Effects of event-by-event *hydrodynamic fluctuations* in an integrated dynamical model

2015/7/27,
Second conference on heavy ion collisions in the LHC era and beyond,
Vietnam

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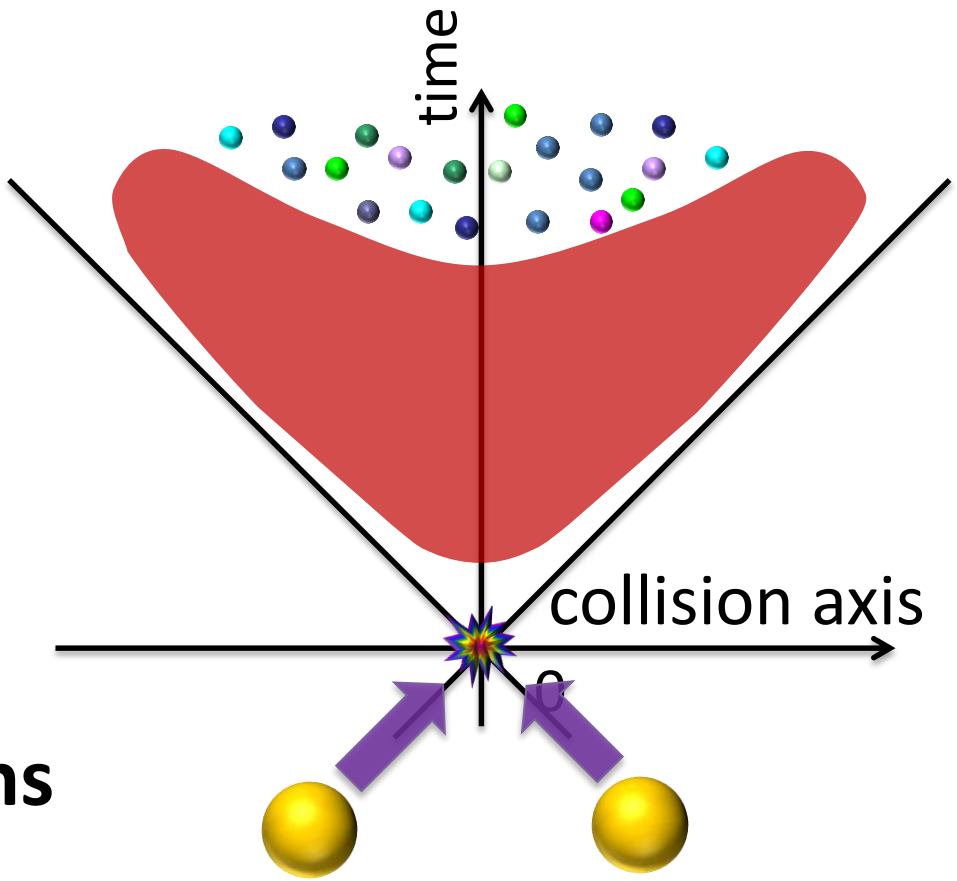
Fluctuations in heavy-ion collisions

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

Response of Matter

EoS, η, ζ, τ_R, λ, …

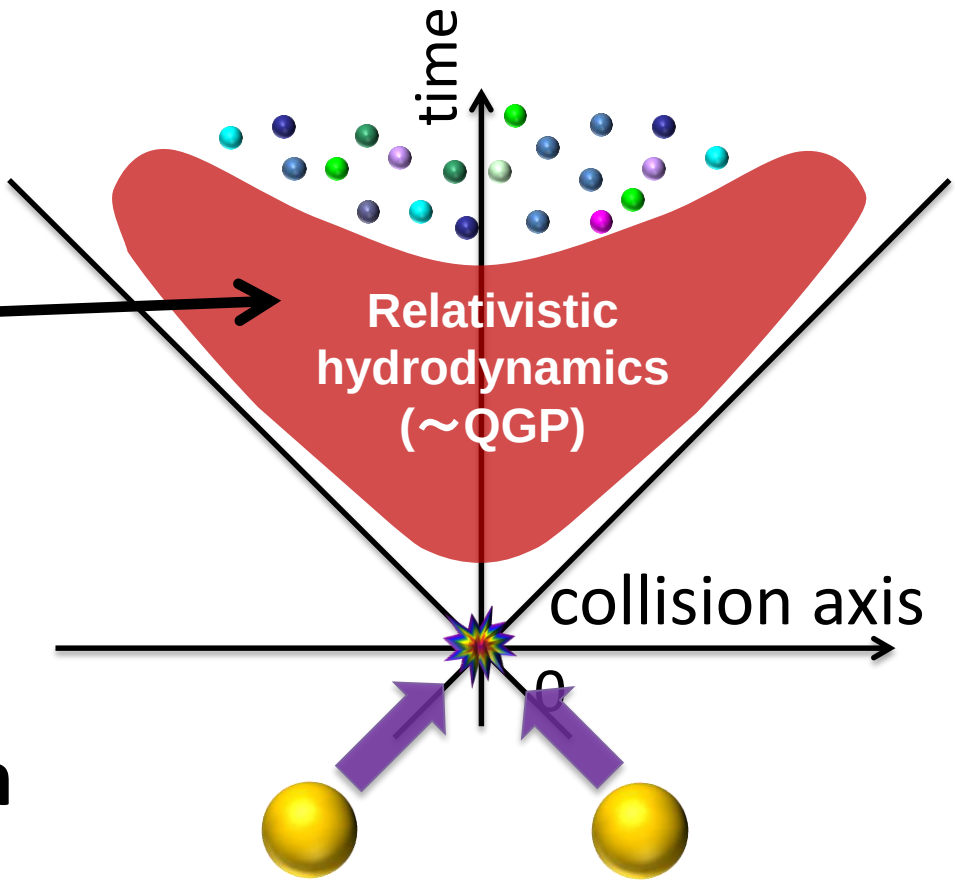


- **Initial-state fluctuations**
  - nucleon distribution
  - quantum fluctuations

Fluctuations in heavy-ion collisions

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

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



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

Hydrodynamic Fluctuations

HF = *Thermal fluctuations 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

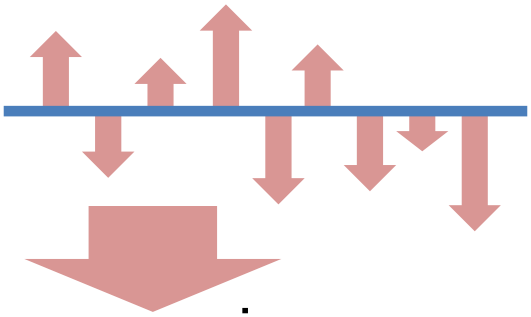
thermal fluctuations at each spacetime *x*

