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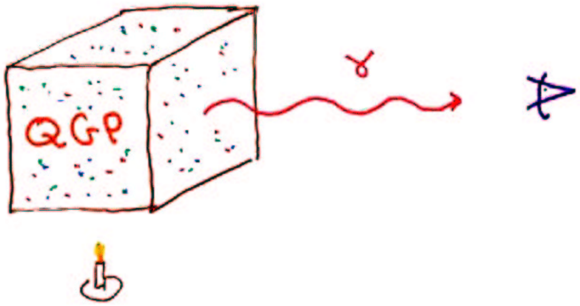
Photon Emission from QGP



What is the emission rate $\frac{d\Gamma_\gamma}{d^3k}$?

P. Arnold
G. Moore
L. Y.

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(Over) simplifications :

Equilibrium plasma

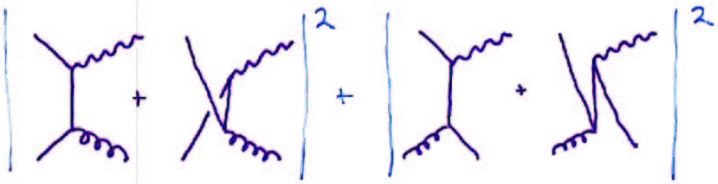
Very hot – $\alpha_s(T) \ll 1$

On-shell hard photon – $k \sim T$

Leading order in α_s only

(neglect Λ_{QCD}/T, m_q/T)

Kapusta, Lichard, Seibert
& Baier, Nakkagawa, Niegawa, Redlich :



$$\frac{d\Gamma_\gamma}{d^3k} = \frac{2}{3\pi^2}\,\alpha_{EM}\,\alpha_s\,\frac{n_f(k)}{k}\left[\ln\frac{T}{m_\infty} + \frac{1}{2}\ln\frac{2k}{T} + C_{2\leftrightarrow 2}\left(\frac{k}{T}\right)\right]$$

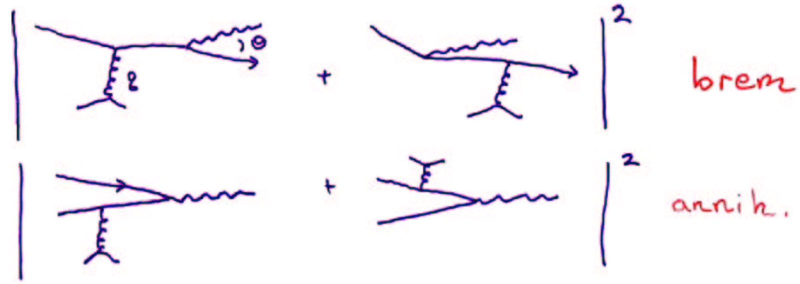
m_∞ = asymptotic thermal quark mass = $g_s T/\sqrt{3}$

$$\lim_{k/T\to\infty} C_{2\leftrightarrow 2}(k/T) = -0.361\cdots$$

End of story ?

Aurenche, Gelis, Zaraket :

Near-collinear bremsstrahlung + annihilation also contribute to leading order result



$q \sim gT$, $\theta \sim g$ } soft + collinear enhancements compensate extra explicit α_s

virtuality $\delta E = O(g^2 T)$ $\Rightarrow$
photon formation time = $O(1/g^2 T)$

But: mean free time [for $O(gT)$ collisions] is also $O(1/g^2 T)$.

