Effects of hydrodynamic fluctuations in high energy heavy ion collisions

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Collaborators: Koichi Murase and Tetsufumi Hirano

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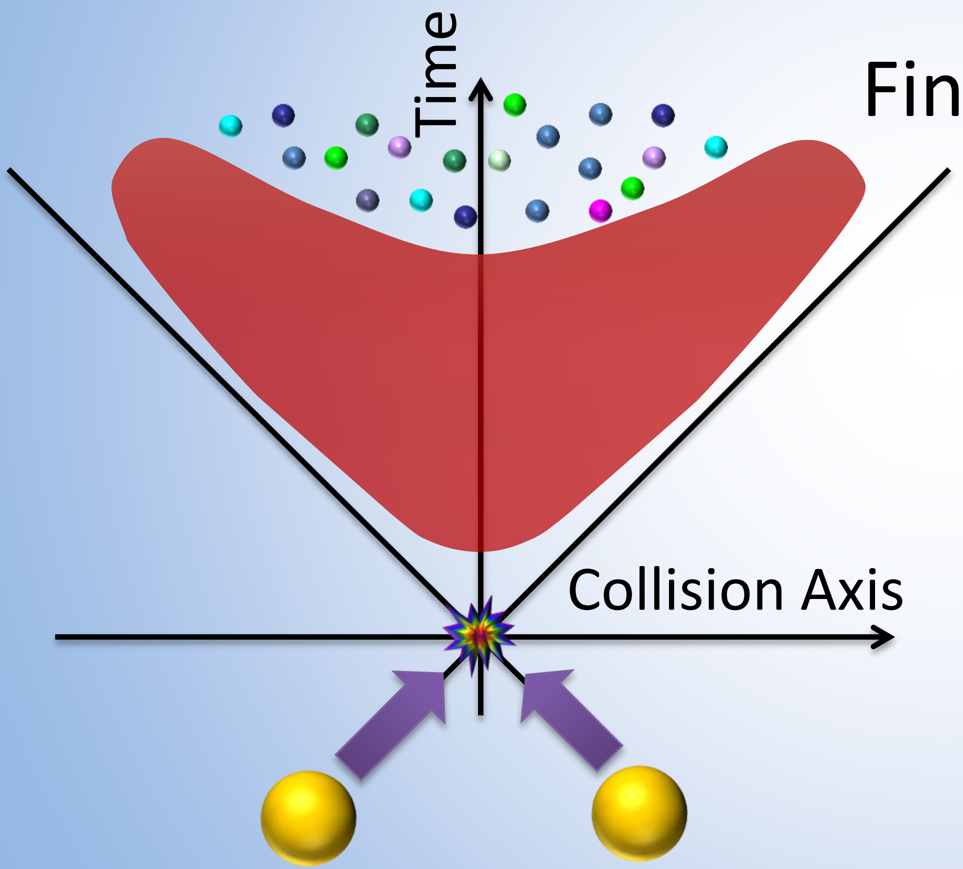
Introduction

Fluctuations in heavy ion collisions



Space-time evolution of high-energy nuclear collisions

Final observables

↑

Hadron gas

↑

QGP fluid

↑

Initial state

Thermal Fluctuations

Initial state fluctuations

Hydrodynamic fluctuations

<u>Shear stress tensor</u>

Fluctuating hydro

Viscous hydro

$$\pi^{\mu\nu}(x) = 2\eta\partial^{\langle\mu}u^{\nu\rangle} + \delta\pi^{\mu\nu}(x)$$

η: shear viscosity

u^μ: four fluid velocity

Thermodynamic force

Hydrodynamic fluctuations

Note: Relaxation term needed in actual simulations

Fluctuation dissipation relation for shear stress tensor

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

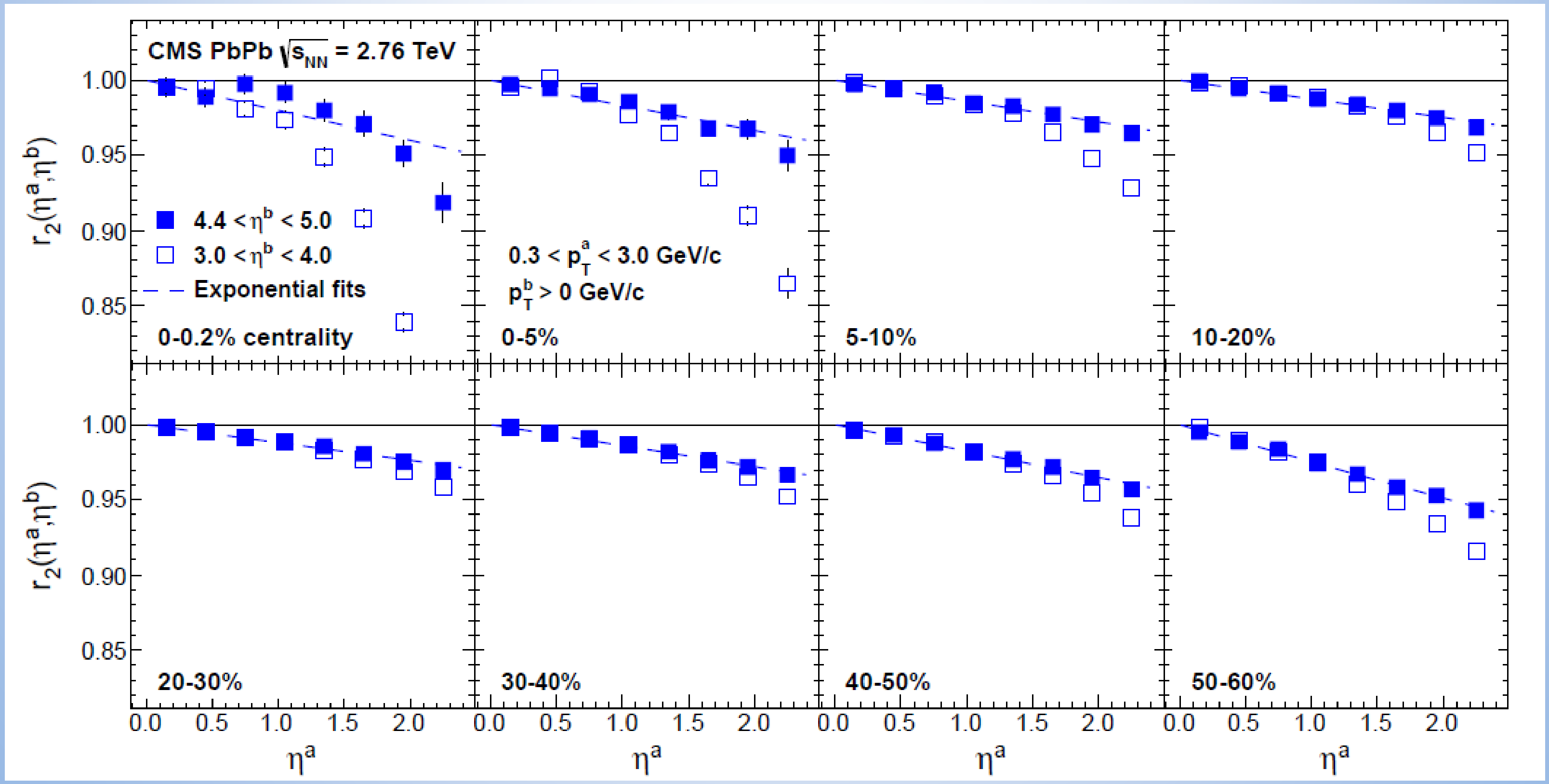
Increase of entropy ⟷ Balance ⟷ Decrease of entropy

