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Low-Mass Lepton Pair Production in Pb-Au Collisions at 40 AGeV

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Abstract: The CERES/NA45 experiment at the CERN SPS has previously measured e^+e^- pair production in 160 AGeV Pb-Au collisions. In the mass region m>0.2 GeV/c^2, an enhancement of $2.7 \pm 0.4(statist.) \pm 0.5(syst.)$ compared to the expectation from known hadronic decay sources was observed. In the 40 AGeV data taken in 1999, an enhancement is again found; a preliminary analysis gives the even larger value of $4.5 \pm 1.2(statist.)$. The results are compared to theoretical model calculations based on $\pi^+\pi^-$ annihilation with a modified ρ-propagator.

1. Introduction

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. High-energy nucleus-nucleus collisions have been used since about 15 years to experimentally investigate this issue in the laboratory. Dileptons are a particularly attractive observable. In contrast to hadrons, they directly probe the early stages of the fireball evolution; the instantaneous emission after creation and the absence of any final state interaction conserves the primary information within the limits imposed by the space-time folding over the emission period. In the low-mass region, the thermal radiation is dominated by the decays of the light vector mesons ρ, ω, and ϕ. The ρ is of particular interest, due to its direct link to chiral symmetry and its short lifetime of 1.3 fm/c; its in-medium behaviour around the critical temperature T_c for deconfinement should therefore reflect the associated restoration of chiral symmetry. Experimentally, low-mass dileptons are very much the domain of NA45/CERES, the only electron pair spectrometer at the SPS. This article focuses on recent results from CERES, obtained for Pb-Au collisions at 40 AGeV (1999 data).

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2. Experimental set-up

The CERES spectrometer (Fig. 1) is optimized to measure low-mass electron pairs close to mid-rapidity ($2.1<\eta<2.65$) with full azimuthal coverage. Two silicon drift chambers (SIDC1,2), located 10 cm and 13.8 cm behind a segmented Au target, provide a precise angle measurement of the charged particles and precise vertex reconstruction. Electron identification is done with two Ring Imaging Cherenkov detectors (RICH1,2) operated at a

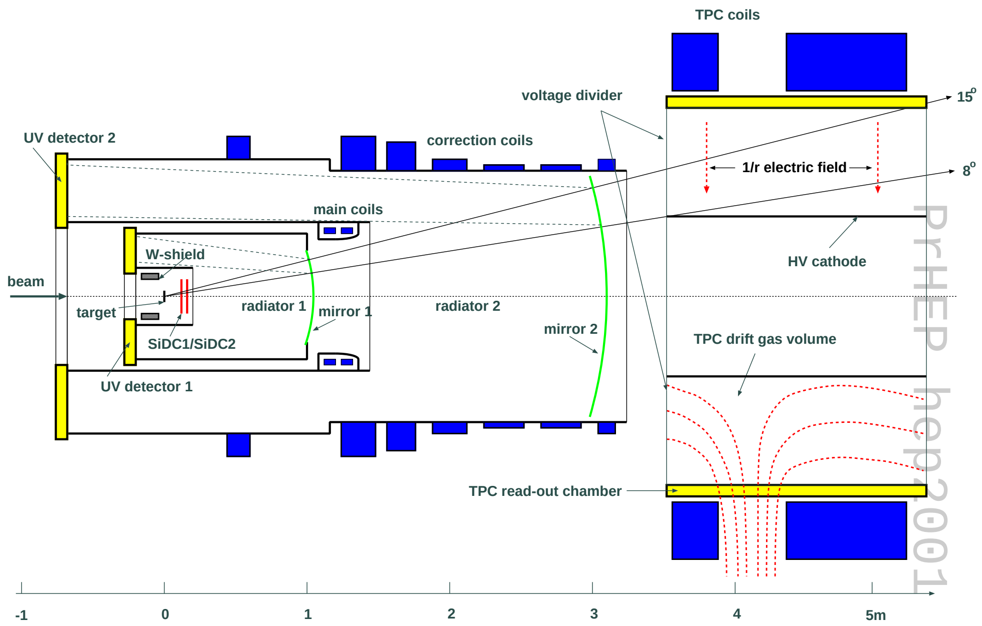

Figure 1: The upgraded CERES spectrometer at the CERN SPS

high threshold γ_{th}=32 which rejects 95 % of all charged hadrons. In the 1995/96 set-up[1], a suitably shaped magnetic field provided a well localized momentum kick between the two RICH detectors. A mass resolution of ∼5.5 % in the region of the ρ/ω was achieved. For the running period 1999/2000, the spectrometer was upgraded with a radial-drift Time Projection Chamber (TPC)[2] and a new magnetic field configuration. With an active length of 2 m, an outer diameter of 2.6 m, up to 20 space points for each track and a maximal radial field component of 0.5 T, the mass resolution is improved to a level of ∼2 % in the region of the ρ/ω; only ∼4 % was, however, reached for the 1999 data set (the experiment was not quite ready yet). The two RICH detectors are now used as an integral unit, resulting in improved electron efficiency (0.94 instead of 0.70 in 1995/1996) and improved rejection power.

