Theoretical Statussec:ts

The theoretical prediction and calculation of the photon emission, i.e. yields and spectra, from a thermal system has a long tradition, culminating in the discovery of quantum physics Planck00. In astrophysics the detection of electromagnetic radiation from the hot surfaces of stars and other objects, even from the entire universe (Cosmic Microwave Background), provides the most essential information, such as temperature, size, chemical composition etc. In particular deviations from the pure black-body spectrum are of utmost interest, e.g. to learn about the composition, evolution, and structure formation in the universe from the Cosmic Microwave Background Wight92.

The photon emission from the nuclear fireball, created in a relativistic heavy-ion collision, differs from the one of macroscopic stellar objects in the following respect. Whereas the photons in the latter case are thermalized when they leave the surface, the mean-free path of the photons produced in nucleus-nucleus collisions is large compared to the size of the fireball. Hence, the photons do not interact after their production and leave the fireball undisturbed. As a consequence they carry information about the stage of the fireball at the time of their creation. The photon spectrum, containing photons from all stages, allows therefore to study the entire evolution of the fireball. Direct photons, together with dileptons and to some extent hard probes like jet quenching, are therefore a unique diagnostic tool for the different phases and the equation of state (EOS) of the ultradense matter produced in high-energy nuclear collisions. Photon production in high-energy nuclear and particle physics provides information on the momentum distributions of the emitting particles. In particle physics this may be used to extract information on structure functions. In thermalized systems, expected in nuclear collisions, it should yield information on the thermal distributions.

To draw conclusions about the state of the matter in the fireball, created in relativistic heavy-ion collisions, it is necessary to compare the experimental data for direct photons with theoretical calculations. The ideal theoretical description would be a comprehensive treatment of the entire space-time evolution of the fireball from the first contact of the cold nuclei to the freeze-out and subsequent decay of hadrons, e.g. in a dynamical lattice QCD approach. At the same time all participating particle species and their interactions should be included. Due to the complexity of the problem, e.g. the consistent treatment of hadronization and the non-perturbative nature of the strong interaction, such a systematic investigation is presently only wishful thinking. Alternatively, the different stages of the fireball (initial stage, pre-equilibrium QGP, thermal QGP, mixed phase and hadronization, hot hadron gas, freeze-out and hadronic decays) are treated separately. Furthermore, one computes first the production rates of the photons from the different stages, e.g. at a given temperature. Then these rates are convoluted with the space-time evolution of the fireball using mostly hydrodynamical models. In this way, estimates of the photon spectra are obtained, which can be compared to experimental results.

In the present chapter we will discuss in detail the status and problems of calculating production rates of direct photons from a thermal QGP and hadron gas as well as from hard scatterings in the initial non-equilibrium stage. In addition, the various hydrodynamical approaches and their applications to photon spectra will be critically reviewed.

Photon Production Ratessubsec:ppr

In this Section the calculation of the production rates of direct photons with experimentally relevant energies $E \gg T$ from a thermal QGP, a hot hadron gas (HHG) and of prompt photons from the initial phase will be considered. Since direct photons have been proposed as a promising signature of the QGP formation in relativistic heavy-ion collisions Shuryak78,Kajantie81,Halzen82,Kajantie83,Sinha83,Hwa85,Staadt86,Neubert89, emphasis is put on the photon production from the QGP and the calculation of this rate will be discussed first in detail.

Particle production rates can be computed from the amplitudes of the basic processes for the particle production, convoluted with the distribution functions of the participating particles Weldon83. For example, the production rate of a particle A with energy E follows from $\Gamma_{\mathrm{prod}}(E) = 12E \int d^3p_1 (2\pi)^3 2E_1 ... d^3p_m (2\pi)^3 2E_m d^3p'_1 (2\pi)^3 2E'_1 ... d^3$

