Partonic Energy Loss in Hot and Cold Nuclear Matter

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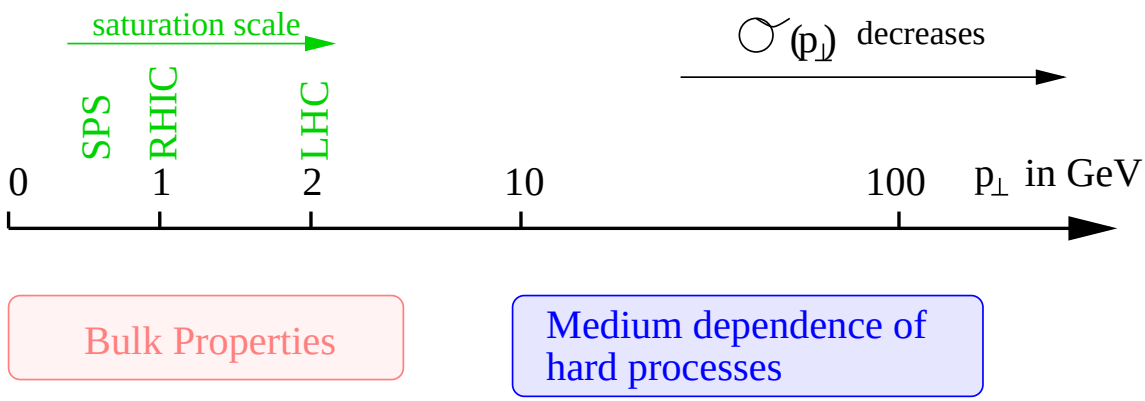
I.1. Propagation of hard partons in matter



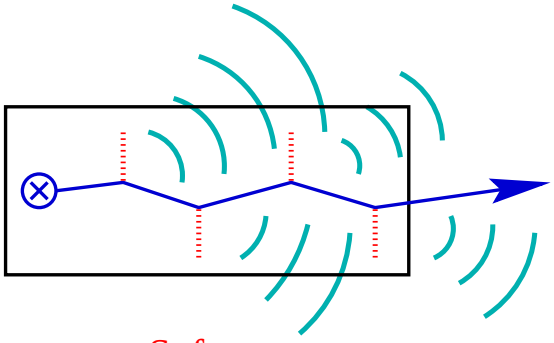
Medium dependence of hard processes:

1. provides information about bulk properties
   $\Longrightarrow$ QGP-signal + tool for quantitative studies

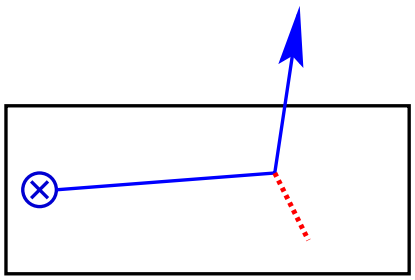
2. Observable consequences:

   - pt-broadening observed in p+A, difficult to observe in HIC
   - E-loss so far not observed in p+A

