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Two-photon production processes at high energy. III

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We discuss several two-photon processes in the energy region covered by the new e^+e^- colliding-beam machines at DESY and SLAC. In particular we study the observable cross section for η_c (and η_b) production using (1) its two-γ decay mode and (2) missing-mass techniques. We also discuss the single-photon production of new heavy leptons in the presence of a two-photon background via a measurement of the visible energy. Other methods for reducing the two-photon contamination are discussed.

I. INTRODUCTION

The experimental study of two-photon processes[1] will receive considerable attention in the next few years with the construction of the high-energy machines PETRA at DESY[2] and PEP at SLAC.[3] The interest in such reactions is two-fold. First they constitute a new area of physics which is relatively unexplored and second they are a source of background for the study of other reactions in this energy region. In this paper, the third of a series devoted to the study of two-photon reactions at high energies, we consider several interesting processes. The first paper[4] dealt with the basic reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ and the second paper[5] gave results for the production and decay of heavy leptons and D mesons via the two-photon process. We now consider the production of the hypothetical η_c state of the charmonium model[6] and a corresponding η_b state in the Υ system. The present situation concerning the η_c state is one of confusion. The discovery of a signal at 2.82 GeV/c^2 by the DASP group at DORIS[7] has not been substantiated by further experimentation at SPEAR. One expects the η_c state to be close in mass to that of the $J/\psi(3.1)$ and to decay into C-even states. In the original experiment the DASP group detected the monochromatic photon emitted in the $M1$ transition $J/\psi \to \eta_c + \gamma$ together with the two photons emitted when the η_c decayed. Unfortunately the mass of the η_c was so low that it caused considerable anxiety to theorists working on the charmonium model. Since then several papers have proposed solutions to this problem[8] without any resounding success. There is now a suggestion that the state at 2.82 GeV/c^2 may actually be a $(c\bar{c}q\bar{q})$ state[9] and the real η_c is very close in mass to that of the J/ψ. Clearly new experiments to search for this $^1S_0$ state are necessary.

Two-photon processes are ideal for the study of even-charge-conjugation states, either in e^+e^- colliding beams[10] or in the Primakoff effect.[11] Previous theoretical studies of the former reaction have been carried out for the lower energies obtainable by the machines SPEAR and DORIS. In the first section of this paper we calculate the production cross section of the η_c via the two-photon mechanism[12] and discuss the possibility of its detection via either its two-photon decay mode or a missing-mass technique if both the e^+ and the e^- are observed. The results are compared with the background due to other two-photon processes. The same calculation is also done for a hypothetical η_b in the region of the $\Upsilon(9.46)$. Since the "background" due to the reaction $e^+e^- \to e^+e^- q\bar{q}$ is proportional to the fourth power of the quark charge, it is also shown that the exact size of this "background" can be a rather strong check on whether quarks are indeed fractionally charged.

In the next section, Sec. III, we discuss the feasibility of the detection of heavy leptons via a measurement of the visible energy. Such an experiment has been proposed by several groups.[13] The idea is that roughly half the energy is invisible for a heavy-lepton event while for hadronic events all the energy can in principle be observed. The background from two-photon events gives usually a small visible energy. Since the total two-photon cross section is very large the question arises whether the tail of the two-photon visible-energy distribution can overshadow any heavy-lepton signal. Surprising results are obtained, and it is shown that electron identification near the beam pipe is necessary in order to detect heavy leptons.

In the next section, Sec. IV, we discuss some characteristic properties of two-photon interactions that can be used to design experimental cuts to reduce the two-photon cross section. To this end we discuss variables in which cuts can be made without any serious consequences for most single-photon processes. Alternatively one could invert these cuts to allow for a rather clean study of many two-photon reactions. Finally in Sec. V we give a summary of our conclusions.

