Results from storage rings

1972 J. Phys. A: Gen. Phys. 5 179

(http://iopscience.iop.org/0022-3689/5/2/001)

J. Phys. A: Gen. Phys., Vol. 5, February 1972. Printed in Great Britain

Results from storage rings†

B BORGIA

Istituto di Fisica, Università di Roma, Istituto Nazionale di Fisica Nucleare (Sezione di Roma)

MS received 17 September 1971

Abstract. A review of experimental results obtained with electron storage rings is presented. The fields of physics investigated by storage rings range from pure quantum electrodynamics to hadron interactions. Particular attention is given to the new aspects brought to light by the results of Adone, in Frascati.

1. Introduction

The first storage ring was designed to study quantum electrodynamics (QED) at high values of momentum transfer. This was the Stanford storage ring operating with e^-e^- colliding beams (Barber *et al* 1959, O'Neill 1959; see also Zyngier and Cremieu-Alcan 1966. For results on e^-e^- scattering see Barber *et al* 1966, 1969 and 1971). As soon as it was feasible to obtain high intensity positron beams to be injected in a ring, e^+e^- colliding beams were proposed to investigate the annihilation of leptons into a time-like photon and its coupling to hadronic final states with the same quantum numbers of the intermediate photon (Bernardini *et al* 1960, 1962, 1964; see also Touschek 1964 for previous bibliography). Recently there have also been proposals to consider $\gamma\gamma$ interaction processes, where the initial e^+e^- beams provide virtual photon beams that in the Weizsaecker–Williams approximation are described by a bremsstrahlung frequency spectrum (see *Proc. 15th Int. Conf. on High Energy Physics, Kiev* 1970).

This paper will follow the historical development of the fields of physics investigated by storage rings, and it will be divided into three parts: (i) QED validity; (ii) vector meson dominance (VMD) investigation; (iii) new aspects and preliminary results at high energy.

2. Storage rings in operation

In table 1 some characteristics of the existing machines are collected. (For a review of machines until 1966 see Zyngier and Cremieu-Alcan (1966) and also Amman (1969a, 1969b).) We recall that the luminosity of a storage ring is measured by recording in a determined time interval the number of events given by a process, the cross section of which is well known. The relation between these quantities is obviously

$$\dot{n} = L\langle\sigma\rangle.$$

† Invited paper at Lancaster Conference on Elementary Particle Physics, Lancaster, 5–7 April 1971.

Table 1. Storage rings in operation

Name	Place	Beams	E per beam (GeV)	Luminosity ($cm^{-2}\ h^{-1}$)
ACO	Orsay	e^-e^-	0·5	2×10^{32}
VEPP2	Novosibirsk	e^+e^-	0·7	$0{\cdot}5 \times 10^{32}$
Adone	Frascati	e^+e^-	1·2	15×10^{32}

The reactions usually employed to this end are:

$$e^+e^- \rightarrow e^+e^-\gamma$$

$$e^+e^- \rightarrow e^+e^-\gamma\gamma$$

$$e^+e^- \rightarrow e^+e^- \qquad \text{at small } \theta \text{ (low momentum transfers).}$$

I will now give some details of Adone because it has been producing results for a relatively short time, while the other two machines have been in operation for some years. (For further details, see Amman *et al* (1969), Tazzari (1971) and Report LNF 71/7 of the Adone Group, Laboratori Nazionali di Frascati.)

Adone was also intended to run at sufficiently low energy to look at least at the ϕ meson, but the luminosity drops with a very strong energy dependence ($\simeq E^6$), because of beam–beam interaction, which makes it very inefficient to run at energies lower than 700 MeV per beam. In figure 1 the average luminosity is plotted against

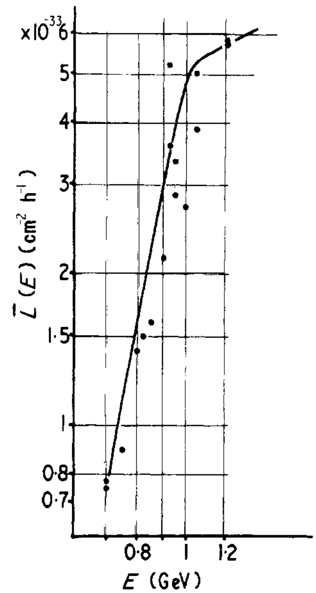


Figure 1. Average luminosity of Adone against energy.

energy, showing the fast increase of this quantity with energy. The maximum energy is at present limited by the RF power available to 1·2 GeV, but a second cavity is now being installed, so that the energy will rise to a value of 1·5 GeV per beam. In Adone, as in the other rings, the e^+e^- beams collide head on so that the source of the events has a gaussian distribution with a standard deviation $\sigma = 20\,E^{3/2}$ cm (E in GeV). This method of operation permits the simultaneous running of four experiments, three of which are permanently on the floor and two are alternating on the same straight section.

In figure 2 is represented the Adone layout with the experiments working at present on the various straight sections. The experiments investigate several reactions† and

