CERN/SPSC 2002-033
SPSC-P-280
October 21, 2002

ADDENDUM 2 TO PROPOSAL SPSC-P-P280

STUDY OF ELECTRON PAIR AND HADRON PRODUCTION WITH IN AND PB BEAMS AT THE CERN SPS

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Abstract

Since the upgrade with a radial-drift TPC, the CERES/NA45 experiment has had a low statistics run for 40 *A* GeV Pb+Au in 1999, and a very successful high statistics run for 158 *A* GeV Pb+Au in 2000. To complete our program, we propose to participate in the full energy run with an indium beam foreseen for 2003. We also propose to take data for a shorter period at a lower energy, preferentially with a 25 *A* GeV Pb-beam. Both runs would yield an unprecedented level of precision and would therefore provide a serious test of the present theoretical interpretations of the observed excess in low-mass e^+e^- pair production. Important new results would also be obtained for hadronic observables, in particular concerning correlations and fluctuations.

1 Status quo of CERES/NA45

CERES has taken data for about 10 years. A strong excess of e^+e^- pairs in the invariant mass range $0.2 < M_{ee} < 1$ GeV/c^2 above the expectation from neutral meson decays was first observed for the reaction 200 *A* GeV S+Au [1] and later confirmed with higher accuracy for 158 *A* GeV Pb+Au [2]. A possibly even stronger excess was found in the more recent Pb+Au data taken in 1999 at the lower beam energy of 40 *A* GeV [3]. The 450 *A* GeV p+Be and p+Au data from 1993 [4] were essential in proving the anomaly to be specific to nucleus-nucleus collisions.

The invariant mass spectra of e^+e^- pairs for the combined 1995/96 158 *A* GeV and the 40 *A* GeV Pb+Au data are shown in Fig. 1. The enhancement factors relative to meson decays, shown as a 'cocktail' of different sources in the figures, are 2.3 ± 0.2 (stat) ± 0.6/0.7 (syst data/decays) and 5.1 ± 1.3 (stat) ± 1.0/1.5 (syst data/decays), respectively. The observation of the excess has initiated an enormous theoretical activity with more than 200 publications by now. There is a general consensus that one observes direct thermal radiation from the fireball, dominated by two-pion annihilation with an intermediate ρ vector meson $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$. The ρ is of particular interest due to its short lifetime of 1.3 fm/c and its direct link to chiral symmetry restoration. Indeed, a proper description of the observed excess does require a strong modification of the intermediate ρ in the hot and dense medium. The main contenders for this modification are 'Brown-Rho scaling' with an explicit connection to the medium dependence of the chiral condensate [5], reducing the mass of the ρ below the vacuum value, and calculations of the ρ spectral density on the basis of ρ-hadron interactions [6, 7], increasing the width

