Thermal Radiation from Au + Au Collisions at $\sqrt{s} = 200$ GeV/A Energy

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Motivation

Relativistic Heavy Ion Collisions:
A + A $\longrightarrow$ [Hadrons] (?)

$\longrightarrow$ [Hadrons]* (?),

$\longrightarrow$ Quark Gluon Plasma (?)

Can photon spectra distinguish these scenarios?

Advantages of Electromagnetic Probes

- No final state interactions
- Emitted at all stages of the collisions

What can we learn:

• Estimations of initial conditions, e. g. T_i or equivalently equilibration time

• Accurate determination of T_i could help to answer the question whether QGP is formed or not

• Study of photon interferometry for the estimation of source sizes.

Sources of photons

- Prompt photons: $A + B \rightarrow \gamma + X$ (Compton, Annihilation, Bremsstrahlung).

- Thermal: QGP

  : Hadrons

- Decay photons: $\pi^0(\eta) \rightarrow \gamma\,\gamma$ etc

- Jet - Thermal partons interactions (Compton, Annihilation).
Fries, Muller & Srivastava- 2003

• Prompt photons: $A + B \to \gamma + X$
From the interactions of quarks/anti-quarks and gluons of the colliding nucleons:

(Gordon & Vogelsang- 1994)

$E\frac{dN}{d^3p} = \frac{n_{coll}}{\sigma_{NN}}.\frac{d\sigma}{d^3p}$

Initial state effects: Shadowing, Cronin Effects.

Final state effects: E-loss state partons (bremsstrahlung).

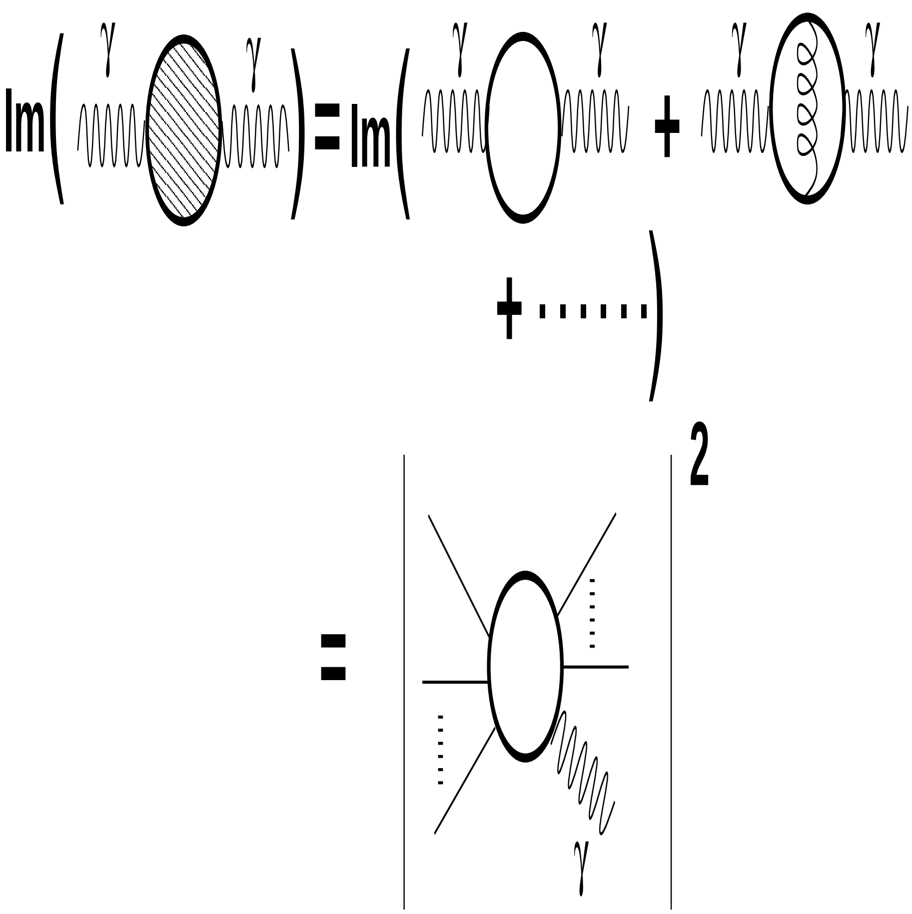
Zakharov - 2004

Thermal (real) photons:

$$E\frac{dR}{d^3p} = -\frac{g^{\mu\nu}}{(2\pi)^3}\frac{\mathrm{Im}\Pi^R_{\mu\nu}}{e^{E/T}-1}$$

McLerran & Toimel - 1985, Weldon - 1990,
Gale & Kapusta -1991

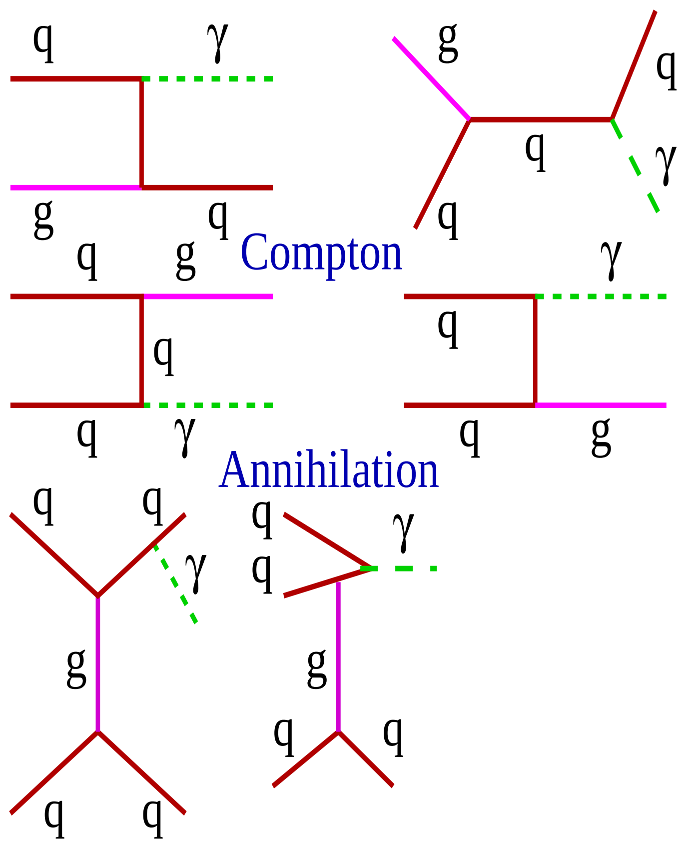
Optical Theorem in QFT:



The photon rate is $(1+2 \rightarrow 3+\gamma)$

$$
\begin{aligned}
E\frac{dR}{d^3p} &= \frac{\mathcal{N}}{16(2\pi)^7 E} \int_{(m_1+m_2)^2}^{\infty} ds \\
&\times \int_{t_{\text{min}}}^{t_{\text{max}}} dt \, |\mathcal{M}|^2 \int dE_1 \\
&\times \int dE_2 \frac{f(E_1)\, f(E_2)\, [1+f(E_3)]}{\sqrt{aE_2^2 + 2bE_2 + c}}
\end{aligned}
$$

Photons from Quark Gluon Plasma:



Quark (anti) brems. and annihilation with scattering

Evaluated within the framework of Hard Thermal Loop Approximations:

1. Kapusta et al., Phys. Rev D44 (1991) and Baier et al. Z. Phys. C53 (1992): 1-loop

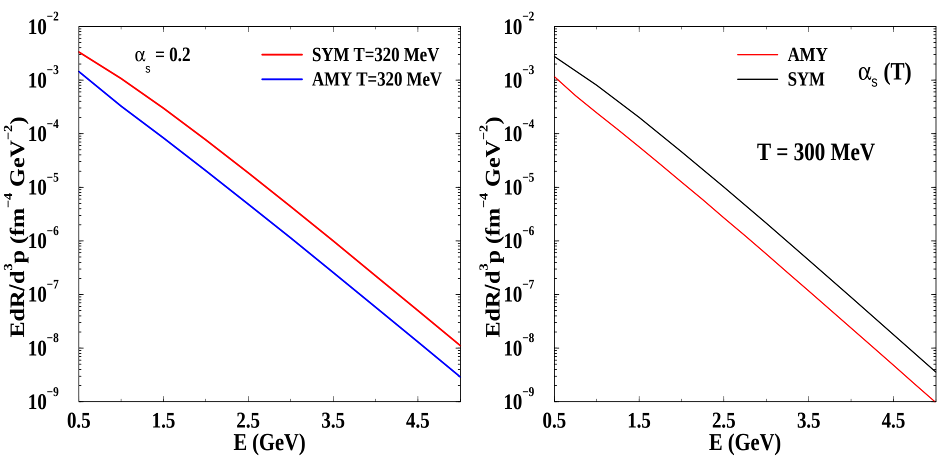
2. Auranche et al., Phys. Rev. D58 (1998): 2-loop

3. Arnold et al. JHEP (2001): Resummation of multi-loop contributions up to all orders.

Resummation of Ladder diagrams (LPM effects)

Photon production in supersymmetric Yangs-Mills plasma:
(Pavel Kovtun, SEWM 2006, BNL).

Caron-Huot, Kovtun, Moore, Starinets, Yaffe - hep-th/0607237



Hadronic Photons (Thermal):

Set of reactions:

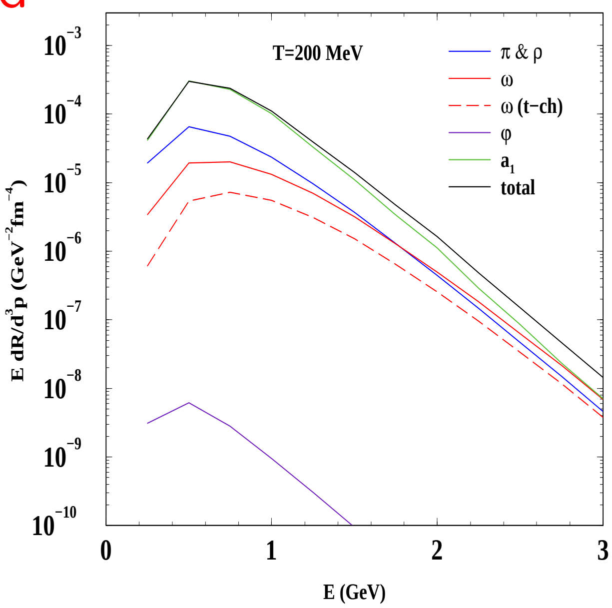
$$\pi\,\pi\;\longrightarrow\;\rho\,\gamma$$
$$\underline{\pi\,\rho\;\longrightarrow\;\pi\,\gamma}$$
$$\pi\,\pi\;\longrightarrow\;\eta\,\gamma$$
$$\pi\,\eta\;\longrightarrow\;\pi\,\gamma$$
$$\rho\;\longrightarrow\;\pi\,\pi\,\gamma$$
$$\omega\;\longrightarrow\;\pi\,\gamma$$

