フローと相関から探る QGP 物質の性質

Kobayashi Maskawa Institute

Department of Physics, Nagoya University

Chiho NONAKA

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Hydrodynamic Model:

Yukinao Akamatsu, Shu-ichiro Inutsuka, Makoto Takamoto

Hybrid Model:

Yukinao Akamatsu, Steffen Bass, Jonah Bernhard

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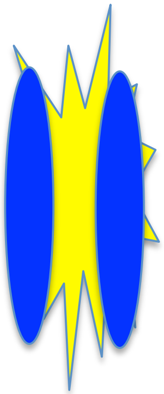
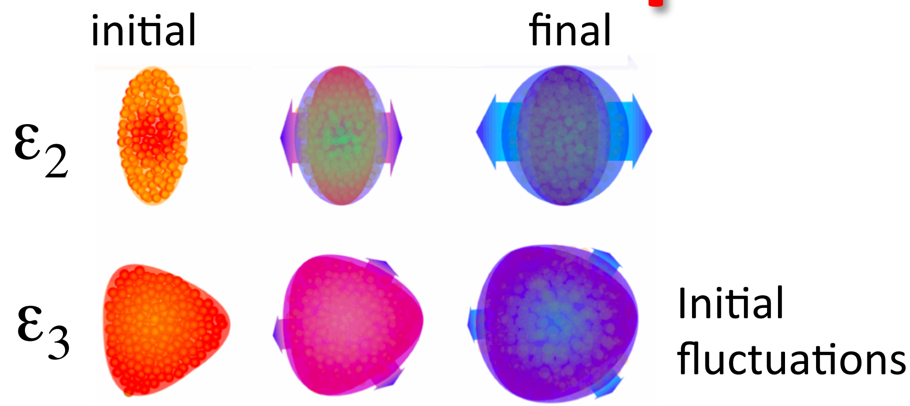
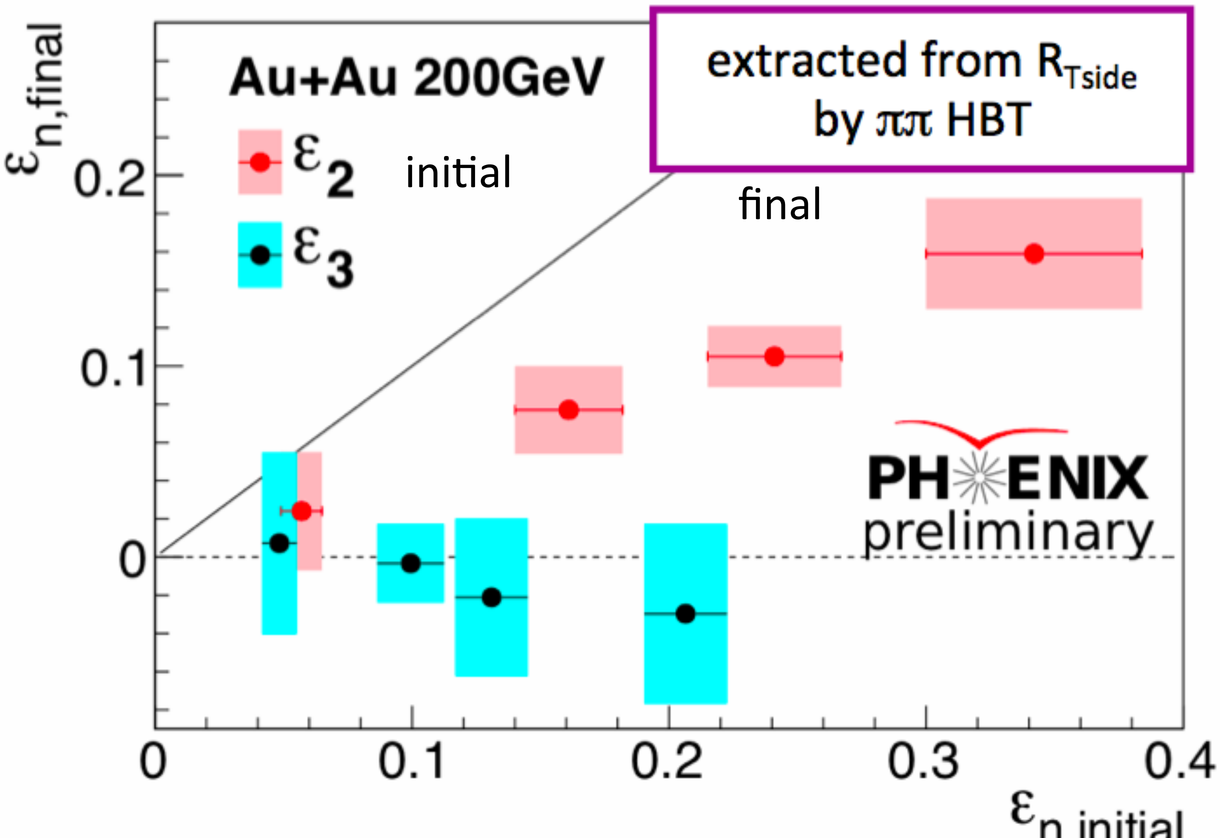
Initial vs Final Spatial Anisotropy





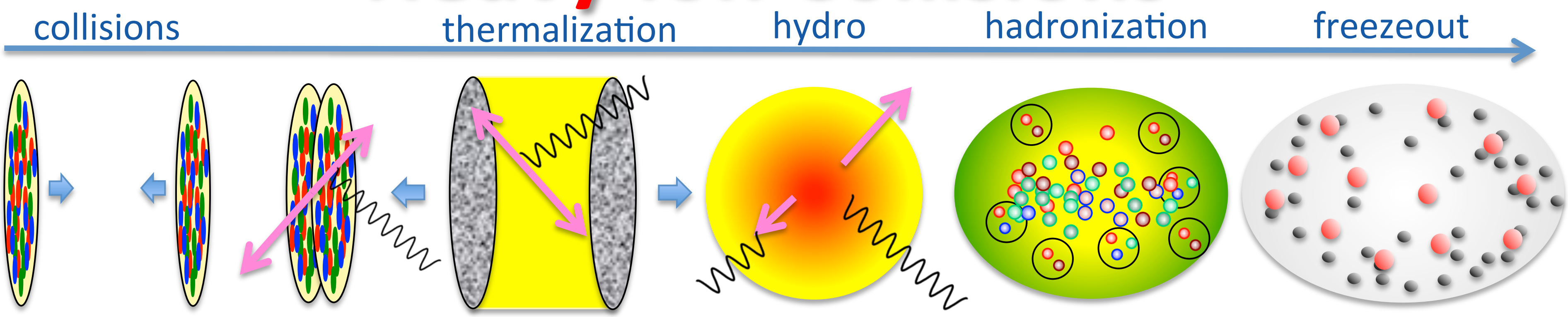


- Initial pressure gradient
  ➡ flow
  final anisotropy
- Initial vs final
  - Medium response
  - QGP property

PHENIX@RHIC

- $\varepsilon_{2,f}$ finite, linear to $\varepsilon_{2,i}$
- $\varepsilon_{3,f}$ ~ 0, no central dependence

Heavy Ion Collisions



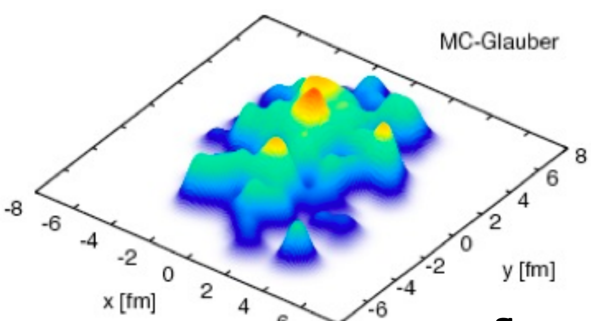
Hydrodynamic models: application to HIC, Landau 1953, Bjorken 1986

sQGP

Initial condition → **Hydrodynamics** → **Freezeout process**

Input
?

