Enhanced Production of Low-Mass Electron-Positron Pairs in 40 AGeV Pb-Au Collisions at the CERN SPS*

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* Doctoral Thesis of S. Damjanović, University of Heidelberg (2002)

Abstract

We report on first measurements of low-mass electron-positron pairs in Pb-Au collisions at the SPS beam energy of 40 AGeV. The observed pair yield integrated over the range of invariant masses 0.2<m≤1 GeV/c^2 is enhanced over the expectation from neutral meson decays by a factor of 5.9±1.5(stat.)±1.2(syst. data)±1.8(syst. meson decays), somewhat larger than previously observed at the higher energy of 158 AGeV. The results are discussed with reference to model calculations based on $\pi^+\pi^-\to e^+e^-$ annihilation with a modified ρ-propagator. They may be linked to chiral symmetry restoration and support the notion that the in-medium modifications of the ρ are more driven by baryon density than by temperature.

According to finite temperature lattice QCD, strongly interacting matter will, at sufficiently high energy densities, undergo a phase transition from a state of hadronic constituents to quark matter, a plasma of deconfined quarks and gluons. At the same time, chiral symmetry, spontaneously broken in the hadronic world, will be restored. High-energy nucleus-nucleus collisions provide the only way to investigate this issue in the laboratory. Among the different observables used for diagnostics of the hot and dense fireball formed in these collisions, lepton pairs are particularly attractive. In contrast to hadrons, they directly probe the entire evolution of the fireball; the prompt emission after creation and the absence of any final state interaction conserve the primary information within the limits imposed by the space-time folding over the emission period.

The CERES/NA45 experiment at the CERN SPS is the only dielectron spectrometer in the field of ultrarelativistic nuclear collisions, focused on the measurement of electron-positron pairs in the invariant mass range $m_{ee} \leq 1$ GeV/c^2. In a series of systematic measurements, CERES has previously found pronounced differences between proton-induced reactions like p-Be, p-Au at 450 GeV [1, 2] and nucleus-nucleus collisions like S-Au at 200 AGeV [1] and Pb-Au at 158 AGeV [3, 4]. While the superposition of known electromagnetic decays of produced neutral mesons can successfully account for the measured e^+e^- mass spectra in the proton case, a strong excess of e^+e^- pairs above the expectation from meson decays has consistently been observed in the nuclear case, amounting for 158 AGeV Pb-Au collisions to a factor of 2.4 ± 0.2(stat.)± 0.6(syst. data)± 0.7(syst. meson decays) in the mass interval $0.2 < m_{ee} \leq 1$ GeV/c^2(combined 1995/96 data [3–5]). The observation of this excess has initiated an enormous theoretical activity (see [6, 7] for recent reviews). There is a general consensus that one observes direct thermal radiation from the fireball, dominated by two-pion annihilation $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ with an intermediate ρ vector meson. The ρ is of particular relevance (more so than the other light vector mesons ω and ϕ), due to its short lifetime of 1.3 fm/c and its direct link to chiral symmetry restoration [8]. Indeed, a proper description of the observed dilepton excess does require a strong modification of the intermediate ρ in the hot and dense medium. The two main theoretical alternatives for this modification are (i) 'Brown-Rho scaling' with an explicit connection to the medium dependence of the chiral condensate [7, 9–11] , reducing the mass of the ρ below the vacuum value, and (ii) calculations of the ρ spectral density on the basis of ρ-hadron interactions [6, 12, 13], spreading the width of the ρ above the vacuum value. Theoretically, the modifications are more sensitive to the baryon density than to the temperature of the fireball.

To critically examine the relative importance of baryon density and temperature, an experimental variation of these parameters seemed mandatory. In this Letter, we present first results [14] on the production of e^+e^- pairs for Pb-Au collisions at the SPS beam energy of 40 AGeV, where a lower temperature and a higher baryon density (by a factor of 1.5) are expected as compared to 158 AGeV [15]. We indeed observe a strong excess of pairs again; the enhancement factor relative to the expectation from meson decays is now found to be 5.9±1.5(stat.)±1.2(syst. data)±1.8(syst. decays), i.e. somewhat greater than at the higher beam energy.

