Gluon radiation by heavy quarks at intermediate energy

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collaboration with Joerg Aichelin and Pol Gossiaux

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Context

Heavy ion collisions at ultra-relativistic energies

- high-energy density QCD medium ('Quark-Gluon Plasma')
- hard probes

$\longrightarrow$ heavy quarks and their transport properties

in analogy to interaction of a highly energetic charge with matter

$\longrightarrow$ interested in collision and radiation processes

use pQCD inspired model for exploring these phenomenons
$\longrightarrow$ MC@$_S$HQ project [Gossiaux et al., PRC78(2008)014904]

Brief history

- Bjorken (1982): energy loss of partons in a QGP $\Rightarrow$ extinction of high p_T jets
- radiative energy loss (mid 1990's): coherence $\longrightarrow$ Landau-Pomeranchuck-Migdal effect in the QCD context

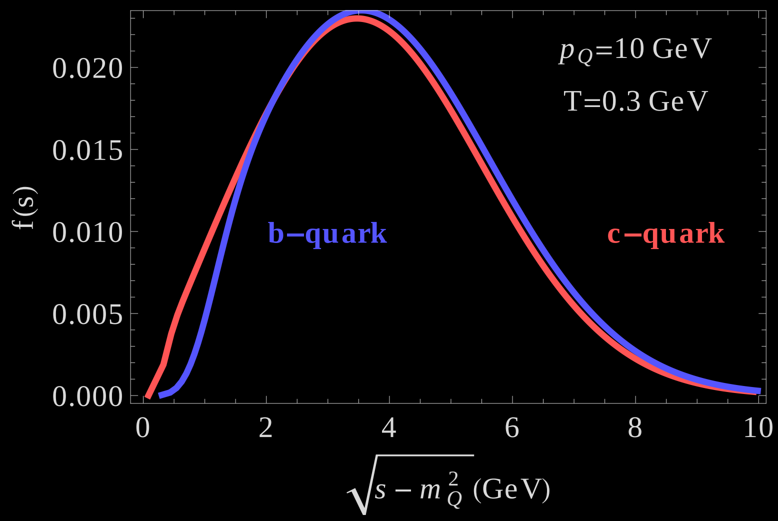
$\longrightarrow$ mainly light partons and asymptotic energies

For heavy quarks:

- Dokshitzer and Kharzeev [PLB519(2001)199]: 'dead cone' effect
- Armesto-Salgado-Wiedemann [PRD69(2004)114003]: path-integral framework
- Djordjevic and Heinz [PRC77(2008)024905]: dynamical QCD medium

This work

■ considers intermediate energy since heavy flavor observables $\sim 3 - 50$ GeV



invariant mass distribution of scatterings for an heavy quark in a QGP
$\rightarrow$ $s - m_Q^2 \gg \perp$-momentum scales for most scatterings but not $s \gg m_Q^2$

$\rightarrow$ HQ are relativistic

■ considers Gunion-Bertsch approach who proposed a pQCD model for light quark radiation phenomenology in high-energy collisions

This work (cont'd)

but intermediate energy:

showering time: $\tau_Q = E_Q/(m_Q^2 + Q_0^2)$ smaller than 0.5 fm for

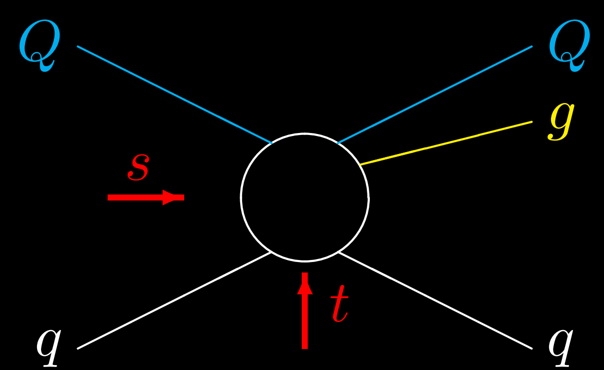
$E_Q < 7$GeV (charm) $E_Q < 50$ GeV (bottom)

bottom quark is close to mass shell before the medium is formed

coherence effects are not dominant

- extension of the Gunion-Bertsch model to heavy quarks
- investigating the influence of a finite energy

Kinematics



p, q two light-like vectors such that $2\,p \cdot q = s - m_Q^2$

$$Q: \quad P = p + \frac{m_Q^2}{s - m_Q^2} q$$

$$g: \quad k = x\,p + k_q\,q + \vec{k}_\perp$$

$$q: \quad \text{momentum transfer } q - q' = \ell,\ t = \ell^2$$

High-energy

At large s

$$\frac{d\sigma}{dx d^2k_\perp d^2\ell_\perp} \approx \frac{d\sigma_{\rm el}}{d^2\ell_\perp} \times P_g(x, \vec{k}_\perp, \vec{\ell}_\perp)$$

high-energy is when $s - m_Q^2 \gg |t|, \vec{k}_\perp^{\,2}$

where s-dependence disappears from the cross section (either *differential* or *integrated*)

- since $\frac{d\sigma_{\rm el}}{d^2\ell_\perp} \propto \frac{1}{t^2}$ at large $|t|$
- and $P_g \propto \frac{1}{k_\perp^4}$ at large $k_\perp$

