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MUON PAIR PRODUCTION BY ELECTRON-POSITRON COLLISIONS IN THE GeV REGION.

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Muon Pair Production by Electron-Positron Collisions in the GeV Region.

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Electron-positron annihilation into muon pairs

(1) $$e^+e^- \to \mu^+\mu^-$$

has been investigated experimentally with the Frascati storage-ring « Adone » (¹). The same detecting apparatus was employed also to record, simultaneously, e^+e^- scattering at wide angle (WAS events)

(2) $$e^+e^- \to e^+e^- .$$

We have already shown in a previous paper (²) that this last process is correctly described by quantum electrodynamics (QED) up to a total energy of the colliding beams ($E_+ + E_- = 2E$) of 2.4 GeV. We report in this letter results of measurements taken in the period April 1970-February 1971 at $2E = 1.5, 1.6, 1.9$ and 2.1 GeV. The experiment can be regarded as a test of electron-muon equivalence (³) and of the validity of QED for process (1), which involves purely timelike momentum transfers ($q^2 = 4E^2$). It yields also, of course, a specific test of crossing symmetry (⁴), since process (2) is dominated by spacelike momentum transfers.

(¹) F. AMMAN, R. ANDREANI, M. BASSETTI, M. BERNARDINI, A. CATTANI, V. CHIMENTI, G. F. CORAZZA, D. FABIANI, E. FERLENGHI, A. MAZZAROTTI, C. PELLEGRINI, M. PLACIDI, M. PUGLISI, F. SOSO, S. TAZZARI, F. TAZZIOLI and G. VIGNOLA: *Lett. Nuovo Cimento*, **1**, 729 (1969).
(²) B. BORGIA, F. CERADINI, M. CONVERSI, L. PAOLUZI, W. SCANDALE, G. BARBIELLINI, M. GRILLI, P. SPILLANTINI, R. VISENTIN and A. MULACHIÈ: *Phys. Lett.*, **35** B, 340 (1971).
(³) See, *e.g.*, L. M. LEDERMAN: in *Old and New Problems in Elementary Particles*, edited by G. PUPPI (New York, 1968), p. 159.
(⁴) M. GELL-MANN and M. L. GOLDBERGER: *Phys. Rev.*, **96**, 1433 (1954).

Process (1) was previously investigated at ACO ([5]), Novosibirsk ([6]) and, more recently, at Frascati ([7,8]). The results reported here confirm that the muon behaves as a « heavy electron », in the way predicted by QED, over all the energy region explored.

The apparatus shown in Fig. 1 was also used to detect simultaneously events involving two or more hadrons in the final states. But the results relative to these last events will not be considered in this paper ([9]). We recall here that the apparatus, already described elsewhere ([2,7,10]), consists of two identical telescopes containing scintillators (numbered from 0 to 5), spark chambers (C_1 to C_4) and Pb and Fe absorber plates. The two telescopes, placed on opposite sides of Adone's vacuum chamber, cover nearly $\frac{1}{4}$ of the total solid angle from the center of the collision region of the e^+ and e^- bunches. This region defines the source S of the « good events ». It has small transverse dimensions (~ 1 mm) ([11]), but its Gaussian distribution along the beam direction (perpendicular to the plane of Fig. 1) has a measured ([2]) standard deviation of $(20 \pm 1.5)E^{\frac{3}{2}}$ cm, if E is expressed in GeV.

For the interpretation of the measurements reported in this letter, no use has been made of the supplementary information derivable from the monitoring system installed at the same straight section of Adone and described elsewhere ([12]).

We point out that the rate of cosmic-ray muons crossing the solid angle of the apparatus of Fig. 1 (~ 1/s) (*) is by several orders of magnitude greater than the rate of events expected from process (1) ($\sim \frac{1}{2}\cdot 10^{-4}$/s at $E = 1$ GeV/beam, for an average machine luminosity). A strong rejection against cosmic ray which might simulate events from process (1) was therefore needed. A first reduction of the cosmic-ray rate down to less than 1/min was achieved at the level of the « master » used to trigger the spark chambers and the film advance. In forming this master trigger, which involved the penetration of at least one charged particle down to counter 4 in each telescope, the following requirements had, in fact, to be fulfilled:

a) Correct timing relative to the collision instant of the bunches at S; this was obtained by measuring the time of flight between the pulse from either one of counters 1 and a signal from the machine RF (T_{1FR}).

