Parton energy loss: an update

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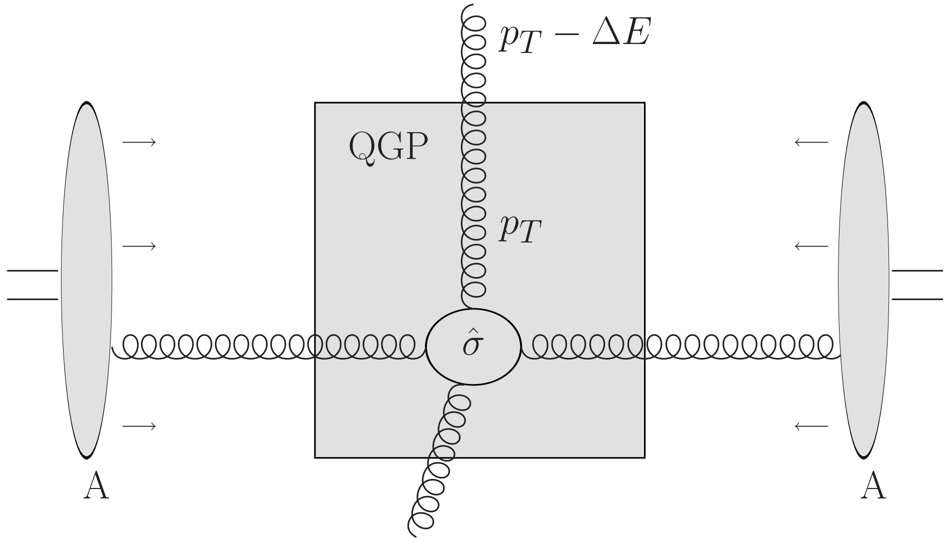
Rencontres QGP-France 2013

Etretat – Sept. 9-11

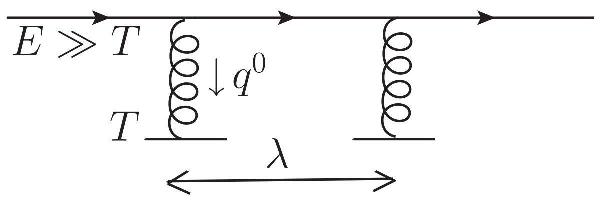
- *medium-induced parton energy loss* Bjorken (1982)



$\longrightarrow$ jet-quenching

$\longrightarrow$ QGP signal

- Bjorken estimated parton *collisional* loss



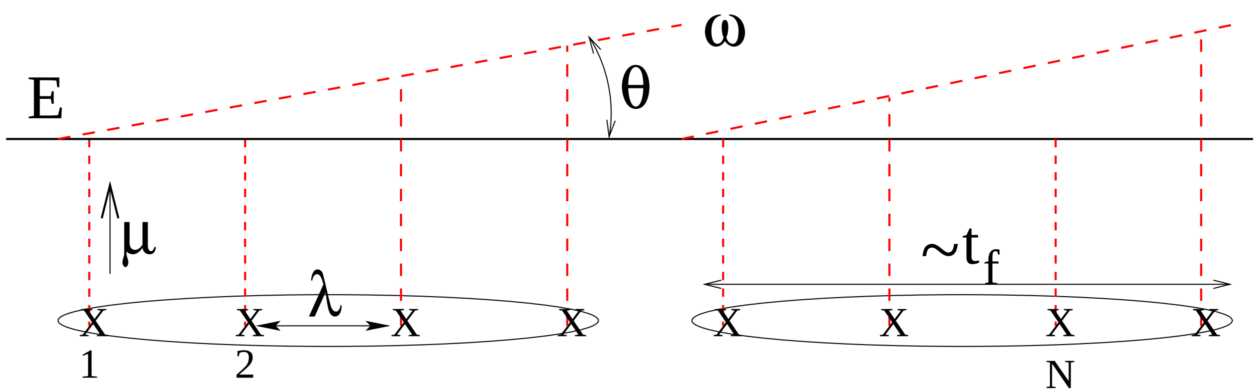
$$\Rightarrow \quad \Delta E_{coll} \sim \frac{L}{\lambda} \cdot \langle q^0 \rangle$$