II. η_c PRODUCTION AND DETECTION

The two-photon process leading to the production of the pseudoscalar η_c is shown in Fig. 1. Apart from the momenta assigned in the figure we use the following invariants:

$$t_1 = (p_1 - q_1)^2\,,\quad t_2 = (p_2 - q_3)^2\,,$$
$$s_1 = (q_1 + q_2)^2\,,\quad s_2 = (q_2 + q_3)^2\,.$$

The coupling of the η_c is taken to be analogous to that of the π^0 so we take the interaction Lagrangian as

$$\mathcal{L} = \tfrac{1}{2} g_c \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \phi_{\eta_c}\,. \qquad (1)$$

The two-photon decay rate is therefore

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{g_c^{\,2}}{g_\pi^{\,2}} \left(\frac{M_{\eta_c}}{M_{\pi^0}} \right)^3 \Gamma(\pi^0 \to \gamma\gamma)\,. \qquad (2)$$

The ratio g_c/g_π is model dependent resulting in estimates of the two-photon decay width for the η_c that range from 8 to 250 keV.[11]

For the two-photon decay branching ratio one can use experimental bounds. The DASP group reports[7] that $B_{\psi\to\eta_c\gamma} B_{\eta_c\to\gamma\gamma} = (1.4 \pm 0.4) \times 10^{-4}$ while the MPPSSD collaboration obtains[14] $B_{\psi\to\eta_c\gamma} \leqslant 1.7\%$ at the 90% confidence level. This gives that $B_{\eta_c\to\gamma\gamma} \geqslant 8 \times 10^{-3}$. Because of these uncertainties in the width and the branching ratio, we cannot of course give absolute cross sections, but for a rough estimate we choose $\Gamma(\eta_c \to \gamma\gamma) = 10$ keV and $B_{\eta_c\to\gamma\gamma} = 1\%$. For the η_b we choose $\Gamma(\eta_b \to \gamma\gamma) = 20$ keV and $B_{\eta_b\to\gamma\gamma} = 1\%$. These are of course quite pessimistic values with respect to the observability of the η_c so the corresponding cross sections should be considered as minima.

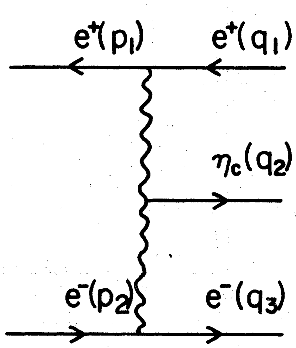

FIG. 1. Feynman diagram for the two-photon production of η-like particles.

Let us first consider the process $e^+e^- \to e^+e^-\eta_c \to e^+e^-\gamma\gamma$. Although the production process has been calculated before,[10] these previous papers did not consider the decay of the η_c nor did they present results at higher energies. We select the two-photon decay mode here because it allows for an easy reconstruction of the η_c.

In calculating the cross section for the production it turns out to be convenient to use the variable $\Delta = s_1 s_2 - s m_{\eta_c}^{\,2}$ as one of the integration variables because Δ^2 is the coefficient of the $t_1^{-2} t_2^{-2}$ term in the square of the matrix element, and gauge invariance demands it to be very small for small t_1, t_2. Therefore we used the set $\ln t_1$, $\ln t_2$, $\ln s_2$, and Δ. The $\ln t_1$ and $\ln t_2$ variables are standard because the leading term in the matrix element is proportional to $t_1^{-1} t_2^{-1}$ and the $\ln s_2$ compensates for the fact that the Jacobian of the transformation to obtain Δ contains s_2^{-1}. The Monte Carlo integration converges very rapidly in these variables. Our results for the total cross section are given in the first column of Table I and in Fig. 2. The decay into two photons is very straightforward as there are no spin-spin correlations to take into account. We allow the η_c to decay in its rest frame and then transform the four-vectors into the laboratory frame. To simulate a realistic experimental configuration we then require an experimental cut of $|\cos\theta_\gamma| < 0.9$ for both photons. Assuming a 1% branching ratio this leads to the "observable" rates in column 2 of Table I.

The actual energy and angle spectra for the η_c are shown in Figs. 3 and 4. These distributions are of academic interest because the η_c decays so quickly that only its decay products can be detected. The upper curves are taken without the cuts on the photons while the lower curves are with the cuts. Figures 3 and 4 demonstrate that

TABLE I. Production cross sections for the η_c and η_b assuming a width of $\Gamma(\eta_c \to \gamma\gamma) = 10$ keV and $\Gamma(\eta_b \to \gamma\gamma) = 20$ keV. We also give the two-photon event rates $\sigma_{\gamma\gamma}$ with an angle cut, assuming a two-photon branching ratio of 1%. The beam energy is 15 GeV.

