PHYSICAL REVIEW D VOLUME 4, NUMBER 9 1 NOVEMBER 1971

Comment on the Experimental Investigation of Photon - Photon Collisions in Electron - Positron Storage Rings*

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(Received 11 May 1971)

Continuing our calculations on photon-photon collisions in electron-positron storage rings, i.e., reactions of the type $e^-e^+ \to e^-e^+A^-A^+$ (where $A = e, \mu, \pi, K, \ldots$), we now introduce realistic experimental conditions, in particular two cutoff parameters: a minimal emission angle ($\psi_{\min}$) with respect to the beam axis for the particles $A^\pm$ to be produced, and a minimal relative energy loss ($\chi_{\min}$) for the outgoing electron and positron (to be detected practically in their forward directions). Taking realistic values for $\psi_{\min}$ and $\chi_{\min}$, their effect on the invariant mass spectrum of the pair A^-A^+ and on the integrated cross section is shown. In particular, the modification of the energy behavior, due to these cutoffs, is exhibited. In spite of the drastic character of the restrictions considered, it is shown that fairly high counting rates may still be expected (for $A = e, \mu, \pi$) in the four-fold coincidence experiments suggested, with electron-positron storage rings of the next generation (beam energy 2–3 GeV, luminosity $\sim 10^{32}$ cm^{-2} sec^{-1}).

I. INTRODUCTION

The idea of studying particle production through photon-photon collisions (involving "almost real" photons) in electron-electron or electron-positron storage rings was put forward as early as 1960,[1,2] but practically forgotten afterwards for many years. It has been revived recently and has nowadays become quite popular among high-energy physicists involved in quantum electrodynamics and in particular in $e^\pm$ colliding-beam physics.[3-16] Moreover, some experimental evidence for these processes has been found lately.[17]

In our previous work,[13] we have shown the following facts:

(a) The problem of background elimination can be properly solved, in four-fold coincidence experiments on the process $e^- + e^+ \to e^- + e^+ + A^- + A^+$ (where $A = e, \mu, \pi, K, \ldots$), by detecting both the scattered electron and positron at very small angles (a few milliradians) with respect to their incident directions. Under these conditions, the diagram shown in Fig. 1(a) is practically the only one which contributes to the cross section. On the other hand, both spacelike photons exchanged in this diagram are then "almost real," so that this process becomes practically equivalent to $\gamma + \gamma \to A^- + A^+$. (As we have shown,[13] treating those photons as real involves errors of the order of t/M^2, where t is the invariant mass squared of one photon and M the invariant mass of the pair A^+A^- created; under the kinematic conditions considered, t/M^2 is at most a few percent.)

(b) The cross sections found are high enough (for $A = e, \mu, \pi$) to insure that fairly high counting rates should in principle be obtained in future experiments of this type with electron-positron storage rings of the next generation (beam energy 2–3 GeV, luminosity ~10^{32} cm^{-2} sec^{-1}).

However, in this former work,[13] we did not yet consider entirely realistic conditions, i.e., all cutoff parameters which should appear in the experiments.

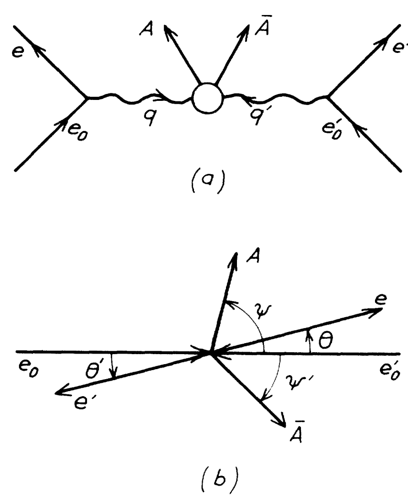


FIG. 1. (a) Main diagram for $e^-e^+ \to e^-e^+A^-A^+$. (b) Kinematic scheme for $e^-e^+ \to e^-e^+A^-A^+$ (for simplicity, azimuthal angles were left out).

