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# CERES/NA45 Status Report

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# Contents

# 1 Introduction

In this report we give an account of the CERES achievements since the last presentation to the SPSLC in September 92. For completeness we have included a few results from previous oral reports. This status report is presented in connection with a proposal to continue the CERES program with an upgraded spectrometer using Pb beams [1]. With that goal in view, we have made a special effort in the last few months to understand the relevant features which allows us to make realistic extrapolations towards central Pb-Pb collisions and to assess the performances of the upgraded spectrometer in terms of signal and background.

The report is organized as follows. Section 2 gives a short history of the CERES experiment. In Section 3 we give a detailed account of the 1993 proton run. In Section 4 we present the data samples collected so far. In Section 5 and 6 we discuss in detail the performance of the RICH detectors and of the silicon drift chamber. The procedure used in the electron-pair analysis is described in Section 7, with special emphasis on the rejection of the pairs originating from conversions and $\pi^\circ$-Dalitz decays. In Section 8 we present preliminary results on all the physics topics covered by CERES: electron pair production in p-Be, p-Au and S-Au collisions, direct photons, high-$p_\perp$ pions, and QED electron pairs. The data analysis is not yet final; we nevertheless discuss the performance of the spectrometer on the basis of the presently achieved results, placing particular emphasis on the reconstruction efficiency, close-pair rejection and signal-to-background ratio for open electron pairs. Section 9 contains a short summary.

# 2 Short CERES History

CERES belongs to the second generation of heavy-ion experiments at the CERN SPS. The main goal is to systematically study the pair continuum in the mass region from 100 MeV/c$^2$ to beyond 3 GeV/c$^2$ and the vector mesons $\rho/\omega$ and $\phi$. It also measures real photons using the target as a converter. The spectrometer is shown in Fig. 1. Its essential components are two Ring-Imaging CHerenkov (RICH) counters, one (RICH-1) situated before, the other (RICH-2) after a superconducting solenoid, and a silicon radial drift chamber. The spectrometer covers the central rapidity region $2 < \eta < 2.6$ with $2\pi$ azimuthal symmetry. In the following we will briefly review the CERES history (see previous documents submitted to the SPSLC for more details [2, 3, 4]).

The construction of the CERES spectrometer started after approval of the proposal in February 89. The installation in the zone of the major components (UV-detectors, radiators, mirrors, coils and gas handling systems) started in early 1990 and was completed in July 1990. The silicon drift chamber was not installed since the first production failed to give useful detectors. Preliminary tests were then performed using proton and $^{32}$S-beams, the UV-detectors being equipped with only 10% of the pad readout electronics. Most components and the general installations (heating, cooling, and gas systems) performed according to specifications. The most severe problem encountered was the very large probability of the UV detectors to spark due to an unforeseen large yield of slow, highly ionizing particles traversing the detectors which reduced the effective detector lifetime during burst in the $^{32}$S-run to the level of a few percent.

The spectrometer installation was completed in 1991, with 84% equipped pad readout electronics and including a silicon drift chamber from a new production with an acceptable quality and 20% dead anodes. Following intense laboratory tests, the UV-detectors were modified by the addition of a MWPC as a third amplification stage which solved the sparking problem in such a radical way that the dead-time losses became negligible altogether and the detectors could be operated in an ungated mode (see [5] for a detailed account on the spark problem and its solution). Detailed tests of the individual components and of the whole spectrometer were then carried out with proton and $^{32}$S-beams in the fall of 1991.

In 1992 the intelligent second-level trigger (SLT) was used for the first time. A revised production scheme, with only minor changes in the lithography masks yielded a new silicon drift chamber with only 5% dead anodes. The physics program started and we succeeded in taking first data on S-Au and p-Au collisions, although of limited statistical significance (see Section 4). After these runs, the original UV-1 pad electronics was replaced by a second generation. In the new electronics the analog-to-digital conversion is done on the modules resulting in much more stable pedestals; it also allows a faster readout speed (increased from 2.5 MHz to 10 MHz).

In 1993 we had a relatively long proton run. We expect that the data accumulated will allow us to complete the CERES p-p and p-nucleus physics program. A detailed account of the run is given in the next section.

# 3 The 1993 Proton Run

The main goal of this run was to perform a precision measurement on a possible excess of the $e^+e^-$-continuum above the hadronic decay sources with an accuracy better than 10%. For a direct determination of the $\eta$, $\eta'$ and $\omega$-Dalitz decays including the associated electromagnetic transition form factors, the CERES spectrometer, which measured $e^+e^-$-pairs, was used in conjunction with the $BaF_2$ electromagnetic calorimeter of the TAPS collaboration, which measured the associated $\gamma$-rays. The experimental arrangement is shown in Fig. 1. The physics goals and the set-up are described in detail in ref. [3]. In this section we will limit the discussion to the improvements in the CERES hardware and to the run performances. Preliminary analysis results are presented in Section 8.

## 3.1 Hardware Modifications

Several hardware changes and additions to the CERES spectrometer were implemented for this run. The most important one was the development of the intermediate-level trigger (ILT). Originally, we planned to correlate the analog sum information of the RICH-1 pad readout with the hit information from the silicon drift chamber [3]. After further simulation studies we found a simpler and more efficient scheme, which operates only on the pad data of UV-1. The principle is similar to that of the second-level trigger (SLT), but with a 16 times coarser granularity (see refs. [6, 7] for details on the SLT and ILT). One ILT pixel contains the analog sum information of 16 pads from an array of $8 \times 8$ original pads (every second pad in x and y). The sum is performed in two steps. First, four pads (in a row of 8 pads which we call a strip) are summed in the module itself by simultaneously addressing them on the chips. Four of these strips, representing one ILT pixel, are then summed up and passed to a processor whenever their sum exceeds a chosen ILT pixel threshold. This processor operates on a total of $36 \times 36$ pixels. It first performs a cluster removal and then a simple pattern recognition: a minimum number of set pixels within a ring mask is considered as a ring candidate. A trigger is generated whenever the number of candidates is $\geq 2$, otherwise the readout sequence is aborted. The total decision time of the ILT is 35 $\mu$s, dominated by the readout time of 18 $\mu$s, the electron drift time and the analog storage on the CAMEX chip (9 $\mu$s). The time to process the algorithm is only about 1.5 $\mu$s. The whole processor, based on programmable logic cell arrays (XILINX LCA), fits on three VME cards. In the proton running this trigger gave reduction factors of 5 to 7 with a signal efficiency of 90 to 95%.

Another important hardware modification was the installation of new motherboards on the UV-1 pad plane for the interconnection of the modules. They were designed to allow a higher clock frequency, up to 20 MHz instead of the 2.5 MHz of the previous boards. In practice the readout frequency was 14 MHz, limited by other elements of the readout chain. This is a significant increase for the performance of the ILT; it also increased considerably the SLT speed, from 500 $\mu$s (in the 1992 $^{32}$S-run) to 140 $\mu$s per event. We also improved the data acquisition speed, from 13 msec to 4 msec per event.

In addition to that, we made an optimization of the beam line configuration upstream of the target, following indications that in the 1992 data a considerable fraction of the events originated from upstream interactions (or from the superposition of an upstream and a genuine target interaction), leading to relatively dirty events in particular in RICH-1. By systematically removing material along the beam path, upstream of the target, and by having a large diameter vacuum pipe extending as close to the target as possible, those shower-type events disappeared. As a consequence the events were much cleaner than ever before. This is illustrated in Fig. 2 which shows the distribution of hits per event in UV-1 in p-Au collisions as measured in 1992 and in 1993 with comparable conditions.

## 3.2 Trigger Performance

The sophisticated new trigger scheme performed very well. A total of five weeks of beam time were spent for the installation and debugging of the hardware, and for the optimization of the algorithms. The ILT and SLT together reached rejection factors of ~110 both in p-Be and p-Au (as compared to ~25 in the 1992 p-Au run), with an efficiency for the detection of open pairs of 60%. The trigger efficiency was assessed by overlaying Monte Carlo generated rings into real events and analyzing them with a software emulation of the trigger. The first-level trigger (FLT) introduced an additional enhancement factor: the trigger threshold of $n$ charged particles in the acceptance of the spectrometer is effectively reduced to $n-2$ for those events containing an $e^+e^-$-pair, i.e. a larger fraction of the cross section is accepted by the trigger. The threshold was $n = 4$ in p-Be and 6 in p-Au, resulting in enhancement factors of 2.4 and 1.4 respectively. Thus the total enrichment factor of the whole trigger scheme was ~160 in p-Be and ~90 in p-Au collisions.

### 3.3 Measurements

The sample sizes of $e^+e^-$-pairs measured together with the TAPS calorimeter are presented in Table 1 (see Section 4 below). They represent about 22% and 6% of the proposal values [3] for p-Be and p-Au, respectively. We note, however, that we got almost a factor of two less beam time than requested, and that the overall run efficiency, once we started to take data, was ~60% (CERES-TAPS data-taking efficiency of 80% and SPS efficiency of 75%). We lost further beam time because of a severe quench of our magnet.

During the set-up of the trigger, we also took data with the TAPS calorimeter alone using a minimum-bias interaction trigger. The aim was to determine the relative production cross sections of the $\pi^\circ$, $\eta$ and $\eta'$ via their $\gamma\gamma$ decay channels and (possibly) the $\omega$ via its $\gamma\pi^\circ$ channel. These data will allow redundancy and complementarity to the $e^+e^-\gamma$ data. The stand-alone TAPS data sample sizes together with the expected signal-to-background ratios ($S/B$) are shown in Table 2. Fig. 3 shows the reconstructed $\pi^\circ$ and $\eta$ from a preliminary analysis of ~20% of the p-Be data sample. We expect that the yield as well as the $S/B$-ratio will increase by a factor of ~2 by improving the reconstruction efficiency and using the better energy calibration of the crystals obtained in a dedicated run with a low-energy electron beam which took place at the end of the run.