3. Analysis procedure

The physics signal to be analyzed consists of electron-positron pairs in the invariant-mass range 0.2<m<1.2 GeV/c^2. The abundance of these pairs is only of order 10^{-5} relative to (i) hadrons and (ii) photons. The double RICH system is powerful enough to essentially control the problem (i) of hadron misidentification; in the 1999 data, the remaining hadronic contamination in accidental matches between the RICH's and the TPC is completely removed with the dE/dx information from the TPC. The problem (ii) is much more severe. While the total detector material up to the volume of RICH2 has been optimized down to a level of $\sim$1 % of a radiation length, photons converted in the target and in the SDC1 together with π^0-Dalitz decays still exceed the number of high-mass pairs by a factor of $\sim 10^3$. Although the characteristics are different (small pair opening angles and masses $<$0.2 GeV/c^2), limited track reconstruction efficiency and acceptance leads to a *combinatorial high-mass background* for events in which two or more low-mass pairs are only partially reconstructed. In other words: low-mass pairs would have to be rejected on the level of a factor of 10^3 to assure an (idealized) signal-to-background ratio of 1/1. This is *the* problem of low-mass dilepton measurements. It is dealt with in the following way.

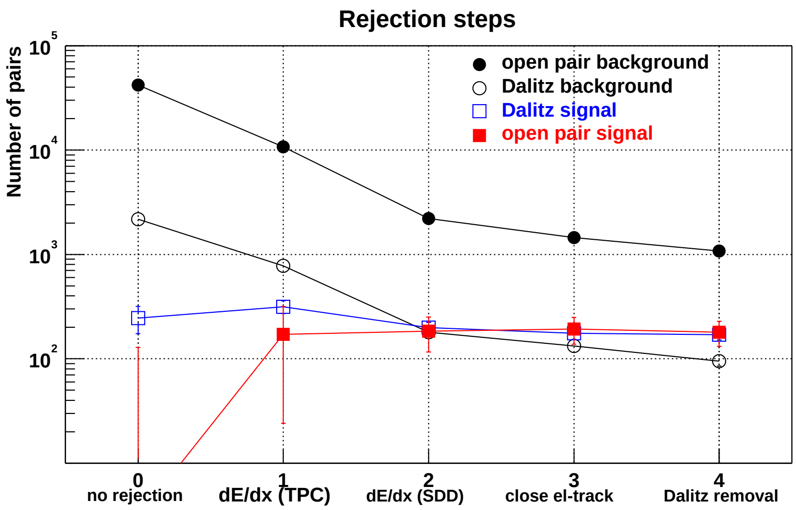

Figure 2: Evolution of the total number of pairs after various rejection steps, shown for the open-pair signal ($m_{ee} > 0.2$ GeV/c^2), open-pair background ($m_{ee} > 0.2$ GeV/c^2), Dalitz signal ($m_{ee} < 0.1$ GeV/c^2) and Dalitz background ($m_{ee} < 0.1$ GeV/c^2)

A reduction of the combinatorial background by a factor of $>$10 is obtained by pairing only electron tracks with transverse momenta p_t>0.2 GeV/c. The most important remaining rejection steps are illustrated in Fig. 2. Conversion and Dalitz pairs with opening angles $<$10 mrad which are not recognized as two individual electron rings in the RICH detectors are rejected by a double (correlated) dE/dx cut in the two SIDC's (a factor of $\sim$5). Electron tracks which have a second SIDC-RICH electron candidate track within $<$70 mrad are also rejected. Finally, identified Dalitz pairs (m$<$0.2 GeV/c^2) are excluded from further combinatorics. Altogether, a rejection factor of $>10\cdot10=100$ is obtained. At the same time, the efficiency losses for open pairs associated with the rejection cuts are less than a factor of 2, as illustrated by the positively identified Dalitz pairs with opening angles $>$35 mrad and masses $<$0.1 GeV/c^2 (Fig. 2). The physics signal, i.e. high-mass pairs with m$>$0.2 GeV/c^2, is finally extracted by subtracting the remaining like-sign pairs from the remaining unlike-sign pairs as $N_{e^+e^-} - 2(N_{e^+e^+} * N_{e^-e^-})^{1/2}$.

4. Results

The measured e^+e^- invariant-mass spectrum within the quoted rapidity acceptance, normalized to the number of charged particles $<N_{ch}>=<dN_{ch}/d\eta> \cdot\Delta\eta=115$ in that acceptance, is shown in Fig. 3 [3]. The data have been corrected for an overall pair reconstruction efficiency of $\epsilon=0.05$, evaluated by overlaying open pairs of known characteristics on raw events and simulating the whole set-up ("overlay Monte Carlo"). The unusually low num-