The CERES/NA45 experiment is optimized for the measurement of e^+e^- pairs in the invariant mass range of tens of MeV/c^2 up to 1 GeV/c^2. The acceptance, azimuthally symmetric, covers the pseudorapidity region $2.11 \leq \eta_L \leq 2.64$ in the laboratory frame, i.e. a window of $\Delta\eta$=0.53 around mid-rapidity. A detailed description of the experiment can be found in [16–18]. Here we summarize the most relevant features. Two Si drift detectors (SIDC1/2) [17], located 10/14 cm downstream of a segmented Au target, provide an angle measurement of the charged particles and reconstruction of the vertex; at the same time, they serve as a powerful handle to recognize photon conversion- and Dalitz electron-positron pairs with their small opening angles. The basic discrimination between the rare electrons and the abundant hadrons is done with two Ring Imaging Cherenkov detectors (RICH1/2) [16, 17]. For the run periods 1999/2000, the spectrometer was upgraded by the addition of a cylindrical Time Projection Chamber (TPC) [18] with a radial electric drift field, operating inside a new magnetic field configuration. As a consequence, the mass resolution is potentially improved from the 1995/96 value of 5.5% to about 2% in the region of the ρ/ω. Since the original magnetic field between the RICH's is no longer required, it is turned off, and the two detectors are now used as an integral unit, resulting in an improved electron efficiency (∼0.9) and rejection power.

The results reported in this Letter were obtained from the analysis of data taken during the SPS run period in the fall of 1999, the first on e^+e^--pair production after completion of the upgrade. The centrality threshold, based on a lower limit of the integrated signal of the SIDC1 detector (proportional to the total number of hits), was set to correspond to the 30% most central fraction of the geometrical cross section (same as for the 1996 data). Since the new TPC readout was still being commissioned, only about 8 million events were taken. Related problems also limited the track efficiency of the TPC to about 0.43 and the mass resolution actually achieved to about 6% in the region of the ρ/ω (inferred from an independent analysis of Λ and K_0 production).

The physics signal to be analyzed, e^+e^- pairs with masses m$_{ee}$>0.2 GeV/c^2, has an abundance of only 10^{-5} both relative to hadrons and to photons. The experimental challenges to minimize the associated background are therefore extremely high. The electron track reconstruction and hadron suppression proceed in the following way. First the event vertex is reconstructed from 100 or more particle trajectories traversing both SIDC's. Track segments are then formed in the SIDC's. Independently, Cherenkov ring candidates are reconstructed according to a pattern recognition algorithm based on a two-step Hough-transformation for candidate search and a subsequent ring fitting procedure [16, 17]. Track segments from the SIDC's and RICH's are then matched, defining electron track candidates, and these candidates are linked to the TPC and matched there to TPC track segments, independently preselected by dE/dx information characteristic for relativistic electrons. With a RICH radiator threshold of γ_{th}=32, more than 99% of all charged hadrons are already rejected on the SIDC-RICH level. The remaining small pion contamination, due to accidental matches with fake-ring electron track candidates and to true matches with high-p_t pions with asymptotic ring radii, is completely removed by the (momentum-dependent) dE/dx-cut in the TPC, a considerable improvement compared to the 1995/1996 analysis. Finally, the remaining electron and positron tracks are combined into pairs, and the type of pair is defined.

The photon-related background is much more severe. Even with minimal material in the experiment, photons converting in the target and in SIDC1 together with π^0-Dalitz decays still exceed the expected high-mass signal by a factor of about 10^3, thus constituting the vast majority of the electron tracks. Although the characteristics are different (small pair opening angles and very low masses m$_{ee}$<0.2 GeV/c^2), the limited track reconstruction efficiency and acceptance lead to a *combinatorial high-mass background* for events in which two or more of these low-mass pairs are only partially reconstructed. This is *the* central problem of the experiment. It is dealt with in the following way [14]. Since the inclusive electron p_t-spectra from low-mass pairs are considerably softer than those of pairs with m$_{ee}$>0.2 GeV/c^2, a reduction of the combinatorial background by more than a factor of 10 can be obtained by pairing only electron tracks with transverse momenta p$_t$>0.2 GeV/c. Further, a global selection on opening angles $\Theta_{ee}\geq$35 mrad is applied to all pairs with complete tracks. Next, conversion- and Dalitz pairs with opening angles Θ_{ee}<10 mrad which are not recognized as separate tracks with two individual electron rings in the RICH detectors are rejected by a correlated double-dE/dx cut in each of the two SIDC's [17]. Electron tracks which have a second SIDC-RICH electron candidate track within 70 mrad are also rejected. Finally, identified Dalitz pairs ($m_{ee}\leq 0.2$ GeV/c^2) are excluded from further combinatorics. Altogether, a rejection factor of more than 100 is obtained.

