Light from Cascading Partons in Relativistic Heavy-Ion Collisions

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- Motivation
- The PCM: Fundamentals & Implementation
- Photon production in the PCM
- Medium Effects: Jet-Photon Conversion (FMS Photons)

Part #1:
Photon Production in the PCM

• *Light from cascading partons in relativistic heavy-ion collisions*
- S.A. Bass, B. Mueller and D.K. Srivastava, Phys. Rev. Lett. **90** (2003) 082301

• *Intensity interferometry of direct photons in Au+Au collisions*
- S.A. Bass, B. Mueller and D.K. Srivastava, Phys. Rev. Lett. **93** (2004) 162301

• *Dynamics of the LPM effect in Au+Au Collisions at 200 AGeV*
- T. Renk, S.A. Bass and D.K. Srivastava, nucl-th/0505059

Basic Principles of the PCM

Goal: provide a microscopic space-time description of relativistic heavy-ion collisions based on perturbative QCD

- degrees of freedom: quarks and gluons
- classical trajectories in phase space (with relativistic kinematics)
- initial state constructed from experimentally measured nucleon structure functions and elastic form factors
- an interaction takes place if at the time of closest approach d_{min} of two partons

$$d_{\min} \le \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad \sigma_{tot} = \sum_{p_3,p_4} \int \frac{d\sigma\left(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4\right)}{d\hat{t}} d\hat{t}$$

- system evolves through a sequence of binary (2→2) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation (2→N)
- binary cross sections are calculated in leading order pQCD with either a momentum cut-off or Debye screening to regularize IR behavior
- guiding scales: initialization scale Q_0, p_T cut-off p_0 / Debye-mass μ_D

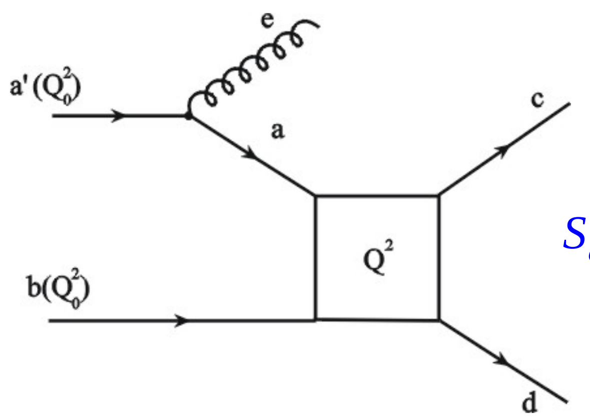
Parton-Parton Scattering Cross-Sections

g g → g g	$\frac{9}{2}\left(3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right)$	q q′ → q q′	$\frac{4}{9}\frac{s^2+u^2}{t^2}$
q g→ q g	$-\frac{4}{9}\left(\frac{s}{u}+\frac{u}{s}\right)+\frac{s^2+u^2}{t^2}$	q qbar→ q′ qbar′	$\frac{4}{9}\frac{t^2+u^2}{s^2}$
g g → q qbar	$\frac{1}{6}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{3}{8}\frac{t^2+u^2}{s^2}$	q g →q γ	$-\frac{e_q^2}{3}\left(\frac{u}{s}+\frac{s}{u}\right)$
q q → q q	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{s^2}{tu}$	q qbar → g γ	$\frac{8}{9}e_q^2\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → q qbar	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{u^2+t^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	q qbar → γ γ	$\frac{2}{3}e_q^4\left(\frac{u}{t}+\frac{t}{u}\right)$
q qbar → g g	$\frac{32}{27}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{8}{3}\frac{t^2+u^2}{s^2}$		

- a common factor of $\pi\alpha_s^2(Q^2)/s^2$ etc.
- further decomposition according to color flow

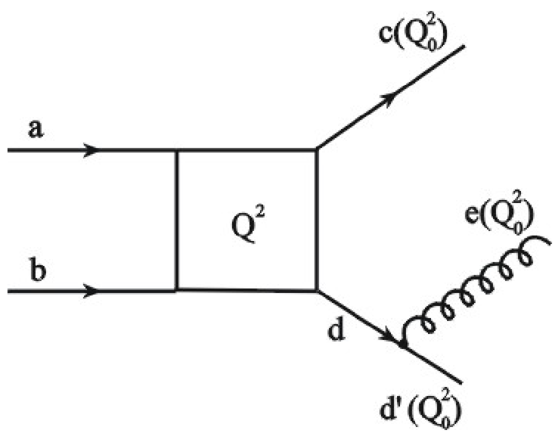
Initial and final state radiation

Probability for a branching is given in terms of the Sudakov form factors:



space-like branchings:

$$S_a\left(x_a, t_{\max}, t\right) = \exp\left\{ -\int_t^{t_{\max}} dt' \frac{\alpha_s(t')}{2\pi} \sum_{a'} \int dz \, P_{a' \to ae}(z) \frac{x_{a'} f_{a'}(x_{a'}, t')}{x_a f_a(x_a, t')} \right\}$$

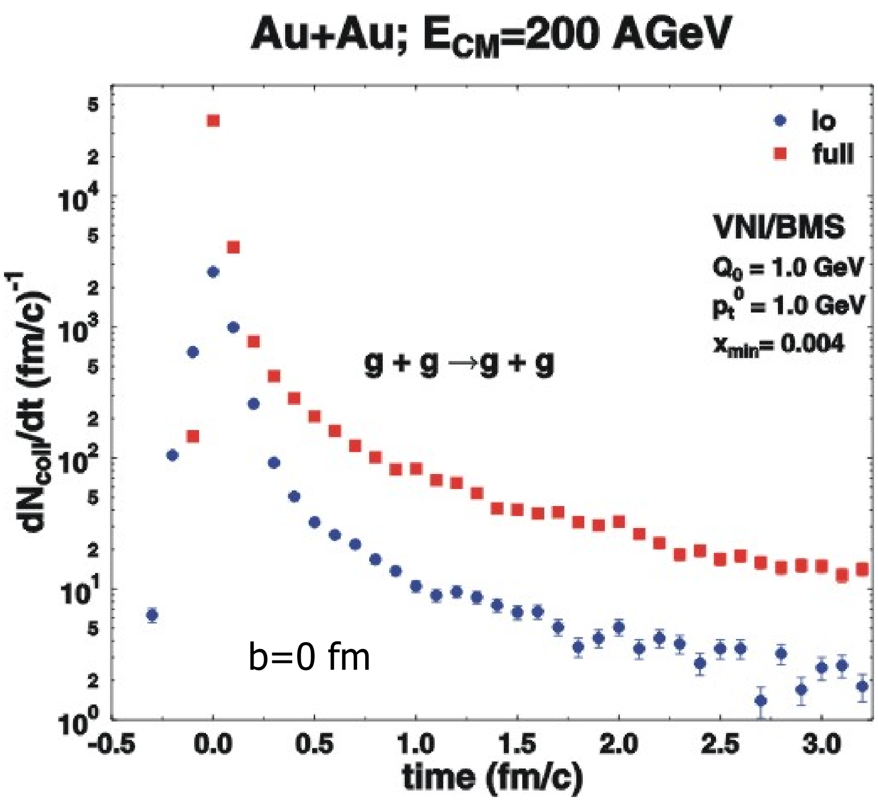


time-like branchings:

$$T_d\left(x_d, t_{\max}, t\right) = \exp\left\{ -\int_t^{t_{\max}} dt' \frac{\alpha_s(t')}{2\pi} \sum_{a'} \int dz \, P_{d \to d'e}(z) \right\}$$

