

**Dielectron Production in  $^{12}\text{C} + ^{12}\text{C}$  Collisions at 2A GeV with the HADES Spectrometer**

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The invariant-mass spectrum of  $e^+e^-$  pairs produced in  $^{12}\text{C} + ^{12}\text{C}$  collisions at an incident energy of 2 GeV per nucleon has been measured for the first time. The measured pair production probabilities span over 5 orders of magnitude from the  $\pi^0$ -Dalitz to the  $\rho/\omega$  invariant-mass region. Dalitz decays of  $\pi^0$  and  $\eta$  account for all the yield up to 0.15 GeV/ $c^2$ , but for only about 50% above this mass. A comparison with model calculations shows that the excess pair yield is likely due to baryon-resonance and vector-meson decays. Transport calculations based on vacuum spectral functions fail, however, to describe the entire mass region.

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The properties of hot and dense hadronic matter represent a key problem in heavy-ion physics, with far-reaching applications for other fields. They are governed by non-perturbative QCD and cannot be derived directly from the

underlying Lagrangian. Models predict that hadron properties, such as mass and lifetime, depend on the temperature and density of the medium. While some hadronic many-body calculations give a broadening of the meson

in-medium spectral function, other approaches predict dropping meson masses as precursors of chiral symmetry restoration [1].

Experimentally, in-medium properties are difficult to observe. Suitable probes are dileptons ( $\mu^+\mu^-$  or  $e^+e^-$ ) from decays of short-lived resonances produced inside the hadronic matter created in the course of relativistic or ultrarelativistic heavy-ion collisions. At the CERN Super Proton Synchrotron (SPS), the CERES Collaboration has established a significant excess of the dielectron yield as compared to that expected from the decays of hadrons after chemical freeze-out in 40 and 158A GeV Pb + Au collisions [2]. At 1A GeV, the DLS Collaboration found unexpectedly large electron-pair yields in C + C and Ca + Ca collisions [3]. In contrast to the situation at SPS beam energies, the DLS results cannot be described satisfactorily within the various scenarios proposed for possible changes of the in-medium spectral functions [1,4,5]. Indeed, the pair yields in the invariant-mass range between 0.15 and 0.6 GeV/ $c^2$ , i.e., just below the  $\rho$  meson pole mass, still remain to be explained [6–9]. Recently, the NA60 Collaboration has published new data on dimuon production which allow a determination of the in-medium spectral function of the  $\rho$  meson in 158A GeV In + In collisions [10].

The High-Acceptance DiElectron Spectrometer HADES at GSI, Darmstadt, operates in the SIS/Bevalac energy regime of 1–2A GeV. In this Letter we report on the first measurement of inclusive electron-pair production in  $^{12}\text{C} + ^{12}\text{C}$  collisions at a kinetic beam energy of 2A GeV.

A carbon beam of  $10^6$  particles/s was incident on a twofold segmented carbon target with a thickness corresponding to  $2 \times 2.5\%$  interaction lengths. The HADES spectrometer, described in detail in Refs. [11,12], consists of a 6-coil toroidal magnet centered on the beam axis and six identical detection sections located between the coils and covering polar angles between  $18^\circ$  and  $85^\circ$ . In the measurement presented here, each sector was composed of a gaseous Ring-Imaging Cherenkov (RICH) detector, two planes of Mini-Drift Chambers (MDC-I and MDC-II) for track reconstruction, and a Time-of-Flight wall (TOF/TOFino) supplemented at forward polar angles with Pre-SHOWER chambers. The interaction time was obtained from a fast diamond start detector located upstream of the target. This geometry results in a smooth dielectron acceptance, shown in Fig. 1 as a function of invariant-mass and transverse momentum, averaged over the rapidity range  $0 < y < 2$ . The data readout was started by a first-level trigger (LVL1) decision, requiring a charged-particle multiplicity  $MUL \geq 4$  in the TOF/TOFino detectors, accepting 60% of the total cross section. It was followed by a second-level trigger (LVL2) requesting at least one electron track. With this trigger condition, a tenfold pair enrichment at a pair efficiency of  $\geq 92\%$  was achieved. Furthermore, the LVL2 introduced no bias on the shapes

