Higher Harmonics from causal hydrodynamic fluctuation

2014/8/6, ATHIC 2014, Osaka

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Outline

1. Introduction:
   hydrodynamic fluctuation
2. Causal hydrodynamic fluctuation
3. Numerical model
4. Numerical results

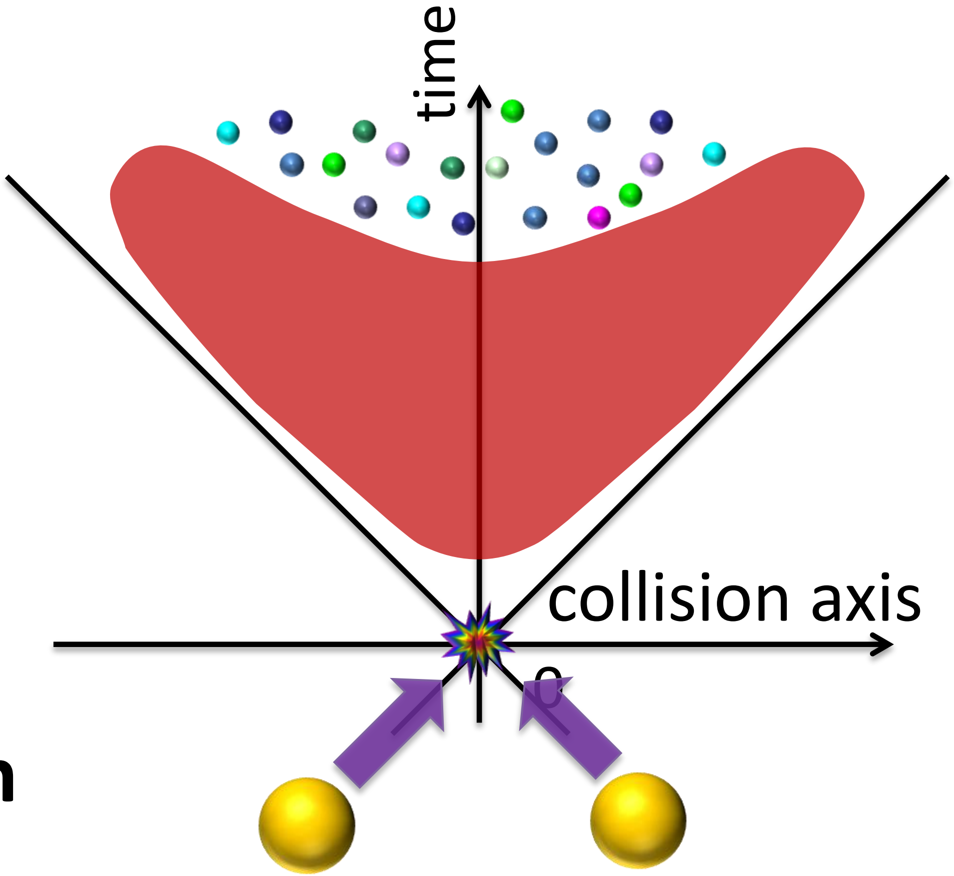
Introduction

Fluctuations in heavy-ion collisions

- **Final observables**
  - flow harmonics v_n, etc.

