Instituto de Física
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Understanding the bulk viscosity of QCD matter

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ULtra-RelatIvistiCH HEavy IoNZ

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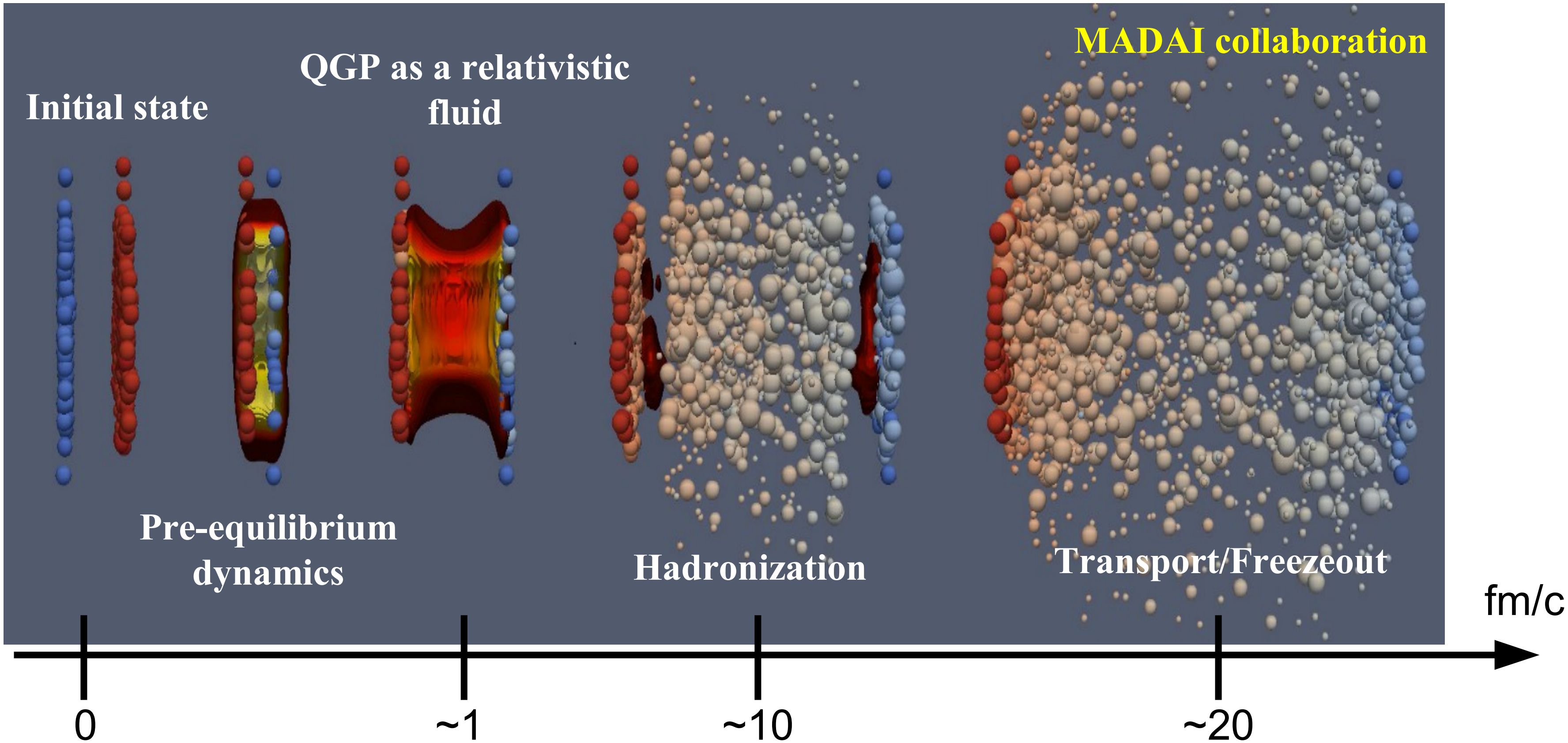
Ultra-relativistic Heavy Ion Collisions

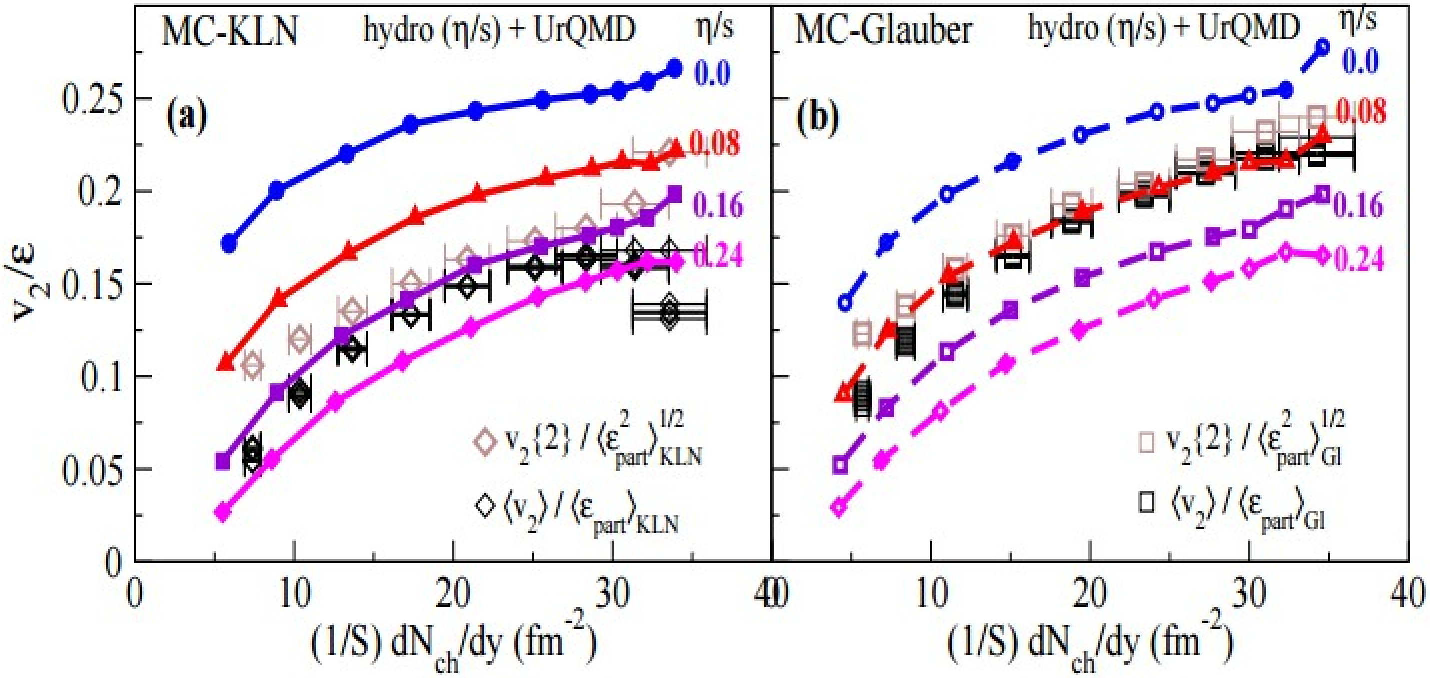
Best (and often only) option to understand certain properties of bulk nuclear matter



Bulk QCD matter is only created transiently
Need to reverse-engineer its properties

Extraction of shear viscosity

Shear viscosity can be estimated using elliptic flow data (IC uncertainty)



Song *et al*, PRL 106, 192301 (2011)

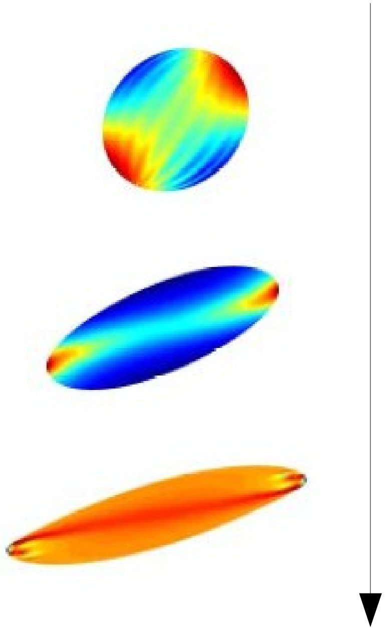
Major contribution from Heinz's group

What about other transport properties?

