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Electron-positron pairs as a probe for hadrons in dense matter

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Abstract. In this paper the latest results from the analysis of e^+e^--pairs emitted in Pb + Au collisions at 40 AGeV/c and a combined analysis of all data available at 158 AGeV/c are presented. The enhancement of low-mass e^+e^--pairs ($m_{ee} > 0.2\,\mathrm{GeV}/c^2$) with respect to the expected yield from hadron decays first reported at 158 AGeV/c is also found at 40 AGeV/c and is even larger there. Comparing to various theoretical models based on $\pi^+\pi^-$ annihilation, the data can only be reproduced, if the properties of the intermediate ρ in the hot and dense medium are modified. Hadron data taken at the same beam energies sheds light on the dynamical evolution of the fireball and addresses the question whether the medium modification is linked to baryon density rather than temperature. In the future e^+e^--pairs emitted in heavy-ion collisions will be measured at the LHC with the ALICE Transition Radiation Detector (TRD). Here, special emphasis will be put on the production of heavy vector mesons (J/ψ, Υ).

PACS. 25.75.-q Relativistic heavy-ion collisions – 12.38.Mh Quark-gluon plasma – 13.85.Qk Inclusive production with identified leptons, photons, or other nonhadronic particles

1 Introduction

Along with the deconfinement phase transition to the quark gluon plasma (QGP), chiral symmetry is expected to be restored. The energy density at which the phase transition is predicted by two-flavor lattice calculations is $\epsilon \approx 0.7\,\mathrm{GeV/fm}^3$ [1] with large errors due to uncertainties in the critical temperature. Simple estimates employing the Bjorken expansion scenario [2] show that the initial energy density reached in central Pb + Pb collisions is about $3\,\mathrm{GeV/fm}^3$ at the full SPS energy. The totality of the observables has led to the announcement that a new state of matter is indeed formed in central heavy-ion collisions at the SPS [3]. The measurement of e^+e^--pairs is particularly well suited to study this matter since they are emitted throughout the entire collision and are themselves not subject to the strong final-state interaction. In this context, the decay of the ρ vector meson into e^+e^--pairs is of particular interest, due to its direct link to chiral-symmetry restoration. Because of the short lifetime (1.3 fm/c), e^+e^--pairs from ρ decays are dominated by decays within the hot and dense medium, directly mirroring its properties. Experimentally, however, the study of e^+e^--pairs is notoriously difficult, because of the small production cross-section as well as the large combinatorial background in heavy-ion collisions. This paper will be subdivided into two parts. The first part focuses on data taken at two different beam energies with the CERES-Experiment at the SPS. We briefly describe the experimental setup, followed by a description of the electron analysis procedure. We then present results from a combined analysis of all the data that were taken at the full SPS energy of 158 AGeV and the final results of the data taken at 40 AGeV are shown. A comparison of the data to models and a discussion of the fireball evolution concludes this part.

The second part will deal with future measurements of e^+e^--pairs with the ALICE Transition Radiation Detector (TRD) at the LHC with focus on the prospects of heavy vector mesons (J/ψ, Υ) measurements.

2 The CERES experimental setup

The CERES spectrometer is optimized to measure e^+e^--pairs in the mass range up to about $1\,\mathrm{GeV}/c^2$ in the range $2.1 < \eta < 2.65$ close to midrapidity. A cross-section through the azimuthally symmetric setup is shown in fig. 1.

A segmented micro target (8 disks of Au of $25\,\mu$m thickness and $600\,\mu$m diameter evenly spaced along 22 mm) is followed by a set of two Silicon Drift Detectors (SDD1/ SDD2) at a distance of 10 cm and 13 cm, respectively. The segmentation minimizes conversions of photons in the target. The set of silicon drift detectors provides precise determination of the angles of all charged particles, determination of the event vertex, and the total charged-particle multiplicity for each event. Along

