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Non-equilibrium effects on hard and electromagnetic probes from a quark-gluon plasma

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HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

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Outline of the talk

- **Introduction and Motivation**
  - ►need of experimental signatures
  - ►hard and electromagnetic probes
  - ►role of non-equilibrium effects

- **Memory effects in radiative jet energy loss**
  - ►dynamic calculation of energy loss -ΔE
  - ►comparison to quasi static calculation

Phys.Rev.D80:045011,2009
arXiv:0905.2930 [hep-ph]

- **Finite lifetime effects on photon emission**
  - ►previous approaches / problems coming up
  - ►time dependent occupation numbers
  - ►achievements / aspects not yet under control
  - ►revision of hitherto ansatz

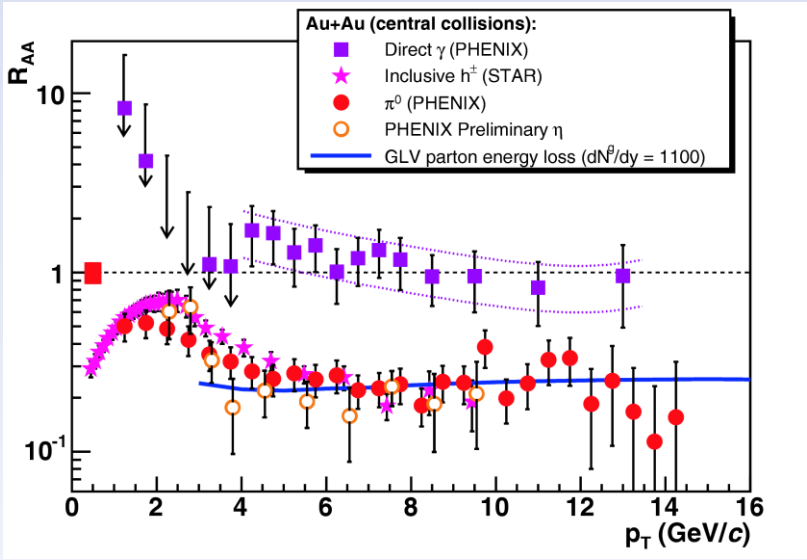
arXiv:0906.1734 [hep-ph]

- **Summary and Outlook**

Introduction and Motivation

Hard probes

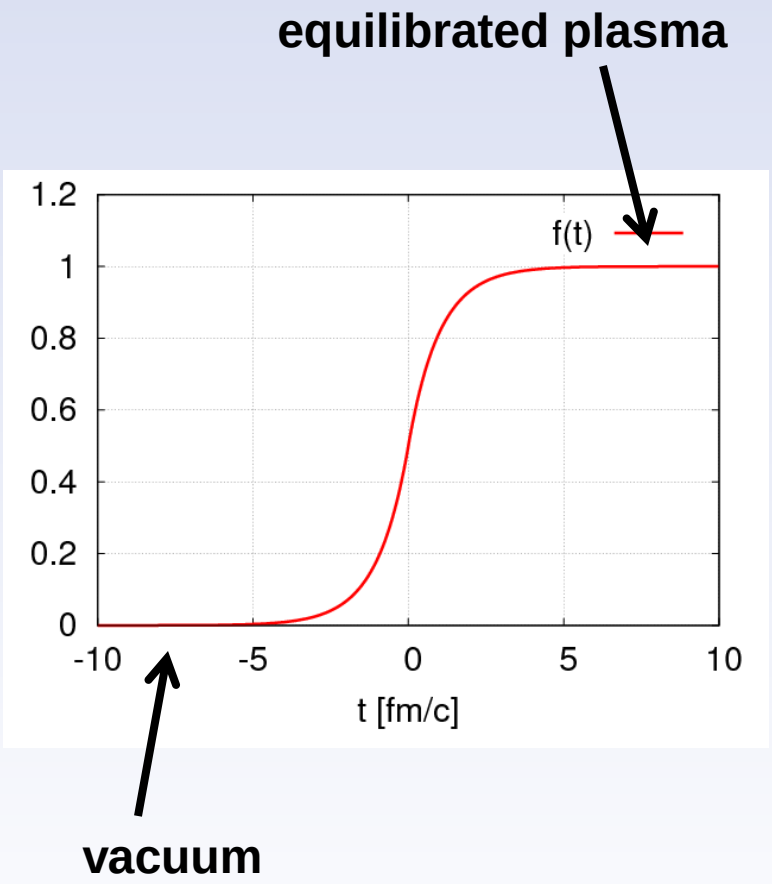
- **direct access to QGP not possible**
  - ►experimental signatures needed
- **hard probes / jet quenching**
  - ►energy loss of high p_T partons described by R_{AA}
  - ►strong jet quenching occurs
  - ►radiative processes play a significant role
- **plasma expands and cools down**
  - ►memory effects in jet energy loss
- **investigation by real time formalism**
  - ►dynamic calculation of energy loss over expansion time
  - ►compare to quasi static calculation
  - ►consider photon emission / scale up to gluon emission



