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Observation of the Reactions $e^+e^- \to \pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$. A Test of Weizsäcker-Williams Approximation for Virtual Electrons.

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(ricevuto il 22 Novembre 1979)

We present experimental results on the cross-sections for the reactions

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

and

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

obtained at the Adone storage ring ($\gamma\gamma 2$ experiment) in the total c.m. energy range $W = (1500 \div 1600)$ MeV.

The experimental set-up is described in detail elsewhere ([1]). It consists of two telescopes of scintillation counters, optical spark chambers and lead converters placed above and below the interaction region. The solid angle is $0.41 \times 4\pi$ sr covered by trigger counters and $0.66 \times 4\pi$ sr covered by optical spark chambers. Track direction can be measured within a cone of $\sim 10^{-2}$ sr.

The trigger logic requires a coincidence between the two telescopes. In order to fire a telescope a muon (pion) must have a kinetic energy of at least 110 (120) MeV.

([1]) R. BALDINI CELIO, M. BERNARDINI, G. CAPON, R. DEL FABBRO, M. GRILLI, E. IAROCCI, L. H. JONES, M. LOCCI, C. MENCUCCINI, G. P. MURTAS, M. A. SPANO, M. SPINETTI, V. VALENTE, C. BACCI, V. BIDOLI, G. PENSO and B. STELLA: *Lett. Nuovo Cimento*, **11**, 711 (1974); C. BACCI, G. PENSO, B. STELLA, R. BALDINI CELIO, M. BERNARDINI, M. BOZZO, G. CAPON, R. DEL FABBRO, M. GRILLI, E. IAROCCI, L. H. JONES, C. MENCUCCINI, G. P. MURTAS, M. SPINETTI and V. VALENTE: *Lett. Nuovo Cimento*, **12**, 269 (1975); R. BALDINI CELIO, G. BATTISTONI, G. CAPON, R. DEL FABBRO, E. IAROCCI, C. MENCUCCINI, S. MORIGGI, G. P. MURTAS, M. SPINETTI, L. TRASATTI, C. BACCI, G. DE ZORZI, G. PENSO and B. STELLA: *Phys. Lett. B*, **78**, 167 (1978); R. BALDINI CELIO, G. CAPON, R. DEL FABBRO, M. GRILLI, E. IAROCCI, G. LA ROSA, C. MENCUCCINI, G. P. MURTAS, M. SPINETTI, V. VALENTE, C. BACCI, G. DE ZORZI, G. PENSO and B. STELLA: *Lett. Nuovo Cimento*, **24**, 324 (1979).

The apparatus does not allow a clean discrimination between pions and muons; therefore the events from reactions (1) and (2) have been lumped together.

The main contribution to reactions (1) and (2) comes from the diagrams of fig. 1 where a Bremsstrahlung photon is emitted in the very forward direction, by the incident electron or positron, while the pions or muons are emitted at wide angles with respect to the beam line.

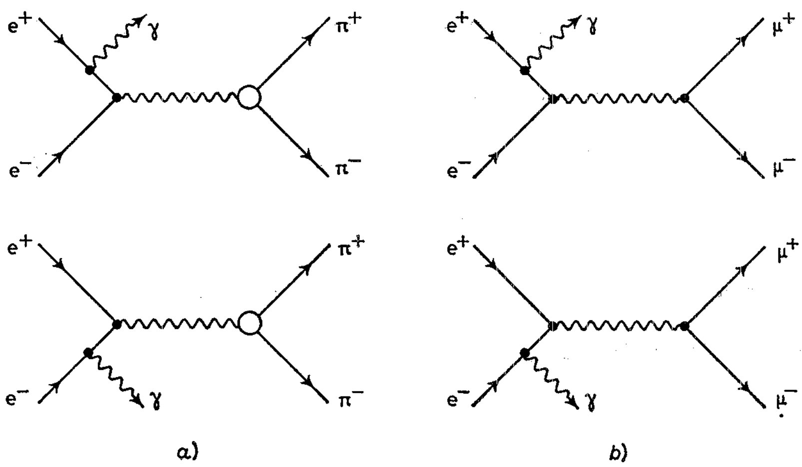

Fig. 1. – Feynman diagrams which contribute: *a*) to reaction (1); *b*) to reaction (2).

Therefore we have selected the events with only one charged track in each telescope. In order to eliminate soft Bremsstrahlung events and cosmic-ray background, only noncollinear events ($\Delta\theta_D \geqslant 20°$) (*) have been considered, the emitted photon being not detected. Furthermore contamination from beam-gas interactions is strongly reduced by considering only the events with $\Delta\theta_D \leqslant 120°$.

