Dileptons as Probes of
High-Density Hadronic Matter:
Results from the SPS Heavy-Ion Programme

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Abstract The most recent results on dileptons obtained in the CERN heavy-ion programme are reviewed. The emphasis is on the excess of low-mass lepton pairs observed in the CERES, HELIOS-3 and NA38/50 experiments which seems to point at modifications of the vector meson properties, and in particular the $\rho$ meson, in a high density baryonic medium. Recent results on intermediate mass dileptons are also presented.

1 Introduction

The heavy-ion programme at the CERN SPS started in 1986 with the acceleration of O beams at an energy of 200 GeV/c per nucleon followed soon after by a S beam at the same energy. Since 1994 the programme uses a Pb beam of 158 GeV/c per nucleon. Among the vast amount of experimental results that have been gathered the observation of an excess emission of low-mass dilepton pairs appears as one of the most notable and intriguing achievements of the programme along with the $J/\psi$ suppression and strangeness enhancement [1].

Dileptons emitted in ultra-relativistic heavy-ion collisions are considered unique probes in the study of hadronic matter under extreme conditions of temperature and baryon density and in particular the conjectured deconfinement and chiral phase transitions. These penetrating probes have a relatively large mean free path and consequently can leave the interaction region without final state interaction, carrying information about the conditions and properties of the matter at the time of their production and in particular of the early

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stages of the collision when temperature and energy density have their largest values.

A prominent topic of interest is the identification of thermal radiation emitted from the collision system. This radiation should tell us about the nature of the matter formed, a quark-gluon plasma (QGP) or a high-density hadron gas (HG). The elementary processes involved are well known: $qar{q}$ annihilation in the QGP phase and $\pi^+\pi^-$ annihilation in the HG phase and the two sources should be distinguishable by their characteristic properties in appropriate mass windows. At SPS energies, the initial temperature is believed to be close to the critical temperature, and therefore one expects the dense hadron gas to be the dominant source of thermal radiation. The window to search for it is at low masses, around and below the $\rho$-meson mass, since the $\pi^+\pi^-$ annihilation cross section is dominated by the pole of the pion electromagnetic form factor at the $\rho$ mass. On the other hand, theoretical calculations have singled out the mass range of 1-3 GeV/$c^2$ as the most suitable window to observe the thermal radiation from the QGP phase at initial temperatures likely to be reached at RHIC or LHC.

The physics potential of dileptons is further emphasized by the capability to measure the vector mesons through their leptonic decays. Of particular interest is the decay of the $\rho$ meson into a lepton pair since it provides a unique opportunity to observe in-medium modifications of the vector meson properties which might be linked to chiral symmetry restoration. Due to its very short lifetime ($\tau = 1.3$ fm/c) compared to the typical fireball lifetime of 10-20 fm/c at SPS energies, most of the $\rho$ mesons produced in the collision will decay inside the interaction region with modified mass and/or width if the temperature or the baryon density are large enough. The relation of in-medium modifications to chiral symmetry restoration is a highly debated topic and will be addressed again in this paper. The situation is very different for the other vector mesons, $\omega, \phi$ or $J/\psi$. Because of their much longer lifetimes they will be re-absorbed in the medium or they will decay well outside the interaction region after having regained their vacuum masses.

The three experiments, CERES, HELIOS1-3 and NA38/50 involved in the measurement of dileptons ($e^+e^-$ and $\mu^+\mu^-$ pairs) at the CERN SPS have indeed confirmed the unique physics potential of these probes. The results cover measurements with p, S and Pb beams, and the most notable one is the observation with the ion beams of an enhancement of the dilepton yield.

\[\text{The same argument is in principle valid for real photons, since real and virtual (dileptons) photons are expected to carry the same physics information. However, the physics background for real photons is larger by orders of magnitude as compared to dileptons, making the measurement of photons much less sensitive to a new source.}\]
over a very broad range of invariant masses. The enhancement is particularly pronounced in the continuum at low-masses (0.2 < m < 0.7 GeV/c²) but it is also significant in the continuum at intermediate masses (1.5 < m < 3.0 GeV/c²) and in the φ meson yield. The low-mass pair enhancement has triggered a huge amount of theoretical activity mainly stimulated by interpretations based on in-medium modifications of the vector mesons and in particular a decrease of the ρ-meson mass as a precursor of chiral symmetry restoration.