$\therefore$ Multiple scattering during photon emission is important

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Leading order calculation requires complete treatment of LPM effect = interference among multiple collisions

Ex: Re 

Complications:

Frequency dependent soft scattering
– not static scattering centers

Non-Abelian gluon interactions

Sensitivity to non-perturbative $O(g^2T)$ interactions [AGZ]

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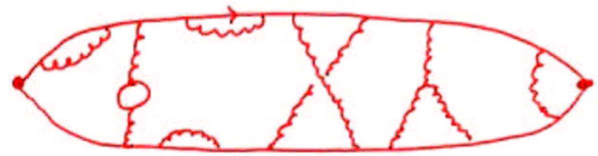
Diagrammatic analysis

$$\frac{d\Gamma_\gamma}{d^3k} = \frac{1}{(2\pi)^3\, 2k}\, \epsilon^\mu_\alpha(k)\, \epsilon^\nu_\alpha(k)\, \langle J_\mu(k)\, J_\nu(k)^+ \rangle$$

$= \Sigma$ 

Detailed power counting of real time thermal diagrams

⇒ all ladder diagrams with HTL resummed propagators contribute

⇒ crossed ladders, vertex corrections, … do not contribute

⇒ $q \ll gT$ exchanges cancel $q \ll gT$ self-energies

∴ leading order emission rate insensitive to non-perturbative physics

Sum ladders ⇒ linear integral equation

$$\frac{d\Gamma_\gamma^{LPM}}{d^3k} = \frac{2}{\pi^2}\int\frac{dp_\parallel}{2\pi}\int\frac{d^2p_\perp}{(2\pi)^2}\, n_f(p_\parallel+k)\,[1-n_f(p_\parallel)]$$

$$\cdot \left|\mathcal{J}_{p_\parallel \leftarrow p_\parallel+k}\right|^2\, 2\vec{p}_\perp\cdot \mathrm{Re}\,\vec{f}(p_\perp;p_\parallel,k)$$

$$2\vec{p}_\perp = i\,\delta E\,\vec{f}(p_\perp;p_\parallel,k) + \int\frac{d^2q_\perp}{(2\pi)^2}\,\mathcal{C}(q_\perp)\left[\vec{f}(p_\perp;p_\parallel,k)-\vec{f}(p_\perp-q_\perp;p_\parallel,k)\right]$$

$$\delta E = k\,(p_\perp^2+m_\infty^2)/2p_\parallel(k+p_\parallel) \simeq E_{\vec{p}}+|\vec{k}|-E_{\vec{p}+\vec{k}}$$

collision kernel

$$\mathcal{C}(q_\perp) = g^2\frac{C_F}{2\pi}\int dq^0\,dq_\parallel\,\delta(q^0-q_\parallel)\,\left\langle A^+(Q)\,A^+(Q)^*\right\rangle$$

soft gauge field variance

$$\left\langle A^+(Q)\,A^+(Q)^*\right\rangle\Big|_{q^0=q_\parallel} = \frac{\pi m_D^2 T}{2q}\left\{\frac{2}{|q^2-\Pi_L^{HTL}(Q)|^2}+\frac{(q_\perp/q)^4}{|q^2-(q^0)^2+\Pi_T^{HTL}(Q)|^2}\right\}$$

Amazing sum rule (~~Gelis~~ AGZ) ⇒

$$\mathcal{C}(q_\perp) \propto \frac{1}{q_\perp^2} - \frac{1}{q_\perp^2+m_D^2}$$

Solve integral eqn. using variational formulation

(or convert to local Schrodinger eqn in impact parameter)

Results:

$$\frac{d\Gamma_\gamma}{d^3k} = \frac{2}{3\pi^2}\,\alpha_{EM}\,\alpha_s\,\frac{n_f(k)}{k}\left[\ln\frac{T}{m_\infty} + C_{tot}(k/T)\right]$$

$$C_{tot}\left(\tfrac{k}{T}\right) = \tfrac{1}{2}\ln\frac{2k}{T} + C_{2\leftrightarrow 2}\left(\tfrac{k}{T}\right) + C_{brem}\left(\tfrac{k}{T}\right) + C_{annih}\left(\tfrac{k}{T}\right)$$

domain of validity: $k \gg g_s^4\, T \ln g_s^{-1}$

$+\ k \gg m_\gamma = eT/\sqrt{3}$

near collinear processes:

$\gtrsim$ 50% of emission rate for all k,

bremsstrahlung dominant for $k \lesssim 2T$,

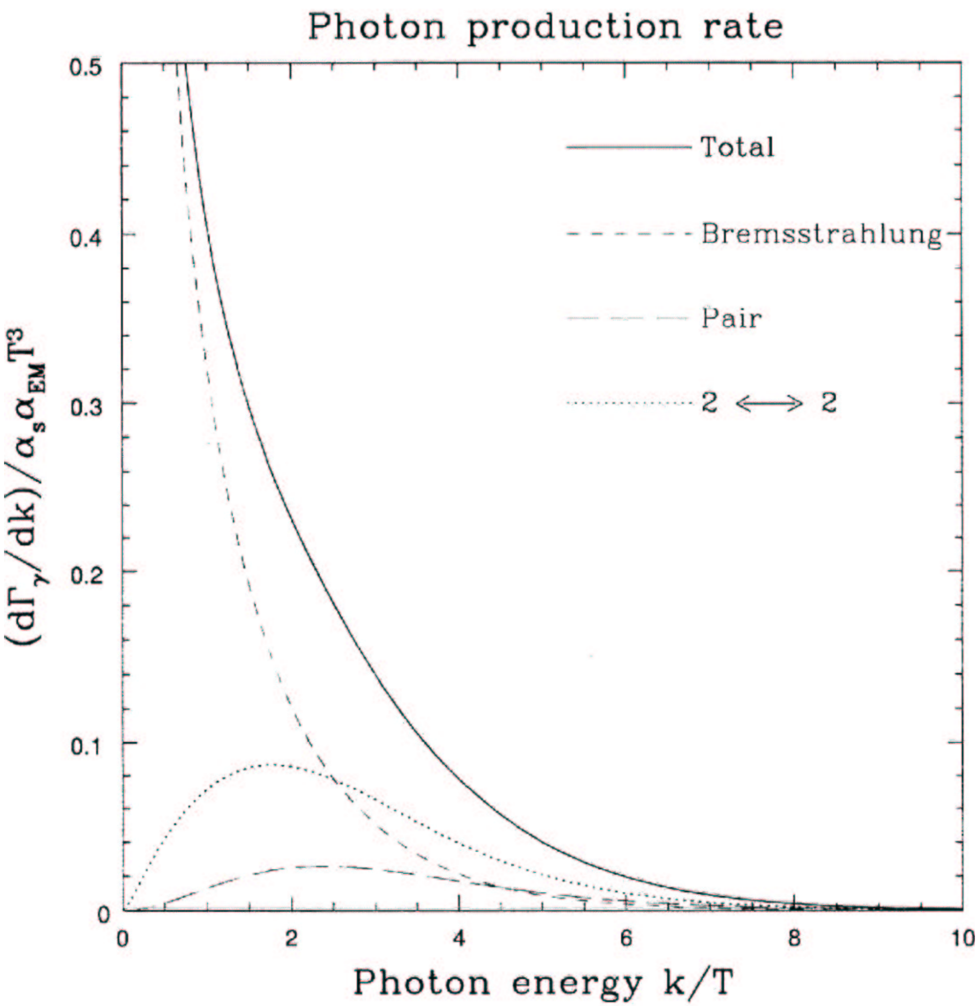
collinear annihilation dominant for $k \gtrsim 10T$.

