Electromagnetic signals from the passage of jets through QGP

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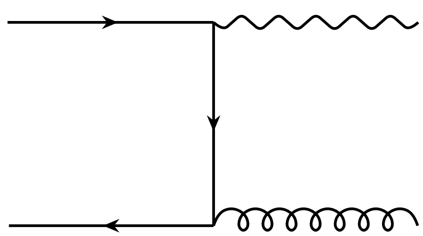
Introduction

- Jet quenching at RHIC: strong interactions of fast partons with the hot and dense medium.
- Electromagnetic analogon: induced radiation of real and virtual photons by interactions of fast partons with the medium.
- Can this be an electromagnetic probe for jet quenching?
- From back-to-back jet-photon production: photon tagging (Wang,Huang,Sarcevic), dilepton tagging (Srivastava,Gale,Awes) of jets.
- Electromagnetic interactions with the medium happen during the entire lifetime of a fast parton in the plasma phase.
- But in order to be experimentally accessible, this new photon source must be bright!

Annihilation and Compton processes with real photons

- Real photons from $q\bar{q}$ annihilation

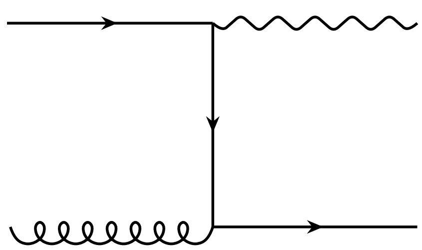


$$\frac{d\sigma}{dt} = \frac{8\pi\alpha\alpha_s e_q^2}{9s^2}\left(\frac{u}{t}+\frac{t}{u}\right)$$

$t \approx 0$, $u \approx 0$ are dominant regions of phase space, corresponding to $\mathbf{p}_\gamma \approx \mathbf{p}_q$, $\mathbf{p}_\gamma \approx \mathbf{p}_{\bar{q}}$.

$$\Longrightarrow E_\gamma \frac{d\sigma}{d^3p_\gamma} \approx \sigma(s)\tfrac{1}{2}[\delta(\mathbf{p}_\gamma - \mathbf{p}_q) - \delta(\mathbf{p}_\gamma - \mathbf{p}_{\bar{q}})]$$

- Real photons from Compton



$$\frac{d\sigma}{dt} = -\frac{\pi\alpha\alpha_s e_q^2}{3s^2}\left(\frac{u}{s}+\frac{s}{u}\right)$$

$u \approx 0 \Longleftrightarrow \mathbf{p}_\gamma \approx \mathbf{p}_q$

$$\Longrightarrow E_\gamma \frac{d\sigma}{d^3p_\gamma} \approx \sigma(s)\delta(\mathbf{p}_\gamma - \mathbf{p}_q)$$

Photon yield from the plasma

$$E_\gamma \frac{dN^{(a)}}{d^4x d^3p_\gamma} = \frac{16 E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(\mathbf{p}_\gamma) \int d^3p\, f_{\bar{q}}(\mathbf{p})[1 + f_g(\mathbf{p})]\sigma^{(a)}(s) \frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

Total cross section $\quad \sqrt{s(s-4m^2)}\sigma^{(a)}(s) = 4\pi\alpha\alpha_s \left[\ln \frac{s}{m^2} - 1\right]$

$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16 E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(\mathbf{p}_\gamma) \int d^3p\, f_{\bar{g}}(\mathbf{p})[1 - f_q(\mathbf{p})]\sigma^{(C)}(s) \frac{s-m^2}{2E_\gamma E} + (q \to \bar{q})$$

Total cross section $\quad (s-m^2)\sigma^{(C)}(s) = 2\pi\alpha\alpha_s \left[\ln \frac{s}{m^2} + \frac{1}{2}\right]$

- Distribution of partons: $f(\mathbf{p}) = f_{\text{thermal}}(\mathbf{p}) + f_{\text{jet}}(\mathbf{p})$

Dominated by thermal part < 1 GeV and by perturbative part > 4 GeV.