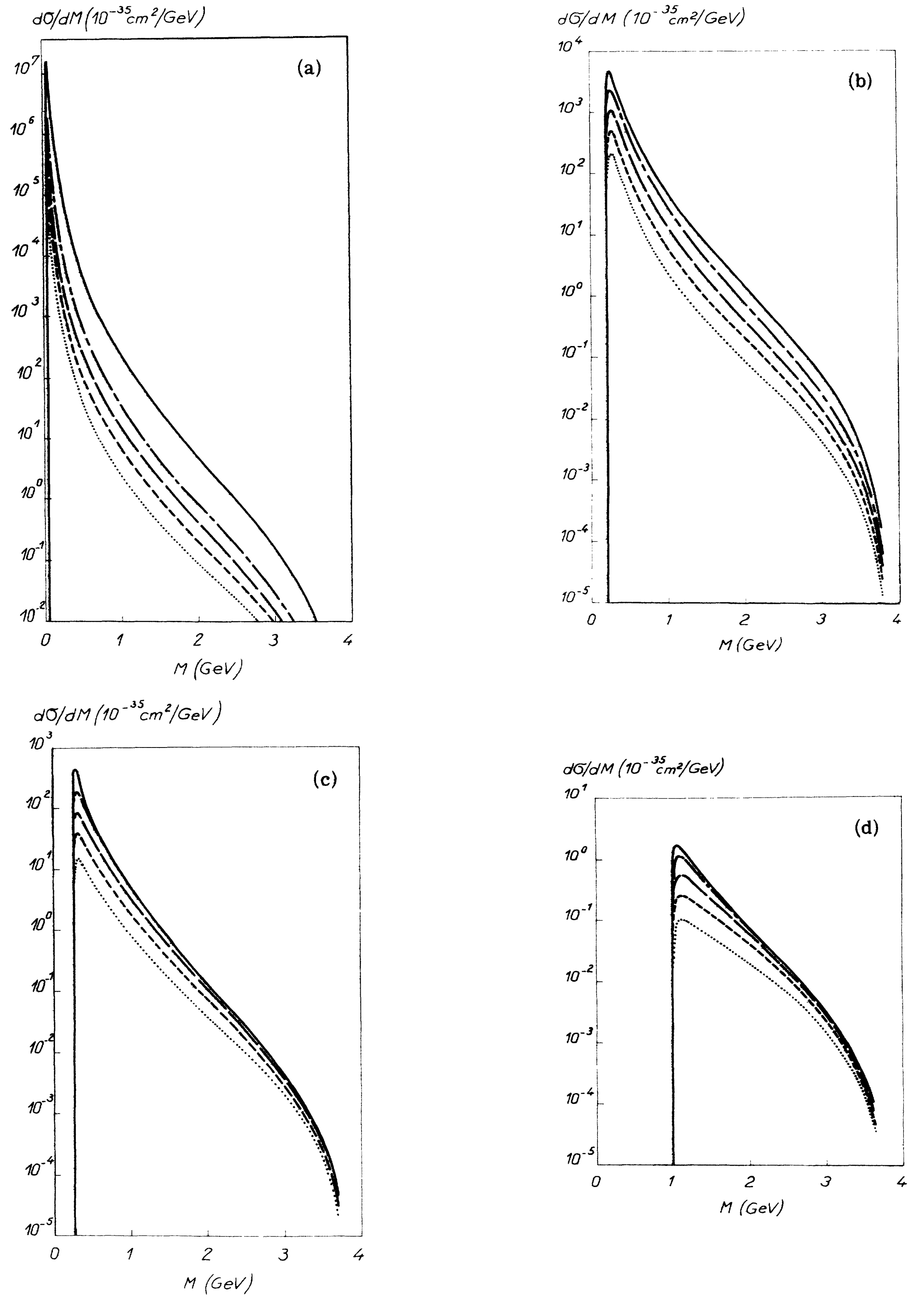
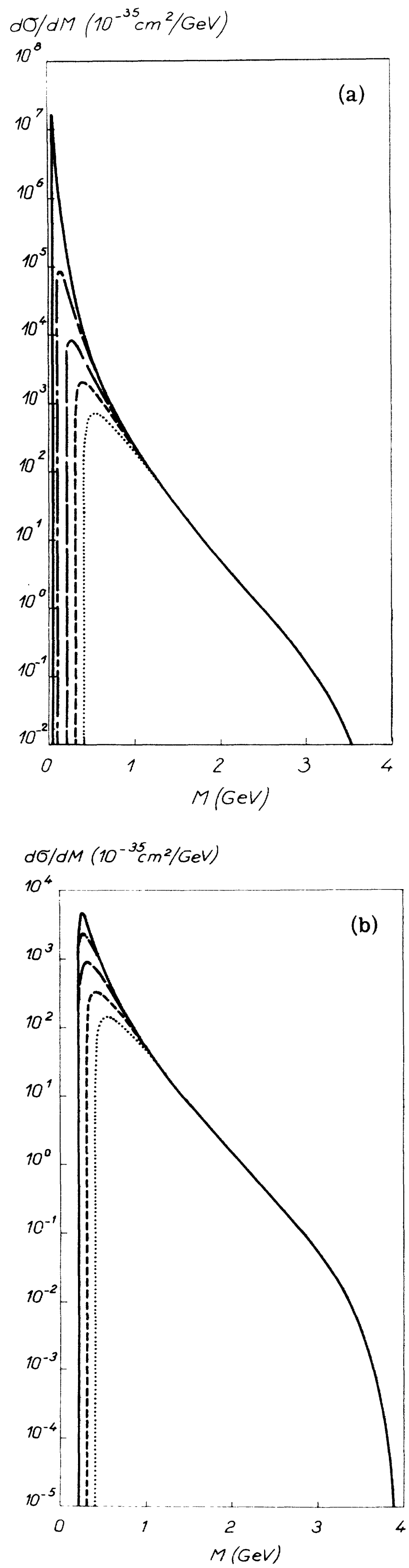


FIG. 2. Effect of ψ_{min} on the invariant mass distribution $d\sigma/dM$ in the process $e^-e^+ \to e^-e^+A^-A^+$ at $E_0 = 2$ GeV, $\theta_{max} = 4$ mrad. (a) $A = e$ ($M > 50$ MeV); (b) $A = \mu$; (c) $A = \pi$; (d) $A = K$. ——— $\psi_{min} = 0$; — —— — $\psi_{min} = 15°$; —— —— $\psi_{min} = 30°$; — — — $\psi_{min} = 45°$; · · · · $\psi_{min} = 60°$.



