Measurement of electromagnetically produced e^+e^--pairs in distant S-Pt collisions *

The CERES/NA45 collaboration

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Abstract

We have for the first time identified e^+e^--pairs produced by strongly varying electromagnetic fields in distant S-Pt collisions at 200 GeV/u projectile energy at the CERN-SPS. The differential cross section for the mass range $10\,\mathrm{MeV}/c^2 \leq m_{ee} \leq 100\,\mathrm{MeV}/c^2$ and the polar angle range 141 mrad $\leq \theta_e \leq$ 260 mrad agrees well with a lowest-order perturbation QED-calculation.

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1 Introduction

Electron-positron pairs are produced in large quantities by the strong transient electromagnetic fields during the collision of heavy nuclei at high energies. This process is generally referred to as QED pair production. It is well known in e^+e^- collisions [1,2]. Since the coupling constant is proportional to $Z\alpha$, the cross section is much larger in nuclear collisions than in collisions of singly charged particles. The cross section was first calculated in 1934 by Landau and Lifschitz [3]. The availability of heavy ions at ultrarelativistic energies and, in particular, the perspective of the future heavy ion colliders RHIC and LHC have brought a renewed interest in this process from the theoretical point of view [4–11]. As the energy and the charge of the colliding nuclei increase, unitarity violation is expected, i.e. the lowest-order perturbative approach becomes invalid and higher-order effects should play an increasing role. This also implies that multiple pair production will start to occur [10]. At sufficiently high ion energies also new particles could be produced in distant nuclear collisions [13,14]. In addition to these basic questions, it is important to understand the QED pair production, since it may be a significant background source [12] in the measurement of thermal e^+e^--pairs in central nuclear collisions. There is also a more practical interest, because this process may limit the lifetime of the fully stripped beams of the future heavy-ion colliders, RHIC and LHC. Only one measurement exists so far on this process, of the $p_\perp$ and angular distributions of inclusive e^+ [15]. We report here the first results on the production of electron-positron pairs with invariant masses $m_{ee} > 10$ MeV/c^2 in S-Au at 200 GeV/u.

2 The experimental setup

CERES/NA45 (Fig. 1) is an experiment dedicated to the measurement of nuclear e^+e^--pair production in pp, pA and AA-collisions in the mass range $100\,\mathrm{MeV/c^2} < m_{ee} < 2000\,\mathrm{MeV/c^2}$. The experimental setup is described in detail in [16], here we only summarize its main features. Particle identification and directional tracking are based on two azimuthally symmetric RICH detectors, one (RICH-1) situated before, the other (RICH-2) behind a superconducting solenoid. The magnetic field provides a local azimuthal momen-

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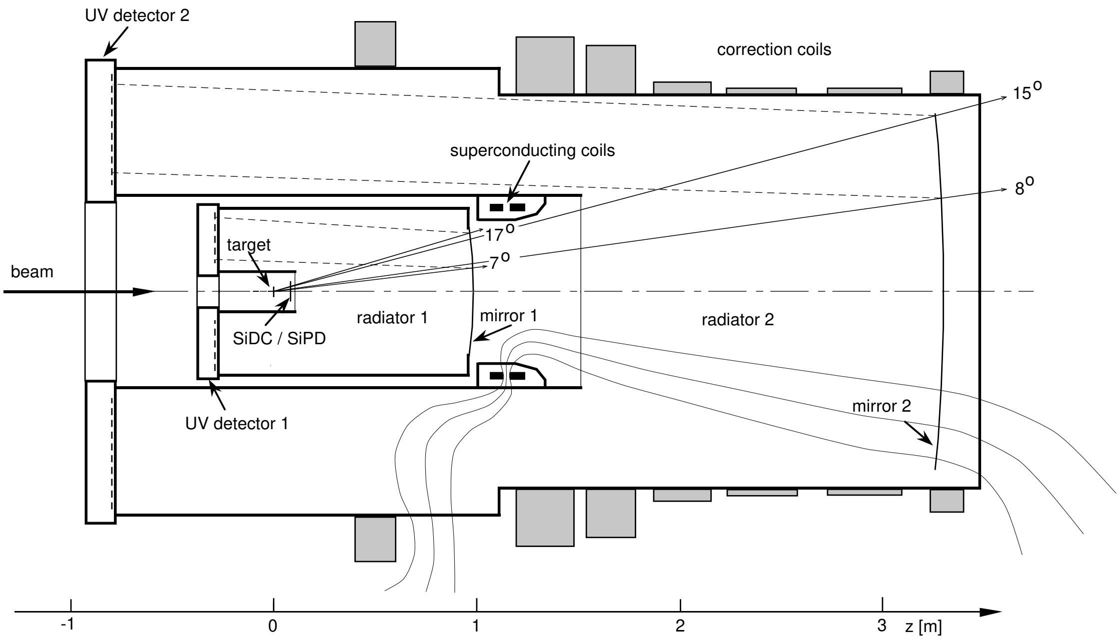