With these criteria, we have selected 433 events corresponding to a total integrated luminosity of $80\,\text{nb}^{-1}$ measured by wide-angle Bhabha scattering in our apparatus.

For each event we calculate the acoplanarity angle ψ between the plane of the two charged tracks and the beam line.

In fig. 2 we report the ψ-spectrum for the 433 selected events. Those coming from reactions (1) and (2), which are expected to be almost coplanar with the beam line, appear as a narrow peak at low ψ values superimposed to a smoothly decreasing background which is due to multihadrons events with only two charged particles detected. The ψ-spectrum of these events (fig. 2, line *a*)) has been calculated using the multihadrons cross-sections (2) measured in our apparatus. The contribution from reactions (1) and (2) (fig. 2, line *b*)) has been calculated assuming the photon emitted along

(*) $\Delta\theta_D$ is the acollinearity angle between the projections of the two tracks on the vertical plane which contains the beam line; $\Delta\theta_D = 0°$ corresponds to collinear particles.

(2) C. Bacci, G. De Zorzi, G. Penso, B. Stella, D. Bollini, R. Baldini Celio, G. Battistoni, G. Capon, R. Del Fabbro, E. Iarocci, M. M. Massai, S. Moriggi, G. P. Murtas, M. Spinetti and L. Trasatti: *Phys. Lett. B*, **86**, 234 (1979); M. Spinetti: *Proceedings of the International Symposium on Lepton and Photon Interactions* (Batavia, Ill., 1979).

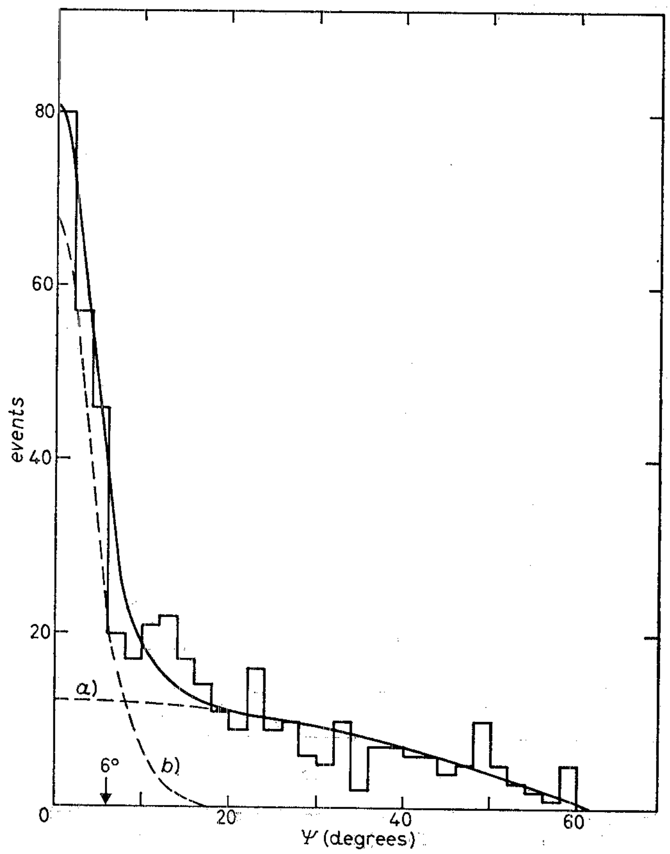

Fig. 2. – Acoplanarity angle spectrum for the two-track events. The full line is the sum of: multihadrons background (line *a*)); contribution from reaction (1) and (2) (line *b*)), calculated by Monte Carlo method (see text). Only events with $20° \leqslant \Delta\theta_p \leqslant 120°$ have been considered.

the beam line and taking into account the experimental angular resolution on the detected tracks.

In order to improve the signal-to-background ratio, we now consider the 183 events with $\psi \leqslant 6°$. From curve *a*) of fig. 2 we expect that 36 ± 3 out of these 183 events are still due to multihadrons background.

Furthermore, from a previous measurement (3) we expect that among these 183 events only $\leqslant 3$ events are due to $\gamma\gamma$ interactions; therefore this contribution has been neglected. Also contamination from beam-gas interactions, measured by running the machine with a single beam, is practically negligible.

