Radiative energy loss in absorptive media

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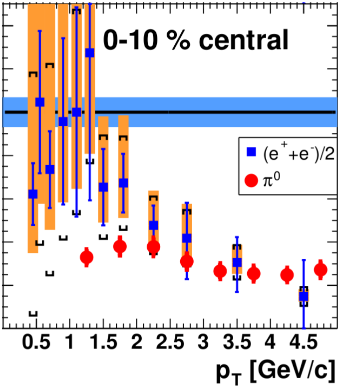
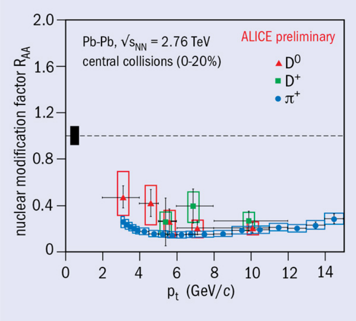
Heavy Ion Collisions in the LHC Era - Rencontres du Vietnam
Quy Nhon, Vietnam, July 15-21, 2012

based on: MB, P. B. Gossiaux, J. Aichelin, arXiv:1106.2856
MB, P. B. Gossiaux, J. Aichelin, arXiv:1201.1890
MB, P. B. Gossiaux, T. Gousset, J. Aichelin, arXiv:1204.2469

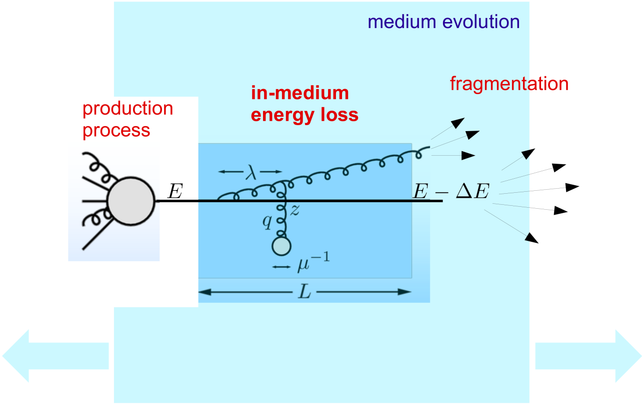
Motivation - Experimental observations





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

Sensitivity of observables in nuclear collisions



in-medium energy loss - some features:

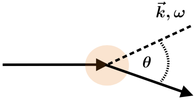
- $\Delta E_{rad} \gg \Delta E_{coll}$ for large E (for light partons)
- less radiative energy loss for heavy quarks (dead cone effect)

Outline

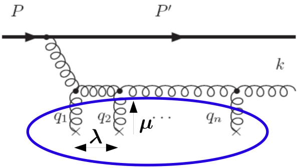
- Introduction
  $\rightarrow$ formation time (length) of bremsstrahlung
- Damping of photon radiation in an absorptive QED plasma
- Damping of gluon radiation in the absorptive QGP
- Conclusions

Intro - 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, $\tau_f \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\theta^2}$

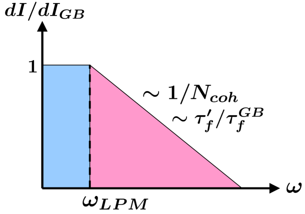


- in case $\tau_f \gg \lambda$ (parton mean free path in medium), $N_{coh} \simeq \tau_f/\lambda$ scatterings contribute coherently to formation of radiation



Intro - 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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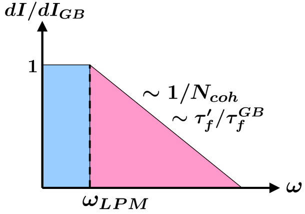

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$\rightarrow$ What is influence of damping mechanisms?