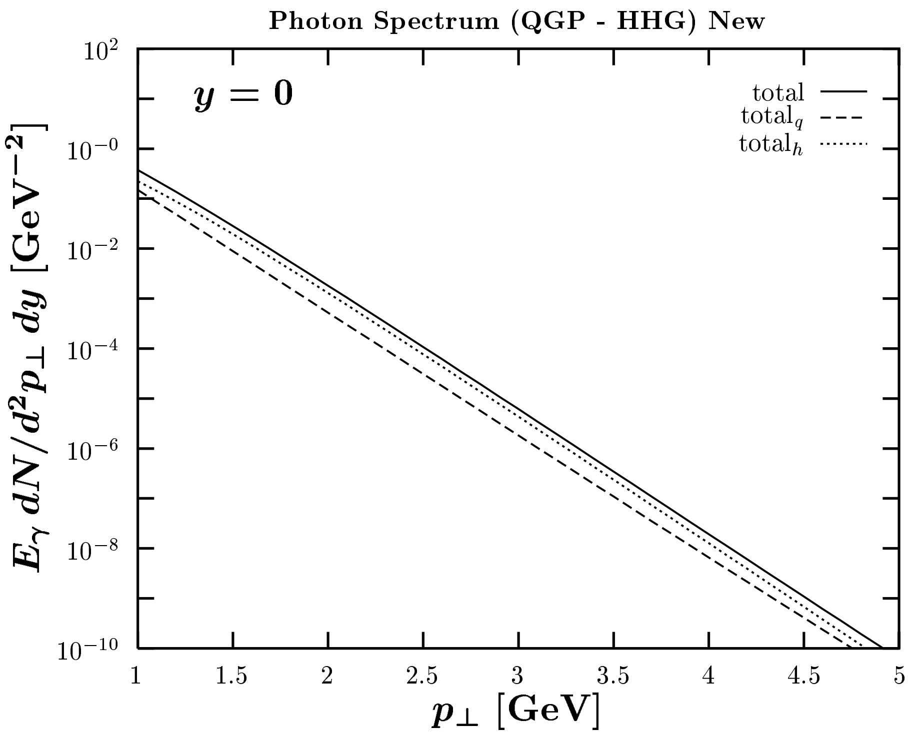
Thermal Rates from the QGPsubsubsec:trq

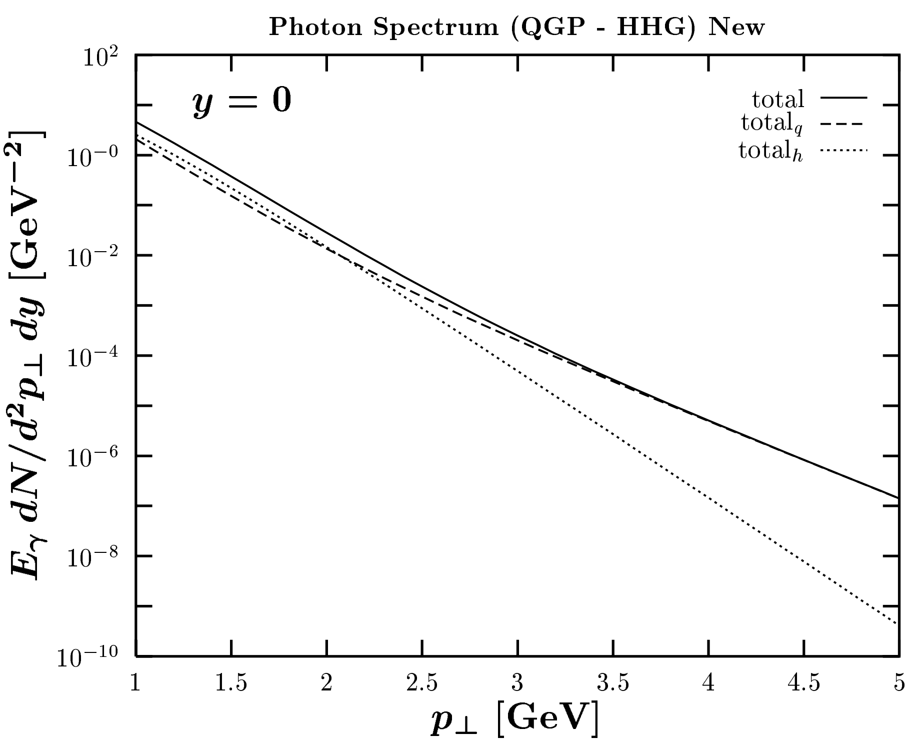
A QGP emits photons as every thermal source does. The microscopic process is the photon radiation from quarks having an electric charge. Due to energy-momentum conservation, these quarks have to interact with the thermal particles of the QGP in order to emit a photon. Hence, an ideal, non-interacting QGP cannot be seen. However, there will always be (strong and electromagnetic) interactions in the QGP, such as quark-antiquark annihilation. However, due to energy-momentum conservation the direct annihilation of quarks and anti-quarks into real photons is also not possible but only into virtual photons which can decay into lepton pairs. The production of dileptons is another promising signature for the QGP Gale01, which, however, is not the topic of the present review. To lowest order perturbation theory, real photons are produced from the annihilation of a quark-antiquark pair into a photon and a gluon ($q\bar{q} \rightarrow g\gamma$) and by absorption of a gluon by a quark emitting a photon ($qg \rightarrow q\gamma$), similar to Compton scattering in QED (see Fig. fig2.1). A higher order process for the photon production is, for example, bremsstrahlung, where a quark radiates a photon by scattering off a gluon or another quark in the QGP.