Equation of State
lattice QCD
transport coefficients



fluctuations

Relativistic viscous hydrodynamic
Shock wave

Viscous Hydrodynamic Model

- Relativistic viscous hydrodynamic equation

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - g^{\mu\nu} + \Delta T^{\mu\nu}$$

  – First order in gradient: acausality
  – Second order in gradient: which one is suitable for HIC?
    - Israel-Stewart, Ottinger and Grmela, AdS/CFT, Grad's 14-momentum expansion, Renormalization group

Numerical scheme

  – First order accuracy: large dissipation
  – Second order accuracy : numerical oscillation
    -> artificial viscosity, flux limiter
  – Heavy Ion Collisions: SHASTA, KT
    -> Godunov scheme: Riemann solver

Numerical Scheme

- Israel-Stewart Theory

Akamatsu, Inutsuka, CN, Takamoto, arXiv:1302.1665、J. Comp. Phys. (2014)34

1. Dissipative fluid equation

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \tau^{\mu\nu}$$
$$= T_{\rm ideal} + T_{\rm dissip}$$

Ideal part:

Riemann solver for QGP: Godunov method

Two shock approximation *Mignone, Plewa and Bodo, Astrophys. J. S160, 199 (2005)*

2. Relaxation equation

$$\hat{D}\Pi = \frac{1}{\tau_\Pi}(\Pi_{NS} - \Pi) - I_\Pi,$$

$$\hat{D}\pi^{\mu\nu} = \frac{1}{\tau_\pi}(\pi^{\mu\nu}_{NS} - \pi^{\mu\nu}) - I^{\mu\nu}_\pi,$$

$$\hat{D}q^\mu = \frac{1}{\tau_q}(q^\mu_{NS} - q^\mu) - I^\mu_q,$$

$$\hat{D} = u^\mu \partial_u$$

I: second order terms

$$\tau^{\mu\nu} = \Pi\Delta^{\mu\nu} + \pi^{\mu\nu}$$

→

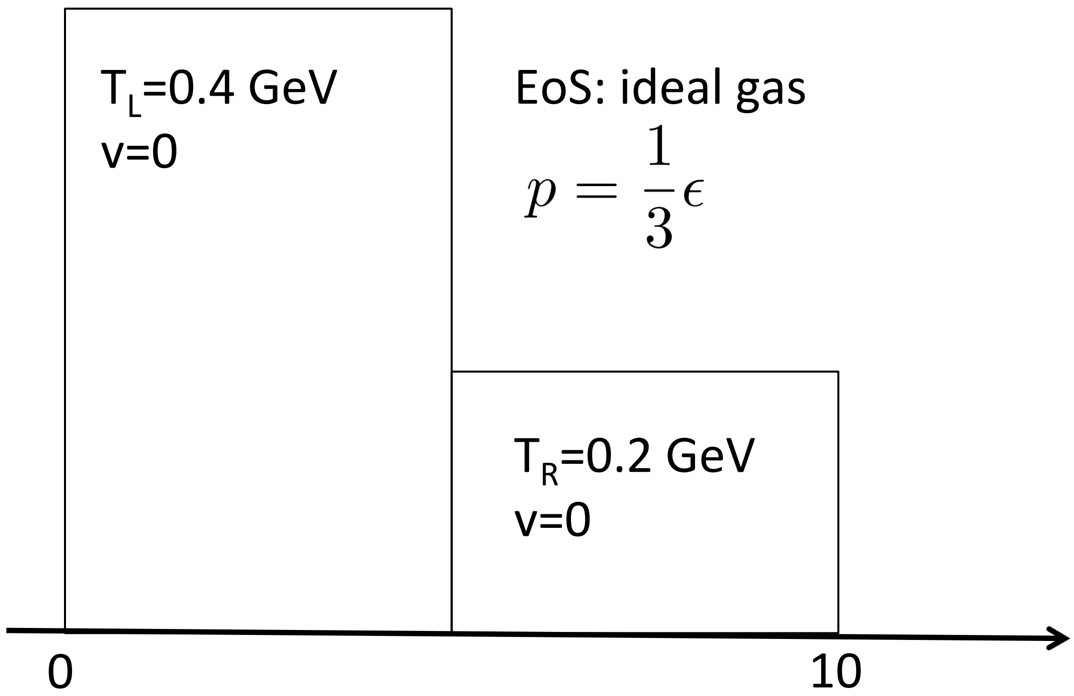
$$\left(\frac{\partial}{\partial t} + v^j \frac{\partial}{\partial x^j}\right)\Pi = -\frac{I_\Pi}{\gamma}, \quad + \quad \frac{\partial}{\partial t}\Pi = \frac{1}{\gamma\tau_\Pi}(\Pi_{NS} - \Pi),$$

advection + stiff equation

$$\Delta t < \tau_{\rm relax} << \tau_{\rm fluid}$$

Comparison

- Shock Tube Test : *Molnar, Niemi, Rischke*, Eur.Phys.J.C65,615(2010)

