Parton Collisional Energy Loss in a Quark Gluon Plasma

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Outline

- CONTEXT
  - jet-quenching phenomenology
  - Warning: heavy quark may suffer *gluon* energy loss
- COLLISIONAL LOSS
  - Definition of dE/dx: 'tagged' or 'untagged'
  - Calculating dE/dx
  - Relating dE/dx, m_D^2, and $\hat{q}$
- SUMMARY


CEBE
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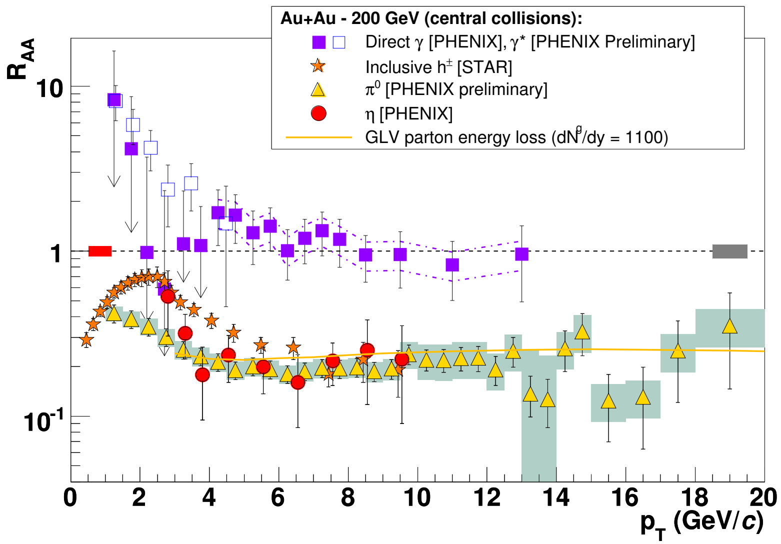
CONTEXT

Jet-quenching

$$R^h_{AA}(p_T) = \frac{1}{N_{\rm coll}} \times \frac{dN^h_{\rm AA}}{dp_T} \Big/ \frac{dN^h_{pp}}{dp_T}$$



$E \gg M, T \Rightarrow$

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

(at least for large L)

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

Zakharov, 2007

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

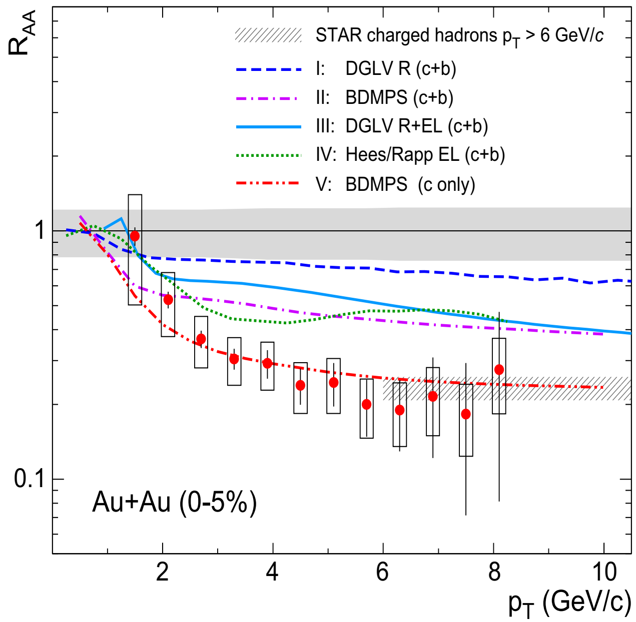
- collisional
- radiative

ΔE_{coll} neglected in *light* hadron quenching

Gyulassy, Levai, Vitev
Salgado, Wiedemann et al

Non-photonic electron data

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



problem:

$\mathrm{B}/(\mathrm{B}+\mathrm{D}) \simeq 0.5$

in pp @ $\sqrt{s} = 200$ GeV

'dead cone effect'

