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Extracting the bulk viscosity of the quark-gluon plasma

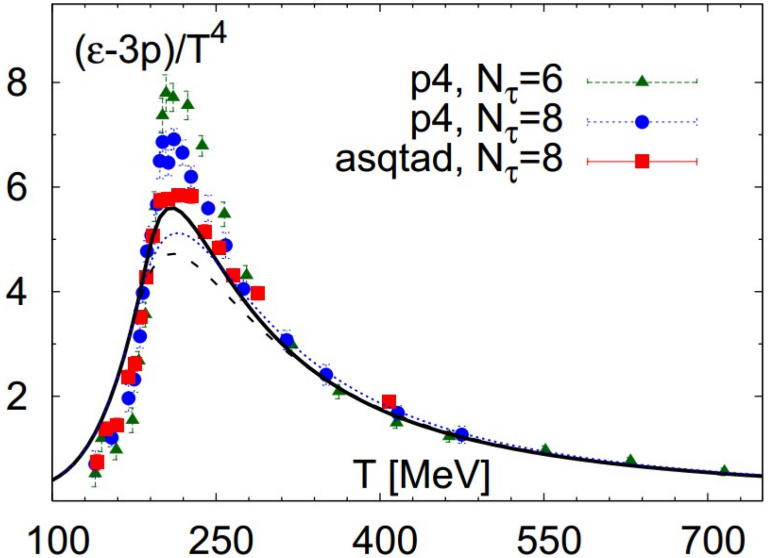
Gabriel S. Denicol

with:

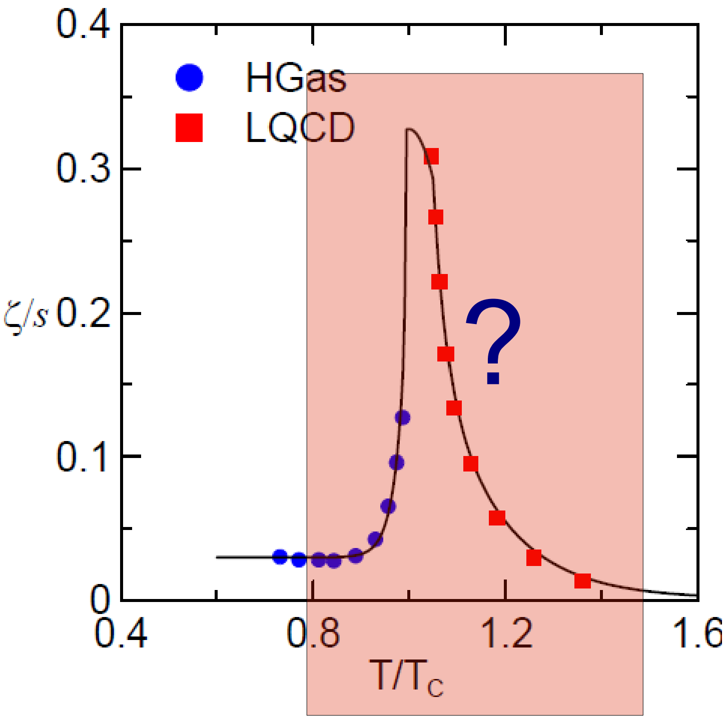
J.B. Rose, **J.F. Paquet**, M. Luzum, B. Schenke, S. Jeon, C. Gale

XXIV QUARK MATTER
DARMSTADT 2014

QCD is not conformal



Lattice QCD calculations demonstrate that the EoS of QCD matter deviates from that of a conformal fluid



Bulk viscosity should also be nonzero in this temperature range

How large can it get?

Goal

• Understand the magnitude of the bulk viscosity coefficient using ultracentral heavy ion collisions

Why ultracentral? we don't need to do EbE

Gardim&Grassi&Luzum&Ollitrault, arxiv:1111.6538

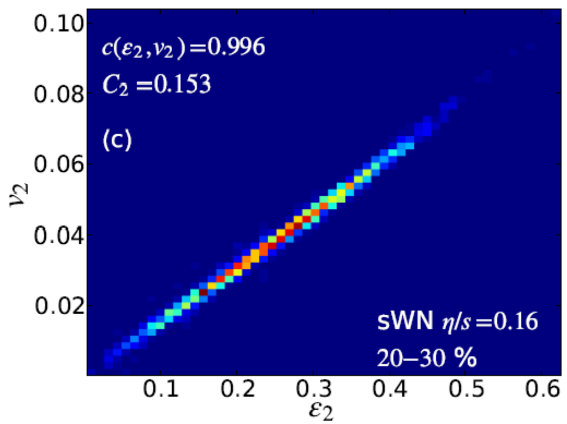
$$v_n = C_n \epsilon_n$$

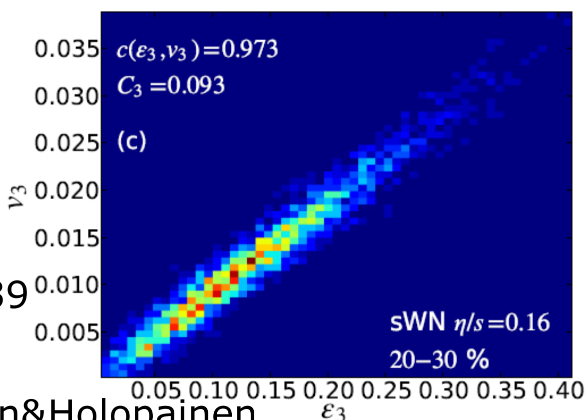
Contains all the information about the hydrodynamic response

We compute the coefficient C_n as a function of viscosity, T_{fo}, etc ...

Same as Luzum&Ollitrault, arxiv:1210.6010

Similar philosophy to Retinskaya&Luzum&Ollitrault, arxiv:1311.5339





Niemi&GSD&Huovinen&Holopainen

Strategy

Teaney&Yan, Luzum&Ollitrault

- Start from a central **optical Glauber** initial condition

- **Deform it** so that it obtains an eccentricity, $\mathbf{e_n}$

- Perform hydrodynamic simulation and calculate: $\mathbf{C_n = v_n/e_n}$

- Repeat for several η and ζ until the response function $\mathbf{C_n}$ is mapped

