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Rapidity decorrelation caused by hydrodynamic fluctuations and initial longitudinal fluctuations

Azumi Sakai
Sophia University
Collaborators: Koichi Murase and Tetsufumi Hirano

Outline

- Introduction
- Model
- Results
- Summary

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Rapidity decorrelation and fluctuations

Properties of QGP

Dynamics

Longitudinal Dynamics

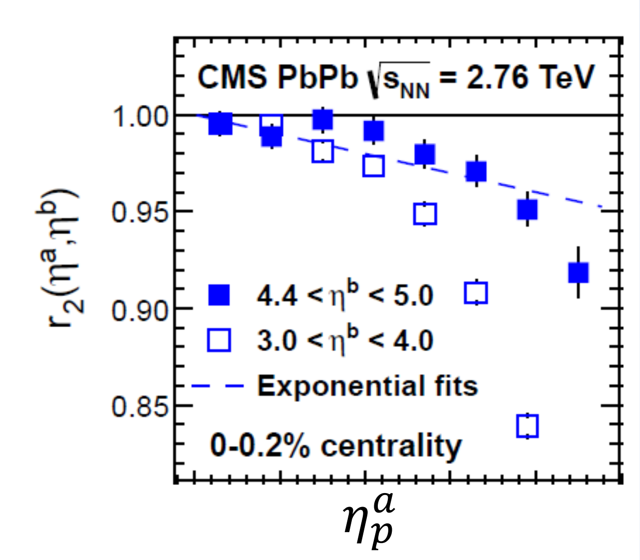
- Hydrodynamic fluctuations
- Initial fluctuations

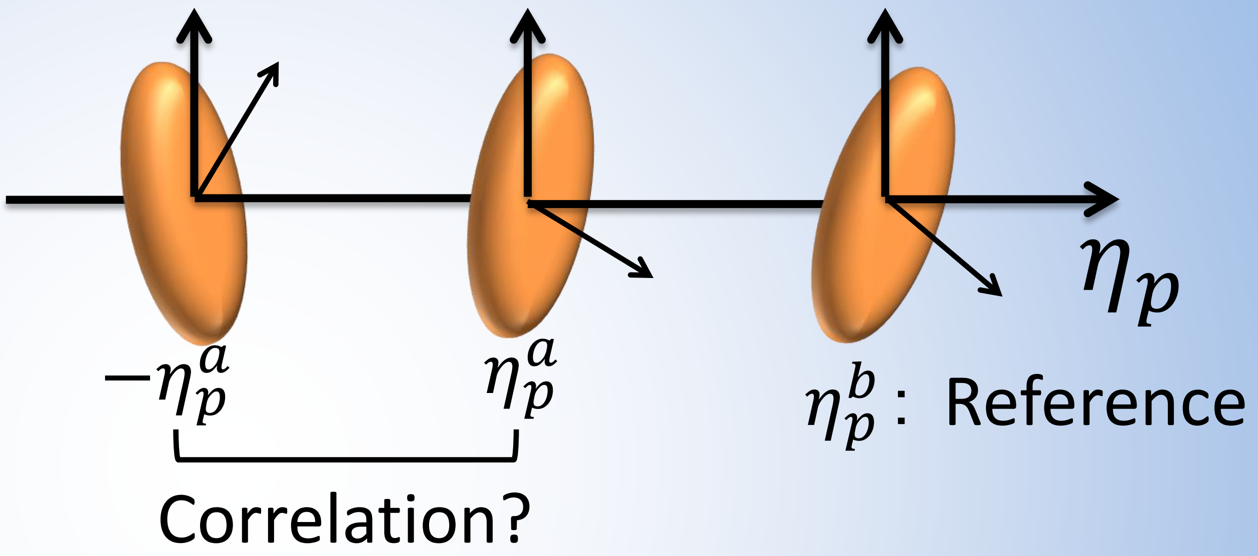
Observables

Rapidity decorrelation

- Factorization ratio $r_n(\eta^a, \eta^b)$

Factorization ratio r_n





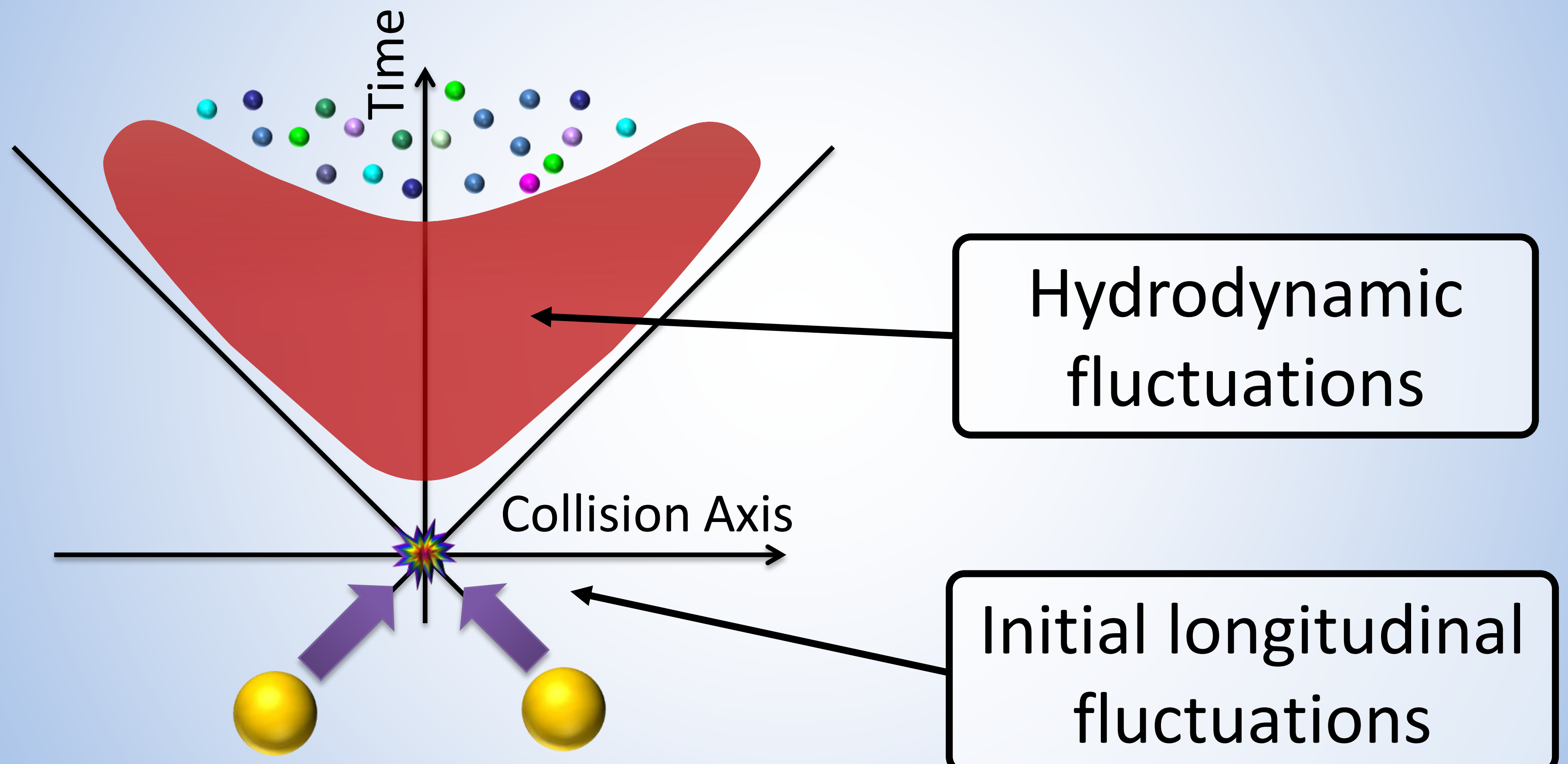
$$r_n(\eta_p^a,\eta_p^b)=\frac{V_{n\Delta}(-\eta_p^a,\eta_p^b)}{V_{n\Delta}(\eta_p^a,\eta_p^b)}\ ,\quad V_{n\Delta}=\langle\cos(n\Delta\phi)\rangle$$

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

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

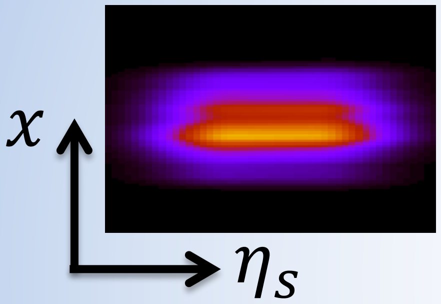
CMS Collaboration, Phys. Rev. C 92, 034911 (2015)
F.G. Gardim *et al.*, Phys. Rev . C 87, 031901 (2013)