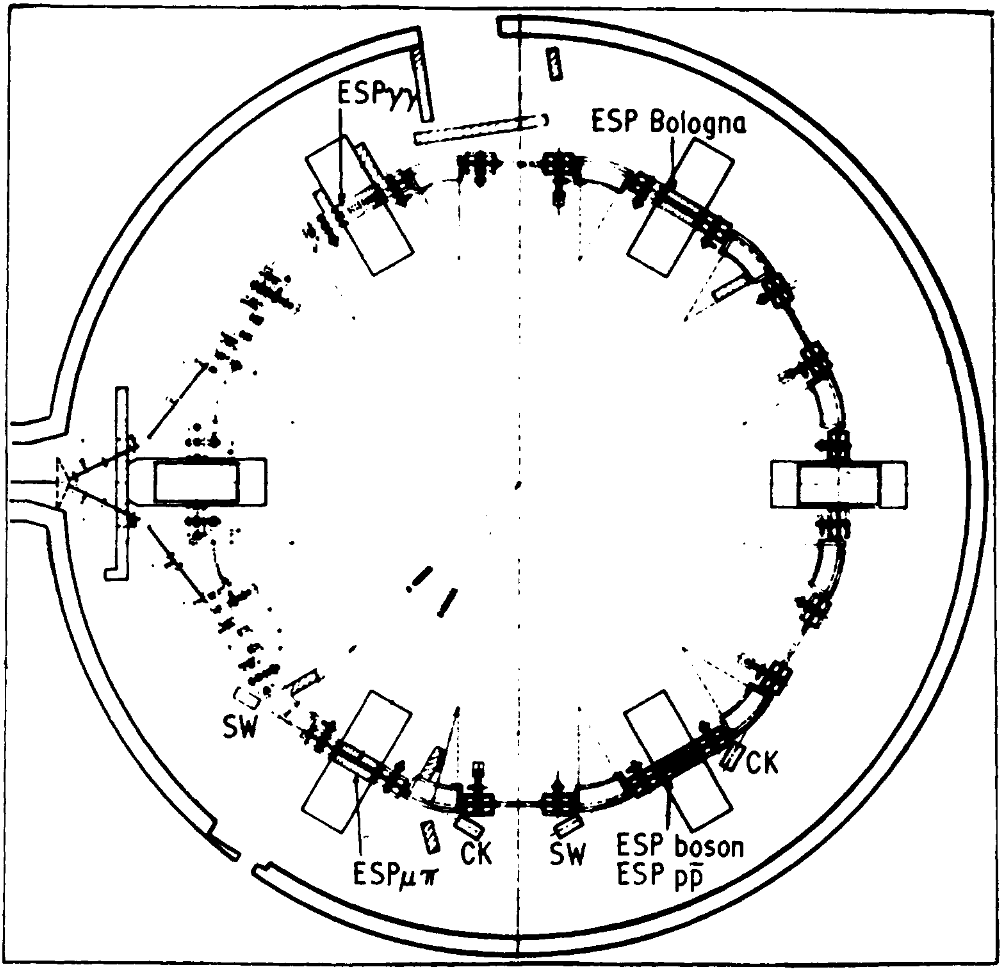


Figure 2. Adone ring layout with experimental sites.

table 2 describes the present situation. The luminosity of the colliding beams is continuously measured by the 'μπ' group using Bhabha scattering at small angles ($3{\cdot}5° \leqslant \theta \leqslant 6°$) where no breakdown of QED is expected because of the low momentum transfer involved. The apparatus actually used (Barbiellini *et al* 1968) is shown in figure 3 where the solid angle is determined by only one small counter P for each coincidence between opposite telescopes. In this way an approximate compensation for source displacement is attained.

† For some experimental proposals see Zyngier and Cremieu-Alcan (1966).

Table 2. Reactions $e^+e^- \rightarrow$

Name	e^+e^-	$\mu^+\mu^-$	$\gamma\gamma$	$\pi^+\pi^-$ (K^+K^-)	multibody	$p\bar{p}$
BCF	×	×		×	×	
Boson	×				×	
$\mu\pi$	×	×		×	×	
$\gamma\gamma$			×		×	
$p\bar{p}$						×

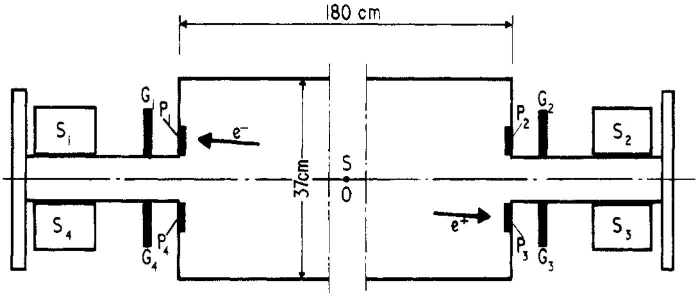


Figure 3. Luminosity monitor apparatus using e^+e^- scattering at small angles. P_iG_i are scintillation counters, S_i are shower counters made of layers of Pb and plastic scintillators.

The experimental set-ups of various groups, shown in figures 4, 5, 6 and 7, consist essentially of optical spark chambers (magnetostrictive in the case of the boson group) alternated with scintillation counters and several g cm^{-2} of absorbers. Criteria for identification of particles are mainly based on: (i) pulse heights; (ii) shower development;

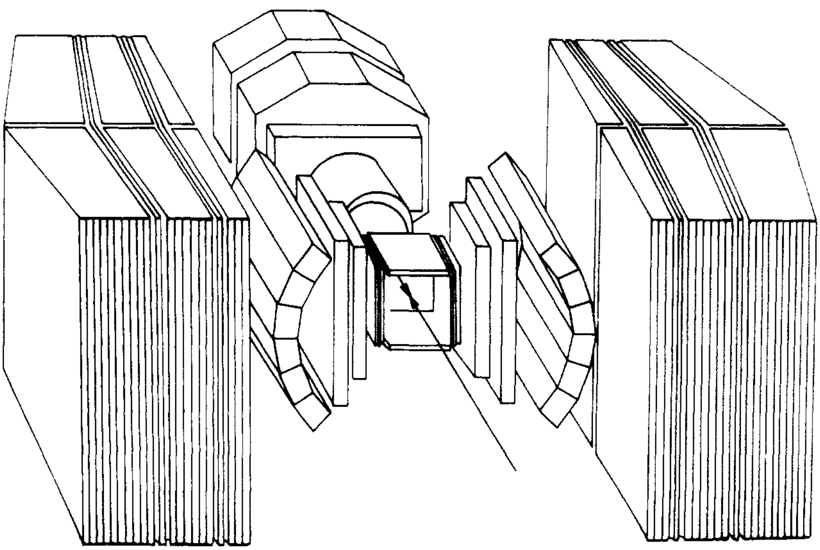


Figure 4. BCF apparatus.

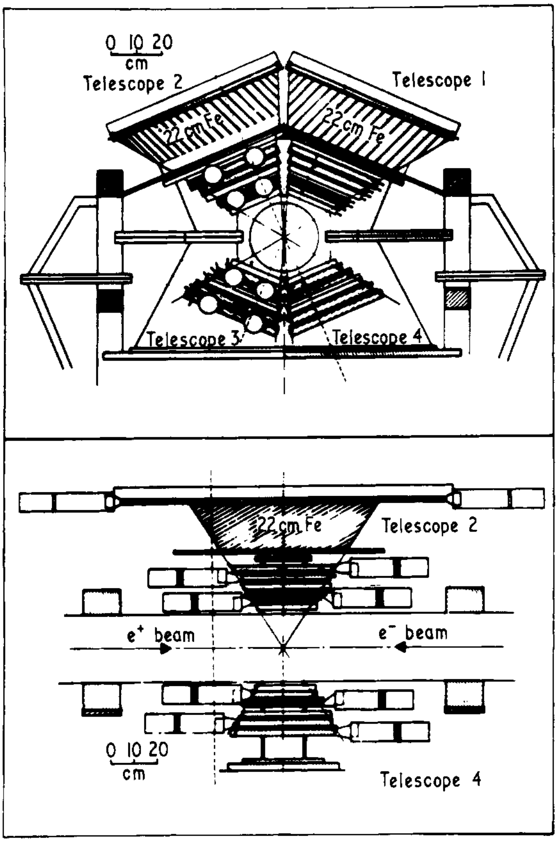


Figure 5. Boson apparatus.