Fig. 1. The layout of the CERES spectrometer

tum kick for momentum and charge measurement. Due to the high Cherenkov threshold of the CH_4 radiator gas, only electrons produce rings with a saturated radius while almost no hadrons are detected. The multiple scattering is reduced to a very low level by minimizing the amount of material in the spectrometer acceptance (1.6% X_0). A silicon pad detector (SIPD) [17] serves as a multiplicity-dependent first level trigger. The counter is segmented into 64 pads arranged in 8 rings and 8 azimuthal sectors.

QED pairs were measured with a slightly modified setup and different trigger conditions. The magnetic field was reduced to 20% of its nominal value to extend the range of measurable electron momenta down to 25 MeV/c. Two scintillation counters located downstream of the spectrometer were used to trigger on distant nuclear collisions. The first counter identified the sulfur beam by its energy loss, the second counter covering the area adjacent to the beam axis vetoed collisions with nuclear overlap. In order to trigger on electron pairs, 2 or 3 particles were required in the silicon pad detector within the RICH acceptance. This trigger was dominated by multiple δ-electron production in the material of the target area. To minimize the fraction of background triggers we used a platinum target of only 50 μm thickness, and δ-electrons with energies below 250 keV/c were stopped in a 240 μm thick mylar foil in front of the silicon pad detector. In addition, all material in the target area not needed for the measurement was removed. In spite of all the precautions, δ-electrons remained the main background source in the RICH detectors and in the silicon pad detector.

