Jet quenching with strong coupling

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Absence of quasiparticles?

Most satisfactory description of QGP involves an **almost ideal liquid** phase.

Studies of QGP formation in small systems suggest a common hydrodynamic origin for flow effects.

Weller & Romatschke ‘17
Absence of quasiparticles?

Most satisfactory description of QGP involves an **almost ideal liquid** phase.

Studies of QGP formation in small systems suggest a common hydrodynamic origin for flow effects.

Small value of shear viscosity over entropy density ratio

\[
\frac{\eta}{s} \sim 0.08
\]

Challenges quasiparticle description

\[
\tau_{qp} \sim 5\frac{\eta}{s} \frac{1}{T} \sim \frac{1}{T}
\]

Predicted by Policastro, Son and Starinets (2001) for a large class of non-abelian gauge theories at strong coupling which have a gravity dual.
Absence of quasiparticles?

Most satisfactory description of QGP involves an **almost ideal liquid** phase

Studies of QGP formation in small systems suggest common hydrodynamic origin for flow effects

Hydrodynamics at work with large gradients at very early times

Even for system sizes of order $R \sim \frac{1}{T}$, hydrodynamic gradient expansion is well behaved

Consistent picture of hydrodynamization for all system sizes within strong coupling
Absence of quasiparticles?

need to have description of jet/QGP interaction in harmony with sQGP hypothesis

traditional pQCD computations need to assume separation of scales

\[ \lambda_D \ll \lambda_{\text{m.f.p.}} \quad \Rightarrow \quad g \ll 1 \]

neglect correlations among scatterers
Absence of quasiparticles?

need to have description of jet/QGP interaction in harmony with sQGP hypothesis

traditional pQCD computations
need to assume separation of scales

\[ g \ll 1 \]

\[ T \sim 0.2 \text{ GeV} \]

\[ \beta^{1\text{loop}}(T) \]

but for collider relevant temperatures
this does not seem to be the case

- can we study energy loss problem without relying on quasiparticles?

use strong coupling techniques such as holography
Absence of quasiparticles?

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traditional pQCD computations need to assume separation of scales

\[ \lambda_D \ll \lambda_{\text{m.f.p.}} \]
\[ g \ll 1 \]

for ex: neglect correlations among scatterers

but for collider relevant temperatures this does not seem to be the case

\[ T \sim 0.2 \text{ GeV} \]
\[ g \sim 2 \]

• can we study energy loss problem without relying on quasiparticles?
  use strong coupling techniques such as holography

• construct phenomenological models that capture the essential physics
  compare to data to confront the underlying assumptions
Holography: a non-perturbative tool

- quarks are dual to open strings attached to probe flavour branes
- having a plasma in the gauge theory is equivalent to a black hole in the bulk
- bulk metric perturbations encode boundary stress energy variations

\[ \mathcal{N} = 4 \] SYM and QCD have very different vacuums

but

\[ \mathcal{N} = 4 \quad T \neq 0 \] and QCD \( T > T_c \) share similarities
the heavy quark transfers energy to the plasma via frictional drag
external force required to keep quark’s velocity constant

\[
\frac{dE}{dt} = \frac{\pi}{2} \sqrt{xT^2} \frac{v^2}{\sqrt{1 - v^2}} \quad \gamma < \left( \frac{2M}{\sqrt{xT}} \right)^2
\]

Herzog et al., Gubser, Casalderrey & Teaney ‘06 (validity regime)
Heavy quark trailing string

the heavy quark transfers energy to the plasma via frictional drag
external force required to keep quark’s velocity constant

\[ \frac{dE}{dt} = \frac{\pi}{2} \sqrt{\chi T^2} \frac{v^2}{\sqrt{1 - v^2}} \]

\[ \gamma < \left( \frac{2M}{\sqrt{\chi T}} \right)^2 \]

Herzog et al., Gubser, Casalderrey&Teaney ‘06 (validity regime)

need to consider the fluctuations within the thermal bath
for a sensible phenomenology

\[ \frac{dp_i}{dt} = -\mu p_i + F_i^L + F_i^T \]

