Dilepton radiation and bulk viscosity in heavy-ion collisions

Gojko Vujanovic, Jean-François Paquet, Chun Shen, Gabriel Denicol, Sangyong Jeon, Charles Gale, and Ulrich Heinz

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Outline

Part I: Modelling of the QCD Medium
- Viscous hydrodynamics

Part II: Thermal Sources of Dileptons
- QGP Rate (w/ dissipative corrections)
- Hadronic Medium Rates (w/ dissipative corrections)

Part III: Dileptons & Dissipative Evolution
- Effects of bulk viscous pressure on dilepton yield and $v_n$

Conclusion and outlook
An improvement in the description of hadronic observables

- IP-Glasma + Viscous hydro + UrQMD [PRL 115, 132301]

- Crucial ingredient: Bulk Viscosity

- Via the same modelling, an improved description of $\nu_n$ of direct photons [PRC 93, 044906] was done.

- Thermal dileptons are now also included.
Viscous hydrodynamics & bulk pressure

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

\[ \partial_\mu T^{\mu \nu} = 0 \]
\[ T^{\mu \nu} = T_0^{\mu \nu} - \Pi \Delta^{\mu \nu} + \pi^{\mu \nu} \]
\[ T_0^{\mu \nu} = \varepsilon u^\mu u^\nu - P \Delta^{\mu \nu} \]
\[ \tau_\Pi \dot{\Pi} + \Pi = -\zeta \theta - \delta_{\Pi \Pi} \Pi \theta + \lambda_{\Pi \Pi} \pi^{\mu \nu} \sigma_{\mu \nu} \]
\[ \tau_\pi \dot{\pi}^{\langle \mu \nu \rangle} + \pi^{\mu \nu} = 2\eta \sigma^{\mu \nu} - \delta_{\pi \pi} \pi^{\mu \nu} \theta + \phi_7 \pi_\alpha^{\langle \mu \nu \rangle} + \lambda_{\pi \Pi} \Pi \sigma^{\mu \nu} \]

\[ T_c = 180 \text{ MeV} \]

Other than \( \zeta \) and \( \eta \), all transport coefficients are in PRD 85 114047, PRC 90 024912.

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

\[ \eta/s = \text{constant} \]
Dileptons and goal of this presentation

Unlike photons, dileptons have an additional d.o.f. the invariant mass.

Goal: Use the invariant mass distribution to investigate the influence bulk viscous pressure on thermal dileptons at RHIC and LHC.

Note: Only dileptons from the hydro will be studied.
Thermal dilepton rates from HM

The rate involves:

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

- Self-Energy [Eletsky, et al., PRC 64, 035202 (2001)]

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

- Viscous extension to thermal distribution function

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

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

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

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

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

- Shear viscous correction is obtained using Israel-Stewart approx.

- 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]

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

- Therefore:

\[
\frac{d^4R}{d^4q} = \frac{d^4R^{\text{ideal}}}{d^4q} + \frac{d^4\delta R^{\text{shear}}}{d^4q} + \frac{d^4\delta R^{\text{bulk}}}{d^4q}
\]
**Anisotropic flow**

- **Flow coefficients**

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

- **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

\[
v_n\{SP\} = \frac{\langle v_n^* \, v_n^h \cos \left[ n \left( \Psi_n^* - \Psi_n^h \right) \right] \rangle}{\langle (v_n^h)^2 \rangle^{1/2}}
\]

- **Lastly the temperature at which hydrodynamics (\& dilepton radiation) is stopped is** $T_{\text{switch}} = 145 \, MeV$ at LHC, while at RHIC $T_{\text{switch}} = 165 \, MeV$. 

- **References:**
  - **PRC 93**, 044906
  - **PRC 94**, 014904
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 at late times.

- Dilepton yield is increased in the HM sector, since for $T < 184 \, MeV$ purely HM rates are used.
Bulk viscosity and QGP $v_2$ at LHC

\[ \langle T^{xx} \pm T^{yy} \rangle \equiv \frac{1}{N_{\text{events}}} \sum_{i}^{\tau} \int_{\tau_0}^{\tau} \tau' d\tau' \int d\tau'_{\perp} (T_{i}^{xx} \pm T_{i}^{yy}) \]

where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d\tau'_{\perp}$ integrates only over the QGP phase.
At early times, hydrodynamic ($T^{\mu\nu}$) momentum anisotropy increases under the influence of bulk viscosity.

