Two-photon production processes at high energy. II*

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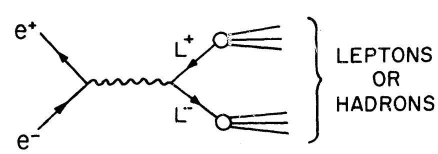
We discuss the production of pairs of heavy leptons and pairs of heavy spinless mesons in e^+e^- colliding beams. The two-photon production cross section of these particles is large in the energy region covered by the new machines at DESY and SLAC, and competes favorably with the one-photon production cross section. Leptonic decays of the new particles are incorporated in the analysis. We present both total cross sections and distributions in several important variables. Backgrounds from the regular two photon reaction $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ are also discussed.

I. INTRODUCTION

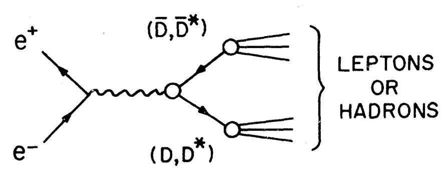
The first observation by Perl *et al.*[1] of the reaction $e^+e^- \rightarrow e^\pm\mu^\mp +$ "missing energy" has led to considerable speculation about the existence of heavy leptons[2] with masses around 1.8 GeV/c^2. Recent papers[3] have discussed the production and decay of such particles via the one-photon-exchange diagram depicted in Fig. 1(a). However, the discovery of new spin-zero strongly interacting particles[4] with masses 1.86 GeV has complicated the picture. The decays[5] of the D (and D^* meson which may exist with mass ~2 GeV), can also lead to leptons in the final state as well as hadrons, via the one-photon reaction depicted in Fig. 1(b). However, they are more easily detected by examining their hadronic decays. New experimental results,[6] which are relevant to both heavy-lepton production and heavy-hadron production, have recently been published in the form of single-lepton inclusive spectra.

If we consider the situation regarding heavy-lepton or heavy-hadron pair production at much higher energies, then the cross sections for the single-photon production mechanism decrease like E^{-2}, where E is the beam energy, while the cross sections for the two-photon production processes depicted in Fig. 2 grow like $\ln^3 E$. The form factors in the single-photon production of heavy hadrons make an additional suppression which is not present in the corresponding two-photon production process. Note that branching ratios into leptons or hadrons are identical for both reactions so they do not alter any of our conclusions. It is therefore important to examine the two-photon production processes with a view to the continued study of dilepton or dihadron signals at the new accelerators. In fact, if there exist even *heavier* leptons and hadrons then it will be necessary to subtract out the backgrounds from known sources. We deal here with the case of spinless mesons only. When vector mesons are produced (or vector and scalar mesons together) the analysis is more complicated owing to the great variety of decay modes and coupling constants, so we will discuss this case separately in the third article.

This paper relies heavily on the computer programs developed to study the reactions $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ and $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ at high energies. We chose to give many details in the first paper[7] of this series, which we refer to as I, so we can make this paper rather brief. Section II contains a discussion of the matrix elements and the techniques used for the integrations. Our cross sections and distributions are discussed in Sec. III.



(a)



(b)

FIG. 1. Single-photon diagrams. (a) Production and decay of heavy-lepton pairs in e^+e^- collisions, (b) production and decay of heavy spin-zero or spin-one hadrons in e^+e^- collisions.

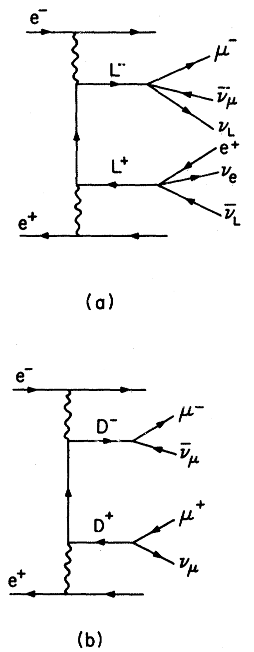


FIG. 2. Two-photon diagrams. (a) Production and leptonic decay of heavy-lepton pairs in e^+e^- collisions. The crossed Feynman graph is not drawn here but is included in the analysis. (b) Production and leptonic decay of heavy-spinless-hadron pairs in e^+e^- collisions. The crossed Feynman graph and the seagull term are not drawn here but are included in the analysis.

Finally, we give some conclusions in the last section.