Fluctuation dissipation relation
=Stability condition of thermal system

$$\langle\delta\pi^{ij}\delta\pi^{ij}\rangle \sim 4T\eta\delta^4(x-x')$$

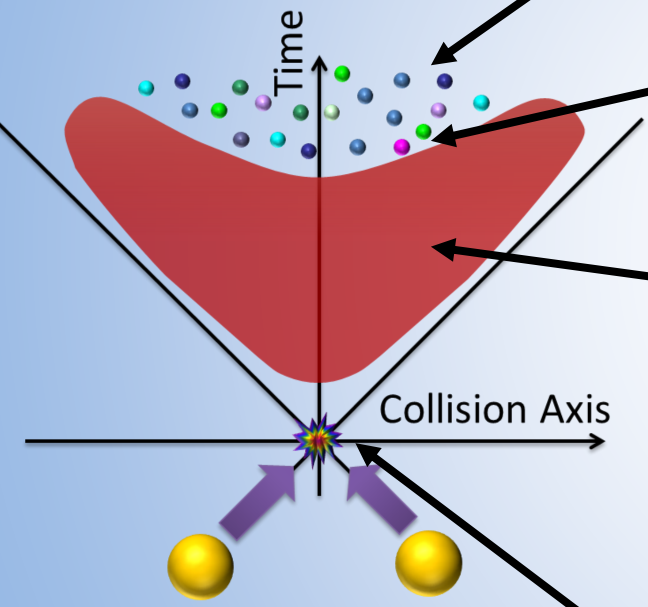
Purpose of study

To evaluate effects of hydrodynamic fluctuations on rapidity decorrelation



CMS, Phys. Rev. C 92, 034911 (2015).

Integrated dynamical model



4.Hadron gas

Hadron cascade model (JAM)

3.Particlization

Cooper-Frye formula (T_{sw}= 155 MeV)

2.QGP fluid

Full 3D relativistic fluctuating hydrodynamic simulations

K. Murase: Ph. D thesis The Univ. of Tokyo (2015).

EoS: s95p-v1.1 (Lattice QCD+HRG)