FDR

Fluctuation-Dissipation Relation

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

V: 3+1 dim. volume



decrease anisotropy

increase anisotropy

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

Integrated dynamical model

Integrated Dynamical Model

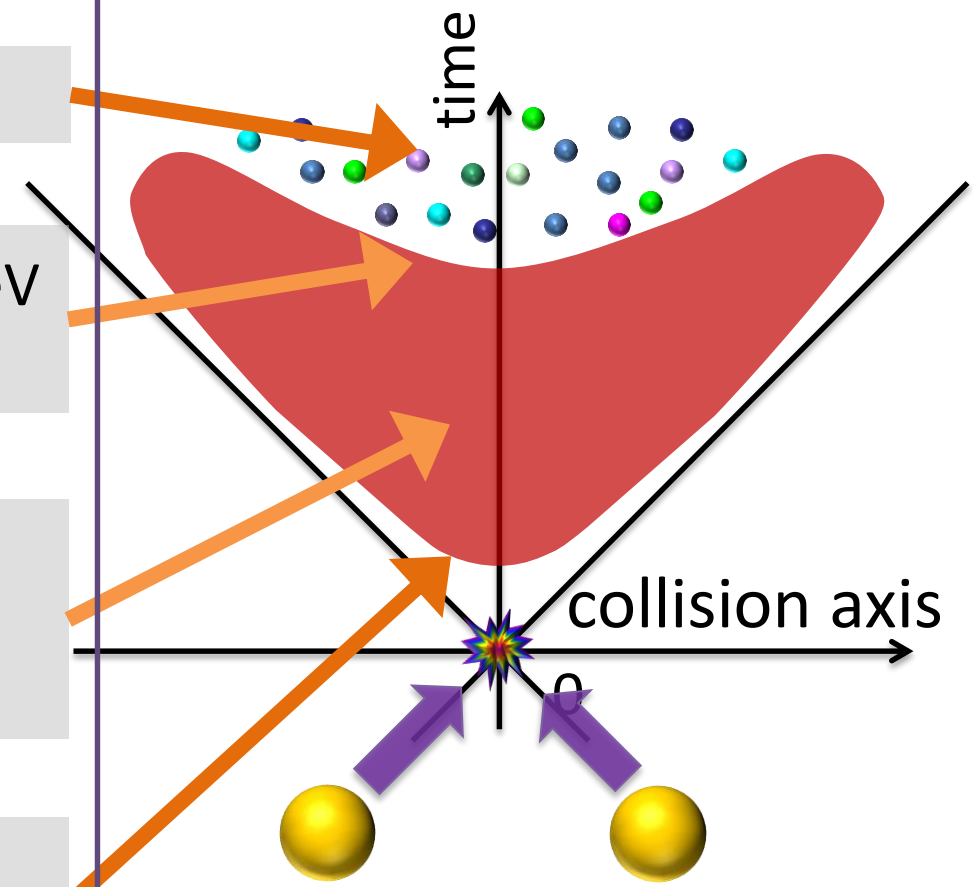
5. **Analysis** of hadron distribution

4. **Hadronic cascades** (JAM)

3. **Particlization** at T_{sw} = 155 MeV
   Cooper-Frye formula: $f + \delta f$

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

1. **Initial condition**
   MC-KLN

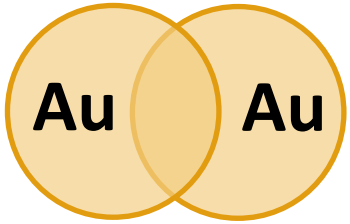


Updates of T. Hirano, P. Huovinen, KM, Y. Nara, PPNP **70**, 108 (2012) [arXiv:1204.5814]

Two types of calculations

Collision system

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



Setup A: HF Only

→ Qualitative behavior of the effects

Setup B: Both of Initial-state fluctuations and HF

→ Comparison between the effects of each fluctuations

Setup A:
HF only

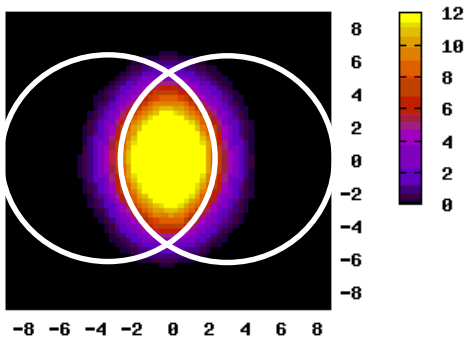
Setup A: HF only

- **Initial condition**

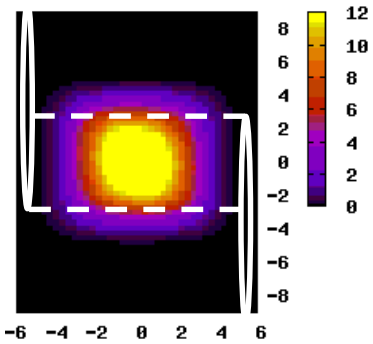
  b = 6.45 fm (～Centrality 20%)

  Averaged MC-KLN (CGC)