Detour: Absorptive QED-plasma

→ investigation of photon damping effects on the energy loss of a traversing charge with energy E for $\omega = xE \ll E$:

- complex medium index of refraction $n(\omega)^2 = 1 - \frac{m^2}{\omega^2} + \frac{2i\Gamma}{\omega}$
- photons are **time-like** with in-medium mass m and width Γ
- mechanical work → energy loss spectrum:

$$-\frac{dW}{d\omega} = -\mathrm{Re}\left(i\frac{\alpha}{\pi}\int dt \int dt' \omega e^{-i\omega(t-t')}\mathcal{A}(t,t')\right) \text{ with}$$

$$\mathcal{A}(t,t') = \left\{\vec{v}(t)\vec{v}(t') + \frac{\left(\nabla_{\Delta r}\vec{v}(t)\right)\left(\nabla_{\Delta r}\vec{v}(t')\right)}{\omega^2 n(\omega)^2}\right\}\frac{e^{i\omega|n_r|\Delta r}e^{-\omega|n_i|\Delta r}}{\Delta r}$$

- infinite, isotropic, absorptive e-m plasma and charge created in remote past
- essential → **exponential damping factor**
- for $\vec{v}(t)$ as in Landau's work and $n_r = 1$, $n_i = 0$ spectrum reduced to LPM radiation spectrum

Detour: Absorptive QED-plasma

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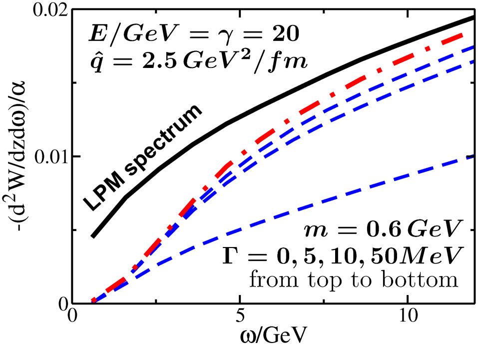
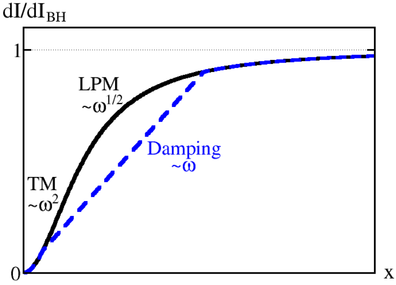


- suppression of spectrum due to finite m and/or Γ

Detour: Absorptive QED-plasma

→ investigation of photon damping effects on the energy loss of a traversing charge with energy E for $\omega = xE \ll E$:

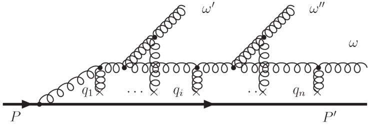
- estimate for formation time t_f: phase in spectrum ~ 1
- difference to formation time in QCD: $t_f' \simeq \sqrt{E/(\hat{q}x)}$
  → LPM-suppression of spectrum in soft ω-region
- photon damping → competing damping time scale $t_d \sim 1/\Gamma$
- spectra scaling ($t_{BH} \simeq E^2/(\omega M^2)$):



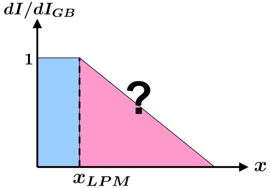
$$\frac{dI}{dI_{BH}} \simeq \frac{\min(t_f, t_d)}{t_{BH}}$$

Absorptive QCD plasma: Damping of gluon radiation

- Is it possible that damping mechanisms influence the formation of gluon radiation itself?
- assume gluons to be **time-like** with in-medium effective *mass* m_g and *width* (associated with damping rate Γ)
- damping mechanisms: $q\bar{q}$-pair creation or secondary bremsstrahlung
- higher-order effects in pQCD: $\Gamma \sim g^4 T \ln(1/g)$



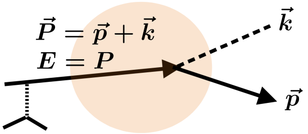
- influence on the spectrum?
- formation influenced if associated **damping time** $t_d \sim 1/\Gamma \lesssim t_f$