Response of Matter

EoS, η, ζ, τ_R, λ, …

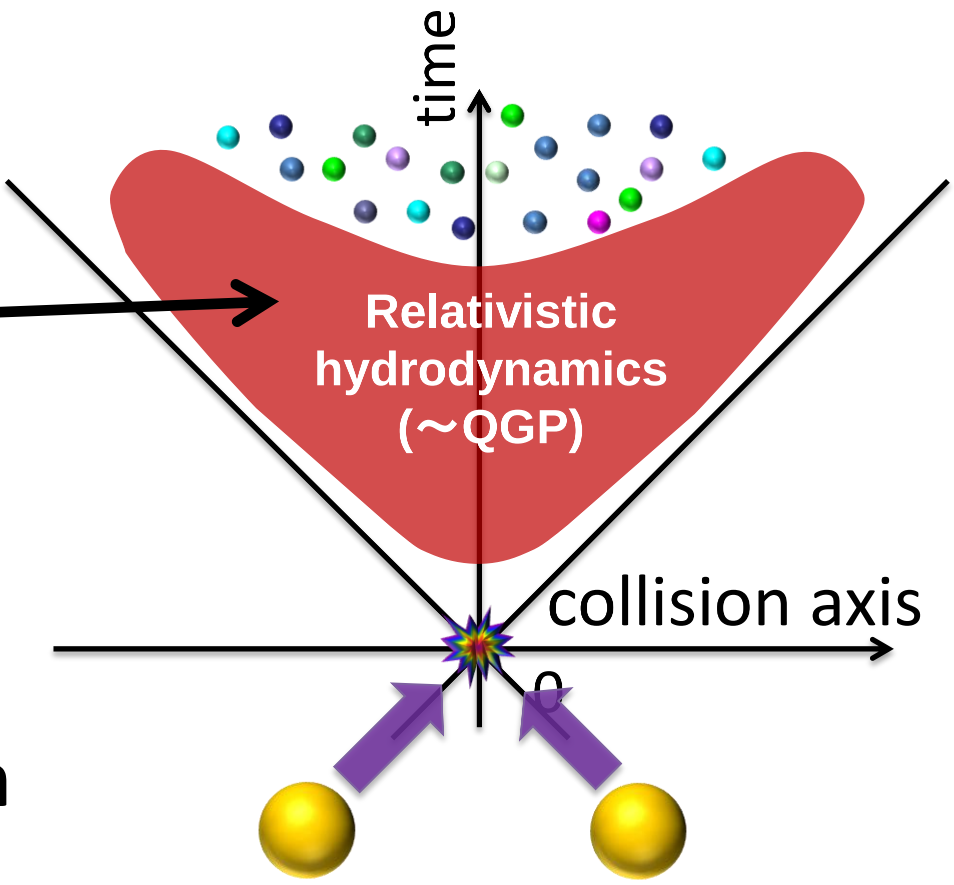


- **Initial-state fluctuation**
  - nucleon distribution
  - quantum fluctuation

Fluctuations in heavy-ion collisions

- **Final observables**
  - – flow harmonics v_n, etc.

Other fluctuations
+ **hydro fluctuation**
+ jets/mini-jets
+ critical phenomena
+ …



- **Initial state fluctuation**
  - – nucleon distribution
  - – quantum fluctuation

Hydrodynamic fluctuation

HF = *Thermal fluctuation of dissipative currents*

e.g. $$\pi^{\mu\nu} = 2\eta\partial^{\langle\mu}u^{\nu\rangle} + \delta\pi^{\mu\nu},$$

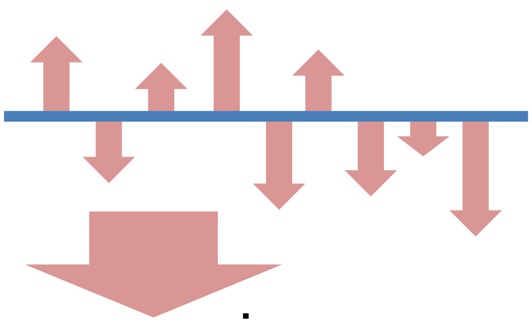
HF

ensemble/event averaged

Balance

thermal fluctuation

at each spacetime *x*



decrease anisotropy

FDR

Fluctuation-Dissipation Relation

$$\langle\delta\pi^{ij}\delta\pi^{ij}\rangle \sim 4T\eta/V$$

V: 3+1 dim. volume

increase anisotropy

HF is important in e-by-e description of HIC

Causal hydrodynamic fluctuation

Causal hydrodynamic fluctuation

In causal theory (2nd-/higher-order dissipative hydro.)

Integral form of constitutive equation (CE)

$$\Gamma = \int d^4x' G(x-x') \underline{\kappa F(x')} \quad \underline{+\delta\Gamma}$$

thermodynamic force — HF

Differential form of CE

$$\underline{\mathscr{L}} \Gamma = \kappa F \quad \underline{+\xi}$$

Linear operator operating on Γ — **noise**

$$\xi = \mathscr{L}\delta\Gamma$$

e.g. $\mathscr{L} = 1 + \tau_\Pi D$

$$\tau_\Pi D\Pi + \Pi = -\zeta\theta,$$

FDR of noise in causal theory

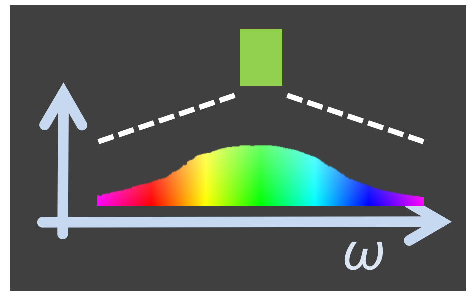
KM, T. Hirano [arXiv:1304.3243]

