Dilepton radiation and bulk viscosity in heavy-ion collisions

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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 $v_n$ 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:

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

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

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

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

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

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

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

\[
\zeta/s = \text{constant}
\]

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

- \(P(\epsilon)\): Lattice QCD EoS [Huovinen & Petreczky, NPA 837, 26]. (s95p-v1)
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)]
  \[
  \Pi_{Va} = -\frac{m_a m_V T}{\pi q} \int \frac{d^3 k}{(2\pi)^3 k^0} \sqrt{s} f_{Va}(s)n_a(x); \text{ where } x = \frac{u \cdot k}{T}
  \]

- Viscous extension to thermal distribution function
  \[
  T_0^{\mu\nu} + \pi^{\mu\nu} - \Pi^\Delta^{\mu\nu} = \int \frac{d^3 k}{(2\pi)^3 k^0} k^\mu k^\nu \left[ n_{a,0}(x) + \delta n_{a,\text{shear}}(x) + \delta n_{a,\text{bulk}}(x) \right]
  \]
  \[
  \delta n_{a,\text{shear}} = n_{a,0}(x)[1 \pm n_{a,0}(x)] \frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2(\varepsilon + P)}
  \]
  \[
  \delta n_{a,\text{bulk}} = -\frac{\Pi \left[ \frac{z^2}{3x} - \left( \frac{1}{3} - c_s^2 \right) x \right]}{15(\varepsilon + P)\left( \frac{1}{3} - c_s^2 \right)} n_{a,0}(x)[1 \pm n_{a,0}(x)]; \text{ where } z = \frac{m}{T}
  \]

- Therefore: \( \Pi_{Va} \rightarrow \Pi_{Va}^{\text{ideal}} + \delta \Pi_{Va}^{\text{shear}} + \delta \Pi_{Va}^{\text{bulk}} \)

\( \delta n_{a,\text{shear}} \) in Israel-Stewart approx. [PRC 89, 034904]

\( \delta n_{a,\text{bulk}} \) in RTA approx. [PRC 93, 044906]
Bulk viscous corrections: QGP rate

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

- 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:
  \[
  \frac{d^4 R}{d^4 q} = \frac{d^4 R^{ideal}}{d^4 q} + \frac{d^4 \delta R^{shear}}{d^4 q} + \frac{d^4 \delta R^{bulk}}{d^4 q}
  \]
Flow coefficients

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

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 \(184 \text{ MeV} < T < 220 \text{ MeV}\), given by the EoS [NPA 837, 26]

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

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


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.
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

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

where the \( \int_{\tau_0}^\tau \tau' \, d\tau' \int d^2x_\perp \) integrates only over the QGP phase.
At early times, hydrodynamic $(T^{\mu\nu})$ momentum anisotropy increases under the influence of bulk viscosity.

$\delta n^{\text{bulk}} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP $v_2$, as $\frac{\Pi}{\varepsilon+P}$ doesn't change sign.
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 $\int_0^\tau \tau' d\tau' \int d^2 x_\perp$ in $\langle T_{xx}^\tau \pm T_{yy}^\tau \rangle$ 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, $v_2(M)$ ↑ 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 $\eta/s$. 

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**Graphs**

- Top graph: Bulk viscosity and dileptons diagram showing $V_2^c(M)$ for different temperatures with $T_{\text{switch}} = 165$ MeV.

- Bottom graph: $v_2^{ch}$ behavior over centrality with data from STAR.

- Inset graph: HM + QGP $T_{\text{switch}} = 165$ MeV.
Bulk viscosity and dileptons at RHIC

- 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 $T_{switch} = 150 \text{ MeV}$.
- 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. $\nu_n^{ch}$ 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 $T_{\text{switch}}$ 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
\[
\frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle} \text{ evolution at LHC with different } T_{\text{switch}}
\]

\[
\begin{align*}
T_{\text{switch}} &= 145 \text{ MeV} \\
T_{\text{switch}} &= 165 \text{ MeV} \\
T_{\text{switch}} &= 175 \text{ MeV}
\end{align*}
\]

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 $v_2(M)$

![Graph showing $v_2(M)$ for Pb-Pb 20-40% with and without shear and bulk corrections at $\sqrt{s_{NN}}=2.76$ TeV]
NLO QGP dilepton results

- Diagrams contributing at LO & NLO