Aspects of parton energy loss in cold QCD media

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Outline

- **Motivations**
  - why energy loss
  - why cold nuclear matter
- **Energy loss in various observables**
  - Drell-Yan production in p A collisions
  - hadron production in semi-inclusive DIS
- **Recent developments**
  - revisiting scaling properties of energy loss

References

Energy loss and gluon radiation

Multiple soft collisions of the hard parton

- Gluon radiation $dI/d\omega$ proportional to the medium density

\[ \text{[ Baier, Dokshitzer, Mueller, Peigné, Schiff 1996, 1997 ]} \]
\[ \text{[ Gyulassy, Wang 1994; Gyulassy, Léai, Vitev 2000 ]} \]
\[ \text{[ Zakharov 1996 1997 1998 ; Wiedemann 2000 2001 ]} \]

- Energy loss huge in quark-gluon plasma

How to probe this mechanism?
Jet quenching

A clear experimental observable

Quenching of jets in heavy ion collisions

[ Bjorken 1982; Gyulassy & Wang 1992 ]
Jet quenching

What about energy loss in ***cold nuclear matter***?
Energy loss in cold vs. hot matter

Transport coefficient

Typical energy loss is proportional to the transport coefficient $\hat{q}$ which characterizes the scattering property of the medium [BDMPS 97]

$$\hat{q} = \frac{\mu^2}{\lambda}$$

- $\mu$: typical momentum transfer in single rescattering (of the order of the Debye mass $m_D \sim gT$)
- $\lambda$: radiated gluon mean free path
Energy loss in cold vs. hot matter

**Transport coefficient**

Typical energy loss is proportional to the transport coefficient $\hat{q}$ which characterizes the scattering property of the medium \[ \text{[BDMPS 97]} \]

Energy loss in cold/hot nuclear matter (medium length $L$)

\[ -\Delta E = \frac{\alpha_s C_R}{4} \hat{q} L^2 \]

Relationship between energy loss and momentum broadening

\[ -\frac{dE}{dz} = \frac{\alpha_s N_c}{4} \langle p_{\perp}^2 \rangle \]

- independent of $\hat{q}$
- independent of the nature of the parton
Perturbative estimates

Cold matter

\[
\hat{q} = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} \rho xG(x, Q^2) \simeq 0.02 \text{ GeV}^2/\text{fm}
\]

\[-dE/dz \simeq 0.1 \text{ GeV/fm} \left( \frac{L}{5 \text{ fm}} \right)\]

Hot matter (e.g. \( T = 250 \text{ MeV} \))

\[\mu \sim 500 \text{ MeV}, \ \lambda \sim 0.5 \text{ fm} \Rightarrow \hat{q} \simeq 0.5 \text{ GeV}^2/\text{fm}\]

Parton energy loss much larger in hot matter than in cold matter
Extracting energy loss from data

**Ideal process:** Drell-Yan production in p A collisions

\[ q^p \bar{q}^A \rightarrow \gamma^* \rightarrow \ell^+\ell^- \]

- Multiple scattering of the incoming quark in large nuclei
- No energy loss in the final state
- Very precise measurements by E866/Nusea over a wide range in \( x_F \)
Extracting energy loss from data

\[ \sigma(pA \rightarrow \mu^+ \mu^- X) \propto A^\alpha \]

\( \alpha \lesssim 1 \): slight suppression at large \( x_F \)

Is the suppression coming from energy loss?
Longstanding debate on the origin of the nuclear dependence of E866/NuSea p A data

- First attributed as coming from nuclear PDF effects \cite{Vasiliev:1999in}
  
  - small energy loss: upper limit $-dE/dz < 0.5 \text{ GeV/fm}$
Energy loss and DY data

**Longstanding debate** on the origin of the nuclear dependence of E866/NuSea p A data

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  - small energy loss: upper limit $-dE/dz < 0.5$ GeV/fm

**Issue**

Conclusions were based on the use of EKS98 nPDF set which already included E772 data (i.e. same kinematic conditions as E866/NuSea)

- Agreement between E866/NuSea and EKS98 somewhat inconclusive
- No room left for energy loss processes
Longstanding debate on the origin of the nuclear dependence of E866/NuSea p A data

- First attributed as coming from nuclear PDF effects [Vasiliev et al. 1999]
- Later accounted for by significant energy loss effects [Johnson et al. 2001]

\[-\frac{dE}{dz} = 2.7 \pm 0.4 \pm 0.5 \text{ GeV/fm}\]

