Comparing Elastic and Radiative Energy Loss Mechanisms in a dense medium

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Outline

- Motivations;
- Energy Loss Mechanisms:
  - Radiative Energy Loss - LCPI formalism;
  - Elastic Energy Loss - a conservative view;
- The Quenching Factor;
- Results;
- Conclusions.

Motivations

- High-$p_\perp$ hadron suppression $\rightarrow$ Jet Quenching;
- Partons propagating through a dense QCD medium created in HIC are expected to suffer energy degradation before their hadronization;
- This energy loss affects the final momentum transverse ($p_\perp$) spectra;
- The quenching factor for parton spectra is expected to be sensitive to the magnitude of the energy loss;
- At RHIC energy regime, the radiative processes really dominate over elastic ones ? What is the critical energy where both mechanisms contribute equally ?

Energy Loss - Mechanisms

- Total energy loss can be decomposed:
  - **Radiative** (gluon bremsstrahlung)
    $\Rightarrow$ the particle propagates in the medium and strongly interacts with the background field, radiating gluons;
  - **Collisional** (or elastic)
    $\Rightarrow$ the particle experiences multiple elastic scatterings with the partons in the plasma;
- Current works in parton energy loss assume that the radiative energy loss dominates and disregard the collisional one.
- However, the inclusion of the elastic energy loss can be necessary to correctly analyze the high-$p_\perp$ hadron suppression.

Radiative Energy Loss

- LCPI formalism (Zakharov)
  - describes the evolution of a singlet $q\bar{q}g$ system in a dense medium;
  - used to compute the induced gluon emission.
- Cross section for gluon production

$$\frac{d\sigma_{\rm eff}^{\rm BH}(x,z)}{dx} = \mathrm{Re} \int d\rho \psi^*(\rho,x)\sigma_3(\rho,x)\psi(\rho,x,z),$$

$\Rightarrow \rho \rightarrow$ transverse distance between quark and gluon;
$\Rightarrow \sigma_3 \rightarrow$ cross section for interaction between the $q\bar{q}g$ system and a particle in the medium;

Radiative Energy Loss

- Light-Cone Wave Functions :
  - for transitin $q \to qg$ in the vacuum

$$\psi(\rho, x) = p(x) \left(\frac{\partial}{\partial \rho'_x} - \imath s_g \frac{\partial}{\partial \rho'_y} \right) \int_0^\infty d\xi \, \exp\left(-\frac{\imath \xi}{L_f} \right) \mathcal{K}_0(\rho, \xi | \rho', 0)|_{\rho'=0}$$

  - medium modified, describing transition in the medium

$$\psi(\rho, x, z) = p(x) \left(\frac{\partial}{\partial \rho'_x} - \imath s_g \frac{\partial}{\partial \rho'_y} \right) \int_0^z d\xi \, \exp\left(-\frac{\imath \xi}{L_f} \right) \mathcal{K}_0(\rho, z | \rho', z - \xi)|_{\rho'=0}.$$

$\Rightarrow p(x) = \imath\sqrt{\alpha_s/2x}[s_g(2-x) + 2s_q x]/2M(x)$;
$\Rightarrow M(x) = Ex(1-x)$;
$\Rightarrow L_f = 2Ex(1-x)/\epsilon^2$, with $\epsilon^2 = m_g^2(1-x) + m_q^2 x^2$
$\Rightarrow s_{q,g} \to$ parton helicities

- Green Function for two dimensional Hamiltonian

$$\mathcal{K}_0(\rho_2, z_2 | \rho_1, z_1) = \frac{M(x)}{2\pi\imath(z_2 - z_1)} \exp\left[\frac{\imath M(x)(\rho_2 - \rho_1)^2}{2(z_2 - z_1)} \right],$$

Radiative Energy Loss

- Induced Gluon Spectrum

$$\frac{dp}{dx} = \int_0^L dz\, n(z) \frac{d\sigma_{\rm eff}^{\rm BH}(x,z)}{dx}.$$

$\Rightarrow n(z) \rightarrow$ number (partons) density of in the medium (QGP).

