Rapidity decorrelation from hydrodynamic and initial longitudinal fluctuations

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The 36th Heavy Ion Café Dynamics of High-Energy Nuclear Collisions

Outline

- Introduction
- Integrated dynamical model
- Rapidity decorrelation
- Other observables
- Summary

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Fluctuations and rapidity decorrelation

Properties of QGP

Longitudinal Dynamics

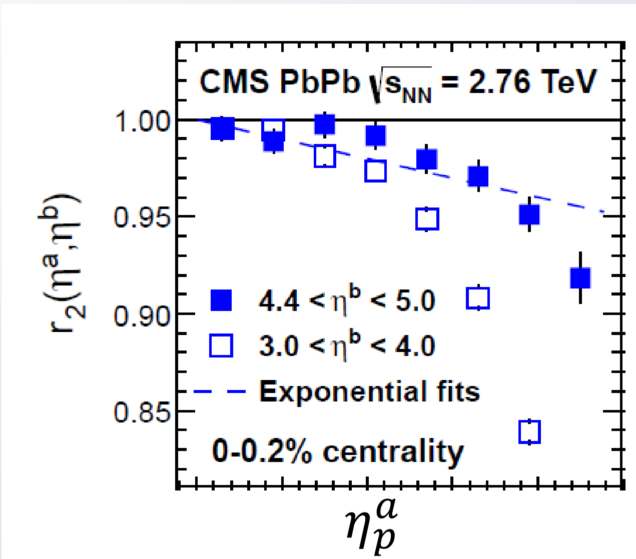
<u>Fluctuations</u>

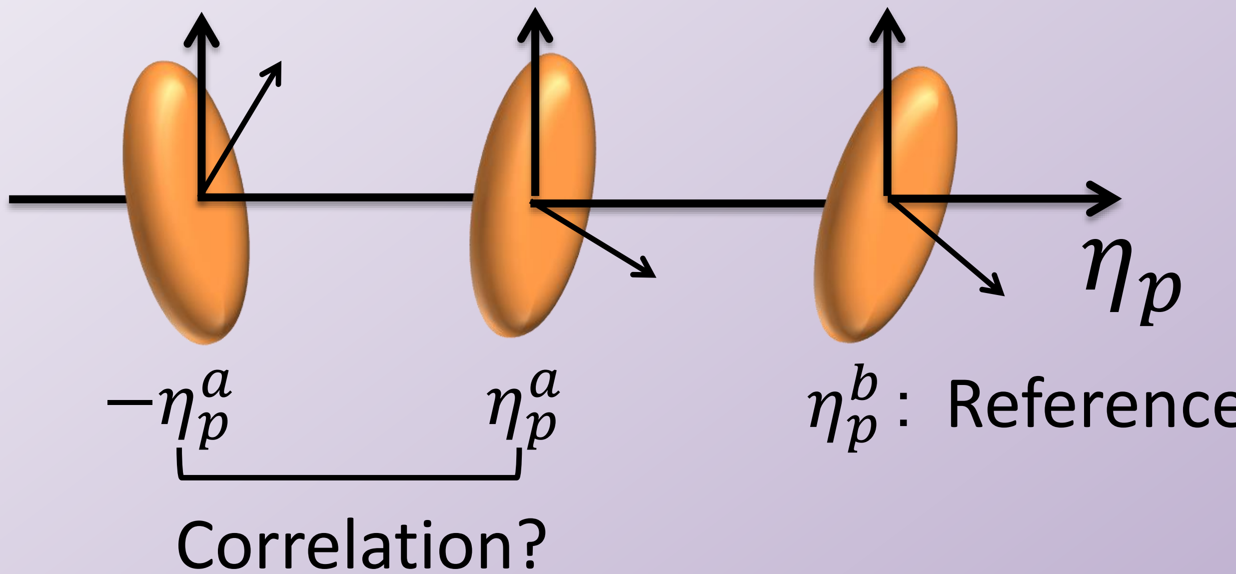
- Hydrodynamic fluctuations
- Initial fluctuations

<u>Observables</u>

- Rapidity decorrelation

Rapidity decorrelation





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

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

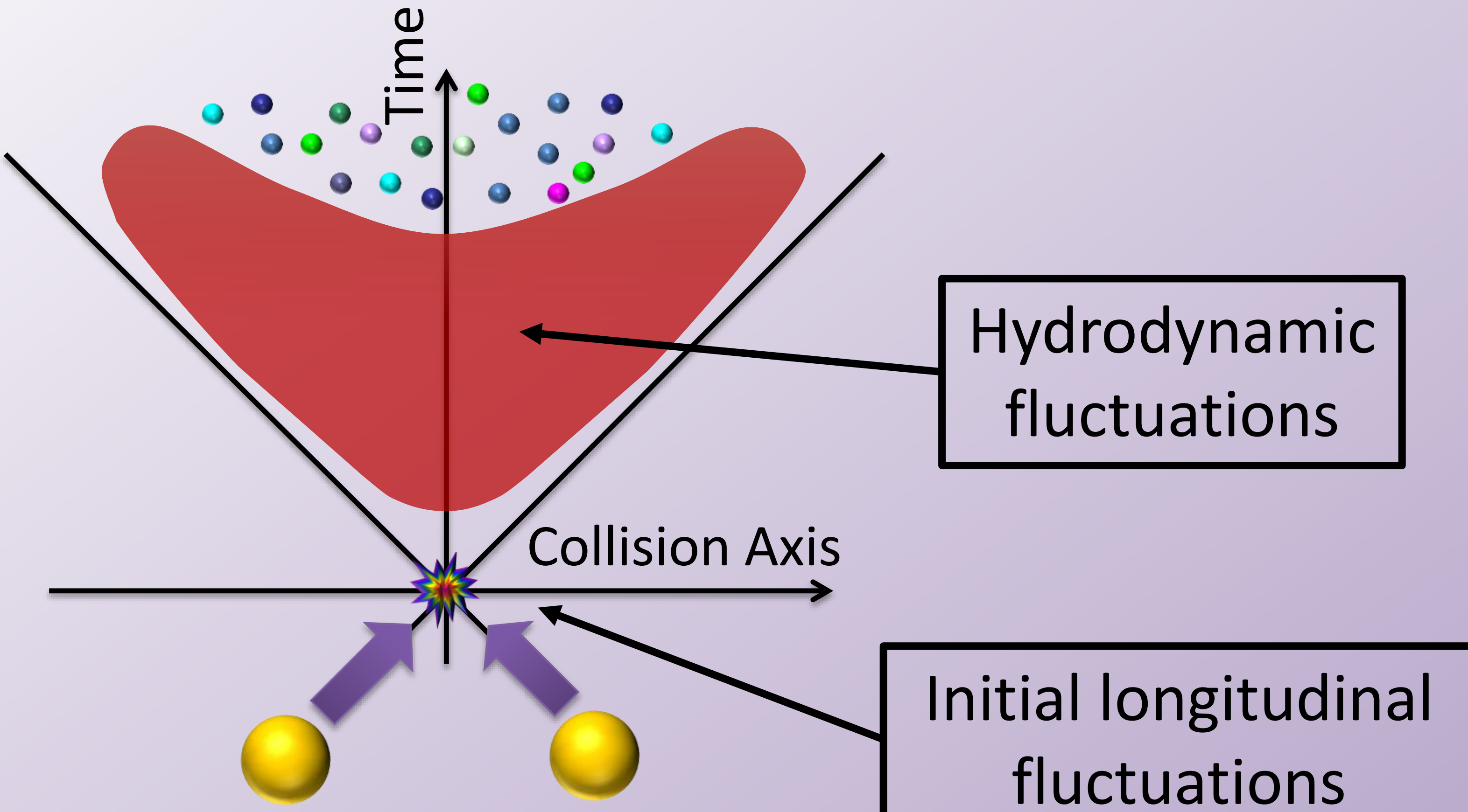
Unique event plane

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

Decorrelation

CMS Collaboration, Phys. Rev. C 92, 034911 (2015)
F.G. Gardim *et al.*, Phys. Rev . C 87, 031901 (2013)