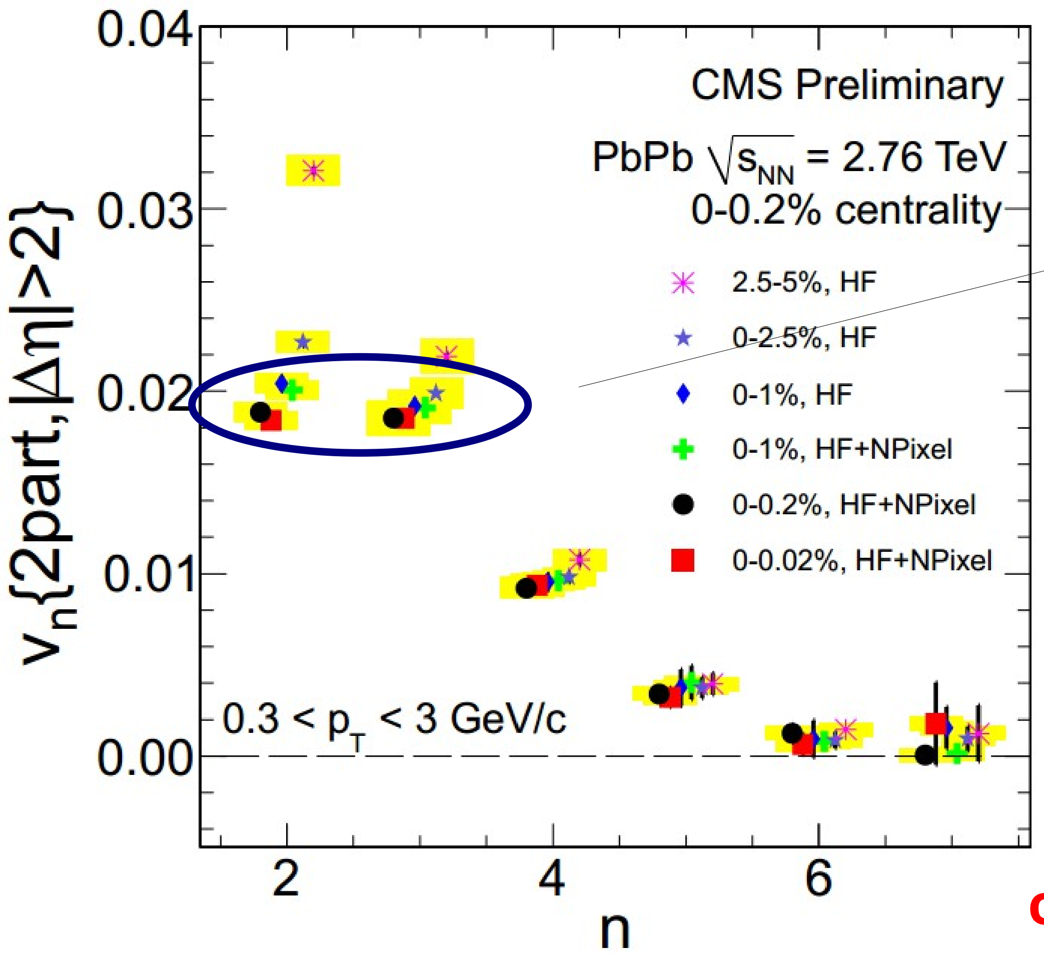
At the end, we have $C_n(\eta,\zeta)$

$$v_n = C_n \epsilon_n$$

IC model

Issue with ultracentral data

- **Nonhydrodynamic**(?) behaviour in ultracentral PbPb collisions



In ultracentral collisions

$v_2 \sim v_3$

This starts to happen in ~ 0-1% centrality class

hard to understand with hydrodynamical simulations

but may provide better constraint for bulk viscosity ...

Fluid-dynamical model:

Bulk viscosity included

Simulation

- ✔ We solve the fluid-dynamical equations using a relativistic version of the KT algorithm – **MUSIC**

  Schenke&Jeon&Gale

  Phys.Rev. C82 (2010) 014903

- ✔ Freeze-out via Cooper-Frye, T=140 MeV

- ✔ δf from Monnai&Hirano, Phys. Rev. C80 (2009) 054906

  Detailed study of δf → J.Noronha-Hostler *et al* Phys. Rev. C88 (2013) 044916

- ✔ lQCD + HRG EoS by Huovinen&Petrescky

  Nucl.Phys. A837 (2010) 26-53

- ✔ τ_0=1 fm, equilibrium; τ_0=0.4 fm (IPGlasma)

Fluid-dynamical equations

MUSIC 2.0

GSD&Niemi&Molnar&Rischke, arXiv:1202.4551

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

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

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

Fluid-dynamical equations

MUSIC 2.0

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Second-Order Nonlinear source terms

Bulk viscous pressure

Coupling between bulk viscous pressure and shear-stress tensor

Coefficients employed

MUSIC 2.0

GSD&Jeon&Gale, arXiv:1403.0962

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

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Transport coefficients computed within the 14-moment approximation

$$\beta_\pi = \frac{\varepsilon_0 + P_0}{5}, \ \delta_{\pi\pi} = \frac{4}{3}\tau_\pi , \quad \tau_{\pi\pi} = \frac{10}{7}\tau_\pi , \quad \varphi_7 = \frac{9}{70P_0}\tau_\pi .$$

$$\beta_\Pi = \frac{\zeta}{\tau_\Pi} = 14.55 \times \left(\frac{1}{3} - c_s^2\right)^2 (\varepsilon_0 + P_0) + \mathcal{O}\left(z^5\right) ,$$

$$\frac{\delta_{\Pi\Pi}}{\tau_\Pi} = 1 - c_s^2 + \mathcal{O}\left(z^2 \ln z\right) ,$$

$$\frac{\lambda_{\Pi\pi}}{\tau_\Pi} = \frac{8}{5}\left(\frac{1}{3} - c_s^2\right) + \mathcal{O}\left(z^4\right) ,$$

$$z \equiv m/T,$$

Viscosity Ansatz

Shear viscosity

$$\frac{\eta}{s} = \mathrm{const}$$

"effective" shear viscosity

Bulk viscosity

$$\frac{\zeta}{s} = \underbrace{\mathrm{const}}_{b} \times \frac{\eta}{s} \left(\frac{1}{3} - c_s^2 \right)^2$$

inspired in the weakly coupled limit

Keep in mind

other functional forms are allowed

Bulk viscosity from kinetic theory

Weinberg (matter coupled to radiation)

$$\zeta = 15\,\eta\left(\frac{1}{3} - c_s^2\right)^2$$

Dusling&Schaefer (pure glue)

$$\zeta \approx 50\,\eta\left(\frac{1}{3} - c_s^2\right)^2$$

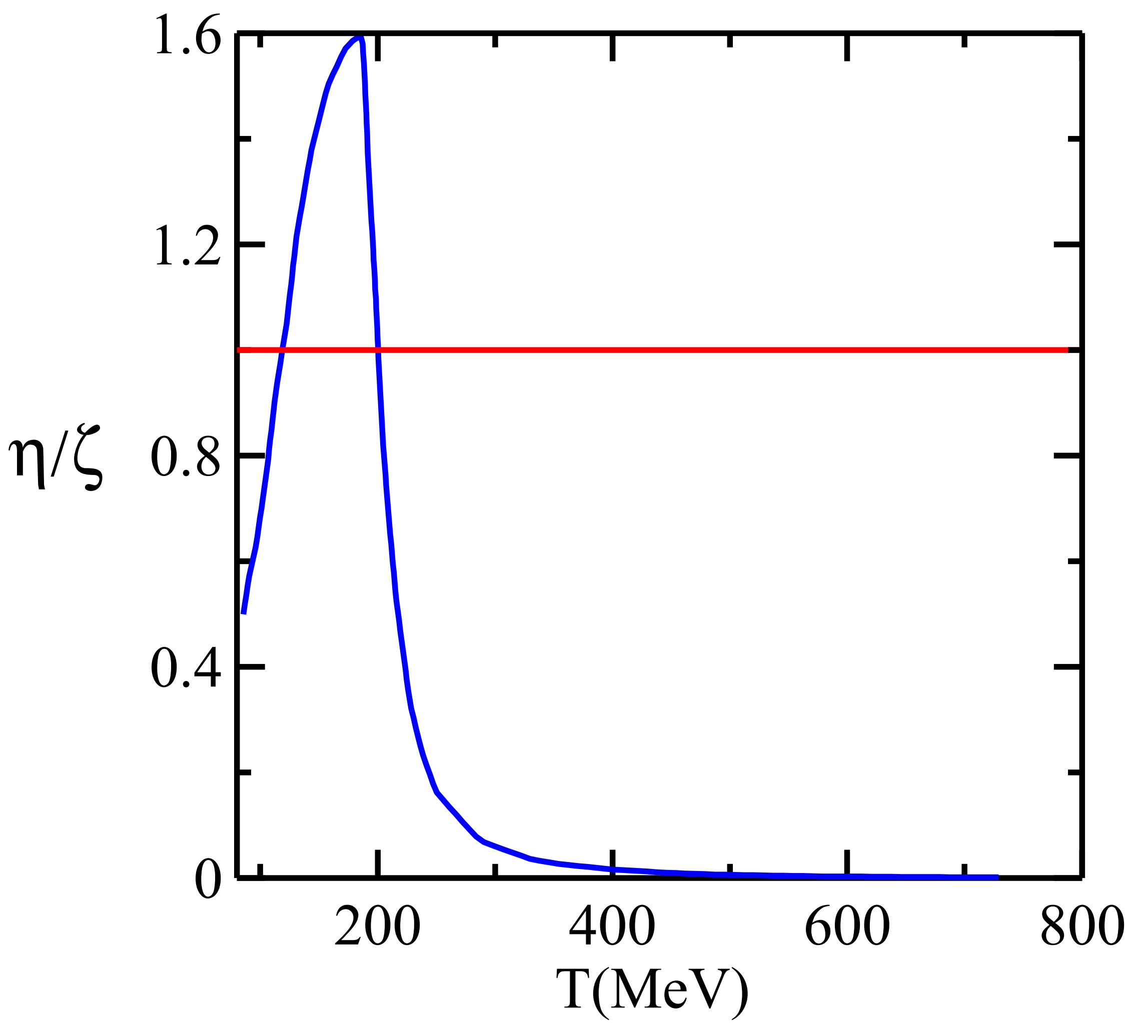
QGP?