([5]) See, *e.g.*, J. PEREZ-Y-JORBA: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies* (Liverpool, 1969), p. 3. Recently the ACO group has also measured the $\mu^+\mu^-$ yield at the φ-energy (reported at the *International Symposium on Electron and Photon Interactions at High Energies* (Ithaca, 1971)).

([6]) V. E. BALAKIN, G. I. BUDKER, L. M. GURDADZE, A. P. OHACHIN, E. V. PAKHTUSOVA, V. A. SIDOROV, A. N. SHRINSKY and A. G. KHABAKHPASHEV: reported at the *XV International Conference on High-Energy Physics* (Kiev, 1970); and at the *International Symposium on Electron and Photon Interactions at High Energies* (Ithaca, 1971).

([7]) FRASCATI-ROMA-PADOVA COLLABORATION: Frascati Internal Report LNF-70/38 (1970), unpublished. See also: R. WILSON: Rapporteur talk at the *XV International Conference on High-Energy Physics* (Kiev, 1970).

([8]) V. ALLES BORELLI, M. BERNARDINI, D. BOLLINI, P. L. BRUNINI, E. FIORENTINO, T. MASSAM, L. MONARI, F. PALMONARI and A. ZICHICHI: *Lett. Nuovo Cimento*, **2**, 376 (1971).

([9]) Preliminary results have been presented at the *Kiev 1970 International Conference* (see ref. ([7])) and at the *International Symposium on Electron and Photon Interactions at High Energies* (Ithaca, 1971).

([10]) F. CERADINI: Thesis, University of Rome (1970) (unpublished).

([11]) GRUPPO ADONE: Frascati Internal Report LNF-70/48 (1970) (unpublished), and Frascati Internal Report LNF-71/7 (1971) (presented at the *1971 National Particle Accelerator Conference, Chicago*).

([12]) G. BARBIELLINI, B. BORGIA, M. CONVERSI and R. SANTONICO: *Atti Accad. Naz. Lincei*, **44**, 233 (1968).

(*) This rate is that of the coincidences among the eight counters 1, 2, 3, 4 of the two telescopes, adopted in the early measurements to form the « master trigger » defined below. Later, however, we added the two counters « *O* », each of which is made up of three slabs parallel to the beam line (Fig. 1), thus reducing by a factor ~ 2.5 the master trigger rate due to cosmic rays.

b) Correct times of flight between counters $3(T_{33})$ and between counters $4(T_{44})$ of the two telescopes; the members of each of these two counter pairs being traversed simultaneously only by particles from two-body events produced at S.

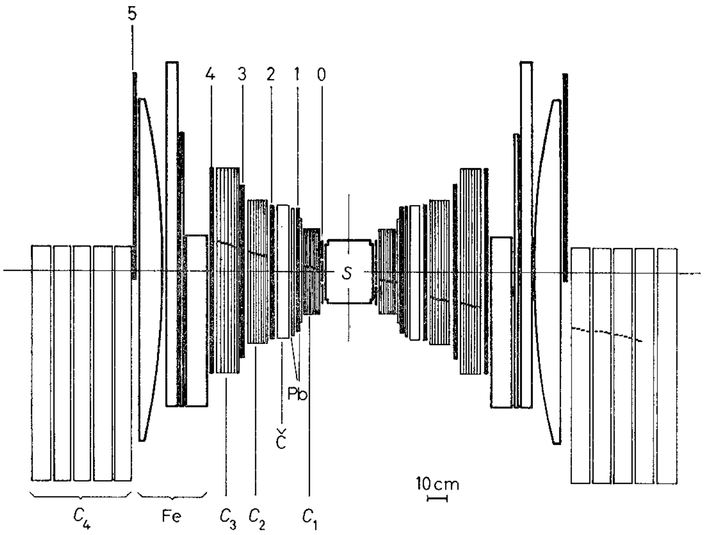

Fig. 1. – Vertical cross-section of the apparatus. C_1 are thin-foil spark chambers employed for space reconstruction of the events. C_2, C_3 are thick-plate chambers, in which e^+ and e^- from process (2) develop electromagnetic showers. C_4 are thick-plate chambers in which muons from process (1) are stopped. Č are Čerenkov counters giving information on events not considered in this paper. Sparks from a real $e^+e^- \to \mu^+\mu^-$ event are shown.

