Radiative energy loss in the absorptive QGP

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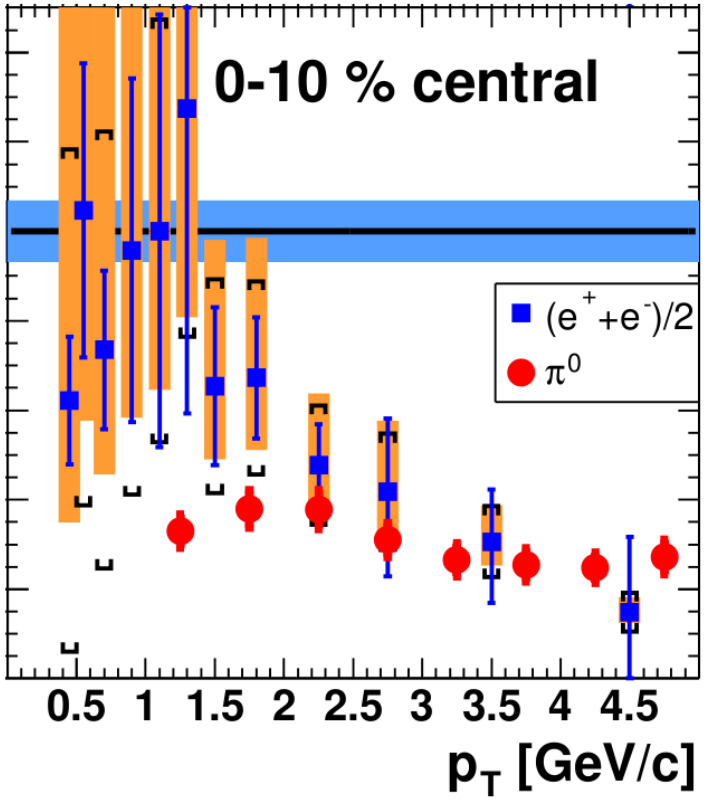
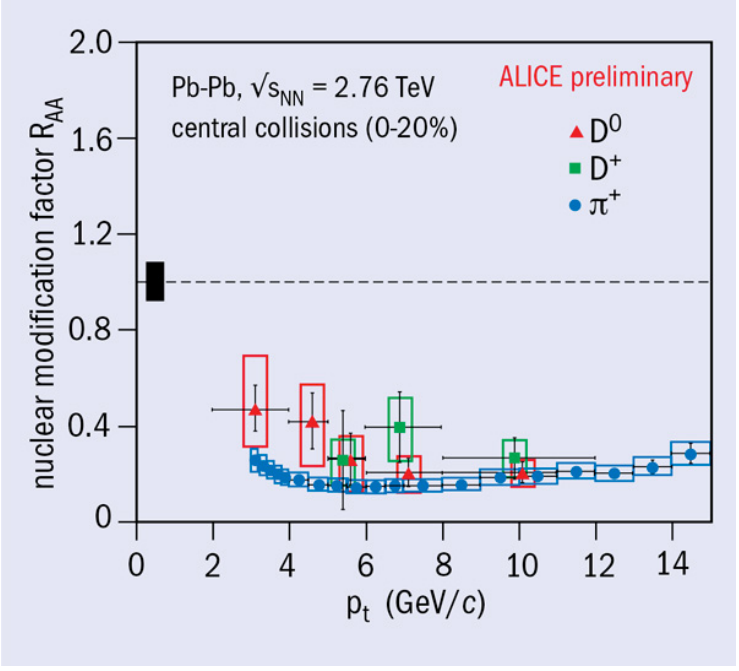
based on: MB, P. B. Gossiaux, J. Aichelin, arXiv:1106.2856
MB, P. B. Gossiaux, T. Gousset, J. Aichelin, arXiv:1204.2469

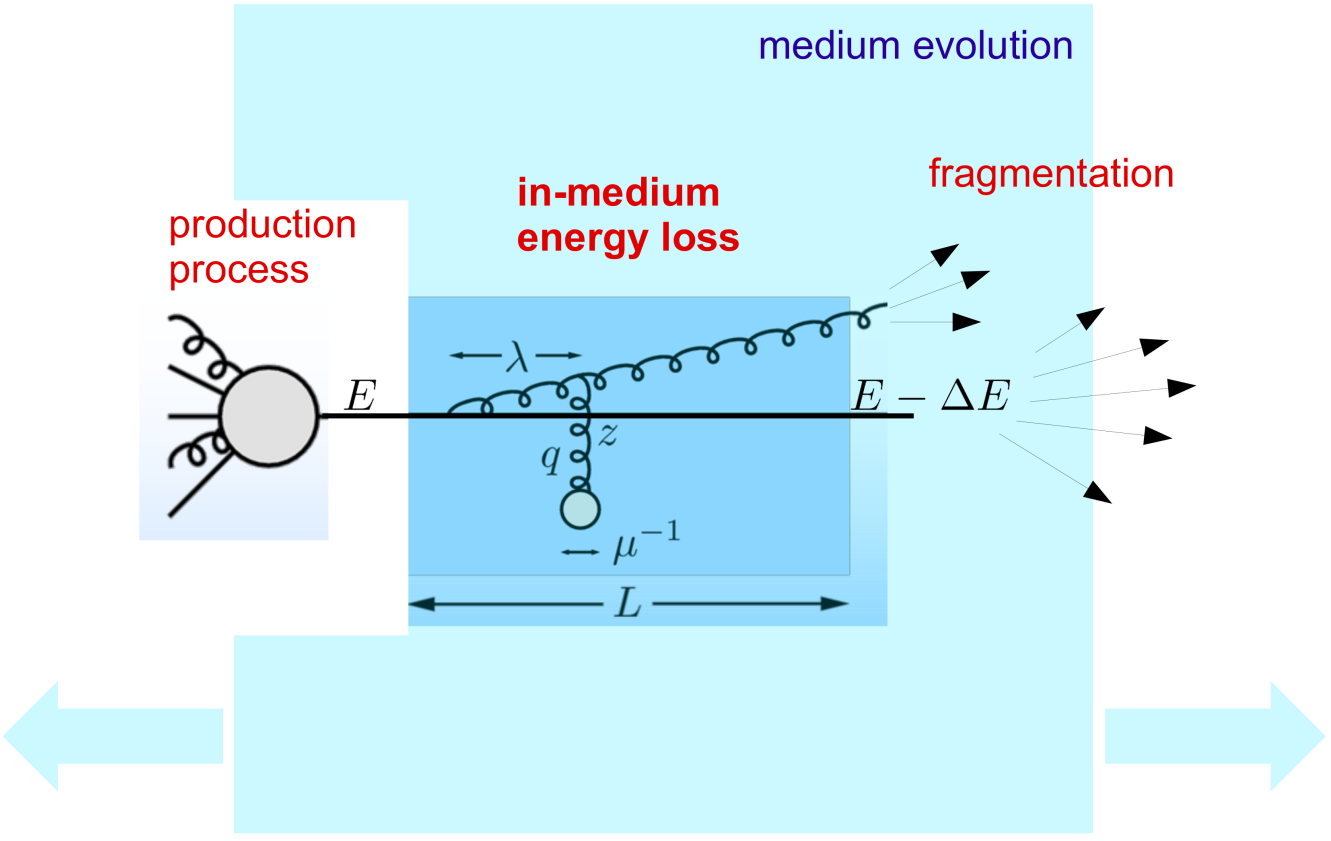
Experimental observations





- RHIC and LHC: strong suppression of hadron spectra
  $\longrightarrow$ medium is opaque for coloured excitations (large in-medium energy loss)
- influence of medium (nearly) same for different parton masses

