Effects of running coupling on photons from jet-plasma interaction in relativistic heavy ion collisions

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Plan of the discussion

- Motivation
- Probes of QGP: Jet-Quenching, Di-leptons, **Photons** e.t.c.
- Sources of **Photons**
- **Jet-photon** production rate
  - Radiative and collisional energy loss of jet parton
  - Effects of running coupling of QCD
- Results
- Summary & Conclusions

Motivation

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A system of thermalized matter where the properties of the system are governed by the quarks and gluons degrees of freedom.

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QGP is expected to be formed in relativistic nucleus nucleus collisions.

Probes of QGP & Advantages

Indirect probes for QGP

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I am interested only on **"Photons"**

Advantages of Photons

- Weak final state interaction ⇒ Minimal re-scattering
- Large mean free path

Photon: **Good probe of initial condition**

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- **Decay photons:** Decay product of long lived secondaries $(\pi^0 \rightarrow \gamma\gamma, \eta \rightarrow \gamma\gamma)$
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- **Decay photons:** Decay product of long lived secondaries $(\pi^0 \rightarrow \gamma\gamma, \eta \rightarrow \gamma\gamma)$
- **Hard or Direct photons:**
    - **Prompt photons:** Initial hard scatterings
    - **Pre-equilibrium photons:** Produced before thermalization of the QGP
    - **Thermal photons:** From hot medium (Quark Matter & Hadronic Matter)
    - **Jet-thermal photons:** Photons from passage of jets through plasma.

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- The differential Photon production rate for these processes

$$\frac{dN}{d^4x d^2p_T dy} = \frac{\mathcal{N}(2\pi)^4}{2(2\pi)^3} \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} f_{jet}(\mathbf{p_1})$$
$$f_2(\mathbf{E_2}, T)\delta(p_1 + p_2 - p_3 - p)|\mathcal{M}|^2[1 \pm f_3(\mathbf{E_3}, T)]$$

The phase space distributions of jet quark are given by,

$$f_{jet}(\mathbf{p_1}) = \frac{1}{g_q} \frac{(2\pi)^3}{\pi R'^2 \tau p_1} \frac{dN_{jet}}{d^2p_{1T}dy} R(r) \times \delta(\eta - y)\, \Theta(\tau_f - \tau_i)\, \Theta(R' - r)$$

where

$$\frac{dN_{jet}}{d^2p_{1T}dy}|_{y=0} = T_{AA}\frac{d\sigma_{jet}}{d^2p_Tdy}|_{y=0} = K\frac{a}{(1+p_1/b)^c}$$

(For details see R. J. Fries, B. Muller and D. K. Srivastava, PRL, **90** 132301 (2003))

Advantage of jet-photon as a signal

- The p_T distribution of the jet-photon $\propto$ p_T distribution of the jet quarks at an early stage of interaction (without any energy-loss).

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- The p_T distribution of the jet-photon $\propto$ p_T distribution of the jet quarks at an early stage of interaction (without any energy-loss).
- Measured p_T distribution of hadrons $\propto$ p_T distribution of partons after leaving QGP medium.
- Comparative study of both the spectra could provide the quantitative determination of energy loss of a parton within plasma.

Effects of running coupling of QCD

- **Scales** in high temperature effective field theory

  Temperature, T **Parton momentum,** k

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QCD coupling depends on both T and k: $\alpha_s = \alpha_s(k, T)$

$$\alpha_s(k, T) = \frac{u_1(\frac{k}{T})}{1 + exp(u_2\frac{k}{T} - u_3)} + \frac{v_1}{(1 + exp(v_2\frac{k}{T} - v_3))(ln(e + (\frac{k}{\lambda_s})^a + (\frac{k}{\lambda_s})^b)}$$

- $k = \sqrt{|\omega^2 - q^2|}$ and the value of a, b and λ_s are 9.07, 5.90 and 0.263 GeV respectively.
- For the limiting behavior ($k << T$), we choose, $u_1 = {\alpha^*}_{3d}(1 + exp(-u_3))$
- ${\alpha^*}_{3d}$ and ${\alpha^*}_s$ are the IR fixed point of $SU(3)$ Yang-Mills theory in $d = 3$ and $d = 4$ dimensions respectively.
- The remaining four parameters ($u_2 = 5.47$, $u_3 = 6.01$, $v_2 = 10.13$ and $v_3 = 9.27$) fit the numerical results for pure Yang-Mills theory obtained from the RG equations.