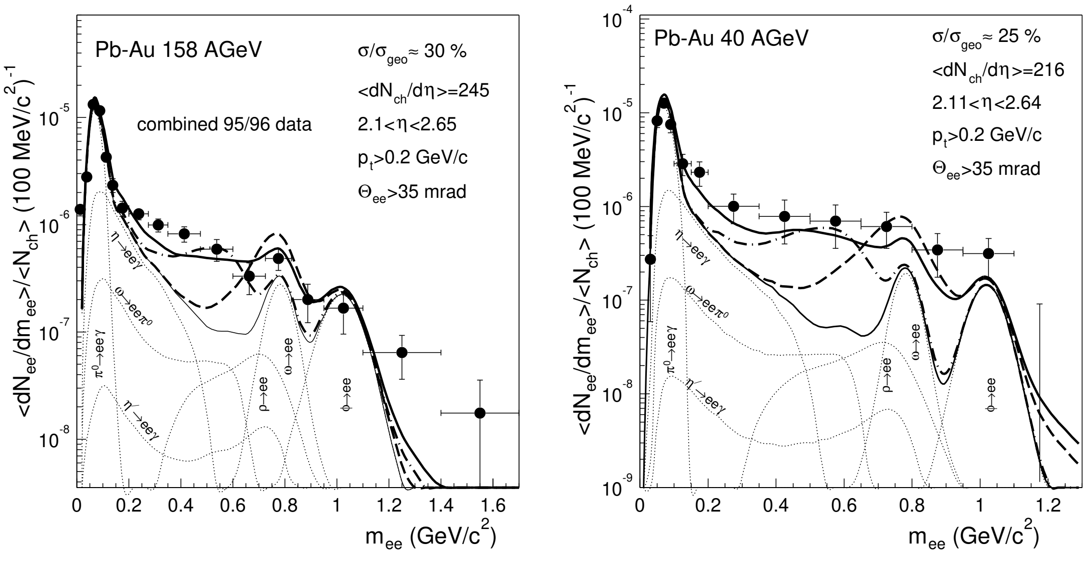

Figure 1: Invariant mass spectrum of e^+e^- pairs emitted in 158 *A* GeV (left) and 40 *A* GeV (right) Pb+Au collisions. The thin solid line represents the 'cocktail' of e^+e^- pairs from meson decays; the thin dotted lines show the individual contributions. Model calculations with a vacuum ρ spectral function (thick dashed line), with dropping in-medium ρ mass (thick dash-dotted line), and with a medium-modified ρ spectral function (thick solid line) are also shown; the hadron decay 'cocktail' is added to the model calculations without the ρ to avoid double-counting.

of the ρ beyond the vacuum value. Theoretically, the modifications are more sensitive to the baryon density than to the temperature of the fireball. The results from both approaches after adding the decay cocktail are contained in the figures and are seen to describe the data within errors, while descriptions based on the unmodified (vacuum) ρ fail to do so. All in all, the experimental results obtained so far together with the intriguing interpretation linked to the chiral transition are considered to belong to the most important results of the field. They are also unique to CERES/NA45 (see below).

Unfortunately, as also visible in Fig. 1, the available statistical accuracy is very limited, due both to a lack of sufficient integrated luminosity and to a low signal-to-background ratio $S/B \ll 1$; the combinatorial background arising from unrecognized conversion and Dalitz pairs is indeed *the* problem of any low-mass pair experiment. The two model alternatives cannot yet be distinguished, let alone details of the spectral shape. The expected $\sqrt{s}$ dependence, associated with the role of baryon density, is only marginally verified (within 1-2 standard deviations). Table 1 summarizes the present situation. The statistical errors of the sum pair yields for $M_{ee} > 0.2$ GeV/c^2 for all data up to 1999 vary between 10% and 27%. The 1999 beam time was the first after the upgrade of CERES with a radial-drift TPC. Since the new readout did not work properly, only about 8 million events were taken and only a part of the TPC was actually read out, severely limiting the data sample.

However, the 2000 run with 158 A GeV Pb+Au and with a new TPC readout, conceived and built by F. Formenti and L. Musa and their group with the support of CERN, was very successful. A total of 32 million events were taken, and 5300 e^+e^- pairs with an S/B ratio 8.5 are expected from an extrapolation of the 1999 data analysis experience (see Section 3 for details), reducing the statistical error of the sum signal to 6%. At the same time, the mass resolution in the region of the ρ is improved to a level of about 2.5%, compared to 5.7% in 1995/1996. After a careful calibration of the TPC, data production as the first step in the analysis chain is just about to start. Beyond the improvement in statistics, we should now be able to isolate the narrow ω meson and then get sensitive to its environment, i.e. see the 'disappearance' of the vacuum ρ as an inevitable consequence of its 'appearance' at lower masses. The study of possible medium influences on the longer-lived ω and ϕ mesons may also be in reach. Further insight into the non-linear, possibly quadratic multiplicity dependence found in the 1995/1996

Table 1: Measured yields of e^+e^- pairs with $M_{ee} > 0.2$ GeV/c^2. 'S+Au 200 1992' means S+Au collisions at 200 A GeV measured in 1992. The numbers with an asterisk* are estimates. See Section 3 for nomenclature.