***x-y* plane**



***η*$_s$-*x* plane**



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

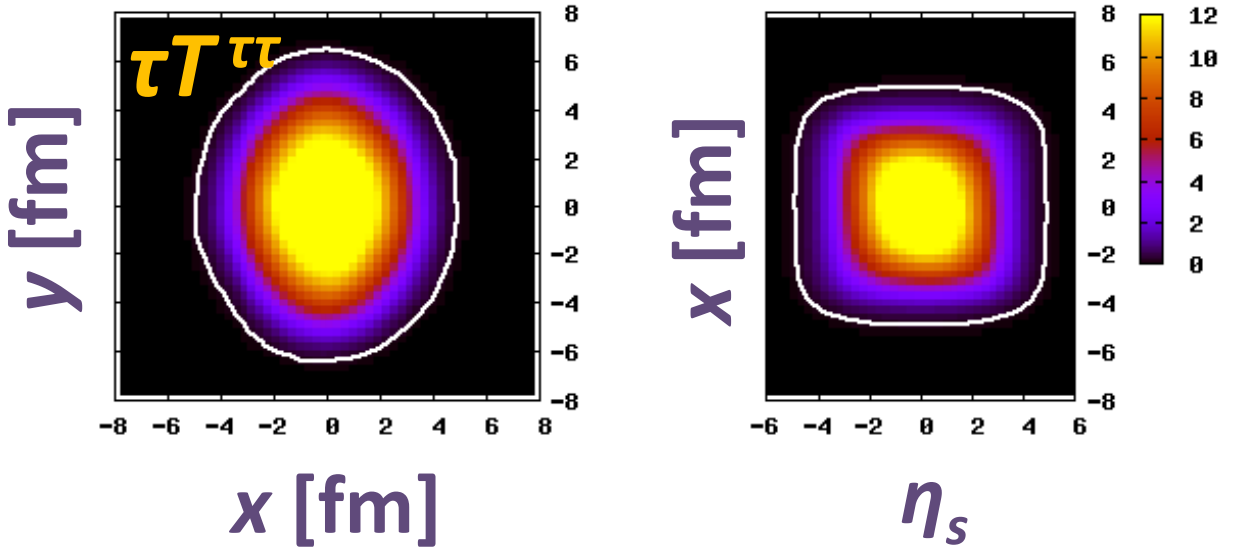
Type	*η/s*	HF	Hydro	Cascades
Ideal	0	none	1 event	10^4 events
Viscous	**1/4π**	none	1 event	10^4 events
Fluctuating	**1/4π**	**σ=0.8, 1.0, 1.2 (fm)** *	10^4 events×3	10^4 events×3

