Loss of energy loss and quenching of self-quenching

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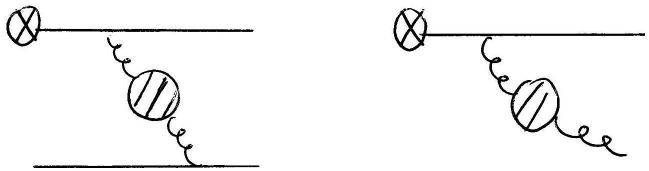
Outline

- Motivations
- Retardation effect for ΔE_{coll} and theoretical model

$$\Delta E_{coll} = \quad \Delta E_1 \quad + \quad \Delta E_2$$



- Summary
- Domain of validity
- Implications on jet-quenching phenomenology?

[S. P., P.-B. Gossiaux, T. Gousset, hep-ph/0509185]

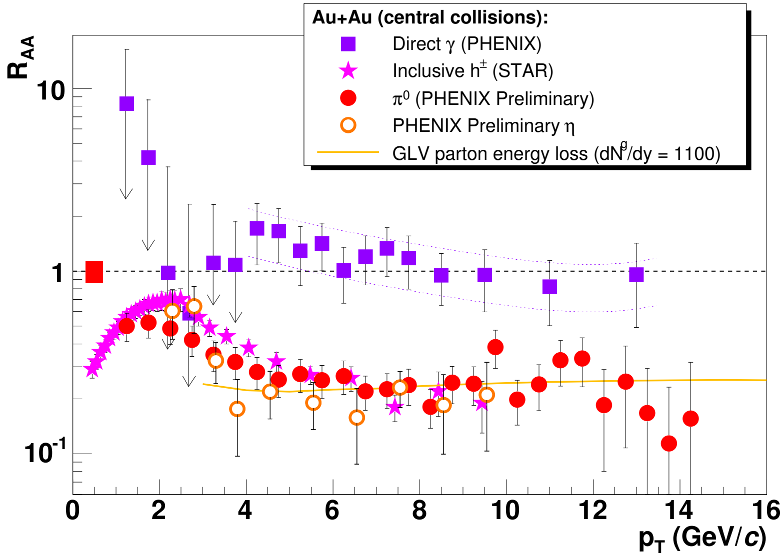
Special thanks to Joerg, Dominique and Yuri

Motivations

Jet-quenching in AA collisions as a possible QGP signal

[Bjorken, 1982]

Effect observed at RHIC



D. d'Enterria, nucl-ex/0504001

consistent with parton energy loss models

Gyulassy, Levai, Vitev

Salgado, Wiedemann

Physics of jet-quenching not fully understood

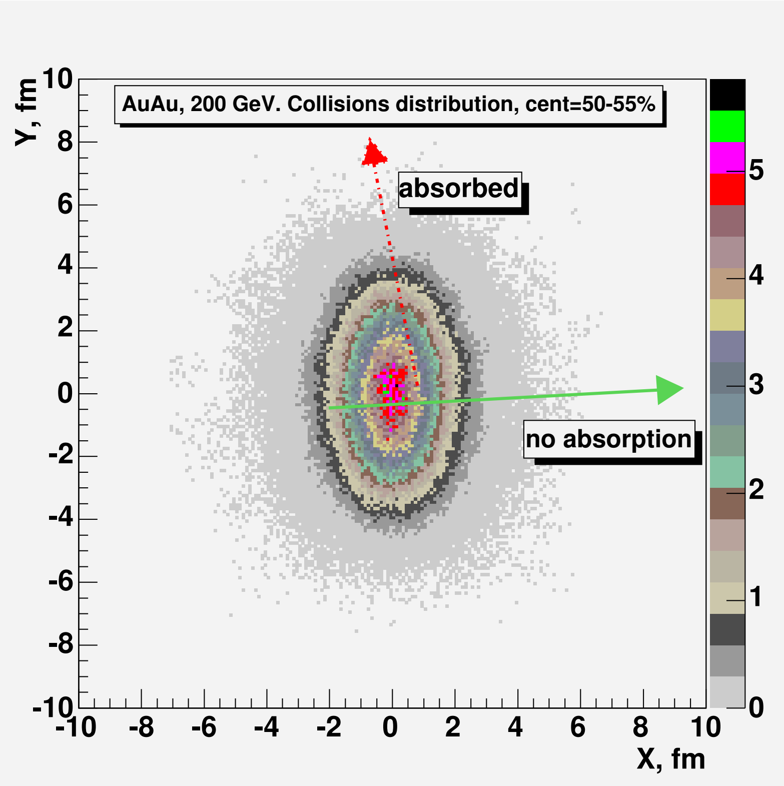
- nuclear attenuation due to parton absorption provided

$$t_{hadr} = \frac{2z(1-z)E}{k_\perp^2} \gg L$$

Leading hadron production $\Rightarrow z \to 1 \Rightarrow t_{hadr} \lesssim L \Rightarrow$ "prehadron" absorption can play a role

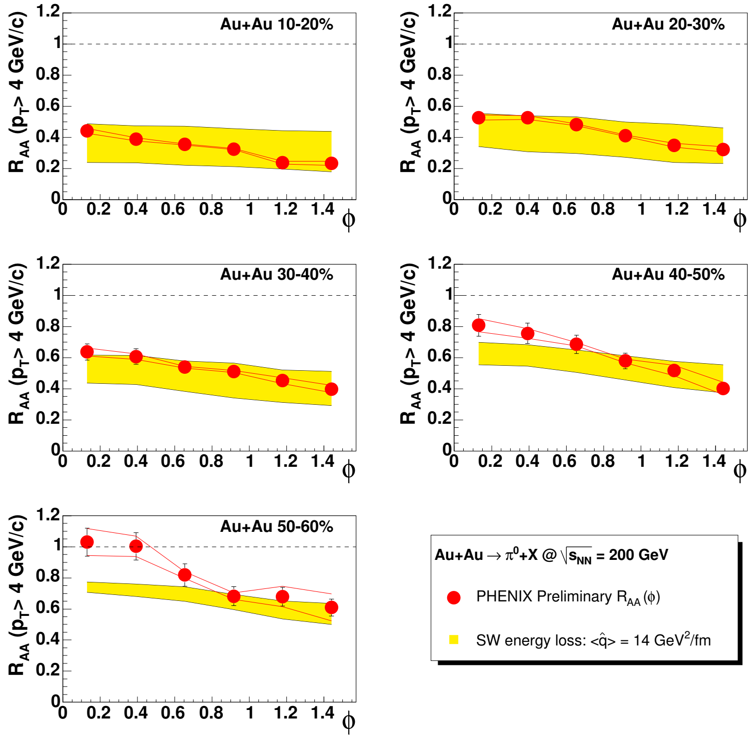
[Kopeliovich]

- some unexplained features
baryon/meson suppression, heavy/light quark suppression, path-length dependence [d'Enterria]



Pantuev, hep-ph/0506095

$\Rightarrow$



d'Enterria, nucl-ex/0504001

$\Rightarrow \Delta E(\text{parton}) \simeq 0$ for $L \leq 2\text{fm}$ [Pantuev]

retardation effect?

