Effects of hydrodynamic fluctuations on azimuthal flow in ultra-central heavy-ion collisions

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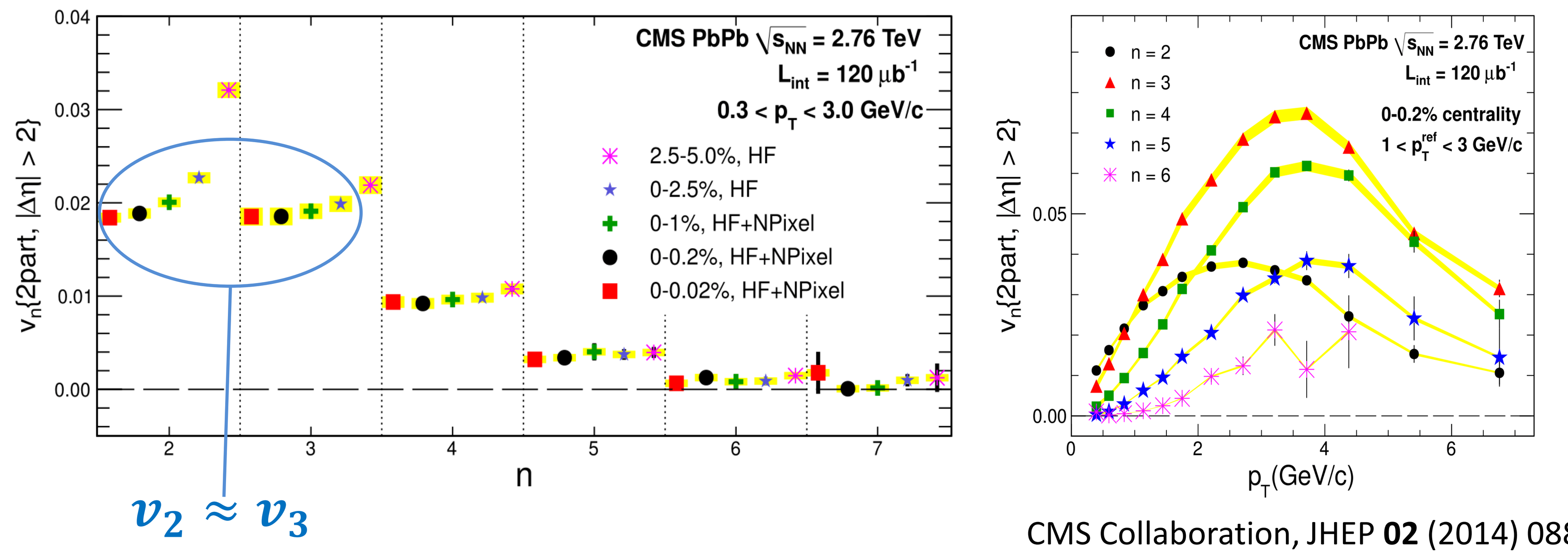
Abstract : In ultra-central heavy-ion collisions, because of lack of collision geometry, fluctuations play very important roles to generate anisotropic flow. While initial state fluctuations are actively studied, hydrodynamic fluctuations during the space-time evolution of QGP are also important. We simulate with and w/o hydrodynamic fluctuations and initial state fluctuations using Integrated Dynamical Model and analyze the effects of hydrodynamic fluctuations on anisotropic flow quantitatively.

1. Introduction

Experimental Data "ultra-central" : 0-0.2% Centrality

Flow harmonics



CMS Collaboration, JHEP **02** (2014) 088

In ultra-central collisions
Little collision geometry → **Fluctuations** are very important

Purpose of this study

- Massive numerical simulations with & w/o fluctuations
  Evaluate the effects of hydrodynamic fluctuations on anisotropic flow
- Compare simulation results with experimental data
  Importance of hydrodynamic fluctuations in ultra-central heavy-ion collisions

2. Integrated Dynamical Model and Analysis

Describe the whole process of heavy-ion collision reaction using several models for different stages of reaction

