Quark Matter 2017

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Hydrodynamic fluctuations in Pb+Pb collisions at LHC

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Outline

- Introduction
- Model & Settings
- Results
- Summary

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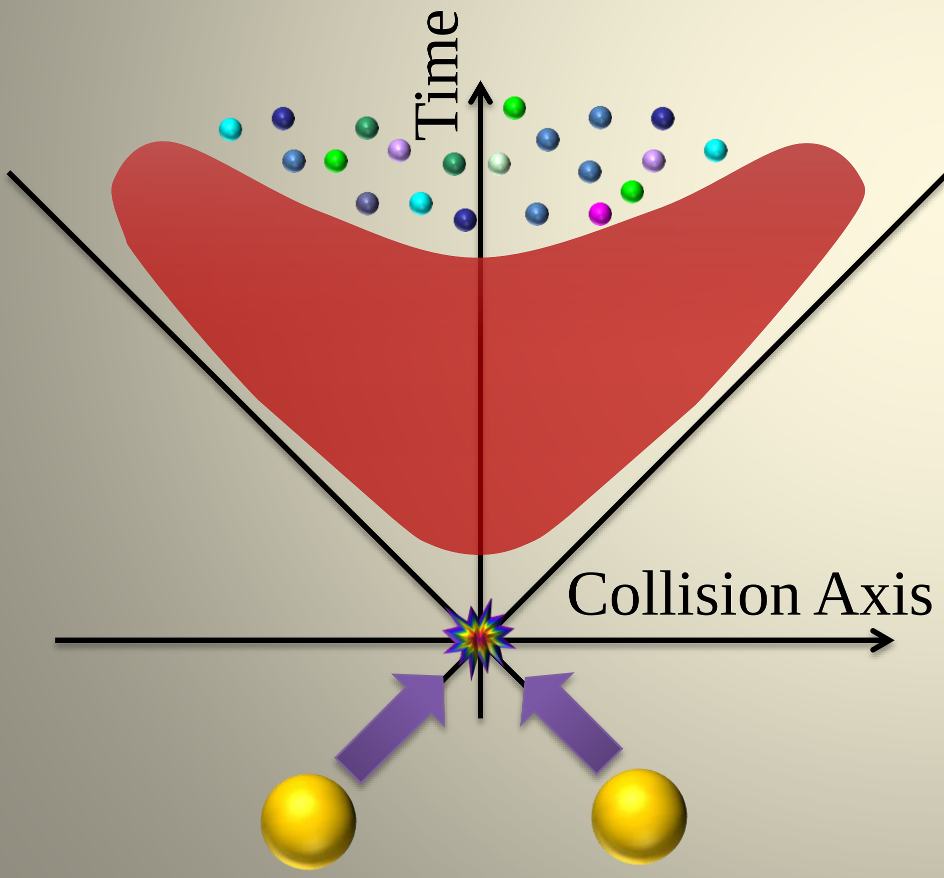
Introduction

Fluctuations in heavy ion collisions



Final observables

Hadron gas

QGP fluid

Initial state

Thermal Fluctuations

Initial state fluctuations

Hydrodynamic fluctuations

Shear stress tensor

Fluctuating hydro

Viscous hydro

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

η: shear viscosity

u^{μ}: four fluid velocity

Ensemble average

Fluctuations around mean value
→Hydrodynamic fluctuations

Note: Relaxation term needed in actual simulations

Fluctuation dissipation relations

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

Increase of entropy

Balance

Decrease of entropy

Fluctuation dissipation relation
=Stability condition of thermal system

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

Event plane fluctuations and decorrelations

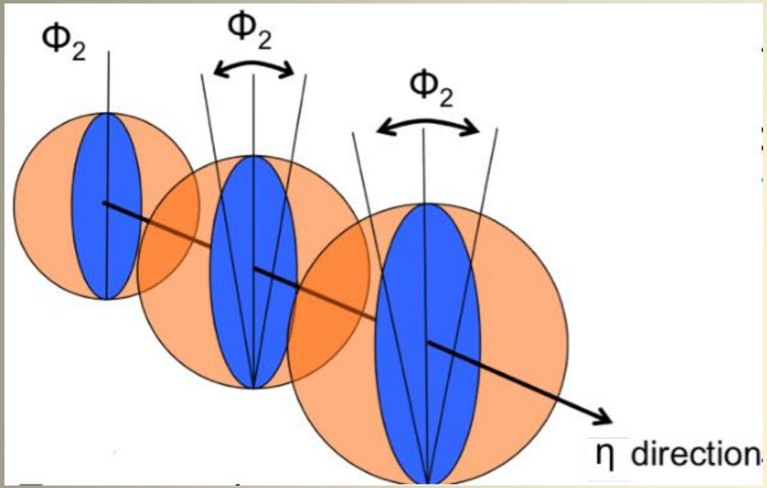


Figure taken from J. Jia, and P. Huo, Phys. Rev. C 90, 034905 (2014)