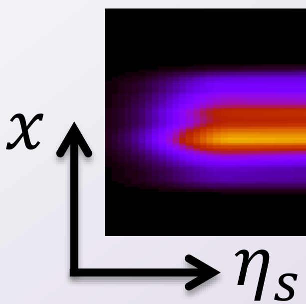
Dynamics



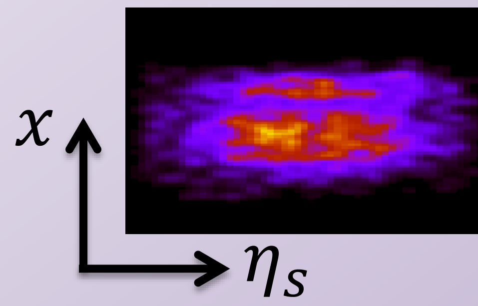
Time
Collision Axis
Hydrodynamic fluctuations
Initial longitudinal fluctuations

Fluctuations in heavy ion collisions

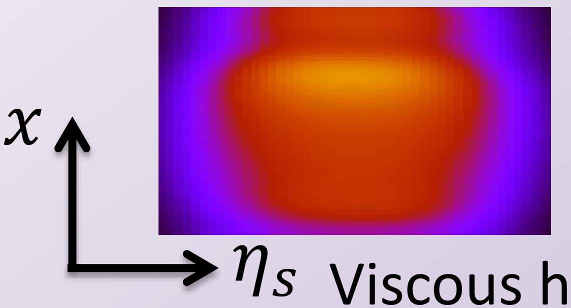
Initial state fluctuations



Initial longitudinal fluctuations

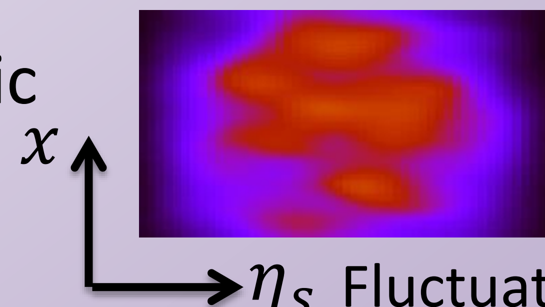


Fluctuations during hydrodynamic evolution



Viscous hydro

Hydrodynamic fluctuations



Fluctuating hydro

Purpose of study: Understand QGP longitudinal dynamics by

- Hydrodynamic fluctuations
- Initial longitudinal fluctuations

- Rapidity decorrelations

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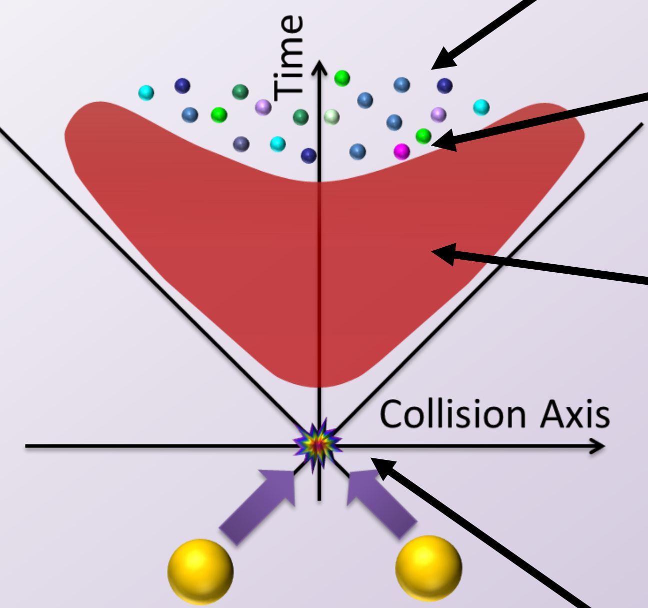
Integrated dynamical model



4.Hadron gas

Hadron cascade model (JAM)

3.Particlization

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

2.QGP fluid

Hydrodynamic fluctuations

Full 3D relativistic fluctuating hydrodynamics

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

Shear viscosity: $\eta/s = 1/4\pi$

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

1.Initial state

Longitudinal fluctuations

Longitudinal: PYTHIA x BGK

Transverse: MC-Glauber model

M. Okai et al., Phys. Rev. C 95, 054914 (2017)

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

Hydrodynamic fluctuations

<u>Shear stress tensor</u> (in 1st order for illustration)

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 included 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

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

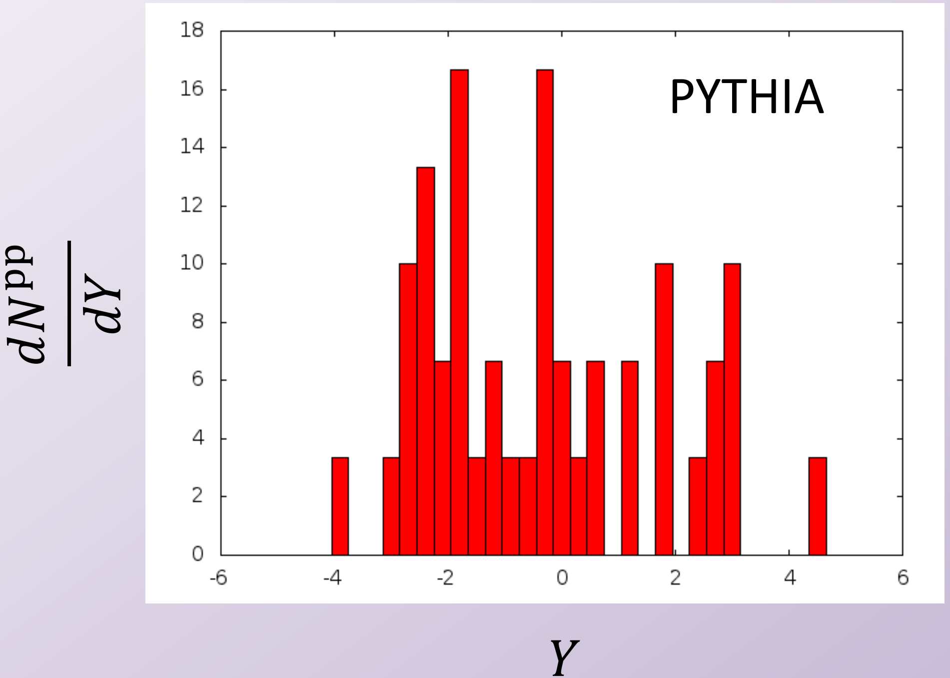
$$\delta^4(x - x') \Rightarrow \frac{1}{\Delta t}\frac{1}{(4\pi\lambda^2)^{\frac{3}{2}}}e^{-\frac{(x-x')^2}{4\lambda^2}}$$