Introduction and Motivation

Photons as electromagnetic probes

- **photons / electromagnetic probes**
  - ►can only interact electromagnetically
  - ►they leave the medium undisturbed
  - ►provide direct insight into early of the collision
- **plasma created over finite timescale**
  - ►can be modeled by “switching on” of occupation numbers
  - ►non equilibrium situation occurs during creation period
- **question of interest**
  - ►How does the finite lifetime itself affect the resulting photon spectra?



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Part I

Radiative jet energy loss

Radiative jet energy loss

- **non-equilibrium photon production rate**

$$k\frac{d^7n}{d^4x d^3k} = \frac{1}{(2\pi)^3}\mathrm{Re}\left\{\int_{-\infty}^{t} du\; i\Pi_T^{<}(\vec{k},t,u)e^{ik(t-u)}\right\}$$

  ▶ relates photon production rate to full history of emitting system
  ▶ non local in time / accounts for possible memory effects

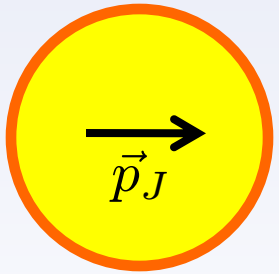
- **one loop approximation for photon self energy**

$$i\Pi_{\mu\nu}^{<}(\vec{k},t,u) = e^2\int\frac{d^3p}{(2\pi)^3}\mathrm{Tr}\left\{\gamma_\mu S_F^{<}(\vec{p}+\vec{k},t,u)\gamma_\nu S_F^{>}(\vec{p},u,t)\right\}$$

  ▶ non-equilibrium / explicit dependence on both time arguments

- **assume local thermal equilibrium / ansatz for fermion jet**

$$\begin{aligned} S_F^{<}(\vec{p}+\vec{k},E) &= i(2\pi)^4V^{-1}\delta^{(3)}(\vec{p}+\vec{k}-\vec{p}_J)A_F(\vec{p}+\vec{k},E) \\ S_F^{>}(\vec{p},E) &= -2\pi i A_F(\vec{p},E) \end{aligned}$$



  ▶ medium effects / time involution incorporated in spectra function

Radiative jet energy loss

- **parameterize spectral function as Lorentzian curve**

$$A_F(\vec{p}, E) = \frac{1}{2\pi\varepsilon_{\vec{p}}} \left\{ \frac{\gamma_0\varepsilon_{\vec{p}} - \vec{\gamma}\cdot\vec{p} + m}{(E-\varepsilon_{\vec{p}})^2 + \Gamma^2} \right\}$$ fermion component only !