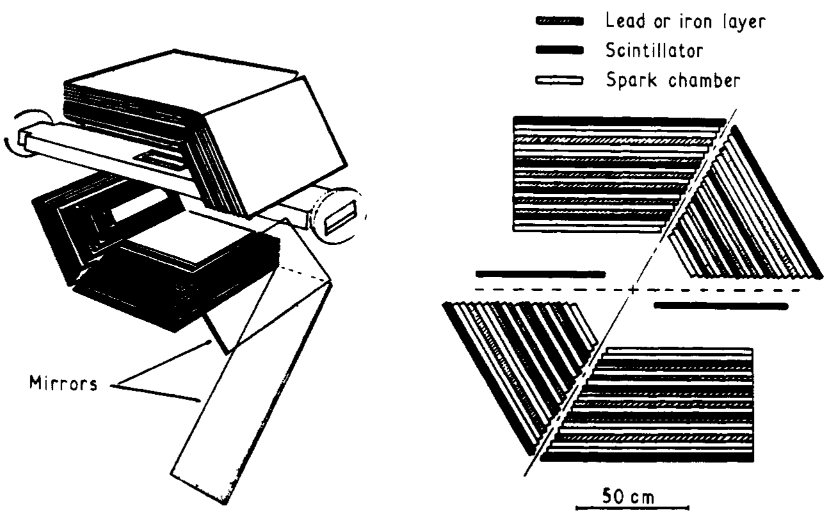


Figure 6. $\gamma\gamma$ apparatus.

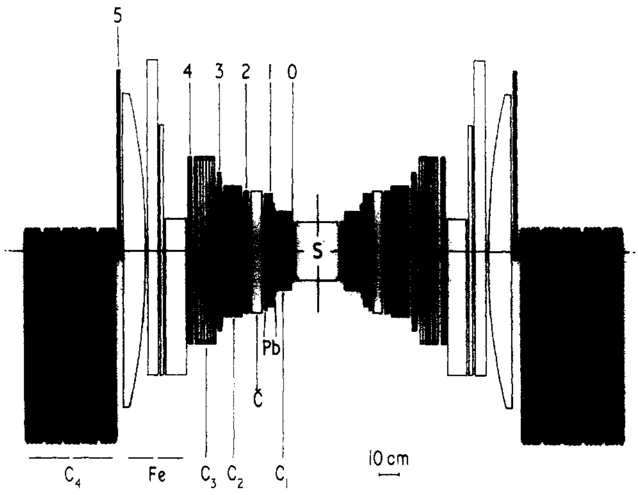


Figure 7. μπ apparatus.

(iii) nuclear interactions; (iv) range measurement; (v) RF phase timing; (vi) source fiducial volume reconstruction. Energy balance is not possible except in a few cases.

3. QED validity

The experiments involving high momentum transfers that can be performed with colliding beams in order to verify the validity of QED are the following:

$$e^+e^- \to \gamma\gamma$$

$$e^+e^- \to e^+e^-$$

$$e^+e^- \to \mu^+\mu^-$$

3.1. γγ annihilation

The propagator in the first order Feynman graph is a space-like virtual lepton (figure 8(*a*)). Its momentum is given by

$$q^2 = -4E^2 \sin^2\tfrac{1}{2}\theta$$

or

$$q^2 = -4E^2 \cos^2\tfrac{1}{2}\theta.$$

The customary Feynman modification to the propagator, in terms of a cut-off parameter K, is given by

$$F(q^2) = \left(1 - \frac{q^2}{K^2}\right)^{-1}$$

(Feynman 1961, McClure and Drell 1965). An alternative parametrization of QED breakdown has been given by Kroll (1966) in such a way as to take into account, in the simplest way, vertex and propagator modifications, in order to satisfy the Ward identity.

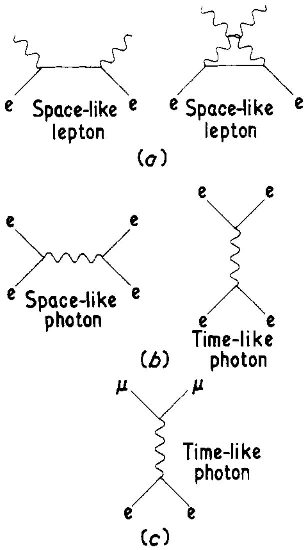


Figure 8. Feynman graphs of e^+e^- going into (*a*) $\gamma\gamma$; (*b*) e^+e^-; (*c*) $\mu^+\mu^-$.

The deviation from QED is expressed by the formula

$$\frac{\sigma_{\text{exp}}}{\sigma_{\text{th}}} = \left(1 \pm \frac{4Q_{\text{L}}^4}{\Lambda^4}\right)$$

where Q_{L} is the virtual lepton invariant mass.

The $\gamma\gamma$ group represent their results (figure 9) by plotting the ratio R of counting rate due to γ rays observed at small angles ($\simeq 30°$) to the counting rate at large angles ($\simeq 90°$). In the same figure is also shown the effect of introducing a finite parameter K or Λ in the two above-mentioned modifications of quantum electrodynamics.

3.2. e^+e^- *scattering*

Here the propagator is a virtual photon that can be either space-like or time-like (figure 8(*b*)) but with a small contribution from the annihilation term and the interference between the annihilation and scattering diagrams. The four-momentum transfers are respectively

$$q^2 = -4E^2 \sin^2\tfrac{1}{2}\theta \quad \text{or} \quad -4E^2 \cos^2\tfrac{1}{2}\theta \qquad \text{for space-like } \gamma$$

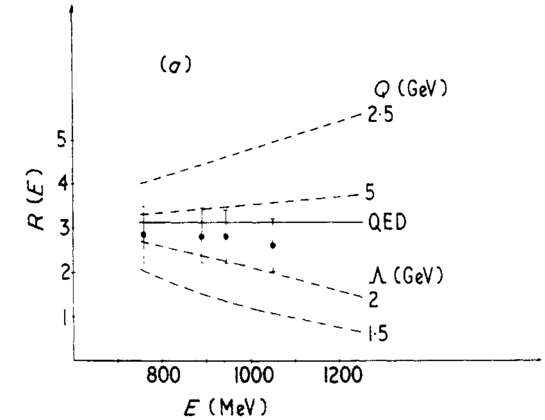
$$q^2 = 4E^2 \qquad \text{for time-like } \gamma.$$

The virtual propagator modification is given by

$$F(q^2) = \left(1 - \frac{q^2}{K^2}\right)^{-1}.$$

Lee and Wick (1969) have shown that a heavy photon with negative metric will produce a form factor of this type, if it exists.

Figures 10, 11 and 12 show the results of the BCF group, boson group (Bartoli *et al* 1970) and $\mu\pi$ group (Barbiellini *et al* 1971) where in each case also plotted are the



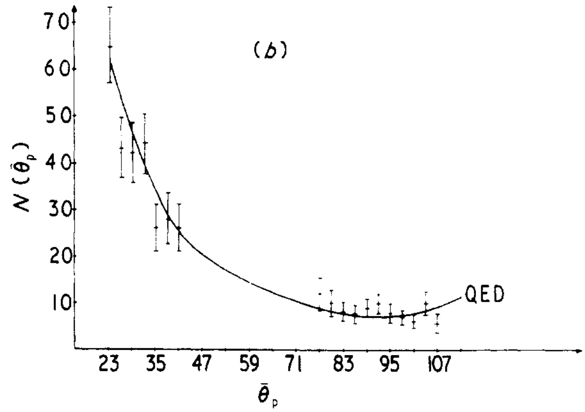


Figure 9. (*a*) Results of e^+e^- annihilation into $\gamma\gamma$. R is the ratio between events observed at about 30° divided by the number of events at approximately 90°. (*b*) Experimental angular distribution of $e^+e^- \to \gamma\gamma$ process compared with QED prediction.

