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G. Barbiellini, F. Ceradini, M. Conversi, S. d'Angelo, M.L. Ferrer, S. Orito, L. Paoluzi, R. Santonico, T. Tsuru and R. Visentin: MUON PAIR PRODUCTION BY PHOTON-PHOTON INTERACTION IN THE ADONE e^+e^- STORAGE RING.

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(x) - The results of the present paper were reported in a preliminary form to the "International Colloquium on Photon-Photon Collisions in Electron-Positron Storage Rings", Paris (3-4 September, 1973). See also: F. Ceradini, M. Conversi, S. d'Angelo, M. L. Ferrer, L. Paoluzi, R. Santonico, G. Barbiellini, S. Orito, T. Tsuru and R. Visentin, Rome internal report n. 486 (July 30, 1973).

MUON PAIR PRODUCTION BY PHOTON-PHOTON INTERACTION IN THE ADONE e^+e^- STORAGE RING

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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 the 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 74 events from process $e^+e^- \to e^+e^-e^+e^-$ are also reported.

Electron colliding beam provide a means, at present unique, for investigating the photon-photon interaction at high energy, as pointed out by many authors.[1]

In the present experiment the outgoing $e^{(+,-)}$ are detected at very small angles with respect to their incident directions, in coincidence with other particles produced at wide angles (WA particles). This arrangement selects events in which two "quasi-real" photons, γ^*, are emitted and annihilate according to the reaction

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X \tag{1}$$

where X is a system with C=+1. In our experiment X is a pair of WA particles present in the final state as a result of one of the annihilation processes:

$$\gamma\gamma \rightarrow \mu^+\mu^- \tag{2}$$

$$\gamma\gamma \rightarrow e^+e^- \tag{3}$$

$$\gamma\gamma \rightarrow \pi^+\pi^- \tag{4}$$

These particles, emitted at angles θ_1, θ_2, with momenta p_1, p_2, are detected by a system of two wide angle telescopes (WA) as sketched in Fig. 1.

The experiment has been carried out with the Frascati e^+e^- storage ring, Adone,[2] in runs performed at an average total energy ($E_+ + E_- = 2E = \sqrt{s}$) of 2.7 GeV, for an integrated machine luminosity $\int L dt = 290\ nb^{-1}$. The results consist of 34 well identified events corresponding to process (2), 76 events corresponding to process (3) and 2 candidates for process (4).

The experimental results on processes (2) and (3) agree with the theoretical predictions based on the equivalent photon approximation (EPA).[1]

The forward emitted electron and/or positron are recorded by "tagging counters", as also shown in Fig. 1. The tagging technique adopted[3] utilizes the machine bending magnet as a momentum analyzer. The momentum of the e^+ and/or e^- is determined with a typical accuracy of ±5% by measuring the propagation time of the scintillation light. The tagging counter system accepts scattered $e^{(+,-)}$ of energy $(0.2 \div 0.85)E$, with approximately 50% efficiency, as calculated assuming EPA.