We also measured, during the set-up of the trigger, the charged particle multiplicity distributions over a large pseudo-rapidity range ($0.8 < \eta < 5.2$) for a variety of targets, Be, Al, Ag and Pt.

## 4 Data Sample Sizes

All data collected during the 1992 and 1993 runs are listed in Table 1. The number of minimum-bias events is obtained by multiplying the number of events on tape by the estimated trigger enrichment factor, i.e. the rejection factor × efficiency of the trigger. The table also includes an estimate of the total number of $e^+e^-$-pairs (with a mass cut of 200 MeV/$c^2$ and a $p_\perp$-cut of 200 MeV/c in each track) expected from hadronic decays (of the $\eta$, $\eta'$, $\rho$, $\omega$ and $\phi$). It is obtained from the number of minimum-bias equivalent events, the known cross sections relative to $\pi^\circ$ as measured in p-p collisions [8], and the pair acceptance of the spectrometer. For p-Be and p-Au, the total sample sizes for a $p_\perp$-cut of 50 MeV/c (which is sufficient for the suppression of the combinatorial background) are about 21 000 and 6000, respectively. All numbers quoted do not contain the pair-reconstruction efficiency.

There has been a dramatic improvement in the performance of the spectrometer in two respects between the 1992 and 1993 proton data. First, the data quality improved considerably, with cleaner events and much less background hits in the UV-counters. This was achieved by the systematic optimization of the beam line as described in the previous section. Second, the improvements in the trigger scheme (the implementation of the ILT and faster SLT) and the increased speed of the DAQ resulted in an increase of the trigger enrichment factor and of the number of good events written to tape. The combined effect of these improvements is immediately apparent in Table 1 by noting that the p-Au data sample of 1992 was accumulated in a total of 17 running days, whereas the much larger 1993 sample was taken in 9 days.

Most of these data sets are still being analyzed. But there are preliminary results on all the physics topics addressed by CERES, and these will be presented in Section 8.

## 5 Performance of the RICH Detectors

The RICH detectors are the heart of the CERES spectrometer. Their performances and properties have been discussed in detail in previous reports and in [6]. We will concentrate here on additional information, but for completeness we will also include the most important results of the previous reports.

An example of a p-Be event with a $\rho$-candidate is shown in Fig. 4 as seen in RICH-1 and RICH-2. The cleanliness of the event and the quality of the ring images are excellent. There is a clear difference in the cleanliness of the two detectors: one sees some pedestal fluctuations in RICH-2, whereas RICH-1 with its second generation of pad readout electronics is much cleaner. Fig. 5 is an enlargement of a ring shown in Fig. 4, exhibiting the details of the hit structure as seen by the pads. One notices the large dynamic range of the hit amplitudes, due to their exponential distribution. In addition to photon hits which are clearly associated with Cherenkov rings, one sees a very low background of scattered single hits in Fig. 4. Sources of such hits are pions just above threshold and low energy $\delta$-electrons either close to the threshold or undergoing large multiple scattering.

The situation is quite different in a central S-Au collision as shown in Fig. 6. The background is much more severe; it should be stressed, however, that the 1992 $^{32}$S-data were taken without beam-line optimization as in the 1993 proton run, and without the on-detector analog-to-digital conversion that proved very effective in reducing the pedestal fluctuations. The pad occupancy is still at a relatively low level of about 5% for a central collision. Apart from these single photon hits one observes clusters due to charged particles. Those coming from the target produce (i) diffuse spots due to the production of Cherenkov light in the window material and (ii) short intense tracks due to $\mathrm{d}E/\mathrm{d}x$, if they traverse the conversion gap. There are also occasionally particles from showers traversing the UV-detectors. The clusters do not represent a problem for the pattern recognition; they can be recognized, and the dead area per event, due to their rejection, is not significant.

## 5.1 Number of Photons per Ring

The average number of photoelectrons $N$ in an asymptotic ring for a radiator of length $L$ is given by $N = N_0 \cdot L/\gamma_{th}^2$, where $N_0$ is the figure of merit of a RICH detector. The quantity $N$ is of crucial importance for recognizing a ring in the presence of background hits, in particular in our case where the ring center is not known *a priori*. Fig. 7 shows the number of hits per ring as measured in the proton run of 1993. The distribution was obtained from a sample of $e^+e^-$-pairs with a mass around the $\rho/\omega$ peak (see Fig. 21 below). The high $S/B$-ratio in this mass range ensures that the sample contains mainly single rings, thus avoiding the abundant very close double rings which are not resolved by the analysis. There is an average of about 11 resolved photo-electrons per ring in RICH-1 and 12 in RICH-2. The value in RICH-1 is higher by about one photoelectron than previously reported [6]. This is due to the change of the detector quencher gas to $CH_4$ which has a slightly higher UV cut-off than the previously used $C_2H_6$.

The number of converted UV-photons/ring can also be directly determined from the pad pulse height summed over the ring area, divided by the mean hit amplitude. The average values are 13.7 and 12.9 in RICH-1 and RICH-2 respectively, i.e. $\sim$15-20% higher than those shown in Fig. 7, due to the pile-up losses of hits as expected from the double-hit resolution.

These numbers as well as those obtained in the previous runs are all very well understood within less than 10%, demonstrating that there are no UV-photon losses of unknown origin. The figure of merit $N_0$ can be obtained by folding the quantum efficiency of TMAE with the UV-transmission of the radiator gas, the detector gas and the UV-windows over the sensitive band width of the detector. RICH-2 is sensitive between 5.4 eV and 7.4 eV, i.e. between the ionization threshold of TMAE and the quartz window cut-off. RICH-1 has a $CaF_2$ window. Its upper cut-off is therefore higher and given by the radiator gas, 8.5 eV in the case of 6% $CH_4$. The larger bandwidth of RICH-1 results in a larger $N_0$ which compensates for its shorter radiator length. The theoretical values of $N_0$ are 276 (135) $cm^{-1}$ using the TMAE quantum efficiency from ref. [9] (about 10% higher values in the relevant wavelength band have been reported in ref. [10]). This figure gets degraded by other photon losses, like the mirror reflectivity, radiator transmission, etc., see ref. [6]. All these losses result in an effective figure of merit $N_0^{eff}$ of 157 (75) $cm^{-1}$, see Table 3. The expected number of photoelectrons/ring before the pile-up losses is then 14.3 (12.5), in very good agreement with the measured values. For comparison we also include in Table 3 the corresponding values obtained with $C_2H_6$ as a quencher gas in RICH-1. These are slightly higher than those reported in ref. [6] due to an improved analysis.

We notice also that these numbers have been rather stable since our first spectrometer tests in 1990. From our experience we conclude that TMAE operation does not cause problems if great care is taken to have very clean and tight gas systems for the UV-detectors and the radiators.

## 5.2 Single-Hit Resolution

The momentum and mass resolution of the spectrometer depend on the ring-center resolution $\sigma_\theta$ which itself depends on the single UV-photon hit resolution $\sigma_h$ as $\sigma_\theta = \pi\sigma_h/2\sqrt{N-2}$. The single-hit resolution is important for CERES in another respect. The resolution on the ring radius is $\sigma_r = \sigma_h/\sqrt{N-2}$; it is decisive for the discrimination between electrons and high-momentum pions.

The single-hit resolution has a momentum-dependent contribution due to multiple scattering. The momentum independent contributions are the chromatic dispersion, the mirror quality, the single-electron diffusion in the conversion region and the readout accuracy (including the effect of the discreteness of the anode wires in the MWPC). All contributions are listed in Table 4, yielding a total single-hit resolution of 1.08 (0.69) mrad in the high-momentum limit, i.e. without multiple scattering. Fig. 8 shows the distribution of the distance of the hits from the fitted ring center for asymptotic rings as measured in S-Au collisions. The data were taken from tracks with $p_\perp > 0.2$ GeV/c, belonging to fully reconstructed Dalitz pairs. This is also a clean selection of single rings which avoids the problem of the abundant conversion pairs which are often so close that the two rings are not resolved, resulting in an apparently worse resolution in RICH-1. The measured single-hit resolution $\sigma_h$, i.e. the rms scatter of the distribution in Fig. 8 is

1.02 (0.78) mrad, in very good agreement with the expected values.

The RICH-1 single-hit resolution is expected to be slightly worse (1.22 mrad) with $CH_4$ as the quencher gas, due to the larger chromatic aberration arising from the increased bandwidth.

### 5.3 Hits as a Function of Multiplicity

The number of hits in the two RICH detectors is proportional to the charged particle rapidity density as shown in Fig. 9. There is an offset, very small in RICH-2, and somewhat larger in RICH-1. This offset depends on the beam line conditions (it was reduced by a factor of 3 in the p-Au data of 1993 as compared to the data taken in 1992) and on the interaction rate. It is mainly due, as discussed in Section 3.1, to the pile-up of interactions. Fig. 9 shows also the results of a general Monte Carlo simulation, which includes event generation, full GEANT tracking of all particles through the spectrometer, detector response, and event reconstruction with the same software as used in the data analysis. The hit contributions from the various sources (conversions, $\pi^{\circ}$-Dalitz pairs, pions, $\delta$-electrons) in the simulation are separately indicated in the figure. The simulation is in very good agreement with the results of RICH-2; in RICH-1, however, the measured slope is larger by a factor of about 1.7 compared to the simulations. The origin of this discrepancy is not yet understood. For central S-Au collisions, the pad occupancy is of the order of 4% and 2% for RICH-1 and RICH-2, respectively; the extrapolation to central Pb-Pb collisions still gives a reasonably low pad occupancy.