T. Hirano *et al.* , Prog. Part. Nucl. Phys. **70**, 108 (2013)

Fix impact parameter $b = 0$ fm
Absence of collision geometry effects → Only fluctuation effects
Analyze the effects of hydrodynamic fluctuations
Initial state model: ON/OFF initial state fluctuations
QGP hydro model: ON/OFF hydrodynamic fluctuations

5. Anisotropic flow Analysis

Flow 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: event plane angle

Methods to evaluate v_n
Two-particle correlation method $v_n\{2\}$

$$v_n\{2\} = \sqrt{\frac{\left\langle \sum_i^N e^{in\phi_i} \sum_j^N e^{-in\phi_j} - N \right\rangle_{ev}}{\langle N(N-1)\rangle_{ev}}}$$

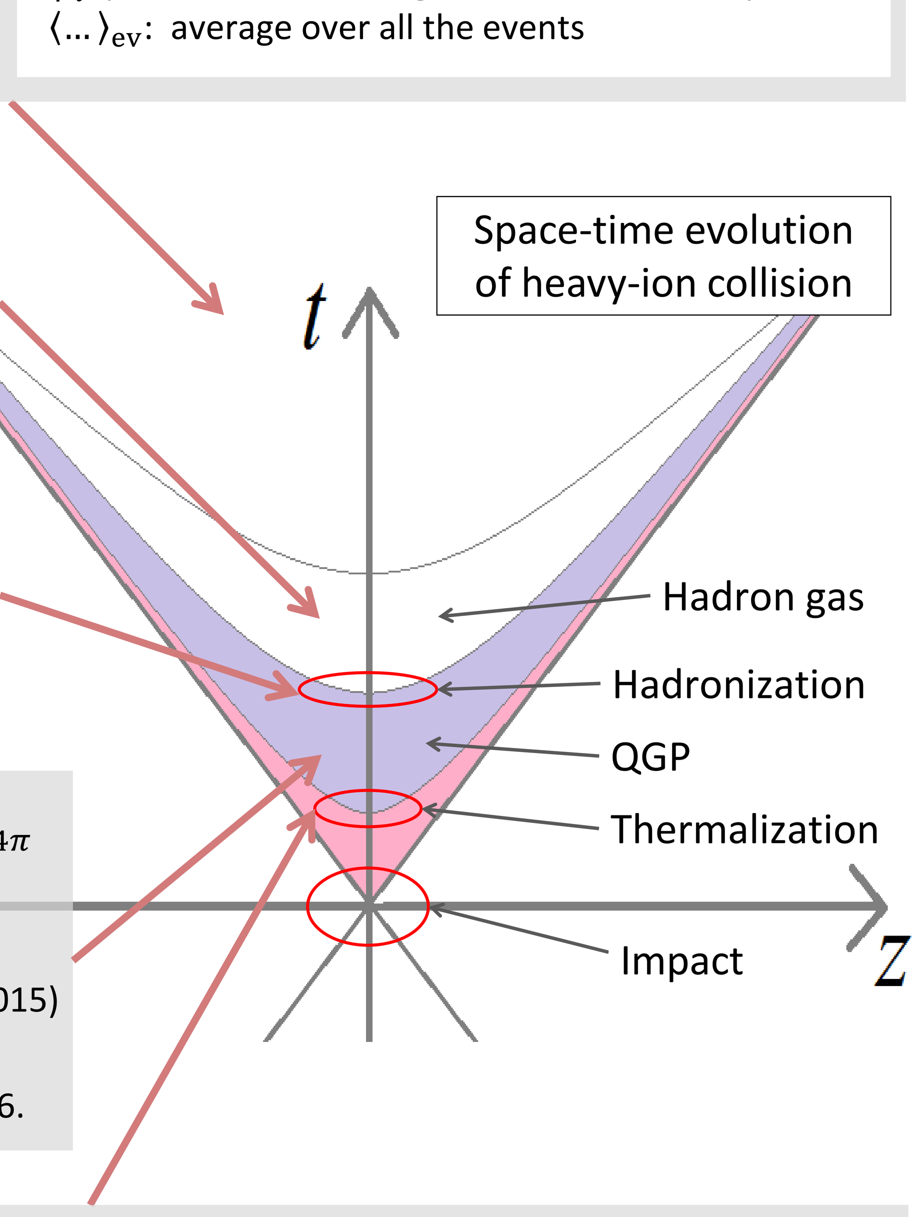
ϕ_i: particle emission angle from the reaction plane
$\langle \dots \rangle_{ev}$: average over all the events