- Integrals given by thermal distributions for partons from the plasma.

$$E_\gamma \frac{dN}{d^4x d^3p_\gamma} = \frac{\alpha\alpha_s}{4\pi^2} \frac{2}{3} [f_q(\mathbf{p}_\gamma) + f_{\bar{q}}(\mathbf{p}_\gamma)] T^2 \left[\ln \frac{4E_\gamma T}{m^2} + C\right]$$

for annihilation + Compton. $C = -1.916 \qquad m^2 = g^2T^2/6$

Input: jets and the fireball

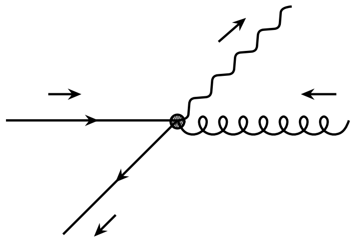
Initial minijet distribution:

$$f_{\text{jet}}(\mathbf{p}) = \frac{1}{6}\frac{(2\pi)^3}{\pi R_\perp^2 \tau p_\perp}\frac{dN_{\text{jet}}}{d^2p_\perp dy}\delta(\eta-y)\Theta(\tau-\tau_i)\Theta(\tau_{\text{max}}-\tau)\Theta(R_\perp-r)R(r)$$

- $\tau_{\text{max}} = \min[$life time τ_f, time of travel $\tau_d]$
- travel distance $d = -r\cos\phi + \sqrt{R_\perp^2 - r^2\sin^2\phi}$, $\cos\phi = \hat{\mathbf{v}}\hat{\mathbf{r}}$
- transverse profile $R(r) = 2(1 - r^2/R_\perp^2)$
- temperature profile $T(r) = T_0[2(1 - r^2/R_\perp^2)]^{1/4}$
- $d^4x = \tau d\tau r dr d\eta d\phi$
- $T_f = 160$ MeV
- $T_0 = 446$ MeV (RHIC) $\Leftrightarrow \tau_0 = 0.147$ fm
- $T_0 = 897$ MeV (LHC) $\Leftrightarrow \tau_0 = 0.073$ fm

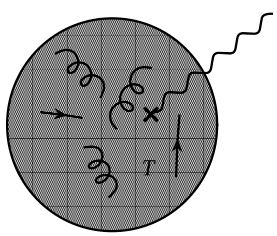
Photon sources in the quark phase

• Hard direct photons



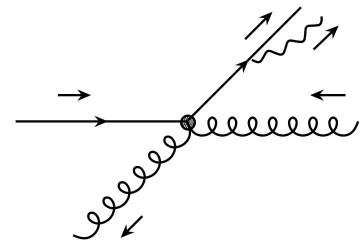
pQCD calculation including shadowing

• Thermal photon radiation from the hot medium



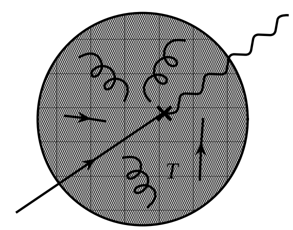
Use above formula with thermal quark distributions