## 6 Performance of the Silicon Radial Drift Chamber

CERES is the first full-scale experiment using a silicon drift chamber. This novel detector offers the possibility to measure coordinates of hundreds of charged particles with high spatial resolution and free of ambiguities, together with their energy loss. To match the symmetry of the spectrometer, the drift detector was designed with an annular shape and radial symmetry. The silicon radial drift chamber plays an important role in the CERES spectrometer:

(i) The rings in RICH-1 together with the hits in the drift detector allow the reconstruction of the vertex in $(x, y, z)$.

(ii) Once the vertex is known, the silicon drift chamber helps very effectively the pattern recognition in RICH-1: Fake rings and conversions produced downstream of the silicon chamber are rejected by requiring a matching hit. Tracks originating from gamma conversions or $\pi^\circ$-Dalitz decays upstream of the silicon drift detector are recognized by a double-amplitude signal or by two close hits.

(iii) Finally, the detector provides an accurate off-line event characterization due to its high granularity and excellent position resolution.

We present here a condensed account of the performance of the silicon drift chamber. The results are compared to a full Monte Carlo simulation of the detector and its readout chain. A more detailed discussion of the design, construction and operating conditions of the CERES/NA45 radial silicon drift chamber is given in [11, 12], of the laser tests and the in-beam performance in ref. [13]. The main properties of the detector are summarized in Table 5.

## 6.1 Characteristics and Operating Conditions

The chamber is made of a 3" diameter, 280 $\mu$m thickness silicon wafer. It has a central hole of 6.4 mm diameter for the beam to pass; its active area extends from an inner radius of 4.5 mm to an outer radius of 32 mm with full azimuthal coverage. The electrons liberated in the silicon by charged particles drift radially outward to an array of 360 anodes (560 $\mu$m pitch) located at the periphery of the detector. With a drift field of 500 V/cm the maximum drift time is 4.2 $\mu$s. The drift time determines the radial coordinate $r$ whereas the charge distribution among neighboring anodes gives the azimuthal coordinate $\varphi$. The detector is located at a distance of 78 mm from the center of the target which has a length of 65 mm in the beam direction; its maximum drift length of 28 mm ensures a complete overlap with the rapidity coverage $2.0 \leq y_{lab} \leq 2.6$ of the spectrometer.

The anode signals are read out by charge-sensitive hybrid preamplifiers mounted on the motherboard, followed by a quasi-Gaussian shaping amplifier (equivalent noise charge 950 electrons, $\sigma_{el} = 38$ ns) outside the spectrometer. The pulses are then sampled by FADC's with a rate of 50 MHz. An on-line amplitude threshold of 15 mV, corresponding to $6.5\sigma$ of the noise, was applied to the analog signals. This high threshold was found necessary to avoid excessive event lengths due to pick-up induced by the readout electronics of the UV-1 detector that could not be adequately shielded.

The mean pulse amplitude decreases with increasing drift distance because of (i) the ballistic deficit, and (ii) the loss of charge distributed among several anodes due to the detection threshold. The combined influence on the mean amplitudes as a function of $r$ is displayed in Fig. 10; it is well reproduced by a Monte Carlo simulation (solid line).

## 6.2 Spatial Resolution

### 6.2.1 Resolution in Radial Direction

The intrinsic position resolution of the silicon drift chamber has been measured with an infrared (904 nm) laser pulse focused onto the detector. In the radial direction, the single-hit resolution $\sigma_r$ stays below 10 $\mu$m ( Fig. 11) and the deviations from linearity below 30 $\mu$m ( Fig. 12), over the entire range. We have not tried to correct for the systematic non-linearities, since the resolution is anyhow much better than the quality of matching with the RICH detectors (see below).

The double-hit resolution in the radial direction is limited by the diffusion width $\sigma_{diff}$ of the charge cloud arriving at the anodes, and the subsequent smearing by the shaping amplifier. Fig. 13 shows the distribution of the radial distance between two hits that cannot be resolved in $\varphi$. The value of the distance read off at the one-half point is $\sigma_{double} \approx 400$ $\mu$m. This value is also very well reproduced by the detector simulation as shown by the histogram in the same figure.

### 6.2.2 Resolution in Azimuthal Direction

The resolution in the azimuthal direction is deteriorated by the fact that the drift field deviates from ideal radial symmetry, to an extent not anticipated during the design of the detector. The drift field is defined by field rings – there are 241 p-implantations on both sides of the detector with 120 $\mu$m spacing – which had to be approximated by $3^{\circ}$-polygons. This restriction was imposed by limitations in the software used to produce the lithography masks. The lower symmetry of the drift field distinguishes the 'central anodes' (those in the center of the $3^{\circ}$-polygon) from 'side anodes'. Due to the parallel drift field over the largest part of the detector area, charge collection by central anodes is enhanced by a factor of 2.6, compared to the expectation for ideal radial geometry. The most unfavorable consequence of this excessive charge focusing on every third anode is a drastic loss of charge division, especially in the inner part of the detector. More than two thirds of all hits in that part are collected by one anode only. For those hits without charge sharing, the resolution deteriorates from $\sigma_{\varphi}= 1^{\circ}/\sqrt{12} = 5$ mrad close to the anodes up to $3^{\circ}/\sqrt{12} = 15$ mrad in the center. For the other hits (35% of the total) which distribute charge on more than one anode, we find a single-hit resolution of 2.5 mrad, and a double-hit resolution of $<$40 mrad in the azimuthal direction.

### 6.3 Efficiency

The intrinsic efficiency of a silicon detector is usually close to 100 %. The present drift chamber has 5% dead anodes. In addition to that it has an inefficiency caused by the ballistic deficit, together with the rather large detection threshold, that becomes significant at $r < 15$ mm. This region is well within the acceptance of the spectrometer due to the segmented target. Fig. 14 displays the chamber efficiency vs. radius, measured with 200 GeV/u S-Au, using the segmented target. The efficiency reaches the 95 % limit at large radii as expected. The average efficiency within the acceptance of the spectrometer (marked by the vertical lines in the figure) is 0.85. These data are also well reproduced by the Monte Carlo simulation of the detector, shown by the histogram in the figure. The simulations also demonstrate that a lower detection threshold would cure the efficiency loss at small radii altogether.

## 7 Electron-Pair Data Analysis

### 7.1 Overview

The low-mass $e^+e^-$-spectrum ($0.2 < m < 1$ GeV/c$^2$) originates, in the absence of new physics, from the known hadronic decays (Dalitz decays: $\eta, \eta' \to \gamma e^+e^-$, $\omega \to \pi^\circ e^+e^-$, resonance decays: $\rho, \omega, \phi \to e^+e^-$). The integral yield (for masses $m > 200$ MeV/c$^2$ and with a $p_\perp$-cut of 200 MeV/c on each track) is of the order of $3 \cdot 10^{-5}/\pi^\circ$. We will refer to those pairs as the hadronic signal or shortly the signal. New physics would have to appear as a deviation from that signal.

The major difficulty of the experiment is the need to detect this weak source and possible deviations from it in the presence of an overwhelming yield of pairs originating from gamma conversions and $\pi^\circ$-Dalitz decays, which lead to a huge combinatorial background if they are not rejected at the level of $\geq$90%. We will denote them as 'close pairs' since they have a small opening angle as opposed to the pairs from the signal which have a relatively large opening angle.

The primary task of the event analysis, once the rings have been found and matched in RICH-1 and RICH-2, is the rejection of the close pairs. In the present analysis, this is done in three steps:

(i) A strong suppression is achieved by the $p_\perp$-cut. The number of single tracks per conversion or $\pi^\circ$-Dalitz decay, which survive a $p_\perp$-cut of 200 MeV/c, is ~20%.

(ii) RICH-1 provides a powerful rejection of the remaining single tracks. Since the original direction of the particles is preserved, most of the close pairs produce an unresolved double ring in RICH-1. The tracks can therefore be rejected by a cut on the number of photons or by a cut on the total amplitude of the ring. The effectiveness of these cuts and the resulting signal loss are discussed in detail below. A small fraction of them belongs to a slightly opened pair and can therefore be recognized by the presence of a nearby ring in RICH-1, i.e they can be rejected by an opening-angle cut. This cut is effective and almost does not cause any signal loss.

(iii) The silicon drift chamber also plays an essential role in the pattern recognition and in the rejection of close pairs. The rings in RICH-1 together with the hits in the drift detector allow the reconstruction of the vertex in $(x, y, z)$. With the known vertex position, the pattern recognition in RICH-1 is supported in two ways: (a) Fake rings and conversions produced downstream of the silicon chamber are effectively rejected by requiring a matching hit; (b) tracks from close pairs, originating upstream of the silicon detector, are recognized by a double-amplitude signal or by two close hits. This role of the silicon drift chamber will be discussed in detail below.