	S+Au 200 1992	Pb+Au 158 1995/1996	Pb+Au 40 1999	Pb+Au 158 2000
total events	6 M	51 M	8 M	32 M
centrality $\sigma_{\text{trig}}/\sigma_{\text{geom}}$	0.08	0.30	0.25	0.08
total electron pairs S	445	2666	184	5300*
background-to-signal B/S	4.3	11	6	8.5*
effective electron pairs S_{eff}	46	113	14	290*
statistical error	15%	9.4%	27%	6%*

Pb+Au data can, however, hardly be obtained, due to the relatively central trigger selection used for the 2000 data.

We note also that CERES made a significant impact in the area of hadron observables by the two recent publications on HBT interferometry from which a novel freeze-out scenario was deduced [8, 9]. These findings and the motivation for further hadron studies will be described in more detail in Section 2.3.

2 Extending the experimental program of CERES/NA45 to the year 2003

2.1 Lepton motivation for a 170 A GeV In+Ag run

We propose to participate in the full energy run with an indium beam foreseen in 2003 for NA60. There are basically three reasons for continued investigation of the observed e^+e^- excess signal: the A-dependence, the multiplicity dependence, and a further strong improvement of the statistical accuracy. The latter can be read-off from Table 3 in Section 3 and will be used throughout this discussion.

CERES has so far measured S+Au [1] and Pb+Au [2] at full SPS energies. The enhancement factors relative to hadron decays are 5.0 ± 0.7 (stat) ± 2.0 (syst) and 2.3 ± 0.2 (stat) ± 0.6/0.7 (syst data/decays), respectively, and the normalized yields (in units of 10^{-6}) 10.8 ± 1.6 (stat) ± 4.4 (syst) and 4.6 ± 0.45 (stat) ± 1.2 (syst), respectively. The error bars are too large to draw any conclusions on a possible difference between S and Pb, in particular if the S-result (centrality 0.08) is scaled down to 7.7 ± 1.1 (stat) ± 3.1 (syst) for a centrality of 0.30, assuming a quadratic multiplicity dependence. A high energy indium run would have a statistical accuracy of 3%, compared to that of the 2000 lead run of 6% (Table 3). The systematic errors of the upgraded CERES spectrometer have been brought down to a level of 20% in the 1999 data analysis [3], and the relative systematic errors in the comparison between two runs with the same setup are expected to be less than 10%. Note that the sulphur run with its large errors was performed under conditions very different from the following runs. High energy indium 2003 compared to high energy lead 2000 will therefore have a very much improved sensitivity to a possible A-dependence.

Evidence for a roughly quadratic dependence of the observed e^+e^- excess signal in the associated charged particle multiplicity has so far only been seen in the 1995/1996 data [2]. The finding (see Fig. 2) is intriguing since such a dependence is expected for thermal radiation from two-body processes like $\pi^+\pi^-$ or $q\bar{q}$ annihilation [10, 11]. The indium data will have an effective signal statistics of 1130 pairs (Table 3), compared to 113 pairs for the 1995/1996 lead data (Table 1). This improvement by a factor of 10 should put the multiplicity dependence on much more solid grounds.

The overall improvement of the effective signal statistics of 1130 pairs will still be a factor of 4 compared to the best run so far, 2000 lead with 290 pairs (Table 3). We should then be able to test in detail the various theoretical scenarios shown in Fig. 1.