With this setup a total of 3.1 million events were written to tape. 1.4 million

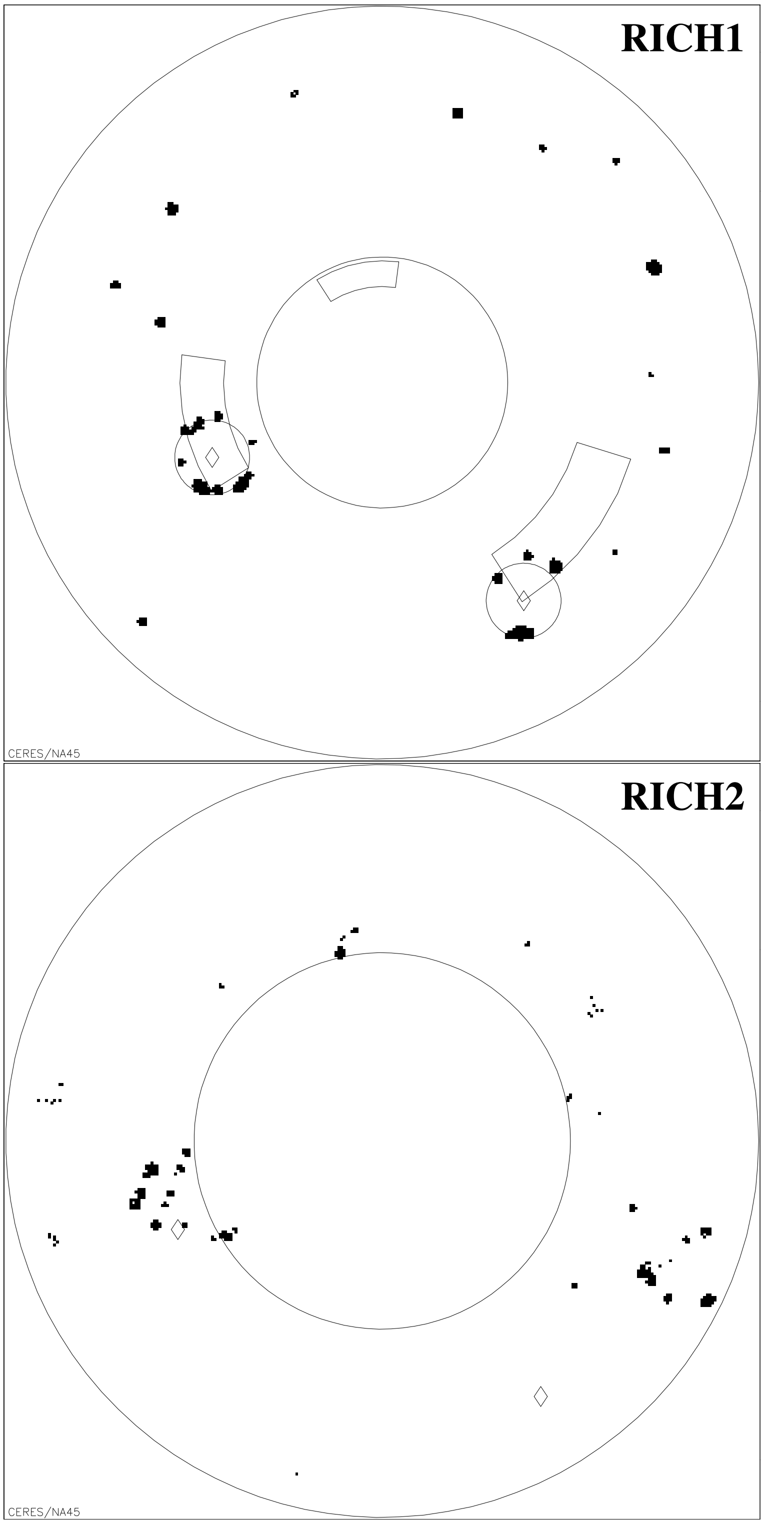

Fig. 2. A QED candidate pair in the RICH detectors. The sectors drawn in the display are a projection of hit pads of the silicon pad counter on the RICH-1 acceptance. The diamonds mark the RICH-1 ring centers in RICH-2.

