Bulk viscous effects on flow and dilepton radiation in a hybrid approach

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Outline

Part I: Modelling of the QCD Medium
- Viscous hydrodynamics & Hadronic observables

Part II: Sources of Dileptons
- Quark Gluon Plasma (QGP) Rate (w/ dissipative corrections)
- Hadronic Medium (HM) Rate (w/ dissipative corrections)
- Dilepton Cocktail

Part III: Dilepton yield and elliptic flow
- Effects of bulk viscosity on thermal (HM+QGP) dileptons
- Dilepton cocktail contribution

Conclusion and outlook
An improvement in the description of hadronic observables

- IP-Glasma + Viscous hydrodynamics + UrQMD [Ryu et al., PRL 115, 132301]

- $T_{\text{switch}} = 145$ MeV at LHC
- Crucial ingredient: Bulk Viscosity
- Via the same modelling, an improved description of $v_n$ of direct photons [Paquet et al., PRC 93, 044906] was done.
- Dileptons are now also included.
Viscous hydrodynamics & bulk pressure

- Dissipative hydrodynamic equations including coupling between bulk and shear viscous terms:

\[ \partial_\mu T^{\mu \nu} = 0 \]

\[ T^{\mu \nu} = T_0^{\mu \nu} - \Pi \Delta^{\mu \nu} + \pi^{\mu \nu} \]

\[ T_0^{\mu \nu} = \varepsilon u^\mu u^\nu - P \Delta^{\mu \nu} \]

\[ \tau_\Pi \dot{\Pi} + \Pi = -\zeta \theta - \delta_{\Pi \Pi} \Pi \theta + \lambda_{\Pi \Pi} \pi^{\mu \nu} \sigma_{\mu \nu} \]

\[ \tau_\pi \dot{\pi}^{(\mu \nu)} + \pi^{\mu \nu} = 2 \eta \sigma^{\mu \nu} - \delta_{\pi \pi} \pi^{\mu \nu} \theta + \phi_7 \pi_\alpha^{(\mu} \pi^{\nu)} \alpha \]

\[ -\tau_\pi \pi_\alpha^{(\mu} \sigma^{\nu)} + \lambda_{\pi \Pi} \Pi \sigma^{\mu \nu} \]

- Other than \( \zeta \) and \( \eta \), all transport coefficients are in G.S. Denicol et al. PRD 85 114047, PRC 90 024912.

- \( P(\varepsilon) \): Lattice QCD EoS [P. Huovinen & P. Petreczky, NPA 837, 26]. (s95p-v1)
Thermal dilepton rates from HM

- The rate involves:

\[
\frac{d^4 R}{d^4 q} = \frac{\alpha^2 L(M) m_V^4}{\pi^3 M^2 g_\nu^2} \left\{-\frac{1}{3} \left[ \text{Im} D^R_V \right]_\mu \right\} n_{BE} \left( \frac{q \cdot u}{T} \right)
\]

- Self-Energy [Eletsky, et al., PRC 64, 035202]

\[
\Pi_{Va} = -\frac{m_a m_V T}{\pi q} \int \frac{d^3 k}{(2\pi)^3} \frac{\sqrt{s}}{k^0} f_{Va}(s) n_a(x); \text{ where } x = \frac{u \cdot k}{T}
\]

- Viscous extension to thermal distribution function

\[
T_0^{\mu\nu} + \pi^{\mu\nu} - \Pi^{\mu\nu} = \int \frac{d^3 k}{(2\pi)^3 k^0} k^\mu k^\nu \left[ n_{a,0}(x) + \delta n_a^{\text{shear}}(x) + \delta n_a^{\text{bulk}}(x) \right]
\]

\[
\delta n_a^{\text{shear}} = n_{a,0}(x) \left[ 1 \pm n_{a,0}(x) \right] \frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2 (\epsilon + P)}
\]

\[
\delta n_a^{\text{bulk}} = -\frac{\Pi \left[ \frac{z^2}{3x} - \left( \frac{1}{3} - c_s^2 \right) x \right]}{15 (\epsilon + P) \left( \frac{1}{3} - c_s^2 \right)^2} n_{a,0}(x) \left[ 1 \pm n_{a,0}(x) \right]; \text{ where } z = \frac{m}{T}
\]

- Therefore: \( \Pi_{Va} \rightarrow \Pi_{Va}^{\text{ideal}} + \delta \Pi_{Va}^{\text{shear}} + \delta \Pi_{Va}^{\text{bulk}} \)
Bulk viscous corrections: QGP rate

- The Born rate

\[
\frac{d^4 R}{d^4 q} = \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} n_q(x)n_{\bar{q}}(x)\sigma_{12} \delta^4(q - k_1 - k_2); \text{ where } x = \frac{u \cdot k}{T}
\]

- Shear viscous correction is obtained using the usual 14-moment expansion of the Boltzmann equation in the RTA limit.