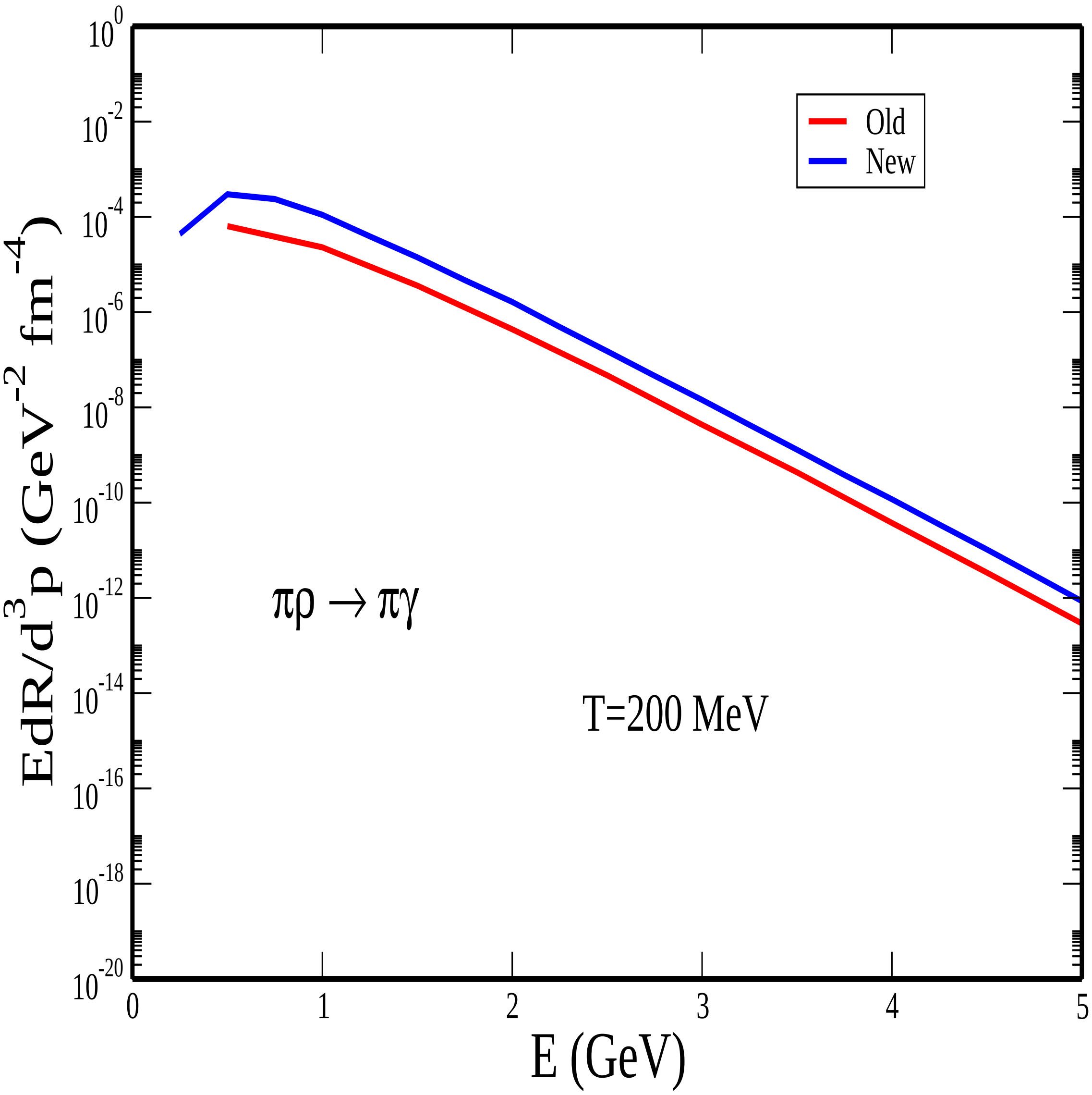
with all possible isospin combinations.

- S. Sarkar *et al.* Nucl. Phys. A634 (1998) 206; P. Roy *et al.* Nucl. Phys. A653 (1999) 277; S. Sarkar *et al.* Phys. Rev. C60 (1999) 054907, Alam *et al.* 286 (2000) 159; Alam *et al.* Phys. Rev. C71 (2005) 059802; Turbide *et al.* Phys. Rev. C 69 (2004) 014903.

$\pi\,\rho\ \longrightarrow\ \pi\,\gamma$

- ω, ϕ, π, ρ, a_1 exchange diagrams are considered





Old
New
$\pi\rho \rightarrow \pi\gamma$
T=200 MeV
EdR/d^3p (GeV^{-2} fm^{-4})
E (GeV)

In-medium properties of hadrons

Mass shift ? Broadening ? or both?

• KEK: p (12 GeV) + C, Cu, dilepton data indicate significant shape changes in e^+e^- invariant mass spectrum from $p+C$ to $p+Cu$

• TAGX: γ (800 - 1200 MeV) + $^3He \longrightarrow m_\rho \sim$ 642 MeV

• CHAOS: $\pi^+ A \to \pi^+ \pi^\pm A'$ at $T_{\pi^+} = 283$ MeV

Medium modification is observed in $I = 0$, $J = 0$ (σ meson)

• J-Lab: $\gamma + A \to V + X$

• CERES/NA45/NA60: Heavy Ion Experiments at CERN.

- p_T distribution of photons

$$\frac{dN}{d^2p_T dy} = \int d^4x \, E\frac{dR}{d^3p} = \int_{QGP} + \int_{Mix} + \int_{Had}^{T_F} : \text{(QGP)} \quad (1)$$

Space-time evolution

- Relativistic Hydrodynamics

What is the initial temperature?

$$\frac{dN}{dy} \sim \frac{\pi R^2 \tau_i}{4} \times 4 \frac{\pi^2}{90} g_{\text{eff}} T_i^3$$

SPS : $dN/dy \sim 700$, $\tau_i \sim 1$ fm/c, $g_{\text{eff}} \sim 42.25 \rightarrow T_i \sim 200$ MeV.