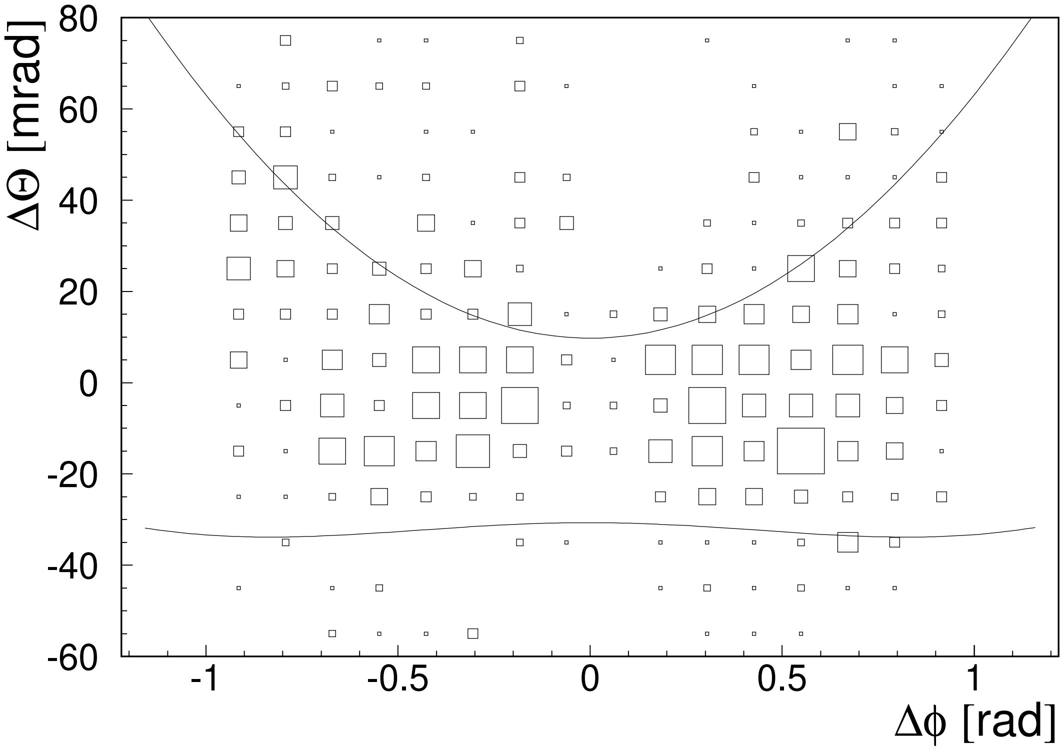

Fig. 3. $\Delta\theta$ versus $\Delta\phi$ of positrons (left) and electrons (right) for QED-pair candidates. The lines drawn are determined by multiple scattering and reconstruction resolution (1.5σ). The asymmetric shape in $\Delta\theta$ for large $\Delta\phi$ is due to the second order field effect.

events were recorded with the described first-level trigger. The rest, 1.7 million events, was measured with a second-level trigger [18] which enriched the data sample by a factor of 1.7. This trigger required the recognition of one electron ring in RICH-1.

3 Data analysis

The events in the RICH detectors are almost free of background (see Fig. 2) in contrast to events of nuclear collisions. Nevertheless the recognition of low momentum electrons is difficult, because the ring images are strongly distorted by multiple scattering. In addition, the electrons are deflected towards the beam axis by a second order magnetic field effect which further distorts and shifts the ring image in RICH-2, for very low momenta even out of the acceptance.

In the first step of the analysis, hits of Cherenkov photons are reconstructed. Electron ring candidates are defined by a minimum of 4 and 5 hits in RICH-1 and RICH-2, respectively, within a mask chosen to account for the strongly distorted Cherenkov images. Tracks are reconstructed by matching the ring

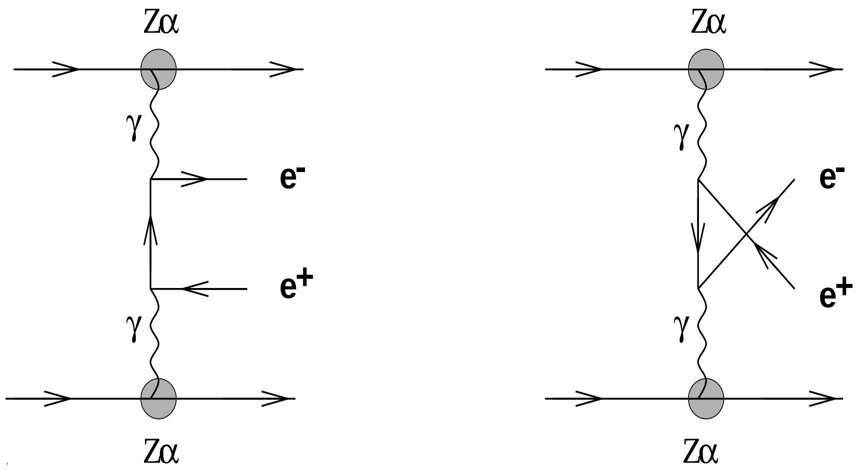

Fig. 4. The Feynman-diagrams of lowest-order on which the VEGAS calculation is based.