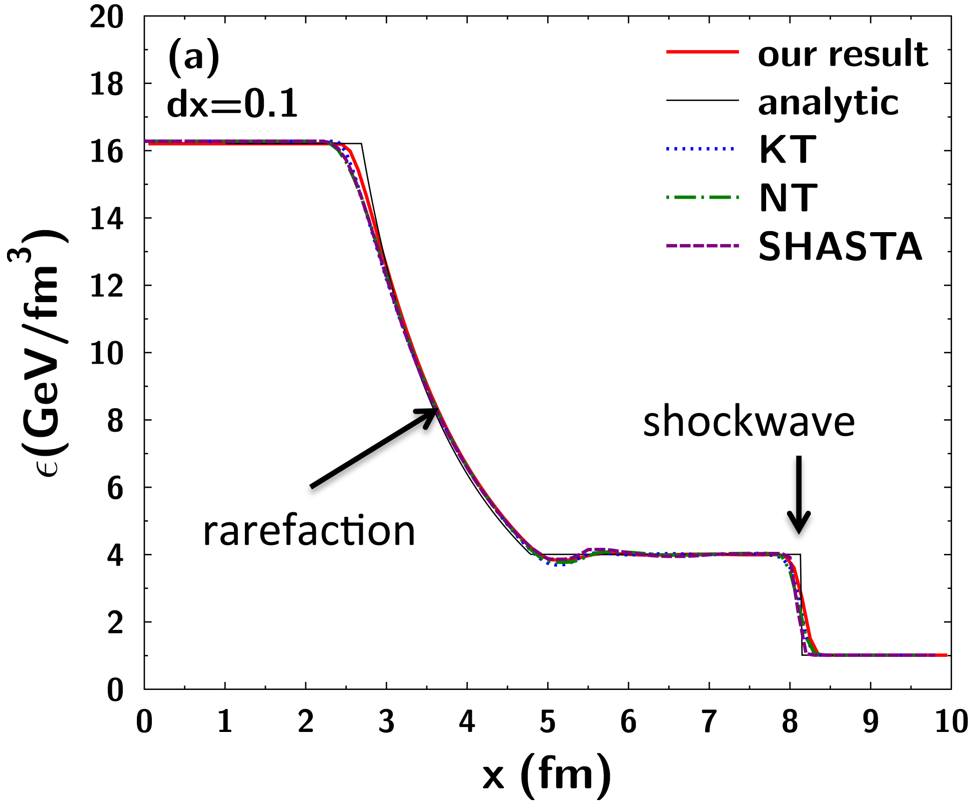


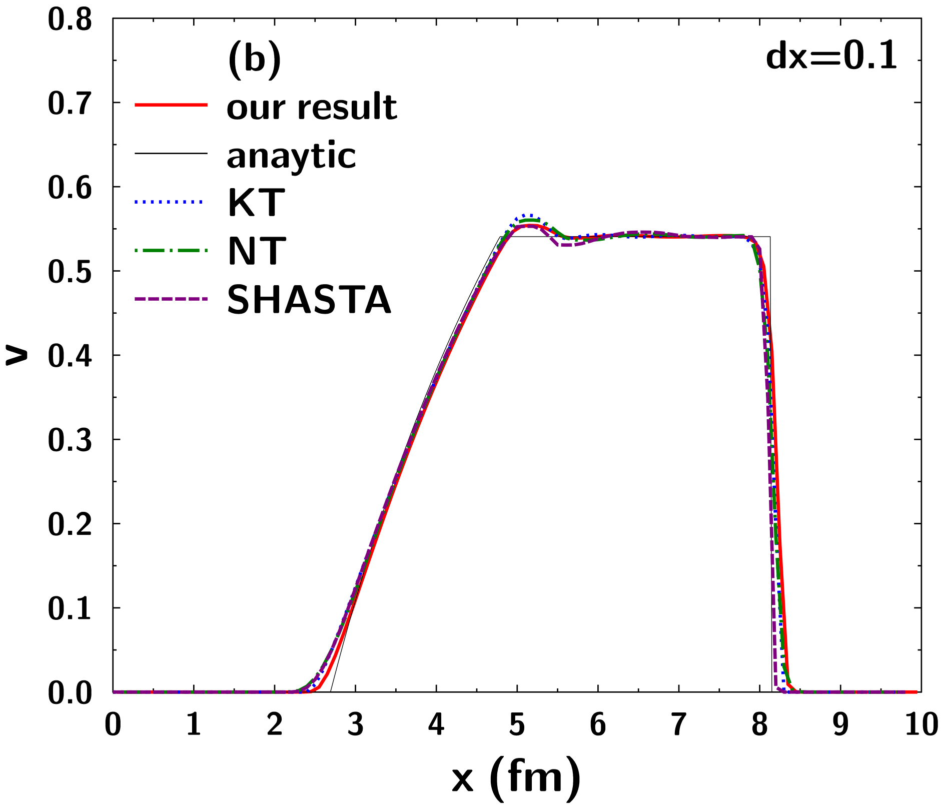
Nx=100, dx=0.1, dt=0.04

- Analytical solution
- Numerical schemes
  SHASTA, KT, NT
  Our scheme

Shocktube problem

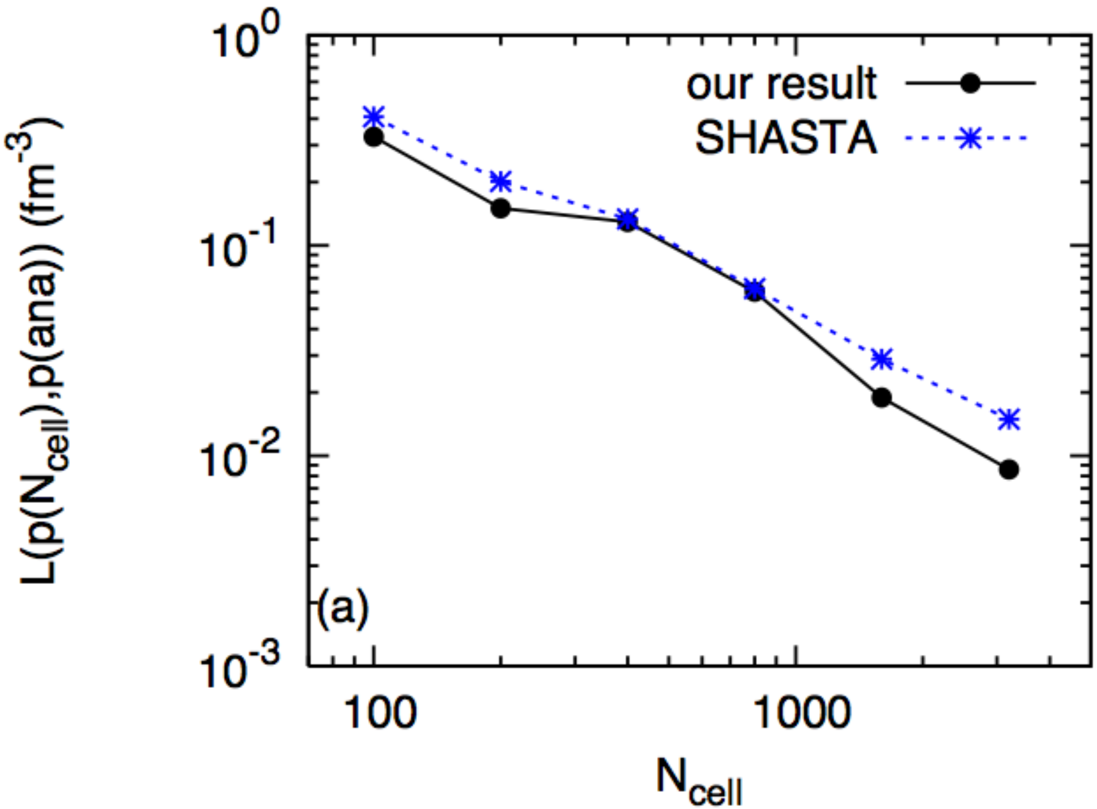
- Ideal case

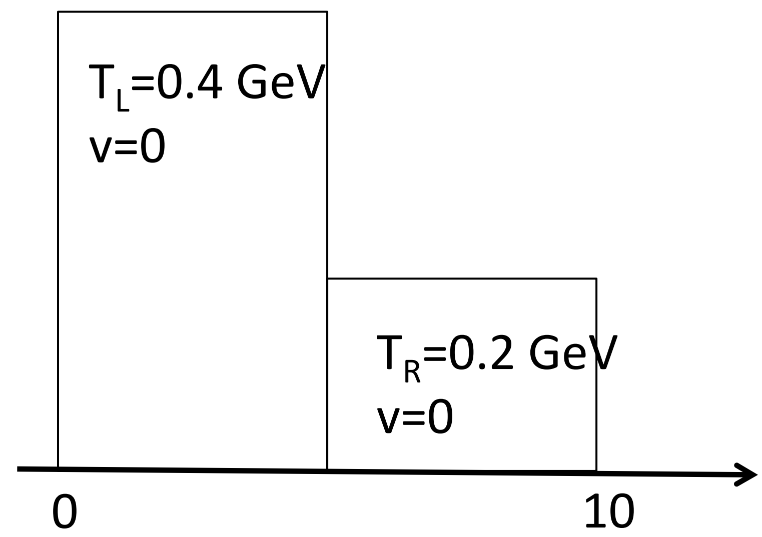




L1 Norm

- Numerical dissipation: deviation from analytical solution





For analysis of heavy ion collisions

N_{cell}=100: dx=0.1 fm

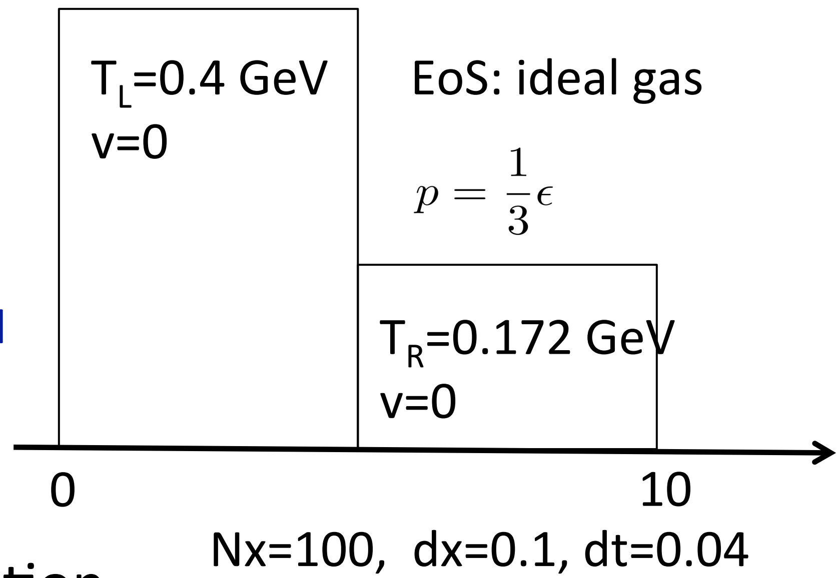
$$L(p(N_{\rm cell}), p({\rm anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p({\rm analytic})| \frac{\lambda}{N_{\rm cell}}$$

λ=10 fm

Large Δ*T* difference

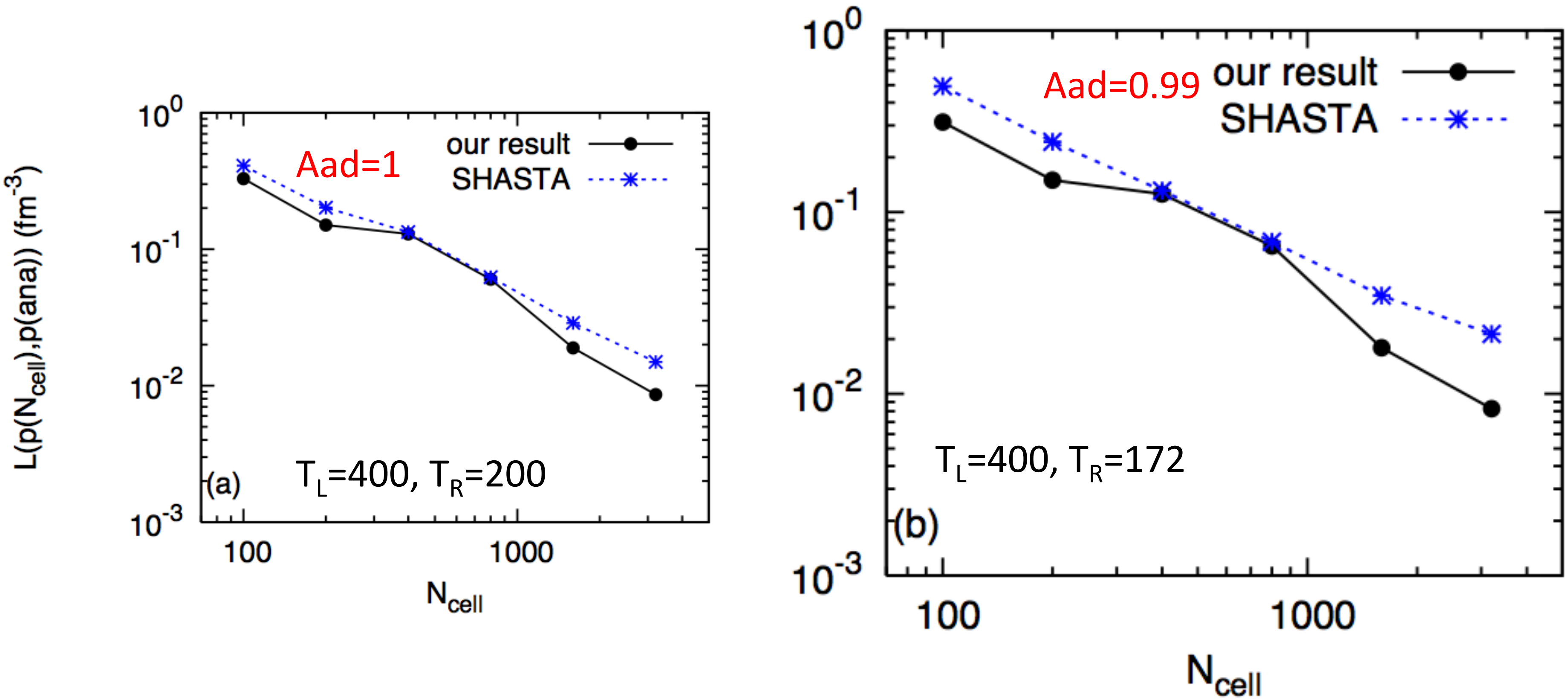
- T_L=0.4 GeV, T_R=0.172 GeV
  - SHASTA becomes unstable.
  - Our algorithm is stable.
- SHASTA: anti diffusion term, A_{ad}
  - A_{ad} = 1 : default value, unstable
  - A_{ad} =0.99: stable,