Retardation effect

delay of parton energy loss?

$\rightarrow$ consider collisional energy loss

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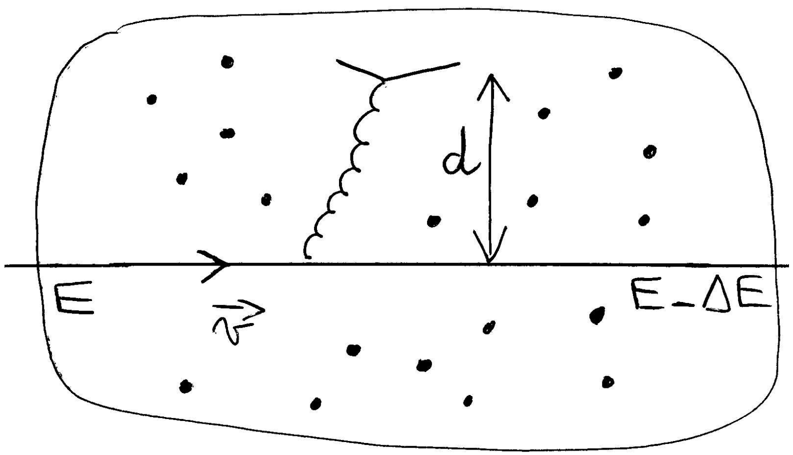
- ΔE_{coll} for a parton produced at $t = -\infty$



$$d \lesssim \frac{1}{\mu}$$

(Debye screening length)

$$\vec{\mathcal{E}}^a(t, \vec{x} = \vec{v}t) = \int \frac{d^4k}{(2\pi)^4}\, e^{-i(\omega - \vec{k}.\vec{v})t} \cdot \frac{4\pi}{i\omega} \left[\frac{\vec{j}_L^{\,a}}{\epsilon_L} + \frac{\vec{j}_T^{\,a}}{\epsilon_T - \vec{k}^2/\omega^2} \right]_{\rm ind}$$

- abelian approximation
- causality $\Rightarrow$ retarded prescription $\omega \to \omega + i\eta$
- $\epsilon_{L,T}$: QGP dielectric functions $(T \gg \Lambda_{QCD},\, g \ll 1,$ HTL approximation)
- $\vec{j}$: classical current of the parton $(V^\mu = (1, \vec{v}))$
  $j_\infty^{\mu\, a}(x) = q^a V^\mu \delta^3(\vec{x} - \vec{v}\, t) \Rightarrow j_\infty^{\mu\, a}(k) = 2\pi q^a V^\mu \delta(\omega - \vec{k}.\vec{v})$

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$$\Delta E(L) = \vec{v} \cdot \int_0^{L/v} dt\, q^a \vec{\mathcal{E}}^a(t, \vec{x} = \vec{v}t)$$

$$= q^a \vec{v} \int \frac{d^4k}{(2\pi)^4} \int_0^{L/v} dt\, e^{-i(\omega - \vec{k}.\vec{v})t} \cdot \frac{4\pi}{i\omega} \left[\frac{\vec{j}_L^a}{\epsilon_L} + \frac{\vec{j}_T^a}{\epsilon_T - \vec{k}^2/\omega^2} \right]_{\text{ind}}$$

$\Rightarrow \Delta E(L) \propto L \Rightarrow -dE/dx$

Thoma, Gyulassy (1991)
Braaten, Thoma (1991)

$\Delta E(L)$ is real $\to$ originates from

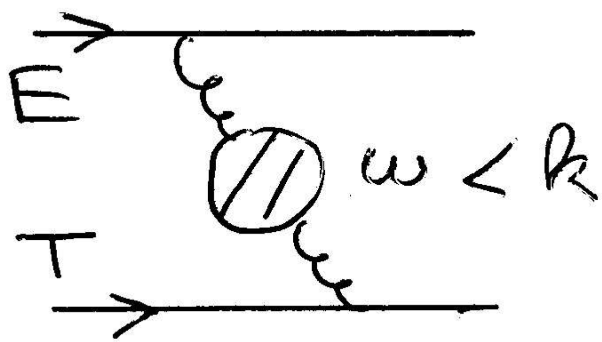
$$\mathrm{Im}\left[\frac{\vec{j}_L}{\epsilon_L} + \frac{\vec{j}_T}{\epsilon_T - \vec{k}^2/\omega^2}\right] \propto \mathrm{Im}\left[\frac{\vec{v}_L}{\epsilon_L} + \frac{\vec{v}_T}{\epsilon_T - \vec{k}^2/\omega^2}\right] \delta(\omega - \vec{k}.\vec{v})$$

In general, two types of contribution:

- $\mathrm{Im}\,\epsilon_{L,T} \neq 0$

QGP: $\mathrm{Im}\,\epsilon \neq 0$ in spacelike region $|\omega| < k$?

Yes: “Landau damping”



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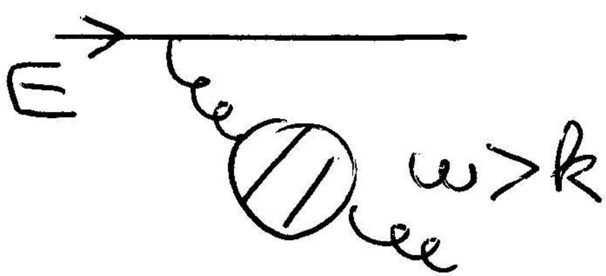
In general, two types of contribution:

- $\mathrm{Im}\,\epsilon_{L,T} = 0$ but transverse propagator $\frac{1}{\epsilon_T \omega^2 - \vec{k}^2}$ singular on real axis

When $\epsilon_T \omega^2 - \vec{k}^2 = 0$ in spacelike region $\omega - \vec{k}.\vec{v} = 0 \Rightarrow$ Cerenkov radiation:



$$\epsilon > 1$$
$$v > \frac{1}{\sqrt{\epsilon}}$$
$$\cos\theta = \frac{1}{v\sqrt{\epsilon}}$$