  - ►time representation exponentially damped / finite lifetime in medium
  - ►Γ can be identified with scattering rate
  - ►relation to scattering cross section: $\Gamma = n^*v^*\sigma_{tot} = n^*v^*(\sigma_{QED}+\sigma_{QCD})$

- **calculate photon self energy and photon production rate**
  - ►inclusion of both Landau-Pomeranschuk-Migdal effect and Bethe-Heitler cross section

Radiative jet energy loss

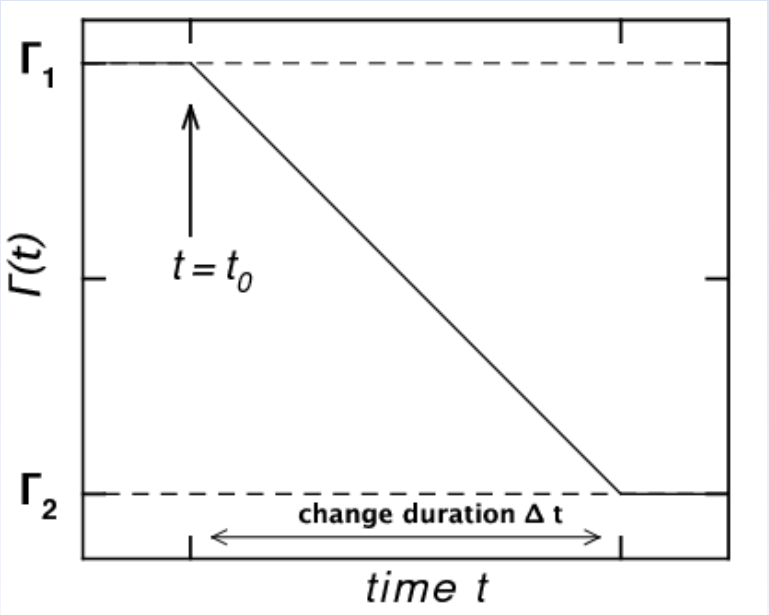
Implementation of time dependencies

- **model medium evolution by time dependent scattering rates**
  - ►at $t=t_0$, we vary Γ linearly over Δt
  - ►calculate energy loss over Δt

- **quasi static calculation**
  - ►instantaneous adaption of radiative behavior to change of Γ

- **choice of parameters**
  - ►Γ_1 = 1.0 GeV, Γ_2 = 0.3 GeV
  - ►switching time Δt = 4 fm/c,
  - ►jet momentum p_J=20 GeV

- **energy rate ~ const. for large k**
  - ►radiation power dE/dt linearly divergent
  - ►introduce cutoff at $k=p_J$



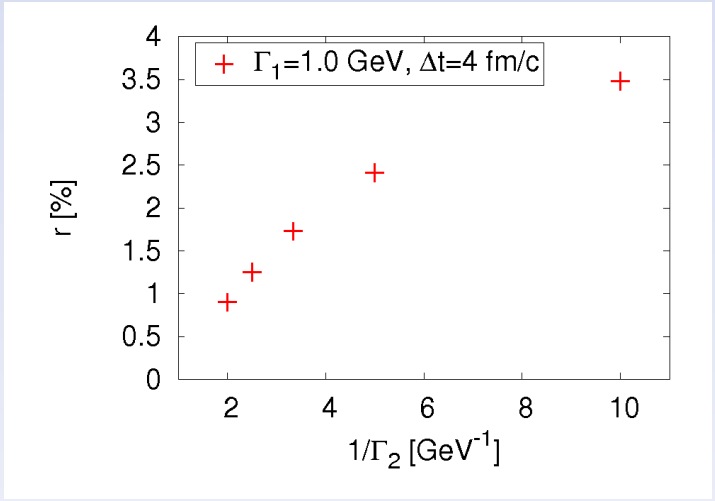
Radiative jet energy loss

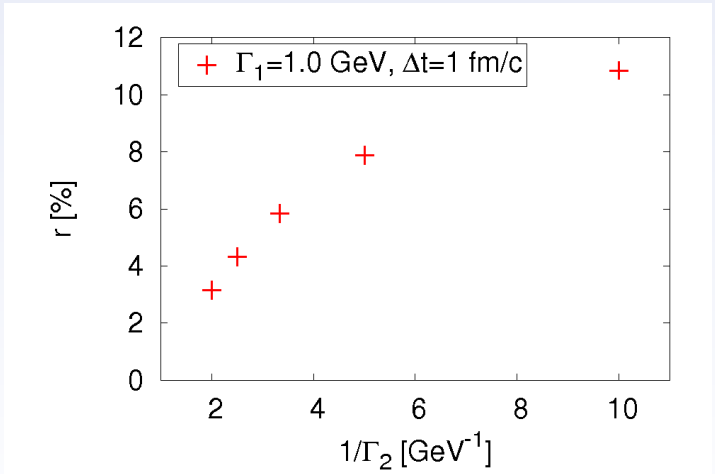
Numerical investigations

- **comparison to quasi static calculation**
  - ►difference less than 5 % for $\Delta t = 4$ fm/c; $-\Delta E \approx 6.32$ GeV
  - ►significant aberration (≥ 10 %) only for $\Delta t = 1$ fm/c ($-\Delta E \approx 1.58$ GeV)
  - ►dynamic treatment not crucial