$$\Delta E_{coll} \sim \frac{L}{\lambda \sigma_{el}} \int \mathrm{d}t \, \frac{\mathrm{d}\sigma_{el}}{\mathrm{d}t} \, q^0 \sim L\rho \int_{t_{min}}^{t_{max}} \mathrm{d}t \, \frac{\alpha_s^2}{t^2} \, \frac{t}{T}$$

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

radiative loss might be dominant Gyulassy, Wang (93)

$\longrightarrow$ generalization of LPM effect to QCD Baier *et al.* (94)

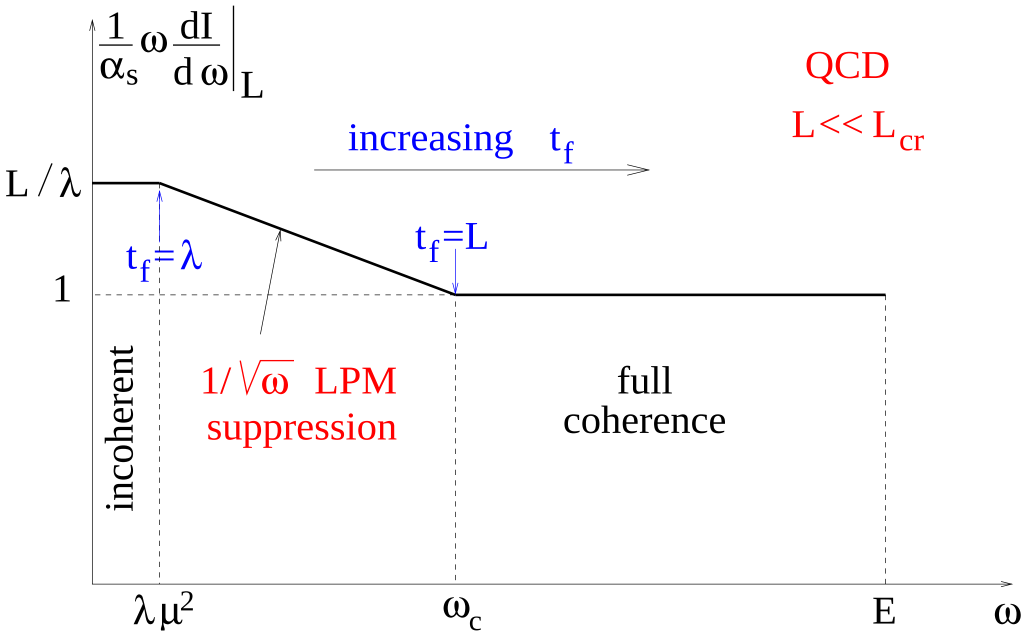


$$t_f \sim \frac{\omega}{k_\perp^2} \gg \lambda \quad \Rightarrow \quad \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \frac{L}{t_f} \cdot \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_1 \sim \frac{L}{t_f} \cdot \alpha_s$$

$$t_f \sim \frac{\omega}{k_\perp^2(t_f)} \sim \frac{\omega}{\mu^2 t_f/\lambda} \Rightarrow t_f \sim \sqrt{\frac{\omega\lambda}{\mu^2}} \Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \alpha_s \sqrt{\frac{\omega_c}{\omega}}$$

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

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



average loss:

$$\Delta E = \int_0^E \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L$$

- large medium: $L > L_{cr} \equiv \sqrt{\frac{\lambda E}{\mu^2}} \Leftrightarrow \omega_c > E$

$$\Rightarrow \Delta E \sim \int^E d\omega\, \alpha_s \sqrt{\omega_c/\omega} \sim \alpha_s L \sqrt{\frac{\mu^2}{\lambda} E}$$