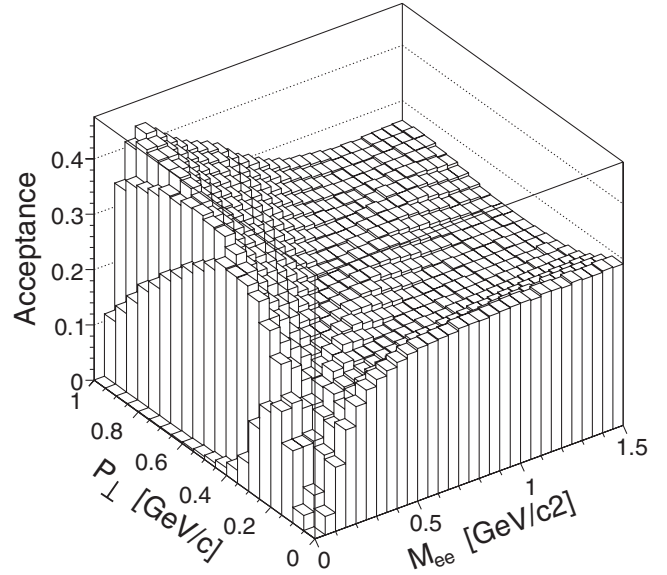


FIG. 1. Geometrical acceptance of the HADES spectrometer for  $e^+e^-$  pairs with laboratory opening angle  $\theta_{e+e-} > 9^\circ$  as a function of their invariant mass and transverse momentum.

of measured pair distributions, as checked by a direct comparison to the unbiased LVL1 events.

The results presented below were obtained from events with a positive LVL2 decision with a total statistics corresponding to  $6.5 \times 10^8$  LVL1 events. The electron track reconstruction proceeded in four steps (see also [12]): (1) the RICH ensures electron detection for momenta  $p > 0.05$  GeV/ $c$ . From the measured ring positions, polar ( $\theta$ ) and azimuthal ( $\phi$ ) angles are calculated assuming electron emission from the target. (2) The  $\theta$ ,  $\phi$  values of electron candidates in the RICH were correlated with the track angles reconstructed in the MDC within windows corresponding to  $\pm 2$  standard deviations, as derived from the electron distributions. (3) Candidate tracks were then matched with those hits in the TOF or TOFino/Pre-SHOWER detectors fulfilling electron conditions, i.e., (a) a particle velocity of  $\beta = 1 \pm 3\sigma_\beta$ , with  $\sigma_\beta$  given by the time-of-flight resolution, and (b) an electromagnetic shower signal in the Pre-SHOWER. (4) Finally, the track momentum was determined by a fit of an appropriate track model to the reconstructed hit positions making use of the deflection in the known magnetic field.

The identified single-electron tracks were combined into opposite-sign pairs from which invariant-mass distributions, with the mass resolution  $\sigma_{M_{ee}}/M_{ee} = 9\%$  at  $M_{ee} = 0.8$  GeV/ $c^2$ , were built. Many of these  $e^+e^-$  pairs, however, represent combinatorial background (CB) which has to be reduced and subtracted. The CB is mostly due to uncorrelated electrons from  $\pi^0 \rightarrow \gamma\gamma$  decays followed by photon conversion, either in the target or in the RICH radiator, and/or from  $\pi^0 \rightarrow e^+e^-\gamma$  Dalitz decays. Such pairs have small opening angles and often produce partially overlapping tracks in the MDC. They are rejected effi-