• EM Bremsstrahlung connected to primary hard interactions



pQCD calculation including shadowing

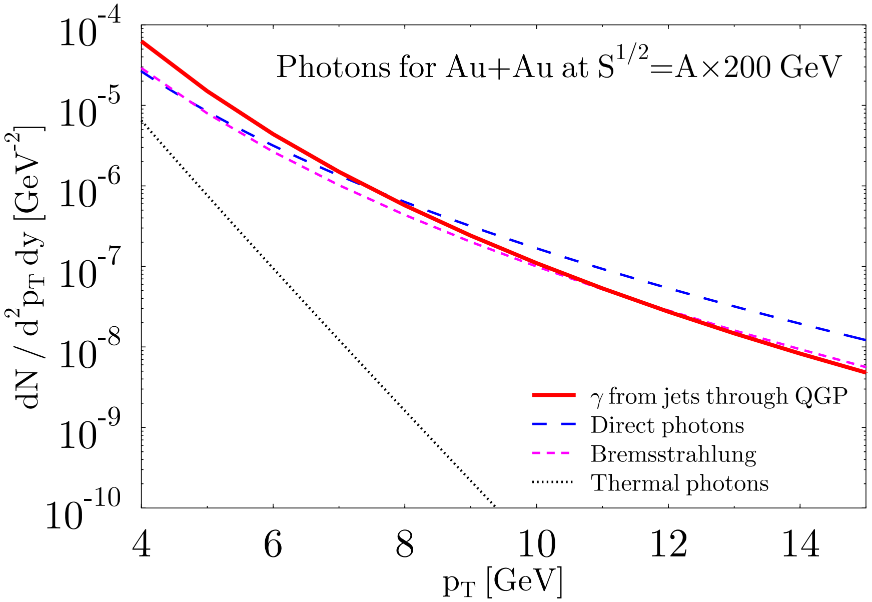
• Jet-photon conversion in the medium



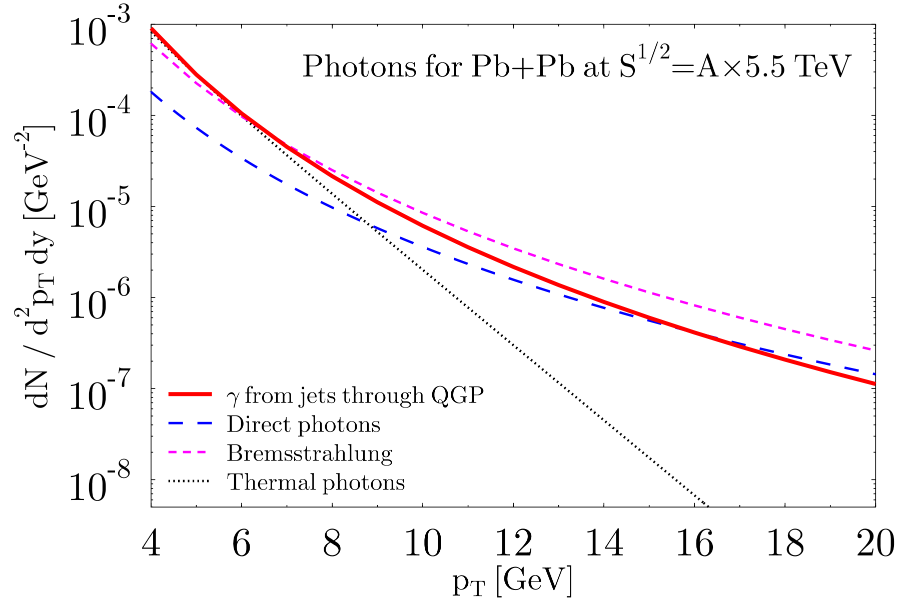
Use above formula with perturbative quark distributions

Results for real photons

- RHIC



- LHC



- Jet-photon conversion is of the same order of magnitude as other direct photon mechanisms.
- P_T slope is larger (typical for higher twist).

Dileptons from jet-plasma interactions

Contribution to the mass spectrum from jet plasma interactions.

$$\frac{dN}{d^4x dM^2} = \frac{M^4 \sigma(M^2)}{(2\pi)^5} \int x_a \, dx_a \, x_b \, dx_b \, dy_a \, dy_b$$
$$\times f_a f_b \{4x_a^2 x_b^2 - [2x_a x_b \cosh(y_a - y_b) - 1]^2\}^{1/2}$$

$$x_a = p_\perp^a / M, \qquad x_b = p_\perp^b / M$$

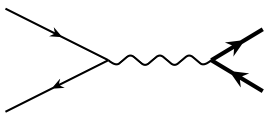
- If both distributions thermal, $f(\mathbf{p}) = e^{-E/T} = e^{-p_\perp \cosh y / T}$:

$$\frac{dN}{d^4x dM^2} = \frac{M^3 T \sigma(M^2)}{2(2\pi)^4} K_1(M/T)$$

- Contribution from jet-γ^* conversion: numerical integration.