II. CALCULATIONAL DETAILS

The matrix elements for the reactions depicted in Fig. 2(a) and Fig. 2(b) follow rather trivially from the corresponding matrix elements in I. We note that bremsstrahlung-type diagrams are smaller than in the case of dimuon production[7] and we neglect them completely. The only additional work is to add on the decays of the particles. We concentrate here on leptonic decay modes. For the spinless mesons the two-body decay can be added exactly even though it is not expected to be the most important decay channel. In the case of heavy leptons we neglect any polarization effects in the production process and average over the spin vectors in the decay. This is justified because polarization effects are very small in this energy region. In our previous analysis of the photoproduction of heavy leptons[8] we computed the cross sections both including and neglecting polarization effects. We found only a minute difference in the two cases when the beam energy was large compared to the mass of the leptons. This is obviously true for the two-photon reaction considered here.

Regarding the decays of the heavy leptons we assume that they have the usual three-body leptonic-decays of the $V-A$ current-current type. Hence the analysis is identical to the incorporation of the decays in the photoproduction reaction and we refer the reader to Ref. 8 for further details. The neutrinos were integrated over analytically and the extra integrations over the charged particles in the decay products were added on to the seven-dimensional integral for the production cross section. The rest of the analysis was handled easily on the CDC 7600 computer at Brookhaven National Laboratory.

III. RESULTS

The total cross sections for the reactions considered are given in Fig. 3. Here we plot the single-photon cross section for lepton pairs $e^+e^- \to L^+L^-$, and for spin-0 (pointlike) hadron pairs, $e^+e^- \to D^+D^-$, and compare them with the corresponding two-photon cross sections $e^+e^- \to e^+e^-L^+L^-$ and $e^+e^- \to e^+e^-D^+D^-$. We have chosen masses of 1.8 GeV/c^2 for L and 1.86 GeV/c^2 for D. The crossover point for these reactions is approximately the

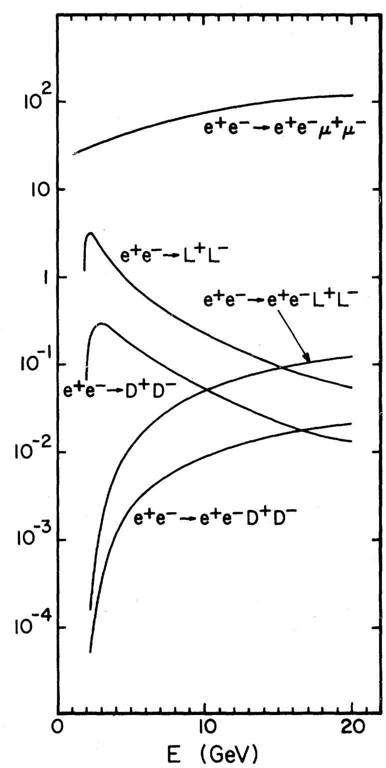


FIG. 3. Total cross sections for the two-photon reactions $e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to e^+e^-L^+L^-$, and $e^+e^- \to e^+e^-D^+D^-$. For comparison we also give the total cross sections for the single-photon reactions $e^+e^- \to L^+L^-$ and $e^+e^- \to D^+D^-$.

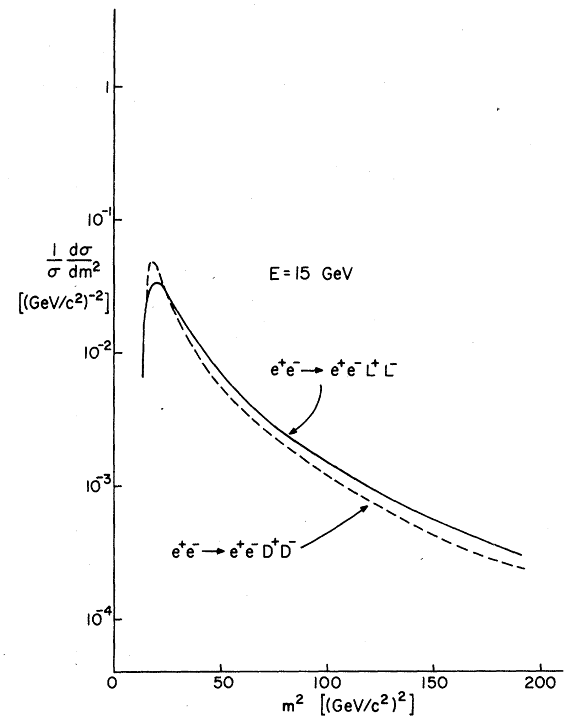


FIG. 4. The distributions in m^2, the invariant mass squared of the heavy-lepton pair (solid line) and heavy-meson pair (dashed line).

