

**Modification of the  $\rho$ -meson detected by low-mass  
electron-positron pairs in central Pb-Au collisions at 158A GeV/c**

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## Abstract

We present a measurement of  $e^+e^-$  pair production in central Pb-Au collisions at  $158A$  GeV/ $c$ . As reported earlier, a significant excess of the  $e^+e^-$  pair yield over the expectation from hadron decays is observed. The improved mass resolution of the present data set, recorded with the upgraded CERES experiment at the CERN-SPS, allows for a comparison of the data with different theoretical approaches. The data clearly favor a substantial in-medium broadening of the  $\rho$  spectral function over a density-dependent shift of the  $\rho$  pole mass at SPS energy. The in-medium broadening model implies that baryon induced interactions are the key mechanism to in-medium modifications of the  $\rho$ -meson in the hot fireball.

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Only a small fraction of the visible mass in the universe is furnished by the rest masses of its fundamental constituents. The masses of hadrons are created dynamically by the strong interaction, when confinement forces quarks and gluons to form color-neutral bound states. The generation of hadronic masses is connected to spontaneous chiral symmetry breaking, a basic feature of the vacuum structure of Quantum-Chromo-Dynamics (QCD). Evidently, the mechanism of chiral symmetry breaking is of fundamental importance for the properties of matter in the universe. However, the quantitative understanding of the dynamics in this non-perturbative regime of QCD is still rather incomplete, and additional information from experiment is essential.

According to investigations of the non-perturbative properties of QCD on a discrete space-time lattice a plasma of deconfined quarks and gluons (QGP) should be reached at energy densities  $\epsilon \geq 1 \text{ GeV/fm}^3$ . Simultaneously with this deconfinement transition, chiral symmetry is expected to be restored (see [1] for a recent review). In collisions of heavy nuclei at high energies such energy densities are exceeded significantly and there is by now strong, albeit indirect evidence for the formation of a QGP (for recent reviews see [2, 3, 4, 5]). On the way to chiral symmetry restoration in such matter, significant modifications of the properties of hadrons are expected [6], such as of their mass and width or more generally of the hadronic spectral function.

The  $\rho$ -meson ( $J^P = 1^-$ ) is an ideal probe to investigate modifications of such in-medium properties. In a hot hadronic medium close to the phase boundary,  $\rho$ -mesons are abundantly produced by annihilation of thermal pions. Due to its short lifetime ( $c\tau = 1.3 \text{ fm}$ ), the decay of the  $\rho$ -meson occurs inside the medium, and spectral modifications may be observable via the kinematic reconstruction of the decay products. Finally, its decay into lepton pairs provides essentially undisturbed information from the hot and dense phase, because leptons are not subject to final state rescattering in the strongly interacting medium.

Enhanced low-mass  $e^+e^-$  pair production in nucleus-nucleus collisions at full energy of the CERN-Super-Proton-Synchrotron (SPS) has been reported by the CERES experiment. In particular, in the mass region  $0.2\text{-}0.6 \text{ GeV}/c^2$ , the measured di-lepton yield exceeds expectations from hadron decays by a factor 2-3 [8, 9, 10]. Even bigger enhancement factors have been found at  $40A \text{ GeV}/c$  [11], albeit with large statistical uncertainties.

Significant  $\rho$ -meson production via annihilation of thermal pions in the hot and dense hadronic medium is a likely mechanism for enhanced electron pair production. Implementing

this mechanism, substantial temperature and baryon density dependent modifications of the  $\rho$ -spectral function [7, 12, 13] needed to be considered to explain the mass spectrum of the pair enhancement. However, the detailed behaviour of the spectral function as chiral symmetry is restored is still up to speculation. Quite different theoretical approaches exist which could not be discriminated by the previous di-electron data.

