INTERMEDIATE-MASS DILEPTONS
AT THE CERN-SPS AND RHIC

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Abstract

The significance of thermal dilepton radiation at intermediate invariant masses (1 GeV $< M <$ 3 GeV) in ultrarelativistic heavy-ion collisions is investigated. At CERN-SpS energies, a consistent explanation of the excess observed by NA50 can be given. At RHIC energies the thermal signal is dominated by early emission indicative for QGP formation. Chemical under-saturation effects and the competition with open-charm contributions are addressed.

1 Introduction

Due to their penetrating nature dilepton probes are among the most promising observables to access the high temperature/density zones formed in the early phases of (ultra-) relativistic heavy-ion collisions (URHIC's). In the low-mass region (LMR, $M \leq 1$ GeV) dilepton emission is governed by the light vector mesons ρ, ω and ϕ attaching the main interest to their medium modifications and possible signatures for the restoration of chiral symmetry in strongly interacting matter. In the high-mass region (HMR, $M \geq 3$ GeV), the focus is on the dissolution of the heavy quarkonium bound states (J/Ψ, Υ) to detect the onset of deconfinement. In this talk we will address the intermediate-mass region (IMR) between the ϕ and J/Ψ (1 GeV $\leq M \leq$ 3 GeV). Here, the thermal dilepton production rate is essentially structureless and can be rather well approximated by perturbative $q\bar{q} \to l^+l^-$ annihilation for both hadronic and quark-gluon phases (as can be inferred from the well-known total cross section $\sigma(e^+e^- \to hadrons)$ above $M \simeq 1.5$ GeV). With final-state hadron decays being concentrated in the LMR, the main competitors with thermal radiation from an interacting fireball are primordial processes, most notably Drell-Yan (DY) annihilation and the simultaneous decays of associatedly produced open-charm (or bottom) mesons, *e.g.*, $D \to l^-\bar{\nu}X$ and $\bar{D} \to l^+\nu X$. An excess over these from proton-proton collision extrapolated sources has long been proposed as a suitable signal for the early high-temperature phases in

URHIC's [1]. Since the expected temperatures $T \ll M$ in the IMR, the thermal signal might be sufficiently sensitive to reflect the initial temperature and lifetime of a possibly formed Quark-Gluon Plasma (QGP).

In the following we will investigate these issues in the context of data from the CERN-SpS (Sect. 2) and then apply our current understanding to assess upcoming measurements at RHIC (Sect. 3). We finish with some concluding remarks in Sect. 4.

2 I-M Dileptons at the SpS

2.1 Experimental Results and Previous Theoretical Analyses

At the CERN-SpS I-M dilepton spectra have been measured by the NA38/50 and HELIOS-3 collaborations. Both have found a significant excess of a factor ~ 2 in central A-A collisions over open-charm and Drell-Yan sources scaled up from p-A systems.

Fig. 1 shows a comparison of the HELIOS-3 data with transport calculations of Li and Gale [3]: apparently the additional yield from in-medium hadronic annihilation processes satisfactorily explains the data (left panel); note that the prevailing channels, πa_1 and $\pi \omega$, are of '4-pion type' (right panel). Within the hadronic transport framework, QGP formation could not be explicitly addressed. In the context of the NA50 data [4, 5] other possibilities for the origin of the additional yield have been elaborated:

 (i) the NA50 collaboration pointed out that an enhancement of the open-charm contribution by a factor of ~ 3 gives a good account of the data in central Pb(158 AGeV)+Pb. From the theoretical side, however, such an effect is difficult to justify;

 (ii) Lin and Wang investigated whether a broadening of transverse-momentum distributions due to a (strong) rescattering of charm quarks in matter might enrich the yield within the NA50 acceptance [6]. The resulting increase amounts to about 20% [5];

 (iii) Spieles *et al.* [7] evaluated 'secondary' Drell-Yan processes (*e.g.*, $\pi N \to l^+ l^- X$) arising in the later stages of the collision and found a 10% enhancement of the primordial Drell-Yan around $M \simeq 2$ GeV;

 (iv) thermal radiation from an equilibrated expanding fireball [8, 9].