- Altarelli-Parisi splitting functions included: $P_{q\to qg}$, $P_{g\to gg}$, $P_{g\to qqbar}$ & $P_{q\to q\gamma}$

Collision Rates & Numbers



# of collisions	lo	full
q + q	70.6	274
q + qbar	1.3	38.52
q + g	428.3	2422.6
g + g	514.4	4025.6

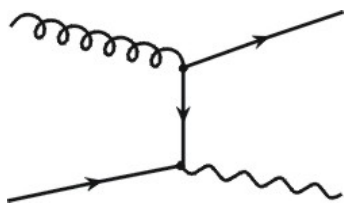
- lifetime of interacting phase: ~ 3 fm/c
- partonic multiplication due to the initial & final state radiation increases the collision rate by a factor of 4-10

➢ are time-scales and collision rates sufficient for thermalization?

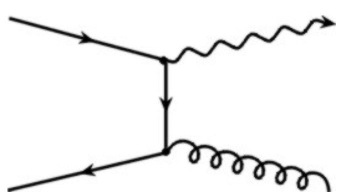
Photon Production in the PCM

relevant processes:

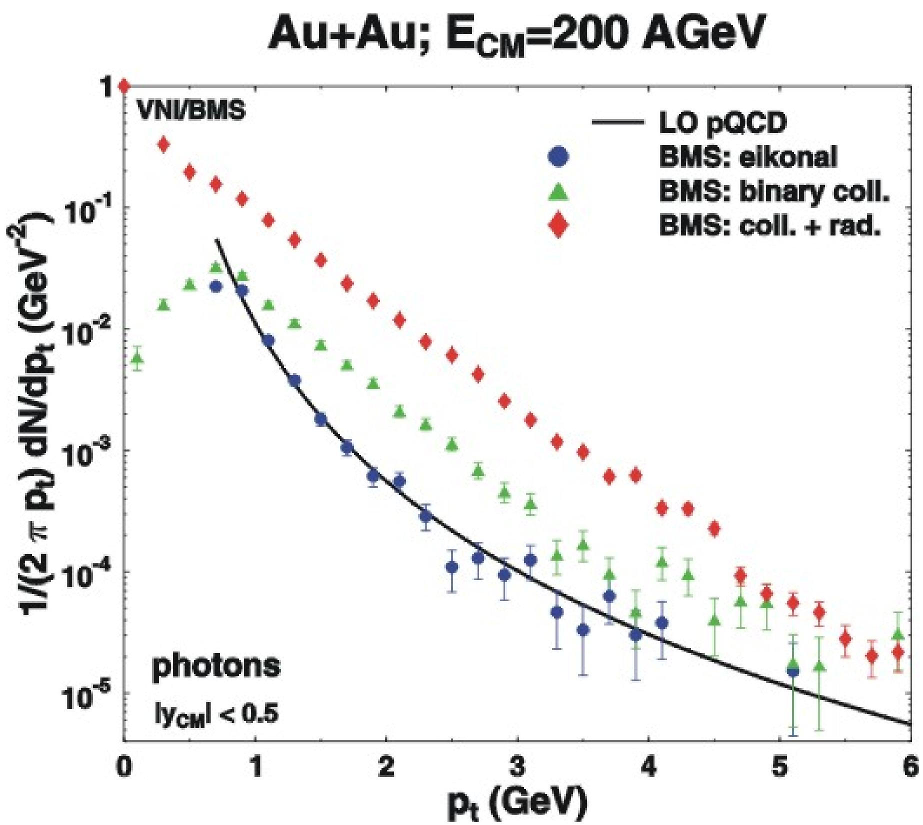
- Compton: **q g →q γ**



