PHOTONS, DILEPTONS,

AND

HADRONS

FROM

RELATIVISTIC HEAVY ION COLLISIONS

AND

QUARK-HADRON PHASE TRANSITION

<u>Collaborators</u>

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Dinesh Srivastava, Calcutta

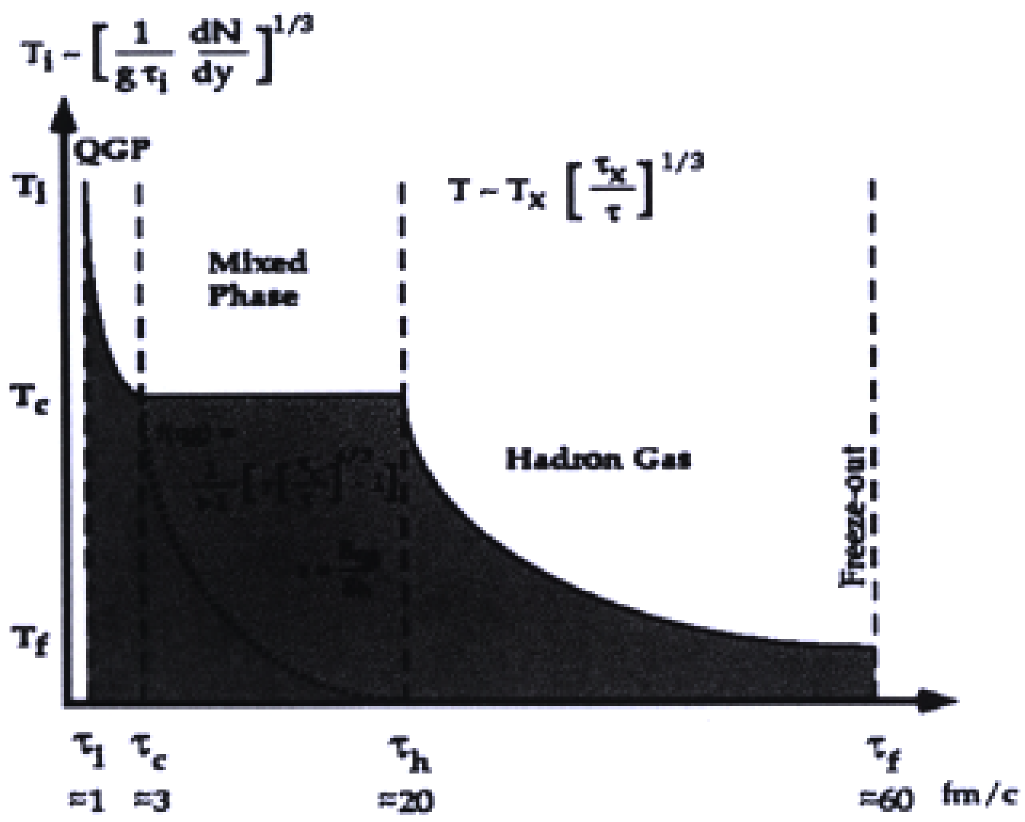
- Photons, either radiated or scattered, have remained one of the most effective probes of every kind of terrestrial or celestial matter over the ages.

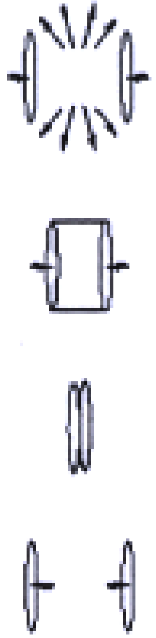
- **Once produced, photons leave the system without any further interaction and thus they provide information about the circumstances of their birth.**

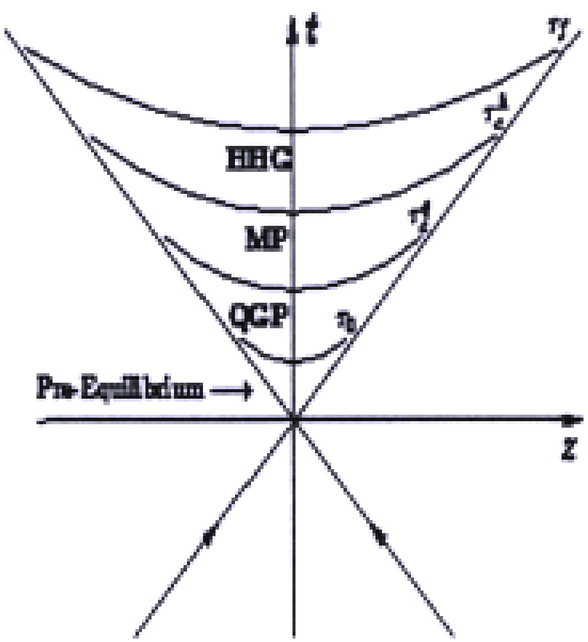
Evolution of Relativistic Heavy-ion Collision

Temperature Evolution

- Bjørken Hydrodynamics -



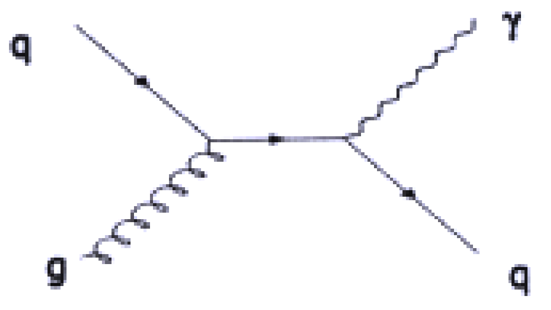
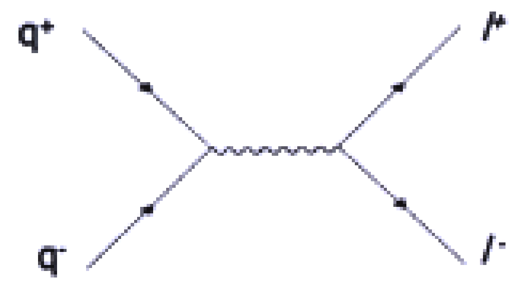




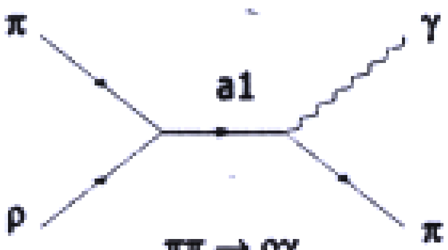
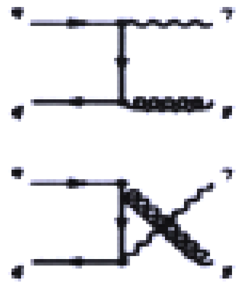
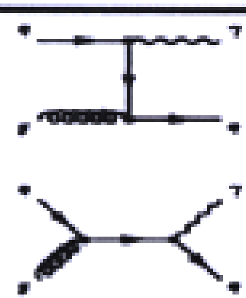
Total single photon production
QGP + Mixed + Hadronic Gas

DKS

Real versus Virtual Photons

	Photons	**Lepton Pairs**
Elementary Process:		
Coupling:	$\alpha_s\ \alpha_e$	$\alpha_e\ \alpha_e$
Variable:	Transverse momentum: p_T	Transverse mass: $m_T^2 = p_T^2 + m^2$
Backgrounds:	$\pi^0 \rightarrow \gamma\gamma$ (~85%) $\eta^0 \rightarrow \gamma\gamma$ (~15%) $x \rightarrow x' \gamma$ (<2%)	$\pi^0 \rightarrow e^{\pm}\ \gamma$ (~1%) $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\ \nu$ $\eta, \eta \rightarrow l^{\pm}\ \gamma$
Difficulty for A-A Collisions	Combinatorial Background in $\gamma\gamma$ to extract π^0 and η^0	Combinatorial Background in l^+l^- to extract true l^+l^-

Single Photons from A-A Collisions

	Hadron Gas	QGP	N-N (prompt)
Elementary Process:	 $\pi\pi \rightarrow \rho\gamma$ $\pi\rho \rightarrow \pi^0\gamma$ $\omega \rightarrow \pi^0\gamma$ ...	 Annihilation	 QCD Compton
Distribution:	Thermal (ε,T,S_{HG},...) + Radiative Decays	Thermal (ε,T,S_{QGP},...)	Structure Functions
Total Yield:	Integration over Space-Time History		Superposition of N-N Collisions
Relevant p_T Range:	Resonance Decays $p_T \leq 1$ GeV/c	"Thermal" Photons $p_T \sim 1 - 3$ GeV/c	"Prompt" Photons $p_T \geq 3$ GeV/c

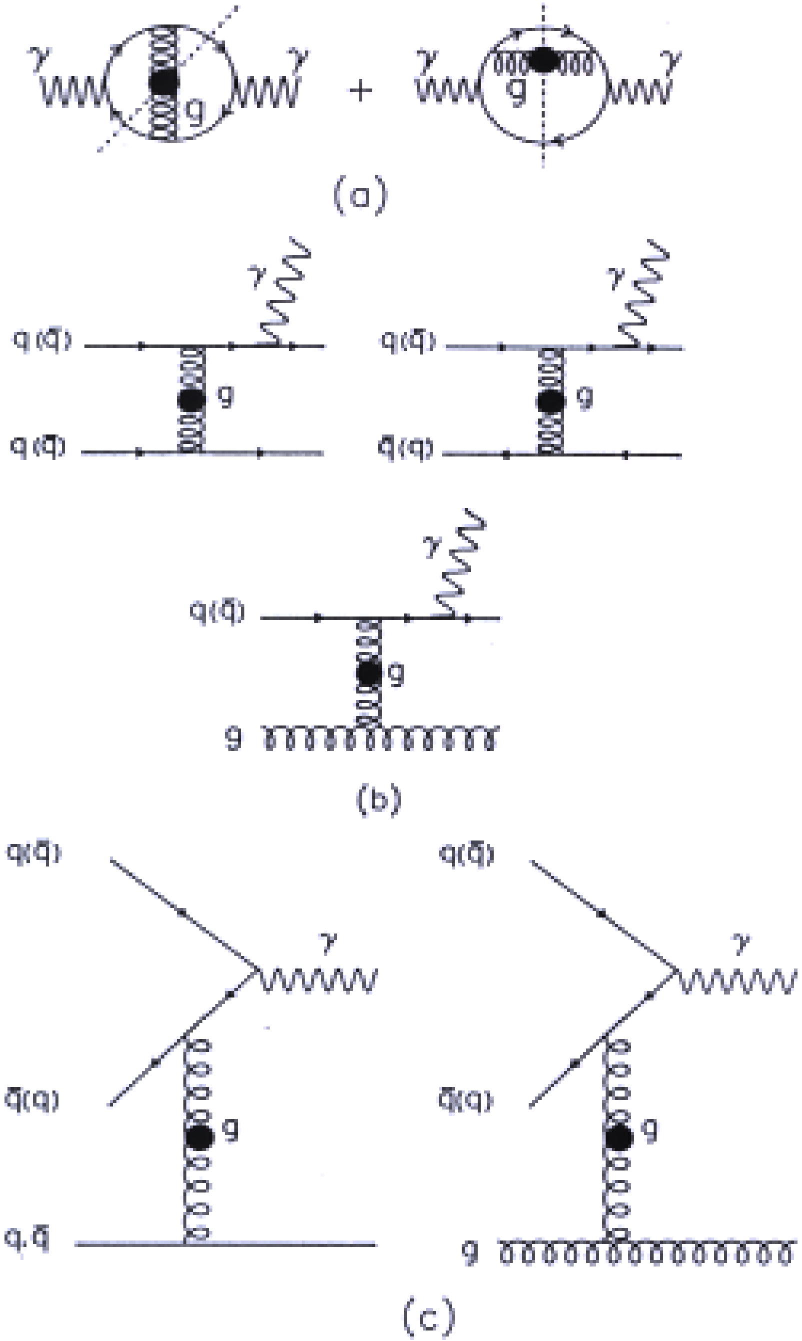
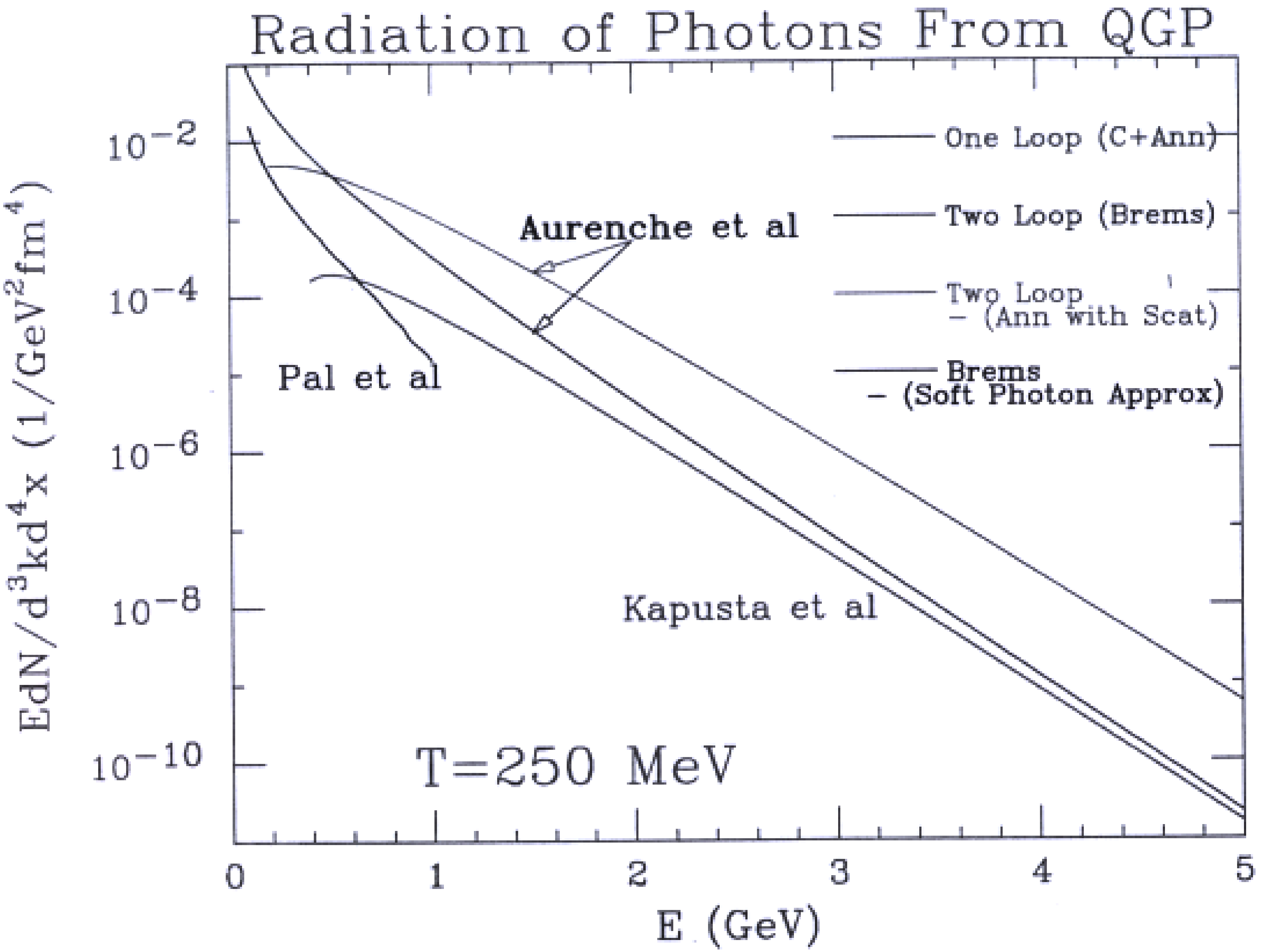


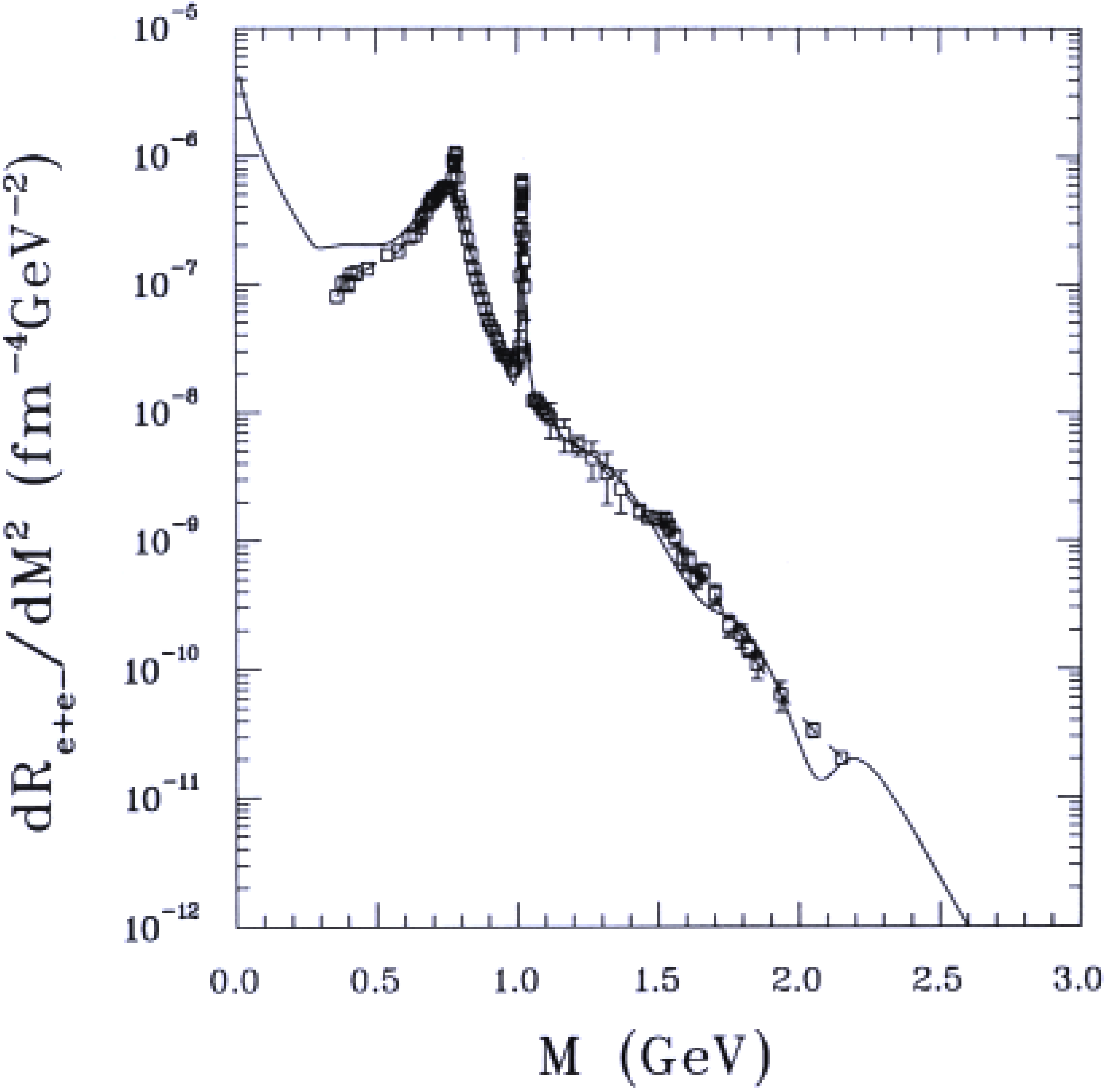
FIG. 2. (a) Simplified two-loop photon self-energy diagrams with bare vertices and propagators everywhere except for the gluon propagator since the gluon can be soft. Cutting these two-loop diagrams along the dashed lines leads to (b) bremsstrahlung and (c) annihilation with scattering off a quark, antiquark or gluon.

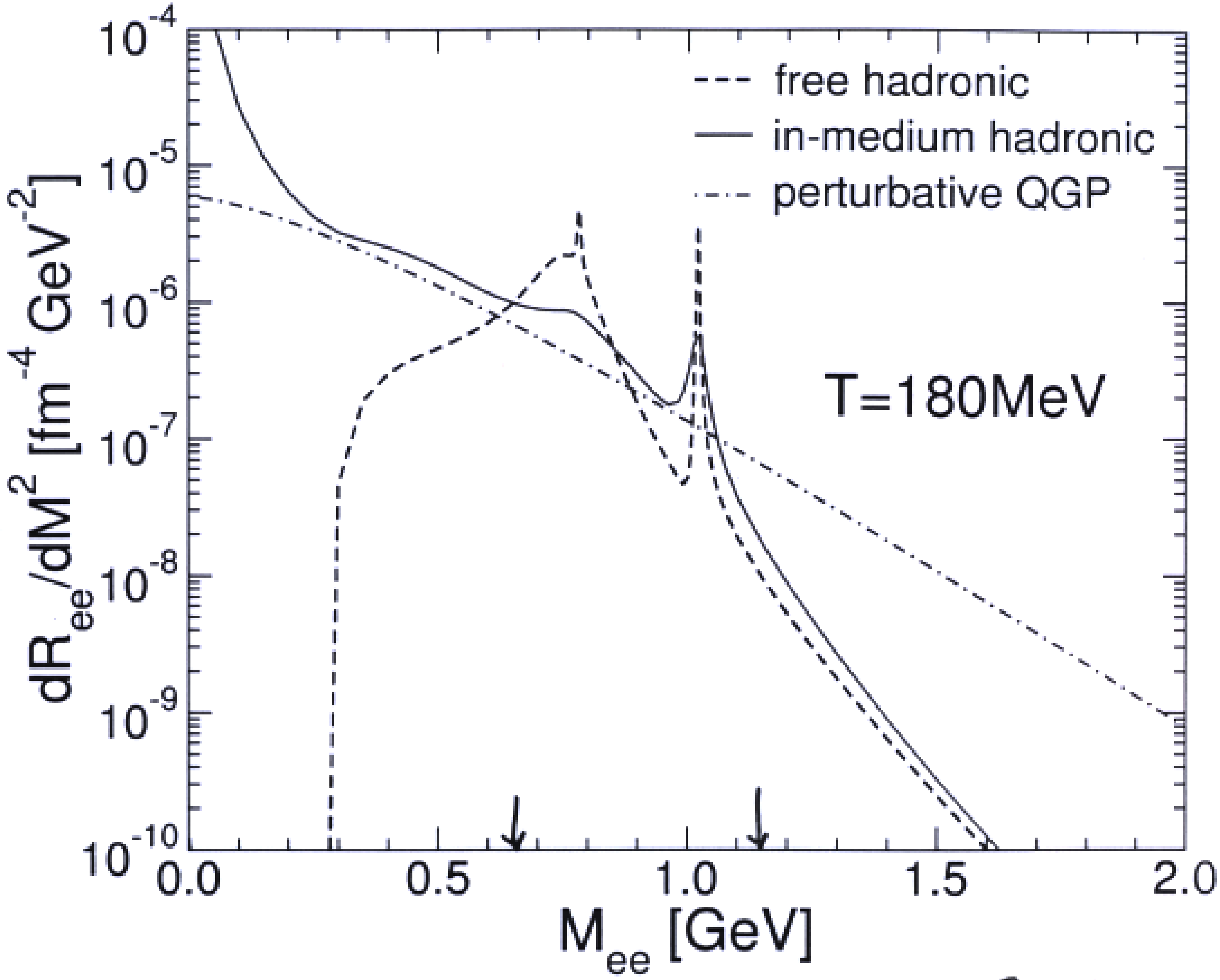


Radiation of Photons From QGP
One Loop (C+Ann)
Two Loop (Brems)
Two Loop
- (Ann with Scat)
Brems
- (Soft Photon Approx)
Aurenche et al
Pal et al
Kapusta et al
T=250 MeV
10−2
10−4
10−6
10−8
10−10
EdN/d³kd⁴x (1/GeV²fm⁴)
0
1
2
3
4
5
E (GeV)

I. Kvasnikova et al.

T = 150 MeV





free hadronic
in-medium hadronic
perturbative QGP
T=180MeV
dR_{ee}/dM^2 [fm^{-4} GeV^{-2}]
M_{ee} [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.0
0.5
1.0
1.5
2.0

Rapp

Formualtion

We assume that

- a thermally and chemically equilibrated QGP is formed at time τ_0 and has temperature T_0:

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{A_T}\frac{dN}{dy} = 4aT_0^3\tau_0 \tag{1}$$

  where A_T is the transverse dimension of the colliding system, dN/dy is particle rapidity-density, $a = 42.25\pi^2/90$ for a plasma of u, d, and s quarks, and gluons.

- The plasma undergoes a boost-invariant longitudinal expansion and radially symmetric transverse expansion, and cools.

- It gets into a mixed phase at $T = T_C$ and then into a hot hadronic matter, having all hadrons with $M \leq 2.5$ GeV, in thermal and chemical equilibrium and undergoes a freeze-out at $T = T_f$.

- **The initial energy-density profile is taken as**

$$\epsilon(\tau_0, r) \propto \int_{-\infty}^{\infty} \rho(\sqrt{r^2 + z^2})\, dz \tag{2}$$

  corresponding to 'wounded-nucleon distribution'.

- Then we get, single-photons from:

$$E\frac{dN_\gamma}{d^3p} = \int d^4x \left[f_Q \left(E\frac{dN}{d^3pd^4x} \right)_{QGP} + f_H \left(E\frac{dN}{d^3pd^4x} \right)_{Had} \right], \tag{3}$$

dileptons from:

$$E\frac{dN_{\mu^+\mu^-}}{dM^2d^3p} = \int d^4x \left[f_Q \left(E\frac{dN}{dM^2d^3pd^4x} \right)_{QGP} + f_H \left(E\frac{dN}{dM^2d^3pd^4x} \right)_{Had} \right] \tag{4}$$

and hadrons from:

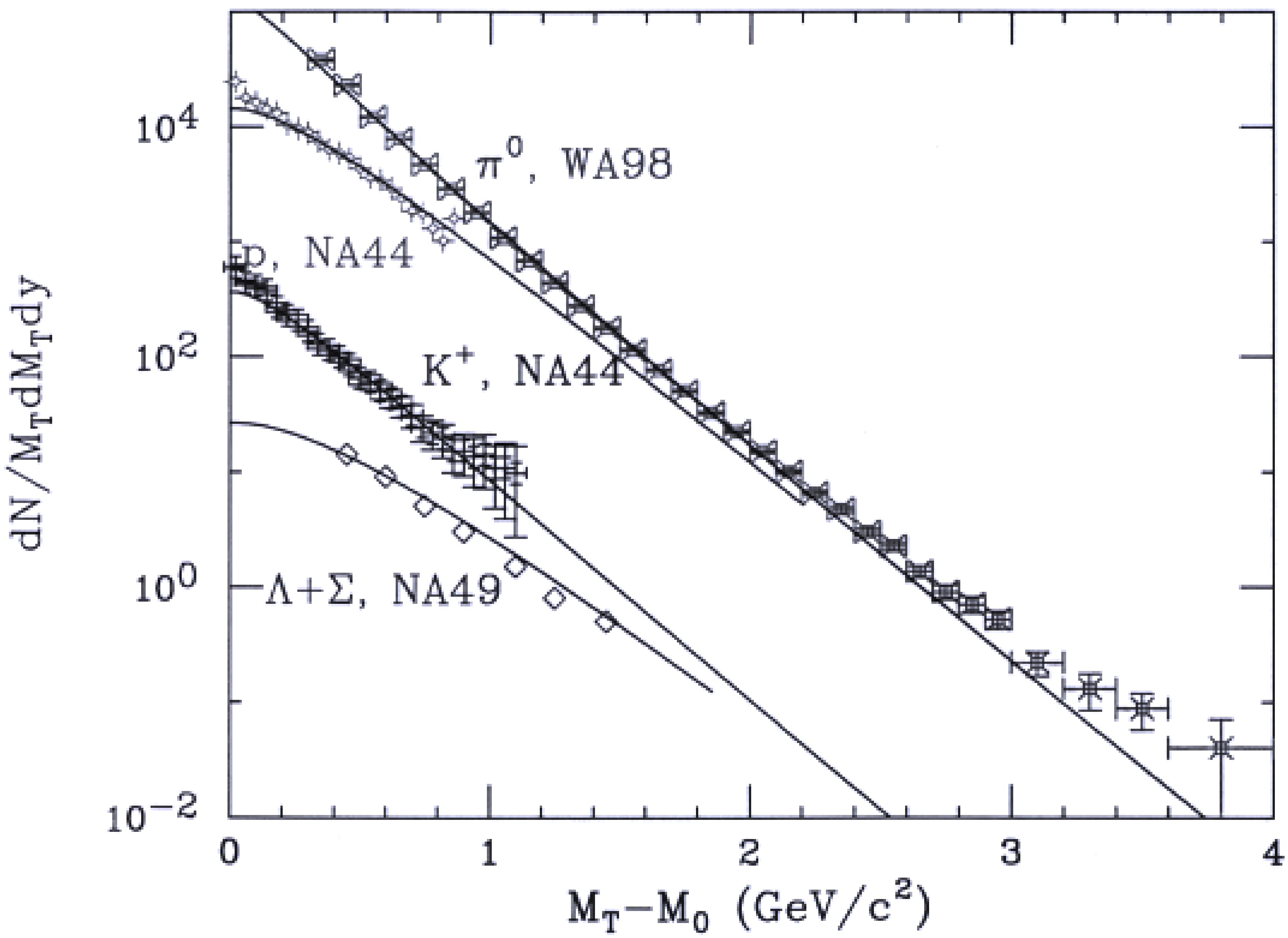
$$E\frac{dN_i}{d^3p} = \int d\sigma \cdot p f(p \cdot u) \tag{5}$$

where u^μ is the four-velocity of the local rest-frame, and is obtained from numerical integration of hydrodynamic equations. σ describes the freeze-out surface.

- And finally, Drell-Yan, for example, is estimated as:

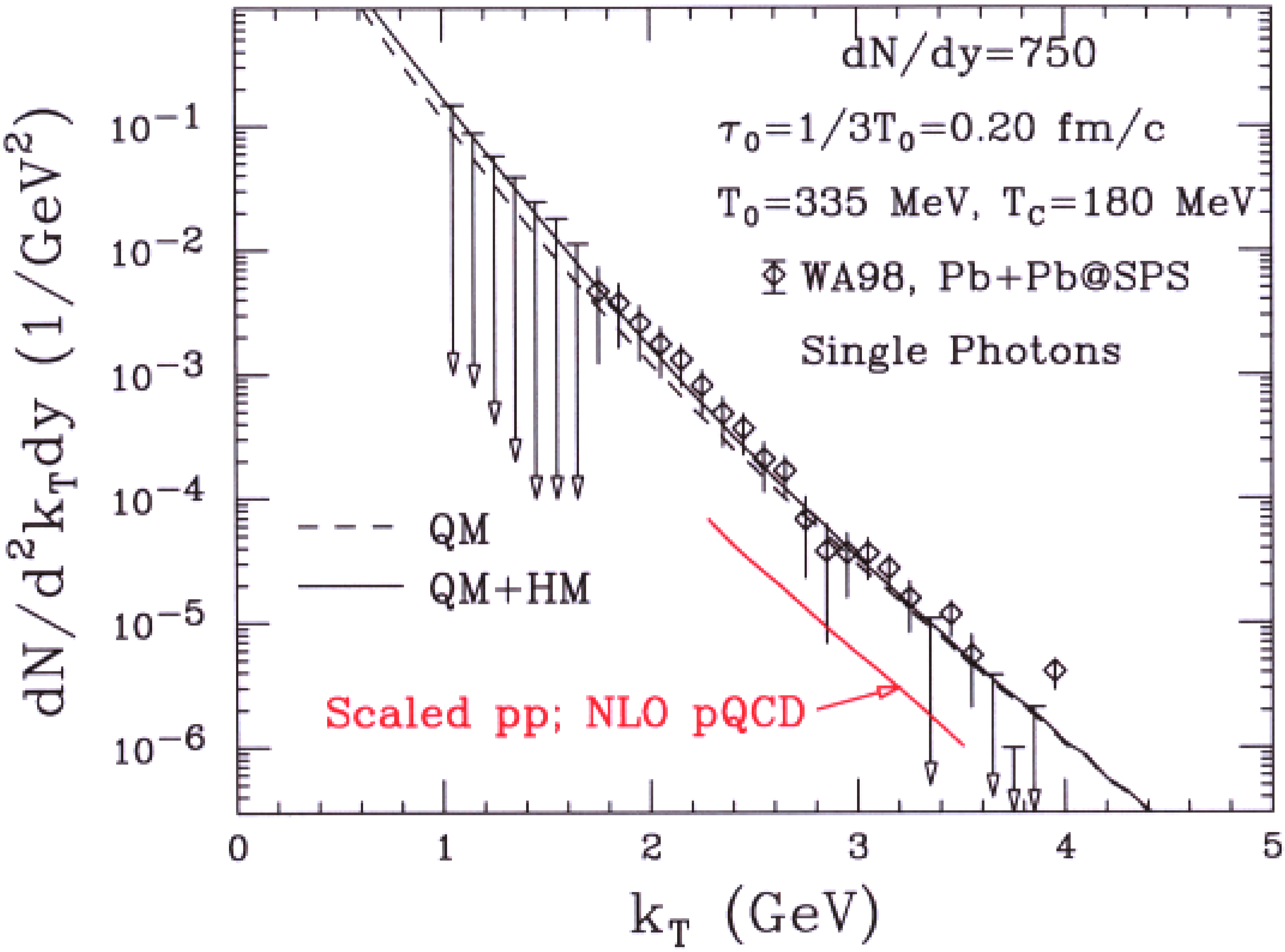
$$\frac{dN_{AA}}{dM^2dy} = T_{AA}(b)\frac{dN_{pp}}{dM^2dy} \tag{6}$$

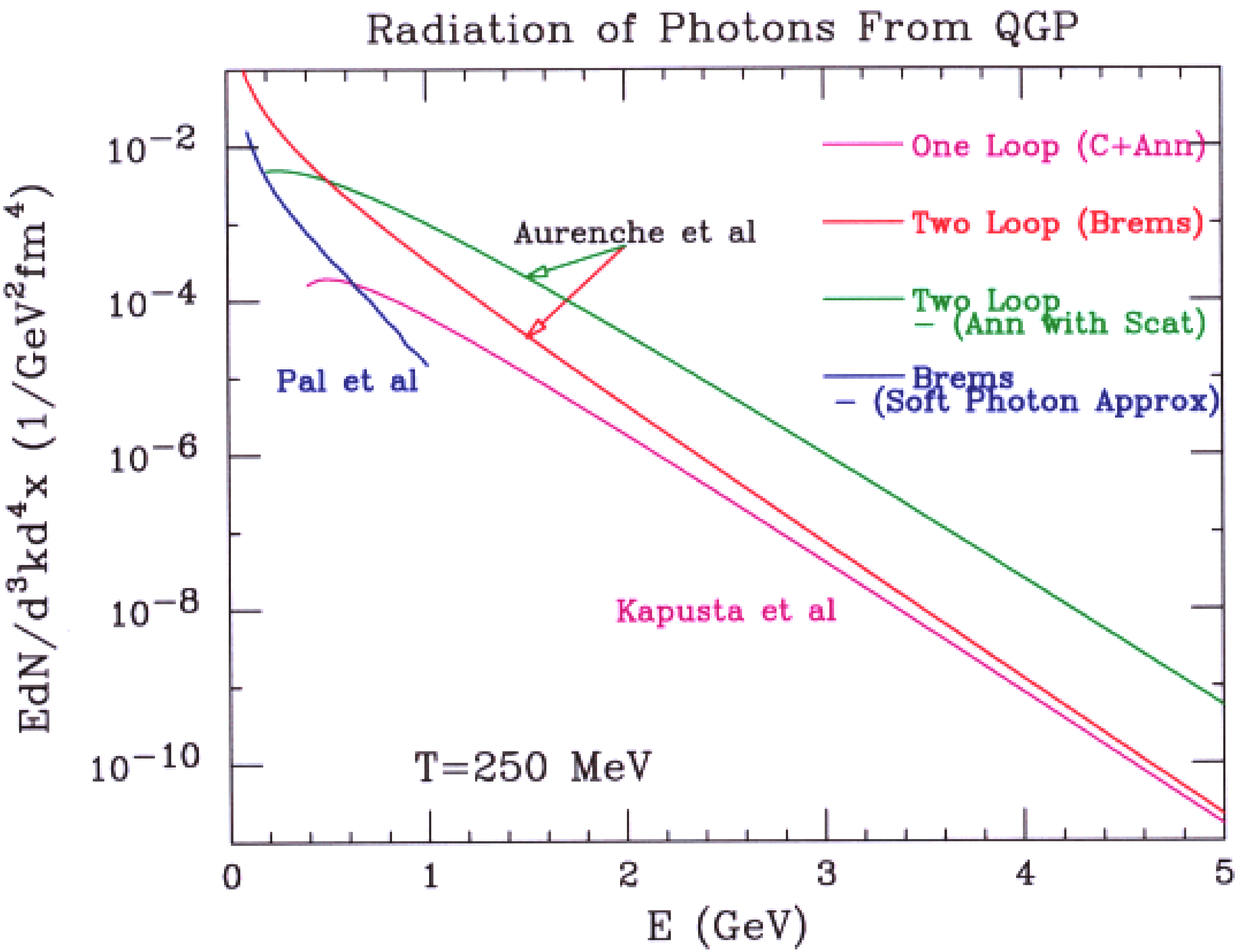
where T_{AA} is the nuclear thickness.



dN/M_TdM_Tdy
10^4
10^2
10^0
10^-2
π^0, WA98
p, NA44
K^+, NA44
Λ+Σ, NA49
0
1
2
3
4
M_T−M_0 (GeV/c^2)

"FLOW"


dN/dy=750
τ0=1/3T0=0.20 fm/c
T0=335 MeV, Tc=180 MeV
WA98, Pb+Pb@SPS
Single Photons
QM
QM+HM
Scaled pp; NLO pQCD
10−1
10−2
10−3
10−4
10−5
10−6
0
1
2
3
4
5
dN/d2kTdy (1/GeV2)
kT (GeV)


Radiation of Photons From QGP
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Brems (Soft Photon Approx)
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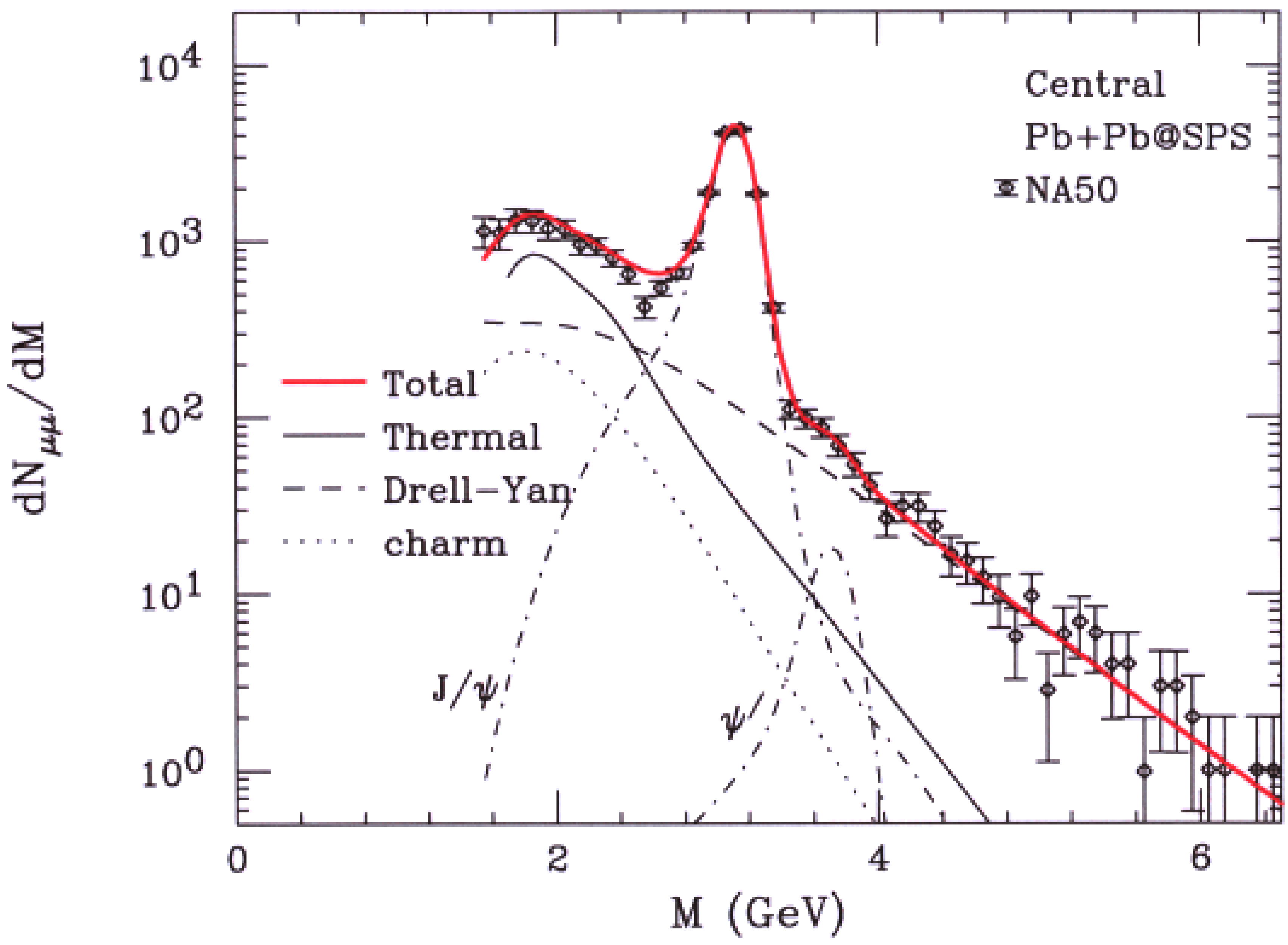
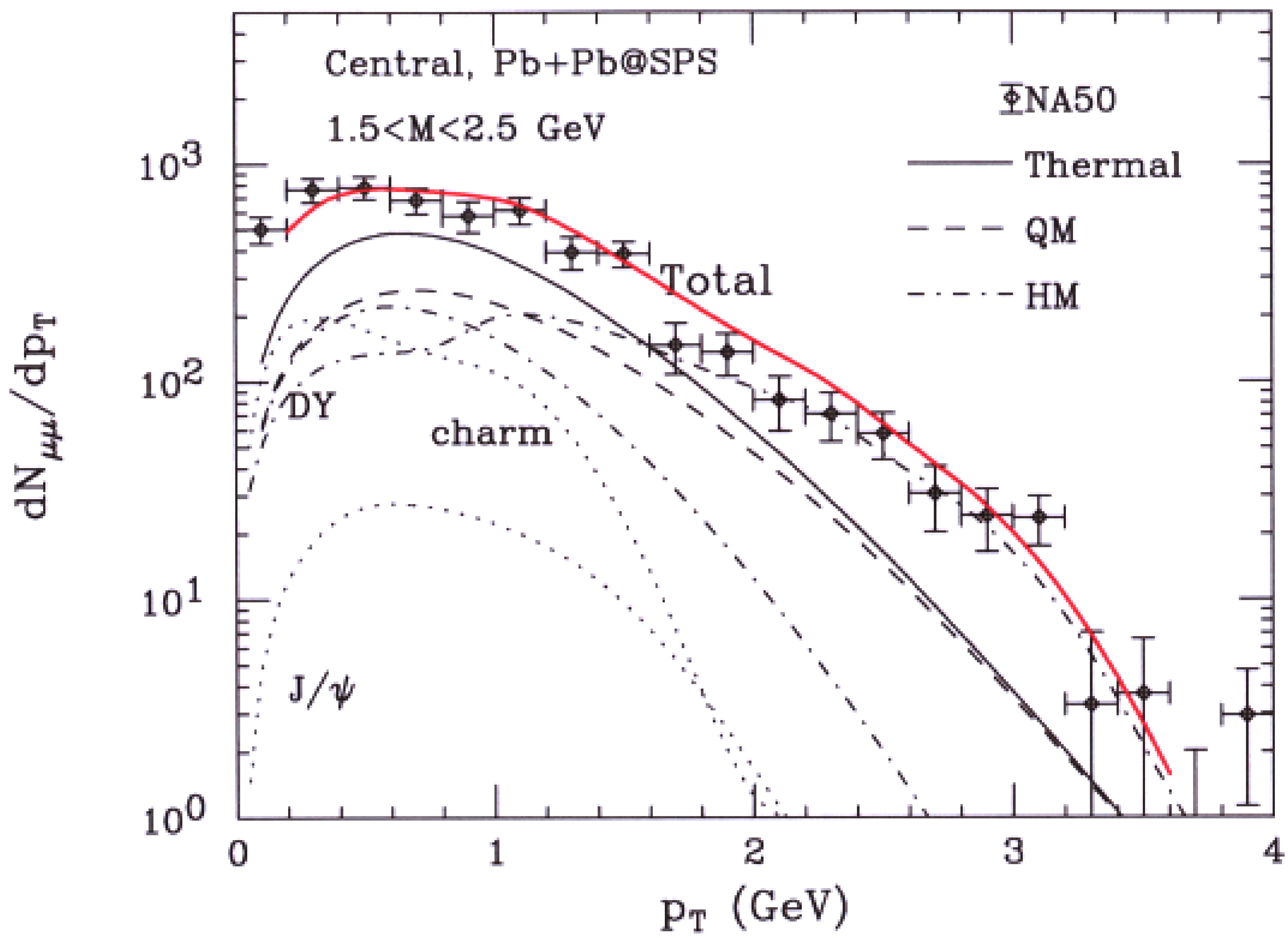
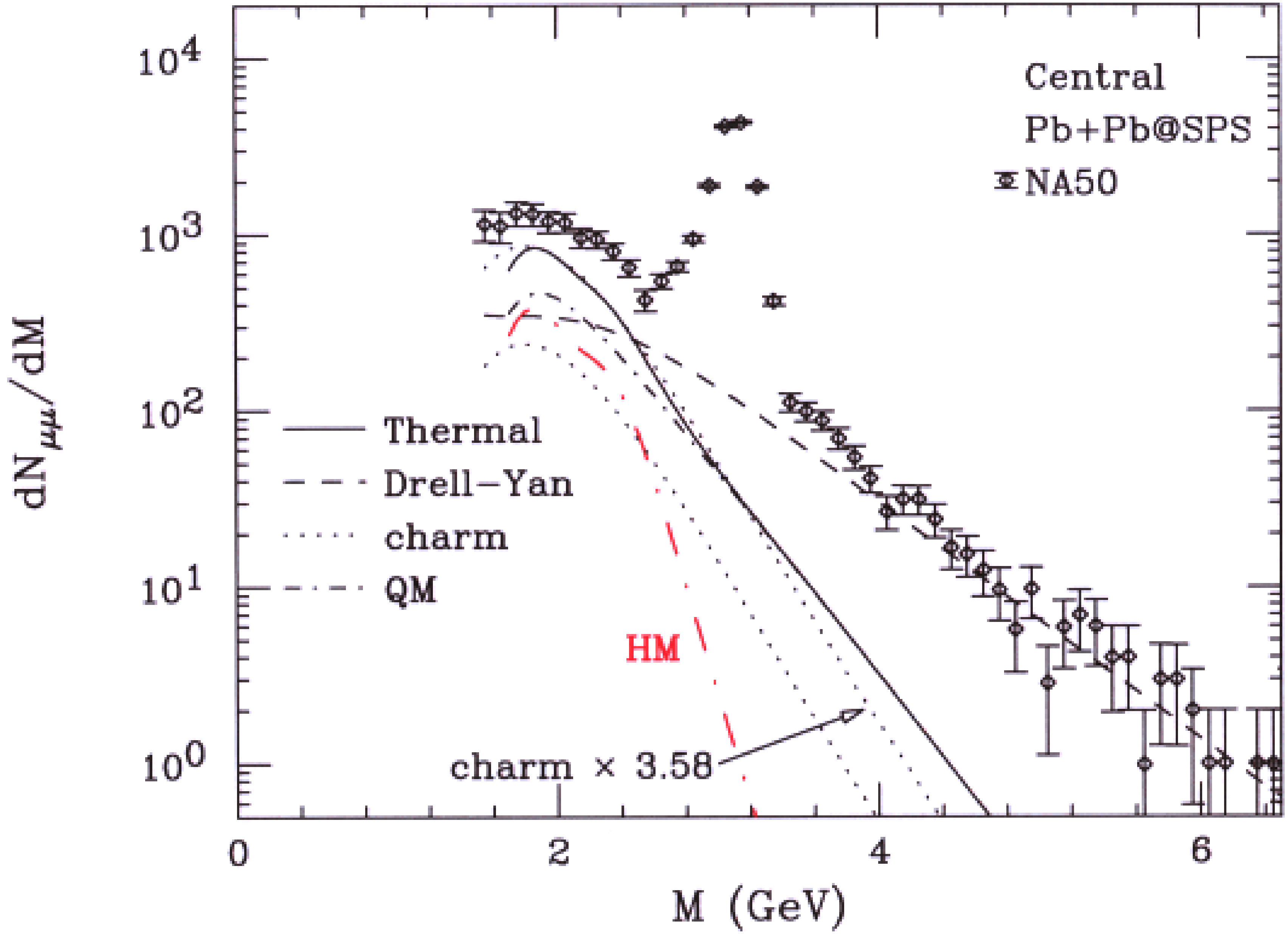
T=250 MeV
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
EdN/d^3kd^4x ($1/GeV^2fm^4$)
0
1
2
3
4
5
E (GeV)

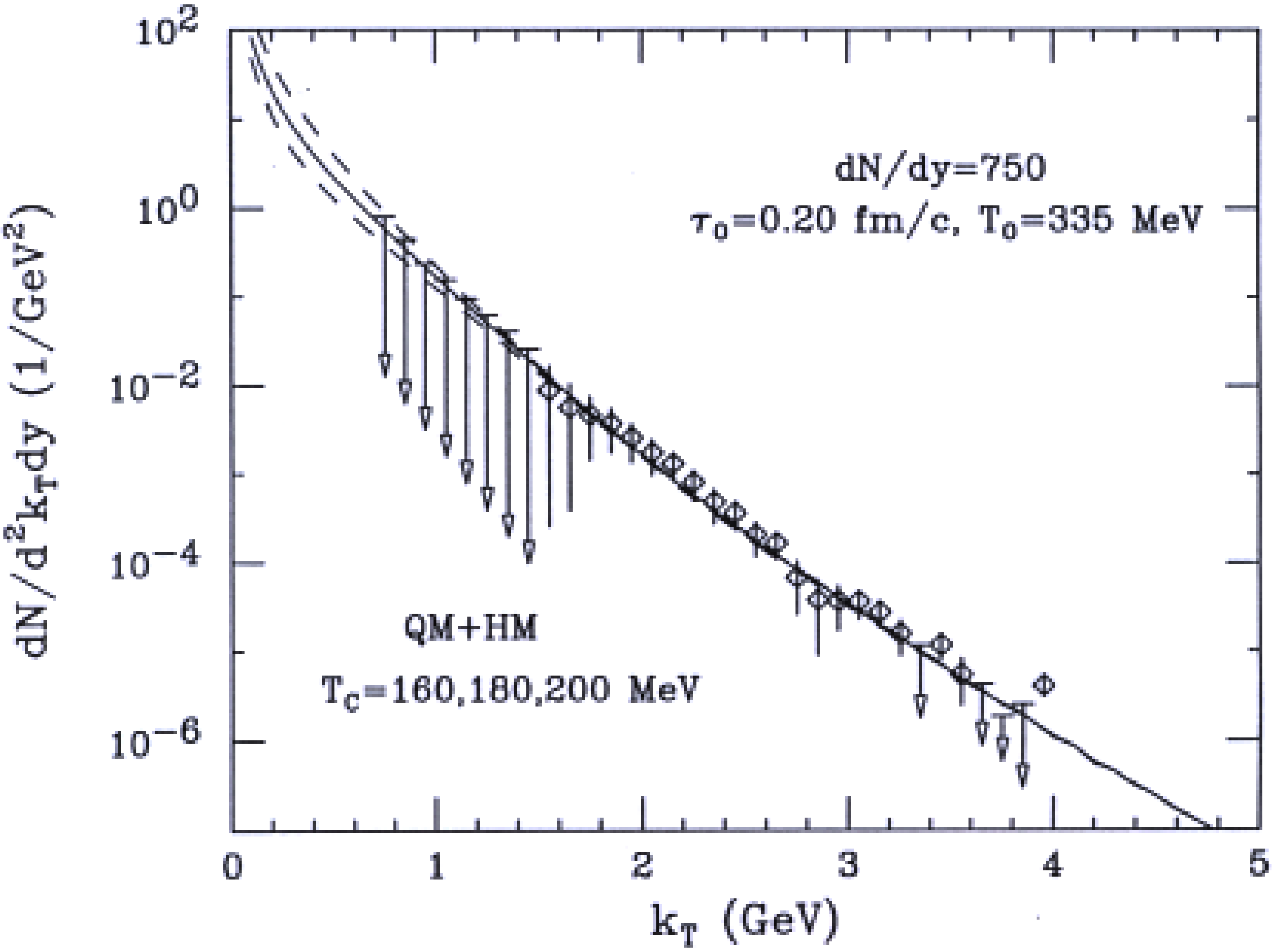

Central
Pb+Pb@SPS
NA50
Total
Thermal
Drell−Yan
charm
J/ψ
ψ'
$dN_{\mu\mu}/dM$
M (GeV)



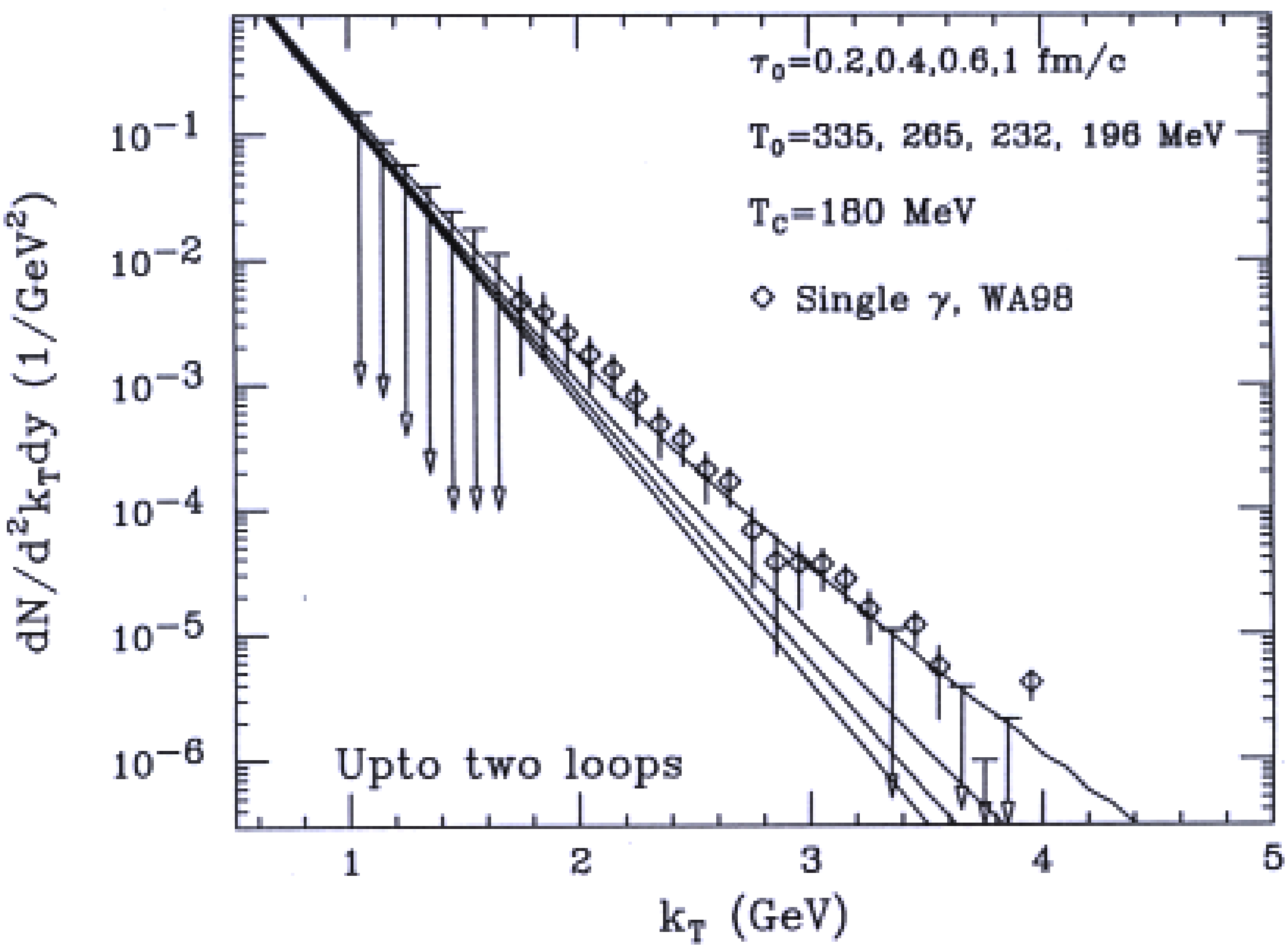
Central, Pb+Pb@SPS
1.5<M<2.5 GeV
NA50
Thermal
QM
HM
Total
DY
charm
J/ψ
10^3
10^2
10^1
10^0
0
1
2
3
4
$dN_{\mu\mu}/dp_T$
p_T (GeV)



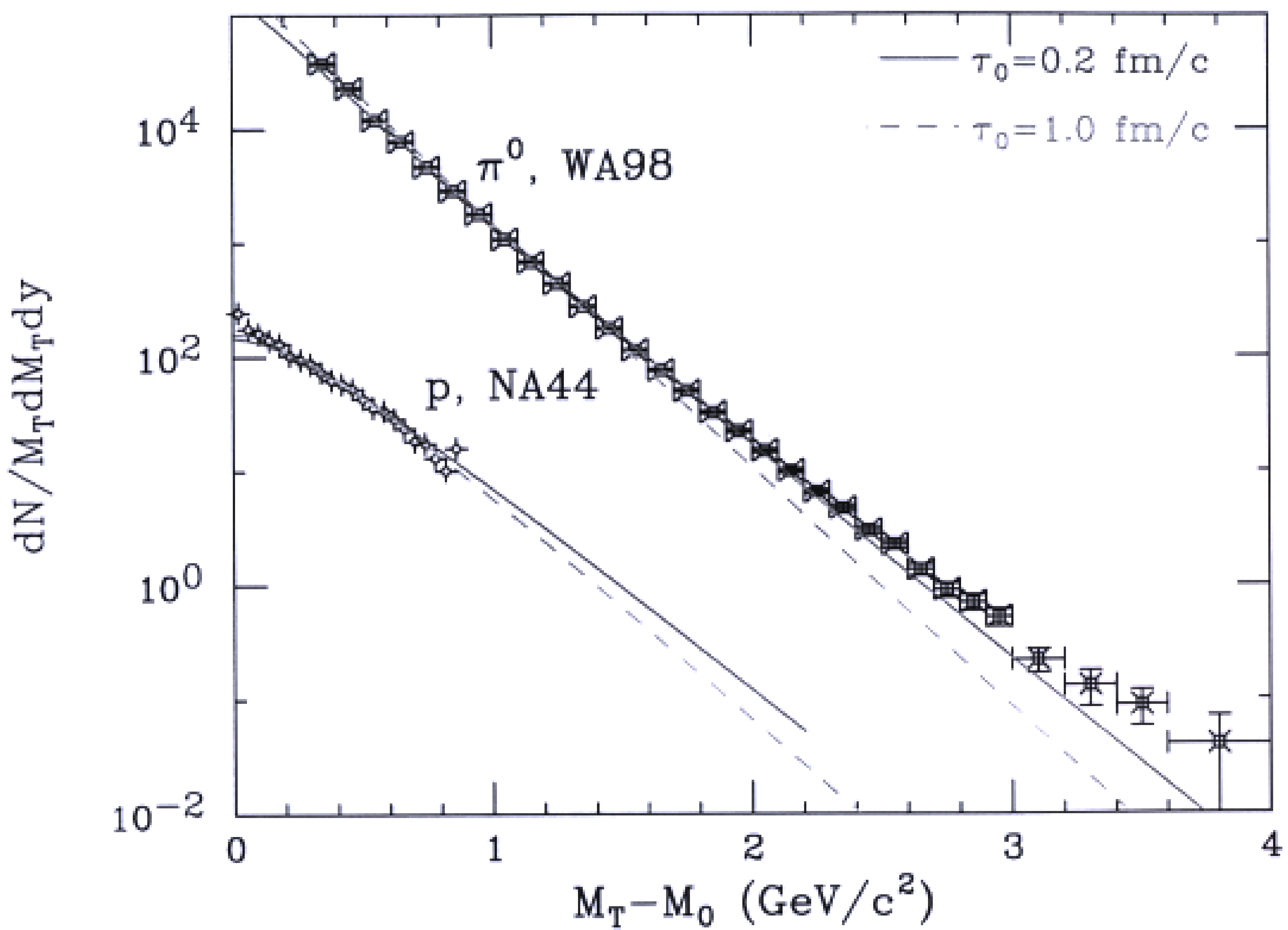
Central
Pb+Pb@SPS
NA50
Thermal
Drell−Yan
charm
QM
HM
charm × 3.58
$dN_{\mu\mu}/dM$
M (GeV)
10^4
10^3
10^2
10^1
10^0
0
2
4
6

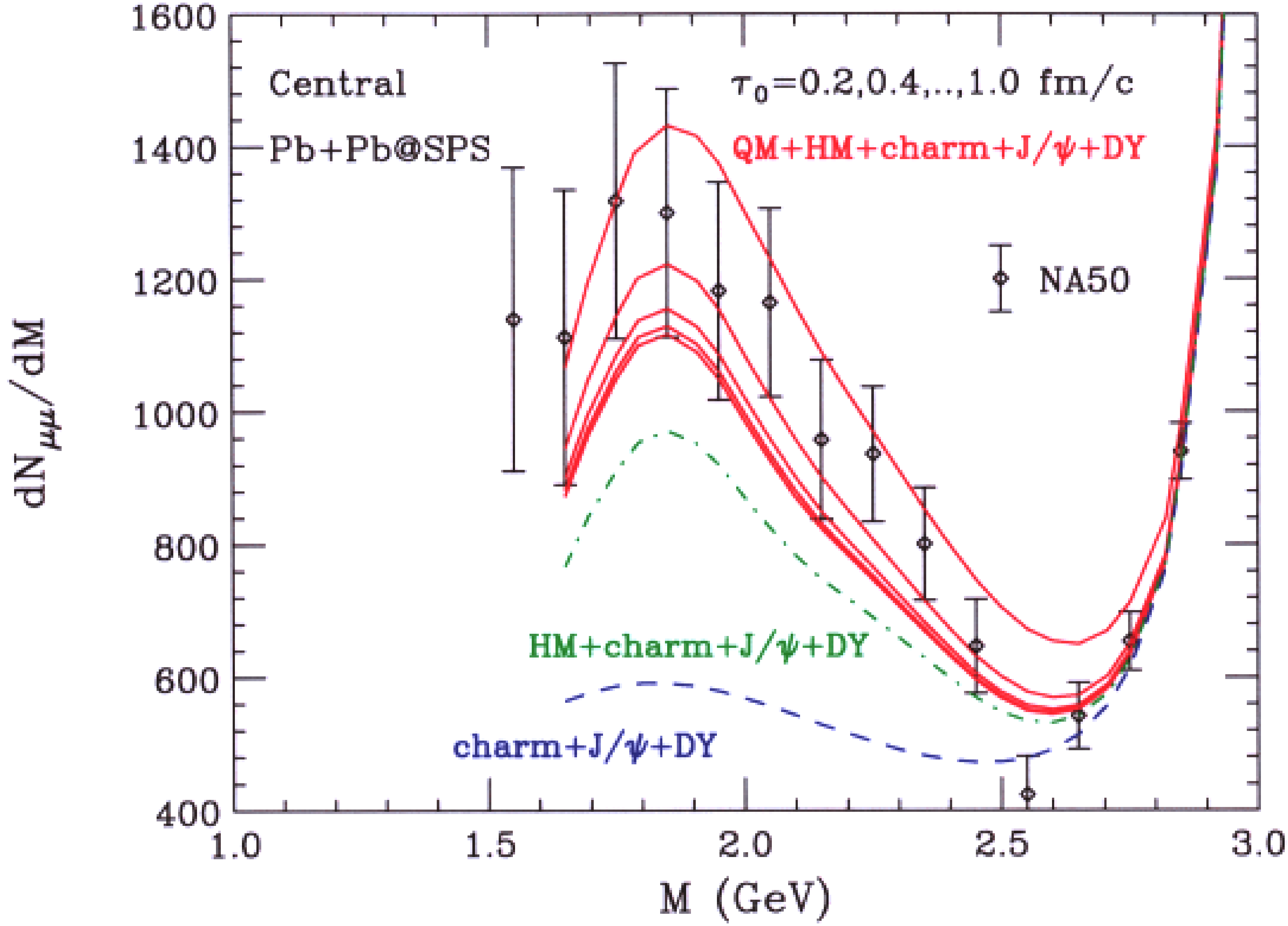


dN/dy=750
τ_0=0.20 fm/c, T_0=335 MeV
QM+HM
T_c=160,180,200 MeV
$dN/d^2k_T dy$ $(1/GeV^2)$
k_T (GeV)

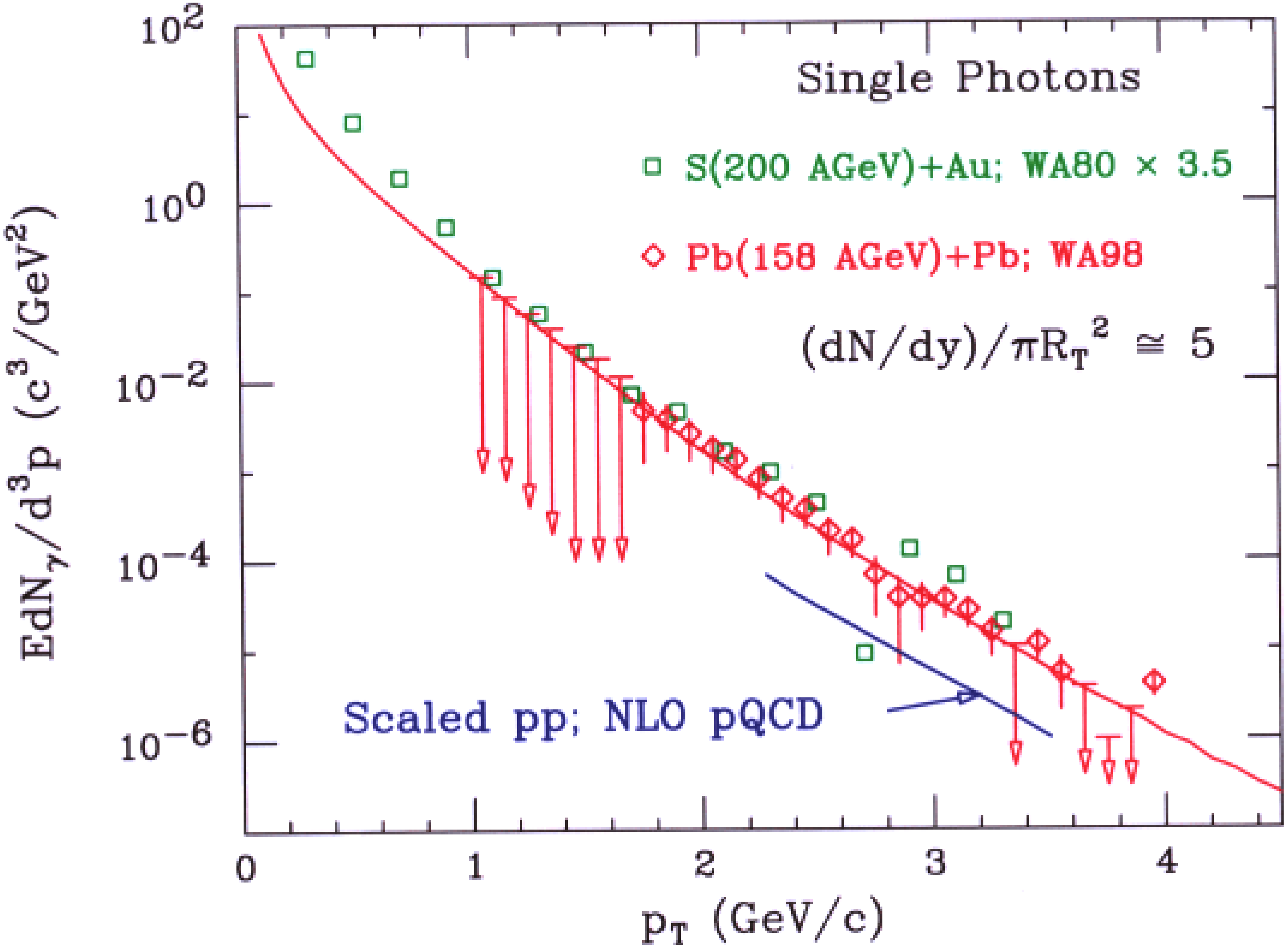


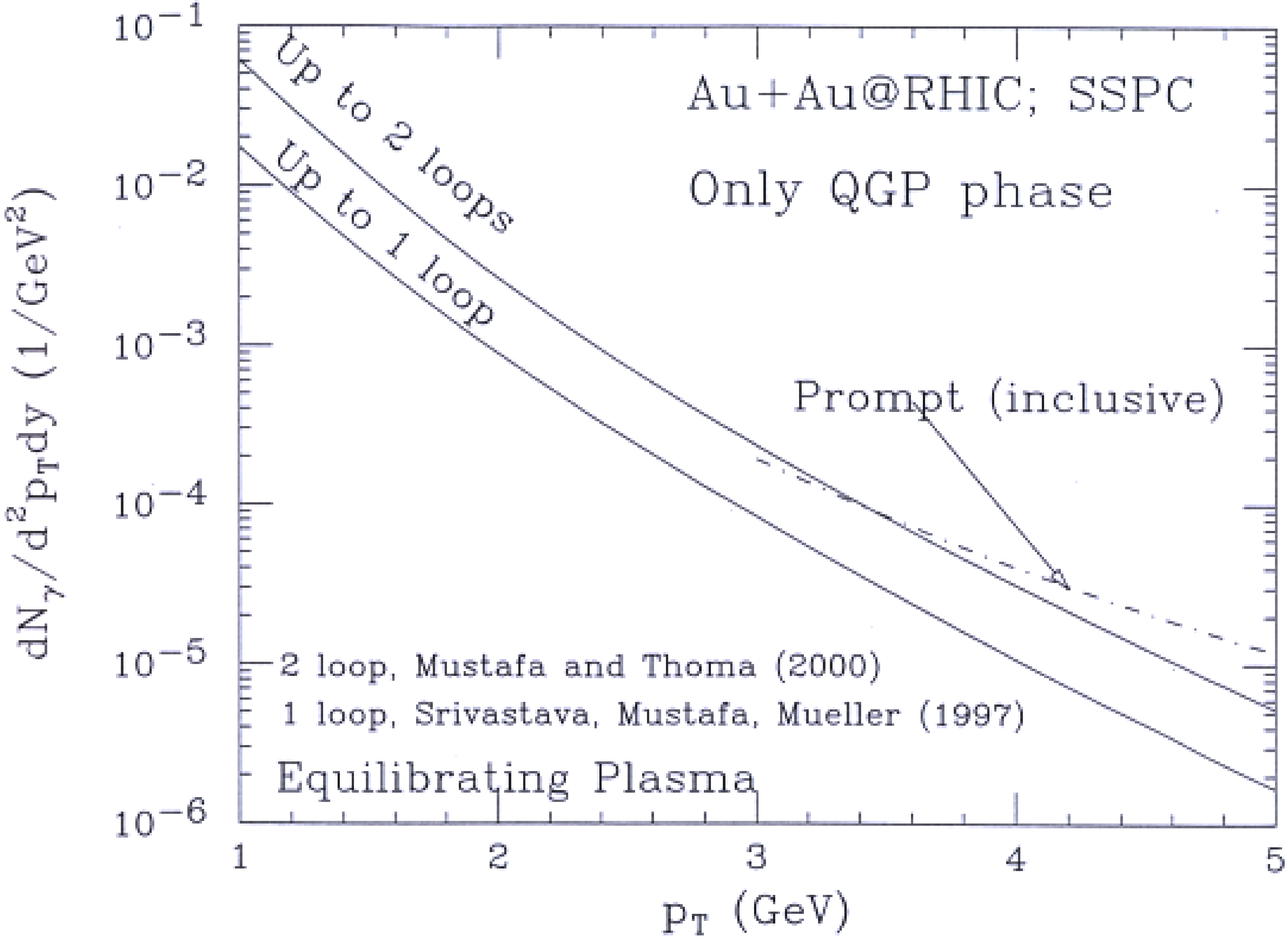
τ_0=0.2,0.4,0.6,1 fm/c
T_0=335, 265, 232, 196 MeV
T_c=180 MeV
◇ Single γ, WA98
Upto two loops
$dN/d^2k_T dy$ (1/GeV^2)
k_T (GeV)


τ0=0.2 fm/c
τ0=1.0 fm/c
π0, WA98
p, NA44
dN/MTdMTdy
MT−M0 (GeV/c2)
0
1
2
3
4
10−2
100
102
104



Central
Pb+Pb@SPS
τ0=0.2,0.4,..,1.0 fm/c
QM+HM+charm+J/ψ+DY
NA50
HM+charm+J/ψ+DY
charm+J/ψ+DY
dNμμ/dM
M (GeV)
1600
1400
1200
1000
800
600
400
1.0
1.5
2.0
2.5
3.0


Single Photons
S(200 AGeV)+Au; WA80 × 3.5
Pb(158 AGeV)+Pb; WA98
$(dN/dy)/\pi R_T^{\ 2} \cong 5$
Scaled pp; NLO pQCD
$EdN_\gamma/d^3p\ (c^3/GeV^2)$
p_T (GeV/c)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3
4



Au+Au@RHIC; SSPC
Only QGP phase
Up to 2 loops
Up to 1 loop
Prompt (inclusive)
2 loop, Mustafa and Thoma (2000)
1 loop, Srivastava, Mustafa, Mueller (1997)
Equilibrating Plasma
$dN_\gamma/d^2p_T dy$ $(1/GeV^2)$
p_T (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
2
3
4
5

Discussions

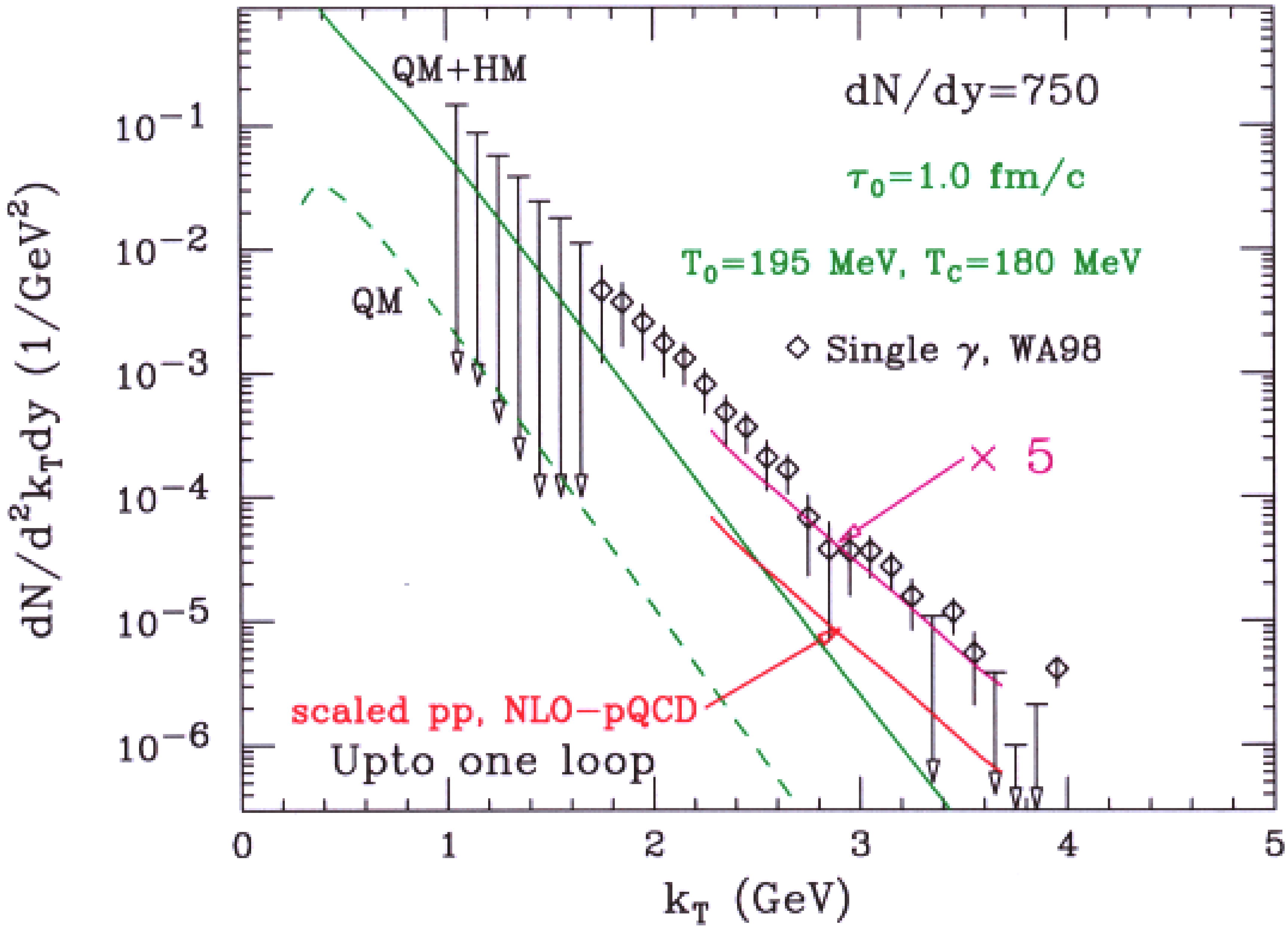
- Very small $\tau_0 \sim 0.2$ fm/c:
  - Parton saturation at SPS for $Pb + Pb$ collisions for $p_T^{\text{cut-off}}$of $\sim$ 1 GeV/c or $\tau_0 \sim 1/p_T \sim 0.2$ fm/c.
- Thermal and Chemical Equilibration of Hadrons:
  - All particle ratios measured are described by a thermal model with a (chemical) freeze-out temperature of $\sim$ 180 MeV and $\mu_b \sim 250$ MeV. Hadronic reactions *can-not* achieve this.
- Pre-equilibrium contribution:
  - Parton cascade model will be used to re-estimate this. Our earlier estimates are (perhaps) incorrect.

Summing up

- Significant direct photon excess has been observed in central $Pb+Pb$ collisions for $p_T \geq 1.5$ GeV/c, by the WA98 experiment
- Excess production of IMR dileptons has been reported by the NA50 experiment in these collisions.
- Hadron spectra from central collisions demonstrate thermal and chemical equilibrium and flow.
- All these data are satisfactorily explained with a SINGLE set of initial conditions which suggest that a quark gluon plasma is formed in the initial state which undergoes a phase transition to a hot hadronic matter at $\approx$ 180 Mev.
- As far as single photons are concerned; one loop rates fail to describe the data. In view of the fact that 3-loop rates are quite intractable at the moment, the fact that two-loop rates provide a good description is of great interest.

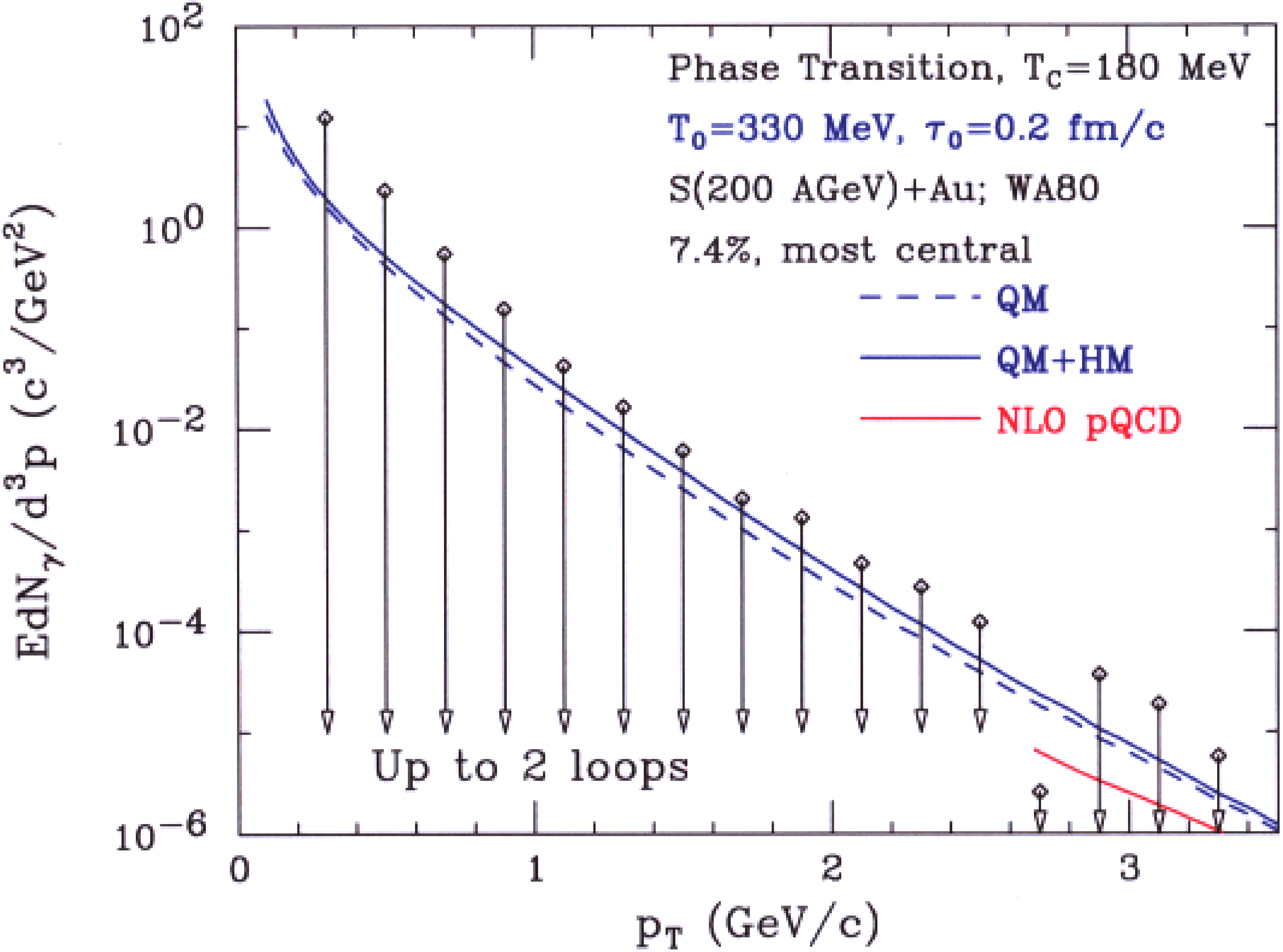
Caveats

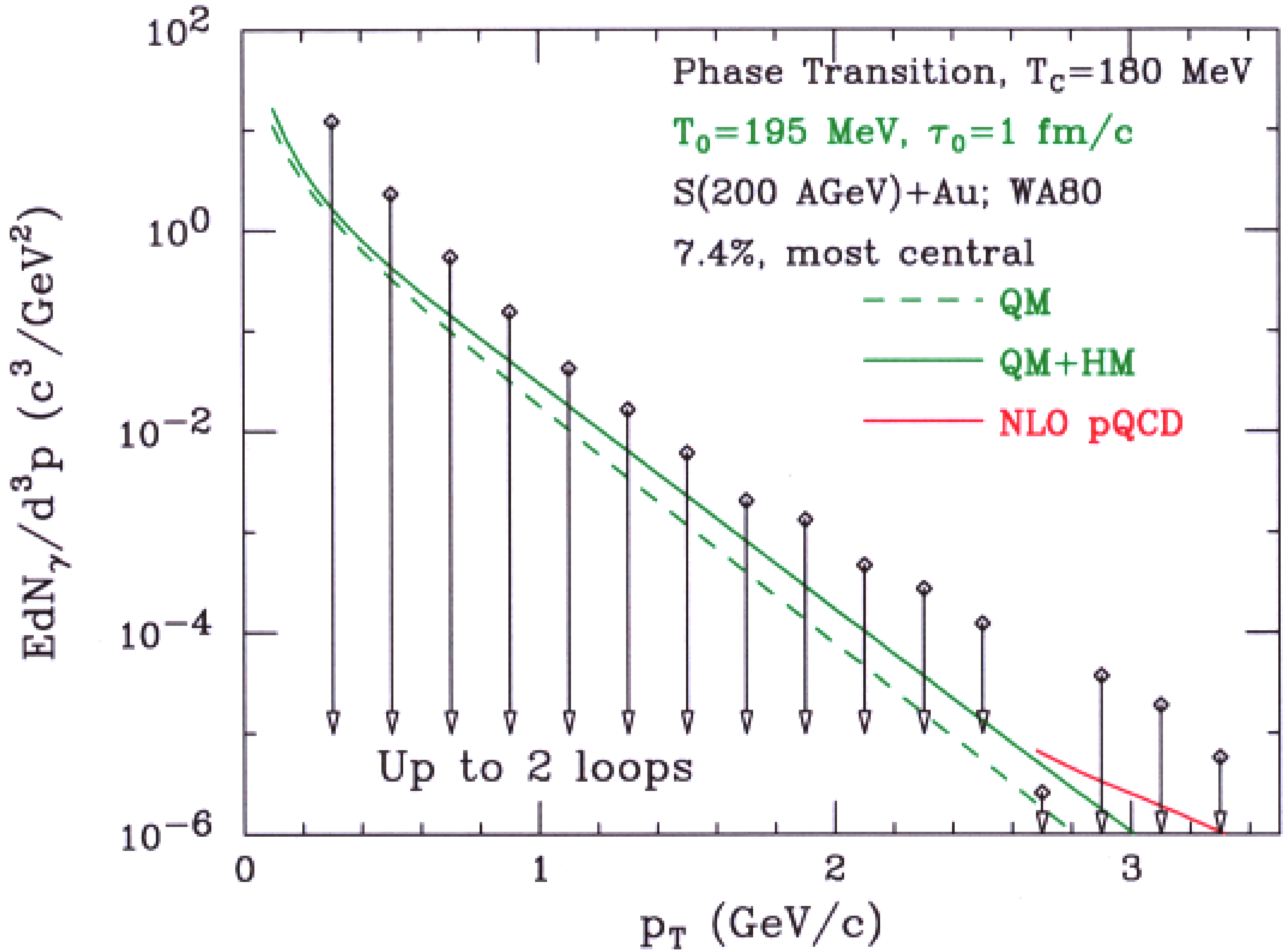
- What about baryons?
  - They should be there, at least at SPS. And contribute to single photons. But,
  - $\frac{dN_{B-\overline{B}}/dy}{dN/dy} \approx 0.10$
- What about intrinsic k_T?
  - The present estimates depend on
    - quark mass- to avoid singularity
    - (should have a) p_T cut-off to retain applicability of pQCD
    - it is not certain that the introduction of intrinsic k_T via $f(x, Q^2) \rightarrow f(x, Q^2) g(k_T)$ is consistent with the requirement that $[\Sigma_i E_i]^2 - [\Sigma_i p_{x_i}]^2 - [\Sigma_i p_{y_i}]^2 - [\Sigma_i p_{z_i}]^2 = M^2_{\text{nucleon}}$
- It is likely that when these effects are (properly) included and a more accurate rate of photons is used we may need a lower initial temperature to explain the data.


dN/dy=750
τ0=1.0 fm/c
T0=195 MeV, Tc=180 MeV
◇ Single γ, WA98
QM+HM
QM
× 5
scaled pp, NLO−pQCD
Upto one loop
dN/d2kTdy (1/GeV2)
kT (GeV)
10−1
10−2
10−3
10−4
10−5
10−6
0
1
2
3
4
5

CONSIDERING ALL THE THINGS

- Minimalist Approach
- You can either enhance the NLO pQCD by a factor of 5
- or
- Take 2 loop rates


Phase Transition, T_C=180 MeV
T_0=330 MeV, τ_0=0.2 fm/c
S(200 AGeV)+Au; WA80
7.4%, most central
QM
QM+HM
NLO pQCD
Up to 2 loops
EdN_γ/d^3p (c^3/GeV^2)
p_T (GeV/c)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3



Phase Transition, T_C=180 MeV
T_0=195 MeV, τ_0=1 fm/c
S(200 AGeV)+Au; WA80
7.4%, most central
QM
QM+HM
NLO pQCD
Up to 2 loops
p_T (GeV/c)
EdN_γ/d^3p (c^3/GeV^2)