# Comprehensive Interpretation of Thermal Dileptons at the SPS

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Employing thermal dilepton rates based on a medium-modified electromagnetic correlation function we show that recent dimuon spectra of the NA60 collaboration in central In-In collisions at the CERN-SPS can be understood in terms of radiation from a hot and dense hadronic medium. Earlier calculated in-medium $\rho$-meson spectral functions provide an accurate description of the data up to dimuon invariant masses of about $M\simeq 0.9$ GeV, with good sensitivity to the predicted $\rho$-meson line shape, identifying baryon-induced modifications as the prevalent ones. A reliable evaluation of the $\rho$ contribution enables the study of further medium effects: at masses $M>0.9$ GeV, 4-pion type annihilation accounts for the experimentally observed excess (possibly augmented by effects of "chiral mixing"), while predictions for thermal emission from in-medium $\omega$ and $\phi$ mesons may be tested in the future.

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*Introduction.* Electromagnetic probes occupy a special role in the study of strongly interacting matter produced in energetic collisions of heavy nuclei: once produced, photons and dileptons leave the reaction zone essentially undistorted, carrying direct information from the hot and dense medium to the detectors. While the ultimate goal in analyzing pertinent experiments is to infer signatures of QCD phase transitions (chiral symmetry restoration and/or deconfinement), the more imminent (and relatively easier) objective is to extract medium modifications of the electromagnetic (e.m.) spectral function [1, 2]. Recent data from the NA60 collaboration [3] on dimuon invariant-mass spectra in In-In collisions at the CERN Super-Proton-Synchrotron (SPS) have raised the experimental precision to an unprecedented level, posing serious challenges to theoretical models. After subtraction of late hadronic decay sources ("cocktail"), the excess dimuon radiation exhibits features of a (broadened) peak around the free $\rho$-mass ($m_\rho\simeq 0.77$ GeV) with a substantial enhancement at both lower and higher invariant masses. Theoretical predictions [4, 5] based on an expanding fireball have confirmed that a broadened $\rho$-meson, as following from hadronic many-body theory, is in line with the NA60 dimuons, while a dropping $\rho$-mass [6, 7], characterized by a spectrum centered around a mass of 0.4-0.5 GeV, is inconsistent with the data[30]. Both scenarios were consistent with earlier dilepton data by the CERES collaboration [9].

The objective of the present letter is twofold: First, we improve on earlier (shape-based) comparisons of our predictions to data based on in-medium $\rho$ spectral functions. With a slight modification of the expanding fireball model, we quantitatively reproduce (shape and absolute magnitude of) the low-mass NA60 data in central In-In collisions.

The spectral shape turns out to be sensitive to properties of the $\rho$ in some detail. Second, having determined in this way the contributions of the 2-$\pi$ piece to the in-medium e.m. correlator, we investigate remaining enhancements in the $\mu^+\mu^-$ spectrum. Above $M_{\mu\mu}\simeq 0.9$ GeV, using empirical fits to the isovector-vector ($V$) and -axialvector ($A$) spectra in vacuum, a calculation with the free emission rate tends to underestimate the data. When including medium effects due to chiral $V$-$A$ mixing [10], with an assumed critical temperature of $T_c$=175 MeV (consistent with the fireball), the description improves. While more precise conclusions have to await more accurate data and calculations, our estimates indicate that dilepton radiation from heavy-ion collisions at the SPS emanates from matter close to the expected QCD phase boundary. Finally, we address medium effects on the narrow vector mesons $\omega$ and $\phi$.

*Thermal Dileptons and Medium Effects.* The differential rate for thermal lepton-pair production per unit 4-volume and 4-momentum can be expressed as [11, 12, 13]

$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\,\mathrm{Im}\Pi^{\mu}_{\mathrm{em},\mu}(M,q)\; f^B(q_0;T) \quad (1)$$

in terms of the retarded e.m. current-current correlator

$$\Pi^{\mu\nu}_{\mathrm{em}}(q) = \mathrm{i}\int \mathrm{d}^4x \mathrm{e}^{\mathrm{i}q\cdot x}\Theta(x^0)\,\langle[\mathbf{J}^{\mu}_{\mathrm{em}}(x),\mathbf{J}^{\nu}_{\mathrm{em}}(0)]\rangle \ , \quad (2)$$

a final-state lepton phase-space factor, $L(M)$, and the thermal Bose function, $f^B(q_0;T)$. $\alpha=e^2/(4\pi)=1/137$ denotes the fine structure constant and $M^2=q_0^2-q^2$ the dilepton invariant mass with energy $q_0$ and 3-momentum $q$. The central objective in the following is the evaluation of medium modifications of the e.m. spectral function.