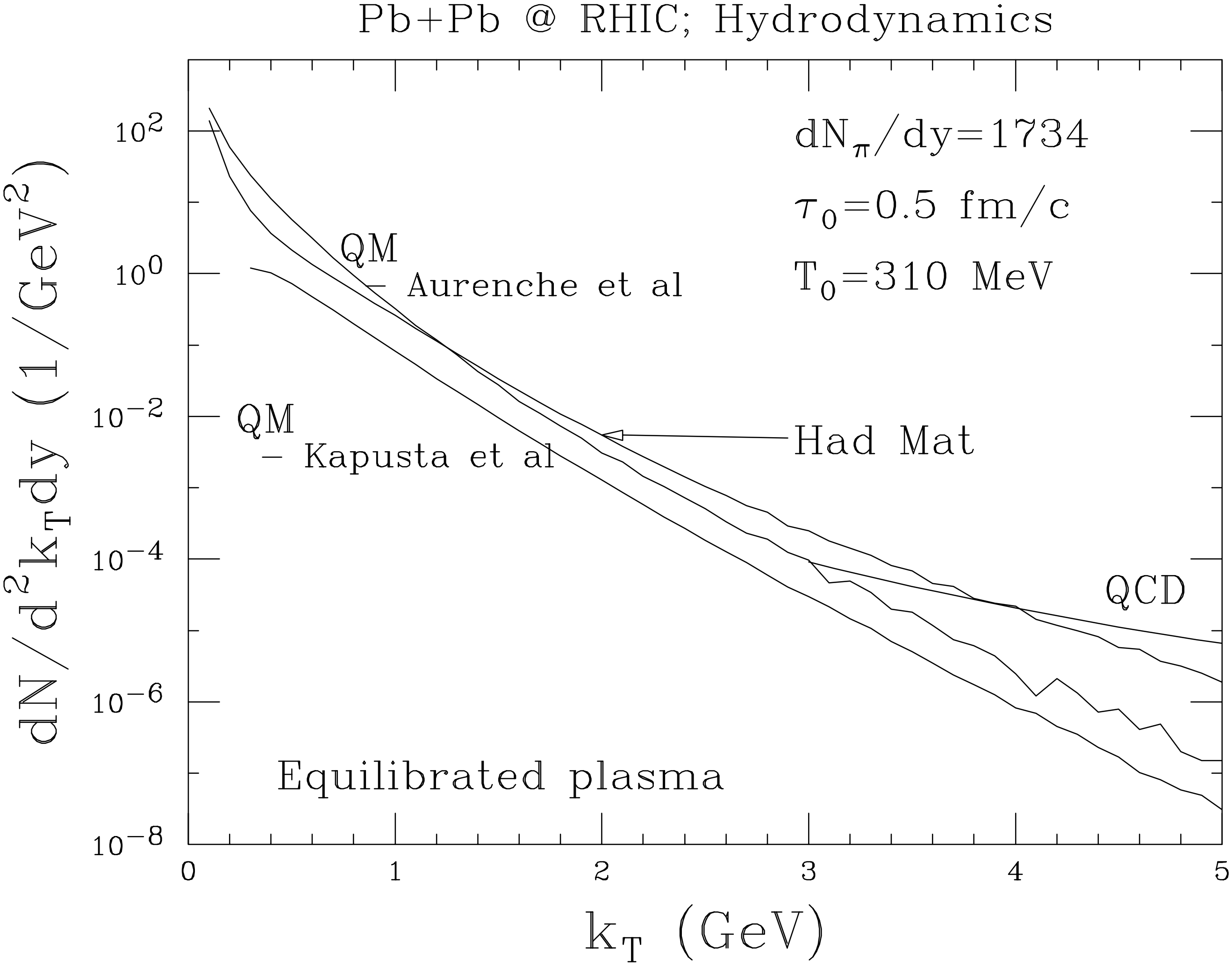
*0.7cm

figure[hbt] 12cm!fig21.eps

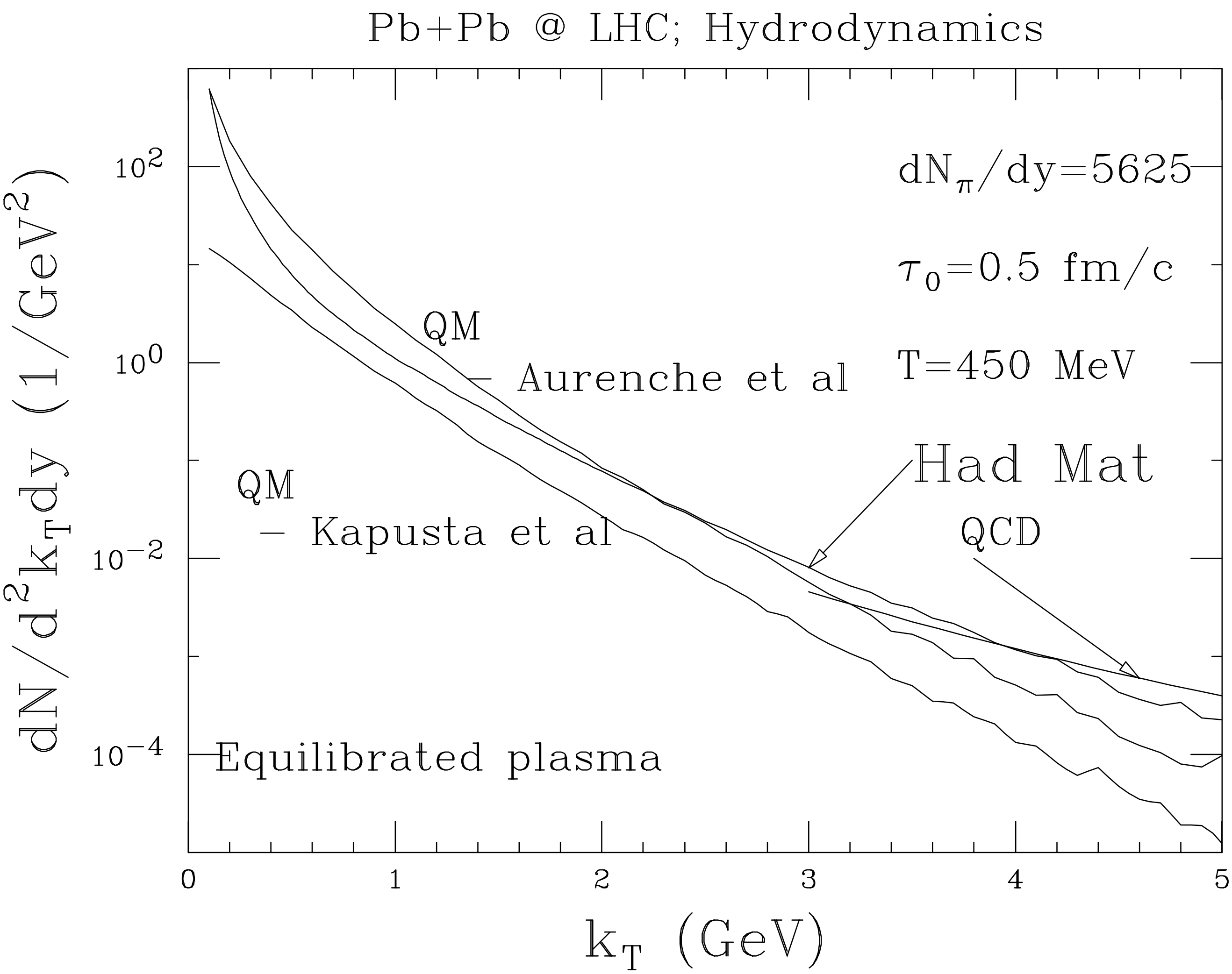
Lowest order contributions to photon production from the QGP: Compton scattering (left) and quark-antiquark annihilation (right). fig2.1