Event plane angle $\Phi_n(\eta)$

$\Phi(\eta) = \text{const. or not?}$

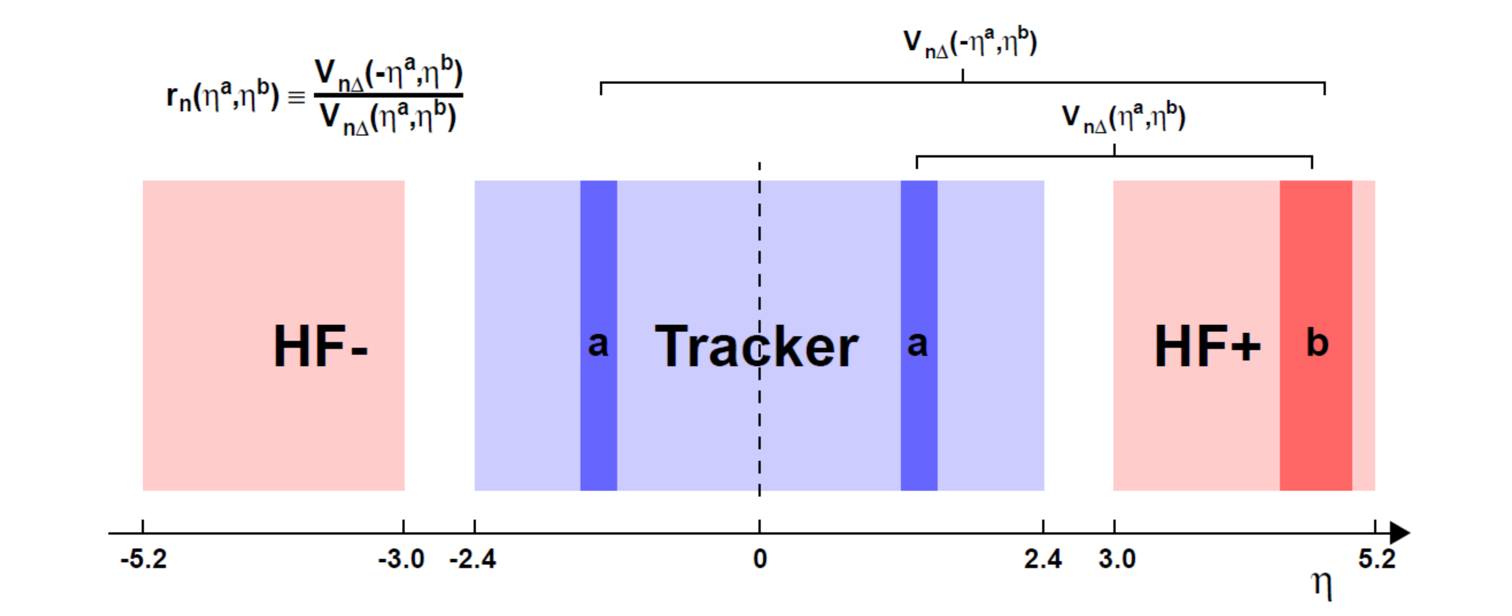
Factorization breaking down

$V_{n\Delta} \neq v_n^a v_n^b$

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

→ Event plane fluctuations/decorrelations

Factorization ratio



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

Purpose of study: Effects of hydrodynamic fluctuations on factorization ratios

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

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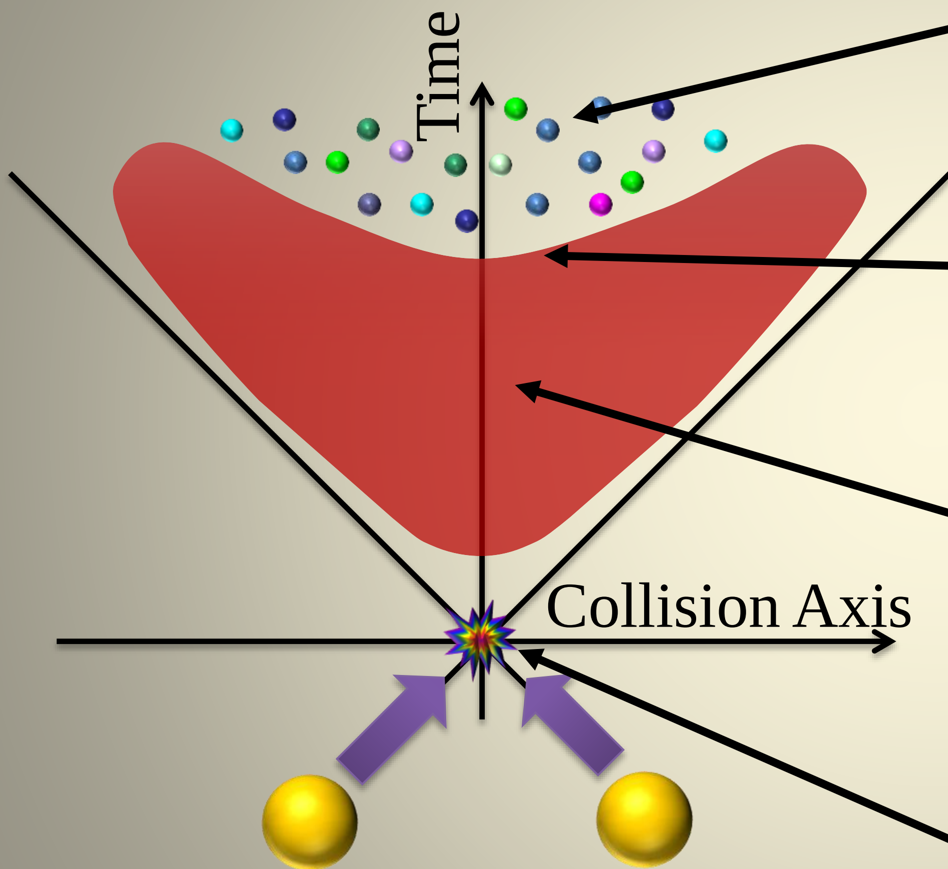
Integrated dynamical model



4.Hadron gas

Hadron cascade model (JAM)

3.Particlization

Cooper-Frye formula

2.QGP fluid

Full 3D relativistic hydrodynamic simulations

1.Initial state

MC-Glauber model