3. Partonic Mechanisms

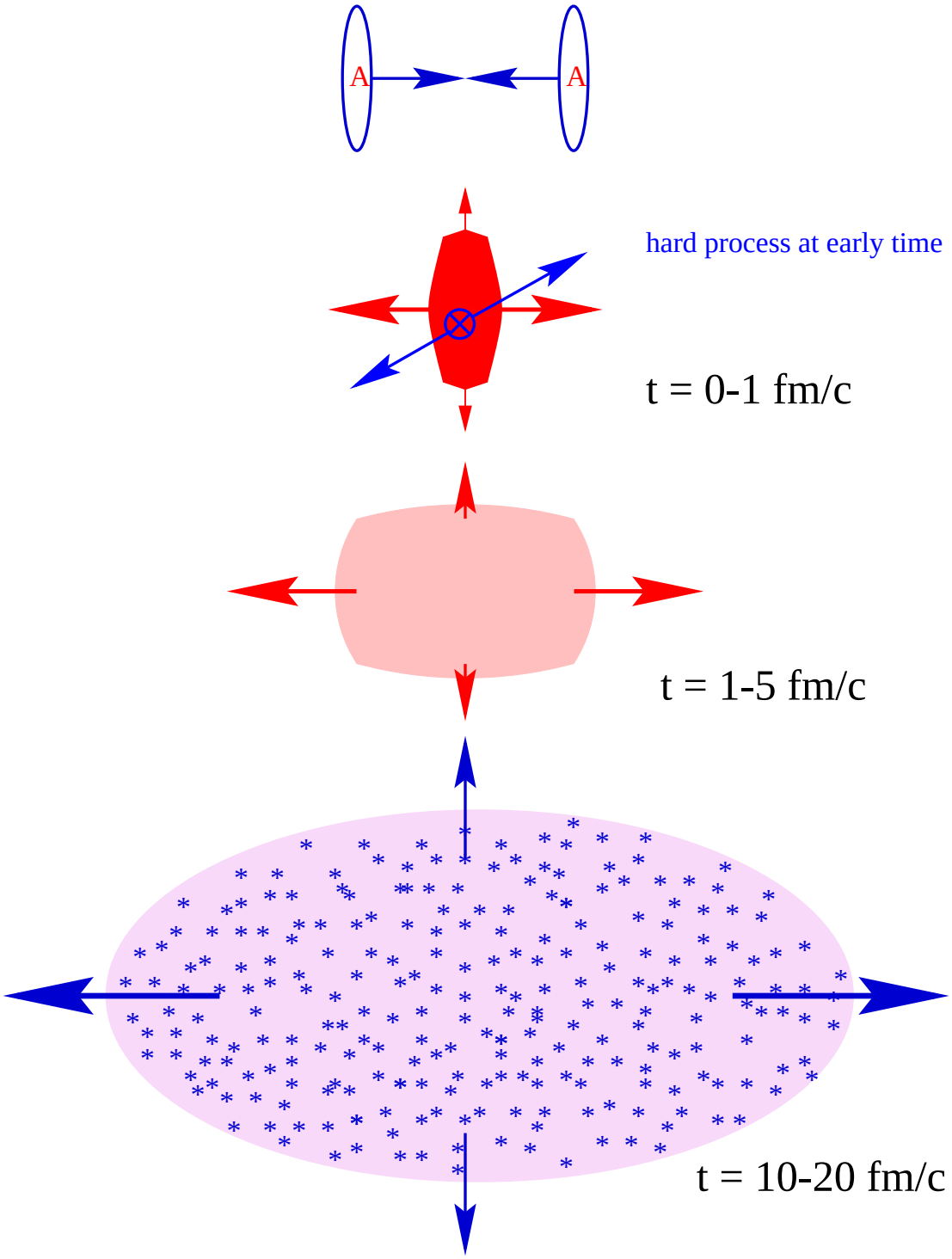


Multiple Soft Rescattering



Secondary Hard Reinteraction

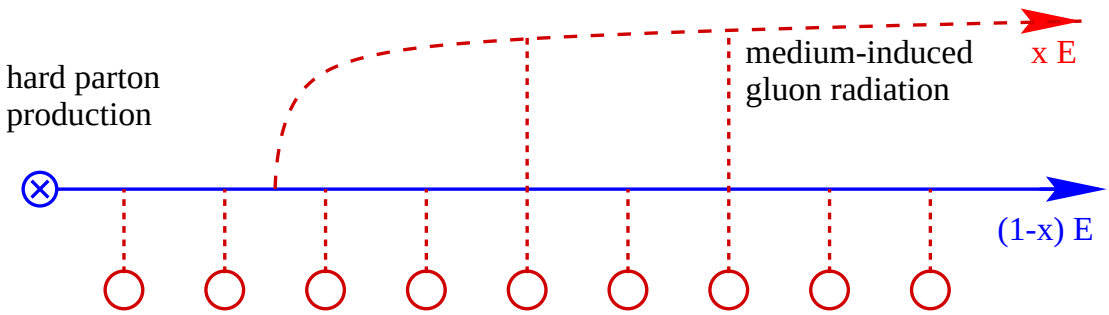
I.2. Schematic view



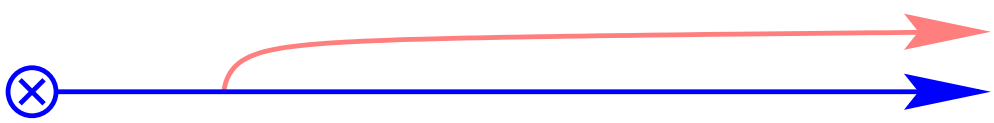
I.3. Radiative E-loss off hard parton

Gyulassy+Wang 1994, BDMPS 1997, Zakharov 1997, Wiedemann 2000, GLV 2000

1. Medium-induced contribution:



2. BUT: Vacuum-induced (hard) contribution $\propto \frac{1}{k_\perp^2}$ is hugh. It is the building block of DGLAP !



$\Longrightarrow$ calculation has to include:

- interference between medium-induced and vacuum term reduces medium-induced radiative energy loss

- rescattering of vacuum-induced radiation

  changes $k_\perp$-distribution of gluon radiation but not $k_\perp$-integrated spectrum.

II.1. Gluon radiation cross section

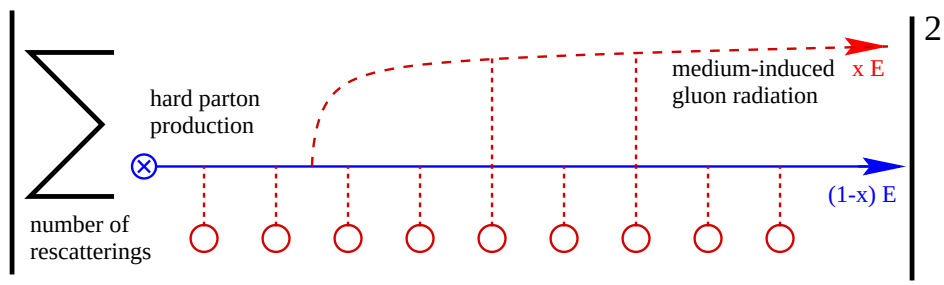
opacity expansion: $O\left(\alpha_s \int_0^L d\xi\, n(\xi)\right)$, Wiedemann NP**B588** (2000) 303.

$$\frac{d^3\sigma}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{(2\pi)^2}\frac{1}{\omega^2} N_C\, C_F\, 2\mathrm{Re} \int_{\mathbf{z}_-}^{z_+} dy_l \int_{y_l}^{z_+} d\bar{y}_l$$

$$\times e^{-\epsilon|y_l| - \epsilon|\bar{y}_l|} \int d\mathbf{u}\, e^{-i\mathbf{k}_\perp\cdot\mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^{z_+} d\xi\, n(\xi)\,\sigma(\mathbf{u})}$$

$$\times \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}} \mathcal{K}(\mathbf{y}=0, y_l; \mathbf{u}, \bar{y}_l|\omega)\,,$$

$$=$$



depends on density and dipole cross section:

$$\mathcal{K} = \int \mathcal{D}\mathbf{r} \exp\left[\int_{y_l}^{\bar{y}_l} d\xi \left(i\frac{\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2} n(\xi)\sigma(\mathbf{r})\right)\right]\,,$$

$$\sigma(\mathbf{r}) = 2\, C_A \int \frac{d\mathbf{q}_\perp}{(2\pi)^2} |a_0(\mathbf{q}_\perp)|^2 \left(1 - e^{-i\mathbf{q}_\perp\cdot\mathbf{r}}\right)\,.$$

$\Longrightarrow$ Consequences of this expression

II.2. Dipole cross section $\sigma(\mathbf{r})$

- satisfies $\sigma(\mathbf{r}) \propto C\,\mathbf{r}^2$

- bulk properties characterized by one parameter only:

$$n_0\,C =: \frac{\langle \mathbf{q}_\perp^2 \rangle}{L_{\rm medium}}\,.$$

- Phenomenological determination of rescattering parameter, $n_0\,C_{\rm cold}$ versus $n_0\,C_{\rm hot}$:

$$n_0\,C_{\rm cold} < \frac{(200\,{\rm MeV})^2}{\rm fm} = 1.0\,{\rm fm}^{-3}$$

- Theoretical calculation of rescattering parameter:

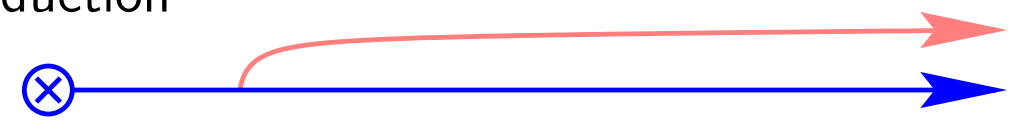
$$n_0\,\sigma(\mathbf{r}) \propto \langle F_{i0}(0)\,F^{i0}(\mathbf{r})\rangle_{\rm med}$$

  Only this transverse colour field strength enters the calculation.