- E722 and E866/NuSea binned in DY mass
- small shadowing computed within a dipole model
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E722 and E866/NuSea binned in DY mass

Small shadowing computed within a dipole model

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...disfavoured by older DY measurements [FA 2002]

- DY data in $\pi$ A collisions at SPS
DY data analysis

Ingredients of the model

- Computation of DY production in QCD at leading order
- Shift of the momentum fraction $x_1$ carried by the quark in the projectile proton to account for energy loss processes
- Nuclear shadowing (using EKS98) turned on or off
- Amount of energy loss fitted to E866 (FNAL) and NA3 (SPS) data

\[
\frac{d\sigma(hA)}{dx_1} = \frac{8\pi\alpha^2}{9x_1s} \sum_q e_q^2 \int \frac{dM}{M} \int d\epsilon \mathcal{P}(\epsilon)
\[
\left[ Zf_q^h(x_1 + \Delta x_1) f_q^{p/A}(x_2) + (A - Z) f_q^h(x_1 + \Delta x_1) f_{\bar{q}}^{n/A}(x_2) \right.
\]
\[
\left. + Zf_{\bar{q}}^h(x_1 + \Delta x_1) f_q^{p/A}(x_2) + (A - Z) f_{\bar{q}}^h(x_1 + \Delta x_1) f_{\bar{q}}^{n/A}(x_2) \right]
\]

with $\mathcal{P}(\epsilon)$: probability distribution in the energy loss [Baier et al. 2001]
Probability distribution

Poisson approximation

\[ P(\epsilon) \propto \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int d\omega_i \frac{dl(\omega_i)}{d\omega} \right] \delta \left( \epsilon - \sum_{i=1}^{n} \omega_i \right) \]

- Uniquely related to the medium-induced gluon spectrum \( dl/d\omega \) characterized by the transport coefficient \( \hat{q} \)

![Graph showing the probability distribution function \( P(\epsilon) \) with different values of \( E/\omega_c \).]
Main results

DY in p A collisions at FNAL ($\sqrt{s} \simeq 40$ GeV)

- Amount of quark energy loss crucially depends on the poorly known sea-quark shadowing at small $x_2$
- No reliable extraction of quark energy loss due to nPDF uncertainties
Many global fit analyses (EKS, EPS, HKM, HKN, nDS) and models

Huge uncertainties at small $x$ and low scales

see talk by T. Stavreva
Main results

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DY in π A collisions at SPS ($\sqrt{s} \approx 20$ GeV)

- Larger error bars, but . . .
- nPDF effects small and well constrained
  - $x_2 = \mathcal{O}(10^{-1})$ between shadowing and EMC region
  - Valence quark (pion beam) constrained in e A DIS
Energy loss and NA3 data

- Large energy loss disfavoured
- Effects stronger at large $x_1$ due to phase-space restriction for medium-induced gluon radiation

$$
\epsilon < (1 - x_1) E_{\text{beam}}
$$
Results

NA3 fit gives

\[-\frac{dE}{dz} = 0.20 \pm 0.15 \text{ GeV/fm}\]

Result independent on the assumption regarding nPDF effects (unlike p A collisions at higher energy)
Energy loss and NA3 data

Results

- NA3 fit gives
  \[ \frac{-dE}{dz} = 0.20 \pm 0.15 \text{ GeV/fm} \]

- Result *independent* on the assumption regarding nPDF effects (unlike p A collisions at higher energy)

Remarks

- Smaller error bars would help tremendously!
- Exciting data to come at FNAL at lower beam energy (E906)
- Complementary results at J-PARC
  - P-04: High mass di-muon measurements in p A collisions
Results

- NA3 fit gives

\[-\frac{dE}{dz} = 0.20 \pm 0.15 \text{ GeV/fm}\]

- Result independent on the assumption regarding nPDF effects (unlike p A collisions at higher energy)

What about energy loss in hadron production?
Energy loss in hadron production

Simplest model for medium-modified “fragmentation functions”

- Fragmentation variable \( z \) rescaled to a larger value
  \[
  z^* = \frac{E_h}{k_\perp - \epsilon} = \frac{z}{1 - \epsilon/k_\perp}
  \]

