The importance of the bulk viscosity and hadronic afterburner in ultrarelativistic heavy-ion collisions

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McGill
(Montreal, Canada)

Sangwook Ryu, Jean-Francois Paquet, Chun Shen, Gabriel Denicol, Bjoern Schenke, Sangyong Jeon and Charles Gale

Department of Physics, McGill University, 3600 University Street, Montreal, QC, H3A 2T8, Canada
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

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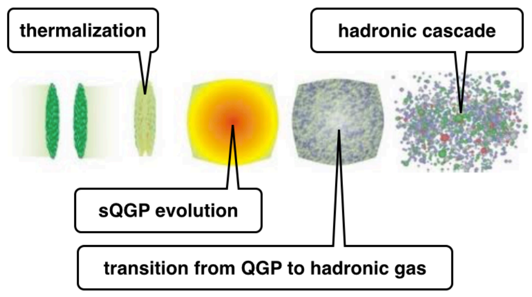
Introduction

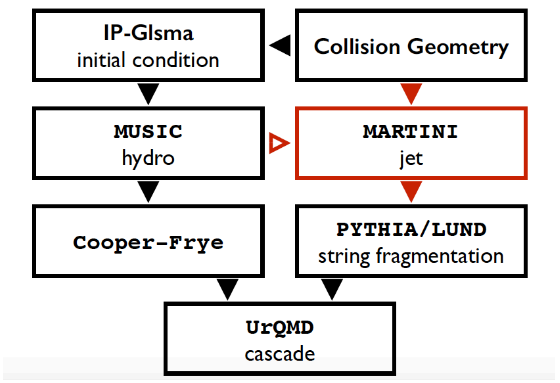
In heavy ion collisions, we create and study the properties of **hot QCD matters**.

Relativistic heavy ion collision at a glance



What do we need to improve our understanding?
A realistic event generator

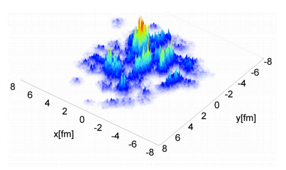
Model Overview



Full event generator : includes **fluctuations in every stage**

Model – IP-Glasma Initial Conditions

nucleon + partonic fluctuations



In the IP-Glasma picture [1], partons with high x provide color sources for classical Yang-Mills fields. The color gauge field in terms of the path-orderd Wilson line is given by

$$A^i(\mathbf{x}_\perp) = \frac{i}{g} V(\mathbf{x}_\perp)\partial_i V^\dagger(\mathbf{x}_\perp) \quad (1)$$

$$V(\mathbf{x}_\perp) = P \exp\left[-ig\int dx^- \frac{\rho(x^-,\mathbf{x}_\perp)}{\nabla_T^2 - m^2}\right] \quad (2)$$

The fluctuation of color charges carried by high-x partons in nuclei are described as

$$\langle \rho^a(x^-,\mathbf{x}_\perp)\rho^b(y^-,\mathbf{y}_\perp)\rangle = g^2\mu_A^2(\mathbf{x}_\perp)\delta^{ab}\delta(x^- - y^-)\delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp) \quad (3)$$

where $g^2\mu$ depends on the transverse position inside the nucleus. These fluctuations are not present in the MC-Glauber model.

Model – MUSIC Hydro

Second-order viscous hydrodynamics

MUSIC [2] solves 3 + 1D hydrodynamic conservation equations $\partial_\mu T^{\mu\nu}(t,\mathbf{x}) = 0$, along with the equations for the dissipative currents

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \quad (4)$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} . \quad (5)$$

The transport coefficients are determined using the relaxation time and 14-moment approximation [3].

Model – Cooper-Frye Sampling

switching from hydro to particles

Hadrons are sampled on the freeze-out hypersurface Σ according to the Cooper-Frye formula [4].

$$\left.\frac{dN}{d^3\mathbf{p}}\right|_{1\text{-cell}} = \begin{cases} \dfrac{d}{(2\pi)^3}\left[f_0(x,\mathbf{p}) + \delta f_{\text{shear}}(x,\mathbf{p}) + \delta f_{\text{bulk}}(x,\mathbf{p})\right]\dfrac{p^\mu\Delta\Sigma_\mu}{E_\mathbf{p}} \\ \quad \text{if} \quad f_0 + \delta f_{\text{shear}} + \delta f_{\text{bulk}} > 0 \quad \text{and} \quad p^\mu\Delta\Sigma_\mu > 0 \\ 0 \quad \text{otherwise} \end{cases} \quad (6)$$

where f_0 is the local equilibrium distribution function and the bulk [5] and shear [6] viscous corrections are given by

$$\delta f_{\text{shear}} = f_0(1\pm f_0)\frac{\pi_{\mu\nu}p^\mu p^\nu}{2(\epsilon_0 + P_0)T^2} \quad (7)$$

$$\delta f_{\text{bulk}} = -f_0(1\pm f_0)\frac{C_{\text{bulk}}}{T}\left[\frac{m^2}{3(p\cdot u)} - \left(\frac{1}{3} - c_s^2\right)(p\cdot u)\right]\Pi \quad (8)$$

We assume a grand canonical ensemble where particles on each fluid cell are sampled independently.