$\Delta E(L)$ is real $\to$ originates from

$$\mathrm{Im}\left[\frac{\vec{j}_L}{\epsilon_L}+\frac{\vec{j}_T}{\epsilon_T-\vec{k}^2/\omega^2}\right]\propto \mathrm{Im}\left[\frac{\vec{v}_L}{\epsilon_L}+\frac{\vec{v}_T}{\epsilon_T-\vec{k}^2/\omega^2}\right]\delta(\omega-\vec{k}.\vec{v})$$

In general, two types of contribution:

- $\mathrm{Im}\,\epsilon_{L,T}=0$ but transverse propagator $\frac{1}{\epsilon_T\omega^2-\vec{k}^2}$
  singular on real axis

In QGP: $\epsilon_T\omega^2-\vec{k}^2\neq 0$ on real spacelike domain

$\Rightarrow$ no Cerenkov radiation

- ΔE_{coll} for a parton produced at $t = 0$ in the QGP

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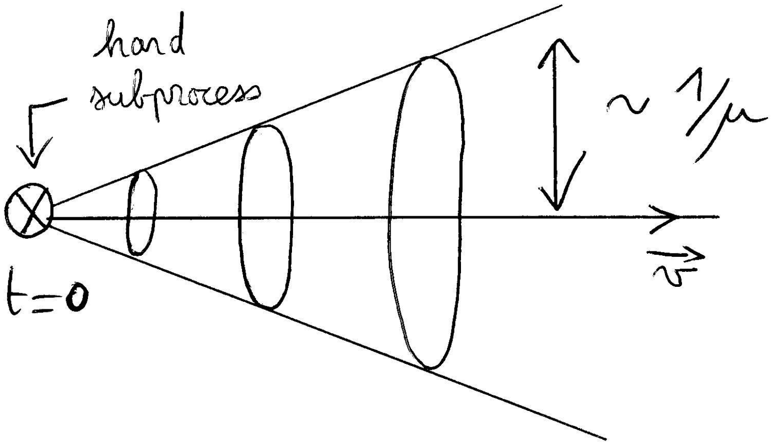
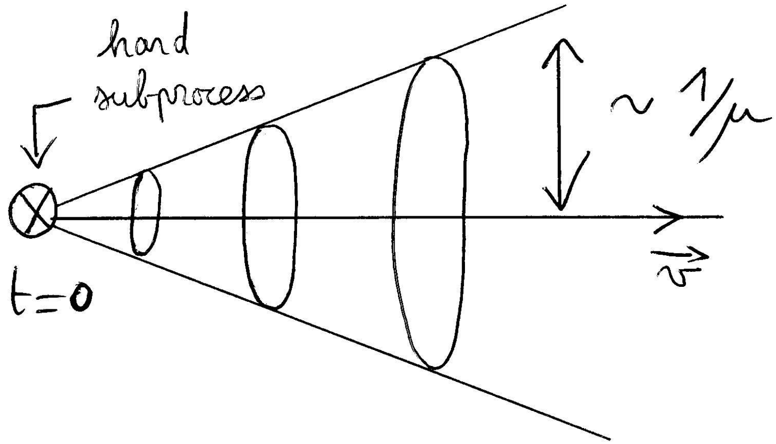
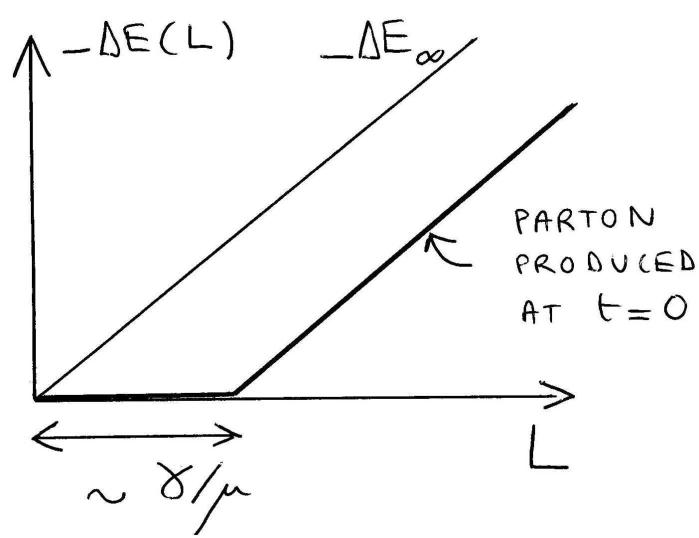