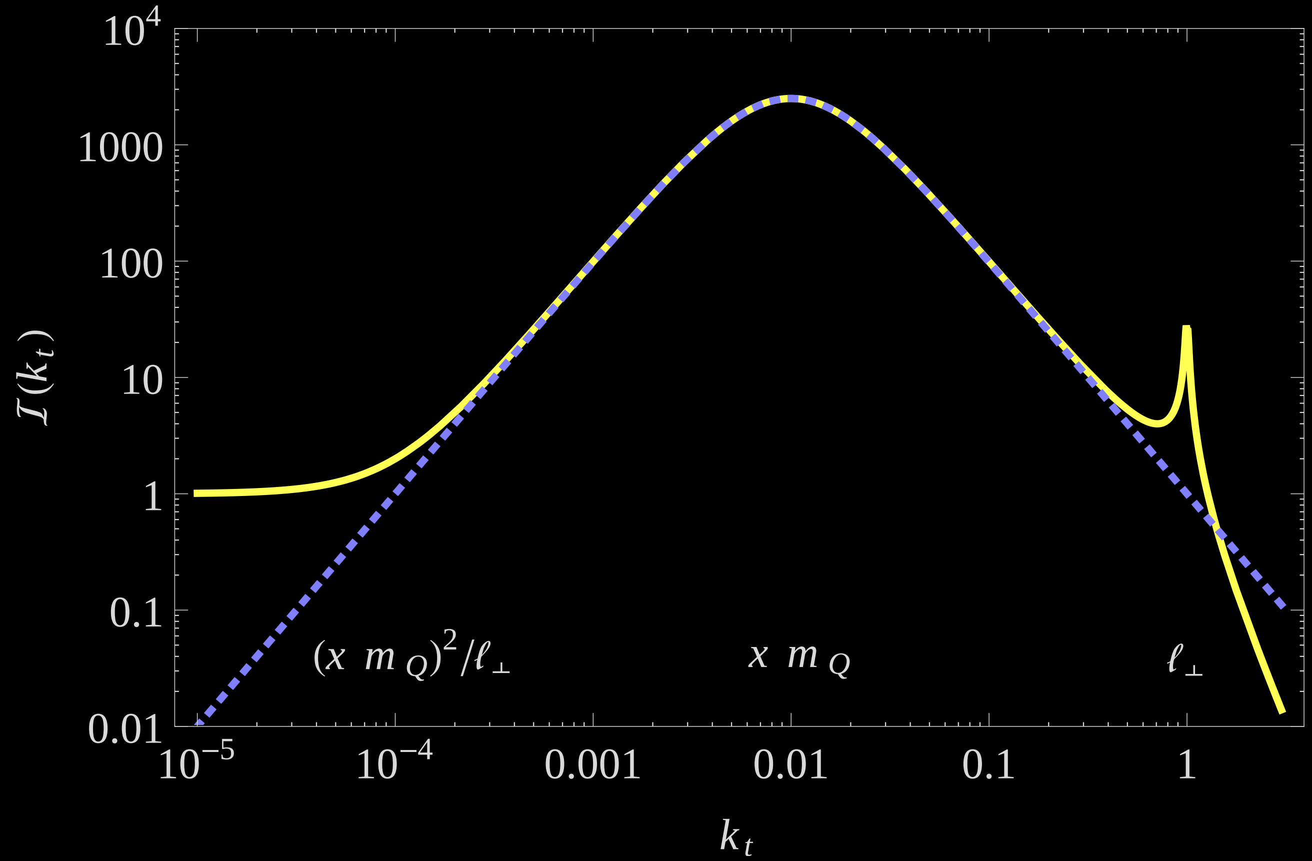
Debye screening effect

at small $t \longrightarrow$ will use prescription

$$\frac{d\sigma_{\rm el}}{d^2\ell_\perp} \propto \frac{1}{t^2} \longrightarrow \frac{1}{(t-\mu^2)^2}$$

with μ related to $m_D \longrightarrow$ natural scale for $\ell_\perp \sim \mu$

$\ell_\perp \gg x\, m_Q$ — hard scattering regime



$$P_g \propto \left(\frac{\vec{k}_\perp}{\vec{k}_\perp{}^2 + x^2 m_Q^2} - \frac{\vec{k}_\perp - \vec{\ell}_\perp}{(\vec{k}_\perp - \vec{\ell}_\perp)^2 + x^2 m_Q^2} \right)^2$$

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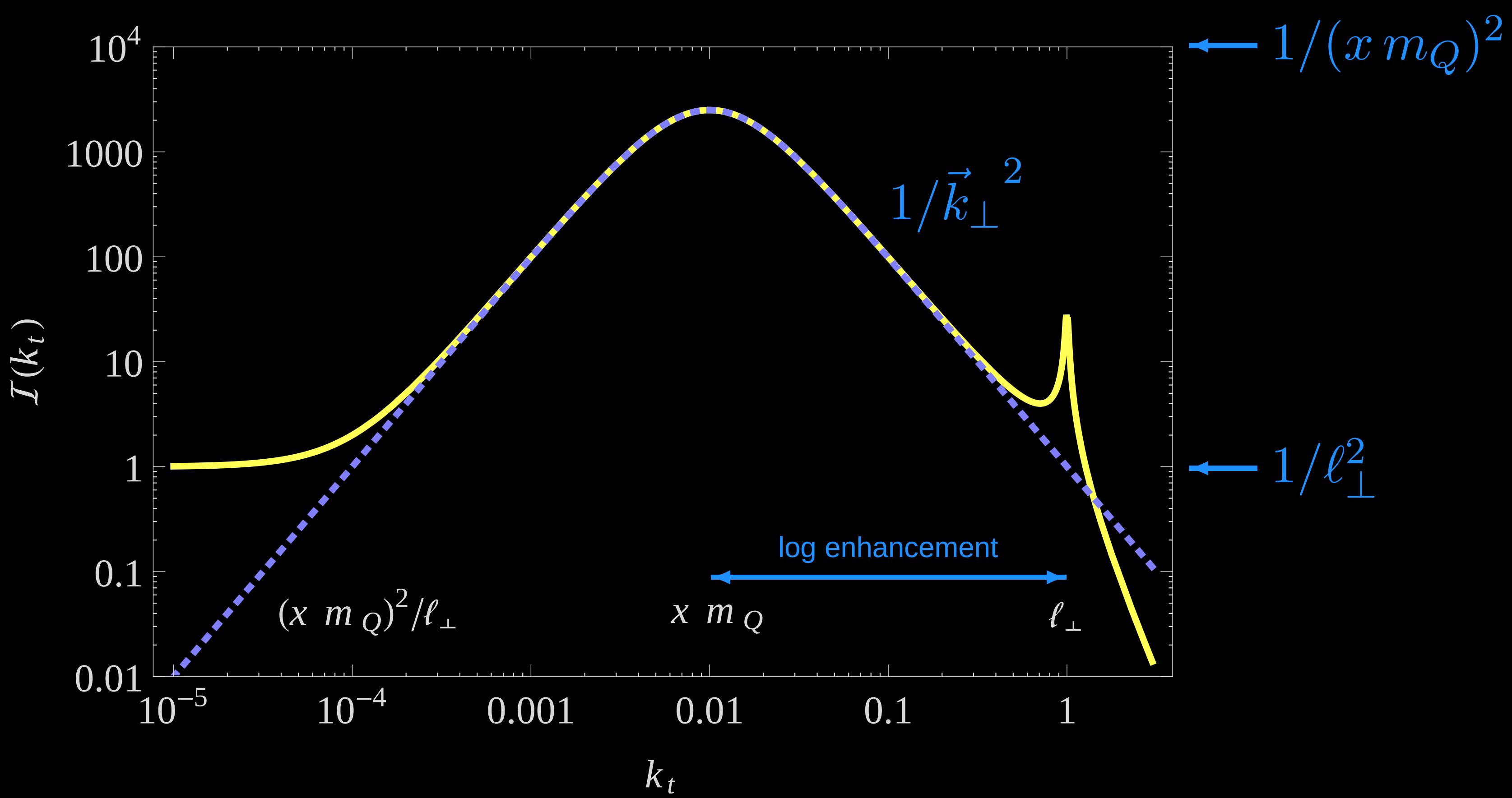