1.Initial state

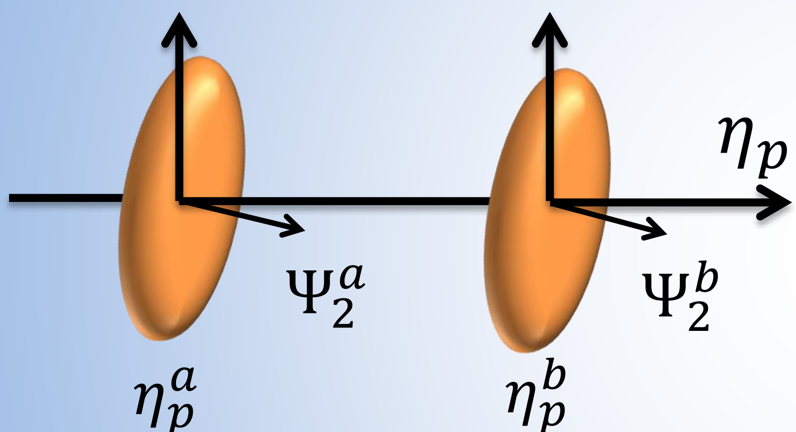
Pb+Pb, $\sqrt{s_{NN}}$=2.76 TeV

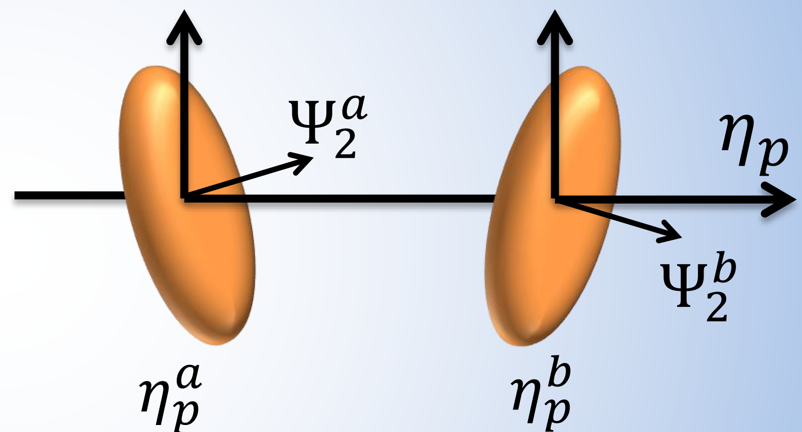
MC-Glauber model + Modified BGK model

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

Event plane fluctuations and decorrelations

Event plane angle $\Psi_n(\eta_p)$





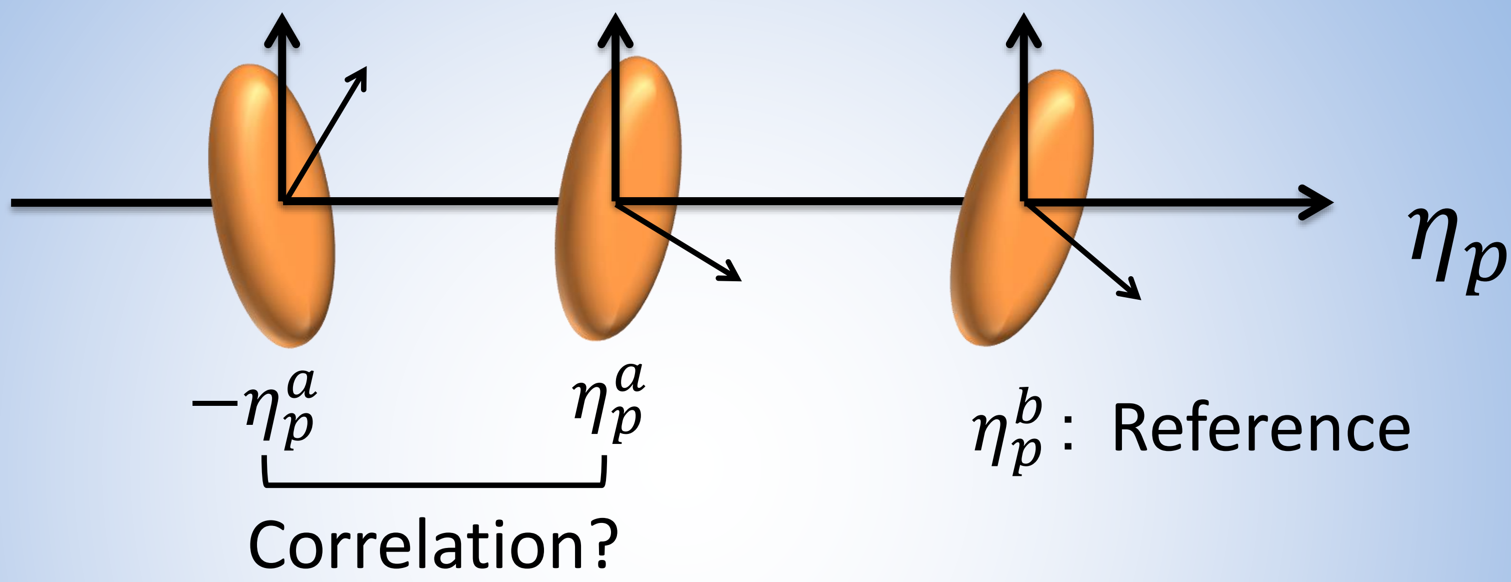
$$\Psi_2(\eta_p) = \text{const}$$
$$\Rightarrow V_{2\Delta} = v_2^a v_2^b$$

$$\Psi_2(\eta_p) \neq \text{const}$$
$$\Rightarrow V_{2\Delta} \neq v_2^a v_2^b$$

Factorization breaking

$$\frac{dN_{\text{pair}}}{d\Delta\phi} \propto 1 + 2\sum V_{n\Delta}\cos(n\Delta\phi)$$

Factorization ratio



$$r_n(\eta_p^a, \eta_p^b) = \frac{V_{n\Delta}(-\eta_p^a, \eta_p^b)}{V_{n\Delta}(\eta_p^a, \eta_p^b)}, \quad V_{n\Delta} = \langle \cos(n\Delta\phi) \rangle$$

$r_n(\eta_p^a, \eta_p^b) \sim 1$

Unique event plane

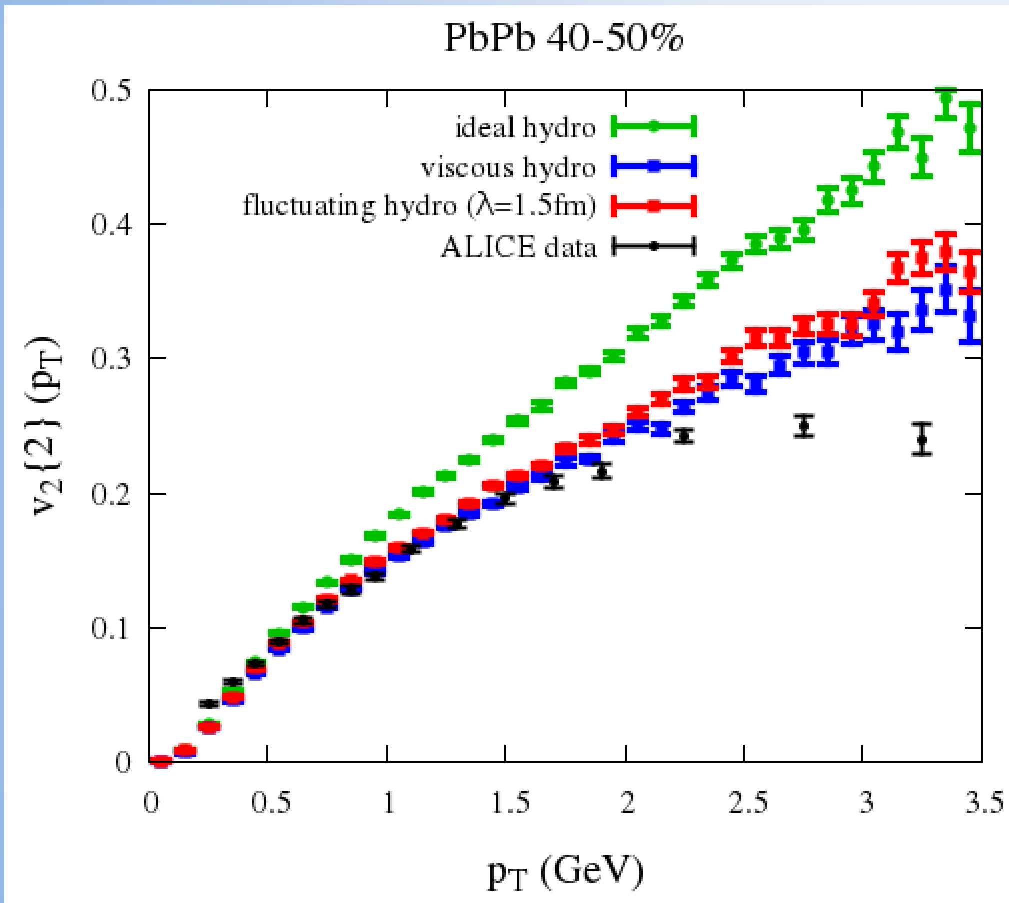
$r_n(\eta_p^a, \eta_p^b) < 1$

Decorrelation

CMS Collaboration, Phys. Rev. C 92, 034911 (2015)