Space-time evolution of heavy ion collisions

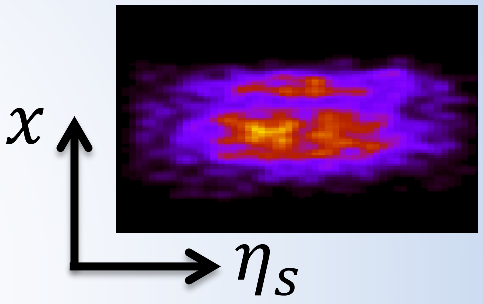


Fluctuations in heavy ion collisions

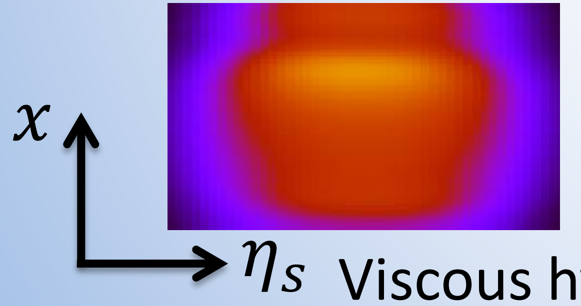
Initial state fluctuations



Initial longitudinal fluctuations

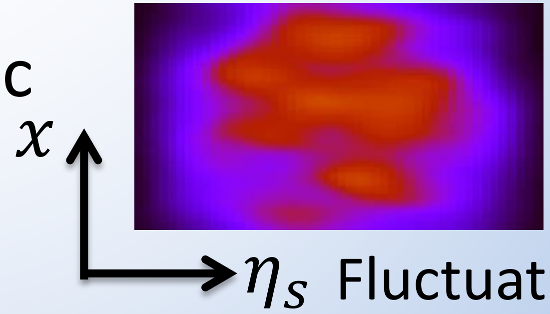


Fluctuations during hydrodynamic evolution



Viscous hydro

Hydrodynamic fluctuations



Fluctuating hydro

Purpose of study

Understand QGP longitudinal dynamics by

hydrodynamic fluctuations

+

initial longitudinal fluctuations

Examine the effect by

Rapidity decorrelations

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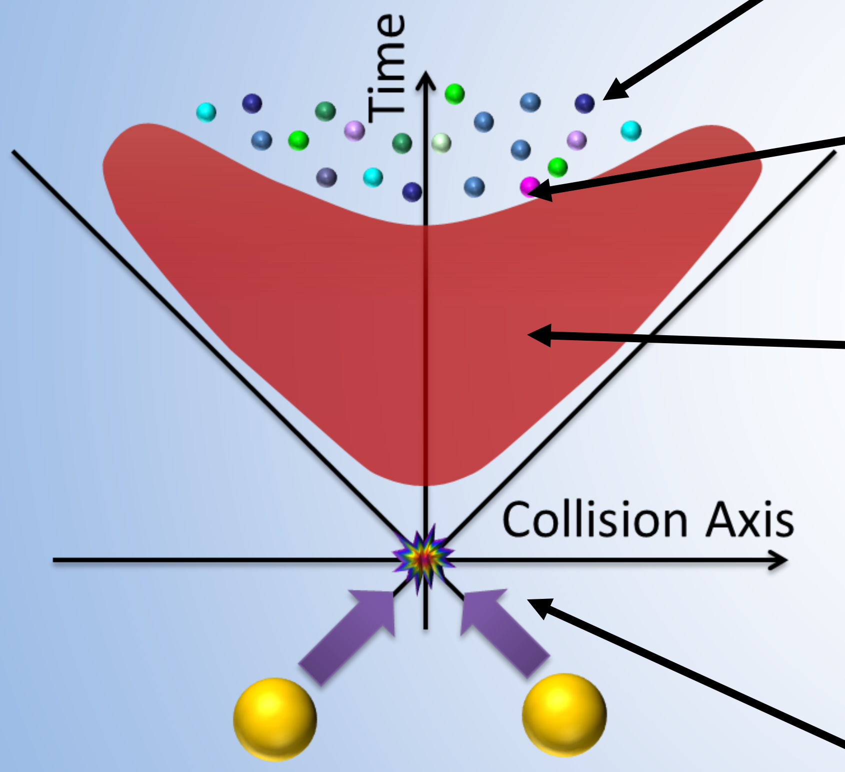
Integrated dynamical model



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

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 modified BGK

Transverse: MC-Glauber model

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

Hydrodynamic fluctuations

Shear stress tensor (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 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

