IV Sakharov Conference
Moscow, 21/05/09

ENERGY LOSSES IN PLASMA REVISITED

based on

S. Peigné + A.S., arXiv:0810.5702[hep-ph]
(to be published in Uspekhi)

USUAL MATTER:

collisional losses vs. radiative losses

1. Collisional losses

- scattering on electrons

$$\left(\frac{dE}{dx}\right)^{\text{usual matter}}_{\text{coll}} \sim nZ \int \left(\frac{d\sigma}{dt}\right)_{\text{Coulomb}} \Delta E(t)\, d|t| \ \sim nZ \int \frac{\alpha^2}{t^2}\, \Delta E(t)\, d|t| \ ,$$

nZ - density of electrons, $\Delta E(t) \simeq |t|/(2m)$ (m - electron mass).

We obtain, up to a logarithm,

$$\left(\frac{dE}{dx}\right)^{\text{usual matter}}_{\text{coll}} \sim \ \frac{n\, Z\alpha^2}{m} \, .$$

2. Radiative (Bethe-Heitler) losses

a) in hydrogen

$$\left(\frac{dE_{\rm BH}}{dx}\right)^{\rm hydrogen} \sim n \int \frac{\alpha^2}{t^2}\,(\alpha E)\,\frac{|t|}{m^2}\,d|t| \;\sim\; \frac{n\,\alpha^3 E}{m^2}\,.$$

- αE — char. energy emitted in a scattering act.
- $|t|/m^2 = q_\perp^2/m^2$ — "dead cone" suppression factor

$$R \;=\; \frac{dE_{\rm BH}}{dE_{\rm coll}} \;\sim\; \frac{\alpha E}{m}\,,$$

- $R \approx 1$ at $E \approx 350$MeV.

b) massive particle, atoms with Z electrons

$$R(M,Z) \;=\; \frac{dE_{\rm BH}}{dE_{\rm coll}} \;\sim\; \frac{Z\alpha E m}{M^2}\,.$$

HOT ULTRARELATIVISTIC PLASMA

• density $n \sim T^3$.

two important scales:

•Debye screening mass $\mu \sim gT =$ charateristic momentum transfer during scatterings.

• mean free path λ with respect to scatterings with momentum transfer $\sim \mu$,

$$\lambda = \frac{1}{n\sigma_{\rm tot}} \sim \frac{1}{\alpha T}$$

with

$$\sigma_{\rm tot} \sim \int_{\mu^2} \frac{\alpha^2}{t^2} d|t| \sim \frac{\alpha^2}{\mu^2} \sim \frac{\alpha}{T^2}$$

(λ is related to the so called anomalous damping of quark and gluon collective excitations).

collisional losses (Bjorken)

$$\frac{dE_{\rm coll}}{dx} = \pi c_F \, \alpha^2 T^2 \left(1 + \frac{n_f}{6}\right) \ln \frac{ET}{\mu^2} \, ,$$

radiative (Bethe-Heitler) losses

$$\frac{dE_{\rm BH}}{dx} \sim T^3 \int \frac{\alpha^2}{t^2} \, (\alpha E) \, d|t| \;\; \sim \alpha^2 ET \, .$$

- the second formula is WRONG !

MULTIPLE SCATTERING AND LPM EFFECT

• bremsstrahlung — shedding the radiation field coat

• newborn (or freshly hard-scattered) particle is NAKED and is not able to radiate.

• different Fourrier components of the coat grow with different speed.

formation length for massless particle radiation (in vacuum)

$$L_f^{\rm vac}(\omega, \theta) \sim \frac{1}{\omega\theta^2}$$

• in average, $\langle\omega\rangle \sim E$, $\theta^2_{\rm scatt} \sim \mu^2/E^2$. Hence

$$\langle L_f^{\rm vac}\rangle \sim \frac{E}{\mu^2}$$

• If $\langle L_f^{\rm vac}\rangle \gg \lambda$, the particle undergoes many ($\mathcal{N}$) scatterings before one photon is emitted.