F.G. Gardim *et al.*, Phys. Rev . C 87, 031901 (2013)

p_T-differential v_2



ALICE Collaboration,
Phys. Rev. Lett. 116 (2016) 132302

Ideal hydro

→ Larger than ALICE data

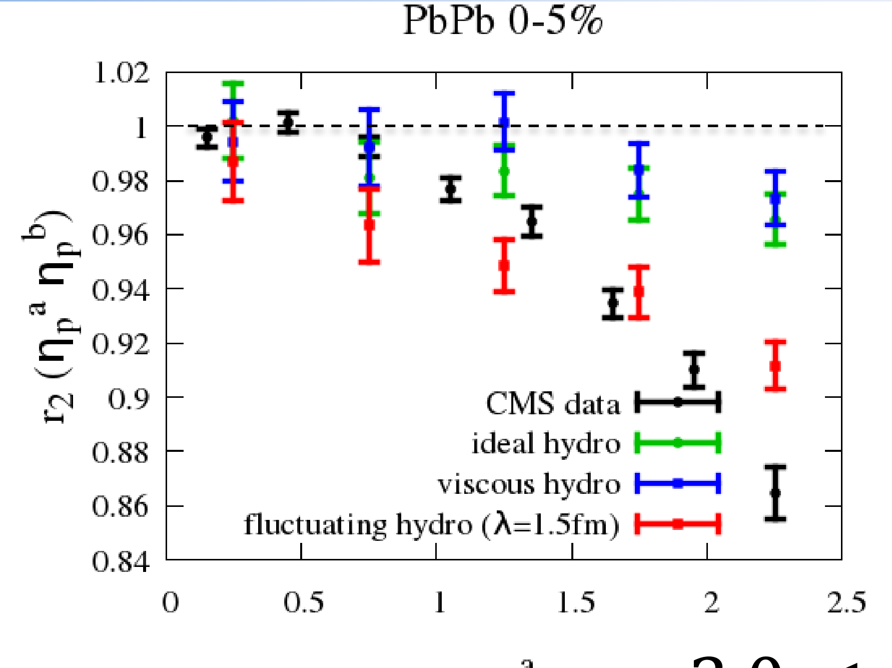
Viscous & Fluctuating hydro ($\eta/s = 1/4\pi$)

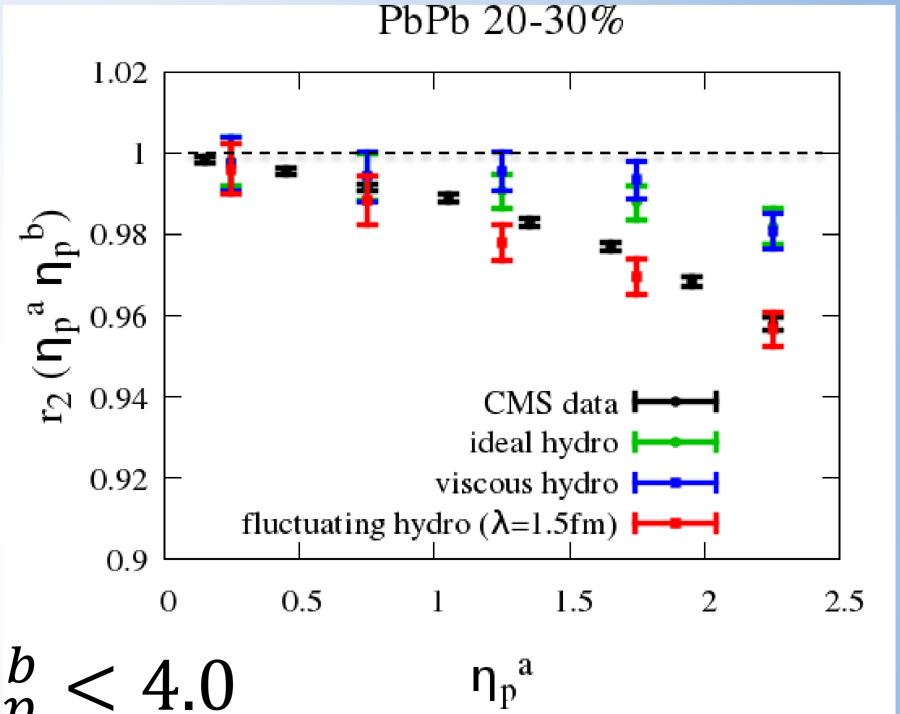
→ Good agreement with ALICE data below $p_T \sim 1.5$ GeV

Effect of fluctuations

→ What observable?

Factorization ratio $r_2(\eta_p^a, \eta_p^b)$





$3.0 < \eta_p^b < 4.0$

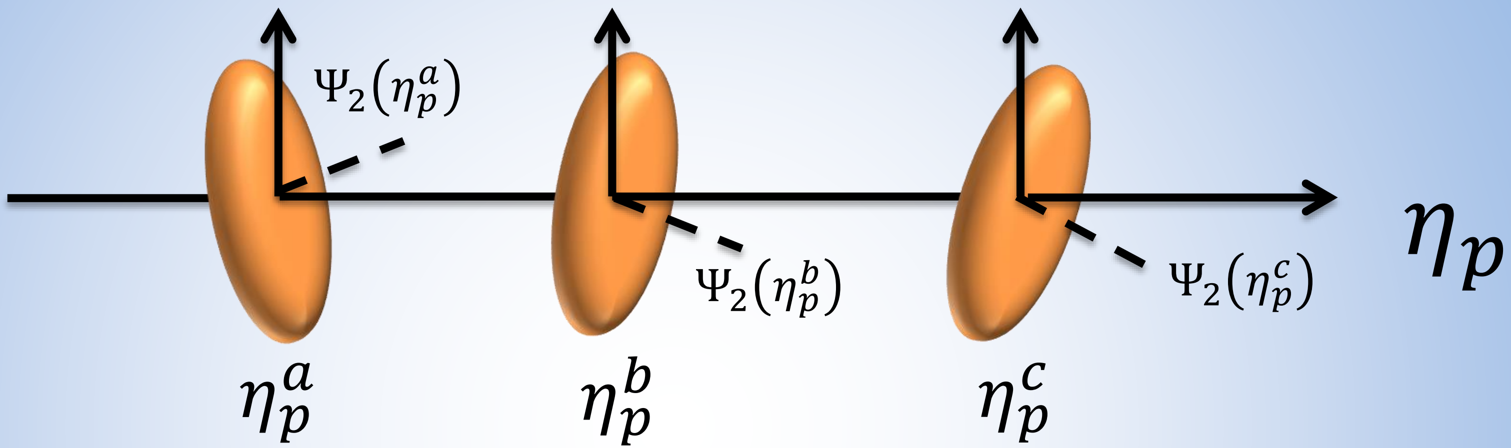
Ideal ≈ Viscous > CMS data ≈ Fluctuating hydro

Hydrodynamic fluctuations

→ Factorization more broken

CMS, Phys. Rev. C 92, 034911 (2015).