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

Settings of model

1. Initial conditions (see next slides):

- MC-Glauber model (Pb+Pb, 2.76 TeV)

  $\rho_{\mathrm{part}}(x,y), \rho_{\mathrm{coll}}(x,y) \rightarrow s(\tau=\tau_0, x, y, \eta_{\mathrm{s}})$

2. Full 3D fluctuating hydrodynamics:

- EoS: *s95p*-v1.1 (lattice QCD+resonance gas)
- Shear viscosity: $\eta/s = 1/4\pi$
- Relaxation time: $\tau_\pi = 3/4\pi T$
- Cutoff length scale (Gaussian width): $\lambda = 1$ fm

3. Particlization:

- Cooper-Frye formula with $T_{\mathrm{sw}} = 155$ MeV

4. Hadron cascade:

- JAM

Initial conditions

Assumption:

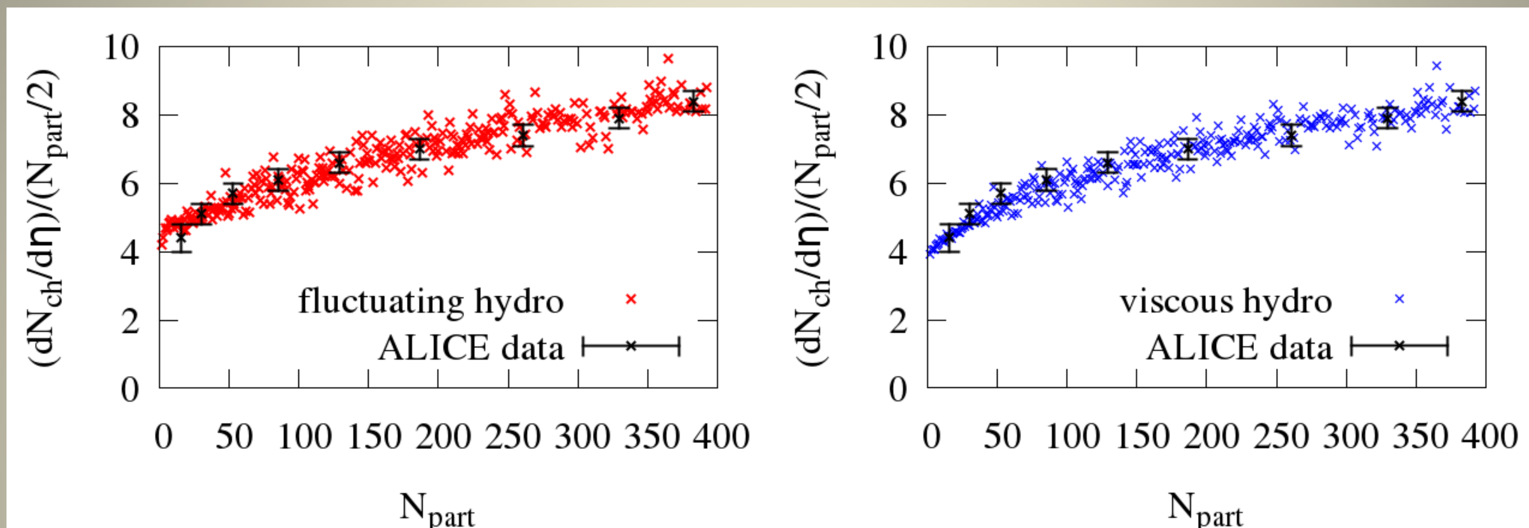
$$s_0(\tau = \tau_0, r_\perp, \eta_s = 0) \propto \frac{1-\alpha}{2}\rho_{\mathrm{part}}(r_\perp) + \alpha\rho_{\mathrm{coll}}(r_\perp)$$