14-moment approximation (Anderson-Witting equation)

$$\zeta \approx 73\,\eta\left(\frac{1}{3} - c_s^2\right)^2$$

Bulk viscosity from kinetic theory: example

$$\zeta \approx 50\,\eta\left(\frac{1}{3} - c_s^2\right)^2$$



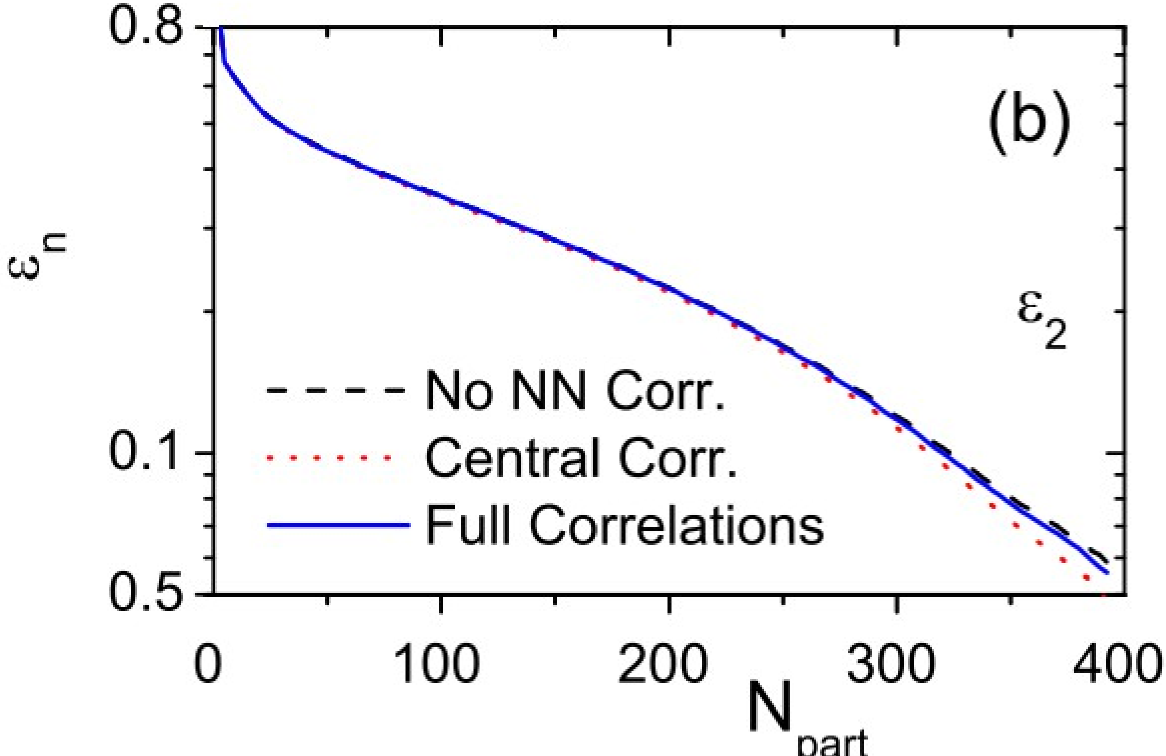
What about the initial state?

N-N correlations

N-N correlations (repulsive)

Usual MC Glauber (and all other models) sample the position of the nucleons independently via WS distribution

Correlations can be introduced (Alvioli&Strickman), but have small effect on other centrality classes