- **but keep in mind**
  - ►gluon emission / **-**ΔE scaled up by a factor of $\alpha_g/\alpha_e \sim 40$
  - ►fermion damped off at once

- **unphysical UV-behavior**
  - ►ansatz allows for transitions between arbitrarily offshell energy states





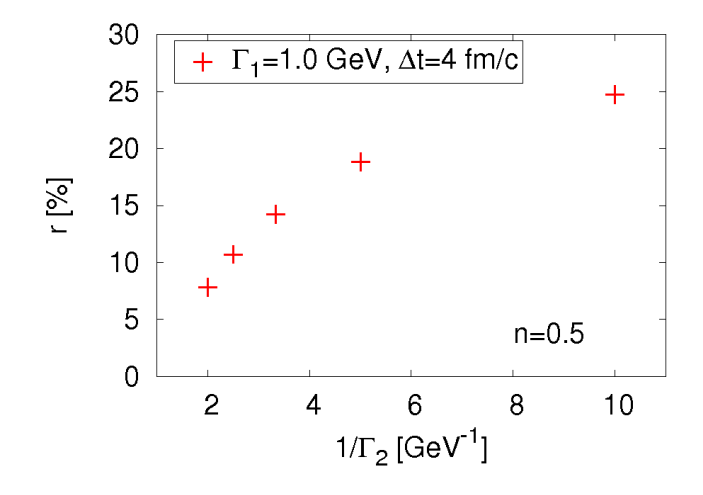
Radiative jet energy loss

Numerical investigations

- **consider modified ansatz**
  - ►restrict available energy states to interval of $2n\Gamma$ around ω_p
  - ►suppression of hard photon modes with $|\omega_{\mathbf{p}}-\omega_{\mathbf{p-k}}-k| > 2n\Gamma$

- **$-\Delta E$ tremendously reduced for small n**
  - ►$-\Delta E \approx 0.22$ GeV for n=0.5
  - ►scales up to $-\Delta E \approx 8.8$ GeV / ~ 50 % of jet energy
  - ►reasonable from phenomenological point of view

- **memory effects are of importance**
  - ►aberration of ~25 % for n=0.5



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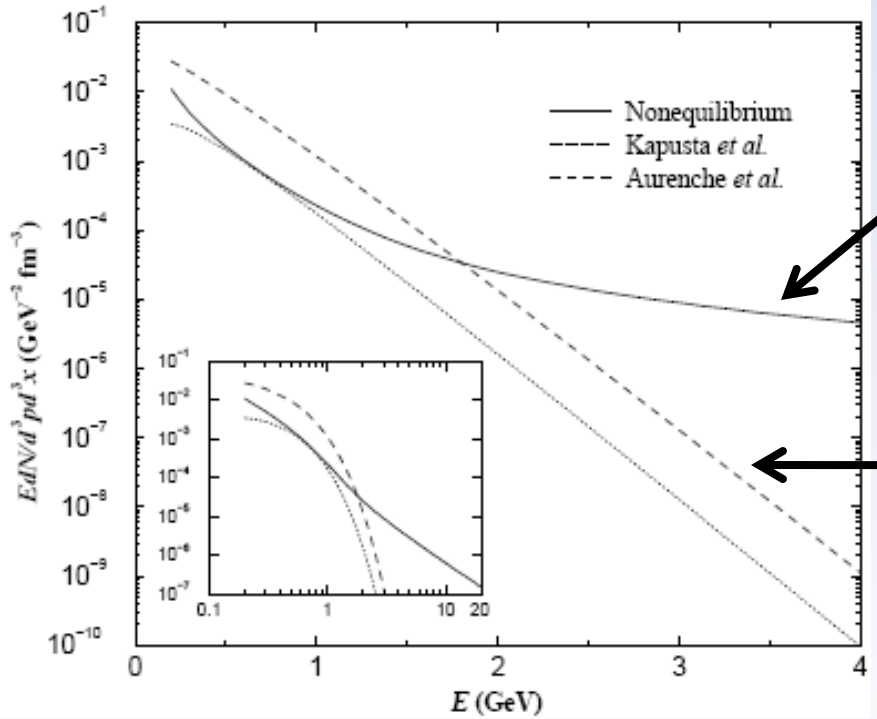
Part II