$\delta\Gamma$: Noise in Integral form of CE

$$\langle \delta\Gamma(x)\delta\Gamma(0)\rangle = \kappa T[G(x)+G(-x)]$$

||

FDR

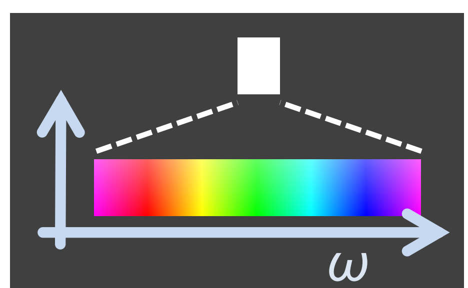


$\delta\Gamma$: always colored noise

$\xi = L\delta\Gamma$: Noise in Differential form of CE

- **FDR**
- **G: relaxing**
- **G: retarded**
- **G: causal**

$$\langle \xi(x)\xi(x')\rangle = 2T\kappa\delta^{(4)}(x-x')$$



ξ: always white noise

Numerical simulation: Model

An Integrated Dynamical Model

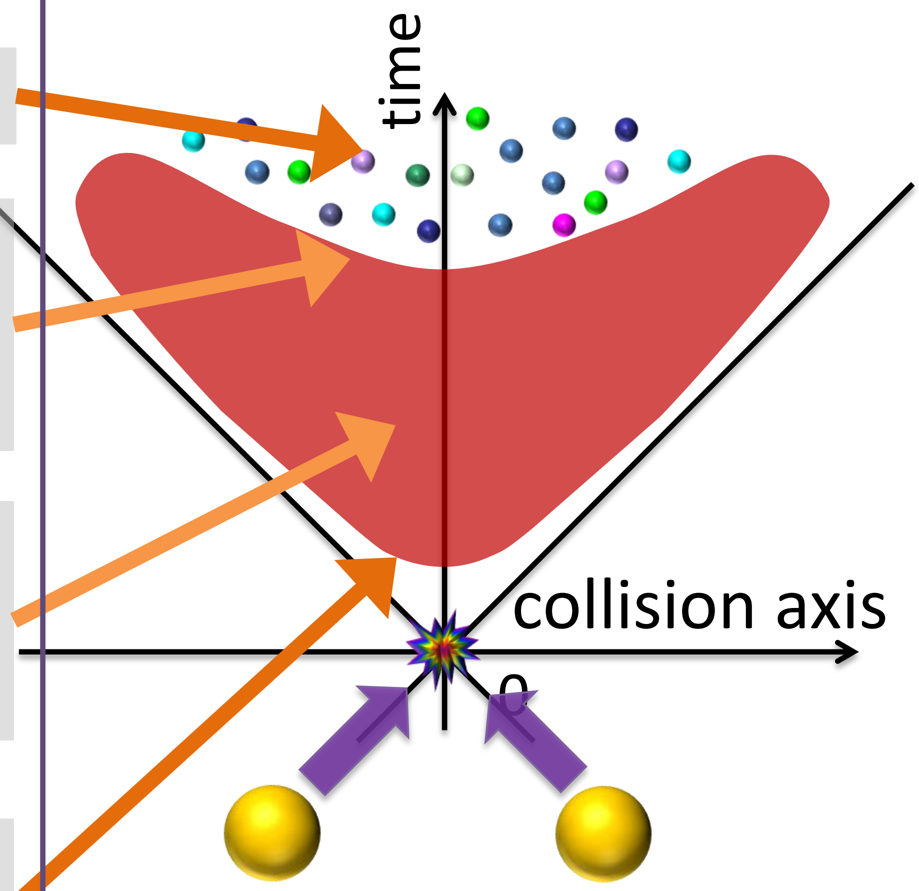
5. **Analysis** of hadron distribution

4. **Hadron cascade** (JAM)

3. **Particlization** at T_{sw} = 155 MeV
   Cooper-Frye formula
   Note: no viscous distortion

2. **(3+1)-dim. Relativistic Fluctuating Hydrodynamics**
   EoS: lattice QCD&HRG, $\eta/s = 1/4\pi$

1. **Initial condition**
   Smoothed MC-KLN



Updates of T. Hirano, P. Huovinen, KM, Y. Nara, PPNP **70**, 108 (2012) [arXiv:1204.5814]

Setup: Initial state & Hydro.