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

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

Dokshitzer & Kharzeev, 2001

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

Here, in view of LHC applications:

$$E_{parton} \simeq p_T \to \infty \Rightarrow \tau_{form} > L$$

$\Rightarrow$ partonic picture OK

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

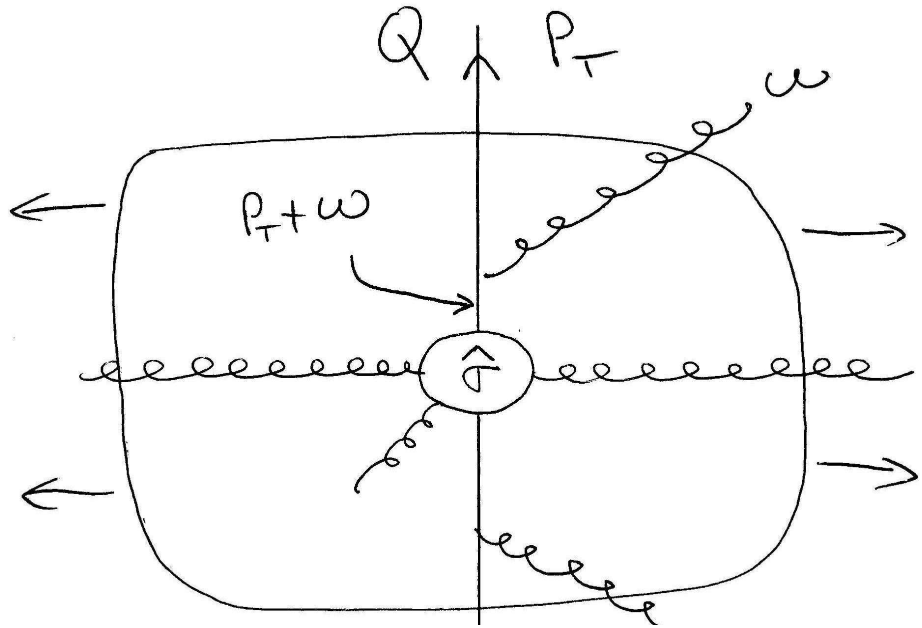
Calculating $\Delta E_{coll}(Q, q, g)$ nice theoretical problem:

- no model-dependence
- PQCD at finite T

Warning

Under some conditions: $\Delta E_Q \propto N_c$

with T. Sami and D. d'Enterria

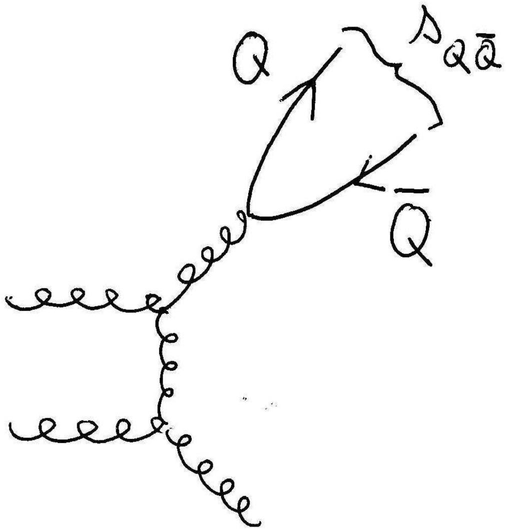


$$\frac{d\sigma_Q^{\text{med}}}{dp_T^2} = \int d\omega P(\omega) \frac{d\sigma_Q^{\text{vac}}}{dp_T^2}(p_T + \omega)$$

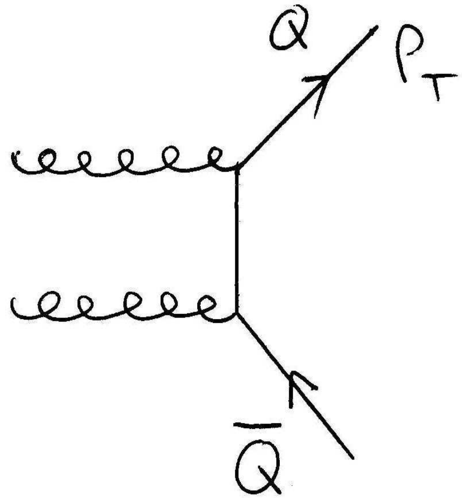
$$\langle \omega \rangle = \int d\omega P(\omega)\omega = \Delta E_Q(p_T) \propto C_F$$

When $p_T \gg M$:

Halzen & Hoyer, 1984



competes
with

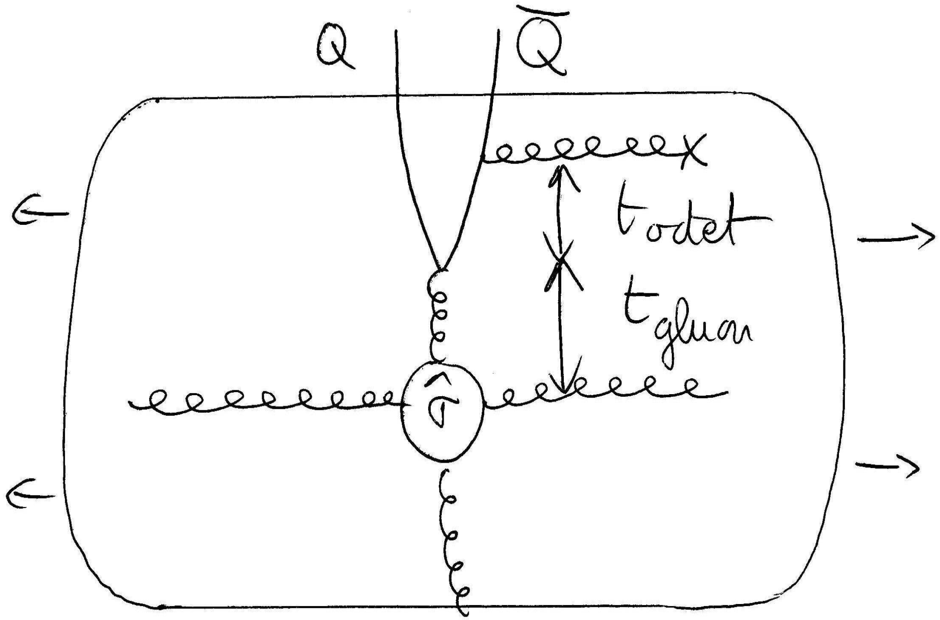


In kinematical region $4M^2 \lesssim k^2 = s_{Q\bar{Q}} \ll 4p_T^2$:

$$\sigma(\mathrm{gg} \to Q(p_T)\bar{Q}\mathrm{g}) \simeq \int dx\, \sigma(\mathrm{gg} \to \mathrm{g}(\tfrac{p_T}{x})\mathrm{g}) \int \frac{ds_{Q\bar{Q}}}{s_{Q\bar{Q}}} \frac{\alpha_s}{2\pi} P_{\mathrm{g}\to Q\bar{Q}}(x)$$

$$\Rightarrow \frac{\mathrm{NLO}}{\mathrm{LO}} \sim \frac{\alpha_s}{\pi} \ln \frac{p_T}{M}$$

In fragmentation process, Q is produced in compact ($r_{Q\bar{Q}} \sim 1/M$) color octet state



$q \sim m_D \Rightarrow Q\bar{Q} =$ pointlike octet as long as $r_{Q\bar{Q}} \lesssim 1/m_D$

$$t_{\rm prod} \sim t_{\rm gluon} + t_{\rm compact} \sim \frac{p_T}{M^2} + \frac{1}{m_D}\frac{p_T}{M} \sim \frac{1}{m_D}\frac{p_T}{M}$$

Numerical estimate for $t_{\rm prod}$

$$m_D \simeq 1\,\text{GeV} \Rightarrow 1/m_D \simeq 0.2\,\text{fm}$$

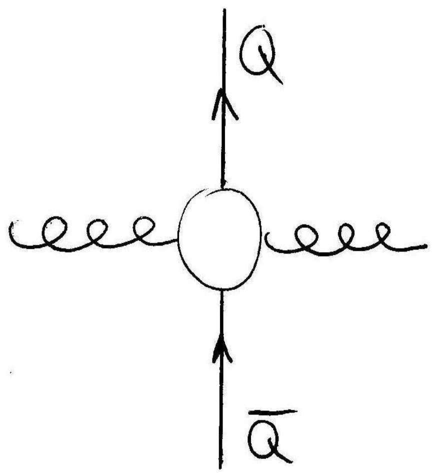
	$p_T = 15\,\text{GeV}$	$p_T = 150\,\text{GeV}$
$M_c = 1.5\,\text{GeV}$	$2\,\text{fm}$	$20\,\text{fm}$
$M_b = 5\,\text{GeV}$	$0.6\,\text{fm}$	$6\,\text{fm}$

LHC: $t_{\rm prod} > L \Rightarrow Q\bar{Q}$ loses energy as a gluon

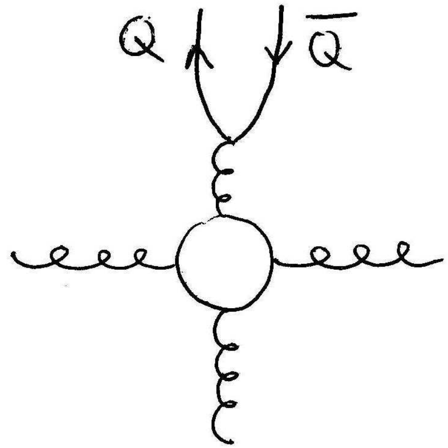
In symmetric configuration

$$"\Delta E_Q(p_T)" \simeq \frac{1}{2}\Delta E_{\rm g}(2p_T) \propto N_c$$

$$p_T \gg M$$



$$\Delta E_Q(p_T) \propto C_F$$



$$\Delta E_Q(p_T) \propto N_c$$

Heavy quark energy loss can depend on underlying hard production process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COLLISIONAL LOSS