- small $L < L_{cr} \Leftrightarrow \omega_c < E$ (or: $E \to \infty$ at fixed L)

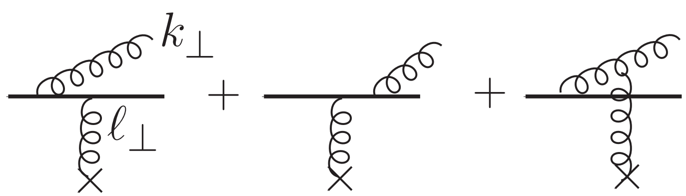
$\Rightarrow$ fully coherent domain $t_f \gg L$ dominates

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

- 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:

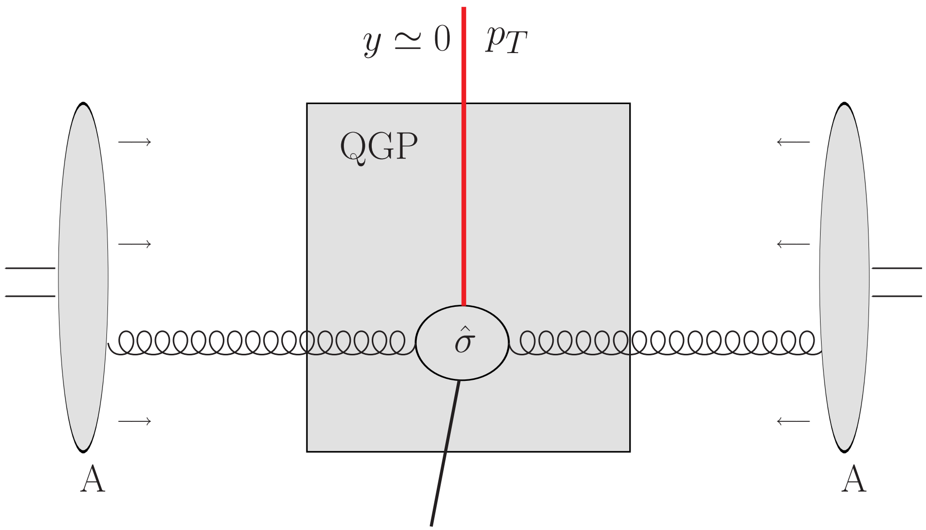


$$\Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega\, \mathrm{d}^2\vec{k}_\perp} \sim \alpha_s \frac{\ell_\perp^2}{k_\perp^2 (\vec{k}_\perp - \vec{\ell}_\perp)^2}$$

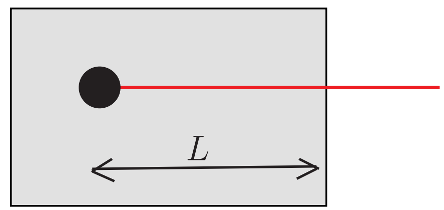
by replacing $\ell_\perp^2 \to \ell_\perp^2(L) \sim \mu^2 \frac{L}{\lambda} \Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \sim \alpha_s \int_{\Lambda^2}^{\ell_\perp^2(L)} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}$

Why is the fully coherent term ΔE_{coh} never discussed?

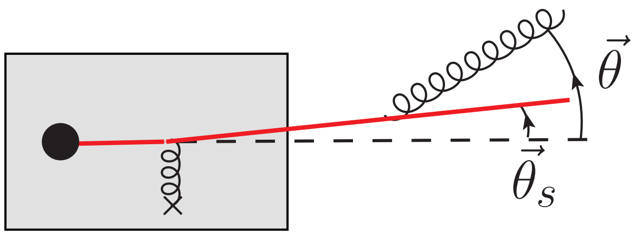
- main focus has been on parton ΔE through QGP:



$\sim$ particle suddenly accelerated in a medium



suppose radiation with $t_f \gg L$:



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

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

no fully coherent term in this case

$$\Rightarrow t_f \sim \frac{\omega}{k_\perp^2} \lesssim L$$

$$\Rightarrow \Delta E_{\rm LPM} \sim \alpha_s \langle \omega \rangle \sim \alpha_s L \langle k_\perp^2 \rangle \sim \alpha_s L \, \ell_\perp^2(L)$$

$$\Delta E_{\rm LPM} \sim \alpha_s \frac{\mu^2}{\lambda} L^2$$

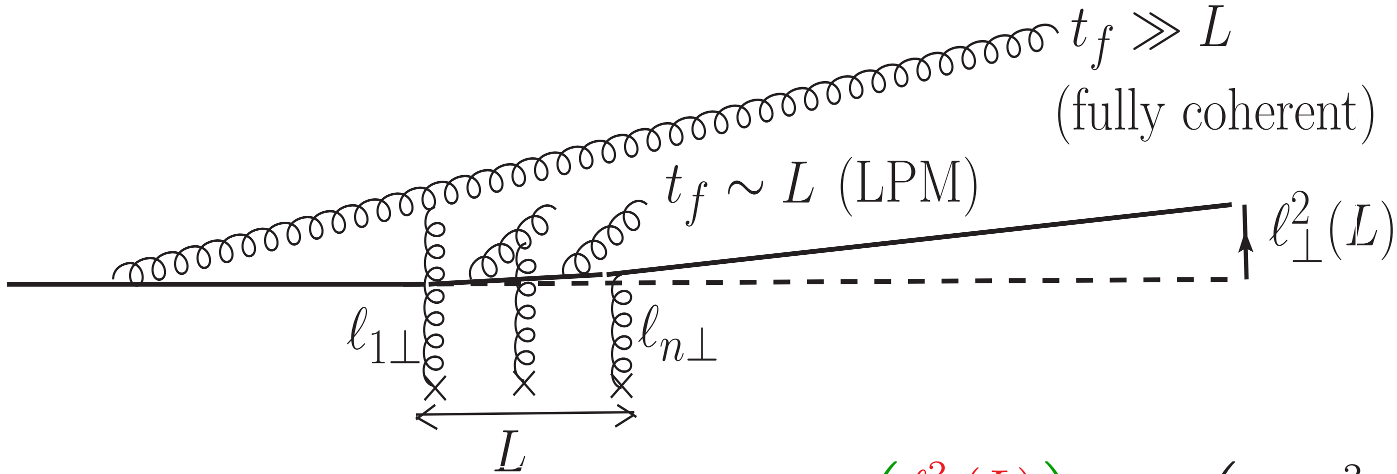
Baier *et al.* (96)
Zakharov (97)

- remark:

in present case radiative loss is dominated by $\Delta E_{\rm LPM} \sim L^2$ independent of E

$\Rightarrow \Delta E_{rad} \gg \Delta E_{coll}$ not guaranteed here

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



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

ΔE_{coh} claimed to cancel in *medium-induced* loss

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

$\longrightarrow$ ‘bound on energy loss’ Brodsky & Hoyer 93

B & H assume very specific setup:

QED model *and* $\ell_\perp^2(L_A) = \ell_\perp^2(L_p)$

(i) in practice, σ_{pA} and σ_{pp} are compared in some p_T-bin of width:

$$\delta p_T \sim 1\,\mathrm{GeV} \gtrsim \sqrt{\hat{q}_{cold}\, L} \quad (\hat{q}_{cold} \simeq 0.08\,\mathrm{GeV}^2/\mathrm{fm})$$

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

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

(ii) in QCD, even when $\ell_\perp^2(L_A) = \ell_\perp^2(L_p)$, fully coherent radiation can occur due to parton *color rotation*

