Distributions
  • Sensitivity of Elliptic and Triangular Flow
  • Comparison to experimental data from RHIC
• Going to Higher Energies: LHC
• Summary
Motivation

- Different initial conditions ~ factor of 2 difference in $\eta/s$ → Major uncertainty to constrain transport coefficients in the quark gluon plasma

H.Song et al, PRL 106, 192301 (2011)
Initial Conditions from Dynamical Approaches

- The initial $T^{\mu\nu}$ for hydrodynamics has to be given via:

\[ \epsilon(x, y, z), \ p(x, y, z) \text{ and } n(x, y, z) \]

- **Energy deposition** model needs to describe final $dE_T/dy$ in p-p and A-A correctly.
- Granularity is influenced by:
  - Shape of the incoming nuclei
  - Distribution of binary collisions
  - Interaction mechanism
  - Degree of thermalization
- Differences in **shape** and **fluctuations** need to be quantified
  - First attempt: use **higher** Fourier coefficients
• Fluctuations introduce higher order flow coefficients that have been observed at the RHIC and LHC experiments (see QM 2011)

• How can we quantitatively learn something from this observable?

B. Alver and G. Roland, PRC 2010; NExspheRIO, PRL 103, 242301, 2009; P. Sorensen, JPG, 37, 094011, 2010 ... and many more, results taken from PHENIX in arXiv: 1105.3928
Hybrid Approach

- Use advantages of transport and hydrodynamics and create combined model
- Modular Setup: Fix the hydro evolution and freeze-out
  → learn something about the influence of different initial conditions

1) Non-equilibrium initial conditions via UrQMD
2) Hydrodynamic evolution
3) Freeze-out via hadronic cascade (UrQMD)

H.P. et al., PRC 78:044901, 2008

UrQMD-3.3p1 is available at http://urqmd.org
Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle:

\[
\epsilon(x, y, z) = \left( \frac{1}{2\pi} \right)^{\frac{3}{2}} \frac{\gamma_z E_p}{\sigma^3} \exp \left( -\frac{(x - x_p)^2 + (y - y_p)^2 + (\gamma_z(z - z_p))^2}{2\sigma^2} \right)
\]

- Changing \(\sigma\) leads to different granularities, but also changes in the overall profile.

To fit yields and elliptic flow: \(\sigma \sim 1\) fm and \(t_{\text{start}} \sim 0.5\) fm.
Constraining Granularity

- Dialing different **granularities** by averaging initial configuration over 1, 2, 5, 10, ... 100 events
- Yields, spectra and elliptic flow are **identical**
- **Triangular flow** ranges from zero (smooth) to a few percent
Non-Central Collisions

- Different averages lead to different granularities
- Overall features of the initial state profile are preserved
- Direct connection to initial state dynamics lost
- Good setup for systematic study
Eccentricity and Triangularity

• Coefficients are calculated from the initial energy density distribution in the hydrodynamic calculation.

- Probability distribution of $\varepsilon_2$ gets narrower, while for $\varepsilon_3$ the mean value decreases for smoother initial conditions.
From Initial to Final State

- $v_n$ and $\varepsilon_n$ and initial and final event plane angles are correlated on an event-by-event basis
- Confirms collective behaviour

**Initial State Coordinate Space Asymmetry**

$$\Phi_n = \frac{1}{n} \arctan \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \cos(n\phi) \rangle}$$

$$\varepsilon_n = \sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2} / \langle r^n \rangle$$

**Final State Momentum Space Asymmetry**

$$\Psi_n = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi_p) \rangle}{\langle p_T \cos(n\phi_p) \rangle}$$

$$v_n = \langle \cos(n(\phi_p - \Psi_n)) \rangle$$

H.P. et al, PRC 82, 041901
Bulk Observables

- First check: Transverse mass spectra and elliptic flow are very similar for different granularities
- Reasonable agreement with experimental data, using EoS that fits lattice calculations
Anisotropic Flow Results

- $v_3$ is more **sensitive** to the fluctuations as expected
- **NO** resolution correction applied to see qualitative behavior
- How does that compare to the measured values?
Comparison to PHENIX