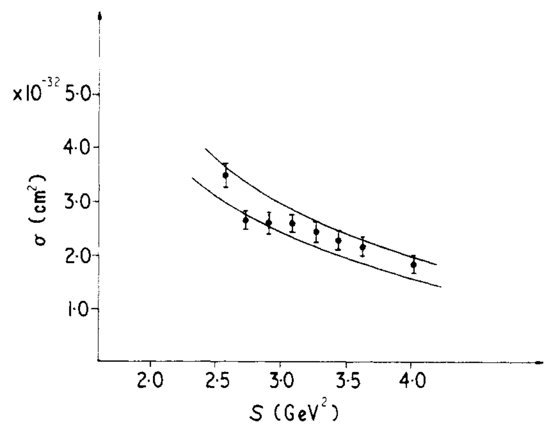


Figure 10. Experimental cross section for $e^+e^- \to e^+e^-$ process against energy observed by BCF group. Full curves, theoretical predictions; ⫯ experimental data.

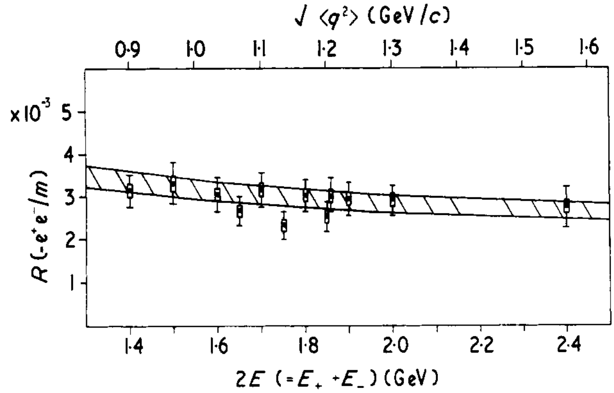


Figure 11. Ratio of large angle e^+e^- scattering events divided by small angle events (as measured by luminosity monitor) measured by boson group.

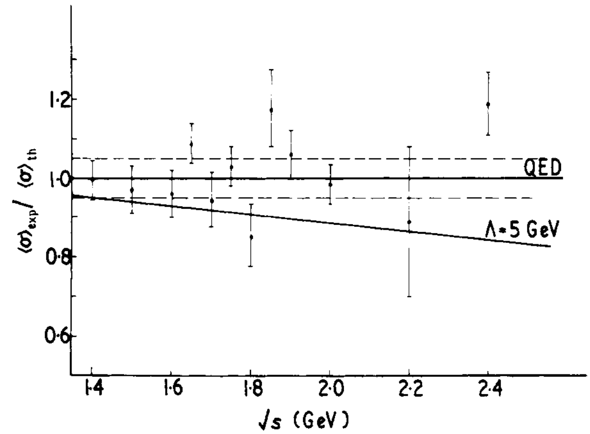


Figure 12. Ratio of experimental cross section of $e^+e^- \rightarrow e^+e^-$ process divided by standard QED prediction. Measurements made by $\mu\pi$ group.

estimated systematic errors. In all three experiments the scattering events at large angles are compared to the small angle scattering to obtain the experimental cross section.

3.3. $\mu^+\mu^-$ *annihilation*

In this reaction the photon propagator is only time-like; no interference terms arise, and the number of $\mu^+\mu^-$ pairs has to be normalized with a 'monitor' reaction, which can be specifically the e^+e^- scattering at large angle. The four-momentum transfer is

$$q^2 = 4E^2$$

and the QED breakdown is represented by the Feynman form factor. Figure 13 shows the results of the BCF group.

For a recent review of other work on QED, see Wilson (1970); see also Balakin *et al* (1971a). In table 3 all storage ring results, as well as some from other accelerators, are

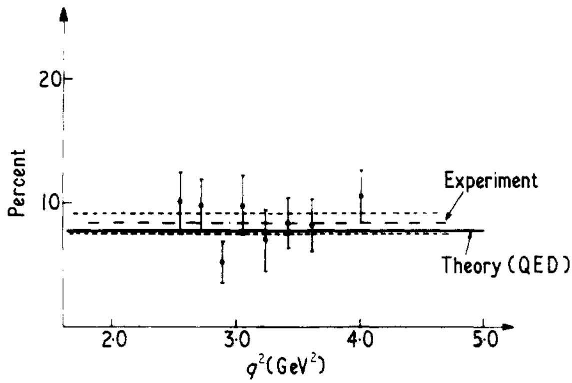


Figure 13. Ratio of μ pair events divided by e^+e^- scattering events observed simultaneously in the same apparatus by the BCF group.

Table 3. High energy tests of QED

Experiment	Laboratory	Propagator	95 % confidence limits on Λ or K (GeV)
$e^+e^- \to \gamma\gamma$	Novosibirsk	lepton	>1·3
	Frascati (γγ)		>2·1
$\gamma C \to e^+e^-C$	Desy–MIT		>1·2
	CEA–Harvard		>0·6
	Daresbury		>0·7
$\gamma C \to \mu^+\mu^-C$	CEA–NEU		>1·6
	Cornell		>2·1
$e^-C \to e^-\gamma C$	Cornell		>1·3
$\mu C \to \mu\gamma C$	AGS–Harvard		>0·6
$e^+e^- \to e^+e^-$	Stanford–Princeton	photon	>4·4
$e^+e^- \to e^+e^-$	Novosibirsk		>0·4
	Orsay		>2
	Frascati (BCF)		>3
	Frascati (boson)		>3
	Frascati (μπ)		>6
$e^-C \to e^-\mu^+\mu^-C$	CEA–NEU		>0·75
$e^+e^- \to \mu^+\mu^-$	Orsay		>1·7
	Novosibirsk		>2·7
	Frascati (BCF)		>3
	Frascati (μπ)		>3
$(g-2)$ for μ	CERN		>5

listed. For the reactions with an intermediate lepton propagator, the Kroll parametrization of QED has been chosen; in the processes involving a virtual photon, the interpretation is made using the Feynman representation. The situation on the validity of QED can thus be summarized by saying that all measurements up to the highest momentum transfer agree with standard QED predictions within the experimental errors (usually $\simeq 10\,\%$).

4. Other experiments

4.1. $p\bar{p}$ *annihilation*

The total luminosity collected at $E = 1050$ MeV is $L = 2{\cdot}5 \times 10^{35}$ cm^{-2}. A similar statistic has been accumulated below threshold at 950 MeV. The total cross section, taking in account the solid angle of the apparatus, is given by

$$\langle\sigma\rangle = \frac{5N_{p\bar{p}}}{L} = 2 \times 10^{-35} N_{p\bar{p}}$$

for the data taken so far. Previous experiments (Conversi *et al* 1965) at $t = 5{\cdot}1$ and $6{\cdot}8$ $(\mathrm{GeV}/c)^2$ set an upper limit of 2×10^{-34} cm^2 when recalculated for the kinematical conditions of the Adone experiment ($t = 4\ (\mathrm{GeV}/c)^2$).