In the low-mass region (LMR, $M\leq 1$ GeV), the free e.m. correlator is saturated by the light vector mesons $\rho$, $\omega$ and $\phi$. Our main focus is on the $\rho$-meson (which dominates the dilepton yield in the LMR), but we also investigate radiation from (and medium effects on) the $\omega$ and $\phi$. Although their contribution is suppressed relative to the $\rho$, it is an inevitable consequence of our assumption of the formation of a thermalized medium.

Medium modifications of the $\rho$-meson are implemented using hadronic many-body theory [4], accounting for interactions in hot hadronic matter via (i) a dressing of its pion cloud with baryon-hole excitations and thermal Bose factors, (ii) direct resonances on surrounding mesons ($\pi$, $K$, $\rho$) and baryons (nucleons, $\Delta$'s, hyperons, etc.). The effective interaction vertices (coupling constants and form factors) have been carefully constrained by a combination of hadronic and radiative decay branchings, by photoabsorption on nucleons and nuclei, and by $\pi N \to \rho N$ scattering. The resulting $\rho$ spectral functions in cold nuclear matter comply with constraints from QCD sum rules [14]; they have successfully been employed to dilepton spectra at full SPS energy [9], and to predict an even larger enhancement at lower SPS energies [15, 16]. When averaged over a typical space-time evolution, the in-medium $\rho$ width at SPS amounts to $\Gamma_\rho^{\rm med} \simeq 350$ MeV, almost 3 times the vacuum value. Close to the expected QCD phase transition the $\rho$-resonance has melted, $\Gamma_\rho(T_c) \simeq m_\rho$. "Rhosobar" excitations ($\rho \to BN^{-1}$) lead to low-mass strength in the $\rho$ spectral function that cannot be represented in Breit-Wigner form.

Medium effects on the $\omega$ and $\phi$ have thus far received less attention, especially in the context of ultrarelativistic heavy-ion collisions (URHICs). For the $\omega$ we will employ the same approach as for the $\rho$ [17]. The predicted average $\omega$ width in the hadronic phase of URHICs is $\Gamma_\omega^{\rm med} \simeq 100$ MeV [16]. For the $\phi$, collision rates in a meson gas amount to a broadening by $\sim$20 MeV at $T$=150 MeV [18]. The dressing of the kaon cloud is presumably the main effect for $\phi$ modifications in nuclear matter, increasing its width by $\sim$25 MeV at saturation density $\varrho_0$=0.16 fm$^{-3}$ [19]. Recent data on $\phi$ absorption in nuclear photoproduction suggest even larger values [20]. Since a comprehensive treatment of the $\phi$ in hot and dense matter is not available at present, we will consider the $\phi$ width as a parameter.

Another important ingredient in our analysis are dilepton production channels beyond the $\rho$, $\omega$ and $\phi$. For the free emission rate these can be inferred from the inverse process of $e^+e^-$ annihilation, or hadronic $\tau$ decays as measured in $Z^0$ decays [21], enabling a decomposition of the (isovector part of) e.m. spectral function into 2- and 4-pion pieces. While the former are saturated by the $\rho$-meson, we fit the latter by an appropriate (onset of a) continuum [22], cf. Fig. 1. Rather than evaluating medium effects in the intermediate-mass region (IMR; 1 GeV$\le M \le$3 GeV) in a phenomenological approach [23], we here employ model-independent predictions based on chiral symmetry. To leading order in temperature one finds a mixing of the free $V$ and $A$ correlators [10],

$$\Pi_{V,A}(q) = (1-\varepsilon)\ \Pi^{\rm vac}_{V,A}(q) + \varepsilon\ \Pi^{\rm vac}_{A,V}(q)\ , \qquad (3)$$