II.3. Opacity Expansion

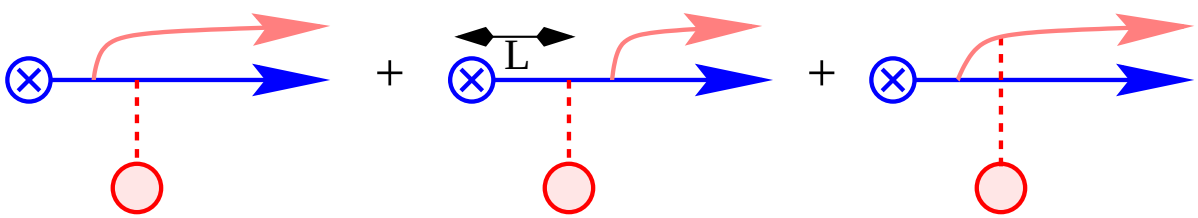
Gluon spectrum to order $(\alpha_s\, n_0)^N$:

- $N = 0$: hard radiation associated to parton production



$$\frac{d^3\sigma(N=0)}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{\pi^2}\, N_C\, C_F\, \frac{1}{\mathbf{k}_\perp^2}\,, \qquad H(\mathbf{k}_\perp) = \frac{1}{\mathbf{k}_\perp^2}\,.$$

- $N = 1$: L-dependent interference pattern:



$$\frac{d^3\sigma(N=1)}{d(\ln x)\, d\mathbf{k}_\perp} = \frac{\alpha_s}{\pi^2}\, \frac{N_C\, C_F}{2\,\omega^2} \int_{\Sigma_1} \frac{-\mathbf{k}_\perp \cdot \mathbf{q}_\perp}{Q\, Q_1}\, n_0\, \frac{LQ_1 - \sin(LQ_1)}{Q_1}\,.$$

- $N \geq 2$: closed expressions involving $(N+1)$ terms known

II.4. Coherent and Incoherent Limits

satisfy classically expected parton cascade picture, e.g.

$$\lim_{L\to\infty} \sum_{m=0}^{N=1} \frac{d^3\sigma(m)}{d(\ln x)\, d\mathbf{k}_\perp}\bigg|_{n_0\, L=\mathrm{const}} = \frac{\alpha_s}{\pi^2} N_C\, C_F$$

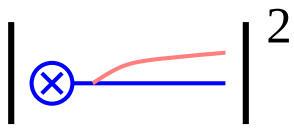
$$\times \left[(1-w_1) H(\mathbf{k}_\perp) + n_0\, L \int_{\mathbf{q}_1} H(\mathbf{k}_\perp + \mathbf{q}_{1\perp}) \right.$$

$$\left. + n_0\, L \int_{\mathbf{q}_1} R(\mathbf{k}_\perp, \mathbf{q}_{1\perp}) \right] .$$

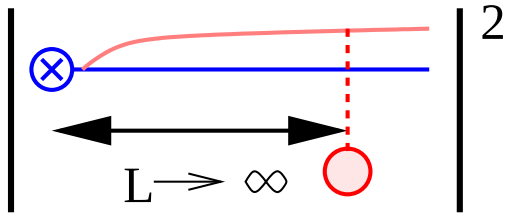
w_1 = probability of one additional scattering

R = GB-radiation term Gunion + Bertsch, PR**D25** (1982) 746.

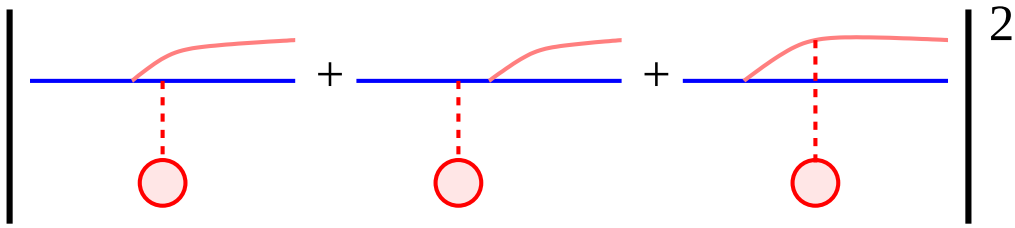
$H(k_\perp) =$



$H(k_\perp + q_\perp) =$



$R(k_\perp, q_\perp) =$



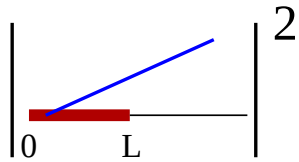
II.5. Harmonic Oscillator Approximation

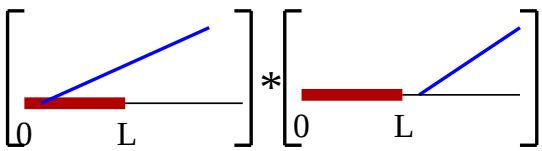
For $\sigma(\mathbf{r}) \equiv C\,\mathbf{r}^2$, and $n(\xi) = n_0$

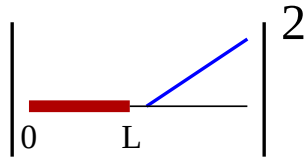
$\Longrightarrow$ complex oscillator frequency $\Omega = \frac{1-i}{\sqrt{2}}\sqrt{\frac{n_0\,C}{\omega}}$

$$\mathcal{K} \longrightarrow \mathcal{K}_{\rm osz}\big(\mathbf{y}, y_l; \mathbf{r}, \bar{y}_l|\omega\big)$$

Radiative energy loss determined by three terms

$I_4 =$ 

$I_5 = 2\,\mathrm{Re}$ 

$I_6 =$ 

$= \frac{1}{\mathrm{k}_\perp^2}$ hard radiation !

$$\left.\frac{d^3\sigma}{d(\ln x)\,d\mathbf{k}_\perp}\right|_{medium-dep} = \frac{\alpha_s}{\pi^2}\,N_c\,C_F\,\left(I_4 + I_5\right)$$

- direct production term I_4
- destructive interference term I_5

III.1. Numerical Evaluation

Input for numerics:

1. quark energy E: $E = 50,\ 100,\ 200$ GeV.
2. energy of radiated gluon $\omega = x\,E$, $x \in [0,1]$.
3. rescattering property of medium: $n_0\,C$:

$$n_0\,C = 0.1\mathrm{fm}^{-3} = (63\,\mathrm{MeV})^2/\mathrm{fm}$$
$$n_0\,C = 0.5\mathrm{fm}^{-3} = (141\,\mathrm{MeV})^2/\mathrm{fm}$$
$$n_0\,C = 1.0\mathrm{fm}^{-3} = (200\,\mathrm{MeV})^2/\mathrm{fm}$$
$$n_0\,C = 2.0\mathrm{fm}^{-3} = (280\,\mathrm{MeV})^2/\mathrm{fm}$$
$$n_0\,C_{\mathrm{BDMPS}} \approx 5.0\mathrm{fm}^{-3} = (450\,\mathrm{MeV})^2/\mathrm{fm}$$