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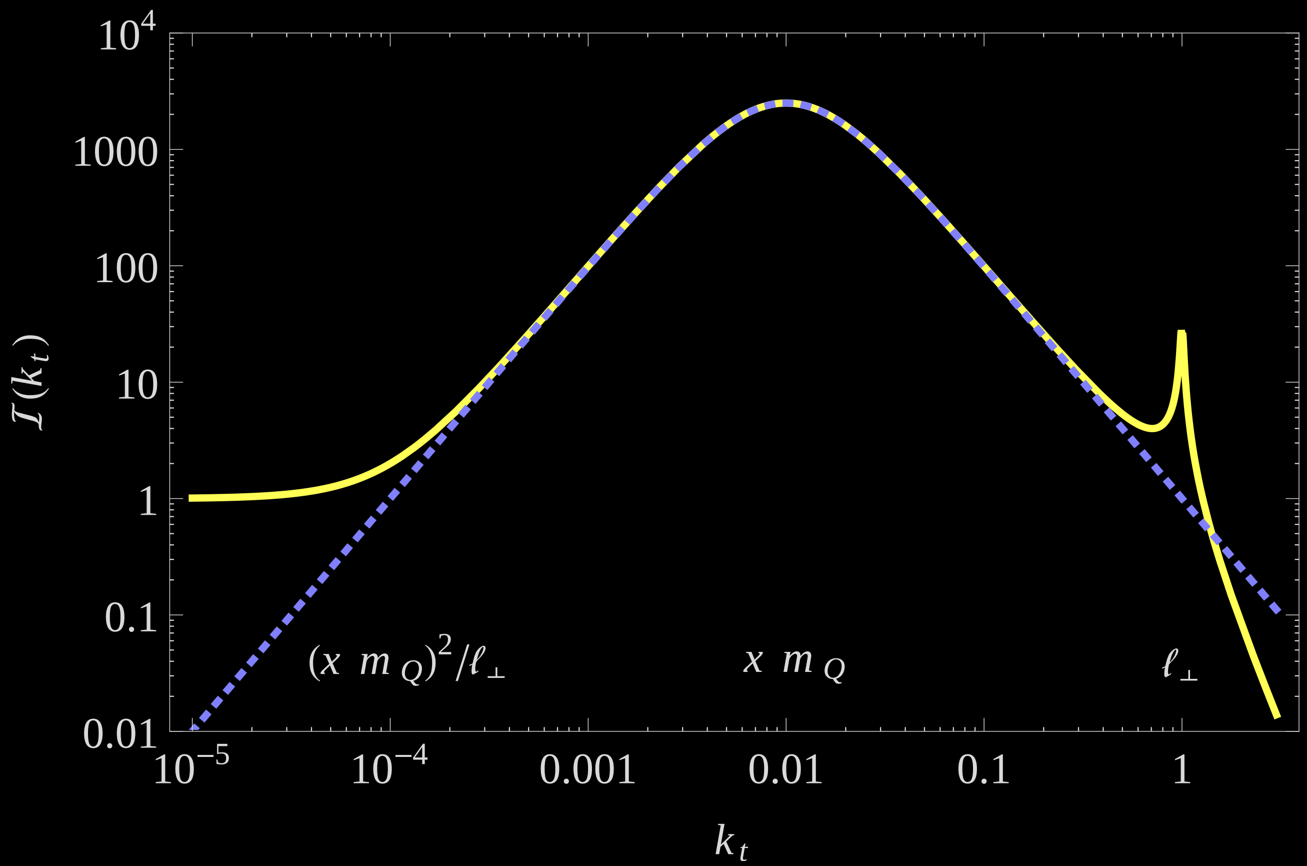
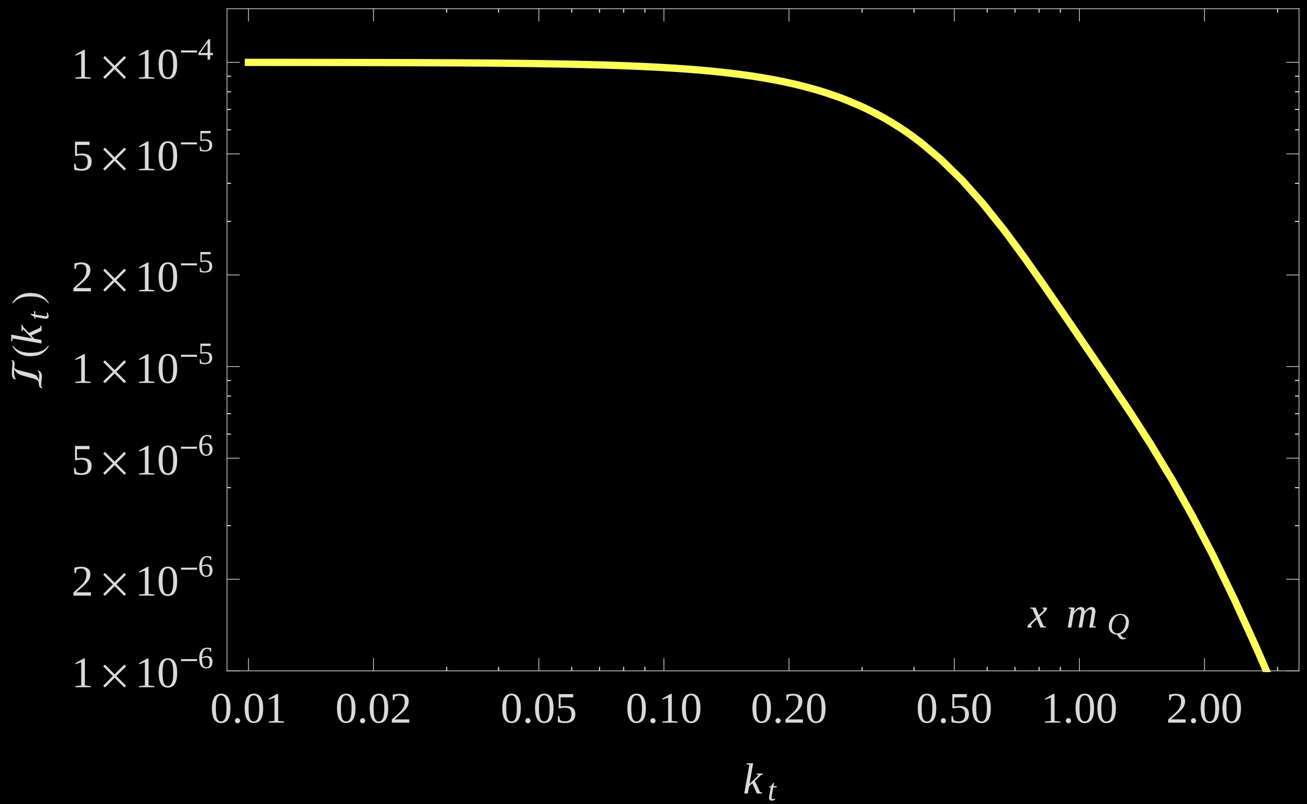