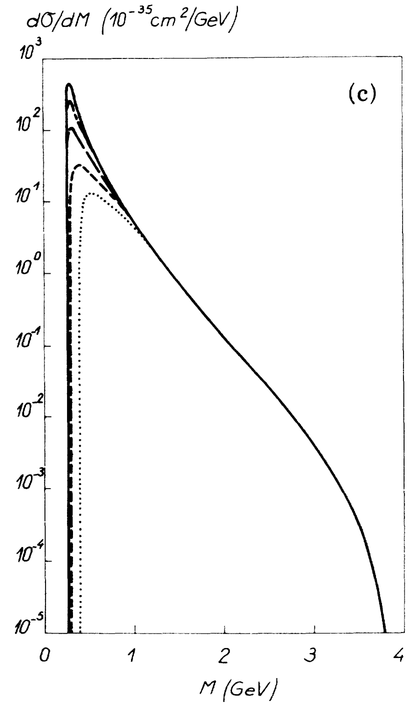


FIG. 3. Effect of χ_{min} on the invariant-mass distribution $d\sigma/dM$ in the process $e^-e^+ \rightarrow e^-e^+A^-A^+$ at $E_0=2$ GeV, $\theta_{max}=4$ mrad. (a) $A=e$ ($M>50$ MeV); (b) $A=\mu$; (c) $A=\pi$. ——— $\chi_{min}=0$; – ——— – $\chi_{min}=2.5\%$; ——— ——— $\chi_{min}=5\%$; – – – – $\chi_{min}=7.5\%$; ···· $\chi_{min}=10\%$.

Now we shall take into account in particular two parameters which both, as we shall see, play a crucial role:

(i) A minimal emission angle ψ_{min} for A^- and A^+, so that [see Fig. 1(b)] $\psi_{min} \leq \psi$, $\psi' \leq \pi - \psi_{min}$. It is indeed well known that – for geometrical reasons related to the shortness of the region of interaction in the storage ring – the detection device for the particles produced cannot be set up too near the beam axis.

(ii) A minimal relative energy loss χ_{min} for both the scattered electron and positron; one has χ, $\chi' \geq \chi_{min}$, where we define

$$\chi = (E_0 - E)/E_0, \quad \chi' = (E_0 - E')/E_0,$$

denoting by E_0 the beam energy, and by E and E' the respective energies of the electron and positron after scattering. This parameter χ_{min} is to be introduced because, in order to separate itself from the beam and thus to be detectable, the (practically forward) scattered electron or positron must have lost some part of its energy.

We also consider two other cutoff parameters, which, however, appear to be much less critical as to their influence on the counting rates, namely:

(iii) A maximal relative energy loss χ_{max} for

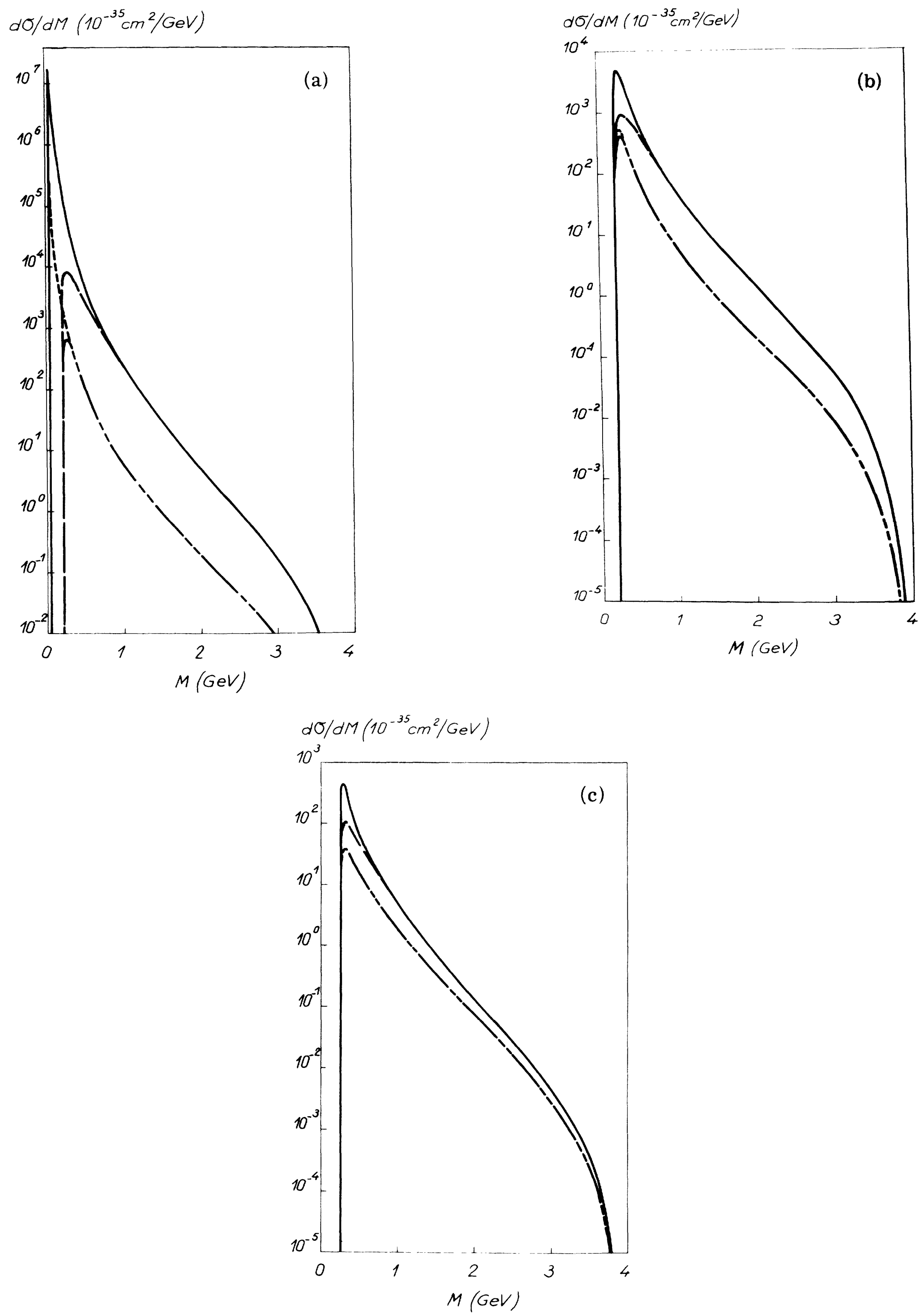


FIG. 4. Combined effect of ψ_{min} and χ_{min} on the invariant-mass distribution $d\sigma/dM$ in the process $e^-e^+ \rightarrow e^-e^+A^-A^+$ at $E_0 = 2$ GeV, $\theta_{max} = 4$ mrad. (a) $A = e$ ($M > 50$ MeV) and (b) $A = \mu$. ——— $\psi_{min} = 0$, $\chi_{min} = 0$; —— —— $\psi_{min} = 0$, $\chi_{min} = 5\%$; – – – – $\psi_{min} = 45°$, $\chi_{min} = 0$; ——– – – —— $\psi_{min} = 45°$, $\chi_{min} = 5\%$. (c) $A = \pi$. ——— $\psi_{min} = 0$, $\chi_{min} = 0$; —— —— $\psi_{min} = 0$, $\chi_{min} = 5\%$; ——– – – —— $\psi_{min} = 45°$, $\chi_{min} = 0$ or 5%.

both scattered $e^{\pm}$ particles, so that $\chi, \chi' \leq \chi_{max}$. Indeed, these particles must have kept some substantial part of their initial energy in order to be detected.

(iv) A maximal scattering angle θ_{max} for both $e^{\pm}$ particles, so that $\theta, \theta' \leq \theta_{max}$ [see Fig. 1(b)]. This parameter θ_{max} was already introduced formerly,[13] as it plays a fundamental role in the background elimination. (That the detection of the electron and positron scattered at extremely small angles is indeed possible, thanks to so-called "tagging windows" made in the storage ring, is a well-known fact for colliding-beam specialists.)

Other possible cutoffs (e.g., on the azimuthal angles) are considered as unimportant and neglected here.

In Sec. II, we first show the separate and the combined effect of ψ_{min} and χ_{min} on the differential cross sections $d\sigma/dM$, where M is the invariant mass of the pair A^-A^+. We then exhibit the influence of ψ_{min}, χ_{min} and also χ_{max}, θ_{max} on the integrated cross sections. Finally, we show the energy behavior of the various cross sections when realistic values are chosen for the cutoff parameters.

The bearing of these results on future experiments is discussed in Sec. III.

Calculational methods and formulas used were the same as in our former work.[13] These calculations are however not trivial, since in most cases simultaneous cutoffs are made on nonindependent parameters.