Shear viscosity

Resistance to deformation

$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$$



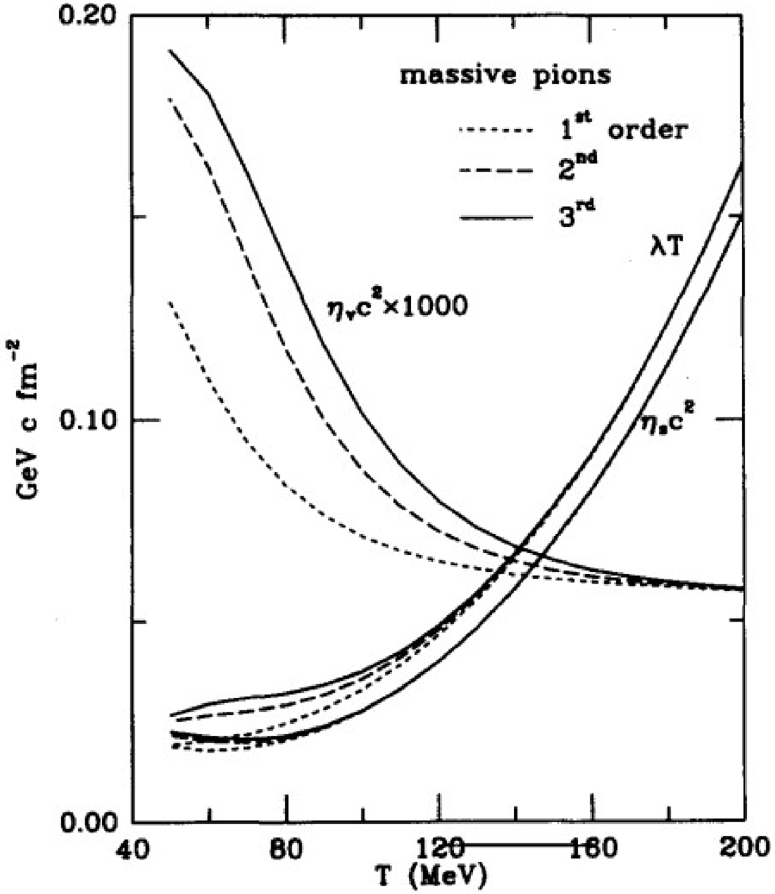
Bulk viscosity

Resistance to volume change

$$\Pi = -\zeta\nabla_\mu u^\mu$$

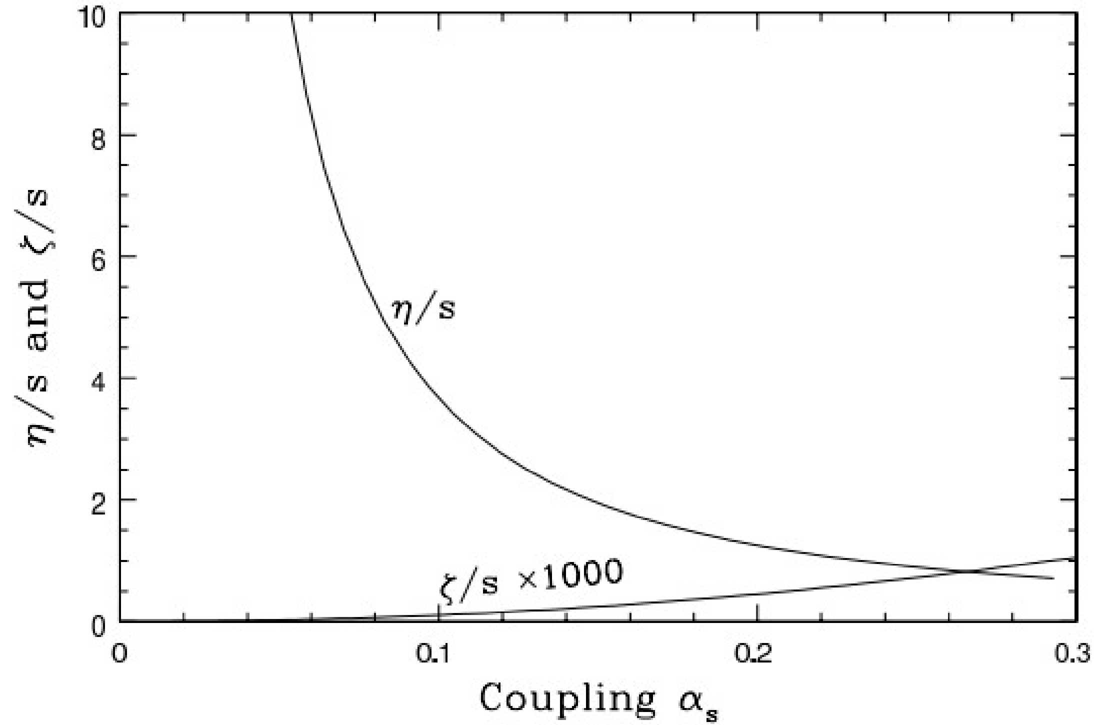
Some limits

pions gas



Prakash *et al*, Phys. Rept. 227, 321 (1993)

pQCD



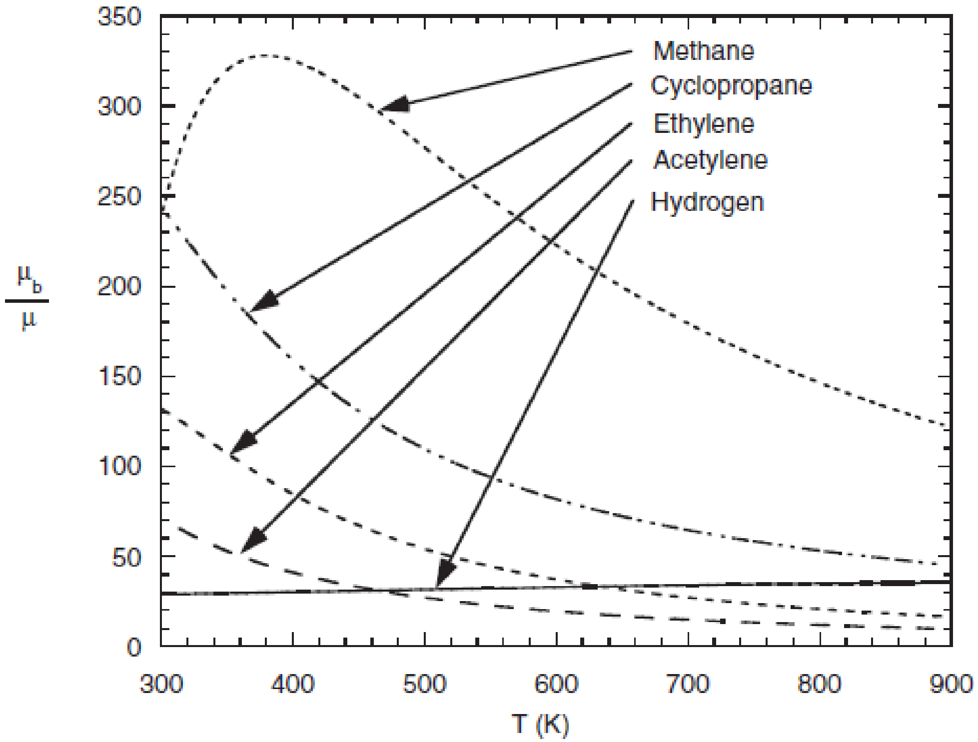
Arnold *et al*, PRD 74, 085021 (2006)

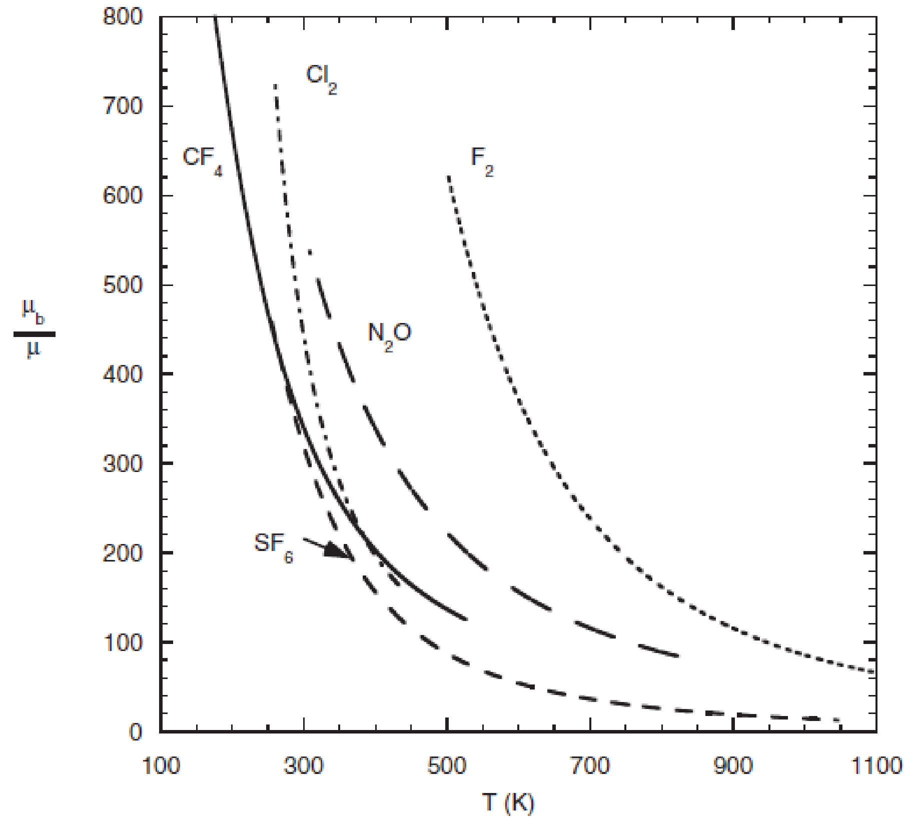
Bulk viscosity ~1000 times smaller than shear

Near phase transition, we do not know ...

Some known examples

Bulk to shear viscosity ratio for several gases



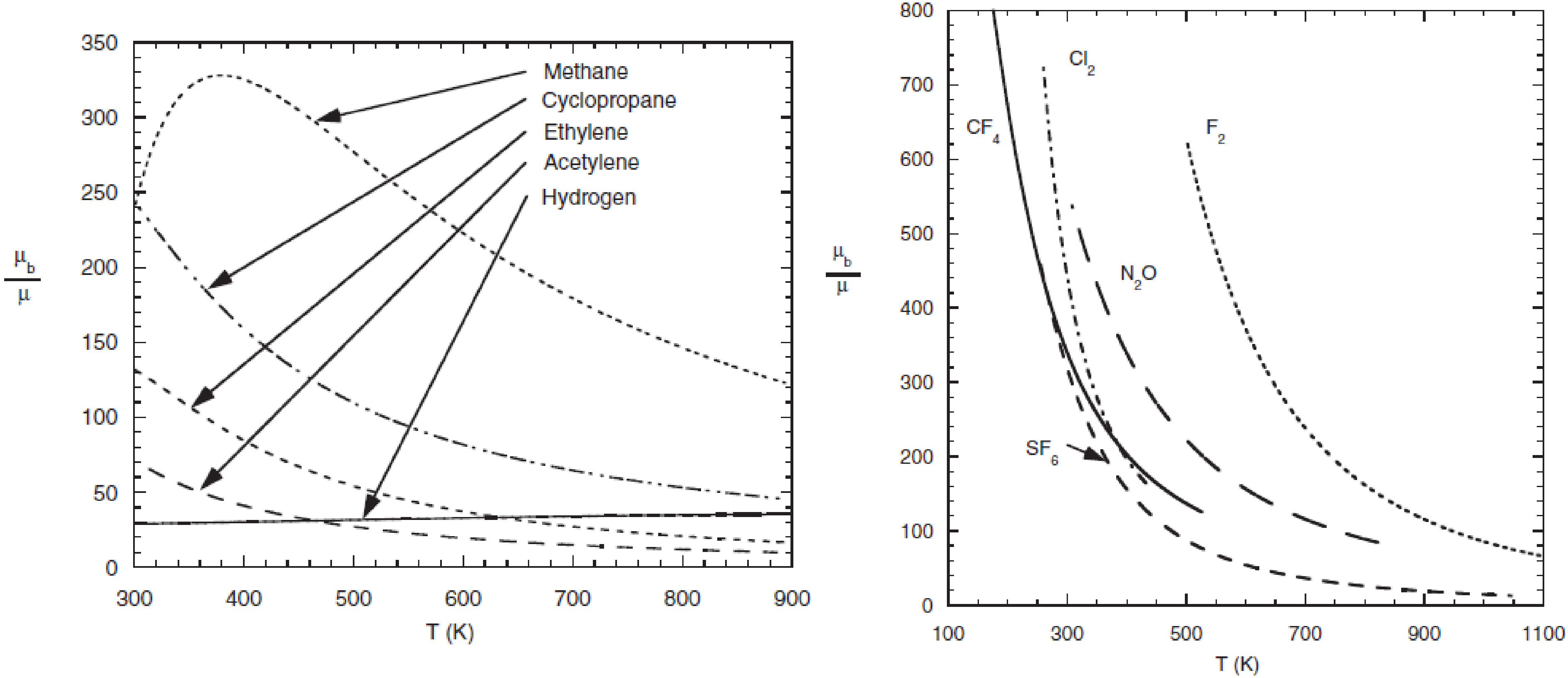


M. Cramer, Phys. of fluids 24, 066102 (2012)

In many cases, bulk viscosity can be larger than shear viscosity (failure of Boltzmann eq.)