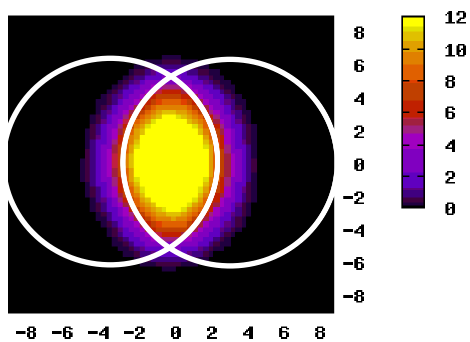
- **Initial condition**

  Au+Au, $\sqrt{s_{NN}}$ = 200 GeV

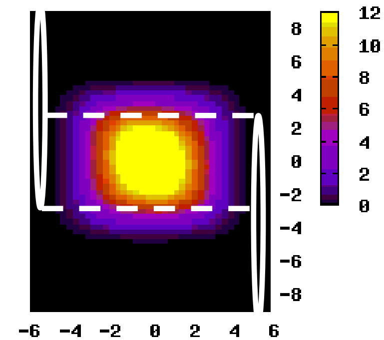
  b = 6.45 fm (～Centrality 20%)

  Smoothed MC-KLN (CGC)

***x*-*y* plane**



***η_s*-*x* plane**



- **(3+1)-dim Relativistic Fluctuating Hydrodynamics:**

  with a new conservative scheme

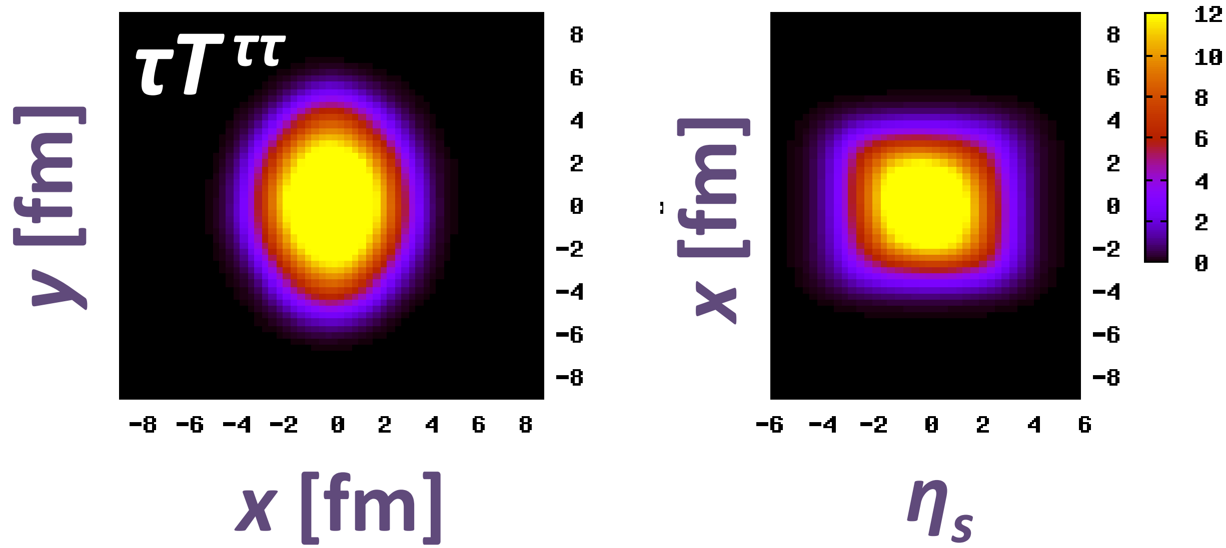
  a. **without fluctuation** →1 hydro + 10k cascades