II. INFLUENCE OF THE CUTOFF PARAMETERS

A. Effect on the Invariant-Mass Distributions

Figure 2 shows the effect of various values chosen for ψ_{min} on the invariant-mass distributions $d\sigma/dM$ at $E_0 = 2$ GeV and $\theta_{max} = 4$ mrad. This effect is quite striking for all four reactions considered ($A = e, \mu, \pi, K$). On the other hand, it involves stronger cutoffs on the cross sections where the mass of A is lower. The latter fact can easily be understood if one looks at the angular distributions of particles produced (Fig. 6 of Ref. 13).

Figure 3 shows the influence of various values of χ_{min} on $d\sigma/dM$, again at $E_0 = 2$ GeV and $\theta_{max} = 4$ mrad. It can be seen that the main effect of χ_{min} is to cut the threshold region away, especially where the threshold is low. The explanation of this fact is obvious since one has $M^2 \simeq 4\chi\chi' E_0^2 \geq 4\chi_{min}^2 E_0^2$. No curves are shown for the case $A = K$, since – because of the high value of the threshold for kaon pair production – no cutoff effect appears there up to $\chi_{min} = 10\%$.

In Fig. 4, we compare the separate and combined effect of ψ_{min} and χ_{min} on $d\sigma/dM$, again at $E_0 = 2$ GeV and $\theta_{max} = 4$ mrad; the values chosen here for ψ_{min} and χ_{min} are 45° and 5%, respectively.[18] Under these conditions, it can be seen that (except for $A = e$) the influence of ψ_{min} is the stronger one. Again, no curves are shown for $A = K$, since in that case only ψ_{min} is effective.

B. Effect on the Integrated Cross Sections

Integrating the distributions $d\sigma/dM$ over M, one obtains the total cross sections, shown in Figs. 5–8, as functions of the various cutoff parameters.

Figure 5 shows $\sigma(\psi_{min})$ at $E_0 = 2$ GeV, $\theta_{max} = 4$ mrad. Again we observe that the decrease with ψ_{min} is stronger where the mass of A is lower.

Figure 6 shows $\sigma(\chi_{min})$ at $E_0 = 2$ GeV, $\theta_{max} = 4$ mrad. The expected mass effect (slower de-

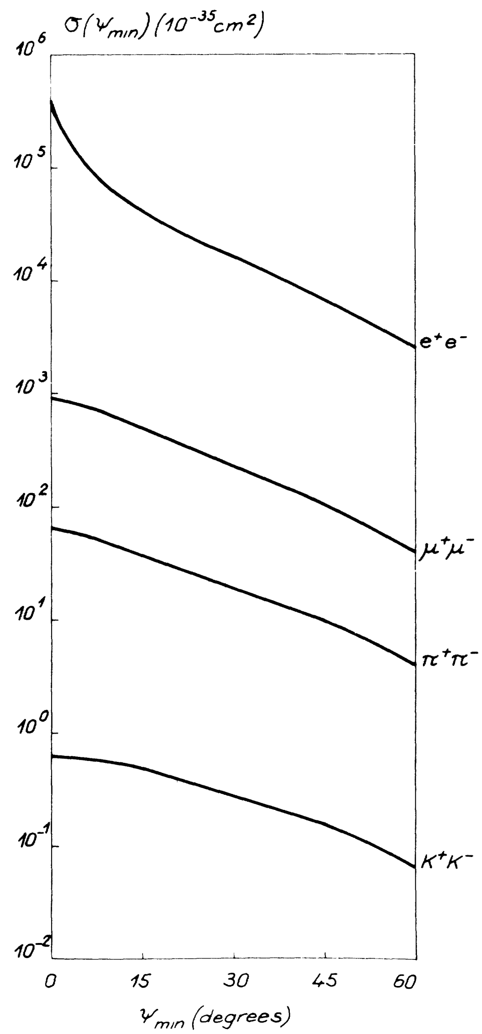


FIG. 5. Effect of ψ_{min} on the total cross section at $E_0 = 2$ GeV, $\theta_{max} = 4$ mrad for the process $e^-e^+ \to e^-e^+A^-A^+$, where $A = e$ ($M > 50$ MeV), μ, π, K.

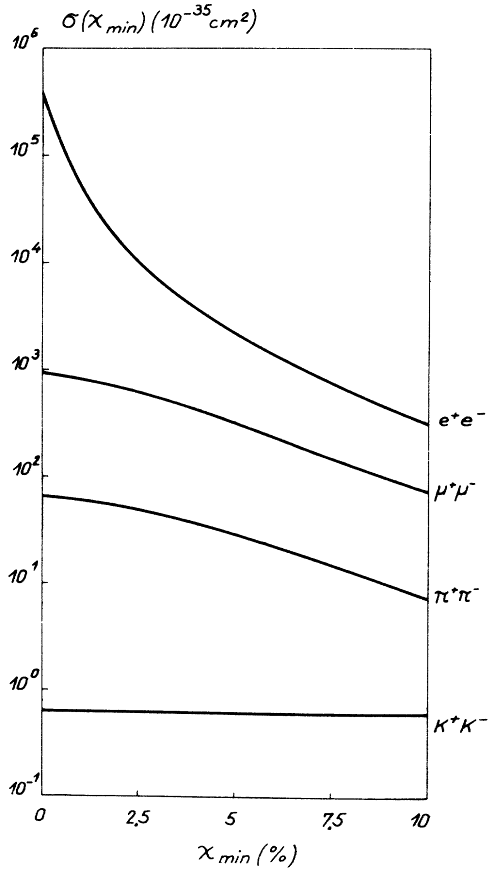


FIG. 6. Effect of $\chi_{\min}$ on the total cross section at $E_0 = 2$ GeV, $\theta_{\max} = 4$ mrad for the process $e^- e^+ \to e^- e^+ A^- A^+$, where $A = e$ ($M > 50$ MeV), μ, π, K.