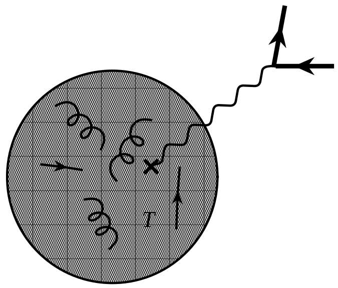
Dilepton sources in the parton phase

- Direct Drell-Yan



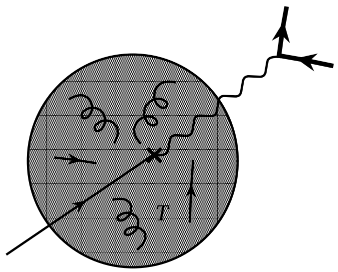
pQCD calculation including shadowing

- Thermal dileptons from the hot medium



Use thermal×thermal as input

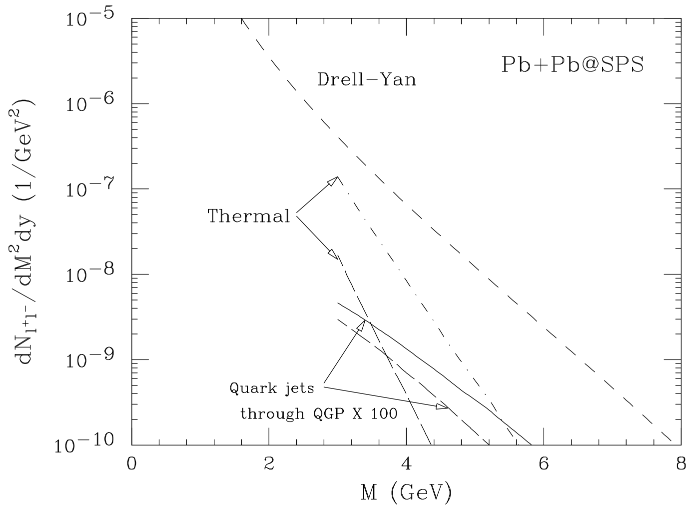
- Jet-virtual photon conversion in the medium



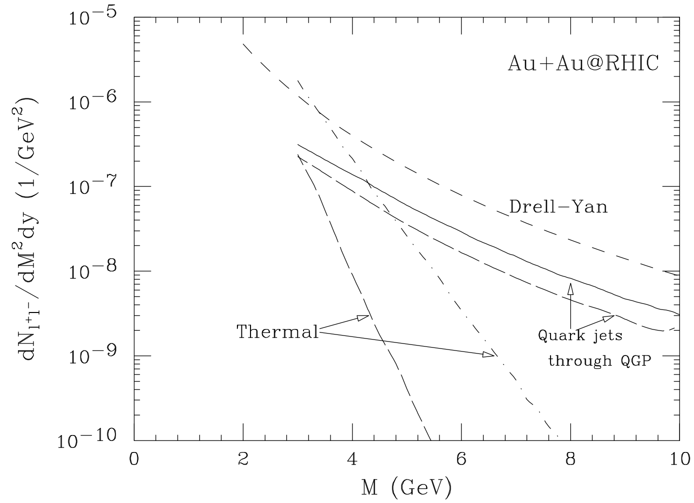
Use pert×thermal as input

Results for dileptons

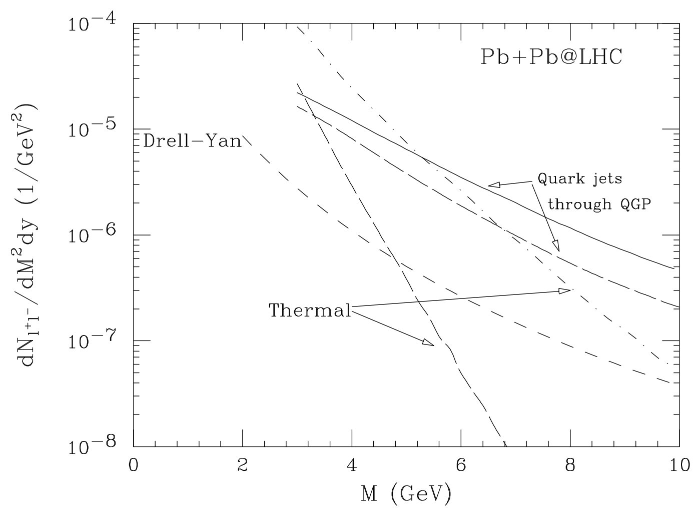
- SPS



- RHIC



- LHC



Further considerations

- Chemical equilibration:
  Rates should be reduced if $f \to \lambda f$, $\lambda < 1$! But in the purely thermal process one more power of λ enters.
  $\Rightarrow$ Thermal part more suppressed!
  Checked for the dilepton calculation.