$$\tau_0 \sim \frac{1}{\mu} \Rightarrow \tau \sim \frac{\gamma}{\mu}$$

- ΔE_{coll} for a parton produced at $t = 0$ in the QGP





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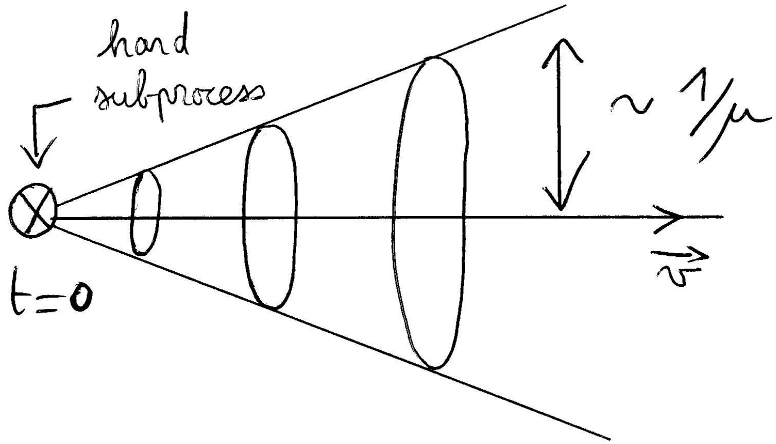
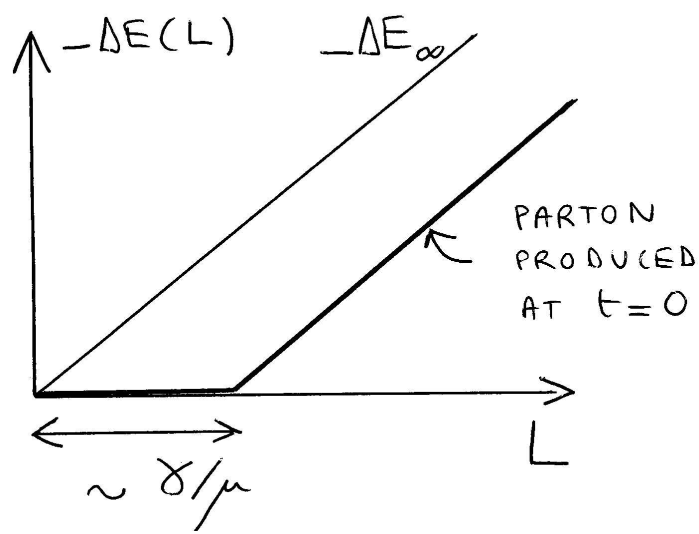
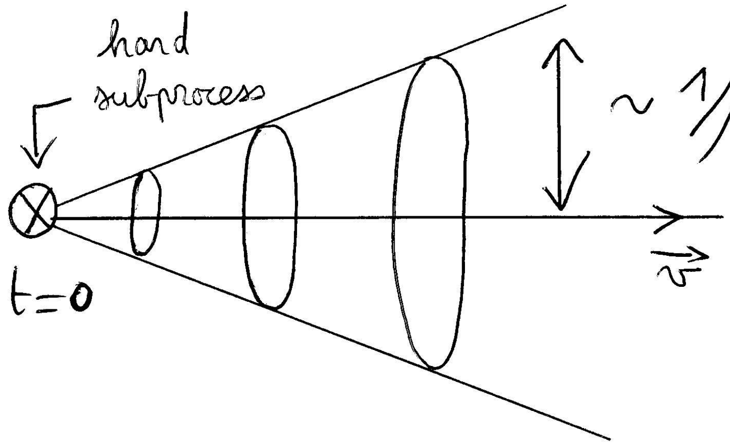
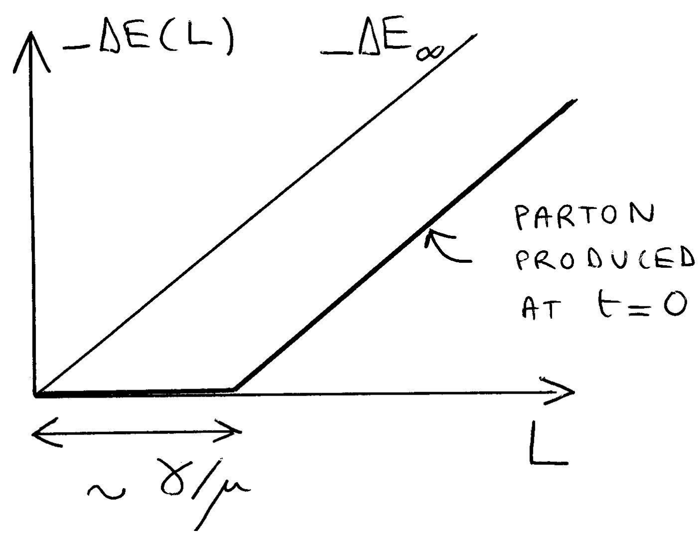




⇒ 'Loss of energy-loss'

- ΔE_{coll} for a parton produced at $t = 0$ in the QGP





$$\delta^3(\vec{x} - \vec{v}\,t) \quad \rightarrow \quad \delta^3(\vec{x} - \vec{v}\,t)\theta(t)$$

$$2\pi\delta(\omega - \vec{k}.\vec{v}) \quad \rightarrow \quad \frac{i}{\omega - \vec{k}.\vec{v} + i\eta}$$

$\Rightarrow$ 'Loss of energy-loss'

$-\Delta E(L)$

$$= \quad q^a \vec{v} \int \frac{d^4k}{(2\pi)^4} \int_0^{L/v} dt\, e^{-i(\omega - \vec{k}.\vec{v})t} \cdot \frac{4\pi}{i\omega} \left[\frac{\vec{j}_L^{\,a}}{\epsilon_L} + \frac{\vec{j}_T^{\,a}}{\epsilon_T - \vec{k}^2/\omega^2} \right]_{\text{ind}}$$

$$= \quad -q^a q^a i v^2 \int \frac{d^3\vec{k}}{4\pi^3} \int_{-\infty}^{\infty} \frac{d\omega}{\omega} \left[k^2 \cos^2\theta\, \Delta_L + \omega^2 \sin^2\theta\, \Delta_T \right]_{\text{ind}}$$

$$\times \left\{ \frac{1 - e^{-i(\omega - \vec{k}.\vec{v})\, L/v}}{i(\omega - \vec{k}.\vec{v})} \left(\frac{i}{\omega - \vec{k}.\vec{v} + i\eta} \right) \right\}$$

instead of $\quad \times \quad \frac{L}{v} \quad 2\pi\delta(\omega - \vec{k}.\vec{v})$

$$\left\{ \quad \right\} \Leftrightarrow 4 \frac{\sin^2\left[(\omega - \vec{k}.\vec{v}) \frac{L}{2v} \right]}{(\omega - \vec{k}.\vec{v})^2} \underset{L \to \infty}{\longrightarrow} \frac{L}{v} 2\pi\delta(\omega - \vec{k}.\vec{v})$$

Two contributions to $-\Delta E(L)$

- from timelike $|\omega| > k$ region ($\mathrm{Im}\,\epsilon_{L,T} = 0$ on real axis but $\Delta_{L,T}$ singular $\to$ QGP plasmon modes)

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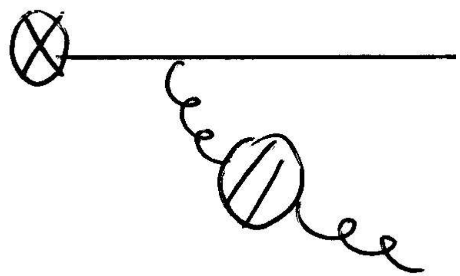

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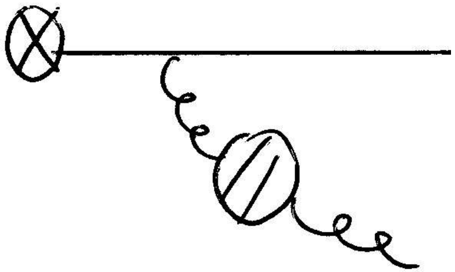

(self-quenching)

