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R. Gatto: ON THE EXPERIMENTAL POSSIBILITIES WITH COLLIDING BEAMS OF ELECTRONS AND POSITRONS.

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ON THE EXPERIMENTAL POSSIBILITIES WITH COLLIDING BEAMS OF ELECTRONS AND POSITRONS

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INTRODUCTION -

Electron-electron colliding beams were proposed at Stanford in 1959 [1]. Two projects of electron-positron colliding beams are presently under development in Frascati. The first project [2], called Ada (abbreviated from "anello di accumulazione"), should produce electron-positron colliding beams of 250 MeV (500 MeV total center of mass energy). The second project [3], called Adone (that in Italian also means big Ada), should reach much higher energies, possibly above 1 BeV (1 BeV total c.m. energy), if technically feasible.

In this paper I shall try to summarize the experimental program with Ada and Adone, and in general with high energy electron-positron clashing beams. The program related to Adone and in general to high energy experiments will be summarized here very shortly [4]. In section I we shall discuss tests of quantum electrodynamics. In section II we examine reactions of annihilation into strongly interacting particles. In section III we discuss production of vector mesons, and section IV contains remarks on weak interactions and on electromagnetic effects of virtual strongly interacting particles.

I - TESTS OF QUANTUM ELECTRODYNAMICS -

I. 1 - The reactions

$$e^+ + e^- \longrightarrow \gamma + \gamma$$

$$e^+ + e^- \longrightarrow e^+ + e^-$$

$$e^+ + e^- \longrightarrow \mu^+ + \mu^-$$

can be used to test the validity of quantum electrodynamics at small distances. The last of the above reactions also tests the muon structure. It was concluded from the g-2 experiment that a possible muon radius must be smaller than 0.4 fermi, and also that quantum electrodynamics is valid up to $\sim$ 0.7 fermi [5]. Together with the above reactions, the less probable reactions with additional gammas emitted must be considered. With any particular detection system it is impossible to discriminate against the emission of additional gammas for particular kinematic conditions. For instance any detection system to measure $e^+ + e^- \longrightarrow \gamma + \gamma$ will also count some fraction (usually very large) of $e^+ + e^- \longrightarrow \gamma + \gamma + \gamma$ due to the finite angular and energy resolution of the detectors. The corresponding correction to the cross-section is part of what we call radiative corrections (which therefore include terms arising from virtual photons and terms due to the emission of additional real photons, however energetic, against which it is impossible to discriminate with the particular detection system employed). The radiative corrections, in the sense we have just explained, can be calculated, at the energies we are interested in, with an accurary better than 2 %. An example on how such corrections are calculated can be found in references [6] and [4].

In the following we shall discuss the consequences of a possible breakdown of electrodynamics with the conventional procedure [8] of introducing in the electrodynamic formulae suitable form-factors, accounting for possible modifications of the electron vertex or of the photon propagator.

I. 2 - $e^+ + e^- \longrightarrow \gamma + \gamma$

The two lowest order graphs are reported in figure 1, where a circle denotes the modified electron vertex and a black rectangle the modified electron propagator. In c.m. the squared momentum trasfers (both space-like) are $q_1^2 = 4E^2 \sin^2 \frac{\vartheta}{2}$ and $q_2^2 = 4E^2 \cos^2 \frac{\vartheta}{2}$, where E is the energy of e^+ (or e^-) and ϑ the production angle. In the relativistic limit and for $\vartheta \gg \frac{m}{E}$

$$\frac{d\sigma}{d(\cos\vartheta)} = (\pi r_o^2) \left(\frac{m_e}{E}\right)^2 \frac{|F(q_1^2)|^2 \cos^4 \frac{\vartheta}{2} + |F(q_2^2)|^2 \sin^4 \frac{\vartheta}{2}}{\sin^2\vartheta} \tag{1}$$

where r_o is the electron radius and F a form factor (which can be thought of as a product $V_e^2 P_e$, with V_e = electron vertex form factor, and P_e = electron propagator form factor). If F = 1

$$\frac{d\sigma}{d(\cos\vartheta)} = (\pi r_o^2) \left(\frac{m_e}{E}\right)^2 \frac{1}{2} \frac{2 - \sin^2\vartheta}{\sin^2\vartheta}$$

which is the standard formula for 2 γ annihilation for $\vartheta \gg \frac{m_e}{E}$. For ϑ near 0°

$$\frac{d\sigma}{d(\cos\vartheta)} = (\pi r_o^2) \left(\frac{m_e}{E}\right)^2 \frac{1}{\sin^2\vartheta + \left(\frac{m_e}{E}\right)^2 \cos^2\vartheta}$$