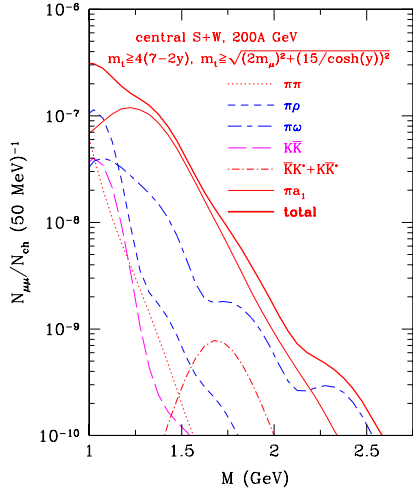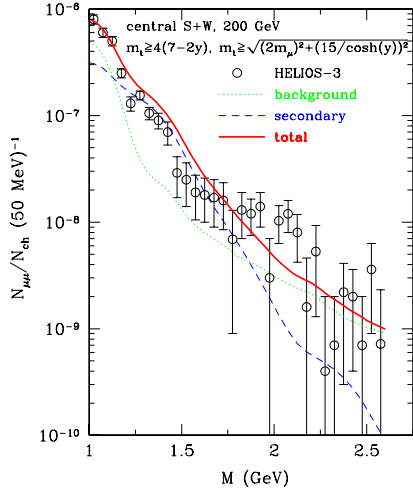In the following, we will pursue the last item in more detail.

Figure 1: Left panel: HELIOS-3 dimuon data [2] from central S+W compared to the 'standard' background (consisting of Drell-Yan and open charm) and the additional yield from secondary hadronic annihilation processes evaluated within a transport model [3]; right panel: decomposition of the secondary reactions [3].

2.2 Drell-Yan Annihilation and NA50 Acceptance

To enable a comparison of our final results with NA50 data we need to determine their normalization and acceptance corrections. To this end we use the primordial Drell-Yan contribution to achieve this. For central A-A collisions

it is given by

$$\frac{dN_{DY}^{AA}}{dMdy}(b=0) = \frac{3}{4\pi R_0^2} \; A^{4/3} \; \frac{d\sigma_{DY}^{NN}}{dMdy} \; , \tag{1}$$

which we also employ for slightly non-central ones with an accordingly reduced $A = N_{part}/2$. Exploiting the fact that the high-mass tail ($M \geq 4$ GeV) of the data is entirely saturated by DY-pairs we obtain the overall normalization which will also be applied to the thermal production. We furthermore use the calculated DY-spectrum to test our approximate acceptance: in addition to geometric cuts [10] on the single-muon tracks imposed by the NA50 spectrometer set-up, the muons experience substantial absorption when traversing the hadron absorber. The latter can be roughly represented by a lower energy cut-off which is determined [9] by requiring to reproduce the DY-results of NA50 detector simulations, cf. Fig. 2.

2.3 Thermal Rates, Space-Time Evolution and Spectra

Based on the assumption that an interacting fireball formed in heavy-ion collisions is in local thermal equilibrium (in the 'comoving' frame of expansion), the evaluation of the thermal dilepton yield requires two ingredients: production rates and the time evolution of volume/temperature. In the IMR the former turns out to be given in a rather model-independent way by the result from perturbative QCD for the $q\bar{q}$ annihilation process,

$$\frac{d^8 N_{\mu\mu}^{therm}}{d^4 x d^4 q} = \frac{\alpha^2}{4\pi^4} f^B(q_0; T) \sum_{q=u,d,s} (e_q)^2 \; + \; \mathcal{O}(\alpha_s) \tag{2}$$

for both QGP and hadron gas (HG) phases. This is a direct consequence of the well-known 'duality' threshold located around 1.5 GeV in the inverse process of $e^+e^- \rightarrow hadrons$ annihilation. It is further corroborated by explicit hadronic rate calculations as evidenced from the compilation displayed in Fig. 3 [3]. α_s-corrections may be as large as 20-30%, whereas higher order temperature/density effects are smaller being of order $\mathcal{O}(T/M)$, $\mathcal{O}(\mu_q/M)$.