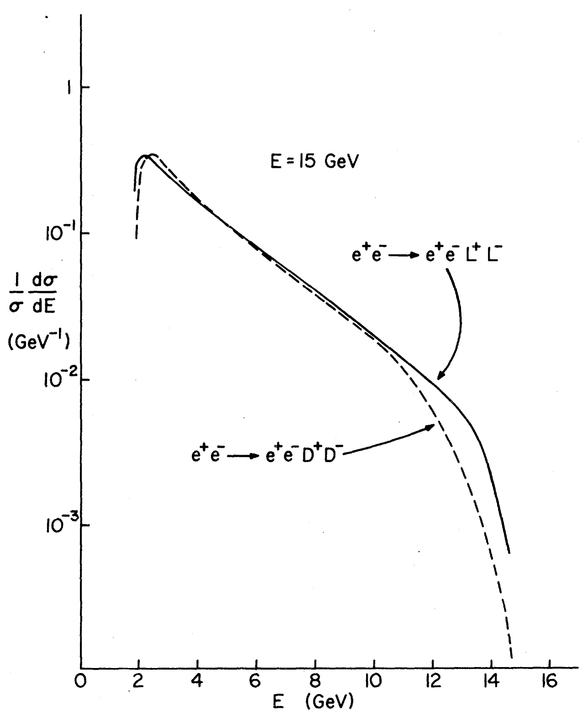


FIG. 5. The energy spectra of one of the heavy leptons (solid line) and one of the heavy spinless mesons (dashed line).

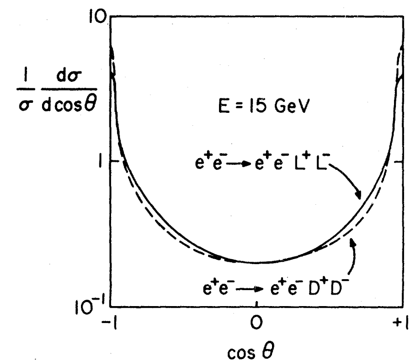


FIG. 6. The angular distributions of one of the heavy leptons (solid line) and one of the heavy spinless mesons (dashed line).

same, namely when each beam has an energy of 16 GeV. For comparison we give the two-photon production cross section of regular muon pairs. The latter cross section is larger by approximately three orders of magnitude. Remembering that leptonic branching ratios for heavy-lepton and heavy-hadron decays are unlikely to be larger than 20% we conclude that it will be difficult and maybe even impossible to separate μe pairs into signal and noise. This problem can only be discussed meaningfully when all the decay-lepton distributions are known. Therefore we have computed several distri-

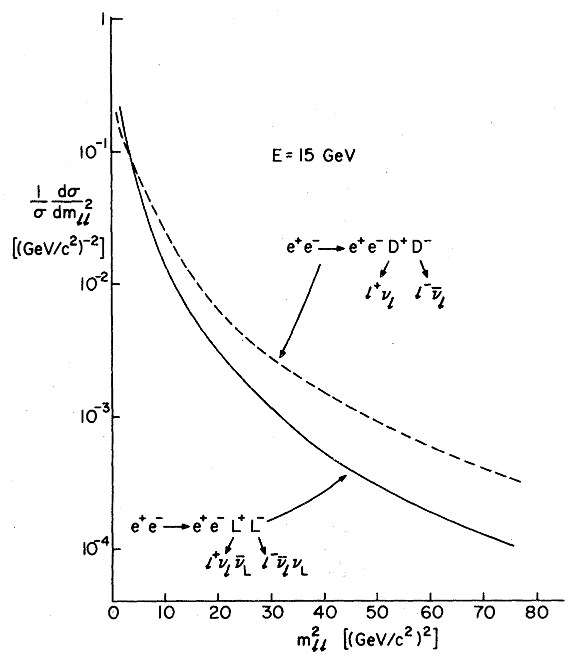


FIG. 7. The distributions in m_{ll}^2 the invariant mass squared of the charged decay leptons from heavy-lepton decays (solid line) and heavy-spinless-meson decays (dashed line).