M (GeV/c^2)	$\sigma_T^{\rm prod}$ (pb)	$\sigma_{\gamma\gamma}^{\rm cut}$ (pb)
2.82	116	0.52
9.2	2.0	0.014

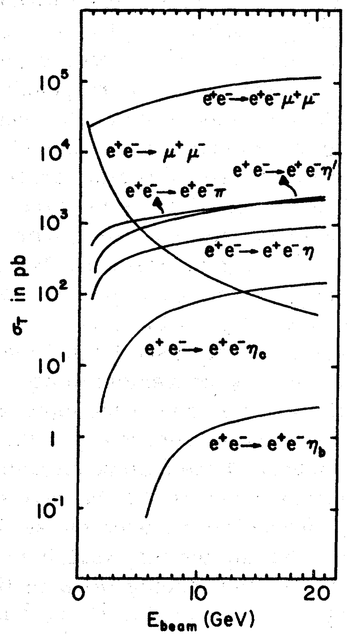

FIG. 2. Total cross sections for various two-photon processes. We took $\Gamma(\eta\to\gamma\gamma)=323$ eV, $\Gamma(\eta'\to\gamma\gamma)=5$ keV, $\Gamma(\eta_c\to\gamma\gamma)=10$ keV, and $\Gamma(\eta_b\to\gamma\gamma)=20$ keV. The curve for the process $e^+e^-\to\mu^+\mu^-$ is also shown for comparison.

those η_c which travel fast along the beam pipe are being excluded by the cuts, leaving those η_c which are slow. This leads to a very sharp energy spectrum for the outgoing photons as shown in Fig. 5 for both the η_c and the η_b. Figure 6 shows $d\sigma/d\theta$ with the cut. The collinearity-angle distribution between the photons is shown in Fig.

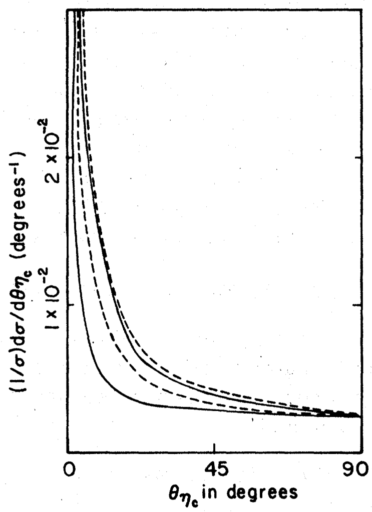

FIG. 4. The distributions in the angle with respect to the beam pipe of the η_c (solid lines) and the η_b (dashed lines) without and with cuts (the lower lines) on the photon angles $E_{beam}=15$ GeV.

7 with and without cuts, and again one can see that the cuts affect the events with a small opening angle, i.e., with a fast η_c. At higher energies there are relatively more fast η_c particles which travel along the beam direction so the cuts become more dramatic, while at lower energies they hardly have any effect.

Another way to look for C-even states that are two-photon-produced is via a missing-mass technique as proposed for the forward detector at PEP.[12] The idea is to observe both the final state electron and the final state positron and calculate

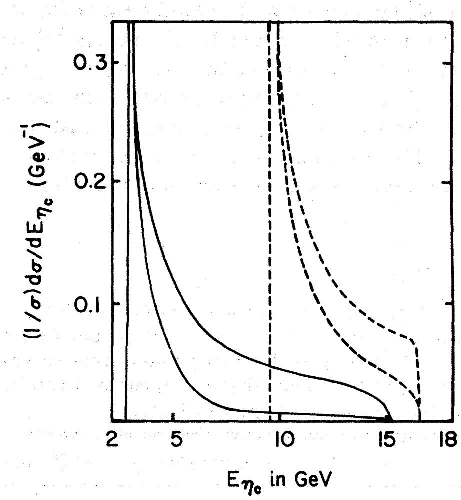

FIG. 3. The distributions in the energy of the η_c (solid lines) and the η_b (dashed lines) without and with cuts (the lower lines) on the photon angles. $E_{beam}=15$ GeV.