$$\int P_g\, d^2k_\perp \sim \ln \frac{\ell_\perp}{x\, m_Q}$$

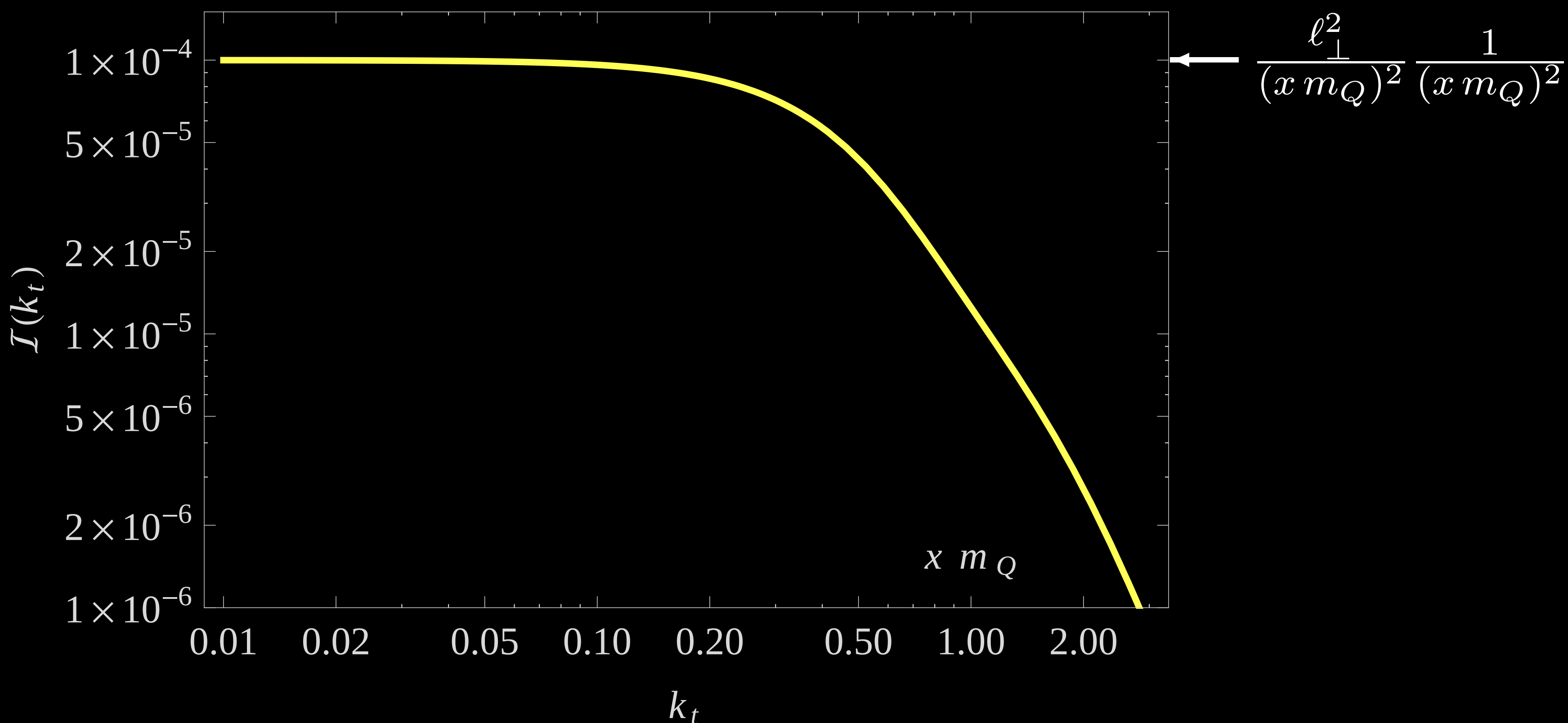
$$\ell_\perp \to \mu : \; x < x_M \equiv \mu/m_Q$$

$\ell_\perp \ll x\, m_Q$ — soft scattering regime



$\longrightarrow$ strong interference

$\ell_\perp \ll x\, m_Q$ — soft scattering regime



$$P_g \propto \left(\frac{\vec{k}_\perp}{\vec{k}_\perp{}^2 + x^2 m_Q^2} - \frac{\vec{k}_\perp - \vec{\ell}_\perp}{(\vec{k}_\perp - \vec{\ell}_\perp)^2 + x^2 m_Q^2} \right)^2$$

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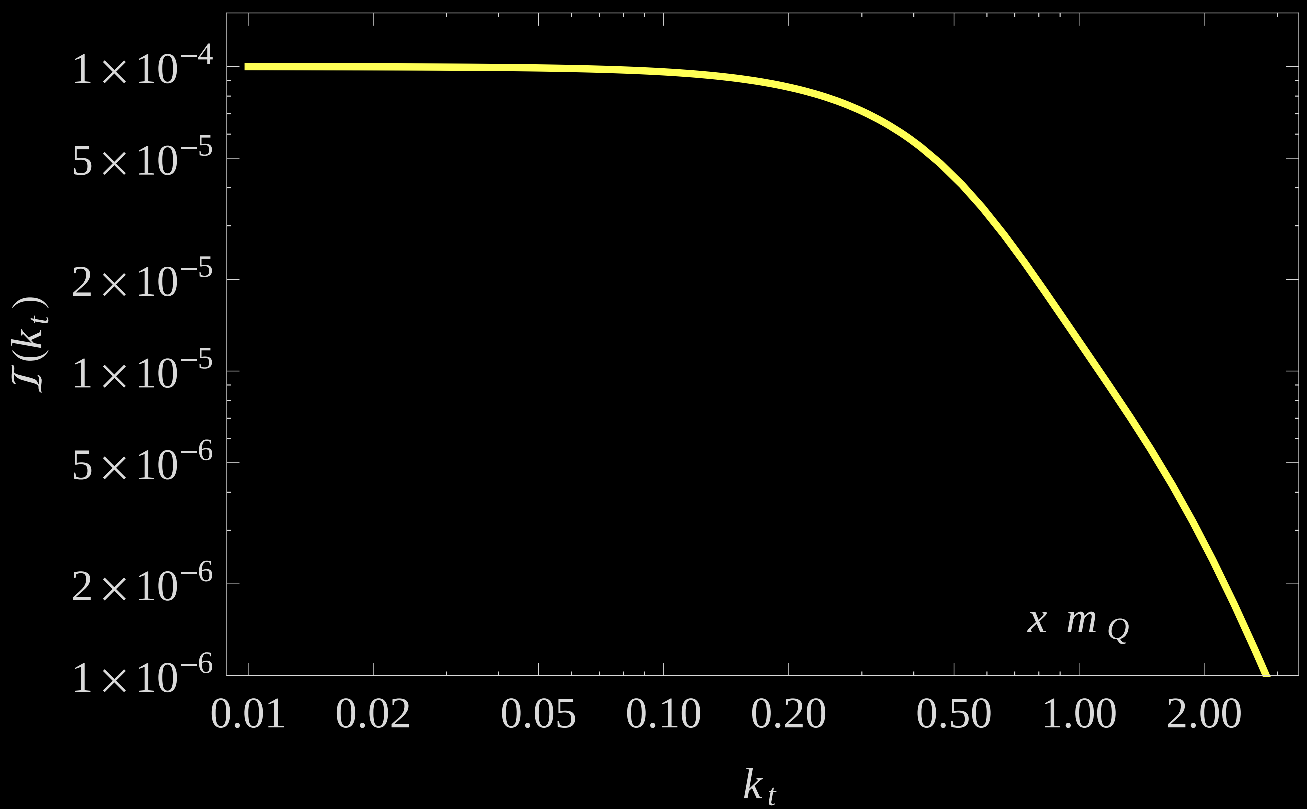

$$\int P_g\, d^2k_\perp \sim \frac{\vec{\ell}_\perp^{\,2}}{x^2\, m_Q^2} \qquad\qquad \ell_\perp \to \mu :\ x > x_M$$