## 7.2 Event Analysis

A prime task of the event analysis is to find the rings with the highest efficiency possible. Since there is not an *a priori* knowledge of the ring center, the whole detector area is searched for hits and rings. This can lead, in the presence of high background, to an excessive amount of additional fake rings resulting from random combinations of hits. In order to minimize that, the first step of the analysis includes an event clean-up procedure which removes electronic noise and clusters produced by highly ionizing particles. The procedure is adapted to the quality of the data set. Ring candidates are then searched for by performing a point-to-ring Hough transformation on the pads (as done by the SLT trigger [6, 7]). The reconstructed hits around the candidates are used to determine the ring position by a fitting procedure. Several quality criteria, like the number of hits per ring, are used to distinguish genuine Cherenkov rings from fake rings. We have also started to use artificial neural network techniques to distinguish fake rings from genuine ones. This approach allows the application of effective cuts in a multidimensional space, and yields better fake rejection than the quality cuts applied in the standard analysis. Once all rings are found, the analysis routine reconstructs the tracks by matching the rings in the two detectors. For a ring found in RICH-1 at $\theta_1$,$\varphi_1$ and corresponding to an infinite momentum particle, its partner in RICH-2 must be located at $\theta_1 = \theta_2$, $\varphi_2 = \varphi_1$. As the momentum of the particle decreases, the area to be searched in RICH-2 develops into a butterfly-like shape resulting from the combined effect of the magnetic field deflection, the multiple scattering and the ring-center resolution. The area is limited by the $p_\perp$-cut applied to the tracks which is usually 200 MeV/c in S-Au collisions and as low as 50 MeV/c in the proton data. Quality cuts are also applied to the tracks, in particular to reject misidentified pions. The tracks are then analyzed to reject the close pairs using the cuts described below. The remaining tracks surviving all the cuts are combined into pairs. The residual combinatorial background in the $e^+e^-$ pair sample is determined by the number of like-sign pairs ($e^+e^+$ and $e^-e^-$). The $e^+e^-$ pair signal is finally obtained by subtracting the like-sign contribution from the $e^+e^-$ pair sample.

## 7.3 Rejection of Close Pairs in RICH-1

The double-ring resolution is of interest, in particular in RICH-1, since it determines the ability to identify those conversion and $\pi^\circ$-Dalitz pairs which have a very small opening angle. Fig. 15 shows the double-ring resolution of RICH-1 and RICH-2. One sees that pairs with an opening angle $\leq$6.4 mrad will give rise to an unresolved double ring in RICH-1. It is extremely important to identify those, in particular if only one track is reconstructed. There are two handles, (i) the number of resolved hits per ring, and (ii) the ring amplitude, i.e. the pad pulse height summed over the ring area.

In Fig. 16a we compare the number of hits per ring in UV-1 for single and double rings. The single rings are selected from a sample of fully reconstructed $\rho/\omega$ mesons (see Fig. 21 below); the double rings are selected from a sample of conversion pairs, identified by their typical V-pattern of one ring in UV-1 matched to two rings in UV-2. One track is required to have a $p_\perp > 200$ MeV/c, and the second one is reconstructed with a $p_\perp$ down to 50 MeV/c. The double rings have significantly less than twice the number of hits in single rings as expected from the pile-up effect which increases strongly with the number of hits. The possibility to recognize them on the basis of an upper cut on the number of hits is illustrated in Fig. 16b.

The ring amplitude of single and double rings is shown in Fig. 17a, using the same samples as used in Fig. 16. This procedure is of course not affected by pile-up; however, it has strong fluctuations due to the convolution of the exponential hit amplitude distribution with the number of hits which has a Poissonian distribution. The average ratio of the two distributions is 2.0 as expected. The corresponding recognition efficiencies are shown in Fig. 17b.

The double-ring rejection probabilities shown in Figs. 16 and 17 represent an upper limit. They were generated with a conversion sample in which both tracks are reconstructed. Monte Carlo simulations show that the rejection of double rings, using the ring-amplitude method, is somewhat worse when one considers conversions in which one track has a $p_\perp > 200$ MeV/c whereas the second one has a $p_\perp < 50$ MeV/c. The softer track gives rise to a more distorted ring (which at the limit of very low energy gets completely lost) due to multiple scattering and therefore contributes less hits and less amplitude to the double ring.

## 7.4 Rejection of Close Pairs by the Silicon Drift Chamber

Since this detector will play a decisive role in rejecting, besides fake rings, close pairs in the upgraded spectrometer for the Pb beam, we will discuss here in condensed form those features which are most relevant for the rejection. We distinguish

(i) *target conversions* which take place inside the target and the material between target and the silicon drift detector,

(ii) *silicon drift conversions* occurring inside the detector, and

(iii) *late conversions* in the material downstream of it.

The following scheme for rejection is adopted. Around the intersection of the electron track on the drift chamber we inspect an area of size $(\pm 2\sigma_\varphi)\times(\pm 2\sigma_r)$ for hits (95%-'signal cell'). The most important handle on target conversions is a double-$\mathrm{d}E/\mathrm{d}x$ hit amplitude in the signal cell. Due to the Landau distribution of the energy loss, the rejection is incomplete, and accompanied by a loss in efficiency ( Fig. 18). At the threshold level for 80% efficiency, the rejection is 90%. In Fig. 19, the recognition of 'double-$\mathrm{d}E/\mathrm{d}x$'-events is demonstrated for a sample enriched in conversions which were identified by the two RICH detectors. For some fraction of the target conversions (i), the opening angle of the pair exceeds the double-hit resolution, and two hits are observed in an inspection area around the track (rejection cell). The rejection in this subclass of (i) is complete, but accompanied by a loss of the signal due to accidental hits in the rejection cell.

Type-(ii) conversions are the worst candidates. Their rejection is almost nil, since their amplitude signal closely resembles that of a single-$\mathrm{d}E/\mathrm{d}x$ particle. Rejection of late conversions (iii) is complete to the extent of the finite random-hit occupancy of this cell, and it is done without any loss in signal efficiency.

The rejection power expected for our detector *without* the two impairments of excessive charge focusing ($\varphi$-resolution) and the high-threshold operation (efficiency loss and increasing level of confusion in vertex reconstruction) has been simulated on a very conservative basis. A rejection of $r = 0.8$ is obtained. For the applied $\mathrm{d}E/\mathrm{d}x$-cut, and because of the incomplete hit containment in the signal cell and the signal-veto by accidental hits in the rejection cell, the signal-pair efficiency is 0.4. The rejection inefficiency for combinatorial pairs, $\eta = (1-r)^2 = 4 \cdot 10^{-2}$, allows to improve the $S/B$-ratio by a factor of about 10.

It has become clear from simulations of the *imperfect* system that this gain factor is severely affected. For a measured conversion sample from the micro-target (200 GeV/u S-Pt, 534 conversions selected by RICH-1 and RICH-2) we deduced a gain factor of $15 \pm 7$; however, the point target disposes with the need of vertex finding, and the region of the drift chamber exposed in the spectrometer acceptance has significantly higher acceptance (see Fig. 14).

In all, by historic reasons of partial malfunction, the experimental performance of the silicon drift detector is significantly below its potential. We have learned our lesson to ensure a much better performance of the new silicon drift detectors for the proposed lead experiment [1] by design, by operation and better technology.

# 8 Preliminary Physics Results

In this section we present preliminary results on all the physics topics addressed by CERES [14, 15, 16].

## 8.1 Electron Pair Production

### 8.1.1 Mass Spectra

Fig. 20a shows the invariant mass spectrum of unlike- and like-sign pairs measured in p-Be at 450 GeV/c from the analysis of ~40% of the whole data sample. The resulting net signal, i.e. the difference between the unlike- and like-sign pairs, is shown in Fig. 20b. In order to illustrate the improvements of the CERES spectrometer between 1992 and 1993, we show in Fig. 21 the signal measured in p-Au collisions in 1992 in a comparable amount of running time [17]. The spectra are not yet corrected for reconstruction efficiency. They include a single-track $p_\perp$-cut of 200 MeV/c to allow for a comparison with the $^{32}$S-data (see below). The bars represent the statistical errors only. The rise of the yield at low masses is due to $\pi^\circ$-Dalitz decays. The $\rho/\omega$ peak is clearly visible. The average $S/B$-ratio for masses $m > 200$ MeV/c$^2$ is $6 \pm 1$, increasing to $10 \pm 1$ at the $\rho$-mass. The sample size in Fig. 20b for masses $> 200$ MeV/c$^2$ is about 800 events. After completion of the full analysis including some improvements of the reconstruction efficiency together with a lowered $p_\perp$-cut of 50 MeV/c, we expect a final sample size for p-Be of about 8000 pairs.

We have calculated the invariant mass spectrum of inclusive e$^+$e$^-$-pairs with a generator containing all the hadronic sources, i.e. the $\pi^\circ$, $\eta$, $\eta'$, $\rho$, $\omega$ and $\phi$. Their $p_\perp$-distributions were generated assuming $m_\perp$-scaling, and the rapidity distribution was a fit to d$n$/d$\eta$ as measured by WA80 [18] for S-Au, modified to reflect the ratio of $\sigma_{central}$ to $\sigma_{tot}$ measured by NA27 [8]. The Dalitz decays were treated according to the Kroll-Wada expression with the experimental transition form factors taken from ref. [19]. The laboratory momenta of the electrons were convoluted with the experimental resolution. The results of this cocktail are shown in Fig. 20b and have been arbitrarily normalized to the data so as to match the integral yield for masses larger than 200 MeV/c$^2$. This cocktail reproduces quite well the shape of the measured spectrum, although the latter has so far not been corrected for reconstruction efficiency. We are not yet in a position to discuss the absolute production rate.