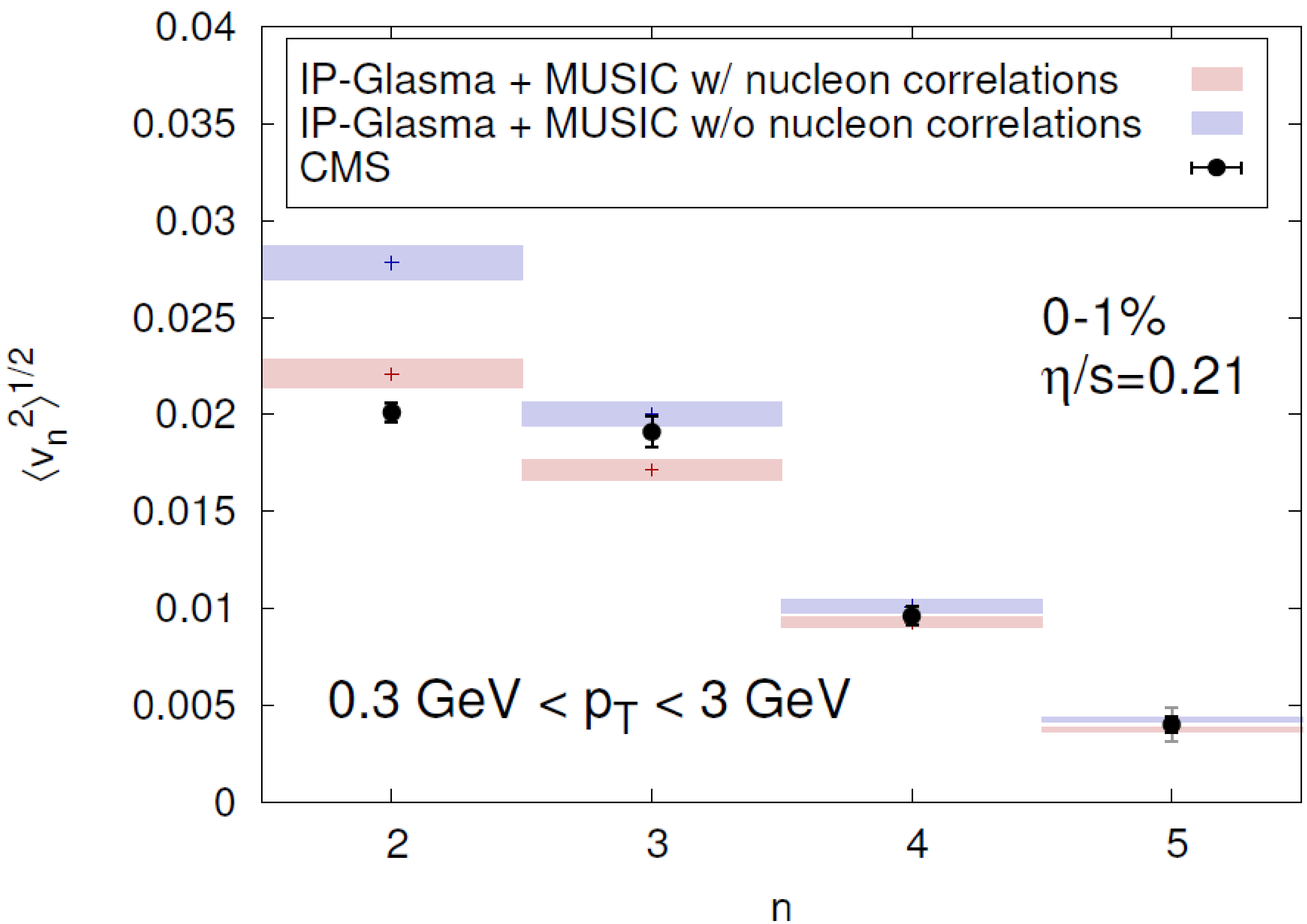
Alvioli&Holopainen &Eskola&Strickman

Nara&Dumitru **showed the same for KLN**

N-N correlations + IPGlasma

0-1% - LHC

N-N correlations were included in IP-Glasma Initial conditions



Large effect of correlations on IP-Glasma initial conditions

agreement with data is improved

N-N correlations + IPGlasma

0-1% - LHC

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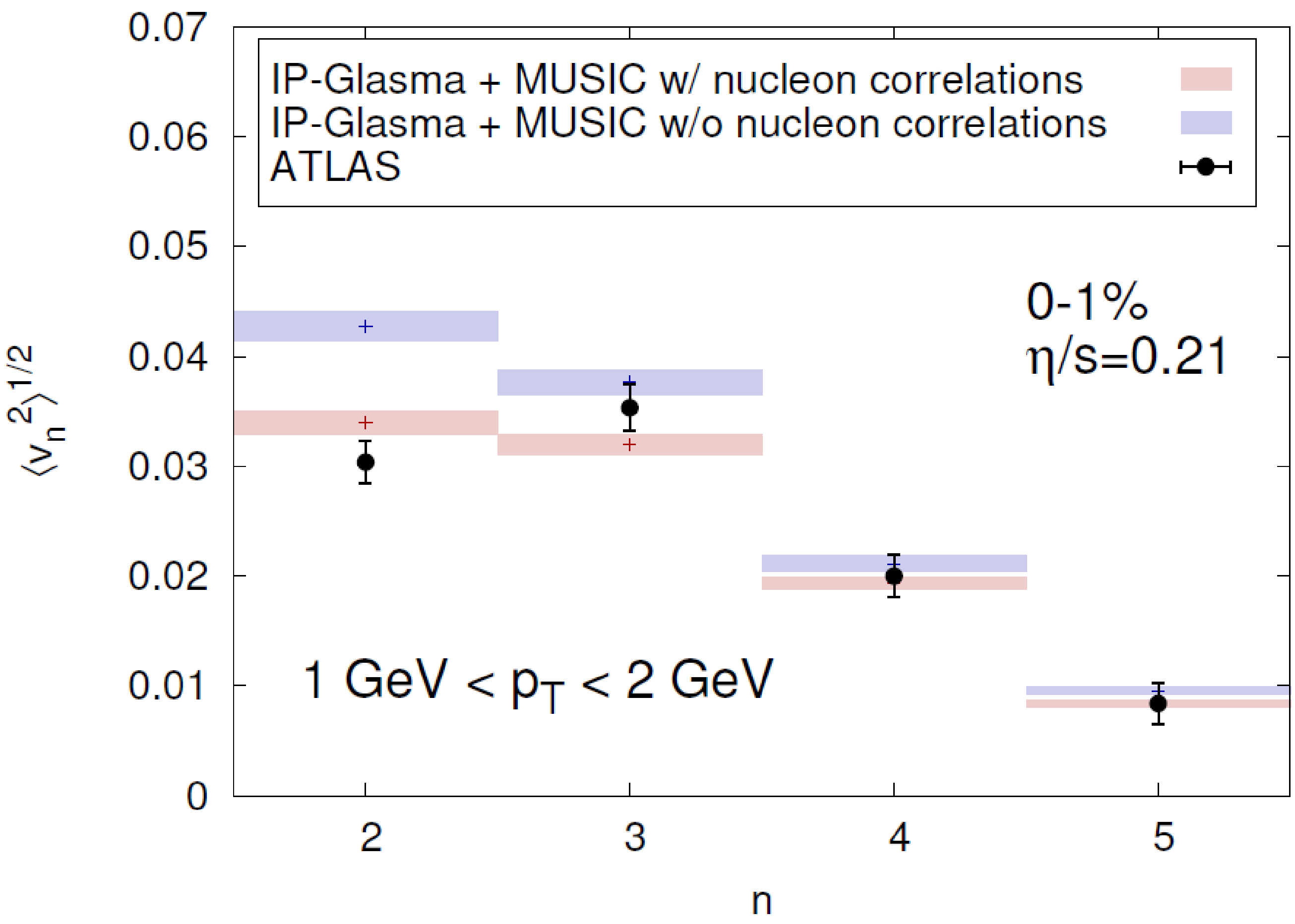


Large effect of correlations on IP-Glasma initial conditions

agreement with data is improved

Results:

Cn coefficients, $v_n = C_n \epsilon_n$

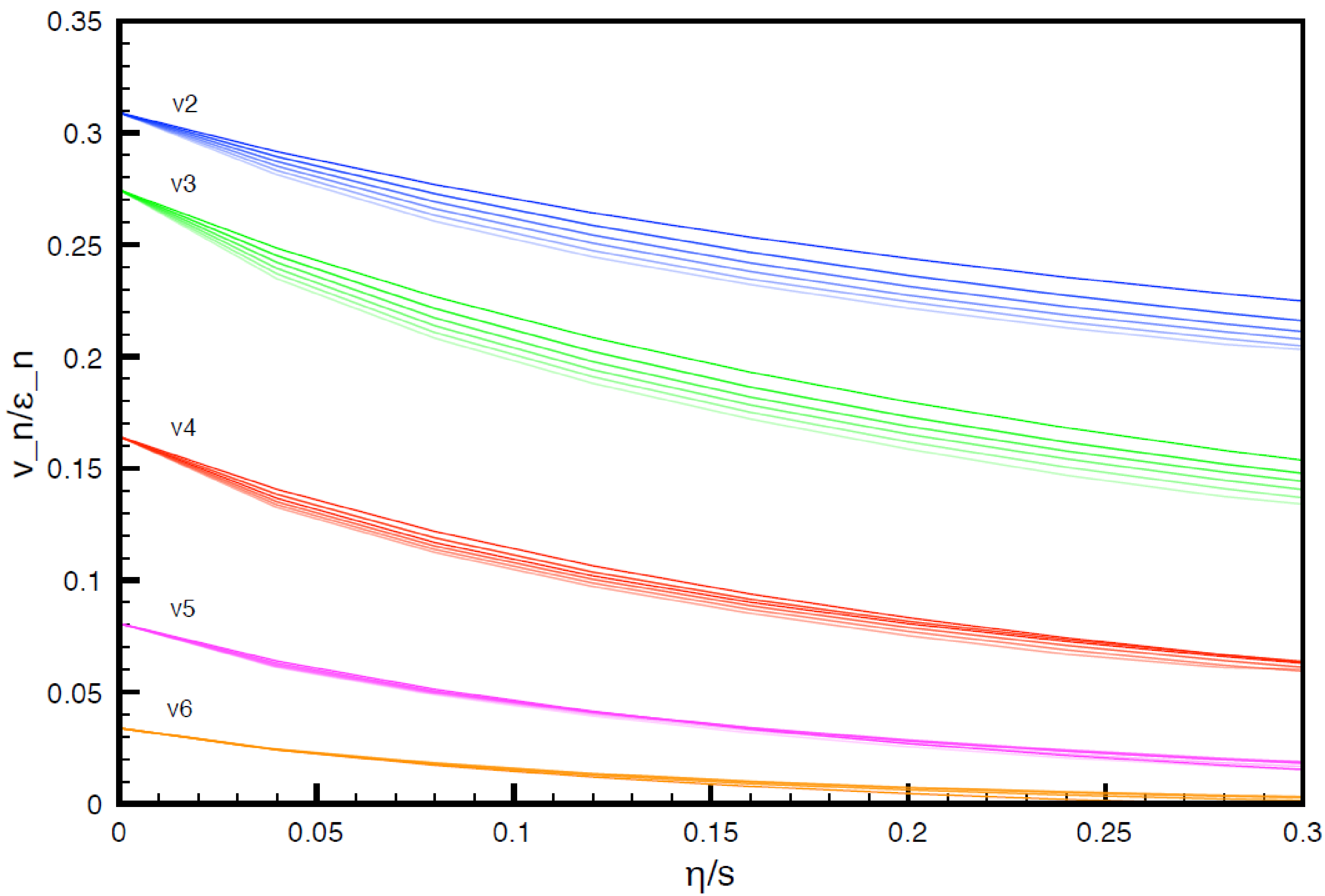
Effect of bulk viscous pressure

MUSIC 2.0

0-1% - LHC

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

b=0, 15, 30, 45, 60, 75

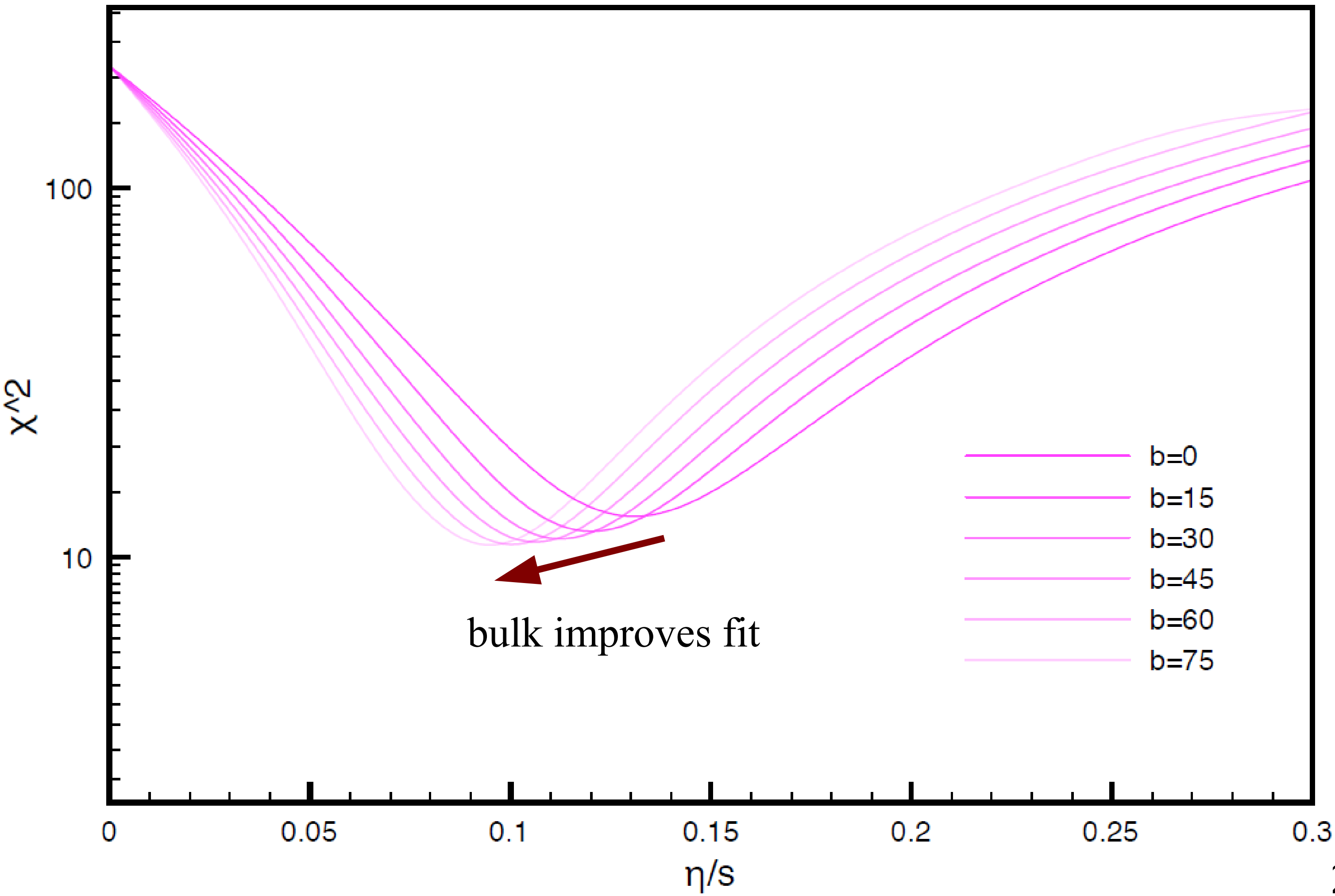


Comparison with data (Glauber)

MUSIC 2.0

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

0-1% - LHC

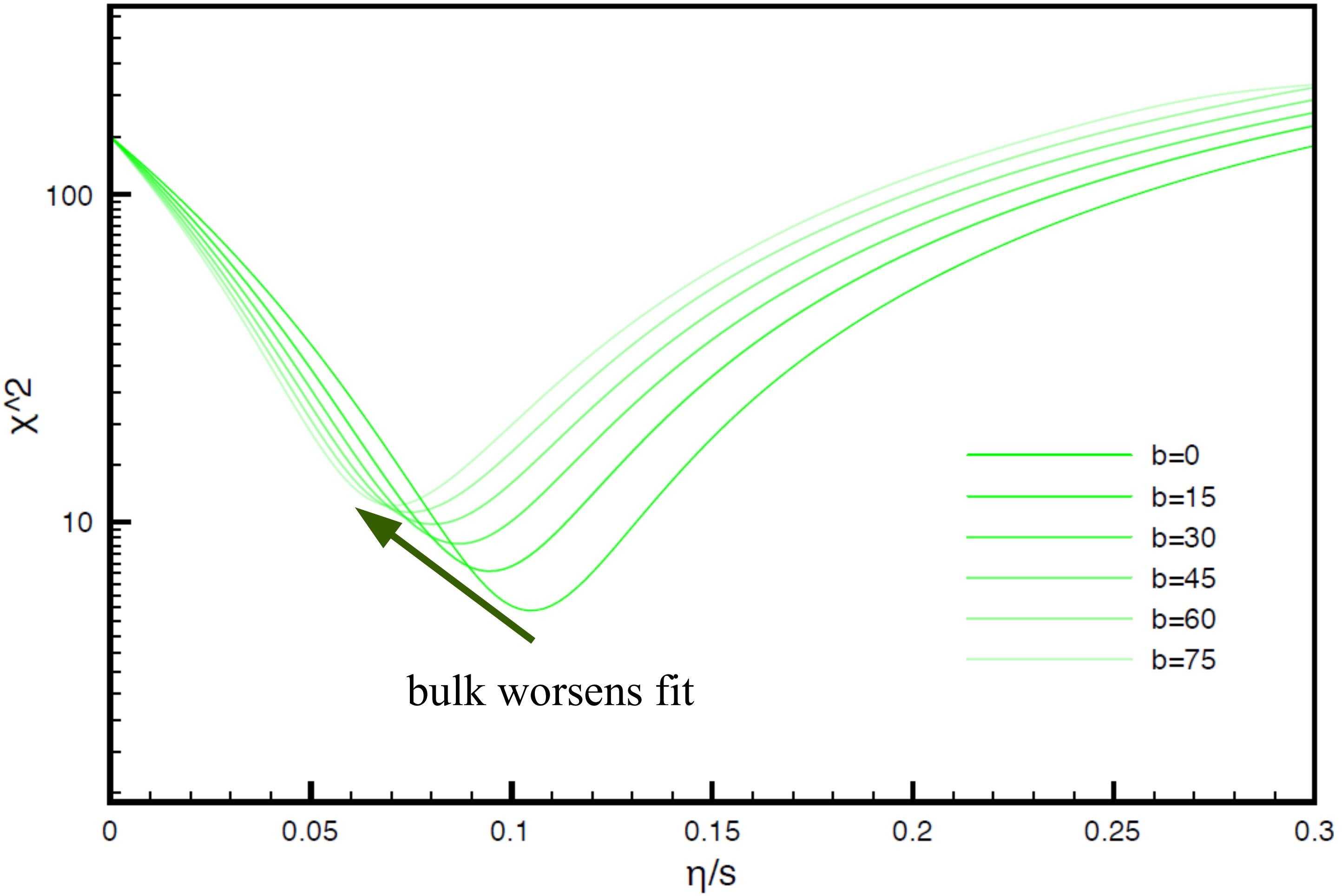


Comparison with data (KLN)

MUSIC 2.0

0-1% - LHC

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s} \left(\frac{1}{3} - c_s^2 \right)^2$$