In the wide angle apparatus (WA)[4] two thin foil spark chambers placed

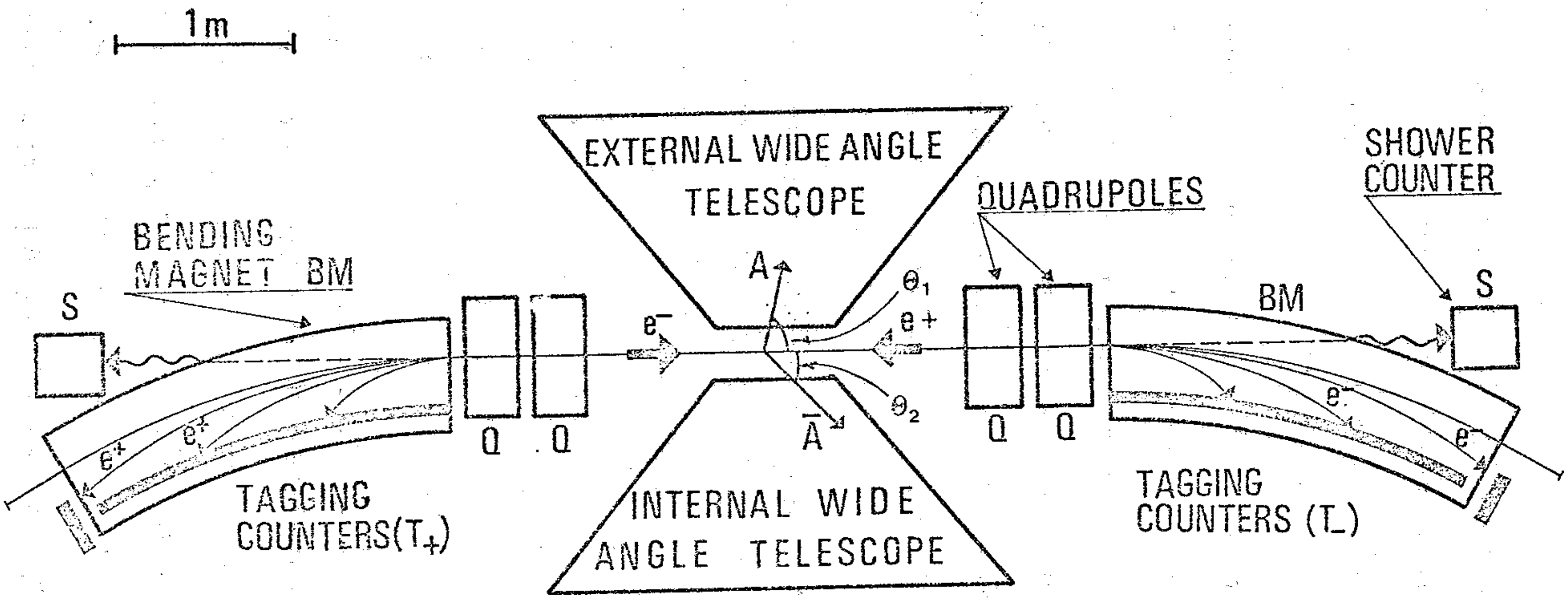

FIG. 1 - Schematic view of the general set-up. The "shower counters", S, were used to veto events involving photons from real bremmsstrahlung. A and $\bar{A}$ are WA particles.

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.

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 about ±10 nsec, 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.

TABLE I

Minimum particle penetration required in the 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 into two categories: 1) Singly tagged (ST) events; 2) Doubly tagged (DT) events. The $\gamma\gamma \to \mu^+\mu^-$ events (below called μ-events for briefness) are searched for among those events which show no shower or nuclear interaction in the thick plate chambers. The $\gamma\gamma \to e^+e^-$ events (e-events) are searched for among those which do exhibit an electromagnetic shower in at least one of the two WA telescopes.

We have recorded 14 DT μ-events, of which 10 had 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

$$\Delta K = K_{rec} - K_{meas}$$

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 Fig. 2a) indeed shows a peak about $\Delta K=0$ as expected if the events were correctly identified.

Further evidence of the correct identification comes from the ΔK distribution of the ST μ-events reported in Fig. 2b). For these events we require that both WA tracks stop in the WA telescopes, so that we have one constraint events. It is seen from Fig. 2b) that 20 out of the 56 recorded ST μ-events cover essentially the same region of 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 in ΔK, clearly separated from the former one. These 36 events are interpreted as "background" events which originated in beam-gas collisions. This interpretation is supported by the results of the background runs, carried out with separated e^+ and e^- beams, in which 7 events were recorded. These last events have indeed the ΔK distribution shown in Fig. 2c) and their number