crease for muons and pions than for electrons, and no decrease for kaons up to $\chi_{\min} = 10\%$) shows up clearly.

Figure 7 shows $\sigma(\chi_{\max})$ for $E_0 \doteq 2$ GeV, $\theta_{\max} = 4$ mrad, and realistic values – 45° and 5%, respectively – for $\psi_{\min}$ and $\chi_{\min}$. It can be seen that the cross sections are very insensitive to $\chi_{\max}$ (except for kaons, and even there they become insensitive above ~50%).

Figure 8 shows $\sigma(\theta_{\max})$ for $E_0 = 2$ GeV, $\psi_{\min} = 45°$, $\chi_{\min} = 5\%$, and $\chi_{\max} = 70\%$. One sees that all curves tend rapidly (after a few milliradians) towards a plateau.

The insensitivity of the total cross section with respect to both $\chi_{\max}$ and $\theta_{\max}$ is simply connected with the fact that extreme-relativistic electrons tend to be scattered with small energy loss and at very small angles.

C. Effect on the Energy Behavior

Figure 9 shows the effect of realistic cutoffs ($\theta_{\max} = 4$ mrad; $\chi_{\max} = 70\%$; $\psi_{\min} = 30°$ or 45°; $\chi_{\min} = 2.5\%$, 5%, or 10%) on $\sigma(E_0)$. For reference,

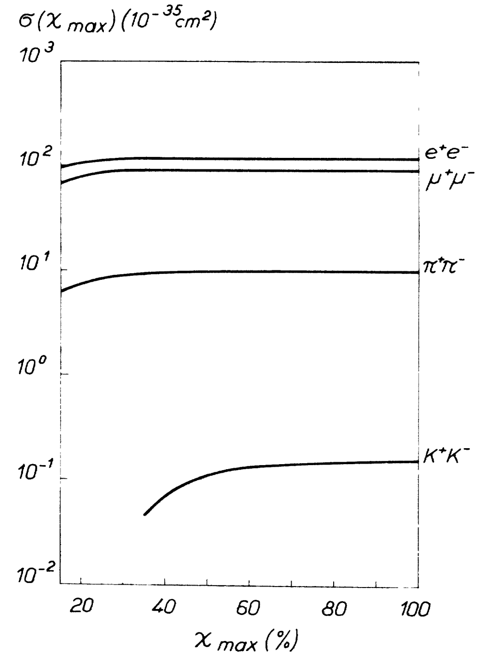


FIG. 7. Effect of $\chi_{\max}$ on the total cross section at $E_0 = 2$ GeV, $\theta_{\max} = 4$ mrad, $\psi_{\min} = 45°$, $\chi_{\min} = 5\%$ for the process $e^- e^+ \to e^- e^+ A^- A^+$, where $A = e$, μ, π, K.

we also show the curves obtained in our former work,[13] i.e., with $\theta_{\max} = 4$ mrad and no other cutoff.

One notices that (except to some extent for $A = K$)

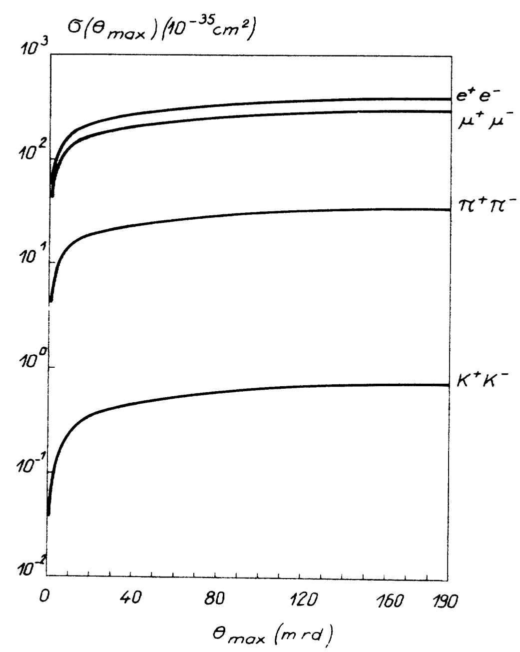


FIG. 8. Effect of $\theta_{\max}$ on the total cross section at $E_0 = 2$ GeV, $\psi_{\min} = 45°$, $\chi_{\min} = 5\%$, $\chi_{\max} = 70\%$ for the process $e^- e^+ \to e^- e^+ A^- A^+$, where $A = e$, μ, π, K.