Photon Spectrum (QGP - HHG) New
$y = 0$
total
total$_q$
total$_h$
10^2
10^{-0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
1.5
2
2.5
3
3.5
4
4.5
5
$E_\gamma\, dN/d^2p_\perp\, dy$ [GeV^{-2}]
$p_\perp$ [GeV]

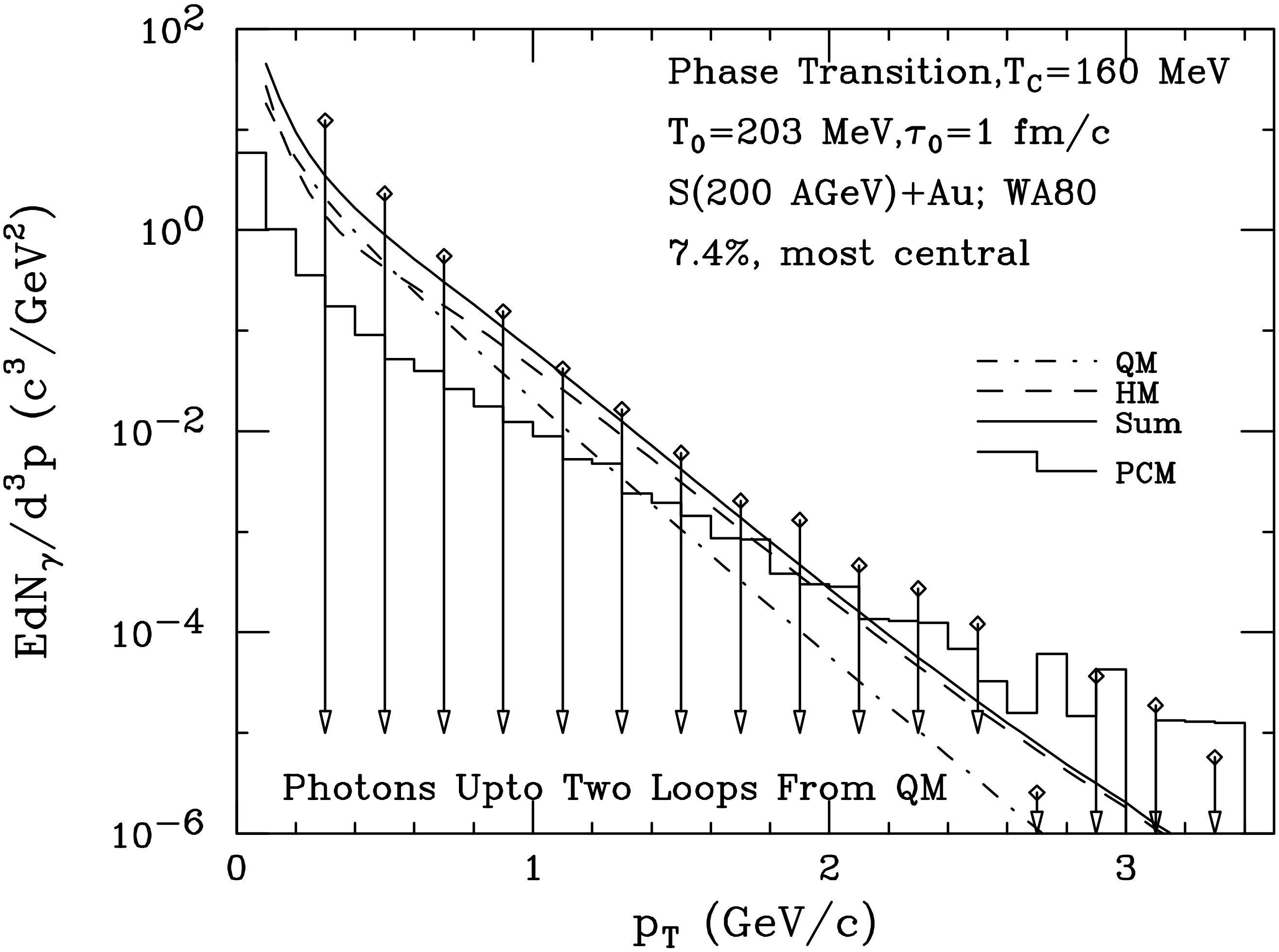

Photon Spectrum (QGP - HHG) New
$y = 0$
total
total$_q$
total$_h$
10^2
10^{-0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
1.5
2
2.5
3
3.5
4
4.5
5
$E_\gamma\, dN/d^2p_\perp\, dy$ [GeV^{-2}]
$p_\perp$ [GeV]



