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

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Abstract

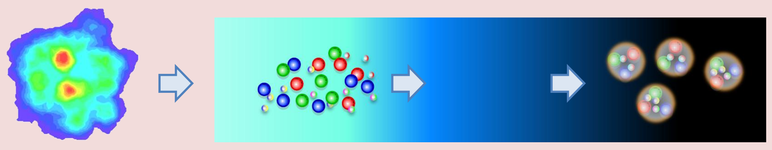
We constructed an integrated simulation framework to study the effect of fluctuating initial conditions of heavy ion collisions quantitatively, and performed a massive event-by-event numerical simulations under the configuration of RHIC and LHC, and compared the analysis methods to obtain the flow harmonics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

1. Introduction

Integrated Dynamical Model Based on Relativistic Hydrodynamics

Describe *the whole process of heavy-ion collision reaction* using several models for each stage of the reaction

- Thermalization
- Quark-gluon plasma
- Hadronization
- Hadron gas



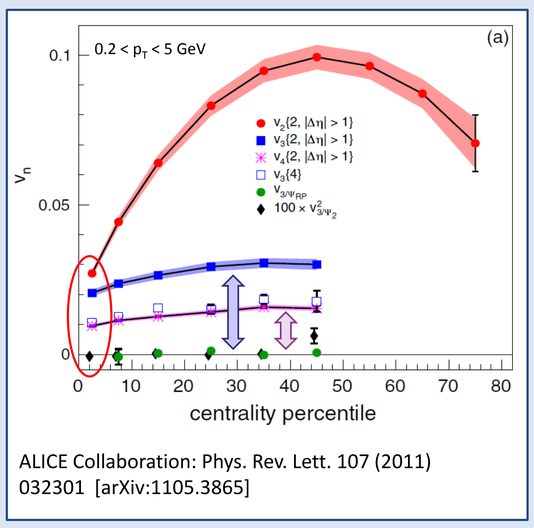
Extract the properties of QGP by comparing the results to experimental data

Initial State of the QGP
- Glauber model
- Color-glass condensate model

Transport properties of QGP
- Shear viscosity η
- Bulk viscosity ζ
- Relaxation time τ

Recent Experimental Data → Event-by-Event Fluctuations

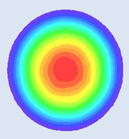
Anisotropic flows



ALICE Collaboration: Phys. Rev. Lett. 107 (2011) 032301 [arXiv:1105.3865]

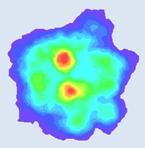
Central collision

The averaged initial condition



v_n=0

An initial condition of a single event



v_n≠0

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*

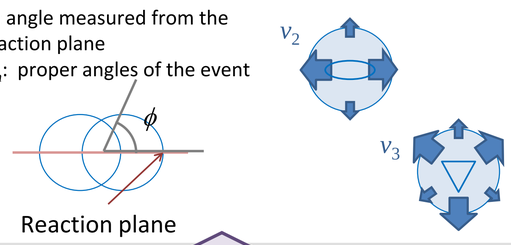
2. Simulation of Integrated Dynamical Model

5. Harmonic Analysis

Harmonics v_n: Fourier coefficient of azimuthal distribution of particles

$$\frac{1}{N'}\frac{dN'}{d\phi} = \frac{1}{2\pi}\left[1+2\sum_{n=1}^{\infty} v_n \cos n(\phi-\Psi_n)\right]$$

ϕ: angle measured from the reaction plane
Ψ_n: proper angles of the event

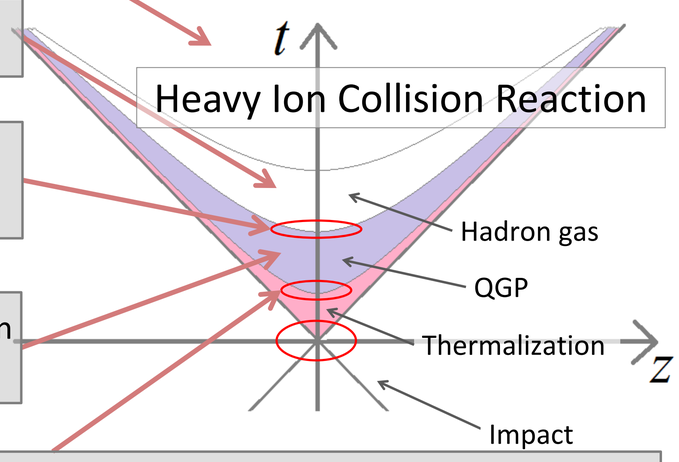


Methods to evaluate v_n
- Reaction plane $v_n\{RP\}$ (calculable only in theory)
- Participant plane $v_n\{PP\}$ (calculable only in theory)
  - Difficult to measure in experiments
- Event-plane method $v_n\{EP\}$
- Scalar-product method $v_n\{SP\}$
  - Measuring v_n with respect to the flow vectors
- Two-particle correlation method $v_n\{2\}$
- Four-particle correlation method $v_n\{4\}$
  - Cumulants using relative angles of particles