- annihilation: **q qbar → g γ**

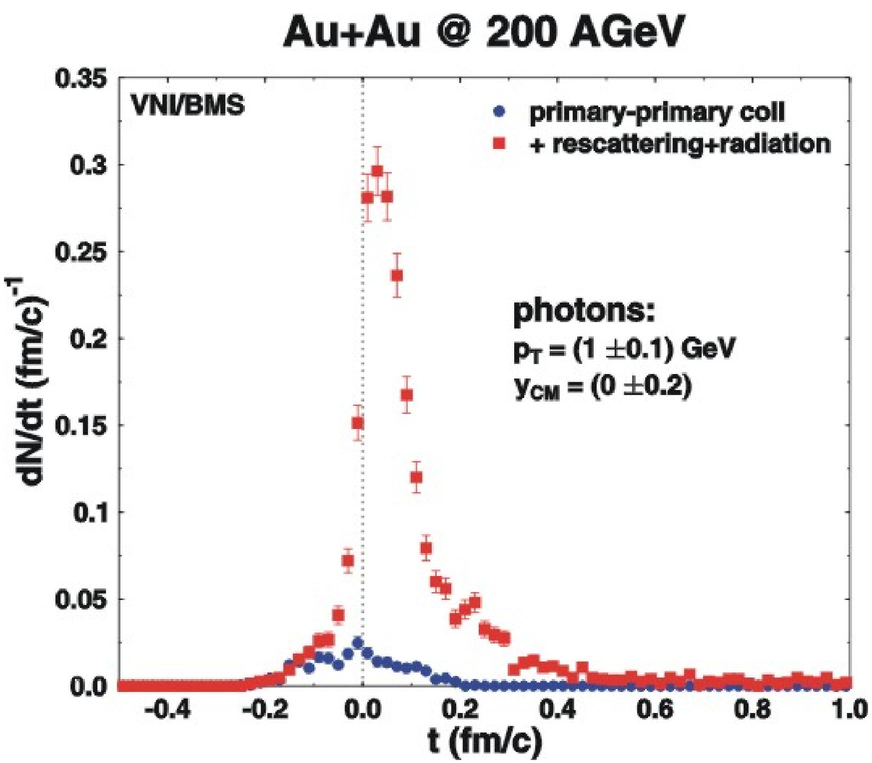


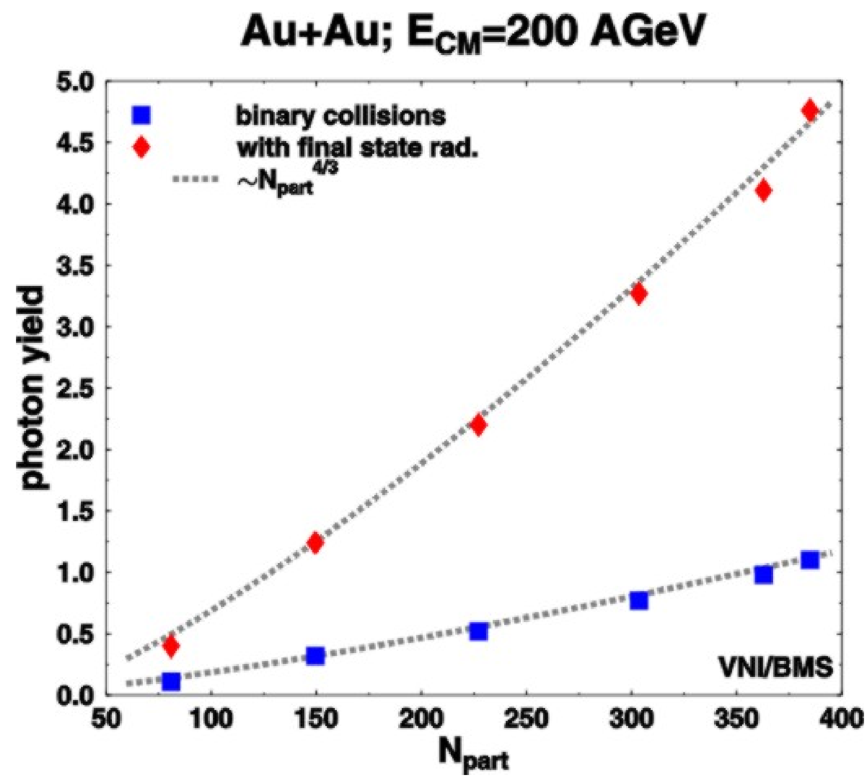
- bremsstrahlung: **q* →q γ**



➢photon yield very sensitive to parton-parton rescattering

What can we learn from photons?





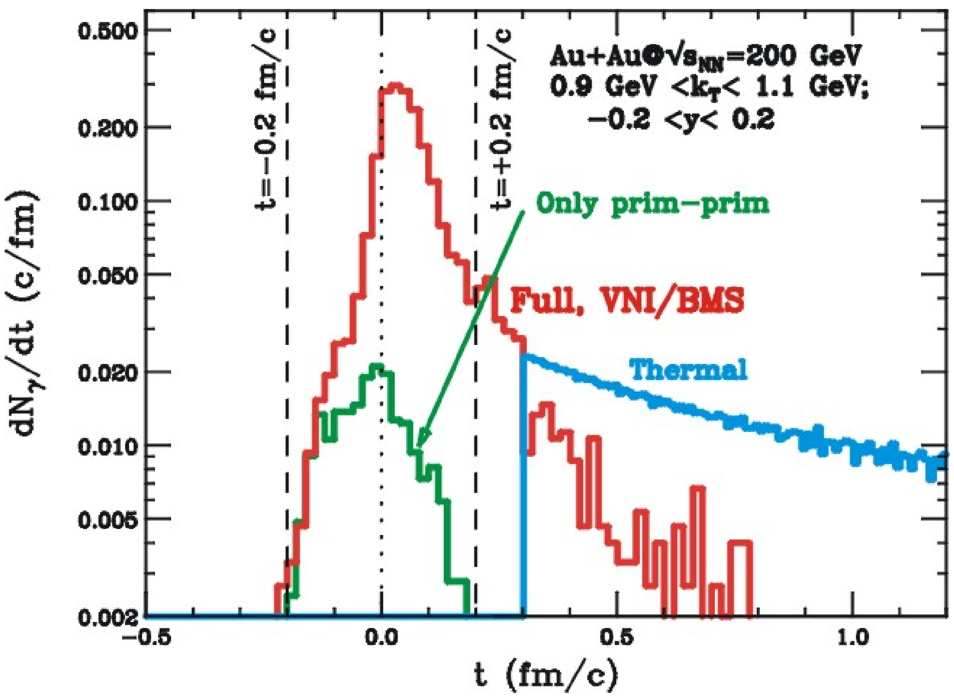
•primary-primary collision contribution to yield is < 10%

•emission duration of pre-equilibrium phase: ~ 0.5 fm/c

•photon yield directly proportional to the # of hard collisions

➢ photon yield scales with $N_{part}^{4/3}$

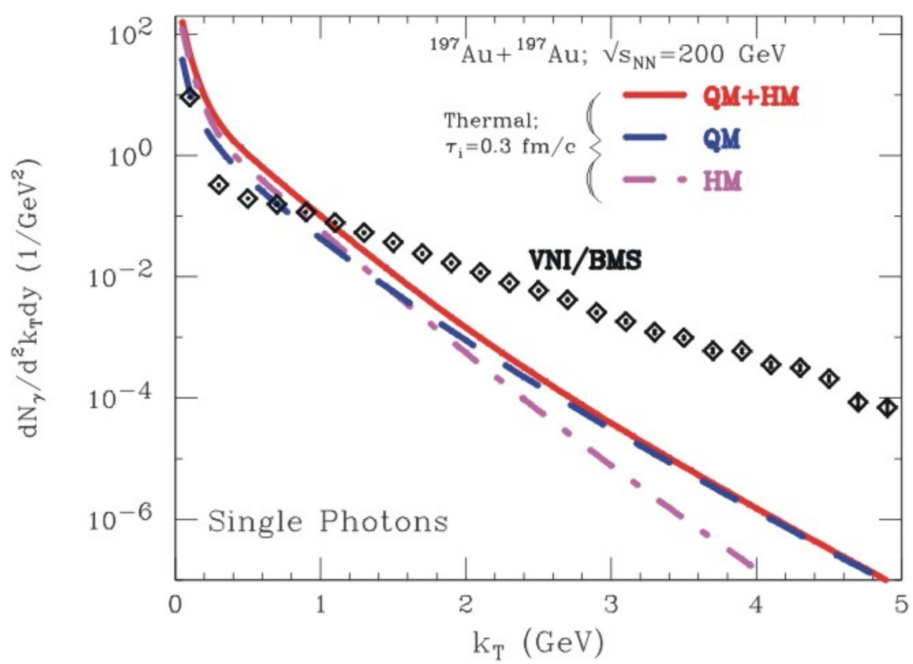
Photons: pre-equilibrium vs. thermal



➢pre-equilibrium contributions are easier identified at large p_t:

•window of opportunity above p_t=2 GeV

•at 1 GeV, need to take thermal contributions into account



•short emission time in the PCM, 90% of photons before 0.3 fm/c

➢hydrodynamic calculation with τ_0=0.3 fm/c allows for a smooth continuation of emission rate

HBT Interferometry: formalism

- Correlation between two photons with momenta k_1 and k_2 is given by:

$$C(\vec{q},\vec{K}) = 1 + \frac{1}{2}\frac{\left|\int d^4x\, S(x,\vec{K})\, e^{ixq}\right|^2}{\int d^4x\, S(x,\vec{k}_1)\int d^4x\, S(x,\vec{k}_2)} \quad \text{with } \vec{q} = \vec{k}_1 - \vec{k}_2 \text{ and } \vec{K} = (\vec{k}_1 - \vec{k}_2)/2$$

with S(x,k) the photon source function for a chaotic source

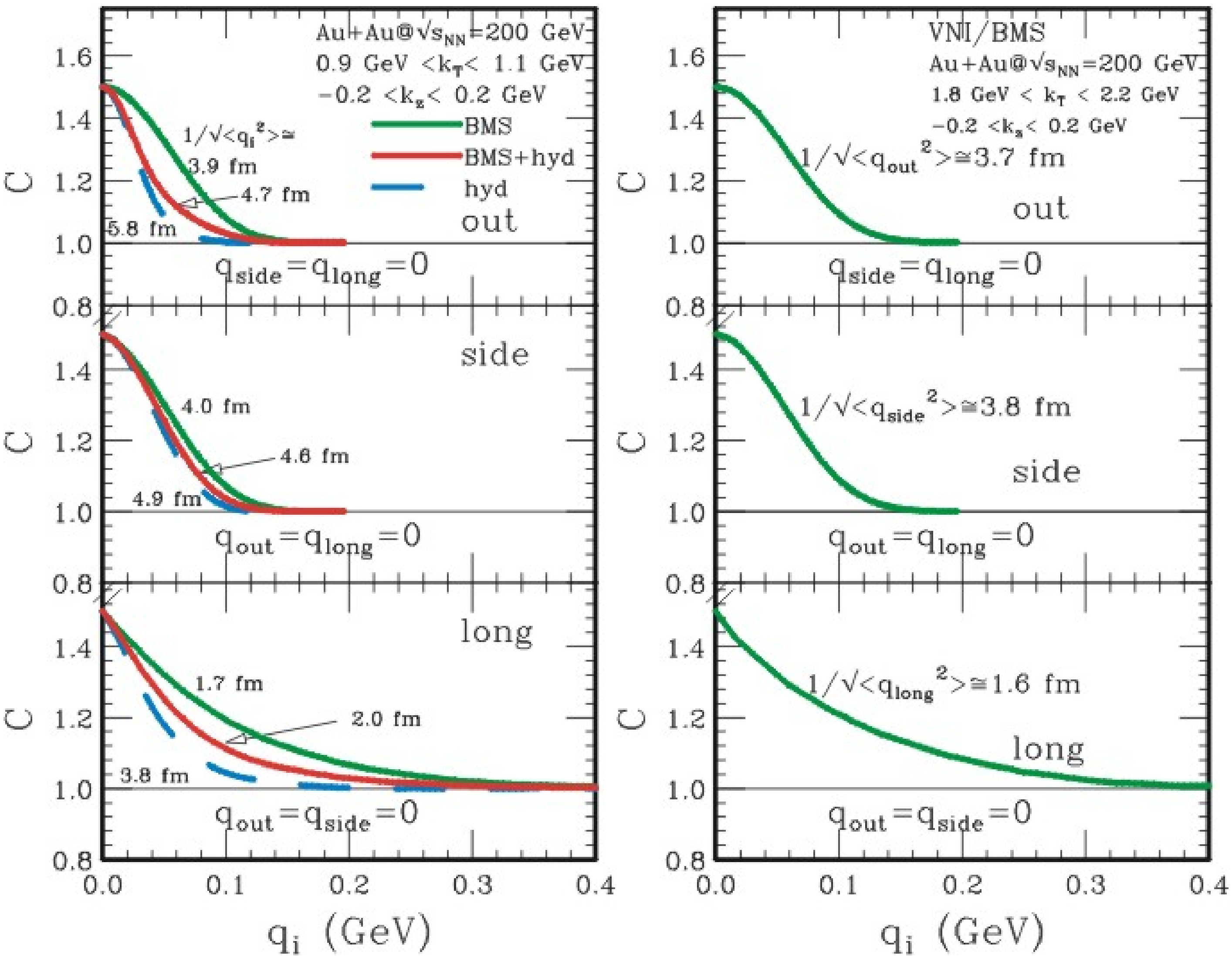
- ➢ use Wigner function scheme (Hansa code by Sollfrank & Heinz)
  - emission vertices of a semiclassical transport are not valid Wigner fnct.
  - ➢ need to smear out emission vertices x_i by $\hbar/p_i$
- ➢ results are given in terms of outward, sideward & longitudinal correlators

$$q_{long} = \left|k_{1z} - k_{2z}\right| = \left|k_{1T}\sinh y_1 - k_{2T}\sinh y_2\right|$$

$$q_{out} = \vec{q}_T \cdot \vec{K}_T / K_T$$

$$q_{side} = \left|\vec{q}_T - q_{out}\vec{K}_T / K_T\right|$$

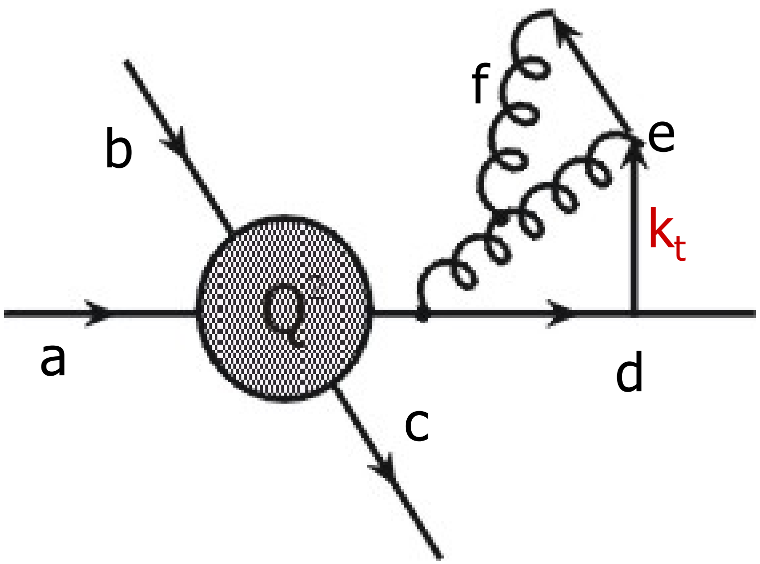
Photons: HBT Interferometry



- p_t=2 GeV: pre-thermal photons dominate, small radii
- p_t=1 GeV: superposition of pre- & thermal photons: increase in radii