The remaining combinatorial background is determined by the number of like-sign pairs. The net physics signal S is then obtained by subtracting the like-sign contribution from the total unlike-sign pairs as $S = N_{+-} - 2(N_{++} \cdot N_{--})^{1/2}$. The final sample after all cuts consists of 532 unlike-sign, 283 like-sign and 249±29 net unlike-sign pairs (signal-to-background ratio of 1/1) for masses $m_{ee}\leq 0.2$ GeV/c^2, and 1236 unlike-sign, 1051 like-sign and 185±48 net unlike-sign pairs (signal-to-background ratio of 1/6) for masses $0.2<m_{ee}\leq 1.15$ GeV/c^2.

The raw net yields require an *absolute* normalization and an *absolute* correction for reconstruction efficiency for further discussion; an acceptance correction is not done. The normalization refers to the total number of events and the average number $\langle N_{ch}\rangle$ of charged particles per event within the e^+e^--pair rapidity acceptance. The charged particle rapidity density distribution is extracted from an independent analysis of the SIDC track segments; for the present centrality selection, one gets $\langle N_{ch}\rangle = \langle dN_{ch}/d\eta\rangle \cdot \Delta\eta = 216 \cdot 0.53 = 115$. The pair reconstruction efficiency ϵ is determined by a Monte Carlo procedure in which simulated lepton pairs from neutral meson decays with known characteristics (see below) are embedded into real data and are then analyzed using the same software chain as used for the data; this 'overlay-MC' provides the highest degree of realism, in particular for the description of event background and instrumental deficiencies. A value of $\langle 1/\epsilon\rangle^{-1}$=0.036 is obtained as the weighted average over the $dN_{ch}/d\eta$-distribution (the only essential functional dependence), using as weights the uncorrected differential pair yield for $m_{ee}\leq 0.2$GeV/c^2. The primary reason for this low value (compared to 0.11 in 1996) is the 1999 status of the TPC readout, while the influence of the low-mass pair rejection cuts on the efficiency is found to be minor. This is confirmed by the stability of the two net pair samples with masses $\leq$ and $>$ 0.2GeV/c^2 as a function of the rejection steps over a wide dynamical range of the signal-to-background ratio [14].

The normalized and efficiency-corrected mass spectra for the total unlike-sign pairs and the like-sign pairs are shown in Fig. 1. The statistical bin-to-bin fluctuations of the mass-differential *net* signal can be reduced by about a factor of $\sqrt{2}$, if the *shape* of the like-sign combinatorial background is determined with much better accuracy. Somewhat different from previous CERES analyses, this is done here by using the like-sign combinatorial background after the first two rejection steps (only p_t- and global Θ_{ee}- cut) which contains about 10 times more entries than the final background. This 'high-statistics' background is included in Fig. 1 as a histogram, rescaled as to give the same integral as the final background; the two are consistent within errors. The pair transverse momentum spectra are treated similarly.

The resulting net invariant-mass spectrum of e^+e^- pairs is shown in Fig. 2. The errors attached to the data points are purely statistical. The systematic errors contain contributions from the normalization procedure and the efficiency correction, amounting to an overall error of 16% for masses $m_{ee} \leq 0.2$ GeV/c^2. In the high-mass region $m_{ee} > 0.2$ GeV/c^2, additional errors of about 20% arise from remaining ambiguities in the rejection cuts and from the statistical error of the background rescaling, raising here the overall error to 26%. All values are quadratically small compared to the individual statistical errors of the data points and are therefore not drawn. Integration of the mass spectrum results in total normalized e^+e^--pair yields per event per charged particle of [7.6±0.8(stat.)±1.2(syst.)] $\cdot 10^{-6}$ for $m_{ee} \leq 0.2$ GeV/c^2, and [5.6±1.4(stat.)±1.1(syst.)] $\cdot 10^{-6}$ for $m_{ee} > 0.2$ GeV/c^2. The background rescaling used to improve the differential spectrum has, of course, no relevance for