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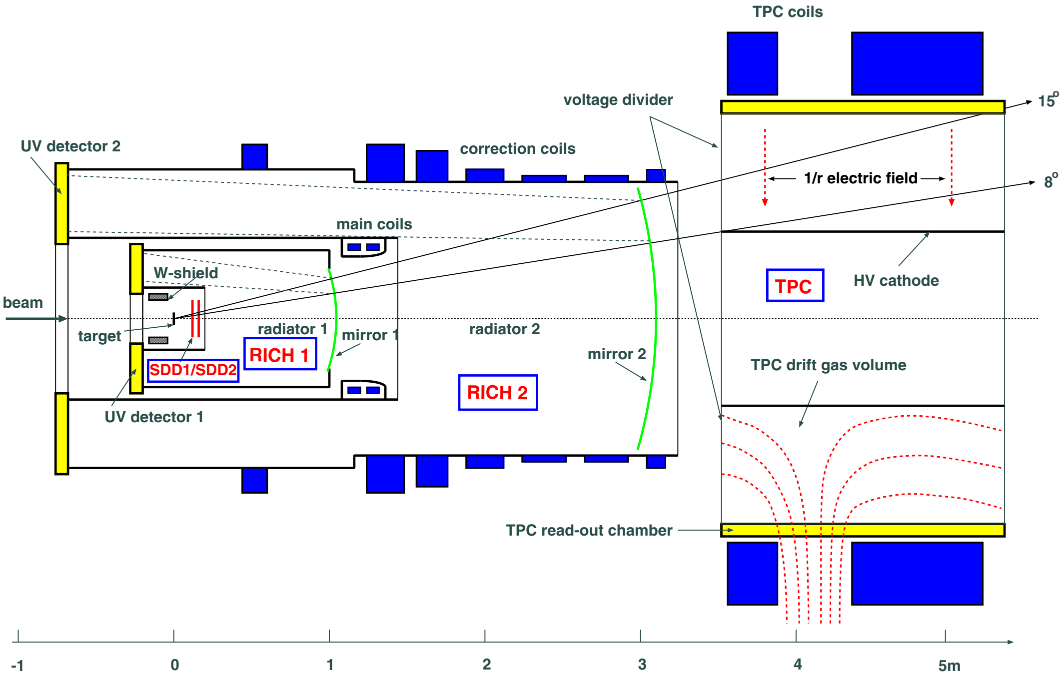

Fig. 1. The CERES experimental setup.

with the position measurement the specific energy loss is recorded for each charged particle.

Electrons are identified with two Ring Imaging Čerenkov counters (RICH1/2) which are operated at a threshold of $\gamma_{\text{th}} = 32$ suppressing more than 99% of all charged hadrons. In 1995/96 the spectrometer was operated with a radial magnetic field provided by two air coils with counter-running current in between the two RICHes [4]. With this setup a mass resolution of about 6% was reached in the mass region of the ρ/ω.

For the runs in 1999/2000 the experiment was upgraded by the addition of a radial TPC [5] inside a separate radial magnetic field ($B_{\max} = 0.5\,\text{T}$). Over the total length of 2 m a maximum of 20 hits are recorded for each charged-particle track. In the 1999 analysis a mass resolution of about 4.2% was achieved in the ρ/ω region, when tracks were fully reconstructed. For the 2000 data the goal is to reach with better calibration about 2%. For runs with the TPC the magnetic field between the RICHes was switched off and electrons were identified by combining the two RICHes, improving the electron efficiency to about 90% (as compared to about 70% in 1995/1996).

The data taken in 1995 and 1996 used the original CERES setup without the TPC. All data taken thereafter employed the upgraded setup shown in fig. 1. The new read-out of the experiment was only partially operational for the low-energy run at 40 AGeV/c in 1999 limiting both statistics and performance. The large data sample with about 36 million central events taken in 2000 at the full SPS energy is still being analyzed.