Landau-Pomeranchuk-Migdal Suppression

• the LPM effect accounts for the suppression of radiation due to coherence effects in multiple scattering



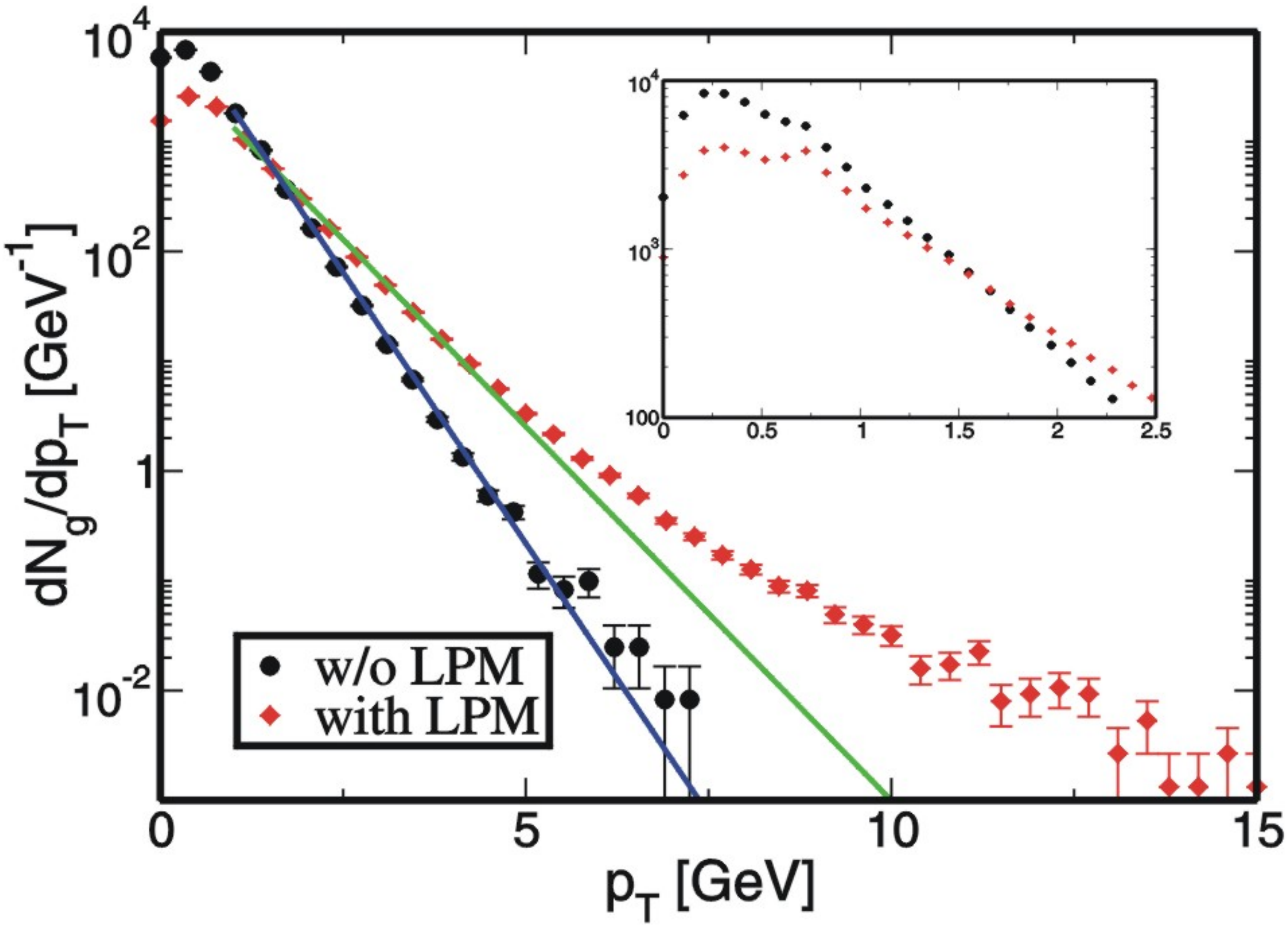
• the radiated parton *e* is assigned a formation time:

$$\tau_{\text{form}} = \frac{z(1-z)E_a}{(1-z)q_d^2 + z\,q_e^2 + k_t^2} \approx \frac{E_a}{q_a^2}$$

• if the radiating parton *d* suffers a collision before τ_{form} has elapsed, then the radiation of parton *e* and it's daughters does not take place