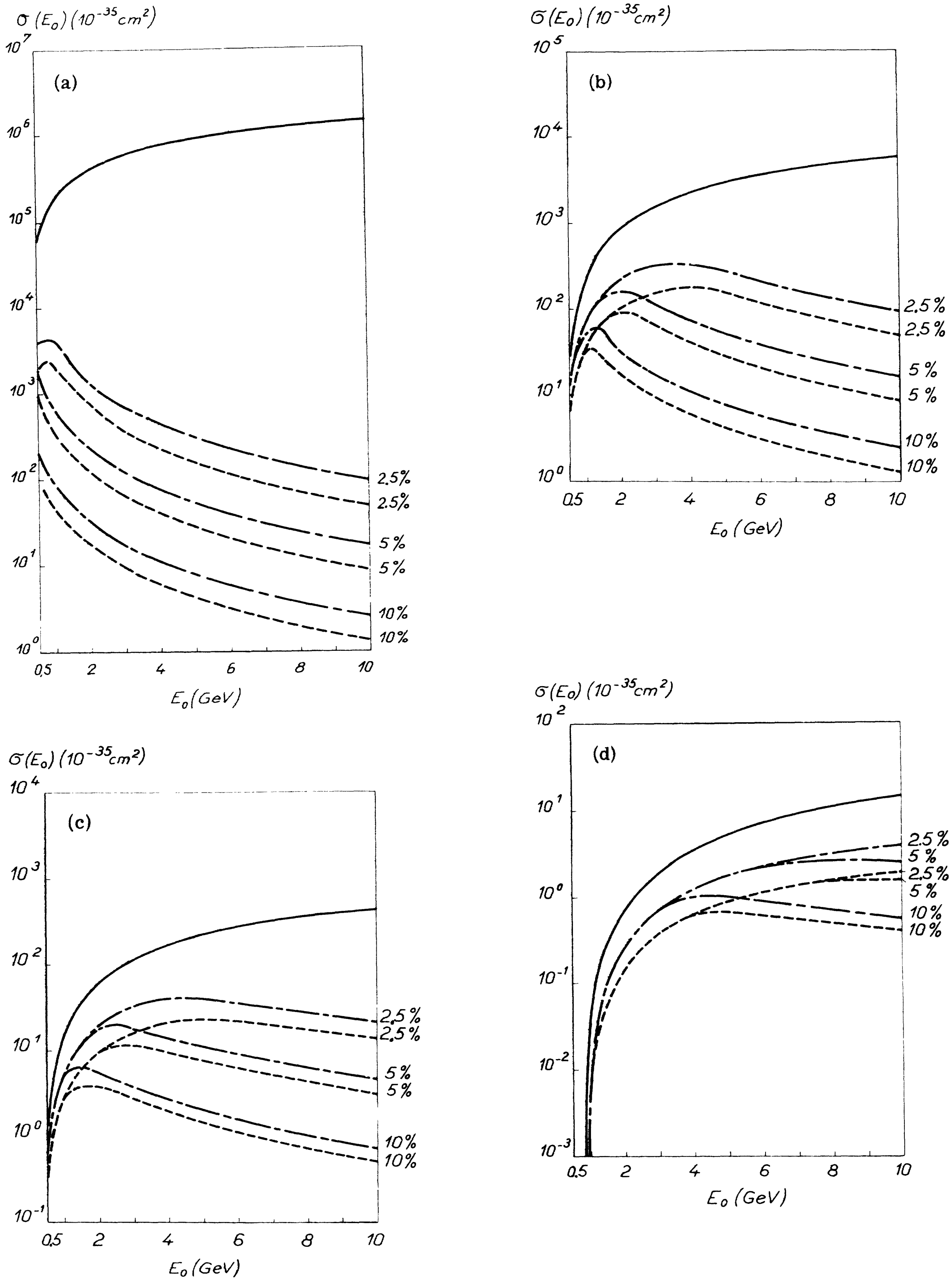


FIG. 9. Combined cutoff effect on the total cross section as a function of beam energy, for the process $e^-e^+ \rightarrow e^-e^+A^-A^+$. (a) $A=e$ ($M>50$ MeV); (b) $A=\mu$; (c) $A=\pi$; (d) $A=K$. —— $\theta_{max}=4$ mrad, no other cutoff. All other curves: $\theta_{max}=4$ mrad, $\chi_{max}=70\%$, χ_{min} as indicated; – —— – $\psi_{min}=30°$; – – – – $\psi_{min}=45°$.

the energy behavior is quite strikingly modified by introducing realistic cutoffs. From the relation $M_{min}=2\chi_{min}E_0$, it can be easily understood that the effect of χ_{min} becomes more and more drastic (in the sense that increasing portions of the threshold region are cut away) as the energy increases. In the case of electron pair creation the energy behavior is completely reversed with respect to the "unrealistic" curve shown for reference. For muon and pion pair production, there appears to be an optimum in E_0; it is a fortunate circumstance that this optimum is essentially located in the region $E_0 \sim 2-3$ GeV, where the beam energy of the storage rings of the next generation should lie. A similar optimum also occurs for kaons, but at higher beam energies.