The differential cross section is reported in figure 2. The total cross section, always in the relativistic limit, is

$$\sigma = (\pi r_o^2) \left(\frac{m_e}{E}\right)^2 \left(\log\frac{2E}{m_e} - \frac{1}{2}\right)$$

To estimate the effect of a breakdown we assume $F(q^2)$ of the form

$$F(q^2) = \frac{1}{1 + (q^2/Q^2)} \tag{2}$$

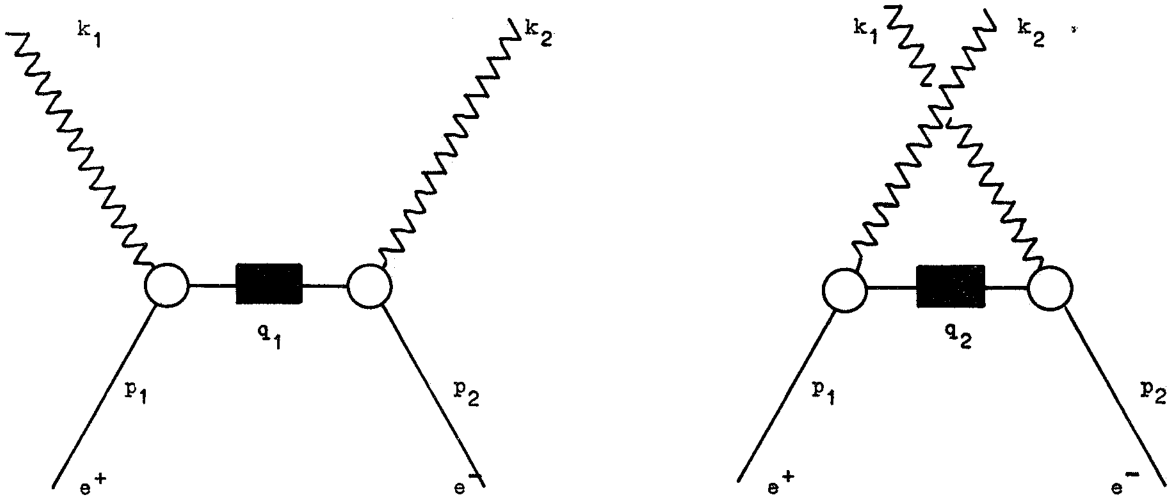

Figure 1

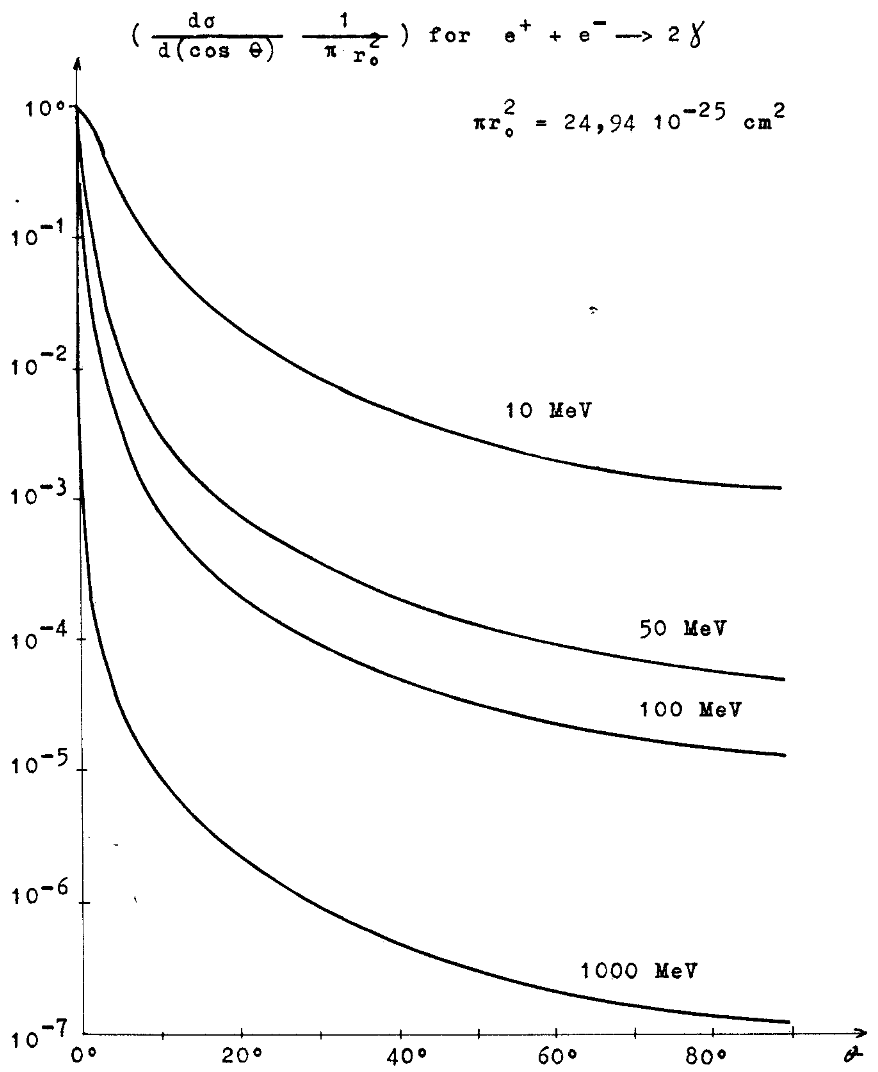

Figure 2

With an energy $E = 250$ MeV, and if Q is 1 GeV (corresponding to 0.2 fermi), according to (1), one expects a relative decrease of the cross-section of 12 % at 90°, 7 % at 60°, 4 % at 45° and only of 0.7 % at 30°. Thus, already of 250 MeV, if one could carry out an experiment at 60°-90° that can distinguish a 7-10 % effect, one can test electrodynamics to distances ~ 0.2 fermi. In this model, where the effect depends on $(E/Q)^2$, a similar experiment at 500 MeV should test electrodynamics to ~ 0.1 fermi.

I. 3 - $e^+ + e^- \longrightarrow e^+ + e^-$

In the lowest order graphs of figure 3 the circle denotes the modified electron vertex and the rectangle the modified photon propagator. In c. m. the squared momentum transfers are $q_1^2 = 4E^2 \sin^2 \frac{\vartheta}{2}$ and $K^2 = -4E^2$ (q_1 is spacelike, K is timelike). In the relativistic limit and for finite angles

