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INVESTIGATION OF PHOTON-PHOTON INTERACTIONS BY e^+ e^- BEAMS COLLIDING WITH 2.7 GeV TOTAL ENERGY

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Résumé. — L'interaction photon-photon a été étudiée dans les collisions $e^+ e^-$ à une énergie totale d'environ 2,7 GeV. Le processus $e^+ e^- \to e^+ e^- \mu^+ \mu^-$, qui n'avait pas été observé jusque-là, a été mis en évidence par 34 événements bien identifiés. On a constaté, pour ce processus, un bon accord entre le résultat expérimental trouvé et les prédictions théoriques basées sur l'approximation des photons équivalents. Par ailleurs, nous donnons également des résultats concernant 76 événements du type $e^+ e^- \to e^+ e^- e^+ e^-$.

Abstract. — The photon-photon interaction has been investigated by e^+ and e^- collisions at about 2.7 GeV total energy. Evidence based on 34 well identified events has been obtained for process $e^+ e^- \to e^+ e^- \mu^+ \mu^-$, hitherto unobserved. Such a process is found to occur in agreement with theoretical predictions based on the equivalent photon approximation. Results on 76 events from process $e^+ e^- \to e^+ e^- e^+ e^-$ are also reported.

1. **Introduction.** — Electron colliding beams provide a means at present unique for investigating the photon-photon interaction at high energy. The appropriate $e^\pm$ e^- collisions are those in which the outgoing $e^\pm$ and e^- are detected at very small angles with respect to their incident directions, in coincidence with other particles produced at large angle. Thus one selects events in which two « quasi-real » photons, γ^*, are emitted and annihilate according to the reaction

$$e^\pm\ e^- \to e^\pm\ e^-\ \gamma^*\ \gamma^* \to e^\pm\ e^-\ X$$

into a system, X, which may be a lepton pair or a hadronic system with $C = +1$.

We report in this paper the results of an experiment carried out with the Frascati e^+ e^- storage ring, Adone, in runs performed at an average total energy $(E_+ + E_- = 2\,E = \sqrt{s})$ of 2.7 GeV, for an integrated luminosity

$$\int L\mathrm{d}t = 290\ \mathrm{nb}^{-1}\quad (^*)\,.$$

The results refer to 76 events corresponding to the process

$$\gamma\gamma \to e^+\ e^- \qquad (1)$$

34 well identified events corresponding to

$$\gamma\gamma \to \mu^+\ \mu^- \qquad (2)$$

and 2 candidate events for the reaction

$$\gamma\gamma \to \pi^+\ \pi^-\,. \qquad (3)$$

The experimental results on process (2) agree with the theoretical predictions based on the equivalent photon approximation (EPA). The same is true for process (1) with the exception of a well identified class of events ($\sim 20\ \%$) where one of the intermediate photons is out of the mass shell and the EPA cannot be applied (see Section 5).

2. **Data recording.** — Figure 1 defines the relevant kinematical quantities. After the e^+ e^- collision, a final state e^+ e^- P_1 P_2 is produced, in which two particles, P_1 and P_2, are present as a result of one of the annihilation processes (1), (2), (3). These particles, emitted at angles θ_1, θ_2 and with momenta $\mathbf{p}_1$, $\mathbf{p}_2$, are detected by a system of two wide angle (WA) telescopes as sketched in figure 2, and will be called « WA particles » in what follows.

(*) Runs were carried out, more precisely, at $E = 1.3$ GeV for $\int L\,\mathrm{d}t = 160\ \mathrm{nb}^{-1}$ and at $E = 1.4$ GeV for 130 nb^{-1}. Other results, obtained at $E = 0.8$ GeV with essentially the same apparatus, were recently reported elsewhere [1].