The preliminary S-Au results at 200 GeV/u are shown in Fig. 22a,b. They are based on almost the whole data sample taken in 1992 and include a mass cut of 200 MeV/c$^2$ and a single-track $p_\perp$-cut of 200 MeV/c. Only statistical errors are shown. They are very large, reflecting the limited statistics of a total sample of $\sim$400 reconstructed pairs, and the increased combinatorial background due to the larger multiplicity of S-Au collisions. (The signal of hadronic sources increases linearly whereas the combinatorial background increases quadratically with the event multiplicity). The $\rho/\omega$ peak is hardly apparent in the spectrum. The hadronic decay cocktail is shown for comparison as in Fig. 20b, again with arbitrary normalization.

### 8.1.2 Reconstruction Efficiency and Signal-to-Background Ratio

The results presented in the previous section on e$^+$e$^-$-pairs are still of a preliminary nature. We will nevertheless discuss now the present understanding of the data analysis in a quantitative way, placing particular emphasis on the pair-reconstruction efficiency, the close-pair rejection and the resulting signal-to-background ratio $S/B$. This discussion is summarized in Table 6 and Table 7 for p-Be and S-Au, respectively. We wish to demonstrate that in both cases, and in particular in the low statistics sample obtained in

S-Au, we do have a fairly good understanding both of the pair reconstruction efficiency and of the $S/B$-ratio.

We first discuss in detail Table 6 and start with the first line ('initial sample'). The spectrum shown in Fig. 20b represents 40% of the whole estimated sample, i.e. the yield of $e^+e^-$-pairs with a mass cut of 200 MeV/$c^2$ and a single-track $p_\perp$-cut of 200 MeV/c is about 3600 pairs (see Table 1). The analysis chain, before applying the close-pair rejection cuts, gives for the same cuts a total signal of 2170 pairs (first column in the table). We therefore deduce the 'measured' pair reconstruction efficiency to be 61% (second column). It follows from this that the 'measured' efficiency is an *absolute* estimate (not just a relative value), containing cross sections, experiment acceptance, trigger enrichment factor etc.; it is therefore subject to large systematic errors. The 'expected' pair reconstruction efficiency, shown in the third column, is based on a full Monte Carlo simulation of the detector system, analyzed with the same analysis chain as the data themselves; this is therefore a *relative* number and much less subject to errors. In view of that difference, the perfect agreement between 'measured' and 'expected' is surely fortuitous. The following two columns refer to the signal-to-background ratio ($S/B$). The 'measured' value is obviously a *relative* number and hardly subject to errors. The 'expected' value is again deduced from the full Monte Carlo simulation. Here, however, a systematic uncertainty arises from the action of the second-level-trigger which is not incorporated in the Monte Carlo chain. Since the close-pair rejection capability of the trigger was not used in the proton run, pairs of conversions or Dalitz decays may have actually been *enhanced* in the trigger, consistent with the somewhat lower value of the 'measured' $S/B$-ratio compared to the 'expected' one.

The following 5 lines refer to a set of cuts applied in order to reject close pairs; the efficiencies quoted refer to each of the applied cuts separately, whereas the $S/B$-ratios are the cumulative results from all the cuts:

- the matching to the silicon drift chamber should eliminate all late conversions occurring after the silicon, without efficiency losses; unfortunately the present chamber is inefficient in the inner part, as discussed in detail in Section 6. Based on that we expect an upper limit of the pair efficiency of 64%, in reasonable agreement with the measured value.
- the close-ring cut or opening-angle cut rejects single tracks from slightly opened Dalitz or conversion pairs (see Section 5). The cut is usually around 35 - 60 mrad; it should have a high efficiency since the signal pairs have a much larger opening

angle.

- the total ring-amplitude cut is applied at the 90% single-ring efficiency level (see Fig. 17), resulting in a pair efficiency of 81%, very close to the observed value of 83%.
- the hit number cut is also applied at the 90% level (see Fig. 16), resulting in a lower limit of 81% for the pair efficiency since this cut is correlated to the previous one.
- the double-d$E$/d$x$ cut on the silicon drift chamber signal is again applied at the 90% efficiency level (see Fig. 19), and the results are also here in reasonable agreement with the expectations.

Each of the cuts discussed above gradually improves the $S/B$-ratio; their combined effect results in an improvement of the $S/B$-ratio by one order of magnitude, reaching a final value of about 6, together with an overall pair reconstruction efficiency of 21%.

The results for the S-Au data are shown in Table 7. (The table only contains the analysis of the second-level trigger data which is $\sim$50% of the final data sample). 'Measured' and 'expected' efficiencies for the initial sample agree again, but the statistical errors are too large to make that comparison very meaningful. The initial values of the $S/B$-ratio are much worse than in the case of p-Be, due to the higher multiplicity. The difference between 'measured' and 'expected' is now reversed compared to p-Be, since the second-level-trigger was indeed set in S-Au to *reject* part of the close pairs on the trigger level. The individual rejection cuts in the following lines bring almost the same relative benefits as in p-Be. The overall pair reconstruction efficiency is 18% together with an improvement in the $S/B$-ratio by a factor of 10, but the final value of the $S/B$-ratio is only about 0.2. This figure can be improved by applying tighter cuts, but this of course will lead to more signal loss (which we cannot afford with the available low-statistics sample).

It is worth noting that the present silicon drift chamber, in spite of the defects described in detail in Section 6.3, is an effective rejection tool. Without these deficiencies, the pair recognition would increase by a large factor. For the continuation of the experiment towards Pb-Pb collisions, we actually envision to install *two* silicon drift chambers with a new, improved design, which will then provide an extremely powerful tool for track matching and close pair rejection.

The extrapolation towards Pb-Pb requires a reasonable understanding of the pair-reconstruction efficiency and signal-to-background ratio as a function of charged multiplicity. A superficial comparison of Tables 6 and 7 shows the final reconstruction efficiency to hardly change from p-Be to S-Au (from 21% to 18%), while the $S/B$-ratio roughly follows the difference in multiplicity density (factor 24 in $S/B$ vs. 32 in d$n$/d$y$). This comparison is, however, not completely fair, since different cuts have been used in the two cases. A more solid extrapolation would rely on S-Au data only, using the range of multiplicity densities from d$n$/d$y$ = 50 to 200 accessible within that reaction. Unfortunately, the statistics of the S-Au sample is insufficient to subdivide it any further. We have instead investigated the multiplicity dependence of the reconstruction efficiency (with some rejection cuts) for a $^{32}$S-sample of sufficiently open $\pi^\circ$-Dalitz pairs, choosing a $p_\perp$-cut of only 50 MeV/c to further increase the statistics. Over the lever arm given above, the efficiency is found to decrease by a factor of 1.5 - 1.8, consistent (within 20%) with a full Monte Carlo simulation. A drop of nearly a factor of 2 is also seen in the pair-reconstruction efficiency of the *initial* sample between Table 6 and 7. The sensitivity of the efficiency to the multiplicity density can be greatly improved by an *a priori* knowledge of the ring centers via additional tracking information, and this is therefore proposed as part of the upgrade program towards Pb-Pb collisions.

We conclude from this discussion that the ingredients to Tables 6 and 7 are reasonably well under control, both in terms of the initial reconstruction efficiencies and the effects of the different rejection cuts. There is no doubt that we are able to extract the signal from the combinatorial background. The S-Au data are marginal in statistics, but we do have a nearly quantitative understanding of why this is so, even at this still preliminary stage of the analysis. It is this understanding which allows us to extrapolate to Pb-Pb collisions with reasonable confidence.

### 8.1.3 Momentum and Mass Resolution

Charged particle momenta are measured by the $\varphi$-deflection $\Delta\varphi = (120\ \text{mrad})/p$ (GeV/c) in the magnetic field between RICH-1 and RICH-2. The resolution is determined by the quality of the track match $\sigma_\theta$, assuming that the radial and azimuthal resolutions are identical. $\sigma_\theta$ depends on the ring-center resolutions of the RICH detectors mentioned in Section 5.2 and the effect of multiple scattering in the material between them ($X/X_0 =$ 0.7%). The expected $\sigma_\theta$ as a function of momentum is shown as a dashed line in Fig. 23. The measured resolution in p-Be data is also shown in the figure. The solid line is a fit to the data. The multiple scattering contribution, which limits the resolution at low momenta, is $1.08/p$ [mrad/GeV/c] and agrees with expectation within about 10%. The high-momentum limit is 1.22 mrad, corresponding to a resolution of $\sigma_p/p = 5.3\%$ instead of the 3.2% expected from the measured values quoted in Table 4. The discrepancy is due to an imperfect intercalibration of the detectors which will be improved in the future.

The ensuing relative mass resolution of the spectrometer as a function of the electron-pair mass is shown in Fig. 24 both for the presently achieved momentum resolution and for the one to be expected after a final intercalibration. Scaling with $m_\perp$ has been assumed for the relation between $m$ and $p_\perp$; in addition, a cut $p_\perp > 0.2$ GeV/c is applied on each track. The p-Be data of Fig. 20 show a mass resolution of $11 \pm 1\%$ at the $\rho/\omega$-peak, in perfect agreement with the mass resolution determined from the track match quality $\sigma_\theta$.

## 8.2 Direct Photons

We have measured the inclusive photon spectra in 200 GeV/u S-Au collisions using the conversion method with the target as converter. We give here a short summary only; more details can be found in refs. [15, 20]. The conversion pairs are identified by their characteristic pattern of an unresolved double ring in RICH-1 matched to two rings in RICH-2. The analysis is restricted to conversions with a $p_\perp$-cut of 60 MeV/c on each track, i.e. to 16% of the total hadronic cross section. Strong quality cuts were applied to the ring selection in order to reduce fake contributions to a negligible level; this resulted in a total pair reconstruction efficiency of 25%. $1.2 \cdot 10^6$ multiplicity-triggered S-Au events have been analyzed, out of which $6 \cdot 10^4$ conversion candidates have been reconstructed.

