First measurement of the ρ spectral function in nuclear collisions

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The NA60 experiment has studied low-mass muon pairs in 158 AGeV Indium-Indium collisions at the CERN SPS. A strong excess of pairs is observed above the expectation from neutral meson decays. The unprecedented sample size of 360 000 events and the good mass resolution of about 2% allow to isolate the excess by subtraction of the known sources. The shape of the resulting mass spectrum is consistent with a dominant contribution from $\pi^+\pi^- \to \rho \to \mu^+\mu^-$ annihilation. The associated ρ spectral function shows a strong broadening, but essentially no shift in mass.

Thermal dilepton production in the mass region <1 GeV is largely mediated by the light vector mesons ρ, ω and ϕ. Among these, the ρ is the most important, due to its strong coupling to the $\pi\pi$ channel and its short lifetime of only 1.3 fm/c. These properties have given it a key role as *the* test particle for "in-medium modifications" of hadron properties close to the QCD phase boundary. Changes both in width and in position were originally advocated as precursor signatures of the chiral transition [1]. There seems to be some consensus now that the *width* of the ρ should increase towards the transition region, based on a number of quite different theoretical approaches [1–5]. On the other hand, no consensus exists on how the *mass* of the ρ should change in approaching the transition: predictions exist for a decrease [1,6], a constant behavior [4,5], and even an increase [3].

The CERES/NA45 experiment at the CERN SPS studied the production of low-mass electron pairs in p-Be/Au [7], S-Au [8] and Pb-Au [9]. The common feature of all results from nuclear collisions was an excess of the observed dilepton yield above the known electromagnetic decays of the produced neutral mesons, by a factor of 2-3, for masses above

0.2 GeV. The surplus yield has generally been attributed to direct thermal radiation from the fireball, dominated by two-pion annihilation $\pi^+\pi^- \to \rho \to l^+l^-$ with an intermediate ρ which is strongly modified by the medium. Statistical accuracy and mass resolution of the data were, however, not sufficient to reach any sensitivity on the *character* of the in-medium changes.

The new experiment NA60 at the CERN SPS has now achieved a decisive breakthrough in this field. The apparatus is based on the muon spectrometer previously used by NA50, and a newly added telescope of radiation-tolerant silicon pixel detectors, embedded inside a 2.5 T dipole magnet in the vertex region [10]. Matching of the muon tracks before and after the hadron absorber both in *coordinate and momentum* space improves the dimuon mass resolution in the region of the light vector mesons from ~80 to ~20 MeV and also decreases the combinatorial background of muons from π and K decays. Moreover, the additional bend by the dipole field leads to a strong increase of the detector acceptance for dimuons of low mass and low transverse momentum. Finally, the selective dimuon trigger and the fast readout speed of the pixel telescope allow to run at very high luminosities.

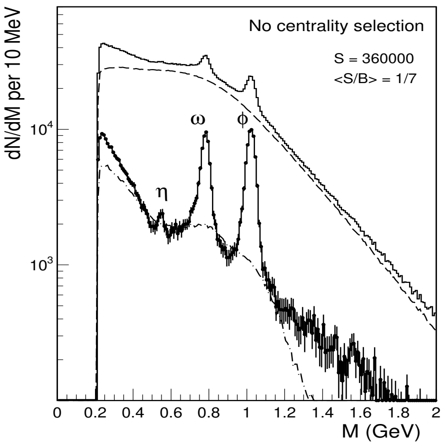

Figure 1. Dimuon mass spectra of the total data (upper histogram), combinatorial background (dashed), fake matches (dashed-dotted), and net spectrum after subtraction of the former two (lower)