- Bulk viscous correction derived from a generalized Boltzmann equation, which includes thermal quark masses \(m\) [PRD 53, 5799]

\[
k^\mu \partial_\mu n - \frac{1}{2} \frac{\partial (m^2)}{\partial x} \cdot \frac{\partial n}{\partial k} = C[n]
\]

- In the RTA approximation with \(\alpha_s\) a constant [PRC 93, 044906]

\[
\delta n_q^{bulk} = -\frac{\Pi \left[ \frac{z^2}{x} - x \right]}{15(\varepsilon + P)\left(\frac{1}{3} - c_s^2\right)} n_{FD}(x)[1 - n_{FD}(x)]; \text{ where } z = \frac{m}{T}
\]

- Therefore:

\[
\frac{d^4 R}{d^4 q} = \frac{d^4 R^{ideal}}{d^4 q} + \frac{d^4 \delta R^{shear}}{d^4 q} + \frac{d^4 \delta R^{bulk}}{d^4 q}
\]
Dilepton Cocktail

- For $M > 0.3 \text{ GeV}$, sources of cocktail dileptons considered here are originating from $\eta, \eta', \omega, \phi$ mesons.

- Dileptons originate from Dalitz decays $\eta, \eta' \to \gamma \ell^+ \ell^-$, $\omega \to \pi^0 \ell^+ \ell^-$ and $\phi \to \eta \ell^+ \ell^-$ as well as direct decays $\omega, \phi \to \ell^+ \ell^-$. 

- Using the Vector Dominance Model (VDM), the dynamics of these decays has been computed in Phys. Rept. 128, 301.

- The goal here to obtain the final hadronic distribution of $\eta, \eta', \omega, \phi$ to be decayed into dileptons. Two methods will be used:
  1. Direct hadron production from hydrodynamic simulation (Cooper-Frye prescription including only hadronic resonance decays)
  2. Hadrons produced after UrQMD (to capture hadronic collisions, in addition to resonance decays).
Anisotropic flow

Flow coefficients

\[
\frac{dN}{dM_{p_T}dp_Td\phi dy} = \frac{1}{2\pi} \frac{dN}{dM_{p_T}dp_Td\phi dy} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi - n\psi_n) \right]
\]

Three important notes:

1. **Within an event**: \(v_n\)'s are a yield weighted average of the different sources (e.g. HM, QGP, ...).

2. The switch between HM and QGP rates we are using a linear interpolation, in the region \(184 \, MeV < T < 220 \, MeV\), given by the EoS [NPA 837, 26]

3. **Averaging over events**: the flow coefficients \((v_n)\) are computed via

\[
\langle v_{n\{SP}\rangle = \frac{\left\langle v_{n}^{\gamma} v_{n}^{\phi} \cos\left[ n \left( \psi_{n}^{\gamma} - \psi_{n}^{\phi} \right) \right] \right\rangle}{\left\langle (v_{n}^{\phi})^{2} \right\rangle^{1/2}}
\]

Paquet et al., PRC 93, 044906
Vujanovic et al., PRC 94, 014904

Lastly, the temperature at which hydrodynamics (or thermal) dilepton radiation are stopped is \(T_{\text{switch}} = 145 \, MeV\) at LHC, while at RHIC \(T_{\text{switch}} = 165 \, MeV\). Cocktail dileptons follow.
Bulk viscosity and dilepton yield at LHC

- Bulk viscosity reduces the cooldown rate of the medium, by viscous heating and also via reduction of radial flow acceleration at late times.
- Dilepton yield is increased in the HM sector, since for $T < 184 \text{ MeV}$ purely HM rates are used.
The effects of bulk viscosity on thermal $v_2(M)$ are quite intricate...
Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:

- $M > 0.8\ \text{GeV}$: the yield goes from being HM dominated to being QGP dominated. Though, $\zeta$ does ↓ $v_2^{HM}(M)$, it also increases HM yield and ∴ weight to $v_2^{HM}(M)$. So, thermal $v_2(M)$ ↑.
Bulk viscosity and dileptons at LHC

Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:

- $M > 0.8 \text{ GeV}$: the yield goes from being HM dominated to being QGP dominated. Though, $\zeta$ does $\downarrow v_2^{HM}(M)$, it also increases HM yield and $\therefore$ weight to $v_2^{HM}(M)$. So, thermal $v_2(M) \uparrow$.

- $M < 0.8 \text{ GeV}$: HM yield dominates. There are cancellation between $\uparrow$ HM yield owing to $\zeta$ and $\downarrow v_2^{HM}(M)$. 
At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65$ GeV.