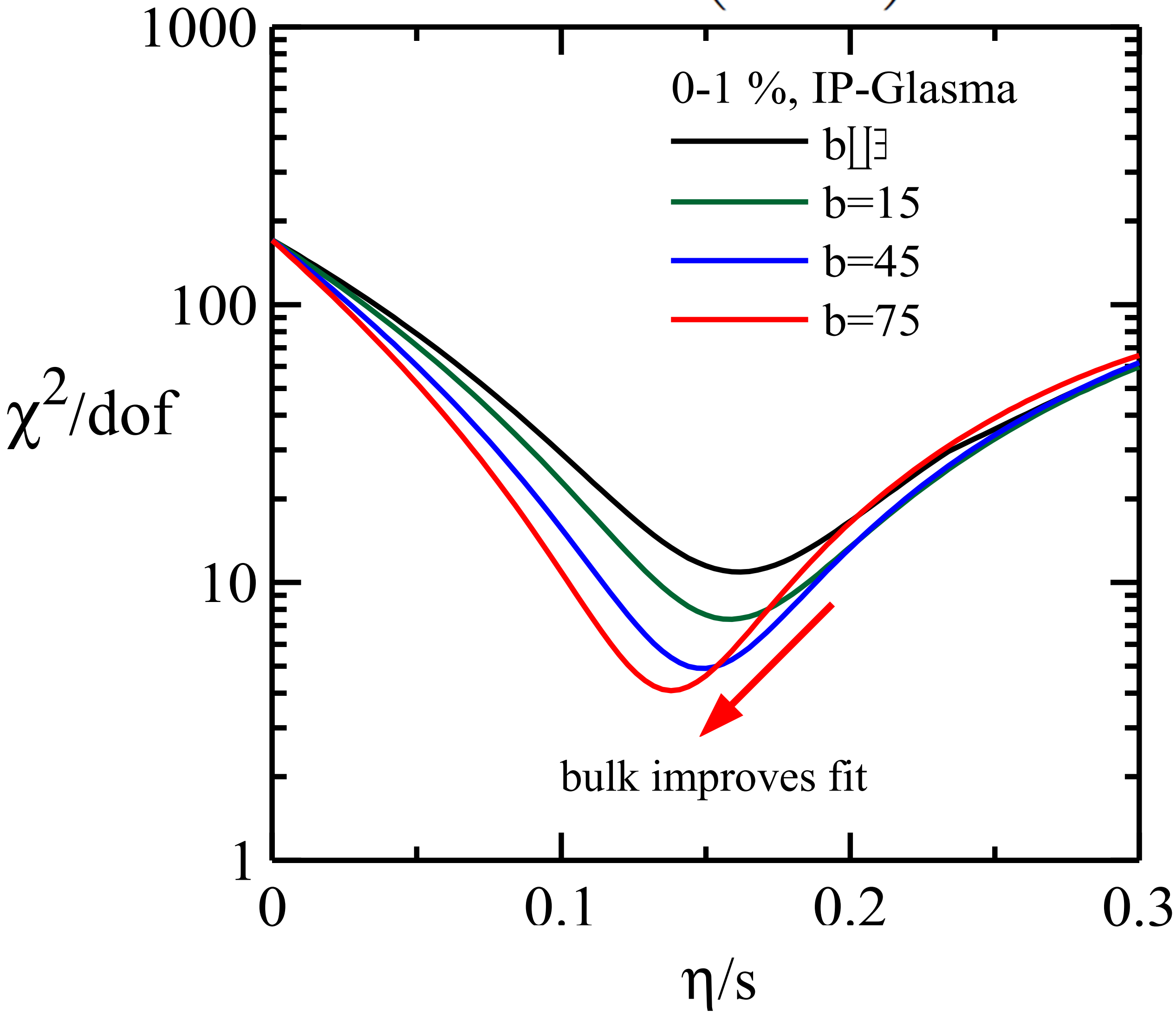


Comparison with data (IP-Glasma*)

MUSIC 2.0

0-1% - LHC

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s} \left(\frac{1}{3} - c_s^2 \right)^2$$