- Assumptions to evaluate it
  - σ_3 can be written in terms of dipole cross section σ_2

$$\sigma_3(\rho, x) = \frac{C_A}{2C_F}[\sigma_2((1-x)\rho) + \sigma_2(\rho) - \frac{1}{C_A^2}\sigma_2(x\rho)] = C_3(x)\rho^2,$$

with

$$\begin{aligned} C_3(x) &= C_2(\rho)A(x) \\ A(x) &= [1 + (1-x)^2 - \frac{x^2}{N_c^2}]\frac{C_A}{2C_F} \end{aligned}$$

  - Spectrum is dominated by contributions of the region $\rho \ll 1/\mu$

$$C_2(\rho) \propto \ln\left(\frac{1}{\rho\mu}\right)$$

Radiative Energy Loss

- For heavy quarks - analytical result

$$\frac{d\sigma_{\rm eff}^{\rm BH}(x,z)}{dx} = \frac{\alpha_s^2 C_F C_T A(x) G(x)}{2M(x)} \left\{ \frac{\pi}{2} L_f \sin\frac{z}{L_f} + L_f(1-\gamma)\left(\cos\frac{z}{L_f} - 1\right) \right.$$

$$\left. + \; L_f \ln\frac{M(x)}{2\mu^2 z}\left(1-\cos\frac{z}{L_f}\right) + \frac{z^2}{4L_f} \right\}, \qquad (1)$$

- $G(x) = \alpha_s C_F [1 - x + x^2/2]/x$
- $\gamma = 0.5772 \rightarrow$ Euler constant
- Radiative energy loss

$$\Delta E_{\rm rad} = E \int_{x_{\rm min}}^{x_{\rm max}} dx\, x \frac{dp}{dx}$$

- $x_{\rm min} = m_g/E$
- $x_{\rm max} = 1 - m_q/E$

Elastic Energy Loss

- First estimated by Bjorken for massless quarks
  $\rightarrow$ problems in the infrared limit $\rightarrow$ coherent multiple scatterings
- Problem solved with combination of techniques of classical plasma physics and HTL corrected propagator $\rightarrow$ Braaten and Thoma
- For heavy quarks (leading order)

$$-\frac{dE}{dL} = \frac{8\pi\alpha_s^2 T^2}{3}\left(1+\frac{n_f}{6}\right)\left[\frac{1}{v}-\frac{1-v^2}{2v^2}\ln\left(\frac{1+v}{1-v}\right)\right]\ln\left[2^{\frac{n_f}{6+n_f}}B(v)\frac{ET}{m_g M}\right]$$

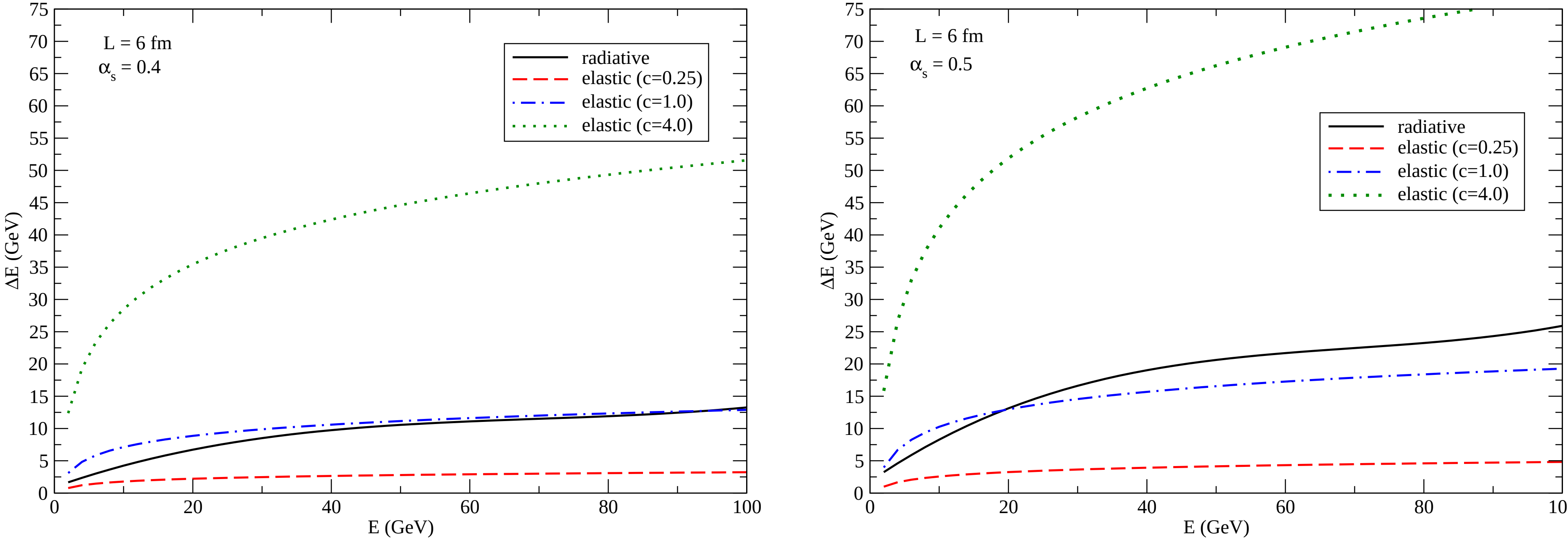
$$-\frac{dE}{dL} = \left(1+\frac{9}{4}\right)\frac{4\pi\alpha_s^2 T^2}{3}\left(1+\frac{n_f}{6}\right)\ln\left[2^{\frac{n_f}{2(6+n_f)}}0.92\frac{\sqrt{ET}}{m_g}\right] \qquad E \gg M^2/T$$