Some known examples

Bulk to shear viscosity ratio for several gases



M. Cramer, Phys. of fluids 24, 066102 (2012)

bulk viscosity: vibrational&rotational relax. time

shear viscosity: mean free path

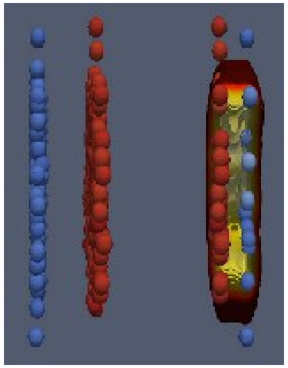
What you will see in this talk

We investigate the effect of bulk viscosity on basic heavy ion collision observables

Is bulk viscosity needed to fit the data?

Can it be extracted? What observable should we use?

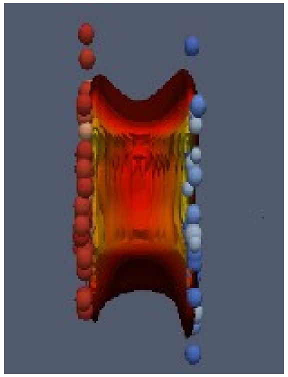
Fluid-dynamical model



IP-Glasma initial condition

$\tau_0 = 0.4$ fm

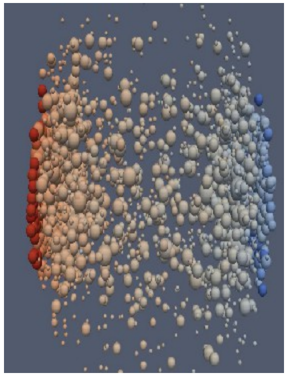
thermalization "by hand"



Relativistic Hydrodynamics (MUSIC)

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu N^\mu = 0$$

+ EoM for dissipative currents



T=const.

fluid elements converted to particles

Hadronic transport (UrQMD)

Fluid-dynamical equations

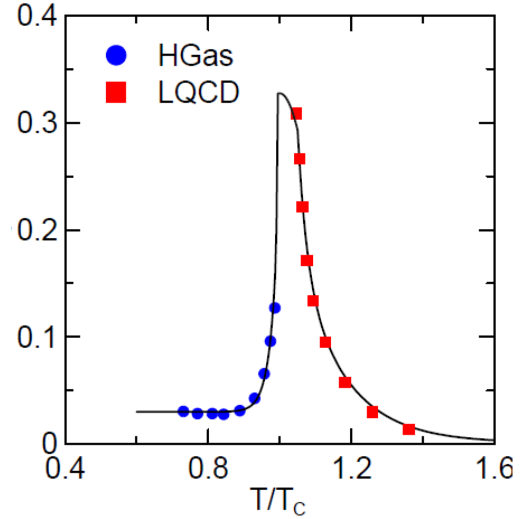
GSD&Niemi&Molnar&Rischke, PRD 85, 114047 (2012)

Inclusion of bulk viscous pressure, shear-stress tensor, and all couplings

$$\dot{\Pi} + \frac{\Pi}{\tau_\Pi} = -\beta_\Pi \theta - \delta_{\Pi\Pi} \Pi \theta + \varphi_1 \Pi^2 + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu} + \varphi_3 \pi^{\mu\nu} \pi_{\mu\nu} ,$$

$$\dot{\pi}^{\langle\mu\nu\rangle} + \frac{\pi^{\mu\nu}}{\tau_\pi} = 2\beta_\pi \sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu} \omega^{\nu\rangle\alpha} - \delta_{\pi\pi} \pi^{\mu\nu} \theta + \varphi_7 \pi_\alpha^{\langle\mu} \pi^{\nu\rangle\alpha} - \tau_{\pi\pi} \pi_\alpha^{\langle\mu} \sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi} \Pi \sigma^{\mu\nu} + \varphi_6 \Pi \pi^{\mu\nu} .$$

✔ η/s=const, ✔ ζ/s =

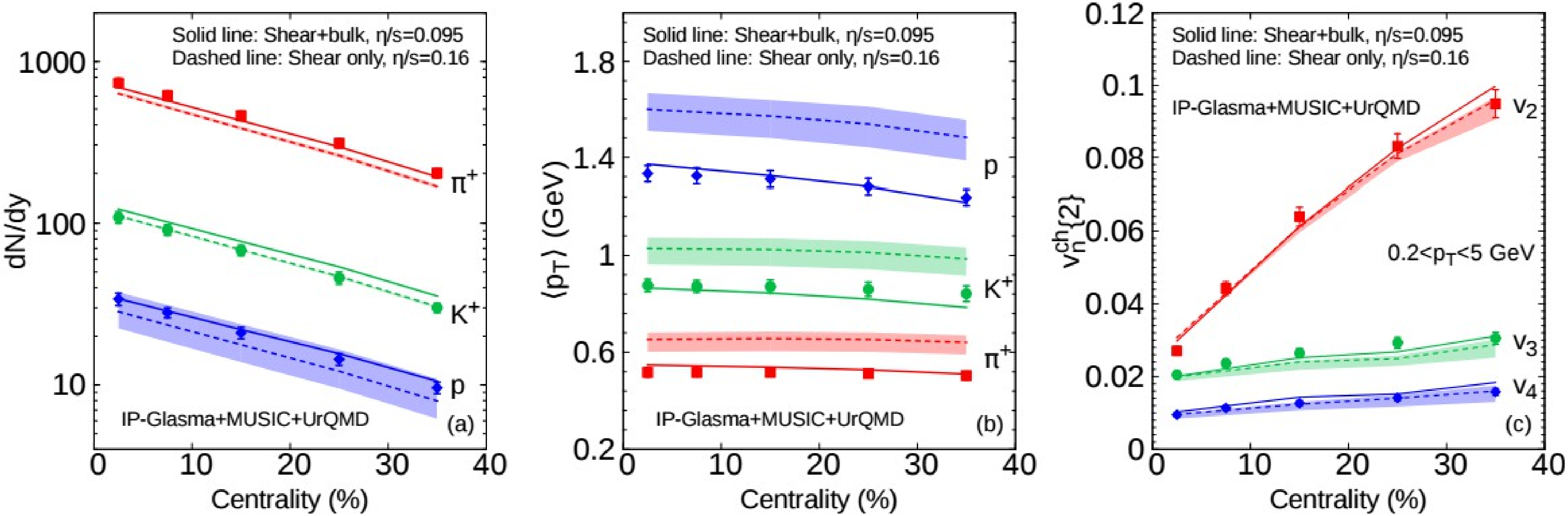


Integrated observables

IP-Glasma+MUSIC+UrQMD

PRL 115, 132301 (2015)

$T_{switch} = 145$ MeV



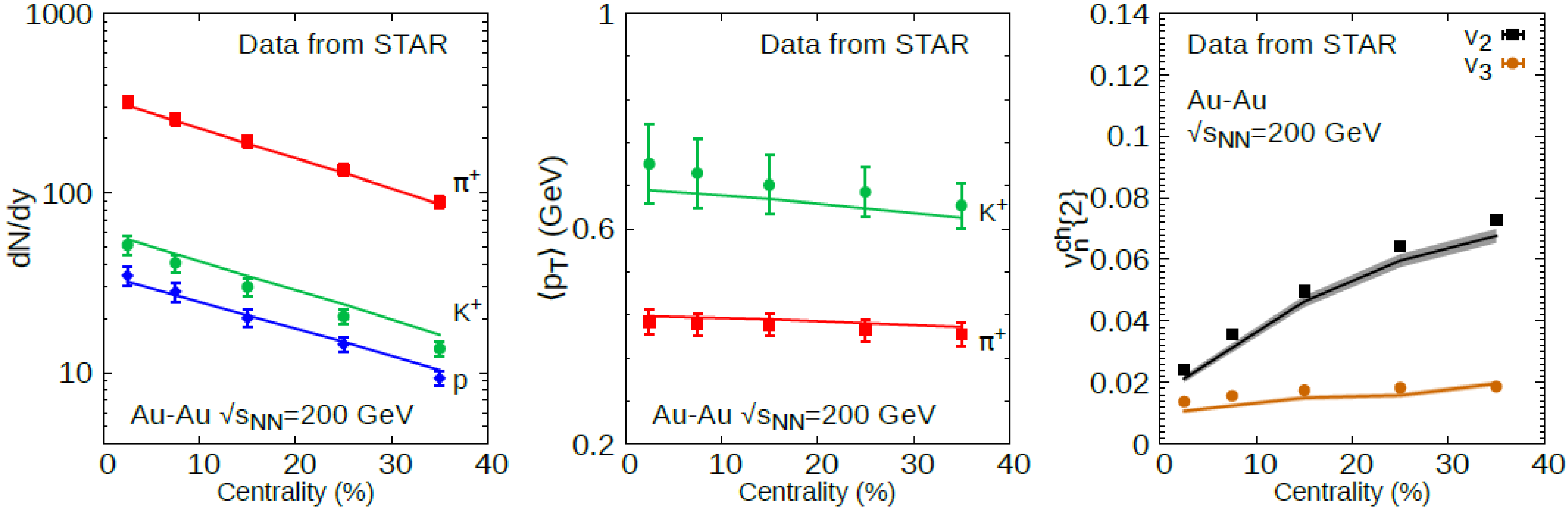
bulk viscosity increases multiplicity, reduces <p_T>, and reduces Vn

Value of shear viscosity extracted changes significantly

η/s=0.16 → 0.095

What about RHIC?