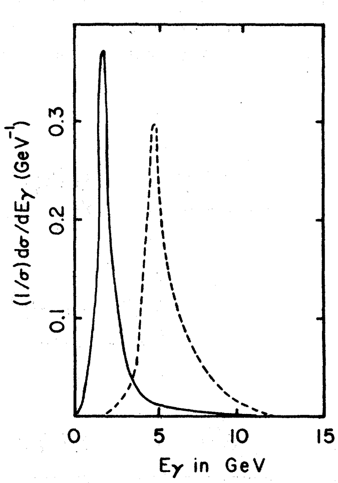

FIG. 5. The energy spectrum of the photon for η_c production and decay (solid line) and for η_b production and decay (dashed line) with the angle cut. $E_{beam}=15$ GeV.

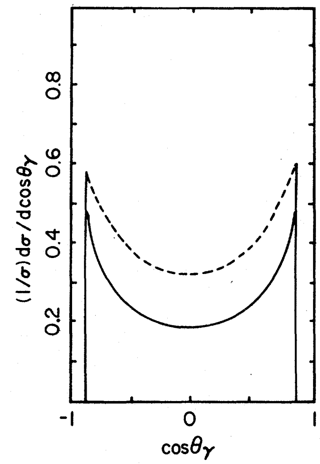

FIG. 6. The $\cos\theta$ distribution for the photons. The notation is the same as in Fig. 4. $E_{\text{beam}} = 15$ GeV.

the missing mass. This has the clear advantage of not depending on any unknown branching ratios, although the observation of the electron and the positron leads to substantial losses due to the poor but calculable acceptance near the beam pipe. This leaves $\Gamma(\eta_c \to \gamma\gamma)$ as the only unknown parameter so an observation of this channel would determine its value.

Figure 8 shows how severly an angle cut on the electron and the positron simultaneously affects

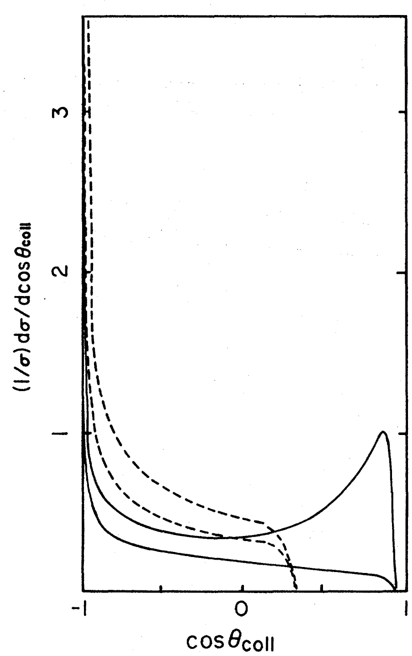

FIG. 7. The collinearity-angle distribution for the two photons. The notation is the same as in Fig. 2. $E_{\text{beam}} = 15$ GeV.

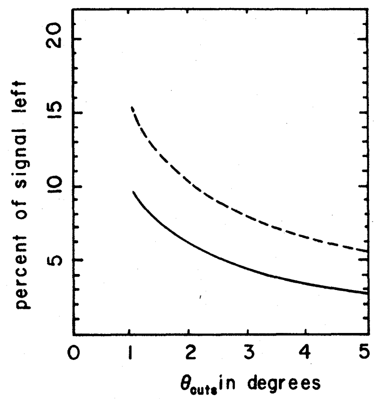

FIG. 8. The effect of cuts in the electron and positron angles on the observable signal for η_c production (solid line) and η_b production (dashed line). $E_{\text{beam}} = 15$ GeV.

the signal for both η_c and η_b. It is clear that the signals here exceed those of the two-photon decay if the two-photon branching ratio is as low as 1%. A combination of this graph and Table I shows that the magnitude of the signal is quite observable with an integrated luminosity of 50–100 pb^{-1} for a complete experimental run. The main worry is therefore the background due to other two-photon processes such as $e^+e^- \to e^+e^-q\bar{q}$ and $e^+e^- \to e^+e^-\mu^+\mu^-$ for the η_c state, while also $\tau^+\tau^-$ and $c\bar{c}$ pairs contribute to the background for the η_b. The results are shown in Fig. 9. We give here only the contribution of the quark-antiquark continuum, as any resonance should be considered as a signal. Using the estimated resolution of the forward detector