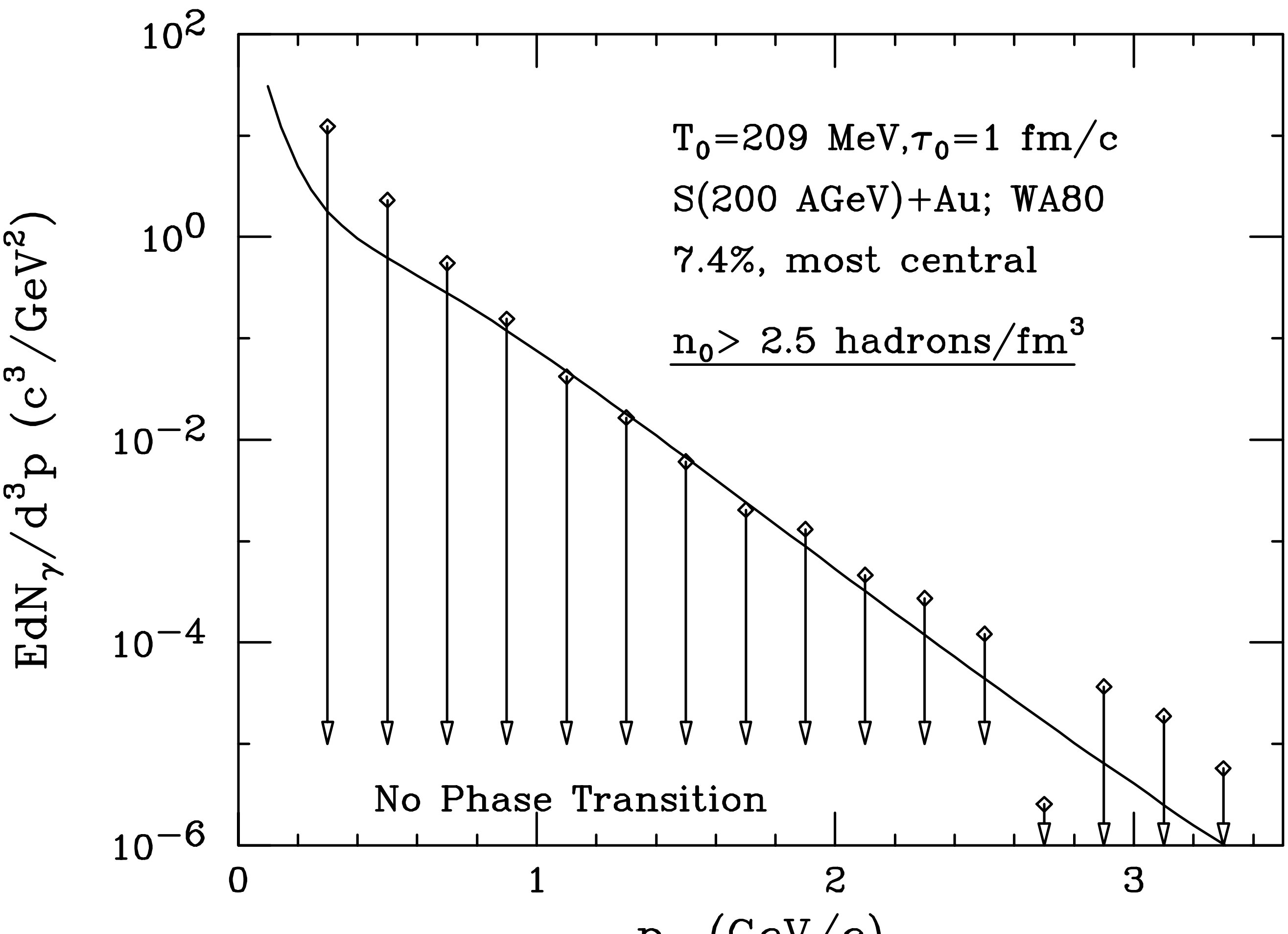
Pb+Pb @ RHIC; Hydrodynamics
dN/d²k_T dy (1/GeV²)
k_T (GeV)
dN_π/dy=1734
τ_0=0.5 fm/c
T_0=310 MeV
QM
– Aurenche et al
QM
– Kapusta et al
Had Mat
QCD
Equilibrated plasma
10^2
10^0
10^-2
10^-4
10^-6
10^-8
0
1
2
3
4
5



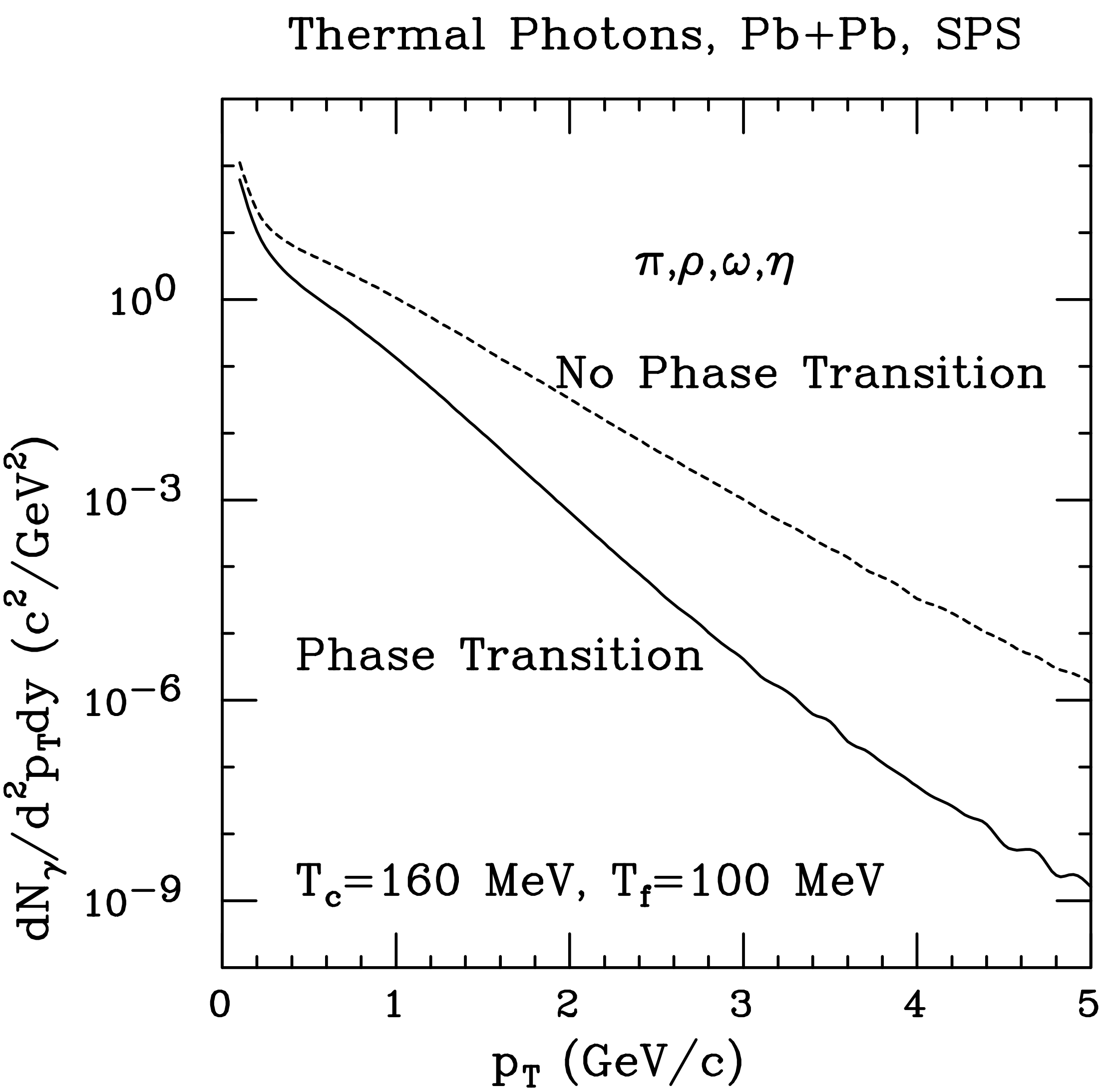
Pb+Pb @ LHC; Hydrodynamics
dN_π/dy=5625
τ_0=0.5 fm/c
T=450 MeV
QM
– Aurenche et al
QM
– Kapusta et al
Had Mat
QCD
Equilibrated plasma
10^2
10^0
10^{-2}
10^{-4}
0
1
2
3
4
5
$dN/d^2k_T dy$ (1/GeV^2)
k_T (GeV)