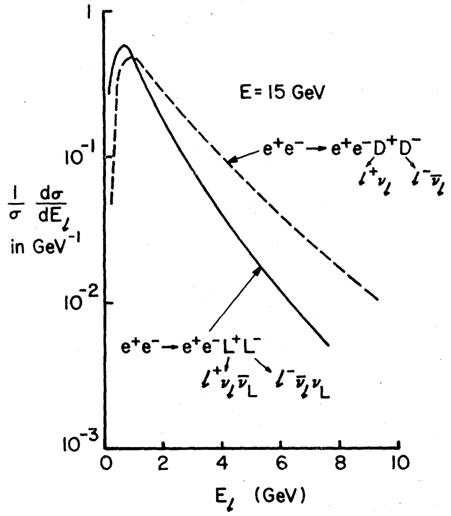


FIG. 8. The energy spectra of the decay leptons from heavy-lepton decays (solid line) and heavy-spinless-meson decays (dashed line).

butions which are next on our discussion list. We first give the results for the heavy lepton L and then the results for the heavy meson D. All the following results are given for a beam energy of 15 GeV.

Figure 4 shows the distribution in m^2 the invariant mass of the heavy-lepton pair. This spectrum peaks for small masses and falls off like m^{-2} for large masses as expected from the double-equivalent-photon approximation (DEPA) which adequately describes the curve. Figures 5 and 6 describe the distributions in energy and in angle of one of the heavy leptons. Obviously the leptons tend to be produced at low energies and along the beam directions, and these features carry over to the decay products. Unfortunately the lifetime of the heavy lepton is expected to be so short that it can only be identified from its decay products. We now

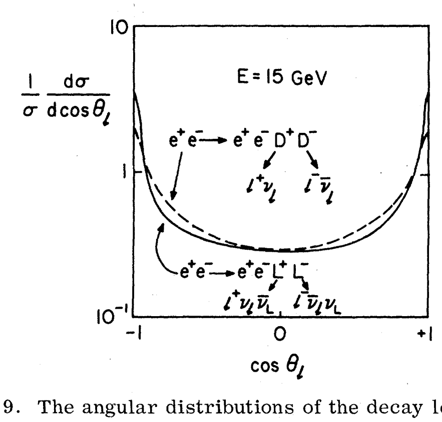


FIG. 9. The angular distributions of the decay leptons from heavy-lepton decays (solid line) and heavy-spinless-meson decays (dashed line).

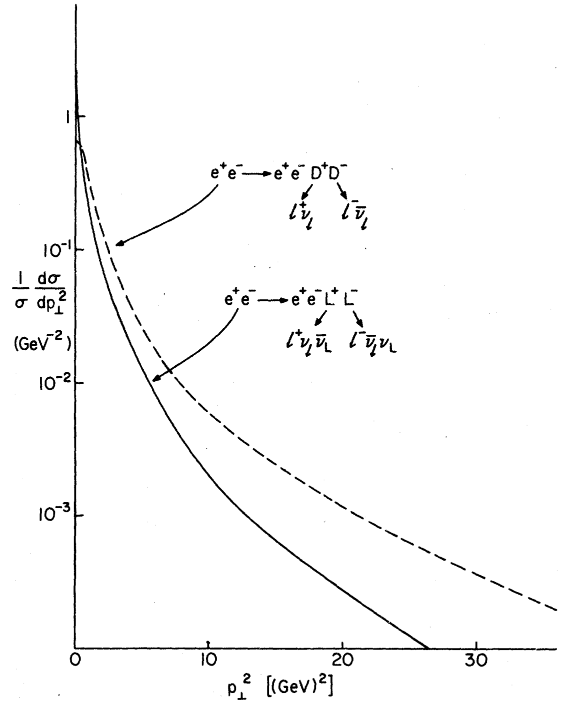


FIG. 10. The distribution in $p_\perp^2$, the square of the transverse momentum of one of the charged decay leptons emitted in heavy-lepton decays (solid line) and heavy-spinless-meson decays (dashed line).