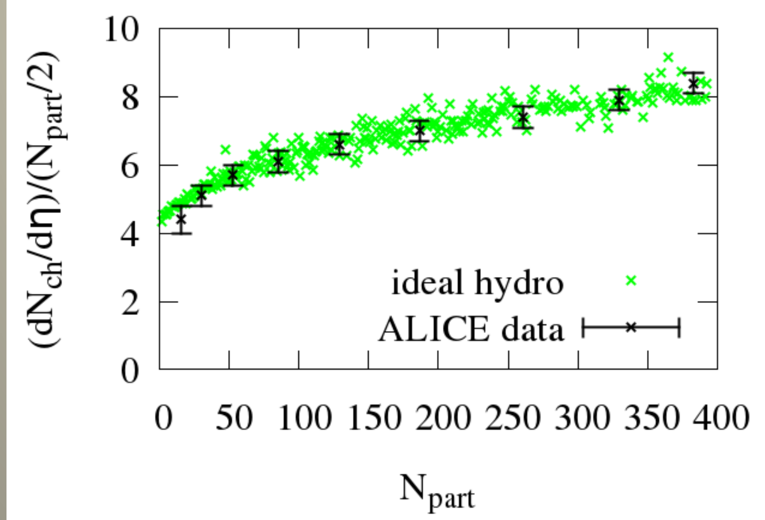
Initial time: $\tau_0 = 0.6$ fm
Soft/hard fraction: $\alpha = 0.20$ (fluctuating hydro)

*Longitudinal profile: Modified BGK model

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

Centrality dependence of multiplicity





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

- Initial parameters tuning
- Centrality cut

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

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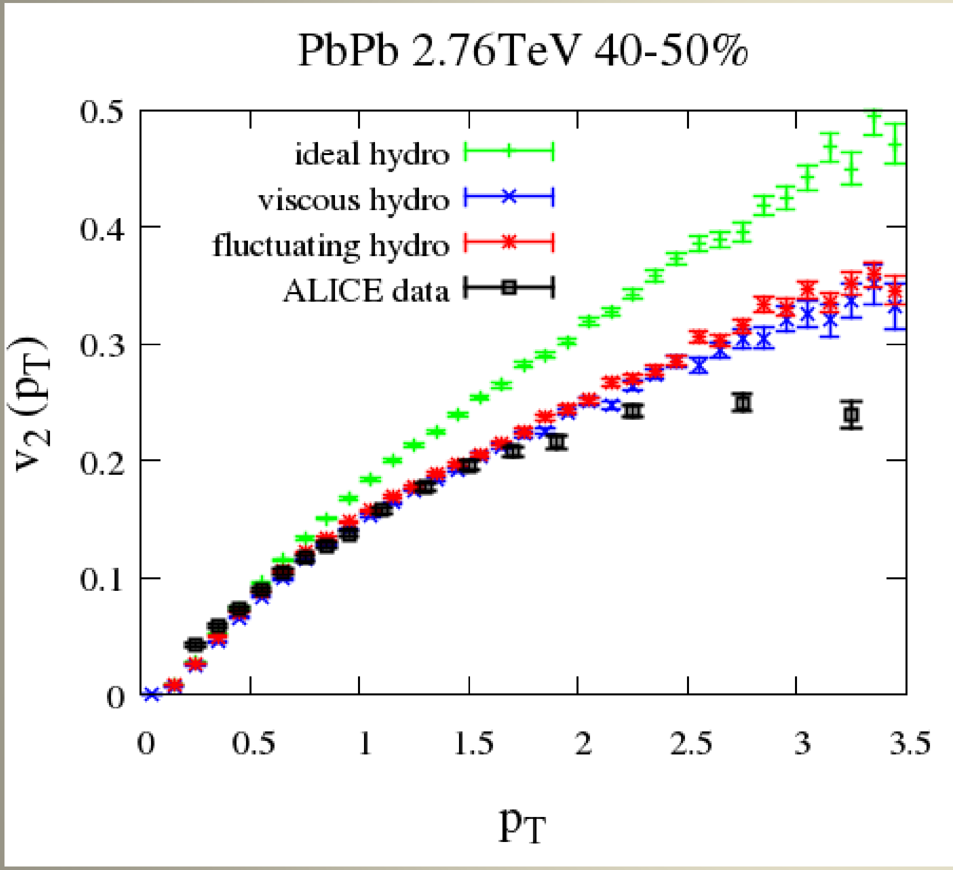
p_T-differential v_2