4. Hadron cascade simulations
– JAM
Y. Nara, N. Otuka, A. Ohnishi, K. Niita, S. Chiba, Phys. Rev. C **61** (2000) 024901

3. Fluid to particles at $T_{SW} = 155$ MeV
– Cooper-Frye formula
F. Cooper and G. Frye, Phys. Rev. D **10** (1974) 186

2. Full (3+1)-D hydro simulations $\eta/s = 1/4\pi$
– rfh (Relativistic Fluctuating Hydro)
– rdh (Relativistic Dissipative Hydro)
K. Murase, Ph.D thesis, The University of Tokyo (2015)
+ EoS $s95p$-v1.1 lattice QCD + HRG
P. Huovinen, P. Petreczky, Nucl. Phys. 837 (2010) 26.

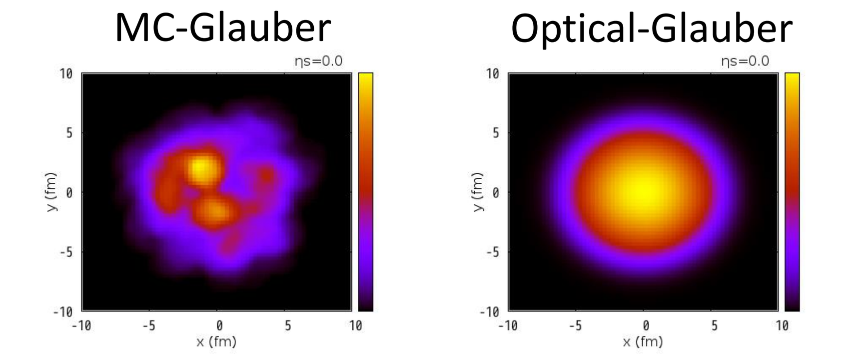
Space-time evolution of heavy-ion collision



1. Generating initial conditions
– MC-Glauber + Modified BGK
– Optical-Glauber + Modified BGK

- Configuration
  ^{208}Pb + ^{208}Pb , $\sqrt{s_{NN}} = 2.76$ TeV
- Fix Impact Parameter
  $b = 0$ fm

An example of initial conditions



Initial state fluctuations $\varepsilon_n > 0$ / Symmetric initial condition $\varepsilon_n = 0$

- 2,000 hydro events x 10 cascade events

3. Relativistic Fluctuating Hydro Model

K. Murase, Ph.D thesis, The University of Tokyo (2015)

= Conservation Law + EoS
+ Constitutive eq. — Hydrodynamic fluctuations

$$\tau_\pi \Delta^{\mu\nu}{}_{\alpha\beta} u^\lambda \partial_\lambda \pi^{\alpha\beta} + \left(1 + \frac{4}{3}\tau_\pi \partial_\lambda u^\lambda\right)\pi^{\mu\nu} = 2\eta \Delta^{\mu\nu}{}_{\alpha\beta}\partial^\alpha u^\beta + \delta\pi^{\mu\nu}$$

τ_π: Relaxation time; η: Shear viscosity; $g^{\mu\nu} := \mathrm{diag}(+,-,-,-)$; u^μ : Landau frame; $\Delta^{\mu\nu} := g^{\mu\nu} - u^\mu u^\nu$; $\Delta^{\mu\nu}{}_{\alpha\beta} := \frac{1}{2}\left(\Delta^\mu{}_\alpha \Delta^\nu{}_\beta + \Delta^\mu{}_\beta \Delta^\nu{}_\alpha\right) - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta}$