Table 1. List of Dilepton Measurements at the CERN SPS

| Experiment | Probe | System | y | Mass (GeV/c²) | Ref. |
|------------|-------|--------|---|--------------|-----|
| CERES      | e⁺e⁻  | p-Be,Au 450 GeV/c | 2.1-2.65 | 0 – 1.4 | 7,8 |
|            |       | S-Au 200 GeV/u |                |         | 9   |
|            |       | Pb-Au 158 GeV/u |        |        | 10-12 |
| HELIOS-1 (completed) | μ⁺μ⁻ | p-Be 450 GeV/c | 3.65-4.9 | 0.3 – 4.0 | 13 |
|            | e⁺e⁻  | u        | 3.15-4.65 |        |     |
| HELIOS-3 (completed) | μ⁺μ⁻ | p-W,S-W 200 GeV/u | > 3.5 | 0.3 – 4.0 | 14 |
| NA38       | μ⁺μ⁻  | p-A,S-U 200 GeV/u | 3.0-4.0 | 0.3 – 6.0 | 15 |
| NA50       | μ⁺μ⁻  | u        |        |        | 0.3 – 7.0 | 16 |

A compilation of all measurements performed so far together with the kinematic phase space covered and relevant references is presented in Table 1.

In this paper, I concentrate on the most recent experimental results on low-mass lepton pairs (Section 2) and current status of the interpretations (Section 3). Other recent reviews can be found in [17]. Section 4 deals with the intermediate mass region and Section 5 gives some concluding remarks and prospects.

2 Low-mass Dileptons: Experimental Results

The low-mass region, m = 200 - 600 MeV/c², has been systematically studied by the CERES experiment [7, 8, 9, 10, 11, 12]. The most recent results were obtained with the Pb beam in two different runs, in 1995 [10, 11] and 1996 [12]. Apart from a slight difference in the centrality trigger (<dnch/dη > = 250 and 220 in the '96 and '95 runs, respectively), the two measurements were performed under identical conditions. The invariant mass spectra from the two data sets, normalized to the measured charged particle rapidity density
are displayed in Fig.1. On the positive side, one notes that the results appear consistent with each other within their error bars. The level of agreement is remarkable if one keeps in mind the huge filtering of the data \(^3\), the fact that these are two different data sets, and that they have been analyzed with the same strategy but with a somewhat different technique \(^4\).

Figure 1: Inclusive \(e^+e^-\) mass spectrum measured by CERES in 158 A GeV Pb–Au collisions in the ’95 and ’96 runs. The figure also shows the summed (solid line) and individual (dotted lines) contributions from hadronic sources in a thermal model \([12]\). The predictions from the pp cocktail previously used by CERES \([7]\) are shown by the dashed line.

As previously observed with the S beam \([9]\), the \(e^+e^-\) pair yield is clearly

\(^3\)Figure 1 contains a total of 2018 (648) \(e^+e^-\) pairs with mass \(m > 200\) MeV/c\(^2\) out of 42.2x10\(^6\) (8.6x10\(^6\)) analyzed events in the ’96 (95) run.

\(^4\) However, one also immediately notices that the ’96 results are systematically lower. The origin of the effect was studied \([18]\) and traced back to subtle differences in the analysis procedure. In ’96 all cuts were tuned without making use of the data themselves, basing them for example on Monte Carlo simulations \([12, 18, 19]\). The ’95 data analyzed with the same Monte Carlo tools as in ’96 yield nice agreement between the two data sets within statistical errors. The differences is Fig.1 are therefore a reflection of the systematic errors of the two analysis methods.
enhanced in the mass range above \( \sim 200 \text{MeV}/c^2 \) and below the \( \rho/\omega \) peak, with respect to the expected yield from known hadronic sources. The solid line shows the total expected yield based on a generator \([12]\) which uses measured particle production ratios whenever available or ratios calculated with a thermal model which describes well all these ratios \([20]\). With respect to this cocktail the measured yield in the mass region \( m = 0.25 - 0.7 \text{GeV}/c^2 \) is enhanced by a factor of 2.6 \( \pm 0.5 \text{(stat.)} \pm 0.6 \text{(syst.)} \). For comparison the figure also shows (dashed line) the standard pp cocktail previously used in the presentation of the CERES results \([7]\) and which is based on yields directly measured in pp collisions, scaled to the nuclear case with the charged particle rapidity density. The two generators predict closely similar results. The total yield of the thermal model is \( \sim 30 \% \) larger than the pp cocktail for masses \( m > 200 \text{MeV}/c^2 \), the main difference occurring in the region of the \( \phi \) meson.