  b. **with fluctuation** →10k hydro&cascades

Hydrodynamic simulation

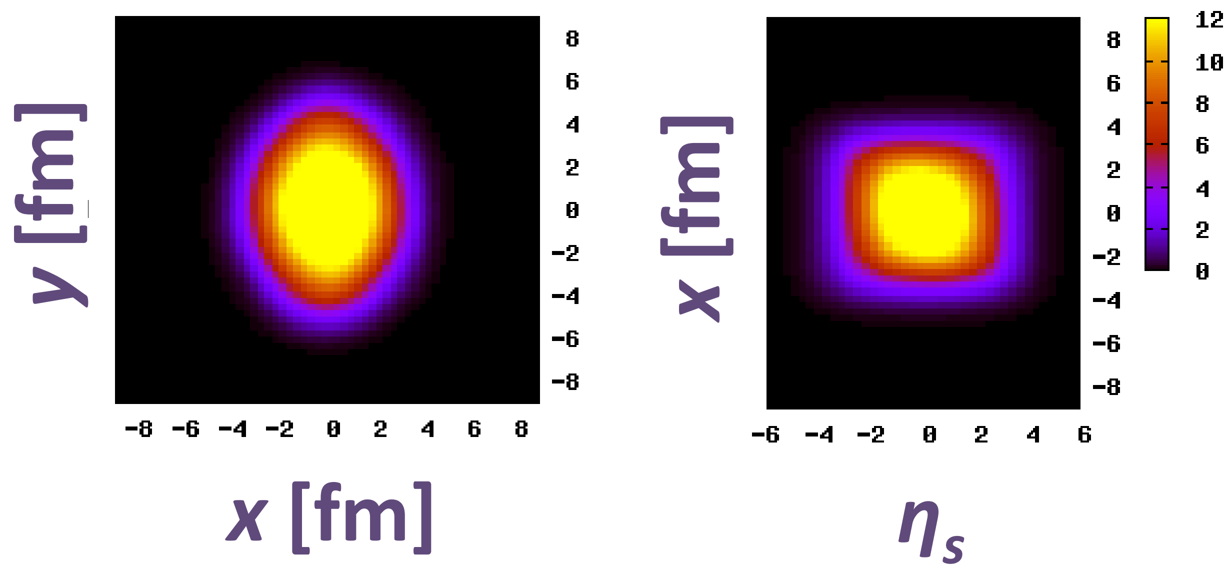
without HF

conventional
2nd-order
viscous hydro



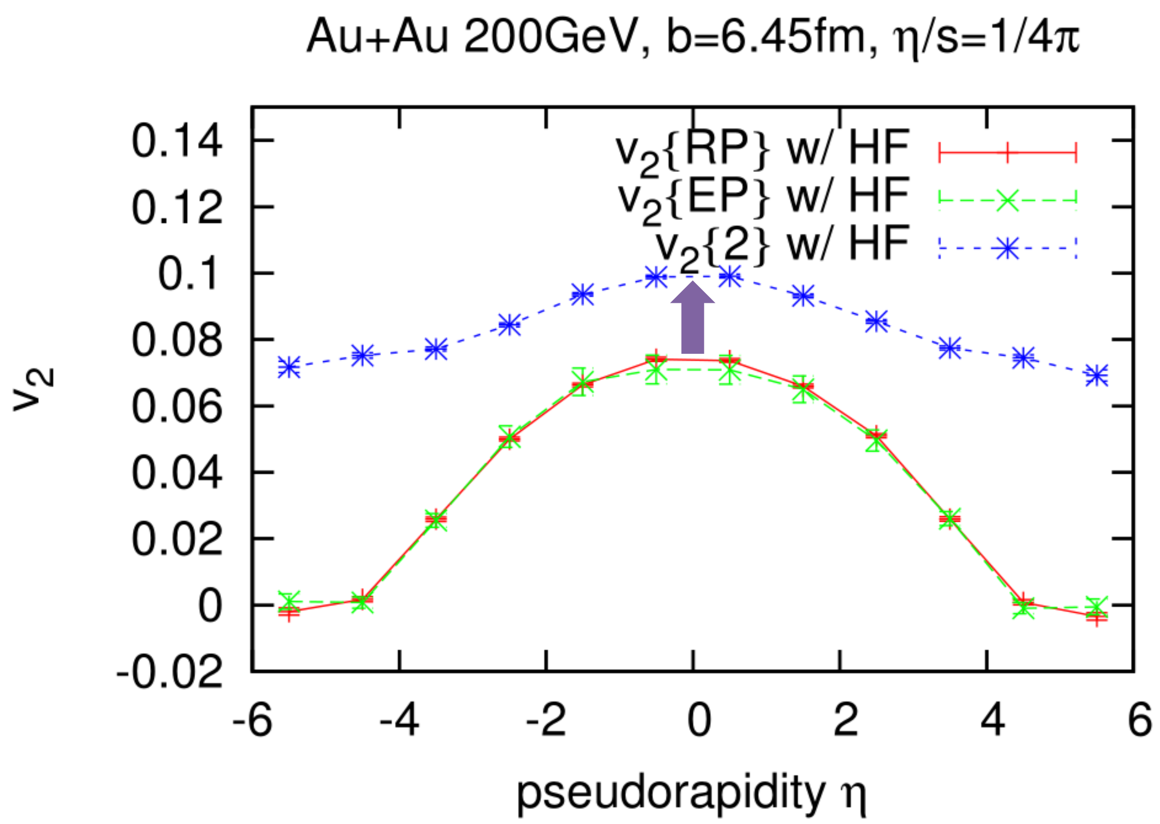
with HF

2nd-order
fluctuating hydro



Numerical simulation: Results

Elliptic flow vs η



EP: η-sub