$\to$

$$-\Delta E_2(L) \underset{L\to\infty}{\propto} \text{const.}$$

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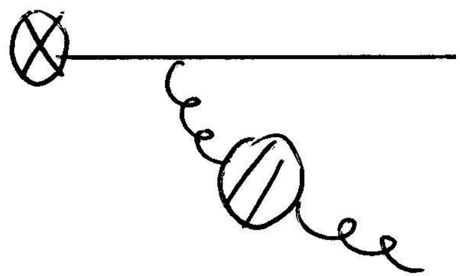

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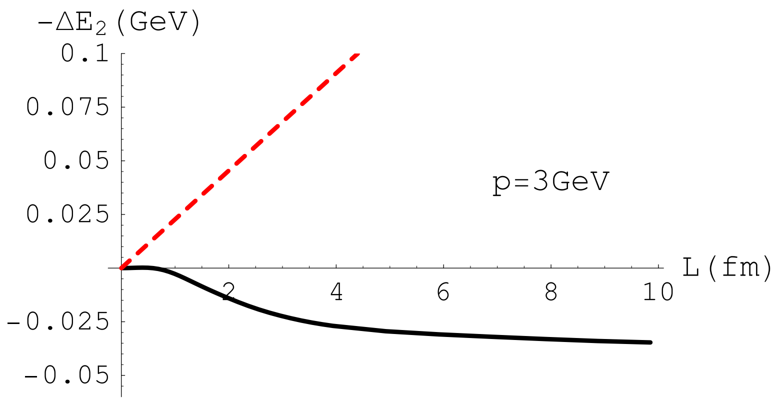

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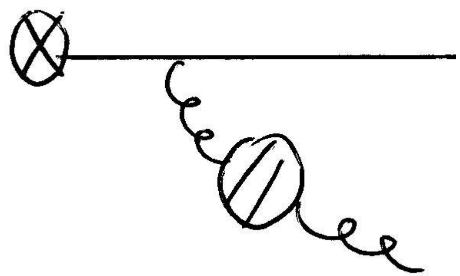

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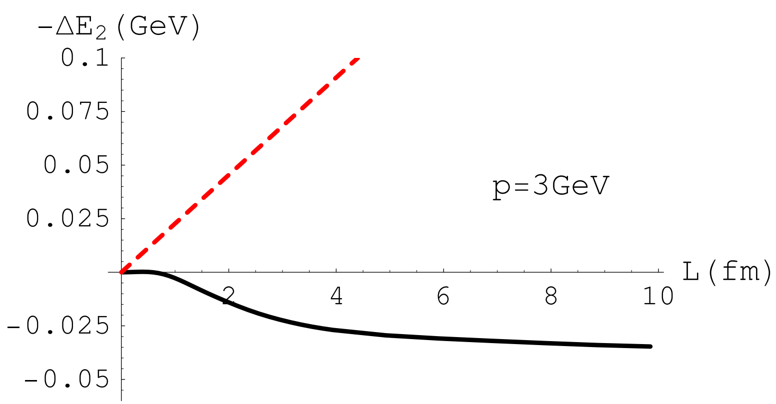

self-quenching is reduced in medium (massive plasmons)

- other contributions ($(\mathrm{Im}\,\epsilon_{L,T} \neq 0$ on real axis $+$ virtual corrections)

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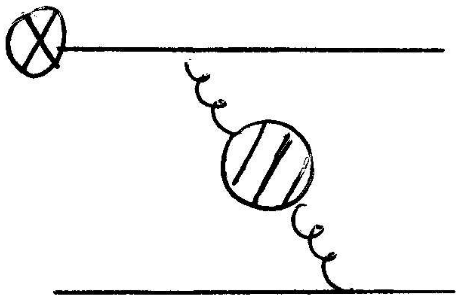

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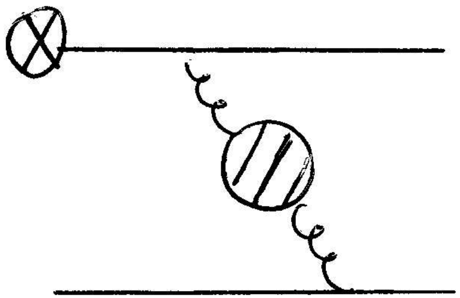

$\rightarrow$

(elastic collisions)

$$-\Delta E_1(L) \underset{L\to\infty}{\propto} L$$

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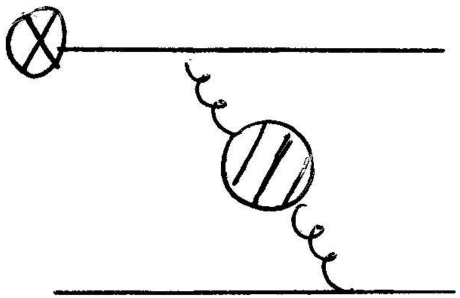

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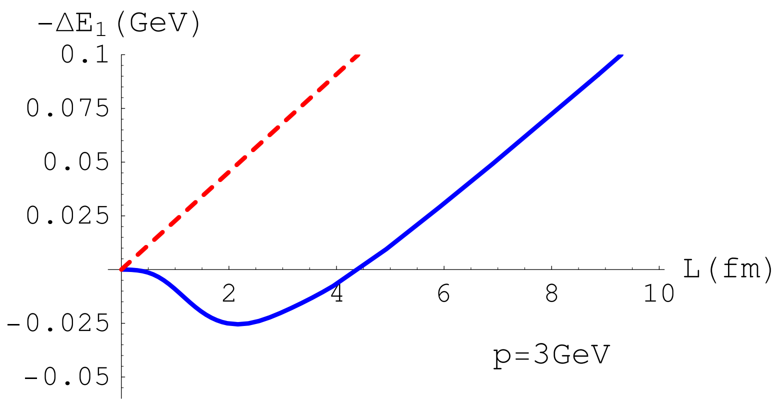

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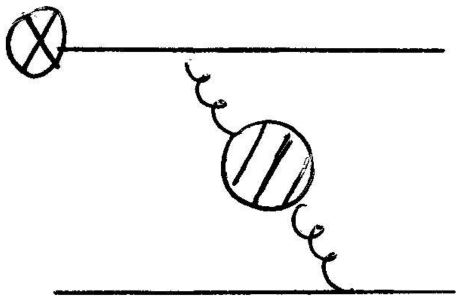