Fig. 25 shows the measured inclusive $p_\perp$-spectrum of photons, normalized to the $\pi^\circ$-yield derived from the analog multiplicity measured by the silicon pad counter. The data are corrected for acceptance, reconstruction efficiency, conversion efficiency and momentum resolution. The correction function is obtained by generating a $p_\perp$-spectrum of photons and tracking them through a GEANT simulation of the CERES detector. The digitized Monte Carlo data are mixed with real data to simulate realistic background conditions. This mixture is then passed through the analysis chain. The correction function is the ratio of the measured to the generated $p_\perp$ spectrum. The contribution of misidentified $\pi^\circ$-Dalitz pairs is also determined using this mixing method.

The results are compared to the predictions of a Monte Carlo generator which includes all the known hadronic sources. The generator uses a measured $\pi^-$ $p_\perp$-spectrum [21] as parent spectrum for $\pi^\circ$. Heavier mesons, like $\eta$, $\eta'$, $\omega$ are taken into account using known production and branching ratios; $m_\perp$-scaling is assumed for their $p_\perp$-dependence. The results of this generator are shown in Fig. 25 by the histogram. The shape and the absolute magnitude are very well reproduced. In the region $0.4 < p_\perp < 2.4$ GeV/c and

$2.0 < y < 2.6$, there is a non-significant excess of $7.5 \pm 11\%$ of the data over the hadronic sources, where the error is dominated by the systematic uncertainties of the order of 10%, as in other measurements [22].

We have also studied the multiplicity dependence of the photon yield. This is of particular interest since the production of direct photons, as well as the production of thermal di-leptons, is predicted to increase *quadratically* with the hadron multiplicity in all QGP models (see e.g. refs. [23, 24]). It is also a more sensitive measurement since the systematic errors of normalization cancel. The results are presented in Fig. 26 as the ratio of the measured inclusive photon yield to the expected one from hadronic decay sources as a function of charged particle rapidity density. The data show no rise above a linear dependence within the present systematical errors. A linear function fit to the data of Fig. 26 gives a slope of about $\alpha = (0.6^{+3.8}_{-5.2}) \cdot 10^{-4}$ as compared to theoretical predictions of $\alpha \approx 4 \cdot 10^{-4}$ [23]. We believe that there is a great potential in this particular approach to real photon measurements, and we expect a significant improvement in the present systematical errors from an ongoing refined analysis.

## 8.3 QED Pair Production

Electron-positron pairs are produced in large quantity in the strong transient Coulomb fields generated in distant collisions of heavy nuclei at high energies. There is an interest from the theoretical point of view, since higher-order QED effects are expected to play an increasing role as the energy and the atomic number of the colliding nuclei increase. There is also a practical interest, since this process may limit the lifetime of the fully stripped beams of the future heavy-ion colliders, RHIC and LHC. We have measured the production of these pairs (generally called QED-pairs) with invariant masses $m_{ee} > 10$ MeV/c$^2$ in S-Au at 200 GeV/u. These are the first results of invariant mass spectra on QED pair production. A detailed account is given in ref. [14, 16, 25]. Only one measurement exists so far on this process, of the $p_\perp$ and angular distributions of inclusive $e^+$ [26].

We have used a slightly modified set-up and trigger for these measurements. Since the main background is due to single delta electrons from the beam, we have used a thin Pt target of 50 $\mu$m thickness, and all material not needed for this measurement was removed from the target area. The first-level trigger required 2 or 3 particles in the silicon pad counter within the spectrometer acceptance, and an identified $^{32}$S-projectile downstream of the spectrometer. Part of the data was taken with the second-level trigger. The magnetic field was lowered to 20% of its nominal value to lower the accessible momentum range. Under these running conditions, electrons could be measured with a momentum down to 25 MeV/c and pairs with a mass down to 10 MeV/c$^2$. The Cherenkov ring images of these electrons are very distorted by the multiple scattering; the pattern recognition, however, is rather unambiguous since the RICH events are practically empty.

Fig. 27 shows the differential cross section as a function of the invariant mass $m_{ee}$ (a) and the azimuthal opening angle $\varphi$ (b) of the QED electron pair. The opening angle is peaked at 180° as expected from the production mechanism. The data are compared to a perturbative calculation of the lowest order [27]. The results are shown in Fig. 27 as dashed lines; they reproduce the differential cross section reasonably well over two orders of magnitude. The integrated cross sections are also in good agreement; the measured cross section, in the kinematical region covered by the experiment, is $\sigma = 13.9 \pm 3.1(\mathrm{stat})\,^{-1.9}_{+3.5}(\mathrm{syst})$ mb compared to a calculated value of $\sigma = 14.0 \pm 0.4(\mathrm{stat})\,^{-1.4}_{+0}(\mathrm{syst})$ mb.

## 8.4 High-$p_\perp$ Pions

The $p_\perp$-distribution of hadrons is used to infer the degree of thermalization reached in the collision; it can also provide evidence of collective flow. The high-$p_\perp$ part can reflect hard parton processes occurring at the early stages of the collision; those can be sensitive to the properties of the surrounding medium.

Pions are identified in the RICH detectors by their non-saturated ring radius. The measurement has a lower momentum limit given by the Cherenkov threshold of the radiators, and an upper momentum limit given by the ability to discriminate between asymptotic and non-asymptotic rings. The pion momentum is determined by the ring radius, with a resolution $\delta_p/p \approx 0.0006\,p^2\,[\mathrm{GeV/c}]^2$, much more accurate (for high-momentum particles) than the resolution $\delta_p/p \approx 0.032\,p\,[\mathrm{GeV/c}]$ as determined from the deflection in the magnetic field.

Fig. 28 shows the invariant transverse-momentum distribution ($\mathrm{d}N/\mathrm{d}p_\perp^2$) for charged pions in the rapidity range $2 < \eta < 2.6$ for central S-Au collisions [28]. In the same figure, our data are compared with a $p_\perp$-spectrum of $\pi^\circ$'s measured by WA80 [29] in a similar rapidity interval ($2.1 < \eta < 2.9$) for the same collision system. Both data sets are in good agreement. We have also investigated the dependence of the slope of the $p_\perp$-spectrum as a function of multiplicity. We observe no variation in the multiplicity range $50 \leq \mathrm{d}n/\mathrm{d}y \leq 160$, similar to previous findings [21] at lower $p_\perp$. At present, the $p_\perp$-range accessible is limited by the electron-pion separation; an improved analysis and a comparison of p-Be and p-Au with S-Au data are in progress.

# 9 Summary and Outlook

We summarize our conclusions on the present status of the CERES/NA45 experiment as follows:

(i) significant improvements in the overall capabilities of the spectrometer and in the data quality have been reached during 1993, concerning cleaner events in the RICH detectors, more stable electronics in the pad readout of RICH-1, implementation of a new intermediate-level trigger, a faster second-level trigger and a faster data acquisition system;

(ii) the performance of the RICH detectors is quantitatively understood;

(iii) the performance of the present-generation Silicon drift chamber is also quantitatively understood; design- and operational defects prevent, however, to fully benefit at present from the excellent potential of this device;

(iv) the 1993 proton run has been quite successful, resulting in an inclusive $e^+e^-$-pair sample for p-Be (after all analysis steps) of conceivably close to $10^4$ events for $m \geq 200$ MeV/c$^2$; the implementation of the $BaF_2$ calorimeter TAPS has been equally successful;

(v) physics results from 1992 $^{32}$S-running exist on open $e^+e^-$-pairs, real photons, QED $e^+e^-$-pairs and high-$p_\perp$ charged pions; the sample of open pairs is, however, statistically marginal and will not allow to reach the original physics goals of CERES in terms of lepton-pair production in heavy-ion collisions.

From the nearly quantitative understanding of the present status of the analysis, we recognize a large potential for future improvements. This understanding allows us to extrapolate to Pb-Pb collisions with reasonable confidence. Our detailed plans for improvements and the anticipated performance of CERES for Pb-Pb collisions are subject of a separate document [1].

# Tables

## Table 1

### Sample Sizes

| | | Trigger | Events on tape | minimum bias equivalent* | Expected signal** |
|---|---|---|---|---|---|
| 1992 | S-Au | FLT | $3.6 \cdot 10^6$ | $3.6 \cdot 10^6$ | 600 |
| | | SLT | $2.7 \cdot 10^6$ | $8.1 \cdot 10^6$ | 1700 |
| | p-Au | SLT | $1.6 \cdot 10^6$ | $4.5 \cdot 10^7$ | 450 |
| | S-Pt | QED | $3.1 \cdot 10^6$ | $5.3 \cdot 10^6$ | – |
| 1993 | p-Be | FLT | $4.1 \cdot 10^6$ | $3.0 \cdot 10^7$ | 140 |
| | | SLT | $1.3 \cdot 10^7$ | $2.1 \cdot 10^9$ | 9000 |
| | p-Au | FLT | $1.9 \cdot 10^6$ | $2.6 \cdot 10^6$ | 30 |
| | | SLT | $3.0 \cdot 10^6$ | $2.7 \cdot 10^8$ | 2600 |

* derived from the number of events on tape, taking into account the trigger enrichment factor.
** calculated from the known cross sections of the hadronic sources (relative to $\pi^\circ$) in p-p collisions [8, 30], the spectrometer pair acceptance and the number of minimum-bias equivalent events. It includes a mass cut of $m > 0.2$ GeV/c$^2$ and a $p_\perp$-cut of 0.2 GeV/c on each track. It does not include the pair reconstruction efficiency.