For the space-time evolution of central A-A collisions we employ an expanding thermal fireball model [11, 12] which is based on an ideal-QGP and resonance-hadron-gas equation of state. Entropy and baryon-number conservation fix a trajectory in the T-μ_N plane with the ratio s/n_B chosen in accord with experimental information on chemical freezeout at the SpS [13], cf. left panel of Fig. 4. Pion- and kaon-number conservation ensure the correct particle abundances at thermal freezeout towards which finite chemical potentials
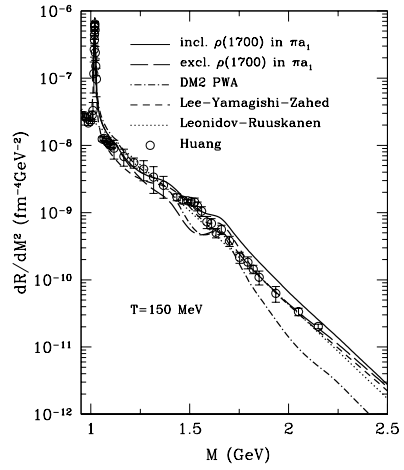
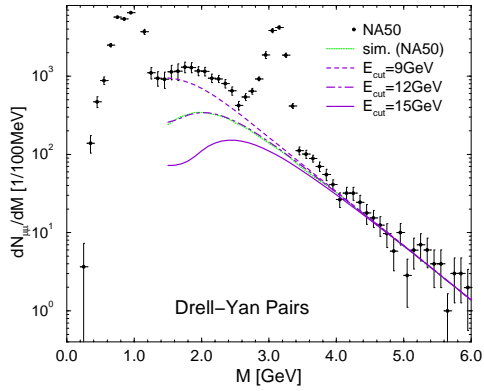Figure 3: Compilation [3] of various approaches to assess the thermal dilepton production rate in the IMR.

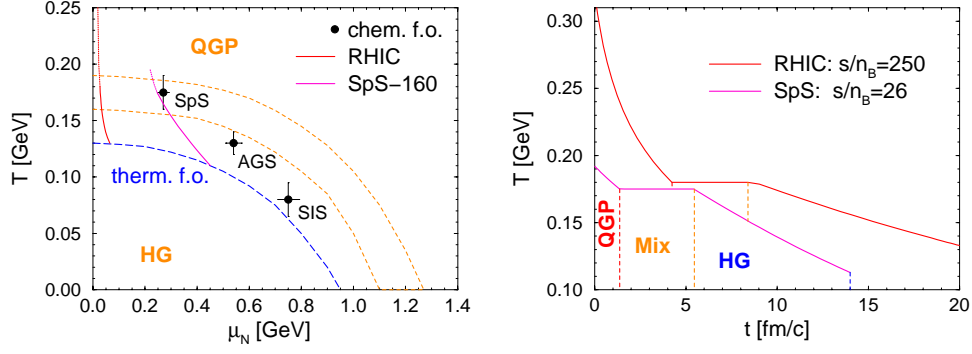Figure 2: DY-calculations compared to NA50 simulations (dotted line) and data [4, 5] in central Pb(158AGeV)+Pb.

Figure 4: Space-time description of central heavy-ion reactions at SpS and RHIC energies within an expanding thermal fireball model.

μ_π, $\mu_{K,\bar{K}}$ build up. A time scale is introduced through a hydro-type volume expansion which yields realistic final flow velocities and transverse sizes [11, 9]. A QGP-HG mixed phase is constructed from standard entropy balancing resulting in a temperature evolution shown in the right panel of Fig. 4.

The thermal dilepton spectra are then computed as

$$\frac{dN_{\mu\mu}^{therm}}{dM} = \int\limits_0^{t_{fo}} dt\, V_{FB}(t) \int \frac{M d^3 q}{q_0}\, \frac{d^8 N_{\mu\mu}}{d^4 x d^4 q}(M, q; T)\, \left[e^{\mu_\pi/T} \right]^4\, \text{Acc}(M, q_t, y) \quad (3)$$

including the experimental acceptance as determined above. Note the explicit appearance of the pion-fugacity factor to the 4-th power to appropriately account for off-equilibrium effects in 4-pion-type annihilation processes which
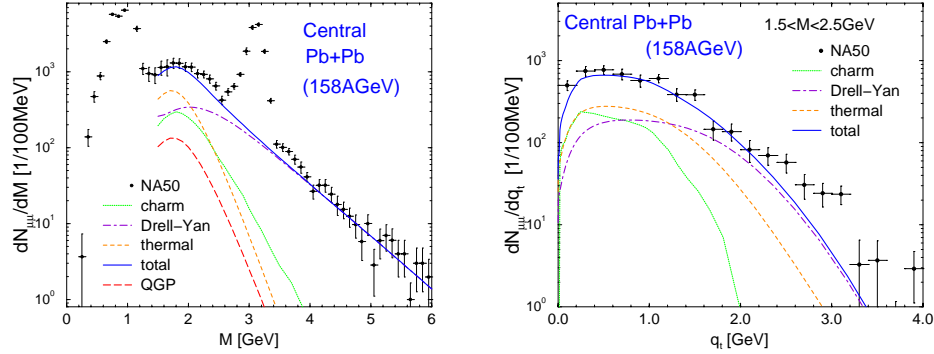

Figure 5: Dimuon invariant-mass (left panel) and transverse-momentum (right panel) spectra confronted with NA50 data from central Pb(158 AGeV)+Pb collisions. In addition to the calculated thermal and DY contributions the open-charm yield as arising from simulations by NA50 [5] has been included.

dominate in the IMR (see right panel of Fig. 1). The final results of our calculation are displayed in Fig. 5: the experimentally observed excess is reasonably well reproduced by thermal radiation in both invariant-mass and transverse-momentum projections (very similar conclusions have been reached in ref. [8]). The contribution from the QGP part of the evolution constitutes a rather moderate fraction of $\sim 20\%$.

3   I-M Dileptons at RHIC

The same approach as described in the preceding section is now applied to central Au+Au collisions at $\sqrt{s}$=200 AGeV. For definiteness the charged particle multiplicity at midrapidity has been fixed at $\langle N_{ch}\rangle$=800 with an entropy per baryon of s/n_B=260. The resulting IMR dilepton spectra are summarized in
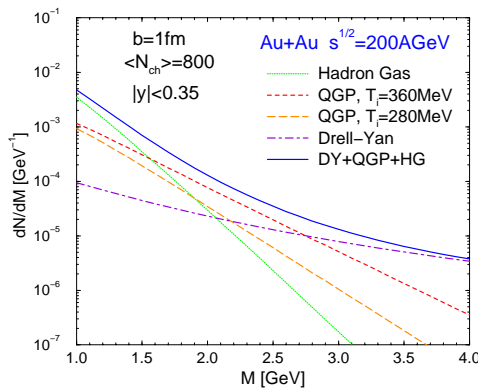

Figure 6: Dilepton spectra in central Au+Au at RHIC from equilibrated hadronic and quark-gluon matter as well as DY annihilation.

Fig. 6: up to $M\simeq 1.5$ GeV the hadron gas radiation dominates; in contrast to SpS conditions, the QGP contribution dominates around 2 GeV before DY annihilation takes over. Not shown is the yield from open-charm decays, which in fact could completely outshine the spectrum by a factor of 10 or so [14]. If, however, charm quarks undergo appreciable energy loss ($dE/dx\simeq-1$-2 GeV/fm) when propagating through hot/dense matter they might thermalize entailing a suppression of their contribution above M=1.5 GeV by factors of $\sim$100 [15].

Another complication at RHIC energies concerns the chemical under-saturation of gluon and especially quark densities in the early stages as predicted in various parton-based models [16]: albeit thermalized, the parton distributions are characterized by fugacities λ_i=$n_i(T)/n_i^{eq}(T)$<1 (i=$q,\bar{q},g$). Naively one would expect a substantial reduction of dilepton production in the $q\bar{q}$

channel as the rate is proportional to $\lambda_q \lambda_{\bar{q}}$. On the other hand, at given entropy (or energy) density, an under-saturated QGP has a larger temperature than in chemical equilibrium which in turn enhances the thermal emission. Using a parameterization of recent hydrodynamic evolution results [17] (see also ref. [18]) we have recalculated the plasma contribution starting at the same initial entropy density as in the equilibrium scenario. The magnitude of the pertinent QGP signal in the final spectrum turns out to be quite similar with a somewhat harder slope for the off-equilibrium calculation (see left panel of Fig. 7), *i.e.*, the reduction in the fugacities is largely compensated by the increase in initial temperature.
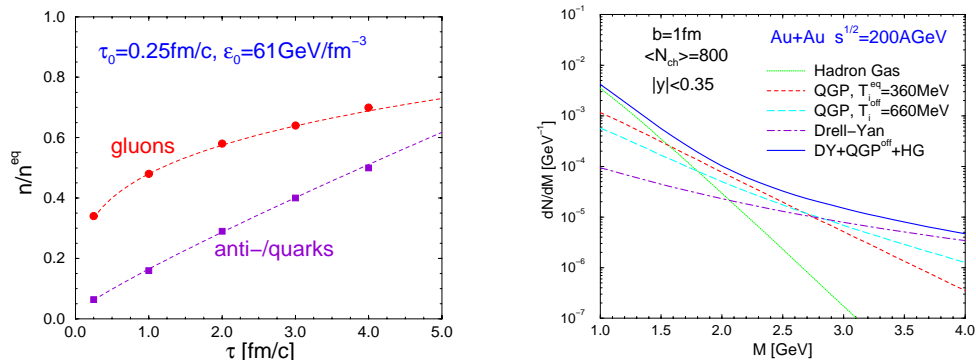

Figure 7: Left panel: evolution of parton fugacities in the QGP phase at RHIC according to ref. [17]; right panel: resulting dilepton spectrum (long-dashed line) compared to equilibrium-QGP (at equal initial entropy density), HG and DY yields.

4   Conclusions and Outlook

Based on a thermal fireball model coupled with 'standard' dilepton production rates we have shown that the excess observed in central Pb(158AGeV)+Pb by NA50 in the IMR can be explained by thermal radiation. The contribution from early phases indicative for a QGP is moderate; however, our results corroborate the present understanding of the conditions probed at the CERN-SpS being consistent with low-mass dilepton spectra, chemical freezeout analyses, etc., indicating that one is indeed producing QCD matter in the vicinity of the expected HG-QGP phase boundary.

The extrapolation of this approach to RHIC suggests that the plasma radiation exceeds HG- and DY-sources around $M \simeq 2$ GeV. Chemical off-equilibrium effects do not seem to alter this conclusion as long as comparable initial energy densities are reached. A big question mark is attached to the

open-charm contribution, *i.e.*, whether energy loss effects significantly redistribute the associated dilepton yields. Experimental input on these issues is eagerly awaited.

Acknowledgment

References

[1] E.V. Shuryak, Phys. Rep. **61** (1980) 71.

[2] N. Masera *et al.* (HELIOS-3 collaboration), Nucl. Phys. **A590** (1995) 93c.

[3] G.Q. Li and C. Gale, Phys. Rev. **C58** (1998) 2914.

[4] E. Scomparin *et al.* (NA50 collaboration), J. Phys. **G25** (1999) 235.

[5] P. Bordalo *et al.* (NA50 collaboration), Nucl. Phys. **A661** (1999) 538.

[6] Z. Lin and X.-N. Wang, Phys. Lett. **B444** (1998) 245.

[7] C. Spieles *et al.*, Eur. Phys. J. **C5** (1998) 349.

[8] K. Gallmeister, B. Kämpfer and O.P. Pavlenko, hep-ph/9908269; see also these proceedings.

[9] R. Rapp and E. Shuryak, hep-ph/9909348.

[10] E. Scomparin, private communication (1999).

[11] R. Rapp and J. Wambach, Eur. Phys. J. **A6** (1999) 415.

[12] R. Rapp and J. Wambach, hep-ph/9909229, to appear in Adv. Nucl. Phys..

[13] P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A638** (1998) 3c.

[14] S. Gavin, P.L. McGaughey, P.V. Ruuskanen and R. Vogt, Phys. Rev. **C54** (1996) 2606.

[15] E. Shuryak, Phys. Rev. **C55** (1997) 961.

[16] B. Müller, M.G. Mustafa and D.K. Srivastava, Heavy Ion Phys. **5** (1997) 387; K.J. Eskola and K. Kajantie, Z. Phys. **C75** (1997) 515.

[17] D.M. Elliott and D.H. Rischke, nucl-th/9908004.

[18] B. Kämpfer, O.P. Pavlenko, A. Peshier and G. Soff, Phys. Rev. **C52** (1995) 2704.