Measuring QGP thermalization time with dileptons

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KITP - Nonequilibrium Dynamics in Particle Physics and Cosmology
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Heavy-ion collision timescales and “epochs” @ RHIC

- Hot Hadron Gas: $5 < \tau < 7$ fm/c
- Equilibrium QGP: $2 < \tau < 5$ fm/c
- Non-equilibrium QGP: $0.2 < \tau < 2$ fm/c
- Semi-hard particle production: $0 < \tau < 0.2$ fm/c

Freezeout: $\tau > 7$ fm/c

$*1\,\text{fm/c} \approx 3 \times 10^{-24}$ seconds
Heavy-ion collision timescales and “epochs” @ LHC

- **Semi-hard particle production**: $0 < \tau < 0.1 \text{ fm/c}$
- **Non-equilibrium QGP**: $0.1 < \tau < 2 \text{ fm/c}$
- **Equilibrium QGP**: $2 < \tau < 15 \text{ fm/c}$
- **Hot Hadron Gas**: $15 < \tau < 18 \text{ fm/c}$
- **Freezeout**: $\tau > 18 \text{ fm/c}$

*1 fm/c $\approx 3 \times 10^{-24}$ seconds

\[1 \text{ fm/c} \approx 3 \times 10^{-24} \text{ seconds}\]
Determining plasma initial conditions

- The fact that hydrodynamic modeling of RHIC collisions seems to describe the elliptic flow, $v_2$, for $p_T < 2$ GeV has been taken as evidence for early isotropization/thermalization of the QGP.

- Early ideal hydro fits indicate $\tau_{iso} = 0.6$ fm/c (Kolb et al); however, recent results (Romatschke et al) seem to indicate that larger $\tau_{iso} \sim 2$ fm/c are also consistent with low-$p_T$ elliptic flow.

- Hydro results depend on initial conditions and also details of the late-time modeling of the plasma lifetime: hadronization prescription (Cooper-Frye), viscous hadronic phase, nuclear resonance “feed-downs”, radial flow, etc.

- It would be better to have observables which were primarily sensitive to the first 1-2 fm/c (and not dependent on fully 3d viscous hydro simulations + . . . ).
Hydro Results 1

Min. Bias v2 (Glauber)

PR+UR, arxiv:0706.1522v1

http://online.itp.ucsb.edu/online/partcosmo08/romatschke/oh/60.html
Hydro Results 2

http://online.itp.ucsb.edu/online/partcosmo08/romatschke/oh/60.html

Dependence on $\tau_0$

Preliminary
What does theory have to say?

• The weak-coupling QCD “bottom-up” thermalization scenario predicted $\tau_{\text{therm}} = \frac{13}{5} \alpha_s^{-1} Q_s^{-1}$. [Baier, Mueller, Son, Schiff]

• Assuming $\alpha_s = 0.3$ at RHIC energies this implies $\tau_{\text{therm}} = 2 - 3 \text{ fm/c}$ and at LHC energies that $\tau_{\text{therm}} = 1 - 2 \text{ fm/c}$.

• Nonabelian chromo-Weibel plasma instabilities will accelerate thermalization but it is currently unknown by precisely how much. [Mrowczynski, Strickland, Romatschke, Arnold, Lenaghan, Moore, Rebhan, Yaffe, Venugopalan, Dumitru, Nara, Bödeker, Rummukainen, Fukushima, Gelis, McLerran, Berges, Sexty, Scheffler, . . .]

• AdS/CFT $\rightarrow$ time should scale inversely with the temperature of the extra-dimensional black hole so it should be $\tau_{\text{therm}} \lesssim 1 \text{ fm/c}$. Question of formation of the black hole itself from anisotropic initial state is very much unsolved. AdS/QCD? Initial Conditions?
E&M Probes to determine plasma isotropization time

- Can we experimentally determine when/if the plasma becomes locally isotropic in momentum-space?
- Need observables which provide complementary ways of probing early-time dynamics.
- Ideal candidates for this are E&M observables, eg photon and dilepton emission.
- Dependence of photon rate on anisotropy has been evaluated to LO (Schenke and MS, hep-ph/0611332); rates folded over model evolution are forthcoming.
- Dilepton spectra contain more information since one can study production as a function of invariant pair mass (photon virtuality) and transverse momentum.
Dileptons from an Anisotropic Plasma

- The dilepton rate $d^4 R / d^4 p$ depends on plasma anisotropy and the angle of the dilepton pair with respect to the anisotropy (beam) axis.