images in RICH-1 to those in RICH-2 if the azimuthal deflection corresponds to a momentum larger than 25 MeV/c. Fake tracks (false combinations of rings to tracks) are suppressed by ring and match quality cuts. To ensure that the tracks originate from the target, we require a match with the silicon pad detector. These tracks are combined to electron-positron pairs, if the opening angle is larger than 90°. For smaller opening angles the tracks are so close that the ring match between RICH-1 and RICH-2 can be ambiguous. Pairs with invariant masses below $10\,\mathrm{MeV/c^2}$ are rejected because the reconstruction efficiency decreases significantly and the combinatorial background increases to an unacceptable level. The $\Delta\theta$-$\Delta\phi$-distribution of the tracks from candidate pairs is shown in Fig. 3, where $\Delta\theta$ ($\Delta\phi$) denotes the polar (azimuthal) deviation between the ring positions in both detectors. Both tracks of a genuine QED pair should lie in the butterfly-shaped area, defined by the ϕ-deflection in the magnetic field, multiple scattering, ring center resolution and second order field effect (the lines in Fig. 3 correspond to ± 1.5 standard deviations of $\Delta\theta$). There is a clear concentration of both electron and positron candidates inside the butterfly area. However, there is also a contribution from background pairs, indicated by the large number of tracks outside the 1.5σ-region. Many of those pairs are combinations of a δ-electron and a fake positron. To subtract the background from the data we use an event-mixing method, i.e. combining positrons and electrons from different events. The mixed background is normalized to the number of positrons outside the 1.5σ-region measured in the data, yielding 79 ± 9 fake pairs, and subtracted from the pair candidates inside the butterfly area. A sample of 70 ± 15 pairs remains.

The reconstruction efficiency correction is determined using a QED electron-pair generator [7] and a GEANT [20] simulation of the detector. The pair generator, henceforth referred to as QED Monte Carlo, is based on the perturbative calculation of the lowest-order Feynman diagrams of $\gamma\gamma$-scattering (Fig. 4) [7] and uses a Monte-Carlo method (VEGAS [19]) for the phase space integration of the corresponding matrix element. The corrected data are normalized to the total number of beam particles recorded during the measurement. The full analysis chain was checked by reconstructing events with two δ-electrons. The trigger efficiency for these events is the same as for events containing a QED electron pair. However, a much larger data sample is available. Since the measured rate differs by only 12% from the calculated event rate, we conclude that low energy electrons – and thus positrons – are reliably measured with our experimental setup. The systematic errors will be discussed in detail in the next section.

4 Results

Fig. 5 shows the differential cross section as a function of mass m_{ee}, transverse momentum $p_\perp$ and azimuthal opening angle ϕ_{op} of the QED electron pair, in the kinematical region $10\,\mathrm{MeV/c^2} \leq m_{ee} \leq 100\,\mathrm{MeV/c^2}$, $E_{e^\pm} \geq 25\,\mathrm{MeV}$, $141\,\mathrm{mrad} \leq \theta_{e^\pm} \leq 260\,\mathrm{mrad}$ and $90^\circ \leq \phi_{op} \leq 180^\circ$. The data are compared to the perturbative calculation of the lowest-order Feynman-diagrams of $\gamma\gamma$-reactions [7] described above, which is shown in Fig. 5 by the solid curves. The measured invariant mass distribution agrees well with the QED calculation. The peak of the azimuthal opening angle distribution at 180° is evident in the data and is expected from the production mechanism. The $p_\perp$-distribution shows a slight enhancement for $p_\perp > 20\,\mathrm{MeV/c}$ compared to the theoretical prediction, which correlates with a slight excess at azimuthal opening angles $\phi_{op} < 120^\circ$. Statistically the effect is not significant and could be due to an imperfect background subtraction. Integrating the differential cross sections in the quoted kinematical region one obtains:

$$\Delta\sigma = (13.9 \pm 3.1(\mathrm{stat})\,{}^{-1.9}_{+3.5}(\mathrm{syst})\,)\,mb \tag{1}$$

This is, as expected from Fig. 5, in very good agreement with the QED calculation:

$$\Delta\sigma = (14.0 \pm 0.4(\mathrm{stat})\,{}^{-1.4}_{+0}(\mathrm{syst}))\,mb \tag{2}$$

Statistical and systematic errors are quoted separately. The main contribution to the systematic errors are the following:

– The reconstruction efficiency relies on the Monte-Carlo simulation of the detector. Uncertainties in the simulation were investigated by varying the critical cuts in the analysis, the resulting cross sections vary from -5% up to $+22\%$.