4. length of nuclear medium: $0\mathrm{fm} < L < 14\mathrm{fm}$
5. $\chi \in [0,1]$, kinematical boundary of $\mathbf{k}_\perp$-integration, $(\int_0^{\chi\,\omega} d\mathbf{k}_\perp)$

Output:

1. differential information on x and $\mathbf{k}_\perp$

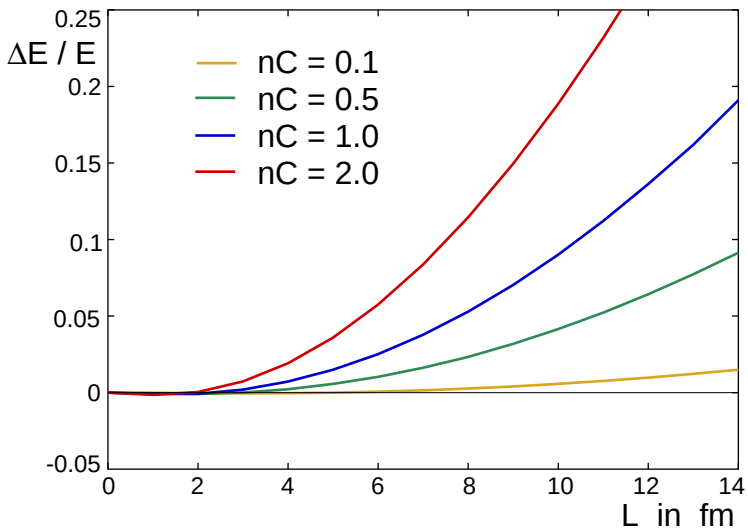
$$\left.\frac{d\sigma}{d(\ln x)}\right|_{medium-dep} (L, n_0 C, E, \chi)$$

2. medium-induced part of radiative energy loss

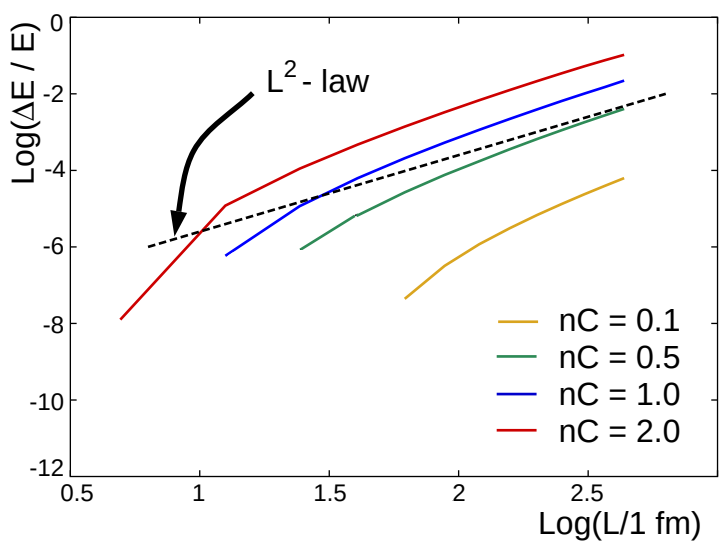
$$\frac{\Delta E}{E}(L, n_0 C, E, \chi) = \int_0^1 dx\, x\, \frac{d\sigma}{dx}$$