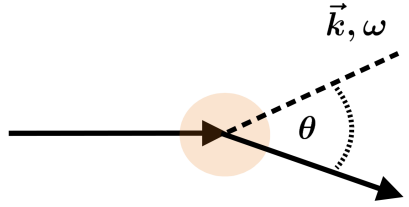
In-medium energy loss



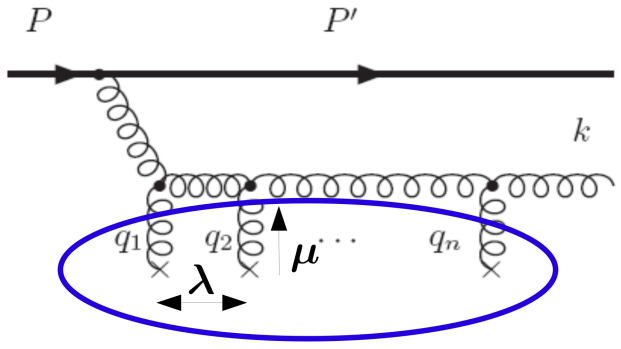
- $\Delta E_{rad} \gg \Delta E_{coll}$ for large E
- less radiative energy loss for heavy quarks (dead cone effect)

Formation of bremsstrahlung in QCD

- formation of gluon radiation is a *quantum phenomenon* (*quantum decoherence* between emitting parton and radiated gluon takes time)
- estimate for **formation time**: their transverse separation is of order of gluon-transverse wavelength, $\tau_f \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\theta^2}$

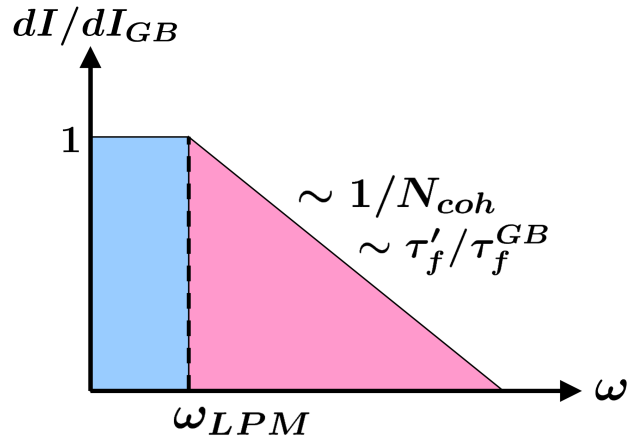


- in case $\tau_f \gg \lambda$ (parton mean free path in medium), $N_{coh} \simeq \tau_f / \lambda$ scatterings contribute coherently to formation of radiation



Formation of bremsstrahlung in QCD

- gluon rescatterings alter the formation time to $\tau_f' \simeq \sqrt{\omega/\hat{q}}$ because $\langle k_\perp^2 \rangle \simeq \hat{q}\tau_f$ with $\hat{q} \sim \mu^2/\lambda$ (*quenching parameter*)
- consequence: radiation spectrum reduced compared with GB-spectrum from independent, successive scatterings for larger ω (**LPM effect**)



- gluon dispersion relation that is not *light-like* (e.g. due to medium polarization) alters the probability of bremsstrahlung production at soft ω (**TM effect** analogon)

Kampfer+Pavlenko (2000), Djordjevic+Gyulassy(2003)

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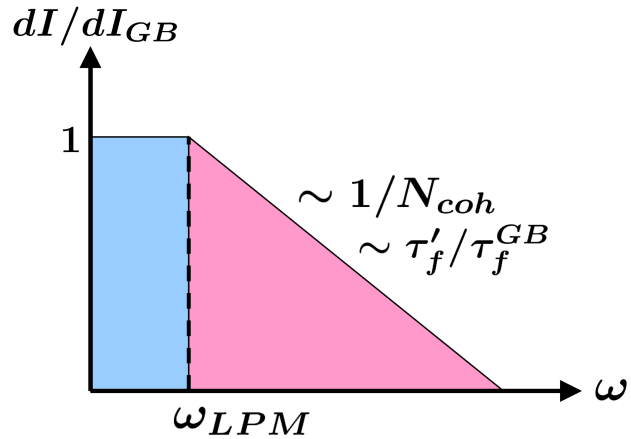

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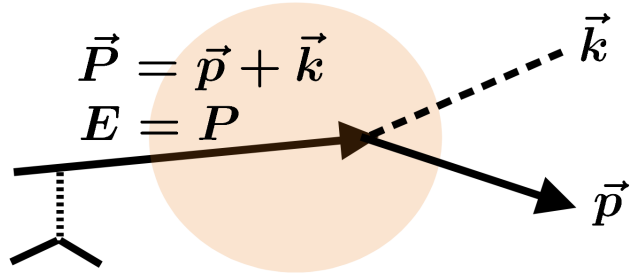
$\longrightarrow$ What is influence of damping mechanisms?