- To leading order it can be obtained using anisotropic momentum space distributions of the form

  $$f^{q,q}(p, x) = f^{q,q}_{iso}(p_T^2 + (1 + \xi)p_L^2)$$

- $\xi = 0$ gives isotropic plasma and $\xi = 10$ corresponds to a squish by a factor of approximately three along the longitudinal momentum direction.

$$\frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} \sim 1 + \xi$$

Dilepton rate depends on degree of QGP anisotropy

\[ \xi = 0 \]
\[ \xi = 10 \]
\[ \xi = 100 \]
Momentum Space Anisotropy Time Dependence

\[ \frac{\langle p_L \rangle}{\langle p_T \rangle} \]

0.1-0.3 fm/c

1-3 fm/c

System is momentarily isotropic

Expansion rate is much faster than the interaction time scale

\[ 1/\tau \gg 1/\tau_{\text{int}} \]

Expansion rate and isotropization via interactions balance

System is momentarily isotropic

Glasma

Boltzmann-Vlasov Transport

Viscous Hydro

\[ \tau_0 \sim Q_s^{-1} \]

\[ \tau_{\text{iso}} \]

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Phenomenological model parameters

\[ \log\left(\frac{\text{Energy Density}}{E_0}\right) \]

\[ \log(\tau) \]

\[ \tau_0 \sim 0.1-0.3 \text{ fm/c} \]

\[ \tau_{\text{iso}} \sim 1-3 \text{ fm/c} \]

1+1 Ideal Hydro

1+1 Free Streaming

\[ (1/\tau)^{4/3} \]

\[ \gamma^{-1} \]
## Model: Break evolution into two pieces

1) $\tau \lesssim \tau_{\text{iso}} - 1\text{d free streaming}$

$$
\langle p_T^2 \rangle \sim 2Q_s^2 \quad \langle p_L^2 \rangle \sim 1/\tau^2 \\
\xi(\tau) = \frac{1}{2} \frac{\langle p_T^2 \rangle}{\langle p_L^2 \rangle} - 1 \\
\downarrow \\
\xi(\tau) = \left( \frac{\tau}{\tau_0} \right)^2 - 1 \\
\
\text{lim}_{\tau \gg \tau_0} E(\tau) \rightarrow E_0 \left( \frac{\tau_0}{\tau} \right)^{4/3} \\
\text{"T"}(\tau) = T_0 \sim \langle p_T \rangle
$$

In the limit $\tau_{\text{iso}} \rightarrow \infty$ the system undergoes indefinite longitudinal free streaming.

2) $\tau \gtrsim \tau_{\text{iso}} - 1\text{d ideal hydro}$

$$
\langle p_T^2 \rangle = 2\langle p_L^2 \rangle \\
\xi(\tau) = \frac{1}{2} \frac{\langle p_T^2 \rangle}{\langle p_L^2 \rangle} - 1 \\
\downarrow \\
\xi(\tau) = 0 \\
\mathcal{E}(\tau) = E_0 \left( \frac{\tau_0}{\tau} \right)^{4/3} \\
T(\tau) = T_0 \left( \frac{\tau_0}{\tau} \right)^{1/3}
$$

In the limit $\tau_{\text{iso}} \rightarrow \tau_0$ the system begins ideal 1d hydrodynamic flow “instantly”.

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Space-time evolution incorporating anisotropies (LHC)

- $\gamma = 2 \Rightarrow \text{“width” of 0.4 fm/c.}$
- $\tau_{\text{iso}} \to \tau_0 : \text{“instant” isotropization/thermalization.}$
- $\tau_{\text{iso}} \to \infty : \text{never isotropizes; 1d free-streaming.}$
LHC Predictions - Dileptons vs $M$ with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $\gamma = 2$, $T_c = 160$ MeV

Cuts: $p_T > 8$ GeV

LHC Predictions - Dileptons vs $P_T$ with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $\gamma = 2$, $T_c = 160$ MeV