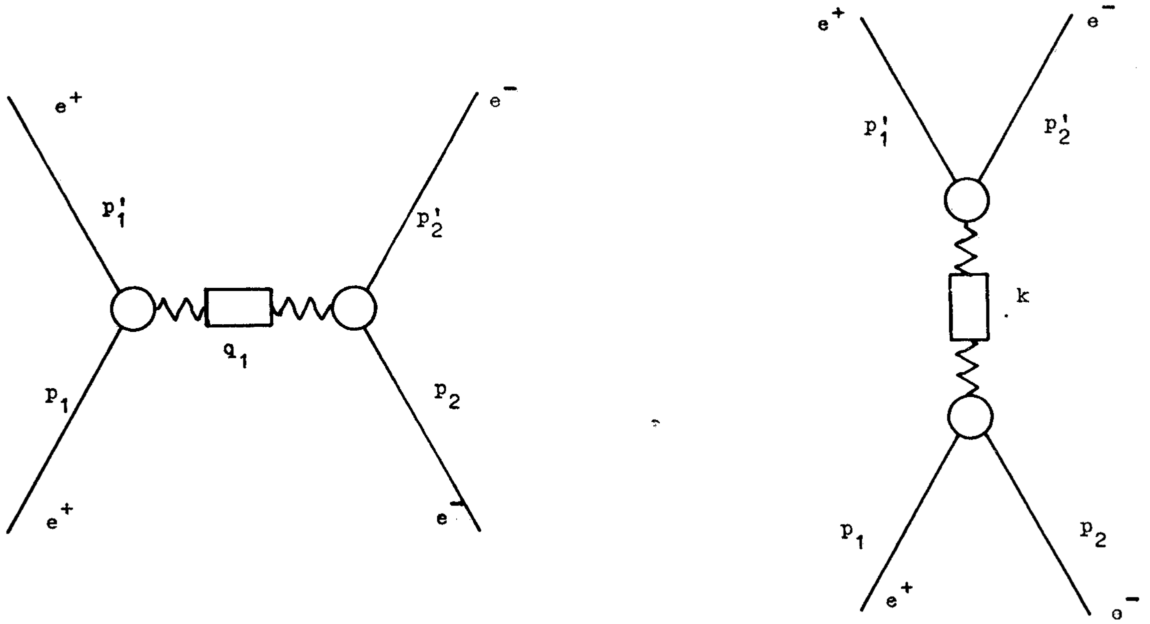

Figure 3

$$\frac{d\sigma}{d(\cos\vartheta)} = (\pi r_o^2)\left(\frac{m_e}{E}\right)^2 \left\{ \frac{1}{4}\,\frac{1+\cos^4\frac{\vartheta}{2}}{\sin^4\frac{\vartheta}{2}}\,|F(q_1^2)|^2 - \frac{1}{2}\,\frac{\cos^4\frac{\vartheta}{2}}{\sin^2\frac{\vartheta}{2}}\,R\,[F(q_1^2)\,F^*(K^2)] + \frac{1}{8}\,(1+\cos^2\vartheta)\,|F(K^2)|^2 \right\} \quad (3)$$

The form factor F can be thought of as a product $V_e^2 P_\gamma$ (P_γ = form factor for photon propagator). Strictly speaking this V_e may be different from that in 2 γ annihilation. Graphs for F = 1 (Bhabha formula) are reported in figure 4. In figure 5 we report the relative correction to the Bhabha formula as computed from (3), with F of the form (2), for different values of Q. One sees from figure 5 that an appreciable effect of the order of 10 % requires an energy larger than about 300 MeV if Q^{-1} = 0.1 fermi (Q = 2 GeV), or an energy larger than 100 MeV if Q^{-1} = 0.3 fermi (Q = 670 MeV). The maximum effect would be around 90°. The net effect results in a decrease of the cross-section.

I. 4 - $e^+ + e^- \longrightarrow \mu^+ + \mu^-$

The black circle in the graph in figure 6 denotes the muon vertex. In c.m. the squared momentum transfer (timelike) is $K^2 = -4E^2$. Neglecting the electron mass

$$\frac{d\sigma}{d(\cos\vartheta)} = \frac{\pi}{4}\,\alpha^2 \lambda\!\!\!^-{}^2\,\beta_\mu \left[\frac{1}{2}\,(1+\cos^2\vartheta) + \frac{1}{2}\left(\frac{m_\mu}{E}\right)^2 \sin^2\vartheta \right] |F(K^2)|^2 \quad (4)$$

with : $\alpha = 1/137$, $\lambda\!\!\!^-$ = reduced wavelength for the incoming e^+ (or e^-), β_μ and m_μ the velocity and mass of the final μ. The form factor F can be thought of as a product $V_\mu F_e P_\gamma$. The angular dependence of the cross section does not depend on F. The total cross-section

$$\sigma = 2.18 \times 10^{-32}\ \mathrm{cm}^2\ \frac{1}{x^2}\left(1 - \frac{1}{x^2}\right)^{\frac{1}{2}}\left(1 + \frac{1}{2x^2}\right) |F(-4E^2)|^2$$

is reported in figure 7, versus x = E/m, for F = 1. On the same figure are reported, for purpose of comparison, the "perturbation theory" cross sections for $e^+ + e^- \longrightarrow \pi^+ + \pi^- \longrightarrow p + p, \longrightarrow K + K$, also as functions of the dimensionless parameter x = E/m, where m is the mass of the produced particle ($m = m_\mu$, m_π, m_p, and m_K respectively). A breakdown can only be felt in the total cross-section (not in the angular dependence). With a form factor of the type (2) one expects a 10 %