Formation time in QCD

cf. P. Arnold Phys. Rev. D **79** (2009) 065025

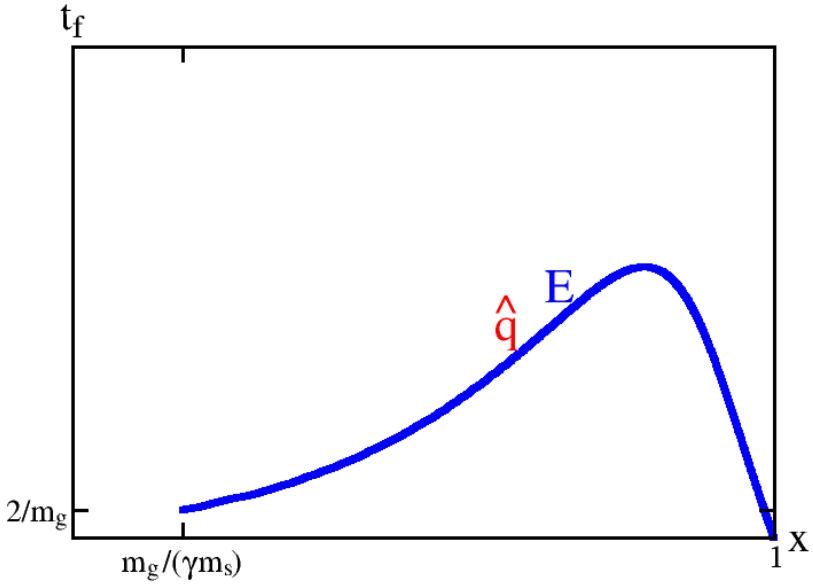
estimate for formation time t_f from *off-shellness* of intermediate particle line



quantum mechanical duration of off-shell "state" $\longrightarrow$ condition for t_f:

$$t_f^2 \frac{(1-x)\hat{q}}{2xE} + t_f \frac{[x^2 m_s^2 + m_g^2(1-x)]}{2x(1-x)E} \simeq 1$$

$$x = \omega / E$$



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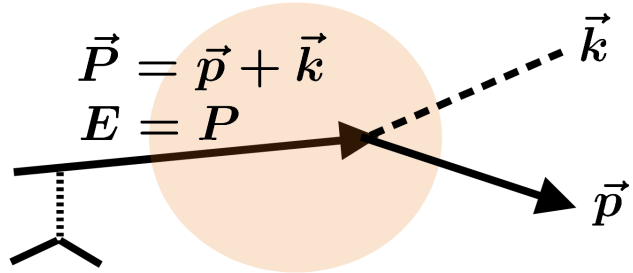

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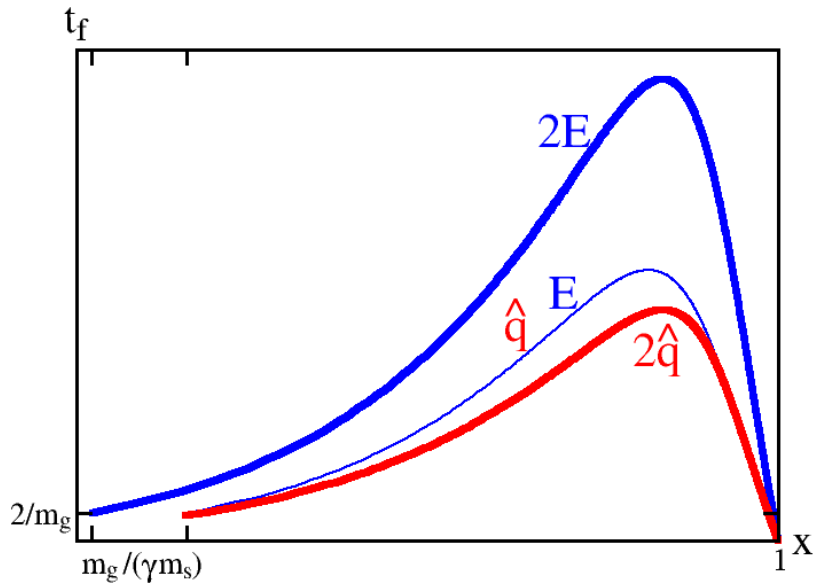
$x = \omega / E$

- t_f increases with E
- t_f decreases with $\hat{q}$



Qualitative study

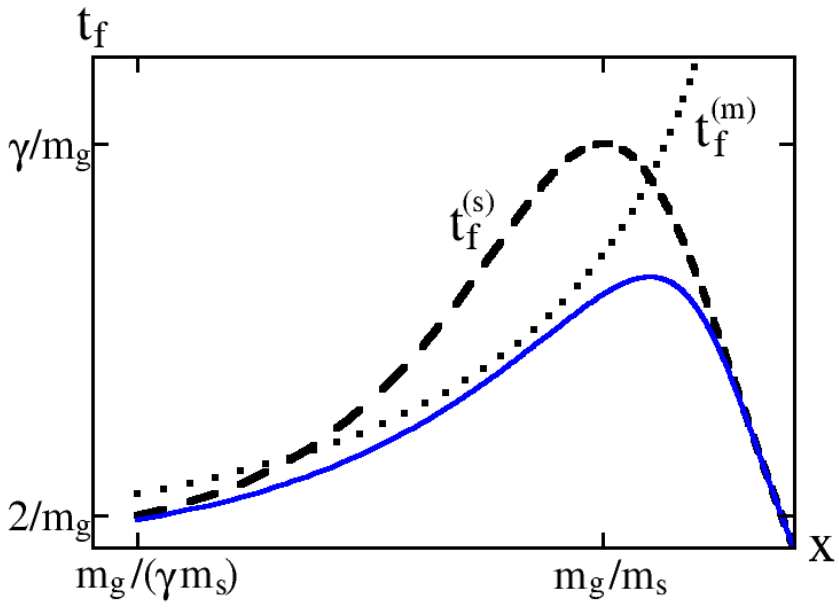
Qualitative behaviour can be discussed via an approximate solution of condition equation

$$t_f^2 \frac{(1-x)\hat{q}}{2xE} + t_f \frac{[x^2 m_s^2 + m_g^2(1-x)]}{2x(1-x)E} \simeq 1$$

by defining

$$t_f^{(s)} = \frac{2x(1-x)E}{x^2 m_s^2 + m_g^2(1-x)}$$

$$t_f^{(m)} = \sqrt{\frac{2xE}{(1-x)\hat{q}}}$$



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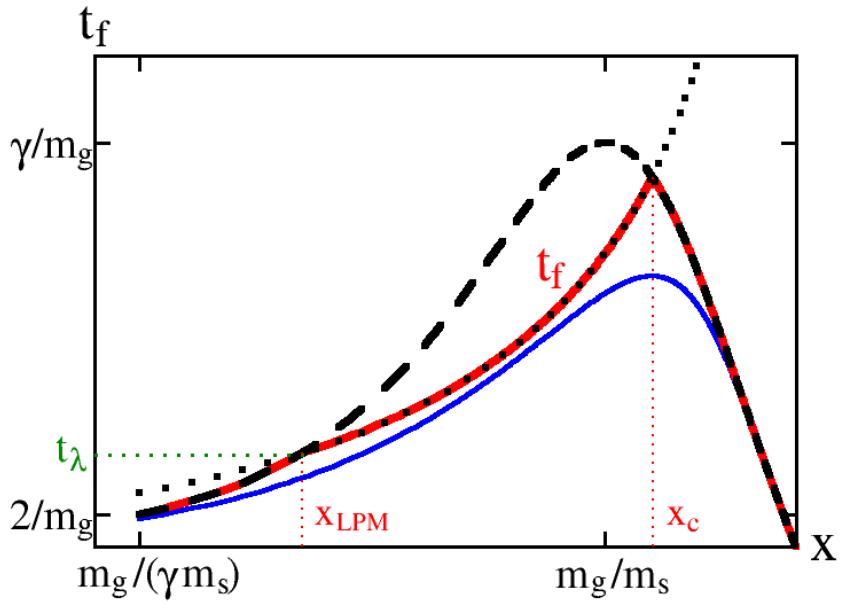