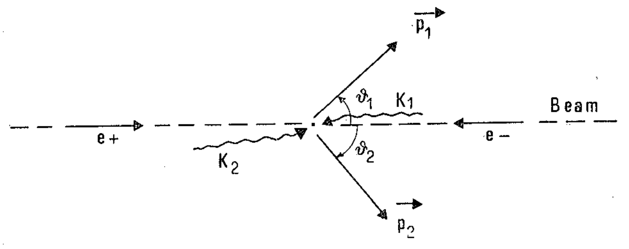

FIG. 1. — Definition of the relevant kinematical quantities characterizing the annihilation of two quasi-real photons into a pair of particles emitted at large angle.

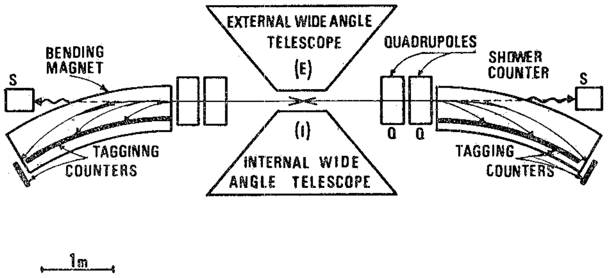

FIG. 2. — Schematic view of the general set-up. The « *shower counters* », S, were used to veto events involving photons from real bremsstrahlung.

The forward emitted electron and/or positron are recorded by « tagging counters », as also shown in figure 2. The adopted tagging technique [2] utilizes the machine bending magnet as a momentum analyzer. The momentum of the e^+ and/or e^- is determined with a typical accuracy of $\pm$ 5 % by measuring the propagation time of the scintillation light. The tagging counter system accepts ~ 50 % of the scattered $e^{\pm}$ with energy in the interval (0.2-0.85) E. The geometrical efficiency is shown in figure 3 versus the electron energy.

Figure 4 presents a cross-sectional view of the WA apparatus, which is an improved version of a previous one described elsewhere [3]. The thin foil spark chambers placed near the machine vacuum chamber are used for kinematical reconstruction of the events. All other track detectors (thick plate chambers) are used to observe particle stops, or nuclear interactions, or the development of electromagnetic showers.

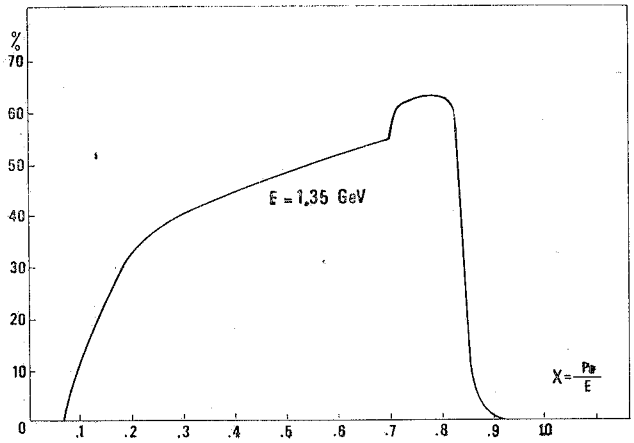

FIG. 3. — Geometrical efficiency of the tagging counter. The sudden change in the curve is due to the effect of the small tagging counter placed out of the bending magnet.

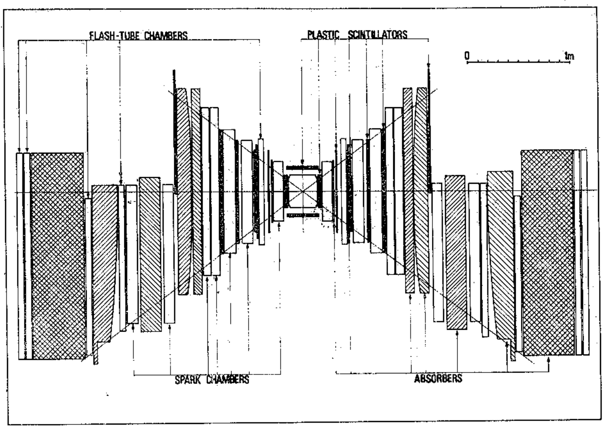

FIG. 4. — Cross-sectional view of the WA telescopes. The outer thick absorbers and track chambers are used for the simultaneous investigation of the one photon channel processes, not considered here.