Legendre series



$$v_2(\eta_p) = \sum_{k=0}^{\infty} a_2^k P_k(\eta_p)$$

$$\Psi_2(\eta_p) = \sum_{k=0}^{\infty} b_2^k P_k(\eta_p)$$

P_k : Legendre polynomial

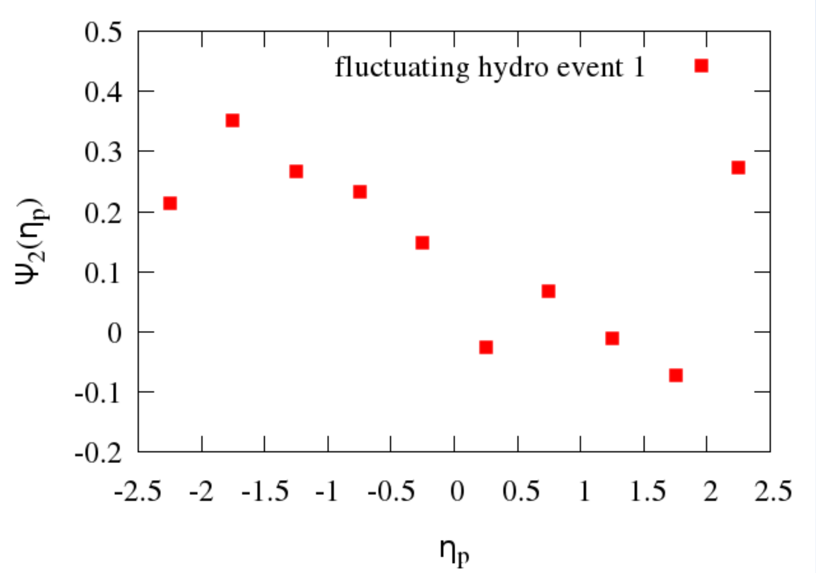
$$P_1(\eta_p) = \eta_p$$

$$P_2(\eta_p) = \frac{1}{2}(3\eta_p{}^2 - 1)$$

a_2^k, b_2^k: Legendre coefficients

⇒Quantity to understand η_p dependence

Legendre series



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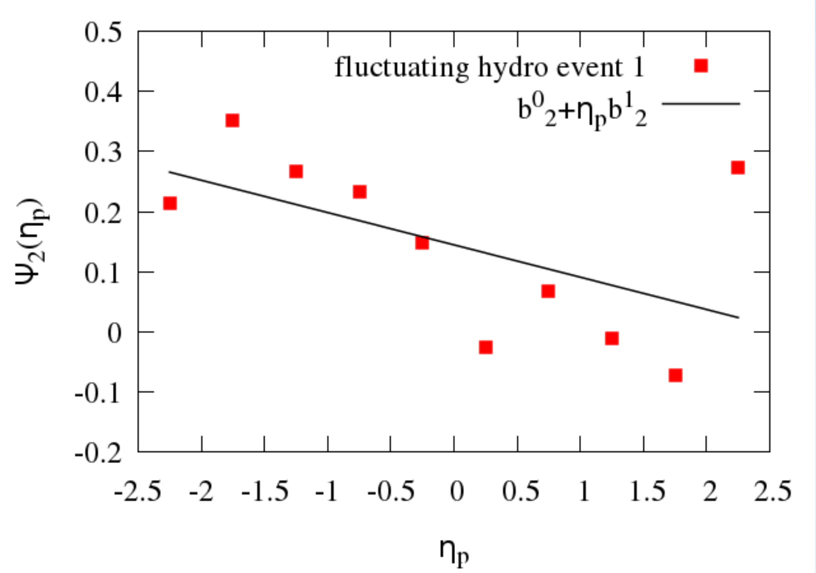

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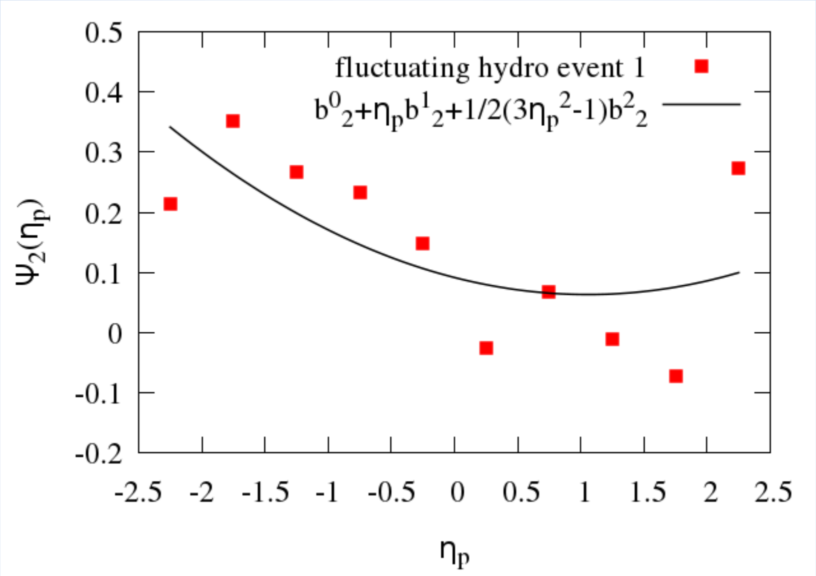