Cross section

$$\frac{d\sigma^{Qq\to Qgq}}{dx d^2k_\perp d^2\ell_\perp} = \frac{1}{2(s-m_Q^2)} |\mathcal{M}|^2 \frac{1}{4(2\pi)^5\sqrt{\Delta}} \Theta(\Delta)$$

$$\begin{aligned}\mathcal{M} \quad &= \quad g\, C_3 \left(\frac{-2\, g^2\, (s - m_Q^2)}{t^2} \right) \\ & \quad \times \vec{\epsilon}_t \cdot \left(\frac{(2(1-x) \quad)\vec{k}_\perp}{\vec{k}_\perp{}^2 + x^2 m_Q^2} - \frac{2(1-x \quad)(\vec{k}_\perp - \vec{\ell}_\perp)}{(\vec{k}_\perp - \vec{\ell}_\perp)^2 + (x \quad)^2 m_Q^2} \right)\end{aligned}$$

Δ: phase-space

Cross section

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$$\mathcal{M} = g\,C_3\left(\frac{-2\,g^2\,(s-m_Q^2)}{t^2}\right) \times\vec{\epsilon}_t\cdot\left(\frac{(2(1-x)-x')\vec{k}_\perp}{\vec{k}_\perp{}^2+x^2m_Q^2} - \frac{2(1-x-x')(\vec{k}_\perp-\vec{\ell}_\perp)}{(\vec{k}_\perp-\vec{\ell}_\perp)^2+(x+x')^2m_Q^2}\right)$$

$x' \equiv x'(x,\vec{k}_\perp,\vec{\ell}_\perp)$ momentum fraction of the outgoing light quark

Cross section

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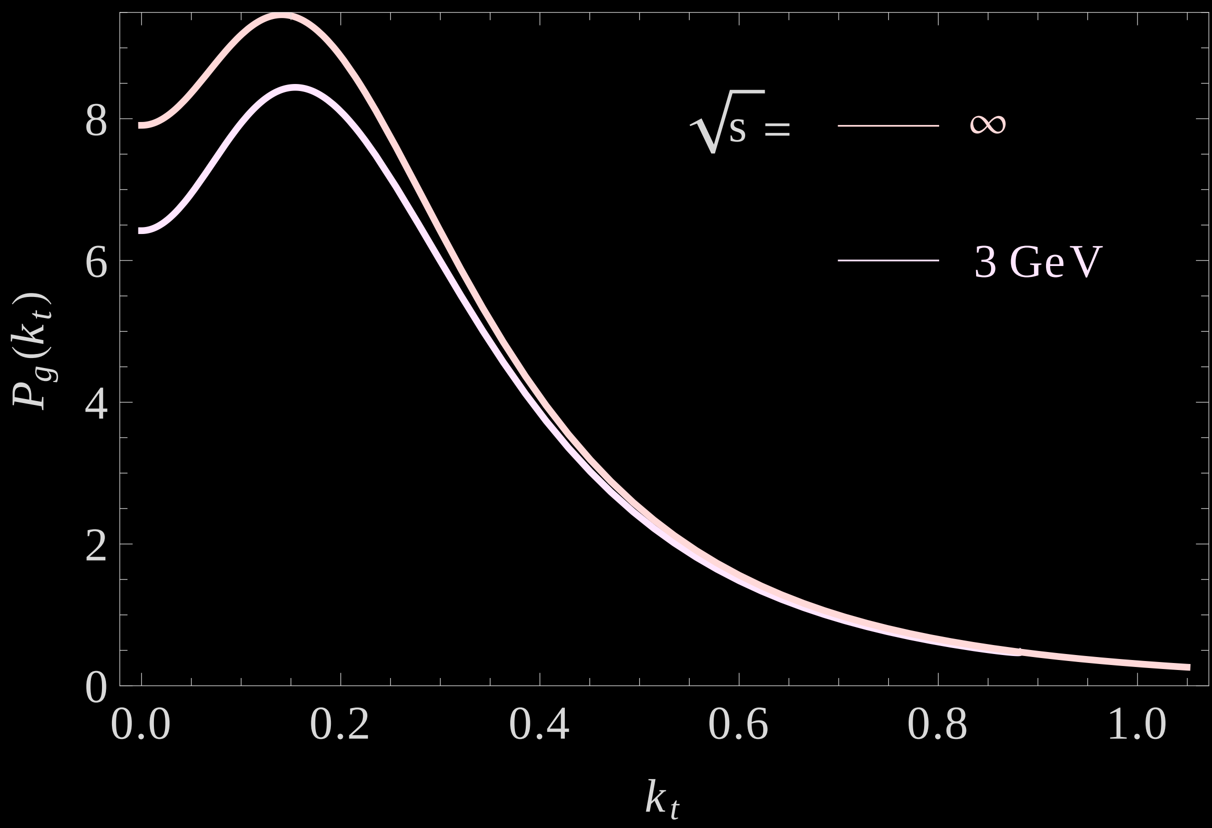
$x' \equiv x'(x, \vec{k}_\perp, \vec{\ell}_\perp)$ momentum fraction of the outgoing light quark