- $m_g = \sqrt{\frac{(1+\frac{n_f}{6})}{3}}gT \rightarrow$ thermal gluon mass
- Elastic Energy Loss

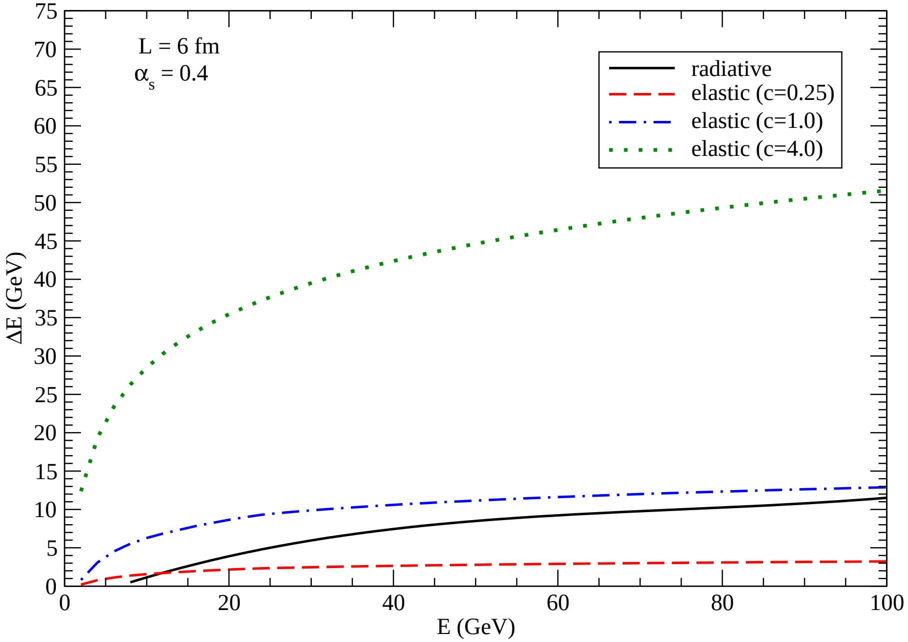
$$\Delta E_{\mathrm{elas}} = -c\int_0^L \frac{dE}{dL}dz,$$

