Study of $\eta/s$ through high-$p_\perp$ tomography

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Introduction

• Low-$p_\perp$ observables are used to explore the bulk properties of the QGP created in heavy-ion collisions.

• High-$p_\perp$ probes also become powerful tomography tools; Sensitive to global QGP features, e.g., different temperature profiles or initial conditions.

• The near perfect fluidity of QGP has been investigated extensively in heavy-ion collision experiments.

• $\eta/s$ is well constrained by Bayesian analysis in low-$p_\perp$ sector in the temperature range $T_c \lesssim T \lesssim 1.5T_c$ and weakly constrained at larger temperatures.

• We try to put constraints on $\eta/s$ by analyzing high-$p_\perp$ observables.
\( \eta / s \) of the medium: Soft-to-hard boundary

- QGP is expected to behave as weakly interacting gas: Weakly coupled
- Fluid dynamics predicts the \( \eta / s \) to be very low: Strongly coupled
- QGP may behave as perfect fluid near \( T_c \) (soft regime) and \( \eta / s \) may increase at high temperature (hard regime).
- Testing the soft-to-hard hypothesis is difficult: Anisotropy is weakly affected by the \( \eta / s \) at high temperature.
- High-\( p_\perp \) data/theory can serve as complementary tool.
High-$p_{\perp}$ energy loss: Generalized DREENA-A

- **Dynamical Radiative and Elastic ENergy loss Approach**
  - Based on finite temperature field theory and generalized HTL approach
    
    M. Djordjevic, PRC 74, 064907, (2006); PRC 80, 064909 (2009), M. Djordjevic and U. Heinz, PRL 101, 022302
  - Finite size dynamical QCD medium is considered
  - Takes into account both radiative and collisional energy losses
  - Generalized to the case of magnetic mass and running coupling
  - No fitting parameter in the theory

- Takes arbitrary temperature profile as input.
  
  D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic Front.in Phys. 10 (2022) 957019

- Optimized to incorporate any arbitrary event-by-event fluctuating temperature profile.
  

- DREENA-A is available on http://github.com/DusanZigic/DREENA-A (Details in talk by Dusan Zigic, tomorrow)
Phenomenological approach

- Three different $(\eta/s)(T)$ parametrizations have been considered.
- Parameters are adjusted to reproduce low-$p_\perp$ data.
- Temperature profile is generated for each case.
- High-$p_\perp$ predictions found using generalized DREENA-A.
- Compared with high-$p_\perp$ data.
Modeling the bulk evolution

- Initial entropy profiles are generated using TRENT0 model.
- $10^4$ events for Pb+Pb ($\sqrt{s} = 5.02$ TeV) and Au+Au ($\sqrt{s} = 200$ GeV) collisions.
- Events are sorted in centrality classes.
- Initial free streaming is not preferred by high-$p_{\perp}$ data.
  

- Onset time for hydrodynamics: $\tau_0 = 1\text{fm}$.
  

- (2+1)-dimensional fluid dynamical model (VISHNew) used to simulate the medium evolution.
Temperature dependence of $\eta/s$

$$(\eta/s)(T) = \begin{cases} 
(\eta/s)_{\text{min}}, & T < T_c, \\
(\eta/s)_{\text{min}} + (\eta/s)_{\text{slope}}(T - T_c)
\left(\frac{T}{T_c}\right)^{(\eta/s)_{\text{c}}v}, & T > T_c
\end{cases}$$


- Pion, kaon, proton multiplicities and $\nu_2\{4\}$ are reproduced by varying the TRENTo normalization factor for three $\eta/s$ parametrizations.
Results


\[ \text{Pb} + \text{Pb (} \sqrt{s} = 5.02 \text{TeV) } \]
Results


$Au + Au \ (\sqrt{s} = 200\ GeV)$
Results


\[ \text{Pb + Pb (} \sqrt{s} = 5.02 \text{TeV) } \]

\[ \text{Au + Au (} \sqrt{s} = 200 \text{GeV) } \]
Theoretical approach:

Transport coefficient from dynamical energy loss formalism

- Transport coefficient ($\hat{q}$) $\equiv$ Squared average transverse momentum exchange between the medium and the fast parton per unit length

- Interaction between the parton and medium is characterized by the HTL resummed elastic collision rate:

$$\frac{d\Gamma_{el}}{d^2q} = \frac{C_A}{\pi} T \alpha(ET) \frac{\mu_E^2 - \mu_M^2}{(q^2 + \mu_E^2)(q^2 + \mu_M^2)}$$

- In fluid rest frame:

$$\hat{q} = \int_{0}^{\sqrt{6ET}} d^2q q^2 \cdot \frac{d\Gamma_{el}}{d^2q} = C_A T \frac{4\pi}{(11 - \frac{2}{3}n_f)} \left( \frac{\mu_E^2 \ln \left[ \frac{6ET + \mu_E^2}{\mu E^2} \right] - \mu_M^2 \ln \left[ \frac{6ET + \mu_M^2}{\mu_M^2} \right]}{\ln \left( \frac{ET}{\Lambda^2} \right)} \right)$$