$\delta n_{bulk} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP $v_2$, as $\frac{\Pi}{\varepsilon + P}$ doesn’t change sign.
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 $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp \langle T_{xx}^{\perp} \pm T_{yy}^{\perp} \rangle$ integrates only over the HM region.
Bulk viscosity and dileptons at LHC

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

- For $M < 0.8$ GeV $v_2(M)$ behaves same as charged hadrons.
- For $M > 0.8$ GeV sector, $v_2(M) \uparrow$ because there is more weight in the HM sector.
Bulk viscosity and dileptons at RHIC

- Bulk viscosity causes an increase in anisotropic flow build-up in both the QGP and the hadronic sector which translates into an $\uparrow v_2(M)$ of thermal dileptons.
- $v_2^{ch}$ behaves in the opposite direction, as they are emitted at later times.
- This anti-correlation is a key feature of bulk viscosity at fixed $\eta/s$. 

**Graphs:**

1. **$V_2^y(M)$ Graph:**
   - For Au-Au 20-40% at $\sqrt{s_{NN}}=200$ GeV.
   - Graphs for $HM + QGP$ with $T_{switch} = 165$ MeV.
   - Different colors represent different conditions (e.g., $\zeta/s(T) + \eta/s = 0.06$ vs. $\eta/s = 0.06$).

2. **$<T^{x+y}>/<T^{x-y}>$ vs. $\tau - \tau_0$ Graph:**
   - For Au-Au 20-40% at $\sqrt{s_{NN}}=200$ GeV.
   - Graph for $HM$ ONLY with $T_{switch} = 165$ MeV.
   - Different colors represent different conditions (e.g., Ideal $T^{HV}$ vs. $\zeta/s(T) + \eta/s = 0.06$ vs. Ideal $T^{HV}$ vs. $\eta/s = 0.06$).

3. **$v_2^{ch}$ vs. Centrality Graph:**
   - Data from STAR Au-Au at $\sqrt{s_{NN}}=200$ GeV.
   - Graph showing the evolution of $v_2^{ch}$ with centrality.
This effect is coming from the switching temperature to UrQMD.

To mimic the effects a hadronic transport evolution would have on dileptons, hydrodynamical evolution was continued until $T_{\text{switch}} = 150 \text{ MeV}$.

Note that hadronic transport will not generate as much anisotropic flow as hydro. Also, shear viscosity was not re-adjusted to better fit hadronic observables; e.g. $v_n^{ch}$ is too large with current (fixed) $\eta/s$.

A dilepton calculation from a transport approach is important. This study is underway.
Conclusions

- Performed a first thermal dilepton calculation starting from IP-Glasma initial conditions, with bulk viscosity in the hydro evolution, at both 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.

- Our calculation shows that, for a fixed $\eta/s$, there is an anti-correlation between the effects of bulk viscosity on dilepton $v_2(M)$ and charged hadron’s $v_2$ at RHIC. This effect depends on the switching temperature $T_{switch}$ between hydro and hadronic transport.

Outlook

- In collaboration with Hannah Petersen’s group at FIAS (in particular Jan Staudenmaier), a computation of dilepton production from the hadronic transport model SMASH is ongoing.
Backup Slides
\[
\frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}
\]
evolution at LHC with different \( T_{\text{switch}} \).

\( T_{\text{switch}} = 145 \text{ MeV} \)

\( T_{\text{switch}} = 165 \text{ MeV} \)

\( T_{\text{switch}} = 175 \text{ MeV} \)

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

where the \( \int d^2 x_\perp \) integrates only the HM phase with \( T > 145 \text{ MeV} \), \( T > 165 \text{ MeV} \), and \( T > 175 \text{ MeV} \).
Viscous correction in the QGP

- Effects of viscous corrections on the QGP $\nu_2(M)$

![Graph showing the effects of viscous corrections on Pb-Pb 20-40% collisions at $\sqrt{s_{NN}}=2.76$ TeV.](image)
NLO QGP dilepton results
• Diagrams contributing at LO & NLO