where $\varepsilon$=$2I(T)/f_\pi^2$ ($f_\pi$=93 MeV: pion decay constant) is determined by the pion tadpole diagram with a loop integral $I(T)$=$\int(d^3k/(2\pi)^3)\ f^\pi(\omega_k;T)/\omega_k$ ($\omega_k$: pion energy). For $\varepsilon$=1/2 (at $T_c^{\rm mix} \simeq 160$ MeV) $V$ and $A$ correlators degenerate signaling chiral symmetry restoration. Eq. (3) holds in the soft pion limit, i.e., when neglecting the pion 4-momentum in $\Pi_{V,A}$. A more elaborate treatment [24, 25] will broaden and reduce the enhancement around $M \simeq 1.1$ GeV. To estimate the mixing effect on the 4-$\pi$ contribution to dilepton emission, we evaluate the vector correlator, Eq. (3), with a mixing parameter $\varepsilon = I(T,\mu_\pi)/2I(T_c,0)$, where critical temperature, $T_c$=175 MeV, and pion chemical potentials ($\mu_\pi$>0) are in accord with the thermal fireball evolution discussed below ($m_\pi$=139.6 MeV). The 2-pion piece has been removed as it is included via the $\rho$.

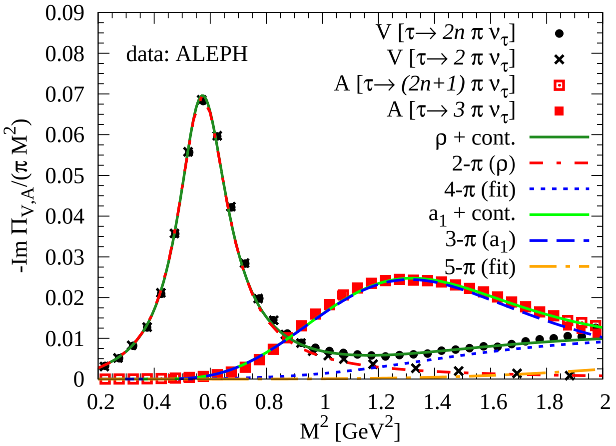

FIG. 1: Free isovector-vector and -axialvector spectral functions as measured in hadronic $\tau$-decays [21], compared to fits to 3- and 4-$\pi$ contributions (the 2-$\pi$ piece follows from the $\rho$).

Finally, we account for emission from the QGP, even though its contribution at SPS energies is small. We employ the hard-thermal-loop improved emission rate for $q\bar{q}$ annihilation [26], which has the conceptually attractive feature that it closely coincides with the rate in hadronic matter when both are extrapolated to the expected phase transition region. This is suggestive for a kind of quark-hadron duality [4] and has the additional benefit that the emission from the expanding fireball becomes rather insensitive to details of how the phase transition is implemented (such as critical temperature or "latent heat").

*Thermal Fireball Model.* To calculate dilepton spectra we need to specify a space-time evolution of A-A collisions. Based on evidence from hadronic spectra and abundances that the produced medium at SPS energies reaches equilibrium [27], we adopt a thermal fireball model focusing on central In-In with collective expansion and hadrochemistry as estimated from data in heavier systems. We use a cylindrical volume expansion [4],

$$V_{\rm FB}(t) = (z_0 + v_z t)\ \pi\ (r_\perp + 0.5 a_\perp t^2)^2\ , \qquad (4)$$

with transverse acceleration $a_\perp$=0.08$c^2$/fm, longitudinal velocity $v_z$=$c$, formation time $\tau_0$=1fm/$c$ and initial transverse radius $r_\perp$=5.15fm. With hadrochemical freezeout at $(\mu_N^{\rm chem},T^{\rm chem})$=(232,175) MeV and a total fireball entropy of $S$=2630 (using a hadron-resonance gas equation of state), we have $\mathrm{d}N_{\rm ch}/\mathrm{d}y\simeq 195\simeq N_{\rm part}$. Isentropic expansion allows to convert the entropy density, $s(t)$=$S/V(t)$, into temperature and baryon density. The evolution starts in the QGP ($T(\tau_0)$=197 MeV), passes through a mixed phase at $T^{\rm chem}$=$T_c$ and terminates at thermal freezeout ($T_{\rm fo}\simeq$120 MeV). In the hadronic phase, meson chemical potentials ($\mu_{\pi,K,\eta}$) are introduced to preserve the observed hadron ratios [4]. When applied to dilepton production, the largest uncertainty resides in the fireball lifetime (being proportional to the dilepton yields), controlled by $a_\perp$ and $T_{\rm fo}$, which can be better constrained once hadronic data for In-In are available. We emphasize, however, that all contributions to the dilepton spectrum (QGP, $\rho$, $\omega$, $\phi$ and 4-$\pi$) are tied to the *same* evolution thus fixing their relative weights.