4.2. Heavy lepton

The BCF group has looked for noncolinear tracks, one of which would appear as a genuine electron and the other as a muon. A lower limit of 780 MeV for the mass of the heavy lepton has been found, with a 95% confidence level (Alles-Borelli *et al* 1970).

5. VMD investigation

The results on the study of γV coupling constants and the branching ratios of the vector mesons ρ, ω, ϕ come from Orsay (Perez-y-Jorba 1969, 1970; see also Bizot *et al* 1970, Benaksas 1970a, 1970b) and Novosibirsk (Sidorov 1969, Balakin 1971b; see also Perez-y-Jorba 1970). The storage ring experiments without any doubt have no competitors either in the simplicity of interpretation, because it is not a hadronic target, or in the extensiveness of the work. If there is a polarization of the e^+e^- beams, this is a possible source of systematic error (Sokolov and Ternov 1963, Baier 1969), but no evidence of this effect was found in either laboratory (Perez-y-Jorba 1969 p 220, Balakin *et al* 1971b p 330).

In the following tables 4, 5 and 6, I report the coupling constants and decay parameters of the vector mesons as measured with storage rings (for other reviews of this subject see Perez-y-Jorba 1970 and Wilson 1970). The ϕ data are outstanding for the

Table 4. Coupling constants and mixing angles of the vector mesons

	Orsay	Novosibirsk
$\frac{g_\rho^2}{4\pi}$	$1{\cdot}99 \pm 0{\cdot}19$	$2{\cdot}7 \pm 0{\cdot}5$
$\frac{g_\omega^2}{4\pi}$	$14{\cdot}0 \pm 2{\cdot}8$	
$\frac{g_\phi^2}{4\pi}$	$11{\cdot}0 \pm 0{\cdot}9$	$11{\cdot}7 \pm 1{\cdot}1$
$\frac{g_Y^2}{4\pi}$	$1{\cdot}55 \pm 0{\cdot}15$	
θ_Y	$(41{\cdot}5 \pm 3)^\circ$	
θ_N	$(13{\cdot}5 \pm 2)^\circ$	
θ	$(23{\cdot}1 \pm 4)^\circ$	

Table 5. ρ, ω decay parameters

ρ	Orsay†	Novosibirsk
m_ρ (MeV)	$780{\cdot}2 \pm 5{\cdot}9$	768 ± 10
σ_{all}(μb)	$0{\cdot}96 \pm 0{\cdot}09$	$1{\cdot}05 \pm 0{\cdot}2$
Γ_ρ (MeV)	$152{\cdot}8 \pm 15{\cdot}1$	$140{\cdot}0 \pm 14$
$B_{e^+e^-}$ ($\times 10^{-5}$)	$4{\cdot}0 \pm 0{\cdot}36$	$5{\cdot}0 \pm 1{\cdot}0$
$\Gamma_{e^+e^-}$ (keV)	$6{\cdot}11 \pm 0{\cdot}53$	$6{\cdot}05 \pm 0{\cdot}50$
ω		
$\Gamma_\omega = (12{\cdot}0 \pm 0{\cdot}18)$ MeV (world average)		
$\Gamma_{\pi\pi}^{1/2}$ (MeV$^{1/2}$)	$0{\cdot}63 \pm 0{\cdot}23$	
$B_{e^+e^-}$ ($\times 10^{-5}$)	$7{\cdot}8 \pm 1{\cdot}4$	
$\Gamma_{e^+e^-}$ (keV)	$1{\cdot}0 \pm 0{\cdot}18$	

Table 6. ϕ decay parameters

	Orsay	Novosibirsk
$\sigma_{K^+K^-}$ (μb)	$2{\cdot}41 \pm 0{\cdot}13$	$2{\cdot}13 \pm 0{\cdot}17$
$\sigma_{K^0K^0}$ (μb)	$1{\cdot}47 \pm 0{\cdot}21$	$1{\cdot}01 \pm 0{\cdot}19$
$\sigma_{3\pi}$ (μb)	$1{\cdot}01 \pm 0{\cdot}21$	$0{\cdot}81 \pm 0{\cdot}21$
σ_{all} (μb)	$4{\cdot}89 \pm 0{\cdot}39$	$3{\cdot}96 \pm 0{\cdot}35$
Γ_ϕ (MeV)	$4{\cdot}09 \pm 0{\cdot}29$	$4{\cdot}67 \pm 0{\cdot}42$
$B_{e^+e^-}$ ($\times 10^{-4}$)	$3{\cdot}45 \pm 0{\cdot}27$	$2{\cdot}81 \pm 0{\cdot}25$
$\Gamma_{e^+e^-}$ (keV)	$1{\cdot}41 \pm 0{\cdot}12$	$1{\cdot}31 \pm 0{\cdot}12$
$B_{K^+K^-}$ (%)	$49{\cdot}3 \pm 4{\cdot}4$	$54{\cdot}0 \pm 3{\cdot}4$
$B_{K^0K^0}$ (%)	$30{\cdot}1 \pm 4{\cdot}1$	$25{\cdot}7 \pm 3{\cdot}0$
$B_{3\pi}$ (%)	$20{\cdot}6 \pm 3{\cdot}6$	$20{\cdot}3 \pm 4{\cdot}2$
$B_{\eta^0\gamma}$ (%)	$2{\cdot}0 \pm 0{\cdot}75$	
$B_{\pi^0\gamma}$ (%)	$< 0{\cdot}24$ (95% conf)	< 1 (95% conf)
$B_{\pi^+\pi^-}$ (%)		$< 0{\cdot}6$ (95% conf)

completeness of the work. It can be observed that the branching ratio for ϕ decaying into $\pi^0\gamma$ is less than 0·24%, in disagreement with the quark model prediction of 8% (van Royen and Weisskopf 1967). The observed leptonic branching ratios can be put into various modifications of the Weinberg sum rule within the framework of the VMD hypothesis, three versions being

(i) $$\tfrac{1}{3} m_\rho \Gamma_{\rho ee} = m_\omega \Gamma_{\omega ee} + m_\phi \Gamma_{\phi ee}$$

(ii) $$\frac{1}{3}\,\frac{4m_{K^*}^2 - m_\rho^2}{3m_\rho}\,\Gamma_{\rho ee} = m_\omega \Gamma_{\omega ee} + m_\phi \Gamma_{\phi ee}$$

(iii) $$\frac{1}{3}\,\frac{\Gamma_{\rho ee}}{m_\rho} = \frac{\Gamma_{\omega ee}}{m_\omega} + \frac{\Gamma_{\phi ee}}{m_\phi}.$$

These versions are due to Das *et al* (1967) and Oakes and Sakurai (1967), Sugawara (1968) and Gourdin (1969) and Cremmer (1970) respectively. The results of the comparison, expressed as the difference between the left and right hand sides of the three

† At the International Symposium on Electron and Photon Interactions, Ithaca in August 1971, J Lefrançois has reported new values for ρ parameters different by more than three standard deviations. Table 5 contains the latest values.

formulae, using the Orsay data are

$$I^v - I^s: \text{(i)} \ -0{\cdot}69 \pm 0{\cdot}25 \ (\text{MeV}^2)$$

$$\text{(ii)} \ 0{\cdot}10 \pm 0{\cdot}28 \ (\text{MeV}^2)$$

$$\text{(iii)} \ (0{\cdot}26 \pm 0{\cdot}40) \times 10^{-6}.$$

The better agreement of the last two versions can be considered as due to the introduction in the sum rule of some breaking of SU_3.