3 Electron analysis

While e^+e^--pairs are an attractive probe, they are notoriously hard to measure due to the small production cross-section and the enormous combinatorial background from unrecognized photon conversions and π^0 Dalitz decays. The analysis steps for the 1995/96 data are detailed in ref. [6]. Here, we only describe the analysis of data taken with the TPC and the field between the RICHes turned off. Electron candidates are selected when ten or more photon hits in RICH1 and RICH2 form a ring with asymptotic radius. To those candidates a transverse-momentum cut of 200 MeV/c is applied reducing contributions from π^0 Dalitz decays and conversions by about a factor of 10. Electron identification is further improved, removing high-p_{t} pions and accidental matches between the RICHes and the TPC, by a cut on specific energy loss in the TPC *vs.* momentum. Those conversions and Dalitz pairs with very small opening angles that do not lead to separate rings in the RICHes are efficiently removed by rejecting tracks with large specific energy loss in both silicon drift detectors. Further, electron candidates without a match in the TPC within 70 mrad of an electron track are also removed. The complete set of cuts employed in the analysis is shown in detail in ref. [7–9]. Finally, the invariant-mass spectrum of e^+e^--pairs is obtained by subtracting twice the geometric average of the remaining like-sign pairs from the remaining unlike-sign pairs ($N_{e^+e^-} - 2\sqrt{N_{e^+e^+} \cdot N_{e^-e^-}}$).

4 Invariant-mass spectrum of e$^+$e$^-$-pairs: Pb + Au at 158 AGeV/c

Analyses of the invariant-mass spectra of e^+e^--pairs from the runs in 1995/1996 have been published [10–12]. In

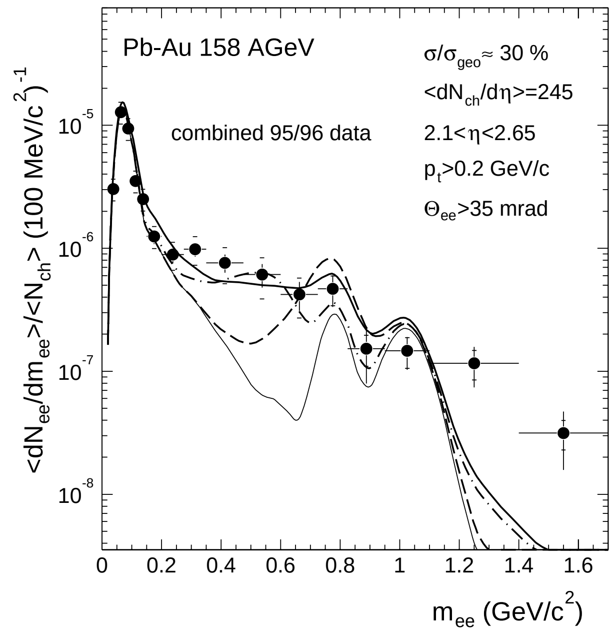

Fig. 2. Comparison of the experimental data to i) free hadron decays without ρ decays (thin solid line), ii) model calculations with a vacuum ρ spectral function (thick dashed line), iii) with dropping in-medium ρ mass (thick dash-dotted line), iv) with a medium-modified ρ spectral function (thick solid line). See text for a discussion of systematic errors.

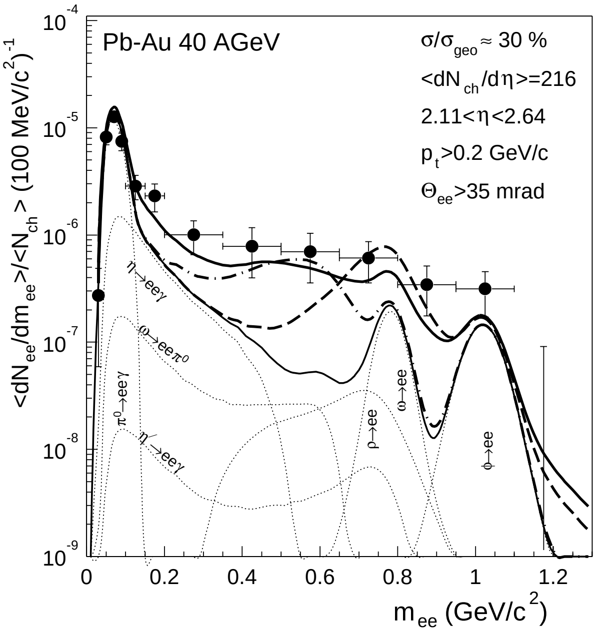

Fig. 3. e^+e^--pair mass spectrum from Pb + Au collisions at 40 AGeV/c compared to free hadron decays and various model calculations (line codes as in fig. 2). Errors shown are only statistical.