Gluon formation time

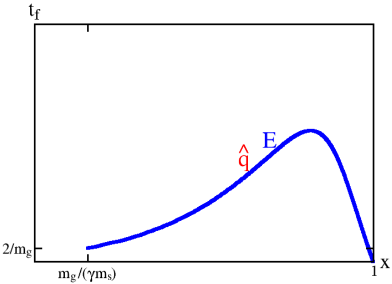
cf. P. Arnold Phys. Rev. D **79** (2009) 065025

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



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

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



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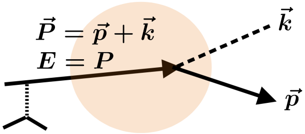

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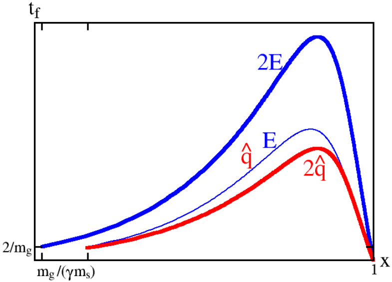
- t_f increases with E
- t_f decreases with $\hat{q}$



Gluon formation time - Qualitative study

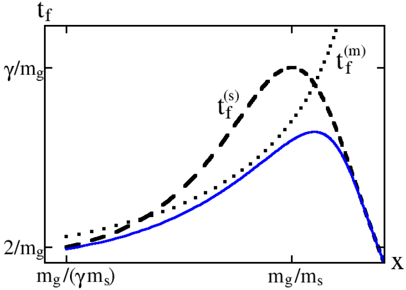
Qualitative behaviour can be discussed via an approximate solution of condition equation

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

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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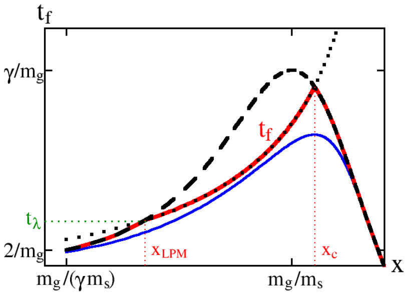

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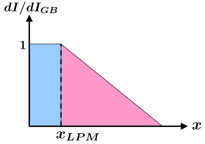
$$t_f^{(m)} = \sqrt{\frac{2xE}{(1-x)\hat{q}}}$$

and assuming

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

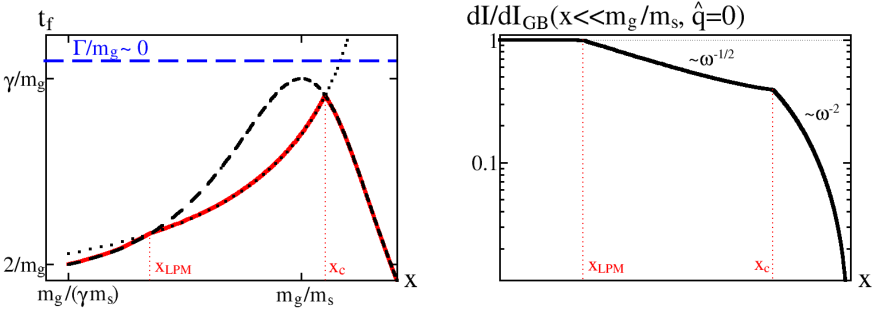
- LPM-suppression for $x \geq x_{LPM} \sim m_g^4/(\hat{q}E)$ when $t_f \geq t_\lambda$



Influence of damping on the radiation spectrum

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

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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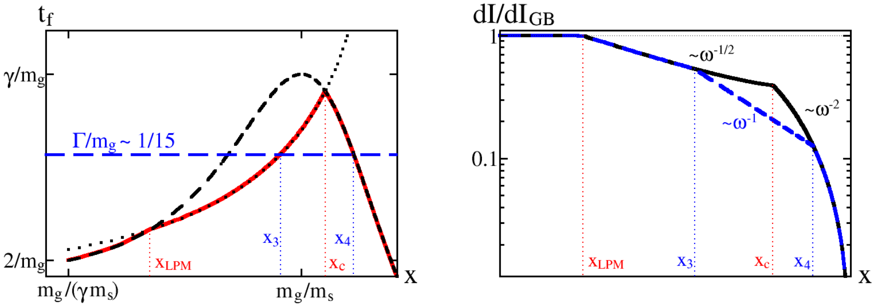
intermediate damping:



- 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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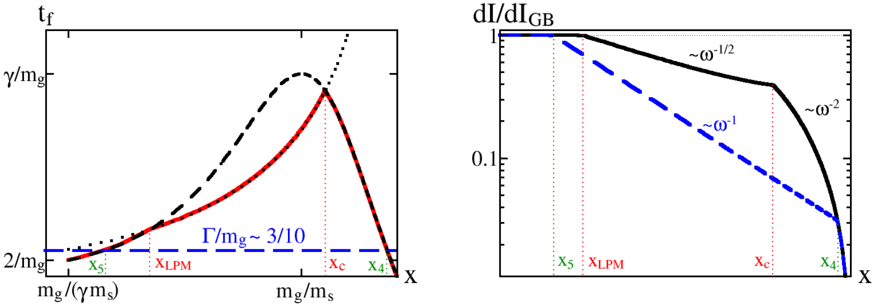
large damping:

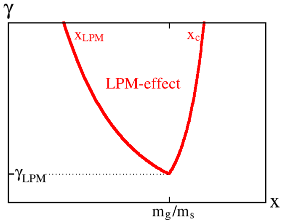


- development of a NEW additional regime due to gluon damping between $x_5 \sim m_g^2/(\Gamma E)$ and $x_4 \sim \Gamma E/m_s^2$
- reduction stronger than due to LPM effect
- for fixed E, increasing Γ influences shape of the spectrum

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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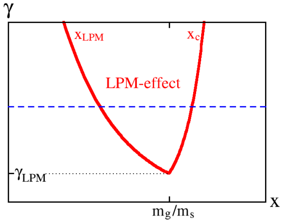

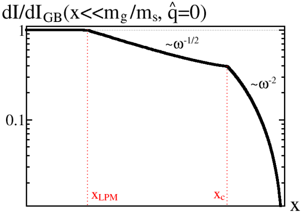

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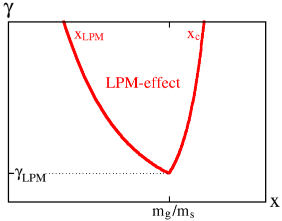
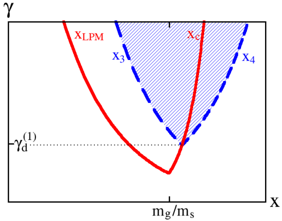


$\gamma_{LPM} \sim m_g^3 / \hat{q}$

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



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

Behaviour with increasing energy

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$\Gamma/m_g = 0$

intermediate
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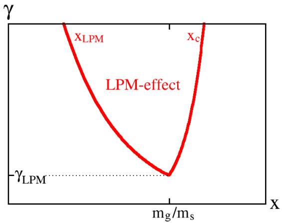

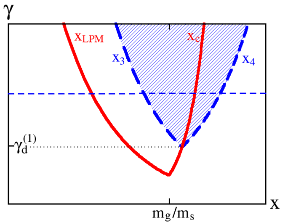

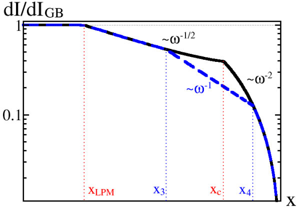

$\gamma_{LPM} \sim m_g^3/\hat{q}$

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

- both increasing E and Γ make effect more pronounced

Behaviour with increasing energy

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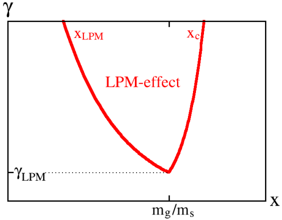
negligible
$\Gamma/m_g = 0$