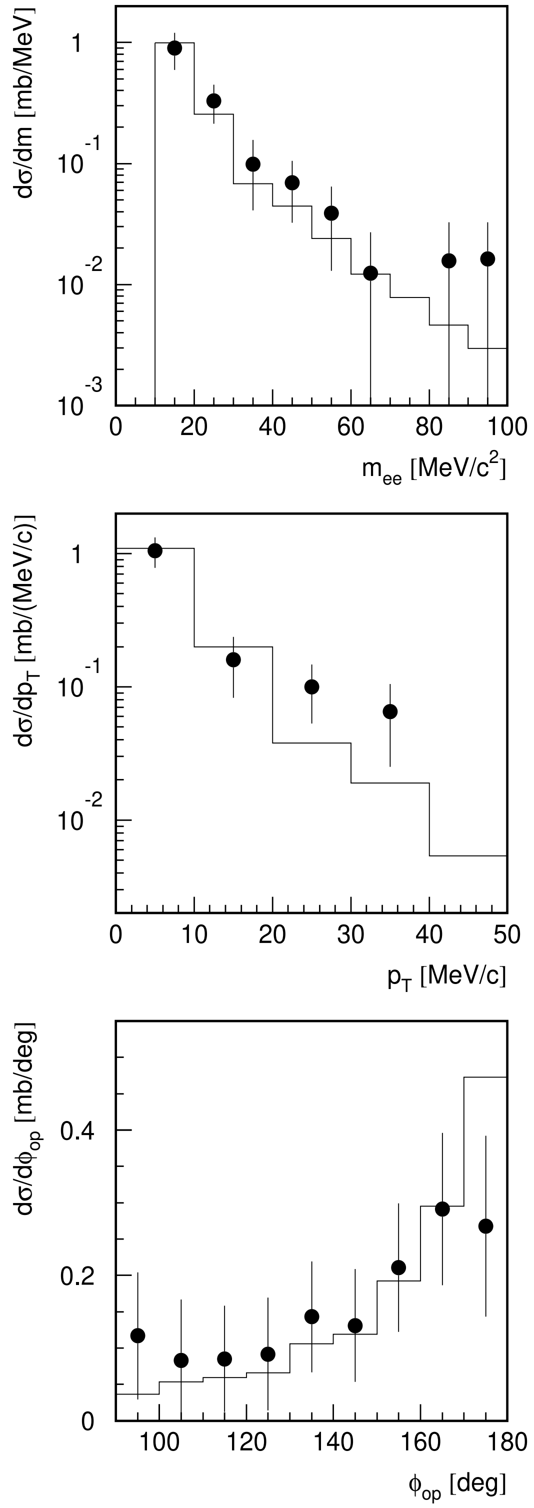

Fig. 5. The differential cross section of QED e^+e^--pair production as a function of m_{ee}, $p_\perp$ and azimuthal opening angle ϕ_{op}. It is valid in the kinematical limits quoted in the text. The measurements are compared with a lowest-order Feynman graph calculation of $\gamma\gamma$-reactions, shown by the histograms.

– The efficiency correction is rather insensitive to variations of the input distributions of the QED Monte Carlo. We observed changes less than $\pm 4\%$.

– Additional δ-electrons in the event can obscure the event reconstruction. Pairs can be lost due to ambiguities in the track match, which will lead to an underestimate of the cross section up to 12%. Occasionally the pair will not be lost but wrongly reconstructed and therefore distort the differential distributions.