4. Hadron-cascade simulation (JAM)

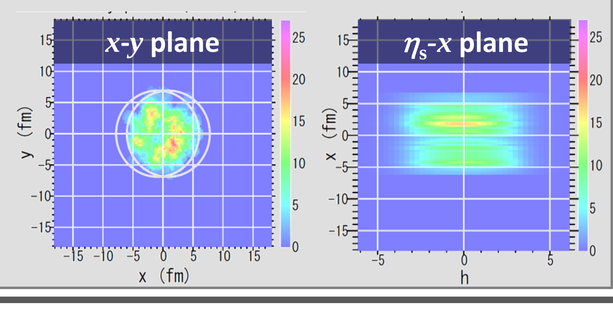
3. Fluid to particles at T_{sw} = 155 MeV (Cooper-Frye formula)

2. Full (3+1)-dim. ideal hydro simulation
EoS: lattice QCD (HRG @ low T)



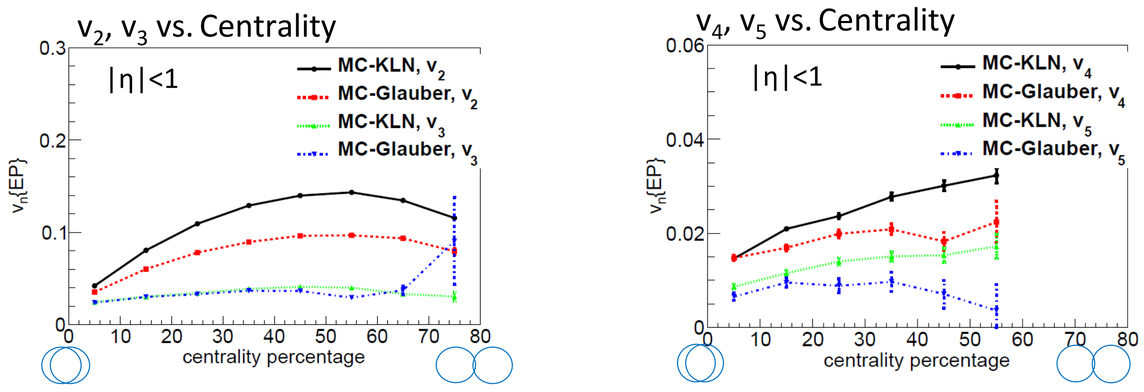
1. Generating initial conditions
- Experimental configuration
  - RHIC: ^{197}Au+^{197}Au, $\sqrt{s_{NN}}$ = 200 GeV
  - LHC: ^{208}Pb+^{208}Pb, $\sqrt{s_{NN}}$ = 2760 GeV
- Monte-Carlo models
  Initial nucleon distribution
  - MC-KLN (Color-glass condensate model)
  - MC-Glauber (Glauber/Modifed BGK model)
- 100,000 events (minimum bias)