λ: Gaussian width

Initial longitudinal profile

PYTHIA

Rapidity fluctuations
in pp collisions

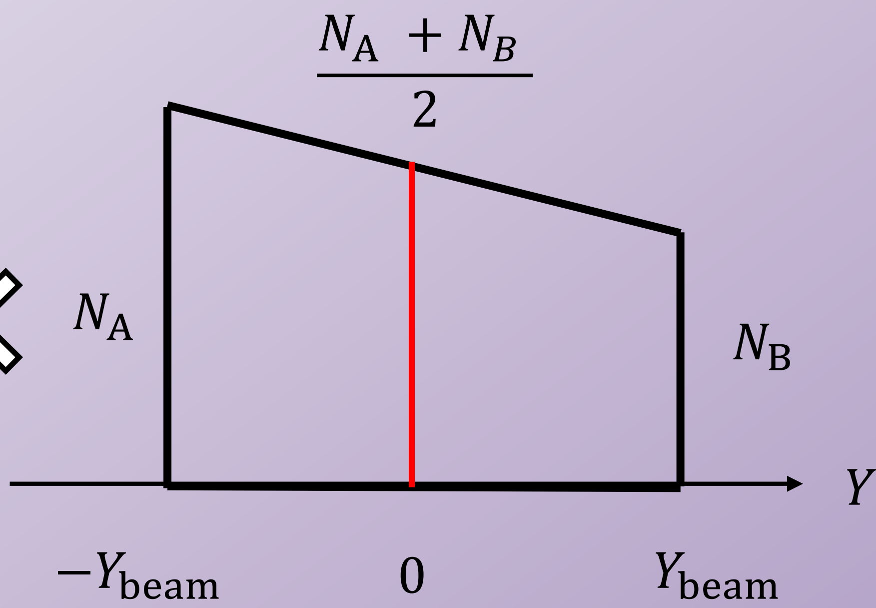


T. Sjöstrand et al., Comput. Phys. Commun. 191, 159 (2015)

BGK

Nuclear effect

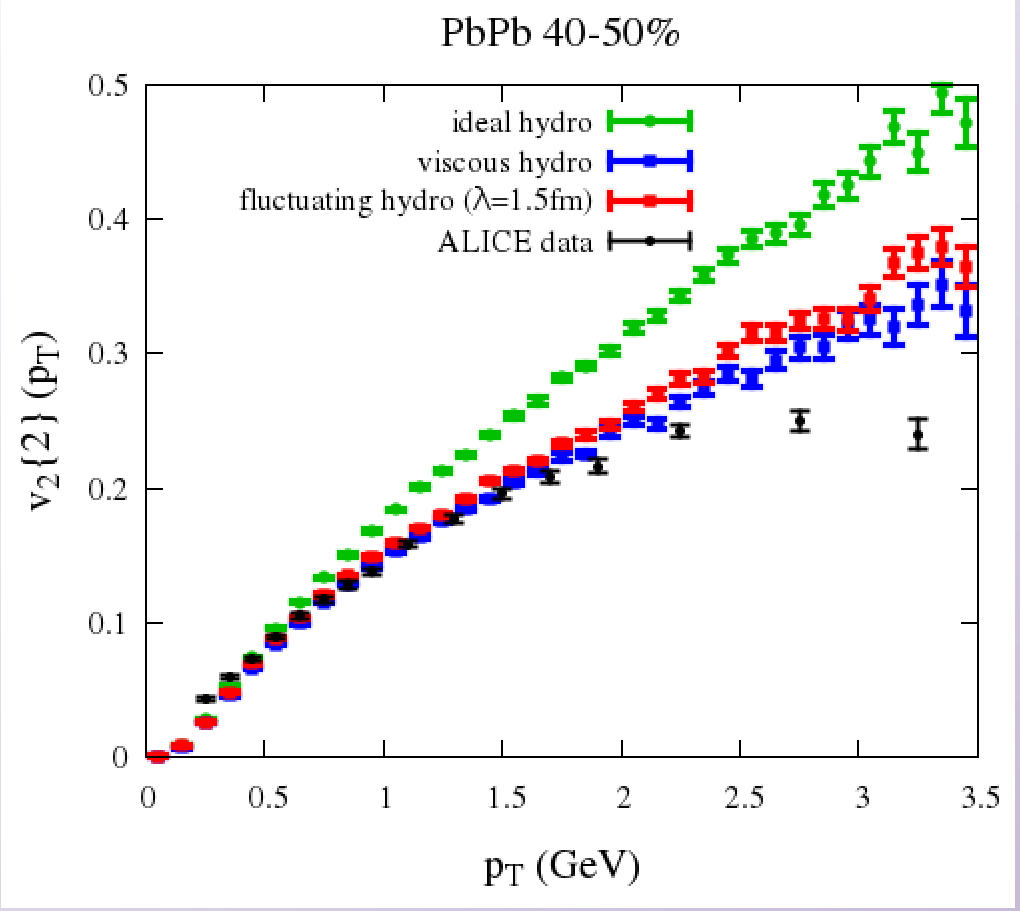
$N_{\rm part}$ scaling, twist



M. Okai et al., Phys. Rev. C 95, 054914 (2017)

p_T-differential v_2

w/o initial longitudinal fluctuations



Ideal hydro

→ Larger than ALICE data

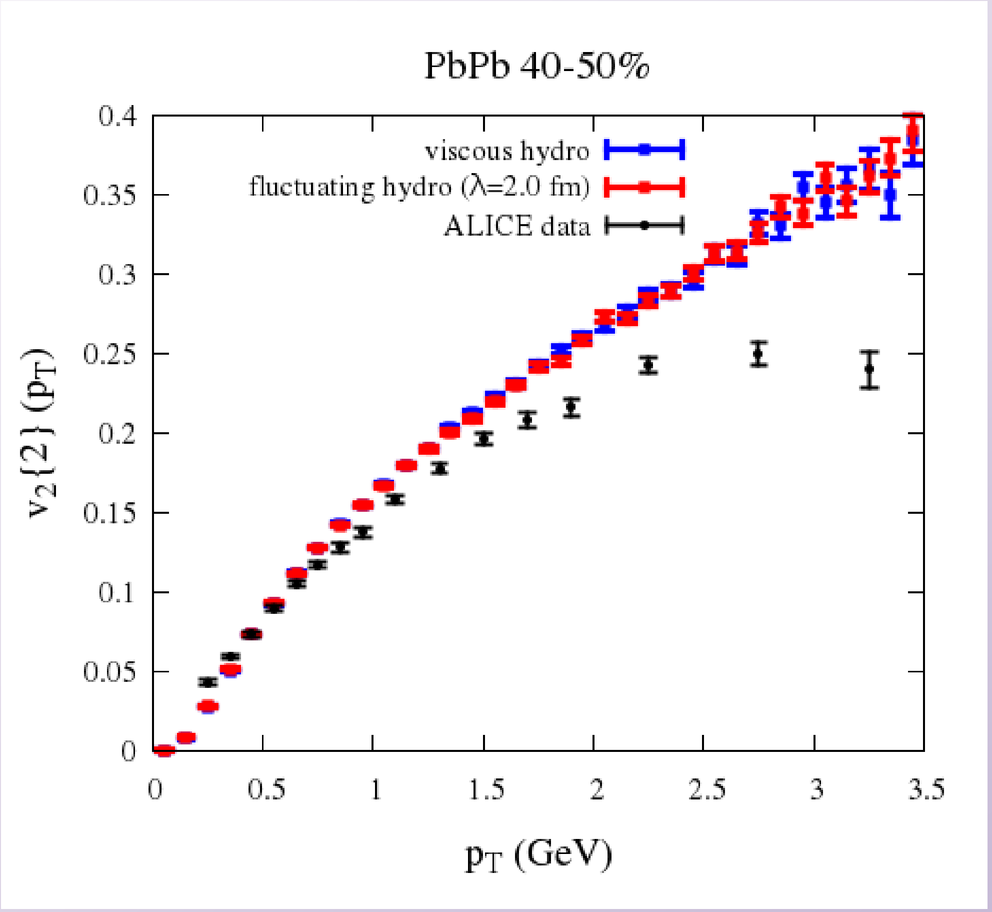
Viscous & Fluctuating hydro ($\eta/s = 1/4\pi$)