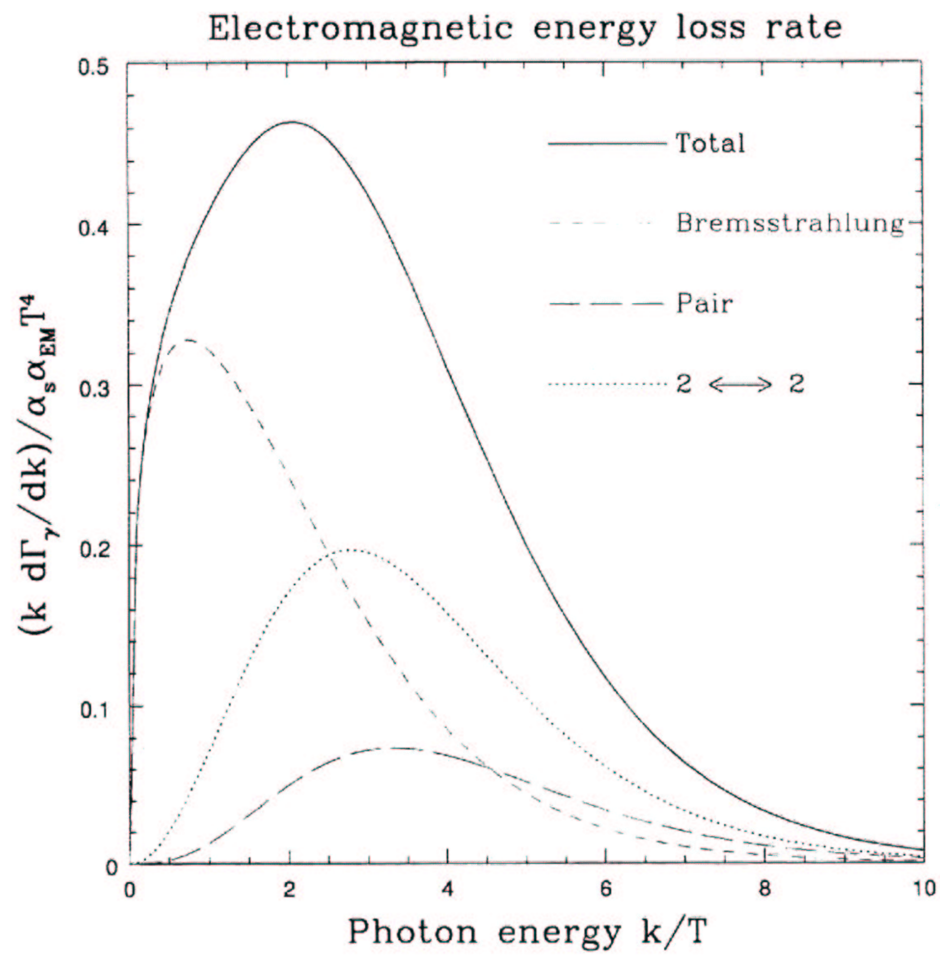
LPM suppression:

$\lesssim$ 30% effect for $2T < k < 10T$,

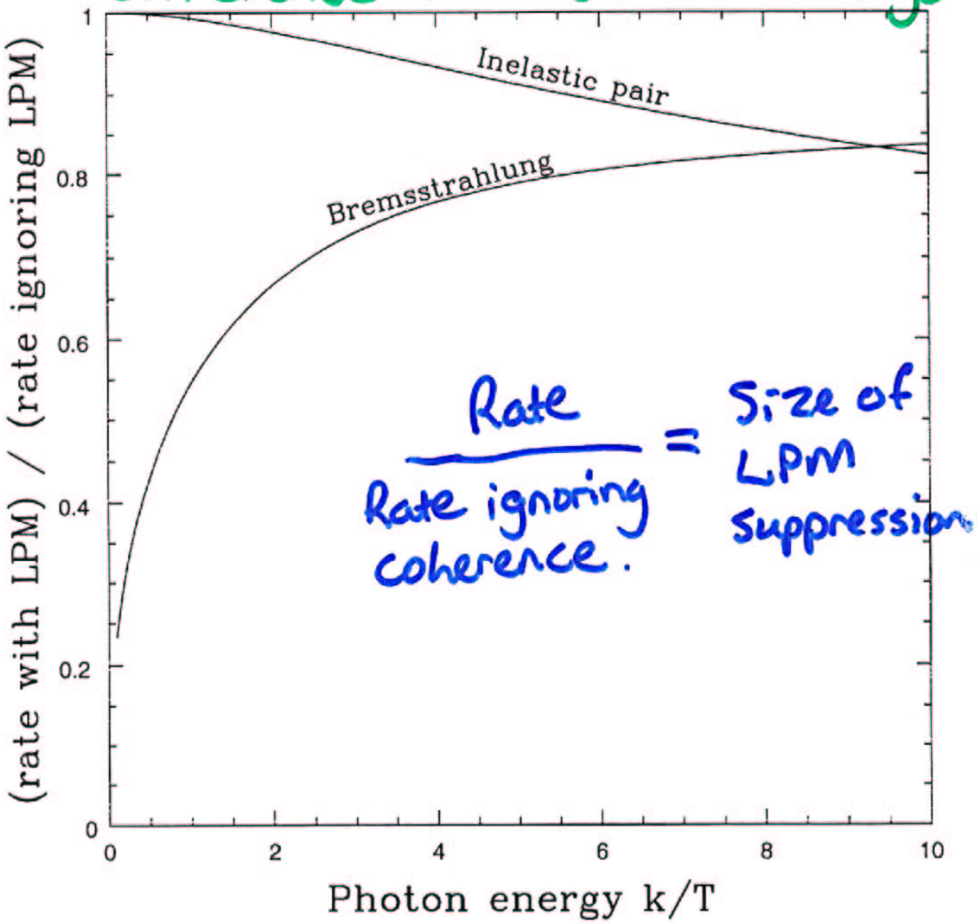
large effect ($\sim\sqrt{k/T}$) for $k \lesssim T$,