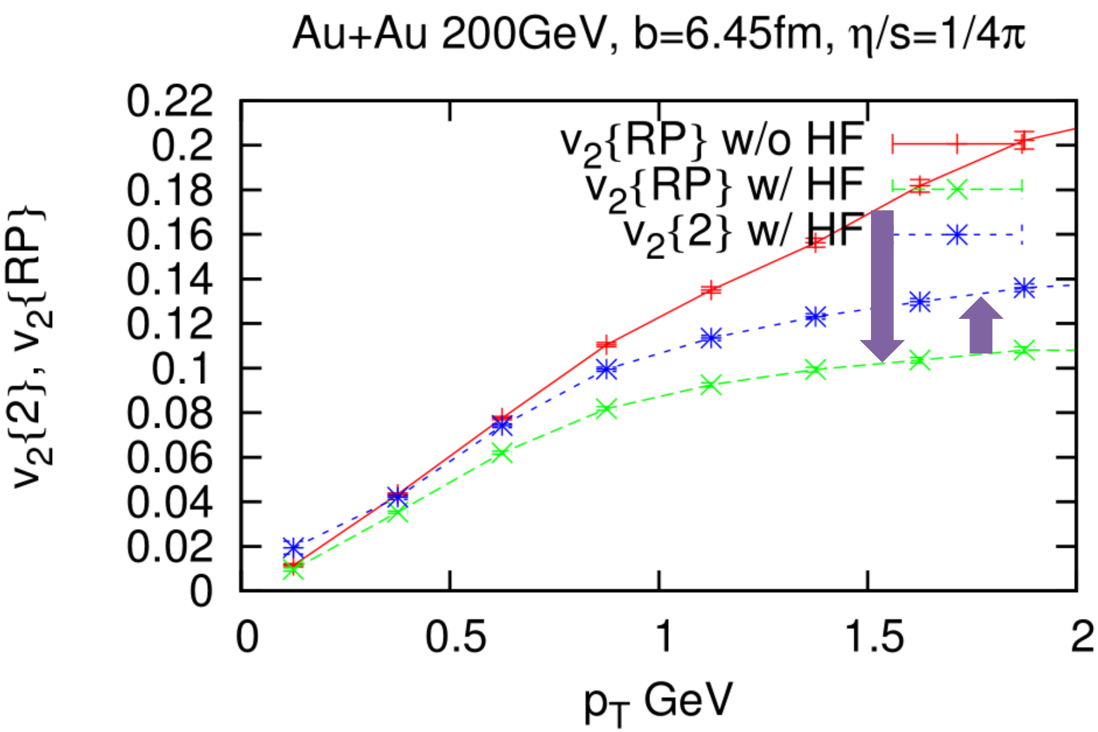
$2.05<|\eta|<3.2$

$v_2\{RP\} \sim \langle v_2 \rangle$

$v_2\{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma^2}$

- $v_2\{RP\} = v_2\{EP\}$: **EP_2** (defined in η-sub) **not changed by HF**
  ← HF in forward/backward are independent
- Considerable amount of v_n fluctuation σ_n