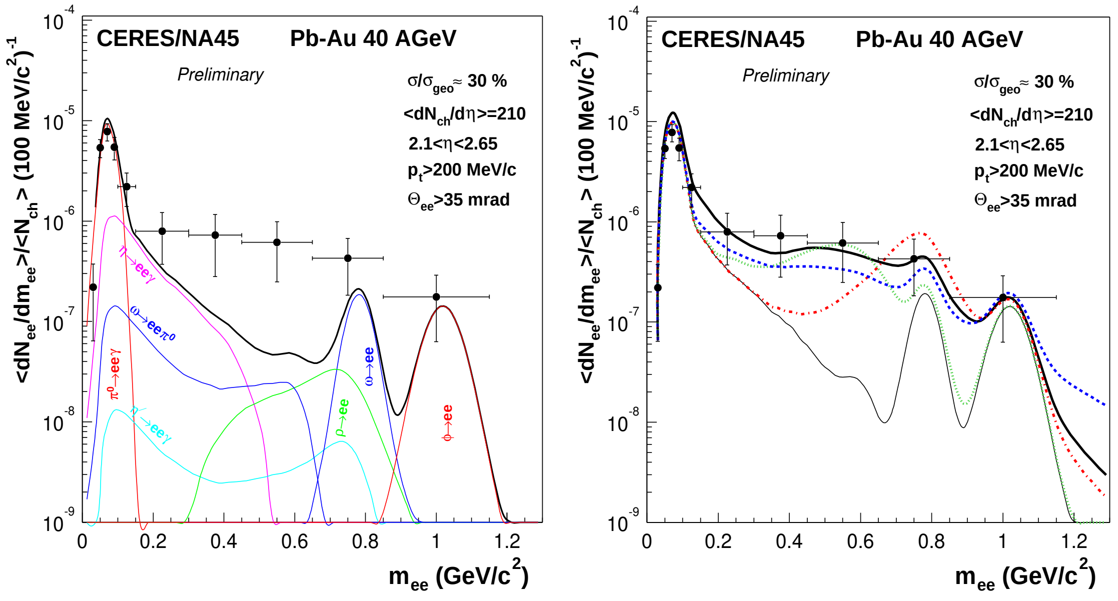

Figure 3: Normalized invariant-mass spectra of e^+e^- pairs at 40 AGeV. Left panel: Comparison of the data to the known hadronic decay sources, showing the individual contributions. Right panel: Comparison of the data to model calculations [10], based either on $\pi^+\pi^-$ annihilation with an unmodified ρ (dashed-dotted), an in-medium dropping ρ mass (dotted) and an in-medium spreaded ρ (thick solid), or on $q\bar{q}$ annihilation in the spirit of hadron-parton duality (dashed); the sum of the hadronic decay sources, but without the ρ, is shown separately (thin solid).

ber of 0.05 (instead of >0.2) is due to an only partially operational TPC in the start-up year 1999. A total number of about 8 Million events has been analyzed. The number of net electron pairs entering into Fig. 3 is 249±28 with a signal-to-background ratio of 1/1 for m<0.2 GeV/c^2, and 180±48 with a signal-to-background ratio of 1/6 for m>0.2 GeV/c^2. The stability of the two samples as a function of the rejection steps, i.e. of varying widely the signal-to-background ratio, can be recognized (within the error limits) in Fig. 2. The left panel of Fig. 3 also contains a comparison to the known hadronic decay sources, folded with a mass resolution of about 4 %. The hadron yields entering this "decay cocktail" include the changes in Pb-Au collisions relative to pp. It should be stressed that in the comparison study on pBe and pAu also done by CERES [4], experimental data and the sum of the hadronic decay sources *agree to within <20 %*. Conversely here, a strong enhancement of the data compared to the decay cocktail is seen, amounting for m>0.2 GeV/c^2 to a factor of $4.5 \pm 1.2(statist.)$. This is consistent with or even larger than the enhancement of $2.7 \pm 0.4(statist.) \pm 0.5(syst.)$ reported by CERES for the full SPS energy of 160 AGeV [5,6]. The excess appears to show a threshold behaviour, i.e. to set in somewhere above 0.2 GeV/c^2 (roughly twice the π rest mass). It is also found, for both energies, to be most pronounced at low transverse momenta p_t^{ee}<0.5 GeV/c.

More than 150 theoretical papers on the possible interpretation of the CERES results have appeared in the last few years (for a review see [7]). There seems to be a general consensus that one observes direct radiation from the fireball, dominated by pion annihilation $\pi^+\pi^-\to\rho\to e^+e^-$. The shape of the e^+e^- invariant-mass spectrum requires a strong medium modification of the intermediate ρ. The two main contenders for this are Brown-Rho scaling [8], reducing the mass (as a precursor of chiral symmetry restoration), and a calculation of the ρ spectral density within the dense hadronic medium [7,9], spreading the width. Both the time-averaged mass reduction and the spread of the width are so large that the whole spectrum can be described, as a parametrization, as if it were due to $q\overline{q}$ annihilation in the spirit of hadron-parton duality. The quantitative description of the data in this case requires an average temperature of 145 MeV at 40 AGeV, compared to 170 AGeV ($\sim$T$_c$) at 160 AGeV [11]. As shown in the right panel of Fig. 3 the data quality clearly rules out an unmodified ρ, i.e. a vacuum spectral function, while a more detailed differentiation between the different medium scenarios is, within the present errors, hardly possible. Much improved data have been taken in 2000 at 160 AGeV, and a further run in 2002 at a reduced SPS energy is also under consideration.

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