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

- Case 1: tagged particle

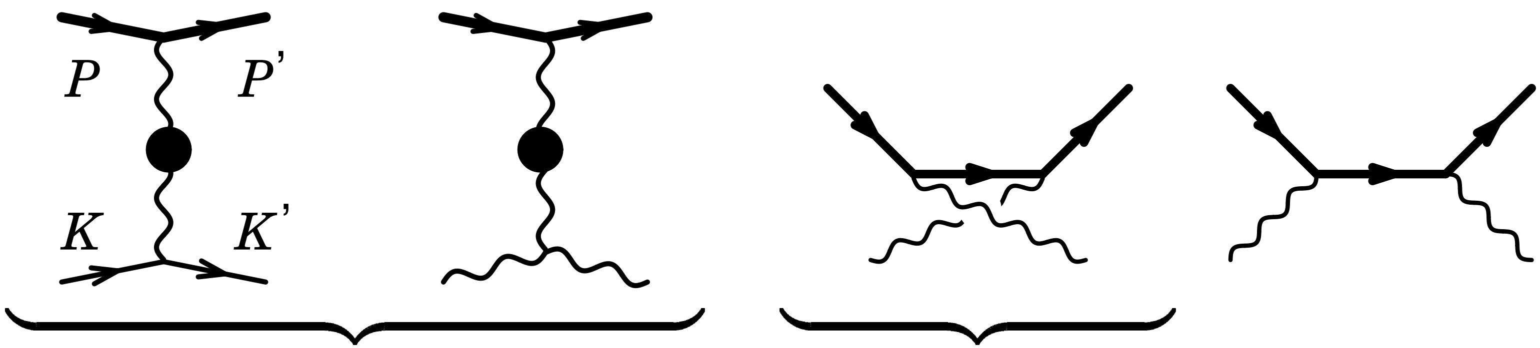
Consider *mean* energy loss of **test particle** $(M \gg T)$ due to scattering off thermal particles

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

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

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

$\mathcal{M}_i$:



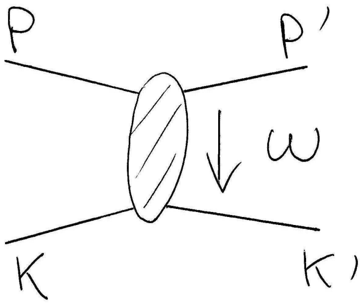
soft divergence

collinear div.

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



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

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

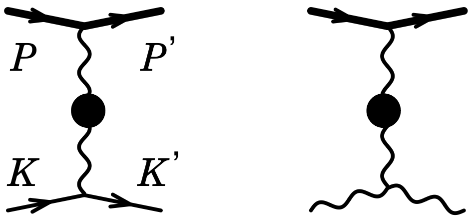
No 'full stopping' by definition

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

Calculating dE/dx

LIGHT PARTON (UNTAGGED), FIXED α_s

Coulomb logarithm from t-channel exchange



$$-t/2 = k\,\omega - \vec{k}\,\vec{q} \Rightarrow \quad \frac{dE}{dx} \sim \alpha_s^2 T^2 \int_{m_D^2}^{t_{\max}/2} \frac{dt}{t^2} \cdot t$$

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

Bjorken, 1982

LIGHT PARTON, RUNNING α_s

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

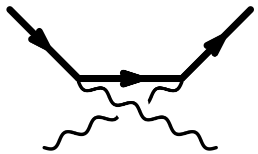
Peshier, 2006

Contrary to common belief

- $dE/dx \propto \alpha_s(m_D^2)\alpha_s(ET)$ instead of $\alpha_s(?)^2$
- $dE/dx \rightarrow$ cst when $E \rightarrow \infty$

TAGGED HEAVY QUARK

Additional logarithm from Compton scattering

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

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

- 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

$$\frac{dE}{dx}\Big|_{Compton} \sim \frac{\langle\omega\rangle}{\lambda_{Compton}} \sim \frac{E}{(E/\alpha_s^2 T^2)} \sim \alpha_s^2 T^2$$

