Heavy Quark Energy Loss

Urs Achim Wiedemann
SUNY Stony Brook
and
RIKEN BNL

Strange Quark Matter 2006
UCLA Los Angeles
March 31, 2006
Strange Quark Matter and Heavy Quarks

• **Strangeness enhancement**  
  + abundant yield, soft probe  
  + manifestation of enhancement and sensitivity to medium accessible  
  - dynamical origin of enhancement difficult to access


• **J/Psi suppression**  
  -/+ rare yield, hard probe  
  + manifestation of dissociation and sensitivity to medium accessible  
  - dynamical origin of enhancement difficult to access


• **Jet quenching**  
  +/+ abundant yield, hard probe  
  + manifestation of quenching and sensitivity to medium accessible  
  + feasible strategy exists for testing the microscopic dynamical origin underlying jet quenching (and testing dynamics of equilibration)

  Bjorken 1982; Gyulassy, Wang 1990; BDMPS 1996; …
High pt hadron suppression ≠ Jet quenching

Only a part of the entire jet.

\[ R_{AA}(p_T, \eta) = \frac{dN^{AA}/dp_T d\eta}{n_{coll} dN^{NN}/dp_T d\eta} \]

Centrality dependence:

- 0-5%
- 70-90%
Centrality dependence: Au+Au vs. d+Au

Final state suppression

Initial state enhancement

partonic energy loss
Conjectured Origin of High-pt hadron suppression

Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

Medium characterized by transport coefficient:

\[ \hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{\text{density}} \]

- energy loss of leading parton

\[ \omega_c = \hat{q}L^2 / 2 \]

- pt-broadening of shower

\[ \kappa^2 \equiv \frac{k_T^2}{\hat{q}L} \]

The suppression of leading hadrons

Parton energy loss calculations account for:

- Nuclear modification factor
- Centrality dependence
- Back-to-back correlations
- \( R_{AA} = 0.2 \) is a natural limit due to surface emission

indicates very \textit{opaque medium}.

- Numerics at face value:
  \[
  \hat{q}(\tau) = c \epsilon^{3/4}(\tau) \iff c_{QGP}^{\text{ideal}} \approx 2
  \]

  \[
  c > 5 c_{QGP}^{\text{ideal}}?
  \]

Open questions:
- tests of the microscopic dynamics underlying high-pt hadron suppression?
- relation of \( \hat{q} \) to model-independent calculation in QCD?

Many works: X.N.Wang; Gyulassy; I. Vitev; Levai, Dainese Loizides Paic; Renk, Ruppert, …
Is radiative energy loss dynamic origin of jet quenching?

+ Flat pt-dependence of $R_{AA}(p_T)$ gives strong support (e.g. collisional effects should die out rapidly with energy)

- Large numerical value of $\hat{q}$ not yet understood
  - flow effects may lead to an apparently large $\hat{q}$
  - existing calculations of $\hat{q} = c \epsilon^{3/4}$ rather model-dependent, improvements needed and feasible
  - medium-modified parton fragmentation may receive quantitatively important refinements

How to disentangle these possibilities?
Testing the dynamical origin of high-pt hadron suppression

How does this parton thermalize?

Where does this associated radiation go to?

What is the dependence on parton identity?

How do we detect recoil in case of collissional energy loss?

$$\Delta E_{\text{gluon}} > \Delta E_{\text{quark, } m=0} > \Delta E_{\text{quark, } m>0}$$
Parton energy loss depends on parton identity

$$\Delta E_{\text{gluon}} > \Delta E_{\text{quark}, m=0} > \Delta E_{\text{quark}, m>0}$$

- Vacuum radiation is suppressed in the `dead cone' due to quark mass
  - Dramatic Consequence: in jets of ~ 100 GeV, leading hadron carries
    - ~1/4 of jet energy for light quark jets
    - ~ 3/4 of jet energy for b-quark jets

- Medium-induced gluon radiation is reduced as well
  - for $m/E > 10\%$

$$\frac{1}{k_T^2} \Rightarrow \frac{k_T^2}{(k_T^2 + \omega^2)^2}$$

$$dI/d\kappa^2$$

- massive
  - $m/E = 0.1$
- massless
  - $\omega_c/\omega = 10$
- dead cone

$$\kappa^2 = \frac{k_T^2}{\hat{q}L}$$

Dokshitzer, Kharzeev, PLB 519 (2001) 199
Armesto, Salgado, Wiedemann, PRD69 (2004) 114003
Djordjevic,, Gyulassy, NPA733 (2004) 265
Pt-dependence disentangles mass-hierarchy

\[ \Delta E_{\text{gluon}} > \Delta E_{\text{quark}, m=0} > \Delta E_{\text{quark}, m>0} \]