(coloured noise)

\[ \mu = \frac{\pi \sqrt{\chi T^2}}{2M_Q} \]

\[ \langle F_i^L(t_1) F_j^L(t_1) \rangle = \kappa_L \hat{p}_i \hat{p}_j g(t_2 - t_1) \]

\[ \langle F_i^T(t_1) F_j^T(t_1) \rangle = \kappa_T (\delta_{ij} - \hat{p}_i \hat{p}_j) g(t_2 - t_1) \]

\[ \kappa_L = \gamma^2 \kappa_T \]

\[ \kappa_T = \pi \sqrt{\chi T^3} \gamma^{1/2} \]

Casalderrey-Solana & Teaney ‘06, Gubser ‘07

Horowitz ‘15
Heavy quark trailing string

The heavy quark transfers energy to the plasma via frictional drag. The external force required to keep quark’s velocity constant is given by:

$$\frac{dE}{dt} = \frac{\pi}{2} \sqrt{\chi T^2} \frac{v^2}{\sqrt{1 - v^2}}$$

with:

$$\gamma < \left( \frac{2M}{\sqrt{\chi T}} \right)^2$$

Herzog et al., Gubser, Casalderrey & Teaney ‘06 (validity regime)

Need to consider the fluctuations within the thermal bath for a sensible phenomenology:

$$\frac{d\mu}{dt} = -\mu p_i + F_i^L + F_i^T$$

(coloured noise)

Casalderrey-Solana & Teaney ’06, Gubser ‘07

Horowitz ‘15
Transverse momentum broadening

Moerman & Horowitz '16

compute distance square travelled by the endpoint as it falls in holographic direction

$$s^2(t; a) := \langle (\hat{X}_{\text{End}}(t; a) - \hat{X}_{\text{End}}(0; a))^2 \rangle$$

- ballistic early times, diffusive late times
- behaviour at late times solely dependent on near horizon dynamics

$$\hat{q} = \frac{\langle p_T^2 \rangle}{\lambda m_{fp}} = \frac{2\kappa_T}{v} = \frac{4T^2}{vD} = \frac{32\pi \sqrt{\lambda} T^3}{(d - 1)^2(1 - a/2)v}$$

(late times)

- fluct. for heavy quarks moving faster than speed limit
- interpolation between heavy quark and light quark results

$$a(t) \quad \text{speed at which endpoint falls}$$

$$\hat{q}_{LRW} \approx 7.5 \sqrt{\lambda} T^3$$

$$\hat{q}_{\text{Gubser}} = \frac{2\pi \sqrt{\lambda} T^3}{v} \sqrt{\gamma}$$
Proxies for HE jets

light quark endpoint can fall unimpeded towards the black brane

\[ z_q \to 0 \]

semiclassical string description

\[ \kappa_{sc} = 1.05 \lambda^{1/6} \]

Chesler et al. ‘09

robust result at strong coupling

\[ x_{\text{stop}} = \frac{1}{2 \kappa_{sc}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}} \]

Arnold & Vaman ‘11

external boosted U(1) fields

\[ \kappa_{sc} \propto \lambda^0 \]
Null falling strings

Chesler & Rajagopal ’14,’15

- approximation of falling strings for very high energy jets
- the rate at which energy flows into hydrodynamic modes:

\[
\frac{1}{E_{\text{init}}} \frac{dE_{\text{jet}}}{dx} = -\frac{4x^2}{\pi x_{\text{therm}}^2 \sqrt{x_{\text{therm}}^2 - x^2}}
\]

as the jet loses energy …

it gets wider

\[
\theta_{\text{jet}} \sim \frac{\theta_{\text{init}}^{\text{jet}}}{\left[1 - \frac{x}{x_{\text{therm}}}\right]^2}
\]

Fractional energy loss only depends on initial jet opening angle

\[
x_{\text{therm}} = \frac{1}{T} \sqrt{\frac{\kappa}{\theta_{\text{init}}^{\text{jet}}}}
\]

most energy at endpoint: Bragg-like peak
Holographic quenching with pure strings

- consider an ensemble of such jets by choosing initial distributions of energy & angle from pQCD
- competing effects: each individual jet widens, while wider jets lose more energy

\[ T_{\text{SYM}} = b T_{\text{QCD}} \]

\[ C_1^{(\alpha)} = \sum_{i,j} z_i z_j \left( \frac{|\theta_{ij}|}{R} \right)^\alpha \]

measures jet angle in pQCD

also observed in pQCD

Milhano & Zapp '15

Rajagopal, Sadofyev, van der Schee '16
Holographic quenching with pure strings

J. Brewer’s talk on Tue

- determine string energy density by considering different initial profiles evolved within **full string dynamics**
  
as the string nullifies, different initial choices tend to converge

- nuclear jet shape modification **captures core dynamics** - lacks contribution from **medium response**
Hybrid strong/weak coupling approach