## Table 2

### Photon samples taken with the TAPS calorimeter

| System | Events | $\pi^\circ$ | S/B | $\eta$ | S/B | $\eta'$ | S/B | $\omega$ | S/B |
|---|---|---|---|---|---|---|---|---|---|
| p-Be | $3.1 \cdot 10^7$ | $5.3 \cdot 10^6$ | 43% | $1.4 \cdot 10^5$ | ~3.5% | $5 \cdot 10^3$ | ~2% | $1 \cdot 10^4$ | ~2% |
| p-Au | $1.8 \cdot 10^7$ | $3.1 \cdot 10^6$ | 34% | $1.2 \cdot 10^5$ | ~2.5% | $4 \cdot 10^3$ | ~1% | $7 \cdot 10^3$ | ? |

The yields are determined with a photon energy cut $E_\gamma > 0.5$ GeV.
The $\eta'$ and $\omega$ results are estimates based on the presently achieved performances of $\pi^\circ$ and $\eta$.

# Table 3

## Cherenkov Photon Yield

| | RICH-1 | | RICH-2 |
|---|---|---|---|
| Detector gas quencher (6%) | $C_2H_6$ | $CH_4$ | $C_2H_6$ or $CH_4$ |
| $N_0^{eff}$ $cm^{-1}$ | 131 | 157 | 75 |
| $\gamma_{th}$ (measured*, $CH_4$ 50° 0.946 atm) | 31.6 | 31.4 | 32.6 |
| radiator length $L_{eff}$ cm | 90 | | 175 |
| $N$ expected | 11.8 | 14.3 | 12.5 |
| $N$ observed (resolved hits) | 10.0 | 11.2 | 10.9 |
| $N$ observed (resolved hits, corrected for pile-up) | 11.9 | 13.6 | 12.8 |
| $N$ observed (summed amplitude) | 12.3 | 13.7 | 12.9 |

* The calculated $\gamma_{th}$ is 3.4% (2.5%) larger.

# Table 4

## Contributions to the Single-Hit Resolution

rms in (mrad)

| | RICH-1 | RICH-2 |
|---|---|---|
| chromatic aberrations in $CH_4$ | 0.95 | 0.53 |
| readout (including discrete anode wires) | 0.33 | 0.25 |
| single-electron diffusion | 0.37 | 0.11 |
| mirror quality | <0.10 | 0.35 |
| total | 1.08 | 0.69 |
| observed value | 1.02 | 0.78 |

# Table 5

## The Radial Silicon Drift Detector (1992)

| | | |
|---|---|---|
| material | | n-type silicon, 280 $\mu$m thick |
| | doping | neutron transmutation |
| | resistivity | 5 k$\Omega$cm |
| geometry | | 3" wafer, central hole $r = 3.2$ mm |
| | sensitive region | $4.5 < r < 32$ mm in r, $2\pi$ in $\varphi$ |
| | $\theta$-acceptance[a] | $3.3 < \theta < 22.3°$ |
| | $\eta$-acceptance[a] | $3.55 > y > 1.62$, 1.93 units |
| device quality | leakage current | typ. <10 nA on anodes |
| | unusable anodes | 12 anodes draw current >600 nA |
| electron drift | field | 500 V/cm[b] |
| | drift velocity | 6.66 mm/$\mu$s |
| | max drift time | 4.2 $\mu$s |
| | max diffusion | $\sigma_t = 26$ ns |
| granularity | in $r$ | given by double-hit resolution |
| | in $\varphi$ | 360 anodes on outer rim, 550 $\mu$m pitch, arranged in 120 sectors of 3° |
| single-hit resolution (laser test) | in $r$, local resolution | $\sigma_r < 10$ $\mu$m over entire acceptance |
| | linearity | $\sigma_r^{lin} < 35$ $\mu$m |
| | in $\varphi$, local resolution | $\sigma_\varphi = 3 \ldots 10$ mrad, depending on $r$ and $\varphi$ of hit within 3° polygon[c] |
| double-hit resolution | in $r$ | $\sigma_r^{(2)} < 400$ $\mu$m |
| | in $\varphi$ | $\sigma_\varphi^{(2)} < 40$ mrad |
| occupancy[d] | mean | 0.57 hits/mm$^2$ |
| | worst case | 2.7 hits/mm$^2$ at $r < 6$ mm |

[a] values refer to the center of the segmented target
[b] intrinsic divider chain supported by external divider on 12 taps
[c] due to the non-ideal drift geometry, the anodes central to the 3° polygons collect, on average, by a factor of 5 more charge than the adjacent ones.
[d] 200 GeV/u S-Au central collisions ($dn_{ch}/dy = 150$); segmented target

# Table 6

## p-Be Second-Level-Triggered Data

Electron pair sample, $m > 0.2$ GeV/c$^2$ and $p_\perp > 0.2$ GeV/c

| | signal | Efficiency | | S/B | |
|---|---|---|---|---|---|
| | | measured | expected | measured | expected |
| Initial sample | $2170 \pm 104$ | 0.61 | 0.60 | 0.5 | 0.8 |
| *Rejection and quality cuts:* | | | | | |
| SIDC match & vertex | $1377 \pm 61$ | 0.61 | 0.64 | 1.2 | 1.6 |
| Close ring cut | $1144 \pm 46$ | 0.83 | $\sim$1 | 2.3 | 2.8 |
| Analog sum cut ($\epsilon = 0.9$) | $949 \pm 39$ | 0.83 | 0.81 | 3.4 | 5.6 |
| Upper hit cut ($\epsilon = 0.9$) | $870 \pm 37$ | 0.92 | >0.81 | 3.6 | |
| SIDC d$E$/d$x$-cut ($\epsilon = 0.9$) | $763 \pm 33$ | 0.88 | 0.76 | 5.6 | 10 |
| Final sample | $763 \pm 33$ | 0.21 | >0.19 | 5.6 | 10 |

# Table 7

## S-Au Second-Level-Triggered Data

Electron pair sample, $m > 0.2$ GeV/c$^2$ and $p_\perp > 0.2$ GeV/c

| | signal | Efficiency | | S/B | |
|---|---|---|---|---|---|
| | | measured | expected | measured | expected |
| Initial sample | $421 \pm 197$ | $0.33 \pm 0.16$ | 0.34 | 1/36 | 1/46 |
| *Rejection and quality cuts:* | | | | | |
| SIDC match & vertex | $313 \pm 121$ | 0.74 | 0.88 | 1/23 | 1/33 |
| Close ring cut | $323 \pm 108$ | $\sim$1 | $\sim$1 | 1/18 | 1/17 |
| Analog sum cut ($\epsilon = 0.8$) | $207 \pm 49$ | 0.64 | 0.64 | 1/5 | 1/7 |
| SIDC d$E$/d$x$-cut (loose) | $227 \pm 43$ | $\sim$1 | 0.94 | 1/4 | 1/6 |
| Final sample | $227 \pm 43$ | $0.18 \pm 0.03$ | 0.17 | 1/4 | 1/6 |

# Figure Captions

**Fig. 1** Layout of the CERES spectrometer. For the 1993 run, the TAPS photon calorimeter was added.

**Fig. 2** Hits per event in p-Au collisions as measured in 1992 and 1993.

**Fig. 3** Invariant mass spectrum of $\pi^{\circ}$'s (left) and $\eta$'s reconstructed in TAPS.

**Fig. 4** A p-Be event (1993) in RICH-1 (a) and RICH-2 (b).

**Fig. 5** Enlargement of a Cherenkov ring from Fig. 4.

**Fig. 6** A typical S-Au event (1992) in RICH-1 (a) and RICH-2 (b).

**Fig. 7** Hits per Cherenkov ring in 1993 proton running. The solid line represents a Gaussian fit to the data.

**Fig. 8** Radial distribution of photon hits referred to the fitted ring centers (S-Au data). In UV-1, resolved Dalitz pairs have been selected. The flat contribution under the peaks is due to the close partner rings, and to single-hit background. The solid line is the result of a fit with a linear and a Gaussian functions.

**Fig. 9** Mean number of hits per event vs. charged particle rapidity density for RICH-1 and RICH-2 for S-Au interactions

**Fig. 10** Average hit amplitude of charged particles vs radius on the silicon drift chamber (200 GeV/u S-Pt, micro-target), data (connected by full line) and simulation (dotted line).

**Fig. 11** Drift time distribution at fixed laser position (6mm drift), abscissa in bins of 20 ns, calibrated in $\mu$m. The width corresponds to $\sigma_r = 7$ $\mu$m; it increases for maximum drift to about 8.5 $\mu$m.

**Fig. 12** Distribution of the deviations from linearity, the rms-width is about 28 $\mu$m.

**Fig. 13** Distribution of hit separation in the radial direction for central 200 GeV/u S-Au collisions (histogram) and by simulation (full curve).

**Fig. 14** Efficiency of the silicon drift chamber for 200 GeV/u S-Pt, micro-target, vs. radial hit location. The efficiency is determined by relating the number of hits observed in a given $\Delta$r window to that expected from the known rapidity distribution (WA80). The histogram (full line) describes the result of the full simulation for the actual threshold setting ($6.6\sigma$ of noise), and the broken line histogram for a lower threshold of $3\sigma$ of noise. The vertical lines indicate the region illuminated by particles entering the effective spectrometer acceptance $136 < \theta < 251$ mrad for the segmented and the micro-target, respectively. The mean efficiency for the segmented target is $\langle \varepsilon \rangle = 0.85$.