(for details see J. Braun and H.-J. Pirner PRD **75**, 054031, (2007))

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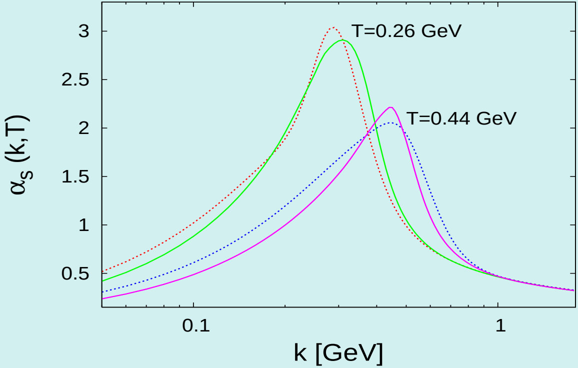


Comparison of the fit of running coupling with the pure Yang-Mills theory

- Taking the running coupling of QCD into account, energy loss of an incident quark in the QGP medium is increased.

Photon rate due to jet plasma interaction

- Jet quarks are not **thermalised** $\Longrightarrow$ Undergo **brownian** motion $\Longrightarrow$ jet quarks loose energy by **collision** and **radiation**.

- **Thermal** distribution function can not be used.

- The **evolution** of the **phase space distribution** of quarks $\Longrightarrow$ **Fokker-Planck** eqn.

$$\begin{aligned} \frac{\partial f}{\partial t} &= \gamma(t)\frac{\partial}{\partial \vec{p}}(\vec{p}f) + D(t)\frac{\partial^2 f}{\partial \vec{p}^2} \\ \text{where} & \\ \gamma &= \frac{1}{E}\left(\frac{dE}{dx}\right) \\ D &= 2T\left(\frac{dE}{dx}\right) \end{aligned}$$

dE/dx $\Longrightarrow$ **differential (both collisional + radiative) energy loss** of the **jet parton**

Solution of Fokker-Planck equation

$$f(t,\vec{p}) = \int d^3\vec{p}_0 G(t,t_0,\vec{p};p_0) f_0(\vec{p}_0)$$

where

$$\begin{aligned} G(t,\vec{p};p_0) &= \left[\frac{1}{4\pi\Delta(t)}\right]^{\frac{3}{2}} exp\left[-\frac{(\vec{p}-\vec{p}_0 exp(-(\Gamma(t)))^2}{4\Delta(t)}\right] \\ \Delta(t) &= exp\left[-2\Delta(t)\right]\int_0^t d\tau D(\tau) exp[2\Delta(\tau)] \\ &\text{and} \\ \Gamma(t) &= \int_0^t d\tau \gamma(\tau) \end{aligned}$$

f_0 → Initial distribution function.

(For details see H. V. Hees and R. Rapp, PRC **71**, 034907 (2005))

Continued....

- The p_T distribution of quark is related to phase space distribution by

$$f_q = \frac{(2\pi)^3}{g_q V} \frac{dN}{d^2 p_T dy}$$

- Using Fokker-Planck eqn we get the time evolution of p_T distribution of quark

$$\frac{dN}{d^2 p_{1T} dy} = \int G(t, t_0, \vec{p}; p_0) \frac{dN}{d^2 p_{0T} dy} d^3 p_{0T}$$

where $\frac{dN}{d^2 p_{0T} dy} d^3 p_{0T} \rightarrow$ initial p_T distribution of quark

Continued.....