large effect ($\sim\sqrt{T/k}$) for $k \gtrsim 20T$


Photon production rate
Total
Bremsstrahlung
Pair
2 ⟷ 2
$(d\Gamma_\gamma/dk)/\alpha_s\alpha_{EM}T^3$
Photon energy k/T
0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
10


Electromagnetic energy loss rate
Total
Bremsstrahlung
Pair
2 ⟷ 2
$(k\ d\Gamma_\gamma/dk)/\alpha_s\alpha_{EM}T^4$
Photon energy k/T
0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
10

Importance of inclusion of Coherence between scatterings



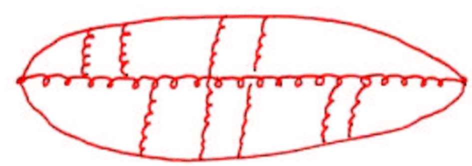
Generalizations:

Off shell photons (= dilepton rates)

straightforward
need to include longitudinal polarization
numerical evaluation in progress [Gelis, Moore]

Gluon emission

straightforward generalization of analysis
⇒ "3-way" ladders



⇒ similar linear integral equation

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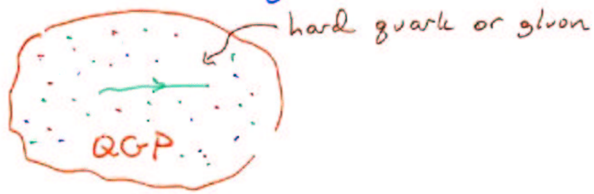
Fate of a quasi-particle ?



A. Small angle (soft) scattering

$q \sim gT$ mean free time = $O(1/g^2T)$

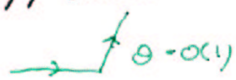
negligible change in momentum

big change in color

relevant for color conductivity, non-pert. $\not{\beta}$

irrelevant for transport of energy, flavor

B. Large angle (hard) scattering



$q \sim T$ mean free time = $O(1/g^4T \ln g^{-1})$

relevant for transport coefficients

C. Near collinear fission/fusion

$q_\parallel = O(T)$
$q_\perp = O(gT)$ mean free time = $O(1/g^4T)$

big change in $|p|$, negligible change in $\hat{p}$

relevant for transport coeffs.