– As already mentioned, comparing the measured and calculated rate of events with two δ-electrons we find a possible overestimate of the cross section by 12%.

Adding positive and negative errors separately in quadrature, we obtain a systematic error of -14% and $+25\%$ on the cross section.

Systematic errors occur also in the QED Monte Carlo. The cross section is calculated integrating over all impact parameters. However, our measurement is restricted to impact parameters above approximately 10 fm, because the trigger selects collisions without nuclear overlap. To study the impact parameter dependence of the calculation, we applied a transverse momentum cut on one of the outgoing nuclei equivalent to a 10 fm impact parameter cut, following the method of ref. [21]. The cross section decreased by about 10%. We have also studied the dependence of the QED Monte Carlo result on the form factor of the colliding nuclei and found a negligible effect.

5 Conclusions

We have measured for the first time completely reconstructed e^+e^- pairs produced by strongly varying electromagnetic fields in distant S-Pt collisions with invariant mass $m_{ee} > 10\,\mathrm{MeV/c^2}$ at 200 GeV/u projectile energies. Within the acceptance of the CERES spectrometer ($\theta = 8°$-$15°$), the pair production is well described by the lowest-order Feynman diagrams of $\gamma\gamma$-reactions. The good agreement of measurement and expectation allows to estimate the rate of e^+e^- pairs from QED production in collisions with nuclear overlap for the CERES acceptance; it is negligible compared to e^+e^- pairs from meson decays.

Acknowledgements

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References

[1] V.E. Balakin et al., Phys. Lett. B 34 (1971) 663
C. Bacci et al., Nuovo Cim. 3 (1972) 709
V.M. Budnev et al., Phys. Rep. C 15 (1975) 181

[2] Ch. Berger, W. Wagner, Phys. Rep. C 146 (1987) 1
H. Kolanoski, Springer Tracts Vol. 105, Berlin (1984)

[3] L.D. Landau, E.M. Lifschitz, Phys. Sz. Sowjet 6 (1934) 244

[4] C.A. Bertulani, G. Baur, Phys. Rep. C 163 (1988) 299

[5] G. Baur, N. Baron, Z. Phys. C 54 (1992) 419

[6] K. Hencken, D. Trautmann and G. Baur, KFA-IKP(TH)-1993-25

[7] J.A.M. Vermaseren, Nucl. Phys. B 229 (1983) 347

[8] M. Vidovic et al., GSI-Preprint 92-52

[9] C. Bottcher, M.R. Strayer, Phys. Rev. D 39 (1989) 1330

[10] M.J. Rhoades-Brown, J. Weneser, Phys. Rev. A 44 (1991) 330

[11] J.S. Wu, M.J. Rhoades-Brown, C. Bottcher and M. R. Strayer, Nucl. Instr. and Meth. A 311 (1992) 249

[12] R.S. Hayano et al., 4th Workshop on Experiments and Detectors for a Relativistic Heavy-Ion Collider, 1990, M. Fatyga, B. Moskowitz (eds.), BNL 52262, p. 143

[13] J. Rau et al., J. Phys. G 16 (1990) 211

[14] M. Greiner et al., GSI-Preprint 93-73

[15] C.R. Vane et al., Phys. Rev. Lett. 69 (1992) 1911

[16] U. Faschingbauer et al., Proposal to the SPSC, CERN SPSC/88-25/P237 and SPSC/88-40/P237/Add 1

R. Baur et al., (Proc. First Workshop on RICH Detectors, Bari 1993), Nucl. Instr. Meth. A 343 (1994) 87

[17] T.F. Günzel et al., Nucl. Instr. and Meth. A 316 (1992) 259

[18] 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

[19] G.P. Lepage, J. Comp. Phys. 27 (1978) 192

[20] R. Brun et al., GEANT3, CERN DD/EE/84-1, September 1987

[21] K.J. Abraham, R. Laterveer, Phys. Lett. B 251 (1990) 186