Tswitch=165 MeV
$\eta/s=0.06$

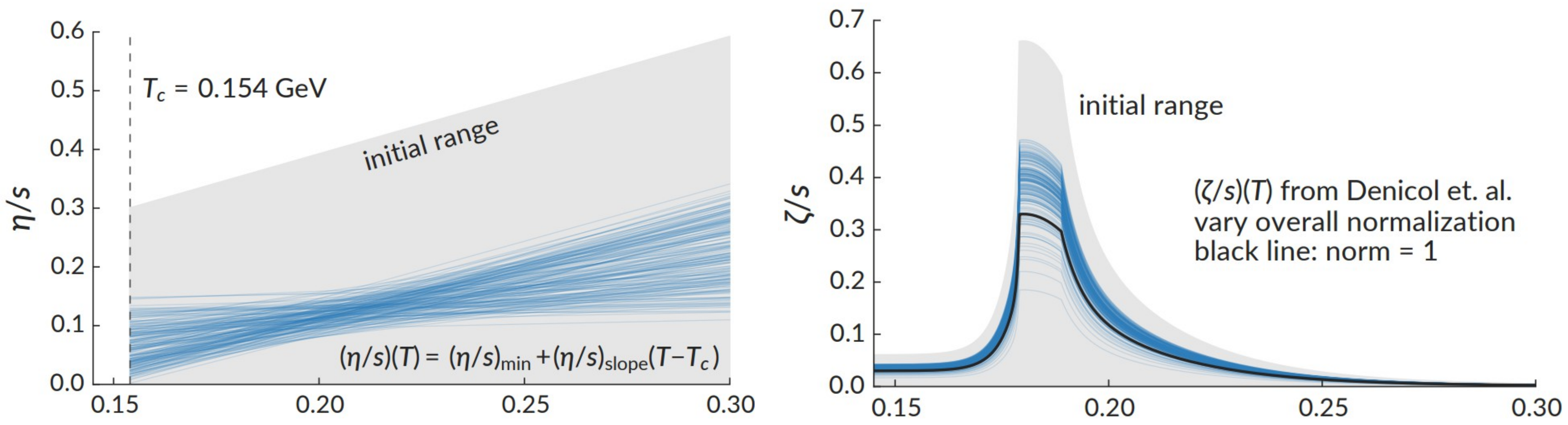


Same bulk viscosity can also describe RHIC data

Results from Duke + Ohio group

arXiv:1605.03954

Model: Trento initial state + Hydro (bulk&shear) + UrQMD
Very good description of Multiplicity, mean-pT, and Vn

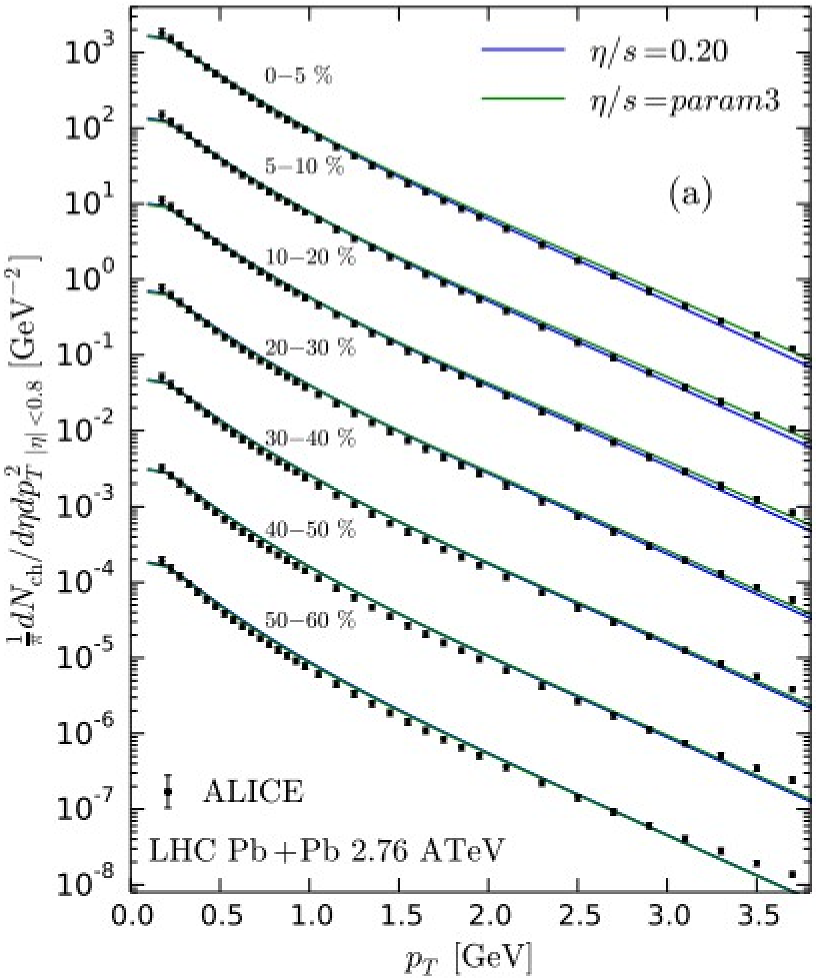


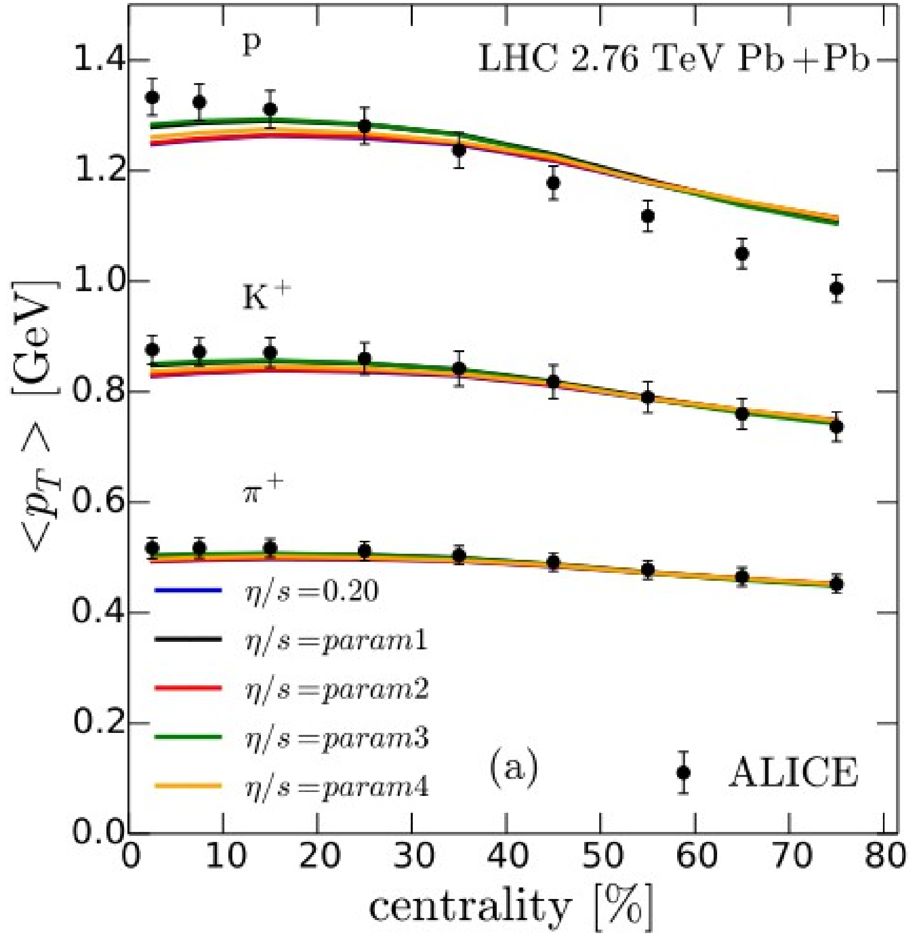
finite bulk viscosity is favored

Similar findings also by Schenke&Monnai for
MC-Glauber with valence quarks

EKRT model + second order viscous hydro

Niemi *et al*, PRC 93, no. 2, 024907 (2016)





Good description without including bulk viscosity!

But, chemical freeze-out at 175 MeV

Non-equilibrium contribution to pressure

$\boxed{\textbf{Pressure} = P_0 + \Pi}$

Π → "δP"

Hydrodynamical picture works, if this is a perturbative correction to the thermodynamic pressure

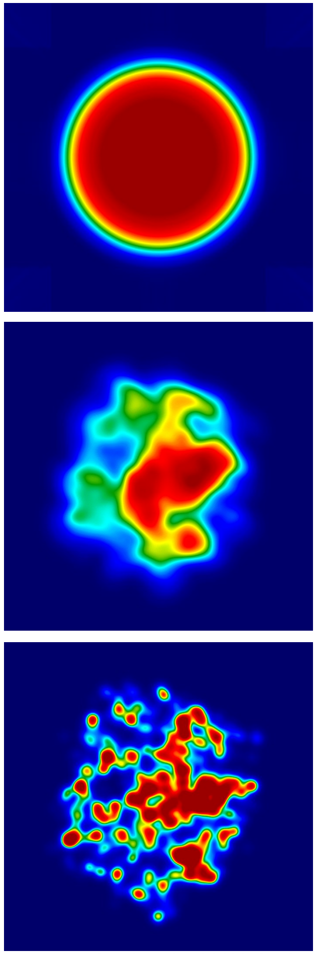
$$\boxed{P_{PCE} = P_0 + \delta P} \rightarrow \text{bulk?}$$

Different descriptions of the same effect?

Why did bulk become necessary?