The NA60 Collaboration recently corroborated previous CERES findings and reported a significant di-muon excess in nucleus-nucleus collisions over the expectation from hadronic decays [14]. The NA60 measurement of the di-muon excess in  $^{115}\text{In-In}$  collisions at 158A GeV/c favors models including significant broadening but no mass shift of the  $\rho$ -spectral function [14, 15].

In this Letter, we present results on  $e^+e^-$  pair production in central  $^{208}\text{Pb-}^{197}\text{Au}$  collisions at 158A GeV/c. The data have been recorded by the CERES experiment at the SPS in the year 2000. Typically,  $10^6$  Pb ions per 5.2 s extraction cycle were focused on 13 thin Au targets aligned along the beam line (25  $\mu\text{m}$  each, totalling 1.2% of a nuclear interaction length). The interaction vertex was reconstructed using charged particle track segments from two silicon drift detectors (SDD) placed 10.4 and 14.3 cm behind the target. Electrons are identified by their ring signature in two RICH detectors, which are blind to hadrons below  $p \approx 4.5$  GeV/c ( $\gamma_{\text{thresh}} \approx 32$ ). The experimental setup was upgraded by a downstream radial drift Time Projection Chamber (TPC) which is operated inside an inhomogeneous magnetic field with a radial component of up to 0.75 T. Employing tracking information from the TPC, the mass resolution of the spectrometer was improved to  $\Delta m/m = 3.8\%$  in the region of the  $\phi$ -meson mass [16]. The TPC also provides additional electron identification via measurement of the specific energy loss  $dE/dx$  with a resolution of about 10%. The spectrometer provides full azimuthal acceptance in the pseudorapidity range  $2.1 < \eta < 2.65$ .

The present results are based on an analysis [17, 18] of 18.2 million Pb-Au events, selected at a centrality of  $\sigma/\sigma_{\text{geo}}=7\%$  [19]. SDD track segments are matched to charged particle tracks in the TPC, where the deflection in the magnetic field determines the momentum with a resolution of  $\Delta p/p \approx ((2\%)^2 + (1\% \cdot p(\text{GeV}/c))^2)^{1/2}$  [16]. Combined electron information from cuts on the ring quality in the RICH detectors and TPC  $dE/dx$  leads to a pion suppression of typically  $4 \cdot 10^4$  at 67% electron efficiency [17].

In the next step, electrons and positrons from the same event are combined to pairs. To minimize the amount of combinatorial background, tracks which form pairs with opening

angle smaller than 35 mrad are treated as recognized conversions or Dalitz pairs and are not used for further pairing. The same applies to pairs with invariant mass  $m_{ee} < 0.2 \text{ GeV}/c^2$  and opening angle smaller than 35 mrad.

Additional checks are done on the remaining tracks to further suppress combinatorial background from unrecognized Dalitz pairs, making use of their characteristic decay topology. Electron and positron tracks are rejected if their  $dE/dx$  significantly exceeds that of a single track in both SDDs, indicating an unresolved close pair. Also, electron/positron tracks are rejected if a soft track with opposite charge and electron-like  $dE/dx$  is found in the TPC at small angular separation. Finally, a low transverse momentum cut of  $0.2 \text{ GeV}/c$  is applied to all electron and positron tracks.

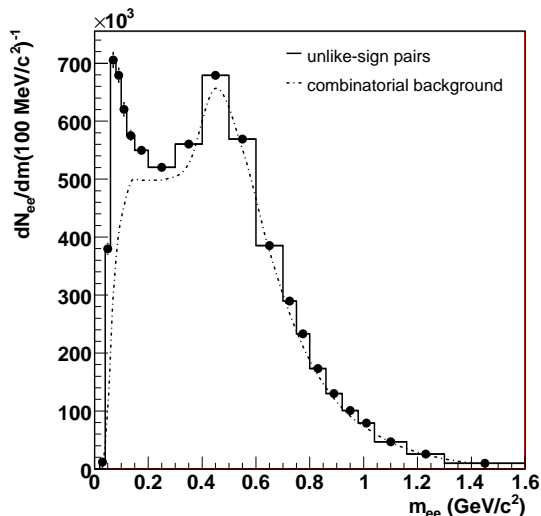


FIG. 1: Unlike-sign pair yield (histogram) and combinatorial background (dashed curve). See text for explanation.