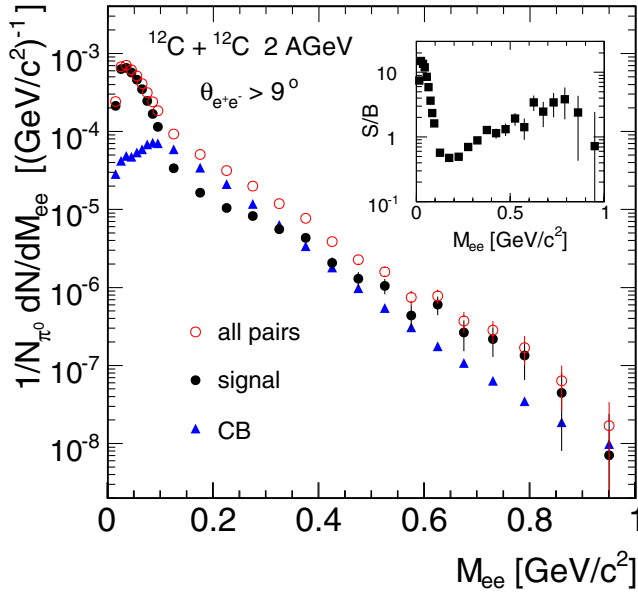


FIG. 2 (color online). Reconstructed (not efficiency corrected)  $e^+e^-$  invariant-mass distributions ( $\circ$ ) for pairs with opening angles  $\theta_{e^+e^-} > 9^\circ$ . The signal distribution ( $\bullet$ ) was obtained by subtracting the combinatorial background ( $\blacktriangle$ ). Errors indicated are statistical only. Inset: signal-to-background ( $S/B$ ) ratio vs invariant mass.

ciently by applying conditions on the opening angle,  $\theta_{e^+e^-} > 9^\circ$ , and on the fit quality ( $\chi^2$ ) of the reconstructed track segments, removing 95% of the conversion pairs while reducing the dielectron signal with  $M_{ee} > 0.15 \text{ GeV}/c^2$  by less than 10%.

Figure 2 shows the resulting  $e^+e^-$  invariant-mass distribution, its signal part, the CB, and the resulting signal/CB ratio. Like-sign  $e^+e^+$  and  $e^-e^-$  pairs were formed and subjected to the same selection criteria as the opposite-sign pairs. From the reconstructed like-sign invariant-mass distributions,  $dN^{++}/dM_{ee}$  and  $dN^{--}/dM_{ee}$ , the respective CB distribution was calculated as  $N_{CB} = 2\sqrt{N^{++}N^{--}}$ . For masses  $M_{ee} > 0.5 \text{ GeV}/c^2$ , where statistics are smaller, the CB was obtained by an event mixing procedure. Uncorrelated opposite-sign  $e^+e^-$  pairs were formed from different events but originating from reactions in the same target segment. It was verified that for  $M_{ee} > 0.15 \text{ GeV}/c^2$  the CB distributions obtained from the event mixing and the like-sign pairs agree within 10%. All distributions were normalized to the number of neutral pions  $N_{\pi^0}$  (see below). In total  $\approx 23\,000$  signal pairs ( $\approx 2000$  with  $M_{ee} > 0.15 \text{ GeV}/c^2$ ) were reconstructed.

We corrected the spectra for detector and reconstruction inefficiencies by Monte Carlo simulations embedding electron tracks with uniform  $1/p$  and isotropic angular distributions into  $^{12}\text{C} + ^{12}\text{C}$  events generated with the UrQMD transport model [13]. The resulting events were digitized and processed through the same analysis chain as the

measured data. The single-electron efficiencies,  $\epsilon_{\pm}$ , were calculated as a function of charge ( $\pm$ ), momentum ( $p$ ), polar ( $\theta$ ), and azimuthal ( $\phi$ ) emission angles. The data were corrected on a pair-by-pair basis with the weighting factor  $1/E_{+-}$ , with  $E_{+-} = \epsilon_+ \epsilon_-$  for given electron momenta and emission angles,  $E_{+-}$  ranging from 12% at  $M_{ee} = 0.1 \text{ GeV}/c^2$  to 25% at  $M_{ee} = 0.8 \text{ GeV}/c^2$ . The CB was treated likewise and subtracted, as described above, to obtain the efficiency-corrected pair signal distribution. This prescription relies on the assumption that the single-leg efficiencies are independent, as was carefully checked in our simulations and proven to be valid within 15% for pairs with opening angles  $\theta_{e^+e^-} > 9^\circ$ . The geometrical pair acceptance of the HADES detector was obtained in analogy to the pair efficiency as the product of two single-electron acceptances  $A_{\pm}(p, \theta, \phi)$ . The resulting matrices, together with a momentum resolution function, constitute the HADES acceptance filter (available upon request). We made no attempt to extrapolate the measured dielectron yields to the full solid angle.