σ: HF cutoff length scale

A: Hydrodynamic evolution

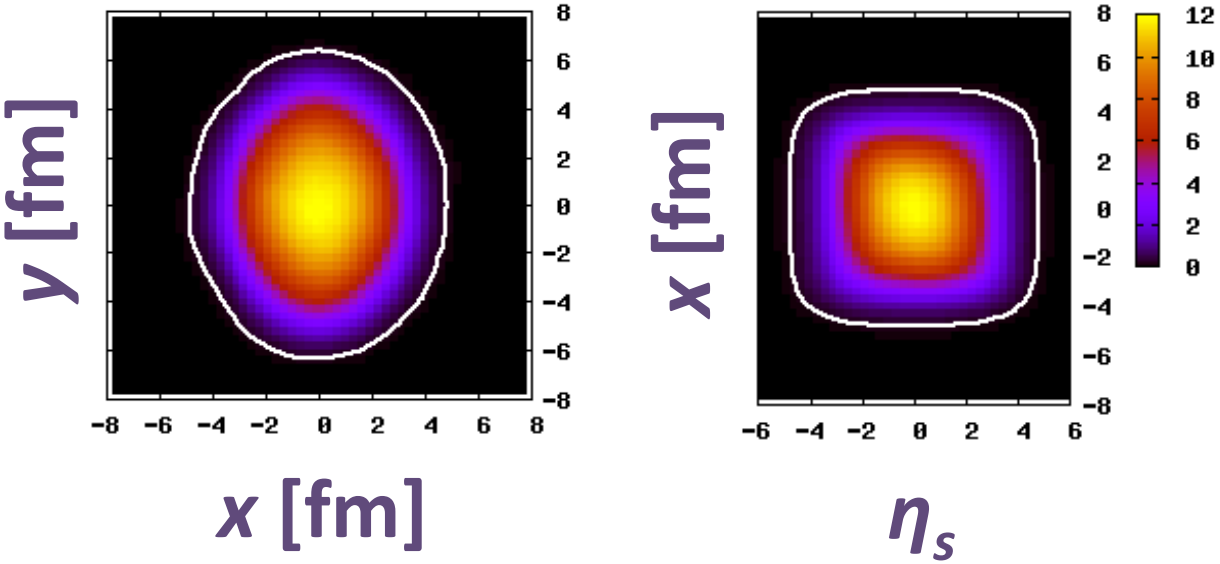
without HF

conventional
2nd-order
viscous hydro

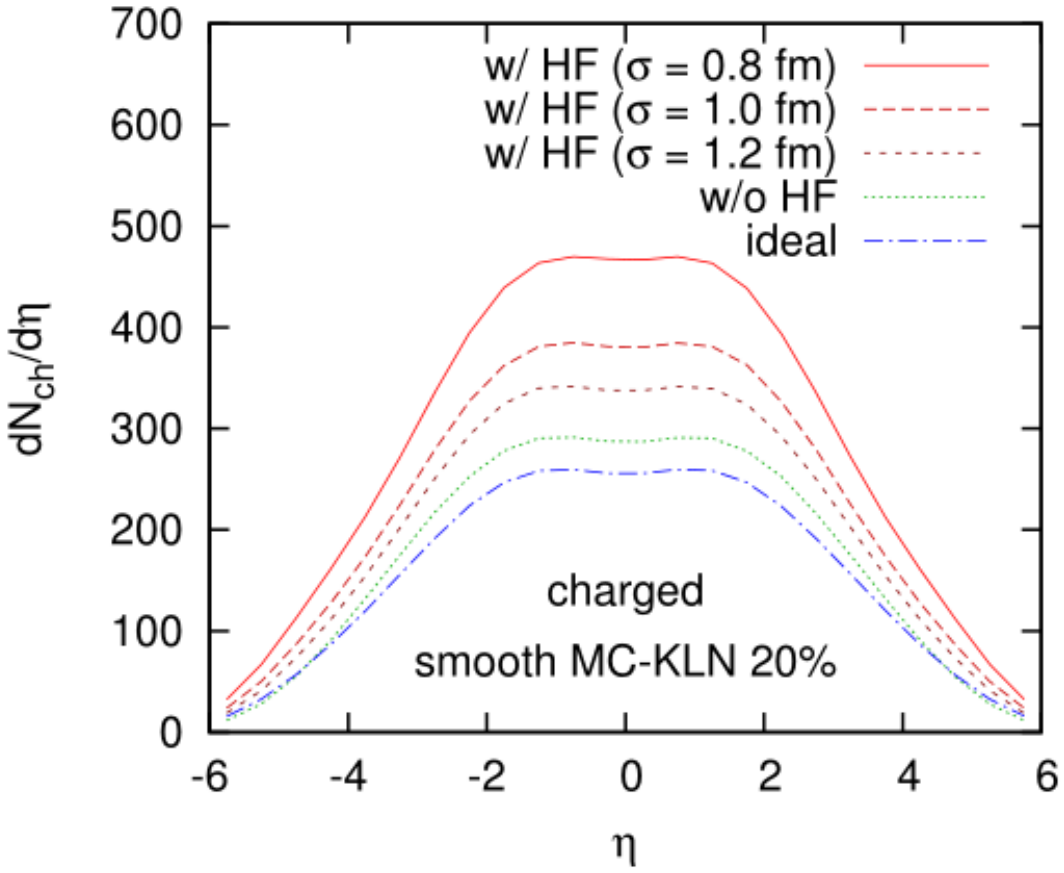


with HF

2nd-order
fluctuating hydro

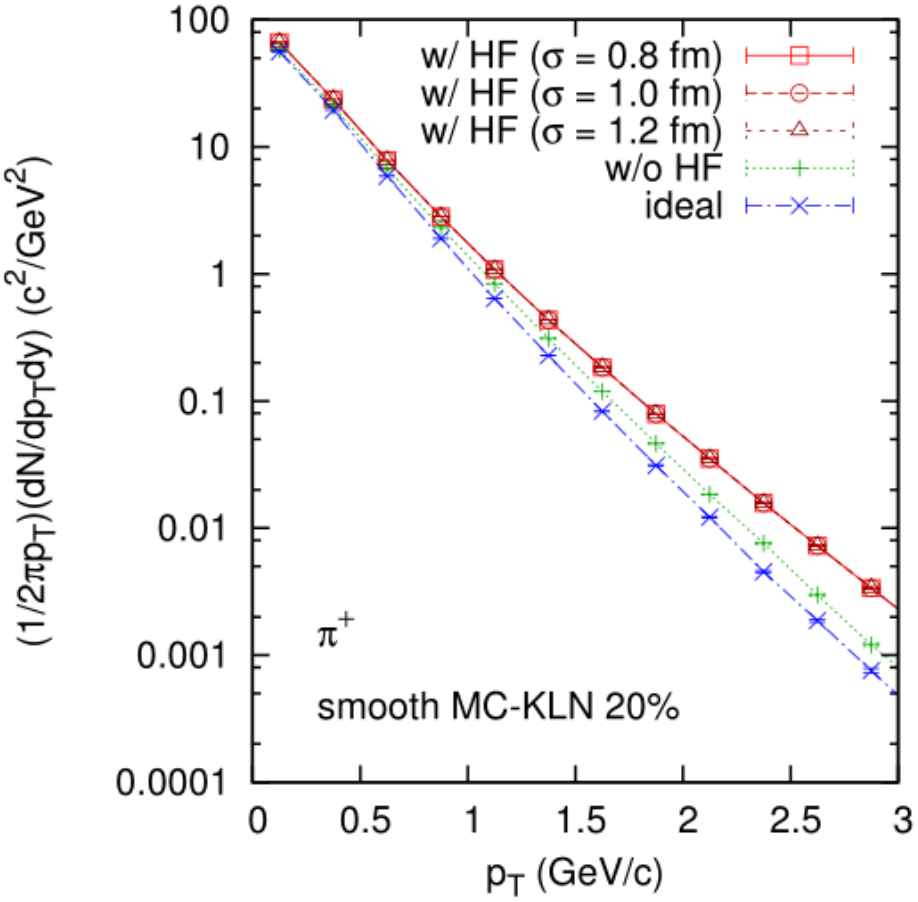


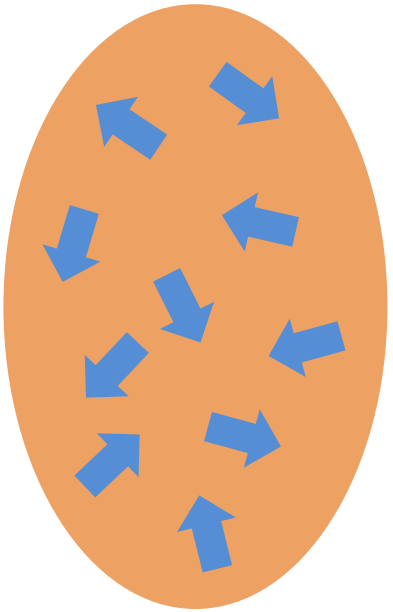
A: $dN_{ch}/d\eta$



- Increase ← entropy production by HF
- Larger effect with a shorter cutoff length σ

A: p_T-spectra (pions)