The remaining combinatorial background can be estimated by combinations of like-sign lepton pairs from the same event. Due to the limited statistics of the like-sign pair sample, this adds a significant statistical error to the final result. Alternatively, a mixed-event technique can be applied, where unlike-sign pairs are formed from electron and positron tracks of different events and the corresponding mixed-event spectrum is normalized to the same-event like-sign yield. This approach reduces considerably the statistical bin-to-bin fluctuations but bears a statistical and systematic uncertainty due to the normalization procedure.

We found that the results from both methods are in good agreement within statistical errors [17]. Small deviations are only visible at invariant masses below  $0.1 \text{ GeV}/c^2$ . This is caused by limitations in the two-ring separation, which are only present in the same-event sample. To account for this effect, which is also present in the 'true' unlike-sign combinatorial background, we have used the same-event like-sign background estimate for masses below  $0.2 \text{ GeV}/c^2$ . No statistical limitation is imposed by this procedure, since the signal-to-background ratio is very good in this mass region. For masses greater than  $0.2 \text{ GeV}/c^2$ , the normalized mixed-event unlike-sign sample is used for background subtraction. The resulting background distribution  $B$  and the unlike-sign signal pair spectrum are shown in Fig.1.

Below  $m_{ee}=0.2 \text{ GeV}/c^2$  the  $\pi^0$ -Dalitz contribution is clearly visible. After subtraction of the background  $B$ , the raw net yield  $S$  in this mass range is  $S = 5470 \pm 168$  pairs at a signal-to-background ratio  $S/B=1/2$ . At masses larger than  $0.2 \text{ GeV}/c^2$ , the number of pairs after background subtraction is  $S = 2818 \pm 348$  at  $S/B=1/21$ .

After background subtraction, the  $e^+e^-$  pair yield is normalized to the total number of events and to the average charged particle multiplicity  $\langle N_{\text{ch}} \rangle$  in the acceptance, and corrected for the pair reconstruction efficiency. The average charged particle multiplicity has been determined by the number of tracks in the SDD. For the 7% most central events we obtain  $\langle N_{\text{ch}} \rangle = 183 \pm 22$  in  $2.1 < \eta < 2.65$ . The reconstruction efficiency has been determined by a Monte-Carlo (MC) procedure where simulated tracks are embedded into real raw data events. The subsequent analysis of the MC sample includes all cuts and methods as applied to the real data. The final pair reconstruction efficiency is typically 20% and is defined by the product of the single electron efficiencies, which depend on the track angle and (slightly) on centrality.

The  $e^+e^-$  invariant mass distribution after normalization and combinatorial background subtraction is shown in Fig. 2 (a). Also shown is the 'hadronic cocktail' which comprises the yield from hadronic decays in A-A collisions (see [10]) [26]. In the mass range  $0.2 < m_{ee} < 1.1 \text{ GeV}/c^2$ , the data are enhanced over the cocktail by a factor  $2.58 \pm 0.32$  (stat)  $\pm 0.41$  (syst)  $\pm 0.77$  (decays). The last error arises from the systematic uncertainty in the cocktail calculation. The enhancement is most pronounced in the mass region  $0.2 < m_{ee} < 0.6 \text{ GeV}/c^2$ , in agreement with earlier findings. In contrast to previous CERES results, the improved mass resolution of the upgraded spectrometer provides access to the resonance