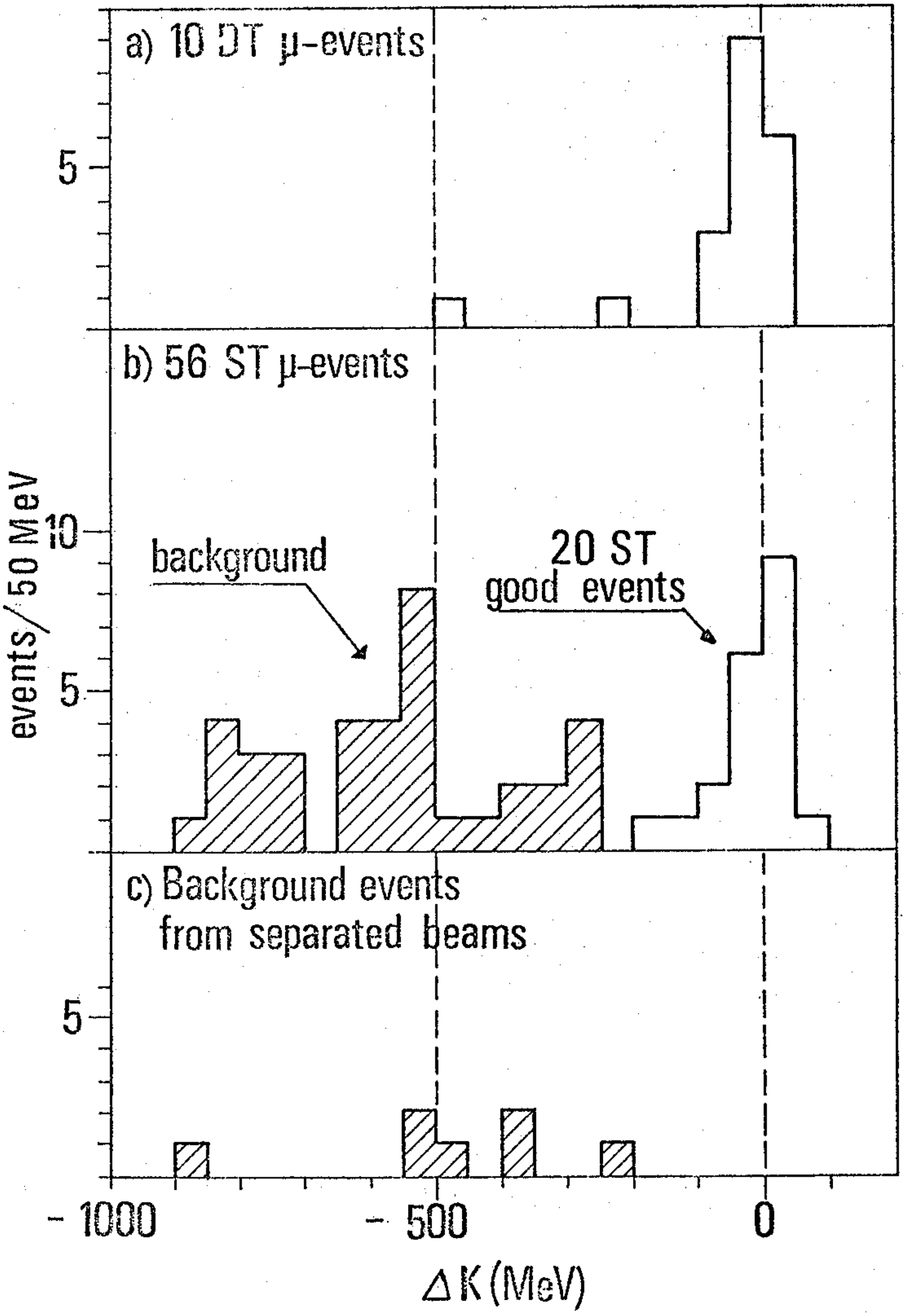

FIG. 2 - $\Delta k = (k_{rec} - k_{meas})$ distribution: a) For 10 DT μ-events; b) For 56 ST μ-events; c) For 7 ST background μ-events obtained with separated e^+ and e^- beams. 36 of the 56 ST events (hystogram b) can be interpreted as background events. Of course each doubly tagged event contributed two points to the Δk distribution.

(7) is consistent with the previous 36 background events, if allowance is made for a normalization factor of ~ 4.5.

The momentum distribution of the quasi-real photons relative to the DT μ-events is shown in Fig. 3a) (full line).

Simultaneously with the μ-events we have collected also the e-events, first observed at Novosibirsk.[5] No event of the e-type was observed during the background runs. Within the energy error $\pm\delta K_{(+,-)}$ the 12 DT e-events are found to fullfil the relationship

$$\beta = \frac{K_- - K_+}{K_- + K_+} = \frac{\sin(\Theta_1 + \Theta_2)}{\sin\Theta_1 + \sin\Theta_2} \qquad (5)$$

where β is the C.M. velocity and $K_{(+,-)}$ the energy of the photon emitted by the $e^{(+,-)}$ scattered into the tagging counter.

Eq.(5) holds for any event involving WA particles of rest energy much smaller than their kinetic energy. For the ST e-events we use then Eq.(5) to derive the energy K_x of the photon associated with 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, $0 \leq K_x \pm \delta K_x \leq E$. These 43 events are interpreted as $\gamma\gamma \to e^+e^-$ events with two "quasi real" photons. Another 9 events do not fullfil the above inequalities, yielding $K \pm \delta K > E$. They are interpreted as due to bremsstrahlung of one of the primary electrons, $e^{(+,-)}$, followed by conversion into a pair, a member of which undergoes an elastic scattering with the other primary, $e^{(-,+)}$. For this process one of the photons is deeply virtual. These events, first observed at Adone by the "$\gamma\gamma$" group[6] and