Elliptic flow vs p_T

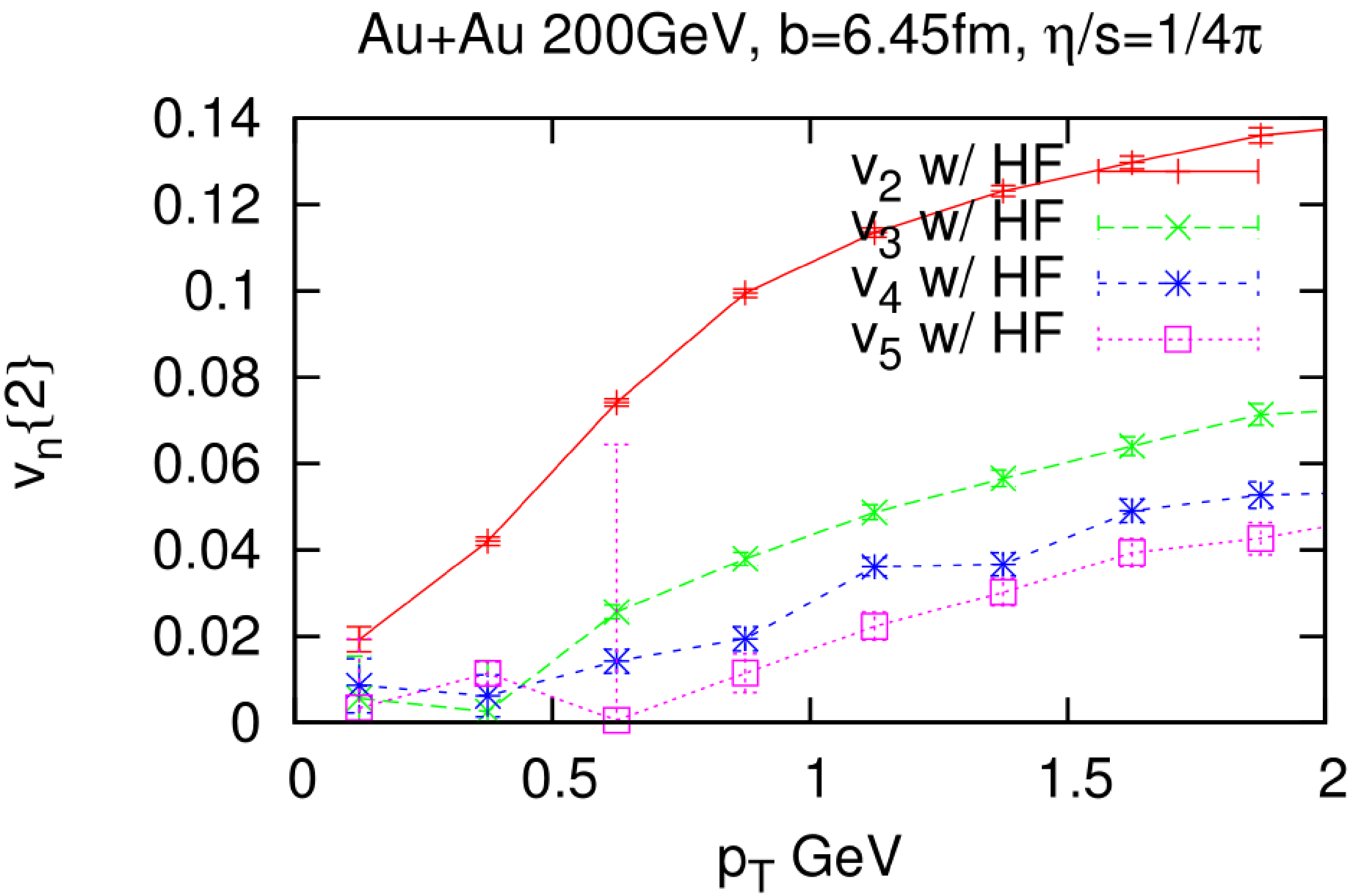


$v_2\{RP\} \sim \langle v_2 \rangle$

$v_2\{2\} = \sqrt{\langle v_2 \rangle^2 + \sigma^2}$

- Note: no viscous correction in Cooper-Frye formula
- Change of $v_2\{RP\}$ ← non-linear hydro. evolution?
- Suppression in higher p_T

Higher harmonic flow vs p_T



- $v_{odd}\{2\}$:
  finite value even without initial-state fluctuation

Summary

- ***Hydrodynamic fluctuation***, thermal fluctuation of hydrodynamics, ***has effects on flow harmonics***
  - event planes are not changed by HF
  - finite v_{odd} even without IS fluctuation
  - decrease of v_2 in higher pt region
- Outlook
  - results with IS fluctuations (jobs are running)
  - viscous correction in CF formula
  - compare results with experiments