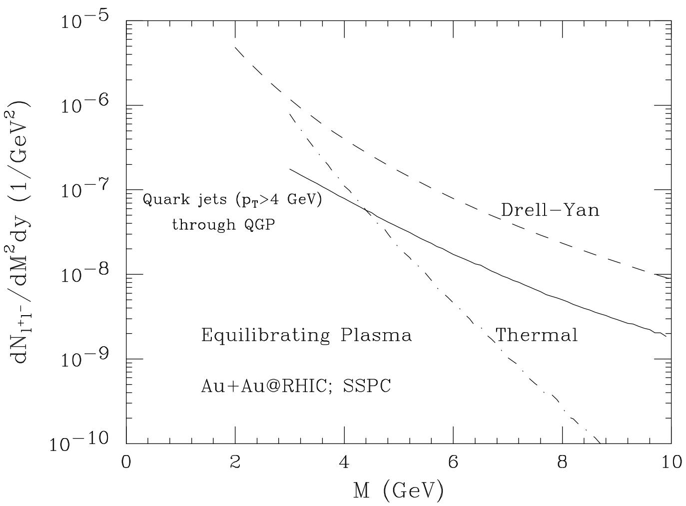
- Dependence on the initial time τ_0: marginal!
  Photon rate only varies weakly with $\tau^{-2/3}$.
  $\Rightarrow$ Considerable contribution from late times!

- Jet quenching:
  Partons will only suffer from reduced energy loss. Photon rates from jets will not be dramatically suppressed. $\Rightarrow$ Photons from jet-photon conversion are sensitive to the jet distribution at early times!

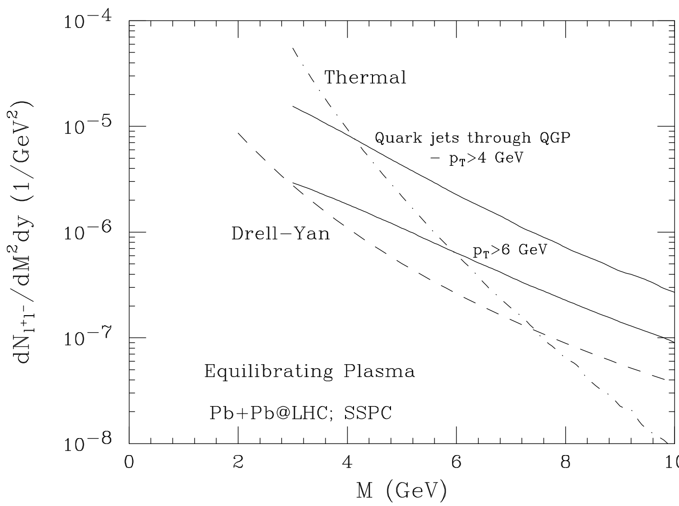
- Missing:
  - Photon bremsstrahlung from strong interactions between fast partons and the hot medium.
  - Interaction of fast partons/jets with hadronic/mixed phases.