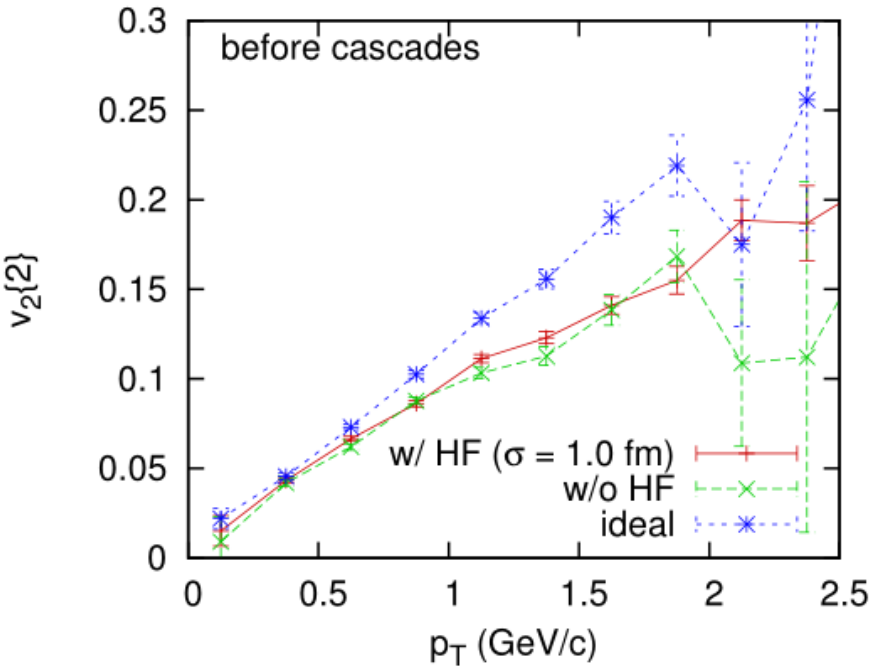


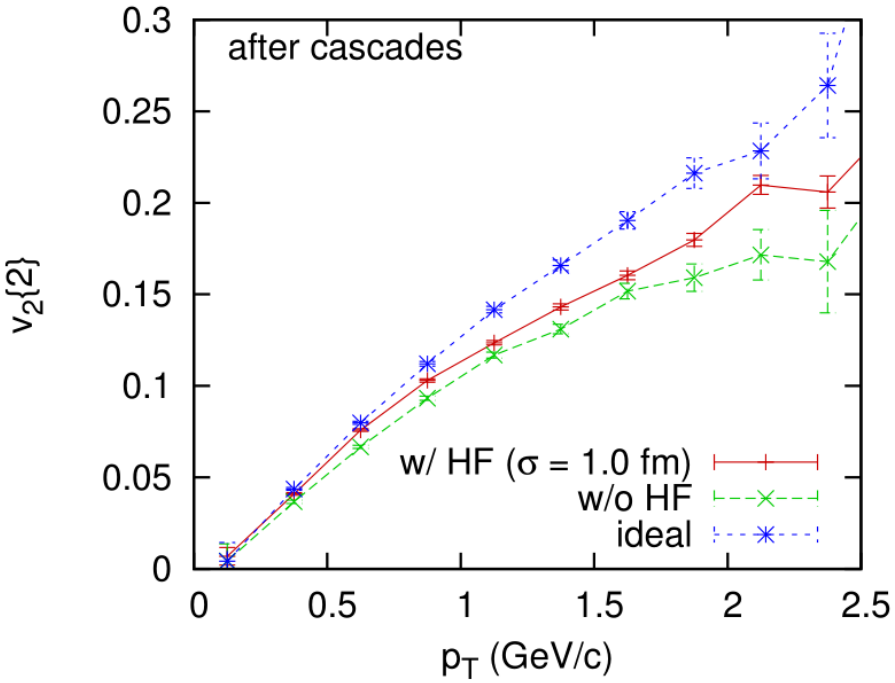


local flows by HF

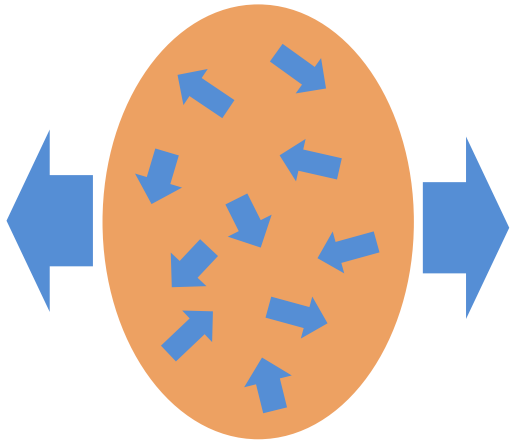
- High-pt particles increase with HF
  ← accelerated by local flows

A: Elliptic flow $v_2\{2\}$



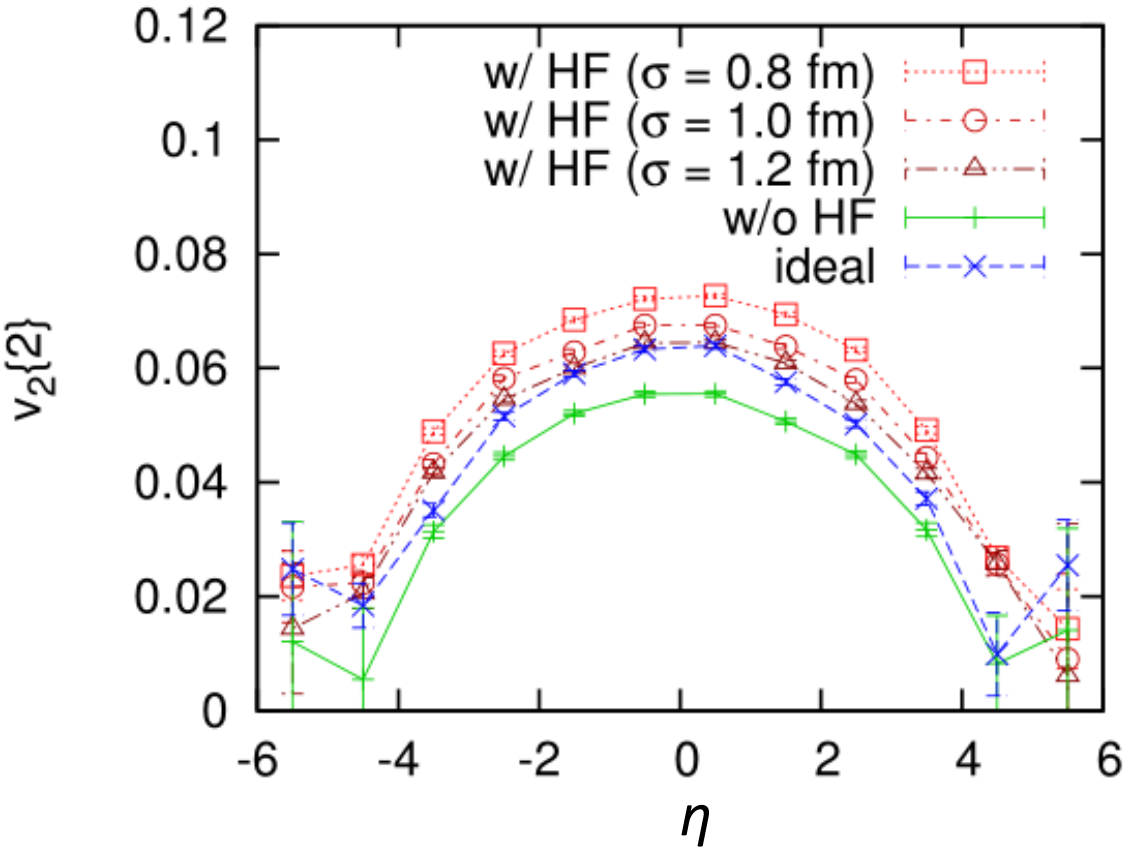


- decreased by viscosity, unchanged by HF
  ← local flows do not change the global flow profile