3. **Event definition and identification criteria.** — The basic requirements for the selection of the events are :

(i) Presence of two single tracks, one in each of the two kinematical chambers, converging in the $e^+ e^-$ interaction region ;

(ii) Time coincidence, within ~ $\pm$ 10 ns, with the instant of beam-beam collision ;

(iii) Coincident pulse in at least one of the two tagging counters ;

(iv) Penetration of the WA particles in the WA telescopes as specified in table I below.

TABLE I

Requirements on minimum particle penetration in WA *telescopes* (*expressed in* g/cm^2 *of iron equivalent*) *for various types of events.*

Event type	Penetration in one telescope	Penetration in other telescope
—	—	—
DT-μ	40	10
ST-μ	40	40
DT-e	40	10
ST-e	40	22

The selected events are subdivided in two categories : 1) Singly tagged (ST) events ; 2) Doubly tagged (DT) events. The $\gamma\gamma \rightarrow \mu^+ \mu^-$ events (briefly called in the following μ-events) are scearched for among those which show no shower or nuclear interaction in the thick plate chambers. The $\gamma\gamma \rightarrow e^+ e^-$ events (e-events) are searched for among those which do exhibit instead an electromagnetic shower in at least one of the two WA telescopes. No event with a shower in one WA telescope and a single track penetrating the other telescope was observed.

4. **Identification of the μ-events.** — We have recorded 14 DT μ-events, of which 10 with at least one track stopping in the WA telescopes. Identification of these 10 events as μ-events is based primarily on the distribution of the quantity

$$\Delta k = k_{\text{rec}} - k_{\text{meas}}$$

where k_{meas} is the photon momentum as derived from the tagging counter information and k_{rec} is the value of the same quantity obtained from a kinematical reconstruction. The latter is based on angle and range measurements of the WA particles, assumed to be muons. The Δk distribution reported in figure 5*a* shows indeed a peak about $\Delta k = 0$, as expected if the events were correctly identified.

Further evidence for the corrected identification comes from the Δk distribution of the ST μ-events reported in figure 5*b*. For these events we require that both WA tracks stop in the WA telescope, since one single muon stop is not sufficient to reconstruct kinematically the ST μ-events. It is seen from figure 5*b* that 20 out of the 56 recorded ST μ-events cover essentially the same region as the DT μ-events distribution. They are interpreted as « good » μ-events ($\gamma\gamma \rightarrow \mu^+ \mu^-$). The remaining 36 events, on the other hand, exhibit a rather flat distribution, clearly separated from the former one. These 36 events are interpreted as « *background* » events originating in beam-gas collisions. This interpretation is supported by the results of background runs, carried out with separated e^+ and e^- beams, in which 7 events were recorded. These last events have the ΔK distribution shown in figure 5*c* that is consistent with that of the 36 « *background* » events of histogram *b*. Also the absolute numbers of events (7 and 36) are consistent with each other, if allowance is made for a normalization factor of ~ 4.