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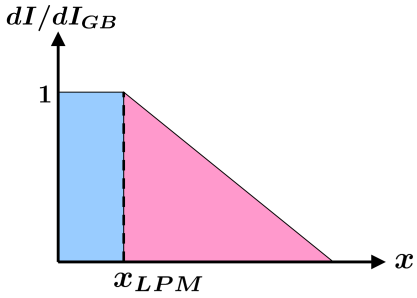
and assuming

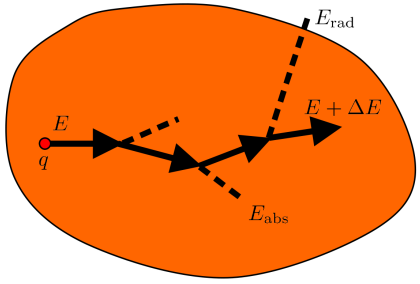
$$t_f = \min(t_f^{(s)}, t_f^{(m)})$$

- LPM-suppression for $x \geq x_{LPM} \sim m_g^4/(\hat{q}E)$ when $t_f \geq t_\lambda$

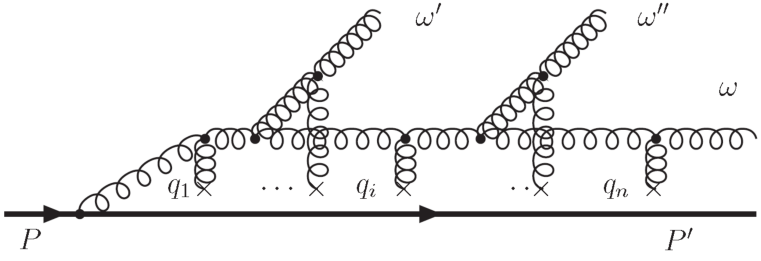


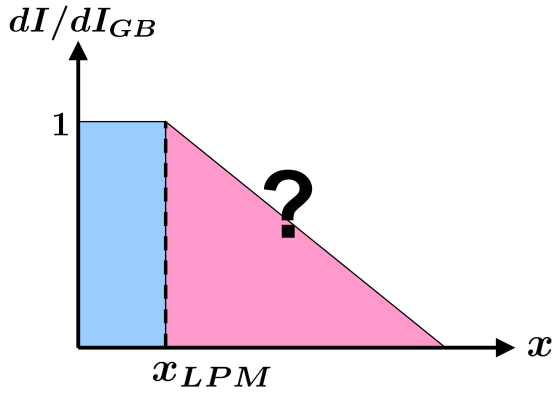
Damping of gluon radiation

- Is it possible that damping mechanisms influence the formation of radiation itself?
- assume gluons to be **time-like** excitations with in-medium effective *mass* m_g and *width* (associated with damping rate Γ)



- mechanisms: $\bar{q}q$-pair creation or secondary bremsstrahlung $\rightarrow$ in pQCD: $\Gamma \sim g^4 T \ln(1/g)$



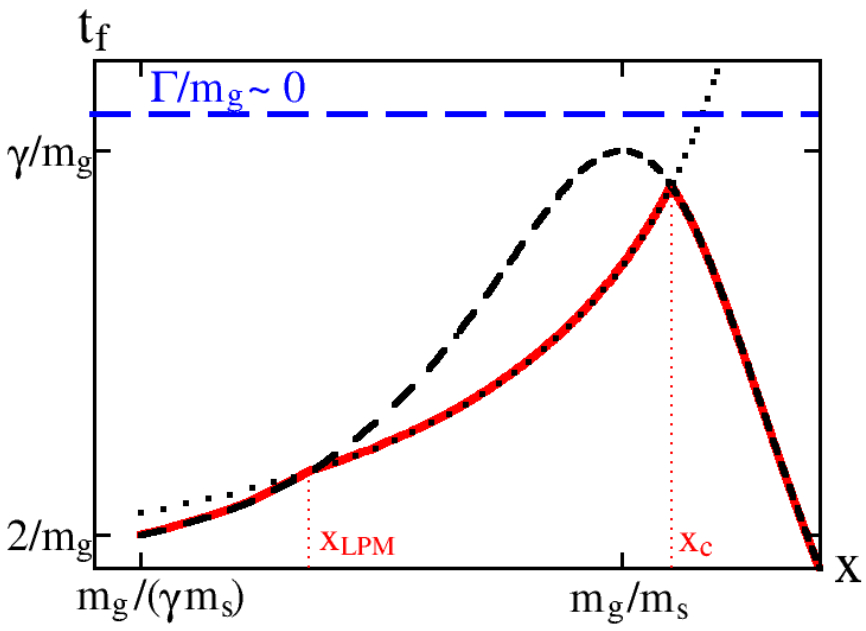


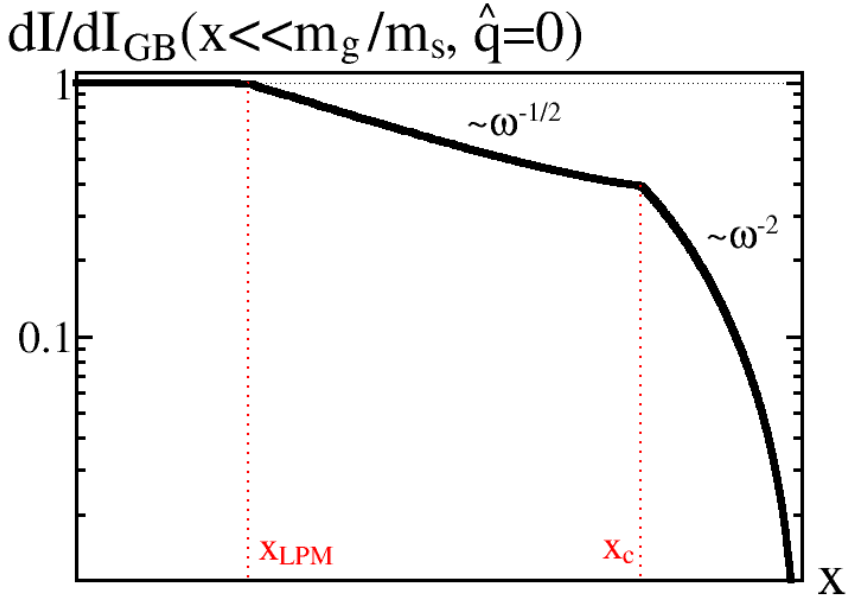
- higher order effect
- associated **damping time** $t_d \sim 1/\Gamma$: formation influenced if $t_d \lesssim t_f$