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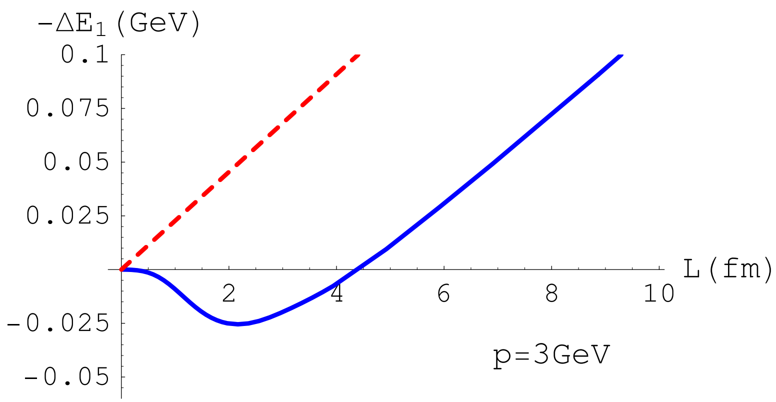

retardation effect

In-medium self-quenching

In-medium self-quenching

- infinite medium

$$\frac{dW}{dk\,d\cos\theta} = \frac{C_R\alpha_s}{2\pi}\left\{\frac{k^2}{\omega_L^2(k)}\frac{z_L(k)\cos^2\theta}{(\cos\theta-\omega_L(k)/(kv))^2} + \frac{z_T(k)\sin^2\theta}{(\cos\theta-\omega_T(k)/(kv))^2}\right\}$$

non-abelian analogue of Ter-Mikayelian effect

Djordjevic, Gyulassy, Phys. Rev. C **68** (2003) 034914

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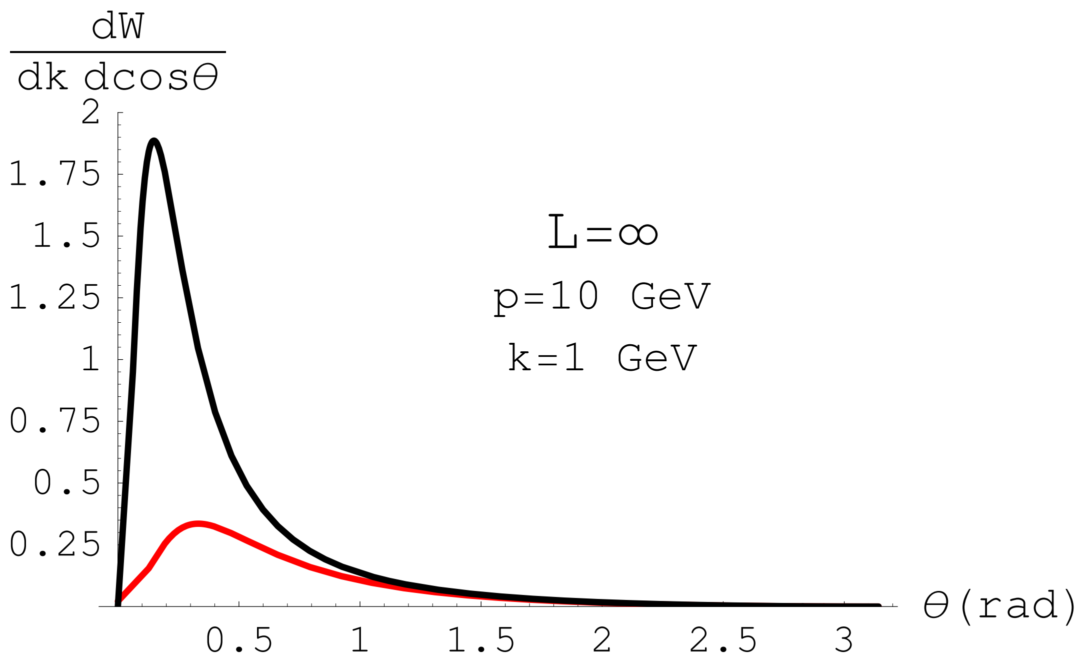

"quenching of self-quenching"

- finite-size medium

$$\frac{dW(L)}{dk\,d\cos\theta} = \frac{C_R\alpha_s}{\pi}\left\{ z_L(k)\frac{k^2}{\omega_L^2(k)}\cos^2\theta\,\frac{\sin^2((\omega_L(k)-kv\cos\theta)\,L/(2v))}{(\cos\theta-\omega_L(k)/(kv))^2} + z_T(k)\sin^2\theta\,\frac{\sin^2((\omega_T(k)-kv\cos\theta)\,L/(2v))}{(\cos\theta-\omega_T(k)/(kv))^2}\right\}$$

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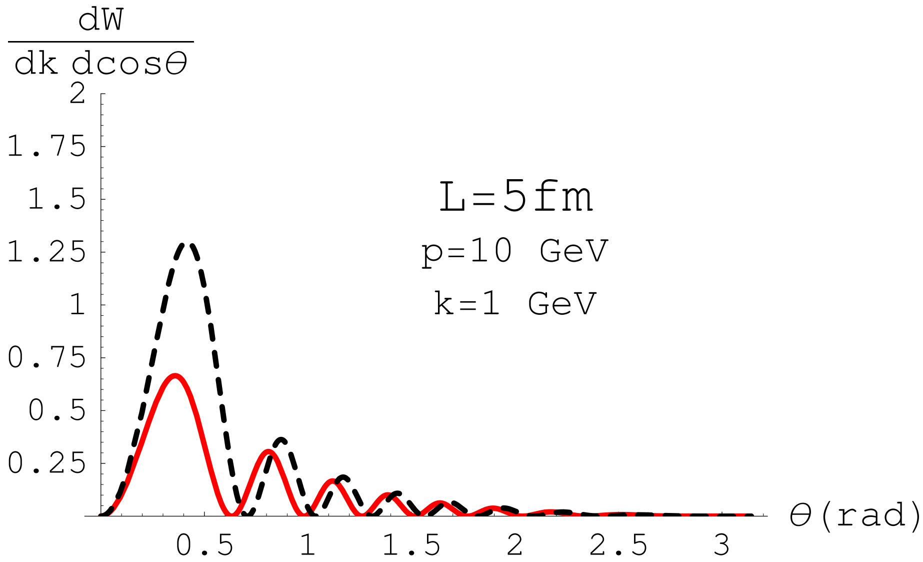
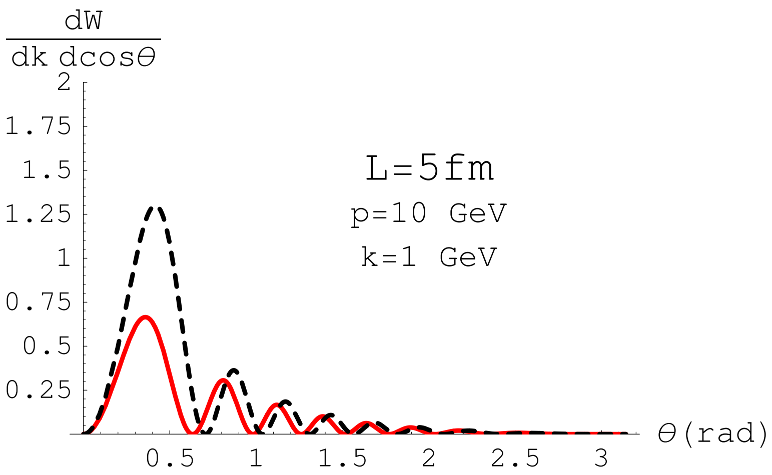