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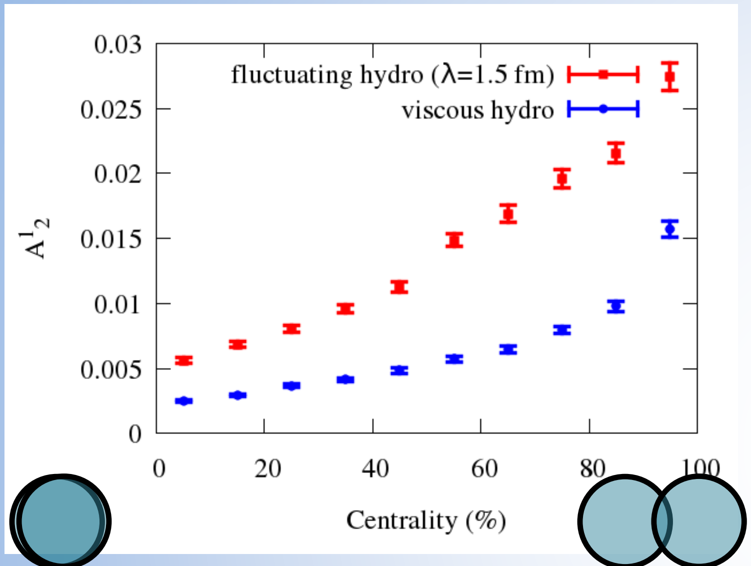
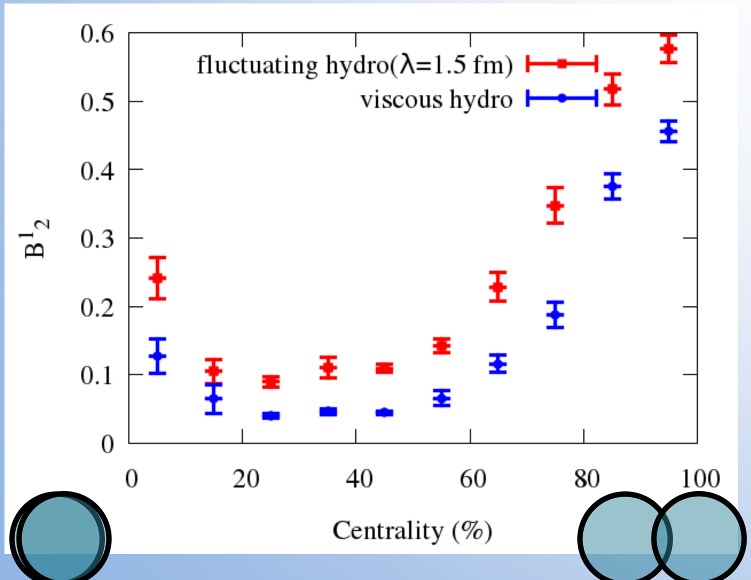
Legendre coefficients





Flow $|\boldsymbol{v}_2|$

$$A_2^1 = \sqrt{\langle (a_2^1)^2 \rangle}$$

Event plane angle Ψ_2

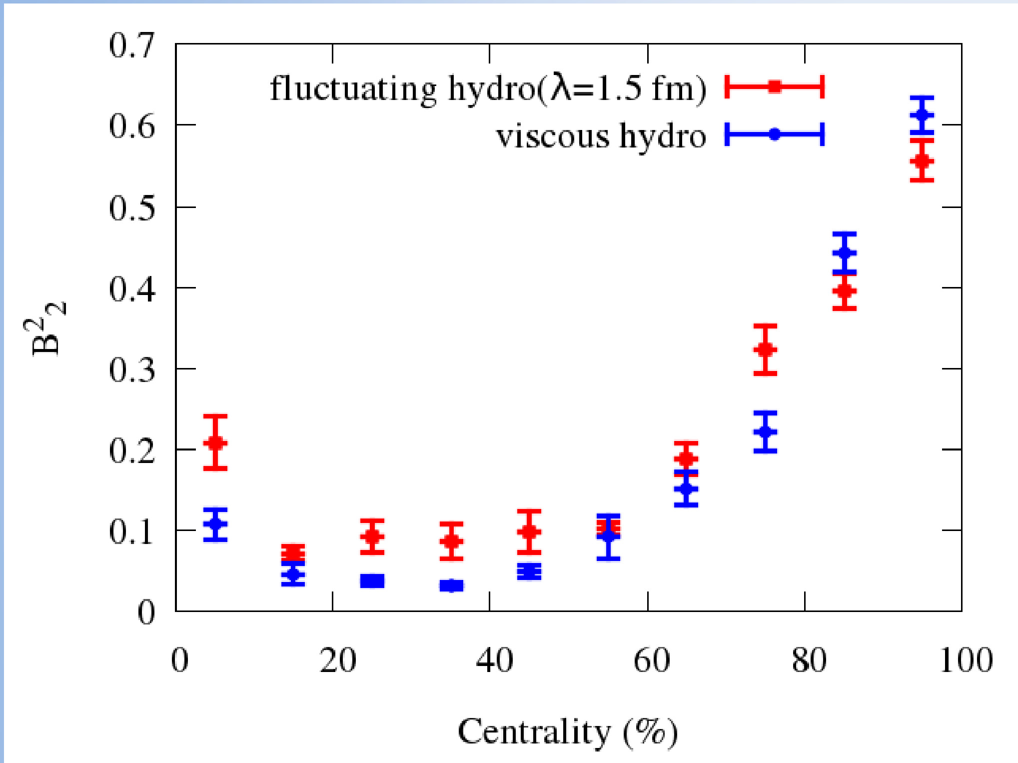
$$B_2^1 = \sqrt{\langle (b_2^1)^2 \rangle}$$