- Parton energy shifted from \( k_\perp \) to \( k_\perp - \epsilon \) with probability \( \mathcal{P}(\epsilon, k_\perp) \)

\[
z D_h^{k_{med}}(z, Q^2) = \int_0^{(1-z)k_\perp} d\epsilon \mathcal{P}(\epsilon, k_\perp) z^* D_h^k(z^*, Q^2)
\]

[ Wang, Huang, Sarcevic 96 ]
Energy loss in hadron production

**Simplest model for medium-modified “fragmentation functions”**

- Fragmentation variable $z$ rescaled to a larger value

  \[ z^* = \frac{E_h}{k_{\perp} - \epsilon} = \frac{z}{1 - \epsilon/k_{\perp}} \]

- Parton energy shifted from $k_{\perp}$ to $k_{\perp} - \epsilon$ with probability $P(\epsilon, k_{\perp})$

  \[ zD_k^{med}(z, Q^2) = \int_0^{(1-z)k_{\perp}} d\epsilon \ P(\epsilon, k_{\perp}) \ z^* D_k^h(z^*, Q^2) \]

- Hadronization takes places on times scales $\gg$ medium length
- Explicit dependence on the parton energy
- No $Q^2$-dependence

[ Wang, Huang, Sarcevic 96 ]
Energy loss in semi-inclusive DIS on nuclei

Example

Semi-inclusive hadron production in DIS on nuclei: \( eA \rightarrow hX \)

\[
R^h_{eA} = \frac{1}{N_{eA}} \frac{dN^h_{eA}(z, \nu)}{d\nu \, dz} \left/ \frac{1}{N_{eD}} \frac{dN^h_{eD}(z, \nu)}{d\nu \, dz} \right.
\]

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Phenomenological consequences

What trends to be expected from the model?

For simplicity let us assume that $D^h(z) \sim (1 - z)^{\eta^h}$ at large $z$

$$R^h_{eA}(z, \nu) \simeq \frac{D^h_{\text{med}}(z)}{D^h_{u}(z)} \simeq 1 + \frac{1}{D^h_{u}(z)} \frac{\partial D^h_{u}}{\partial z} \frac{z \epsilon}{\nu} \approx 1 - \eta^h_u \times \frac{z \epsilon}{\nu(1 - z)}$$
Phenomenological consequences

What trends to be expected from the model?

For simplicity let us assume that $D^h(z) \sim (1 - z)^{\eta^h_i}$ at large $z$

$$R^h_{eA}(z, \nu) \simeq \frac{D^h_{u}^{med}(z)}{D^h_{u}(z)} \simeq 1 + \frac{1}{D^h_{u}(z)} \frac{\partial D^h_{u}}{\partial z} \frac{z \epsilon}{\nu} \approx 1 - \eta^h_u \times \frac{z \epsilon}{\nu(1 - z)}$$

- $R^h_{eA} \ll 1$
  - at small parton energy
  - at large $z$ due to phase space shrinkage
- Suppression sensitive to the (log) slope of fragmentation function $\eta^h_i$
  - stronger suppression for gluon induced processes, on top of the $C_A/C_F$ factor in the energy loss
  - stronger suppression for baryons than for mesons (!)
Comparison to HERMES data

\[ R_h(\nu) \]

\[ R_h(\nu) \]

\( \nu \) and \( z \) dependence well reproduced

\( \eta_u^{K^-} > \eta_u^{K^+} \) leads to a stronger \( K^- \) suppression as seen in HERMES

[ FA 2003, HERMES Airapetian et al. 2003 ]
Comparison to HERMES data

Caveat: nuclear absorption

Inelastic interaction of the produced hadron might play a role too

\[ \text{Kopeliovich et al. 1996, Accardi, Muccifora, Pirner 2003, Falter et al. 2004} \]

- Somewhat depends on hadronization time scales
- (Pre) hadronic cross sections with nuclear matter poorly constrained

Recent effort to disentangle energy loss and nuclear absorption

\[ \text{Accardi 2006-2008} \]
New results

Recent measurements on $\langle k_\perp \rangle$ broadening of produced hadrons in e A semi-inclusive DIS (CLAS, HERMES)

[ in Accardi et al. 2009 ]
Transverse momentum broadening

New results

Recent measurements on $\langle k_\perp \rangle$ broadening of produced hadrons in $eA$ semi-inclusive DIS (CLAS, HERMES)

![Graph showing recent measurements on $\langle k_\perp \rangle$ broadening of produced hadrons in $eA$ semi-inclusive DIS (CLAS, HERMES).](image)

[van Haarlem, Jgoun, Di Nezza 2007]
New results

Recent measurements on $\langle k_\perp \rangle$ broadening of produced hadrons in e A semi-inclusive DIS (CLAS, HERMES)

![Graph showing Δ$p_t^2$ vs. ν (GeV) for different elements: Ne, Kr, Xe, with data points for π^+, π^-, K^+ from HERMES preliminary results.]