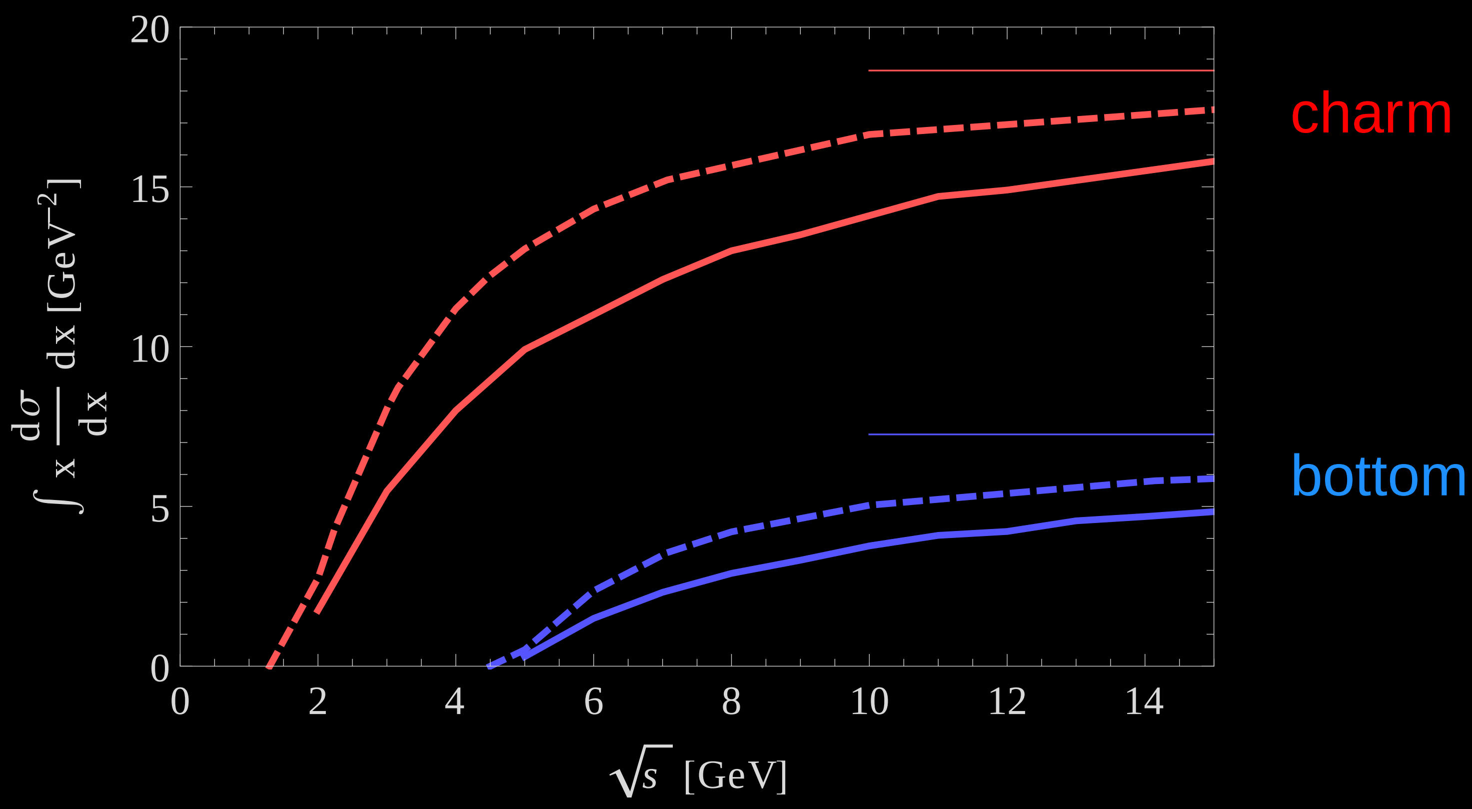
$x' \to 0$ at high-energy

Finite-energy P_g



- high energy approximation captures the main features of radiation

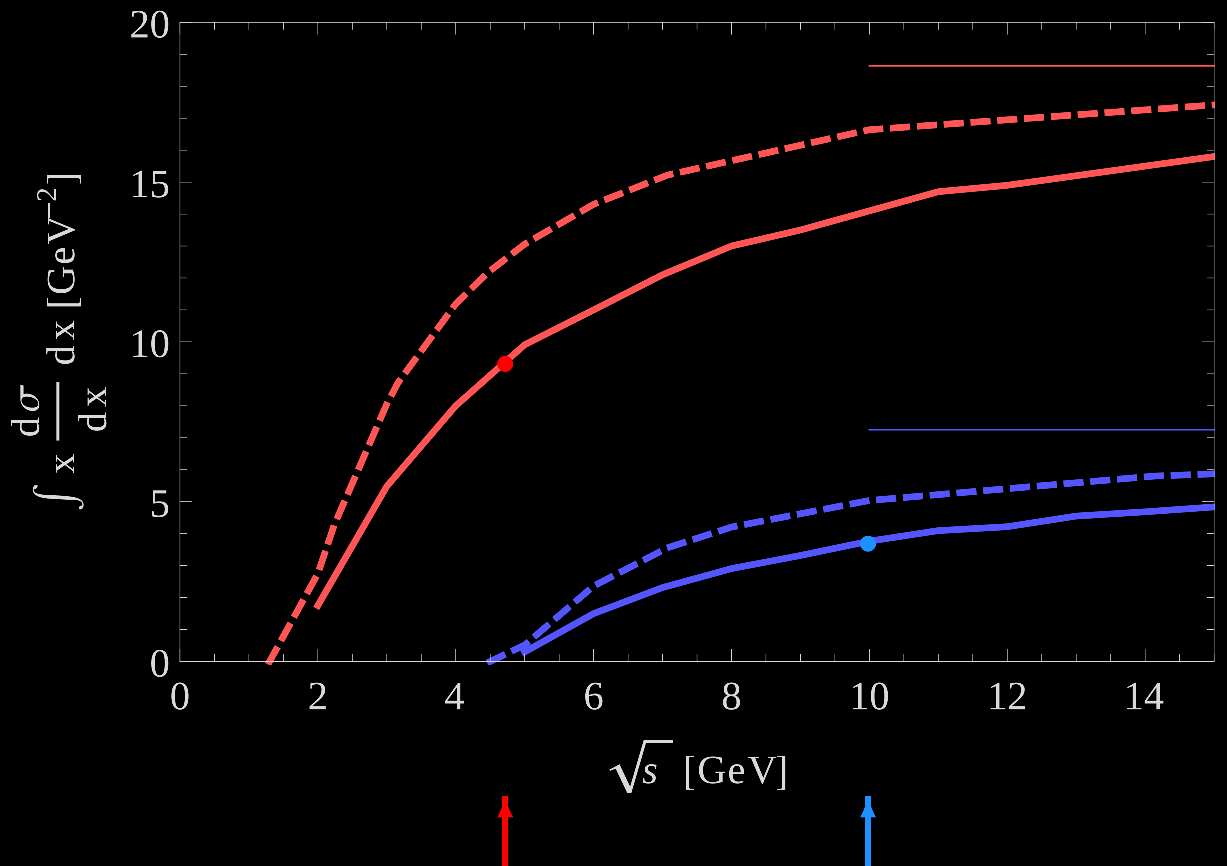
$$\int x \frac{d\sigma}{dx}\, dx$$



$$\int x \frac{d\sigma}{dx} dx \sim \frac{1}{\rho E_{\text{beam}}} \frac{dE_{\text{rad}}}{dz}$$

hybrid model (- - -): $\dfrac{d\sigma}{dx d^2k_\perp d^2\ell_\perp} = \dfrac{d\sigma_{\text{el}}}{d^2\ell_\perp} P_g(x, \vec{k}_\perp, \vec{\ell}_\perp) \times \Theta(\Delta)$