Evolution of initial state

ε(x,y)

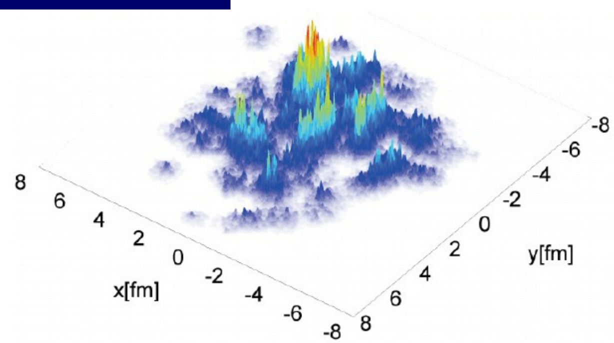


Coarse-graining size

Smooth Initial conditions (v2=0 in central collisions) — λ~5 fm

Fluctuations in nucleon positions (odd harmonics) — λ~1 fm

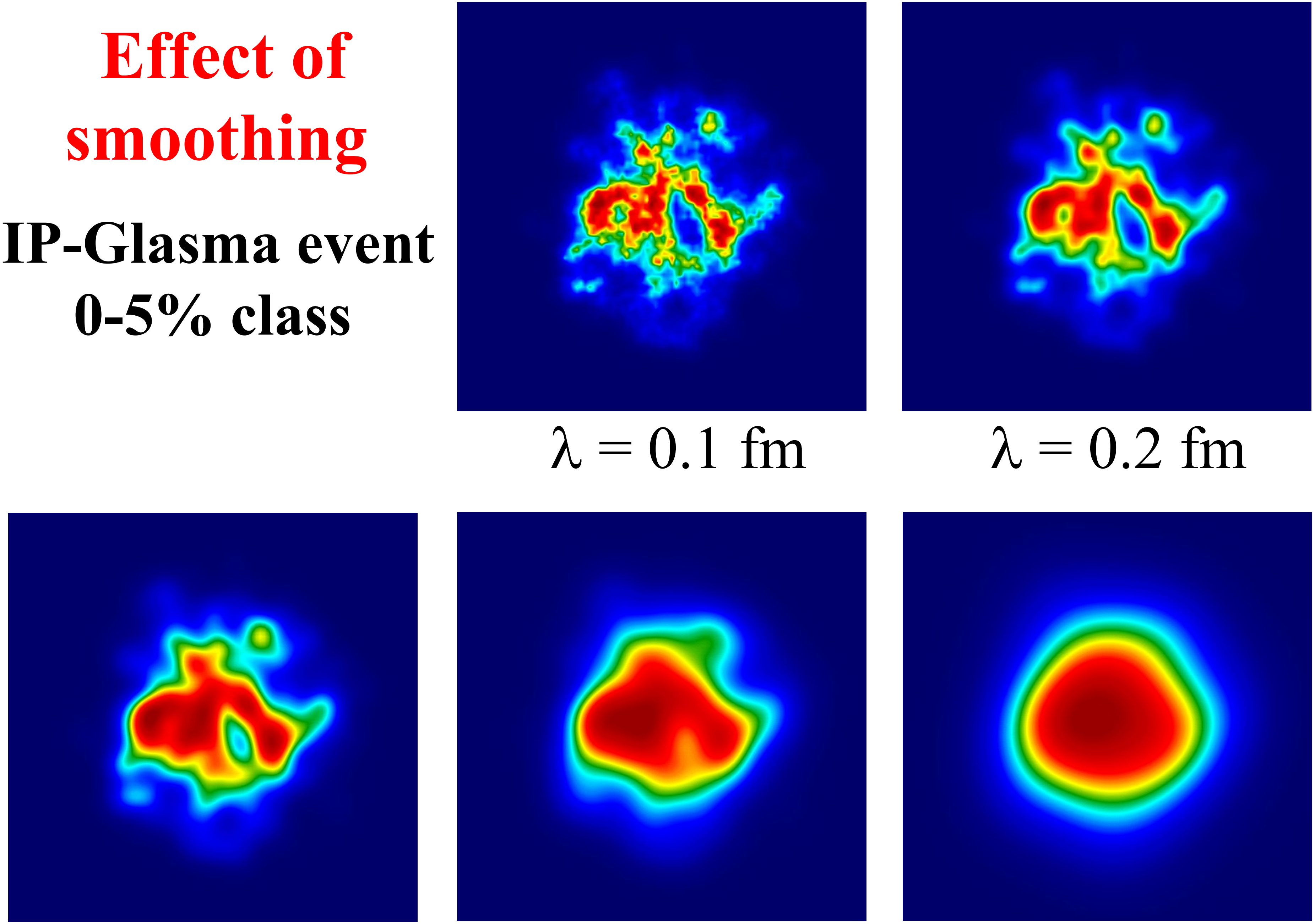
sub-nucleonic fluctuations (vn distributions&correlations) — λ~0.4 fm



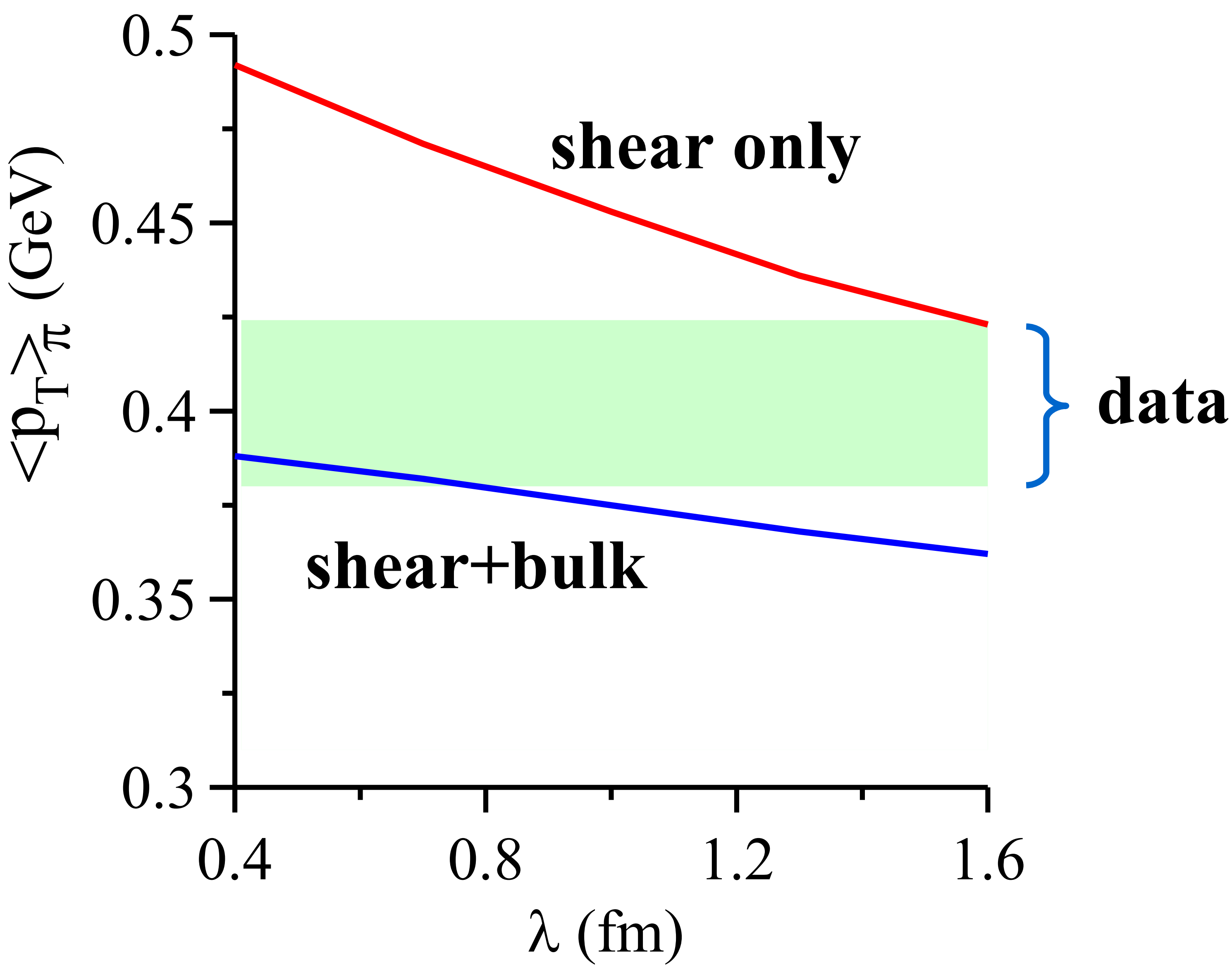
This happens because the IP-Glasma model gives rise to an initial state with large gradients of pressure and the subsequent fluid-dynamic expansion accordingly produces a significant radial flow.

Effect of smoothing

IP-Glasma event
0-5% class



Effect of initial thermalization scale



What else can the spectra tell us?

Azimuthal information – Fourier series

Rapidity information – Legendre polynomials
Bzdak&Teaney, measured by ATLAS

Need of a more systematic expansion

Can we extract more information from spectra?

$$\boxed{f^{(i)}\left(x_T\right) = \frac{1}{\langle N \rangle_i} \frac{dN^{(i)}}{dx_T}}$$

$$x_T = 2p_T / \langle \langle p_T \rangle \rangle$$

Expansion using Laguerre polynomials, Ln

$$\boxed{f^{(i)}\left(x_T\right) = x_T \exp\left(-x_T\right) \sum_{n=0}^{\infty} \frac{\ell_n^{(i)}}{n+1} L_n^{(1)}\left(x_T\right)}$$

characterize spectra

Can we extract more information from spectra? $x_T = 2p_T / \langle\langle p_T \rangle\rangle$