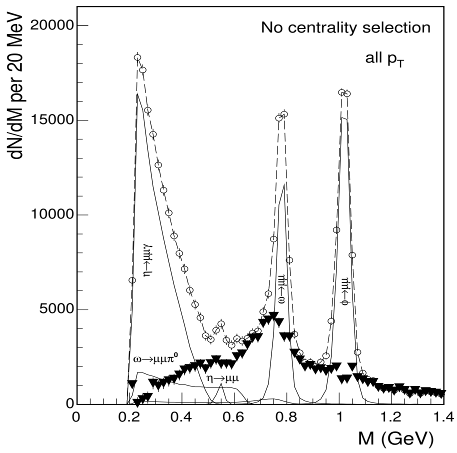

Figure 2. Isolation of the excess (see text). Total data (open circles), decay sources (solid), difference data (thick triangles), sum of decay sources and difference data (dashed)

The results reported here were obtained from the analysis of data taken in 2003 for In-In at 158 AGeV . The main steps of the analysis are reconstruction of the muon-spectrometer tracks, pattern recognition and tracking in the pixel telescope including reconstruction of the interaction vertex, and track matching. The major background left after matching is the combinatorial background of uncorrelated muon pairs from π and K decays. It is assessed with a *mixed-event technique* [11]; the accuracy reached is about 1%. After subtraction of this background, the remaining data still have to be corrected for fake matches, i.e. associations of muons to non-muon tracks in the pixel-telescope. This background is minor, about 7% of the former. It has been estimated both with an overlay MC method and with event-mixing [11]; the two methods agree to within 5%.

The dimuon mass spectra associated with the different analysis steps are shown in

Fig. 1. The net spectrum contains about 360 000 pairs, with a mean signal-to-background ratio of 1/7. For the first time in nuclear collisions, the vector mesons ω and ϕ are clearly visible in the dilepton channel; even the $\eta \to \mu\mu$ decay is seen. The mass resolution at the ω is ~20 MeV. The further analysis is done in 4 different classes of collision centrality, based on the charged-particle multiplicity distribution from the pixel telescope. The nomenclature used below is peripheral ($dN_{ch}/d\eta$=4-30), semiperipheral ($dN_{ch}/d\eta$=30-110), semicentral ($dN_{ch}/d\eta$=110-170) and central ($dN_{ch}/d\eta$=170-240).

The peripheral data can be well described on the basis of known sources. Muon pairs arising from the resonance (η, ρ, ω, ϕ) and Dalitz (η, η', ω) decays of the produced mesons were propagated through the NA60 set-up with GEANT, using the generator GENESIS [7, 12] as input. Four free parameters were used in the fit of this "hadron decay cocktail" to the data: the cross section ratios η/ω, ρ/ω, ϕ/ω and the level of charm decays. The fits were independently done in 3 bins of dimuon transverse momenta: p_T<0.5, 0.5<p_T<1 and p_T>1 GeV/c. The fit results for η/ω agree, within <10%, with the world average for pp, pBe [7]. The ratio ϕ/ω is higher by a factor of 1.8, as to be expected due to ϕ enhancement. Both ratios are, within 10%, independent of the pair p_T. The results imply that the acceptance of NA60, both in mass and p_T, is well under control.