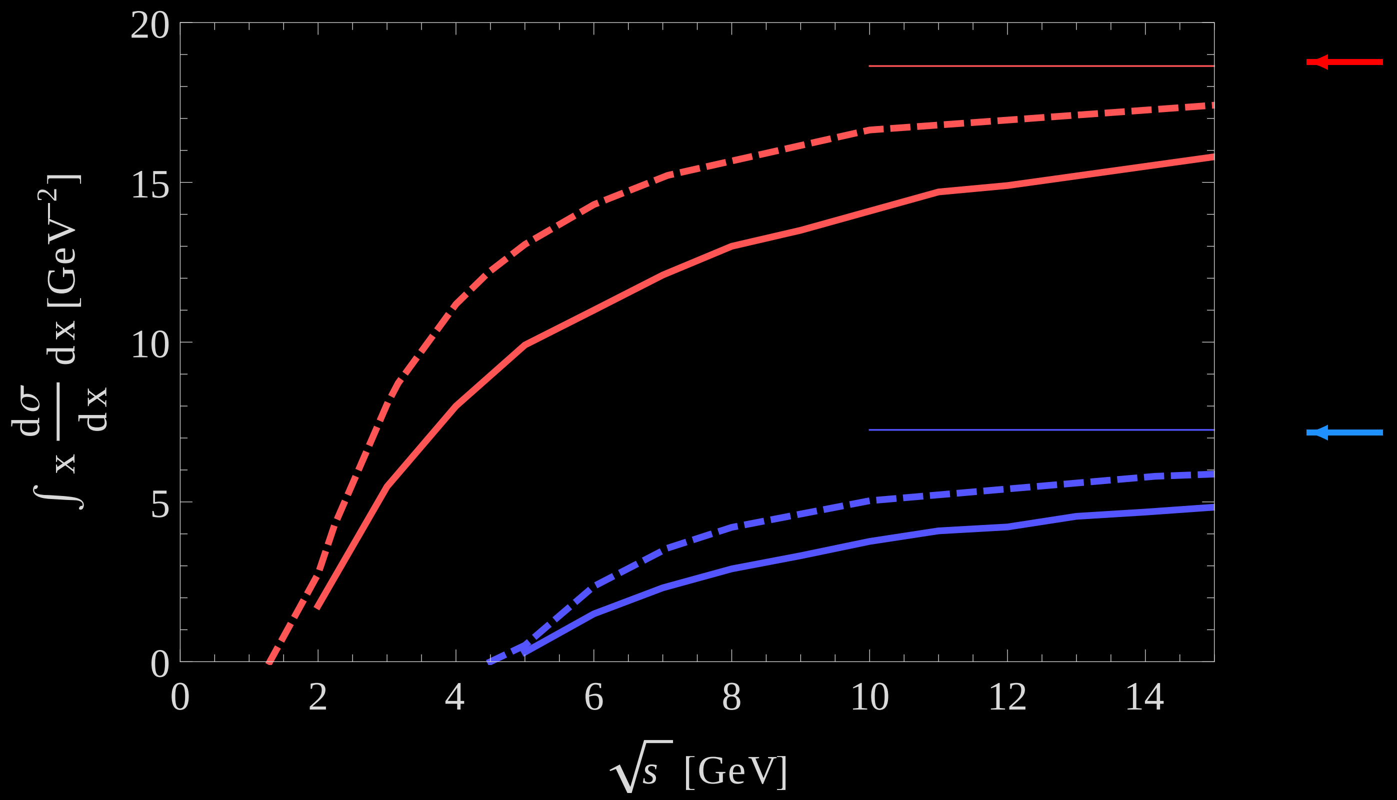
$$\int x \frac{d\sigma}{dx}\, dx$$



$E_c \sim 10$ GeV

$E_b \sim 40$ GeV

$$\int x \frac{d\sigma}{dx}\, dx$$



asymptotic behavior $\propto \dfrac{1}{\mu\, m_Q}$

- suppression of heavy quark radiation $\propto 1/m_Q$
- sensitivity to the details of screening

$$x\frac{d\sigma}{dx}$$

$\frac{1}{\mu\, m_Q} \leftarrow \int x\frac{d\sigma}{dx}\, dx$ receives contributions from both below $x_M = \mu/m_Q$ ('hard' collisions) and above ('soft' collisions)

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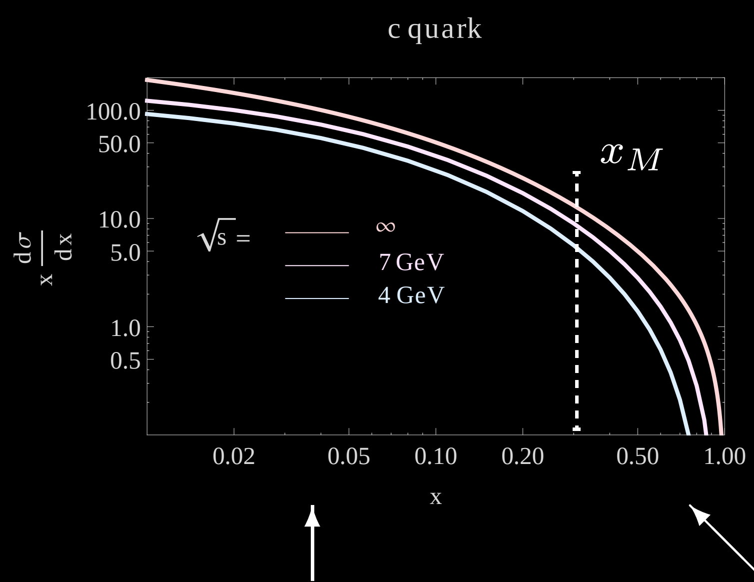

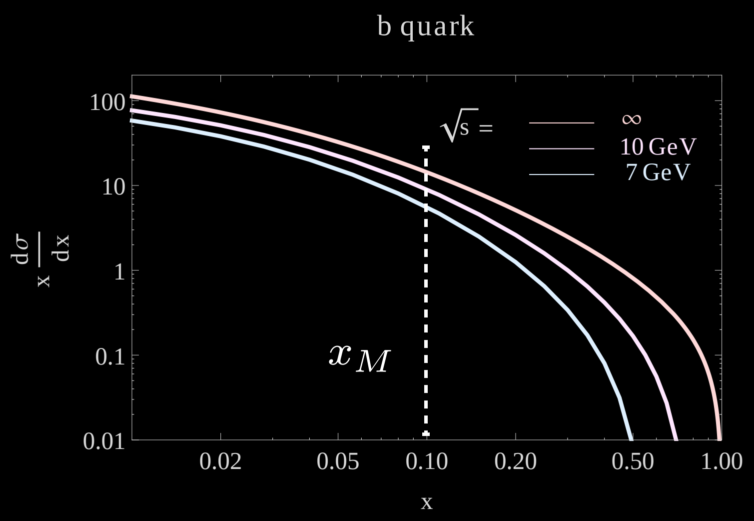

$$x\frac{d\sigma}{dx} \propto \ln\left(\frac{x_M}{x}\right) \qquad x\frac{d\sigma}{dx} \propto \left(\frac{x_M}{x}\right)^2$$