p_T distribution of jet-photon

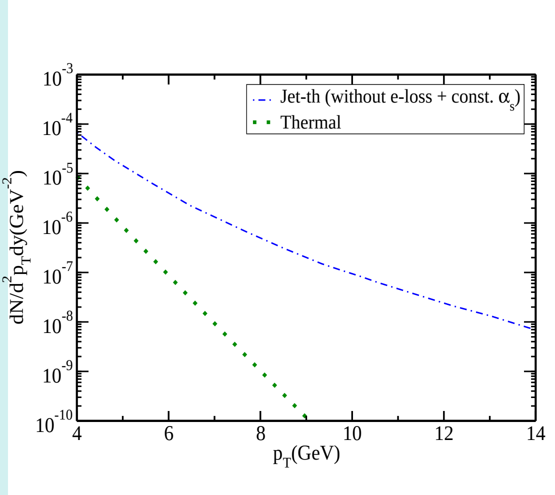
$$\begin{aligned}\frac{dN}{d^2p_T dy} &= \int d^4x \, \frac{dN}{d^4x d^2p_T dy} \\ &= \frac{(2\pi)^3}{\nu_q}\frac{\mathcal{N}_i}{16(2\pi)^7 E}\int_{t_i}^{t_c} dt' \int_0^R r dr \int d\phi \mathcal{P}(\vec{w}_r) \int d\hat{s} d\hat{t} |\mathcal{M}_i|^2 \\ &\times \int dE_1 dE_2 \frac{1}{p_{1T}} \frac{dN}{dp_{1T}^2 dy}(p_{1T}, t') \frac{f_2(E_2)(1 \pm f_3(E_3))}{\sqrt{aE_2{}^2 + 2bE_2 + c}}\end{aligned}$$

$\mathcal{P}(\vec{w}_r)$ is the initial jet production probability distribution at the initial radial position $\vec{w}_r$ in the plane $z_0 = 0$, where

$$|\vec{w}_r| = (\vec{r} - (t' - t_i)\frac{\vec{p}}{|\vec{p}|}).\hat{r} \quad = \sqrt{(rcos\phi - t')^2 + r^2 sin^2\phi} \qquad \text{for} \quad \mathrm{t_i} \sim 0$$

and ϕ is the angle in the plane $z_0 = 0$ between the direction of the photon and the position where this photon has been produced.

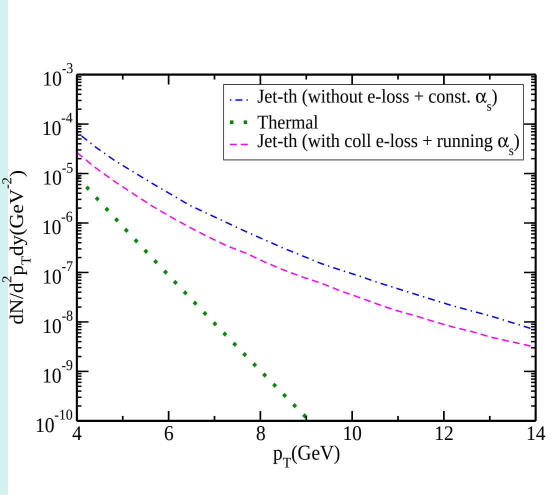
p_T distribution of jet photon @ RHIC energy



- **Photon yield** from the jet-plasma interaction (without eloss + const α_s) is higher than the thermal photon yield.

The p_T distribution of jet-th photons at $T_i = 0.446$ GeV, $\tau_i = 0.147$ fm/c

p_T distribution of jet photon @ RHIC energy



- **Jet photon yield decreases** due to **energy loss** (**collisional** + **running** α_s) jet parton.
- We observe **suppression** of **jet photon** as a consequence of running of **QCD coupling** (α_s).

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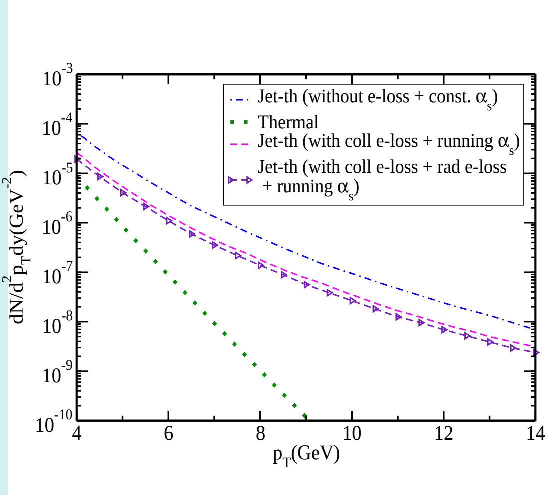
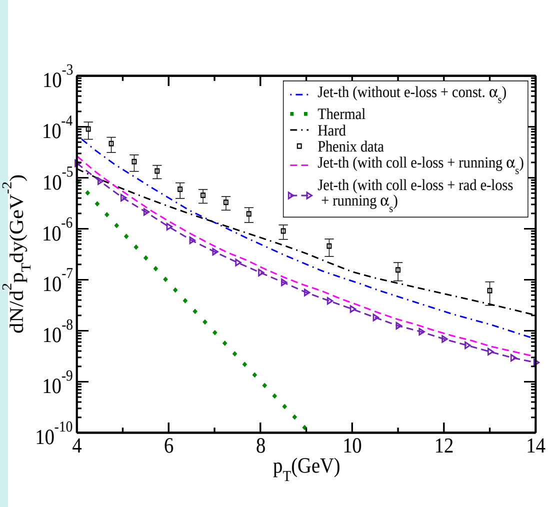