At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant.
At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65$ GeV.

At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant. However, the method employed to obtain the cocktail (e.g. Hydro vs UrQMD) is less important.
Comparing the behaviour of dilepton $v_2(M)$ and charged hadron $v_2^{ch}\{2\}$, one notices that the ordering of the curves is the same, except in for $M \sim 0.9 \text{ GeV}$ & $M > 1.1 \text{ GeV}$.

Thermal radiation contributes significantly in those $M$ regions, and bulk viscosity $\uparrow v_2(M)$. This is an interesting effect, that is currently being investigated further.
Conclusions

Starting from IP-Glasma initial conditions for the hydro evolution, a first thermal and cocktail dilepton calculation was performed, with bulk viscosity in the hydro evolution, both at RHIC and LHC energies.

Bulk viscosity increases the yield of thermal dileptons owing to viscous heating and reduction in radial flow acceleration at later times.

The presence of the dilepton cocktail is more important for the total $v_2(M)$ at top RHIC energy, than at collision LHC energy.

Though bulk viscosity does generate interesting dynamics at RHIC, which are reflected in the thermal dilepton $v_2(M)$, the dilepton cocktail masks part of these dynamics.

Outlook

Investigate the dynamics of elastic vs inelastic collisions in a (hadronic) transport model that includes dynamical dilepton radiation (i.e. SMASH), and study their effects on dilepton $v_2(M)$.
Backup Slides
Bulk viscosity and dileptons at RHIC
Cocktail: Hydro vs UrQMD at RHIC

![Graph 1: Distribution of some variable (M [GeV])](image1)

![Graph 2: Distribution of another variable (V_2 (M))](image2)
As mentioned, the $\uparrow v_2(M)$ with bulk viscosity is influenced by switching temperature.
Bulk viscosity and dileptons at RHIC

As mentioned, the $\uparrow v_2(M)$ with bulk viscosity is influenced by switching temperature.

Indeed, running the hydrodynamical evolution until $T_{\text{switch}} = 150\ MeV$, the effect is reduced, but is still present in the $M \sim 0.9\ GeV \& M > 1.1\ GeV$ regions.
Bulk viscosity causes an increase in $v_2(M)$ of thermal dileptons as there is an increase in the anisotropic flow build-up in the hadronic sector.

$$\langle T^{xx} \pm T^{yy} \rangle \equiv \frac{1}{N_{\text{events}}} \sum_{i} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp (T^{xx}_i \pm T^{yy}_i)$$

where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp$ integrates only over the HM phase.
\[
\frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \text{ evolution at LHC with different } T_{\text{switch}}
\]

\[
\langle T^{xx} - T^{yy} \rangle \equiv \frac{\sum_i \int d^2 x_\perp (T_i^{xx} - T_i^{yy})}{\sum_i \int d^2 x_\perp (T_i^{xx} + T_i^{yy})}
\]

where the \[ \int d^2 x_\perp \text{ integrates only the HM phase with } T > 145 \text{ MeV, } T > 165 \text{ MeV, and } T > 175 \text{ MeV.} \]
Bulk viscosity and QGP $v_2$ at LHC

\[ \langle T^{xx} \pm T^{yy} \rangle \equiv \frac{1}{N_{\text{events}}} \sum_{i}^{\tau} \tau' d\tau' \int d^2x_\perp (T_{i}^{xx} \pm T_{i}^{yy}) \]

where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp$ integrates only over the QGP phase.
\[
\delta n_{a,\text{bulk}} = -\frac{\Pi}{15(\varepsilon + P)} \left[ \frac{z^2}{3x} - \left( \frac{1}{3} - c_s^2 \right)x \right]^2 n_{a,0}(x) \left[ 1 \pm n_{a,0}(x) \right]; \quad z = \frac{m}{T}; \quad x = \frac{u \cdot k}{T}
\]

\(\delta n^\text{bulk} \propto \frac{T}{E} - \frac{E}{T}\) effects are responsible for the shape seen in QGP \(v_2\), as \(\frac{\Pi}{\varepsilon + P}\) doesn’t change sign.
Viscous correction in the QGP

- Effects of viscous corrections on the QGP $v_2(M)$
Bulk viscosity and HM $v_2$ at LHC

- However, HM dileptons are modestly affected by $\delta n$ effects.
- $v_2^{HM}$ is only affected by flow anisotropy.
- Where $\int_{\tau_0}^\tau \tau' d\tau' \int d^2x_\perp$ in $\langle T^{xx} \pm T^{yy} \rangle$ integrates only over the HM region.

![Graph showing bulk viscosity and $v_2$ for Pb-Pb collisions at LHC](image-url)
NLO QGP dilepton results

- Some diagrams contributing at LO & NLO