*Systematic Comparison to NA60 Data.* Thermal $\mu^+\mu^-$ spectra for central In-In are computed by convoluting the emission rate, Eq. (1), over the fireball evolution,

$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}M} = \int\limits_0^{t_{\rm fo}} \mathrm{d}t\; V_{\rm FB}(t) \int \frac{d^3q}{q_0}\; \frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\mathrm{d}^4q}\; z_\pi^n\; \frac{M}{\Delta y}\; A(M,q_t,y), \tag{5}$$

where $A$ denotes the detector acceptance which has been carefully tuned to NA60 simulations [28]. The fugacity factor, $z_\pi^n$=$\mathrm{e}^{n\mu_\pi/T}$, accounts for chemical off-equilibrium in the hadronic phase with $n$=2,3,4 for the $\rho$, $\omega$ and 4-$\pi$ contributions, respectively (for the mixing term in Eq. (3) we adopt $\varepsilon\ \Pi_A^{\rm vac}\propto z_\pi^4$ [25]).

Earlier comparisons [3] of NA60 data to theoretical predictions [5] have focused on the contribution from the $\rho$-meson which dominates in the LMR. While the shape of the in-medium $\rho$ spectral function describes the experimental spectra well, the absolute yields were overestimated by $\sim$20%. This discrepancy can be resolved by an increase of the transverse fireball expansion ($a_\perp$) which, on the one hand, reduces the fireball lifetime by 30% (from 10 to 7 fm/$c$) and, on the other hand, generates harder transverse-momentum ($q_t$) spectra, which is also welcome by preliminary data [3]. Consequently, the $\rho$ contribution is reduced, and once QGP emission and correlated charm-decays ($D,\bar{D}\rightarrow\mu^+,\mu^-X$) are added, the spectra in the LMR are very well described, cf. Fig. 2. Despite the strong $\rho$ broadening, the $\rho$+QGP+charm sources are insufficient to account for the enhancement at $M\geq$0.9 GeV. This is not surprising, as 4-$\pi$ contributions are expected to take over (augmented by a pion fugacity factor, $\mathrm{e}^{4\mu_\pi/T}$). Adding the 4-$\pi$ piece with chiral mixing, Eq. (3), nicely accounts for the missing yield in the IMR, leading to a reasonable overall description (upper dashed line in Fig. 2). Going one step further still, we argue that in-medium decays of the narrow vector mesons, $\omega$ and $\phi$, should be included. Whereas their decays after freezeout are subtracted as part of the "cocktail" assuming a vacuum line shape, contributions whose width goes beyond the experimental mass resolution will survive in the excess spectrum. With the predicted in-medium $\omega$ spectral function [17] the agreement between theory and data for $M$=0.7-0.8 GeV seems to improve. The $\phi$ contribution is implemented with a two-kaon fugacity, $\mathrm{e}^{2\mu_K/T}$, and a strangeness suppression factor $\gamma_s^2$ ($\gamma_s\simeq$0.75 at SPS [29]). The $\phi$ yield following from the fireball model is not incompatible with data, but conclusions on the spectral shape cannot be drawn at present.

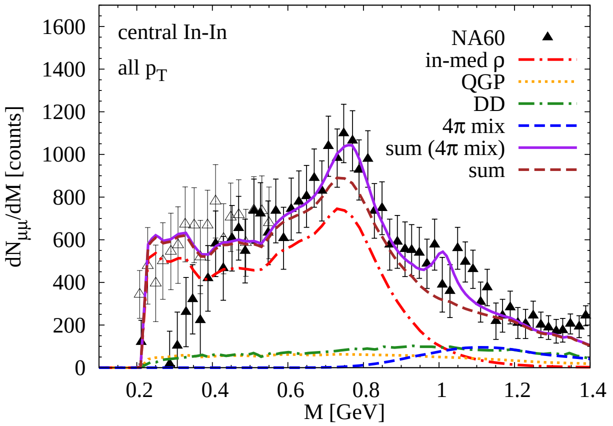

FIG. 2: NA60 excess dimuons [3] in central In-In collisions at SPS compared to thermal dimuon radiation using in-medium e.m. rates. The individual contributions arise from in-medium $\rho$-mesons [4] (dash-dotted red line), 4-$\pi$ annihilation with chiral $V$-$A$ mixing (dashed blue line), QGP (dotted orange line) and correlated open charm (dash-dotted green line); the upper dashed line is the sum of the above, while the solid purple line additionally includes in-medium $\omega$ and $\phi$ decays [17].