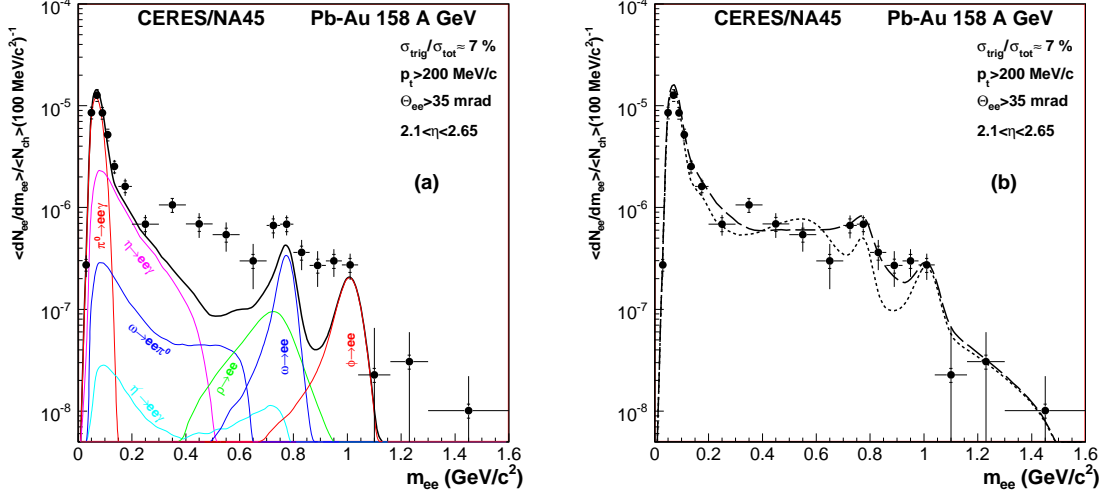


FIG. 2: a: Invariant  $e^+e^-$  mass spectrum compared to the expectation from hadronic decays. b: the same data compared to calculations including a dropping  $\rho$  mass (dashed) and a broadened  $\rho$  spectral function (long-dashed).

structure in the  $\rho/\omega$  and  $\phi$  region. A quantitative study of  $\phi$ -meson production in the  $e^+e^-$  and  $K^+K^-$  channels can be found in [20].

In Fig. 2 (b) the data are compared with a model approach implying enhanced di-lepton production via thermal pion annihilation and a realistic space-time evolution [21]. Thereby, temperature and baryon-density dependent modifications of the  $\rho$  spectral function have been taken into account: the dropping mass scenario which assumes a shift of the in-medium  $\rho$  mass [7, 13], and the broadening scenario where the  $\rho$  spectral function is smeared due to coupling to the hadronic medium [12, 15]. The calculations include as well contributions from QGP, the Drell-Yan process, and 4-pion annihilation with chiral mixing. The calculations for both spectral functions describe the enhancement reasonably well for masses below  $0.6 \text{ GeV}/c^2$ . However, in the mass region between the  $\omega$  and the  $\phi$ , the data clearly favor the broadening scenario ( $\chi^2/\text{dof} = 0.39$ ) over the dropping mass scenario ( $\chi^2/\text{dof} = 2.22$ ).

In order to exhibit the shape of the in-medium contribution, we subtract the hadronic cocktail (excluding the  $\rho$ -meson) from both the data and the calculations (Fig. 3). The vacuum  $\rho$ -decay contribution to the data is completely negligible compared to the measurements (solid line in Fig. 3). The data exhibit a very broad structure reaching very low masses. Again, the data are compared to model calculations which use the normal-