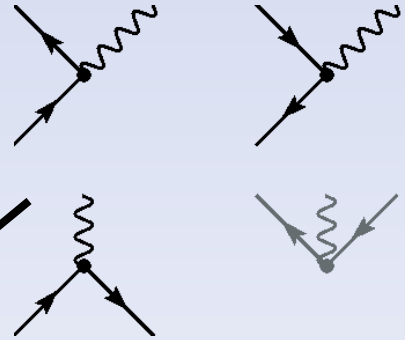
Finite lifetime effects on photon emission

Finite lifetime effects on photon emission

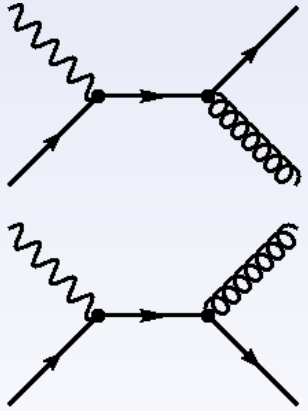
Previous Approaches

- **Boyanovsky et al., Phys.Rev. D63 (2001) 051702**
  - ►contribution of first order processes
  - ►algebraic decay of photon spectrum for k>1.5 GeV





kinematically forbidden in thermal equilibrium



LO-contributions in equilibrium

- ►dominance over higher order equilibrium contributions

Finite lifetime effects on photon emission

Previous Approaches

- **Phys.Rev. D68 (2003) 065018**
  - ►contribution from vacuum polarization divergent
  - ►attempts to “renormalize” it
  - ►other contributions behave as ~$1/k^3$ for large k !
  - ►total photon number and totally emitted energy divergent !

- **Gelis et al., Phys.Rev. D71 (2005) 085015**
  - ►vacuum contribution claimed to be unphysical
  - ►renormalization techniques claimed to be ad hoc

- **actual motivation for present investigations**
  - ►find an ansatz to handle mentioned problems

Finite lifetime effects on photon emission

- **recall photon production rate**

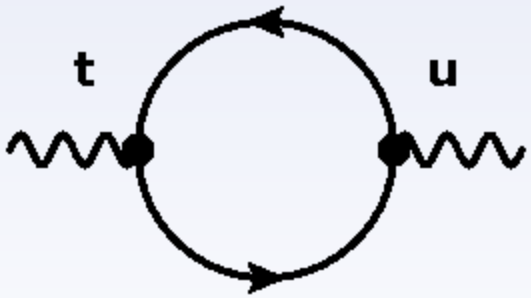
$$k\frac{d^7n}{d^4xd^3k} = \frac{1}{(2\pi)^3}\mathrm{Re}\left\{\int_{-\infty}^{t} du\; i\Pi_T^<(\vec{k},t,u)e^{ik(t-u)}\right\}$$

- **again one loop ansatz for photon self energy**

$$i\Pi_{\mu\nu}^<(\vec{k},t,u) = 3\cdot\sum_{q=u,d} e_q^2\int\frac{d^3p}{(2\pi)^3}\mathrm{Tr}\left\{\gamma_\mu S_F^<(\vec{p}+\vec{k},t,u)\gamma_\nu S_F^>(\vec{p},u,t)\right\}$$