• Char. momentum transfer in a multiple scattering: $\mu_{\rm eff}^2 \sim \mathcal{N}\mu^2$

• In-medium formation length

$$\langle L_f^{\rm med}\rangle \sim \frac{E}{\mu_{\rm eff}^2} \sim \frac{E}{\langle\mathcal{N}\rangle\mu^2}\,.$$

• on the other hand, $\langle\mathcal{N}\rangle \sim \langle L_f^{\rm med}\rangle/\lambda$

Ergo

$$L^* \equiv \langle L_f^{\rm med}\rangle \sim \sqrt{\frac{E\lambda}{\mu^2}}$$

• At length L^*, the energy $\sim \alpha E$ is lost. Hence,

$$\frac{dE}{dx} \sim \frac{\alpha E}{L^*} \sim \alpha\sqrt{\frac{E\mu^2}{\lambda}} \sim \alpha^2\sqrt{ET^3}$$

- In fact, $\mu_{\text{eff}}^2 \sim (\mathcal{N} \ln \mathcal{N})\mu^2$ and $\frac{dE}{dx} = C\alpha^2\sqrt{ET^3 \ln E}$
- C is unknown :(

- the same perturbative behavior for $N = 4$ SYM. Strong coupling ?..

FINITE L

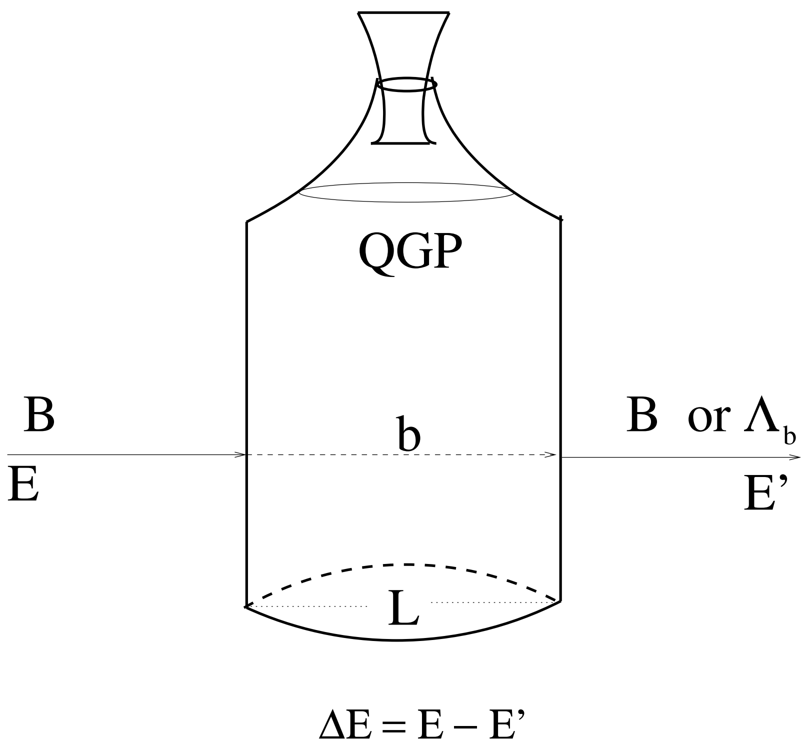
- drastically different behavior in two situations:

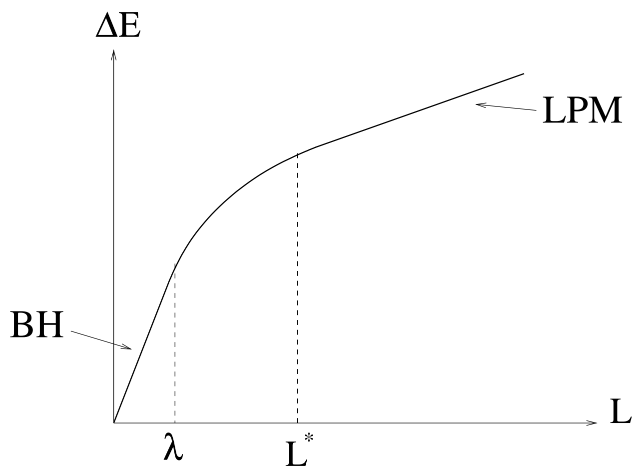
  A) Particle comes from infinity

  B) particle created in plasma.