Model – UrQMD Cascade

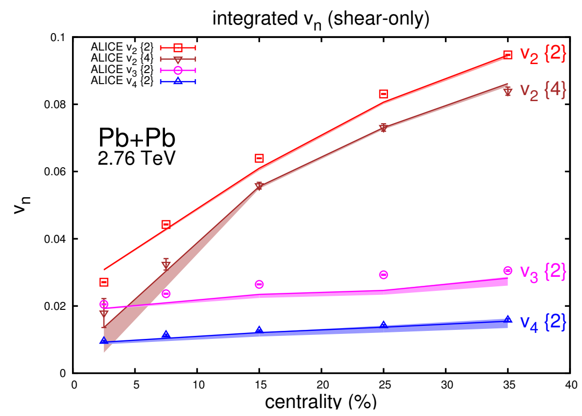
Transport model for dilute hadronic matter

UrQMD (Ultra-relativistic Quantum Molecular Dynamics) [7] is a transport model dealing with the Boltzmann's transport equation

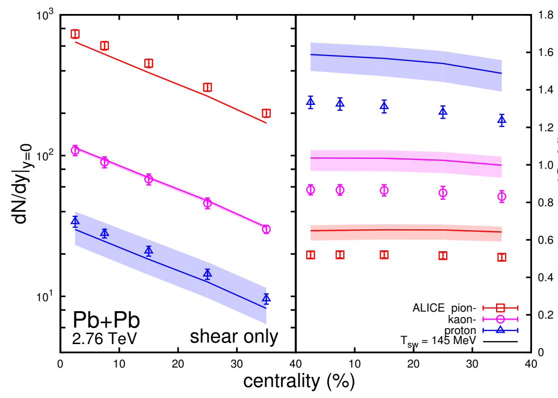
$$p^\mu \frac{\partial f_i}{\partial x^\mu}(t,\mathbf{x},\mathbf{p}) = \mathcal{C}_i[f] \quad (9)$$

by performing scattering and decay in an N-body system. UrQMD includes 55 baryon species and 32 meson species with masses up to 2.25 GeV.
The cross sections and decay rates that enter UrQMD are based on the experimental data.

Results – shear-only case



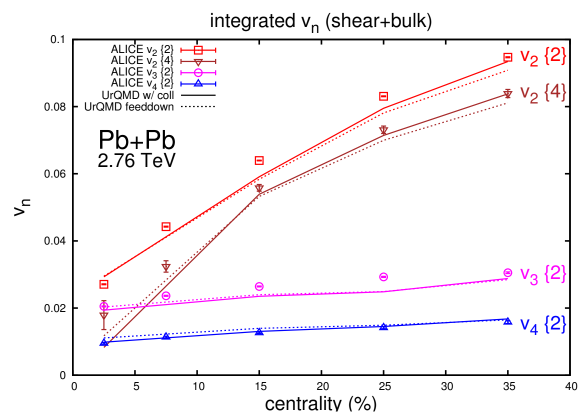
The integrated v_n's favor $\eta/s = 0.16$.



The mean p_T is **largely overestimated**.

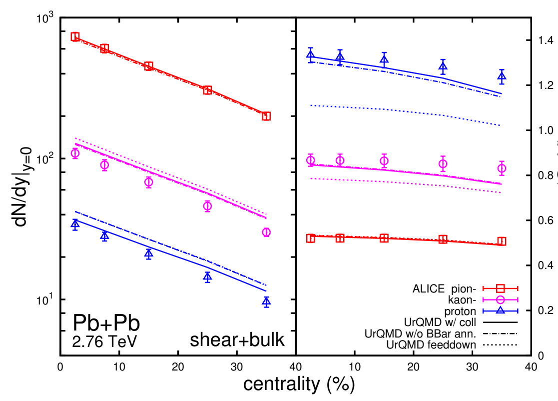
A physical mechanism that reduces the transverse expansion rate of the system is required.