- PHENIX data is in between $n=1$ and $n=3$
- Lower limit for initial state granularity
- Finite shear viscosity during hydro evolution smoothes fluctuations out faster
Higher Energies - LHC

- Probability distribution contains information about initial state profile and fluctuations
- Eccentricity and triangularity in central collisions are very similar
- Mid-central collisions: $\varepsilon_2 > \varepsilon_3$ and $P(\varepsilon_2)$ is wider
• In UrQMD the whole probability distribution is almost identical at RHIC and LHC
• Higher multiplicity has no visible effect on fluctuations
• Energy fluctuation per binary interaction larger?
Comparison to LHC data

• Exact same parameter set as applied at RHIC
• Hybrid approach is in good agreement at low $p_T$
• Different EoS give similar results

H.P., arXiv: 1105.1766
Triangular Flow at LHC

- Triangular flow is almost zero in UrQMD → Very sensitive to viscosity
- Same granularity is in reasonable agreement with experimental data

- Minimum bias result for identified particles
- Mass splitting

Conclusions

- Dynamic transport approaches provide **fluctuating initial conditions**
- The **amount** of initial state fluctuations can be **tuned** by averaging over different numbers of events
- Probability **distributions** of eccentricity and triangularity encode information about shape and fluctuations
- Proof that triangular flow provides a good measure for initial state **granularity** by a **systematic** study that allows to place a lower limit on the initial state granularity
- LHC results from **event-by-event** hydro are in reasonable agreement with the data with the same granularity
- Further strategy to a quantitative understanding:
  - Constrain the shear viscosity by elliptic flow in mid-central collisions
  - Tune the granularity to match the triangular flow result
  - Central collisions, LHC results and smaller systems provide lots of room for determining the shape of the profile
Backup
Longitudinal Correlation

- Idea: look at event plane angles in different rapidity slices
- Important verification of the event plane method which relies on a single plane for the whole event
Longitudinal Correlation

- Calculate overall event plane angle and angle in each bin
- Look at the distribution of the differences of these angles

\[ \text{dN/d}(\alpha(\Delta y)-\alpha) \]

\begin{enumerate}
  \item $1.5<y<2$
  \item $1.0<y<1.5$
  \item $0.5<y<1.0$
  \item $0<y<0.5$
  \item $0.5<y<0.5$
  \item $1.0<y<1.5$
  \item $1.5<y<2.0$
\end{enumerate}

\[ \rightarrow \text{There is a correlation in the initial state generated by string fragmentation} \]
\[ \rightarrow \text{Stronger at midrapidity} \]
\[ \rightarrow \text{Gets smeared out during hydro evolution} \]

Compare to parton cascade initial conditions to explore a different initial scenario

PCM Initial State

- **Time-like branchings** following binary scattering also introduce long-range longitudinal correlation
- **Not unique** to flux tube/string picture

In UrQMD the whole probability distribution is almost identical at RHIC and LHC.

Geometry of overlap region does not change.

Higher multiplicity has no visible effect on fluctuations.
Sensitivity to Granularity

- Central collisions: $\epsilon_2$ and $\epsilon_3$ similar as a function of granularity
- Mid-Central collisions: $\epsilon_2$ constant due to almond-shaped geometry, while $\epsilon_3$ sensitive to amount of fluctuations
Anisotropic Flow Results

- Resolution correction increases the values and is granularity dependent
- General trends are still preserved
From Initial to Final State

- $\Phi_n$ is calculated in initial coordinate space
- $\Psi_n$ from final momentum space distribution
- There is a strong correlation between the two angles
- For elliptic flow stronger in more peripheral events

$$\Phi_n = \frac{1}{n} \arctan \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \cos(n\phi) \rangle} \quad \rightarrow \quad \Psi_n = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi_p) \rangle}{\langle p_T \cos(n\phi_p) \rangle}$$

Event Plane Angles

- $\Psi_2$ is correlated to reaction plane
- $\Psi_3$ distribution is flat
- Only fluctuations, no geometry in contrast to elliptic flow where both are mixed
- Triangular flow can be used for measuring granularity
• Hybrid works well for \( p_T < 3 \) GeV