$\longrightarrow$ 'B-H bound on energy loss' does not apply to asymptotic color charge

$$\Rightarrow \Delta E_{coh,\ ind}\,(\mathrm{asymp.\ parton}) \propto E$$

QCD: asymptotic charges do not exist

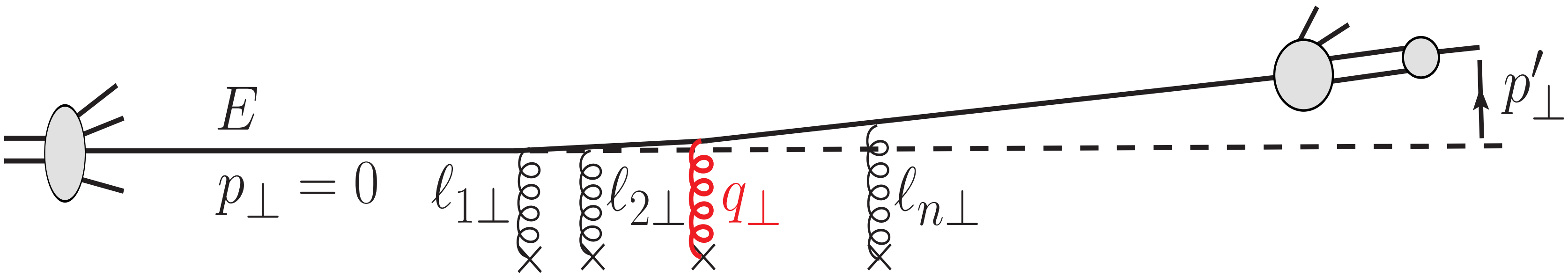
color charge must be resolved via *hard* PQCD process

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

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

S.P., Arleo, Kolevatov (work in progress)

- high-energy p-A collision in nucleus rest frame



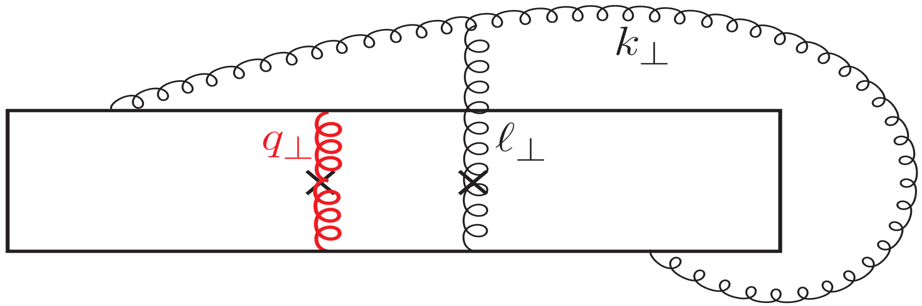
- tag on final energetic hadron with $p'_\perp\big|_{\rm hard} \gg \sqrt{\hat{q}L}$
- energetic parent parton suffers:
  - *single* hard exchange $q_\perp \simeq p'_\perp$
  - soft rescatterings: $\ell_\perp^2 = (\sum \vec{\ell}_{i\perp})^2 \sim \hat{q}L \ll q_\perp^2$

$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{ind}$ rigorously derived using *opacity expansion*

Gyulassy, Levai, Vitev 2000

look for $t_f \gg L$

- order $n = 1$ in opacity ($L \ll \lambda$)