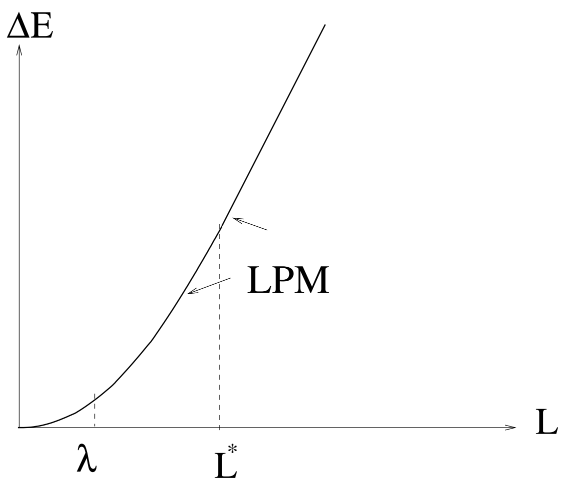
- A) is more natural in QED
- B) is more natural in QCD (jet quenching etc)

However, one can imagine





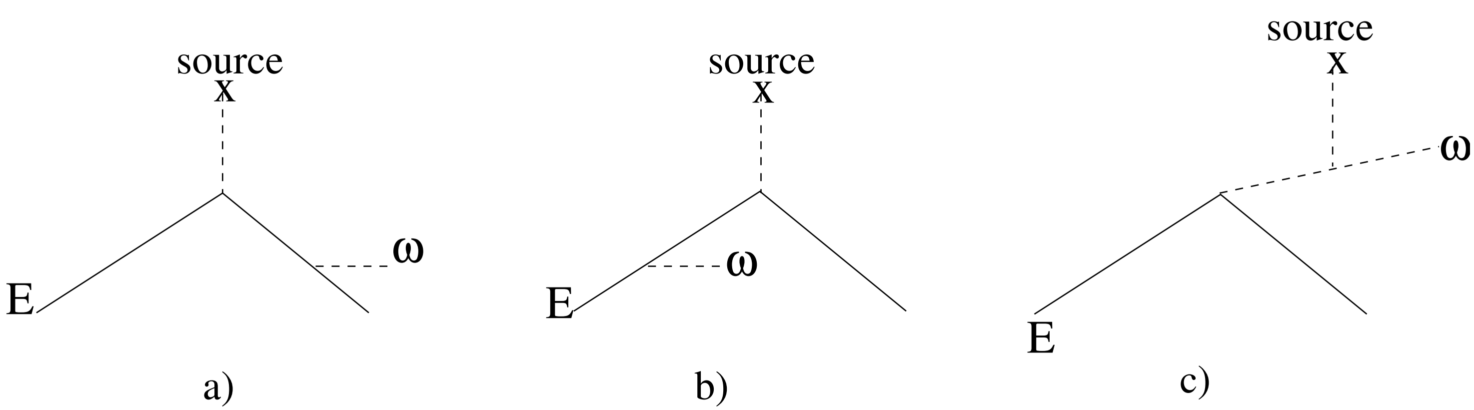
$$\Delta E_A(L)$$



$\Delta E_B(L)$

- at $L < L^*$, $\Delta E_B(L) \sim \alpha E(L/L^*)^2$.
- quadratic law is not specific for QCD
- Capacity to radiate $c(x) \propto x$

Ergo $\Delta E \sim \int_0^L c(x)dx \propto L^2$.