    more numerical dissipation



L1 norm

- SHASTA with small A_{ad} has large numerical dissipation



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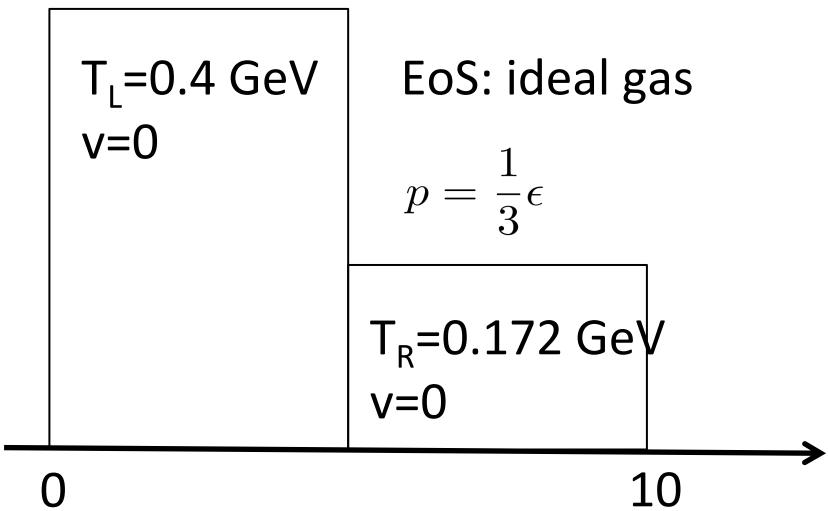
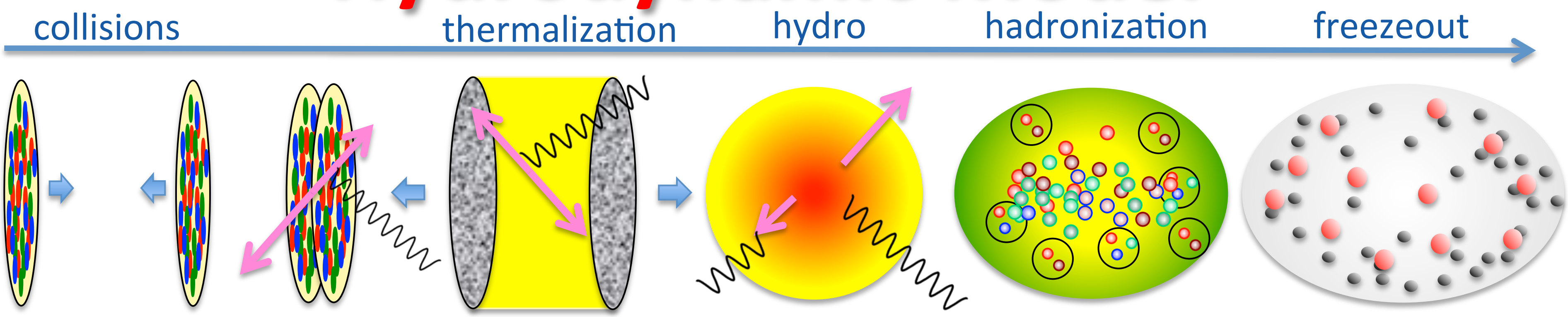


Nx=100, dx=0.1, dt=0.04

- Large fluctuation (ex initial conditions)
  - Our algorithm is stable even with small numerical dissipation.

Hydrodynamic Model



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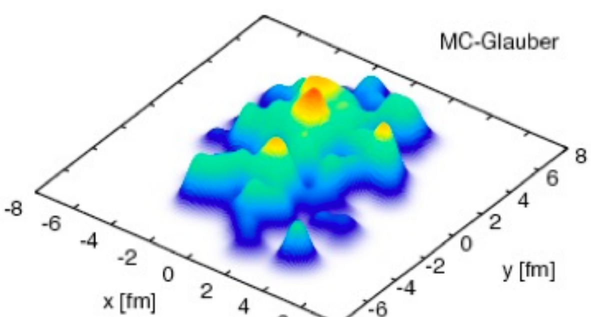


fluctuations

Equation of State
lattice QCD
transport coefficients

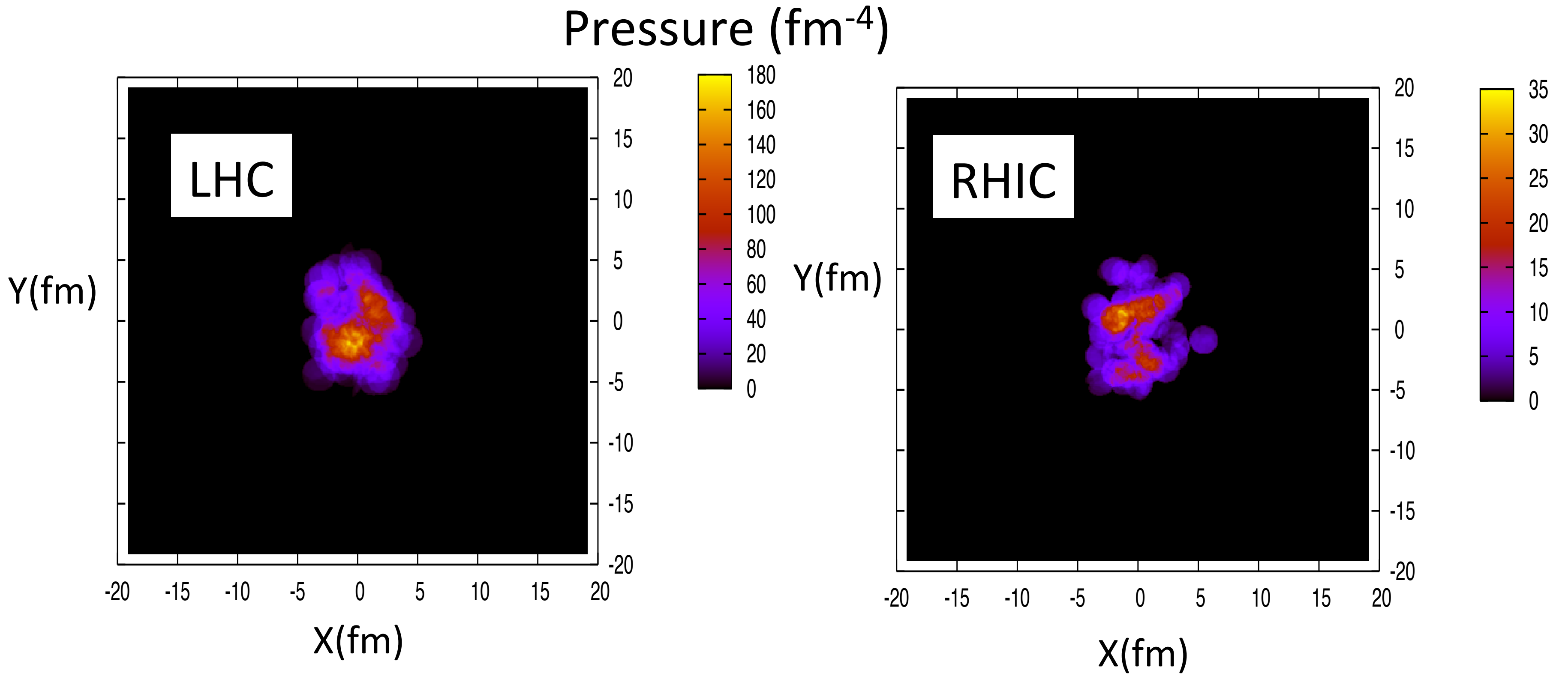
UrQMD

Relativistic viscous hydrodynamic
Shock wave

Initial Pressure Distribution

- MC-KLN (centrality 15-20%)