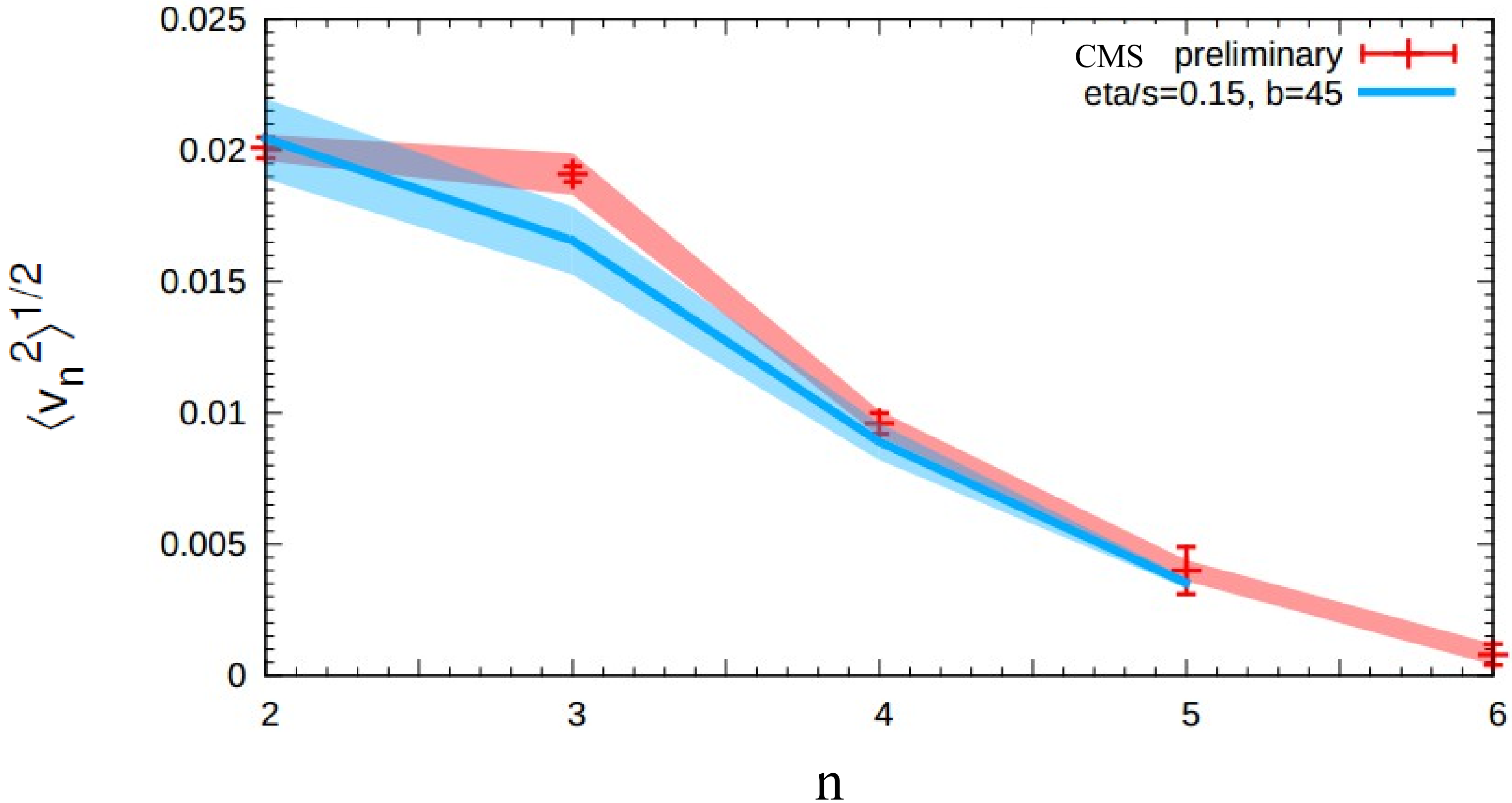


Bulk viscosity + correlations - IPGlasma

MUSIC 2.0

0-1% - LHC

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$



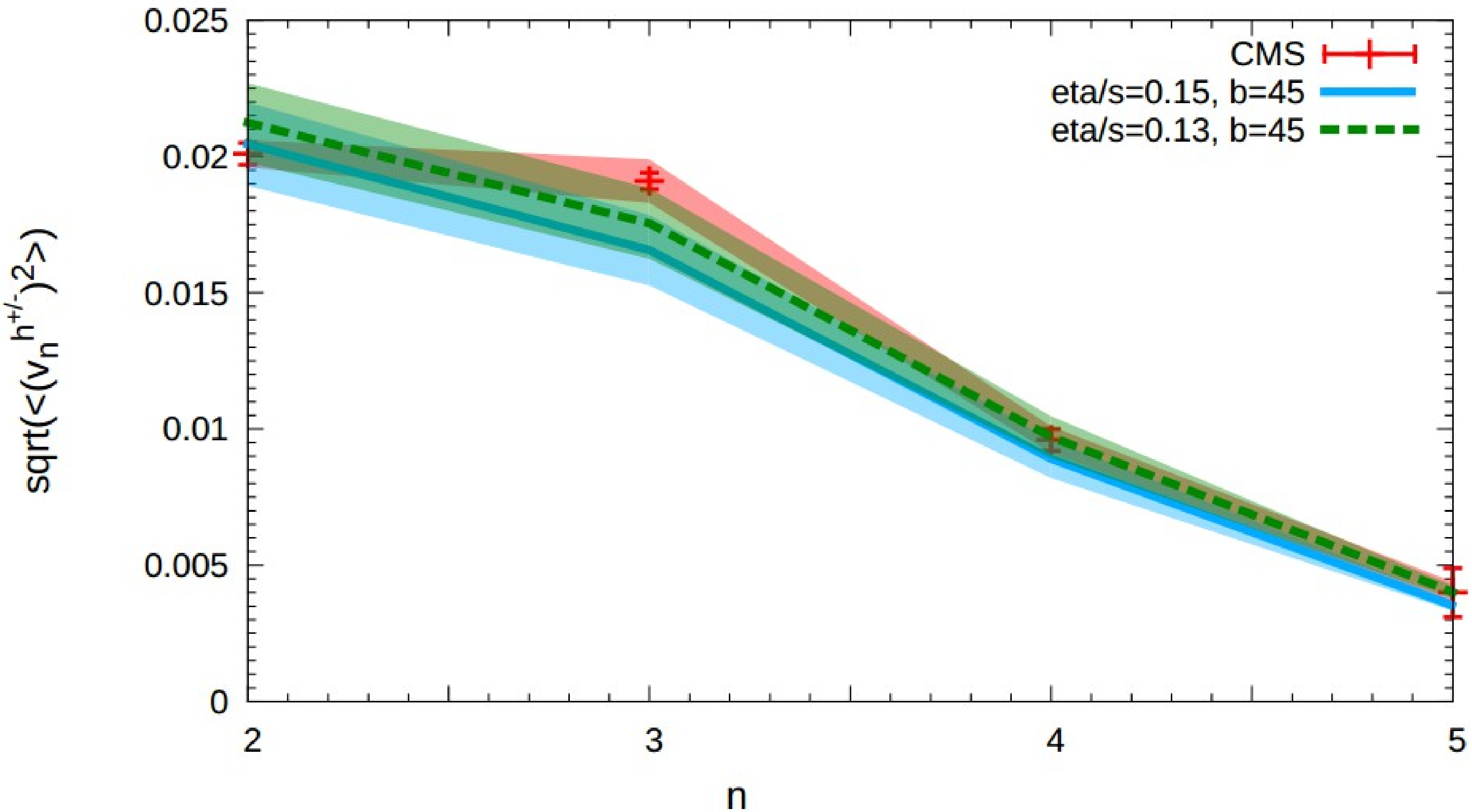
Inclusion of bulk viscosity **further improves** the agreement with data

Bulk viscosity + correlations - IPGlasma

MUSIC 2.0

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

0-1% - LHC



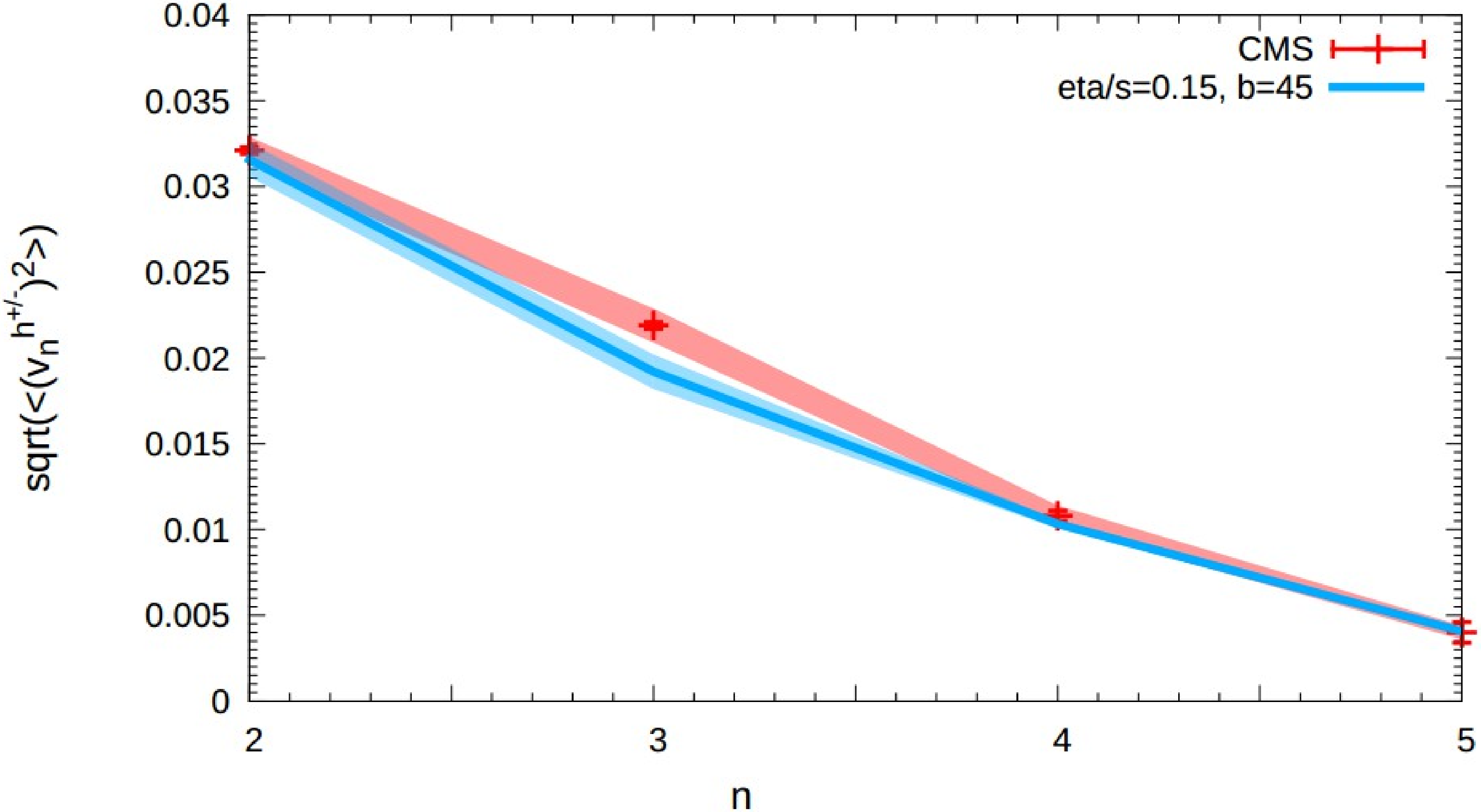
Inclusion of bulk viscosity **further improves** the agreement with data