It should be emphasized that the CERES data on low-mass low-p_t lepton pairs are unique

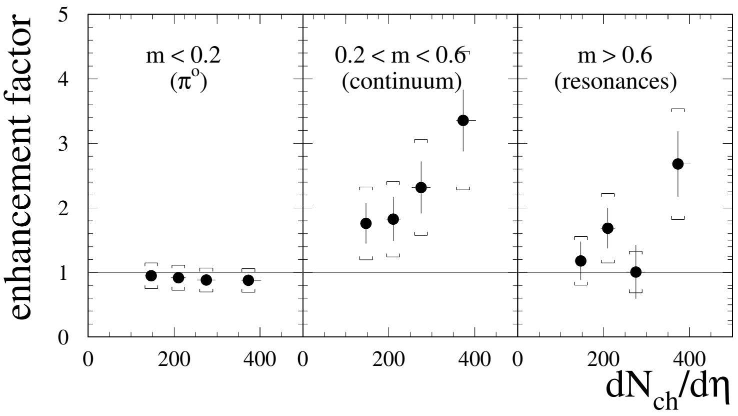

Figure 2: Enhancement of e^+e^- pairs from Pb+Au collisions at 158 *A* GeV with respect to the yield expected from the hadron decay cocktail as a function of multiplicity and pair mass.

and cannot be obtained by any other current experiment. In particular, NA60 will not have competitive sensitivity in the mass region below 0.6 GeV/c^2, where the excess is maximum, due to the m_t-cut which is inevitably coupled to each measurement of muon pairs. On the other hand, they will reach much higher yields for the ω and the ϕ than CERES. A dedicated low-mass low-p_t electron pair experiment is under discussion at RHIC but it cannot start earlier than in a few years from now.

2.2 Lepton motivation for a 25 *A* GeV Pb+Au run

The main argument to run at much lower than full SPS energy has already been formulated in the 1996 CERES/TPC Addendum: the maximum temperature of the fireball should decrease, the maximum baryon density should increase, the ratio of the two should therefore be changed and thus shed light on their relative importance in modifying the spectral function of the ρ meson. The theoretically expected yield from $\pi^+\pi^- \to \rho \to e^+e^-$, incorporating the effects of the "melting" ρ over the whole energy range from 20, 40, 160 *A* GeV SPS to $\sqrt{s}$=200 *A* GeV RHIC is shown in Fig. 3 [12]. The yield, normalized to the charged particle rapidity density, is seen to increase by 10-20% in the mass region 0.2< M_{ee} <0.5 GeV/c^2 with decreasing beam energy, while a corresponding decrease is seen in the region around the vacuum ρ at 770 MeV/c^2. The increase is not at all trivial since the number of annihilating pions monotonically decreases with energy; it actually reflects the dominant role of baryon density in the modification of the ρ spectral function [7]. This then sets the scale for the required accuracy in the investigation of the $\sqrt{s}$ dependence, assuming the (smaller) meson decay part, which has to be added to the yield of Fig. 3 and also changes with $\sqrt{s}$, is sufficiently well under control. Relative to these needs, the 1999 40 *A* GeV Pb+Au data with their large statistical error of 27% (Table 1) are marginal indeed and require more involved arguments to keep some significance.

A new low energy run could drastically improve the situation. Two scenarios are conceivable. One is to run 25 *A* GeV Pb+Au and compare to 158 *A* GeV Pb+Au from 2000. Following Table 3, the comparisons would then have a relative statistical significance of 8.5% and relative systematic errors of roughly 10%, considering that different running years are involved. The other scenario is to run 25 *A* GeV In+Ag and compare to 170 *A* GeV In+Ag. In that case the comparison would have a statistical significance of 5.6%, and the relative systematic error

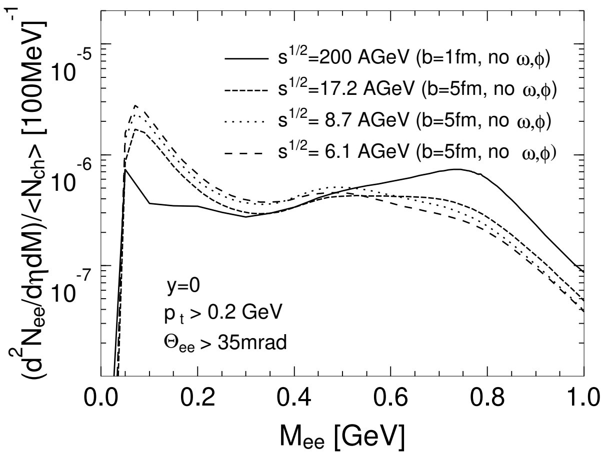

Figure 3: Predictions [12] for thermal e^+e^- production at different beam energies.

could probably reach the same level. Since the fireballs formed in Pb+Au collisions have a significantly larger volume/surface ratio and because of the possibilities with hadronic observables discussed below we prefer the Pb-beam scenario.