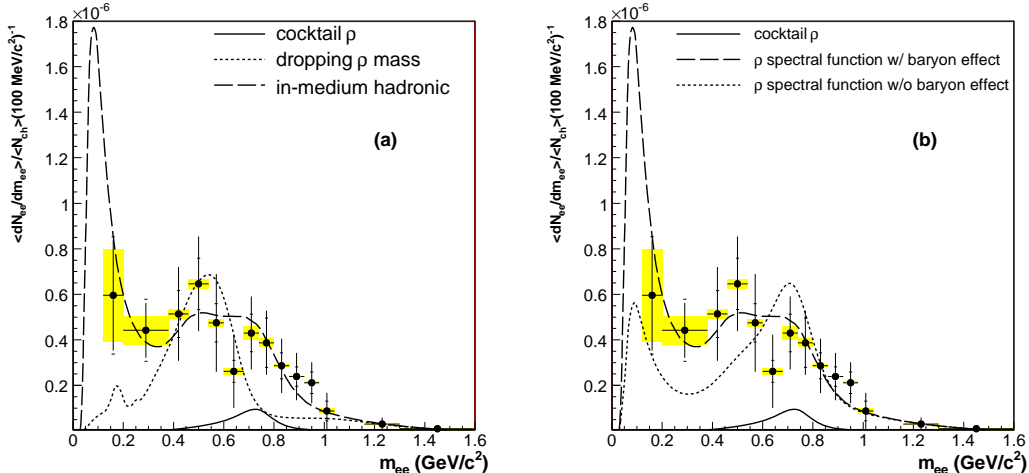


FIG. 3:  $e^+e^-$  pair yield after subtraction of the hadronic cocktail. In addition to the statistical error bars, systematic errors of the data (horizontal ticks) and the systematic uncertainty of the subtracted cocktail (shaded boxes) are indicated. The broadening scenario (long-dashed line) is compared to a calculation assuming a density dependent dropping  $\rho$  mass (a) and to a broadening scenario excluding baryon effects (b).

ization to the number of charged particles as the data. No rescaling of theory to data is used. Yield and spectral shape are well described by the broadening scenario but are not consistent[27] with a dropping  $\rho$  mass (Fig. 3 (a)). While the dropping mass calculation is peaked around  $0.5 \text{ GeV}/c^2$  the measured excess is spread over a significantly wider mass range. Below  $0.2 \text{ GeV}/c^2$ , the large errors arising from the subtraction of large numbers in the  $\pi^0$  Dalitz region do not allow for a definite conclusion. However, the trend indicates a further increase of the in-medium contribution towards the photon point. The agreement of the data with the broadening scenario may imply that the resonance structure of the  $\rho$ -meson is significantly modified in the hot and dense medium, in possible connection to the onset of chiral symmetry restoration [15].

The broadening scenario implies a strong coupling to baryons which adds strength to the di-lepton yield at low masses [12]. The importance of this mechanism is demonstrated in Fig. 3 (b), where the data are compared to broadening scenarios with and without baryon-induced interactions [15, 21]. The calculations differ most in the mass range below  $0.5 \text{ GeV}/c^2$ , which is accessible with good efficiency by the present  $e^+e^-$  data. The



calculation omitting baryon effects falls short of the data for masses below  $0.5 \text{ GeV}/c^2$  while inclusion of baryon interactions describes the measured low-mass yield very well. This indicates that the observed changes in the  $\rho$  spectral function are due to interactions of the  $\rho$ -meson with the dense baryonic medium.

It has been demonstrated that baryon-driven medium modifications lead to a low-mass di-electron spectrum which is very similar to the di-electron rate from lowest order perturbative  $q\bar{q}$  annihilation [22]. Inspired by this apparent emergence of quark-hadron duality at low masses, Gallmeister et al. performed a calculation assuming that di-electron production via  $q\bar{q}$  annihilation at  $T_c$  is dominant. This phenomenological approach also describes the shape of the measured distributions (Fig. 3) very well.

In conclusion, the present  $e^+e^-$  data with improved mass resolution in the resonance region clearly favor models including a strong broadening of the  $\rho$  spectral function in a hot and dense hadronic medium over a density dependent  $\rho$  mass shift. Moreover, the  $e^+e^-$  data at low pair mass and transverse momentum allow to test the relevance of baryonic effects to the modification of the  $\rho$  spectral function. In comparison with models, the present CERES data suggest that baryonic interactions are important to explain the observed di-lepton yield at low masses.

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