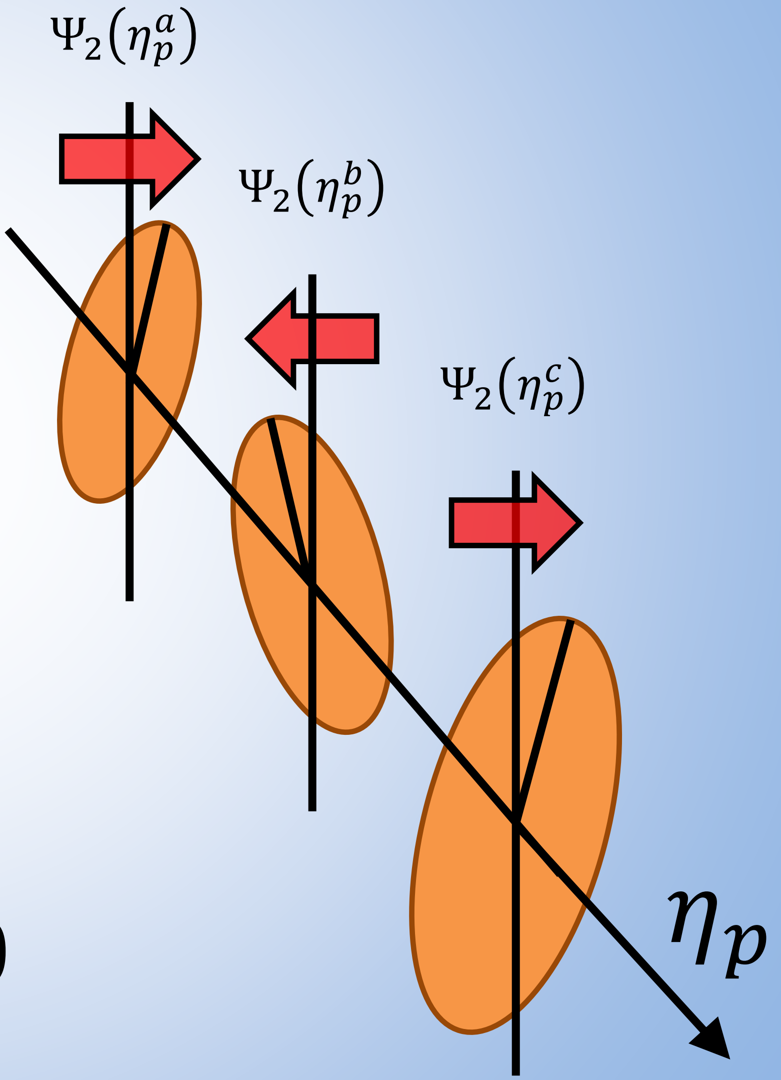
a_2^k, b_2^k: Legendre coefficients

A_2^1 fluctuating > A_2^1 viscous
B_2^1 fluctuating > B_2^1 viscous

Hydrodynamic fluctuations
⇒increase η_p dependence
⇒increase Legendre coefficient

Legendre coefficients





"2nd order twist" : $B_2^2 \neq 0$

Summary

Integrated dynamical model based on full 3D fluctuating hydrodynamics

✓ **Factorization ratio** $r_n(\eta_p^a, \eta_p^b)$

- Fluctuating hydrodynamic model factorization more broken
- Importance of hydrodynamic fluctuations

✓ **Legendre coefficients** $A_2^k,\ B_2^k$

- Fluctuating hydrodynamic model has larger η_p dependence than viscous hydrodynamic model
- 2nd order twist: $B_2^2 \neq 0$