- Heavy quark mass negligible for large \( m_Q/p_T < 10 - 20\% \)
  \[ m_c \approx 1.5 \text{ GeV} \Rightarrow p_T > 10 \text{ GeV} \]
  \[ m_b \approx 4.7 \text{ GeV} \Rightarrow p_T > 30 \text{ GeV} \]

If \( p_T \sim 20 \text{ GeV} \), light-flavored hadrons dominated by gluon parents, then access to \( \Delta E_{\text{gluon}} > \Delta E_{\text{quark}, m=0} \)

by measuring

\[ R_{D/h} = \frac{R_{D}^{\text{gluons}}}{R_{h}^{\text{quarks}}} \]

dominated by quarks gluons at LHC

quarks quarks at RHIC
Testing mass hierarchy of energy loss at RHIC

- Sensitivity to quark mass is limited to relatively low transverse momentum

\[ R_{D/h} = \frac{R^D_{AA}}{R^h_{AA}} \]

- A combined effect of quark mass and color charge dependence should be accessible experimentally.

Armesto, Dainese, Salgado, Wiedemann, PRD71:054027, 2005
Testing mass hierarchy of energy loss at the LHC

- Sensitivity at LHC:

- Color charge dependence dominates
  \[ R_{D/h} = \frac{R^D_{AA}}{R^h_{AA}} \]
  \[ \Delta E_{\text{gluon}} > \Delta E_{\text{quark}} \]

- Mass dependence dominates
  \[ R_{B/h} \]
  \[ \Delta E_{\text{quark}, m=0} > \Delta E_{\text{quark}, m>0} \]

- Daughters trace parents:
  light-flavored mesons - gluon parents
  D - mesons - quark parents \((m_c \sim 0)\)
  B - mesons - quark parents \((m_b > 0)\)

Armesto, Dainese, Salgado, Wiedemann, PRD71:054027, 2005
High-pt electrons at RHIC - Baseline 1

- Baseline: in proton-proton, semileptonic c-, b-decays dominate, 10% contribution from Drell-Yan at pt~10 GeV

- Calculation of c-, b- spectrum: FONLL pt-distribution of c, b plus fragmentation

- Calculation of DY- spectrum: NLO accuracy.

High-pt electrons at RHIC - Baseline 2

- Comparison of FONLL calculation of single inclusive electrons to data from pp collisions at $\sqrt{s_{NN}} = 200\, GeV$ PHENIX, hep-ex/0508034

- Within errors, comparison of FONLL to data is fair. But central values are underpredicted systematically by factor 2-3.

Nuclear modification of high-pt electrons at RHIC

• Within errors, comparison of energy loss calculation to data is fair.
• But central values are under-predicted systematically by 0.1 - 0.2.
• Larger values of $\hat{q}$ are favored.

How to do better?


Much more stringent test of energy-loss is possible if b- and c-decay contributions could be disentangled.

STAR / PHENIX upgrades
BACK-UP SLIDES
Collisional / radiative energy loss

$p_{in} = (E, 0_T, E)$

Collisional energy loss determined by $q_0, q_l \neq 0$

Elastic cross section:

$$\frac{d\sigma_{el}}{dt} = C_{el} \frac{2\pi\alpha_s^2}{s^2} \frac{s^2 + u^2}{t^2}$$

High energy limit: $t \approx q_T^2 + O(1/E)$

Radiative energy loss in high energy limit:

At finite energy:
LHC: the richness of hard probes

The probes:
- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:
- $Q^2, x, A, \text{luminosity}$

**Abundant** yield
of hard probes
+ **robust** signal
  (medium sensitivity
   $>>$ uncertainties)
= **detailed understanding**
of dense QCD matter
Longitudinal Jet Heating

- If **leading hadron** in jet is suppressed then **soft jet multiplicity** must increase

  Medium-modification of hump-backed plateau

- Medium-modified splittings of leading and subleading partons treated equally

- Strength of medium-modified splittings fixed by $R_{AA}=0.2$.

\[ \frac{dN^h}{d\xi} \]

\[ \xi = \ln\left( \frac{E_T^{jet}}{p_T^h} \right) \]

Borghini, Wiedemann, hep-ph/0506218
LHC: extending the range from $E=15$ to 200 GeV

Scale of enhancement roughly consistent with RHIC data (STAR prelim).
Jets in pionic winds and partonic storms

If hard partons are not produced in rest frame comoving with medium, then jets are sensitive to energy density and collective flow:

\[ T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} \]

Armesto, Salgado, Wiedemann, PRL 93 (2004) 242301

Effects:
- broken \( \Delta \eta \times \Delta \phi \) - symmetry of jet shapes and particle correlations.
- increased high-pt elliptic flow.
- increased high-pt suppression at fixed energy density.