- no Compton collinear log in untagged case

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

$$\Rightarrow \frac{dE}{dx}\Big|_{Compton} \sim \alpha_s^2 T^2 \int_{M^2}^{s} du\, u\, \frac{1}{u\, s}$$

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

- Importance of defining the observable!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beyond leading log (tagged case)

- 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

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

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

$$T = 0.2,\ M = 1.3,\ E = 20\,\mathrm{GeV},\ n_f = 3$$

$$\Rightarrow m_D \simeq 0.7\,\mathrm{GeV}\ \text{and}\ \ dE/dx \simeq 0.6\,\mathrm{GeV/fm}$$

RHIC conditions: t-channel log dominates
but LARGE theoretical uncertainty

Keeping only t-channel log, and to log accuracy:

$$\frac{dE_Q}{dx} \simeq \frac{dE_q}{dx} \simeq \frac{1}{3} \underbrace{4\pi T^2 \left(1 + \frac{n_f}{6}\right) \alpha_s(m_D^2)}_{m_D^2} \alpha_s(ET) \ln \frac{ET}{m_D^2}$$

In this approximation, dE/dx is simply related to

- the Debye mass $m_D^2 \propto \alpha_s(m_D^2) T^2$
- the parameter $\hat{q}$

- Debye mass

from A. Peshier, 2006

pole of long. gluon propagator $\frac{1}{q_0^2 - q^2 - \Pi(q_0, q)}$ at $q_0 = 0$

$$t \equiv q_0^2 - q^2 = -q^2 = \Pi(0, q) = \alpha \Pi_{\rm vac}(t) + \alpha \Pi_{\rm med}(0, q)$$

Vacuum part is related to running coupling

$$\frac{\alpha}{t - \alpha \Pi_{\rm vac}(t)} \equiv \frac{\alpha(t)}{t}$$

$$\Rightarrow \frac{t - \alpha \Pi_{\rm vac}(t)}{\alpha} = \frac{t}{\alpha(t)} = \Pi_{\rm med}(0, q)$$

In HTL approximation:

$$\frac{m_D^2}{\alpha_s(m_D^2)} = 4\pi \left(1 + \frac{n_f}{6}\right) T^2 \Rightarrow \frac{dE_q}{dx} \simeq \frac{1}{3}\, m_D^2\, \alpha_s(ET) \ln \frac{ET}{m_D^2}$$

$$\frac{dE_q}{dx} \leq \frac{m_D^2}{12\pi\beta_0} \simeq 1.0\,\mathrm{GeV/fm} \quad (T = 0.2\,\mathrm{GeV}, n_f = 3)$$

- transport coefficient $\hat{q} = \rho \int \frac{d\sigma}{dq_\perp^2} q_\perp^2 \, dq_\perp^2$

$$\Delta E_{rad} \sim \alpha_s \hat{q} L^2 \qquad (L < L_{\rm cr} = \sqrt{E/\hat{q}})$$
$$\Delta E_{rad} \sim \alpha_s L \sqrt{\hat{q} E} \qquad (L > L_{\rm cr})$$

$$\hat{q} = \frac{1}{\lambda\sigma} \int \frac{d\sigma}{dt}(-t)dt = \frac{\langle -t \rangle}{\lambda} \quad \text{vs} \quad \left.\frac{dE}{dx}\right|_{coll} = \frac{\langle \omega \rangle}{\lambda}$$

To leading log, $\hat{q}$ calculated as dE/dx by replacing

$$\omega \simeq -t/(2k) \longrightarrow -t$$

$$\Rightarrow \hat{q} = cst. \times T \left.\frac{dE}{dx}\right|_{coll} \qquad cst. = \frac{6\zeta(3)}{\pi^2} \frac{4+n_f}{1+n_f/6} \simeq 3.4$$

At $T = 0.2\,\mathrm{GeV}$:

$$\hat{q}(E = 20\,\mathrm{GeV}) \simeq 0.35\,\mathrm{GeV}^2/\mathrm{fm}$$
$$\hat{q}(E \to \infty) \simeq 0.7\,\mathrm{GeV}^2/\mathrm{fm}$$


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SUMMARY

- data on jet-quenching not fully understood
- heavy quark energy loss may depend on underlying hard production process
- 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
- basic quantities dE/dx, m_D^2, $\hat{q}$ are closely related

RIEN N'EST ETABLI

(nothing is established)