Nara: http://www.aiu.ac.jp/~ynara/mckln/

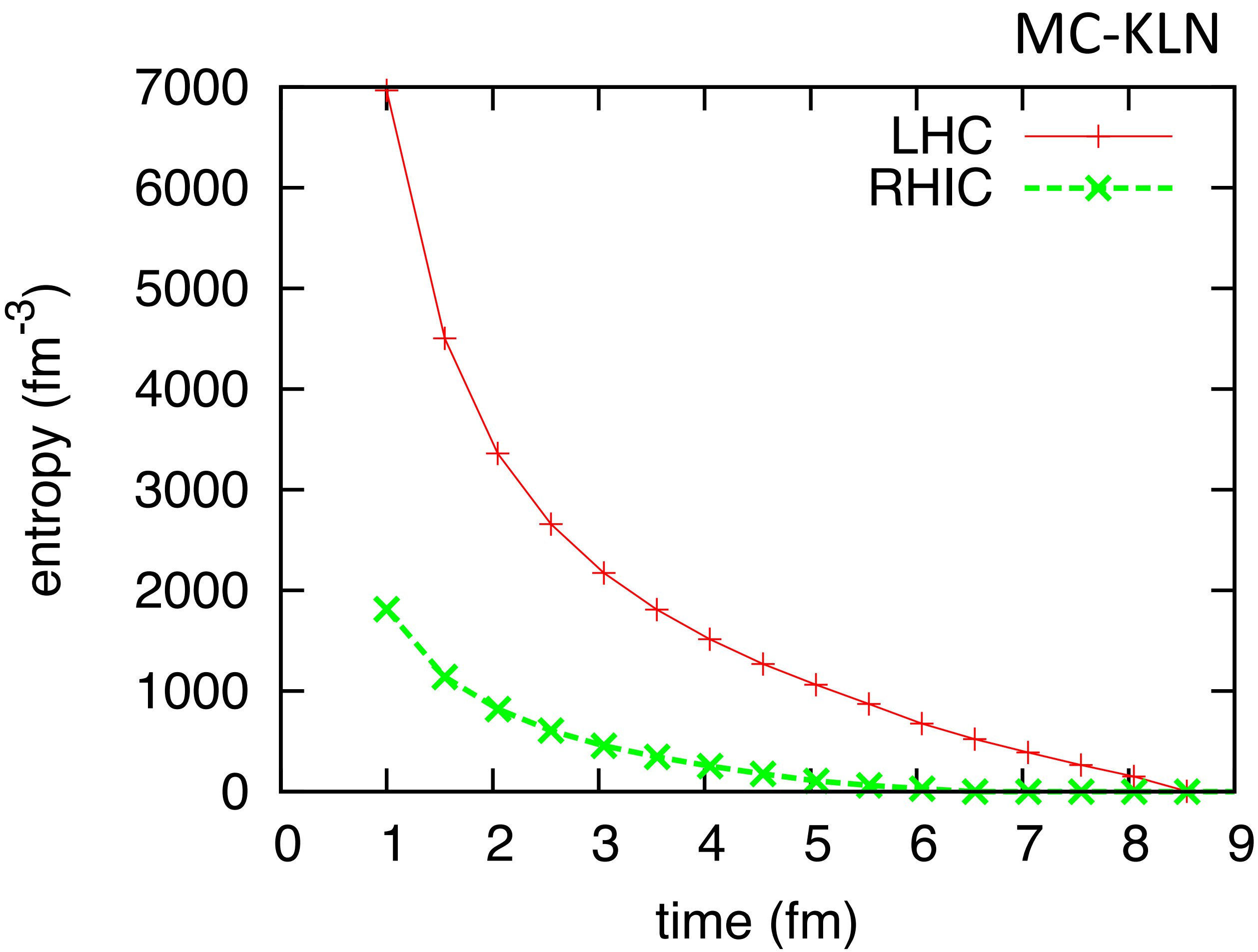


Simulation setups:

- Free gluon EoS
- Hydro in 2D boost invariant simulation

Time Evolution of Entropy

- Entropy of hydro ($T > T_{SW}$=155MeV)



Time Evolution of ε_n and v_n

- Eccentricity & Flow anisotropy

$$\varepsilon_n e^{in\Phi_n} = \langle z^n \rangle \Big/ \langle |z|^n \rangle, \quad z = x + iy$$

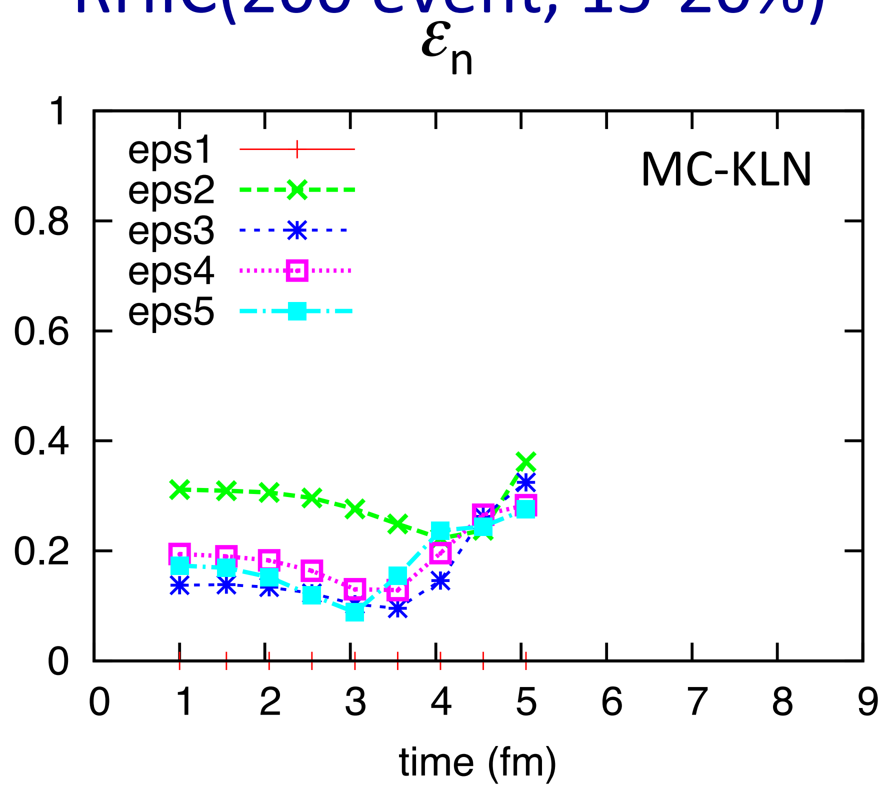
Shift the origin so that $\varepsilon_1=0$

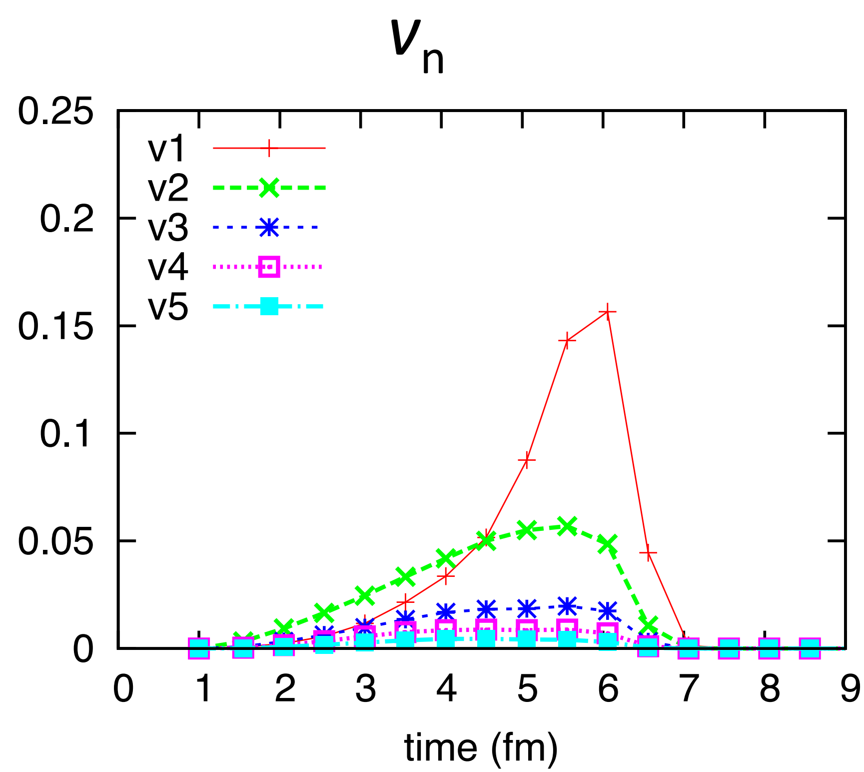
$$v_n e^{in\psi_n} = \langle v^n \rangle, \quad v = v_x + iv_y, \quad (0 \le \varepsilon_n, v_n \le 1)$$

$$\langle \cdots \rangle = \int_{T>T_f=155\mathrm{MeV}} d^2x \cdots S^0(x,y) \Big/ \int_{T>T_f=155\mathrm{MeV}} d^2x\, S^0(x,y)$$