Fluctuation Dissipation Relation
= Stability condition of thermal system

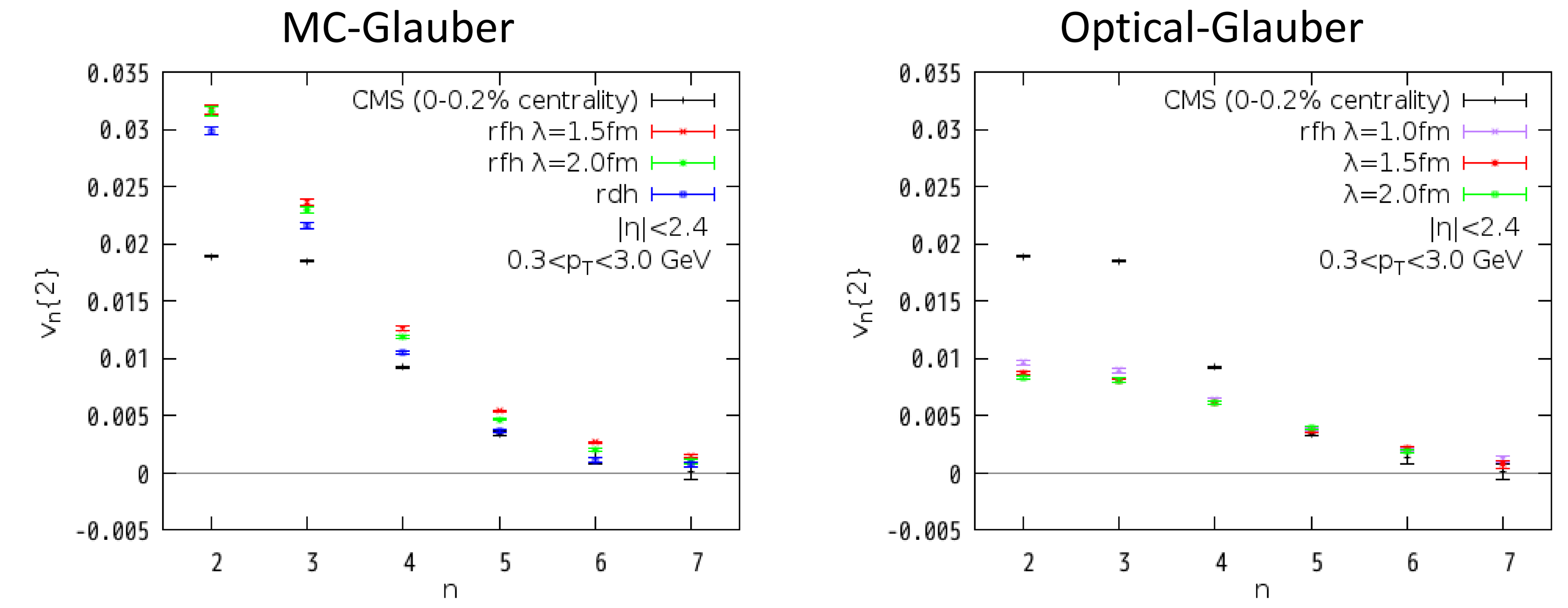
$$\langle \delta\pi^{\mu\nu}(x)\delta\pi_{\alpha\beta}(x')\rangle = 4T\eta \Delta^{\mu\nu}{}_{\alpha\beta}\delta^{(4)}(x - x')$$