2.3 Hadron motivation for a 25 *A* GeV Pb+Au run

In the course of a central heavy ion collision at the SPS the system passes from the QGP through the mixed phase to a hadron gas. The fractional time spent in the mixed phase, softer than the hadron gas and the QGP, is largest if the system starts from the upper (in energy density scale) edge of the mixed phase, when the QGP fills most of the volume. This so-called "softest point" corresponds to an initial energy density of about 1.4 GeV/fm^3, or to a beam energy slightly above AGS [13]. Plotting experimental observables vs the initial energy density, or beam energy, is the best way to detect it. Hadronic signatures indicating the vicinity of the "softest point" include increased reaction duration, reduced elliptic flow, enhanced fluctuations, and an increase of strangeness production. The upgraded CERES spectrometer can address all these signatures by measuring, respectively, two-particle correlations, v_2 for charged particles, mean p_t and net charge fluctuations, and Λ, K^0 to π ratios.

To illustrate the hadronic capabilities of the upgraded CERES experiment we present in Fig. 4 the pion source parameters extracted from an HBT analysis of the 1999 and (a subset of) the 2000 Pb+Au data [8]. The high precision CERES HBT data, combined with AGS data on one side and RHIC data on the other, allowed to study the beam energy dependence of the freeze-out volume. It turned out that the functional shape of this dependence is nearly identical to the shape of the inelastic scattering cross section, properly averaged over the represented particle species and plotted versus beam energy [9]. This means that thermal freeze-out at various energies happens when the mean free path of pions λ_f reaches a constant value. This freeze-out criterium is different from the two commonly used ones, the freeze-out when the mean free paths becomes comparable to the size of the system, and the freeze-out at a fixed spatial density. The small value of $\lambda_f = 1$ fm actually found implies a high degree of opacity at freeze-out.

Hadronic physics has traditionally been a domain of the NA49 experiment. NA49 covers the