In order to avoid any loss of « good events », conditions *a*) and *b*) were imposed in a nonstringet way to the master trigger. A more stringent application of these conditions could be made, however, during the analysis of the events, for all three times of flight (T_{1RF}, T_{33} and T_{44}) were measured and recorded in digital form on each photograph.

Among the recorded events only those exhibiting in chambers C_1 single tracks originated in S, absence of electromagnetic showers in chambers C_2 and C_3 ([13]), and a track in chamber C_4 or a signal from counter 5, were retained (*). Conditions *a*) and *b*) were then imposed more rigorously to the events thus selected, adopting for the three time-of-flight limits which were derived from the corresponding distributions of WAS events, reported in Fig. 2. Reference to the WAS events was convenient because these events are detected at a rate ~ 15 times greater than that of events (1). As a supplementary selective condition we required, furthermore, that when the track was present in one of the chambers C_4, it had also to exhibit a stop in it. The rejection of cosmic-ray events was contributed mostly by the « times of flight » and « stop » requirements. The overall rejection factor was $\sim 5 \cdot 10^4$, and a $5\% \div 10\%$ residual cosmic-ray contamination had to be subtracted.

A few corrections had to be applied to the selected events, to take into account small inefficiencies related to the various selection criteria listed above. These corrections

([13]) We recall (see ref. ([2])) that the probability of missing an e^+e^- pair from process (2) due to lack of shower development in chambers C_2 and C_3 is less than 2 % at $E = 1$ GeV/beam.

(*) Due to border effects, not all muon pairs which give a signal in counter 5 are observed in chamber C_4 of the opposite telescope.