give the distributions for the decay leptons, even though they resemble, to some extent, those of the parent. Figure 7 shows the distribution in m_{ll}^2 the invariant mass of the final l^+l^- pair, assuming a three-body leptonic decay of each heavy lepton. This distribution is also peaked at small invariant mass. The energy spectrum of the decay lepton is given in Fig. 8 and its angular distribution in Fig. 9. For completeness we also show the distribution in the square of the transverse momentum in Fig. 10. By comparison of Figs. 5 and 8, we see that the daughter-lepton energy distribution falls off much more rapidly than that of its parent heavy lepton. Similarly, by comparing Figs. 6 and 9 we see that the angular distribution of the daughter lepton is slightly broader than that of its parent. The next figure, Fig. 11, shows the distribution in the cosine of the collinearity angle, i.e., the angle between the final two decay leptons. There is a slight preference for the daughter particles to go out back-to-back, even though the parent particles tend to be produced predominantly in the same direction. This can only reflect the helicity of the parents. Finally in Fig. 12, we give the distribution in $\cos\theta_{cop}$, the cosine of the coplanarity angle defined as the angle between the e^+l^+ and e^-l^- planes. The dependence on this angle is rather small, even

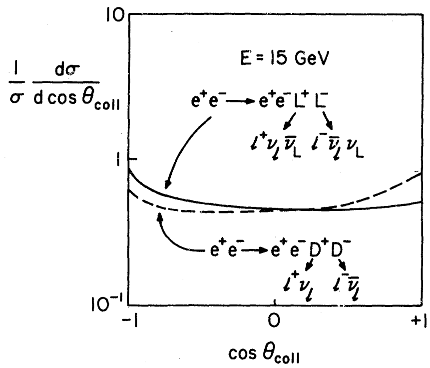


FIG. 11. The distribution in $\cos\theta_{coll}$ the angle between the two decay leptons produced in heavy-lepton decays (solid line) and in heavy-meson decays (dashed line).

though at first glance this does not seem to be the case.

Our results for the production and two-body leptonic decay of spinless mesons are not dramatically different from those of the heavy lepton. We give all our results on the same Figs. 4–12 discussed previously. Note that all our distributions are normalized to the total cross section so the area under all the curves is unity. The difference between the distributions for heavy leptons and heavy mesons can be simply understood in terms of spin effects and the energy partitioning in two-body versus three-body decays.

For completeness we have also calculated the average values of certain quantities and listed them in Table I. We now give an explanation of the table because it may be confusing at first glance. The reactions tabulated are $ee \to ee\mu\mu$ at 5 GeV and 15 GeV, $ee \to eeLL$ at 15 GeV and $ee \to eeDD$ at 15 GeV. The first entry gives the average collinearity angle of the produced muons. The second entry gives the average collinearity angle of the decay leptons.

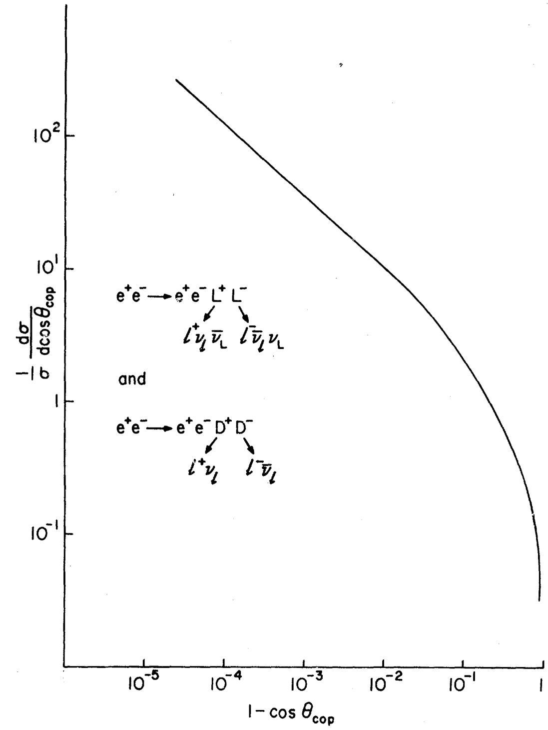


FIG. 12. The distribution in $\cos\theta_{cop}$, the coplanarity angle between the e^+l^+ plane and the e^-l^- plane, for the decays of heavy leptons (solid lines) and heavy mesons (dashed lines).

The third entry gives the average coplanarity angle of the decay leptons. The other entries are now obvious. We give the averages for the produced particles before that of their decays.

IV. CONCLUSIONS

The main objective of our analysis is to determine whether a viable signal for heavy-lepton or

TABLE I. Average values of measurable variables in the reactions $ee \to ee\mu\mu$ at 5 GeV and 15 GeV, and $ee \to eeLL$ +decay, $ee \to eeDD$+ decay at 15 GeV. We give the variable in the production process before the corresponding variable in the decay.