**Fig. 15** Double-ring resolution in RICH-1 (a) and RICH-2 (b) determined from the distance distribution between any pair of rings. 6.4 (5.4) mrad denote the 50% efficiency distance. The solid line is a smooth representation of the data.

**Fig. 16** Single vs. double-ring separation using the number of hits per ring. The single rings are taken from a sample of high-mass pairs and the double rings from a sample of conversions having at least one track with $p_{\perp} > 200$ MeV/c.

**Fig. 17** Single vs. double-ring separation using the total ring amplitude. The ring selections was done as in Fig. 16.

**Fig. 18** Left: Distribution of hit amplitudes (mV) measured from all hits in the silicon drift chamber (200 GeV/u S-Au), and the double-d$E$/d$x$ distribution generated from these data.
Right: Probability distributions vs threshold amplitude (mV) for the efficiency to detect a single-d$E$/d$x$, and the rejection of a double-d$E$/d$x$ hit, as derived from the density distributions shown left.

**Fig. 19** Measured distribution of hit amplitudes for a sample enriched in conversions (200 GeV/u S-Au, segmented target). The relative weight of the double- to the single-d$E$/d$x$ contributions improves with the quality of the vertex definition. Here $\geq$3 tracks have been required. The dashed histogram is the double-d$E$/d$x$ amplitude spectrum obtained by convolution.

**Fig. 20** Invariant mass distributions of unlike and like-sign electron pairs (a), and signal obtained by subtracting them (b), produced in p-Be collisions at 450 GeV/c from the 1993 proton run. A cut of $p_{\perp} \geq 200$ MeV/c is applied to make Fig. 20 comparable to Fig. 22.

**Fig. 21** Invariant mass distribution of electron pairs produced in p-Au collisions at 450 GeV/c from the 1992 proton run.

**Fig. 22** Invariant mass distributions of unlike and like-sign electron pairs (a), and signal obtained by subtracting them (b), produced in S-Au collisions at 200 GeV/u from the 1992 $^{32}$S-run. A cut of $p_{\perp} \geq 200$ MeV/c is applied.

**Fig. 23** Polar angle track match $\sigma_{\theta}$ between RICH-1 and RICH-2 vs. momentum for p-Be 1993 data. The solid line is a fit with the quadratic sum of a constant and a $1/p$-term, the dashed line is the expected $p$-dependence from multiple scattering and ring-center resolution of the RICH detectors (see text).

**Fig. 24** Relative mass resolution vs. mass, as calculated from the presently observed momentum resolution (solid line), and as expected for the expected momentum resolution (dashed). The data point refers to the experimental mass resolution extracted from 1993 p-Be data at the $\rho/\omega$-peak.

**Fig. 25** Transverse momentum distribution of photons measured with the conversion method in S-Au collisions at 200 GeV/u. The data are compared to the predictions of a generator which includes all hadronic sources. Only statistical errors are shown.

**Fig. 26** Dependence of the ratio of observed photon yield and the yield predicted from the generator for hadronic sources on rapidity density.

**Fig. 27** Differential cross sections of QED $e^+e^-$-pair production as function of the mass (a), and azimuthal opening angle (b) of the pair. The results are compared to lowest-order perturbative QED calculations. Only statistical errors are shown.

**Fig. 28** Transverse-momentum distribution of pions

# References


[1] H. Kraner et al., Proposal to the SPSLC, CERN SPSLC/94–1/P280

[2] U. Faschingbauer, M.G. Trauth, J.P. Wurm, A. Drees, P. Fischer, P. Glässel, M. Guckes, D. Irmscher, L.H. Olsen, A. Pfeiffer, H. Ries, A. Schön, H. Sickmüller, H.J. Specht, T.S. Ullrich, E.F. Barasch, A. Breskin, R. Chechik, Z. Fraenkel, D. Sauvage, V. Steiner and I. Tserruya, Proposal to the SPSC, CERN SPSC/88–25/P237 and SPSC/88–40/P237/Add 1

[3] CERES/NA45 Collaboration, Addendum II to Proposal SPSC/P237, CERN SPSLC/92-48/P237/Add 2

[4] Memoranda to the SPSLC, CERN SPSC/90–41/M457 and CERN SPSLC/92–47/M503

[5] R. Baur, A. Drees, P. Fischer, Z. Fraenkel, P. Glässel, H. Klein, A. Pfeiffer, A. Schön, A. Shor, H.J. Specht, V. Steiner, I. Tserruya and T.S. Ullrich, (Proc. First Workshop on RICH Detectors, Bari 1993), Nucl. Instr. Meth. (in print)

[6] R. Baur, A. Breskin, R. Chechik, A. Drees, P. Fischer, Z. Fraenkel, U. Faschingbauer, J. Gläß, P. Glässel, D. Irmscher, R. Männer, L.H. Olsen, A. Pfeiffer, A. Schön, Ch. Schwick, A. Shor, H.J. Specht, V. Steiner, S. Tapprogge, G. Tel-Zur, I. Tserruya and T.S. Ullrich, J.P. Wurm, (Proc. First Workshop on RICH Detectors, Bari 1993), Nucl. Instr. Meth. (in print)

[7] J. Gläß, R. Baur and R. Männer, IEEE Trans. Nucl. Sci. **37** (1990) 241

R. Baur, J. Gläß and R. Männer, Computing in High Energy Physics, Tokyo 1991, Eds. I. Wanatabe and F. Abe, Frontier Science Series 3 (1991) 211

[8] M. Aguilar-Benitez et al., NA27 Collaboration, Z. Phys. **C50** (1991) 405

[9] R.A. Holroyd, J.M. Preses, C.L. Woody, R.A. Johnson, Nucl. Instr. Meth. **261** (1987) 440

[10] R. Arnold, Y. Giomataris, J.L. Guyonnet, A. Racz, J. Sèguinot, T. Ypsilantis, Nucl. Instr. Meth. **A314** (1992) 465

[11] W. Chen, H. Kraner, Z. Li, P. Rehak, E. Gatti, A. Longoni, M. Sampietro, P. Holl, J. Kemmer, U. Faschingbauer, B. Schmitt, A. Wörner and J.P. Wurm, IEEE Trans. Nucl. Sci. **39** (1992) 619

[12] W. Chen, H. Kraner, Z. Li, P. Rehak, G. Bertuccio, E. Gatti, A. Longoni, M. Sampietro, P. Holl, J. Kemmer, U. Faschingbauer, F. Hess, C. Jacob, A. Wörner, J.P. Wurm, R. Baur, A. Drees, P. Fischer, P. Glässel, T.F. Günzel, D. Irmscher, L. Olsen, A. Pfeiffer, B. Schmidt, A. Schön, H.J. Specht, Th. Ullrich, S. Tapprogge, N. Wermes, A. Breskin, R. Chechik, C. de los Heros, V. Steiner and I.Tserruya, Nucl. Instr. Meth. **A326** (1993) 273

[13] U. Faschingbauer, Doctoral Thesis, Heidelberg (1993)

[14] R. Baur, A. Breskin, R. Chechik, A. Drees, U. Faschingbauer, P. Fischer, Z. Fraenkel, Ch. Fuchs, E. Gatti, J. Gläß, P. Glässel, Th. Günzel, C.P. de los Heros, F. Heß, P. Holl, D. Irmscher, C. Jacob, H. Kraner, H. Klein, A. Longoni, R. Männer, H. Nägele, K.H. Noffz, L.H. Olsen, A. Pfeiffer, I. Ravinovich, P. Rehak, M. Sampietro, B. Schmitt, A. Schön, J. Schukraft, Ch. Schwick, A. Shor, H.J. Specht, V. Steiner, S. Tapprogge, G. Tel-Zur, I. Tserruya, Th. Ullrich, N. Wermes, A. Wörner, J.P. Wurm: First results from the CERES Electron Pair Spectrometer on p-Be, p-Au and S-Au collisions; (Quark Matter 93, Proc. Int. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions, Borlänge 1993), to appear in Nucl. Phys.

[15] D. Irmscher, CERES Collaboration, (Quark Matter 93, Proc. Int. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions, Borlänge 1993), to appear in Nucl. Phys.

[16] R. Baur et al., CERES Collaboration, in preparation

[17] V. Steiner, Doctoral Thesis, Rehovot 1993

[18] R. Albrecht et al., Z. Phys. **C55** (1992) 539

[19] L.G. Landsberg, Phys. Rev. **128** (1985) 301

[20] D. Irmscher, Doctoral Thesis, Heidelberg (1993)

[21] T. Åkesson et al., Z. Phys. **C46** (1990) 361

[22] T. Åkesson et al., Z. Phys. **C46** (1990) 369
R. Albrecht et al., Z. Phys. **C51** (1991) 1

[23] M. Neubert, Z. Phys. **C42** (1989) 231

[24] J. Kapusta et al., Phys. Rev. **D44** (1991) 2774
R. Baier et al., Z. Phys. **C53** (1992) 433

[25] T. Günzel, Doctoral Thesis, Heidelberg (1993)

[26] C.R. Vane, S. Datz, P.F, Dittner, H.F. Krause C. Bottcher, M. Strayer, R. Schuch, H. Gao and R. Hutton, Phys. Rev. Lett. **69** (1992) 1911

[27] J.A.M. Vermaseren,Nucl. Phys. **B229** (1983) 347

[28] A. Schön, Doctoral Thesis, Heidelberg (1993)

[29] R. Santo, WA80 Collaboration, (Quark Matter 93, Proc. Int. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions, Borlänge 1993), to appear in Nucl. Phys.

[30] H.J. Specht, internal CERES note No. 74, 1992 (unpublished)