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

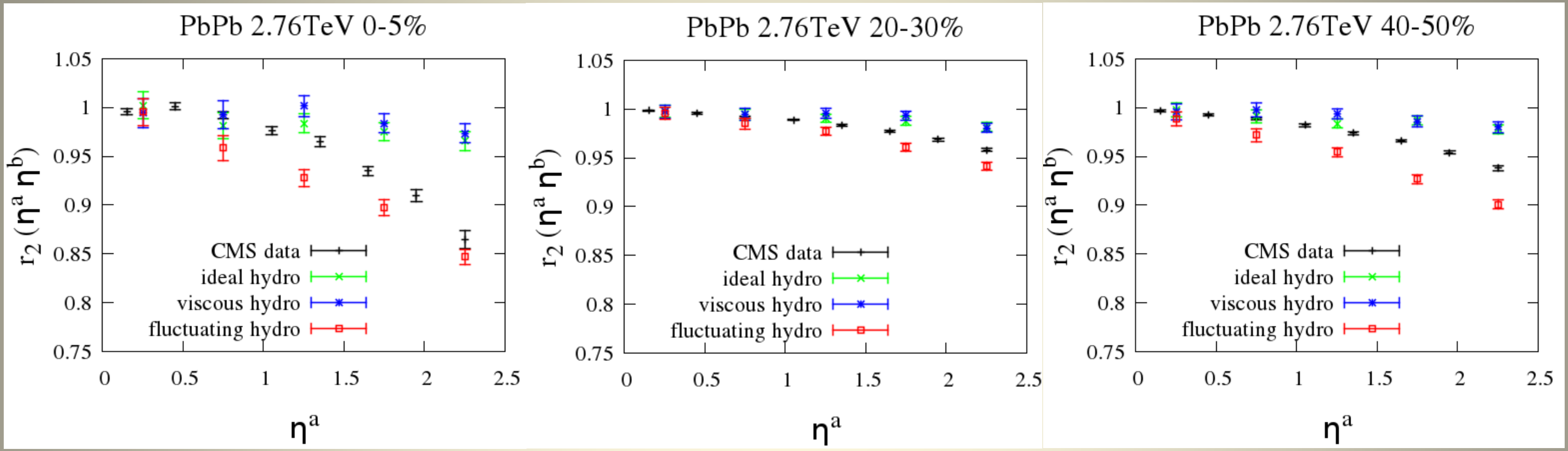
Ideal hydro

→ Larger than ALICE data

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

→ Good agreement with ALICE data below p_T~1.5 GeV

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



$3.0 < \eta^b < 4.0$

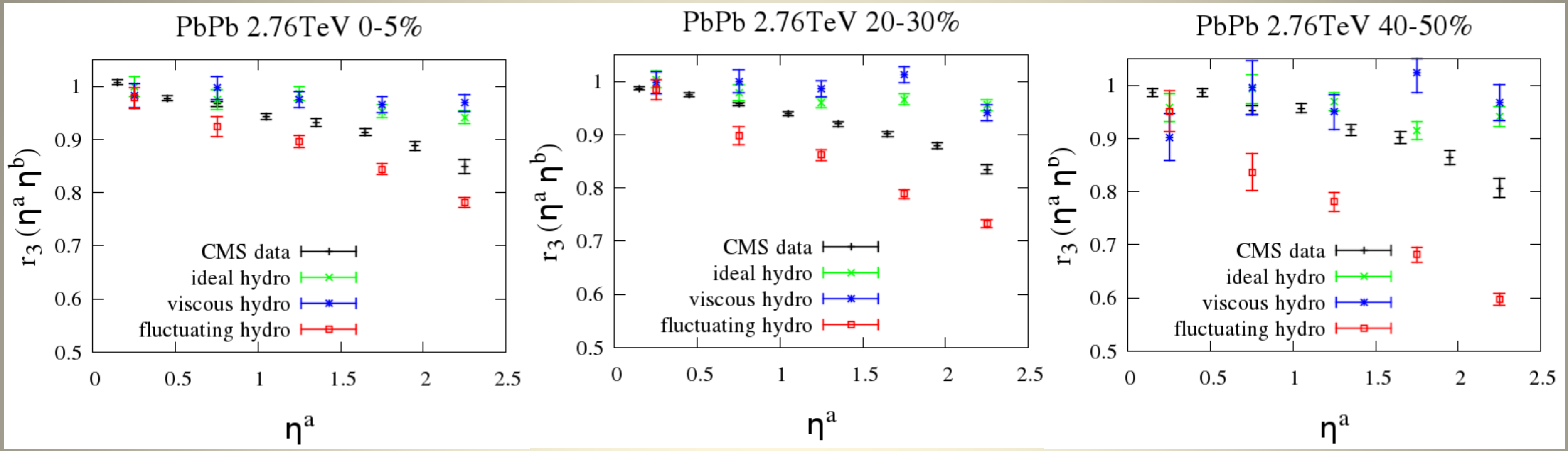
CMS, Phys. Rev. C 92, 034911 (2015).