Figure 3(a) shows the  $e^+e^-$  invariant-mass distribution of the signal pairs after efficiency correction and normalized to the average number of charged pions  $N_{\pi} = \frac{1}{2} \times (N_{\pi^+} + N_{\pi^-})$ . The latter were identified in HADES by means of the time-of-flight measurement [12] and their yield was extrapolated to full solid angle, taking into account our measured angular distributions and found to be in agreement with UrQMD calculations. In the isospin-symmetric system  $^{12}\text{C} + ^{12}\text{C}$ ,  $N_{\pi}$  is in fact a good measure of the  $\pi^0$  yield. This way of normalizing the pair spectra compensates to first order the bias caused by the implicit centrality selection of our trigger. Indeed, simulations based on UrQMD events indicate that LVL2 events have an average number of participating nucleons  $A_{\text{part}} = 9.0$ , instead of 6 for true minimum-bias events. The pion multiplicity per number of participating nucleons  $M_{\pi}/A_{\text{part}} = 0.137 \pm 0.015$  obtained in our experiment agrees with previous measurements of charged and neutral pions [14,15] within the quoted error of 11%. The error is dominated by systematic uncertainties in the acceptance and efficiency corrections of the charged-pion analysis and represents our overall normalization error. In addition, the systematical uncertainties related with the efficiency correction and the CB subtraction, explained above, add up quadratically to an error of 18% on  $dN^{+-}/dM_{ee}$  which appears to be nearly constant over the whole mass range.

We first compare our results with a pair cocktail (cocktail A) calculated from free  $\pi^0$ ,  $\eta$ , and  $\omega$  meson decays only [Fig. 3(a)]. This cocktail aims at representing all contributions emitted after the chemical freeze-out of the fireball. While the first two sources are directly constrained by data with their uncertainties of 10% ( $\pi^0$ ) and 15% ( $\eta$ ), respectively [14], the production rate of the  $\omega$  meson is taken from an  $m_{\perp}$ -scaling ansatz [16]. In our event generator (PLUTO [17]) meson production was hence mod-