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

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

p_T-differential v_2

with initial longitudinal fluctuations



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

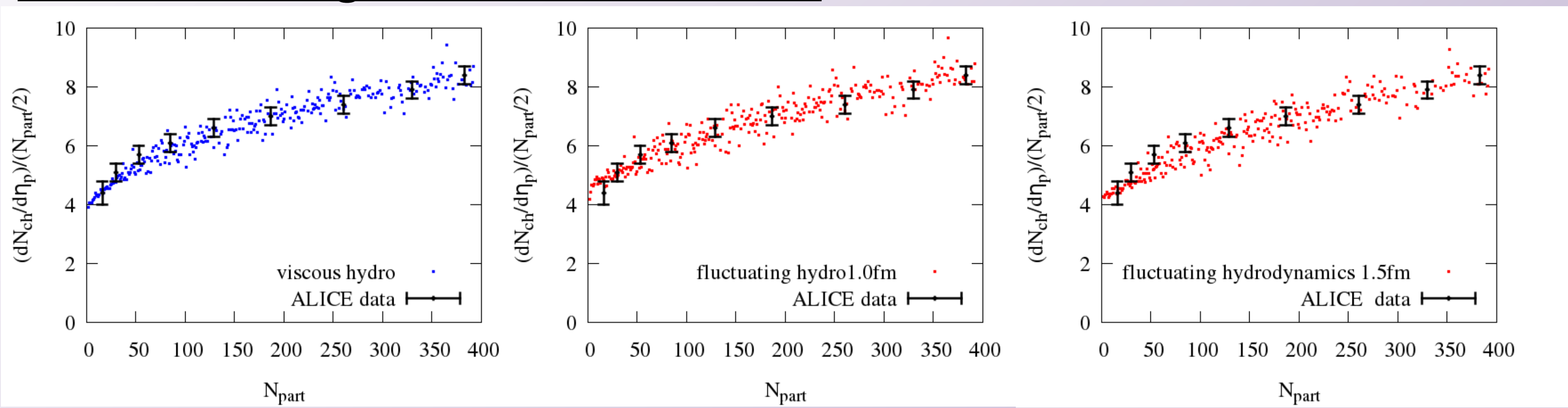
→ Good agreement with ALICE data below $p_T \sim 1.0$ GeV

→ Increase viscosity?

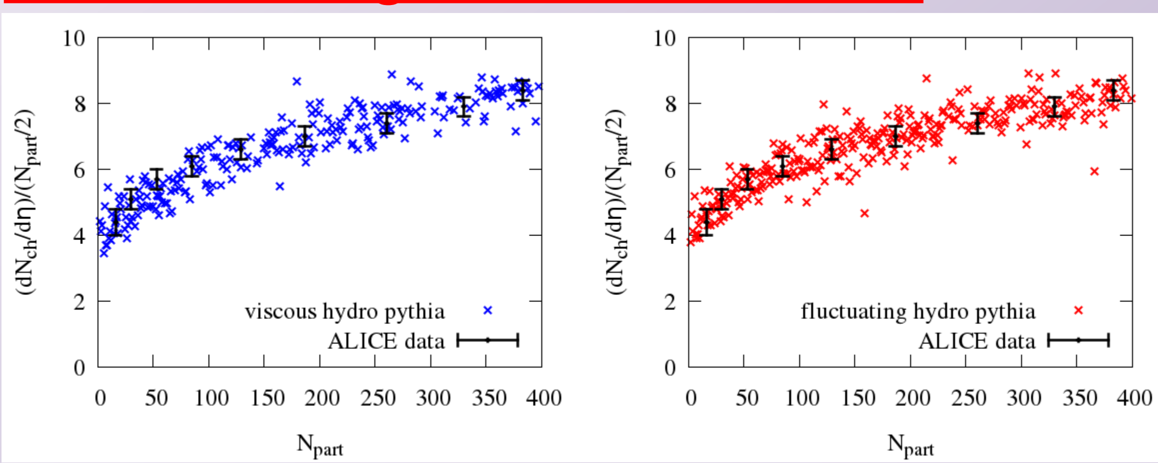
ALICE Collaboration,
Phys. Rev. Lett. 116 (2016) 132302

Centrality dependence of multiplicity

w/o initial longitudinal fluctuations



with initial longitudinal fluctuations



- Initial parameter tuning
- Centrality cut

ALICE Collaboration,
Phys.Rev.Lett.106, 032301 (2011)

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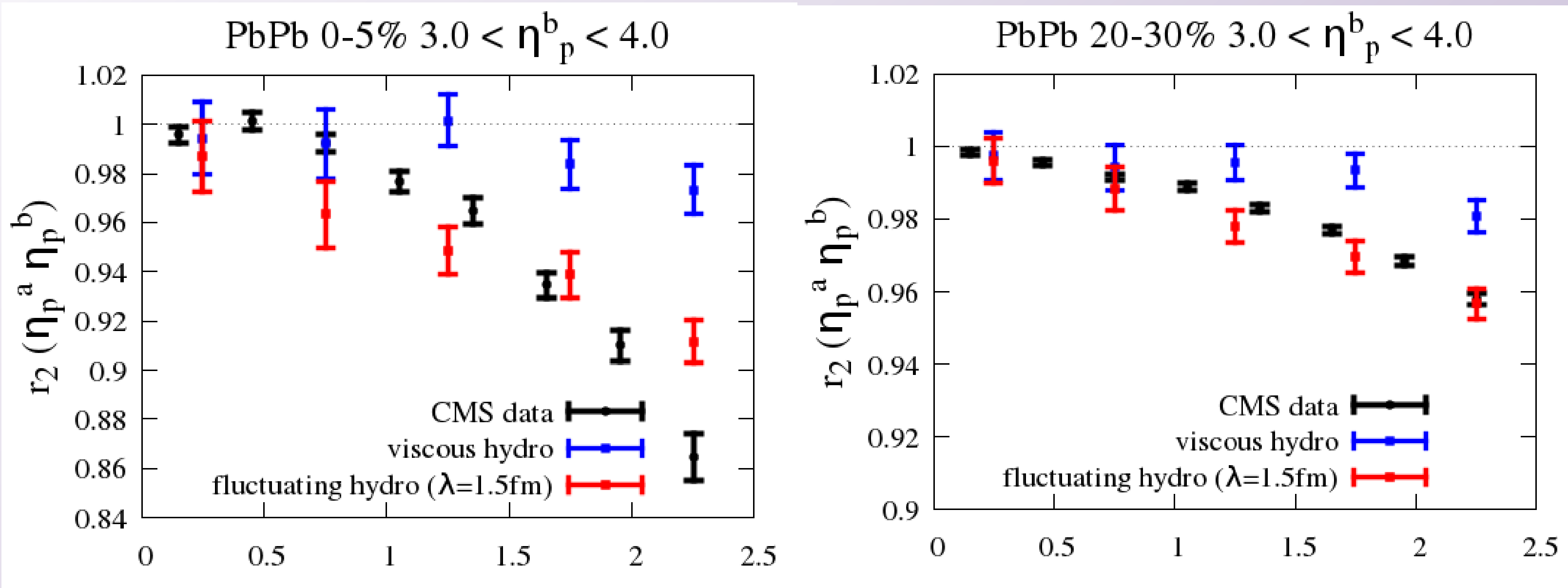
Rapidity decorrelation $r_2(\eta_p^a, \eta_p^b)$