QCD specifics: broader angular spectrum

$$\mathcal{M}_{\rm rad} \propto g \left[\frac{\vec{\theta}}{\theta^2+\theta_M^2} t^a t^b - \frac{\vec{\theta}'}{\theta'^2+\theta_M^2} t^b t^a - \frac{\vec{\theta}''}{\theta''^2+\theta_M^2} [t^a, t^b] \right] \vec{\epsilon}.$$

with

$\vec{\theta} = \vec{k}_\perp/E,\ \theta_M = M/E,\ \vec{\theta}' = \vec{\theta} - \vec{q}_\perp/E,\ \vec{\theta}'' = \vec{\theta} - \vec{q}_\perp/\omega.$

QED:

$$\langle\theta^2_{\rm scatt}\rangle \sim \frac{\mu^2}{E^2}\,,\;\; L_f^{\rm vac}(\omega) \sim \frac{E^2}{\mu^2\omega}\,,\;\; L_f^{\rm med}(\omega) \sim \sqrt{\frac{E^2\lambda}{\mu^2\omega}}\,,\quad \left(\omega\frac{dP}{d\omega}\right)_{\rm QED} \propto \sqrt{\omega}\,.$$

QCD:

$$\langle\theta^2_{\rm scatt}\rangle \sim \frac{\mu^2}{\omega^2}\,,\;\; L_f^{\rm vac}(\omega) \sim \frac{\omega}{\mu^2}\,,\;\; L_f^{\rm med}(\omega) \sim \sqrt{\frac{\omega\lambda}{\mu^2}}\,,\quad \left(\omega\frac{dP}{d\omega}\right)_{\rm QCD} \propto \frac{1}{\sqrt{\omega}}\,.$$

HEAVY QUARKS

three mass regions:

A) $M^2 \ll \alpha_s \sqrt{ET^3}$ — the same as for light quarks.

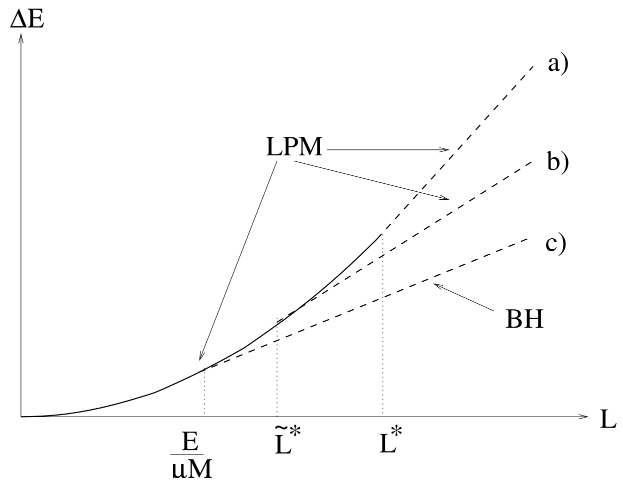
B) $\alpha_s \sqrt{ET^3} \ll M^2 \ll \alpha_s E^2$

$$\frac{dE}{dx}(\text{large } L) \sim \alpha_s^{7/3} T^2 \left(\frac{E}{M}\right)^{2/3}$$

C) $M^2 \gg \alpha_s E^2$

$$\frac{dE^{\text{rad}}}{dx}(\text{large } L) \sim \alpha_s^{5/2} T^2 \frac{E}{M}$$

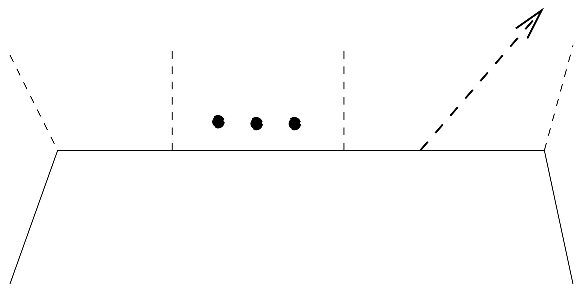
- In this region, collisional losses dominate.



a) $M^2 < \alpha_s \sqrt{ET^3}$; *b)* $\alpha_s \sqrt{ET^3} < M^2 < \alpha_s E^2$; *c)* $M^2 > \alpha_s E^2$.

• At small enough L, $\Delta E(L)$ is the same as for light quarks, however large M is.

• The larger is M, the earlier the curve deviates.

M = Σ 

- Multiple scattering + gluon/photon emission diagrams give the same qualitative results.

- quantitative model-independent calculations are very difficult and are not done yet :(