In fig. 3 we report the effective mass spectrum of the two detected particles for all the events with $\psi \leqslant 6°$, assuming the photon emitted along the beam line; curve *a*) is the expected effective mass spectrum for the 36 multihadron background events, cal-

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(3) R. BALDINI CELIO, G. CAPON, R. DEL FABBRO, P. DE SANTIS, M. GRILLI, E. IAROCCI, C. MENCUCCINI, G. P. MURTAS, M. SPINETTI, V. VALENTE, C. BACCI, G. DE ZORZI, G. PENSO and B. STELLA: *Phys. Lett. B*, **86**, 239 (1979).

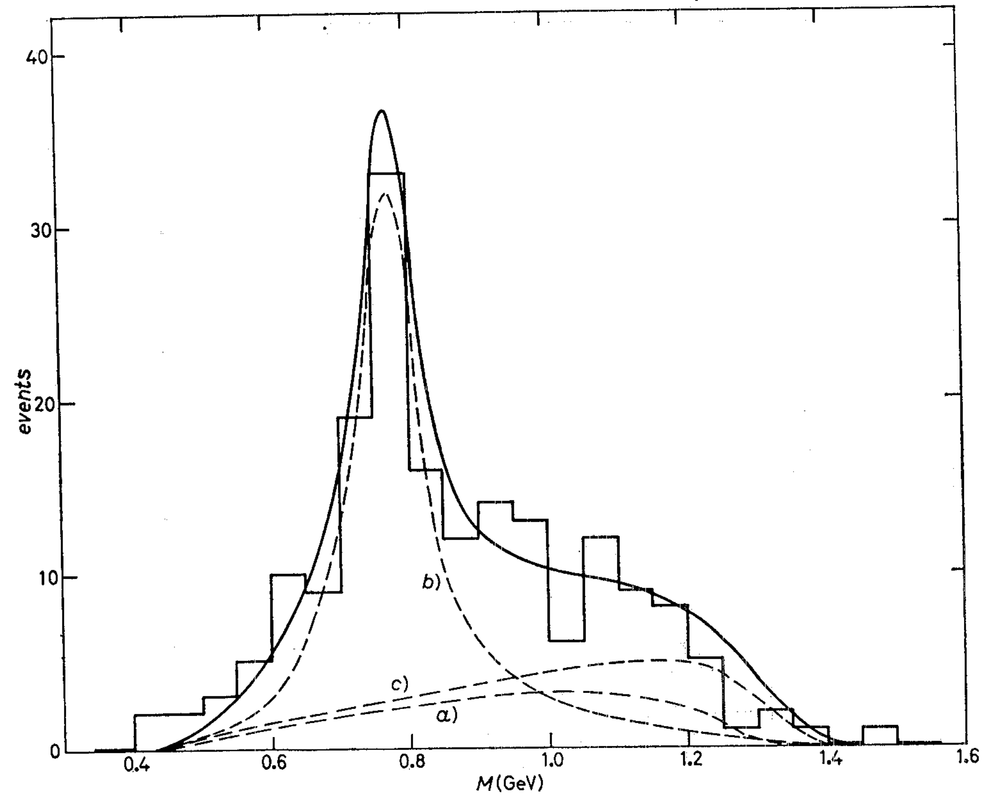

Fig. 3. – Effective mass spectrum of the two detected particles for the selected events. Full line is the sum of multihadrons background (line a)), $e^+e^- \to \pi^+\pi^-\gamma$ contribution (line b)), and $e^+e^- \to \mu^+\mu^-\gamma$ contribution (line c)) (see text). Only events with $20° \leqslant \Delta\theta_p \leqslant 120°$ and $\psi \leqslant 6°$ have been considered.

culated by Monte Carlo method, assuming the measured [2] hadronic cross-sections. In order to obtain the absolute prediction for reactions (1) and (2), we have used a generalization [4] of the semiclassical Weizsäcker-Williams method [5] to the cases where the condition $k \ll E$ is not satisfied, k being the emitted photon energy and $E = W/2$ the single beam energy. Furthermore this generalized formula has been proved [4] to hold also for hard Bremsstrahlung processes, like the present one, in which a real photon and a virtual electron (or positron) are present in the final state. According to this method, the cross-section for reaction (1) or (2) may be factorized in

$$\sigma(W) = \frac{4\alpha}{\pi}\int_{k_{\min}}^{k_{\max}} \frac{\mathrm{d}k}{k}\left(1 - \frac{k}{E} + \frac{k^2}{2E^2}\right)\left(\ln\frac{E}{m} - \frac{1}{2}\right)\sigma_0\left(\sqrt{W^2 - 2Wk}\right), \tag{3}$$

