Collisional Energy Loss of a Fast Parton in a QGP

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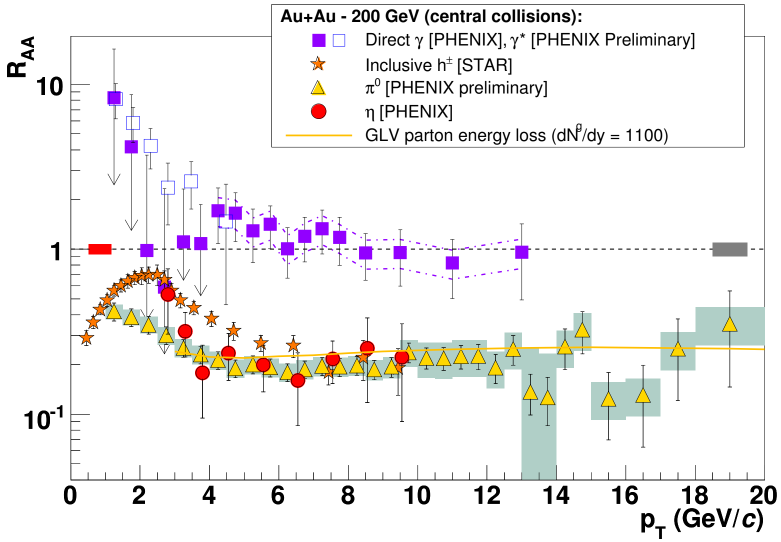
Outline

- Motivation: jet-quenching phenomenology
- Defining dE/dx: 'tagged' or 'untagged'
- Calculating the collisional dE/dx
- Summary

Jet-quenching



$E \gg M, T \Rightarrow$

$\Delta E_{rad} \gg \Delta E_{coll}$

(at least for large L)

$\frac{\text{coll}}{\text{rad}}(L = 5\,\text{fm}) \lesssim 20\%$

Zakharov, 2007

Jet-quenching (Bjorken, 1982)
from parton energy loss
in dense/hot medium:

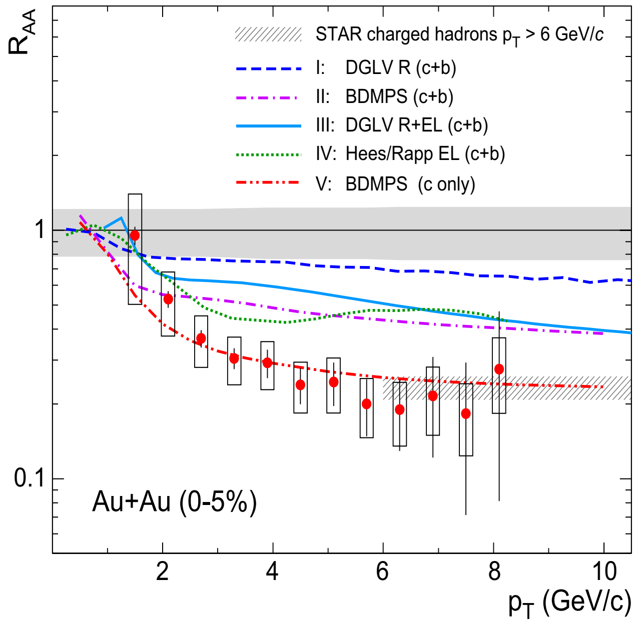
- collisional
- radiative

ΔE_{coll} neglected in *light* hadron quenching

Gyulassy, Levai, Vitev
Salgado, Wiedemann et al

Non-photonic electron data

$e^{\pm}$ from D + B decays: $R_{AA}(Q) \simeq R_{AA}(q,g)$



might be a problem if

$\Delta E_{rad}(Q) \ll \Delta E_{rad}(q,g)$

'dead cone effect'

Dokshitzer & Kharzeev, 2001

$\theta_{rad} < M/p_T$ suppressed

some proposals:

- $\Delta E > \Delta E_{rad}$ for heavy Q?
  $\Rightarrow \Delta E = \Delta E_{rad} + \Delta E_{coll}$
  Wicks et al, 2005

- partonic picture may fail for heavy meson quenching
  $$\tau_{form} \simeq \frac{2z(1-z)E}{k_\perp^2 + (1-z)^2 M^2} < L$$
  Adil & Vitev, 2006

but explaining $R_{AA}(e^{\pm})$ with ΔE_{rad} only is not excluded...

Here: in view of LHC applications

$E_{parton} \to \infty \Rightarrow \tau_{form} > L \Rightarrow$ partonic picture OK

- discuss collisional loss at large E
- is ΔE_{coll} under theoretical control?