Ideal ≈Viscous > CMS data > Fluctuating hydro

Hydrodynamic fluctuations

→ Factorization more broken

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

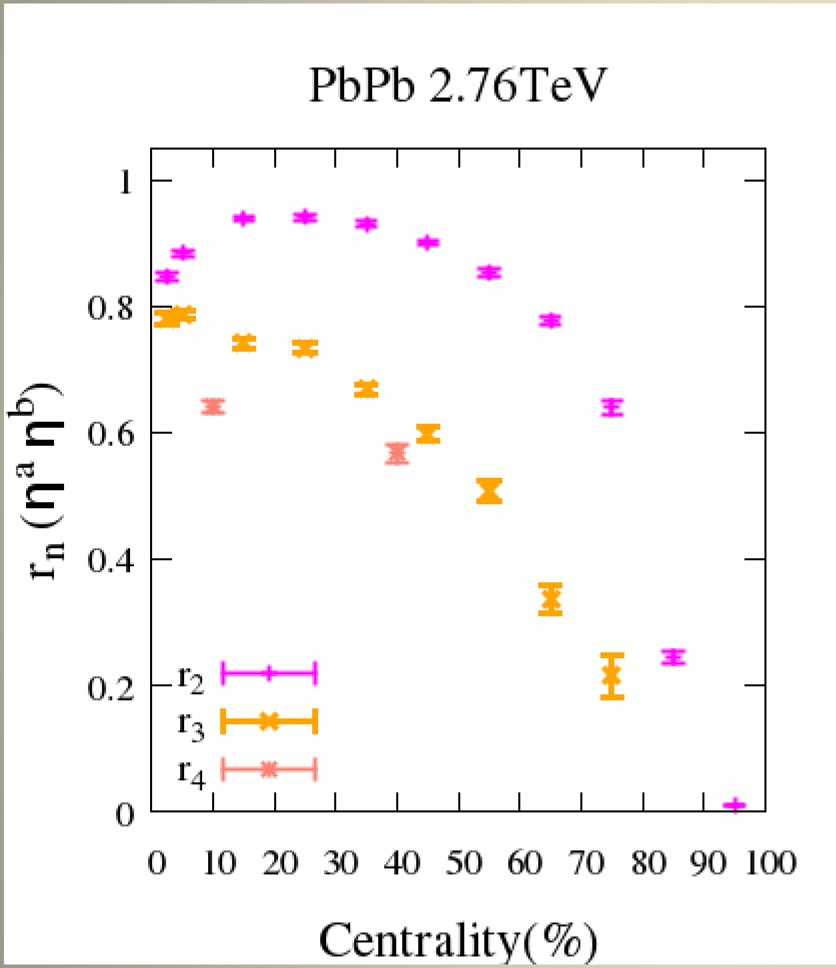


$$3.0 < \eta^b < 4.0$$

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

Ideal ≈Viscous > CMS data > Fluctuating hydro

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



fluctuating hydro

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

$r_2 > r_3, r_4$

r_2:
Maximum at 20-30%
Collision geometry

r_3, r_4:
Monotonic decrease
Initial fluctuations

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Summary

- Integrated dynamical model based on full 3D fluctuating hydrodynamics
  - Tuning of initial parameters
  - Analysis of flow observables
- Factorization ratios $r_n(\eta^a, \eta^b)$
  - Factorization more broken due to hydrodynamic fluctuations
  - Factorization not significantly affected by shear viscosity itself
  - Too decorrelated → Strength of fluctuations?