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

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

T: temperature

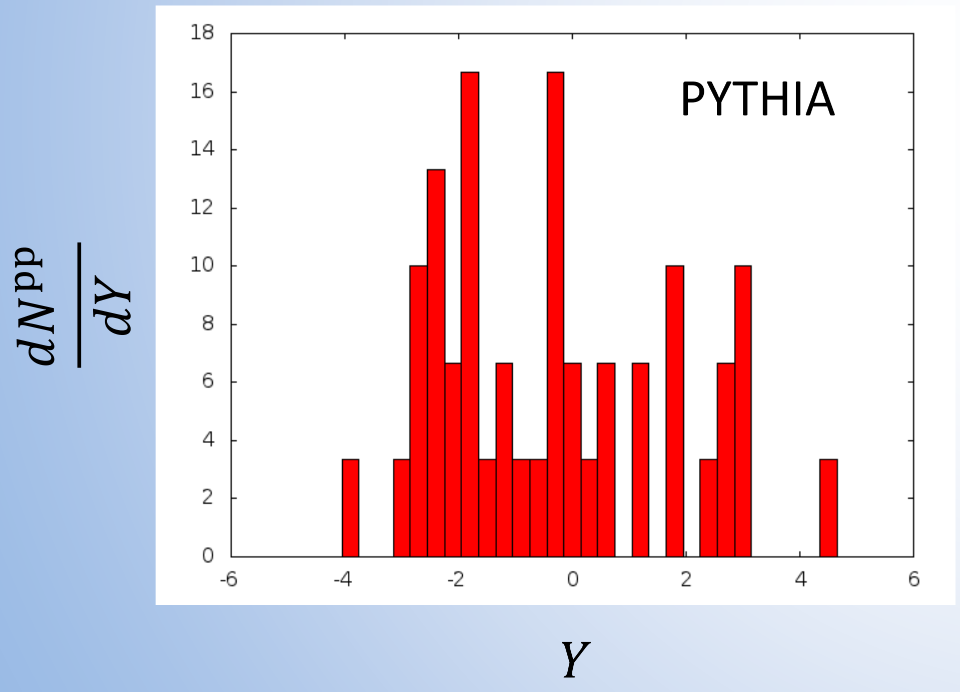
η: shear viscosity

λ: Gaussian width

Initial longitudinal profile

PYTHIA

Rapidity fluctuations
in pp collision at 200 GeV

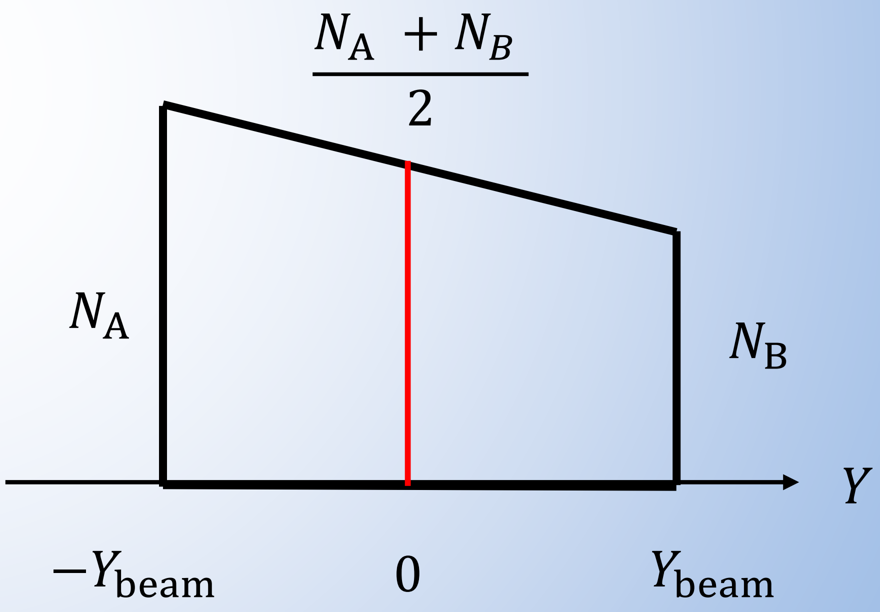


T. Sjöstrand *et al.*, Comput. Phys. Commun. 191, 159 (2015)

Modified BGK

Nuclear effect

N_{part} scaling → twist



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

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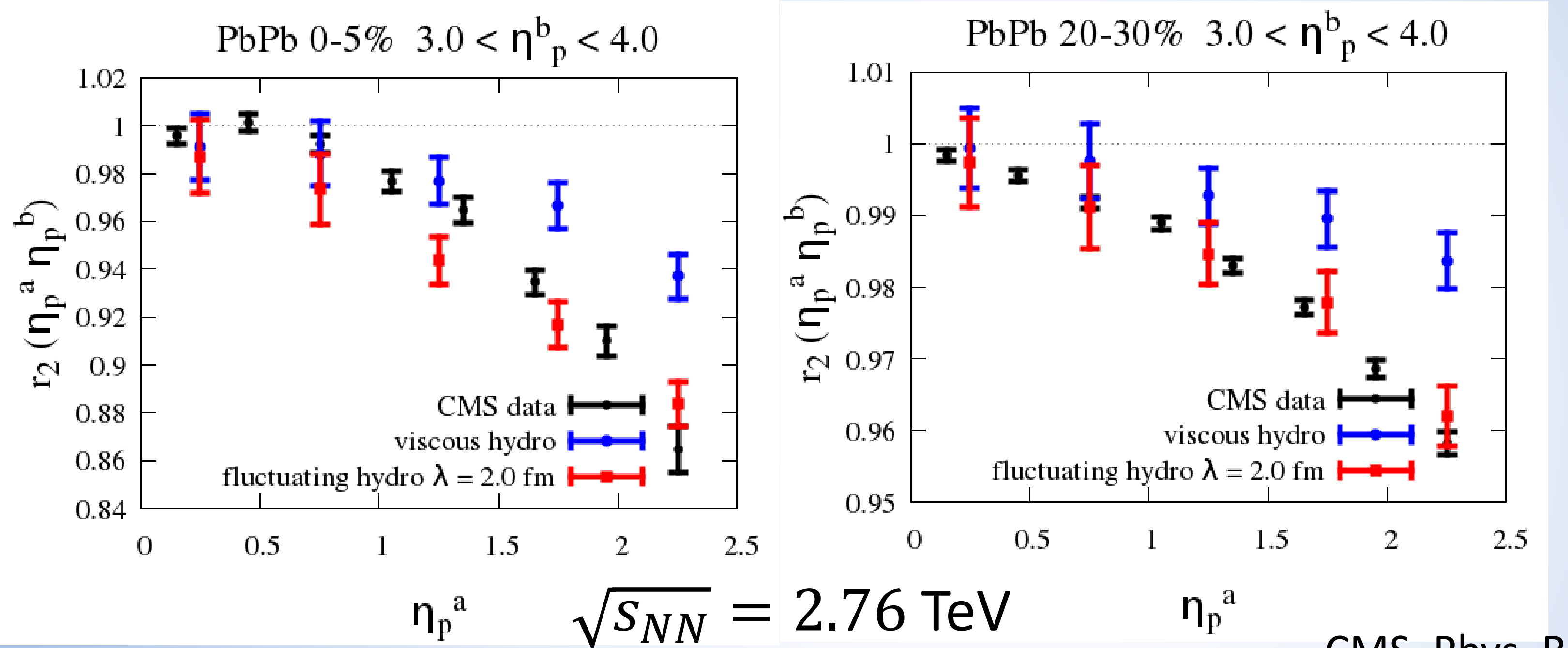
Factorization ratio $r_2(\eta_p^a, \eta_p^b)$

with initial longitudinal fluctuations



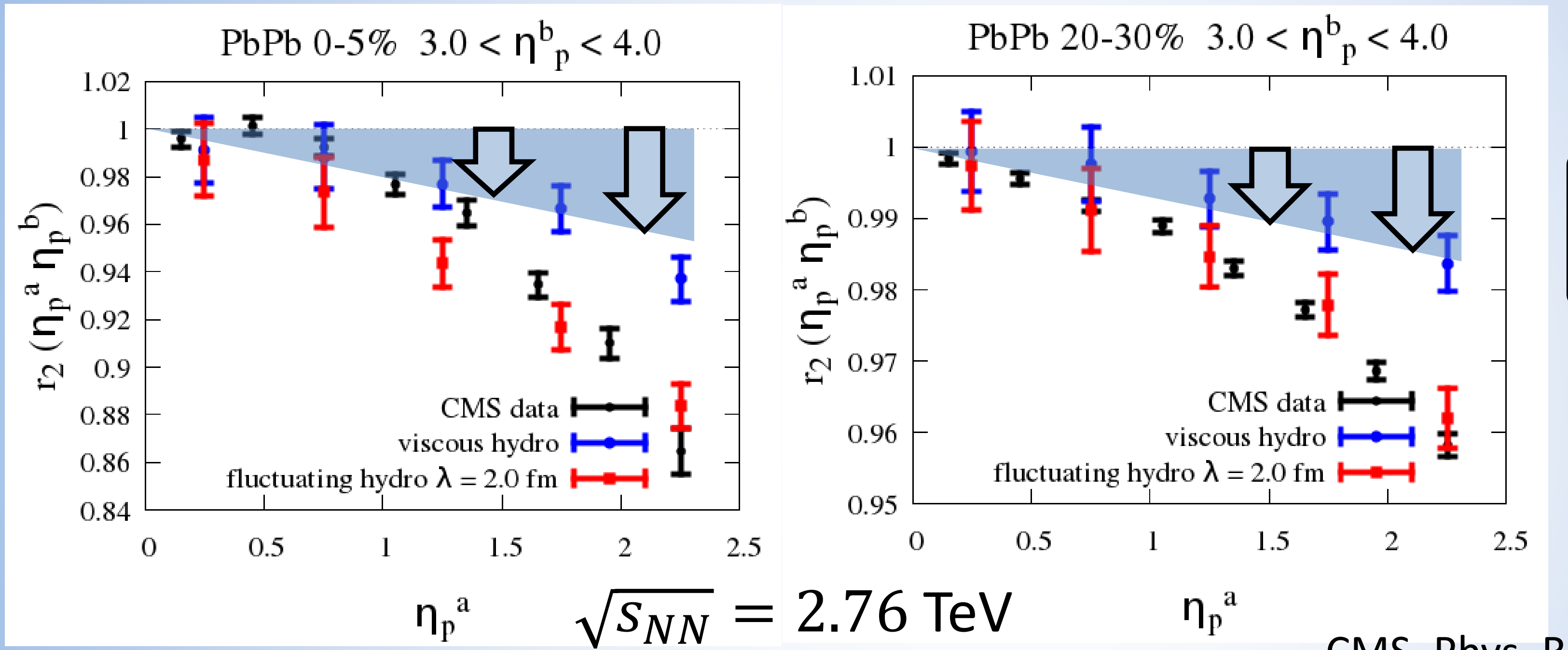
$\sqrt{s_{NN}} = 2.76$ TeV

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

1 > Viscous > CMS data ≈ Fluctuating hydro

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

with initial longitudinal fluctuations



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

Initial longitudinal fluctuations

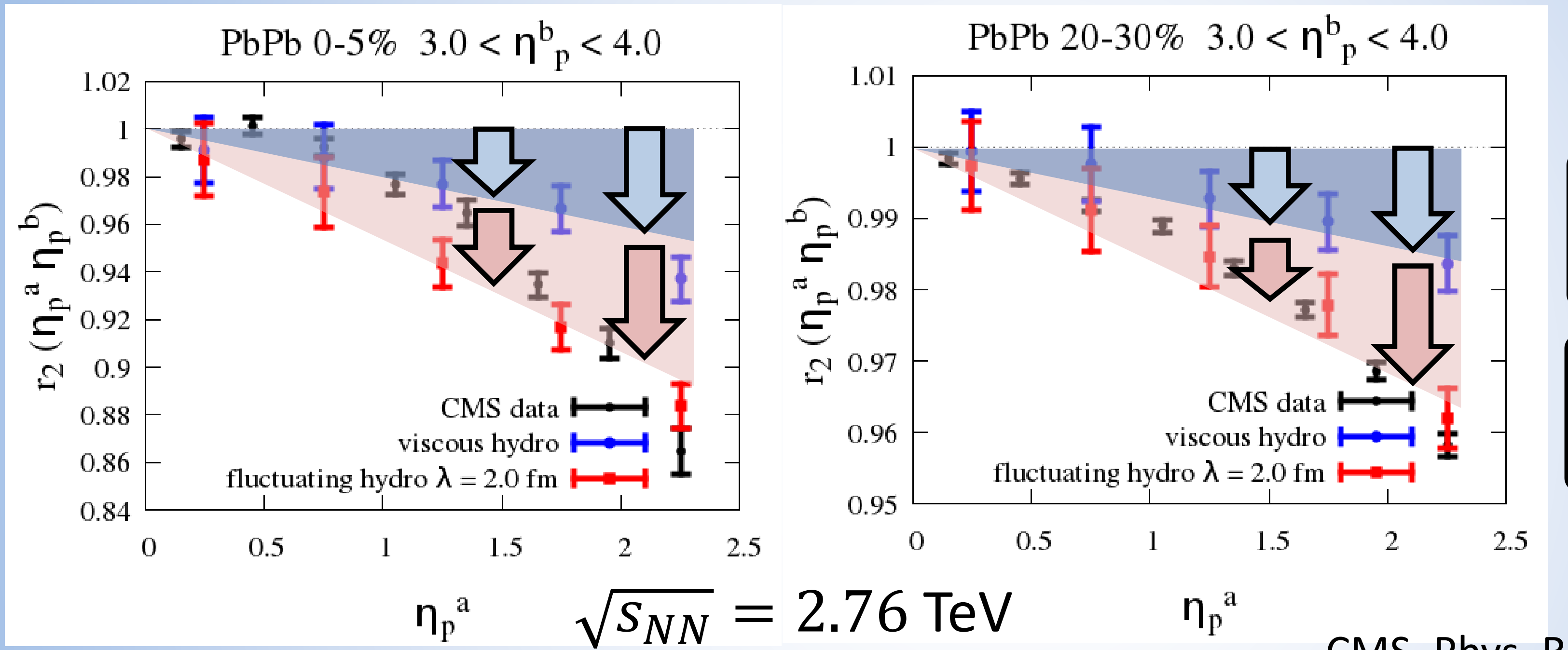
CMS, Phys. Rev. C 92, 034911 (2015).