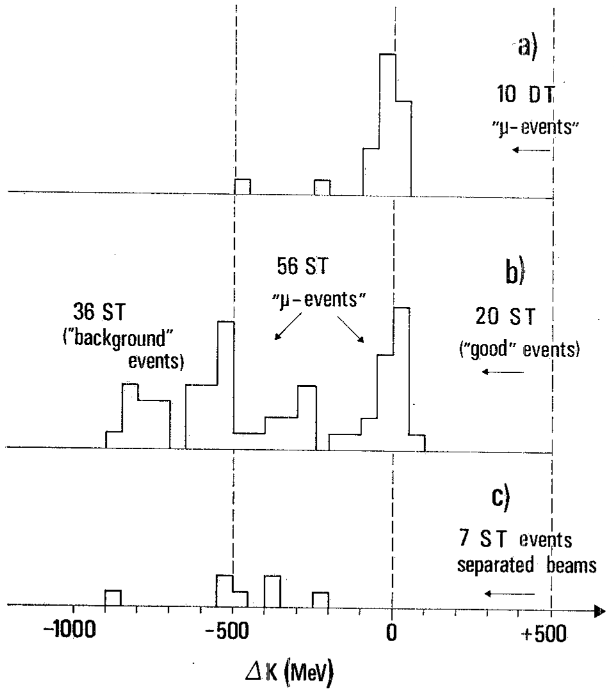

FIG. 5. — Δk ($\equiv k_{\text{rec}} - k_{\text{meas}}$) distribution : *a*) For 10 DT μ-events ; *b*) For 56 ST μ-events ; *c*) For 7 ST background μ-events obtained with separated e^+ and e^- beams. 36 of the 56 ST events (histogram *b*) can be interpreted as background events. Of course each doubly tagged event contributes two points to the Δk distribution.

The momentum distribution of the quasi-real photons relative to the DT μ-events is given in figure 6. The full histogram is the experimental distribution. It is seen to agree very well with the one, represented by the dotted lines, derived by a Monte Carlo calculation based on the EPA.

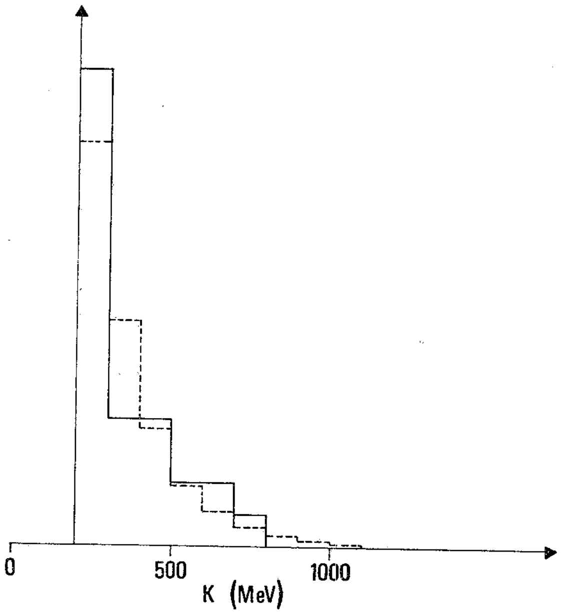

FIG. 6. — Photon momentum distribution relative to the DT μ-events. The dotted histogram is derived from a Monte Carlo calculation based on the equivalent photon approximation.

5. **Identification of the e-events.** — No event simulating the e-events was observed during the background runs. Hence no background contribution needs to be subtracted from the 12 DT and the 64 ST e-events recorded during the main runs.

Within the energy error $\pm\, \delta k_r$, δk_1 k_1, the 12 DT events are found to fulfil the relationship

$$\beta = (k_r - k_l)/(k_r + k_l) = \\ = \sin(\theta_1 + \theta_2)/[\sin\theta_1 + \sin\theta_2] \quad (4)$$

where β is the CM velocity and $k_r(k_l)$ the energy of the photon emitted by the electron scattered into the right (left) tagging counter.

Eq. (4) holds for events involving, as the e-events, WA particles of rest energy much smaller than their kinetic energy.

For the ST e-events, we use eq. (4) to derive the energy k_x of the photon associated to the undetected electron, with an uncertainty of $\pm\ \delta k_x$. For 43 out of the 64 ST e-events, we found that, as expected, $0 < k \pm \delta k < E$. These 43 events are interpreted as $\gamma\gamma \to e^+ e^-$ events with two « *quasi real* » photons. Other 9 events do not fulfil the above inequalities, yielding $k \pm \delta k > E$. They are interpreted as due to bremsstrahlung of one of the primary electrons, $e^\pm$, followed by γ conversion into a pair, a member of which undergoes an elastic scattering with the other primary, $e^\mp$. For this process, one of the photons of figure 1 is deeply virtual. These events (first observed at Adone by the « $\gamma\gamma$ » group [4] and interpreted as above by Cabibbo and Parisi) occur in a kinematical configuration with both the forward emitted particles scattered towards the same tagging counter.