- **Photon yield decreases** due to both **energy losses** (**collisional** + **radiative** + running α_s) jet parton.
- We observe **suppression** of **jet photon** as a consequence of running of **QCD coupling** **(α_s)**.

The p_T distribution of jet-th photons at $T_i = 0.446$ GeV, $\tau_i = 0.147$ fm/c

p_T distributions of photon compared with PHENIX data



p_T distributions of photon at RHIC energy

- The spectra computed with **collisional energy loss** and **running α_s** is depleted by $2-2.5$ compared to **constant α_s**.

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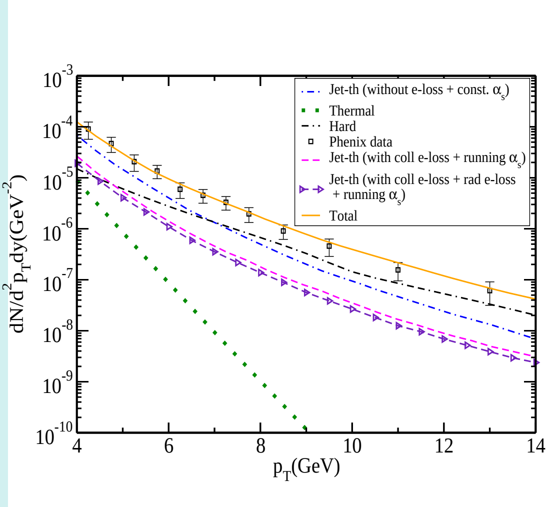

p_T distributions of photon at RHIC energy

- The total photon yield with **jet-parton energy loss** and running α_s describes **PHENIX** photon data well.

Summary & conclusions

- **QGP**: New phase of matter where properties are governed by quarks and gluons.
- At very high temperature or energy density formation of **QGP** is possible.
- Direct detection of QGP is not possible.
- EM observables, like **photon** or dilepton, could be promising probes of plasma dynamics.
- Due to inclusion of both collisional and radiative energy losses photon yield from jet plasma interaction suppresses.
- Taking the running coupling of QCD into account, energy loss of an incident quark in the QGP is increased. Photon yield suppresses much.
- The spectra in the case of energy loss with running coupling is **depleted** by a factor $2 - 2.5$ compared to the case where strong coupling is const.
- The total photon yield in our model described **PHENIX photon data** well.

List of publications

Refereed Journals

- **Photons from anisotropic Quark-Gluon-Plasma**;
  Lusaka Bhattacharya and Pradip Roy; Phys. Rev. C **78**, 064904 (2008).
- **Measuring isotropization time of Quark-Gluon-Plasma from direct photon at RHIC**;
  Lusaka Bhattacharya and Pradip Roy; Phys. Rev. C **79**, 054910 (2009).
- **Rapidity distribution of photons from an anisotropic Quark-Gluon-Plasma**;
  Lusaka Bhattacharya and Pradip Roy; Phys. Rev. C **81**, 054904 (2010).
- **Jet-photons from an anisotropic Quark-Gluon-Plasma**;
  Lusaka Bhattacharya and Pradip Roy; J. Phys. G: Nucl. Part. Phys. 37; 105010 (2010).
- **Photons from jet-plasma interaction in relativistic heavy ion collisions**;
  Lusaka Bhattacharya and Pradip Roy; European Physical Journal C **69**, Issue-3, 445 (2010).
- **Effects of running coupling on photons from jet - plasma interaction in relativistic heavy ion collision**;
  Lusaka Bhattacharya and Pradip Roy; [Submitted for publication in Journal of Phys. G] (under review).

Conference Proceedings

- **Electromagnetic probes** ; Rupa Chatterjee, Lusaka Bhattacharya, Dinesh K. Srivastava; Published in Lect. Notes Phys. 785, 219-264 (2010); arXiv:0901.3610 (hep-ph).

Thank you