• likewise for parton *f* with respect to *e* …

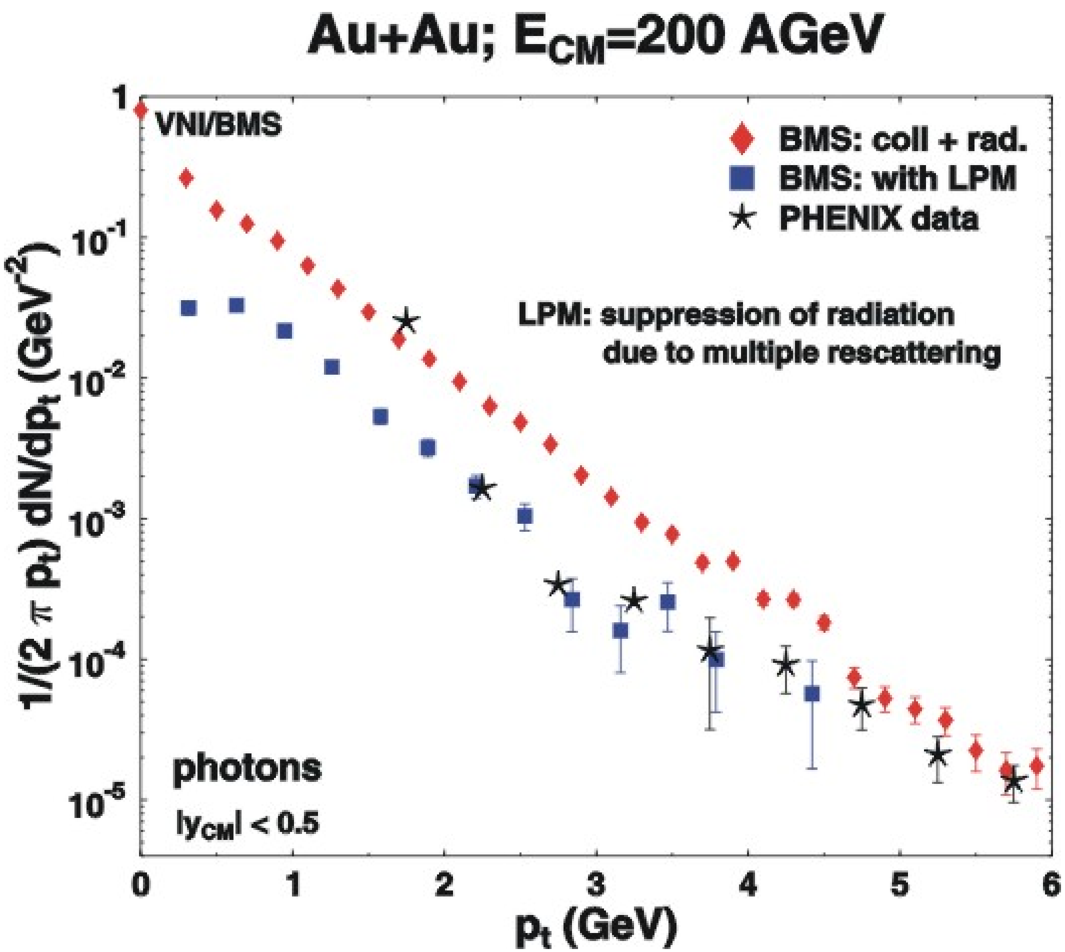
LPM: Reaction Dynamics



gluon p_t distribution

- high p_t: harder slope, enhanced particle production
- low p_t: suppression of particle production

Photon Production: LPM & comparison to data



PCM without LPM:

- overprediction of photon yield

PCM with LPM:

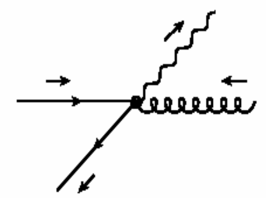
- photon yield for p_t < 6 GeV strongly reduced
- strong p_t dependence of LPM suppression
- good agreement with data

Part #2:
Photons via Jet-Plasma Interactions

R.J. Fries, B. Mueller & D.K. Srivastava, PRL **90**, 132301 (2003)

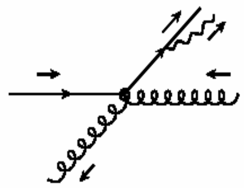
Photon sources

- Hard direct photons



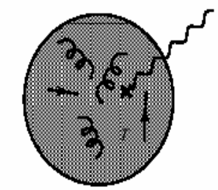
pQCD calculation including shadowing

- EM bremsstrahlung

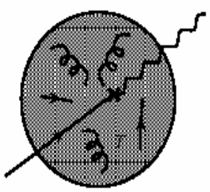


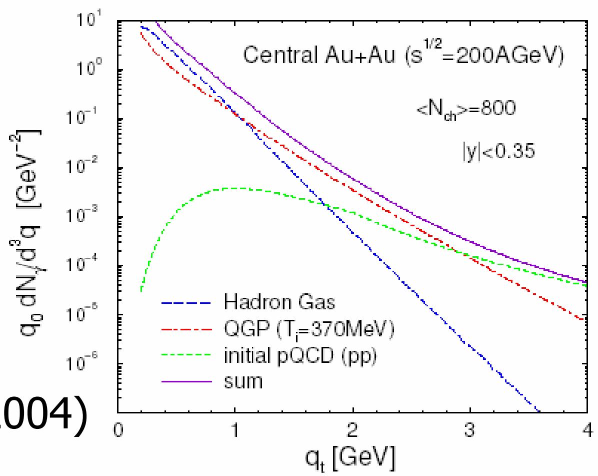
pQCD calculation including shadowing

- Thermal photons from hot medium



- Jet-photon conversion

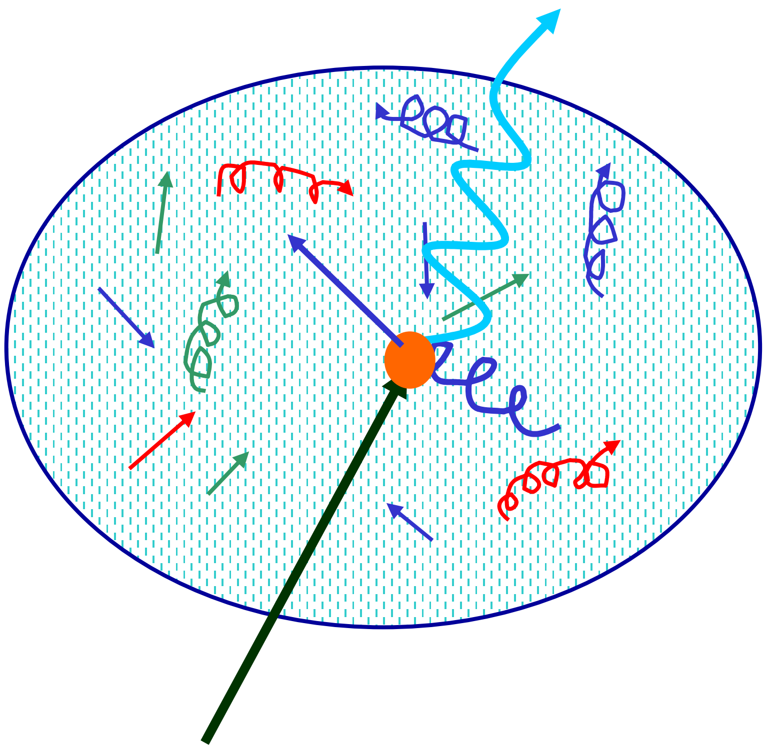




Turbide, Gale & Rapp, PRC 69 014903 (2004)

Jet-Plasma interactions

plasma mediates a jet-photon conversion:



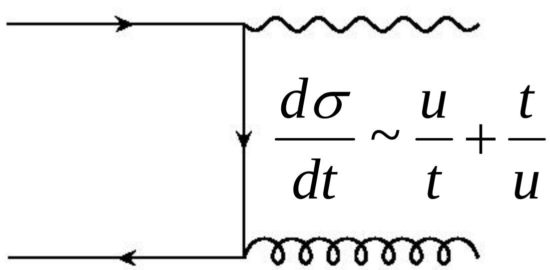
jet passing through the medium:

- •large energy loss: jet quenching
- •electromagnetic radiation (real and virtual photons) from jet-medium interactions
- •suppressed by α_{EM}; negligible as a source of additional jet quenching

- can escape without rescattering
  - ➢use as probe of energy loss?
- ➢ visible among other sources of electromagnetic signals?