Reaction energy	$ee\,\mu\mu$ 5 GeV	$ee\,\mu\mu$ 15 GeV	$eeLL$ + decays 15 GeV	$eeDD$ + decays 15 GeV
$\cos\theta_{coll\,\mu\mu}$	0.2	0.4	···	···
$\cos\theta_{coll\,ll}$	···	···	0.06	−0.06
$\cos\theta_{cop\,ll}$	···	···	0.86	0.86
$E_{L,D,\mu}$ (GeV)	0.63	1.3	4.40	4.29
E_l (GeV)	···	···	1.60	2.15
$M_{LL,DD,\mu\mu}^2$ (GeV^2)	0.34	0.54	47.7	41.5
M_{ll}^2 (GeV^2)	···	···	5.03	8.5
$p_{\perp\mu}^2$ (GeV^2)	0.034	0.05	···	···
$p_{\perp ll}^2$ (GeV^2)	···	···	1.12	2.22

heavy-meson production via the two-photon mechanism exists at beam energies available in the foreseeable future. The largest obstacle is obviously the background from the regular two-photon production of muon pairs. As can be easily seen from Fig. 3, the cross section for this reaction is several orders of magnitude larger than the cross section for L^+L^- or D^+D^- production, especially when we incorporate branching ratios. One must carefully select a signal which vetoes the regular $\mu^+\mu^-$-pair production without drastically altering the heavy-lepton rate.

The observation of μe pairs seems the most favorable way to proceed. Obviously spinless mesons will have an anomalously low branching ratio into two-body leptonic decay channels so the D states cannot be seen in this way. The heavy leptons decay with equal probability into electrons and muons. Hence if the branching ratio is not too low this is the most attractive way to detect such particles. The important question in this regard is to ascertain the size of the μe signal from the ordinary process $e^+e^- \to e^+e^-\mu^+\mu^-$. If we impose a coplanarity cut of 20° and demand an electron and muon at large angles with respect to the beam direction, e.g., $\theta > 20°$, with no other charged tracks seen, this cross section is only approximately 0.1 nb. The reason for this is explained in paper I, however, we repeat it here for emphasis. Although the electrons in the regular two-photon production process tend to go along the beam pipe, there is nevertheless a long flat tail to the electron angular distribution. This means that it is relatively easy to reduce the two-photon background reaction by a factor of 10^{-3}, but it gets difficult to reduce it further and still have a reasonable aperture. One must also understand that imposing strict cuts on this reaction also cuts down the μe signal from the heavy-lepton production process. The observation of $\mu^+\mu^-$ pairs as a signal for heavy leptons or heavy mesons is really hopeless, and the μe signal from the two-photon reaction also seems impossible at the energies considered here. The particular kinematics of the one-photon heavy-lepton-pair production process may yield a μe signal larger than the background discussed above, in the region where the muon is detected with large energy almost perpendicular to the beam direction. This question falls outside the scope of this paper but deserves further study.

In these circumstances the only viable signal seems to be the detection of tridents. Particular charge combinations such as $e^+e^+\mu^-$ or $e^-e^-\mu^+$ cannot be produced in the regular two-photon production of muon pairs. This means that one electron must be detected close to the beam pipe and then another electron at large angles in coincidence with a positively charged muon. Positrons can serve equally well as a signal so long as they are in coincidence with a negatively charged muon. Backgrounds for such signals arise from radiative bremsstrahlung of Dalitz pairs from reactions such as $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to \mu^+\mu^-$. However, such processes are purely quantum electrodynamic in nature so they can be computed if necessary. Also particular charge combinations can be compared to check the signal versus the background. The only problem with detecting three charged leptons in finite apertures is that it cuts into the signal as well as the noise. Further analysis would be required for a specific experimental configuration to check that such signals have a reasonable counting rate.

Semileptonic decay modes seem to be the only way to extract information on heavy mesons. We plan to discuss these decays for both spinless and vector mesons in paper III.

In conclusion we would like to stress that the two-photon production of muon pairs has an extremely large cross section in the region of energies covered by PEP and PETRA. This reaction constitutes an impossible background for detecting μe pairs, and signals from other channels are probably not large enough to be detected. It looks as if trilepton signals are the only way to identify new objects in this energy region.

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