The remaining 12 events cannot be classified unambiguously since, due to the experimental error $\pm\ \delta k$, we cannot establish whether the quantity $E - (k \pm \delta k)$ is positive or negative.

6. **Two candidate events for the reaction $\gamma\gamma \to \pi^+ \pi^-$.** — Two of the recorded DT events may be interpreted as due to process (3), as they fulfil the requirements listed in section 3 and exhibit at least one nuclear interaction in the WA telescopes. They are certainly not e-events (there not being any associated electromagnetic shower) nor μ-events (being also impossible a kinematical reconstruction as such a type of event).

7. **Coplanarity test on DT events.** — The angular acceptance of the tagging counters sets an upper limit of nearly 10 MeV/c for the transverse momentum of the recorded $e^\pm$. This implies that for DT events of any type it is not possible to have coplanarity angles, $\Delta\varphi$, in excess of about 3°.

The $\Delta\varphi$ distribution of all recorded DT events is reproduced in figure 7 and it is seen to be essentially within the expected limit.

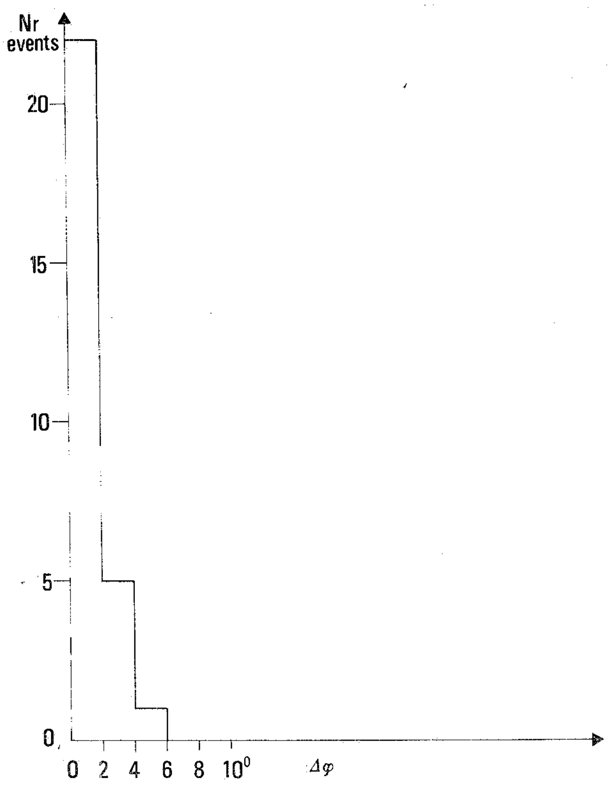

FIG. 7. — Acoplanarity angle distribution for all recorded DT events.

8. **Comparison with theoretical expectations.** — By a Monte Carlo simulation of the experiment, based on the EPA, we have deduced the expected numbers of DT μ-events, ST μ-events and DT e-events. The derivation of the expected number of ST e-events, as calculated from EPA, is very sensitive to small variations of the efficiency of the WA apparatus in detecting low energy electrons. A more sophisticated Monte Carlo calculation is therefore required. Work along this direction is in progress.

The ST e-events with a photon deeply virtual are characterized by relatively high energy electrons at wide angle. For these events, a preliminary calculation gives the results shown in table II, where they are indicated by (ST-e)*.

TABLE II

Comparison between numbers of observed and expected events assuming the equivalent photon approximation (EPA).

Type of event	Expected number	Observed number
DT-μ	10.9 ± 1	14
ST-μ	27.9 ± 2.6	20
(ST + DT)-μ	38.8 ± 3.0	34
DT-e	11.6 ± 1.1	12
(ST-e)*	18 ± 9	15 ± 5

In table II the numbers of expected events are reported together with the corresponding numbers of observed events. Expected and observed numbers of events are seen to be in substantial agreement.

References

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[3] GRILLI, M., *et al.*, *Nuovo Cimento* **13** (1973) 593 ; CONVERSI, M., d'ANGELO, S., GATTO, R. and PAOLUZI, L., *Phys. Lett.* **46B** (1973) 269.