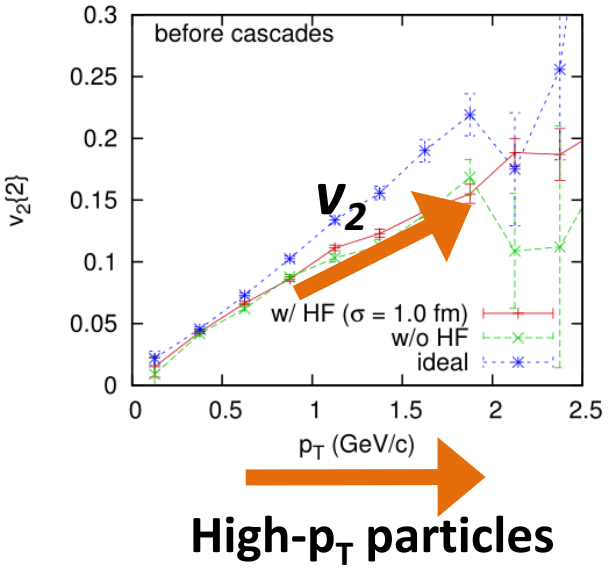


local flows by HF

A: Elliptic flow $v_2\{2\}(\eta)$



v2(p_T) in the last slide



High-p_T particles

- Decrease with viscosity, increase with HF
  ← increase of high-p_T particles

Setup B:
IS fluctuations + HF

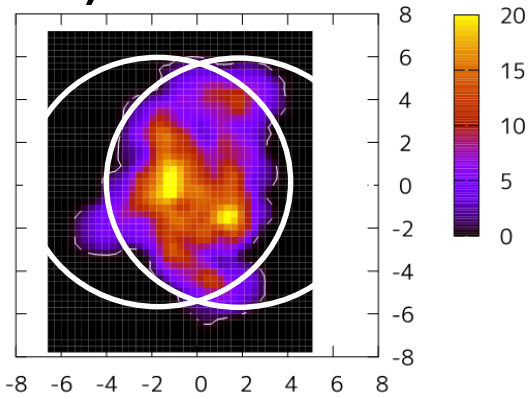
Setup B: IS Fluctuations and HF

- **Initial condition**

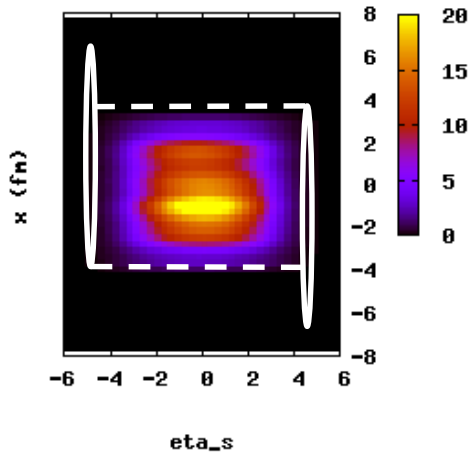
  b: not fixed (Minimum bias)

  MC-KLN (CGC)

***x-y* plane**



***η_s-x* plane**



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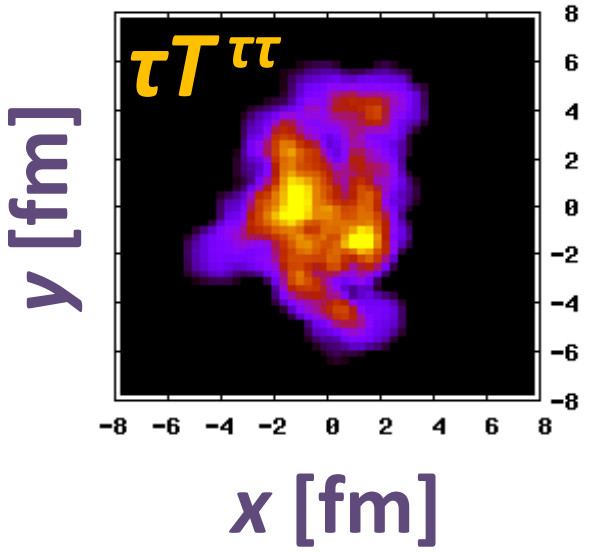
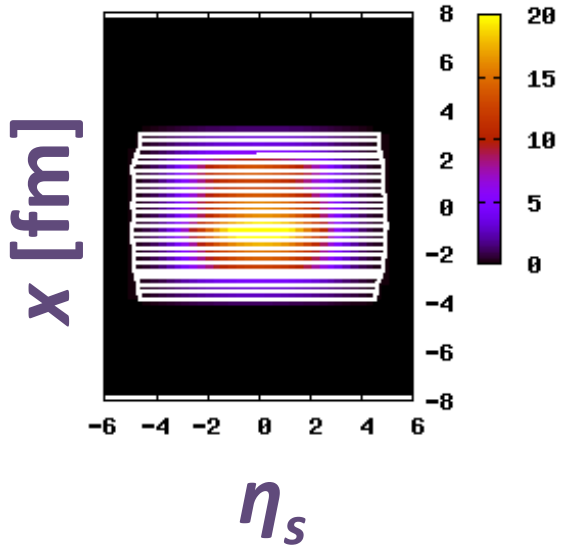
Fluctuating	**1/4π**	**σ = 1.0 (fm)**	10^5 events	10^5 events

