# Event-by-Event Fluctuations in Initial Conditions in Relativistic Hydrodynamic Model

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## Abstract
We constructed an integrated simulation framework to study the effect of fluctuating initial conditions of heavy ion collisions quantitatively, and performed a massive event-by-event numerical simulations under the configuration of RHIC and LHC, and compared the analysis methods to obtain the flow harmonics values.

## 1. Introduction

**Integrated Dynamical Model Based on Relativistic Hydrodynamics**
- Describe the whole process of heavy collision reaction using several models for each stage of the reaction:
  - Thermalization
  - Quark-gluon plasma
  - Hadronization
  - Hadron gas

- Extract the properties of QGP by comparing the results to experimental data
- Transport properties of QGP:
  - Shear viscosity $\eta$
  - Bulk viscosity $\zeta$
  - Relaxation time $\tau$

## 2. Simulation of Integrated Dynamical Model

**Recent Experimental Data → Event-by-Event Fluctuations**

**Anisotropic flows**
- Central collision
- The averaged initial condition
- An initial condition of a single event

**Purpose of this study**
- Event-by-event massive numerical simulations with the fluctuating initial conditions
- The same analysis methods of flow harmonics $v_n$ as in experiment

**5. Harmonic Analysis**
- Harmonics $v_n$: Fourier coefficient of azimuthal distribution of particles
- $v_n = \frac{1}{N} \int dx f(x) \cos(n \phi) dN/dx$ (normalized to the pseudorapidity distribution)
- $\phi$: angle measured from the reaction plane
- $v_n$: proper angles of the event

**Methods to evaluate $v_n$**
- Reaction plane $v_n(RP)$ (calculable only in theory)
- Participant plane $v_n_PP$ (calculable only in theory)
  - Measuring $v_n$ with respect to the flow vectors
- Two-particle correlation method $v_n(2)$
- Four-particle correlation method $v_n(4)$
  - Cumulants using relative angles of particles

## 3. Result: Higher Flow Harmonics

**• MC-KLN vs. MC-Glauber in higher anisotropic flows ($n=2$, 3, 4, 5)**

$\nu_{v_n}(v_0 < v_n(EP)) < \nu_{v_n}(\nu_0, \nu_3, v_n(EP))$

**Differences in methods to evaluate harmonics value**

**• Pseudo-rapidity dependence in a wide range**

**• Differences in methods to evaluate harmonics value**

**Necessity to use the same method to quantitatively compare a model to experiment**

## 4. Result: PP Angles and EP Angles

**• Correlations between an initial condition angle $\phi_{\text{inc}}$ and a resulting flow angle $\Psi$**

**• Significant difference between $\Psi$, $\Psi_1$, and $\Psi_2$**

**• $\phi_2 \rightarrow \Psi_2$, $\phi_1 \rightarrow \Psi_1$**

$\phi_1 \rightarrow \phi_2$ in non-central collisions

$\phi_2 \rightarrow \phi_3$ in non-central collisions

## 5. Summary and Outlook
- We performed harmonic analysis using the results of event-by-event simulations for a large number of events and obtained higher anisotropic flows ($n = 2$–6) as functions of centrality and $\eta$.
- There are significant differences among evaluation methods of $v_n$ which requires special attention in comparison of model results with data.
- We also looked into correlations between initial condition angles and flow angles.
- While $v_2$ and $v_3$ are induced by $\phi_2$ and $\phi_1$ respectively, higher anisotropic flows are generated by lower order anisotropies of initial conditions in non-central collisions.
- In future, we plan to perform similar analysis using $3+1$-dimensional viscous hydrodynamics.