III. DISCUSSION AND CONCLUSION

A comparison of the cross sections predicted for the production of electron, muon, pion, and kaon pairs at beam energies ranging between 0.5 and 10 GeV, and with the standard values chosen for our various cutoff parameters, is shown in Table I.

One notices that from $E_0 = 3$ GeV on, the same figures are obtained for electrons and muons. This fact is quite easily understandable, since the dynamics are the same for both particles, and any effect of the particle mass becomes negligible at high invariant mass M and large emission angles for the pair produced. The same effect occurs when comparing pions with kaons, and here also the figures obtained for both should become identical above a certain value (higher than 10 GeV) of E_0.

Let us recall here (see Ref. 13) that we used the Born-term model throughout for the calculation of pair production by two photons, so that the predictions given for pion and kaon pairs should only be considered as orders of magnitude.

From Table I, we may conclude that, after taking realistic experimental cutoffs into account, our previous statement on the feasibility of future experiments still remains true; namely, for electron, muon, and pion pairs, reasonably high counting rates will be achieved with the electron-positron storage rings of the next generation.

It will perhaps be possible, at the price of some technical effort, to obtain more favorable values for the cutoff parameters, in particular a smaller cutoff angle ψ_{min}. In that case, even kaon pair production may give rise to acceptable counting rates with the next machines.

Anyhow, the first and the most interesting experiment to be performed with these new machines (such as Spear at SLAC, Doris at DESY, and the new storage ring planned at Orsay) should be the investigation of the still hypothetical scalar pion-pion resonance called ϵ or σ, presumably located around $M \sim 700$ MeV. Electron and/or muon pairs produced under the same conditions would serve for calibration. As we have already stressed,[13] there is a double advantage in performing this type of experiment (with respect to any other experiment intended to investigate the ϵ resonance): no ρ produced, no spectator hadron.

For muon pairs, an alternative purpose would be, instead of using them simply for calibration in the pion-pair-production experiment, to look for some hypothetical anomaly of the muon.

Let us conclude by making three remarks:

(a) To produce particle pairs (or many-particle systems) at high invariant masses M, for instance meson resonances (with $C=+1$) above 1 GeV, center-of-mass energies higher than those afforded by the next storage rings will in principle be needed to obtain sufficient counting rates. It may then be interesting to consider a suggestion made recently by Csonka and Rees[19] which is to produce collisions between an accelerator beam (the Stanford Linac beam) and one stored beam. In this project, the luminosity would be relatively weak, but on the other hand the experimental cutoff parameters (in particular ψ_{min}) would probably have more favorable values than those considered here.

(b) As was recently suggested,[20] there are other possibilities of studying high-energy photon-photon collisions, such as using the Coulomb field of a nucleus. These suggestions certainly deserve to be taken into consideration and carefully investigated; we think, nevertheless, that a decisive advantage of the type of reactions considered by us is that they do not involve any background due to spectator hadrons.

(c) So far, we considered photon-photon collisions in electron-positron storage rings *as such*, i.e., from the point of view of the intrinsic interest and experimental feasibility of these reactions. The question, raised recently in connection with the Frascati experiments, of a possible contamina-

TABLE I. $\sigma(E_0)$ in 10^{-35} cm^2 for the reaction $e^- + e^+ \to e^- + e^+ + A^- + A^+$, with $\theta_{max} = 4$ mrad, $\psi_{min} = 45°$, $\chi_{min} = 5\%$, $\chi_{max} = 70\%$.

E_0 (GeV)	$A=e$	$A=\mu$	$A=\pi$	$A=K$
0.5	924	6	0.3	
1	343	38	3	0.01
2	119	91	10	0.15
3	63	63	11	0.4
4	40	40	9	0.6
6	20	20	6	1.1
8	13	13	4	1.5
10	9	9	3	1.8

tion of e^-e^+ annihilation measurements by $\gamma\gamma$ processes involves quite different experimental conditions and must thus be studied separately.

ACKNOWLEDGMENTS

The authors are particularly indebted to Professor J. Haissinski for his advice on all experimental questions involved in this study. They also wish to thank Professor N. Cabibbo, Dr. A. Courau, Professor P. L. Csonka, Professor B. Jouvet, Professor U. Maor, Professor P. Waloschek, and Professor A. Zichichi for useful discussions. They express their gratitude to Professor M. Morand and Professor F. Perrin for their interest and help. Finally, they wish to thank J. P. Jobez and P. Bonierbale for their technical cooperation.

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*Work partly supported by the Commissariat à l'Energie Atomique.

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