Bulk viscosity + correlations - IPGlasma

MUSIC 2.0

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

2.5-5% - LHC



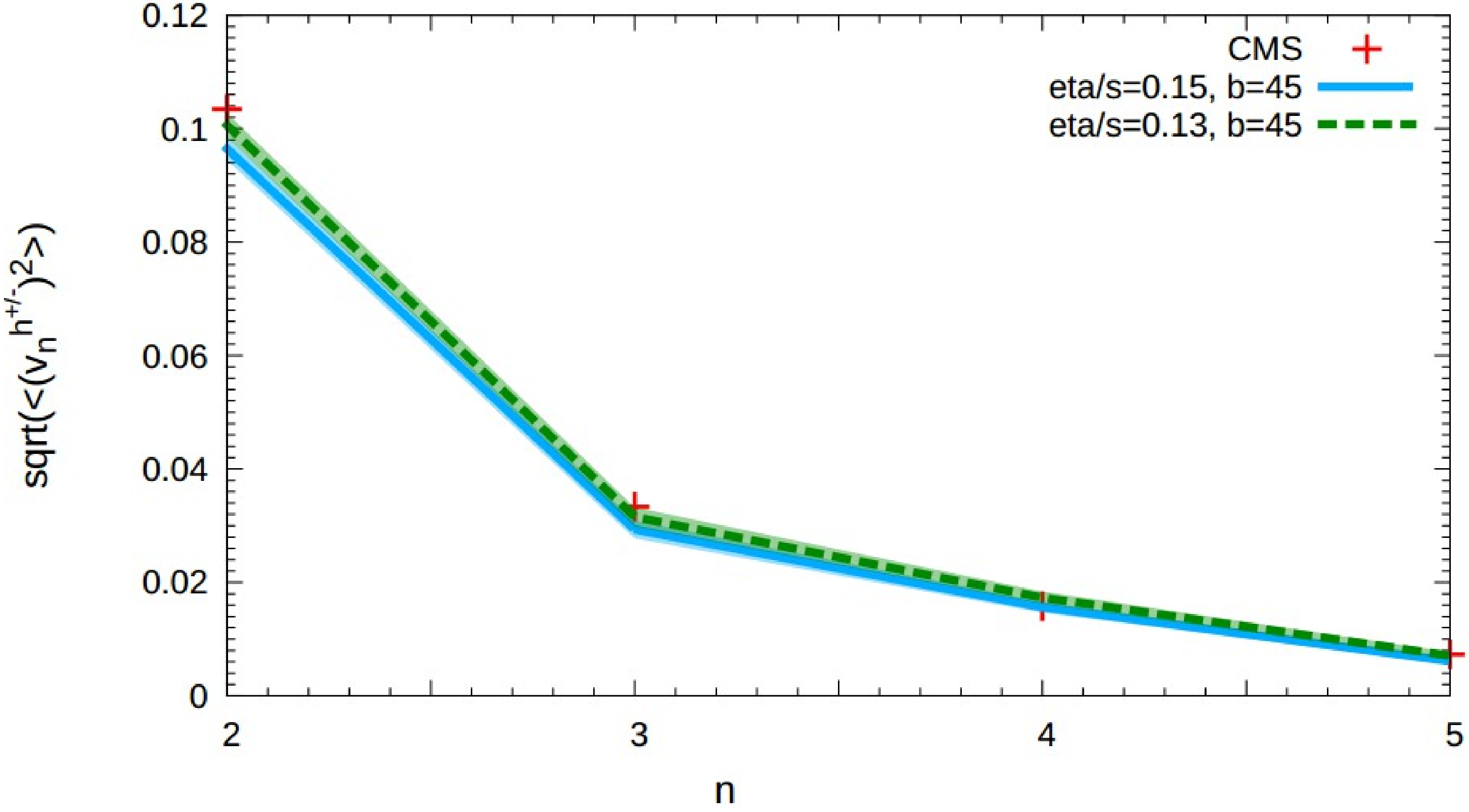
Inclusion of bulk viscosity **further improves** the agreement with data

What about noncentral collisions?

MUSIC 2.0

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

30-40% - LHC



At least for flow harmonics, bulk viscosity **does not** spoil the good agreement at other centrality classes

warning: be careful with differential observables

Summary/conclusions

We studied the effect of bulk viscosity and NN correlations on the azimuthal momentum anisotropies in 0-1% centrality class

- ✔ We see a clear effect of bulk viscosity on flow; specially on v2 and v3
- ✔ Bulk viscosity appears to improve the agreement between theory and experiment in ultracentral collisions
- ✔ NN correlations also improve the agreement between theory and experiment in ultracentral collisions

Parameters of fluid-dynamical simulations of heavy ion collisions may have to be revisited

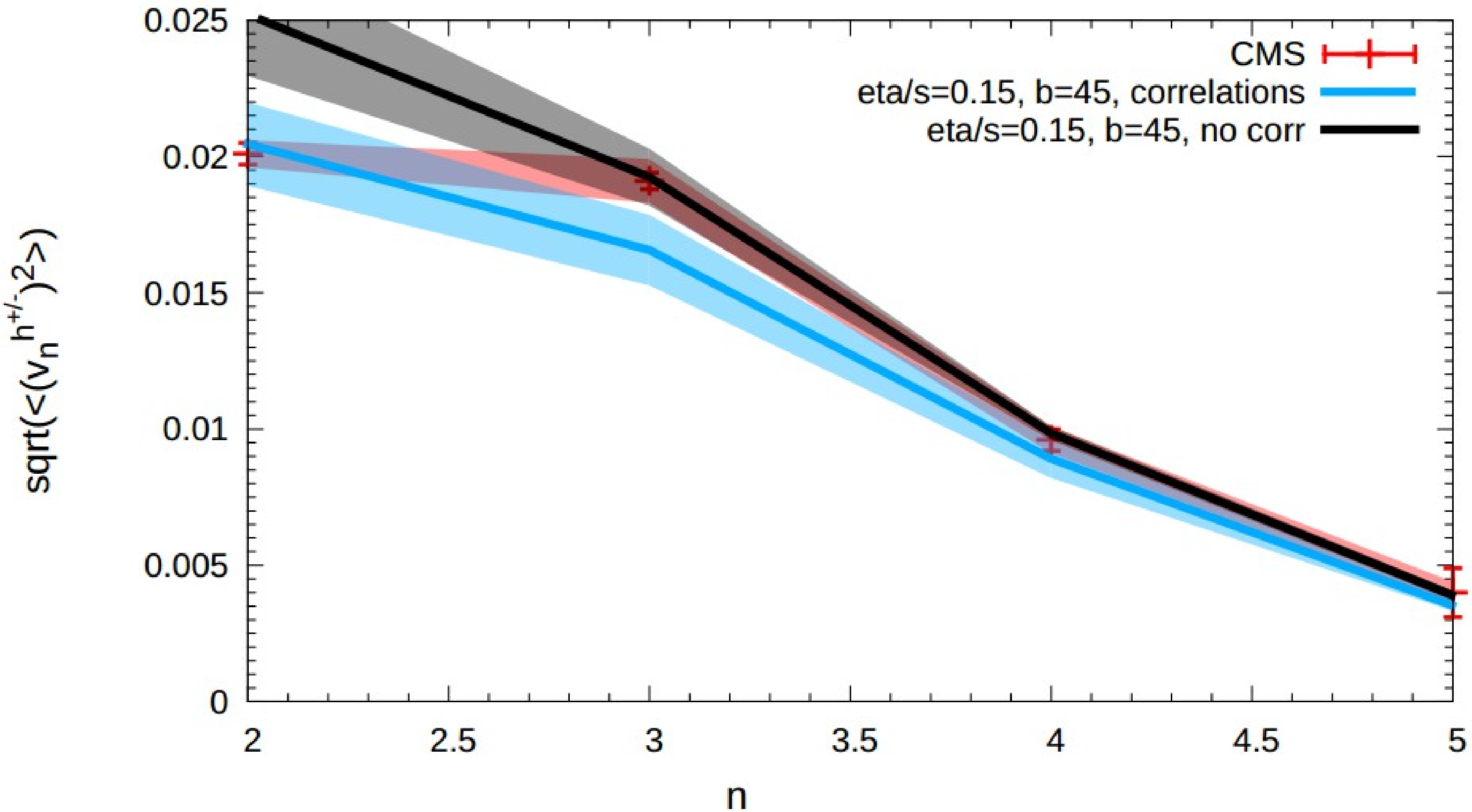
Backup

Bulk viscosity + correlations - IPGlasma

MUSIC 2.0

$$\frac{\zeta}{s} = \mathrm{b} \times \frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$

0-1% - LHC



Effect of correlations: calculations with bulk viscosity