6. High energy region

Above the energy of about 1·4 GeV, an entirely new phenomenology on the production of hadrons has been observed in Adone by all experimental groups. The present, preliminary, knowledge on cross sections, as estimated by the groups, is condensed in table 7. Previous results have been reported by Wilson (1970); see also Report LNF 70/30 of the Frascati–Padova–Rome group, Laboratori Nazionali di Frascati. For preliminary data from the boson group, see Bartoli *et al* (1970b).

Table 7. Hadronic cross sections ($\sqrt{s}$: 1·5 + 2·2 GeV)

Process	BCF	Boson	$\gamma\gamma$	$\mu\pi$
Two body				
$e^+e^- \to \pi^+\pi^-$ (K^+K^-)				
	0·45 ± 0·15†	—	—	0·5 ± 0·15
$\frac{\sigma_{exp}}{\sigma_{point}} = F^2(\bar{s})$				
Many body				
$\sigma \times 10^{33}$ cm^2				
$e^+e^- \to$ 2 charged + neutral hadrons			< 13 ± 5 mpv 10	
$e^+e^- \to \geqslant 4$ charged + neutrals	5 ± 1·5		7·0 ± 3	20 ± 10
$e^+e^- \to \geqslant 2$ charged + neutrals		30 ± 10‡		
Number of events	≃ 60	240	21	26

† Further data on this reaction have been reported at the Bologna European Conference (April 1971) with substantially improved statistics.
‡ The boson group gives the cross section multiplied by a correction factor K depending on the unknown ratio between 2 charged and 4 charged particles cross sections, $K = 1 + 0{\cdot}2\ \sigma_2/\sigma_4$.

Analysis of possible events originated by $\gamma\gamma$ annihilation will be discussed later. The estimated cross section for production of hadron pairs is half of the point-like cross section for bosons, and the cross section for e^+e^- annihilating into more than two pions (or kaons) is of the order of that for annihilation into muon pairs. The collected data are not fully analysed, so the last row in table 7 represents a fraction of the available statistics. Background correction for beam gas interactions is relevant only for $e^+e^- \to 2$ charged + neutrals (≃ 20 %).

The preliminary results reported from the various groups are not in open contradiction since the following observations have to be made:

(i) Different apparatuses have different trigger requirements, like minimum energy of particles observed, number of charged and neutral particles and their spatial distribution.
(ii) Efficiency has been computed at a mean energy with isotropic angular distribution and in some cases it changes drastically with the number of neutral particles accompanying the charged ones. In particular the effect of nuclear interactions has to be evaluated carefully.
(iii) The nature of the particles has been identified by means of their behaviour in the heavy plate spark chambers. A number of tracks exhibit large angle scattering typical of π mesons; but in principle it is not possible to exclude the possibility that a few of them could be low energy electrons.

It must be added that at Novosibirsk a large number of noncolinear tracks were found, at energies around 1250 MeV, about twice the number of muons produced by annihilation (Balakin *et al* 1970; see also Novosibirsk Report 1970). The cross section can be as high as 10^{-31} cm^2.

The general behaviour of the cross section for multibody events with energy is shown in figure 14 and in table 8. No peaks or bumps are observed and the energy dependence is compatible with $1/s$, where $s = 4E^2$. The boson group give also a $\Delta\phi$ distribution (figure 15) without any peculiar structure.

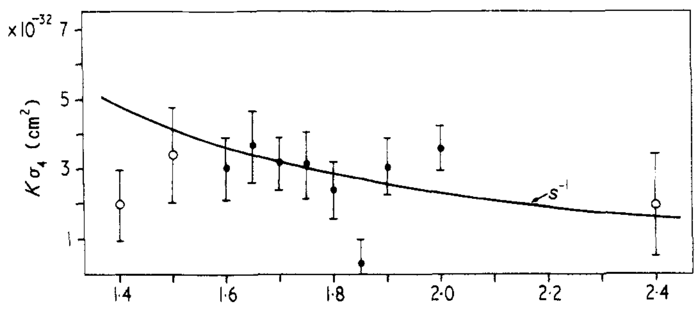


Figure 14. The product $K\sigma_4$ is plotted as a function of total CM energy. Open circles are new data not yet published.

Table 8. Energy distribution of multibody events with greater than or equal to four charged particles ($\mu\pi$ group)

$\sqrt{s}$	$(N \geqslant 4)/N_{e^+e^-}$ (%)
1600	$1{\cdot}7 \pm 0{\cdot}7$
1850	$1{\cdot}6 \pm 0{\cdot}7$
2050	$1{\cdot}9 \pm 0{\cdot}7$

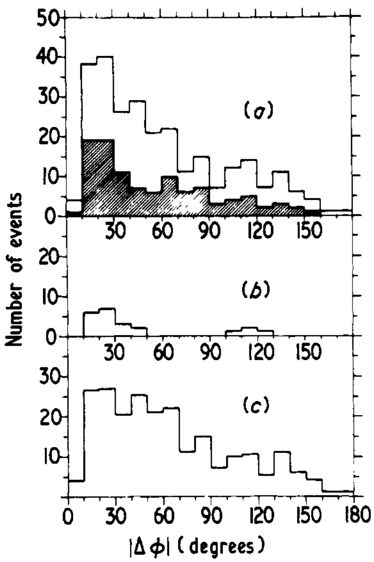


Figure 15. Distribution of $|\Delta\phi|$ for (*a*) in-phase events; (*b*) background events (1 beam), and (*c*) after background subtraction.

7. Tentative interpretations of the data

Simple VMD theory cannot explain either the $\pi\pi$ or the multibody cross section. In fact at Adone energies, $F_\pi^2(q^2) \simeq m_\rho^2/(m_\rho^2+q^2) \simeq 0{\cdot}05$. In the theoretical work of Kramer *et al* (1970) where they calculated contributions coming from the coupling of the vector mesons (ρ, ω, ϕ) to resonances ($A_2\pi, A_1\pi, \omega\pi, \rho\rho, \pi\pi$), a total cross section of about $9\times10^{-33}\,\text{cm}^2$ is obtained at the energy of $\sqrt{s} = 2\,\text{GeV}$.