all cases cuts on the pair opening angle ($\Theta_{ee} > 35\,\mathrm{mrad}$) and the transverse momentum of the single-electron track ($p_\mathrm{t} > 200\,\mathrm{MeV}/c^2$) have been applied, and the spectra were compatible within their respective statistical and systematic errors. Recently [6] the data of 1995 and 1996 were combined in a unified analysis approach. For the two runs the trigger cross-section was slightly different. The cross-section for the combined data corresponds to the 32% most central events. The average charged-particle multiplicity is $\langle N_\mathrm{ch}\rangle = \langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta\rangle \cdot \Delta\eta = 245 \cdot 0.55 = 135$ for the quoted rapidity interval. Since the efficiency for detecting e^+e^--pairs depends on multiplicity, an efficiency correction is applied on an event-by-event basis. In the combination, the data were averaged bin-by-bin with weights according to the inverse squares of the relative errors of the individual measurements.

The combined data along with comparisons to model calculations are shown in fig. 2. The yield of pairs with $m_{ee} > 0.2\,\mathrm{GeV}/c^2$ for the entire data sample is 2666 ± 260 with a signal-to-background ratio of 1/12. On top of the statistical errors, the spectrum has systematic errors of 20% for $m_{ee} < 0.2\,\mathrm{GeV}/c^2$ and 28% on average for $m_{ee} > 0.2\,\mathrm{GeV}/c^2$, larger here due to the background subtraction and smoothing procedure. The background smoothing procedure introduces an additional 7% uncertainty in the overall normalization of the spectrum for $m_{ee} > 0.2\,\mathrm{GeV}/c$. A detailed description of all errors can be found in ref. [9,6]. In the region $m_{ee} > 0.2\,\mathrm{GeV}/c^2$ the data exceed the expected yield from the *cocktail* of hadron decays fitted to statistical model calculations and measured rapidity and p_t-distributions by a factor of $2.3 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})$. An additional systematic error of 0.7 is connected to the decay *cocktail* itself. This enhancement is not observed in proton-induced reactions [13].

The data are compared to the yield from various models based on $\pi^+\pi^-$ annihilation with an intermediate ρ vector meson. The hadron decay *cocktail* is added without any contribution from the ρ to avoid double counting (thin line). Using the vacuum ρ spectral function produces the thick dashed line. The other two model calculations both contain modifications of the ρ spectral function. They involve in-medium ρ spectral functions with either a dropping ρ mass [14] (thick dash-dotted line) or with a spread ρ width [15] (thick line). Clearly, a modification of the ρ properties in the medium is needed to reach agreement with the experimental data. Unfortunately, the data do not allow to discern between the two different scenarios.

5 Invariant-mass spectrum of e^+e^--pairs: Pb + Au at 40 AGeV/c

In 1999 the SPS delivered a 40 AGeV/c Pb-beam when the upgraded CERES spectrometer had just been commissioned. The data shown contain central events with an average multiplicity density at this energy of $\langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta\rangle = 216$. The analysis leading to the invariant-mass spectrum for the 40 AGeV/c data shown in fig. 3 has been outlined in sect. 3 and is described in detail in [9]. The resulting spectrum contains 249 ± 28 e^+e^--pairs in the mass range below $0.2\,\mathrm{GeV}/c^2$ at a signal-to-background ratio of 1/1. The integrated yield for high mass pairs above $0.2\,\mathrm{GeV}/c^2$

is 185 ± 48 pairs at a signal-to-background ratio of 1/6. The systematic errors are 16% and 20% for the low and high mass region, respectively.

For comparison to the hadron decay *cocktail* the particle ratios have again been taken from statistical model fits adjusted to measured ratios from Pb + Pb collisions at 40 AGeV/c. Also the rapidity distributions and transverse-momentum spectra follow the systematics of measurements at 40 AGeV/c. Again the cocktail has been folded with the experimental mass resolution.