CERES has further characterized the properties of the low-mass excess by studying its \( p_t \) and multiplicity dependences, which indicate that the excess is mainly due to soft pair \( p_t \) and increases faster than linearly with the charged particle density \([10, 11, 12]\).

An enhancement of low-mass dileptons has also been observed in the dimuon experiments HELIOS-3 \([14]\) and NA38 \([15]\) with the S beam. NA38 has an interesting set of results including p-U, S-S and S-U collisions at 200 A GeV. Whereas the p-U data are well reproduced by a cocktail of hadronic sources (with the somewhat uncertain extrapolation of the Drell-Yan contribution into low masses), the S data shows an enhancement of low-mass pairs. The enhancement is most apparent in the S-U collision system and there it clearly extends over the intermediate mass region as illustrated in Fig.2.

There is a striking difference in the shape of the low-mass dilepton spectrum as measured by CERES and NA38. A pronounced structure due to the resonance decays is clearly visible in the NA38 spectrum, whereas in the CERES results the structure is completely washed out (see Fig. 1), raising the question of consistency between the two experiments. Resolution effects can be readily ruled out since the low-mass spectrum in p-Be and p-Au collisions measured by CERES with the same apparatus clearly shows the \( \rho/\omega \) peak \([6]\). We also note that the two experiments cover nearly symmetric ranges around mid-rapidity \( \eta = 2.1 - 2.65 \) and \( \eta = 3 - 4 \) in CERES and NA38 respectively). But CERES has a relatively low \( p_t \) cut of 200 MeV/c on each track whereas NA38 is restricted to \( m_t > 0.9 + 2(y_{lab} - 3.55)^2 \text{GeV}/c^2 \). Moreover, NA38 has no centrality selection in the trigger whereas the CERES data corresponds to the top 30\% of the geometrical cross section. These two factors are likely to explain the apparent discrepancy since, as noted previously, the excess observed by CERES is more pronounced at low pair \( p_t \) and increases stronger than linearly with multipli-
Figure 2: Inclusive $\mu^+\mu^-$ mass spectra measured by NA38 in 200 A GeV S-U collisions. The thick line represents the summed yield of all known sources. The individual contributions are also shown [13].

ity. Given enough statistics it should be fairly easy for the two experiments to apply common $m_t$ and centrality cuts thereby making possible a direct and meaningful comparison between their results.

### 3 Low-mass Dileptons: Theoretical Evaluation

The enhancement of low-mass dileptons has triggered a wealth of theoretical activity. Dozens of articles have been published on the subject and clearly it is not possible to review them here. I present thus a summary of the current leading approaches. There is a consensus that an additional source beyond a simple superposition of pp collisions is needed. Furthermore, it is commonly recognized that the pion annihilation channel ($\pi^+\pi^- \rightarrow l^+l^-$), obviously not present in pp collisions, has to be taken into account. This channel accounts for a large fraction of the observed enhancement however it is not sufficient to reproduce the data in the mass region $0.2 < m_{e^+e^-} < 0.5$ GeV/c$^2$. These data have been quantitatively explained by taking into account in-medium modifica-
tions of the vector mesons. Li, Ko and Brown [21] were the first to propose and use a decrease of the $\rho$-meson mass in the hot and dense fireball as a precursor of chiral symmetry restoration, following the original Brown-Rho scaling [22]. With this approach, an excellent agreement with the CERES data is achieved as demonstrated by the solid line in Fig.3 (taken from [6]).

\[ \frac{dN_{\text{ch}}}{d\eta} = 250 \]

Figure 3: CERES results compared to calculations using dropping $\rho$ mass (Brown-Rho scaling), in-medium $\rho$-meson broadening and RBUU transport model. The dash-dotted line represents the yield from hadrons after freeze-out as in Figure 1.