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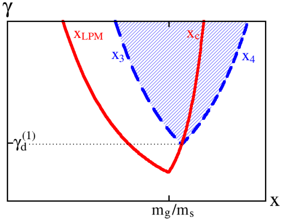
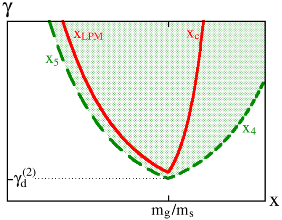


$\gamma_d^{(1)} \sim \sqrt{\hat{q}/\Gamma^3}$

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



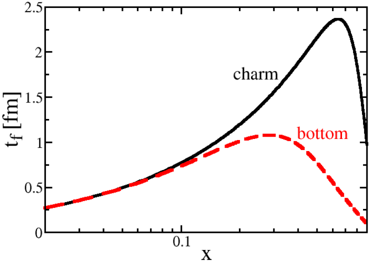
$\gamma_d^{(2)} \sim m_g/\Gamma$

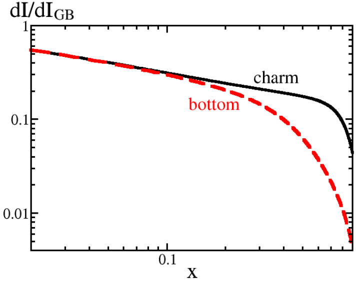
- both increasing E and Γ make effect more pronounced

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

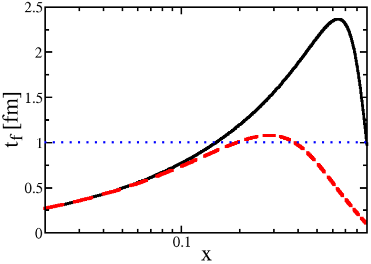


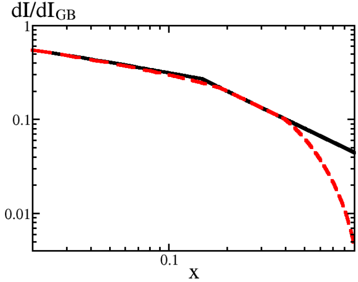


- at small x, parton-mass independent
- clear difference at intermediate and large x

Parton mass dependence

damping rate $\Gamma = 0.2$ GeV

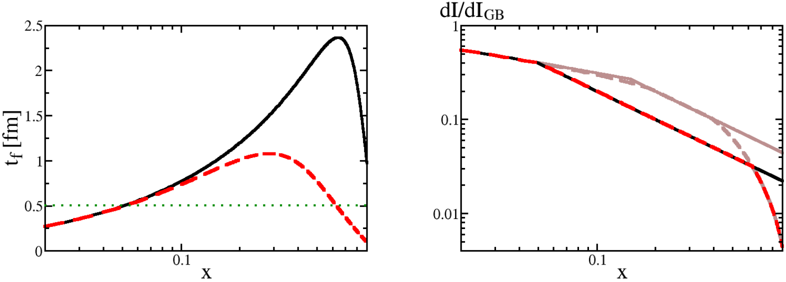




- spectrum parton-mass independent in sizeable x-region

Parton mass dependence

damping rate $\Gamma = 0.4$ GeV



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

Conclusions

- academic study: suppression of energy loss spectrum of charge produced in remote past in an absorptive, infinite e-m plasma
- qualitative discussion of possible effects of gluon damping on radiative energy loss of partons
  $\rightarrow$ development of new, mass-independent scale t_d
  $\rightarrow$ reduction of radiation spectrum stronger than in LPM-regime
  $\rightarrow$ region of effect increases with Γ and/or E
  $\rightarrow$ with increasing Γ (and/or E), radiation spectra become more and more parton-mass independent
- finite size-effects !?
- gluon damping effect on particles produced in the plasma !?
- ω-dependence in Γ !?