Influence on the radiation spectrum

exploit spectra scaling $\frac{dI}{dI_{GB}} \simeq \frac{\tilde{t}_f}{t_{GB}}$: $\tilde{t}_f = \min(t_f, t_d)$, $t_{GB} \simeq \frac{\omega}{m_g^2}$

negligible damping:





- shows influence of multiple, elastic scatterings (LPM effect) and finite parton mass
- LPM-suppression for $m_g^4/\hat{q}E \sim x_{LPM} \leq x \leq x_c \sim (\hat{q}E/m_s^4)^{1/3}$

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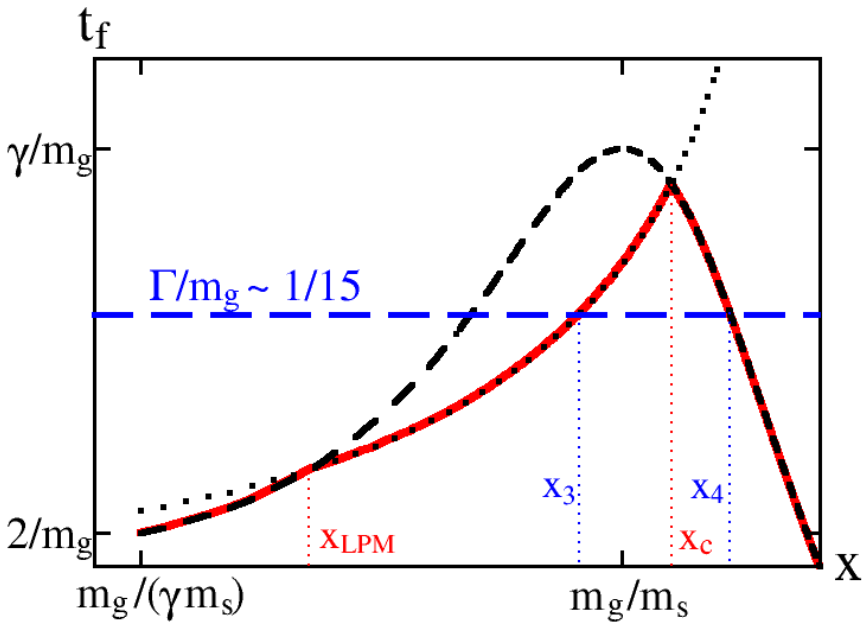
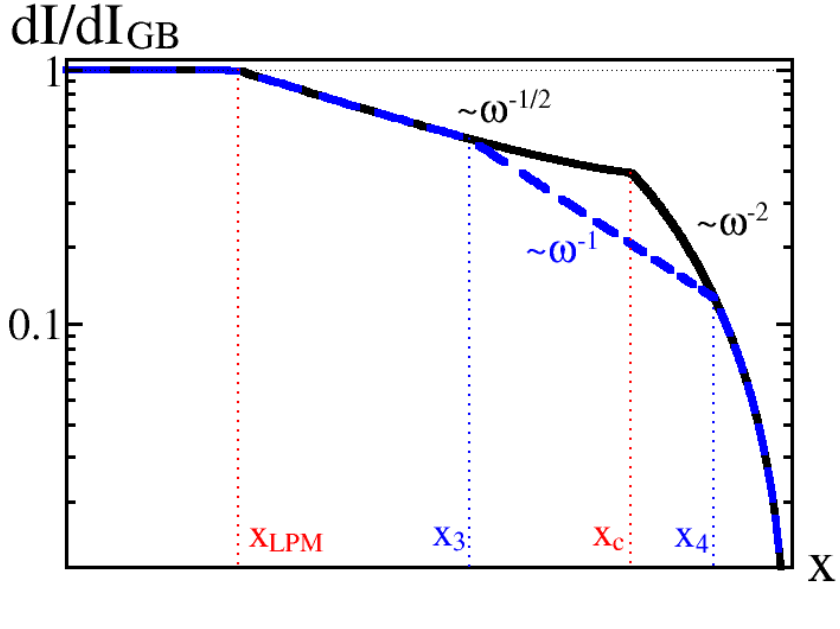
intermediate damping:





- development of a NEW additional regime due to gluon damping between $x_3 \sim \hat{q}/(\Gamma^2 E)$ and $x_4 \sim \Gamma E/m_s^2$
- reduction stronger than due to LPM effect

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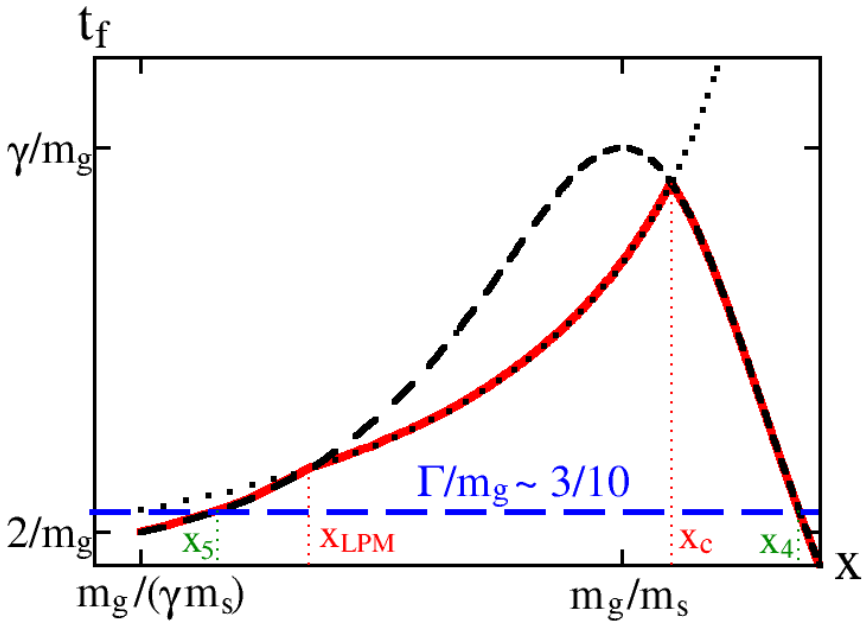
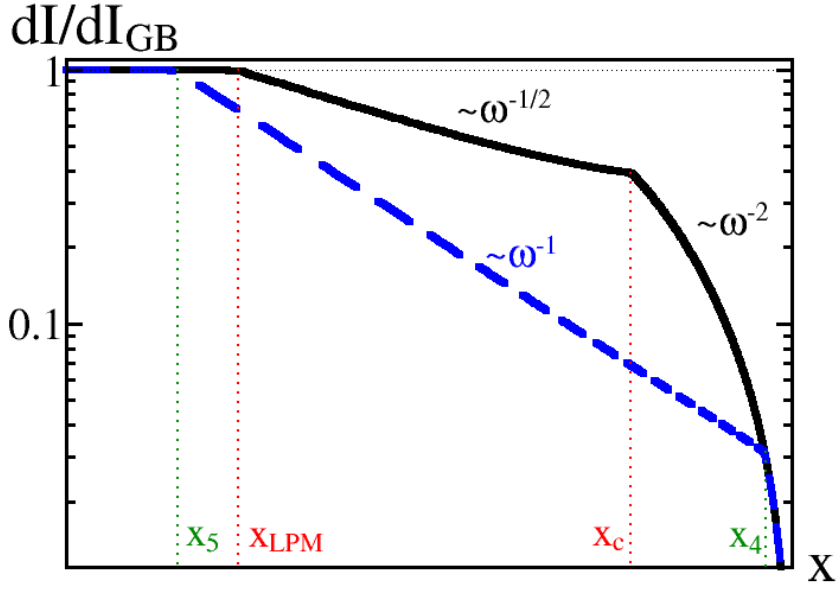
large damping:



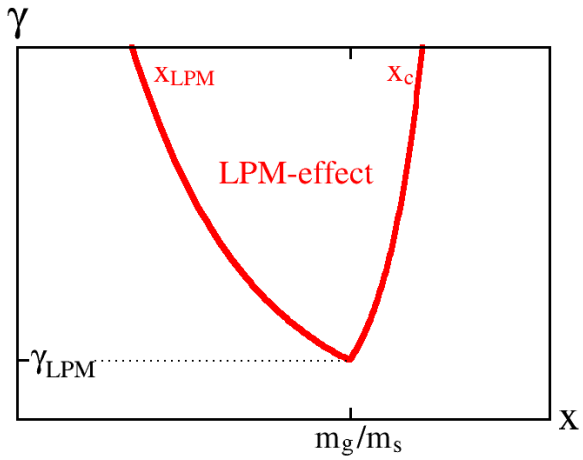


- development of a NEW additional regime due to gluon damping between $x_5 \sim m_g^2/(\Gamma E)$ and $x_4 \sim \Gamma E/m_s^2$
- reduction stronger than due to LPM effect
- for fixed E, increasing Γ influences shape of the spectrum

Behaviour with increasing energy

- for fixed Γ, effect should show up with increasing $\gamma = E/m_s$

negligible
$\Gamma/m_g = 0$



$\gamma_{LPM} \sim m_g^3/\hat{q}$

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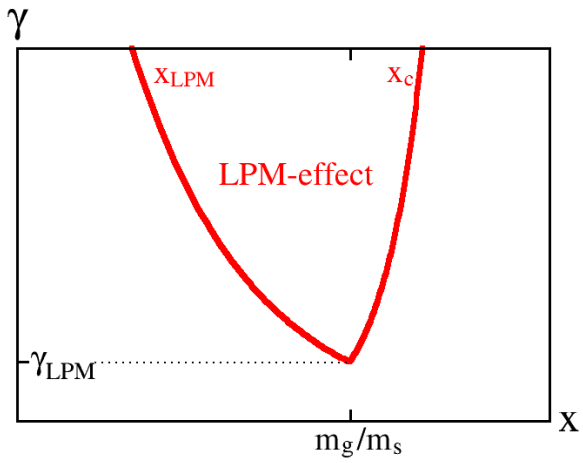
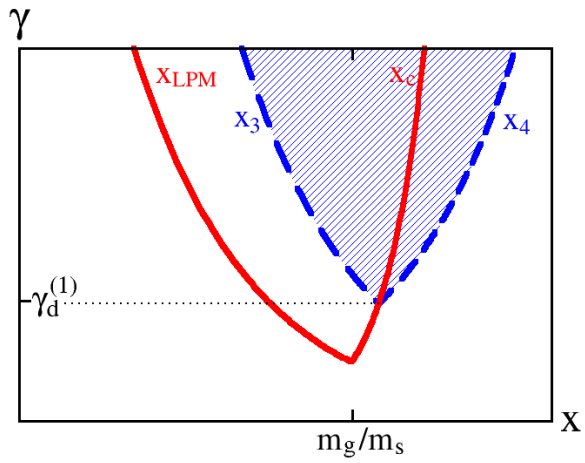


$\gamma_{LPM} \sim m_g^3/\hat{q}$

intermediate
$\Gamma/m_g < \hat{q}/m_g^3$



$\gamma_d^{(1)} \sim \sqrt{\hat{q}/\Gamma^3}$

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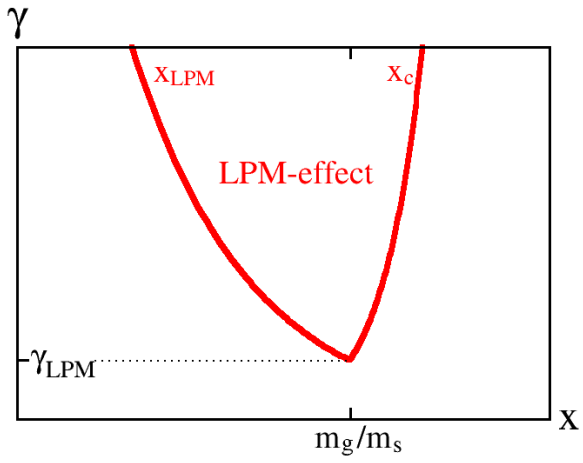

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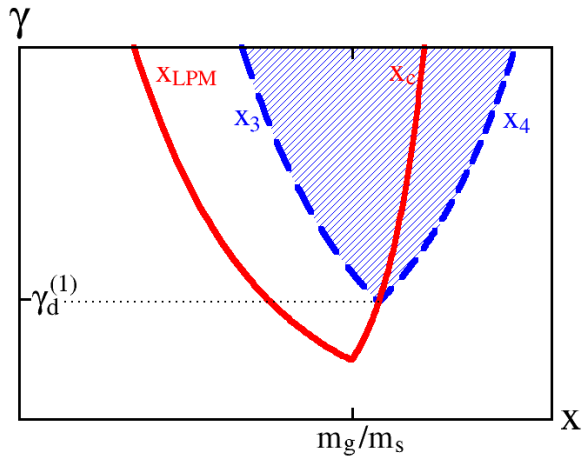
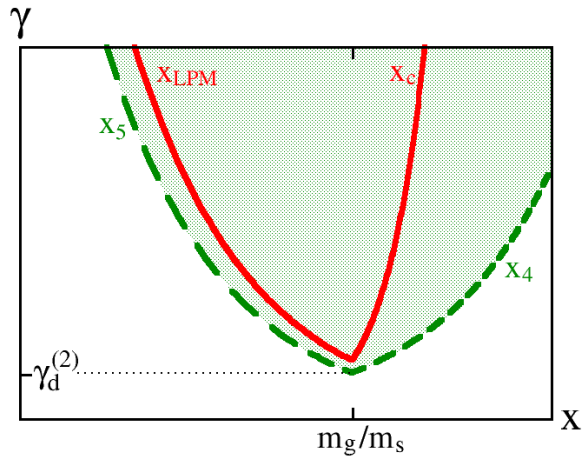