<u>w/o initial longitudinal fluctuations</u>



$\sqrt{s_{NN}} = 2.76$ TeV

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

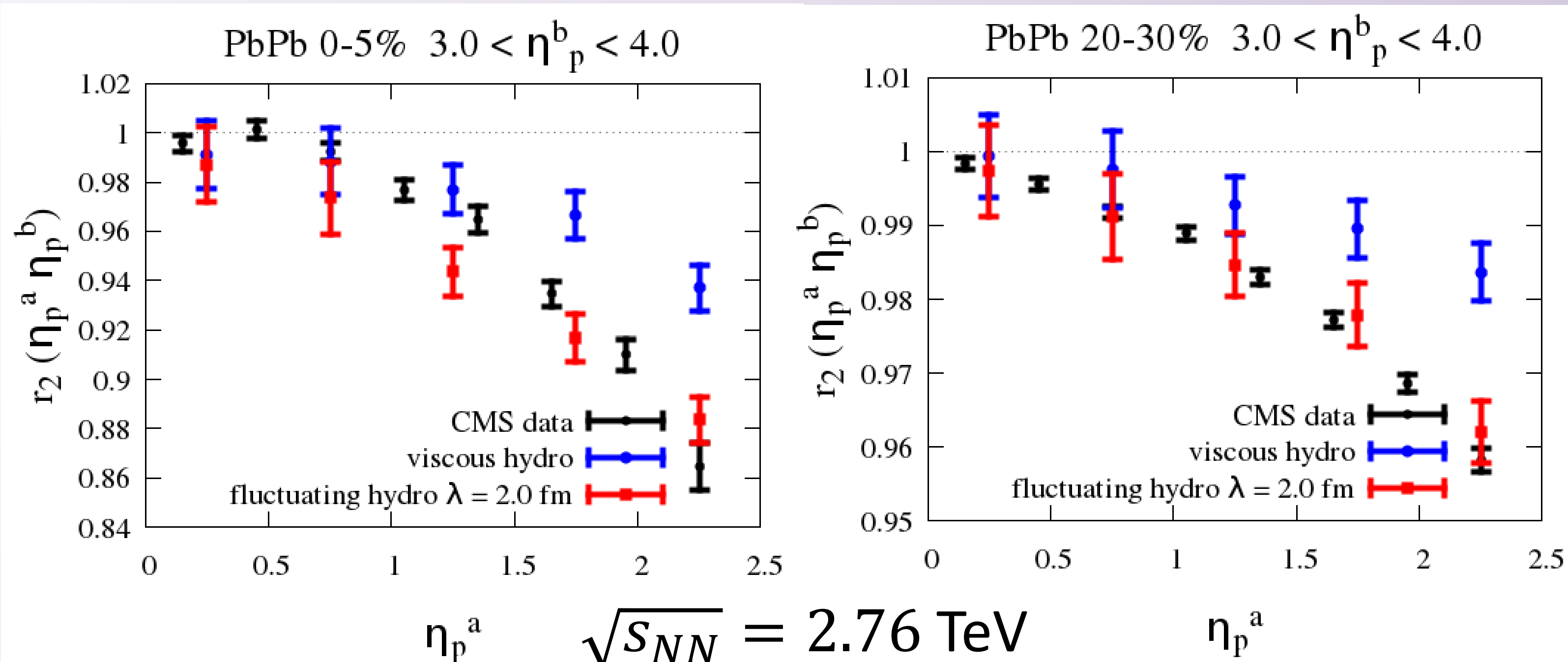
1 > Viscous > CMS data ≈ Fluctuating hydro

Hydrodynamic fluctuations

→ Rapidity decorrelation

Rapidity decorrelation $r_2(\eta_p^a, \eta_p^b)$

with initial longitudinal fluctuations



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

1 > Viscous > CMS data ≈ Fluctuating hydro

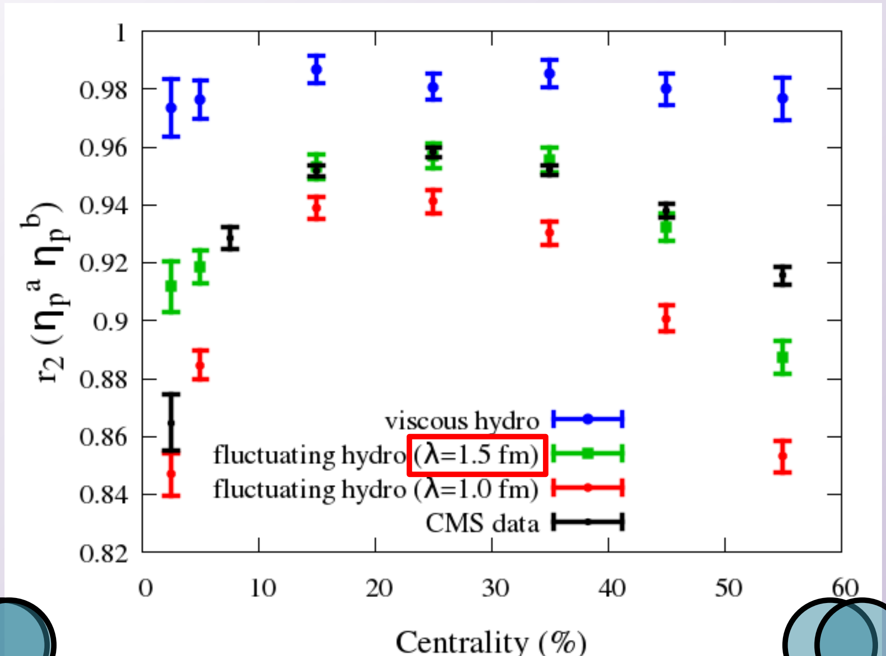
Initial longitudinal fluctuations ➡ Rapidity decorrelation

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Close to experimental data

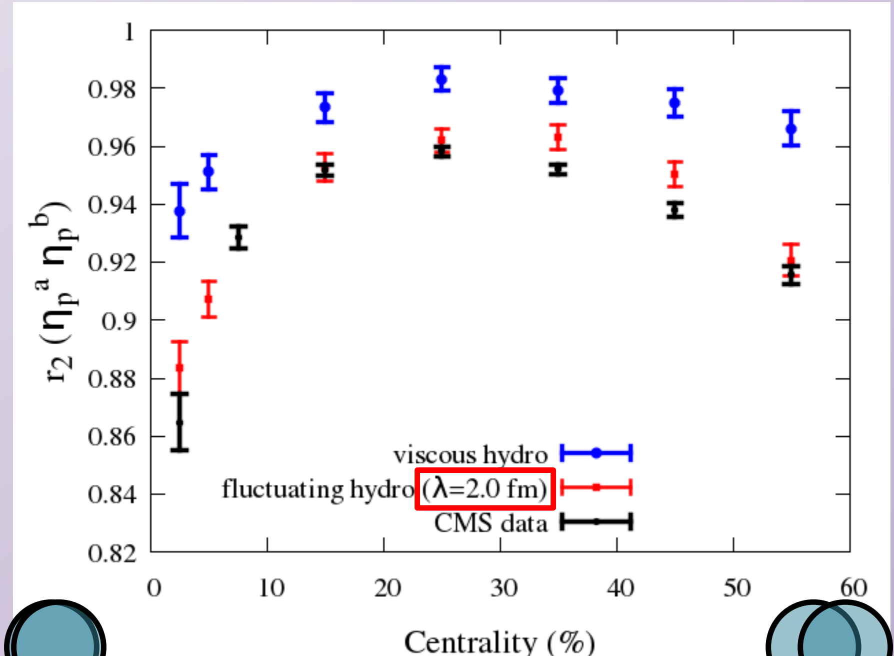
Centrality dependence of $r_2(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