- In weakly coupled limit:

$$\frac{\eta}{s} \approx 1.25 T^3 / \hat{q}$$

\( \eta/s \) from the transport coefficient


- \( \hat{q} \) quantifies the parton coupling strength in the medium
- \( \hat{q}/T^3 \) must rise rapidly near \( T_c \) from above.
- Our formalism valid in weakly coupled regime.
- \( T^3/\hat{q} \) and \( \eta/s \) should agree in the weak coupling regime.
- Soft-to-hard boundary
\( \eta/s \) from the transport coefficient


- \( \hat{q}/T^3 \) shows expected behavior.
- Enhanced quenching near \( T_c \).
- \( \eta/s \) is surprisingly close to the constraints from Bayesian analysis.
\( \eta/s \) from the transport coefficient


- Uncertainty due to initial jet energy is very small
- Surprisingly close to the parametrization inspired by the Bayesian analysis.
- Does not drop significantly below the inferred \( \eta/s \) values near \( T_c \).
- No soft-to-hard boundary.

Blue \( \rightarrow \) Nature Phys. 15, no. 11, 1113-1117 (2019)

Black \( \rightarrow \) Phys. Rev. C 102, 044911 (2020)
Conclusion

• We use generalized DREENA-A to compute high-\(p_\perp\) energy loss.

• In the phenomenological approach:
  ○ Three different \((\eta/s)(T)\) parametrizations have been considered.
  ○ The predictions from the generalized DREENA-A for three \(\eta/s\) scenarios lead to plots that are almost indistinguishable.

• In the theoretical approach:
  ○ Transport coefficient and jet quenching strength are calculated from the dynamical energy loss formalism.
  ○ \(\eta/s\) shows surprisingly good agreement all the way to \(T_c\) with constraints extracted from existing Bayesian analyses. Provides much smaller uncertainties at high temperatures.
  ○ No guidance on locating soft-to-hard boundary.
Thank you for your attention
Average jet perceived temperature


- Pb + Pb $\sqrt{s} = 5.02$ TeV
- Full = LHHQ; DotDashed = Nature,
  Dashed = Constant
- Inset: Dotdashed = Nature,
  Dashed = LHHQ
- Temperature difference during evolution
  is very small.
- Insufficient to lead to observable difference
  in the results.
• Mass of light quark $M = \mu_E/6$
• Mass of charm and bottom quark 1.2 GeV and 4.75 GeV
• Gluon mass $m_g = \mu_E/\sqrt{2}$
• $\mu_M/\mu_E = 0.6$
• $\Lambda_{QCD} = 0.2 GeV$

- Constant $\eta/s$ (0.15 for Pb+Pb and 0.12 for Au+Au collision)
- Nature: $(\eta/s)_{\text{min}} = 0.1, (\eta/s)_{\text{slope}} = 1.11, (\eta/s)_{\text{crv}} = -0.48$
- LHHQ: $(\eta/s)_{\text{min}} = 0.04, (\eta/s)_{\text{slope}} = 3.30, (\eta/s)_{\text{crv}} = 0$
Modeling the bulk evolution

- Particlization is performed using Cooper-Frye prescription at isothermal space time hypersurface at 151 MeV.
- UrQMD is used to simulate microscopic dynamics of hadronic system.
- Bulk viscosity parametrized as
  \[
  (\zeta/s)(T) = \frac{(\zeta/s)_{\text{max}}}{1 + \left(\frac{T - T_0}{(\zeta/s)_{\text{width}}}\right)^2}
  \]
  with \((\zeta/s)_{\text{max}} = 0.03, (\zeta/s)_{\text{width}} = 0.022\) and \(T_0 = 0.183\text{GeV}\).
- We use lattice QCD based EoS from HotQCD (high temperature) + HRG (low temperature) EoS.
\( \eta/s \) from the transport coefficient


• In the limit \( ET \to \infty \):

\[
\hat{q} = C_A \left( \frac{4\pi}{11 - \frac{2}{3}n_F} \right)^2 \frac{4\pi \left( 1 + \frac{n_f}{6} \right)}{W(\xi(T))} (1 - x_{ME}^2)T^3
\]

\[
\xi(T) = \frac{1 + \frac{n_f}{6}}{11 - \frac{2}{3}n_f} \left( \frac{4\pi T}{\Lambda} \right)^2, \quad W \equiv \text{Lambert's W function}, \quad x_{ME} = \mu_M/\mu_E
\]

• \( \hat{q} \) is weakly dependent on jet energy \( E \).

• In weakly coupled limit:

\[
\eta/s \approx 1.25 T^3/\hat{q}
\]