Results – shear+bulk case



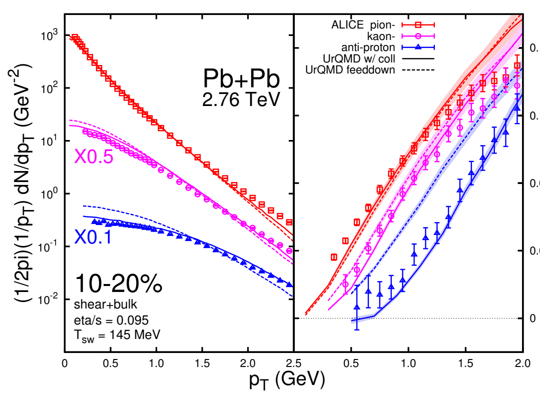
The integrated v_n's favor $\eta/s = 0.095$.

The estimated of the **shear viscosity is significantly altered** by inclusion of the bulk viscosity.



The mean p_T is **well reproduced**.

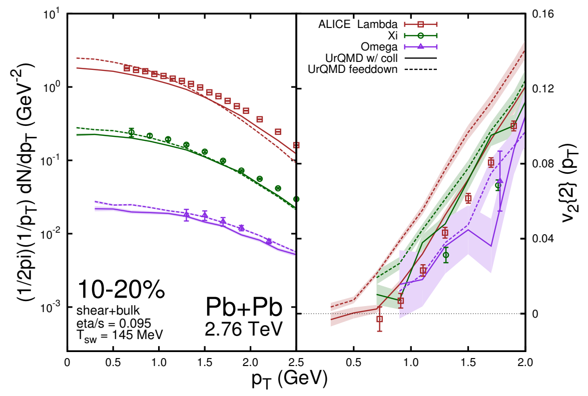
The bulk viscosity slows down the expansion by **reducing the pressure and its gradient**.



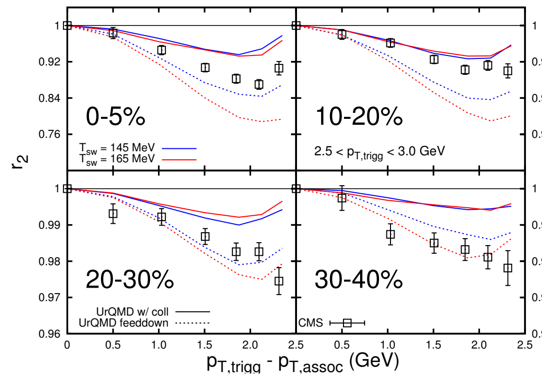
The p_T spectra and $v_2(p_T)$ are **well described**.

Hadronic afterburner is important in describing protons due to **different cross sections and kinetic freeze-out**.

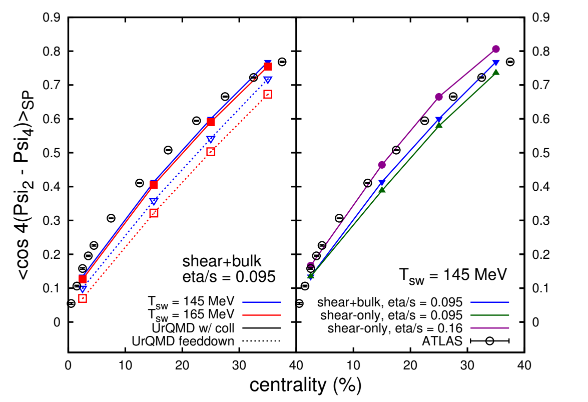
Results – shear+bulk case (continued)



Strange baryons are also reasonably described.

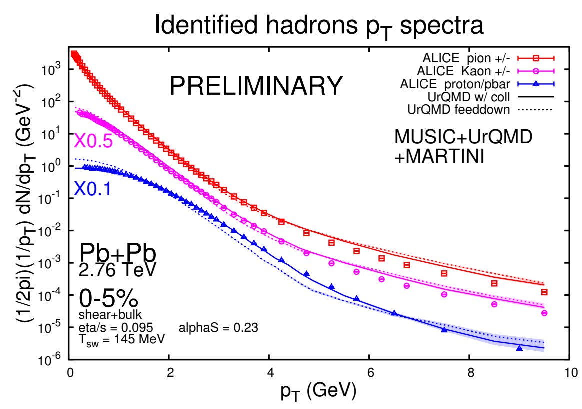


The hadronic re-scattering **reduces the fluctuation of v_n.**



The EP correlations increase **due to the shear viscosity**.

Results – extension to higher p_T with MARTINI



MARTINI jet is necessary to describe **the intermediate and high p_T** spectrum.

Conclusion

Our hybrid model is successful in reasonably describing

the identified hadrons p_T spectra, anisotropic flow coefficients v_n and correlations among v_n and Ψ_n.

observed in heavy ion collisions at the LHC.
Our work indicates that heavy ion simulations with IP-Glasma initial conditions require

a finite bulk viscosity and hadronic afterburner

to fit the data.
MARTINI jet is important in getting **the higher p_T spectra.**

References

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