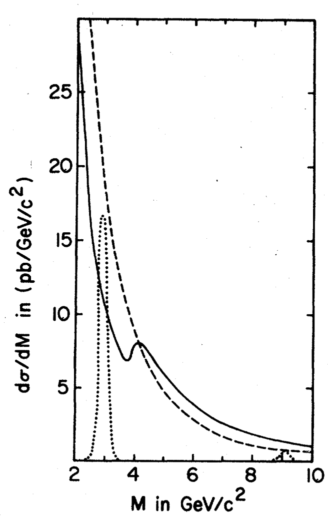

FIG. 9. Missing-mass distributions for the processes $e^+e^- \to e^+e^-\eta_c$, $e^+e^- \to e^+e^-\eta_b$ [dotted lines, $\Gamma(\eta_c \to \gamma\gamma) = 10$ keV, $\Gamma(\eta_b \to \gamma\gamma) = 20$ keV], $e^+e^- \to e^+e^-\mu^+\mu^-$ (dashed line), and $e^+e^- \to e^+e^-q\bar{q}$ with $e^+e^- \to e^+e^-\tau^+\tau^-$ (solid line). $E_{\text{beam}} = 15$ GeV.

we also present the expected signal in this graph for a $\Gamma(\eta_c \to \gamma\gamma) = 10$ keV and $\Gamma(\eta_b \to \gamma\gamma) = 20$ keV. It is clear that the resolution is quite critical here. The muon background which is the dashed curve could of course be reduced if one can identify muons at large angles.

It is also clear that the above detection methods not only hold for the η_c and η_b states but can lead to observation of the χ states between the ψ and ψ' (and their corresponding counterparts in the Υ system) just as well. Even though these states are scalars rather than pseudoscalars, the results are quite similar.

Outside the resonance regions one can obtain other useful information from a measurement of the quantity

$$R'(M) = \frac{\frac{d\sigma}{dM}(e^+e^- \to e^+e^- + \text{hadrons})}{\frac{d\sigma}{dM}(e^+e^- \to e^+e^-\mu^+\mu^-)} \simeq 3 \sum_i Q_i^{\,4}$$

(plus contributions from heavy leptons if appropriate). R' is a function of the missing mass M and the Q_i are quark charges. The sum is over all quarks contributing to the missing mass. The above formula is for fractionally charged quarks. For integer-charge quarks[15] the result is quite different. For example, the u quark contributes a factor $\frac{16}{27}$ if fractionally charged while integer charged Han-Nambu u quarks give $\frac{4}{3}$ below color threshold. For d or s quarks these numbers are $\frac{1}{27}$ and $\frac{1}{3}$, respectively. So just below the η_c mass one expects R' to be $\frac{2}{3}$ for fractionally charged quarks and 2 for Han-Nambu quarks. It should be possible to measure this difference. The background curve in Fig. 9 used the fractional charge assignment. Other backgrounds could come from the reactions $e^+e^- \to e^+e^-\gamma\gamma$ and $e^+e^- \to e^+e^-e^+e^-$ where one e^+e^- pair escapes detection. Although the first process is not believed to be very important in this large-mass region ($\gtrsim 2$ GeV/c^2), it does deserve to be studied in greater detail. We will, however, not attempt this. The background from the second process can be drastically reduced by adding a minimum-invariant-mass cut to the detected e^+e^- pair. In general the kinematical configuration which gives the largest contribution to the cross section is where the fast beam particles continue down the beam pipe leaving behind a low-invariant-mass e^+e^- pair. A cut on the pair mass of say 1 GeV/c^2 will therefore reduce this background to an acceptable level.