1 > Viscous > CMS data ≈ Fluctuating hydro

Initial longitudinal fluctuations ➡ Rapidity decorrelation

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

with initial longitudinal fluctuations



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

Initial longitudinal fluctuations

Hydrodynamic fluctuations

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

1 > Viscous > CMS data ≈ Fluctuating hydro

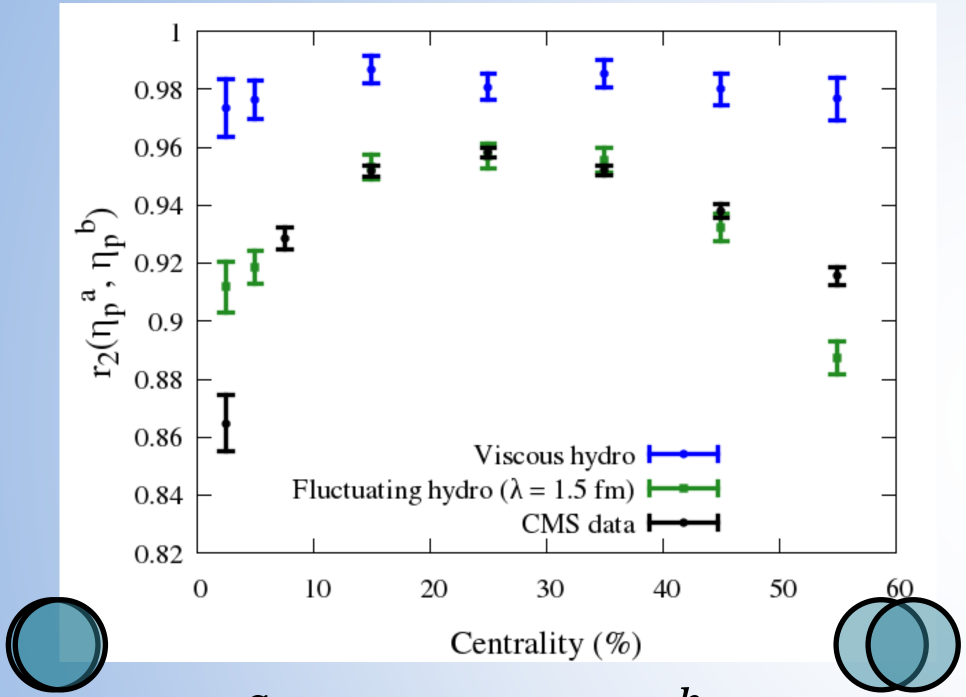
Initial longitudinal fluctuations ➡ Rapidity decorrelation

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Close to experimental data

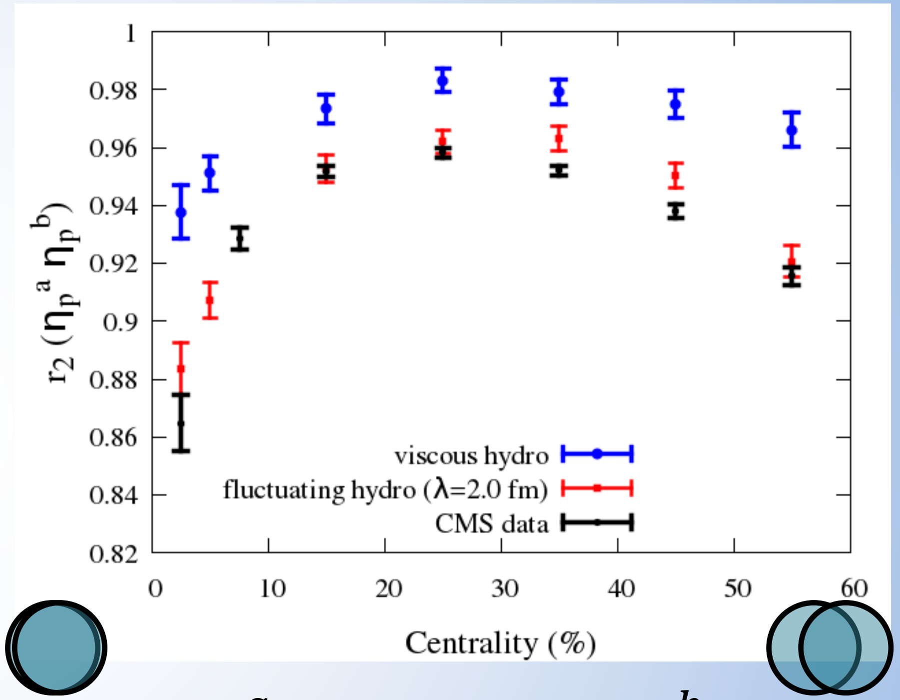
Centrality dependence of $r_2(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



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

with initial longitudinal fluctuations



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

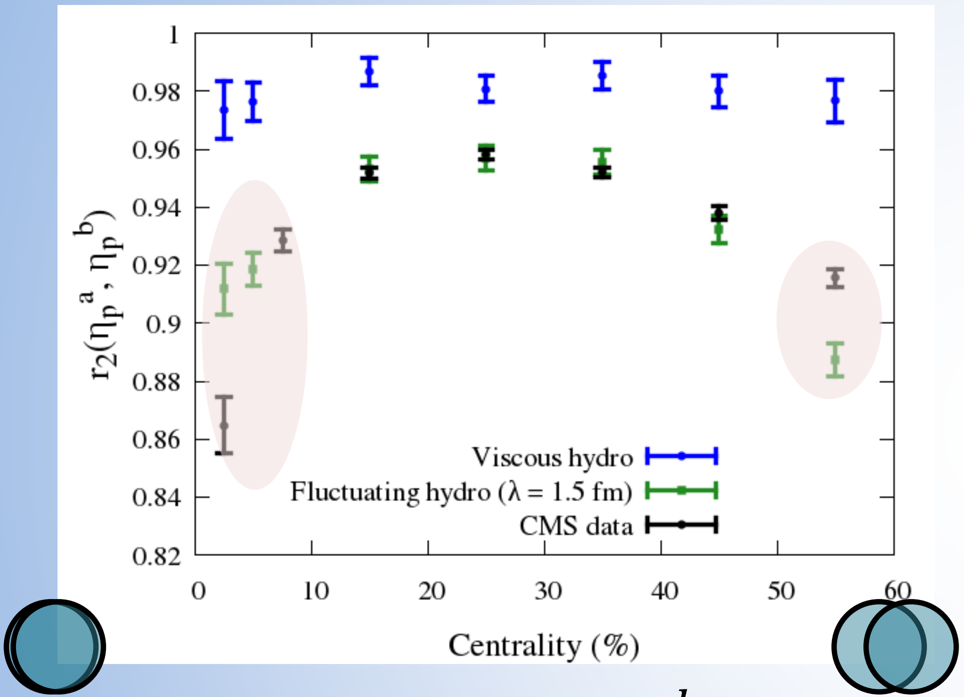
CMS, Phys. Rev. C 92, 034911 (2015).

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Correct centrality dependence of r_2

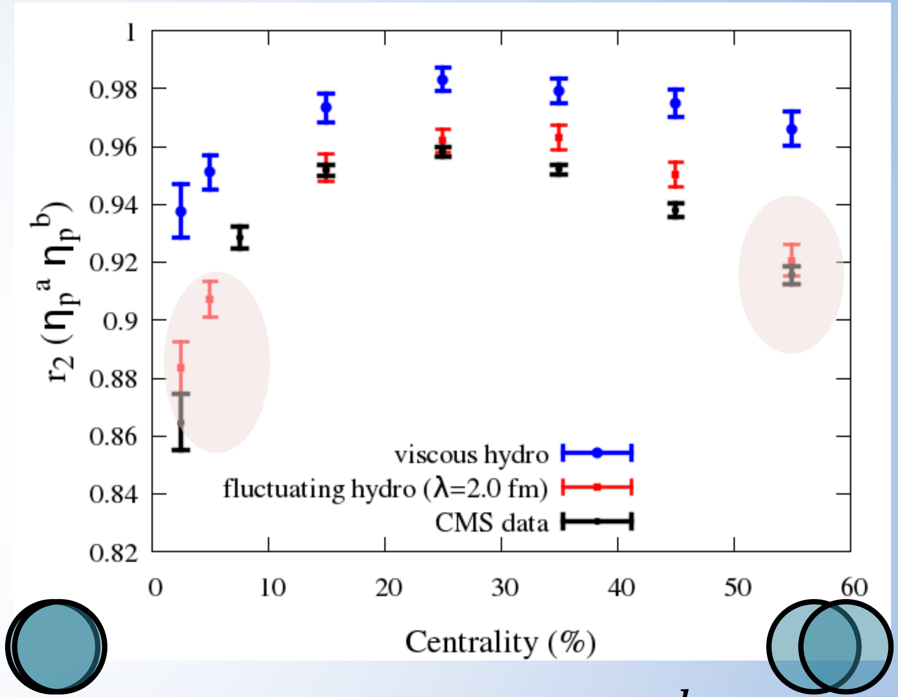
Centrality dependence of $r_2(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



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

with initial longitudinal fluctuations



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

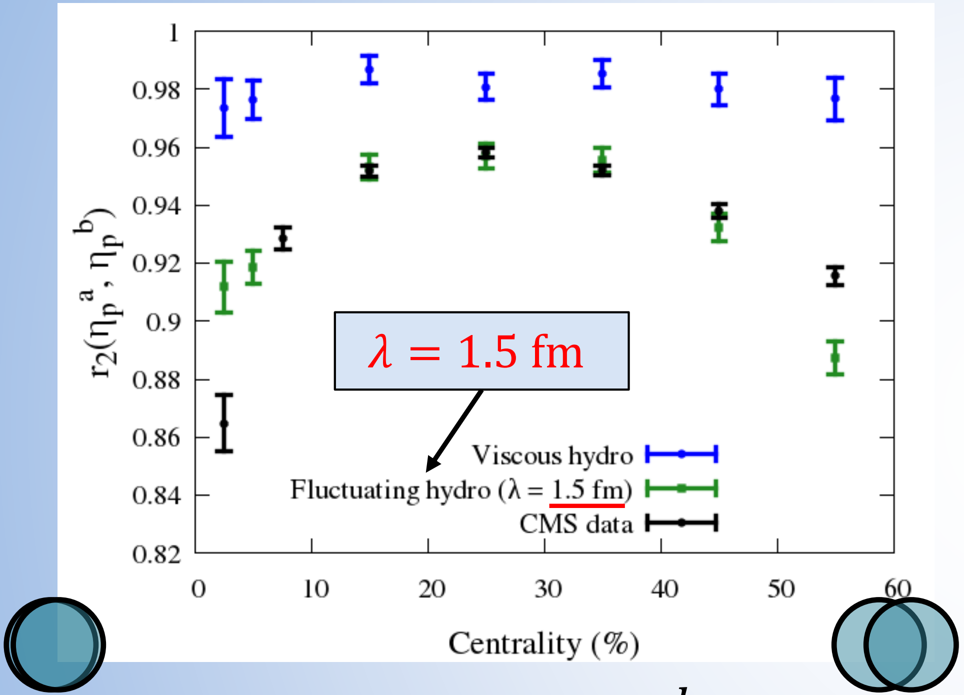
CMS, Phys. Rev. C 92, 034911 (2015).