Similarly Layssac and Renard (1971) take into account even more contributions ($A_2\pi, A_1\pi, \omega\pi, \phi\pi, B\pi, \rho\epsilon, \omega\epsilon, \phi\epsilon, \rho\rho$), necessarily making gratuitous assumptions, and they are able to get a cross section, at $\sqrt{s} = 2\,\text{GeV}$, of $\sigma \simeq 10^{-32}\,\text{cm}^2$ for two charged particles and $\sigma \simeq 2\times10^{-33}\,\text{cm}^2$ for four charged particles. It must be mentioned that radiative production of ρ can give a non-negligible contribution to the total cross section (Bernardini 1971).

Bramon and Greco (1971) assume the VMD model with the additional presence of a vector meson ρ', the parameters of which are deduced from the broad enhancement in the $\pi^+\pi^-$ invariant mass spectrum in the energy range 1·4–1·6 GeV as seen by various groups (McClellan *et al* 1969, Bulos *et al* 1970, Alvensleben *et al* 1971, Davier *et al* 1969). Without invoking contributions from doubtfully established resonances, they obtain a remarkable description of the observed results, that is, a total cross section of

$$\sigma \simeq 24\times10^{-33}\,\text{cm}^2$$

a ratio of two charged to four charged particles of

$$\frac{\sigma_2}{\sigma_4} \simeq 2$$

and a pion form factor $F_\pi(\bar{s}) \simeq 0{\cdot}3$.

A very appealing interpretation is the parton model applied to e^+e^- collision by Cabibbo *et al* (1970) and Ferrara *et al* (1970) where an attempt is made to connect the essential features of the deep inelastic scattering to the e^+e^- annihilation into hadrons. In this model, if the energy is high enough, that is, the process takes place in the asymptotic region, a bare parton–antiparton pair would be produced with a cross section typical of a point-like particle

$$\sigma = \sigma_\mu\left(\frac{1}{4}\sum_{J=0} Q_i^2 + \sum_{J=1/2} Q_j^2\right)$$

with

$$\sigma_\mu = \frac{4\pi\alpha^2}{3s} \simeq \frac{80}{s}\times 10^{-33}\,\mathrm{cm}^2$$

being the cross section for μ pair annihilation. Subsequently the parton pair would convert itself into observable final states, that is, pions or kaons. The specific model of Cabibbo *et al* predicts a suppression of $\pi^+\pi^-\pi^0$ or in general of final states with odd numbers of pions.

Finally the statistical model (Bjorken and Brodsky 1970), again in analogy to hadron processes, predicts the mean multiplicity, but not the absolute value of the cross section. The average number of pions is given by

$$n_\pi = \frac{\sqrt{s}}{0{\cdot}375\,\mathrm{GeV}} + 3 - m \simeq 7$$

for $\sqrt{s} = 1{\cdot}8$ GeV and $m = 1$, where m is the exponent in the fall-off with energy of the cross section $\sigma \propto s^{-m}$.

8. γγ annihilation

So far we have assumed that the origin of multibody events is due to a one-photon annihilation channel. But recently a number of authors have calculated the yield for several final states produced by γγ annihilation, the almost real γ beams being produced by e^+ and e^- beams stored in the ring (Parisi and Kessler 1969, Kessler *et al* 1969, Jaccarini *et al* 1970, Brodsky *et al* 1970, Serbo 1970, Budnev and Ginzburg 1970a, 1970b, Greco 1971, Lyth 1970; see also *Proc. 15th Int. Conf. on High Energy Physics, Kiev* 1970).

According to Weizsacker (1934) and Williams (1934) the energy spectrum of the virtual γ is given by

$$n(k)\,\mathrm{d}k = \frac{2\alpha}{\pi}\frac{\mathrm{d}k}{k}\lg\gamma \qquad \gamma = \frac{E}{m}.$$

Thus the most probable interaction between the two γ, for a fixed total energy, would occur with one of the two photons having $k \simeq 0$. This fact means that the CM system no longer coincides with the laboratory system. The most relevant processes of this type will have the following cross sections at $\sqrt{s} = 2$ GeV (Greco 1971, Touschek 1971, private communication)

	σ_{tot} (cm^2)	$\int_{\Delta\Omega} \sigma \, d\Omega$ (cm^2)
$e^+e^- \to (e^+e^-)+e^+e^-$	7×10^{-27}	$\simeq 10^{-33}$
$e^+e^- \to (e^+e^-)+\mu^+\mu^-$	5×10^{-33}	$\simeq 10^{-33}$
$e^+e^- \to (e^+e^-)+\pi^+\pi^-$	3×10^{-33}†	$\simeq 10^{-34}$
$e^+e^- \to (e^+e^-)+\eta'$	$\simeq 0{\cdot}7\times10^{-35}$	$\Gamma_{2\gamma} = 3\times10^{-33}$ cm^2‡.

The $\mu\pi$ group has analysed two-track events, noncolinear but coplanar with the beam, whose possible origin could be either an emission of γ from an initial e^+ or e^- and subsequent elastic scattering, that is, a 'radiative correction' to the Bhabha scattering, or a product of the annihilation of the virtual photons into a pair of charged particles.

In a sample of 400 wide-angle elastic scattering events the ratio of this kind of event, with a noncolinearity greater than 10° and beam coplanarity better than 10° ($\Delta\theta > 10°$; $\Delta\phi < 10°$), divided by the elastic e^+e^- scattering is

$$\frac{N_{\text{events}}}{N_{e^+e^- \text{ elastic}}} = (7\pm2)\%.$$

If one computes the same ratio, assuming the known probability for a radiative correction with the same restriction in the noncolinearity, one obtains a value of 8%. Thus we can conclude for the observed cross section in our apparatus for $\gamma\gamma$ annihilation into two charged particles, that

$$\langle\sigma\rangle < 10^{-33}\,\text{cm}^2.$$

In conclusion I would like to mention that in the near future a large magnetic field will be available at Adone for momentum measurements, with a volume of about 6 m^3 at a maximum value of 5 kG (Ash *et al* 1969).

This would permit a full kinematic reconstruction of the events thus clarifying the aspects brought to light in this first year of operation of Adone.

Acknowledgments

I would like to thank all experimental groups of Adone for communicating their results prior to publication.

References

Alles-Borelli V *et al* 1970 *Lett. Nuovo Cim.* **4** 1156–9
Alvensleben H *et al* 1971 *Phys. Rev. Lett.* **26** 273–6
Amman F 1969a *Proc. Natn. Particle Accelerator Conference, Washington* 1969 (published as *IEEE Trans. Nucl. Sci.* vol NS-16 no 3)

† In the discussion D H Lyth pointed out that according to his calculations, the $\pi^+\pi^-$ cross section should be of the order of the $\gamma\gamma \to \mu^+\mu^-$ process (Lyth 1970).