Maybe, in the end $\Delta E_{coll}(Q) \ll \Delta E_{rad}(Q)$

Calculating $\Delta E_{coll}(Q, q, g)$ nice theoretical problem

dE/dx: 'tagged' or 'untagged' ?

- Case 1: tagged particle

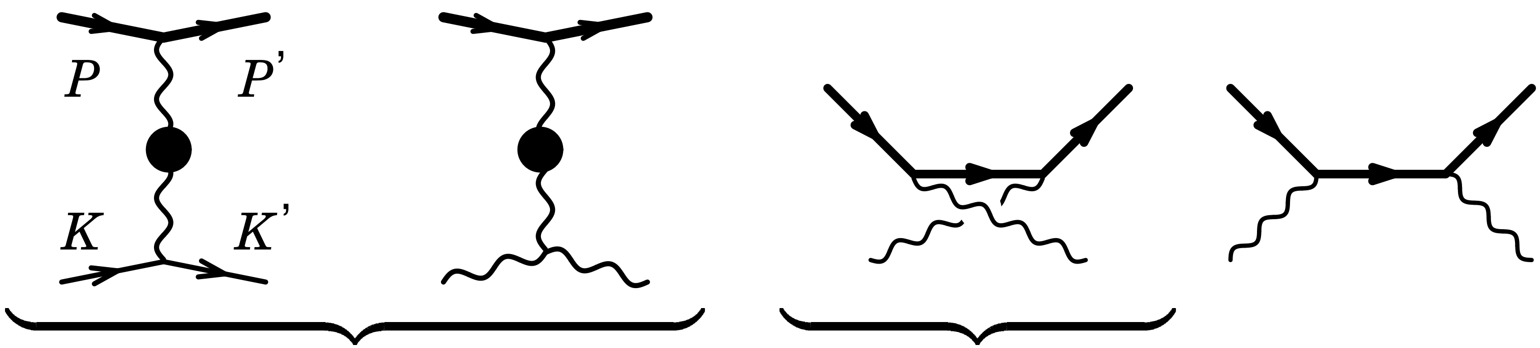
Consider *mean* energy loss of **test particle** ($M \gg T$) in (Spa) thermal bath, due to scattering off target particles

$$\frac{dE_i}{dx} = \frac{v^{-1}}{2E} \int_k \frac{n_i(k)}{2k} \int_{k'} \frac{1 \pm n_i(k')}{2k'} \int_{p'} \frac{(2\pi)^4}{2E'} \delta^{(4)}(P+K-P'-K') \, |\mathcal{M}_i|^2 \, \omega$$

$$\omega = P_0 - P_0' \equiv E - E'$$

$P_0' \ll P_0 \Leftrightarrow \omega \simeq \omega_{\max}$ ('Full stopping') contributes

$\mathcal{M}_i$:



soft divergence   *collinear* div.

dE/dx: ’tagged’ or ’untagged’ ?

- Case 2: untagged ’jet’

no heavy-quark tagged jet $\Rightarrow$ impossible to know if detected jet arises from final quark or final gluon

Define dE/dx with respect to LEADING parton

$$\omega < E/2 \Rightarrow \text{loss} = P_0 - P_0' \equiv \omega$$

$$\omega > E/2 \Rightarrow \text{loss} = P_0 - K_0' = E - \omega < E/2$$

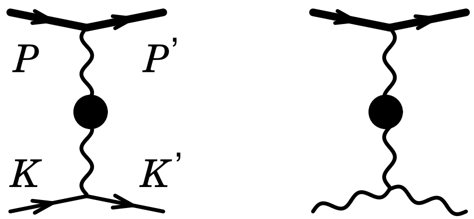
No ’full stopping’ by definition

$$\omega \text{ large} \Leftrightarrow |t| \text{ large} \Rightarrow dE/dx \sim \langle E - \omega \rangle_T \sim \langle u \rangle_T$$

Calculating dE/dx

LIGHT PARTON (UNTAGGED), FIXED α_s

Coulomb logarithm from t-channel exchange



$$\frac{dE}{dx} \sim \alpha_s^2 T^2 \int_{m_D^2}^{t_{\max}/2} \frac{dt}{t^2} \cdot t$$

$$t_{\max} = s \propto ET \Rightarrow \frac{dE}{dx} \sim \alpha_s(?)^2 T^2 \log\left(\frac{ET}{m_D^2}\right)$$