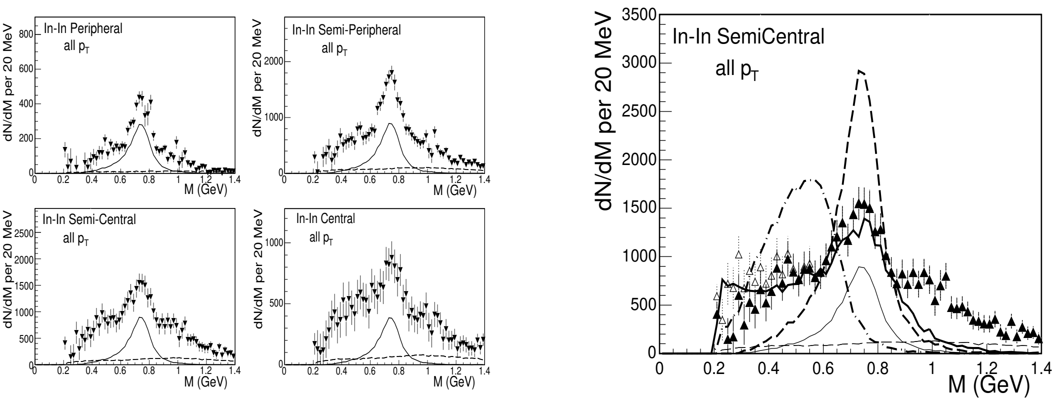

Figure 3. Excess mass spectra of dimuons; the cocktail ρ (thin solid) and the level of combinatorial charm (thin dashed) are shown for comparison. Left: Centrality dependence. Right: Comparison to model predictions [13], made for In-In at $dN_{ch}/d\eta$=140. Unmodified ρ (thick dashed), in-medium broadening ρ (Rapp/Wambach, thick solid), in-medium moving ρ (related to Brown/Rho scaling, dashed-dotted). The open data points reflect the change in the difference spectrum resulting from a decrease of the η-yield by 10%.

In the more central bins, a fit procedure is ruled out, due to the existence of a strong excess with *a priori unknown* characteristics. We have, therefore, used a novel procedure as shown in Fig. 2, made possible by the excellent data quality. The excess is *isolated* by subtracting the cocktail (without the ρ) from the data. The cocktail is fixed, separately in each centrality bin, by a most "conservative" approach. For the η, an upper limit is defined by "saturating" the measured data in the region close to 0.2 GeV; this leads to a *lower* limit (zero) for the excess at very low mass, by construction. The yields of the narrow vector mesons ω and ϕ are fixed such as to get, after subtraction, a *smooth* underlying continuum. The η resonance- and ω Dalitz decays are now bound as well. The *cocktail* ρ (only required in Fig. 3) is bound by the ratio ρ/ω=1.2. The accuracy in the determination of the η, ω and ϕ yields by this subtraction procedure is on the level of 1-2%, due to the remarkable *local* sensitivity.

The excess mass spectra for all 4 multiplicity bins are shown in Fig. 3 (left). The qualitative features of the spectra are striking: a ρ-like structure is seen in all cases, remaining centered at the position of the nominal ρ-pole, but broadening strongly with centrality. At the same time, the total yield increases relative to the cocktail ρ, reaching values >4 for the most central bin. The errors attached to the data points are purely statistical. The systematic errors in the broad continuum region underlying the ρ-like structure are estimated to be about 3%, 12%, 25% and 25% in the 4 centrality bins. The qualitative features of these spectra are consistent with an interpretation of the excess as dominantly due to $\pi\pi$ annihilation. In Fig. 3 (right), two of the theoretical scenarios mentioned in the introduction are confronted with the data. Note that the integrals of the theoretical spectra are normalized to the data in the mass interval 0.2<M<0.9 GeV. The unmodified ρ and the specific moving-mass scenario plotted are clearly ruled out. The broadening scenario appears more realistic; for M>0.9 GeV, however, the data show a nearly symmetrical broadening around the ρ pole. Processes other than 2π, i.e. 4π, 6π... could possibly account for this region [13].

All the data shown have not been corrected for the mass- and p_T- dependent acceptance of the NA60 set-up. The theoretical calculations shown in Fig. 3 were therefore also propagated through the acceptance filter. It is interesting to note that, *by accident*, the propagation of theoretical calculations based on a white spectral function (e.g. $q\overline{q}$ annihilation [13]) yields a white mass spectrum up to about 1 GeV. In other words, the always existing steep rise of the theoretical input at low masses, due to the photon propagator and a Boltzmann-like factor [4–6], is just about compensated by the falling acceptance in this region. The data and model predictions shown in Fig. 3 can therefore be directly interpreted as spectral functions of the ρ, averaged over momenta and the complete space-time evolution of the fireball. The flat part of the measured spectra may thus reflect the early history with a nearly divergent width, while the narrow peak on top may just be due to the late part, approaching the nominal width.

We conclude, independent of any comparison to theoretical modeling, that the ρ primarily broadens in In-In collisions, but does not show any noticeable shift in mass.

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