In the low-mass region $m_{ee} < 0.2\,\mathrm{GeV}/c^2$ excellent agreement between the data and the *cocktail* is obtained. Here, the ratio of data/decays is 0.98 ± 0.11(stat) $\pm$ 0.16(syst). In the high mass region $m_{ee} > 0.2\,\mathrm{GeV}/c^2$, however, the data exceeds the *cocktail* by a factor of $5.1 \pm$ 1.3(stat) $\pm$ 1.0(syst) with an additional systematic error of 1.5 from the *cocktail*. This enhancement is larger than that observed at full SPS energy as quoted above, while the yield itself is not much larger than at 158 AGeV/c. Note that in the comparison of the enhancement factors between the two energies the additional systematic uncertainty from the *cocktail* essentially drops out.

Along with the data, model *predictions* [16] are presented for this energy. Again, a treatment of the ρ unmodified by medium effects is clearly ruled out. However, once more the data do not allow to discern the two scenarios involving in-medium modifications of the ρ propagator with a shifted mass, *i.e. Brown/Rho scaling* [14,16], or with a spread width [16].

6 Discussion of results

We find, both at 158 AGeV/c as well as at 40 AGeV/c, that the production of e^+e^--pairs with $m_{ee} > 0.2\,\mathrm{GeV}/c^2$ is significantly enhanced as compared to expectations from hadron decays. Moreover, the enhancement seems to be larger at 40 AGeV/c compared to 158 AGeV/c. In both cases, theories based on $\pi^+\pi^-$ annihilation are only able to describe the data, if medium modifications of the ρ propagator are included [14–17].

Comparison of the two energies sheds light on the interesting question whether changes in the properties of the ρ propagator are more sensitive to changes in the temperature or changes of the baryon density as favored by theory [14–17]. In order to evaluate the e^+e^--rates one would need complete knowledge of the dynamical evolution of the fireball. There is no direct handle on the time spent in the various stages of the collision (with the exception of the emission duration of at most 2–3 fm/c and the thermal freeze-out time of 6–8 fm/c from HBT measurements [18,19]). The evolution in terms of temperature and baryochemical potential can, however, be determined at chemical and thermal freeze-out. At chemical freeze-out the total baryon density can be estimated from statistical model calculations fitted to measured particle ratios. It is found to be approximately 0.75 in units of normal nuclear matter density ρ_0 at associated temperatures of 168(145) MeV for 158(40) AGeV/c [20]. The baryon density at thermal freeze-out can be derived from the measured HBT-radii [18,21,19] and rapidity densities [22]. It is 0.34(0.53) at temperatures of 120(120) MeV for 158(40) AGeV/c.

Theoretical calculations which evolve the system through higher baryon densities at the lower beam energy are in agreement with the observed increased enhancement [16]. Taken together, these observations therefore lend support to the importance of coupling the ρ propagator in the medium to baryon density rather than temperature.

The TPC calibration for the 2000 data has been completed; the analysis of the large number of events taken at the full SPS energy is about to start. With this data it should also be possible to study the behavior of the ω and the ϕ. It would further be interesting to compare the invariant-mass spectrum of $\pi^+\pi^-$-pairs [23] to that from e^+e^--pairs, which may allow to discriminate between earlier and later stages of the collision.

7 e^+e^--Measurements at the LHC

ALICE [24] is the dedicated heavy-ion experiment at the Large Hadron Collider (LHC) which is currently under construction. At the LHC it will be possible to collide Pb-ions at a center-of-mass energy of $\sqrt{s} = 5.5\,\mathrm{TeV}$ per nucleon pair. At this energy a qualitatively new region for heavy-ion physics will be explored. The energy density will be high enough and the gluon density is large enough that rapid equilibration will be reached and the generated quark-gluon plasma can be treated as an ideal gas. Particle production will be governed by hard processes.

In general, the central barrel of ALICE ($|\eta| < 0.9$), which sits in a solenoidal field of 0.4 T, consists of an Inner Silicon Tracking System (ITS), a Time Projection Chamber (TPC), a Transition Radiation Detector (TRD), a Time-of-Flight detector (TOF). In a limited angular range the system is complemented by a Čerenkov detector (HMPID) and a Photon Spectrometer (PHOS). The combination of theses detectors yields good particle identification capabilities and it provides momentum resolution for $(0.1 < p < 100\,\mathrm{GeV}/c)$. This will *e.g.* allow for the study of jet fragmentation functions up to well over 100 GeV/c jet-p_t.