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Correct centrality dependence of r_2

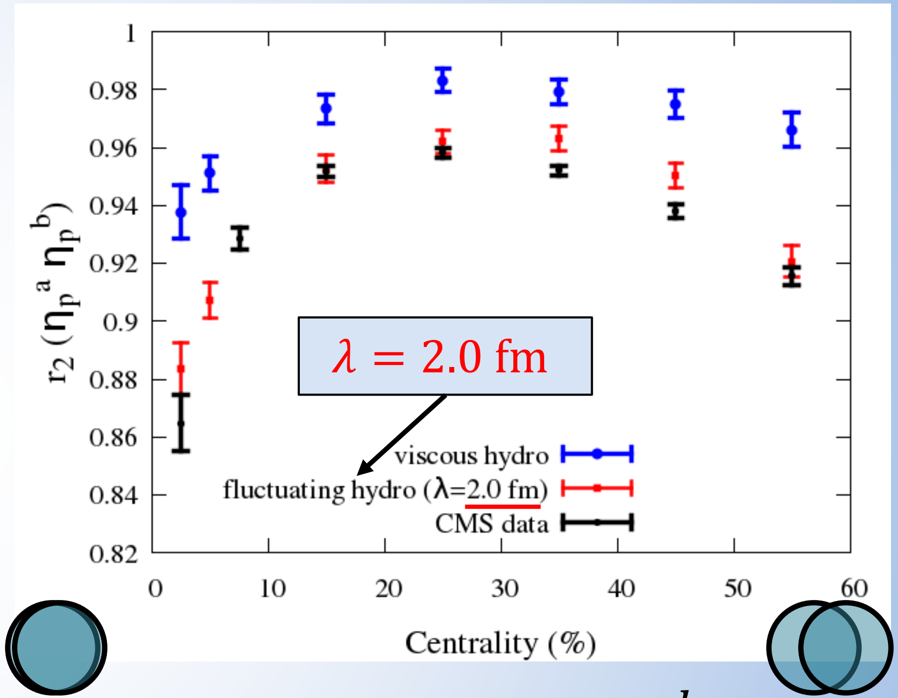
Centrality dependence of $r_2(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



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

with initial longitudinal fluctuations



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

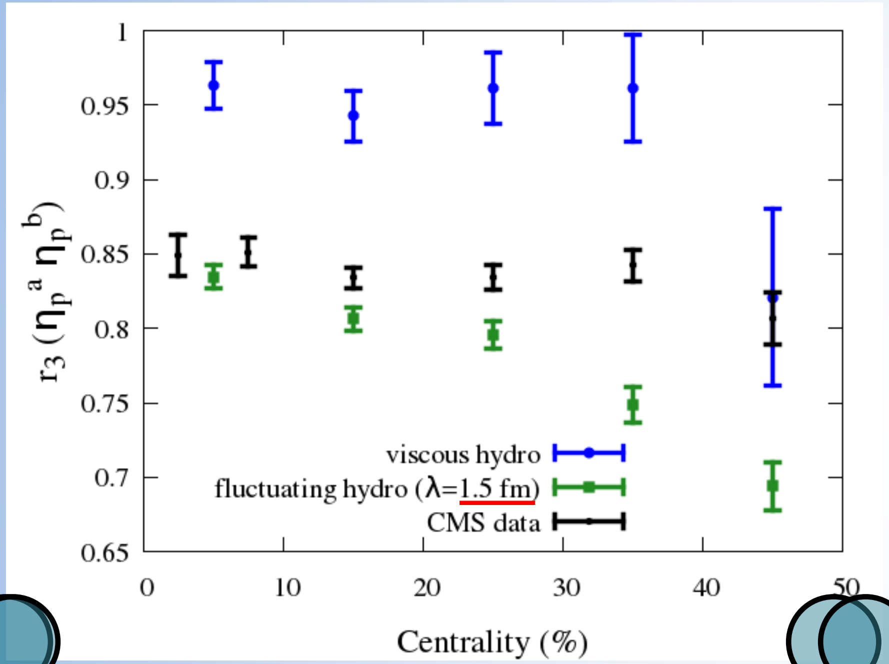
CMS, Phys. Rev. C 92, 034911 (2015).

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Correct centrality dependence of r_2

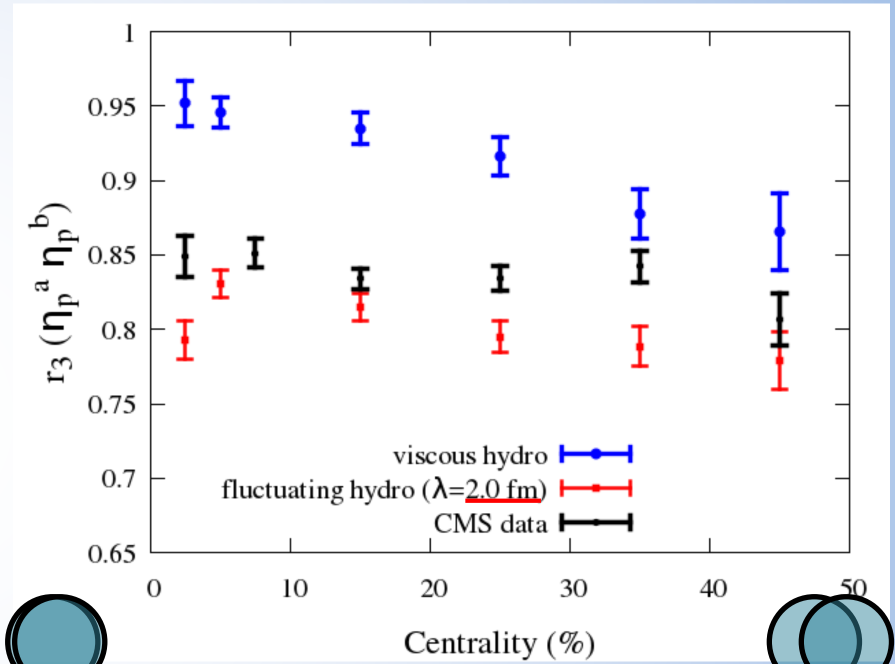
Centrality dependence of $r_3(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



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

with initial longitudinal fluctuations



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

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

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Improvement in reproducing centrality dependence of r_3

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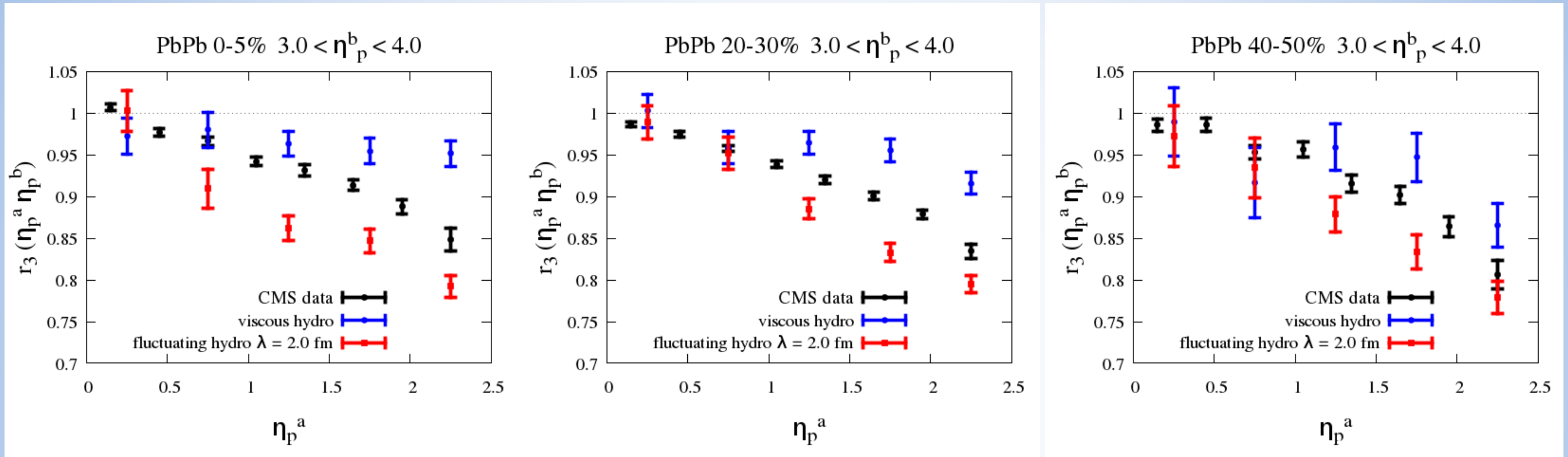
Summary