III.2. L-Dependence of $\frac{\Delta E}{E}$

- very sensitive to transverse colour field strength nC

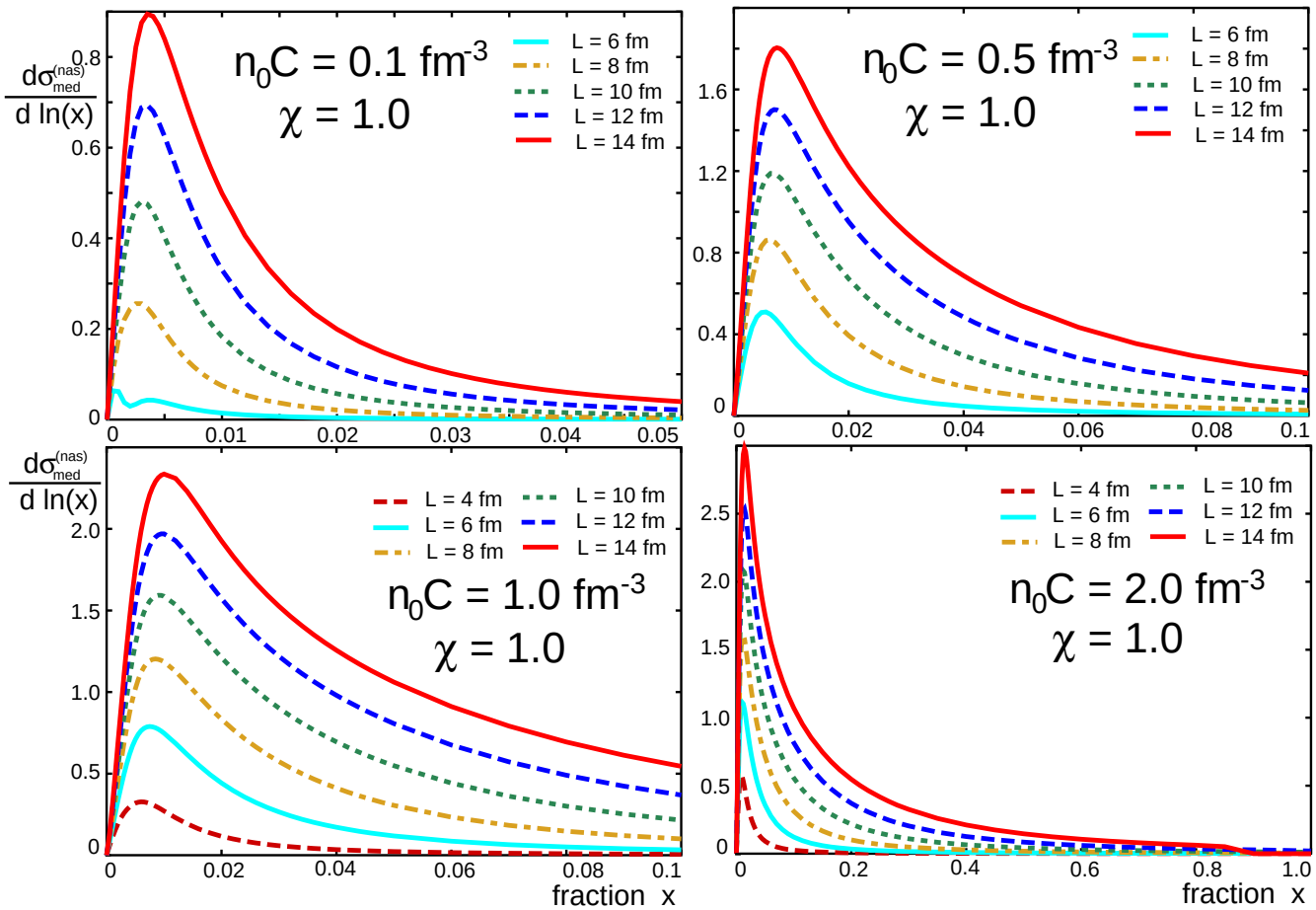


- $\propto L^{2.5}$ in the regime tested experimentally



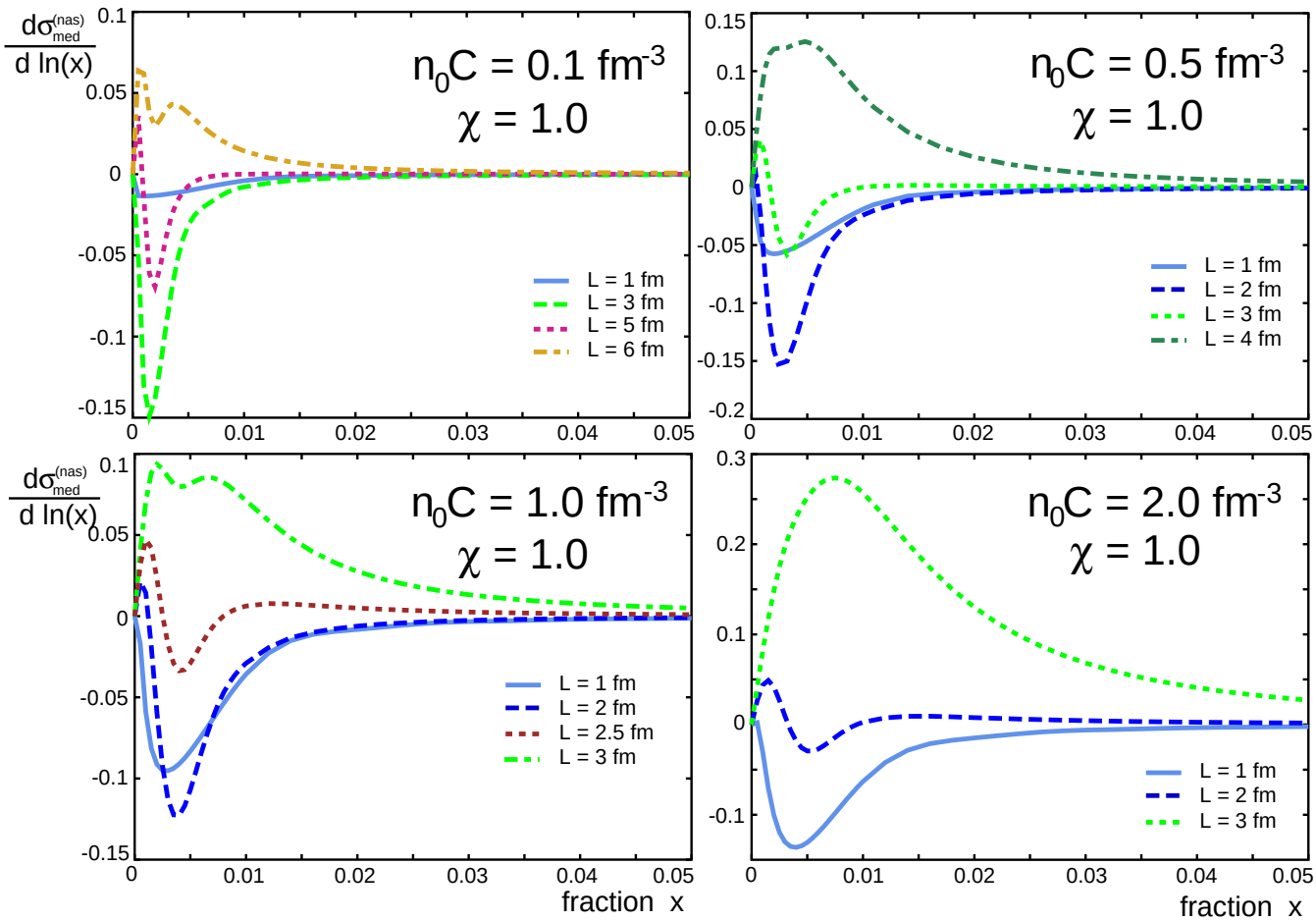
III.3. x-Differential Radiation Spectrum