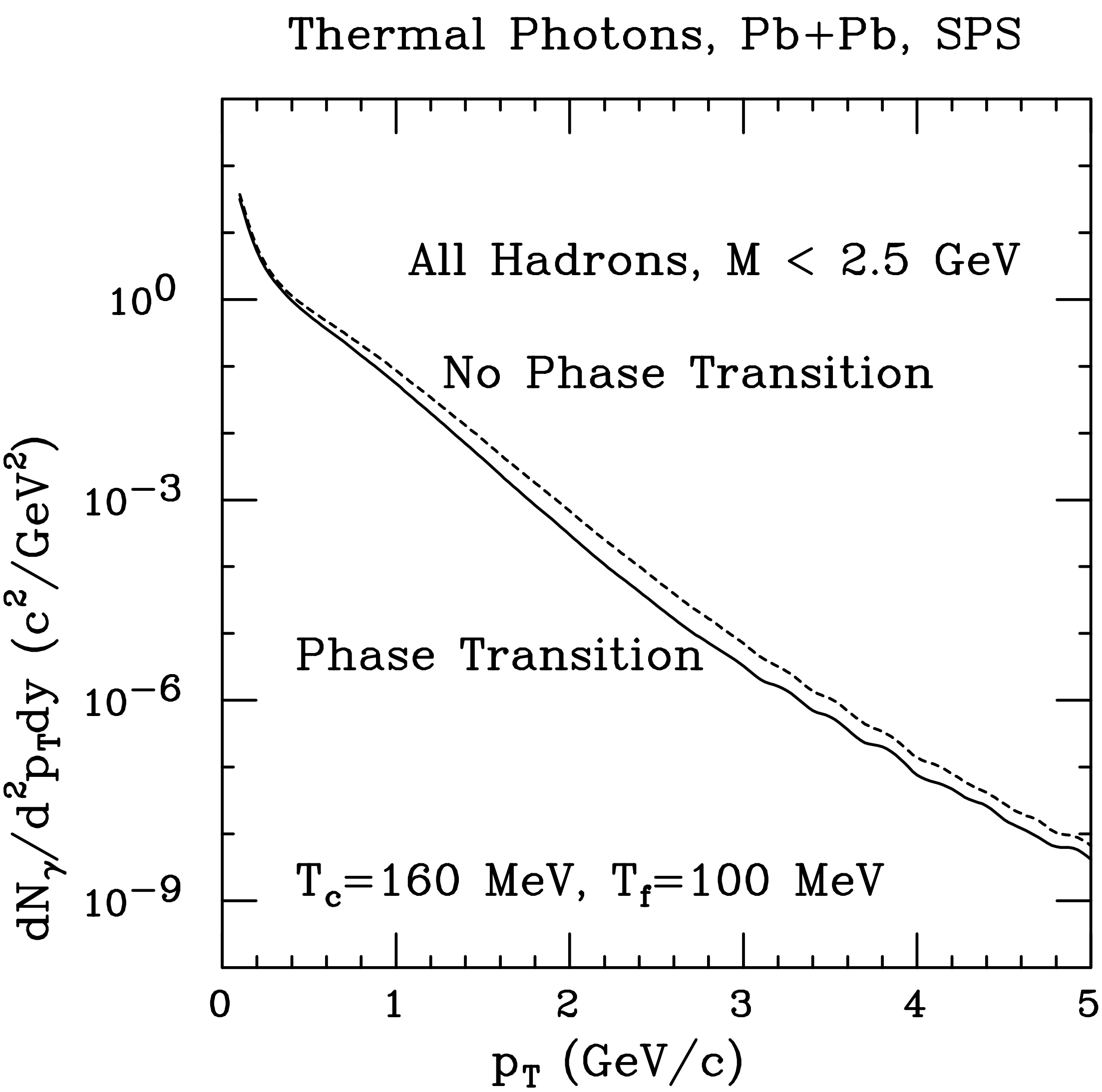
Phase Transition, T_C=160 MeV
T_0=203 MeV, τ_0=1 fm/c
S(200 AGeV)+Au; WA80
7.4%, most central
QM
HM
Sum
PCM
Photons Upto Two Loops From QM
EdN_γ/d^3p (c^3/GeV^2)
p_T (GeV/c)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3



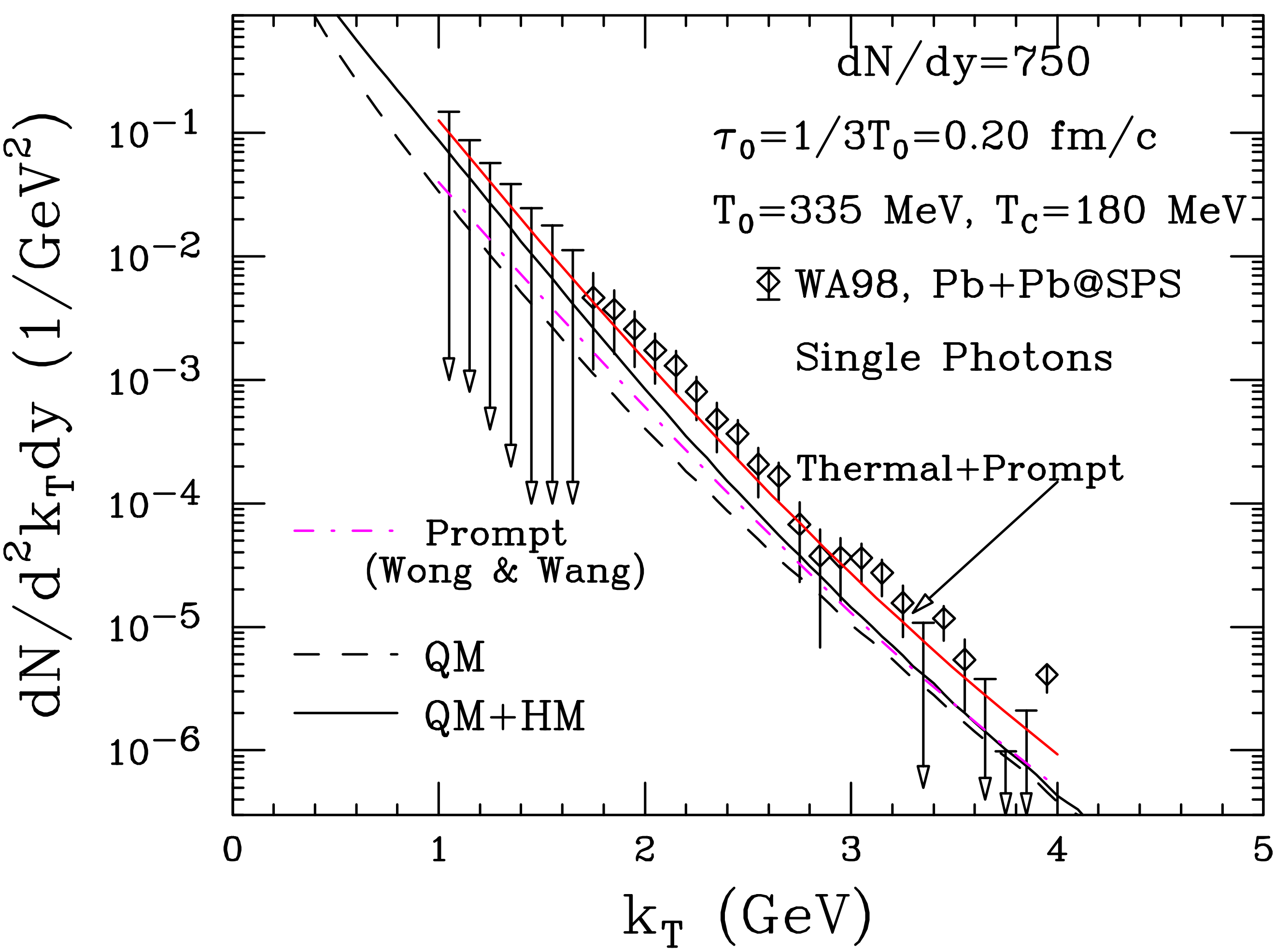
T_0=209 MeV,τ_0=1 fm/c
S(200 AGeV)+Au; WA80
7.4%, most central
n_0> 2.5 hadrons/fm^3
No Phase Transition
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0
1
2
3
EdN_γ/d^3p (c^3/GeV^2)
p_T (GeV/c)



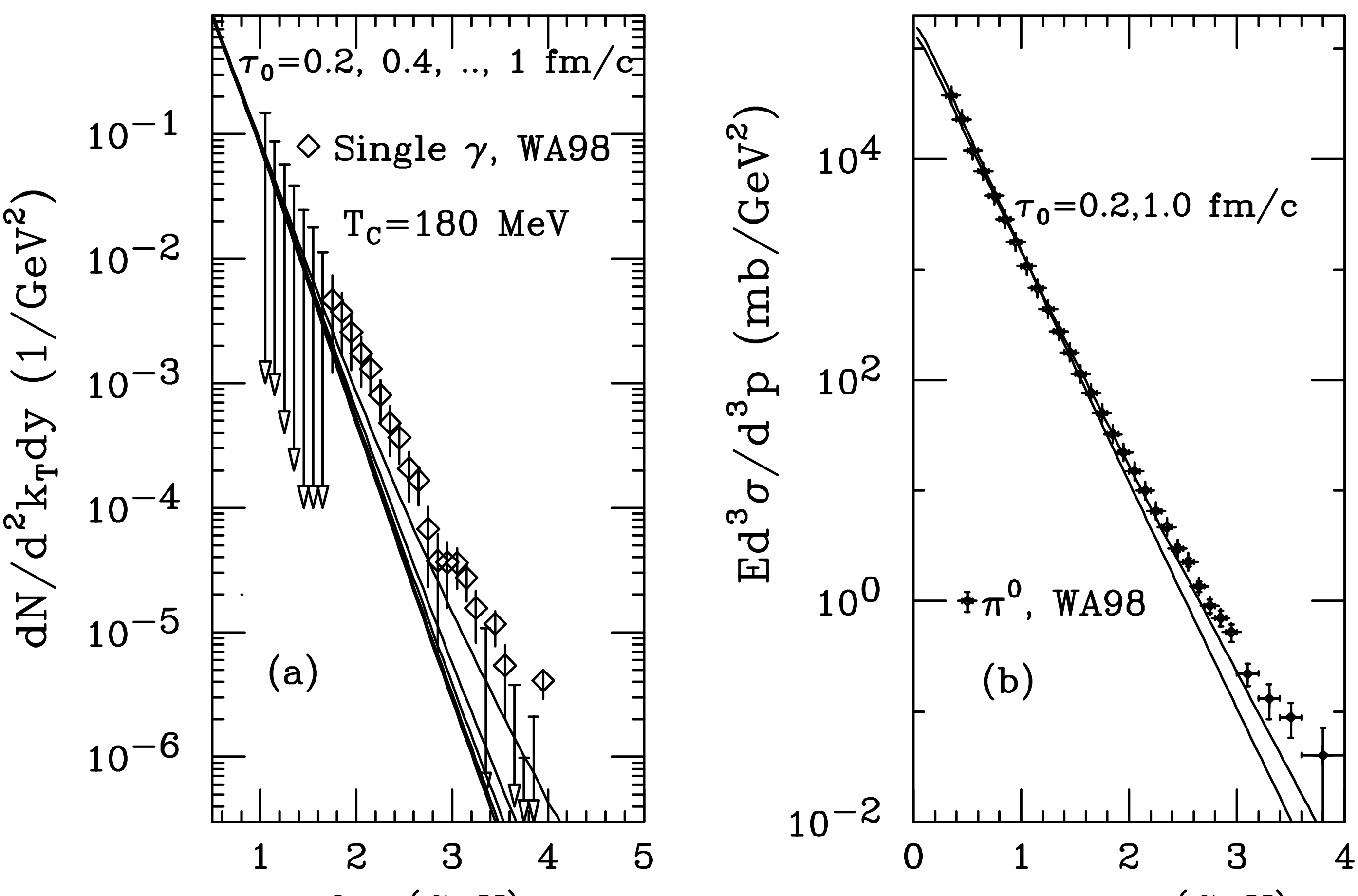
Thermal Photons, Pb+Pb, SPS
π,ρ,ω,η
No Phase Transition
Phase Transition
T_c=160 MeV, T_f=100 MeV
10^0
10^−3
10^−6
10^−9
dN_γ/d²p_Tdy (c²/GeV²)
0
1
2
3
4
5
p_T (GeV/c)



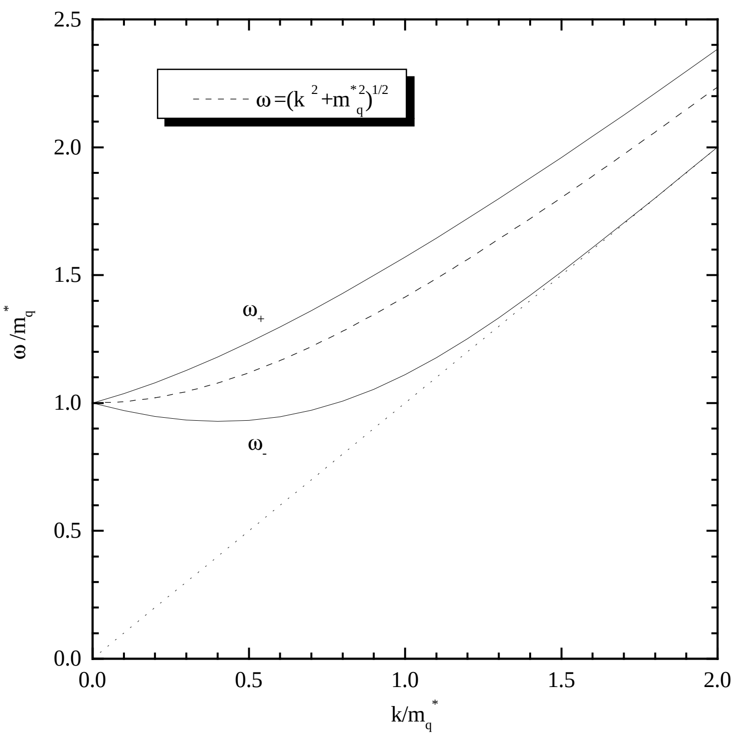
Thermal Photons, Pb+Pb, SPS
All Hadrons, M < 2.5 GeV
No Phase Transition
Phase Transition
T_c=160 MeV, T_f=100 MeV
dN_γ/d^2p_Tdy (c^2/GeV^2)
10^0
10^{-3}
10^{-6}
10^{-9}
0
1
2
3
4
5
p_T (GeV/c)



dN/dy=750
τ_0=1/3T$_0$=0.20 fm/c
T$_0$=335 MeV, T$_C$=180 MeV
WA98, Pb+Pb@SPS
Single Photons
Thermal+Prompt
Prompt
(Wong & Wang)
QM
QM+HM
$dN/d^2k_T dy$ $(1/GeV^2)$
k_T (GeV)



τ_0=0.2, 0.4, .., 1 fm/c
Single γ, WA98
T_C=180 MeV
(a)
dN/d^2k_Tdy (1/GeV^2)
k_T (GeV)
τ_0=0.2,1.0 fm/c
π^0, WA98
(b)
$Ed^3\sigma/d^3p$ (mb/GeV^2)
$m_T-m_{\pi^0}$ (GeV)



$\omega=(k^2+m_q^{*2})^{1/2}$
ω_+
ω_-
ω/m_q^*
k/m_q^*
0.0
0.5
1.0
1.5
2.0
2.5