$2.0 < \eta_p^a < 2.5, 3.0 < \eta_p^b < 4.0$

with initial longitudinal fluctuations



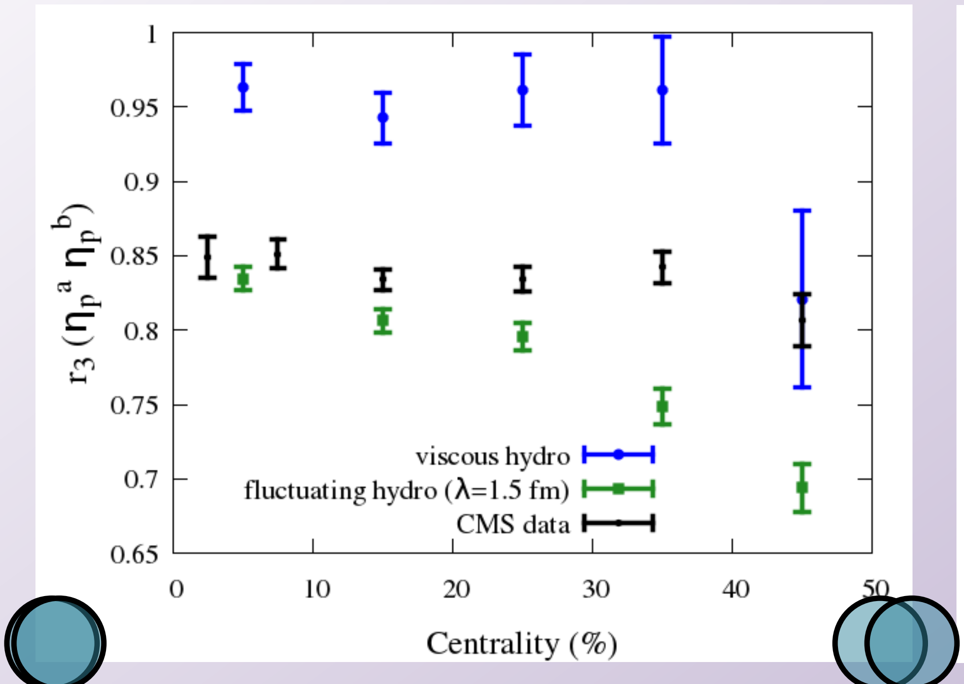
$2.0 < \eta_p^a < 2.5, 3.0 < \eta_p^b < 4.0$

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Correct centrality dependence of r_2

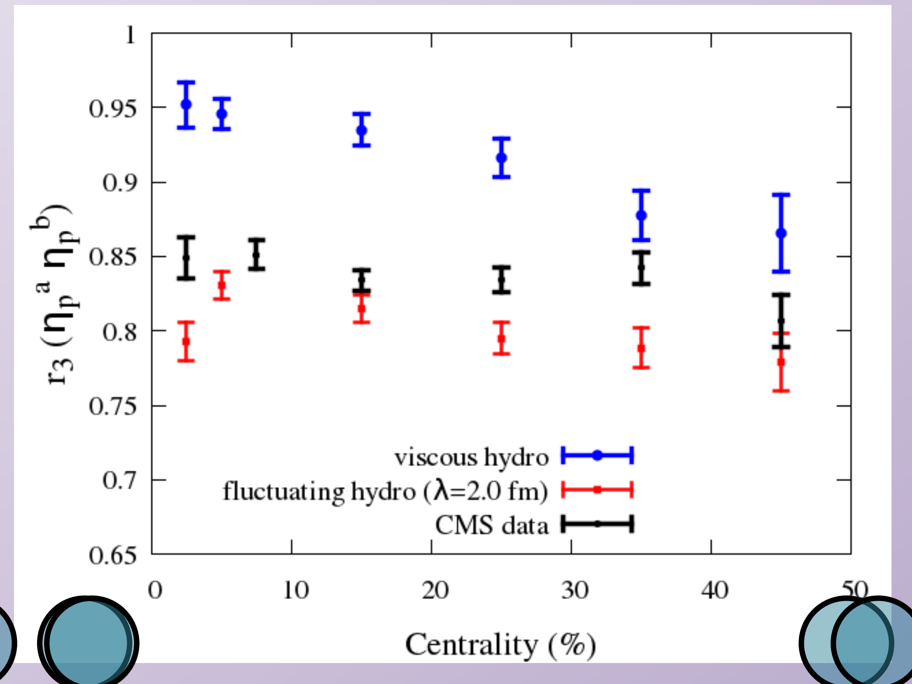
Centrality dependence of $r_3(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



$2.0 < \eta_p^a < 2.5,\ 3.0 < \eta_p^b < 4.0$

with initial longitudinal fluctuations



$2.0 < \eta_p^a < 2.5,\ 3.0 < \eta_p^b < 4.0$

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Improvement in reproducing centrality dependence of r_3

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- **Other observables**
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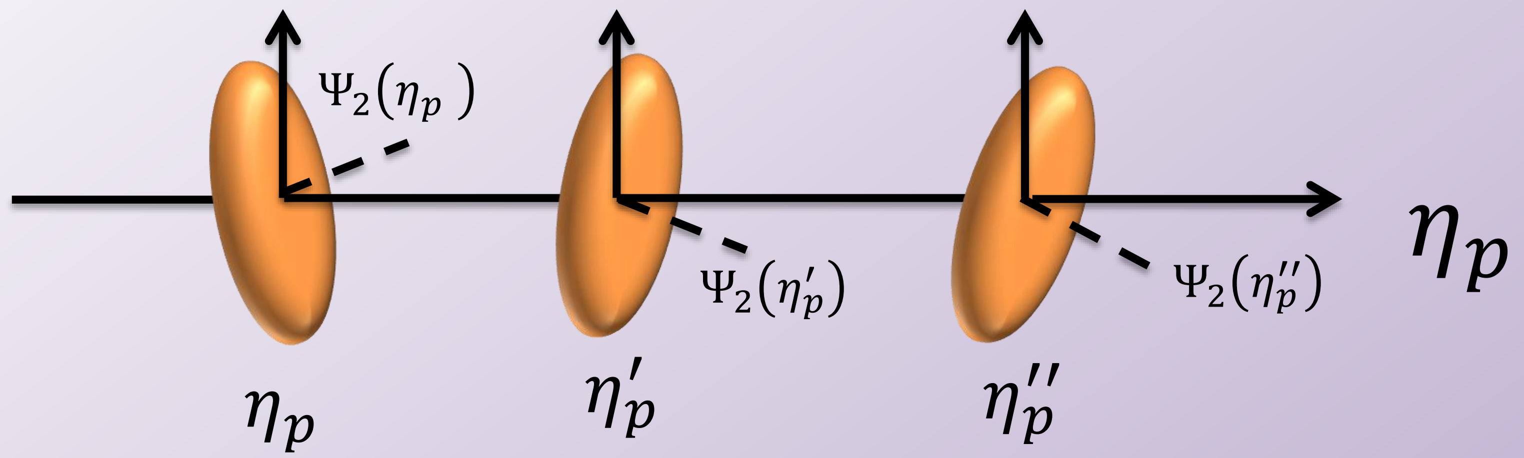
Legendre series