- ◆Integrated dynamical model based on full 3D hydrodynamics
  - Initial longitudinal fluctuations
  - Hydrodynamic fluctuations
- ◆Factorization ratio $r_n(\eta_p^a, \eta_p^b)$
  - r_2 close to experimental data
  - Explain centrality dependence of r_2 and r_3
  - Importance of including

    hydrodynamic fluctuations and **initial longitudinal fluctuations**

Back up

Factorization ratio $r_3(\eta_p^a, \eta_p^b)$



$$3.0 < \eta_p^b < 4.0$$

Viscous > CMS data ≈ Fluctuating hydro

Hydrodynamic fluctuations

→ Factorization more broken

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

Hydrodynamic fluctuations

Shear stress tensor

Fluctuating hydro

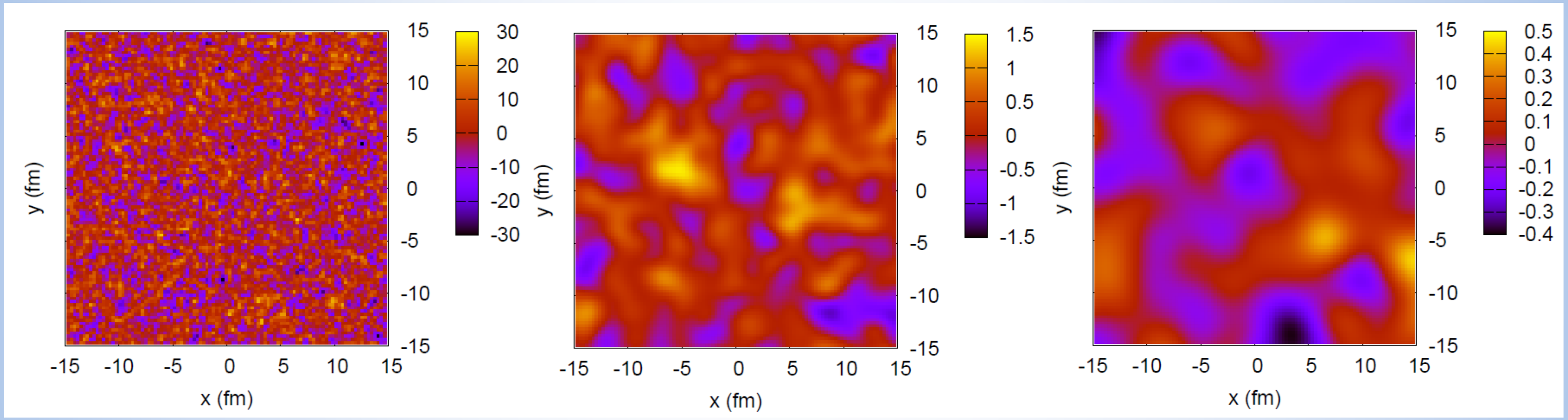
Viscous hydro

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

Actual Equation

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

Cutoff parameter



With out smearing

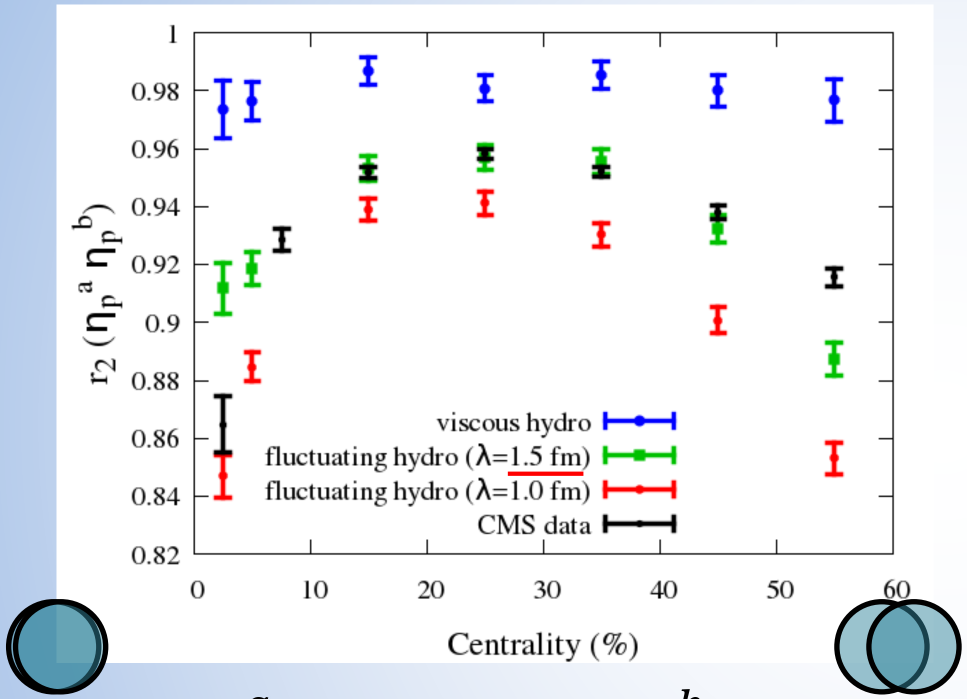
1.0 fm smearing

2.0 fm smearing

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

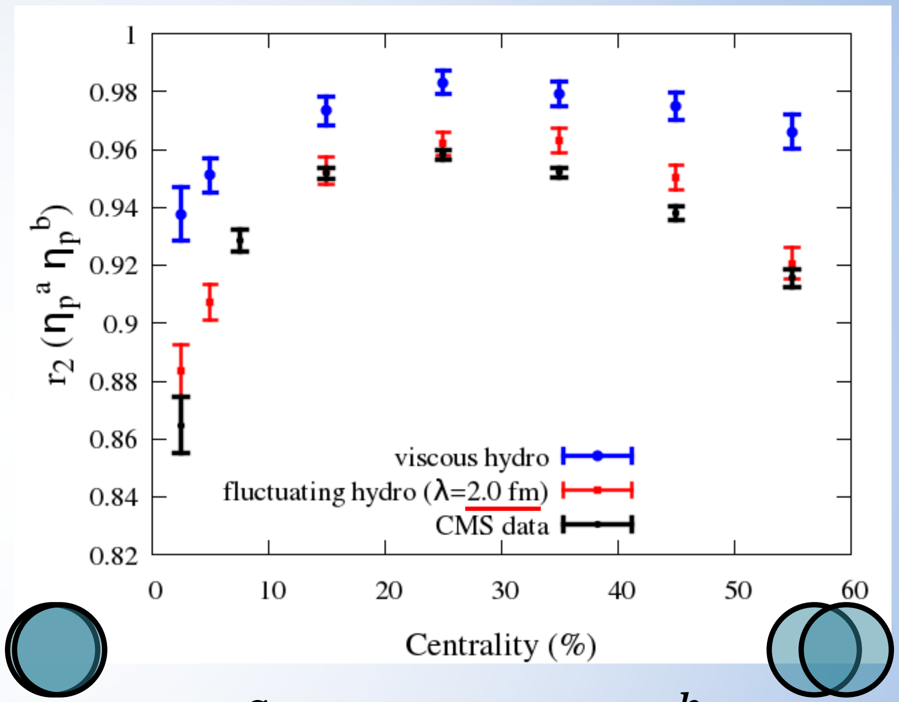
Centrality dependence of $r_2(\eta_p^a, \eta_p^b)$

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



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

<u>with initial longitudinal fluctuations</u>



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

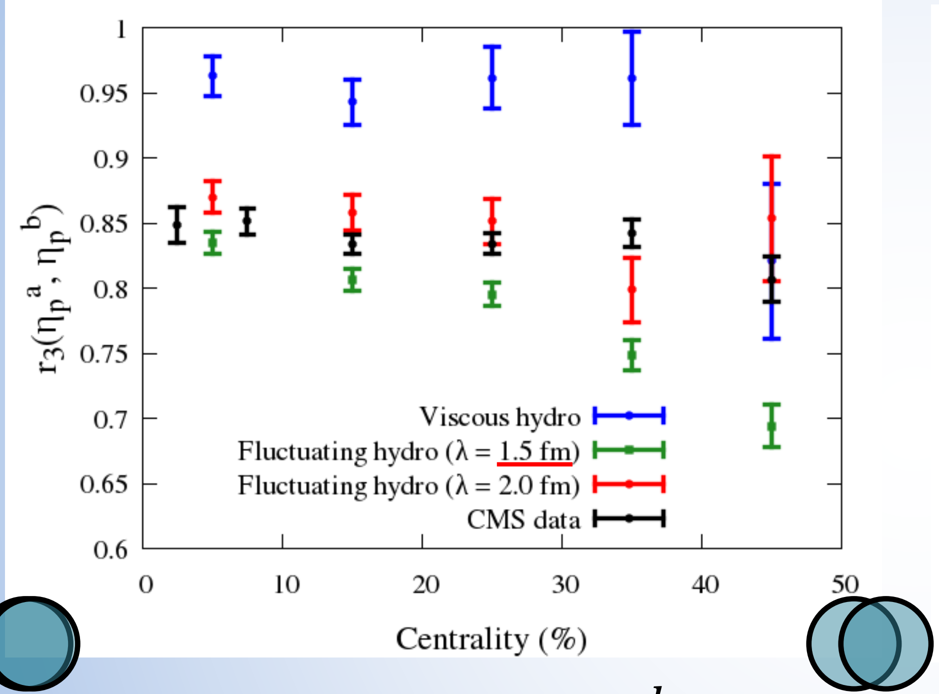
CMS, Phys. Rev. C 92, 034911 (2015).