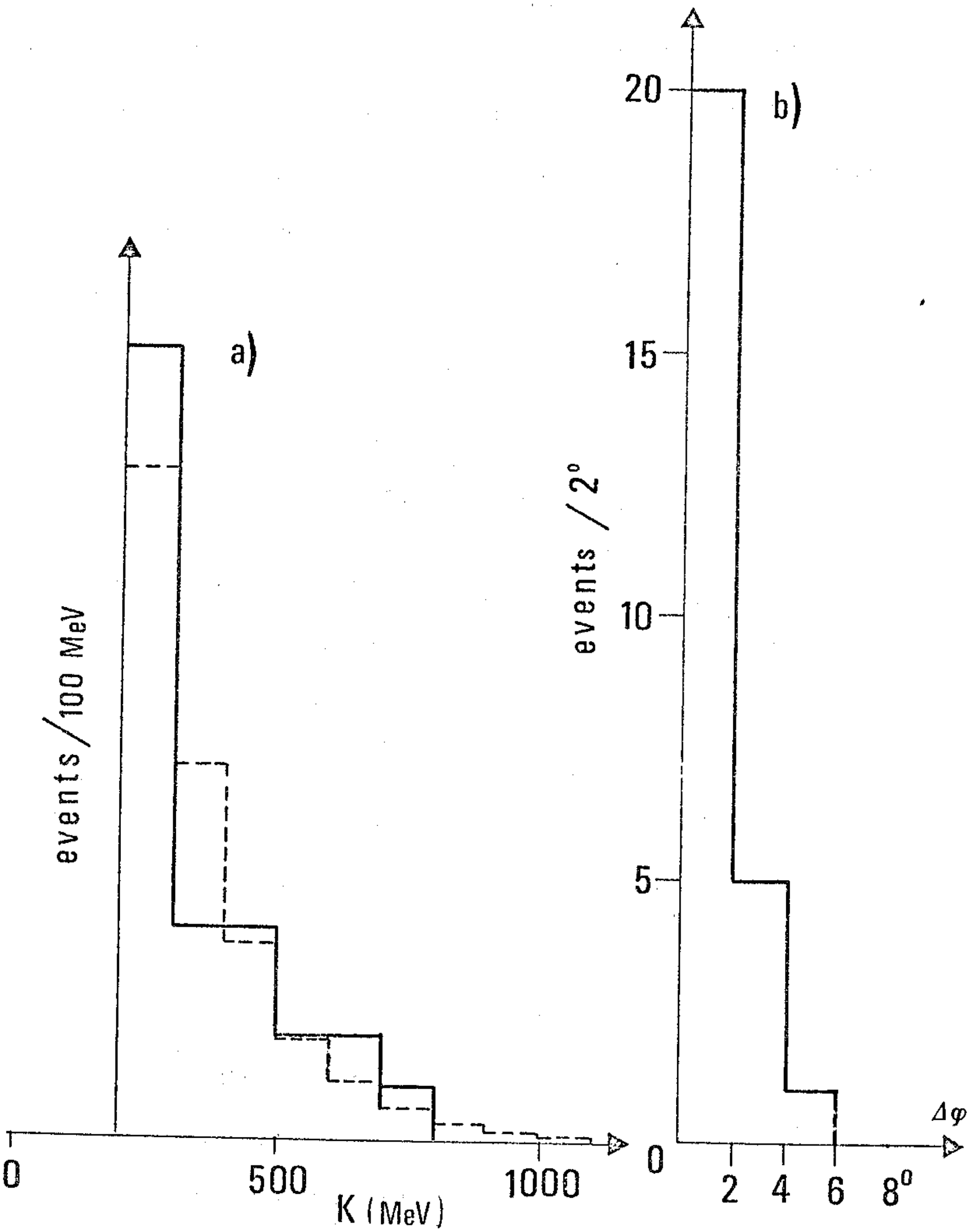

FIG. 3 - a) Photon momentum distribution relative to the DT μ-events. The dotted hystogram is derived from a Monte Carlo calculation based on the equivalent photon approximation.
b) Acoplanarity angle distribution for all recorded DT events.

interpreted as above by Cabibbo and Parisi,[7] 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, giving a systematical error that adds to the statistical one.

The angular acceptance of the tagging counters sets an upper limit of nearly 10 MeV/c for the transverse momentum of the recorded $e^{(+,-)}$. This implies that for DT events of any type it is not possible to have acoplanarity angles $\Delta\phi$ larger than$\sim 3°$. The $\Delta\phi$ distribution of all recorded DT events is reproduced in Fig. 3b) and it is seen to be essentially within the expected limit.

By a Monte Carlo simulation of the experiment based on the EPA, we have deduced the expected numbers of DT and ST μ- and e-events reported in Table II. For the ST e-events with a deeply virtual photon, a "hand" calculation gives the results reported in the last line of the Table.

We conclude that the experimental observations of the processes (2) and (3) are in good agreement with those expected on the basis of EPA and that the $\gamma^{\cdot}\gamma^{v}$ interaction can be efficiently studied with electron storage rings.

TABLE II

Comparison between numbers of observed and expected events. The numbers in brackets indicate systematic errors.

Type of event	Expected number	Observed number
DT - μ	10.9 ± 1	14 ± 4
ST - μ	27.9 ± 2.6	20 ± 5
(ST+DT) - μ	38.8 ± 3	34 ± 6
DT - e	8.0 ± 1	12 ± 4
ST - e	41 ± 5	49 ± (6) ± 7
(ST+DT)-e	49 ± 5	61 ± (6) ± 8
(ST - e)*	18 ± 9	15 ± (6) ± 4

(ST - e)* are e-events involving a deeply virtual photon.[6,7]

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