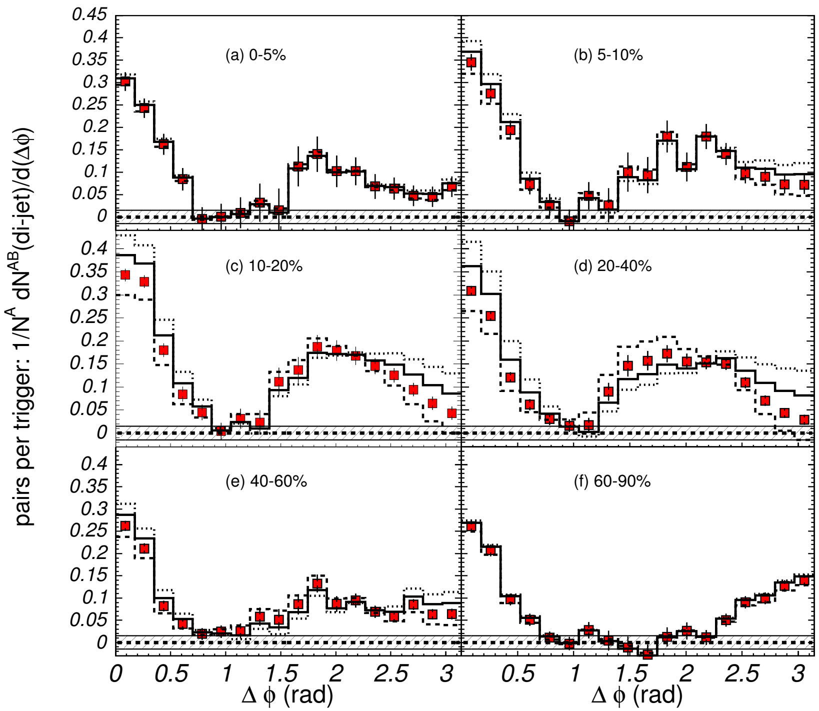
rich angular structure
(not considered before)

Implications on azimuthal correlations?

- finite-size medium



PHENIX, nucl-ex/0507004



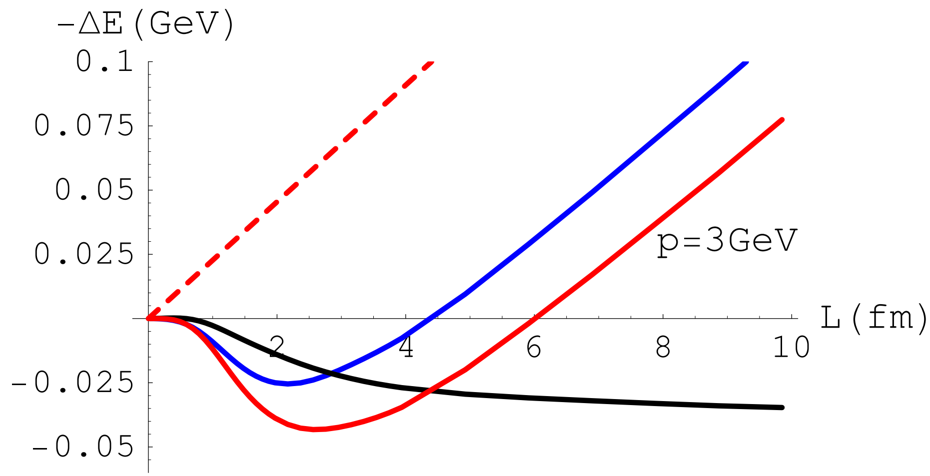
→ needs to include transition radiation

Summary of main results

induced collisional loss for a parton produced at $t = 0$

- elastic collisions
- self-quenching

considered simultaneously



stationary regime is delayed by a large time $\sim 5\text{fm}$

Limitations of the model

- $g \ll 1 \Rightarrow$ (very) high temperature QGP
- $\vec{v} = \vec{cst} \Rightarrow |\Delta E| \ll E$
- classical partonic current $\Rightarrow |\omega|, |\vec{k}| \ll E$ (soft gluon)
- macroscopic description ($\epsilon_{L,T}$) $\Rightarrow |\omega|, |\vec{k}| \ll T$:

$$\text{satisfied if} \qquad \frac{1}{\omega}, \frac{1}{|\vec{k}|} \sim \frac{1}{\mu} \gg \frac{1}{T}$$

typical k in our calculation? $-\Delta E(L) + \Delta E_\infty(L) =$

$$-q^a q^a i v^2 \int \frac{d^3\vec{k}}{4\pi^3} \int_{-\infty}^{\infty} \frac{d\omega}{\omega} \left[k^2 \cos^2\theta \, \Delta_L + \omega^2 \sin^2\theta \, \Delta_T\right]_{\rm ind}$$

$$\times \left\{ 4 \frac{\sin^2\left[(\omega - \vec{k}.\vec{v})\frac{L}{2v}\right]}{(\omega - \vec{k}.\vec{v})^2} - \frac{L}{v} 2\pi \, \delta(\omega - \vec{k}.\vec{v}) \right\}$$

is well-defined (IR and UV safe)

- energy scales at disposal: $1/L$, μ, E
- $L > 1/\mu \Rightarrow k_{typ} \sim \gamma\mu$ $\quad (\gamma = E/M = 1/\sqrt{1-v^2})$