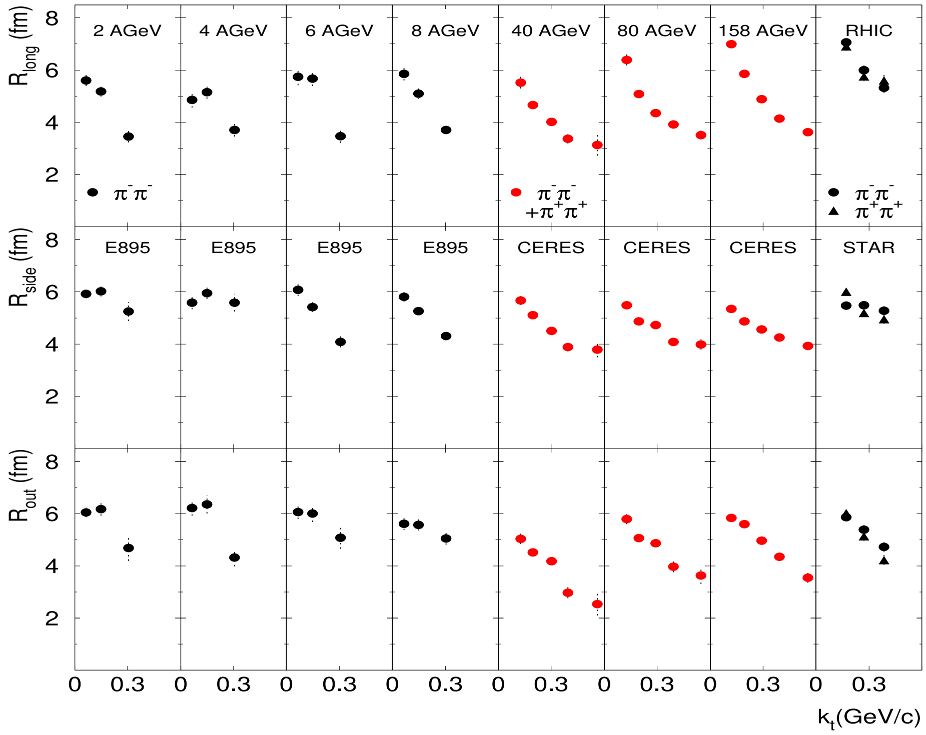

Figure 4: Beam energy systematics of the pion source parameters obtained via HBT analyses at AGS, SPS, and RHIC, including CERES data taken in 1999 and 2000. Only the TPC was used for this analysis. The 80 *A* GeV data were taken during one night of running in 2000.

entire forward hemisphere while CERES detects particles only within 0.55 rapidity units. Using the pion rapidity distribution measured at 40 GeV per nucleon one can estimate that CERES accepts three times less pions than NA49. The data acquisition rate of CERES, on the other hand, exceeds that of NA49 by a factor of ten. Consequently, during a low energy run CERES can collect about three times more particles and close pairs than NA49. The second advantage of CERES comparing to NA49 is the cylindrical symmetry which helps tremendously in the v_2 analysis. The third advantage is the unique high p_t pion identification ability via Cherenkov rings which allows to extend hadronic analyses to high p_t. These features are important for measuring excitation functions of the hadronic observables mentioned above with the precision needed to localize the “softest point”. It is, furthermore, important to use similar systems and centralities at all beam energies. So far central gold-gold or lead-lead collisions have been measured in fixed target experiments at 1, 2, 4, 6, 8, 11, 40, 80, and 158 GeV per nucleon. The largest gap, the one between 11 and 40 GeV, has just been filled by the two short NA49 runs at 20 and 30 *A* GeV. Unfortunately, CERES was unable to participate in these runs because the TPC readout electronics, shared between CERES and HARP, was not returned by HARP, contrary to the agreement from 2000. Especially considering the high data rate of the CERES experiment the low energy Pb beam run could yield a wealth of new information also in the area of hadronic observables.

3 Estimate of rates and electron pair yields

In this section we estimate the expected event- and e^+e^- pair yields for the high energy indium and the low energy lead runs in 2003. To demonstrate how the obtained numbers depend on the system size and the beam energy we also present the yields for a hypothetical low energy run with an indium beam.

For these estimates we proceed as follows. We assume an SPS supercycle duration of 19.2 s with a flat top of 4.2 s for high and up to 10 s for low beam energy. Comparing to the lead-gold run in 2000, in 2003 the average particle multiplicities will be 0.7 times lower because of the lower centrality threshold. The multiplicities in indium induced collisions will be lower also because of the lower mass of the collision system: the A-scaling suggests a factor of (In+Ag)/(Pb+Au) = (115+108)/(208+197) = 0.55. Finally, the multiplicities at 25 GeV are 0.64 times those at 158 GeV. We then scale down the dead times and the event sizes measured in 2000 to get the estimates for 2003. The A-scaling factor is taken as 0.55; the beam energy and the centrality factors are increased by 30% and 20%, respectively, to account for a possible background which might not scale with charged particle multiplicity. As mentioned before, the TPC readout and the data acquisition were new in 2000. Many improvements were introduced during the run, resulting in a continuously increasing data taking efficiency: 0.60, 0.70, 0.75, and 0.85 when averaged over the last 30, 21, 14, and 7 days, respectively. We use 0.75 for our 2003 estimate. The resulting event rates and event yields are presented in Table 2. The entry of 32 million events for 2000 has been actually measured; its detailed understanding gives us confidence to the extrapolation for 2003.