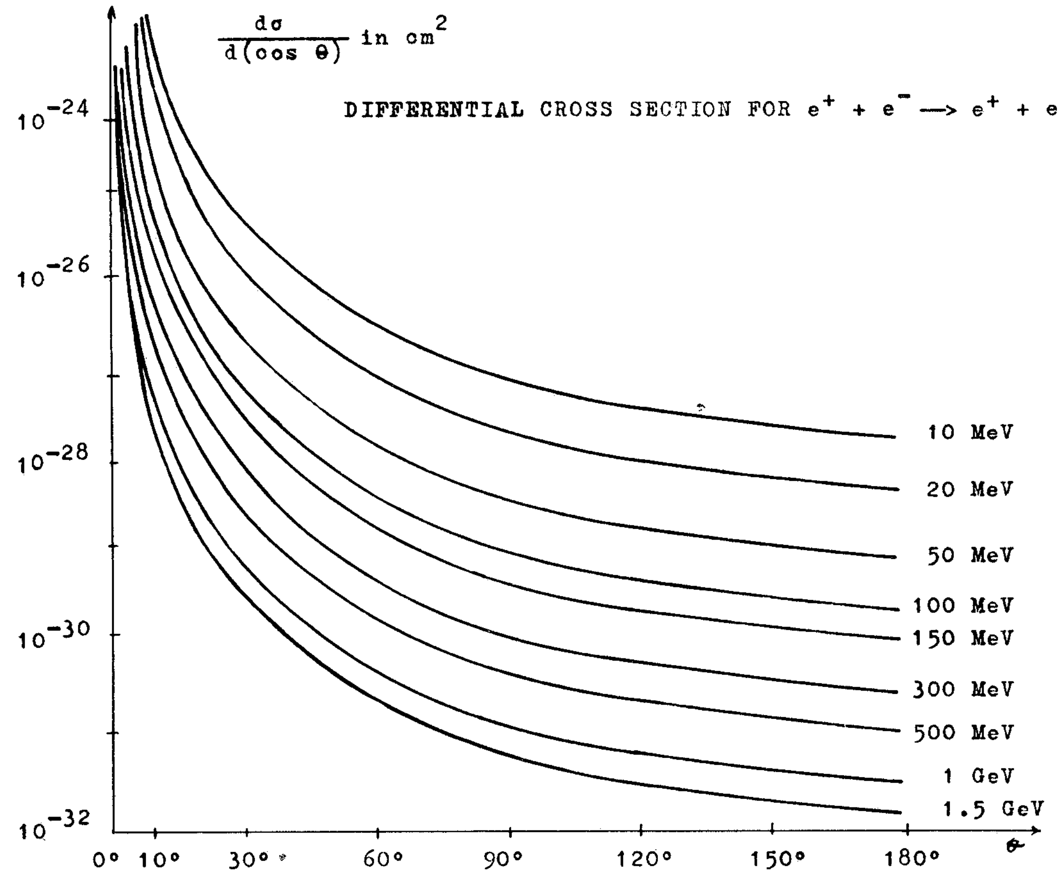

Figure 4

relative increase (increase because of the timelike argument of F) of the total cross-section already at $E \sim 300$ MeV for $Q^{-1} = 0.1$ fermi, and already at 100 MeV for $Q^{-1} = 0.3$ fermi.

II - ANNIHILATION INTO STRONGLY INTERACTING PARTICLES -

II. 1 - The "one-photon channel".

At lowest electromagnetic order (order of e^4 in the intensity) the annihilation occurs through the graph of figure 8. The photon momentum K is timelike. In c.m. $K^2 = -4E^2$. The final particles produced according to the graph in figure 8, must be in a state of total angular momentum $J = 1$ and total parity $P = -1$. This follows from gauge invariance. The transition is described in terms of the matrix element $\langle f | j_\nu | o \rangle$ of the e.m. current j_ν between vacuum and the final state f. In c.m. where $\vec{K} = 0$ the equation $K_\nu \langle f | j_\nu | o \rangle$ gives $\langle f | j_4 | o \rangle = 0$; therefore the amplitude must transform as a polar vector, as expressed by the selections rules we have stated. Moreover the final charge conjugation number is $C = -1$ and the isotopic spin $T = 0$ or 1. Such selection rules are violated at order e^6 by the interference of the lowest order graph with graphs with two photons exchanged between the electron line and the final particles. It can easily be shown however that such terms do not contribute in any experiment that treats charges symmetrically (such as a total cross-section, or $e^+ + e^- \longrightarrow \pi^+ + \pi^-$ without distinguishing the charges, etc.).