Initial parton from hard scattering carries a high virtuality

will split according to perturbative DGLAP evolution

Interactions with the medium take place at a non-perturbative scale

describe the propagation of partons within QGP using holographic falling strings

- captures multi-scale nature of in-medium HE jets dynamics
- neglects parton shower modifications induced by medium injected virtuality
- useful tool as a benchmark to compare to data

Casalderrey-Solana et al. ’14,’15,’16

See K. Rajagopal’s talk on Tue
Jet suppression: Photon-Jet events

Core features of the model have been validated by e.g. photon-jet observables predictions

No strong evidence so far of hard point-like scatterers
Jet induced medium excitations

- String acts as a perturbation in the large Nc limit
- Agreement between hydrodynamics & wake of a quark in gauge/gravity duality

Metric perturbation near the AdS boundary
Change in the SYM stress-energy tensor

Small perturbation on top of hydro
Only valid for soft hadrons
No extra free parameter
Where does lost energy go to?

energy is recovered at large angles in the form of soft particles

data suggests that implementation of back-reaction might mistreat semi-hard particles
Where does lost energy go to?

energy is recovered at large angles in the form of soft particles

data suggests that implementation of back-reaction might mistreat semi-hard particles
wider, more active jets lose more energy as they have more energy loss sources

lost energy does not stay close to the jet axis

mild recovery by increasing jet radius $R$

We can use the $R$ dependence of jet suppression to greatly constrain models assumptions

$\Delta R \downarrow$ has energy been thermalised?  
need strong gluon re-scattering?  $\Delta R \uparrow$

jet spectra ratio among different $R$ offer great systematic uncert. cancellation
wider, more active jets lose more energy as they have more energy loss sources

consistent with trend seen in data

CMS arXiv:1609.05383

We can use the R dependence of jet suppression to greatly constrain models assumptions

$\Delta R \downarrow$ has energy been thermalised? need strong gluon re-scattering? $\Delta R \uparrow$

jet spectra ratio among different R offer great systematic uncert. cancellation
Medium response on jet substructure

Jet fragmentation function

Jet shapes

increasing #soft particles

increasing #wide particles

effect in the right direction, but clearly not enough
Medium response on jet substructure

Jet fragmentation function

Jet shapes

effect in the right direction, but clearly not enough

increasing #soft particles

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cancellation between two effects

quenching  back-reaction

Charged jet mass
Medium response on jet substructure

from D. Caffarri’s talk on Tue

Cancellation between two effects

quenching  back-reaction

Charged jet mass
Medium response on jet substructure

Jet fragmentation function

- **Backreaction**
- **No Backreaction**
- **CMS Data**

Increasing #soft particles

Jet shapes

- **Backreaction**
- **No Backreaction**
- **CMS Data**

Increasing #wide particles

Effect in the right direction, but clearly not enough

What physics is missing?

Cancellation between two effects

Quenching

Back-reaction

JEWEL w/ recoil describes jet shapes, but overestimates mass

How to reconcile?

Charged jet mass
Finite resolution effects

Casalderrey-Solana & Ficnar ‘15

smallest angular separation between two jets that the medium can resolve?

assign a transverse structure to the string such that a quark-gluon system is emulated

study the stopping distances as a function of opening angle and energy

different scaling than pQCD in a dense plasma

\[
\theta_{\text{res}} = \frac{2^{4/3}}{\pi} \frac{\Gamma(3/4)^2}{\Gamma(5/4)^2} \left( \frac{E}{\sqrt{\lambda T}} \right)^{-2/3}
\]

\[
\theta_{\text{res}}^{p\text{QCD}} \propto E^{-3/4}
\]
Phenomenology of 3-jet events

J. Brewer’s talk on Tue

work in progress to study holographically
phenomenology of 3-jet events

crucial to describe dijet asymmetry

speculation: formation time, resolution length?