An example of an initial condition
RHIC, MC-KLN



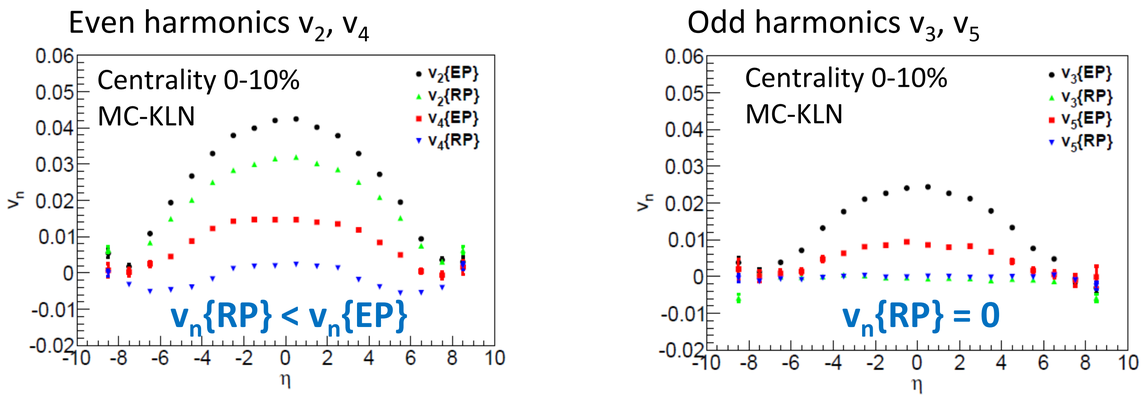
3. Result: Higher Flow Harmonics

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

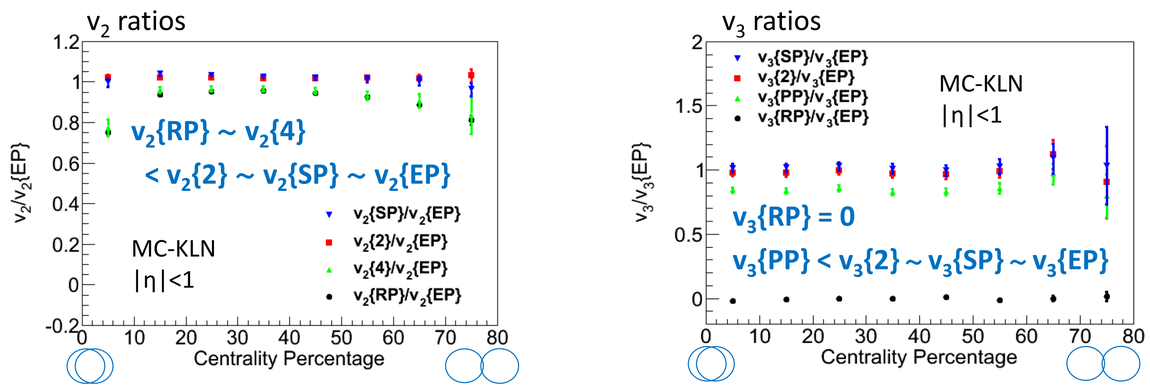


MC-KLN < MC-Glauber in non-central

- Pseudo-rapidity dependence in a wide range



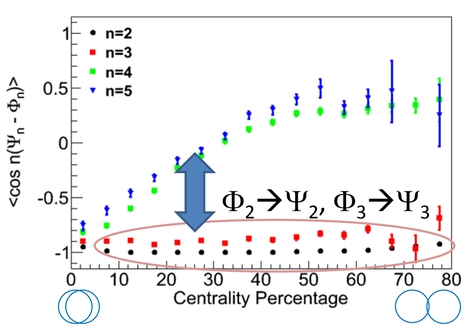
- Differences in methods to evaluate harmonics value

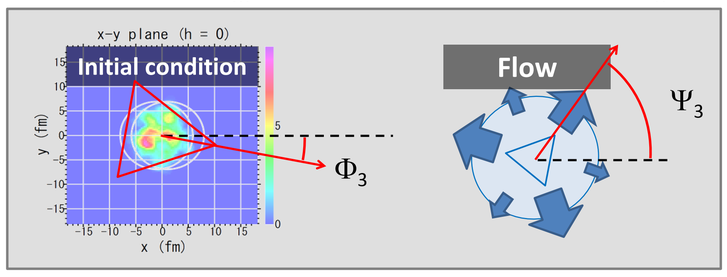


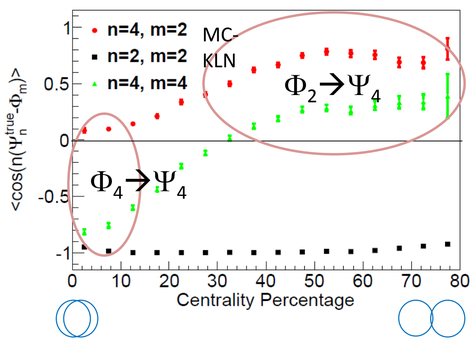
Necessity to use *the same method* to quantitatively compare a model to experiment

4. Result: PP Angles and EP Angles

- Correlations between an initial condition angle Φ_m and a resulting flow angle Ψ_n







- Significant difference between $\{\Psi_2, \Psi_3\}$ and $\{\Psi_4, \Psi_5, \ldots\}$
- $\Phi_2 \to \Psi_2$, $\Phi_3 \to \Psi_3$
- $\Phi_4 \to \Psi_4$ in central collisions
- $\Phi_2 \to \Psi_4$ 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 η*.
- 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 ε_2 and ε_3 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.