ε_n & v_n at RHIC

- RHIC(200 event, 15-20%)





- $\varepsilon_2 > \varepsilon_3 \sim \varepsilon_4 \sim \varepsilon_5$,

- v_1: Bjorken's scaling solution
- $v_2 > v_3 \sim v_5$

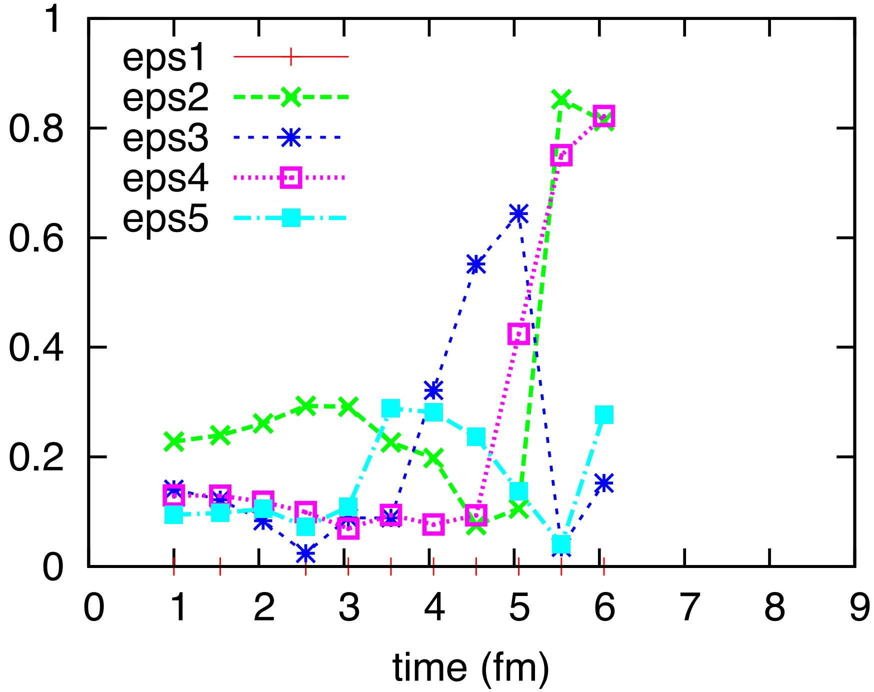
- $\varepsilon_n \to v_n$
- ε_3 has the minimum in time evolution.

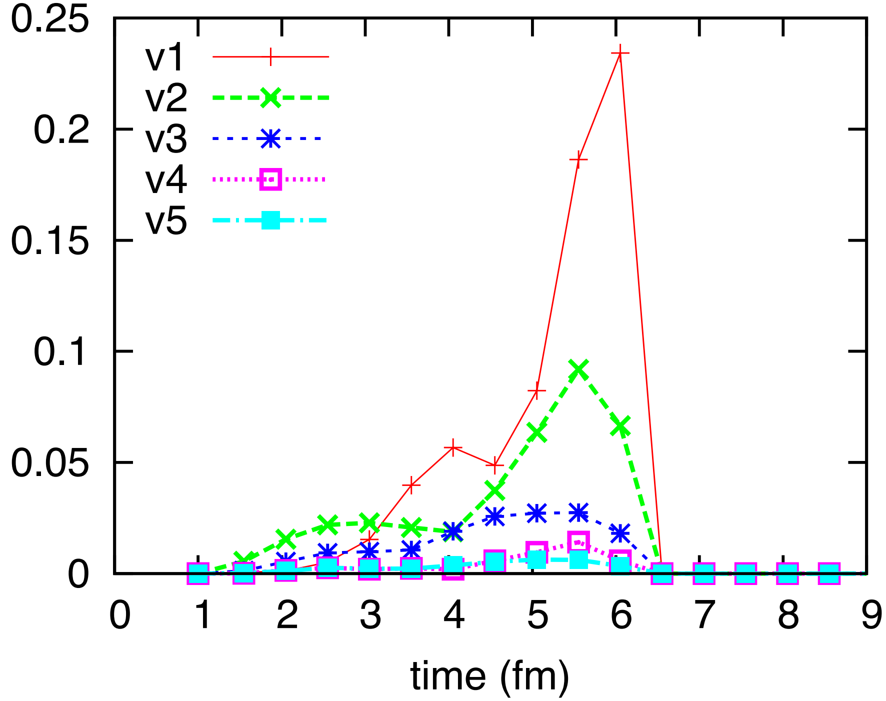
  -> The shape of initial ε_3 changes?

Eccentricities vs higher harmonics

- RHIC (one event, 15-20%)

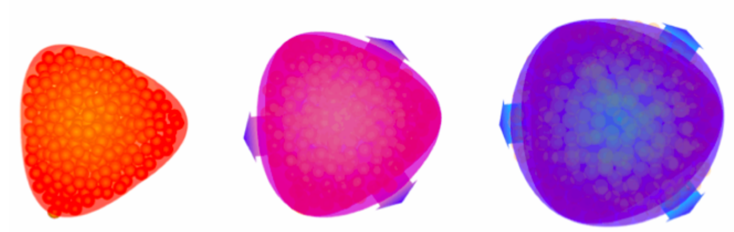
MC-KLN





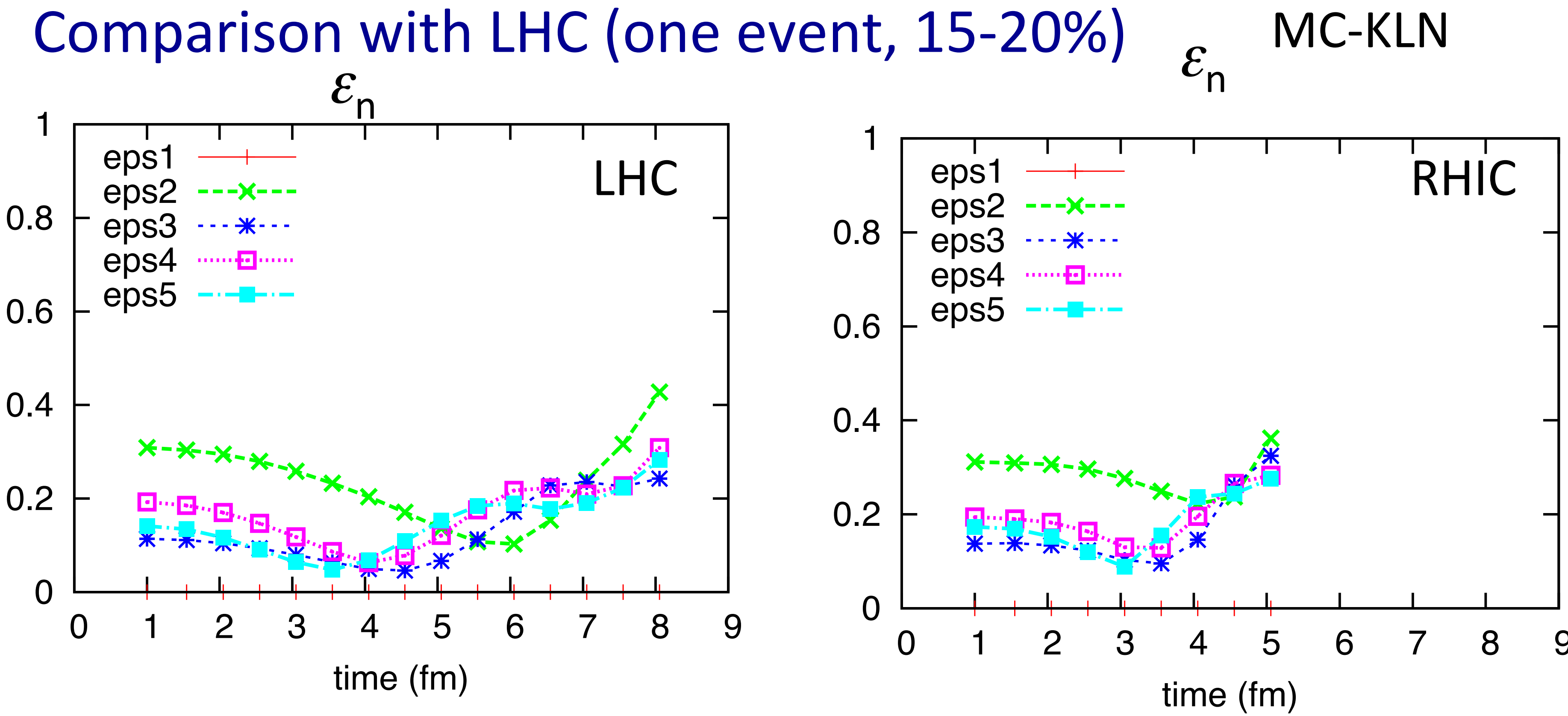
- ε_3 shows the sudden change

-> final ε_3 becomes small.