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DISCUSSION

R. MADARAS : In your measurement of ee → eeee and ee → ee$\mu\mu$, how well could you separate the low energy electrons and muons that you observed ? At the low energies involved, don't the electrons and muons look quite similar ?

R. SANTONICO. — Low energy electron and muon pairs can be separated also in the case where no electron exhibits an electromagnetic shower. In this case, the kinematical reconstruction of the event allows us to distinguish the different rest energy of the $e^+ e^-$ and $\mu^+ \mu^-$ system.

A. ZICHICHI. — Could you please say something on your criterion to discriminate pions from muons ? For instance, what is the probability that a pion looks like a muon in your apparatus, at the various energies of interest to you ?

I also have another question : In your single tagging distribution, you have two peaks. One is interpreted as genuine $e\bar{e} \to e\bar{e}\mu\bar{\mu}$; the other events on the left are interpreted as electroproduction in gas. But this distribution shows a peak at − 500 MeV. Can you exclude that this peak may be due to high-energy pions, mistaken for low-energy muons ? According to our calibrations, a pion of given energy has quite large a possibility to behave like a stopping muon, which of course has lower energy.

S. ORITO. — In rejecting the doubly tagged $\gamma\gamma \to \bar{\pi}\pi$ events which might contaminate the $\gamma\gamma \to \mu\mu$ events, we use the following criteria : (i) Absence of nuclear interaction ; (ii) if both tracks stop, the visible transverse momentum transfer should be balanced within 30 MeV/c ; (iii) the tagged photon energy and the observed range in a possible pion event must be compatible with the kinematics of $\gamma\gamma \to \pi^+ \pi^-$. The probability of a pion reaching its range without visible nuclear interaction is of about 10-20 %. The probability of both tracks reaching their range is thus very small. If otherwise, the kinematical constraints would allow one to reject the possible $\pi^+ \pi^-$ contamination in $\mu^+ \mu^-$ events.

As to your second question, the second peak in the singly tagged $\mu\mu$ events cannot be due to events $\gamma\gamma \to \pi^+ \pi^-$, since it doesn't exist in the doubly tagged events. As demonstrated by the separated-beam runs, it is coming from beam-gas events. Let me stress that we use only the doubly tagged events for the physics. The singly tagged events serve only as a check of our system, for instance as a check of the tagging efficiency we calculated.

B. STELLA. — I think that the actual problem is to separate the seven background events found (by single tagging with two tracks at wide angle) from good events with the same configuration. In my opinion, double tagging is necessary to eliminate beam-gas pion electroproduction. This will also provide a difficult problem in future experiments in this energy range (because of statistics).

S. ORITO. — Yes, I believe that point was made clear in the talk.

H. TERAZAWA. — What are the invariant masses you have observed in the pion pair events?

R. SANTONICO. — About 1.3 GeV and 0.7 GeV.

J. L. MASNOU. — Let me come back to the background problem mentioned by Zichichi. In the single-tagged μ distribution (your graph *b*), can you say what is the background expected from beam-gas collisions in the 20 observed events, if you estimate it on the basis of an extrapolation of the background distribution ? And what is the background due to unsigned π events ?

S. ORITO. — As the double-tagged events show, there is no $\pi\pi$ background. But there might be a few beam-gas background events among the selected single-tagging events.

J. PEREZ Y JORBA. — I would like to insist on the question of the pion background. Are you really sure that, in your $e^+ e^- \mu^+ \mu^-$ events, you did not include some $e^+ e^- \pi^+ \pi^-$ events with pions of the same range not having given any nuclear interaction ?

R. SANTONICO. — We estimate that kind of background to be less than one event.

J. PEREZ Y JORBA. — Let me ask you more precisely : Can you, from the two events $e^+ e^- \pi^+ \pi^-$ with nuclear interaction, estimate the number of $e^+ e^- \pi^+ \pi^-$ events without nuclear interaction which can be mistaken for $e^+ e^- \mu^+ \mu^-$ events ?

R. SANTONICO. — Yes, it is negligible. As I said less than one event.