In simulations

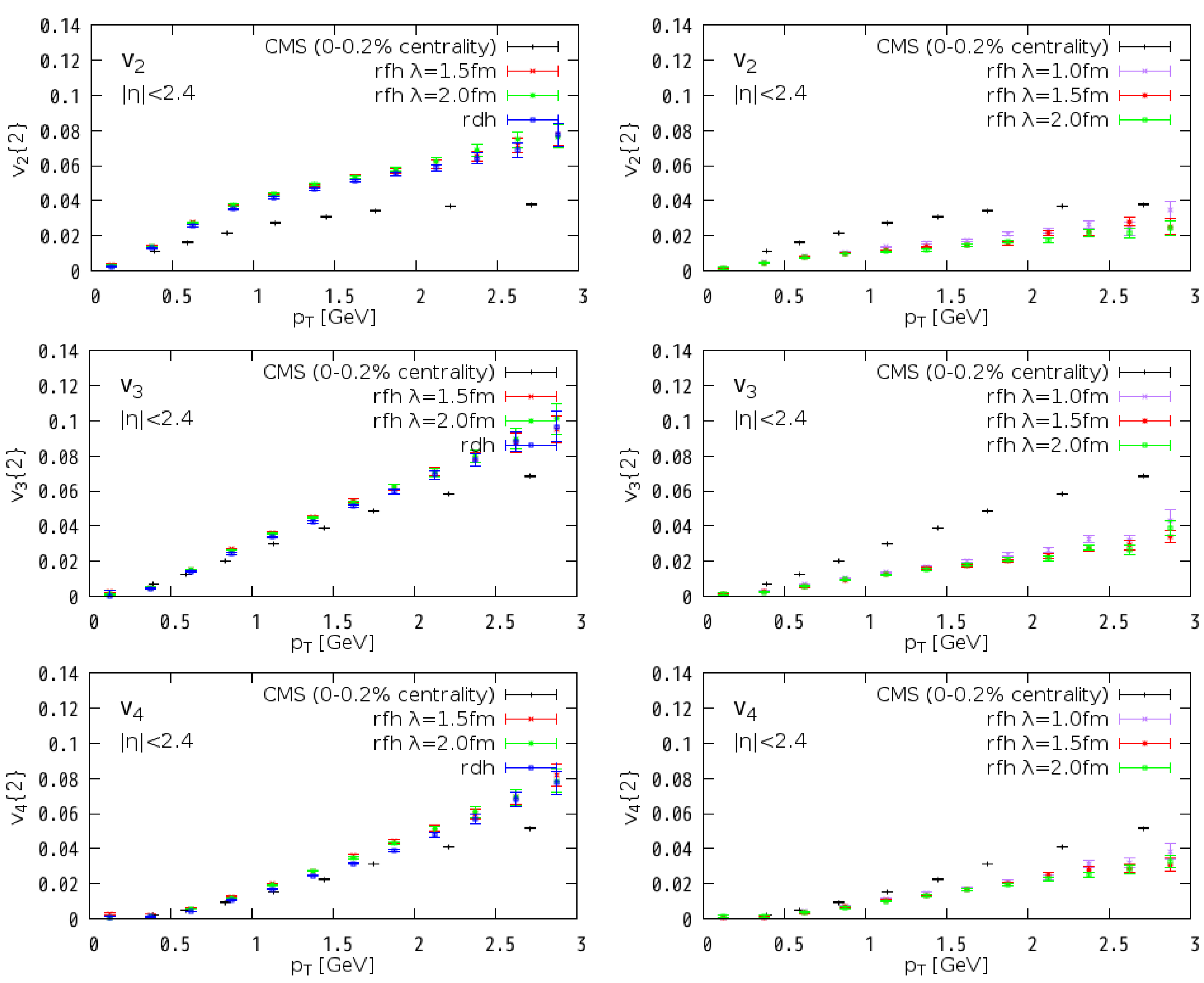
$$\delta^{(4)}(x - x') \to \frac{1}{2\Delta t}\frac{1}{(4\pi\lambda^2)^{\frac{3}{2}}} e^{-\frac{(x-x')^2}{4\lambda^2}}$$

λ : Cutoff parameter

4. Result : Flow Harmonics



- Fluctuating hydro model overestimates the experimental data especially in v_2
- Hydrodynamic fluctuations generate anisotropic flow
- $v_2 \approx v_3$



- v_3 & v_4 are well described in low p_T while v_2 is overestimated
- Anisotropic flow by hydrodynamic fluctuations exhibits a similar tendency to experiment

5. Summary and Outlook

- We analyze the effects of hydrodynamic fluctuations on anisotropic flow using the results of $b = 0$ fixed Integrated Dynamical Model with and w/o initial state fluctuations.
  — Hydrodynamic fluctuations generate anisotropic flow even without initial fluctuations, and elliptic flow v_2 and triangular flow v_3 are almost the same.
- We also compare simulation results with experimental data (0-0.2% Centrality).
  — Simulation results overestimate the experimental data especially in v_2.
- In future, we plan to introduce initial fluctuating flow distributions into Integrated Dynamical Model for better description of experimental results.