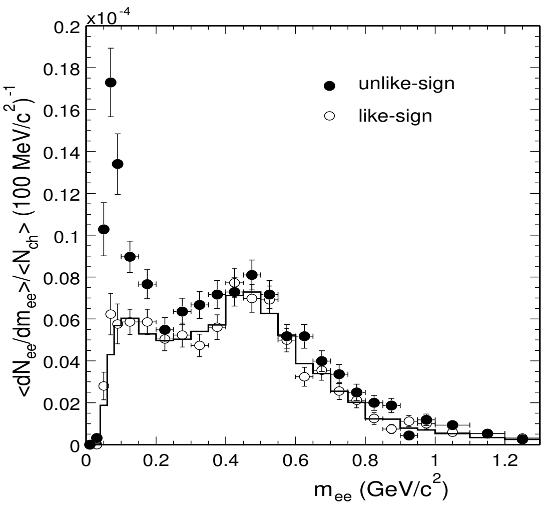

FIG. 1: Mass spectra of unlike-sign and like-sign pairs (circles). A high-statistics like-sign spectrum is shown as a histogram (see text). The peak at $m_{ee} > 0.4$ GeV/c^2 is due to the single-electron cut $p_t > 0.2$ GeV/c.

the integrals. Their statistical errors are those of the primary samples quoted above, and the systematic error of the high-mass integral m_{ee}>0.2 GeV/c^2 is only 20% (instead of 26%).

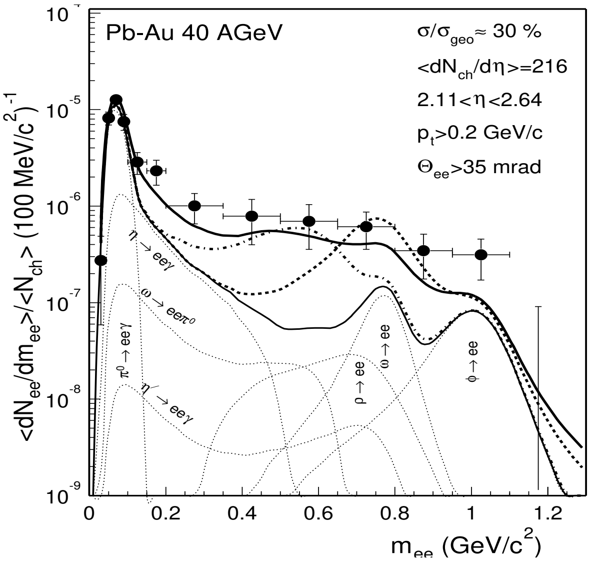

FIG. 2: Inclusive e^+e^- mass spectrum, compared to the hadron decay cocktail (thin solid; individual contributions thin dotted) and to theoretical model calculations [19] based on $\pi^+\pi^-$ annihilation with an unmodified ρ (thick dashed), an in-medium dropping ρ mass (thick dashed-dotted) and an in-medium spread ρ width (thick solid). The model calculations contain the cocktail, but without the ρ to avoid double counting. The low-mass tail of the cocktail ρ is due to the inclusion of a $\pi^+\pi^-$ phase space correction. The (weaker) tails of the ω and ϕ are caused by electron bremsstrahlung.

Fig. 2 also contains a comparison to the electromagnetic decays of the produced neutral mesons. The evaluation of this 'hadron decay cocktail' follows our previous procedure, described in detail for proton-induced reactions in [2] and extended to the Pb-Au case in [4, 5], including the empirical systematics of hadron yields (statistical model values where unmeasured) and of m_t-distributions (influenced by radial flow). The simulations are subject to the same cuts as the data; resolution broadening as inferred from hadron data (see above) and the effects of bremsstrahlung from the electrons traversing a total detector material of 5.8% of a radiation length before the TPC are included. For masses $m_{ee}\leq$0.2 GeV/c^2, the spectrum is dominated by π^0- and η Dalitz decays, and good agreement with a ratio data/decays of 1.18±0.13(stat.)±0.19(syst. data)±0.09(syst. decays) is found. For masses m_{ee}>0.2 GeV/c^2, however, a structureless continuum much above the hadron-decay level is seen, extending all the way up to the region of the ϕ. The enhancement factor data/decays is 5.9±1.5(stat.)±1.2(syst. data)±1.8(syst. decays) in this region, i.e. larger than the value at the higher beam energy of 158 AGeV with a statistical significance of 1.8σ (data errors added in quadrature); the systematic errors 'decays' of the decay cocktail, dominated by uncertainties in the branching ratios and transition form factors, essentially drop out in the comparison.