Chemical equilibration for dileptons

- RHIC



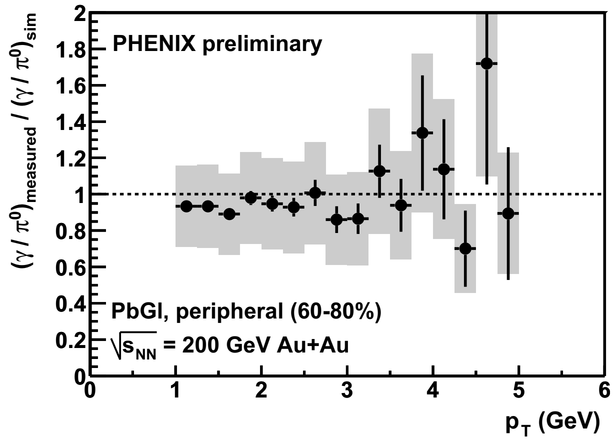
- LHC

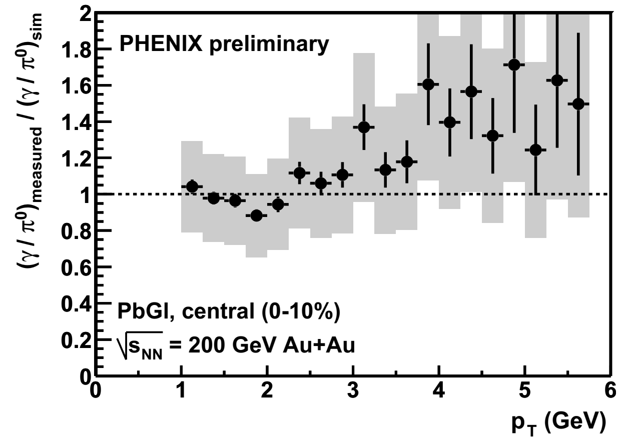


Evolution of fugacities starting with
$\lambda_g = 0.34\ (0.43)$
$\lambda_q = 0.064\ (0.082)$
at $\tau_0 = 0.25$ for RHIC (LHC).

A look at RHIC data: PHENIX

- Extraction of direct photons is very delicate in heavy ion collisions. No direct measurement possible.
- Subtract secondary photons from πs and ηs.
- PHENIX preliminary results for the ratio of inclusive photons to photons from π^0:

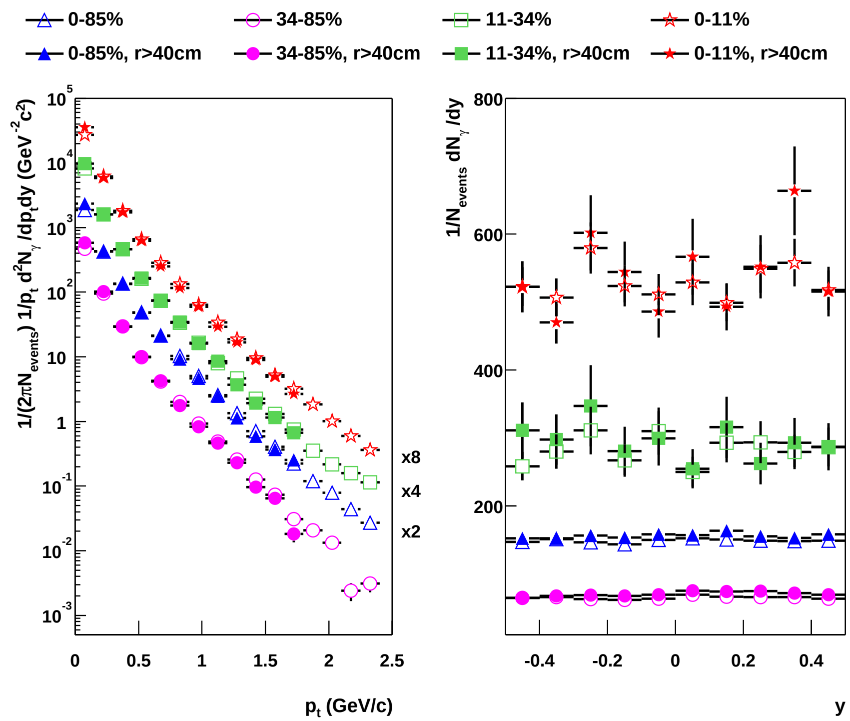




- Extraction of the direct photons has not yet been completed.

A look at RHIC data: STAR

- STAR preliminary results for inclusive photon yields



- Extraction of the direct photons has not yet been completed.

Conclusions

- We have discussed a new source of real and virtual photons in heavy ion collisions by the interaction of fast partons with the hot medium.
- The jet-photon conversion mechanism is comparable in size with other direct photon sources above $p_\perp \approx 4$ GeV at RHIC and LHC.
- The jet-plasma interaction gives a large contribution to the large mass dilepton spectrum at LHC, while it is about a factor of 4 below the direct Drell Yan contribution at RHIC.
- For photons/dileptons the new mechanism is dominant compared to thermal sources at large transverse momentum/mass.
- The photon spectrum from jet-photon conversion is directly proportional to the jet spectrum and sensitive to jet distributions at early times, with only small influence of jet quenching.
- Dependence of the new source on missing chemical equilibration and varying initial times is small.
- To do list: transverse momentum spectrum for Drell Yan, detailed study of jet quenching.