RHIC : $dN/dy \sim 1100$, $\tau_i \sim 1$ fm/c, $g_{\text{eff}} \sim 42.25 \rightarrow T_i \sim 255$ MeV.

• Initial conditions

Initial energy density:

$$\epsilon(\tau_i, r) = \epsilon_0 \frac{1}{e^{(r-R)/\delta} + 1}$$

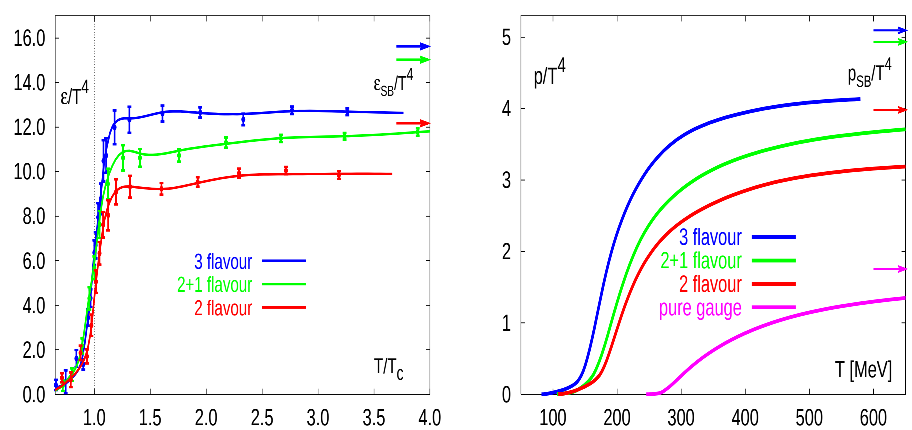
Initial velocity profile:

$$v_r(\tau_i, r) = v_0 \left(1 - \frac{1}{e^{(r-R)/\delta} + 1}\right)$$

• EOS: QGP (Bag Model)

• EOS: Hadronic (Resonances up to mass 2.5 GeV)

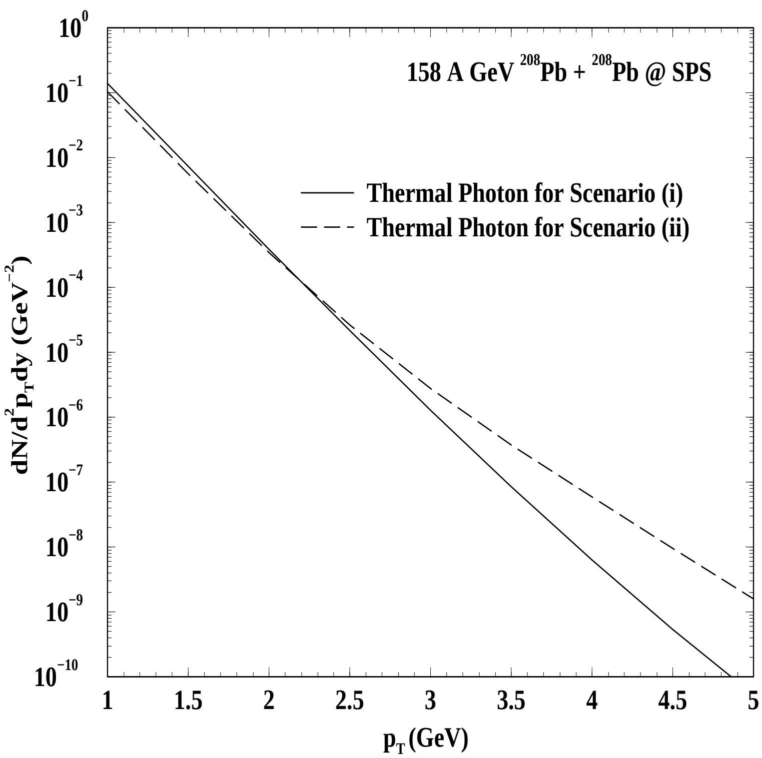
EOS: from Lattice QCD



Karsch, 2002

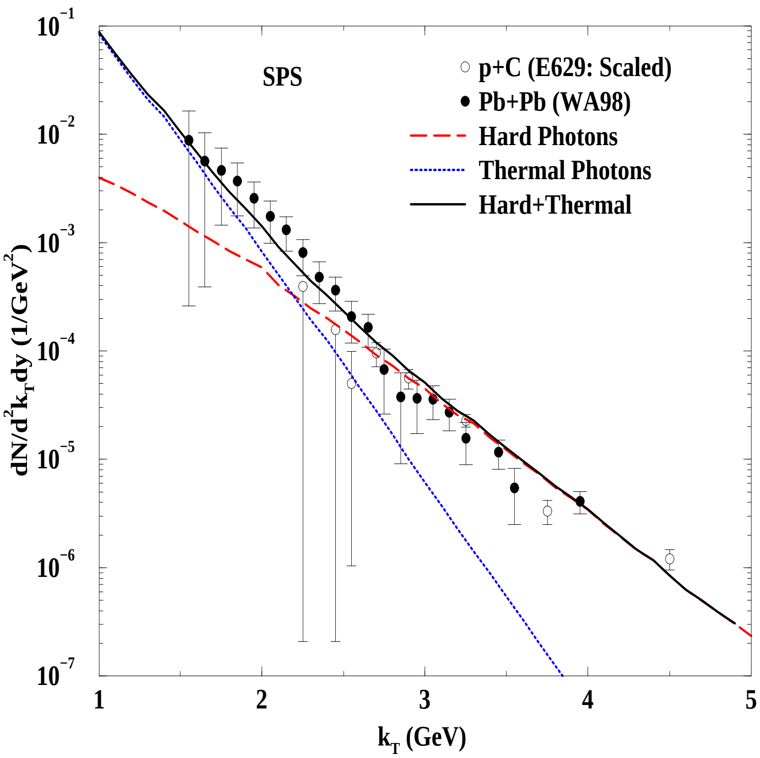
Enhancement due to medium effects

QHD ? Brown-Rho scaling ?



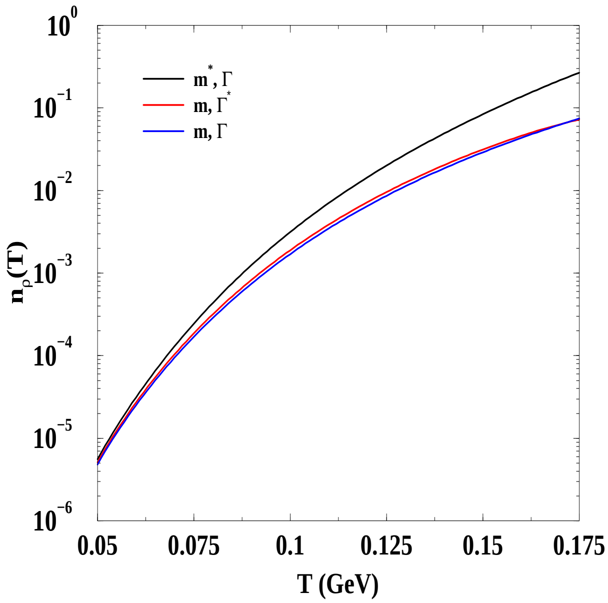
Alam, Sarkar, Hatsuda, Nayak & Sinha 2001.

SPS



WA98 photon data is well described with $T_i \sim 200$ MeV and $\tau_i \sim 1$ fm/c.

- QGP initial state
- Hadronic initial state with in-medium effects



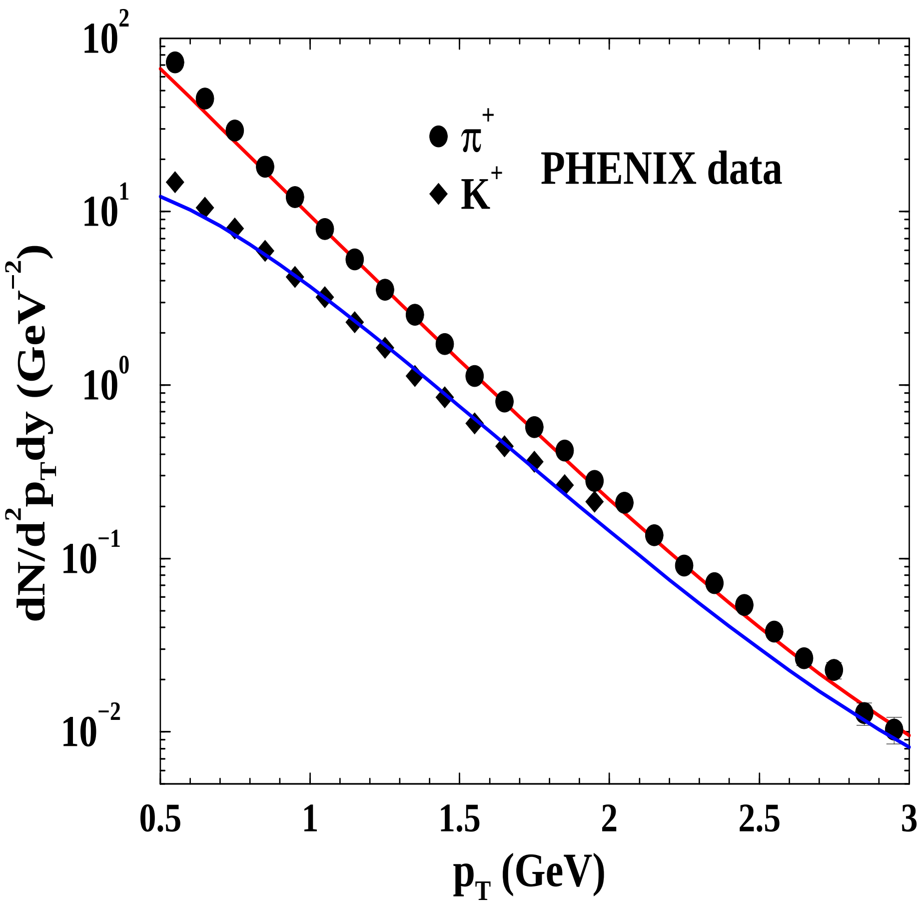
$$n_\rho = \frac{g}{(2\pi)^3} \int d^3p dM^2 f(M,T) \rho_{\text{spec}}$$

$$f(M,T) = \frac{1}{e^{\sqrt{p^2+M^2}/T} - 1}$$

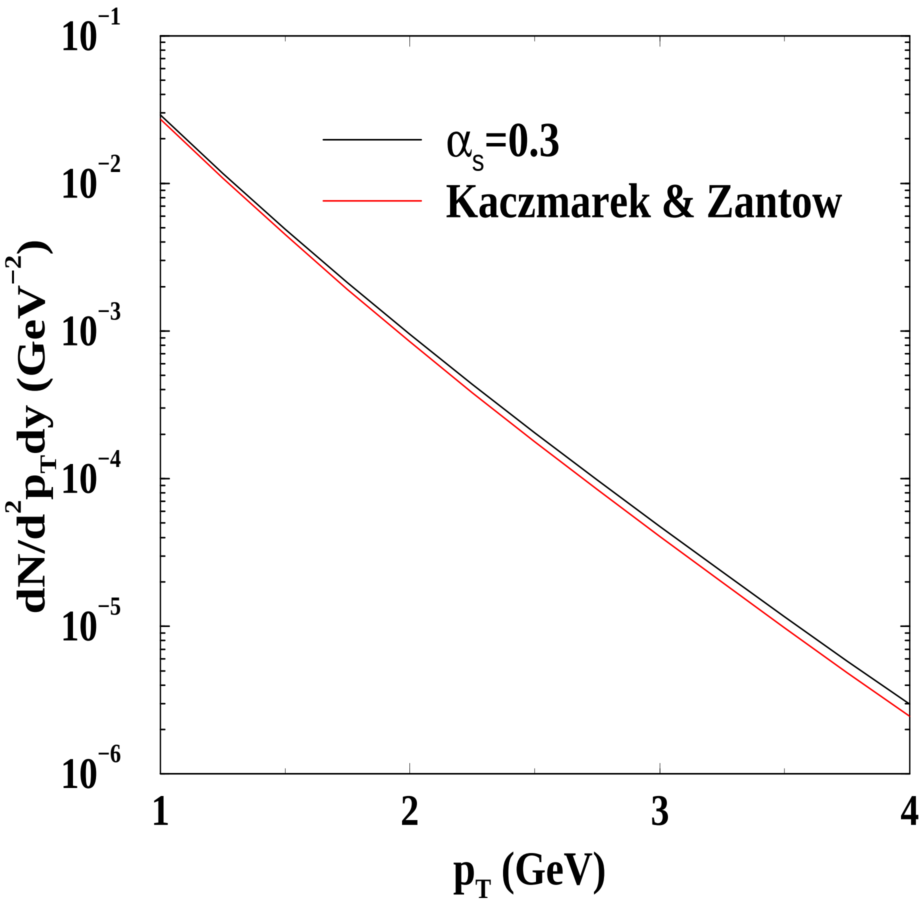
$$\rho_{\text{spec}} \sim \frac{M\Gamma}{(M^2 - m_\rho^2)^2 + M^2\Gamma^2}$$

Alam, Roy, Sarkar & Sinha 2003.

- RHIC: Fixing the Freeze-out condition

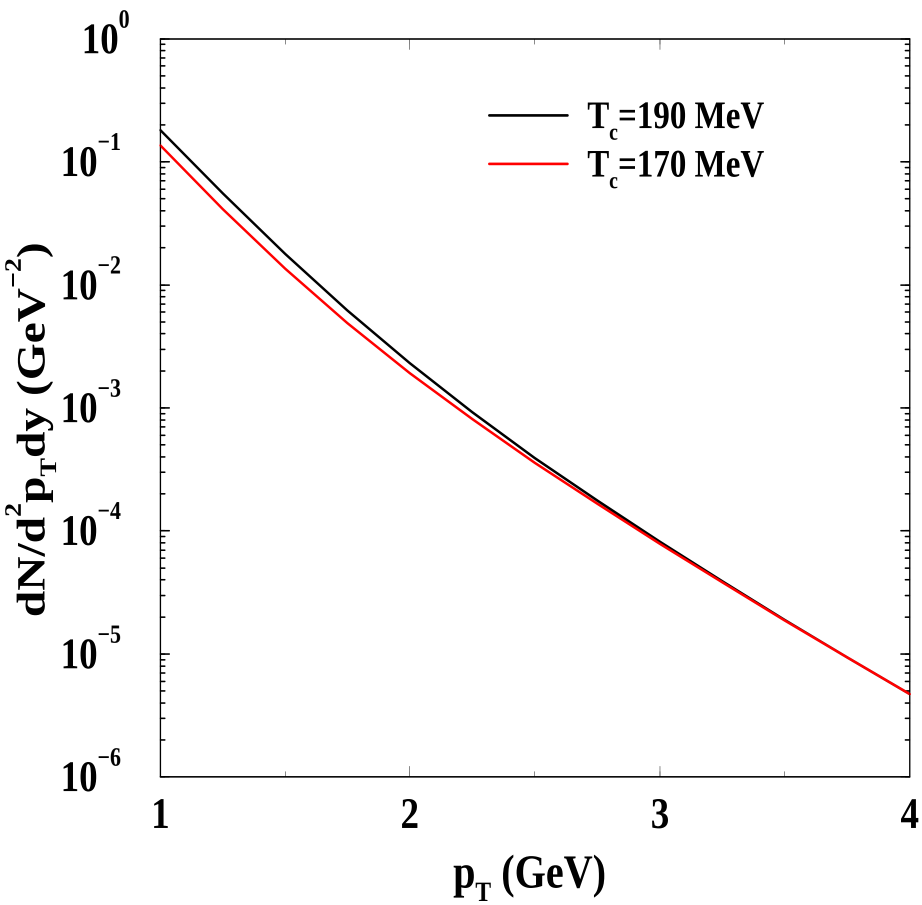


• Photon spectra from QGP : Dependence on α_s



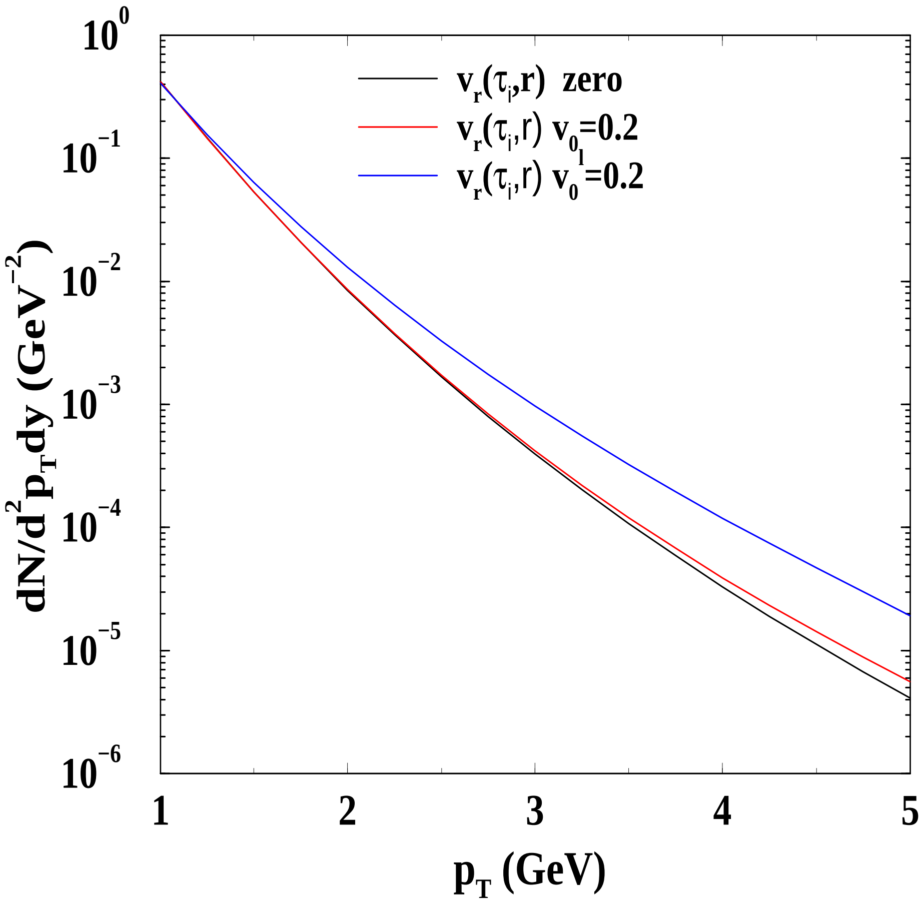
At $p_T = 3$ GeV the difference is $\sim 15\%$.

- Dependence on T_c



at $p_T = 2$ GeV the change is about 10%.

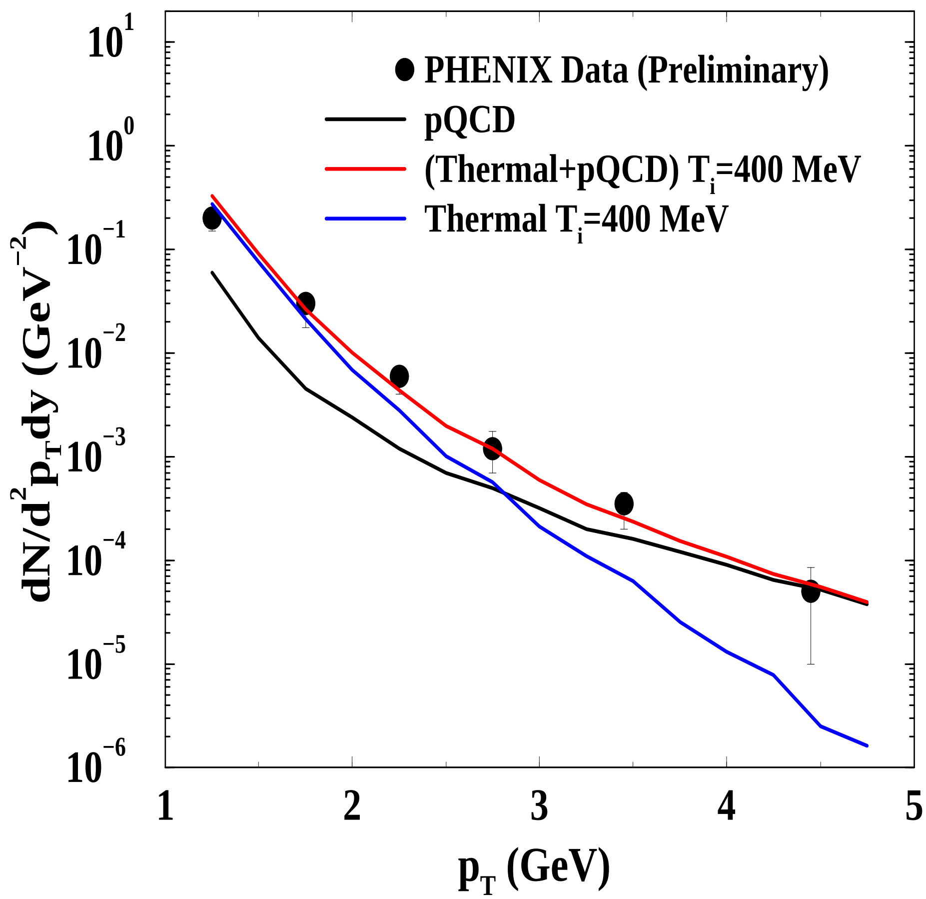
- Non-zero initial radial velocity



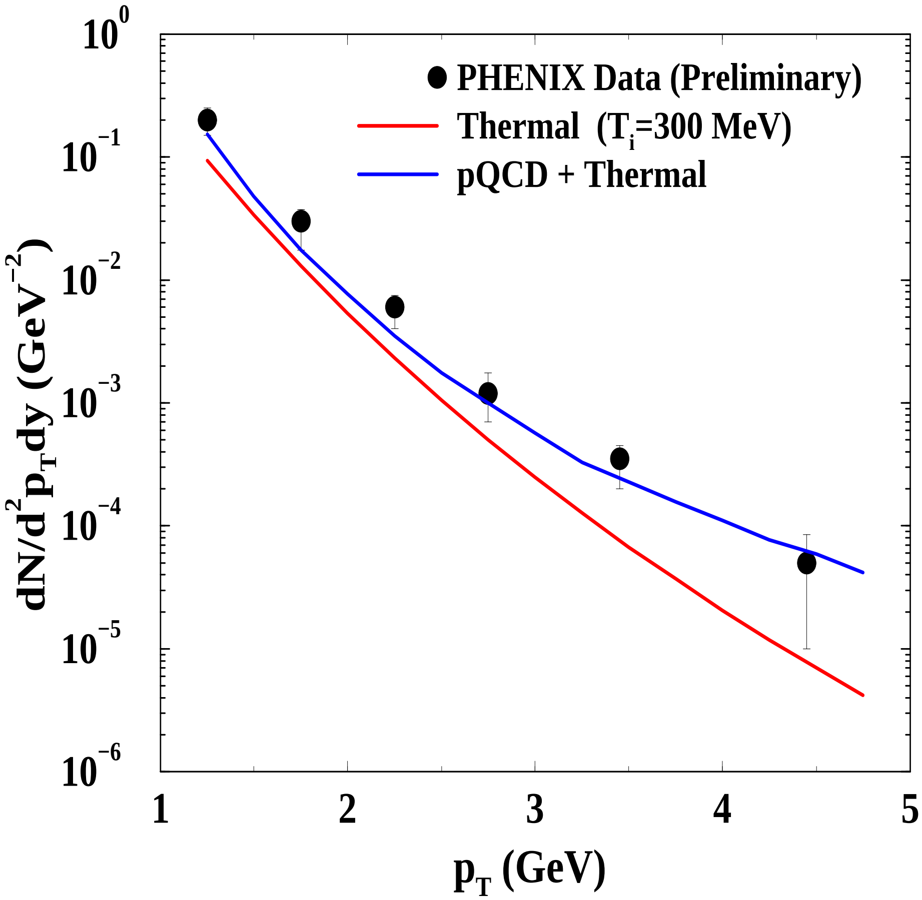
$$v_r(\tau_i, r) = v_0\left(1 - \frac{1}{e^{(r-R)/\delta}+1}\right)$$

$$v_r(\tau_i, r) = v_0^l \frac{r}{R_A}$$

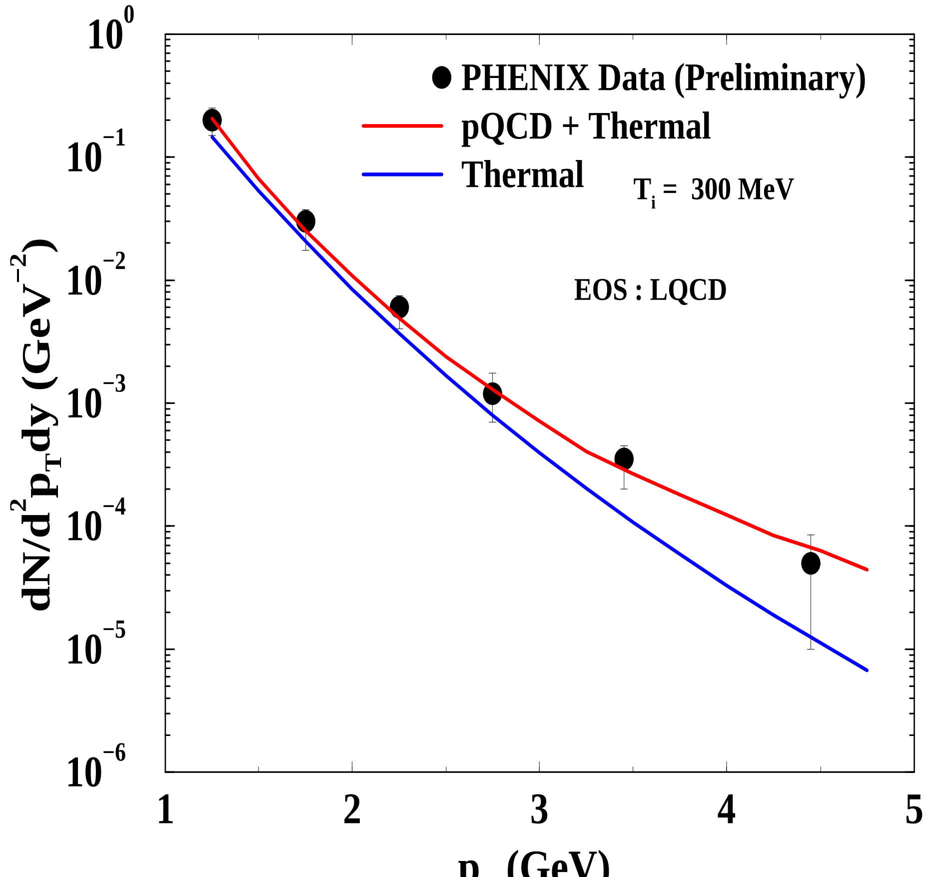
- Photon production in RHIC



• Photon production in RHIC (AMY, EOS form LQCD)



• Photon production in RHIC (SYM, EOS form LQCD)



Conclusions:

• The photon from SPS data cannot distinguish between [hadronic]* and QGP initial states. The picture is clear at RHIC.

• The initial temperature of the system formed at RHIC collision is $\sim 300 - 400$ MeV $\Rightarrow \tau_i \sim 0.2 - 0.6$ fm/c.

(D. d'Enterria and D. Peressounko 2006, $T_i \sim 590$ MeV)

• The dependence of photon spectra on α_s, T_c is small, however, on the space time evolution scenarios found to be substantial.

• Effects of viscosity (Sarkar, Roy, Alam, Raha and Sinha 1997, Chaudhuri 1995).

• Photon spectra is insensitive to the broadening but sensitive to the mass shift.