Eccentricities vs higher harmonics

- Comparison with LHC (one event, 15-20%)

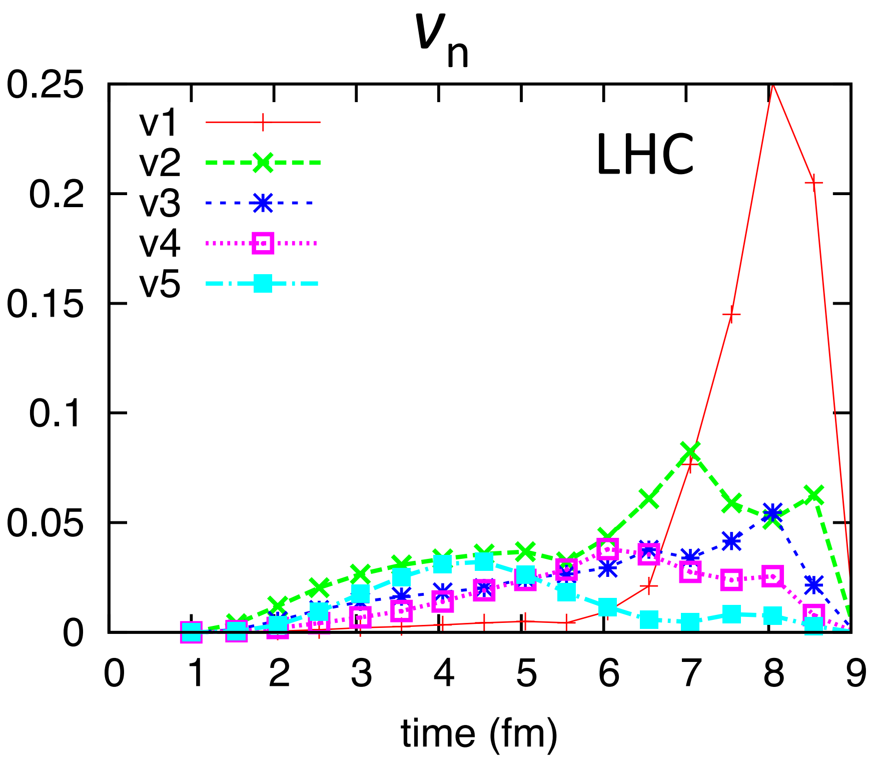


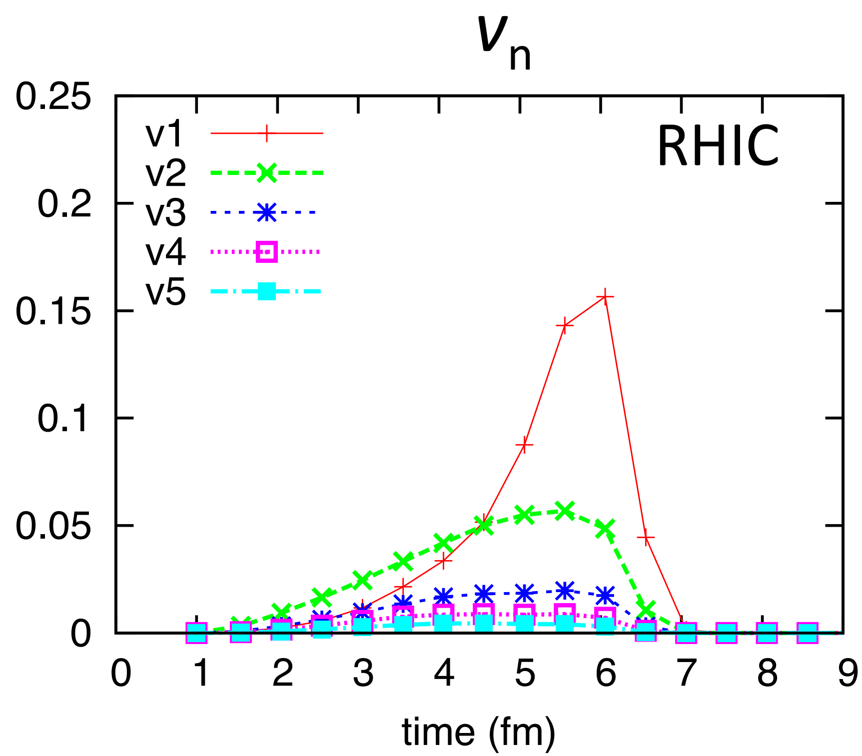
- Initial ε_n at LHC is almost same as that at RHIC.
- ε_3 has the minimum in time evolution.
- Life time of the fireball at LHC is larger than that at RHIC.
- Final ε_3 at LHC becomes small?

Eccentricities vs higher harmonics

- Comparison with LHC (one event, 15-20%)

MC-KLN





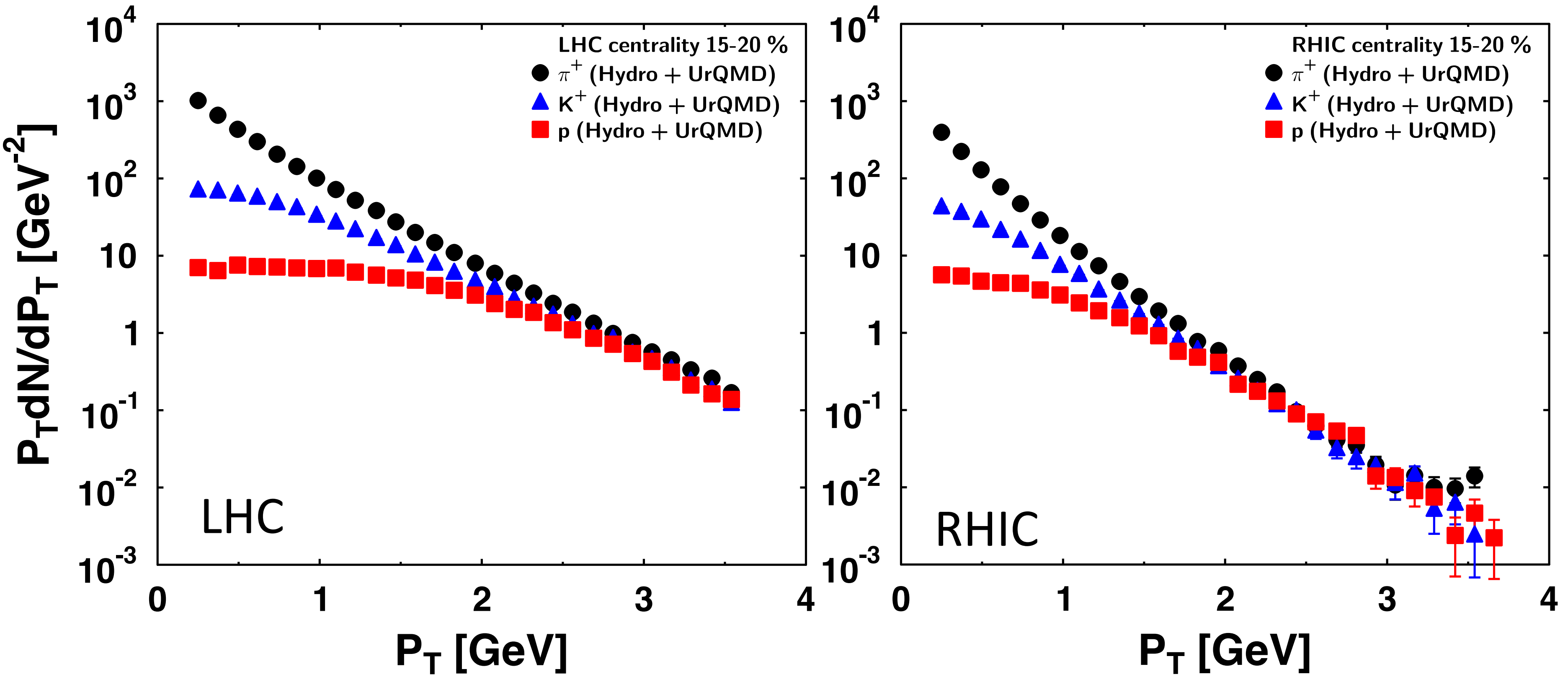
- v_1: Bjorken's scaling solution.
- v_2 is the largest flow in whole time evolution.
- v_5 at LHC grows up in the beginning of the time evolution

  v_5 -> v_2, v_3 ?