- **chose model description of medium evolution**
  - ▶vacuum always persistent / medium only occurs temporarily
  - ▶introduce time dependent occupation numbers

$$\begin{aligned} n_F(\omega_{\vec{p}},t) &= \mathbf{f(t)}n_F(\omega_{\vec{p}}) \\ n_F(\omega_{\vec{p}}) &\to \sqrt{n_F(\omega_{\vec{p}},t)n_F(\omega_{\vec{p}},u)} \\ 1-n_F(\omega_{\vec{p}}) &\to \sqrt{(1-n_F(\omega_{\vec{p}},t))(1-n_F(\omega_{\vec{p}},u))} \end{aligned}$$



  - ▶couple time dependence to vertices
  - ▶keep yield an absolute square

Finite lifetime effects on photon emission

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- **achievements of this ansatz**
  - ▶dynamic change from vacuum polarization to full one loop polarization

$$i\Pi_T^<(\vec{k},t,u) = \begin{cases} i\Pi_{T,0}^<(\vec{k},t-u) & \text{for } f(t), f(u) \to 0 \quad \text{vacuum} \\ i\Pi_{T,M}^<(\vec{k},t-u) & \text{for } f(t), f(u) \to 1 \quad \text{medium} \end{cases}$$

  - ▶decomposition into vacuum part and medium part

$$\begin{aligned} i\Pi_T^<(\vec{k},t,u) &= i\Pi_{T,0}^<(\vec{k},t-u) + i\Pi_T^<(\vec{k},t,u) - i\Pi_{T,0}^<(\vec{k},t-u) \\ &\equiv i\Pi_{T,0}^<(\vec{k},t-u) + i\Pi_{T,M}^<(\vec{k},t,u) \end{aligned}$$

  - ▶resulting photon production rate

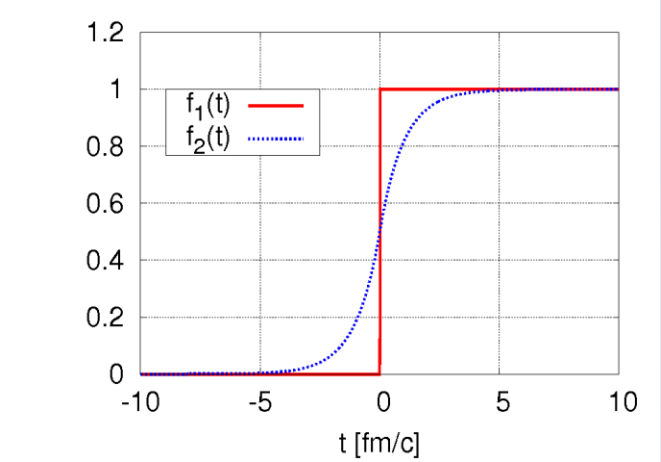
$$k\frac{d^7n}{d^4x d^3k} = \frac{1}{(2\pi)^3}\mathrm{Re}\left\{\int_{-\infty}^{t} du\; i\Pi_{T,M}^<(\vec{k},t,u)e^{ik(t-u)}\right\}$$

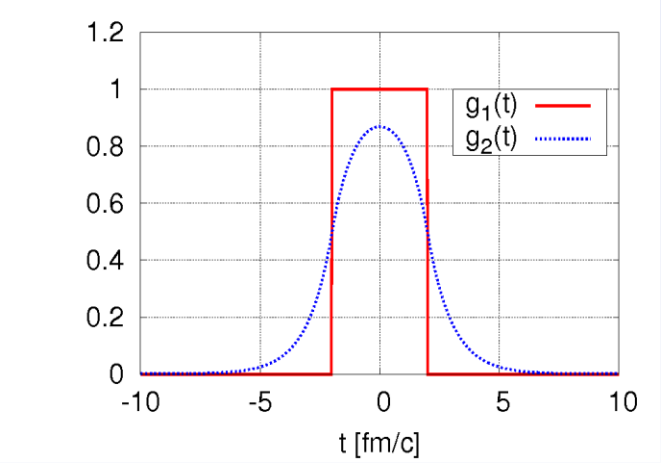
  - ▶vacuum polarization evaluated onshell / no contribution
  - ▶medium contribution evaluated offshell
  - ▶contribution of 1st order processes possible