$$x\frac{d\sigma}{dx}$$

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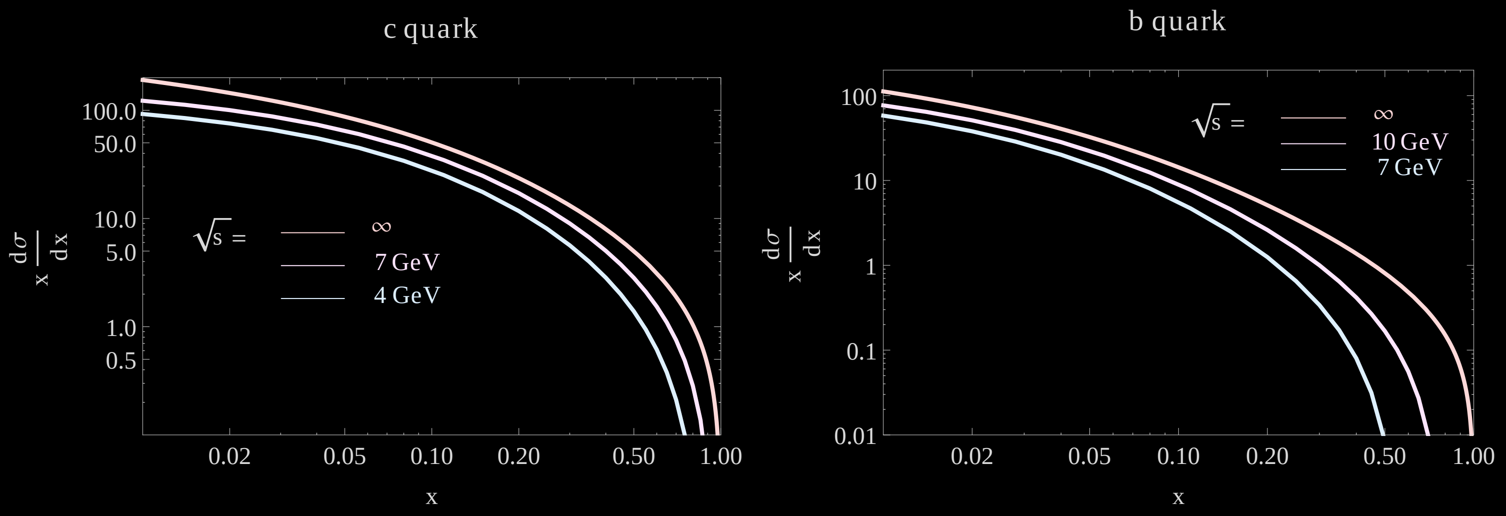


- driven by physics of radiation discussed at high energy
- but sizable finite energy corrections due to both
  - non vanishing x' ($\leftrightarrow$ light quark recoil)
  - limited phase space

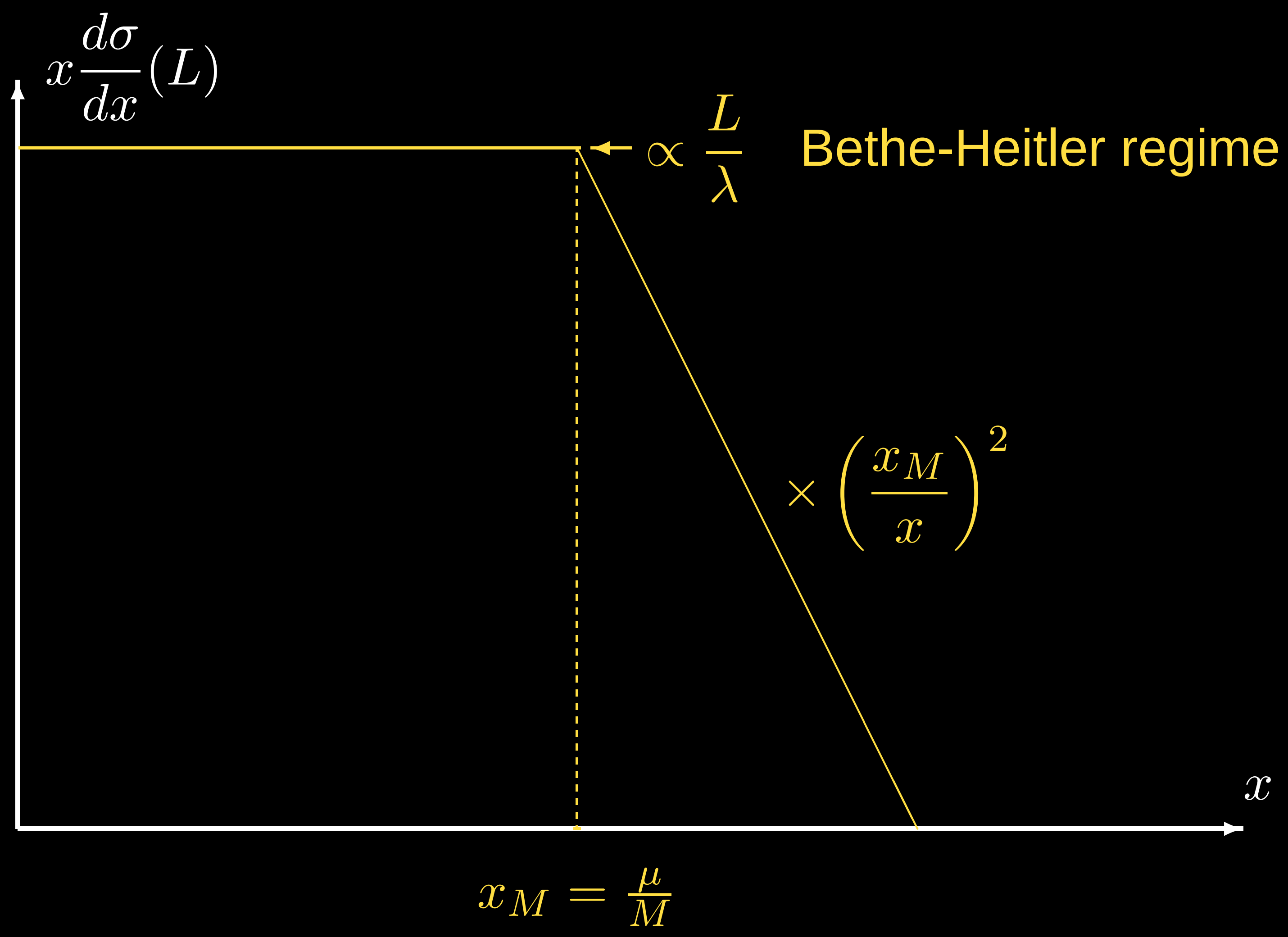
Summary

- pQCD model for gluon radiation by heavy quarks

$\longrightarrow$ detailed discussion on the phenomenon of radiation and its parametric dependence

- mass hierarchy much stronger in radiative energy loss than in collisional energy loss
- large part of the mass hierarchy is not due to the dead cone effect
- sizable reduction of radiation at intemediate energies

Outlook: coherence



Outlook: coherence