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Correct centrality dependence of r_2

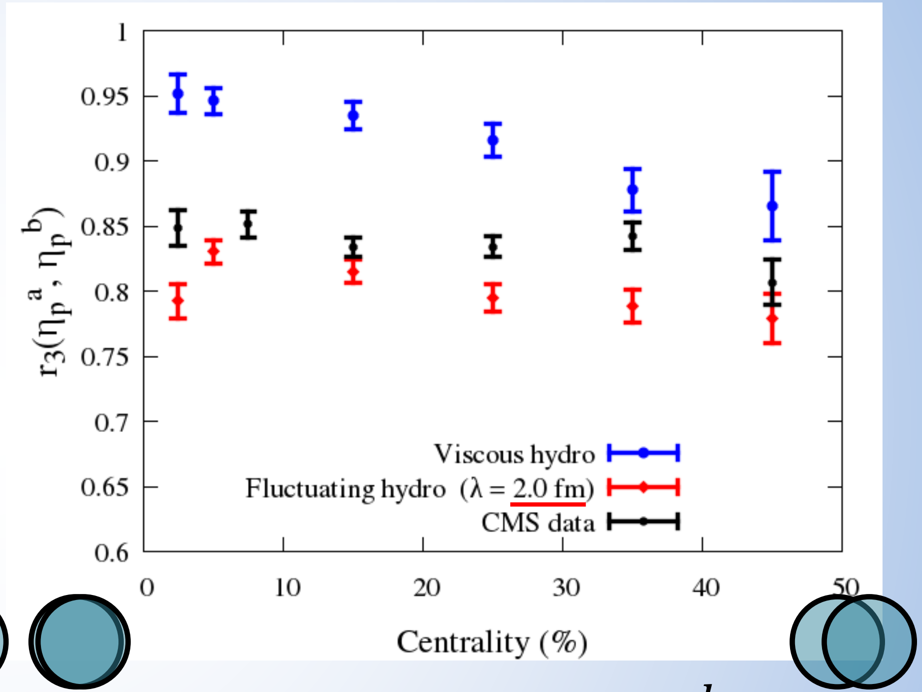
Centrality dependence of $r_3(\eta_p^a, \eta_p^b)$

w/o initial longitudinal fluctuations



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

with initial longitudinal fluctuations



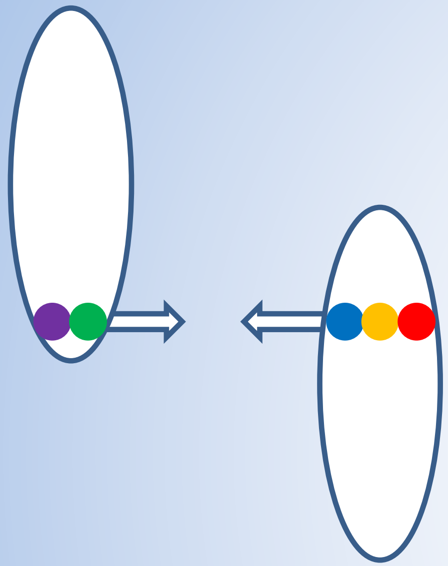
$2.0 < \eta_p^a < 2.5, 3.0 < \eta_p^b < 4.0$

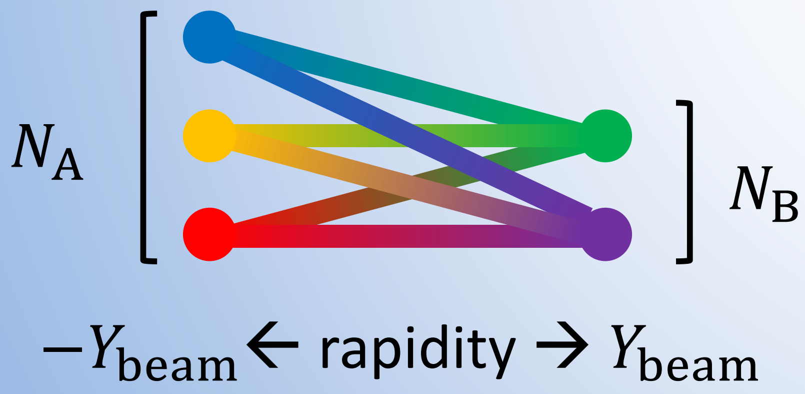
CMS, Phys. Rev. C 92, 034911 (2015).

Hydrodynamic fluctuations + Initial longitudinal fluctuations

➡ Improvement in reproducing centrality dependence of r_2, r_3 with same λ

PYTHIA x Modified BGK model





<u>MC-Glauber model</u>

Number of participants: $N_{\mathrm{A}}(\boldsymbol{x}_{\perp}), N_{\mathrm{B}}(\boldsymbol{x}_{\perp})$

Number of collisions: $N_{\mathrm{coll}}(\boldsymbol{x}_{\perp})$

<u>PYTHIA</u>

Hadrons from $N_{\mathrm{coll}} \times$ pp collisions

Rejection sampling

- Low p_T: N_{part} scaling
- High p_T: N_{coll} scaling

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

S.J.Brodsky, J.F.Gunion and J.H.Kuhn, Phys.Rev.Lett.**39**, 1120 (1977)

T.Hirano *et al.*, Phys.Lett.B **636**, 299 (2006)

Initial entropy density distribution

$$s_0(\tau_0, \eta_s, x_\perp)$$
$$= \frac{K}{\tau_0} \sum_i \frac{1}{\sqrt{2\pi\sigma_\eta{}^2}} \frac{1}{2\pi\sigma_\perp{}^2} \exp\left[-\frac{\left(x - x^i\right)^2 + \left(y - y^i\right)^2}{2\sigma_\perp{}^2} - \frac{\left(\eta_s - \eta_s{}^i\right)^2}{2\sigma_\eta{}^2} \right]$$

Normalization

$K = 4.8$ for $\sqrt{s_{NN}}$ = 2.76 TeV

Smearing parameters

$$\begin{cases} \sigma_\perp = 0.1 \text{ [fm]} \\ \sigma_\eta = 0.3 \end{cases}$$

Position

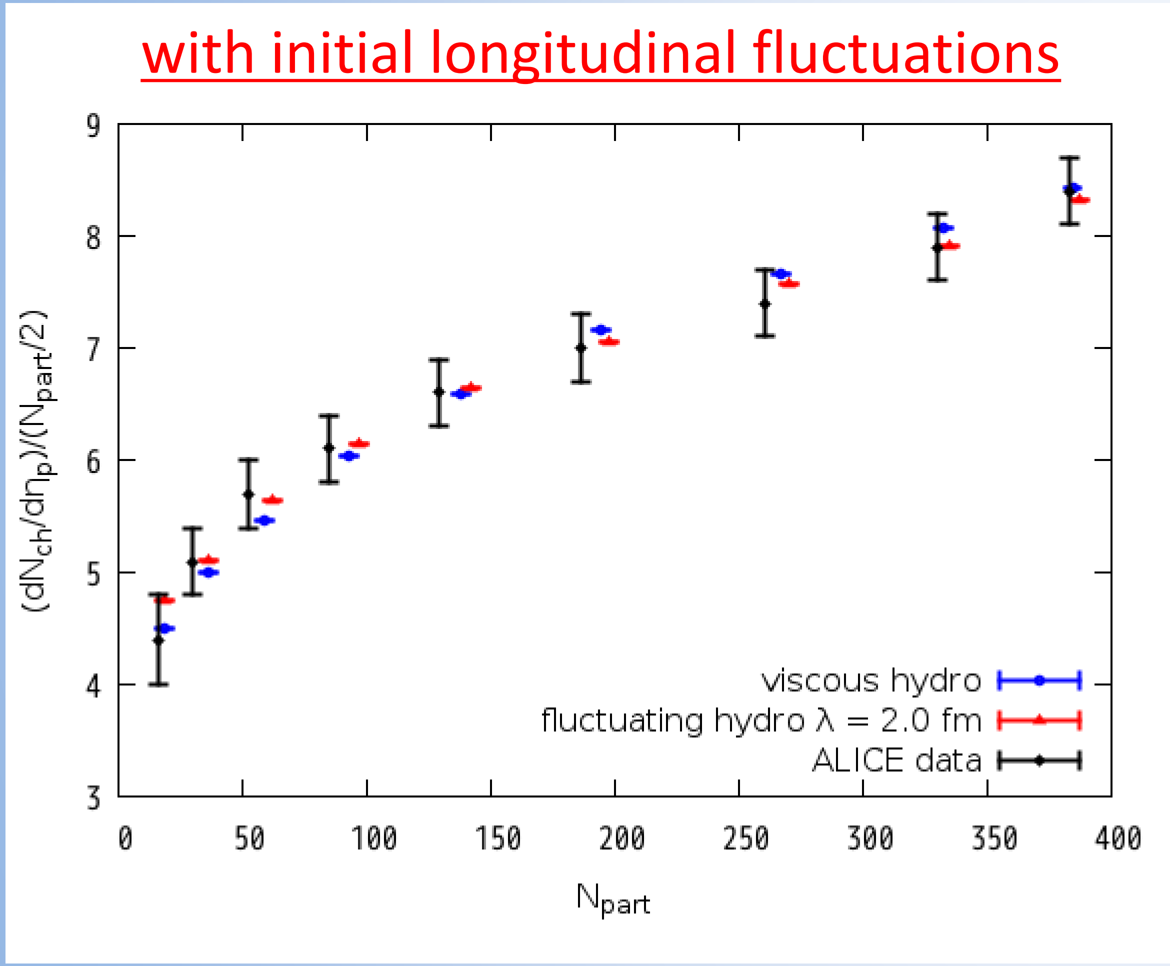
$x^i, y^i, \eta_s{}^i$

from MC Glauber + PYTHIA + modified BGK

Initial time

$\tau_0 = 0.6$ [fm]