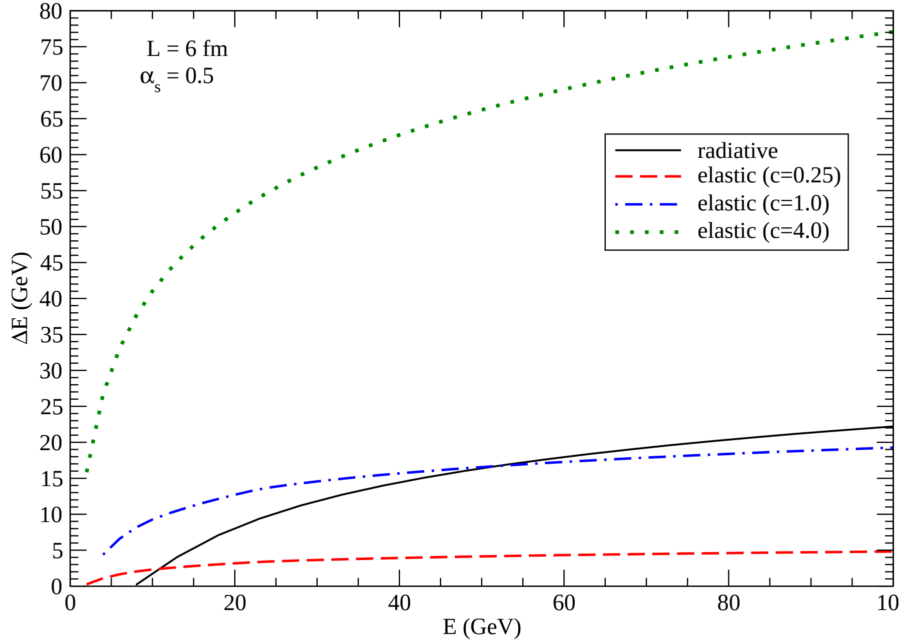
$c \Rightarrow$ ad hoc pre factor $\rightarrow$ used to analyze the effects of different magnitudes