Finite lifetime effects on photon emission

Numerical Investigations

- **properties of quark gluon plasma**
  - ▶ temperature T=0.3 GeV
  - ▶ formation time τ_F=1 fm/c
- **medium switched on and maintained**
- **medium switched on and off again**
  - ▶ scenario for heavy ion collision
  - ▶ consider yield for $t \rightarrow +\infty$ as observable quantity
  - ▶ assume lifetime of τ = 4 fm/c
- **consider different switching functions**
  - ▶ dependence of photon spectra on "smoothness" of switching function



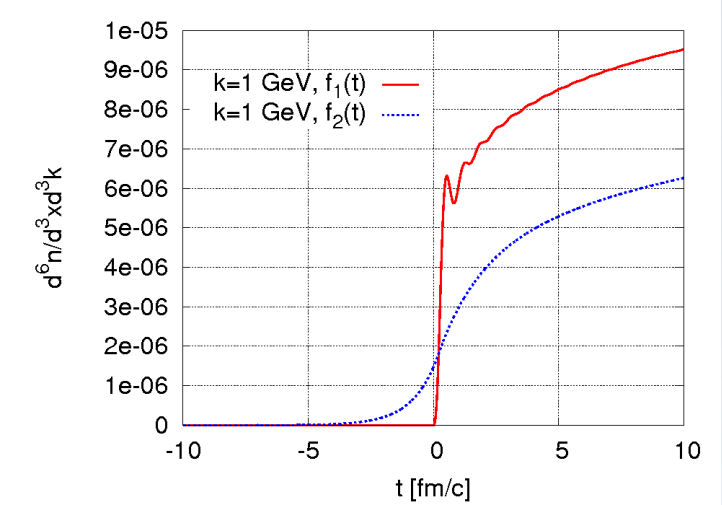


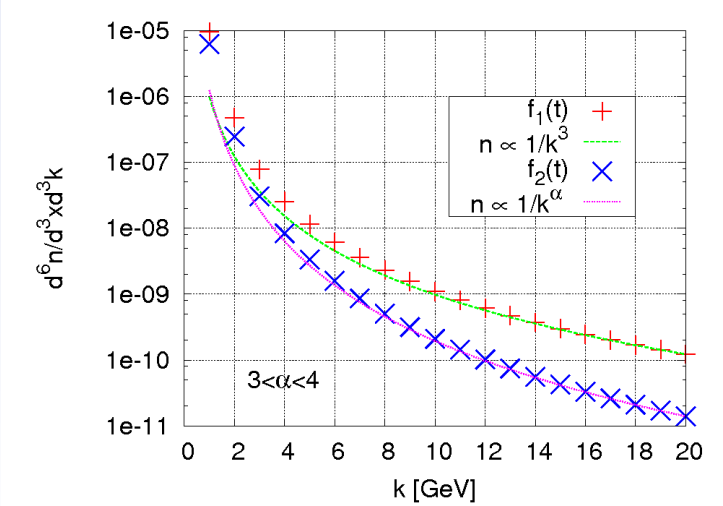
Finite lifetime effects on photon emission

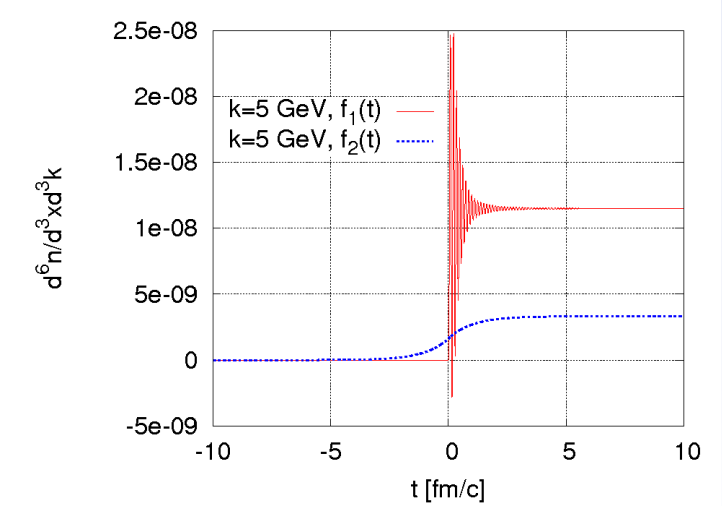
Medium switched on and maintained

- **time dependence of photon yield**
  - ▶ logarithmic growth in time for small k
  - ▶ saturation in time for large k