Centrality dependence of multiplicity



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

- Acceptance function
- Parameters tuning

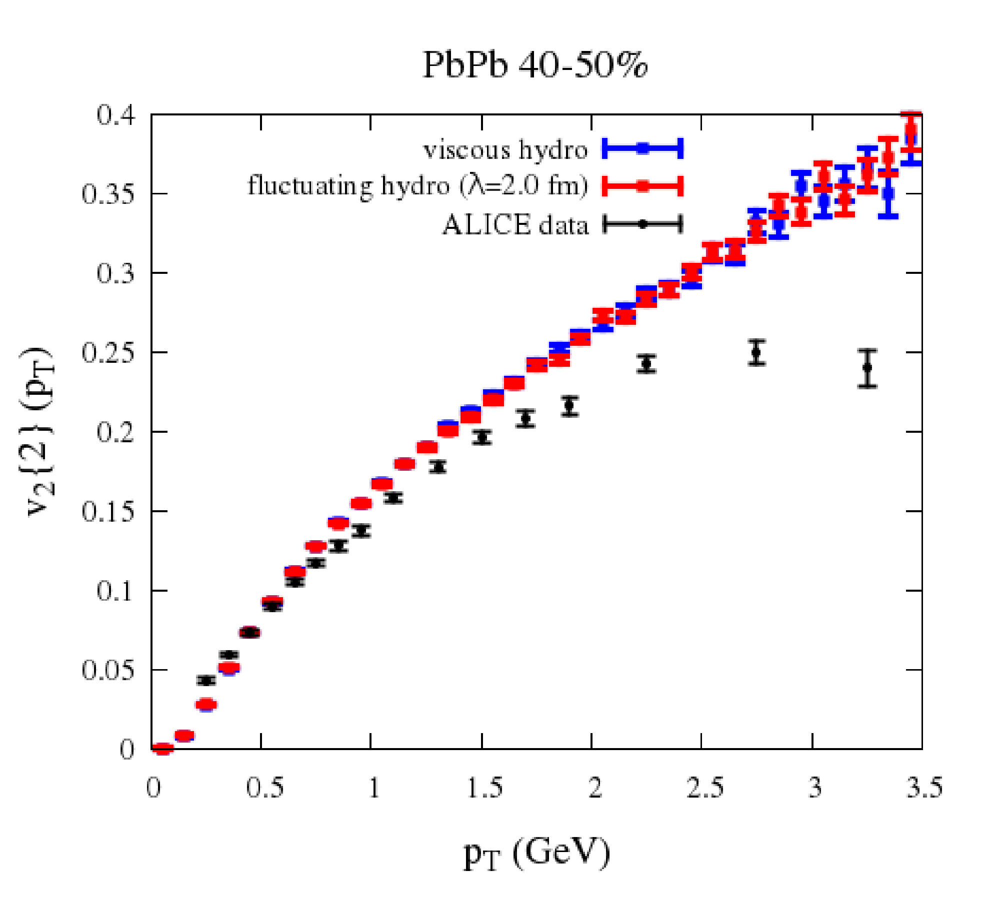
→ Good agreement with ALICE data

- Centrality cut

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

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

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

Rejection method

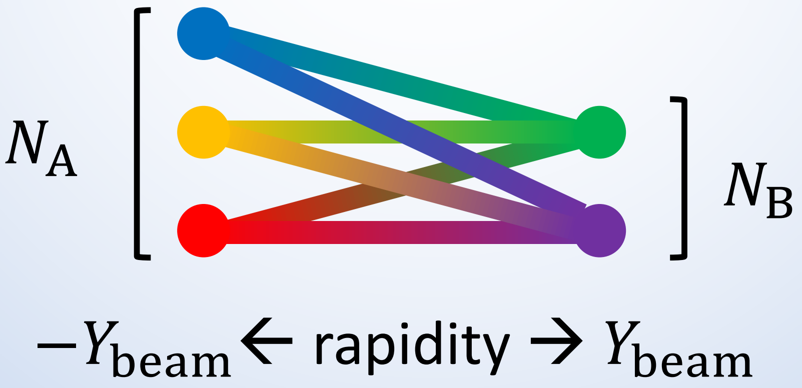
Acceptance function:

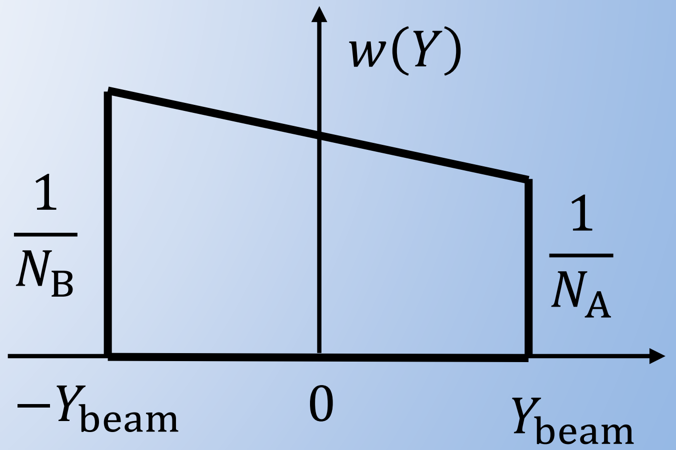
$$w(Y) = \frac{Y_b + Y}{2Y_b}\frac{1}{N_A} + \frac{Y_b - Y}{2Y_b}\frac{1}{N_B}$$

$$w(p_T, Y) = w(Y) \times \frac{1}{2}\left[1 - \tanh\frac{p_T - p_{T0}}{\Delta p_T}\right] + \frac{1}{2}\left[1 + \tanh\frac{p_T - p_{T0}}{\Delta p_T}\right]$$

Fluctuating hydro
$\Delta p_T = 1.0$ GeV
$p_{T0} = 1.80$ GeV

viscous hydro
$\Delta p_T = 1.0$ GeV
$p_{T0} = 1.75$ GeV

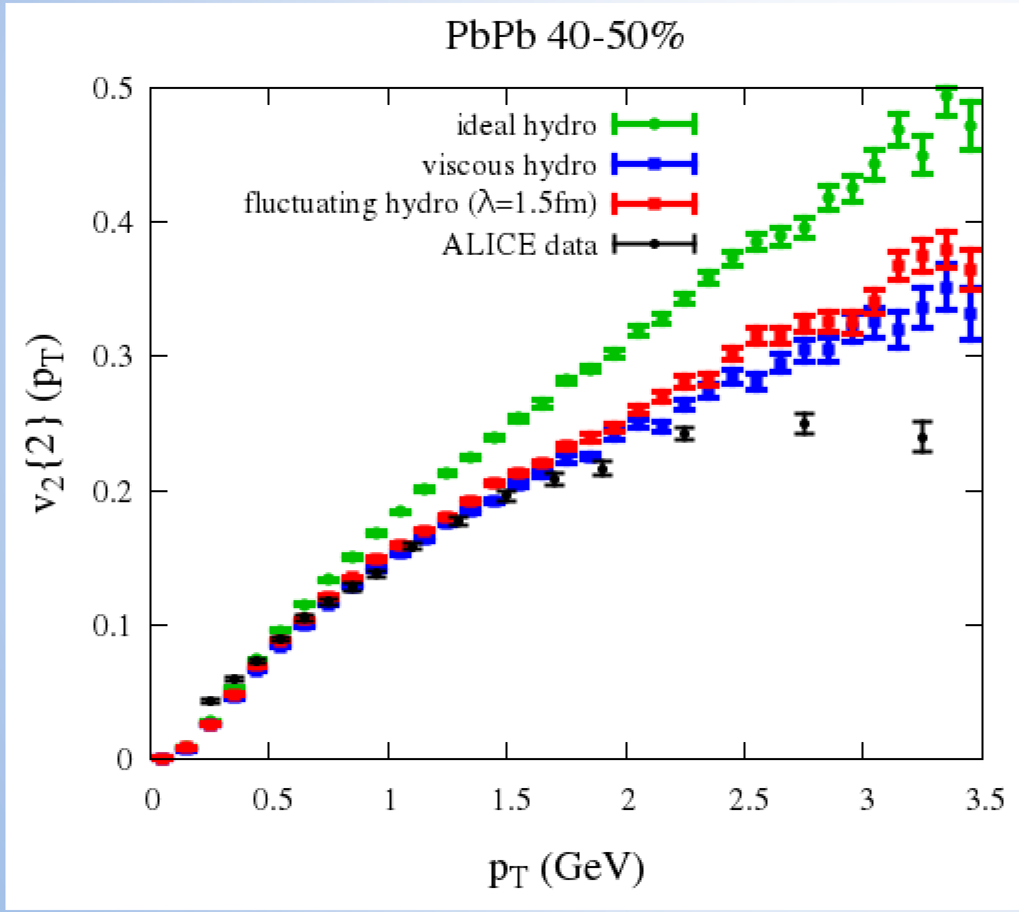




M. Okai *et al.*, Phys. Rev. C **95**, 054914 (2017)

p_T-differential v_2

w/o initial longitudinal fluctuations



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?