Hydro + UrQMD

- Transverse momentum spectrum

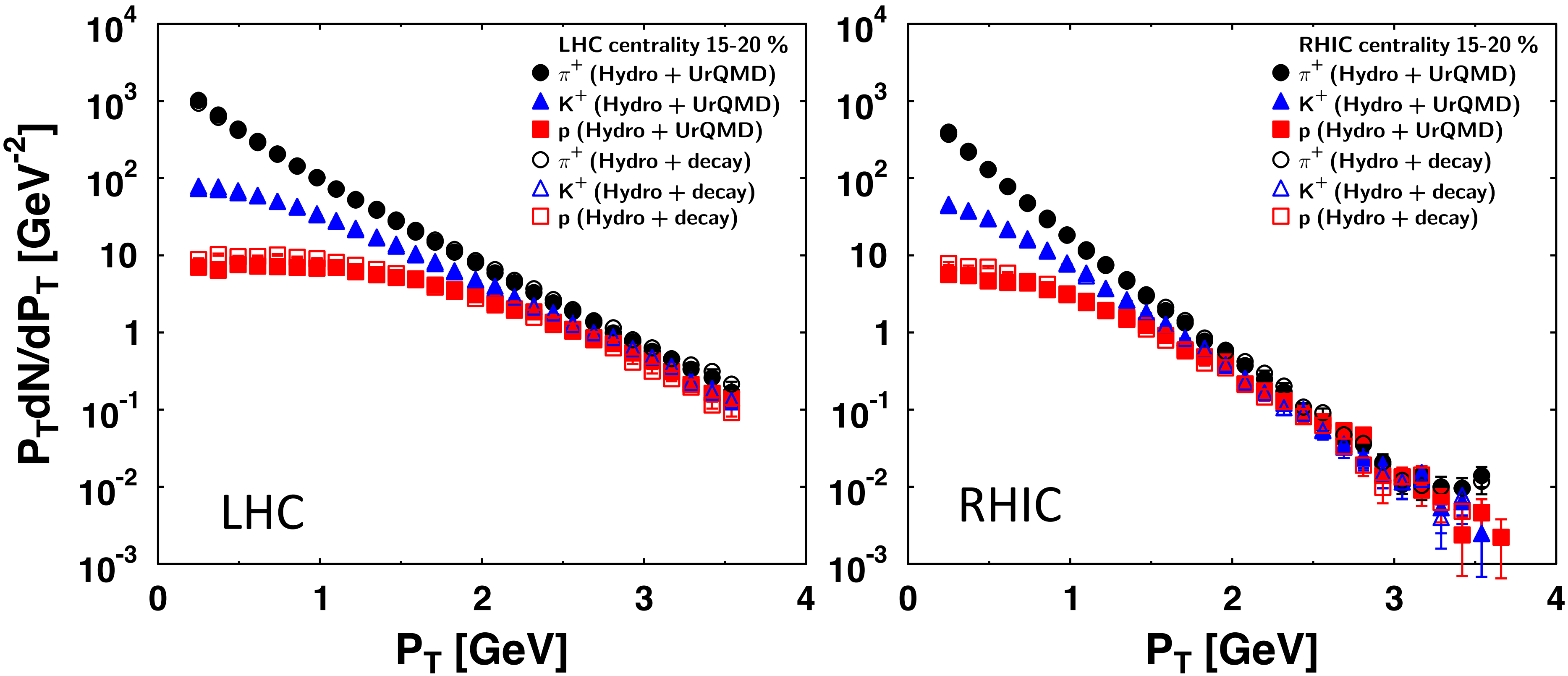
MC-KLN



- Slope of P_T spectra at LHC is flatter that at RHIC.

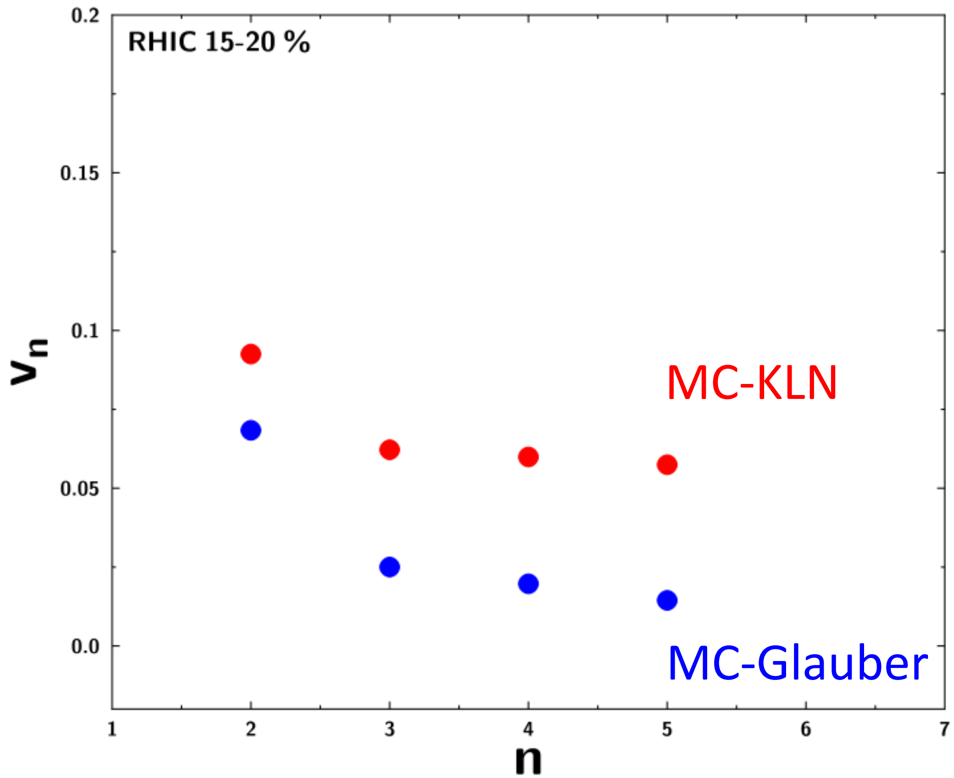
Effect of Hadronic Interaction

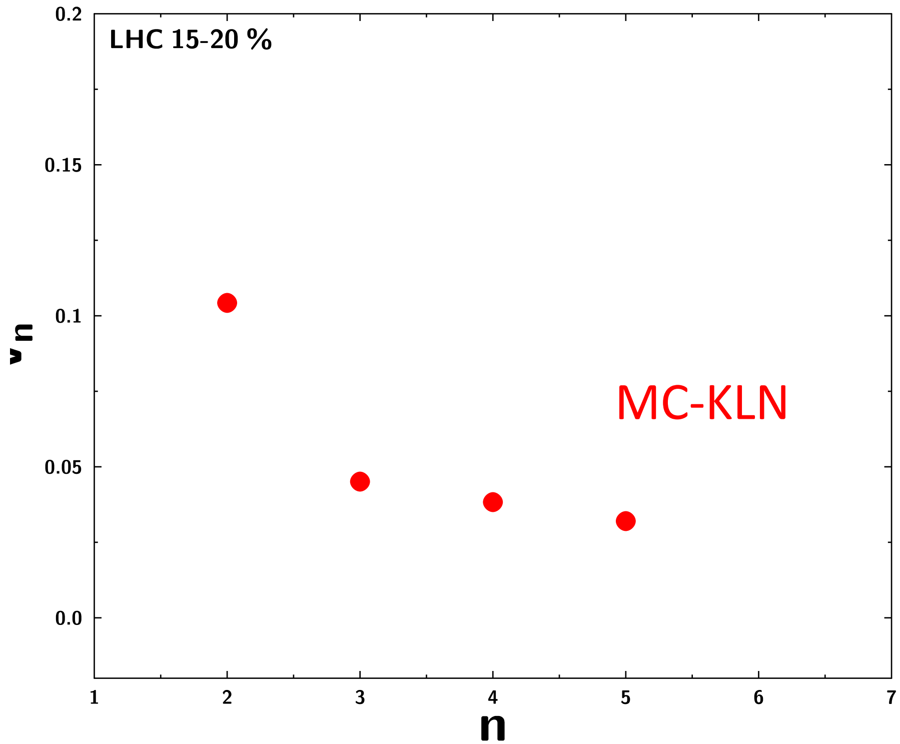
- Transverse momentum distribution



Higher harmonics from Hydro + UrQMD

- Effect of hadronic interaction





- v_n (MC-Glauber) < v_n (MC-KLN)
  $\varepsilon_{n,\ initial}$ (MC Glauber) < $\varepsilon_{n,initial}$(MC-KLN)

Summary

- We develop a state-of-the-art numerical scheme

Our algorithm
  - Less artificial diffusion: crucial for viscosity analyses
  - Stable for strong shock wave

- Construction of a hybrid model
  - Fluctuating initial conditions + Hydrodynamic evolution + UrQMD
- Higher Harmonics
  - Time evolution, hadron interaction
  - Initial conditions, QGP property