Energy Loss Results - Light quarks

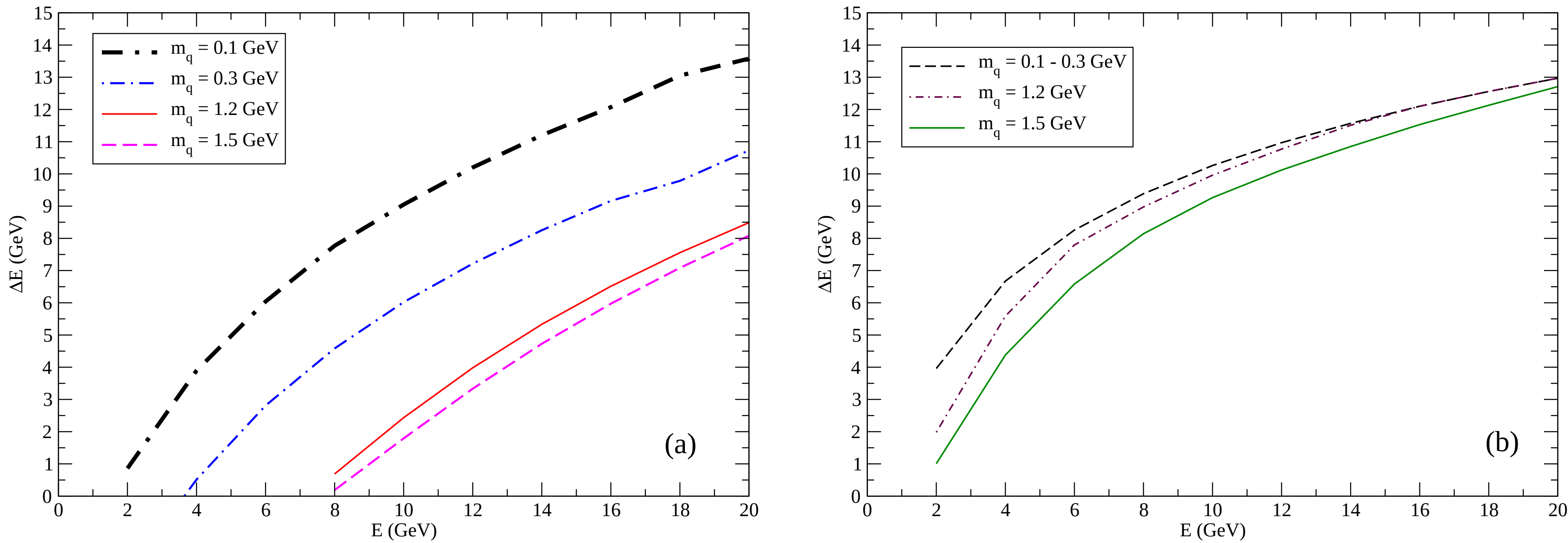


Energy Loss Results - Heavy quarks



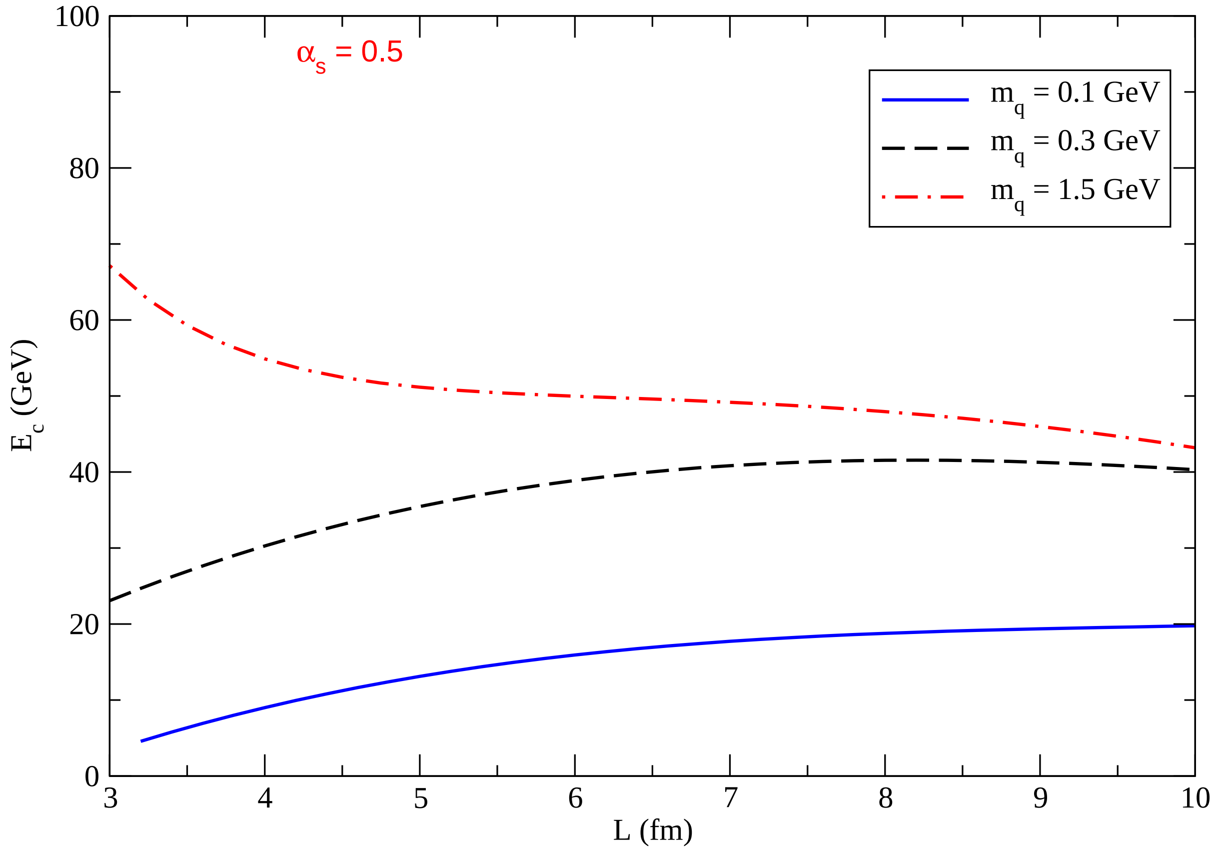


Mass Dependence x Energy Dependence



Critical Energy

- Energy where elastic and radiative contributions are equal



Quenching Factor

- **Basic Idea** - particles produced in $A - A$ collisions would have their $p_\perp$-spectra modified with respect to $h - h$ collisions, due this energy loss;
- it is related to the nuclear modification factor $R_{AA}(p_\perp)$ for hadron spectra;
- transverse momentum of the leading hadron traces the energy of the leading parton;
- high-$p_\perp$ partons hadronize at large lenght scales, outside the medium;
- modifications on the high-$p_\perp$ hafdron spectra is directly associated to modifications in the parent partons due to energy loss effects;
- Quenching factor

$$\frac{dN^{\rm med}}{d^2p_\perp} = \int d\epsilon\, D(\epsilon)\, \frac{dN^{\rm vac}(p_\perp + \epsilon)}{d^2p_\perp} \equiv Q(p_\perp)\frac{dN^{\rm vac}(p_\perp)}{d^2p_\perp}$$