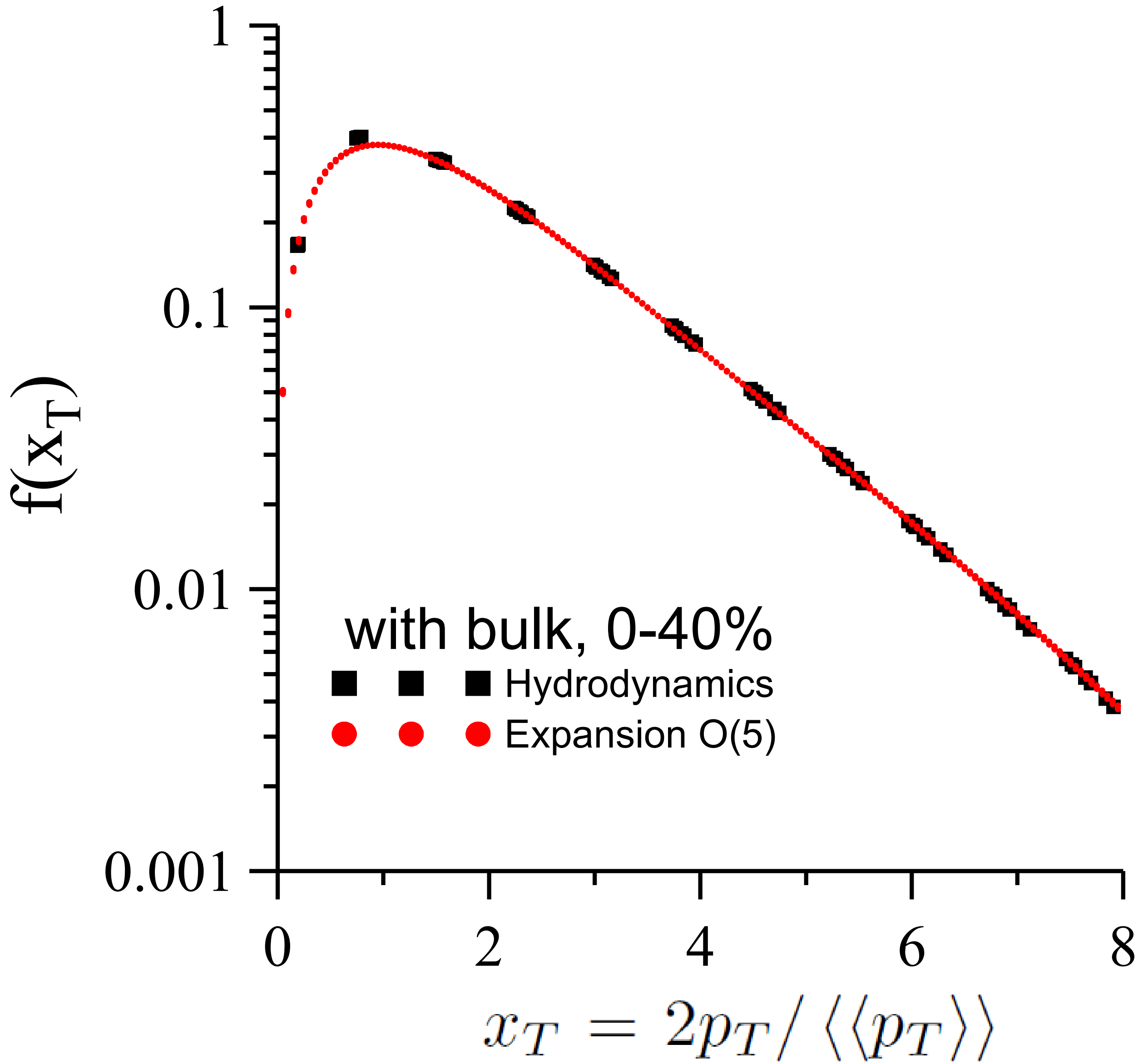
Expansion using Laguerre polynomials, Ln

$$\boxed{f^{(i)}(x_T) = x_T \exp(-x_T) \sum_{n=0}^{\infty} \frac{\ell_n^{(i)}}{n+1} L_n^{(1)}(x_T)}$$

Coefficients: $\ell_n^{(i)} = \left\langle L_n^{(1)} \right\rangle_{(i)}$

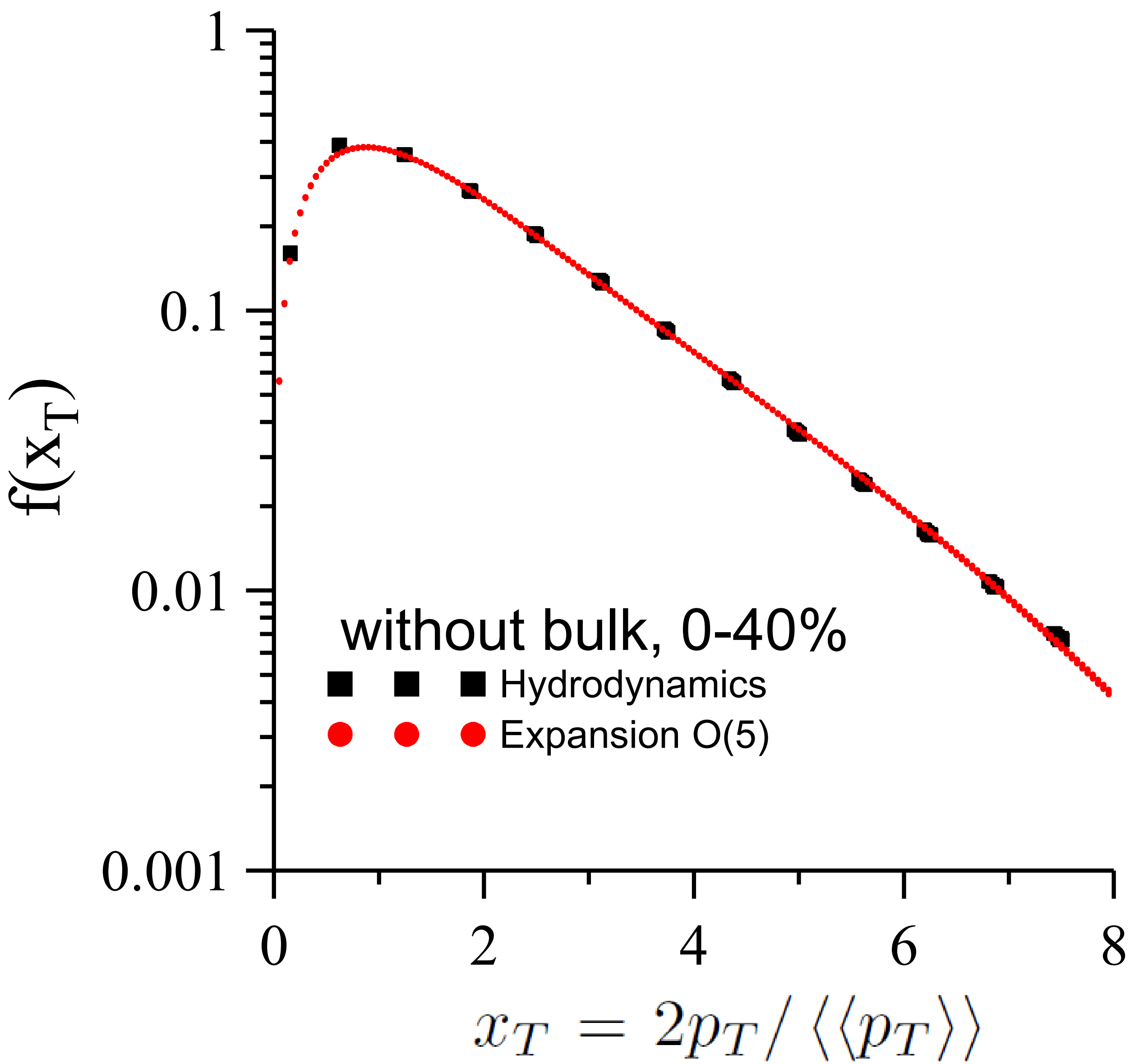
$$\langle A \rangle_{(i)} = \int dx_T f^{(i)}(x_T) A^{(i)}(x_T)$$

Does it work?



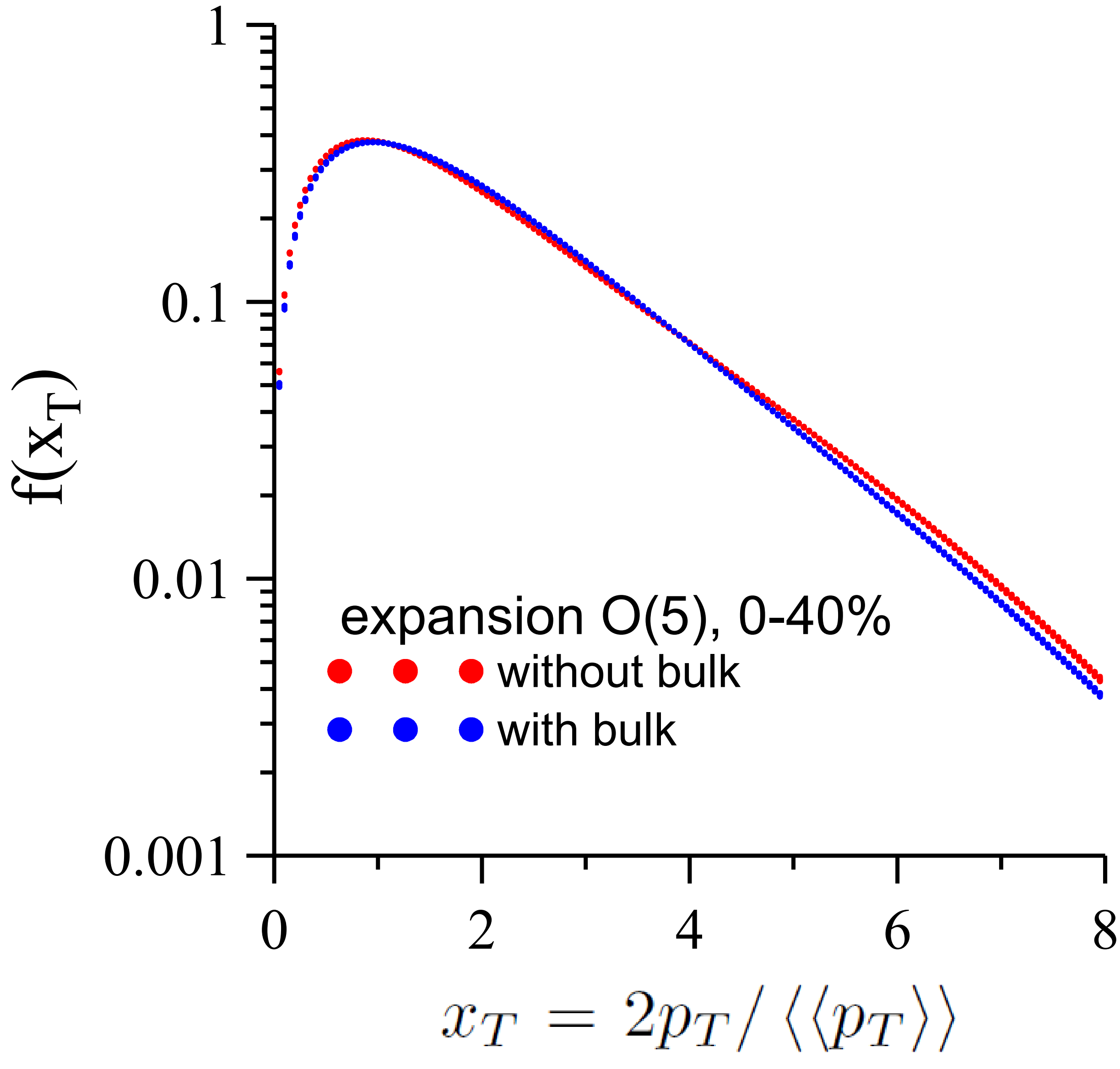
1
0.1
0.01
0.001
f(x_T)
0
2
4
6
8
$x_T = 2p_T / \langle\langle p_T \rangle\rangle$
with bulk, 0-40%
Hydrodynamics
Expansion O(5)

Does it work?