[4] P. KESSLER: *Nuovo Cimento*, **17**, 809 (1960); *J. Phys. (Paris)*, **35**, C2-97 (1974).
[5] E. J. WILLIAMS: *Proc. R. Soc. London Ser. A*, **139**, 163 (1933); *Phys. Rev.*, **45**, 729 (1934); *K. Dan. Vidensk. Selsk. Mat. Fys. Medd.*, **13**, 4 (1935); C. F. VON WEIZSÄCKER: *Z. Phys.*, **88**, 612 (1934).

where $\sigma_0(\sqrt{W^2-2Wk})$ is the cross-section of the reactions $e^+e^- \to \pi^+\pi^-$ or $e^+e^- \to \mu^+\mu^-$ calculated at the total energy which remains after photon has been emitted; m is the electron mass.

Using equation (3) and taking into account the measured pion form factor (6) we obtain (fig. 3, line *b*)) the absolute prediction of the effective mass spectrum, for reaction (1). As expected in the mass range ($400 \div 1000$) MeV the ϱ pole dominates. Similarly, using the standard $\sigma(e^+e^- \to \mu^+\mu^-)$ cross-section, we obtain (fig. 3, line *c*)) the absolute prediction for reaction (2). Full line of fig. 3 is the sum of the three contributions represented by lines *a*), *b*) and *c*). The agreement with the experimental spectrum is quite good ($\chi^2/n_D = 18/22$).

A consistency check of our measurement is performed by comparing the angular

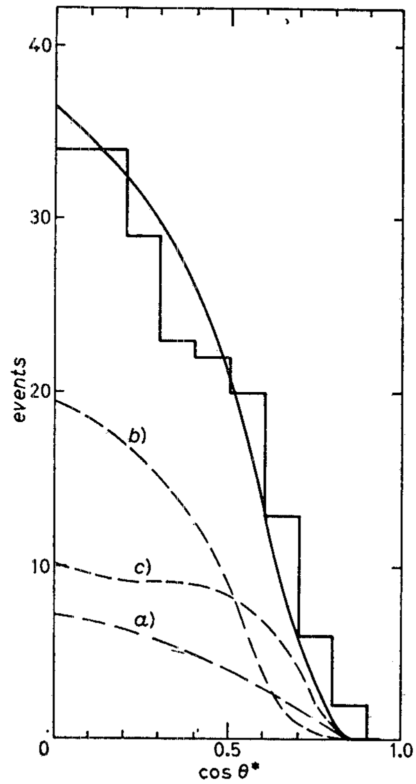

Fig. 4. – Angular distribution of the two detected particles in their own centre of mass. Full and dashed lines as in fig. 3. Only events with $20° \leq \Delta\theta_p \leq 120°$ and $\psi \leq 6°$ have been considered.

(6) A. QUENZER, M. RIBES, F. RUMPF, J. L. BERTRAND, J. C. BIZOT, R. L. CHASE, A. CORDIER, B. DELCOURT, P. ESCHSTRUTH, F. FULDA, G. GROSDIDIER, J. JEANJEAN, M. JEANJEAN, R. J. MADARAS, J. L. MASNOU and J. PEREZ-Y-JORBA: *Phys. Lett. B*, **76**, 512 (1978) and references therein quoted; A. D. BUKIN, I. B. VASSERMAN, I. A. KOOP, L. M. KURDADZE, V. A. SIDOROV, A. N. SKRINSKY, G. M. TUMAIKIN, A. G. KHABAKHPASHEV, A. G. CHILINGAROV, YU. M. SHATUNOV, B. A. SCHWARTZ and S. I. EIDELMAN: *Phys. Lett. B*, **73**, 226 (1978); I. A. KOOP, L. M. KURDADZE, M. YU. LELCHUK, V. A. SIDOROV, A. N. SKRINSKY, A. G. KHABAKHPASHEV, A. G. CHILINGAROV, YU. M. SHATUNOV, B. A. SHWARTZ and S. I. EIDELMAN: Novosibirsk preprint 79-67, presented at the *International Symposium on Lepton and Photon Interactions, Baravia, Ill., August 1979.*

distribution $dN/d\cos\theta^*$ of the two charged particles in their own centre-of-mass, with the expected one; in fig. 4 we report the experimental angular distribution, together with the absolute Monte Carlo prediction for multihadrons background (line *a*)), for reaction (1) (line *b*)), and reaction (2) (line *c*)). The full line is the sum of these three contributions; also here the agreement between the experimental distribution and the calculated one is quite good, confirming the validity of the generalized Weizsäcker-Williams method to the hard Bremsstrahlung processes with a real photon and a virtual electron in the final state.