Stay Tuned!
An *estimate* of finite resolution effects

**Z. Hulcher’s poster**

*within the hybrid strong/weak coupling model*

the medium perceives the system as a *collection of effective emitters*

the number and rearrangement of the effective emitters is governed by the *resolution length*

the effect modifies the space-time picture of the parton shower

resolution length in a *finite* plasma at strong coupling is currently not known

assume as an *exploratory study* that the screening length is the relevant scale

\[ L_{\text{res}} \sim \lambda_D \]
Finite resolution on observables

\[ L_{\text{res}} = \frac{Y}{\pi T} \]

- weak coupling: \( Y \sim 1.3 \)
- strong coupling: \( Y \sim 0.3 \)

\( \alpha_s = 0.3 \)

2nd free parameter

fewer # of effective energy loss sources
reduce stopping distances

jet substructure is modified due to finite resolution:
- energy loss more democratic among partons
- increases survival rate of softer, wider radiation
- leading track gets more quenched

Bak et al. ‘07

see Y. Tachibana’s and W. Chen’s talks

oversimplified medium response?

Z. Hulcher’s poster
Hadron suppression at LHC

triggering on a high energy hadron selects narrow jets that lost little energy

\[ R_{AA}^{\text{had}} > R_{AA}^{\text{jet}} \]

tension in centrality evolution

decrease of stopping distances due to finite resolution

greater quenching on leading tracks

improved agreement

Z. Hulcher’s poster
energy loss at strong coupling is a necessary tool to assess the true nature of QGP dynamics

much progress has been made in developing models that can be compared to data

degree of hydronamisation of lost energy can be tested with currently available observables

further effort is needed on bringing holographic models to a next level of sophistication
- Energy loss at strong coupling is a necessary tool to assess the true nature of QGP dynamics.
- Much progress has been made in developing models that can be compared to data.
- Degree of hydronamisation of lost energy can be tested with currently available observables.
- Further effort is needed on bringing holographic models to a next level of sophistication.

Is data pointing towards this picture?
Backup Slides
Hadron suppression at RHIC

\[ L_{\text{res}} = \frac{2}{\pi T} \]

No Res
PHENIX Data

under scrutiny

AuAu \( \sqrt{s} = 200 \) AGeV

0 – 5%

Nuc PDF
Intra-jet broadening

**Inclusive jets - all tracks**

- strong quenching suppresses the effect of broadening

\[ Q \uparrow, \ \theta \uparrow, \ \tau_f \downarrow \]

early wide fragments quenched

\[ Q \downarrow, \ \theta \downarrow, \ \tau_f \uparrow \]

late narrow fragments survive

- selection bias towards narrower jets, merely a jet axis deflection

\[ \hat{q} = KT^3 \]

**Subleading jets - semi-hard tracks**

- kinematical limits chosen such that:
  - no effect from background (soft tracks)
  - intra-jet activity above average (hard tracks)

- deviations from such Gaussian broadening

- hard momentum transfers from QGP quasiparticles
An *estimate* of the wake spectra

Assuming a *small perturbation* on top of hydro:

- no details on the perturbation needed
- particle distribution is constrained by energy-momentum conservation
- no extra parameters needed

Each parton generates its own wake

One body distribution from Cooper-Frye expansion

\[
E \frac{dN}{d^3p} = \frac{1}{32\pi} \frac{m_T}{T^5} \cosh(y - y_j)e^{-\frac{m_T}{T}\cosh(y-y_j)}
\]

\[
[p_T \Delta P_T \cos(\phi - \phi_j) + \frac{1}{3} m_T \Delta M_T \cosh(y - y_j)]
\]

- well suited for the description of soft hadrons
- not appropriate for harder particles at the tail (details on the source needed)
F.E.M. shooting strings

- finite endpoint momentum strings:
  energy loss
  
  =

  energy flux from endpoint to bulk of string

- string endpoint starts close to the horizon, then stops at boundary and falls back again

from Gubser's '14 talk in ECT*

- including higher derivative corrections (Gauss-Bonnet), but need to rescale LHC temperature

Ficnar et al. '14