$\gamma_d^{(1)} \sim \sqrt{\hat{q}/\Gamma^3}$

large
$\Gamma/m_g > \hat{q}/m_g^3$



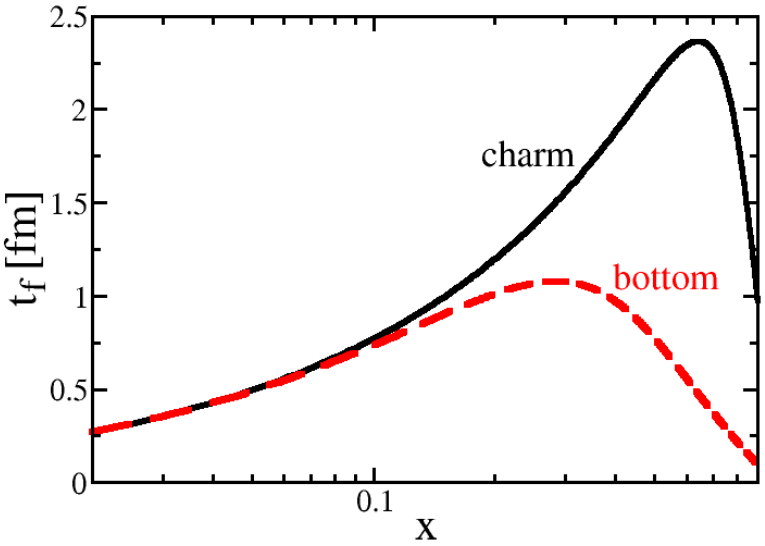
$\gamma_d^{(2)} \sim m_g/\Gamma$

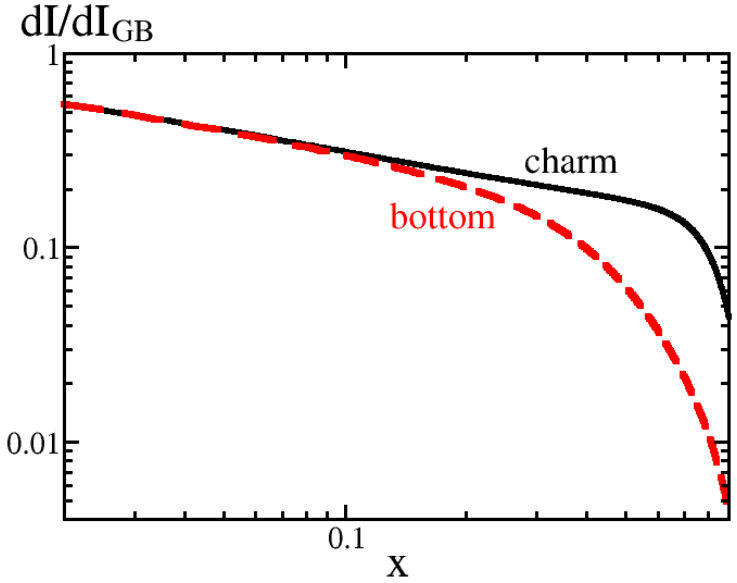
- both increasing E and Γ make effect more pronounced

Parton mass dependence

negligible damping

$E = 40$ GeV, $m_c = 1.3$ GeV, $m_b = 4.2$ GeV, $\hat{q} = 2$ GeV^2/fm, $m_g = 0.8$ GeV

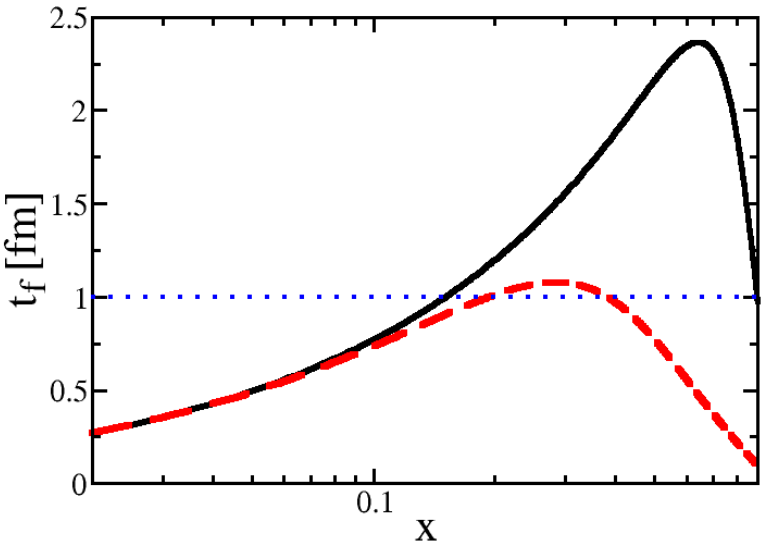


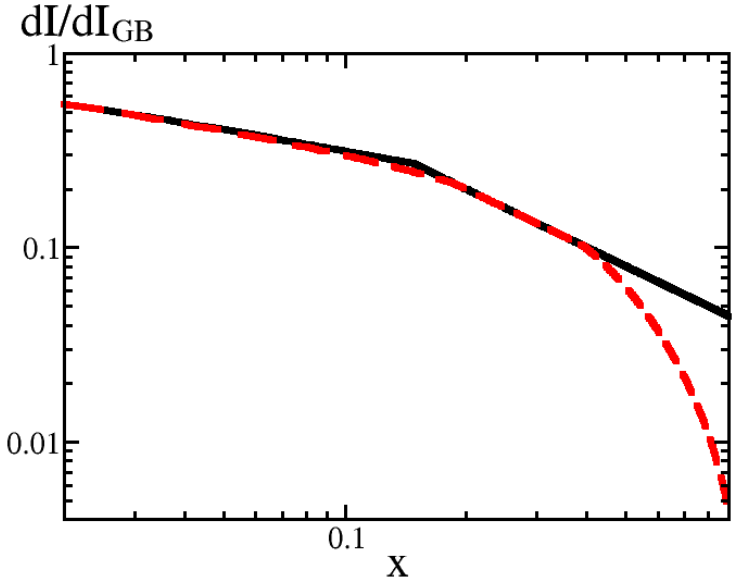


- at small x, parton-mass independent
- clear difference at intermediate and large x