The expected yield of electron pairs with invariant mass above 0.2 GeV/c^2 is given in Table 3. In addition to the discussion above, the following considerations were taken into account. Due to the higher centrality threshold of 0.08 of the 158 A GeV Pb+Au run in 2000, the average multiplicity density $dN_{ch}/d\eta$ is higher by a factor of 1.4 than the value of 250 for a centrality of 30%. The number of electron pairs per million charged particles $10^6 \cdot N_{ee}/N_{ch} = 4.6 \pm 0.45$ (stat) $\pm$ 1.2 (syst) was obtained from the combined 158 GeV Pb+Au data set from 1995/1996 [2]. It corresponds to a centrality of 30% and a $dN_{ch}/d\eta$ of 250 and is assumed to be roughly independent of $\sqrt{s}$ and A. The number actually measured at 40 A GeV Pb+Au is 5.6 $\pm$ 1.4 (stat) $\pm$ 1.1 (syst) [3], that of 200 A GeV S+Au [1] 7.7 $\pm$ 1.1 (stat) $\pm$ 3.1 (syst) if rescaled to a centrality of 30%, consistent with a constant value within errors. The entry for the 158 A GeV Pb+Au run in 2000 is higher by a factor of 1.4, assuming a quadratic multiplicity dependence [2]. The pair reconstruction efficiency ε_p and its dependence on $dN_{ch}/d\eta$ is taken from the analysis of the 1999 40 A GeV data [3], up-scaled to the TPC performance as reached in 2000. The total number of electron pairs N_{ee}, called signal S, follows from the product of $N_{ev} \cdot < dN_{ch}/d\eta > \cdot \Delta\eta (= 0.55) \cdot (N_{ee}/N_{ch}) \cdot \varepsilon_p$. Since S is calculated by subtracting the like-sign pairs (combinatorial background B) from the unlike-sign pairs, and since $B >> S$, the relative statistical error of S is not given by $1/\sqrt{S}$ but by $1/\sqrt{S_{\text{eff}}}$, with the effective signal $S_{\text{eff}} = S/(1 + 2B/S)$. The ratio B/N_{ch} is again taken from the analysis of the 1999 40 A GeV data [3], scaled with $dN_{ch}/d\eta$ and assuming that the relative level of rejection power for unrecognized conversion and Dalitz pairs remains the same. The largely data- and analysis-based ingredients in Table 3 should also here give good confidence to the extrapolations for 2003.

Table 2: Measured (2000) and estimated (2003) event rates. The variables tau1 and tau2 are the dead times of the two pipeline stages. The effective dead time tau_eff is rate dependent.

	Pb+Au 158 2000	In+Ag 170 2003	In+Ag 25 2003	Pb+Au 25 2003
supercycle	19.2 s	19.2 s	19.2 s	19.2 s
flat top	4.2 s	4.2 s	8.2 s	6.2 s
beam per burst	10^6	10^6	$2{\cdot}10^6$	$1.5{\cdot}10^6$
b/a protection	$\pm 1\ \mu$s	$\pm 1\ \mu$s	$\pm 1\ \mu$s	$\pm 1\ \mu$s
good beam per burst	620 k	620 k	1200 k	920 k
beam-on-target fraction	1.0	1.0	0.65	0.65
beam on target per burst	620 k	620 k	800 k	600 k
target thickness	1.3%	1.3%	1.8%	1.8%
centrality $\sigma_{\text{trig}}/\sigma_{\text{geom}}$	0.08	0.30	0.30	0.30
trigger candidates per burst	620	2400	4300	3200
$dN_{ch}/d\eta$	355	138	88	160
tau1	3.8 ms	1.8 ms	1.5 ms	2.7 ms
tau2	5.0 ms	2.3 ms	2.0 ms	3.5 ms
tau_eff	3.9 ms	1.8 ms	1.6 ms	2.8 ms
collected events per burst	400	1200	2300	1300
event size	0.50 MB	0.23 MB	0.20 MB	0.35 MB
collected MB per burst	200 MB	280 MB	460 MB	460 MB
sending overhead	7 s	5 s	5 s	5 s
time for sending	8 s	10 s	8 s	8 s
sending speed	25 MB/s	50 MB/s	50 MB/s	50 MB/s
sent MB per burst	200 MB	280 MB	400 MB	400 MB
sent events per burst	400	1200	2000	1150
bottleneck	sending	collecting	sending	sending
bursts per day	4500	4500	4500	4500
gross days	36	37	10	10
setup days	6	3	2	2
data taking days	30	34	8	8
data taking efficiency	0.60	0.75	0.75	0.75
total events	32 M	140 M	54 M	31 M