B: Hydrodynamic evolution

without HF

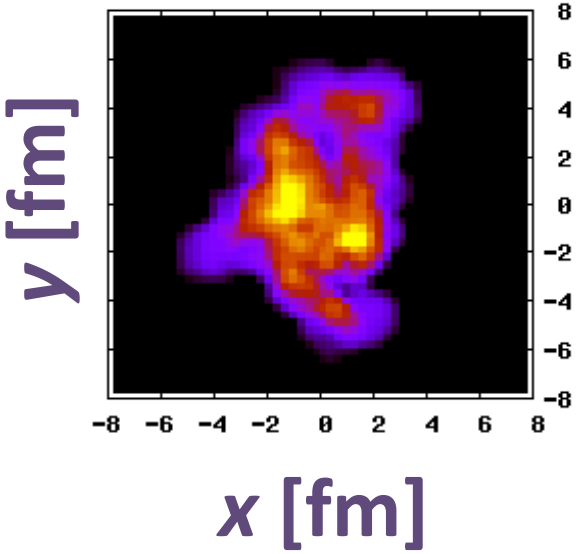
conventional
2nd-order
viscous hydro

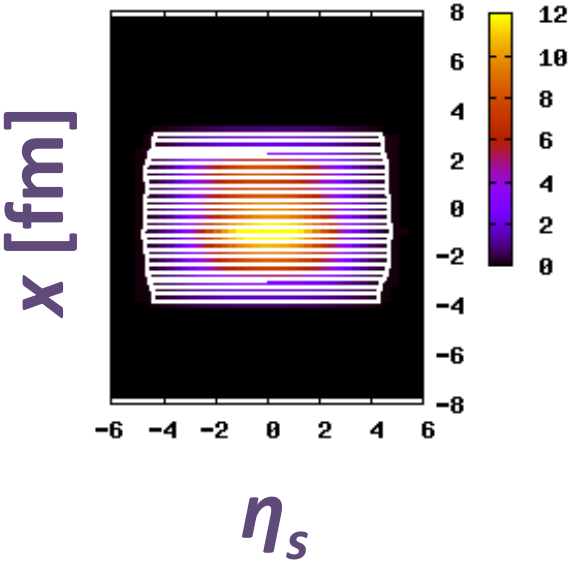




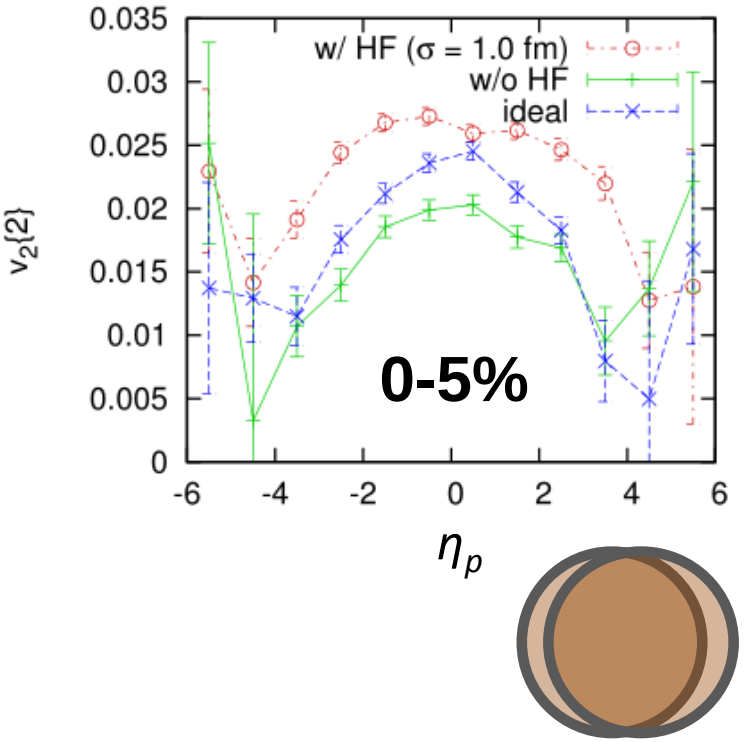
with HF

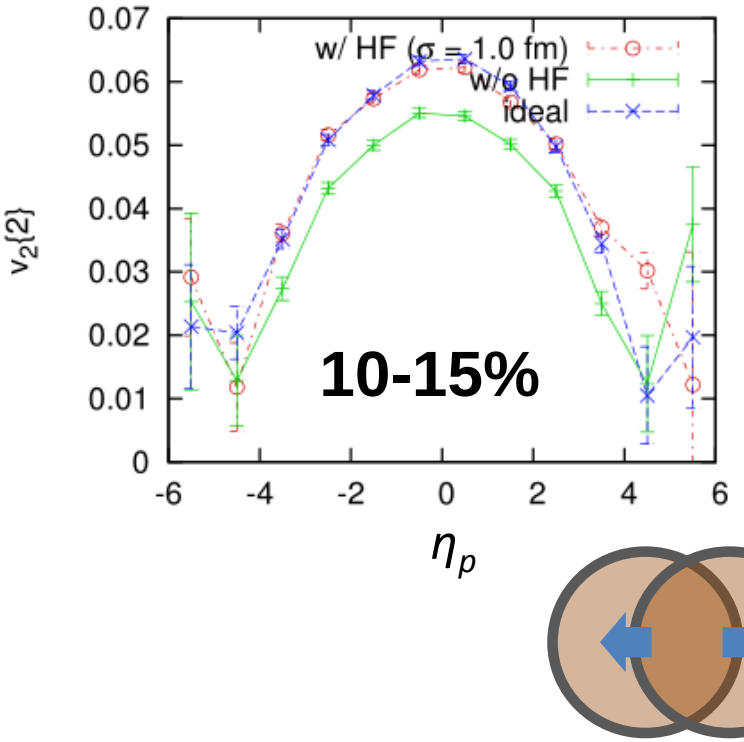
2nd-order
fluctuating hydro





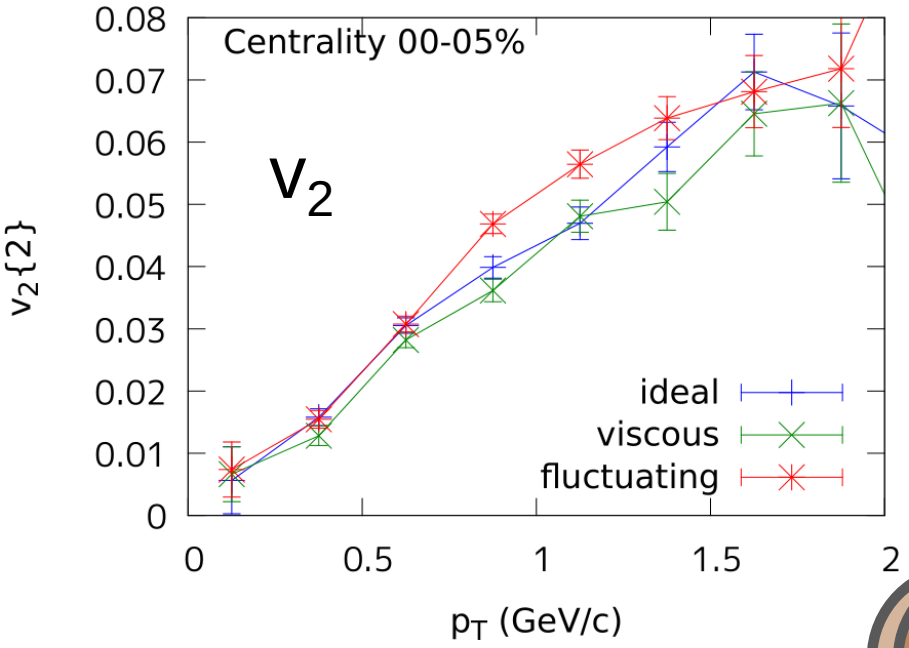
B: Elliptic flow $v_2(\eta)$

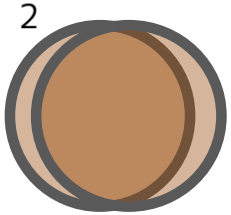


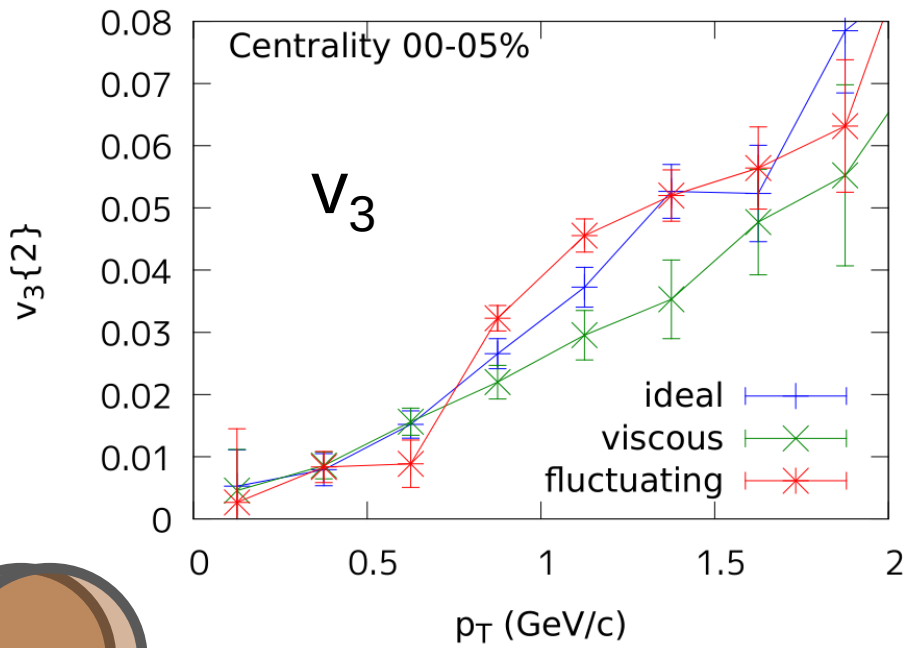


- v2(fluctuating) > v2(ideal) in central collisions
  Central: (IS Fluct.) + (HF)
  Non-central: (IS Fluct.) + (HF) + (Collision geometry)
- Same order with IS fluctuations

B: $v_2\{2\}$ (p_T), $v_3\{2\}(p_T)$







- v_2 increase with HF in central collisions
- Similar behavior for v_3

Summary

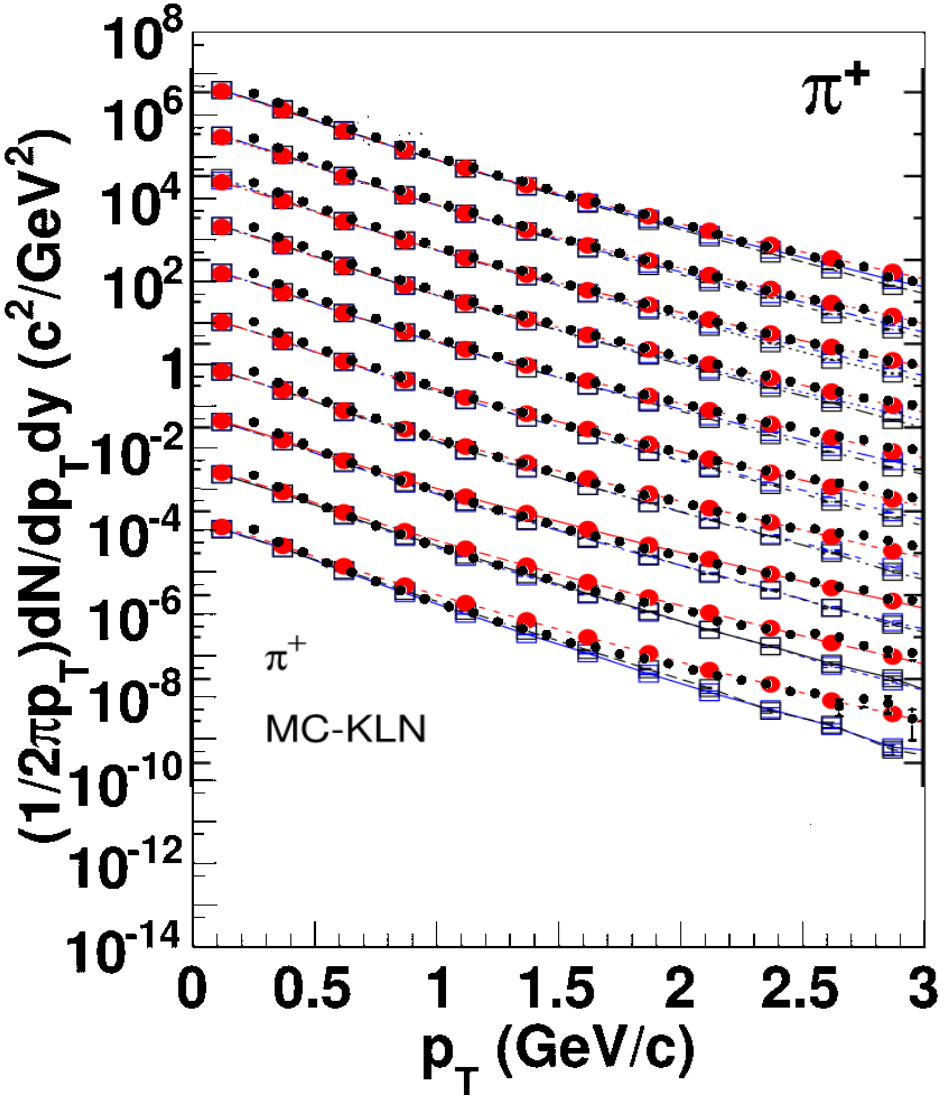
Summary

- ***Hydrodynamic fluctuations*** **(HF):**
  thermal fluctuations of hydrodynamics
- Relativistic fluctuating hydrodynamics
  in an integrated dynamical model
  - Increase of high-p_T hadrons by HF
  - Increase of $v_2(p_T)$, $v_3(p_T)$ in central collisions
  - Increase of integrated v_2

  HF: Important in extracting the transport properties
- Outlook
  - Larger statistics
  - Quantitative analyses

Backup

B: p_T-spectra (pions)



- Points: PHENIX PRC69 (2004) 034909
- Black lines: ideal hydrodynamics
- Blue lines: viscous hydrodynamics
- Red lines: fluctuating hydrodynamics

0-4%, 5-10%, 10-15%, 15-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80% from top to bottom (multiplied by 10^4-10^{-5})

- Increase of high-p_T pions: larger in peripheral collisions ← larger thermal fluctuations in smaller systems
- Correction of distribution in Cooper-Frye formula by HF?