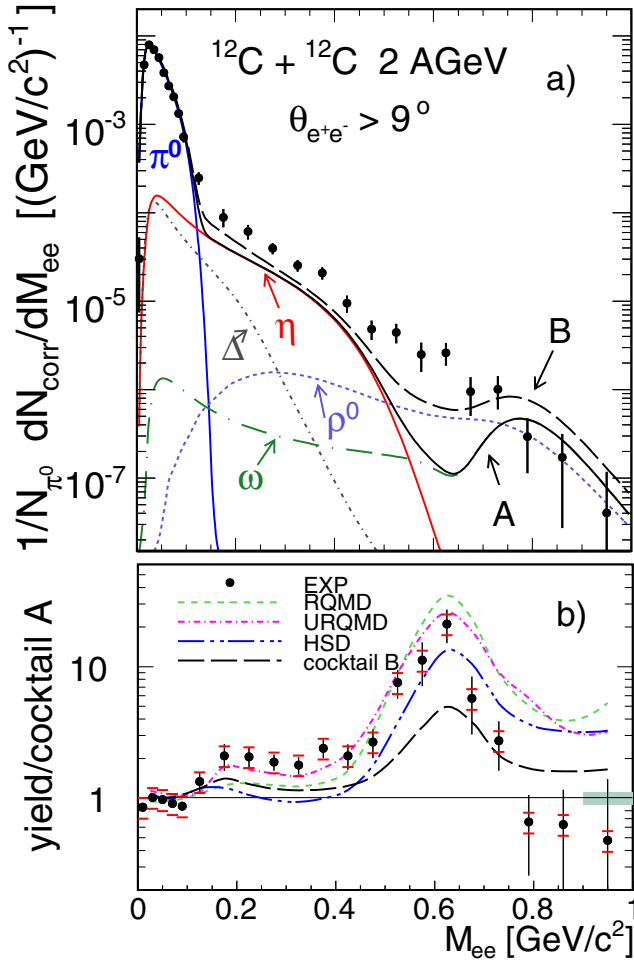


FIG. 3 (color online). (a) Efficiency- and background-corrected  $e^+e^-$  invariant-mass distribution for  $\theta_{e^+e^-} > 9^\circ$  (symbols) compared to a thermal dielectron cocktail of free  $\pi^0$ ,  $\eta$ , and  $\omega$  decays (cocktail A, solid line), as well as including  $\rho$  and  $\Delta$  resonance decays (cocktail B, long-dashed line). Only statistical errors are shown. (b) Ratio of data and cocktail A (●), compared to ratios of various model calculations and cocktail A. All calculations have been filtered and folded with the HADES acceptance and mass resolution. Statistical and systematic errors of the measurement are shown as vertical and horizontal lines, respectively. The overall normalization error of 11% is depicted by the shaded area.

eled assuming emission from a thermal source with a temperature  $T = 80$  MeV, but no radial expansion velocity ( $\beta_r = 0$ ). Furthermore, for the  $\pi^0$  mesons, an anisotropic angular distribution of the type  $dN/d\cos(\theta_{CM}) \sim 1 + a_2\cos^2(\theta_{CM})$  with  $a_2 = 0.7$  was used, as deduced from our charged-pion analysis. The accepted lepton-pair yield was found to change by less than 14% when varying the source parameters over a broad range:  $\beta_r$  (0–0.3),  $a_2$  (0–1.0), and  $T$  (50–90 MeV).

While experimental data and simulated cocktail A [solid line in Fig. 3(a)] are in good agreement in the  $\pi^0$  region, the cocktail undershoots the data for  $M > 0.15$  GeV/ $c^2$

and clearly calls for additional sources. Such contributions are indeed expected from the decay of short-lived resonances, mainly the  $\Delta(1232)$  and the  $\rho$ , excited in the early phase of the collision. To include in our cocktail pairs from  $\Delta^{0,+} \rightarrow Ne^+e^-$  decays, we assumed that the  $\Delta$  yield scales with the  $\pi^0$  yield and employed a calculated decay rate [9]. To add the  $\rho$  meson we used a similar prescription as for the  $\omega$ . For this broad resonance ( $\Gamma_\rho = 150$  MeV),  $m_\perp$  scaling strongly enhances the low-mass tail, resulting in the skewed shape visible in Fig. 3(a). The long-dashed line in this figure shows the comparison of the full thermal cocktail (cocktail B) with our data. As expected, the simulated yield above 0.15 GeV/ $c^2$  is now increased and, in particular, the high-mass region is populated with dielectrons from  $\rho \rightarrow e^+e^-$  decays, but the calculation still falls short of reproducing the data.

To discuss in more detail the excess pair yield, we show in Fig. 3(b) the ratio of the data and cocktail A. Statistical, systematical, and normalization errors are shown separately. In the intermediate mass range of 0.15–0.50 GeV/ $c^2$ , the enhancement factor above the dominant  $\eta$  contribution amounts to  $F(2.0) = Y_{\text{tot}}(2.0)/Y_\eta(2.0) = 2.07 \pm 0.21(\text{stat}) \pm 0.38(\text{sys})$ . Assuming that the excess pairs have, in this mass region, an overall acceptance close to the one of eta Dalitz pairs, one can compare  $F(2.0)$  to the enhancement factor measured in C + C by DLS at a beam energy of 1.04A GeV [3]. Using the DLS data and an appropriately filtered PLUTO cocktail generated for this bombarding energy, we obtain a factor of  $F(1.04) = 6.5 \pm 0.5(\text{stat}) \pm 2.1(\text{sys})$ . Knowing that, going from 1.04 to 2A GeV, inclusive  $\eta$  production in C + C collisions increases by a factor  $Y_\eta(2.0)/Y_\eta(1.04) = 13 \pm 3$  [14,18], the energy scaling factor of the excess pair yield  $Y_{\text{exc}}(2.0)/Y_{\text{exc}}(1.04)$ , where  $Y_{\text{exc}} = Y_{\text{tot}} - Y_\eta$ , can be deduced from the two enhancement factors  $F(2.0)$  and  $F(1.04)$ . It follows that  $Y_{\text{exc}}(2.0)/Y_{\text{exc}}(1.04) = 2.5 \pm 0.5(\text{stat}) \pm 1.5(\text{sys})$ . This energy scaling is remarkably similar to the known scaling of pion production, i.e.,  $Y_\pi(2.0)/Y_\pi(1.04) = 2.3 \pm 0.3$  [14,18]. It suggests that the pair excess is indeed driven by pion dynamics, involving, e.g.,  $\Delta$  and  $\rho$  excitations.