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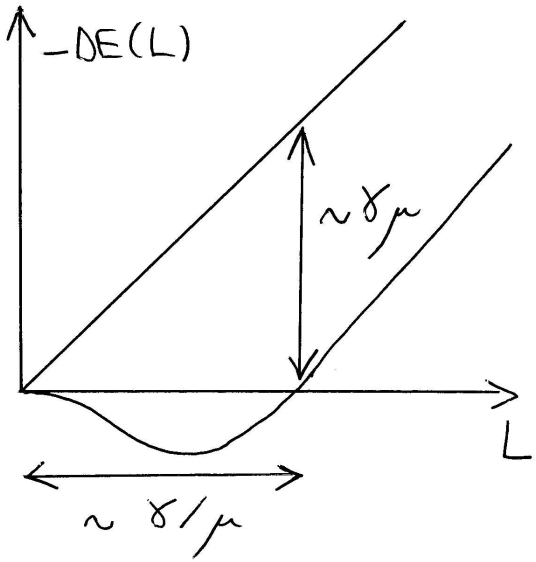


$\rightarrow$

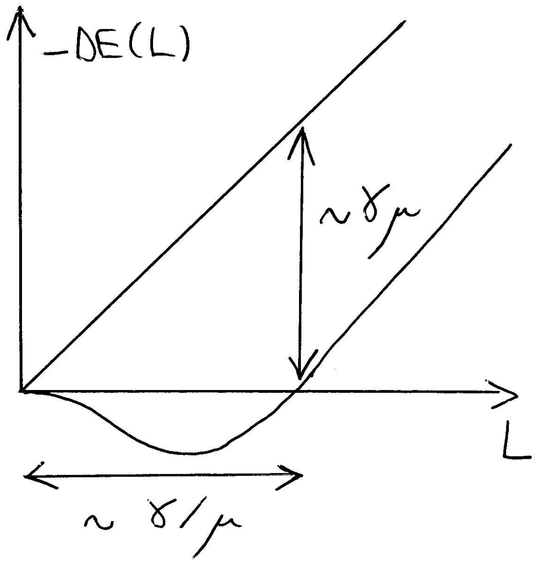
$k_{typ} \ll T \Rightarrow \gamma$ not too big

model consistent for $\gamma \sim 1$

For $\gamma \gg 1$, several problems:

- macroscopic treatment is incorrect
- running of α_s cannot be neglected

- energy scales at disposal: $1/L$, μ, E
- $L > 1/\mu \Rightarrow k_{typ} \sim \gamma\mu$ $\qquad (\gamma = E/M = 1/\sqrt{1-v^2})$



$\rightarrow$

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model consistent for $\gamma \sim 1$

correct treatment for $\gamma \gg 1$ should not modify the qualitative features of retardation effect

(we hope)

Implications on phenomenology?

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- (self-quenching in finite medium $\Rightarrow$ azimuthal distributions)

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Dutt-Mazumder *et al.*, Phys. Rev. D **71** (2005) 094016
Mustafa, Phys. Rev. C **72** (2005) 014905

$\rightarrow$ suggest that $\Delta E_{coll} > \Delta E_{rad}$ for light partons and heavy quarks
$\rightarrow$ based on $\Delta E_{rad} \propto L^2$ but $\Delta E_{coll} \propto L$ at small L

such analyses need to be updated

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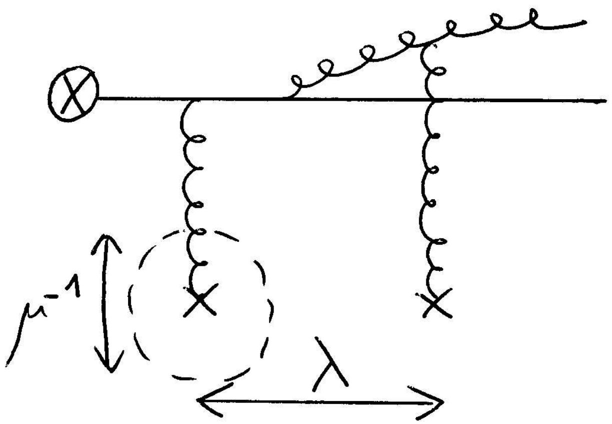

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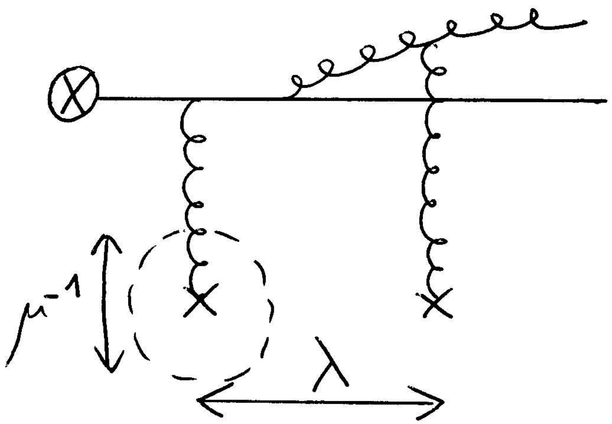

ΔE_{rad} is induced by elastic rescatterings

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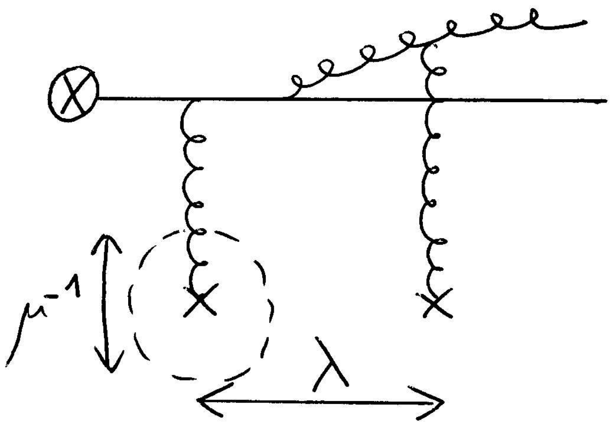

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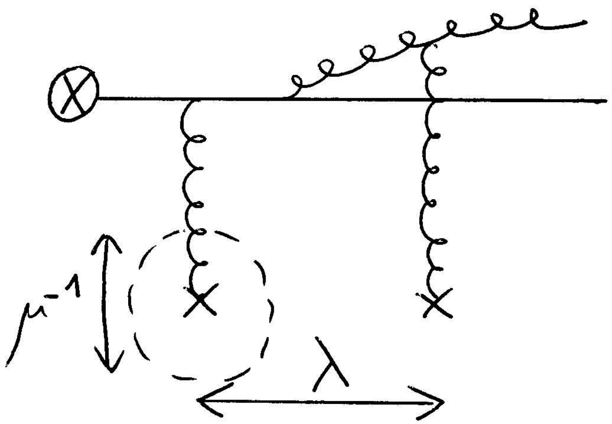

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