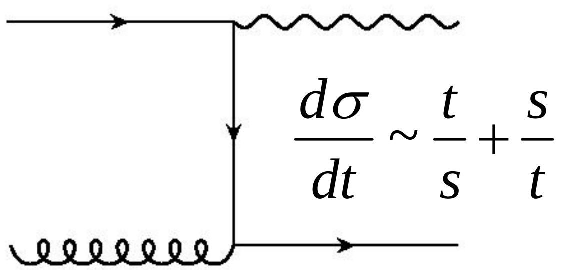
QGP-Induced EM Radiation

- annihilation and compton processes peak in forward and backward directions:



$$\vec{p}_\gamma \approx \vec{p}_q$$

$$\vec{p}_\gamma \approx \vec{p}_{\bar{q}}$$



- one parton from hard scattering, one parton from the thermal medium; cutoff $p_{\gamma,min}$ > 1 GeV/c.

➢ photon carries momentum of the hard parton

➢ Jet-Photon Conversion

Jet-Photon Conversion: Rates

- annihilation and compton rates:

$$E_\gamma \frac{dN^{(A)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

$$\times \int d^3p\, f_{\bar{q}}(p)[1+f_g(p)]\sigma^{(A)}(s) \frac{\sqrt{s(s-4m^2)}}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

$$E_\gamma \frac{dN^{(C)}}{d^4x d^3p_\gamma} = \frac{16E_\gamma}{2(2\pi)^6} \sum_{q=1}^{N_f} f_q(p_\gamma)$$

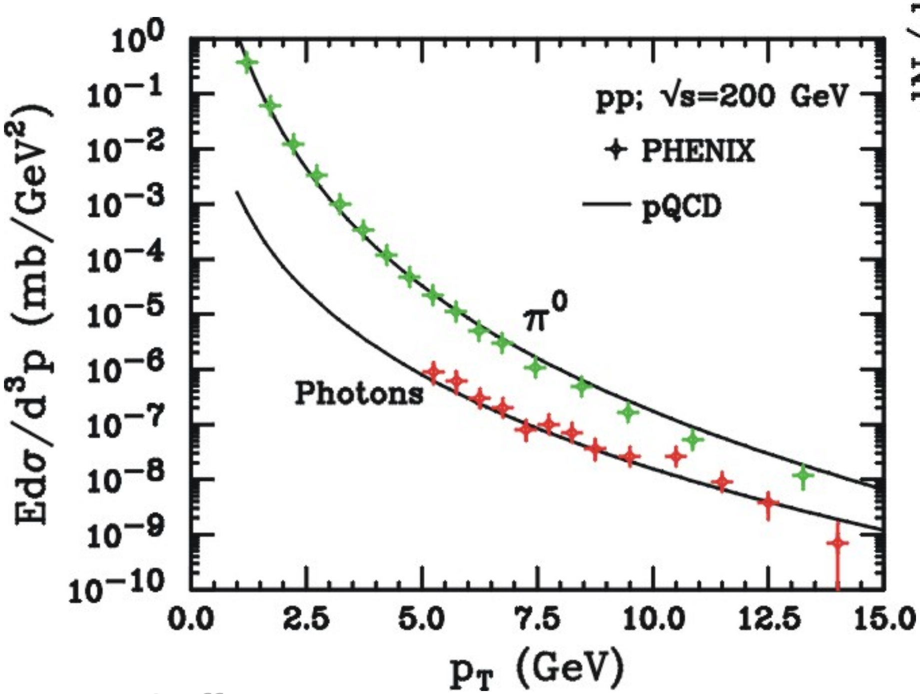
$$\times \int d^3p\, f_g(p)[1-f_q(p)]\sigma^{(C)}(s) \frac{s-m^2}{2E_\gamma E} + (q \leftrightarrow \bar{q})$$

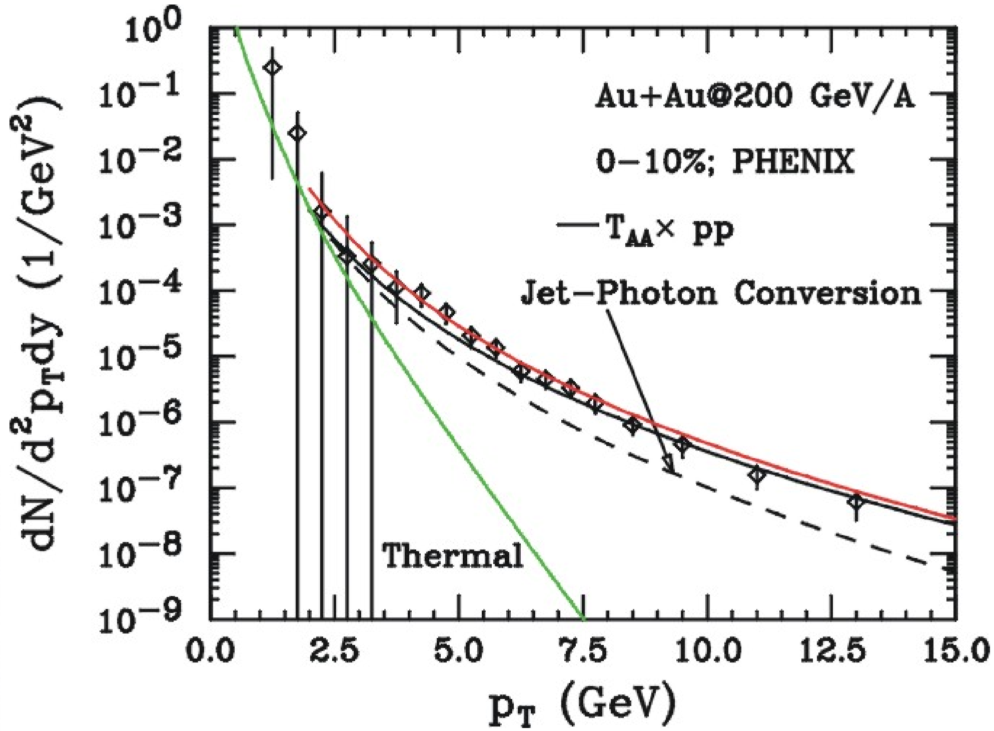
- thermal medium:

$$E_\gamma \frac{dN_\gamma}{d^3p_\gamma} = \frac{\alpha\alpha_s}{8\pi^2} \int d^4x \frac{2}{3}\left[f_q(p_\gamma) + f_q(p_\gamma)\right] T^2 \left(\ln\frac{4E_\gamma T}{m^2} + C \right)$$