III. VISIBLE-ENERGY MEASUREMENTS

When a heavy lepton such as the τ (Ref. 16) decays a fraction of the energy goes into neutrinos. The total energy that can be observed in such events is therefore significantly less than $\sqrt{s} = 2E_{\text{beam}}$. This is in sharp contrast to hadronic events which have, except for an occasional soft neutrino, all their energy in a detectable form. To use this property in an experiment one needs an acceptance of close to 4π, diminishing the chance that hadrons can escape undetected. Unfortunately a full 4π acceptance is not achievable as it is not possible to look in the beam pipe. For the hadronic and heavy-lepton events this small part of the solid angle is of little consequence, but it enables the two-photon processes to become a severe background, since they will give events where a large fraction of the energy is missing because it is in the beam pipe. We have therefore studied the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ with a measurement of the quantity $y_{\text{vis}} = E_{\text{vis}}/E_{\text{beam}}$ in mind. The range of y_{vis} is from zero to two. Usually the electrons will stay in the beam pipe and the muons will be rather soft leading to events with a very small visible energy. The total cross section is, however, so large that one has to worry whether the tail of this peak in the small energy region does not overwhelm the heavy-lepton signal.

The results of our calculations are shown in Fig. 10 for angular cuts of 2°, 6°, 15°, and 30° together with the y_{vis} distributions for the τ (solid line) and a hypothetical 12-GeV/c^2 sequential

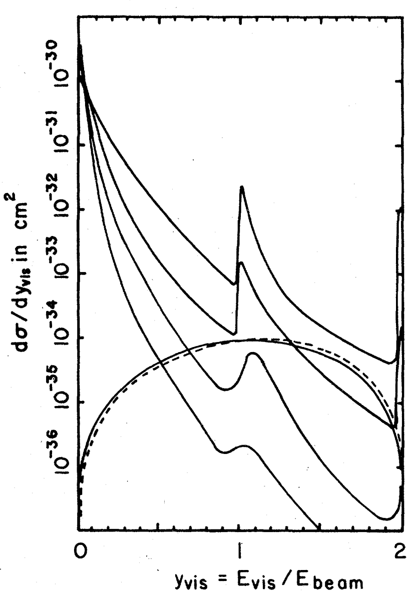

FIG. 10. The distribution y_{vis} for the reactions $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to L^+L^-$ (solid and dashed lines, respectively, $M_L = 2$ GeV/c^2), and $e^+e^- \to e^+e^- \to e^+e^-\mu^+\mu^-$ for angle cuts of 2°, 6°, 15°, and 30° from top to bottom, respectively. $E_{\text{beam}} = 15$ GeV.

heavy lepton (dashed curve). Because one particle cannot carry more than $\frac{1}{2}$ of the total energy, there is a kinematic wall at $y_{vis} = 1$. The surprising bumps near $y_{vis} = 1$ reflect this fact and are due to one of the electrons entering the counter. In that case the other electron is undetected, and, because it is near the beam pipe, it has almost one-half of the available energy. Thus the bump at $y_{vis} \simeq 2$ is caused by all four particles entering the detector, while in the region between $y_{vis} \simeq 1$ and $y_{vis} \simeq 2$ one electron is undetected and finally in the region between $y_{vis} = 0$ and $y_{vis} \simeq 1$ only the muons are seen. It is clear from the figure that one needs a rather drastic angular cut in order to see a heavy lepton. If the effect is too severe, however, one might start to miss energy from purely hadronic final states which yield backgrounds at large values of y_{vis}.

A significant improvement is obtained if one has electron identification near the beam pipe. This does of course reduce the heavy-lepton signal slightly but it eliminates the peaks near $y_{vis} = 1$. If one were to plot the y_{vis} distribution for the muons only, it would be almost the same as in Fig. 9 for $y_{vis} < 1$, but at $y_{vis} = 1$ the background drops several orders of magnitude such that for $y_{vis} > 1$ the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ does not constitute a significant background anymore.

If these conditions can be met it is possible to obtain some interesting physics, as the total heavy-lepton signal in a certain y_{vis} region (say between 0.8 and 1.4) is relatively insensitive to branching ratios. A careful measurement of the heavy-lepton contribution to the cross section in this region can therefore be made at several energies. Near the thresholds for heavy leptons the signal in the region around $y_{vis} = 1$ will change, making it possible to count the number of new heavy leptons.