- **photon spectrum in UV-domain**
  - ▶ behaves as ~$1/k^3$ for $f_1(t)$
  - ▶ slightly steeper decay for $f_2(t)$
  - ▶ problem with UV-finiteness not under control





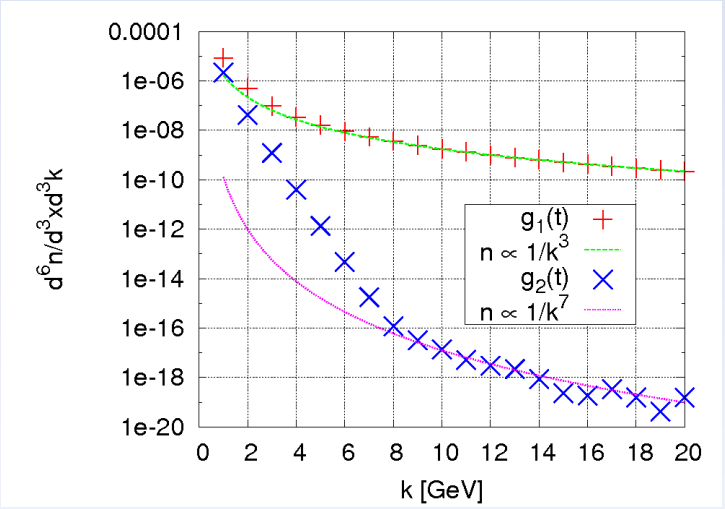


Finite lifetime effects on photon emission

Medium switched on and off again

- **scenario of heavy ion collision**
  - ▶consider yield for $t \rightarrow +\infty$ / observable quantity
  - ▶photon yield saturates for all k

- **spectrum in UV-domain**
  - ▶highly sensitive to choice of g(t)
  - ▶behaves as ~$1/k^3$ for instantaneous switching
  - ▶behaves as ~$1/k^7$ for smooth switching



- **problems not solved but circumvented**
  - ▶switching on and off not always reasonable

Finite lifetime effects on photon emission

Revision of ansatz

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- **consider Ward Takahashi identity / U(1)-invariance of QED**

$$\partial_x^\mu i\Pi^<_{\mu\nu}(x,y) = 0 \Rightarrow \partial_t i\Pi^<_{0j}(\vec{k},t,u) - ik^i i\Pi^<_{ij}(\vec{k},t,u) = 0$$

  - ▶not fulfilled by hitherto ansatz (and either by Boyanovsky et al.)
  - ▶conjectured reason for non UV-finite photon spectra

- **model creation of QGP by Yukawa-like (mass-like) source term**

$$\mathcal{L}(x) = \mathcal{L}_{QED}(x) - g\phi(t)\hat{\bar{\psi}}(x)\hat{\psi}(x)$$

  - ▶source field ϕ(t) classical / only time-dependent
  - ▶time dependent mass / compatible with Ward Takahashi identities

- **currently under investigation**
  - ▶UV-finite photon spectra within new ansatz
  - ▶consider role of Ward Takahashi identity

Summary and Outlook

- **radiative jet energy loss**
  - ►model medium evolution via time dependent scattering rate
  - ►good agreement with quasi static calculation
  - ►energy loss too large / unphysical UV-behavior of photon spectra
  - ►modified ansatz / restriction of initial and final energy states
  - ►energy loss decreased / memory effects clearly larger

- **finite lifetime effects on photon production**
  - ►simulate time evolution of QGP via time dependent occupation numbers
  - ►self energy evaluated offshell / first order contributions
  - ►achievements / problems not yet under control

- **revision of ansatz**
  - ►model time evolution by Yukawa-like source term
  - ►consider role of Takahashi Ward identities
  - ►treatment of possible infrared singularities

- **non-equilibrium quantum field theory remains challenging**