Back up

Hydrodynamic fluctuations

<u>Shear stress tensor</u>

Fluctuating hydro

Viscous hydro

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

<u>Actual Equation</u>

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

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

Initial Condition Setups

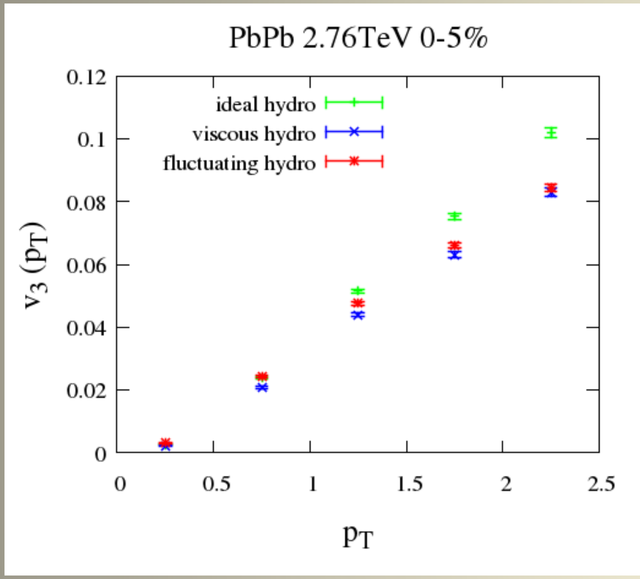
$$s_0(r_\perp) = \frac{C}{\tau_0}\left(\frac{1-\alpha}{2}\rho_{\mathrm{part}}(r_\perp) + \alpha\rho_{\mathrm{coll}}(r_\perp)\right)$$

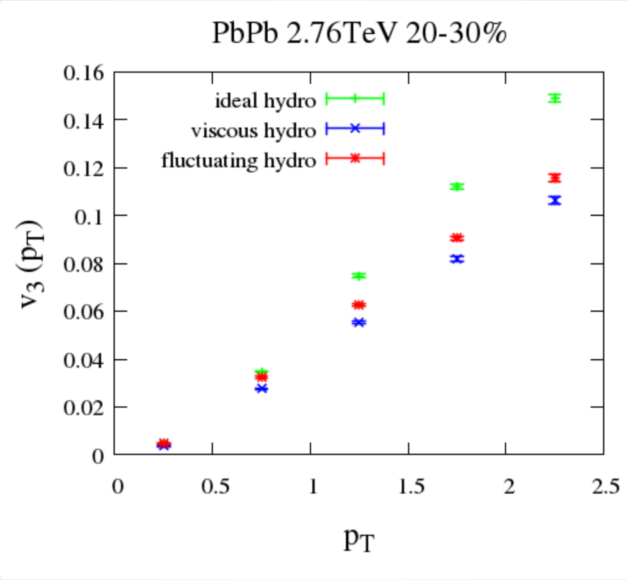
λ: HF cutoff length scale (Gaussian width)

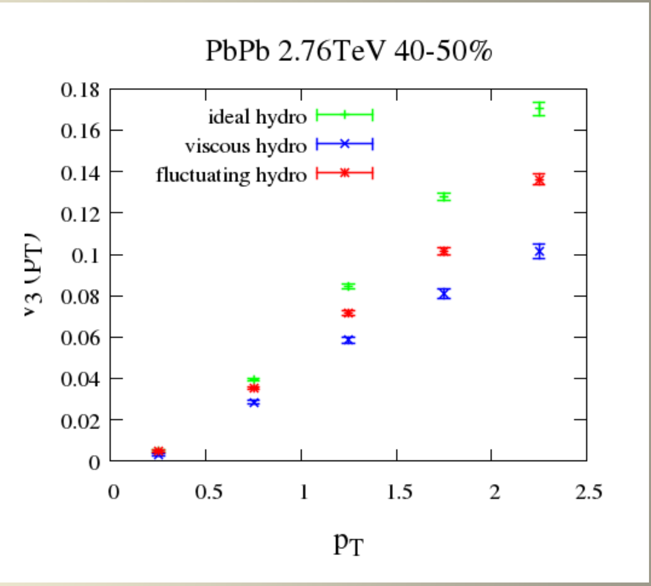
	η/s	HF	C/τ0	α
Ideal	0	None	62	0.08
Viscous	1/4π	None	49	0.13
Fluctuating	1/4π	λ＝1.0(fm)	31	0.20