The invariant differential spectra in pair transverse momentum p_t^{ee} are plotted in Fig. 3 separately for the two mass regions m$_{ee}\leq$ 0.2 and >0.2 GeV/c^2. The steep cut-off in the distribution for p_t^{ee}<0.4 GeV/c (left part) reflects the cut of the single-electron $p_t\geq$0.2 GeV/c. Comparing data and hadron decays, good agreement is seen again for masses m$_{ee}\leq$0.2 GeV/c^2, while the strong excess above the decay expectation reappears for the high-mass region, mostly localized at low $p_t^{ee}\leq$0.6 GeV/c as observed before at 158 AGeV [3–5].

To illustrate most directly the relevance of the new results, Figs. 2 and 3 also contain the *predictions* from theoretical model calculations [19], based on $\pi^+\pi^-$ annihilation as discussed in the introduction and including the hadron decay contribution. The ρ-propagator is treated in three ways - vacuum ρ, modifications through 'Brown-Rho scaling' [7, 9–11], and modifications through ρ-hadron interactions [6, 12, 13]. With reference to the mass spectrum in Fig. 2, the data clearly rule out an unmodified ρ, but agree with the two in-medium scenarios within errors (without being able to distinguish between them). The pair transverse momentum spectra in Fig. 3 are also reasonably well described, but the peculiar low-p_t^{ee} rise (in contrast to the shape of the hadron-decay spectra) appears here as

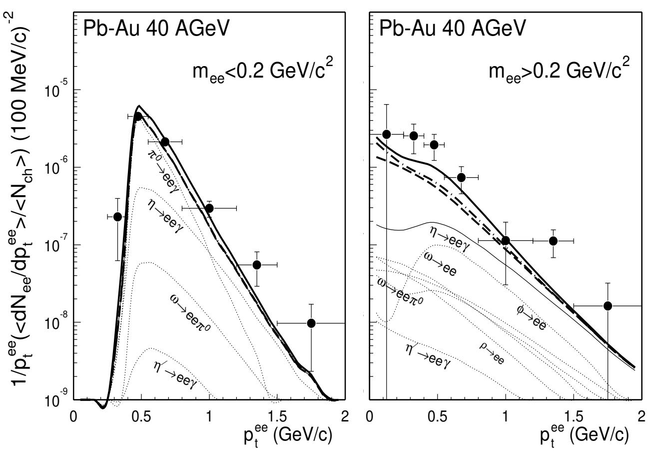

FIG. 3: Invariant pair-p_t^{ee} spectra for masses m$_{ee}\leq$0.2 GeV/c^2 (left) and m$_{ee}$>0.2 GeV/c^2 (right), compared to the hadron decay cocktail and to theoretical model calculations [19]. The cuts, labels and line codes are identical to those in Fig. 2.

a basic feature of the pion-annihilation process without much discrimination power towards in-medium effects. The integral yield of the model calculations (thick solid line in Figs. 2 and 3) corresponds to a 'theoretical' enhancement factor of 4.2 at 40 AGeV, compared to 2.4 at the higher beam energy; the difference is consistent with the observed trend.

We draw the following conclusions. The e^+e^--pair yield for m>0.2GeV/c^2 observed at 40 AGeV is enhanced over the expectation from neutral meson decays. Compared to 158 AGeV, the enhancement factor may even be larger, with a significance of 1.8σ. However, even if it would be the same, that would still be remarkable vis-a-vis the changes in conditions, i.e. less multiplicity and less temperature at the lower energy. The only quantity rising is the baryon density. Therefore, on very general grounds and independent of the details of any model calculations, the sole existence of a strong enhancement at 40 AGeV is consistent with the theoretical description of $\pi^+\pi^-$ annihilation and a ρ propagator dominantly influenced by baryon density rather than temperature [6, 7, 9–13, 19]. It is also consistent with theoretical results that contributions from $q\overline{q}$ annihilation during the QGP phase are minor [19].

Acknowledgments

This work was supported by the German BMBF, the U.S. DoE, the Israeli Science Foundation, and the MINERVA Foundation.

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