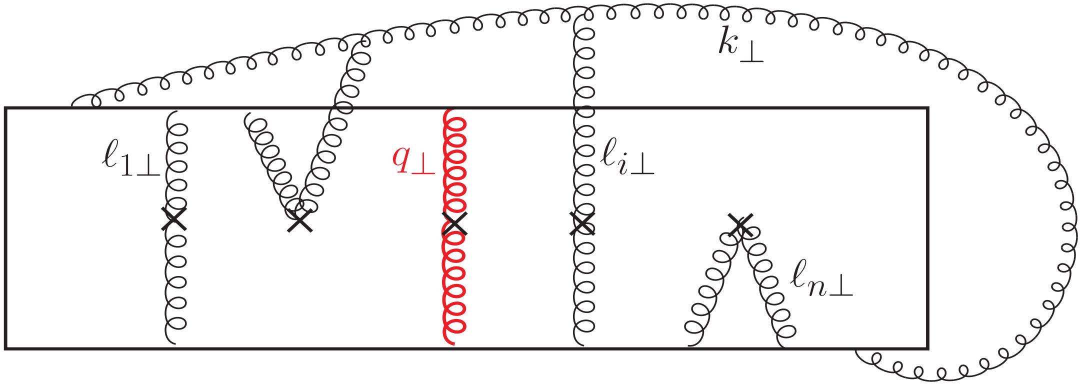
$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{L\ll\lambda} \sim \alpha_s \frac{L}{\lambda} \int \mathrm{d}^2\boldsymbol{k} \int \mathrm{d}^2\boldsymbol{\ell}\, V(\boldsymbol{\ell}) \left[\frac{\boldsymbol{k}}{\boldsymbol{k}^2} - \frac{\boldsymbol{k}-\boldsymbol{\ell}}{(\boldsymbol{k}-\boldsymbol{\ell})^2}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

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

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

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

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



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

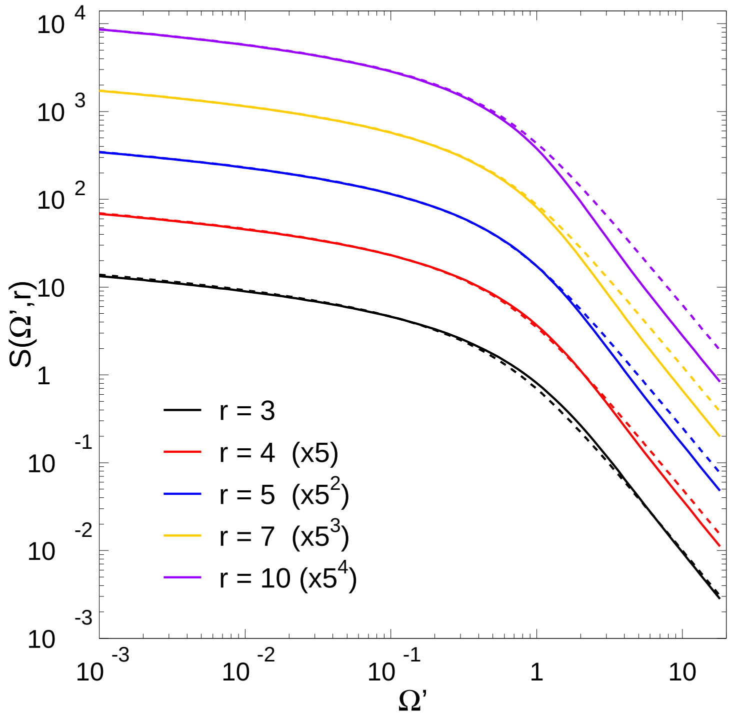
$$S[\Omega; r] = \int_0^\infty \frac{\mathrm{d}B^2}{B^2}\, \mathrm{J}_0(\Omega B)\left\{1 - \exp\left[-r\left(1 - B\,\mathrm{K}_1(B)\right)\right]\right\}$$

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 $\mu^2 \to \mu^2 \frac{L}{\lambda}$

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



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

$$\Delta E|_{L \gg \lambda} \propto N_c \alpha_s \frac{\sqrt{\ell_\perp^2(L)}}{q_\perp} E$$

summary

- *it is probably because of*
  - $\Delta E_{coh} = 0$ for a parton created in a medium (true)
  - spread belief that “B-H bound is universal” (wrong)

  that fully coherent loss $\Delta E_{coh} \propto E$ has been missed

- *when partonic subprocess $\sim$ small-angle scattering of fast parton, the previously missed $\Delta E_{coh} \propto E$ is the dominant contribution to ΔE and should thus have drastic consequences on phenomenology*

for instance: J/ψ nuclear suppression in p-A collisions

$\rightarrow$ see François’ talk this afternoon