For relatively large L



- + main support at $x \ll 1$
- - reaches non-perturbatively high values

III.4. x-Differential Radiation Spectrum



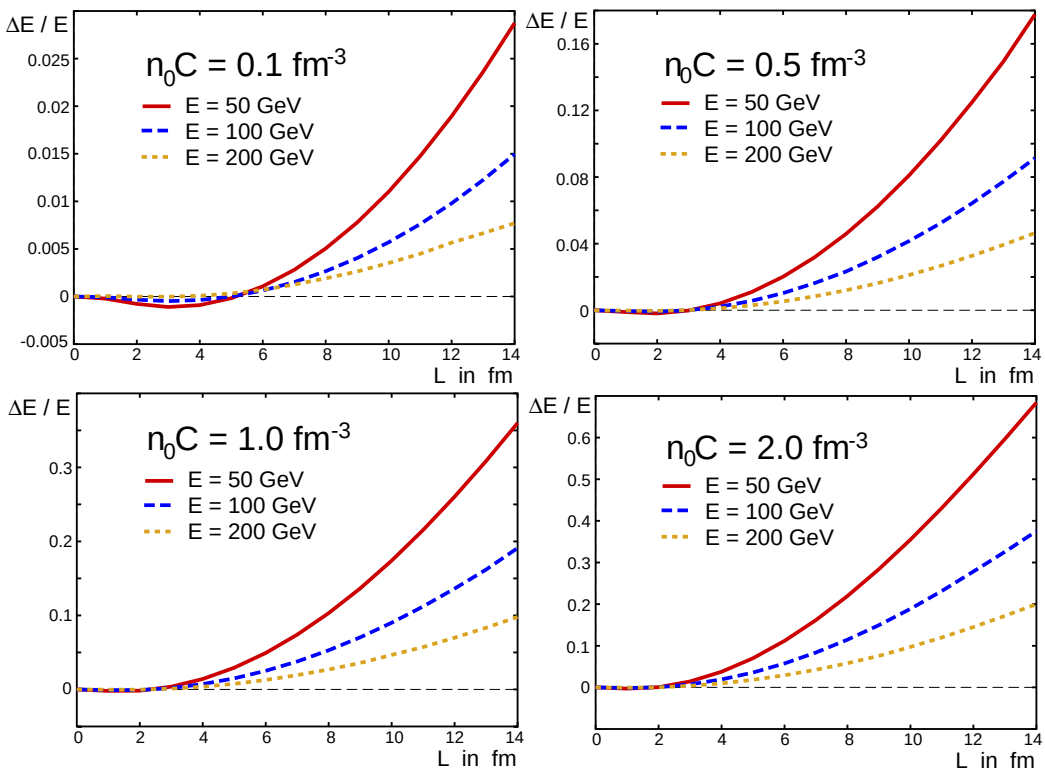
Two competing effects

- destructive interference between medium-induced and hard initial radiation
  $\Longrightarrow$ "Jet Enhancement" $\frac{\Delta E}{E} \propto -\mathbf{L^3}$

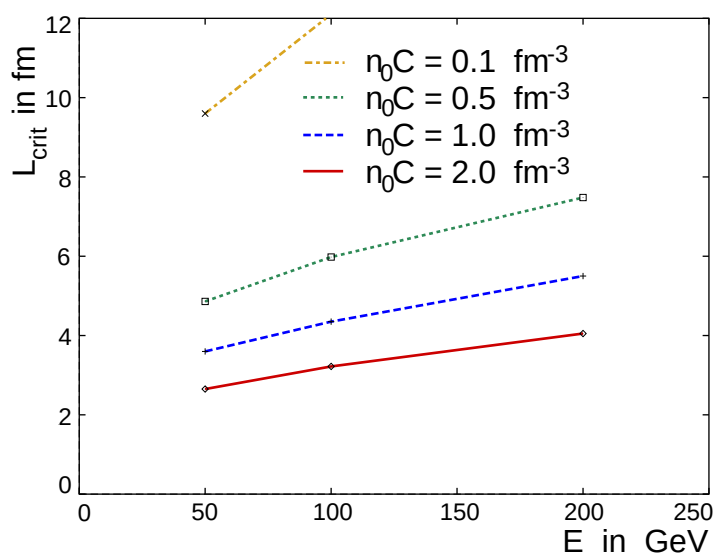
- rescattering induced additional contribution increases with L
  $\Longrightarrow$ Jet Quenching