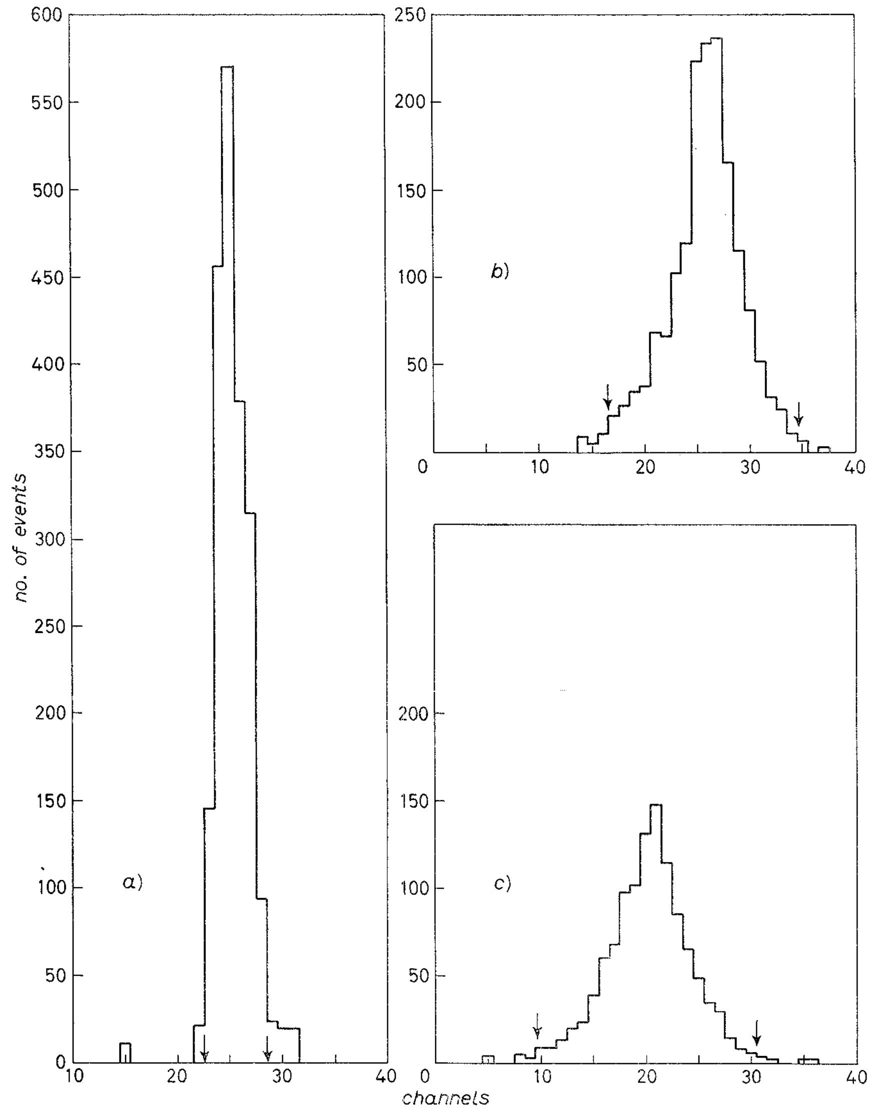

Fig. 2. – Histograms representing time-of-flight distributions for WAS events: T_{1RF} gives the time distribution relative to the instant of crossing of the e^+ and e^- bunches at S; $T_{33}(T_{44})$ gives the distribution of the times of flight between pulses from the two counters 3 (4) of the two telescopes. These distributions are utilized to obtain limits and corresponding efficiencies for accepting the less frequent $e^+e^- \to \mu^+\mu^-$ events: *a*) T_{1RF}, 2047 WAS events; *b*) T_{33}, 1706 WAS events; *c*) T_{44}, 1167 WAS events.

are outlined in the caption of Table I which together with Fig. 3 contains the results of the present experiment.

Radiative corrections to processes (1) and (2) have been treated quantitatively by several authors [14]. A preliminary estimate shows that they have a very small effect

[14] See among other papers: G. LONGHI: *Nuovo Cimento*, **35**, 1122 (1965); R. GATTO: *Erg. exak. Naturwiss.*, **39**, 106 (1965); E. ETIM, G. PANCHERI and B. TOUSCHEK: *Nuovo Cimento*, **51** B, 276 (1965); G. ROSSI: Frascati Internal Report, LNF 66/51 (1966) (unpublished); S. Y. TSAI: *Phys. Rev.*, **120**, 269 (1960).

TABLE I. – *Comparison between experimental results and predictions of* QED *on processes* (1) *and* (2). The corrected numbers of events (column 3) are obtained from the observed ones (column 2) dividing the latter for the overall efficiencies which are found to be $\eta_{\mu\mu} = (90 \pm 5)\%$ and $\eta_{ee} = (96 \pm 2)\%$. The uncertainties in these efficiencies are combined with the statistical error in giving the results reported in columns 3 and 5.

(1)	(2)		(3)	(4)	(5)
Total energy in GeV ($2E$)	Observed numbers of events $e^+e^- \to$		Percent ratio of corrected numbers of events $(N_{\mu\mu}/N_{ee})\%$	Percent ratio of integrated cross-sections $\langle\sigma_{\mu\mu}\rangle/\langle\sigma_{ee}\rangle$	Ratio R between data of (3)/(4)
	$\mu^+\mu^-$ $(N^{obs}_{\mu\mu})$	$\to e^+e^-$ (N^{obs}_{ee})			
1.5	160	2744	6.28 ± 0.77	6.04	1.04 ± 0.13
1.6	23	475	5.30 ± 1.15	6.08	0.87 ± 0.19
1.9	52.5	819	6.24 ± 0.94	6.14	1.02 ± 0.15
2.1	164.5	3154	5.54 ± 0.59	6.18	0.90 ± 0.10