- Might be sensitive to the details of hadronization dynamics

  - [van Haarlem, Jgoun, Di Nezza 2007]
  - [Accardi 2008, Domdey, Kopeliovich, Pirner 2008]
Nuclear dependence of $J/\psi$ production

$J/\psi$ production in p A collisions

- Precise measurements
  - E866/NuSea at FNAL ($\sqrt{s} = 40$ GeV)
  - PHENIX at RHIC ($\sqrt{s} = 200$ GeV)
Nuclear dependence of $J/\psi$ production

- Significant $J/\psi$ suppression observed
- Much larger than in the DY channel

[E866/NuSea 1999]
Nuclear dependence of $J/\psi$ production

Some explanations

- **Nuclear absorption**
  - could explain mid-rapidity $J/\psi$ and $\psi'$ suppression
  - requires unrealistically large cross sections to explain large $x_F$ data

- **Nuclear PDF effects (or saturation)**
  - disfavoured by lack of $x_2$ scaling

- **Intrinsic charm**
  - $J/\psi$ production from $|uudc\bar{c}\rangle$ soft scattering on nuclei
  - requires high charm content disfavoured by $F_2^c$ data

- **Parton energy loss**
  - successful explanation assuming $-\Delta E \propto E$

[ Brodsky Hoyer 1989 ]

[ Gavin, Milana 1992 ]
Energy loss phenomenology

Gavin-Milana model

- \langle \epsilon \rangle \propto E_i \rightarrow \Delta x_1 \propto x_1 : x_1 \text{ scaling of } J/\psi \text{ suppression}
- Should also affect Drell-Yan nuclear dependence
- Energy loss processes also in the final state

[ Gavin Milana 92 ]
Energy loss phenomenology

Gavin-Milana model

- $\langle \epsilon \rangle \propto E_i \rightarrow \Delta x_1 \propto x_1$ scaling of $J/\psi$ suppression
- Should also affect Drell-Yan nuclear dependence
- Energy loss processes also in the final state

Brodsky-Hoyer bound on energy loss

Assumption: Induced gluon radiation needs to resolve the medium

$$t_f \sim \frac{\omega}{k^2_\perp} \lesssim L \quad \omega \lesssim k^2_\perp L \sim q L^2$$

- Bound independent of the parton energy
- Energy loss cannot be arbitrarily large in a finite medium

Apparently rules out energy loss models as a possible explanation
Revisiting energy loss

(i) For a parton produced in the medium, radiation of gluons with large formation times cancels out in the induced gluon spectrum

\[
\frac{dI}{d\omega}\Bigg|_{\text{ind}} = \frac{dI}{d\omega}\Bigg|_{pA} - \frac{dI}{d\omega}\Bigg|_{pp}
\]

leading to Brodsky-Hoyer bound for DIS, DY, large-\(p_\perp\) jets...

(ii) For a color charge produced nearly collinearly to an initial state parton, interference terms dominate the induced spectrum

- induced radiation dominated by large formation times: no bound!
- energy loss proportional to the parton energy \(\Delta E \sim \alpha_s \langle \Delta q_\perp \rangle M E\)

Qualitative consequences

- Might explain \(J/\psi\) suppression at large \(x_F\) due to the propagation of the color octet \(c\bar{c}\) state in the nucleus
- Should also affect open charm production, not DY nor DIS on nuclei
Summary

- **Parton energy loss**
  - powerful tool to investigate scattering properties of QCD media

- **Energy loss in nuclear matter**
  - DY production as a sensitive probe of quark energy loss
  - current situation needs to be clarified with precise data at lower beam energy (e.g. E906 at FNAL and P-04 at J-PARC)
  - wealth of data in SIDIS consistent with DY and small energy loss

- **New considerations**
  - needs to consider in some cases the associated radiation to a hard process in vacuum/medium instead of “parton energy loss”
  - might qualitatively explain the nuclear dependence of $J/\psi$ (and open charm) production in p A collisions