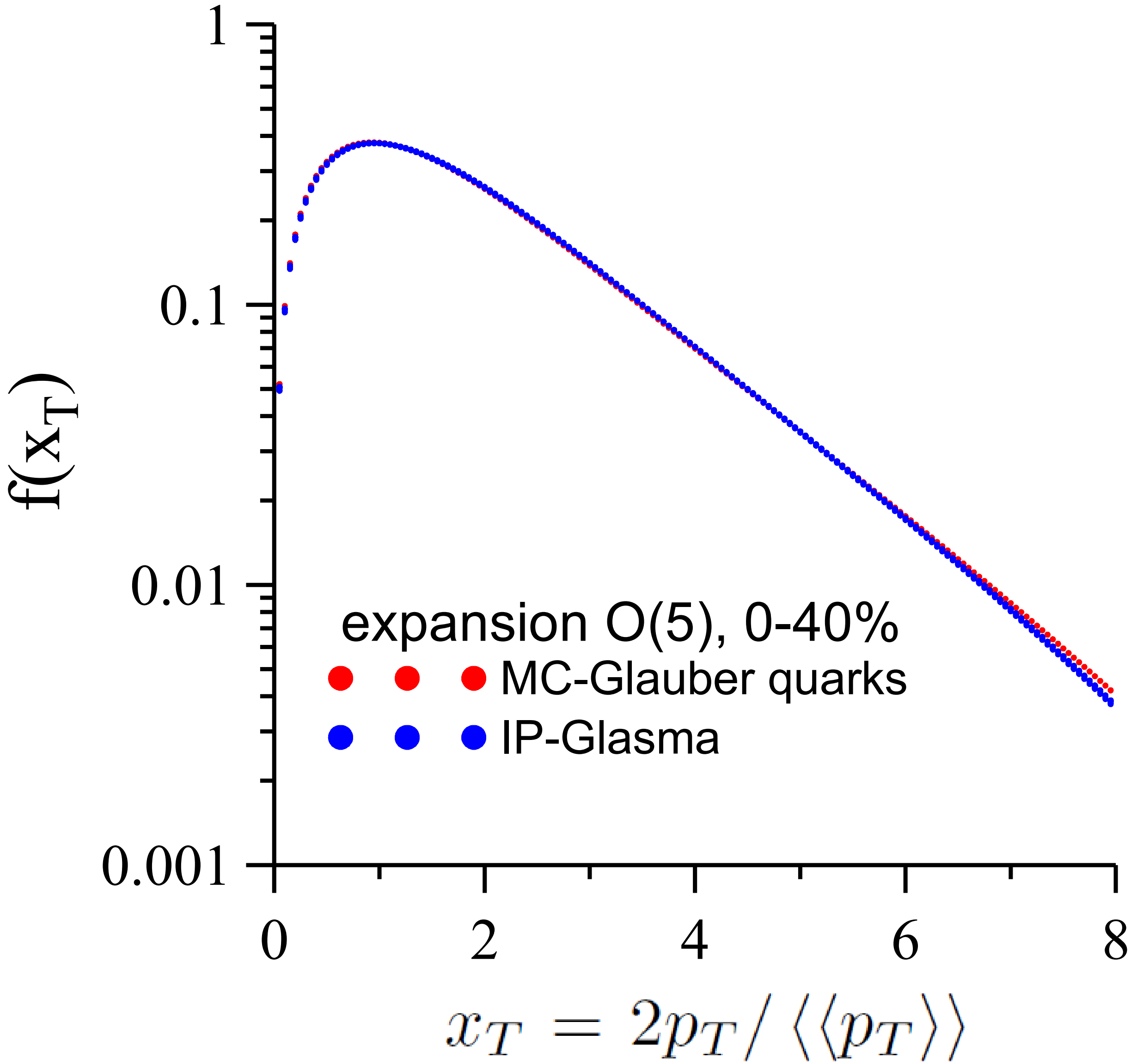


1
0.1
0.01
0.001
f(x_T)
without bulk, 0-40%
Hydrodynamics
Expansion O(5)
0
2
4
6
8
$x_T = 2p_T / \langle\langle p_T \rangle\rangle$

Bulk viscosity changes the shape of f



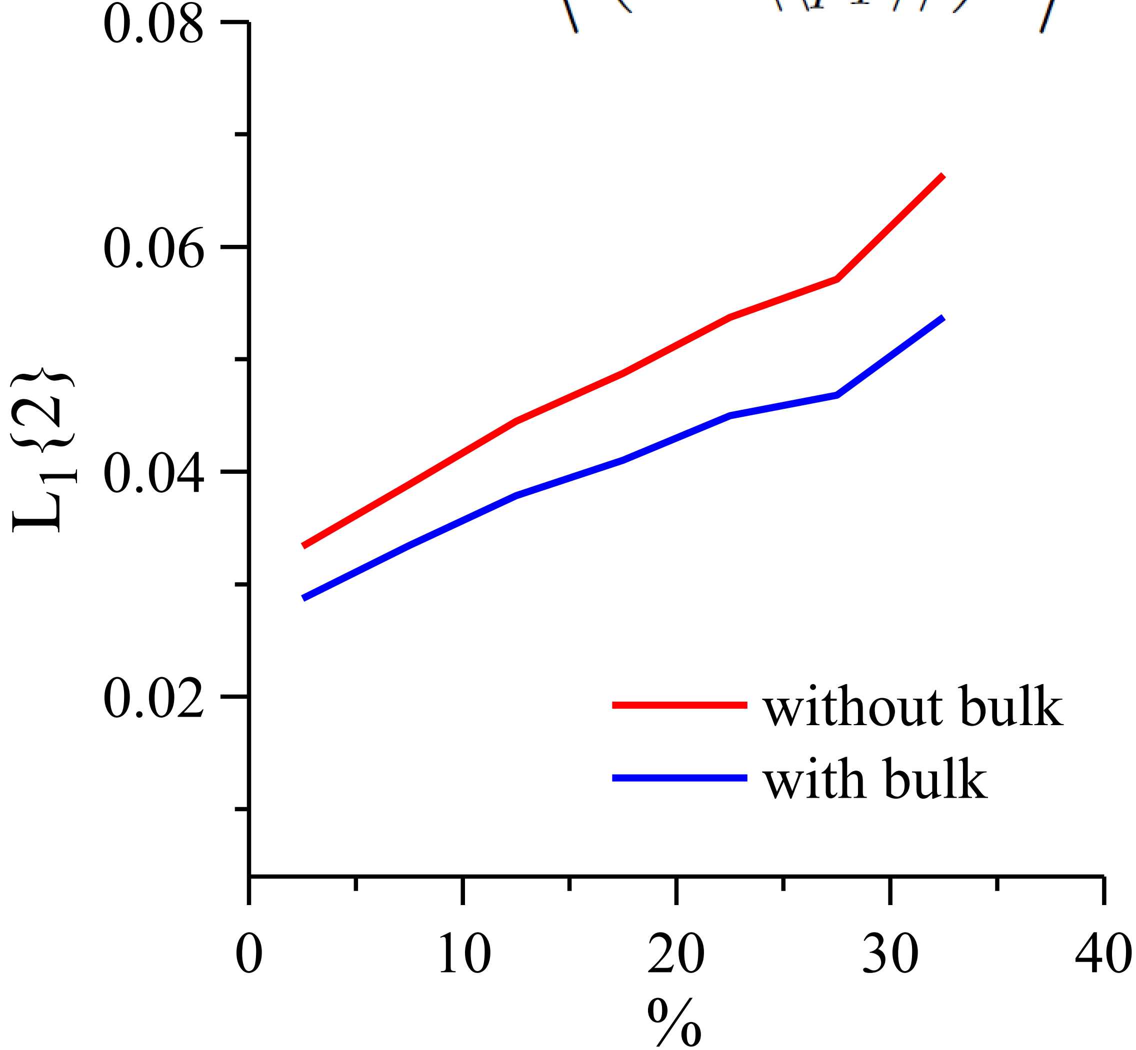
Initial condition does not



Expansion coefficients

$$L_n\{2\} = \sqrt{\left\langle \langle L_n \rangle^2 \right\rangle}$$

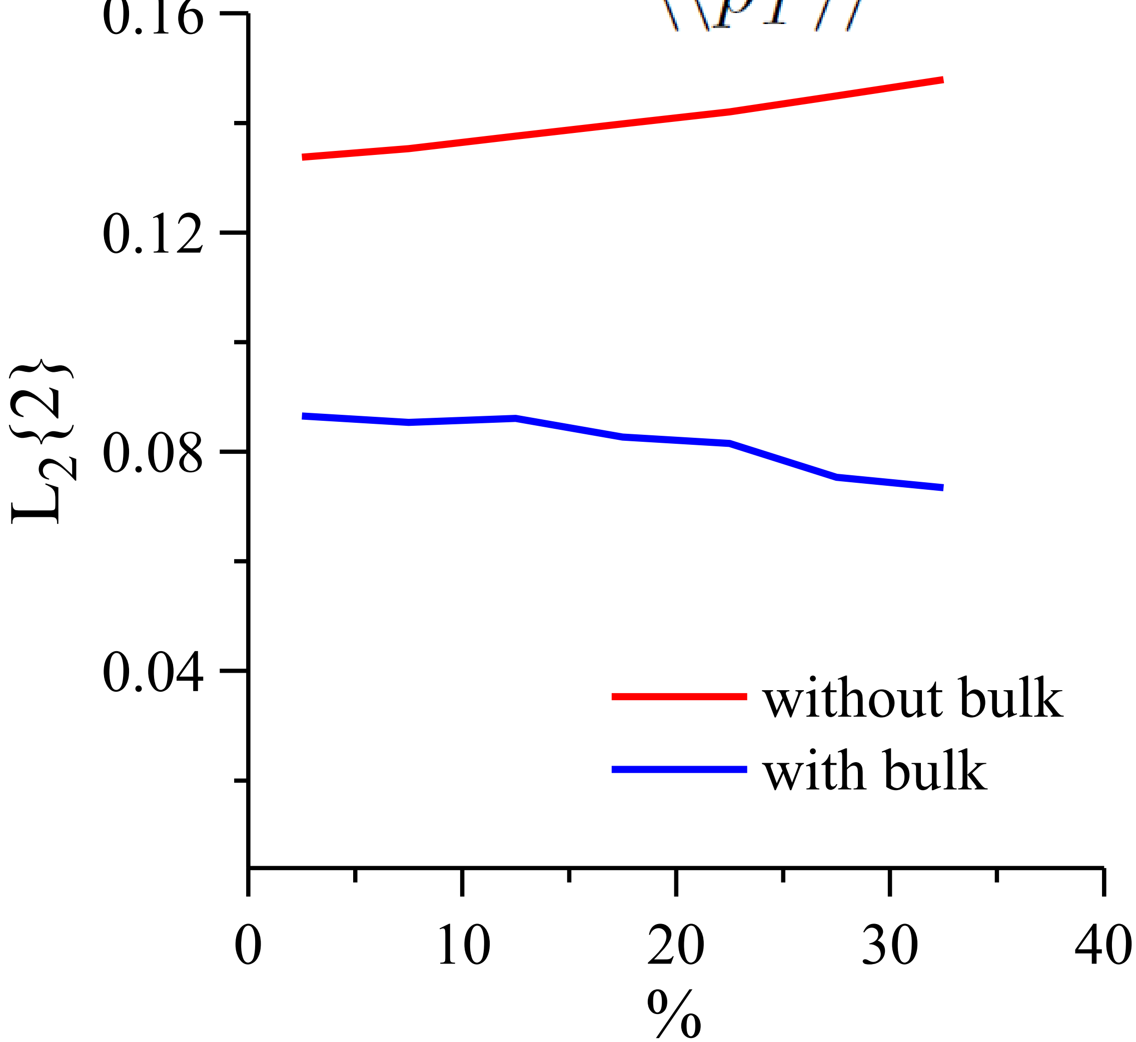
$$\left\langle \langle L_1 \rangle^2 \right\rangle = 4 \left\langle \left(1 - \frac{\langle p_T \rangle}{\langle \langle p_T \rangle \rangle} \right)^2 \right\rangle$$