At still higher masses the ratio of data and cocktail A develops a pronounced maximum around  $M_{ee} \sim 0.6$  GeV/ $c^2$ , mainly due to the lack of  $\rho$  decays in cocktail A. Especially the mass region between the  $\eta$  and the  $\omega$  pole is expected to be dominated by the thermally populated low-mass tail of the broad  $\rho$  resonance. Cocktail B [long-dashed line in Fig. 3(b)], which includes  $\rho$  and  $\Delta$  decays, shows indeed an enhancement, but still does not fully explain the observed pair yield.

Beyond the cocktail calculations discussed above we have also made a comparison with various transport models. The latter, besides offering a realistic treatment of collisions dynamics, also handle the propagation of broad resonances, related off-shell effects, and multistep pro-



cesses, all known to play a crucial role at our bombarding energy. Hence, dielectron distributions were calculated with the HSD [6], RQMD [8], and UrQMD [13] transport models (assuming vacuum spectral functions). All calculations were filtered with the HADES acceptance and normalized to their respective  $\pi^0$  yields. The respective ratios of calculated dielectron yields to our cocktail  $A$  are shown as curves in Fig. 3(b). Because of the normalization, all models agree in the  $\pi^0$  mass region and give ratios consistent with unity. In the intermediate mass region all transport models fall short, with UrQMD coming closest to the data. As checked, all models agree on the  $\eta$  contribution itself within 20%, and the discrepancy can be traced to differences in their respective treatment of population and decay of the baryonic resonances [6,8,13]. At higher masses,  $M_{ee} > 0.5 \text{ GeV}/c^2$ , all models qualitatively reproduce the trend given by the data, but differ in the yield due to different amplitudes used for the couplings to intermediate resonances [8,13]. All transport models consistently overestimate the pair yield at the  $\rho$ ,  $\omega$  meson poles. Final conclusions can be drawn only when more refined calculations with in-medium spectral functions become available.

In summary, we report on the first measurement of inclusive dielectron production in  $^{12}\text{C} + ^{12}\text{C}$  collisions at  $E_{\text{beam}}^{\text{kin}} = 2A \text{ GeV}$ , spanning 5 orders of magnitude in yield. At low masses, i.e.,  $M_{ee} < 0.15 \text{ GeV}/c^2$ , the pair yield is in agreement with the known  $\pi^0$  production and decay probabilities. For  $0.15 \text{ GeV}/c^2 < M_{ee} < 0.5 \text{ GeV}/c^2$  it exceeds expectations based on the known production and decay rates of the  $\eta$  meson by  $2.07 \pm 0.21(\text{stat}) \pm 0.38(\text{sys})$ . This pair yield excess is consistent with that measured by DLS at 1.04 GeV if its energy scaling is similar to that of pion production. Additional sources associated with the radiation from the early collision phase ( $\Delta^{0(+)} \rightarrow Ne^+e^-$ ,  $\rho \rightarrow e^+e^-$ ) are needed to account for the excess observed for  $M > 0.15 \text{ GeV}/c^2$ . However, transport calculations based on vacuum spectral functions only still fail to quantitatively describe the excess yield in the full invariant-mass range.

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