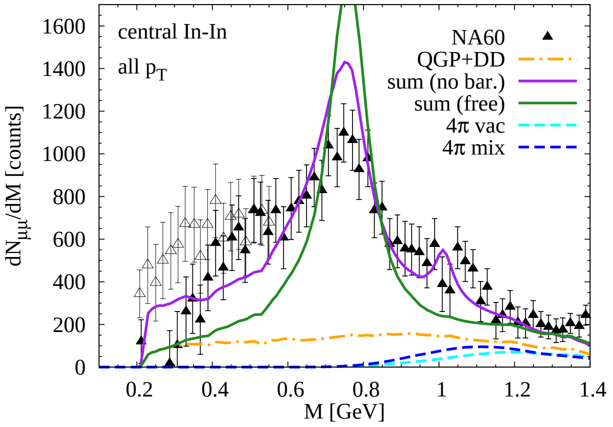

FIG. 3: NA60 data [3] compared to thermal dimuon spectra using (i) in-medium $\rho$-, $\omega$- and $\phi$-mesons without baryon effects (+QGP+charm+in-med.-4-$\pi$; solid purple line), and (ii) free $\rho$ (+QGP+charm+free 4-$\pi$; solid green line).

To better appreciate the relevance of the in-medium

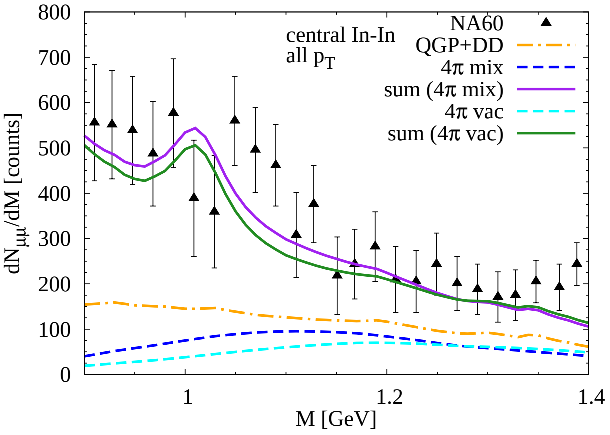

FIG. 4: NA60 data [3] in the IMR compared to thermal dimuon spectra with different implementations of the 4-$\pi$ contribution, using either its vacuum form (lower dashed line) or including chiral mixing (upper dashed line), and corresponding total spectra (lower and upper solid line, respectively).

effects, Fig. 3 shows two scenarios where (i) baryon-induced interactions are neglected, and (ii) the vacuum e.m. rate is employed. The latter is ruled out; the meson-gas scenario, which differs from the full result in Fig. 2 by factors of 1.5-2 in the LMR, is not favored by experiment either. Definite conclusions on the in-medium $\rho$, especially on the baryon-driven enhancement close to the dimuon threshold, require a reduction in systematic uncertainty, indicated by the open and filled data points. Finally, Fig. 4 illustrates the signature of chiral $V$-$A$ mixing in the IMR, where the full result of Fig. 2 is compared to a calculation with the 4-$\pi$ piece in the e.m. rate replaced by its vacuum form (Eq. (3) with $\varepsilon$=0). While the latter is not incompatible with the data, an identification of medium effects requires better precision than currently available (both from theory and experiment).

*Conclusion.* We have conducted a quantitative investigation of the dimuon excess spectrum measured by NA60 in In(158AGeV)-In. Focusing on central collisions, where the notion of thermal radiation is most adequate, we have shown that a medium modified e.m. spectral function properly accounts for absolute yields and spectral shape of the data. While the overall normalization of the spectrum is subject to uncertainties in the underlying fireball model (especially its lifetime), the relative strength of the different components in the spectrum ($\rho$, $\omega$ and $\phi$ decays, 4-$\pi$ type annihilation) is fixed. Our results confirm the prevalent role of a strongly broadened $\rho$-meson in the LMR, but also suggest substantial medium effects on the line shapes of $\omega$ and $\phi$. In addition, the IMR might bear footprints of chiral $V$-$A$ mixing, which would support the notion that the matter produced in A-A collisions at the SPS is close to chiral restoration. A more quantitative connection to chiral order parameters, e.g., by evaluating in-medium chiral sum rules [22], should be pursued with high priority.

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[30] A reinterpretation of the dropping-mass scenario [2] within a Hidden Local Symmetry approach for vector mesons [8] has not been confronted with dilepton data yet. However, any dropping-mass scenario will face the challenge of accounting for the large portion of strength seen in the NA60 data around the free $\rho$-mass.