With the Transition Radiation Detector (TRD) [25] shown in fig. 4 it will be possible to measure electrons and positrons in the central barrel in an environment which is designed to cope with a charged particle density of up to $\mathrm{d}N/\mathrm{d}y = 8000$. The detector consists of 540 individual detector modules. They are arranged in six layers with a five-fold segmentation in z-direction in a total of 18 super modules each subtending 20° in azimuth. Each detector module consists of a sandwich radiator of ROHACELL and polypropylene fibers followed by a gas detector with drift and amplification region operated with a $\mathrm{Xe/CO_2}(85:15)$-mixture. The induced signals are read out from segmented cathode pads, $1.2\cdot10^6$ in total. For good electron identification the total radiation

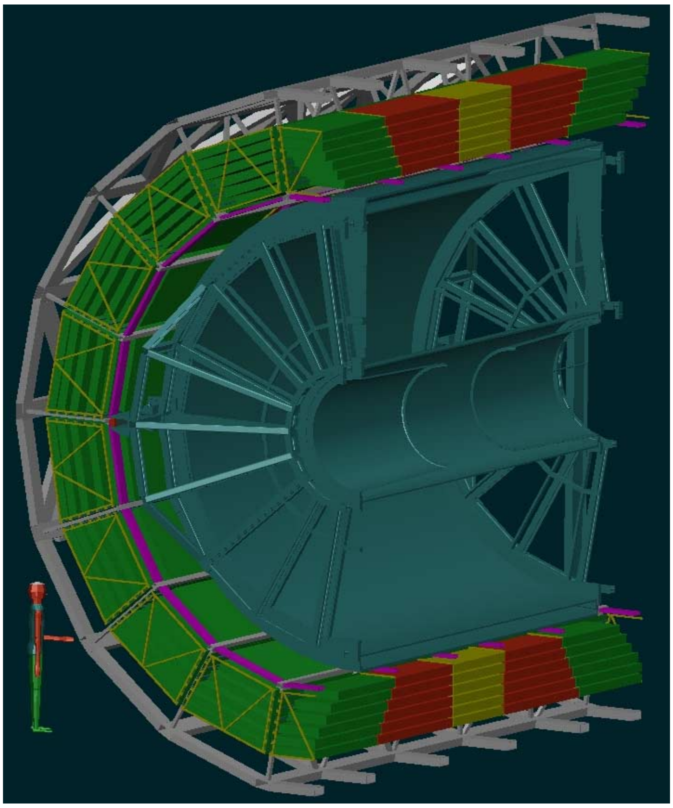

Fig. 4. Cut through the space frame of the ALICE central detectors with the TPC surrounded by six layers of TRDs arranged in five stacks in the z-direction.

thickness of the detector for all six layers is designed to be $X/X_0 < 15\%$. The readout is sampled over the entire drift of $2\,\mu$s. This allows for momentum determination and in conjunction with the fully on the detector integrated electronics fast ($6\,\mu$s) triggering on high-p_t particles. This triggering capability is essential for the study of rare probes like high-p_t J/ψ's and Υ's. Comprehensive test measurements on prototype detectors show that with the TRD a π-rejection of a factor 100 can be reached at 90% electron efficiency [26].

The electron measurement coupled with the vertexing capabilities of the ITS and TPC allow for the direct measurement of the yield of B and D mesons via their semileptonic decay. This provides the natural reference for the measurement of the *charmonium* (J/ψ) and *bottomium* (Υ) states which directly probe properties of the medium that they traverse [27]. The mass resolution for the Υ-states is of the order of 1%. In the absence of full calorimtetric coverage of the central barrel, the study of jets is facilitated by the triggering capability of the TRD, which allows for fast selection particles with high p_t, *i.e.* leading particles of jets.

Current planning foresees that about half of the TRD will be ready in 2006. This will be in time for the first heavy-ion collisions at LHC expected in 2007.

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