FMS Results: Comparison to Data

calibrate pQCD calculation of direct and Bremsstrahlung photons via p+p data:

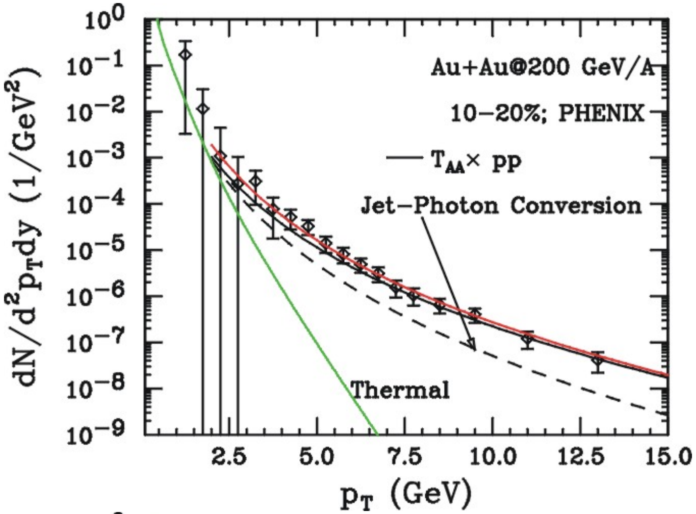


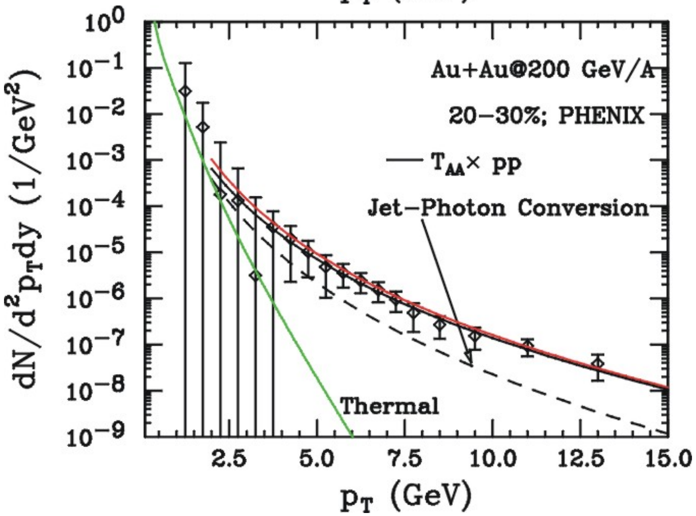


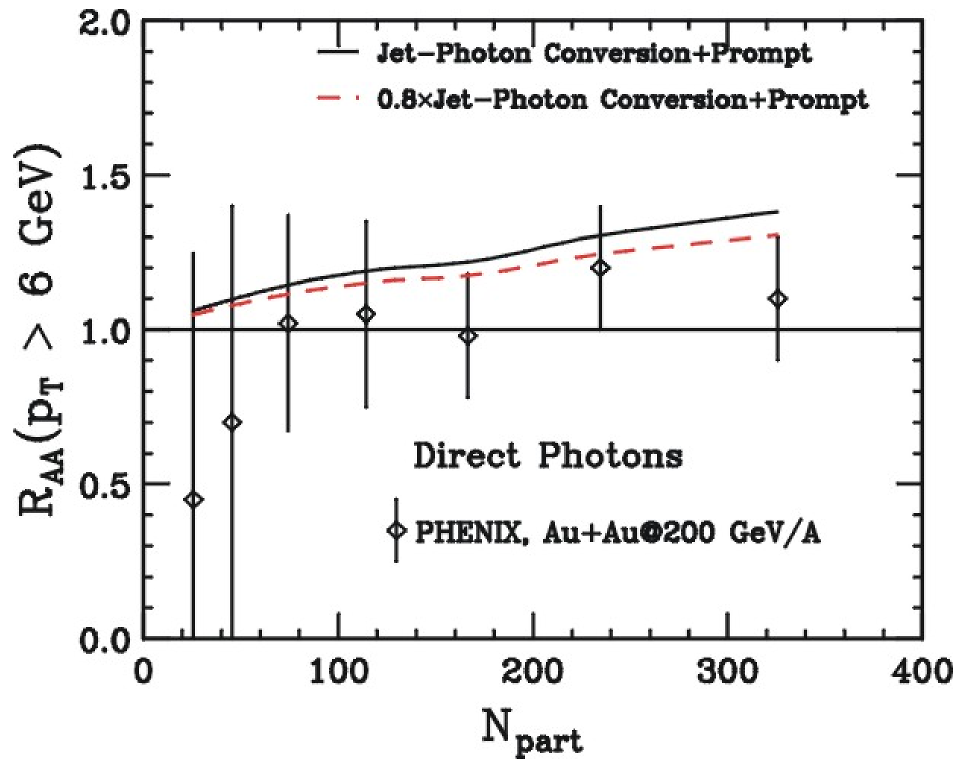
- for p_t<6 GeV, FMS photons give significant contribution to photon spectrum: 50% @ 4 GeV

(Fries, Mueller & Srivastava, ms in preparation)

FMS: Centrality Dependence and Jet-Quenching







- centrality dependence well described
- effect of energy-loss on jets before conversion ~ 20%
  (Turbide, Gale, Jeon & Moore: hep-ph/0502248)

Application: Monitoring Jet Quenching

full jet reconstruction not possible at RHIC:

- ✓ Measure suppression of single inclusive hadron spectra (compare to p+p baseline)
- ❖ better: photon-tagged jets (Wang & Sarcevic)
  - $q+g \rightarrow q+\gamma$: recoil photon knows the initial energy of the jet
  - ➢ measure energy loss of quark as a function of quark energy E
- ❖ photons from jet-photon conversion provide a third, independent measurement. (FMS)
  - ➢ better handle on the L dependence of energy loss
  - ➢ jet-photon conversion is background for photon tagged jets

Summary

Photon Production in the PCM:

- Photon yield very sensitive to parton rescattering
  - ➢ LPM effect needed for proper description of reaction dynamics
- HBT experimentally challenging, but feasible with high statistics data sets
  - ➢ calculable in the framework of PCM and hydro
  - ➢ short emission duration in pre-equilibrium phase: small radii at high p_t
  - ➢ larger source at later times due to emission of thermal photons

Photon Production via Jet-Medium Interactions:

- jet-photon conversion may contribute up to 50% @ 4 GeV to photon yield
- results compatible with PHENIX data (centrality dependence, R_{AA})
- analogous process for virtual photons: contribution to dilepton production