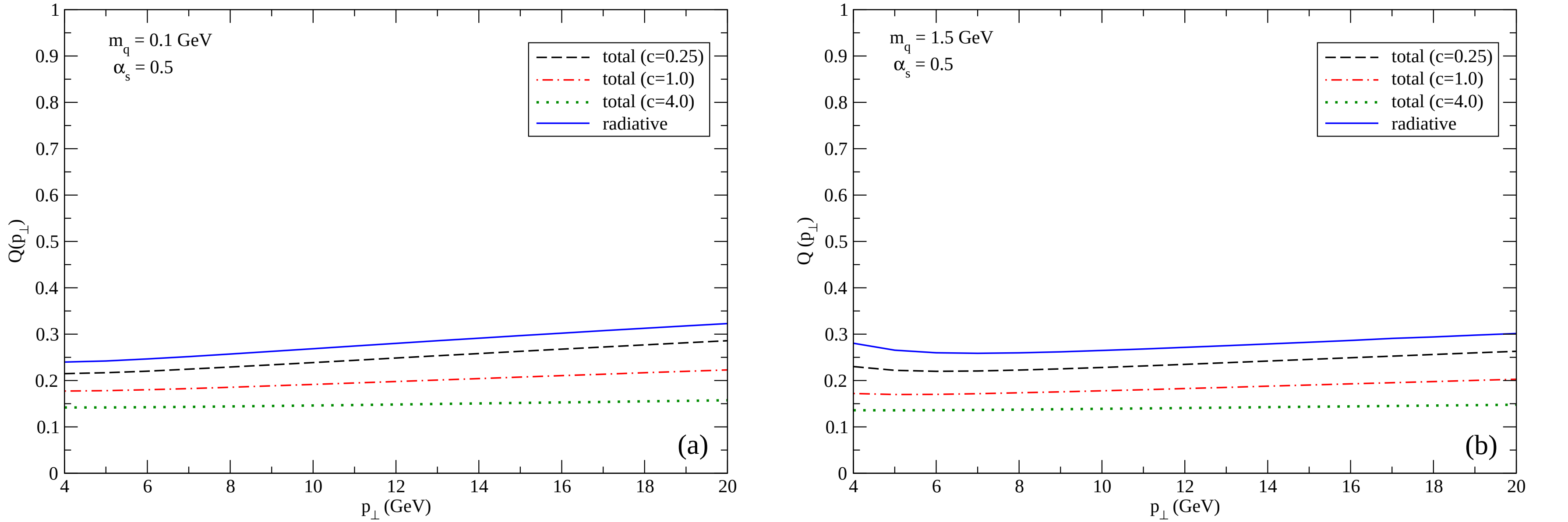
- Calculating $p_\perp$ distribution in the medium

$$\frac{dN^{\rm med}}{d^2p_\perp} = \frac{1}{2\pi^2 R^2} \int_0^{2\pi} d\phi \int_0^R d^2r\, \frac{dN^{\rm vac}(p_\perp + \Delta E)}{d^2p_\perp}$$

- Geometry

$$L(\phi) = (R^2 - r^2 \sin^2\phi)^{1/2} - r\cos\phi$$

Quenching factor results



- Light quarks vacuum parameterization (RHIC hadroproduction data)

$$\frac{dN_L^{\text{vac}}}{d^2p_\perp} = A\left(\frac{1}{p_0 + p_\perp}\right)^\nu$$

- Charm quarks vacuum parameterization (D meson data)

$$\frac{dN_H^{\text{vac}}}{d^2p_\perp} = C\left(\frac{1}{bM_c^2 + p_\perp^2}\right)^{n/2}$$

Conclusions

- We found that the inclusion of elastic processes can provide corrections to the energy loss calculations;
- For light quarks, the quenching factor is ~ 0.2, similar to the results for π^0 R_{AA} results;
- These results motivate the application for heavy quarks $\rightarrow$ preliminary results indicate larger suppression than predicted by radiative EL calculations;
- Other observables have to be studied to extract the correct magnitude of the contribution of elastic processes to total energy loss.