III.5. E-scaling of $\frac{\Delta E}{E}$

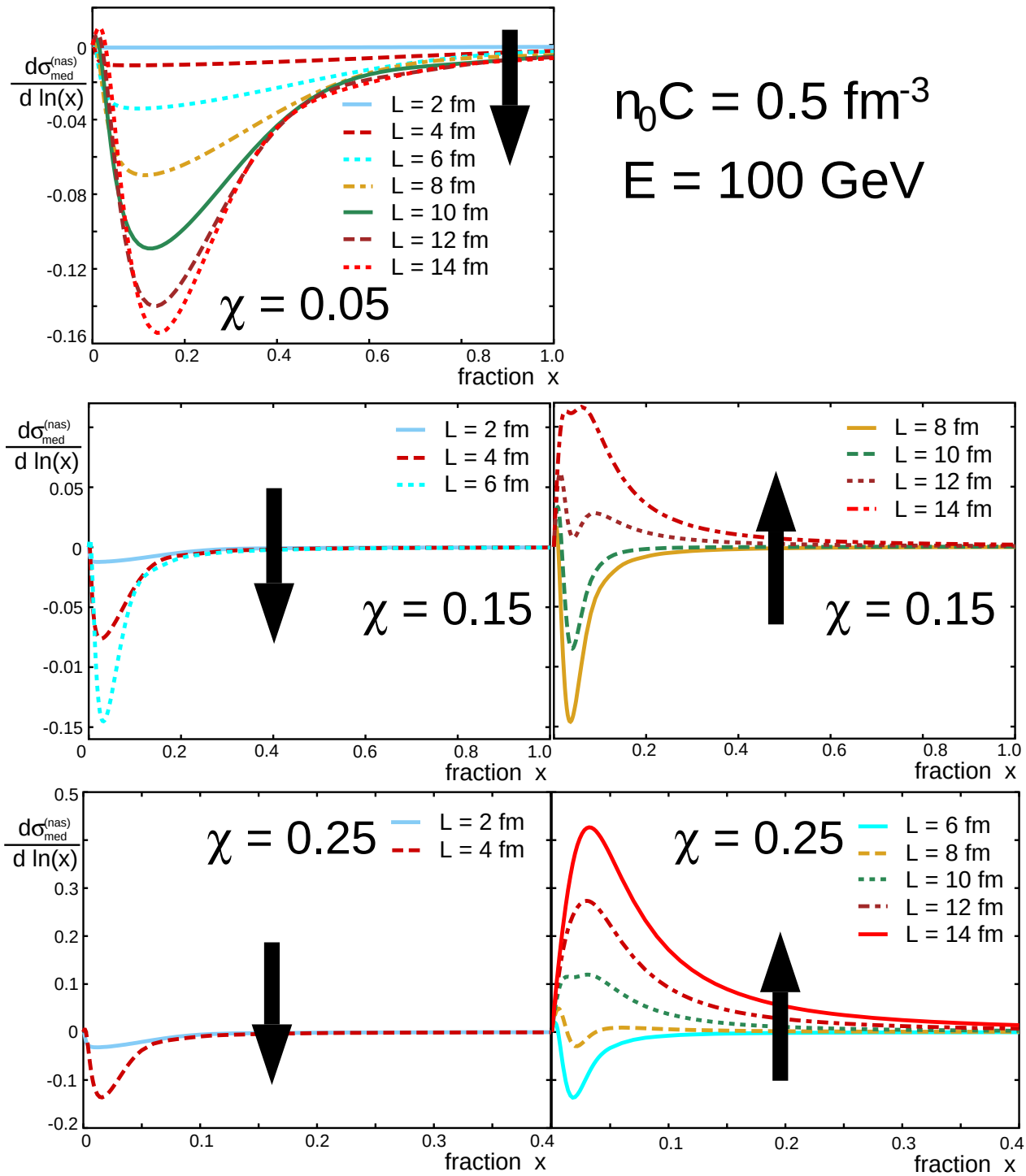
- ΔE is E-independent



- Delayed onset of jet quenching, $\frac{\Delta E}{E}(L_{\rm crit}) \equiv 1\%$

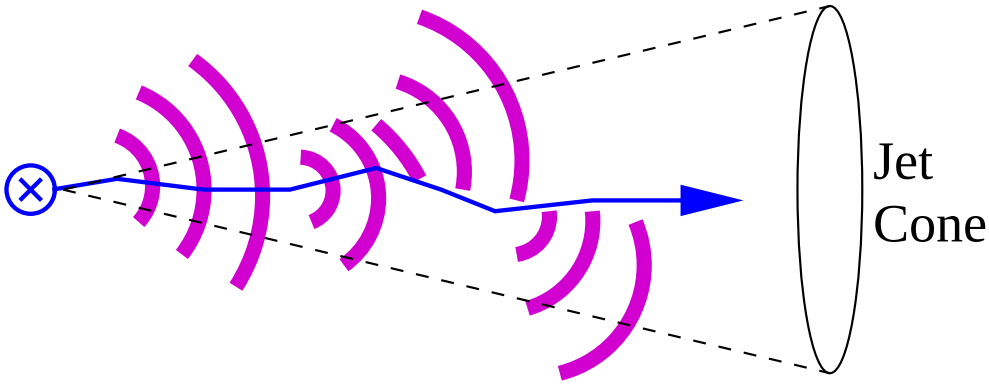


III.6. $\mathbf{k}_\perp$-Differential Radiation Spectrum

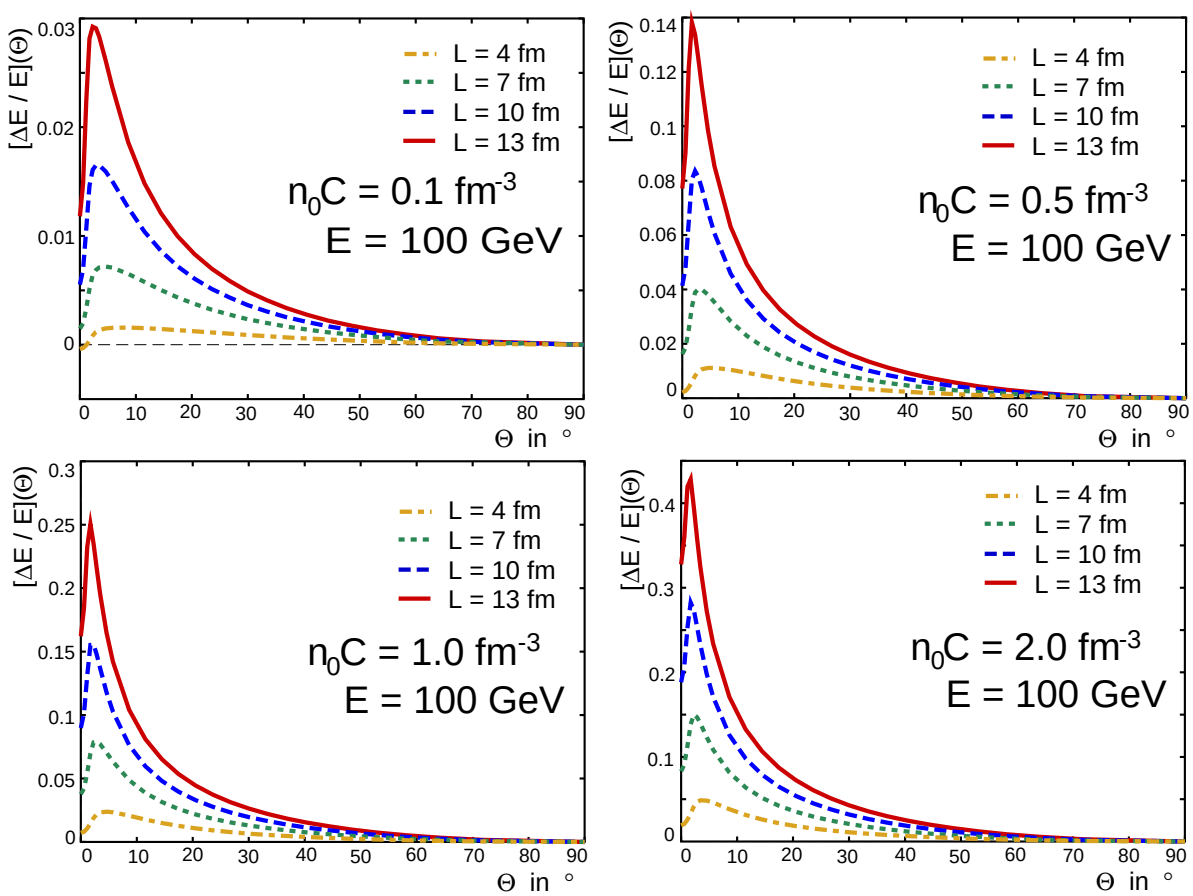


Small $\mathbf{k}_\perp$-region is depleted by Rescattering and Destructive Interference.