‡ The last value has been obtained assuming

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\eta' \to \text{all})} = 0{\cdot}1 \qquad \Gamma_{tot} = 4\times10^{-3}\,\text{keV}.$$

—— 1969b *Laboratori Nazionali di Frascati Report* LNF 69/12
Amman F *et al* 1969 *Lett. Nuovo Cim.* **1** 729–37
Ash W *et al* 1969 *Laboratori Nazionali di Frascati Report* LNF 69/2
Baier V N 1971 *Physics with Intersecting Storage Rings, 46th Int. Sch. Phys. 'Enrico Fermi', Varenna* 1969 ed B Touschek (New York: Academic Press)
Balakin V E *et al* 1970, *Proc. 15th Int. Conf. on High Energy Physics, Kiev*
Balakin V E *et al* 1971a *Phys. Lett.* **34B** 99–100
—— 1971b *Phys. Lett.* **34B** 328–32
Barber W C *et al* 1959 *Stanford University High Energy Laboratory Report* HEPL 170
Barber W C *et al* 1966 *Phys. Rev. Lett.* **16** 1127–30
—— 1969 *Proc. 14th Int. Conf. on High Energy Physics, Vienna* 1968 eds J Prentki and J Steinberger (Geneva: CERN)
—— 1971 *Cornell University Laboratory of Nuclear Studies Report* CLNS 139
Barbiellini G, Borgia B, Conversi M and Santonico R 1968 *Atti Accad. Naz. Lincei* **44** 233
Barbiellini G *et al* 1971 *Phys. Lett.* **35B** 340–4
Bartoli B *et al* 1970a *Nuovo Cim.* A **70** 603–14
—— 1970b *Nuovo Cim.* A **70** 615–31
Benaksas D *et al* 1970a *Proc. 15th Int. Conf. on High Energy Physics, Kiev*
—— 1970b *Laboratoire de l'Accelerateur Lineaire Orsay Report* LAL 1240
Bernardini C 1971 *Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Report* INFN/AE 71/2
Bernardini C, Corazza G F, Ghigo G and Touschek B 1960 *Nuovo Cim.* **18** 1293–5.
Bernardini C *et al* 1962 *Nuovo Cim.* **23** 202–7
Bernardini C *et al* 1964 *Nuovo Cim.* **34** 1473–93
Bizot J C *et al* 1970 *Phys. Lett.* **32B** 416–20
Bjorken J D and Brodsky S J 1970 *Phys. Rev.* D **1** 1416–20
Bramon A and Greco M 1971 *Laboratori Nazionali di Frascati Report* LNF 71/8
Brodsky S J, Kinoshita T and Terazawa H 1970 *Phys. Rev. Lett.* **25** 972–75
Budnev V N and Ginzburg I F 1970a *Proc. 15th Int. Conf. on High Energy Physics, Kiev*
—— 1970b *Novosibirsk Report* TP 55
Bulos F *et al* 1971 *Phys. Rev. Lett.* to be published
Cabibbo N, Parisi B and Testa M 1970 *Lett. Nuovo Cim.* **4** 35–9
Conversi M, Massam T, Muller T H and Zichichi A 1965 *Nuovo Cim.* **40** 690–701
Cremmer F 1970 *Nucl. Phys.* B **15** 131–45
Das T, Mathur V and Okubo S 1967 *Phys. Rev. Lett.* **19** 470–3
Davier M *et al* 1969 *Proc. 4th Int. Symp. on Electron and Photon Interactions at High Energies, Liverpool* 1969 ed D W Braben (Daresbury: Daresbury Nuclear Physics Laboratory)
Ferrara S, Greco M and Grillo A F 1970 *Lett. Nuovo Cim.* **4** 1–3
Feynman R P 1961 *Proc. 12th Solvay Conf. on Physics, Bruxelles* 1961 (New York: Interscience)
Gourdin M 1969 *Orsay Report* (*Phys. Theor.*) 69/12
Greco M 1971 *Nuovo Cim.* A **4** 689–702
Jaccarini A, Arteaga-Romero N, Parisi J and Kessler P 1970 *Lett. Nuovo Cim.* **4** 933–7
Kessler P, Jaccarini A and Arteage-Romero N 1969 *Proc. 4th Int. Symp. on Electron and Photon Interactions at High Energies, Liverpool* 1969 ed D W Braben (Daresbury: Daresbury Nuclear Physics Laboratory)
Kramer G, Uretsky J L and Walsh T F 1970 *DESY Report* DESY 70/44
Kroll N M 1966 *Nuovo Cim.* A **45** 65–92
Layssac J and Renard F M 1971 *Lett. Nuovo Cim.* **1** 197
Lee T D and Wick G L 1969 *Nucl. Phys.* B **9** 209–43
Lyth D H 1970 *Nucl. Phys.* to be published
McClellan G *et al* 1969 *Phys. Rev. Lett.* **23** 718–20
McClure J A and Drell S D 1965 *Nuovo Cim.* **37** 1638–46
Oakes R J and Sakurai J J 1967 *Phys. Rev. Lett.* **19** 1266–70
O'Neill G K 1959 *Proc. Int. Conf. on High Energy Accelerators and Instrumentation, Geneva* 1959 ed L Kowalski (Geneva: CERN)
Parisi J and Kessler P 1969 *Proc 4th Int. Symp. on Electron and Photon Interactions at High Energies, Liverpool* 1969 ed D W Braben (Daresbury: Daresbury Nuclear Physics Laboratory)
Perez-y-Jorba J 1969 *Proc. 4th Int. Symp. on Electron and Photon Interactions at High Energies, Liverpool* 1969 ed D W Braben (Daresbury: Daresbury Nuclear Physics Laboratory)
—— 1970 *Proc. Daresbury Study Weekend on Vector Meson Production, Daresbury* 1970 eds A Donnachie and E Gabathuler (Daresbury: Daresbury Nuclear Physics Laboratory) pp 139–72

Serbo V G 1970 *JETP Lett.* **12** 39
Sidorov V A 1969 *4th Int. Symp. on Electron and Photon Interactions at High Energies, Liverpool* 1969 ed D W Braben (Daresbury: Daresbury Nuclear Physics Laboratory)
Sokolov A A and Ternov I M 1963 *Sov. Phys.–Dokl.* **8** 1203–5
Sugawara H 1968 *Phys. Rev. Lett.* **21** 772–5
Tazzari S 1971 *Proc. Natn. Particle Accelerator Conference, Chicago* 1971 (published as *IEEE Trans. Nucl. Sci.* vol NS-18 no 3)
Touschek B (ed) 1964 *Laboratori Nazionali di Frascati Report* LNF 64/65
van Royen R and Weisskopf V F 1967 *Nuovo Cim.* A **50** 617–45
Weizsacker C F 1934 *Z. Phys.* **88** 612–25
Williams E J 1934 *Phys. Rev.* **45** 729
Wilson R 1970 *Proc. 15th Int. Conf. on High Energy Physics*, Kiev
Zyngier H and Cremieu-Alcan E (eds) 1966 *Proc. Int. Symp. on Electron and Positron Storage Rings, Saclay* 1966 (Paris: Presses Universitaires de France)