Parton mass dependence

damping rate $\Gamma = 0.2$ GeV

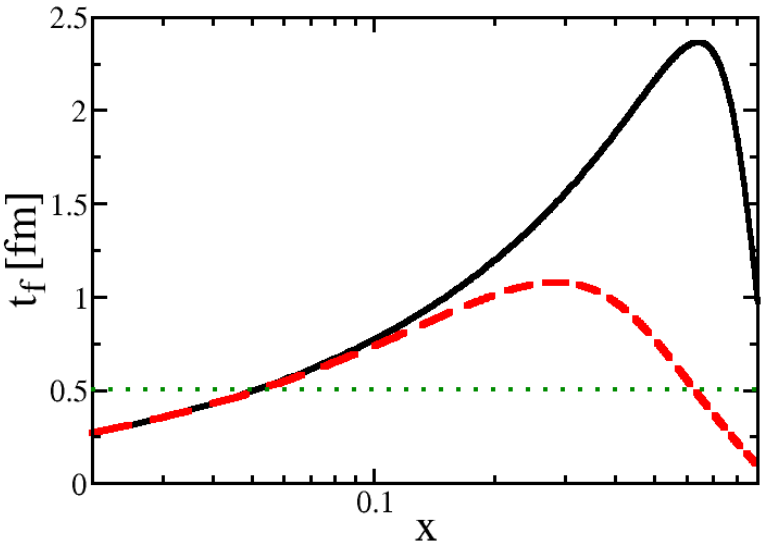


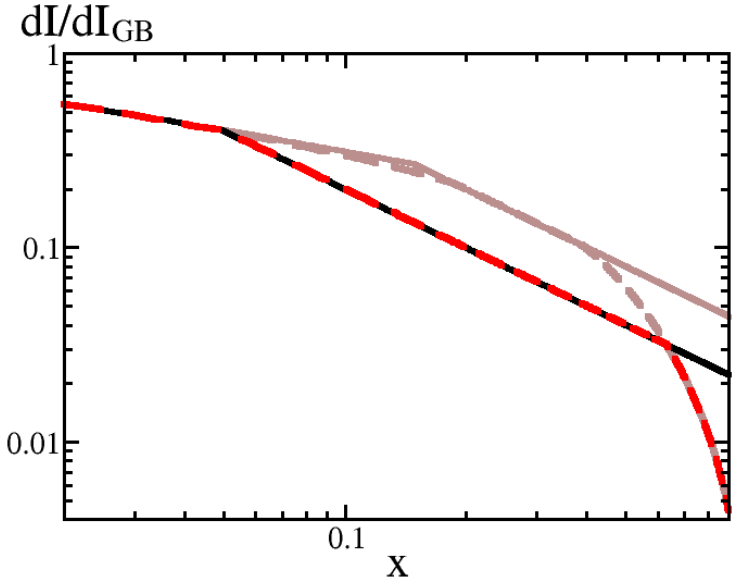


- spectrum parton-mass independent in sizeable *x*-region

Parton mass dependence

damping rate $\Gamma = 0.4$ GeV





- spectrum parton-mass independent in almost entire *x*-region

Conclusions

- qualitative discussion of possible effects of gluon damping on radiative energy loss of partons
  $\longrightarrow$ development of new, mass-independent scale t_d
  $\longrightarrow$ reduction of radiation spectrum stronger than in LPM-regime
  $\longrightarrow$ region of effect increases with Γ and/or E

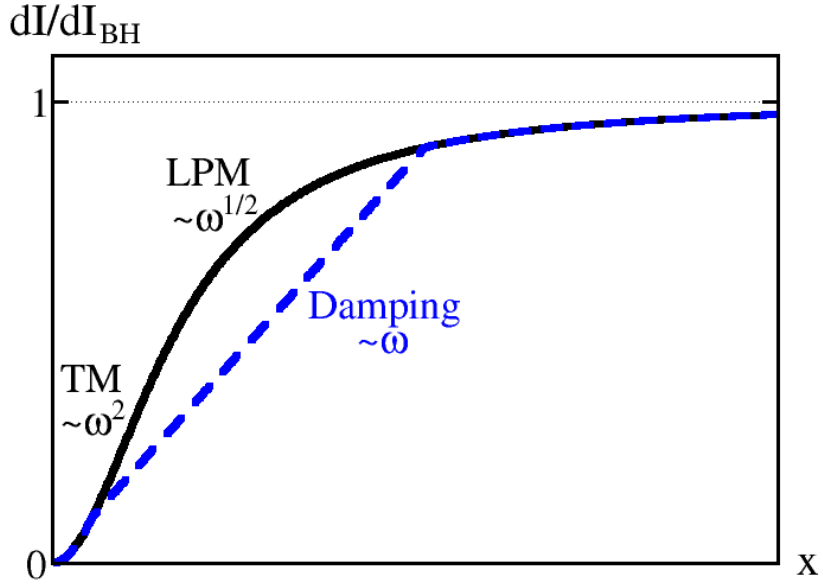
- damping medium hampers formation of hard(er) gluons in favour of soft gluons
  $\longrightarrow$ formation time increases with ω

- with increasing Γ, radiation spectra become more and more parton-mass independent

Absorptive QED-plasma

$\rightarrow$ investigation of photon damping effects for $\omega \ll E$:

- difference to formation time in QCD: $t_f^{(m)} \simeq \sqrt{E/(\hat{q}x)}$
  $\rightarrow$ LPM-suppression of spectrum in soft ω-region
- assume photons to be **time-like** with in-medium mass and width
- photon damping leads to competing time scale $t_d \sim 1/\Gamma$
- spectra scaling ($t_{BH} \simeq E^2/(\omega M^2)$): $\dfrac{dI}{dI_{BH}} \simeq \dfrac{\tilde{t}_f}{t_{BH}}$



Absorptive QED-plasma

$\longrightarrow$ investigation of photon damping effects for $\omega \ll E$:

- complex medium index of refraction $n(\omega) = n_r(\omega) + i n_i(\omega)$
- energy loss spectrum per unit length:

$$-\frac{d^2W}{dz d\omega} \simeq \frac{\alpha}{3\pi}\frac{\hat{q}}{E^2}\int_0^\infty d\bar{t}\, e^{-\omega|n_i|\beta\bar{t}}\ \omega \sin\left[\omega\bar{t}\,(1-|n_r|\beta) + \frac{\omega|n_r|\beta\ \hat{q}}{6E^2}\,\bar{t}^{\,2}\right]$$

- exponential damping factor $\longrightarrow$ damping time scale
- for $n_r = 1$, $n_i = 0$ reduced to LPM radiation spectrum