Table 3: Expected yields of e^+e^- pairs with $M_{ee} > 0.2$ GeV/c^2.

	Pb+Au 158 2000	In+Ag 170 2003	In+Ag 2003	Pb+Au 25 2003
total events	32 M	140 M	54 M	31 M
centrality $\sigma_{\mathrm{trig}}/\sigma_{\mathrm{geom}}$	0.08	0.30	0.30	0.30
$dN_{ch}/d\eta$	1.4*250	138	88	160
N_{ee}/N_{ch}	$1.4{*}4.6{\cdot}10^{-6}$	$4.6{\cdot}10^{-6}$	$4.6{\cdot}10^{-6}$	$4.6{\cdot}10^{-6}$
pair reconstr. efficiency	0.13	0.24	0.27	0.23
total electron pairs S	5300	11700	3200	2800
background-to-signal B/S	8.5	4.7	3.0	5.4
effective electron pairs S_{eff}	290	1130	460	250
statistical error	6%	3%	5%	6%

4 Estimate of costs and effort

The TPC was added to CERES in 1998. In 1999 and 2000 a modern trigger system was devised. A new TPC readout and a new data acquisition system were developed for the run in 2000. All these components worked as expected and will be kept unchanged for the 2003 run. The minor changes of the CERES setup, which would be needed or helpful, are: a new silver target for the indium run, a larger and thicker gold target for the low energy run, replacing air in the beam Cherenkov counters with C_4F_{10}, adapting the RICH gas system to present safety requirements (15 kCHF), safety check of the TPC magnet, upgrading the receiving PC's to double the bus speed and using up-to-date ethernet cards (14 kCHF), and optimizing the run control software to reduce sending overhead from 7 to 5 s (1-2 weeks). The costs of these items would be covered by the CERES collaboration.

CERES is ten years old. The readout electronics of the silicon and RICH detectors worked fine during the 2000 run. In the case of a problem, however, it would be difficult to find replacements for specific modules. We are currently investigating the possibilities of reducing the related risk.

As usually, CERES would cover the running costs of TPC gas, RICH gas, RICH TMAE, monochromator Ar, and data storage at CDR. From CERN we need 37 days of indium beam at 170 A GeV, 10 days of lead beam at 20-30 A GeV, powering and cooling the H8 beam-line (about 30 kW and 1.3 MW at 30 and 170 GeV, respectively), powering and cooling our TPC magnet (2.5 MW), powering the electronics and the counting room, 8 VME crates and MXI interfaces from Electronics Pool available for three months, CDR support for storing the data, and ED group support in emergency cases.

5 General remarks and conclusions

A further run of CERES in 2003 will yield important new and unique results:

1. For low mass dilepton pairs unprecedented statistics and accuracy can be achieved with an In run at full energy and a Pb run at 25 *A* GeV, providing stringent tests for the different models describing the previously observed anomalous enhancement.
2. With the hadron physics capability of the present CERES apparatus important new measurements can be obtained in the area of hadronic observables, in particular concerning correlations and fluctuations.
3. These results are important for our understanding of the SPS data and cannot be obtained with other current experiments.

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Attachments

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