IV. IDENTIFICATION OF TWO-PHOTON EVENTS

The large cross sections for two-photon events at PETRA and PEP will cause them to get a lot of attention, be it as a signal or as a background.[17] We thought it therefore useful to discuss some variables in which it is rather easy to recognize a large fraction of the two-photon events. The first thing to realize is that the electrons tend to come out at very small angles, but that this is less likely to be the case if one produces a heavy object via a two-photon process because the momentum transfer must be reasonably large. Figure 8 illustrates this point. Therefore an angle cut on the electron can significantly reduce the contributions from two-photon processes. At a beam energy of 15 GeV the probability of detecting one electron from the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$ emerging at an angle larger than 30° from the electron beam direction is $\sim 2\times 10^{-5}$. If the muons are visible (i.e., they leave the beam pipe) their spectrum is usually very soft as illustrated in Fig. 10. For a 15-GeV beam energy one could make a cut of 2 GeV/c on the muon momentum and not lose very much from interesting single-photon reactions. A similar energy cut is also very efficient in eliminating the process $e^+e^- \to e^+e^-\tau^+\tau^-$ as the decay products of the heavy leptons are really soft.

For many one-photon reactions these two cuts are sufficient to reduce the two-photon background but it could happen that this is not the case. An example is the search for a very heavy lepton via an $e\mu$ signal.[18] The μe coplanarity angle is frequently used in heavy-lepton searches to further reduce the $e^+e^-\mu^+\mu^-$ background. There exists, however, other variables which can be equally useful. Cuts in the variable $\cos\theta_{missing} \equiv p^{\parallel}_{missing}/E_{missing}$ can be shown not to affect the signal by more than a few percent while simultaneously eliminating about $\frac{2}{3}$ of the two-photon signal remaining after electron angle and muon momentum cuts have been applied. This number does not include the requirement that the remaining e and μ actually stay in the beam pipe. If this were the case the whole $e^+e^- \to e^+e^-\mu^+\mu^-$ process would already be eliminated for all practical purposes.

This type of cut is useful for other reactions too. For example, suppose the two-photon reaction $e^+e^- \to e^+e^-$ + hadrons needs to be distinguished from a hypothetical reaction $e^+e^- \to$ (heavy leptons or heavy hadrons) $\to e^\pm$ + hadrons. If one could measure the momenta of all the hadrons and the momentum of one identified electron then it would in principle be possible to determine whether only one electron is absent. However, in practice this is extremely difficult because some soft hadrons could be missed. If one therefore measures the projection of the momenta along the beam direction of all observed hadrons and the identified $e^\pm$, then the corresponding $\cos\theta_{missing}$ will show a strong peaking along the missing $e^\mp$ direction. The heavy-lepton signal does not show such a feature. An analogous effect can be obtained by considering the missing momentum perpendicular to the beam pipe. If only soft hadrons and an electron in the beam pipe are missing this variable is bound to be small for two-photon events.

Backgrounds from the reaction $e^+e^- \to e^+e^-e^+e^-$ are potentially very dangerous. For this process the beam electron and position will again predominantly continue along the beam pipe leaving a low invariant mass e^+e^- pair. Unless this pair has very little energy or a large invariant mass one will observe both the electron and the positron. A cut on the invariant mass will therefore reduce this signal to the same level as that expected from $e^+e^- \to e^+e^- \mu^+\mu^-$. The additional cuts described above can then reduce the background from $e^+e^- \to e^+e^-e^+e^-$ to a manageable level.

V. CONCLUSIONS

From the numbers in Sec. II it is clear that the η_c should be observable if its two-photon width is larger than 10 keV or its two-photon branching ratio larger than 1%, the value assumed in this paper. Also, the signal-to-background ratio in a missing-mass experiment is 1:2 if one posseses no muon identification and better than 1:1 if one does. The question whether 0.5 pb is a visible signal in the two-photon decay channel is an experimental one. Observability of the η_b is going to be a marginal affair at best unless the two-photon width considerably exceeds our (pessimistic) estimate.

Observation of the total $e^+e^- \to e^+e^- \mu^+\mu^-$ and $e^+e^- \to e^+e^- q\bar{q}$ background at $M_{\text{missing}} \simeq 2$ GeV/c^2 should answer the question whether quarks are fractionally charged. A similar though somewhat less clear result, due to theoretical uncertainties, should be obtained if one could see the $\eta'(958)$ via its two-photon production[9] but this is rather difficult at high energies.

The y_{vis} test seems possible if one can identify electrons near the beam pipe. A decent counter efficiency is needed, however, to avoid problems with hadronic events in which some particles escape detection.

ACKNOWLEDGMENT

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