Back up

Fluctuation dissipation relation for shear stress tensor

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

Increase of entropy

Balance

Decrease of entropy

Fluctuation dissipation relation

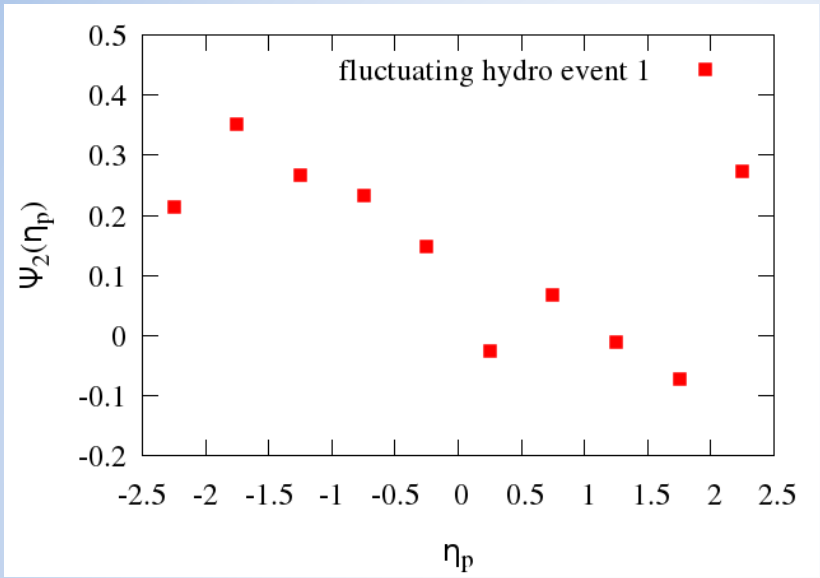
=Stability condition of thermal system

$$\langle \delta\pi^{ij}\delta\pi^{ij} \rangle \sim 4T\eta\delta^4(x-x')$$

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

λ: Gaussian width

Legendre series



Hydro × Cascade
=4000 × 100

Averaged for each hydro event

$$v_2(\eta_p) = \sum_{k=0}^{\infty} a_2^k P_k(\eta_p)$$

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$$P_1(\eta_p) = \eta_p$$

$$P_2(\eta_p) = \frac{1}{2}(3{\eta_p}^2 - 1)$$

a_2^k, b_2^k: Legendre coefficients

⇒Quantity to understand η_p dependence

Initial Condition Setups

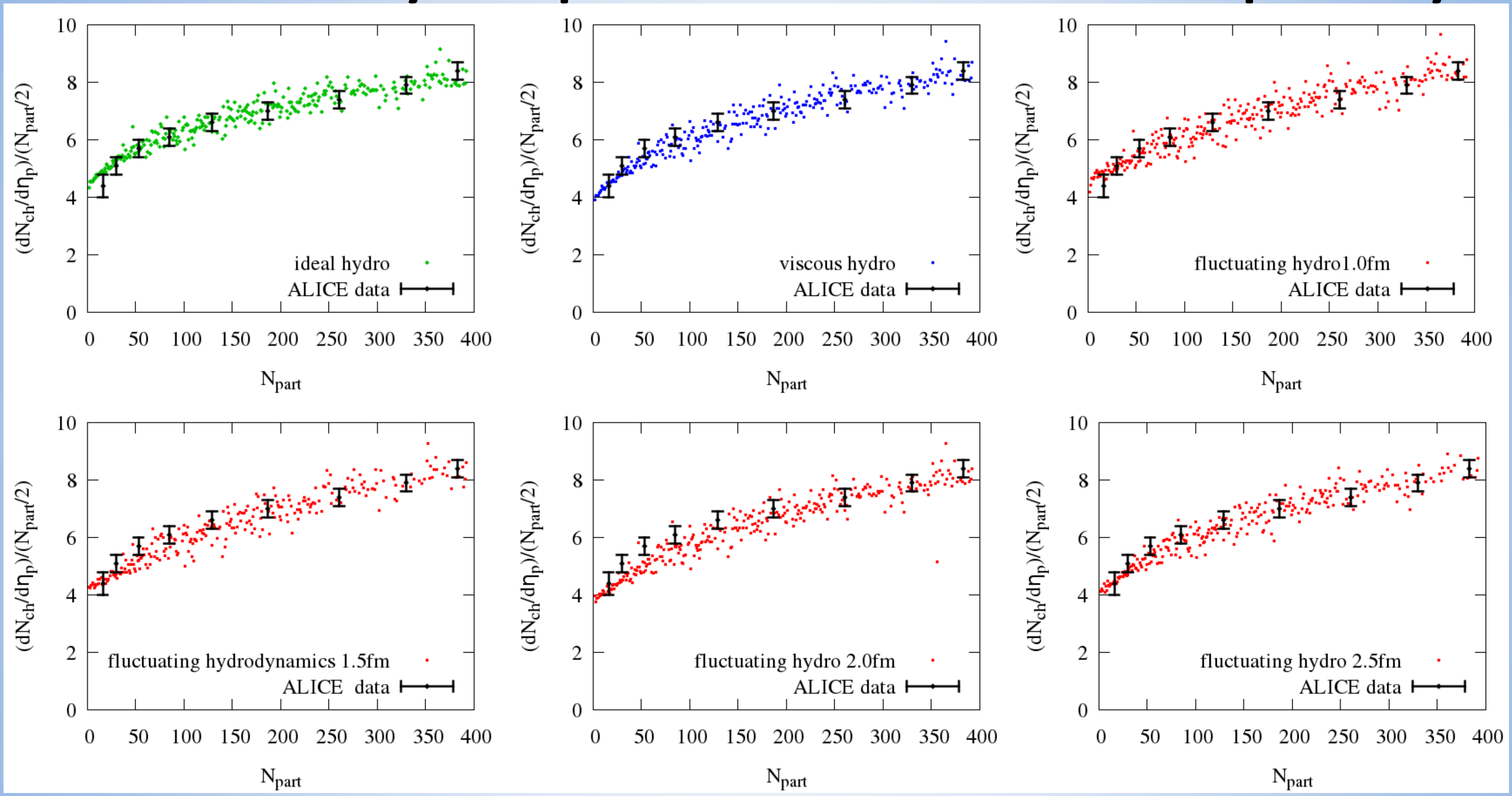
$$s_0(r_\perp) = \frac{C}{\tau_0}\left(\frac{1-\alpha}{2}\rho_{\text{part}}(r_\perp) + \alpha\rho_{\text{coll}}(r_\perp)\right)$$

λ: HF cutoff length scale (Gaussian width)

	η/s	HF	C/τ0	α
Ideal	0	None	62	0.08
Viscous	1/4π	None	49	0.13
Fluctuating	1/4π	λ=1.0 fm	31	0.20
	1/4π	λ=1.5 fm	41	0.16
	1/4π	λ=2.0 fm	42	0.16

Hydro	Cascades
4k events	400 k (4k*100)

Centrality dependence of multiplicity



- Initial parameters tuning
- Centrality cut

Hydrodynamic fluctuations

Shear stress tensor

Fluctuating hydro

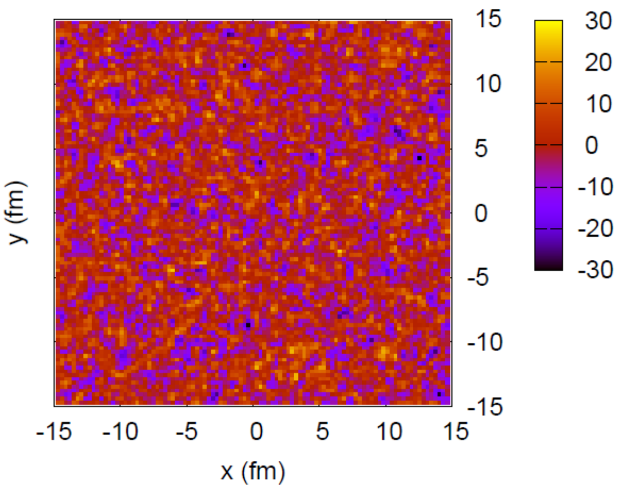
Viscous hydro

$$\pi^{\mu\nu}(x) = 2\eta\partial^{\langle\mu}u^{\nu\rangle} + \delta\pi^{\mu\nu}(x)$$

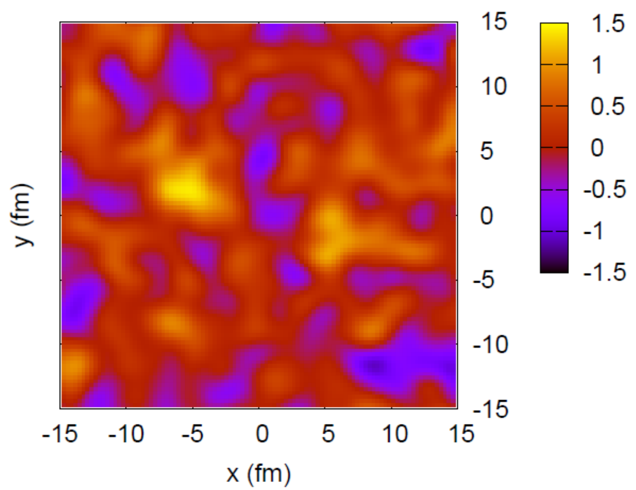
Actual Equation

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

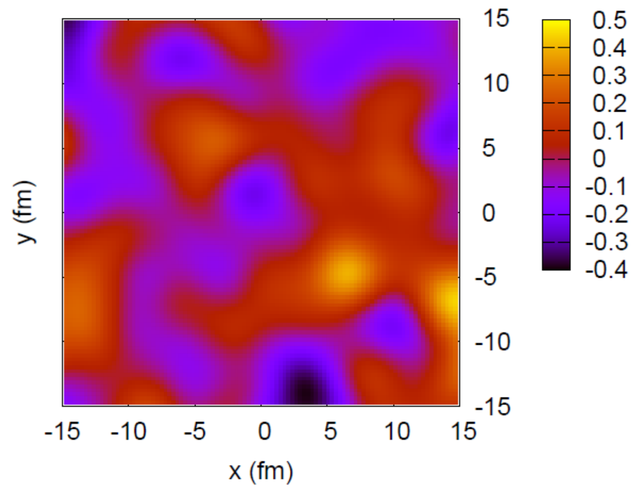
Cut of parameter



With out smearing



1.0 fm smearing



2.0 fm smearing