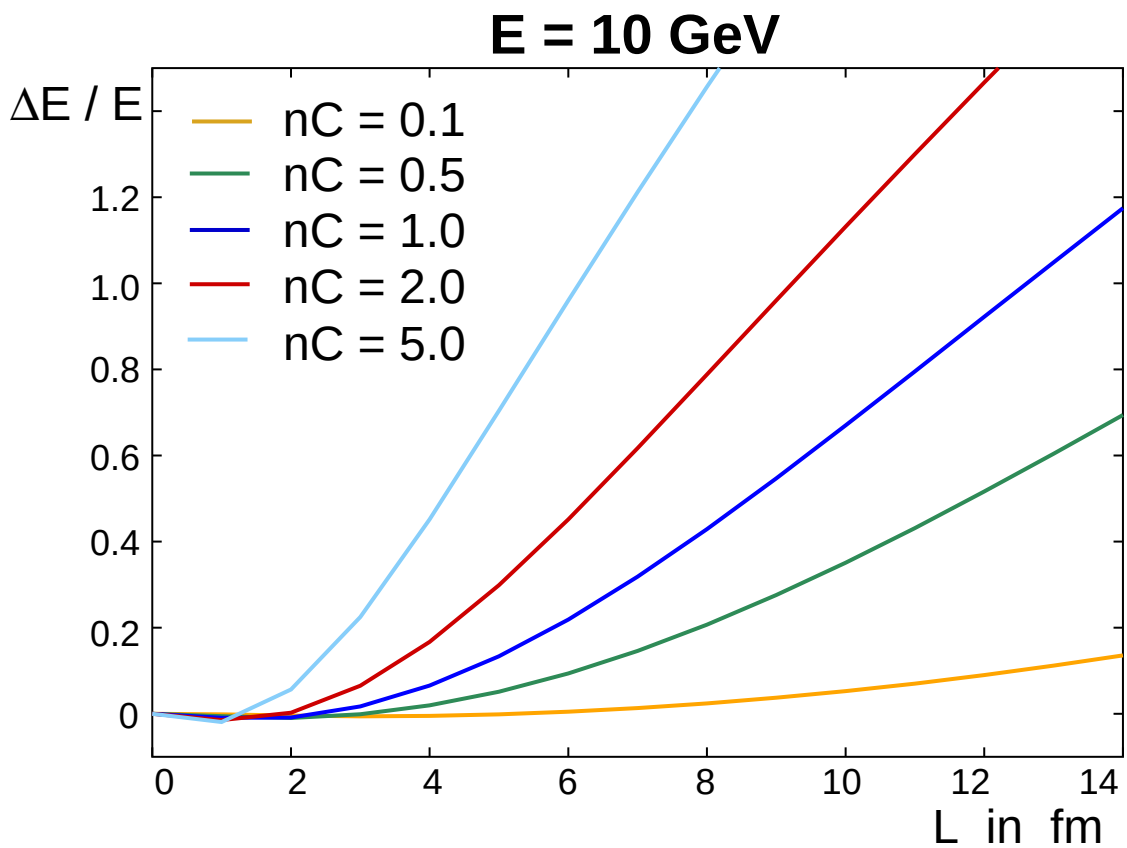
III.7. Energy Loss outside jet cone Θ



Medium-dependent part of $\frac{\Delta E}{E}(\Theta)$ outside Θ does not peak at $\Theta = 0$
due to $\frac{1}{\mathbf{k}_\perp^2} \longrightarrow \frac{1}{(\mathbf{k}_\perp + \mathbf{q}_\perp)^2}$ broadening



IV.1. RHIC p_t-regime

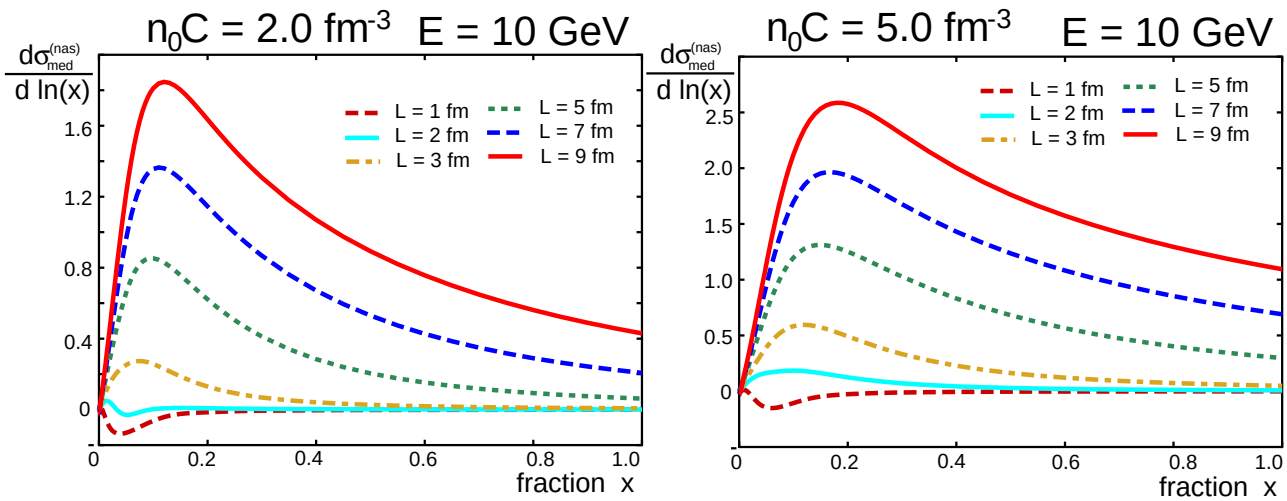


- *corona effect* ensures that $n_0\, C_{\rm cold}$ result consistent with upper bounds on ΔE in p+A.

- linear L-dependence for $L > L_{\rm crit}$.

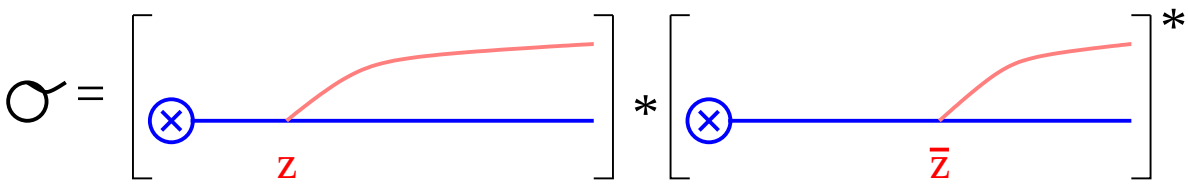
- theoretical uncertainties increase with decreasing jet energy.

IV.2. x-Diff. Spectrum for $E = 10$ GeV



- significant contribution from $x \sim 1 \Longrightarrow$ problematic

V. Conclusion



<u>Results:</u> Wiedemann NP**B582** (2000) 409; NP**B588** (2000) 303 and hep-ph/0008241.

- interference pattern between hard vacuum- and medium-induced radiation
  $\Longrightarrow$ Jet Quenching vs. Jet Enhancement

- $\mathbf{k}_\perp$-differential gluon radiation spectrum
  $\Longrightarrow$ <u>medium-induced</u> E-loss outside jet cone peaks at finite opening angle

- results interpolate between expected coherent and incoherent limiting cases $\Longrightarrow$ Opacity expansion has parton cascade limits

- numerical routine available

- Phenomenology $n_0\, C_{\rm cold}$ versus $n_0\, C_{\rm hot}$: