medium-induced gluon radiation: an update

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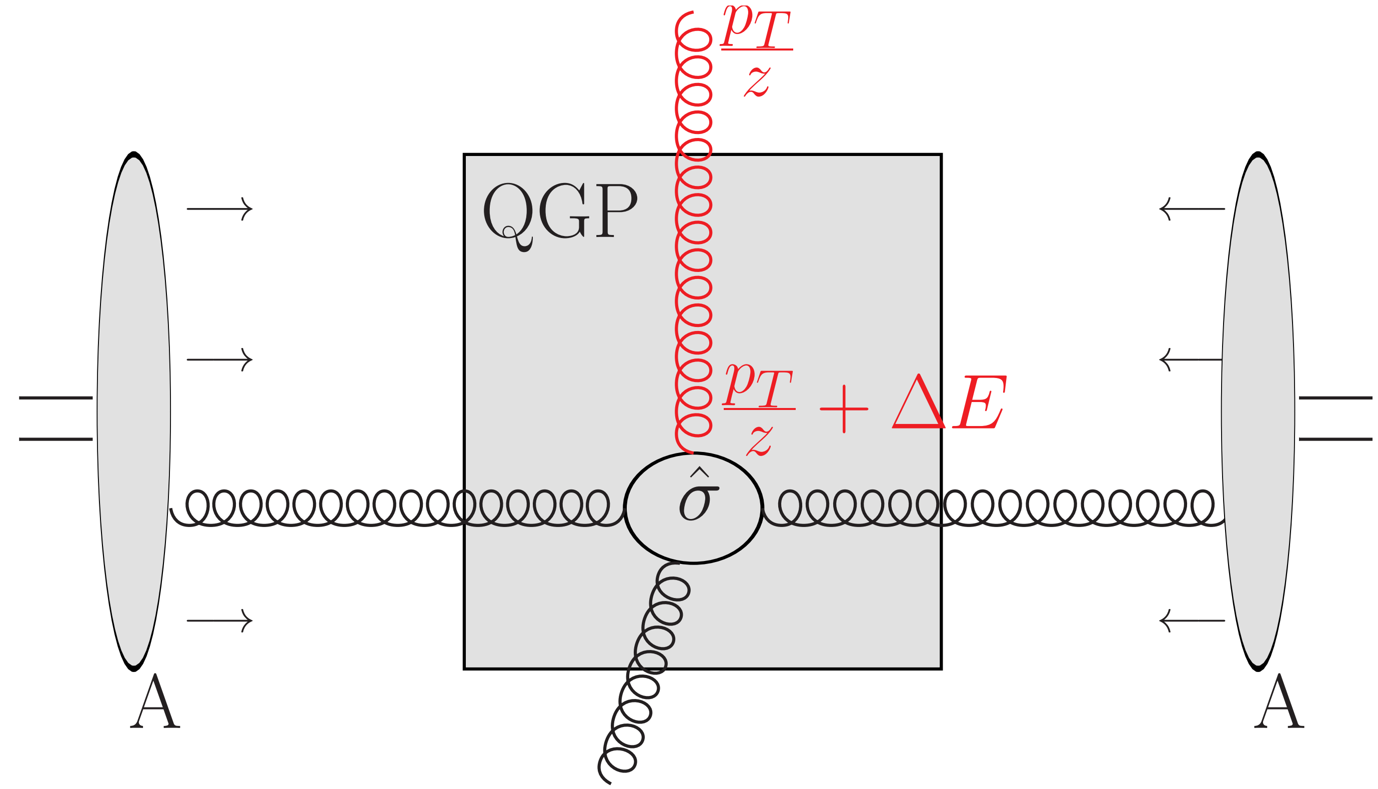
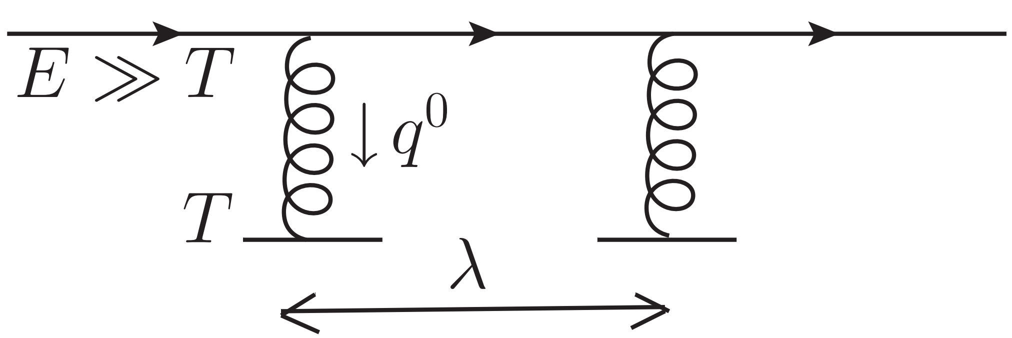
- medium-induced parton energy loss

→ *jet-quenching* in A-A collisions

→ QGP signal (Bjorken, 1982)



- Bjorken estimated *collisional* energy loss



→ $\Delta E_{\rm coll} \sim \frac{L}{\lambda} \cdot \langle q^0 \rangle$

$$\Delta E_{\rm coll} \sim \alpha_s^2 T^2 \, L \, \log\left(\frac{ET}{\mu^2}\right)$$

✦ parton energy loss should be relevant when partonic subprocess occurs in *any* nuclear medium

nuclear medium = hot QGP or cold nucleus

✦ usually, one calls «anomalous nuclear effects» those responsible for $R_{\mathrm{pA}}, R_{\mathrm{AA}} \neq 1$

$$R_{\mathrm{AA}}(p_T, y, \ldots) = \frac{\text{yield in AA}}{n_{coll}^{\mathrm{AA}} \cdot (\text{yield in pp})}$$

→ $R_{\mathrm{pA}}, R_{\mathrm{AA}}$ sensitive to *medium-induced* loss

$$\Delta E = \Delta E_{\mathrm{med}} - \Delta E_{\mathrm{vac}}$$

- *radiative loss* might be dominant
  Gyulassy & Wang (1993)

- in following, basics of $\Delta E_{\rm rad}$ in QCD medium:

  - law $\Delta E_{\rm rad} \propto L^2$ (for static medium) is valid for specific case of *particle suddenly produced in medium*

  - for a parton prepared long before the target and scattered to small angle, $\Delta E_{\rm rad}$ arises from

    fully coherent gluon radiation

$$\Delta E_{\rm coh} \propto \alpha_s \frac{\sqrt{\Delta q_\perp^2(L)}}{Q_{\rm hard}} E$$

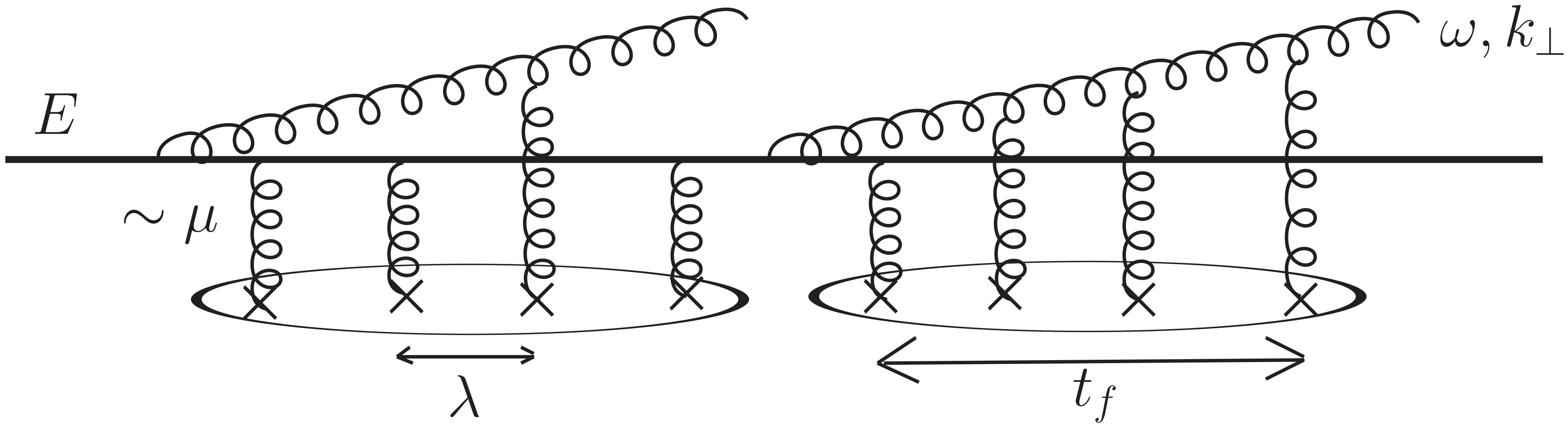
- although simple to evaluate, coherent energy loss is a *non-trivial* effect:
  - looks higher-twist: $\Delta E_{\rm coh}$ is suppressed by a power of $Q_{\rm hard}$ and process-dependent
  - but $\Delta E_{\rm coh}$ suppressed by *odd* power of $Q_{\rm hard}$
- at large energy, $\Delta E_{\rm coh} \propto E$ can have drastic consequences on phenomenology

for instance: quarkonium nuclear suppression

→ see talk of François Arleo

generalization of LPM effect to QCD (Baier *et al*, 94)

'asymptotic color charge'

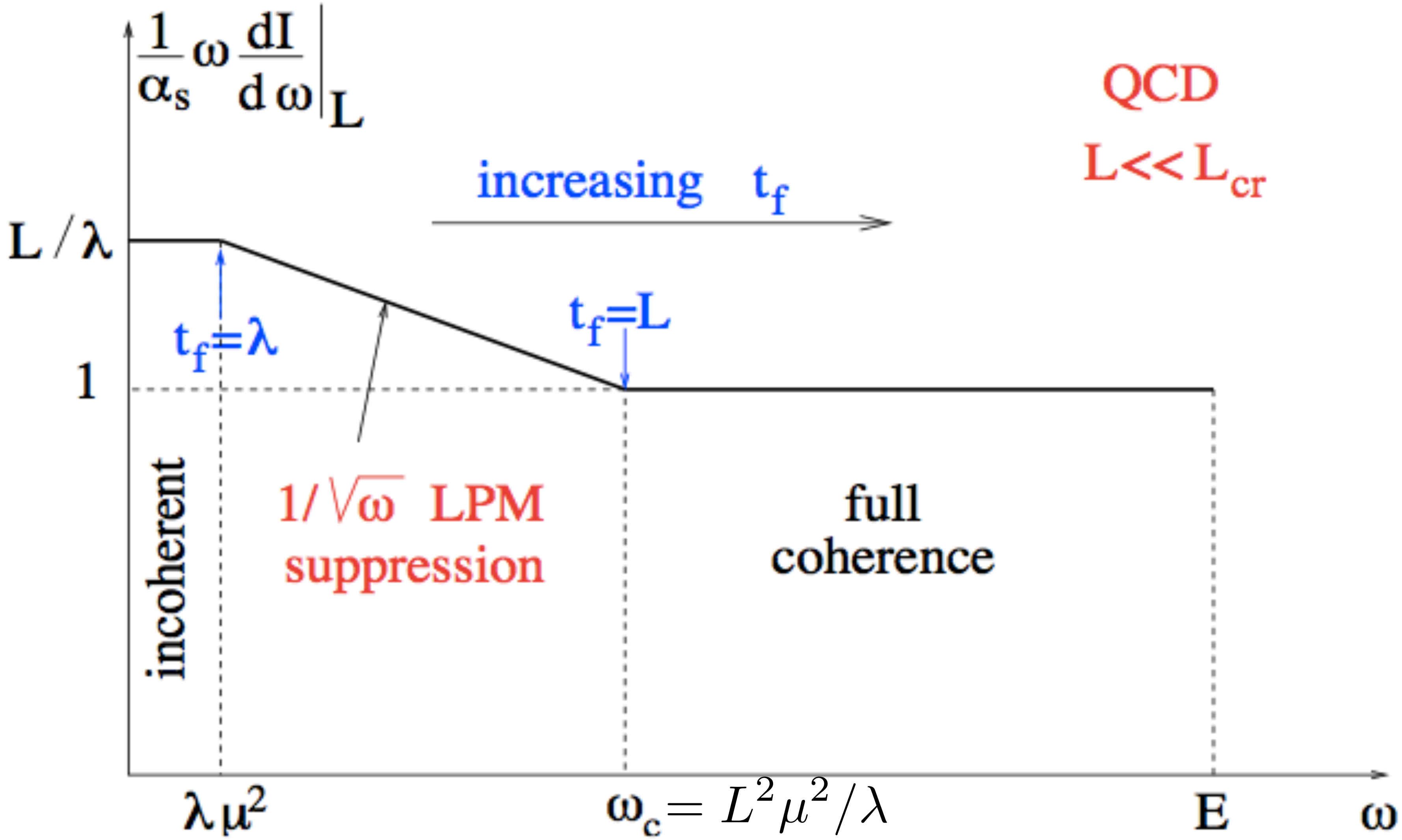


$$t_f \sim \frac{\omega}{k_\perp^2} \sim \frac{\omega}{q_\perp^2(t_f)} \sim \frac{\omega}{\mu^2 t_f/\lambda} \Rightarrow \boxed{t_f \sim \sqrt{\frac{\omega\lambda}{\mu^2}}}$$

$$\Rightarrow \omega\frac{dI}{d\omega}\Big)_L \sim \frac{L}{t_f}\cdot\omega\frac{dI}{d\omega}\Big)_{\text{GB},\,\mu_{eff}} \sim \frac{L}{t_f}\cdot\alpha_s \sim \alpha_s\sqrt{\frac{\omega_c}{\omega}}$$

LPM suppression in QCD $\sim 1/\sqrt{\omega}$

for $\lambda < t_f < L \Leftrightarrow \lambda\mu^2 < \omega < \omega_c \equiv \frac{L^2\mu^2}{\lambda}$



average loss $\Delta E = \int_0^E \mathrm{d}\omega\,\omega\frac{\mathrm{d}I}{\mathrm{d}\omega}\big)_L$:

limit $E \to \infty$ at fixed L

$$\omega_c \ll E \Leftrightarrow L \ll L_{cr} \equiv \sqrt{\lambda E/\mu^2}$$

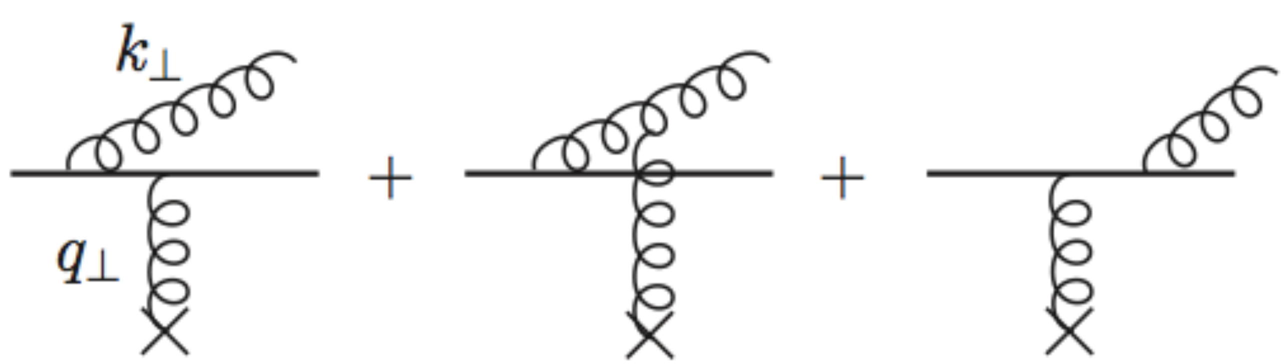
→ *fully coherent domain* $t_f \gg L$ *dominates*

$$\Rightarrow \quad \Delta E \sim \underbrace{\alpha_s E \log\left(\frac{q_\perp^2(L)}{\Lambda^2}\right)}_{\text{fully coherent } (t_f \gg L)} + \underbrace{\mathcal{O}\left(\alpha_s \frac{\mu^2}{\lambda} L^2\right)}_{\text{LPM } (t_f \lesssim L)}$$

the log arises from $k_\perp$-integral:

$t_f \gg L \Rightarrow$ whole medium acts as single effective scatterer

$\Rightarrow \omega \mathrm{d}I/\mathrm{d}\omega$ obtained from Gunion-Bertsch spectrum induced by single scattering:

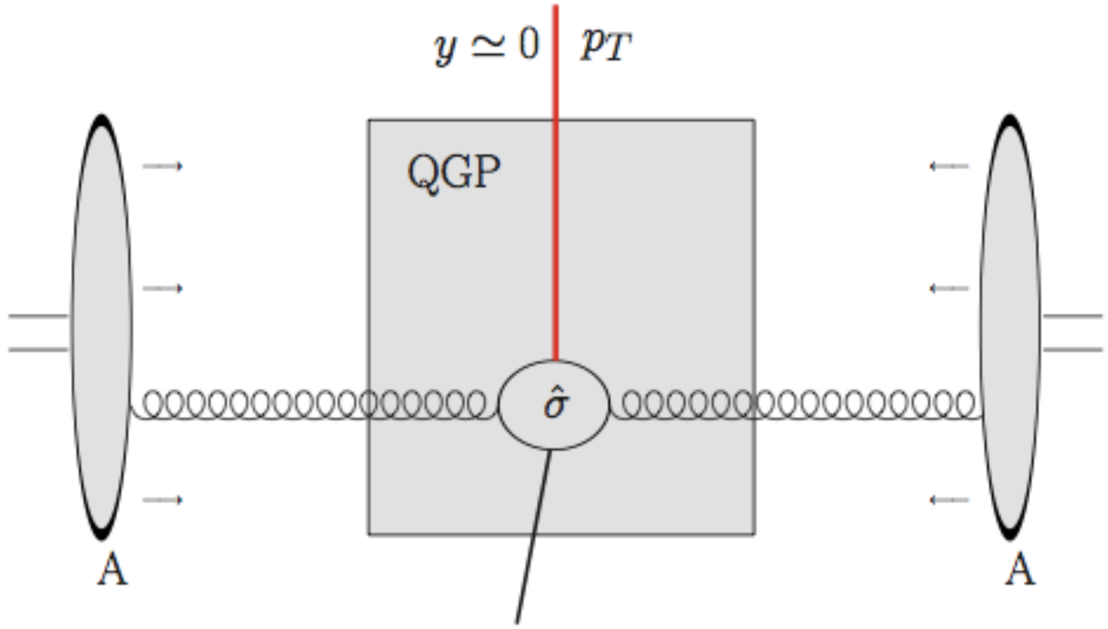


$$\Rightarrow \quad \omega \frac{\mathrm{d}I}{\mathrm{d}\omega\, \mathrm{d}^2\boldsymbol{k}} \sim \alpha_s \frac{\boldsymbol{q}^2}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2}$$

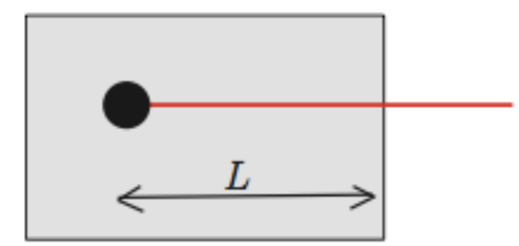
by replacing $q_\perp^2 \to q_\perp^2(L) \sim \mu^2 \frac{L}{\lambda} \Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \int_{\Lambda^2}^{q_\perp^2(L)} \frac{\mathrm{d}\boldsymbol{k}^2}{\boldsymbol{k}^2}$

Why is fully coherent term ΔE_{coh} rarely discussed?

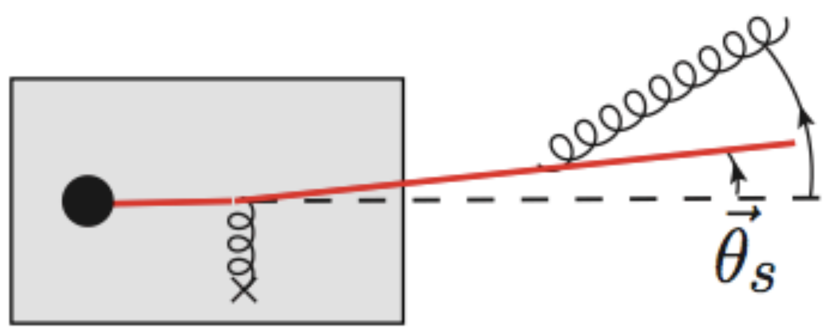
- main focus has been on parton ΔE through QGP:



$\sim$ particle suddenly accelerated in a medium



$t_f \gg L \Rightarrow$



$\sim \int \frac{\mathrm{d}^2\vec{\theta}}{(\vec{\theta}-\vec{\theta}_s)^2}$ L-independent

$\Rightarrow t_f \gg L$ cancels in $\omega \frac{dI}{d\omega}\Big)_{\text{ind}} \equiv \omega \frac{dI}{d\omega}\Big)_L - \omega \frac{dI}{d\omega}\Big)_{L=0}$

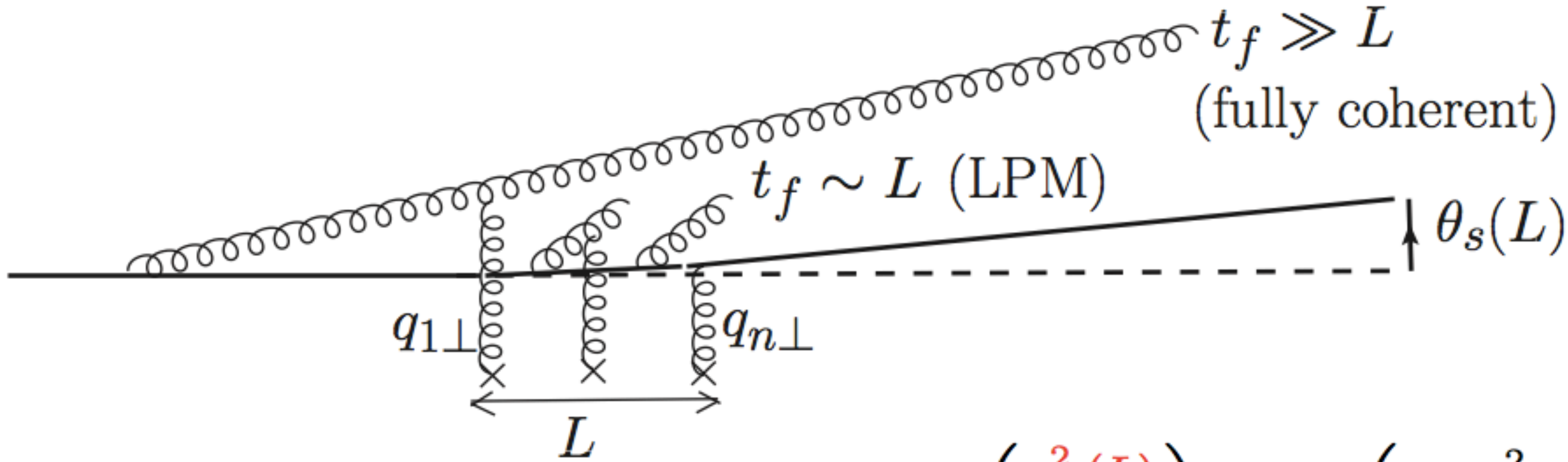
$\Rightarrow$ no fully coherent term in this case

$$\Rightarrow t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \Rightarrow \Delta E \sim \alpha_s \langle \omega \rangle \sim \alpha_s L \langle k_\perp^2 \rangle \sim \alpha_s L\, q_\perp^2(L)$$

$$\boxed{\Delta E \sim \Delta E_{\text{LPM}} \sim \alpha_s \frac{\mu^2}{\lambda} L^2}$$

Baier *et al.* (96)
Zakharov (97)

- back to 'asymptotic parton', L fixed, $E \to \infty$:



$$\Delta E \sim \Delta E_{coh} + \Delta E_{\text{LPM}} \sim \alpha_s E \log\left(\frac{q_\perp^2(L)}{\Lambda^2}\right) + \mathcal{O}\left(\alpha_s \frac{\mu^2}{\lambda} L^2\right)$$

does ΔE_{coh} cancel in *medium-induced* loss?

$$\Delta E_{ind} \equiv \Delta E(L_A) - \Delta E(L_p) \stackrel{?}{=} \alpha_s \frac{\mu^2}{\lambda}(L_A^2 - L_p^2)$$

it *does* in a specific setup Brodsky & Hoyer 93

QED *and* $q_\perp^2(L_A) = q_\perp^2(L_p) \Rightarrow \Delta E \propto E^0$ when $E \to \infty$

'bound on energy loss'

- ΔE_{coh} *does not* cancel in QCD:

in practice, $\sigma_{\rm pA}$ and $\sigma_{\rm pp}$ are either inclusive in p_T or compared in some p_T -bin

$$\delta p_T|_{\rm bin} \sim 1\,{\rm GeV} \gtrsim \mu_{eff}(L) \sim \sqrt{\hat{q}\,L} \quad (\hat{q} \equiv \frac{\mu^2}{\lambda})$$

(take $\hat{q}_{cold} \simeq 0.08\,{\rm GeV}^2/{\rm fm}$)

$\rightarrow$ sufficiently inclusive to have, within a p_T-bin:

$$q_\perp^2(L_A) \simeq q_\perp^2(L_p) + \hat{q}(L_A - L_p)$$

$$\Rightarrow \Delta E_{coh,\,ind} \propto \alpha_s E \log\left(\frac{q_\perp^2(L_A)}{q_\perp^2(L_p)}\right) = \alpha_s E \log\left(1 + \frac{\Delta q_\perp^2}{q_\perp^2(L_p)}\right)$$

remark:

suppression $\sim 1/q_\perp^2(L_p)$ is specific to above model: ‘asymptotic parton’ undergoing soft rescatterings

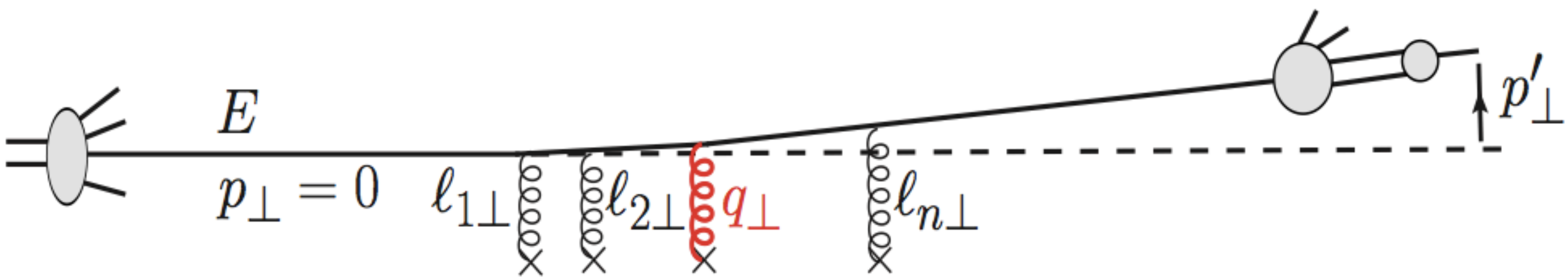
QCD: asymptotic charges do not exist

color charge must be resolved via *hard* PQCD process

does $\Delta E_{coh} \propto E$ extend to realistic QCD situation?

Arleo, S.P., Sami 2011; Arleo, S.P. 2012;

high-energy p-A collision in nucleus rest frame



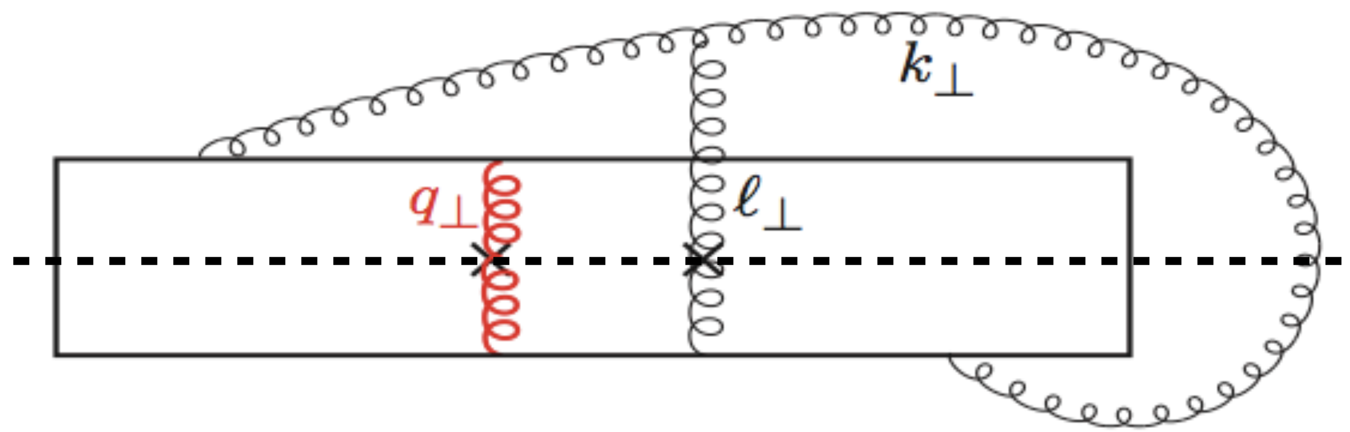
- tag energetic hadron with $p'_\perp|_{\rm hard} \gg \sqrt{\hat{q}L}$ $\quad (\hat{q} \equiv \frac{\mu^2}{\lambda})$
- energetic parent parton suffers:
  - *single* hard exchange $q_\perp \simeq p'_\perp$
  - soft rescatterings: $\ell_\perp^2 = (\sum \vec{\ell}_{i\perp})^2 \sim \hat{q}L \ll q_\perp^2$

use *opacity expansion* (Gyulassy, Levai & Vitev 2000)

to derive $\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{ind}$ (S.P., Arleo & Kolevatov, work in progress)

- order $n = 1$ in opacity ($L \ll \lambda$) (focus on $t_f \gg L$)

generic diagram



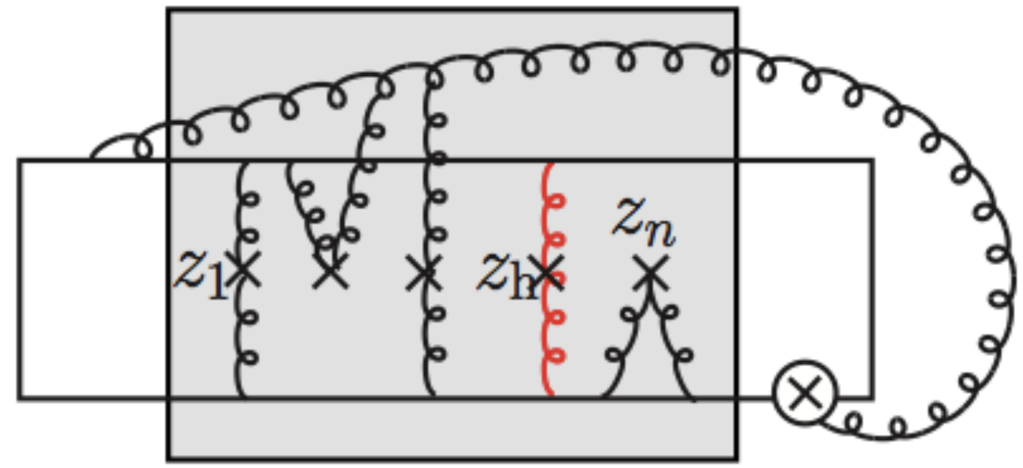
$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L \ll \lambda} \sim \alpha_s \frac{L}{\lambda} \int \mathrm{d}^2\boldsymbol{k} \int \mathrm{d}^2\boldsymbol{\ell}\, V(\boldsymbol{\ell}) \left[\frac{\boldsymbol{k}}{\boldsymbol{k}^2} - \frac{\boldsymbol{k}-\boldsymbol{\ell}}{(\boldsymbol{k}-\boldsymbol{\ell})^2} \right] \cdot \frac{\boldsymbol{k}-x\boldsymbol{q}}{(\boldsymbol{k}-x\boldsymbol{q})^2}$$

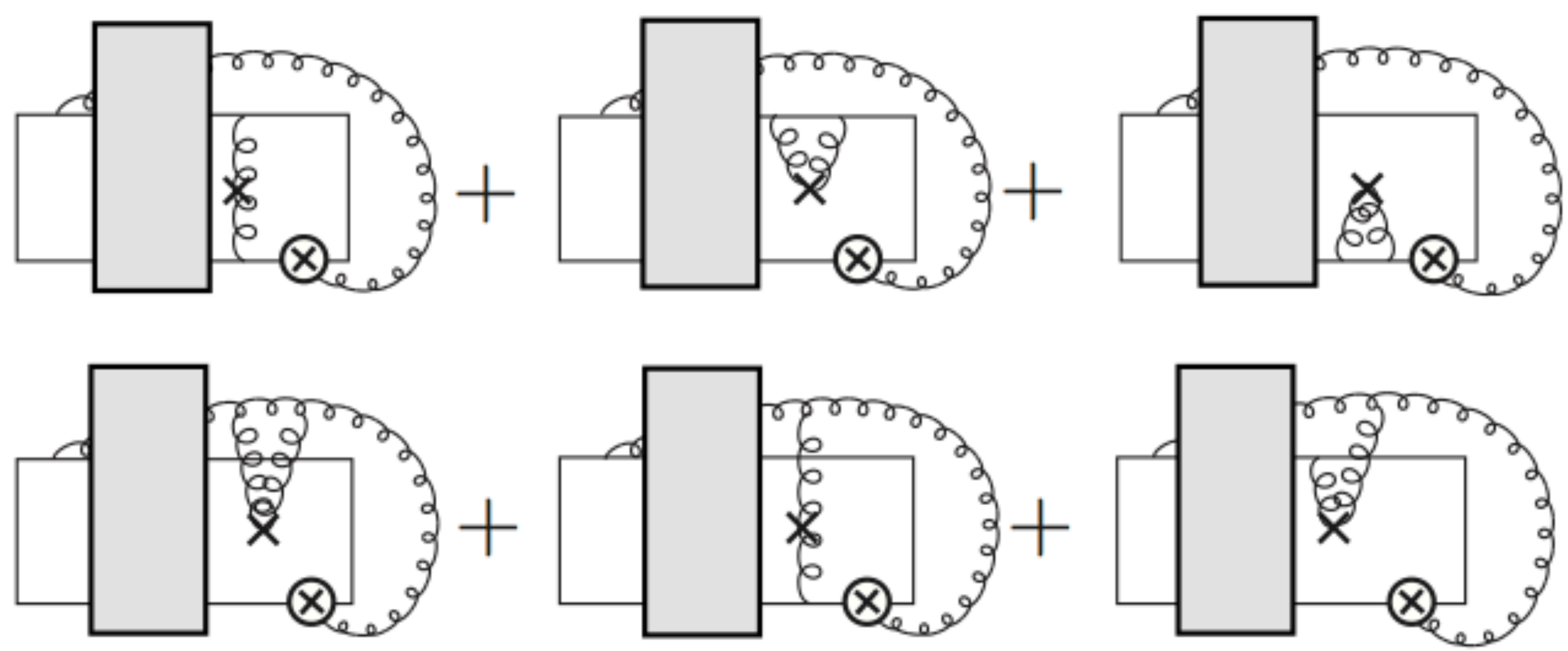
$$x \equiv \frac{\omega}{E}; \quad V(\boldsymbol{\ell}) = \frac{\mu^2}{\pi(\boldsymbol{\ell}^2+\mu^2)^2}$$

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L \ll \lambda} \sim \alpha_s \frac{L}{\lambda} \log\left(1 + \frac{\mu^2 E^2}{q_\perp^2 \omega^2}\right)$$

$$\Delta E\big|_{L \ll \lambda} \sim \alpha_s \frac{L}{\lambda} \cdot \frac{\mu}{q_\perp} E$$

- all orders in opacity ($L \gg \lambda$) ($t_f \gg L$)

$C_n(k, \{\ell_i\}) = 2\text{Re}$ 

$C_{n+1} = 2\text{Re}\{$  $\}$

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L \gg \lambda} = \frac{N_c \alpha_s}{\pi} S[\Omega; r]; \quad \Omega \equiv \frac{x q_\perp}{\mu}; \quad r \equiv \frac{L}{\lambda_g}$$

$$S[\Omega; r] = \int_0^\infty \frac{\mathrm{d}B^2}{B^2} \mathrm{J}_0(\Omega B) \left\{1 - \exp\left[-r\left(1 - B\,\mathrm{K}_1(B)\right)\right]\right\}$$

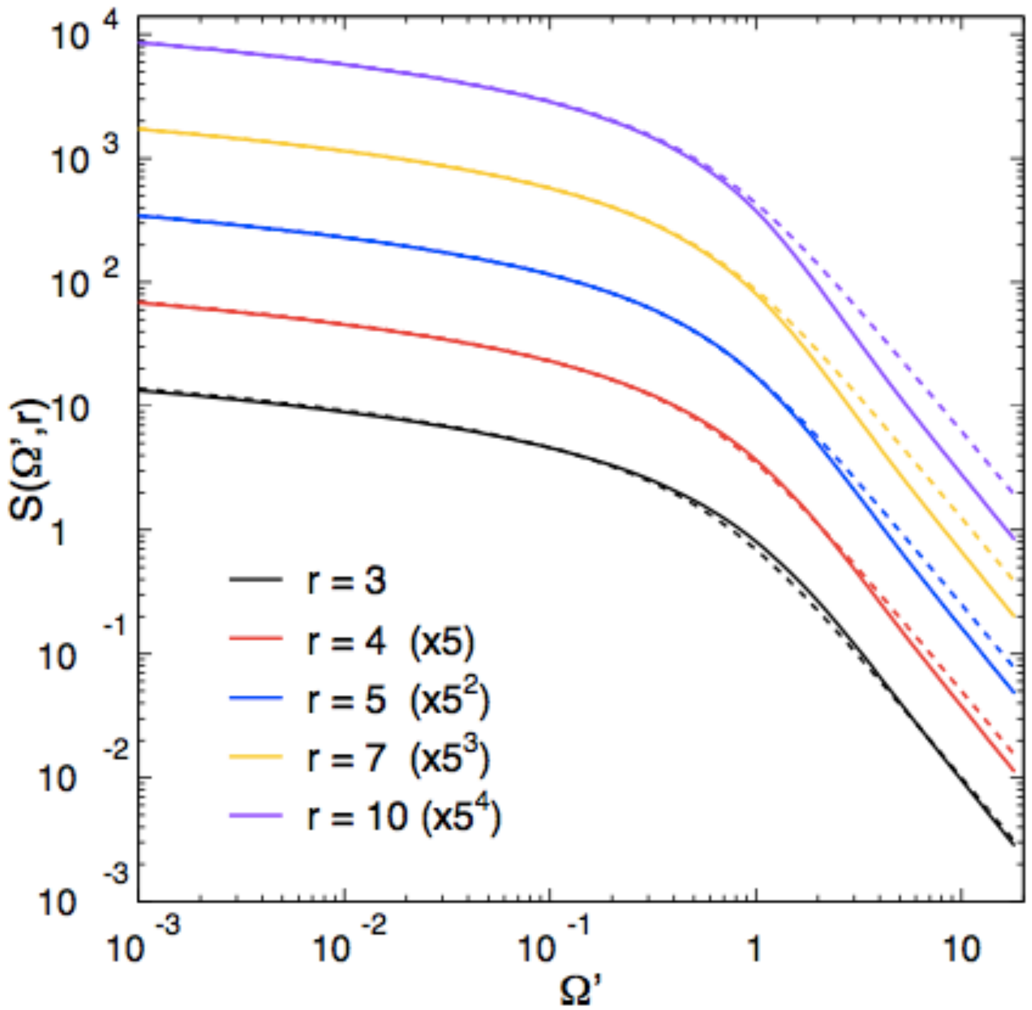
a simple approximation can be inferred from $n = 1$ result

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L \ll \lambda} = \frac{N_c \alpha_s}{\pi} \frac{L}{\lambda} \log\left(1 + \frac{\mu^2 E^2}{q_\perp^2 \omega^2}\right)$$

by replacing $\frac{L}{\lambda} \to 1$ and $\mu^2 \to \mu^2 \frac{L}{\lambda}$

$$\Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L \gg \lambda,\ appr} \simeq \frac{N_c \alpha_s}{\pi} \log\left(1 + \frac{\hat{q} L\, E^2}{q_\perp^2 \omega^2}\right)$$

(color factor corresponds to fast *gluon*)



$$\left(\Omega' \equiv \frac{\Omega}{\sqrt{r \log r}}\right)$$

$S[\Omega; r]$ (solid lines) compared to $S_{appr}[\Omega; r]$ (dashed lines)

$$\Delta E|_{L \gg \lambda} \propto N_c \alpha_s \frac{\sqrt{\hat{q} L}}{q_\perp} E$$

✦ *fully coherent* gluon radiation arises from:

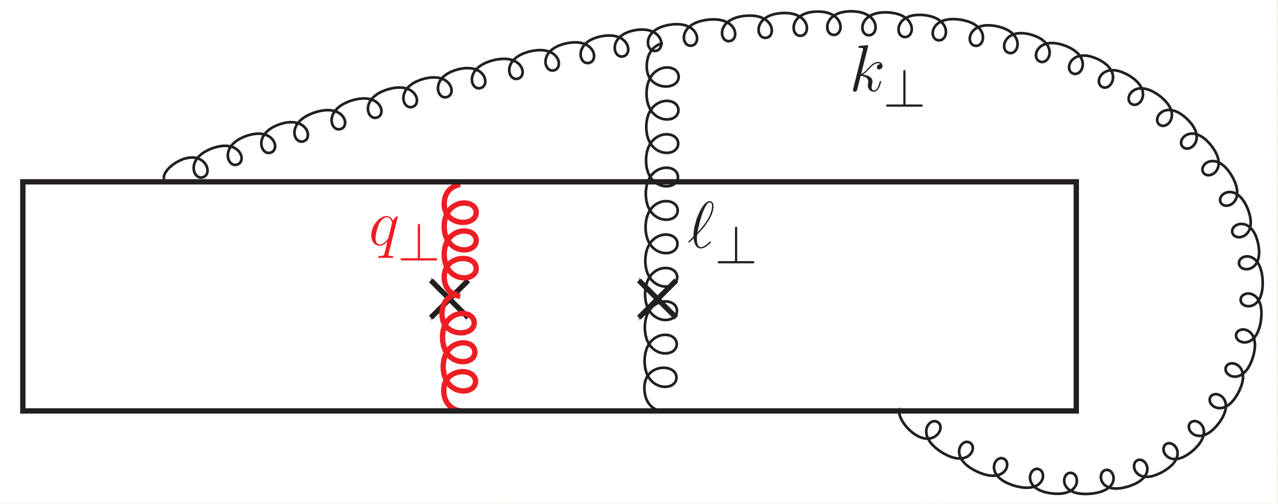
- $\omega \sim \dfrac{\Delta q_\perp}{Q_{\rm hard}} E \ll E \quad \text{and} \quad k_\perp \sim \Delta q_\perp$

(radiated gluon must 'see' a difference between pA and pp in the transverse displacement of parton-gluon fluctuation:

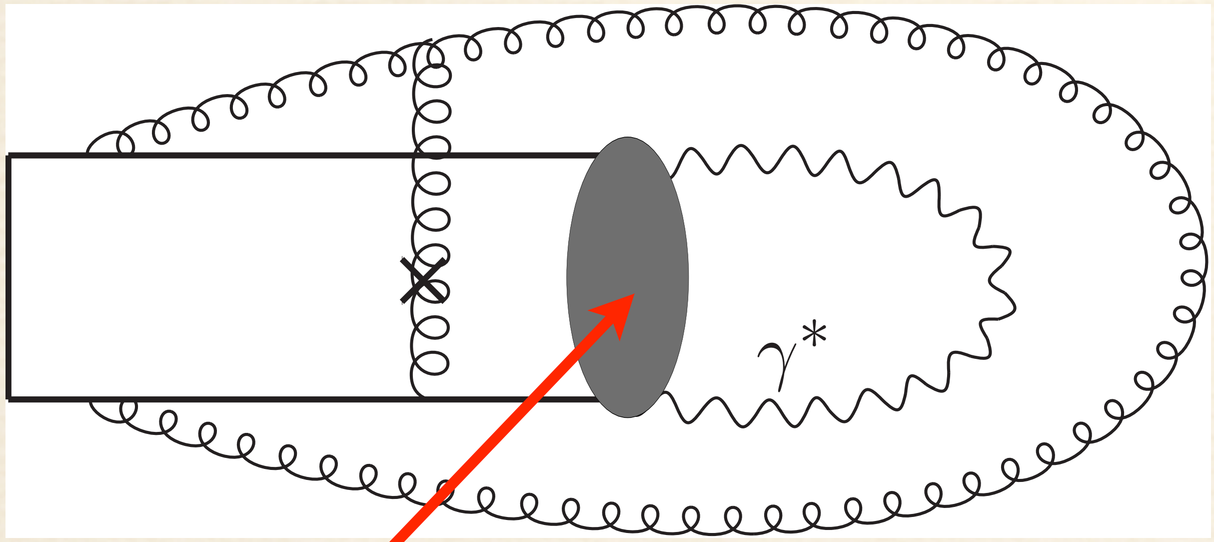
$$\Rightarrow \; k_\perp^{-1} \sim (\Delta q_\perp/\omega)\, t_f \Rightarrow k_\perp \sim \Delta q_\perp \;)$$

$$\Rightarrow t_f \sim \frac{\omega}{k_\perp^2} \sim \frac{E}{\Delta q_\perp \cdot Q_{\rm hard}} \gg L$$

- interference between initial and final state emission:



- coherent energy loss looks «higher-twist»
  - $\Delta E_{\rm coh}$ is suppressed by a power of $Q_{\rm hard}$
  - $t_f \sim \dfrac{E}{\Delta q_\perp \cdot Q_{\rm hard}} \gg t_{\rm hard} \sim \dfrac{E}{Q^2_{\rm hard}}$
  - $\Delta E_{\rm coh}$ is process-dependent
    - for a fast quark, color factor $\propto 1/N_c$
    - effect is absent when no color charge is produced in the hard process:



hard process

in this case radiation is purely from initial state, and $t_f \gg L$ cancels out, giving

$$\Delta E_{\rm initial} \sim L^2$$

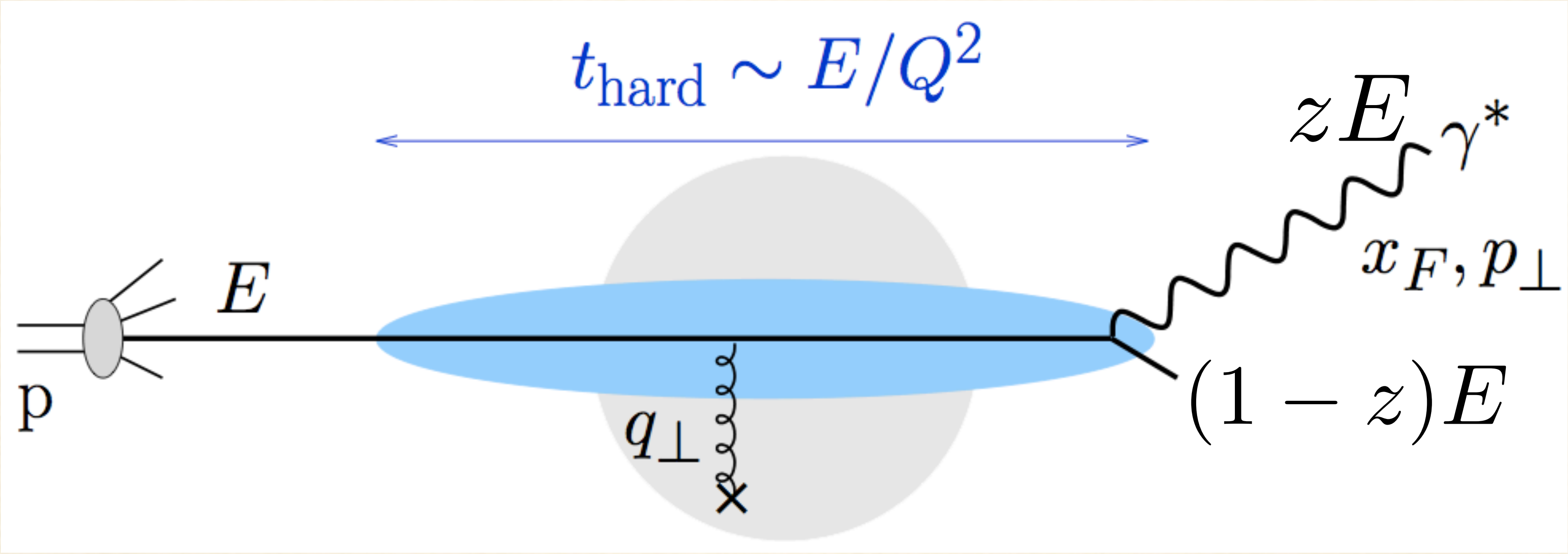
(S.P., Arleo, Kolevatov)

✦ $\Delta E_{\rm coh}$ suppressed by *odd* power of $Q_{\rm hard}$

$\Rightarrow$ cannot be reached in standard twist expansion

Qiu & Sterman

no such effect is expected in Drell-Yan process:



At high energy in the target rest frame:

DY $\sim$ bremsstrahlung of γ^* and $\sigma_{\rm DY} \leftrightarrow \sigma_{\rm dipole}$

Kopeliovich 95; Brodsky, Hebecker, Quack 96

- as in DIS, the DY cross section is dominated by:
  - 'aligned-jet' configuration: $1 - z \sim \Lambda^2/Q^2$

    in this region there *might* be some coherent energy loss in DY, but bounded by $1/Q^2$

$$\frac{\Delta E}{E} < 1 - z \sim \frac{\Lambda^2}{Q^2} \ll \frac{\sqrt{\hat{q}L}}{Q}$$

  - symmetric region: $z \sim 1 - z$

    in this region $\frac{\Delta E}{E} \sim \mathcal{O}(1)$ is possible, but there is a factor $1/Q^2$ to pay for each dipole rescattering

$\Delta E_{coh} \propto E$ *has been widely ignored, probably due to:*

- $\Delta E_{coh} = 0$ for a parton created in a medium
- belief that Brodsky-Hoyer bound is universal

when partonic subprocess is equivalent to small angle scattering of fast color charge, $\Delta E_{\rm coh}$ *is the dominant contribution to* ΔE

⟹ crucial in phenomenology

(François Arleo's talk)