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

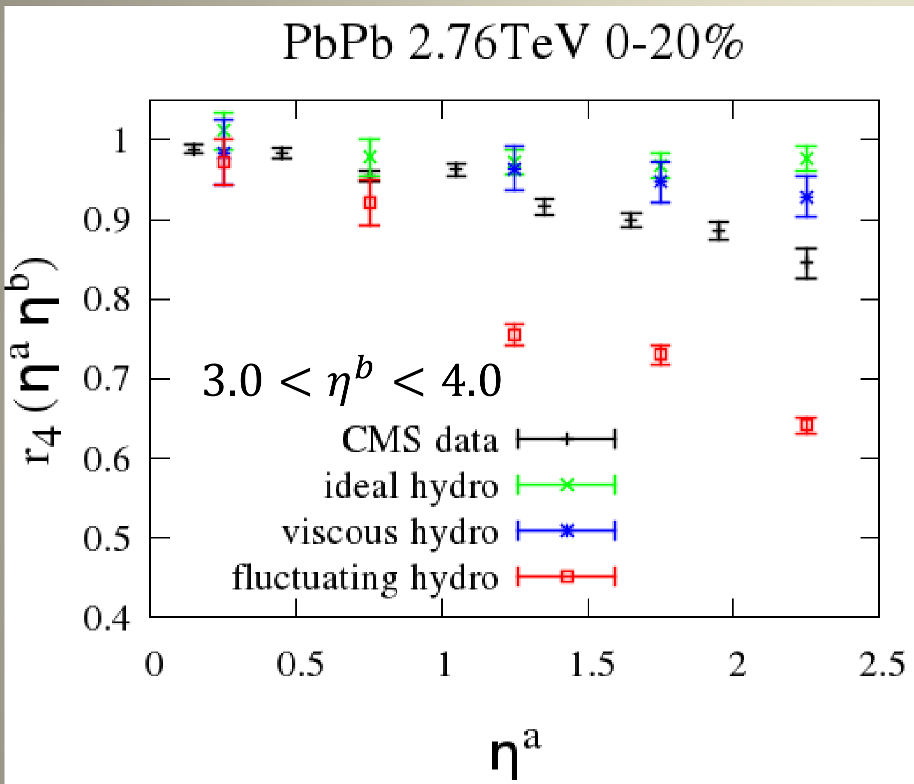
p_T-differential v_3

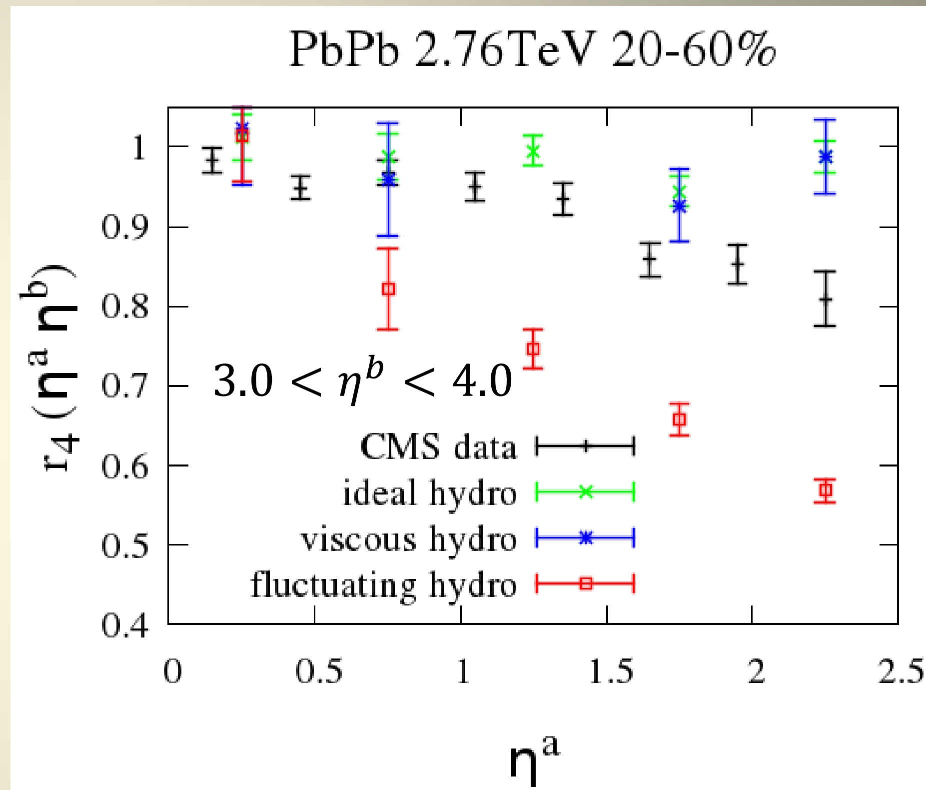






Factorization ratio $r_4(\eta^a, \eta^b)$





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

Similar trends:

Ideal ≈Viscous > CMS data > Fluctuating hydro