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

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

P_k : Legendre polynomial

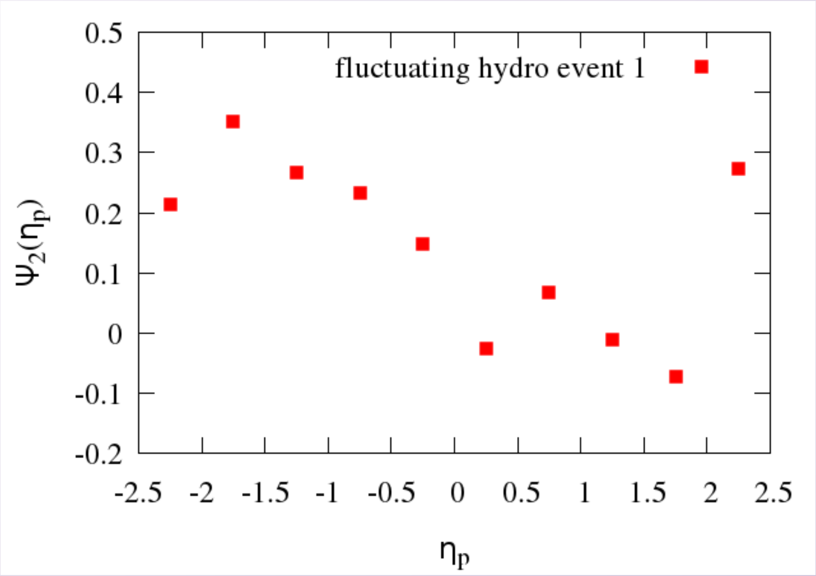
$$P_1(\eta_p) = \eta_p$$

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

a_2^k, b_2^k: Legendre coefficients

⇒Quantity to understand η_p dependent

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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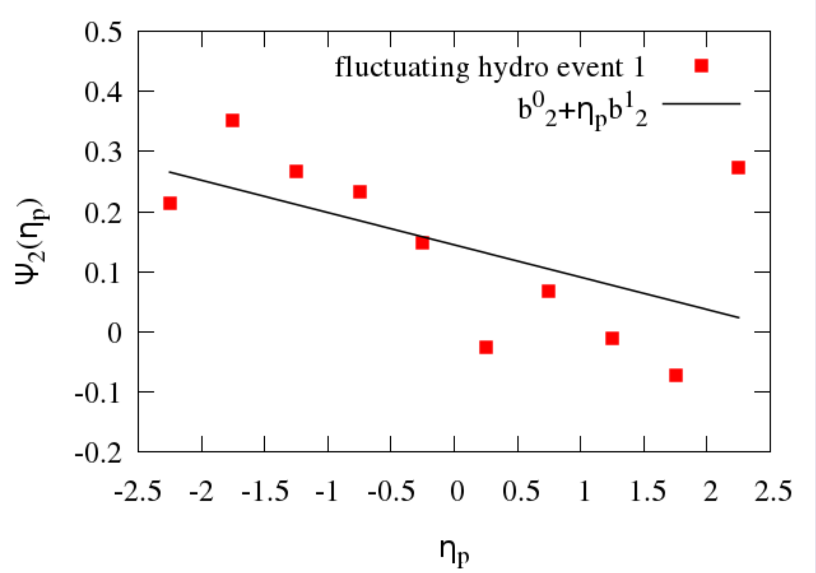
Legendre series



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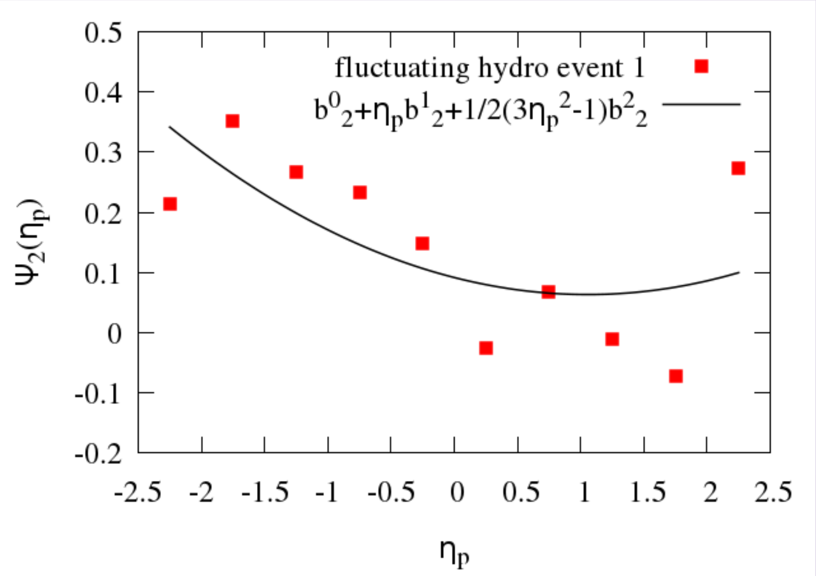

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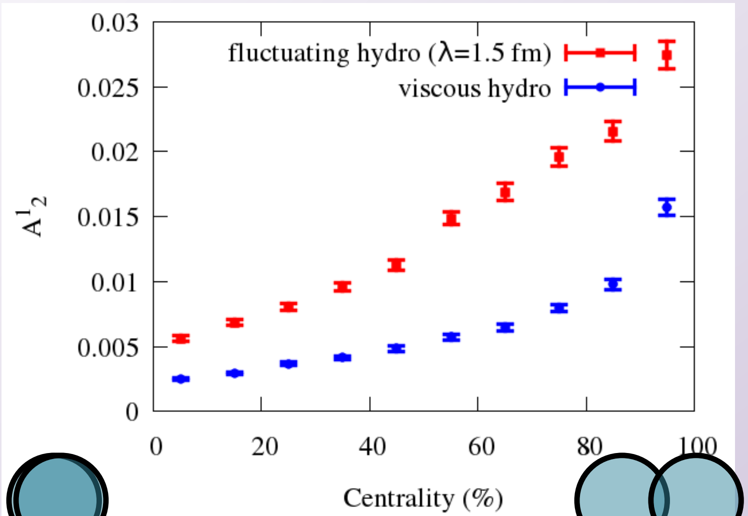
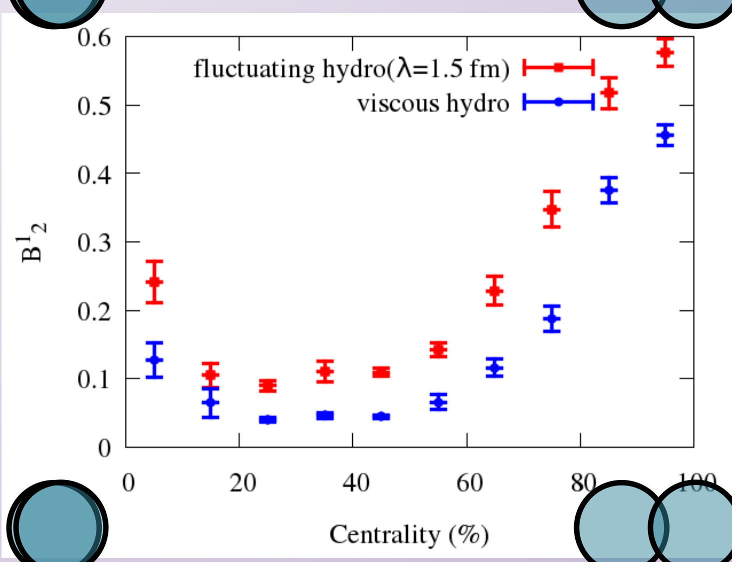
a_2^k, b_2^k: Legendre coefficients

⇒Quantity to understand η_p dependence

Legendre coefficients

w/o initial longitudinal fluctuations





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

Fluctuating hydro $>$ Viscous hydro

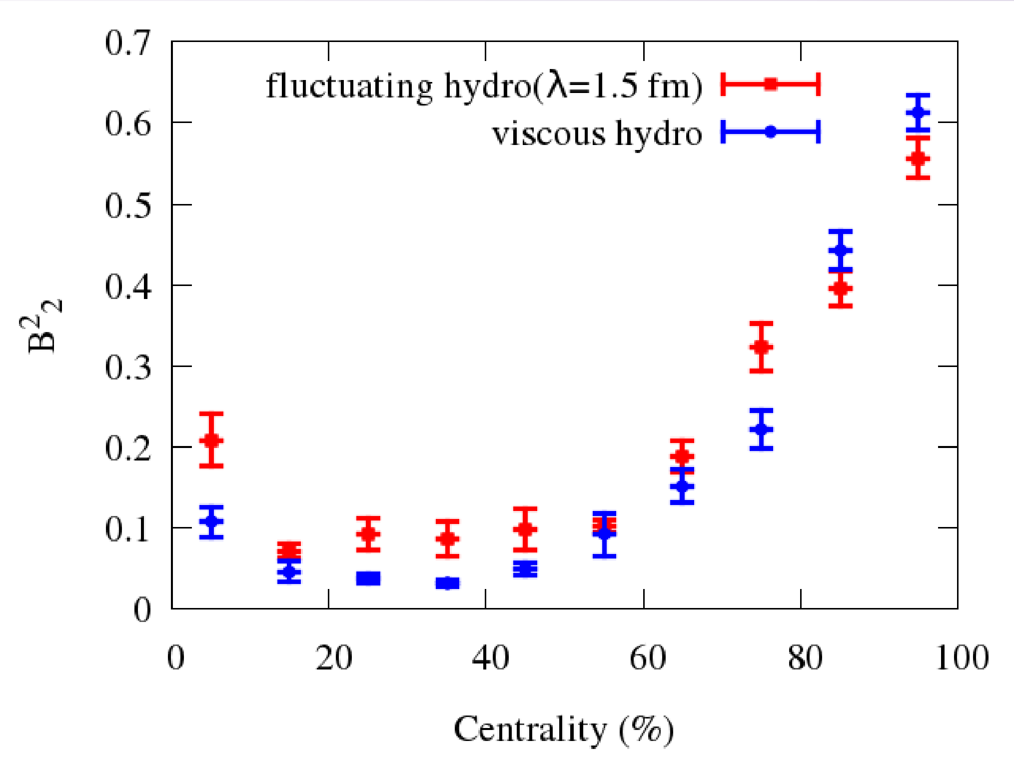
Hydrodynamic fluctuations

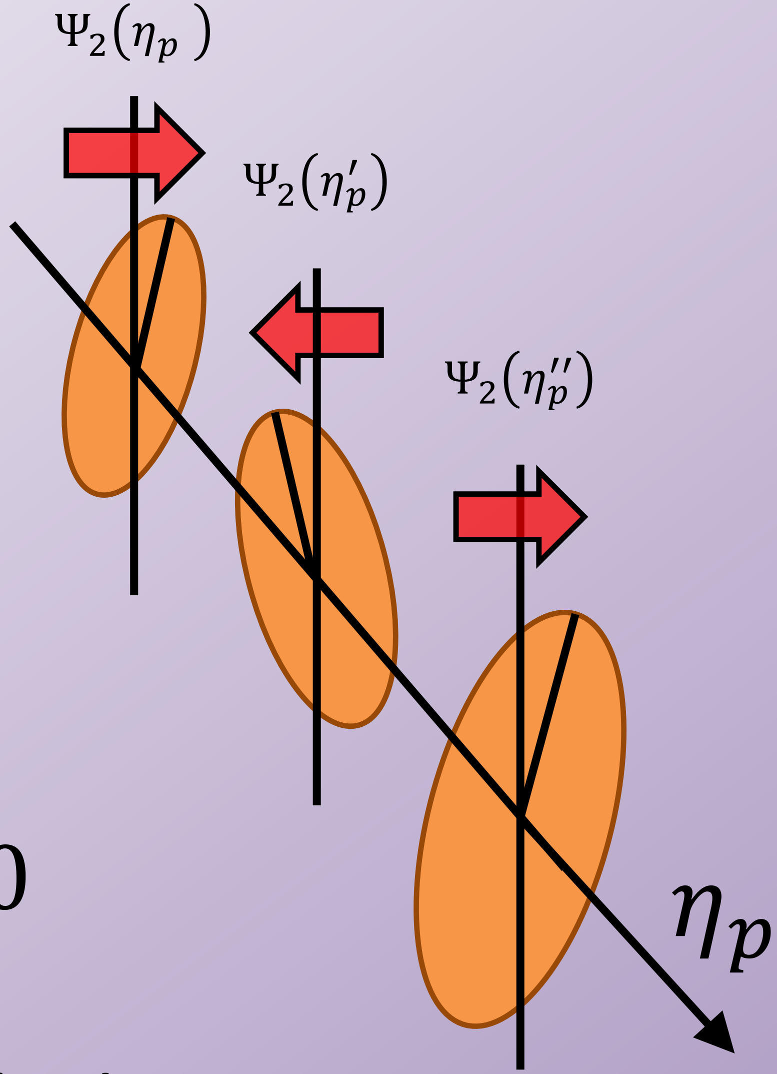
⇒increase η_p dependence

⇒increase Legendre coefficient

Legendre coefficients

w/o initial longitudinal fluctuations





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

Fluctuating hydro > Viscous hydro

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Summary

- Integrated dynamical model based on full 3D hydrodynamics
  - Initial longitudinal fluctuations
  - Hydrodynamic fluctuations
- Rapidity decorrelation $r_2(\eta_p^a, \eta_p^b)$
  - $r_2(\eta_p^a, \eta_p^b)$ close to experimental data
  - Importance of hydrodynamic fluctuations and initial longitudinal fluctuations in understanding centrality dependence of r_2 and r_3
- Legendre coefficients $A_2^k,\ B_2^k$
  - Fluctuating hydrodynamic model has larger $\eta_p$dependence than viscous hydrodynamic model
  - $B_2^2 = 2^{\mathrm{nd}}$ order twist ≠0

Back up

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

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

$$= 2\eta\Delta^{\mu\upsilon}{}_{\alpha\beta}\partial^\alpha \pi^\beta + \delta\pi^{\mu\nu}$$