Another avenue based on effective Lagrangians uses a $\rho$-meson spectral function which takes into account the $\rho$ propagation in hot and dense matter, including in particular the pion modification in the nuclear medium and the scattering of $\rho$ mesons off baryons [23, 24]. This leads to a large broadening of the $\rho$-meson line shape and consequently to a considerable enhancement of low-mass dileptons. These calculations achieve also an excellent reproduction of the CERES results as illustrated by the dashed line in Fig. 3. Although the two approaches are different in the underlying physical picture (in the Brown-Rho scaling the constituent quarks are the relevant degrees of freedom whereas ref. [23] relies on a hadronic description), it turns out that the dilepton production rates calculated via hadronic and partonic models are very similar at SPS conditions [6] thus explaining the similar results of the two approaches.
Several issues remain controversial. Both approaches rely on a high baryon density for the dropping mass or the enlarged width of the $\rho$ meson but the role of baryons is still a question open to debate. Calculations based on chiral reduction formulae, although similar in principle to those of ref. [23], find very little effect due to baryons and are in fact low compared to the data [23]. The RBUU transport calculations of Koch [26] find also very little effect due to the baryons and come to a reasonably close description of the data as shown in Fig. 3 by the dash-dotted line. This could be due to an overestimation of the $\omega$ Dalitz decay yield as a consequence of an increased $\omega$ yield directly reflected in the figure at $m \sim 800$ MeV, which is dominated by the $\omega \to e^+e^-$ decay. Finally, I wish to point out the discrepancy between transport [24] and hydrodynamic calculations [27] in treating the time evolution of the fireball, the former yielding a factor of 2-3 higher yields.

4 Intermediate-mass Dileptons

The results of HELIOS-3 [14] and NA38/50 [15, 16] clearly show an excess of dileptons in the intermediate mass region $1.5 < m < 3.0$ GeV/c$^2$ (see Figs. 2 and 4). The excess refers to the expected yield from Drell-Yan and semi-leptonic charm decay which are the two main contributions in this mass region. The shape of the excess is very similar to the open charm contribution and in fact doubling the latter nicely accounts for the excess. This is the basis for the hypothesis of enhanced charm production made by NA38/50 [16]. However it is very unlikely that at the SPS energies charm production could be enhanced by such a large factor [28]. HELIOS-3 points into a different direction. The excess plotted as a function of the dimuon transverse mass can be fitted by a single exponential shape below and above the vector mesons [14], suggesting a common origin of the excess in the low and intermediate mass regions. Following this line, Li and Gale [29] calculated the invariant dimuon spectrum in central S-W collisions at 200 A GeV. On top of the physics background of Drell-Yan and open charm pairs, they considered the thermal radiation of muon pairs resulting from secondary meson interactions including higher resonances and in particular the $\pi a_1 \to l^+l^-$. The calculations are based on the same relativistic fireball model used to calculate the low-mass dileptons discussed in the previous section [21]. Their results are presented in Fig. 4 showing the total yield (physics background + thermal yield) with the assumption of free masses (dotted line) and dropping vector meson masses (solid line). The latter leads to a much better agreement with the data at low masses (from 0.3 to 0.7 GeV/c$^2$), as already mentioned in the previous section, whereas in the intermediate mass region the difference between free and in-medium meson masses with respect
to the data is not so large. The calculations with free masses slightly overestimate the data whereas with dropping masses the situation is reversed. The intermediate mass region alone cannot be used to validate the dropping mass model, however it is important that the model can explain simultaneously the low and intermediate mass regions.

5 Summary and Outlook

The measurements of dileptons both at low and intermediate masses have provided very intriguing results. The outstanding physics question is to further elucidate the origin of the observed excess and its possible relation to chiral symmetry restoration. There are a number of open questions on the theoretical front: the role of baryons, the difference between transport and hydrodynamic calculations, the approach to chiral restoration (do masses drop to zero and/or do their width increase to infinity?). With the present accuracy of the data it is not possible to discriminate between the various models.

Major new steps are foreseen in the near future. First, CERES is planning to dramatically improve the mass resolution to achieve $\delta m/m = 1\%$, by the addition of a TPC downstream of the present double RICH spectrometer. With this resolution, which is of the order of the natural line width of the $\omega$ meson,
it should be possible to directly measure the yield of all three vector mesons $\rho, \omega$ and $\phi$ including any possible changes in their properties (mass shift or increased width) thereby providing a better experimental tool to reveal possible in-medium modifications of the vector mesons. Second, a measurement is proposed at the lowest energy attainable at the SPS, at about 40 GeV/nucleon, where the effect of baryon density on the vector meson masses is expected to be largest. Last but not least, RHIC start of operations is behind the corner offering the possibility to extend these studies under better conditions of energy density and lifetime and to explore a new domain where temperature rather than baryon density is expected to be the dominant factor.

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