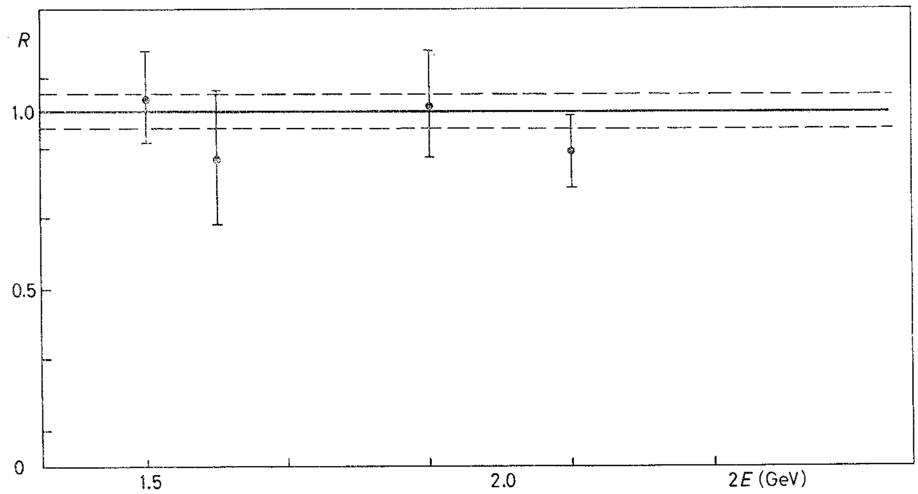

Fig. 3. – The ratio between corrected numbers of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$ events recorded by the same apparatus, plotted as a function of the total energy $2E$, after normalization to the corresponding theoretical cross-sections integrated over the solid angle of the apparatus. The dashed lines represent limits of the estimated systematic uncertainties; $R = (N_{\mu^+\mu^-}/N_{e^+e^-})/(\langle\sigma_{\mu^+\mu^-}\rangle/\langle\sigma_{e^+e^-}\rangle)$, 400 events $e^+e^- \to \mu^+\mu^-$, 7192 events $e^+e^- \to e^+e^-$.

(at most a few percent) on our experimental results (*), due to the loose requirements of energy and momentum determination for the selected events. Radiative corrections have been neglected in giving the ratio

$$R = \frac{[(e^+e^- \to \mu^+\mu^-)/(e^+e^- \to e^+e^-)]_{exp}}{[(e^+e^- \to \mu^+\mu^-)/(e^+e^- \to e^+e^-)]_{QED}} = \frac{N_{\mu^+\mu^-}/N_{e^+e^-}}{\langle\sigma_{\mu^+\mu^-}\rangle/\langle\sigma_{e^+e^-}\rangle}$$

(*) A more accurate evaluation of these effects is now in progress.

reported in Fig. 3. It is apparent from this Figure that our experimental data agree with the predictions of QED within the errors.

Quantitatively we can discuss our results in terms of the hypothesis ([15]) of a negative-metric « heavy photon » of mass m_Γ, by introducing the usual substitution

$$\frac{1}{q^2} \to \frac{1}{q^2} - \frac{1}{q^2 - m_\Gamma^2},$$

which in the model of Lee and Wick preserves unitarity. A best fit through the experimental data of Fig. 3 yields then

$$m_\Gamma > \sim 10 \text{ proton masses}$$

with 95% confidence level.

Alternatively, we can regard our experiment as a direct comparison between the purely timelike process (1) and the essentially spacelike (*) process (2). Such a comparison may be in turn regarded as a specific check of crossing symmetry in QED, since any deviation from this symmetry principle would affect the ratio R, yielding for it a value different from unity. In our experiment, process (1) involves momentum transfers with squared values, $q^2 = 4E^2$, from 2.2 to 4.4 $(\text{GeV})^2$; process (2) involves values of $q^2 = -4E^2 \sin^2(\theta/2)$ which range from -0.45 to $-3.5\,(\text{GeV})^2$, as our apparatus accepts events emitted from S the angular interval $53° < \theta < 127°$. Over the range of energies explored, the average value of R, based on a total of 400 events (1) and 7192 associated events (2), corresponding to a total integrated luminosity of about $2 \cdot 10^3 \cdot \text{cm}^{-2}$, is

$$\bar{R} = 0.96 \pm 0.065 .$$

This agrees with the expected value $R = 1$ within an $\sim 7\%$ error (*), reinforcing a similar result reported recently ([8]) by another group working with Adone.

Effects due to the beam polarization, resulting from synchrotron radiation, have been estimated on the basis of known theoretical work ([16]) and found to be within the quoted errors.

* * *

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([15]) T. D. LEE and G. C. WICK: *Nucl. Phys.*, **9** B, 209 (1969).

(*) The term of the Bhabha scattering cross-section which derives from purely spacelike momentum transfers is dominant, all over the effective angular range of the events accepted by our apparatus, with respect to the annihilation and interference terms.

(*) This error includes the uncertainty in the efficiencies quoted in the caption to Table I.

([16]) See, *e.g.*, V. N. BAIER: *Rendiconti S.I.F.*, Course XLVI (New York, 1971), p. 1, also for previous references. We wish to thank Prof. N. CABIBBO and Dr. G. PARIS for discussions on this subject.