A new calculation of light quark jet energy loss using the AdS/CFT Correspondence

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Quark-Gluon Plasma

- Quark-gluon fluid of RHIC behaves as nearly ideal, strongly coupled fluid (sQGP).
- If produced particles interact → Local equilibration → produce some kind of fluid→ pressure gradients → collective motion → Elliptic Flow
- Rough agreement with hydrodynamic models based on perfect liquid.
- Small shear viscosity → Strongly interacting!
  - Hydrodynamics: \( \eta/s = 0.1 \sim 0.2 \)
  - Naive pQCD: \( \eta/s = 1 \)
  - N=4 SYM: \( \eta/s = 1/4\pi \)
- Rapid thermalization: Less than 1 fm!
- Hard Probes:
  - Jets are produced within the expanding fireball and probe the QGP.
  - Effect of hot matter on properties of jets \( \rightarrow \) Nuclear Modification Factor

AdS/CFT Correspondence

- \( N = 4 \) Super-Yang-Mills theory in 4d in large \( \mathbb{C}P^3 \) space
- Studying the theory at finite temperature \( \Rightarrow \) Adding black hole to the geometry: AdS-Schwarzschild metric
- Fundamental quarks in theory \( \Rightarrow \) Open strings moving in the 10d geometry
  - AdS-Sch metric
    \[
    ds^2 = \frac{L^2}{u^2} \left[ -f(u) dt^2 + dx^2 + \frac{du^2}{f(u)} \right], \quad f(u) = 1 - \left( \frac{u}{u_0} \right)^4
    \] (1)

Light Quark in AdS-Sch

Dynamics of classical string: Polyakov Action
\[
S_p = -\frac{T_0}{2} \int d^2\sigma \sqrt{-\eta} \eta^{ab} \partial_a X^a \partial_b X^b \mathcal{G}_{\mu\nu}
\] (2)

Equations of motion for the embedding functions:
\[
\partial_a \left( \sqrt{-\eta} \eta^{ab} \partial_a X^b \right) = \frac{1}{2} \sqrt{-\eta} \eta^{ab} \frac{\partial \mathcal{G}_{\mu\nu}}{\partial X^a} \partial_b X^a \partial_c X^c
\] (3)

Choosing the world sheet metric:
\[
[\eta_{ab}] = \left( \begin{array}{cc}
\Sigma(x, u) & 0 \\
0 & \Sigma(x, u)^{-1} 
\end{array} \right), \quad \Sigma(x, u) = \left( \begin{array}{c}
1 - u/u_0 \\
1 - u/u_0
\end{array} \right) \left( \begin{array}{c}
u \\
\nu
\end{array} \right)^2
\] (4)

Point like initial conditions:
\[
x(0, \sigma) = 0, \quad u(0, \sigma) = u_c, \quad t(0, \sigma) = t_c
\] (5)

Total energy of string is conserved:
\[
E_{\text{string}} = \int_0^\infty d\sigma \sqrt{-\eta} \Pi^\mu(0, \sigma)
\] (6)

Energy Loss:
\[
\frac{d\rho}{dt} = -\sqrt{-\eta} \left[ \Pi^\mu - \left( t \Pi^t + t' \Pi^{t'} \right) \frac{d\sigma}{dt} \right]_{(\sigma, 1, t)}
\] (7)

Original Jet definition:

Medium

Jet

Energy Loss in a Boost-Invariant Geometry

Asymptotic boost-invariant geometry for the perfect fluid:
\[
ds^2 = \frac{L^2}{u^2} \left[ 1 - \frac{\eta}{\eta_0} \frac{u^4}{4\pi^2} \right] d\tau^2 + \left( 1 + \frac{\eta}{\eta_0} \frac{u^4}{4\pi^2} \right) (\sigma^2 d\sigma^2 + d\chi^2) + du^2
\] (8)

Dimensionfull parameter \( \eta_0 \) determines the energy density as:
\[
f(\tau) = \frac{\eta_0}{\tau^{2/3}}
\]

Rapidity \( y \), and proper time \( \tau \) are defined as:
\[
x^0 = \tau \cosh y, \quad x^1 = \tau \sinh y
\] (9)

The metric (8) looks usual AdS-Sch metric with the horizon moving in the bulk
\[
z_h = \left( \frac{3}{\eta_0} \right)^{1/4} \tau^{1/3}
\] (10)

Temperature is cooling as
\[
T(\tau) = \frac{\sqrt{2}}{\pi} \left( \frac{3}{\eta_0} \right)^{-1/4} \tau^{-1/3}
\] (11)

Next step is choosing the appropriate initial conditions, boundary conditions and stretching function for the string

Quark jet energy loss is highly depends on the initial conditions of string.

Nuclear Modification Factor

\[
R_{AA}^{\text{AdS/CFT}} = \frac{R_{jet}^{\text{AdS}}}{R_{jet}^{\text{empty space}}}
\] (13)

Conclusions

- If we define the jet as a part of string above the energy scale \( 500 \text{MeV} \), Bragg peak appeared!
- If we consider the JP metric, an expanding plasma, the thermalization time and stopping distance for light quark are larger than those on the AdS-Sch metric.
- Light quark energy loss is highly depends on the initial conditions of string.
- If we define the regularized \( R_{AA} \) by dividing to the \( R_{AA}^{\text{AdS}} \), the result are in good agreement with jet data!
- Searching for a new string configuration dual to a high energetic quark in the QGP.