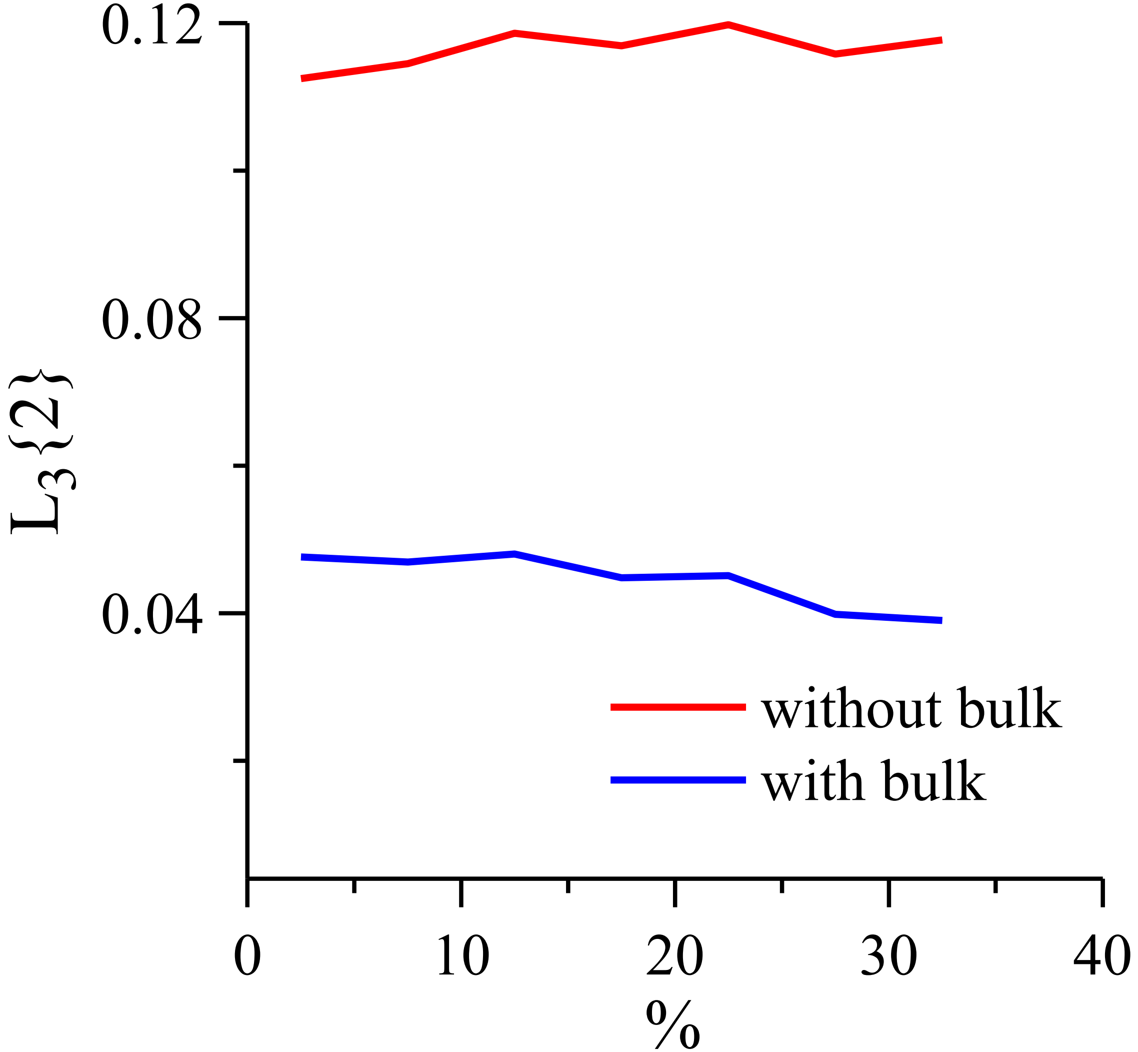
Expansion coefficients

$$L_n\{2\} = \sqrt{\left\langle \langle L_n \rangle^2 \right\rangle}$$

$$\langle\langle L_2 \rangle\rangle = 2\frac{\langle\langle p_T^2 \rangle\rangle}{\langle\langle p_T \rangle\rangle^2} - 3$$

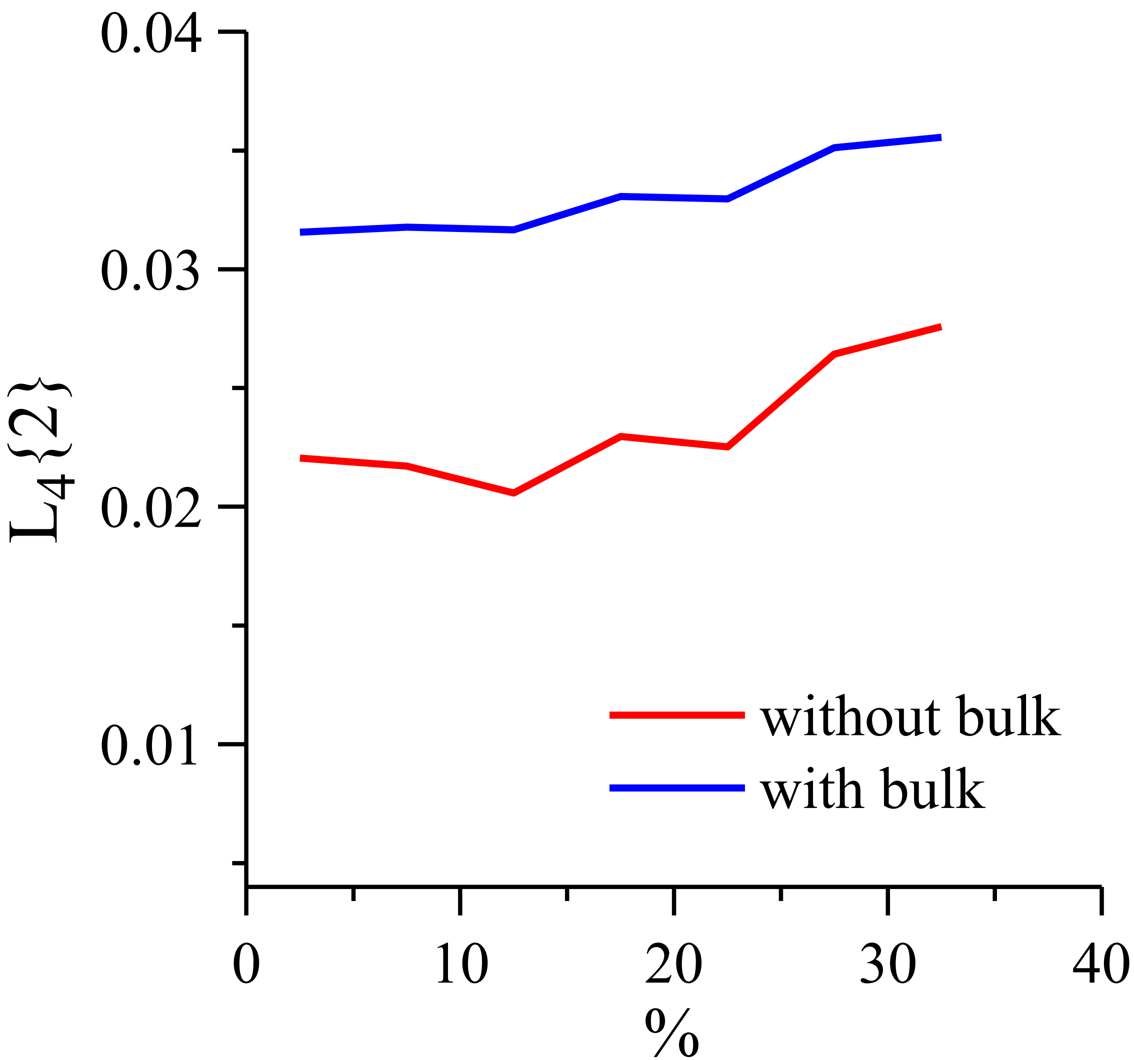


Expansion coefficients $L_n\{2\} = \sqrt{\left\langle \langle L_n \rangle^2 \right\rangle}$



Expansion coefficients

$$L_n\{2\} = \sqrt{\left\langle \langle L_n \rangle^2 \right\rangle}$$



Summary/conclusions

We studied the effect of bulk viscosity on the transverse momentum spectra

✔ Bulk viscosity has a considerable effect on multiplicity, transverse momentum, and flow harmonics

✔ The mean transverse momentum is correlated to the initial energy density gradients

✔ Effect of bulk viscosity on spectra can be studied using Laguerre moments of the distribution function

Happy Birthday Uli!