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Calculation of transport coefficients

(viscosity, conductivity, diffusivity)

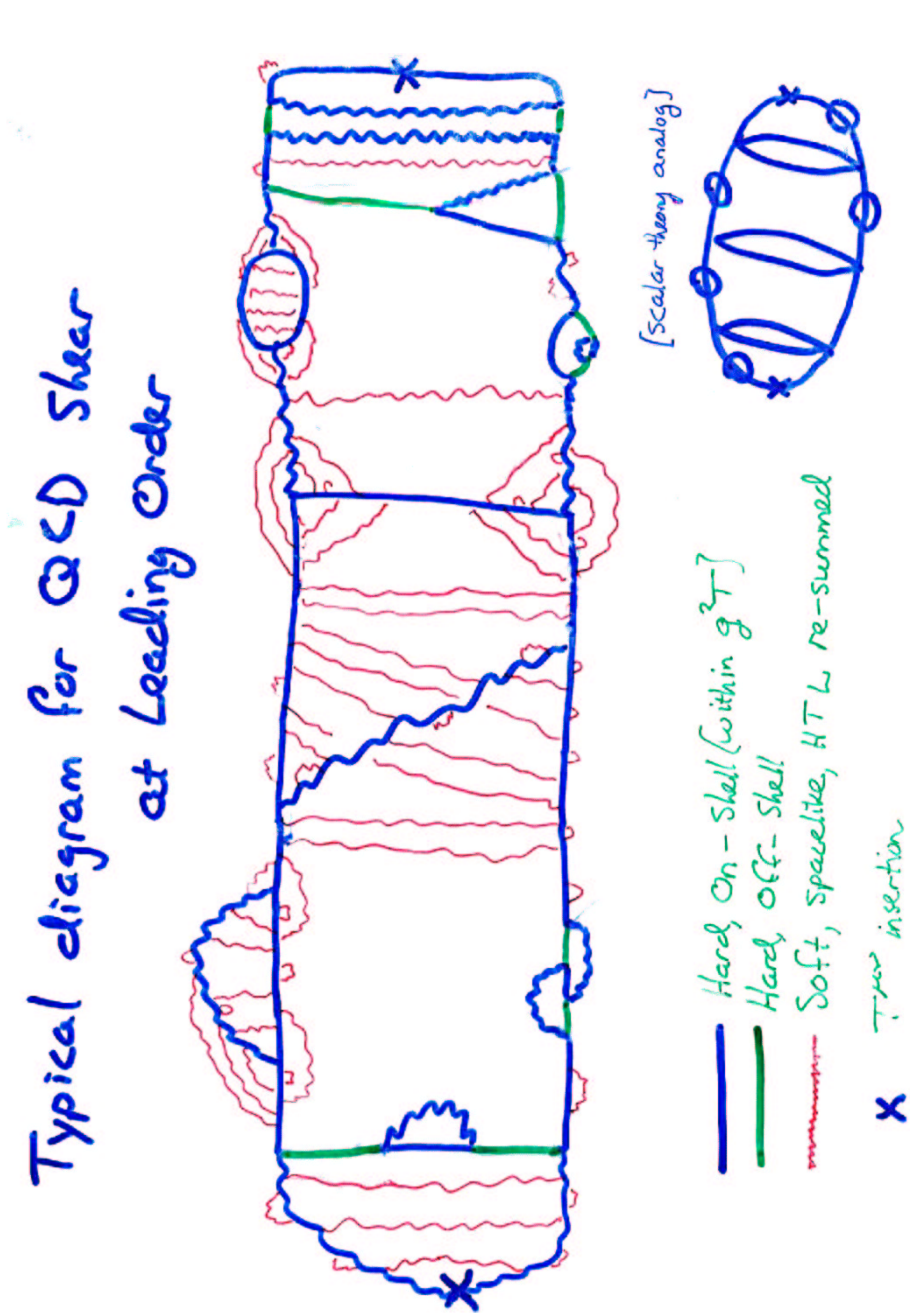
Leading order evaluation requires complete treatment of both hard + LPM suppressed near-collinear processes

$\Rightarrow$ effective kinetic theory with $1 \to 2$ and $2 \to 1$ processes in addition to usual $2 \leftrightarrow 2$ scatterings.

valid for time scales $\tau \gg 1/g^2T$

(not just $\tau \gg 1/T$)

explicit evaluation – in progress


Typical diagram for QCD Shear
at Leading Order
[scalar theory analog]
Hard, On-Shell (within g²T)
Hard, Off-Shell
Soft, Spacelike, HTL re-summed
T^{xy} insertion