Bjorken, 1982

LIGHT PARTON, RUNNING α_s

$$\frac{dE}{dx} \sim T^2 \int_{m_D^2}^{t_{max}/2} \frac{dt}{t} \alpha_s(t)^2 \sim \alpha_s(m_D^2)\alpha_s(ET)\, T^2 \log\left(\frac{ET}{m_D^2}\right)$$

Peshier, 2006

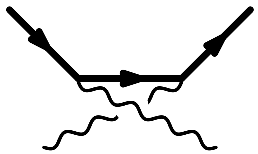
Contrary to common belief

$dE/dx \propto \alpha_s(m_D^2)\alpha_s(ET)$ instead of $\alpha_s(?)^2$

$dE/dx \to$ cst when $E \to \infty$

TAGGED HEAVY QUARK

Additional logarithm from Compton scattering

u-channel  collinear div. when $M \to 0$

$$\left.\frac{dE}{dx}\right)_C \sim \int_k \frac{n_B(k)}{2k} \int dt\, t\, \frac{d\sigma_C}{dt} \sim \alpha_s^2 T^2 \int_{M^2}^{s} du\, t\, \frac{1}{u\, s}$$

- collinear $\log\left(\frac{s}{M^2}\right) \sim \log\left(\frac{ET}{M^2}\right)$ from broad interval

$$M^2 \ll |u| \ll s \sim ET$$

- $s + t + u = 2M^2 \Rightarrow t \simeq -s$ "full stopping"
  - must be included in dE/dx for tagged particle
  - previously overlooked (Thoma & Gyulassy, 1991) (Braaten & Thoma, 1991)
  - see: Compton backscattering of laser beams

- Compton scattering is rare but efficient

$$\left.\frac{dE}{dx}\right)_C \sim \frac{\langle\omega\rangle}{\lambda_C} \sim \frac{E}{(E/\alpha_s^2 T^2)} \sim \alpha_s^2 T^2$$

- no collinear log in untagged case

$$\omega \sim \omega_{\rm max} \Rightarrow \text{loss} = P_0 - K_0' \propto u$$

$\Rightarrow$ Bjorken's t-channel leading log result is correct but specific to untagged parton

beyond leading log (tagged case)

- to determine the constant beyond leading log:
  - Subtract leading logs $\int_{m_D^2}^{ET} \frac{dt}{t}$ and $\int_{M^2}^{ET} \frac{du}{u}$
  - Remaining integrals are dominated by
    - $|t| \sim m_D^2 \Rightarrow$ use HTL gluon propagator for t-channel exchange
    - $|t| \sim s \sim ET \Rightarrow$ use exact kinematics
  - Running does not affect the 'constant'

first attempts to go beyond leading log were misleading
('Compton log' was missing)

dE/dx of heavy tagged particle

S. P. & A. Peshier, PRD 77 (2008) 014015
and 0802.4364[hep-ph]

QED $$\frac{dE}{dx} = \frac{e^4T^2}{48\pi}\left[\ln\frac{ET}{m_D^2} + \frac{1}{2}\ln\frac{ET}{M^2} + c\right]$$

QCD, fixed α_s

$$\frac{dE}{dx} = \frac{4\pi\alpha_s^2T^2}{3}\left[\left(1+\frac{n_f}{6}\right)\ln\frac{ET}{m_D^2} + \frac{2}{9}\ln\frac{ET}{M^2} + c(n_f)\right]$$

QCD, running α_s

$$\frac{dE}{dx} \Big/ \frac{4\pi T^2}{3}\alpha_s(m_D^2)\alpha_s(ET) =$$

$$\underbrace{\left(1+\frac{n_f}{6}\right)\ln\frac{ET}{m_D^2}}_{3.31} + \underbrace{\frac{2}{9}\frac{\alpha_s(M^2)}{\alpha_s(m_D^2)}\ln\frac{ET}{M^2}}_{0.12} + \underbrace{c(n_f)}_{0.49} + \underbrace{\mathcal{O}\left(\alpha_s\ln\frac{ET}{m_D^2}\right)}_{1.29}$$

(For $T = 0.2$, $M = 1.3$, $E = 20$ GeV, $n_f = 3$

$\Rightarrow m_D \simeq 0.7$ GeV and $dE/dx \simeq 0.6$ GeV/fm)

Summary

meaningful dE/dx requires

- defining correctly the observable (tagged/untagged)
- identifying all leading logs before going beyond...
- implementing running of α_s
  $\Rightarrow$ predictability and theoretical uncertainty

RHIC conditions: t-channel log dominates

but LARGE theoretical uncertainty

RIEN N'EST ETABLI

(nothing is established)

$T = 250$ MeV charm quark $M = 1.3$ GeV