Cuts: $0.5 < M < 1$ GeV

RHIC Predictions - Dileptons vs $M$ with backgrounds

$T_0 = 370$ MeV, $\tau_0 = 0.26$ fm/c, $\gamma = 2$, $T_c = 160$ MeV

Cuts: $p_T > 4$ GeV

M. Martinez and MS, forthcoming.
RHIC Predictions - Dileptons vs $P_T$ with backgrounds

$T_0 = 370$ MeV, $\tau_0 = 0.26$ fm/c, $\gamma = 2$, $T_c = 160$ MeV

Cuts: $0.5 < M < 1$ GeV

$\log_{10}(dN^{e^+e^-}/dydp_T^2$ [GeV$^{-2}$]) vs $P_T$ [GeV]

- Drell Yan
- Jet–Thermal
- Jet Fragmentation
- Medium ($\tau_{iso} = 0.26$ fm/c)
- Medium ($\tau_{iso} = 2$ fm/c)

M. Martinez and MS, forthcoming.
Conclusions

• We need more observables which are sensitive to the initial 1-2 fm/c of the plasma lifetime. Dileptons seem to be promising.

• We now have simple models which allow us to calculate the effect of anisotropies on experimental observables, eg jet and E&M signatures. More to come . . .

• Our dilepton results show a window from $p_T \sim 2 - 6$ GeV where it may be possible to determine much-needed information about the initial 1 fm/c of the QGP’s lifetime.

• TODO: Calculation of NLO rate underway; inclusion of possible chemical non-equilibrium (effect will remain but overall rates will be modified); modification of jet-medium production due to early-time anisotropies; . . .
Latest RHIC Experimental Results

Enhancement seen at low invariant masses.

Latest RHIC Experimental Results

Enhancement concentrated at low transverse momentum, $p_T < 1$ GeV.

Model - Smaller Gamma

Can take larger transition widths, say $\gamma = 0.05$. 

\[ \frac{\varepsilon}{\varepsilon_0} \]

\[ \frac{\rho_{\text{hard}}}{\rho_0} \]

\[ \xi \]

\[ a_{iso} = 1 \]
\[ a_{iso} = 4 \]
\[ a_{iso} = 8 \]
\[ a_{iso} = 16 \]
LHC Results - Model variation

\[ T_0 = 845 \text{ MeV}, \ \tau_0 = 0.088 \text{ fm/c}, \ T_c = 160 \text{ MeV} \]

Cuts: \[ 0.5 < M < 1 \text{ GeV} \]

Model Variation: \[ 0.05 < \gamma < 10 \]

$T_0 = 845 \text{ MeV}, \quad \tau_0 = 0.088 \text{ fm/c}, \quad T_c = 160 \text{ MeV}$

**Cuts:** $0.5 < M < 1 \text{ GeV}$

Naive application of resummed finite-temperature perturbation theory to thermodynamics fails to converge at any reasonable temperature so should we abandon it?

\[ \mathcal{P}_{\text{QCD}} / \mathcal{P}_{\text{ideal}} = 1 - \frac{15}{4} \frac{\alpha_s}{\pi} + 30 \left( \frac{\alpha_s}{\pi} \right)^{3/2} + \frac{135}{2} \left( \log \frac{\alpha_s}{\pi} - \frac{11}{36} \log \frac{\mu}{2\pi T} + 3.51 \right) \left( \frac{\alpha_s}{\pi} \right)^2 + \frac{495}{2} \left( \log \frac{\mu}{2\pi T} - 3.23 \right) \left( \frac{\alpha_s}{\pi} \right)^{5/2} + \mathcal{O}(\alpha_s^3 \log \alpha_s) \]
Cause for (limited) hope

- NLO Approximately Self-Consistent HTL Phi-Derivable (Blaizot, Iancu, Rebhan)
- Hard Thermal Loop Perturbation Theory (Andersen, Braaten, Petitgirard, MS)
- 4d Lattice "Pure Glue" (Boyd et al)

\[
\frac{P}{P_{\text{ideal}}}
\]

- HTLpt LO
- HTLpt NLO
What about strong-coupling AdS/CFT?

Strong-coupling calculations in $\mathcal{N} = 4$ SUSY theories show that the high-energy photon rate is insensitive to whether you take the weak or strong coupling limits. [Caron-Huot, Kovtun, Moore, Starinets, Yaffe, arXiv:hep-th/0607237]