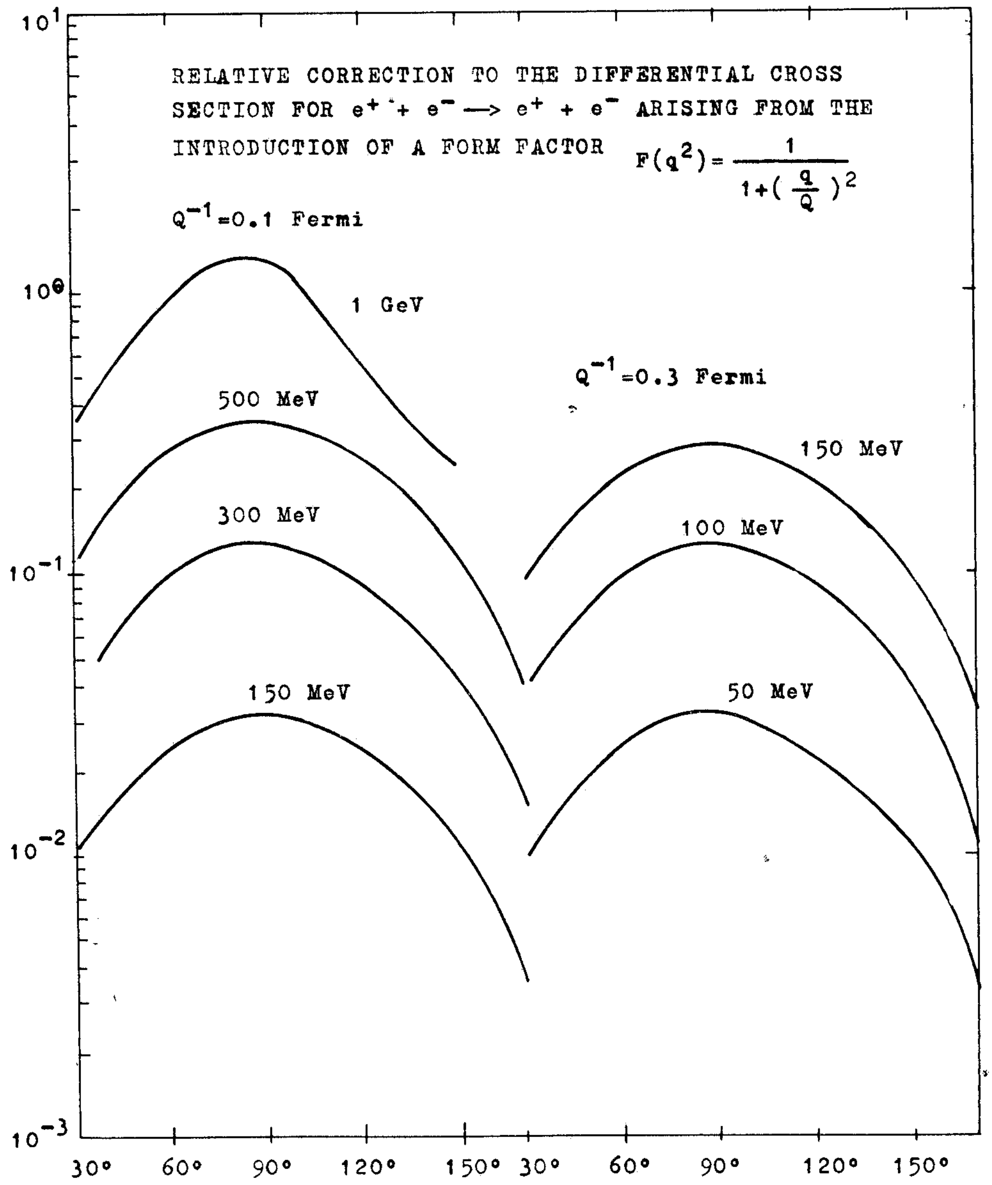

Figure 5

II. 2 - $e^+ + e^- \longrightarrow$ pions [9] (and Kaons).

The final pions must be in a state with J = 1, P = - 1, C = - 1 and T = 1 if the number of pions is even, T = 0 if it is odd. In particular they cannot all be neutral. For $e^+ + e^- \longrightarrow \pi^+ + \pi^-$

$$\frac{d\sigma}{d(\cos\vartheta)} = \frac{\pi}{16}\,\alpha^2\,\lambda\!\!\!^{-2}\,\beta_\pi^3\,|F(K^2)|^2\,\sin^2\vartheta \tag{5}$$

where F is the pion form-factor. The fotal cross-section is reported in figure 7 as a function of E/m_π for F = 1. But F is quite certainly different from 1. With the form factor proposed by Bowcock, Cottingham and Lauriè σ reaches a maximum at E = 330 MeV of 0.7×10^{-30} cm^2 (33 times larger than with F = 1). For $e^+ + e^- \longrightarrow \pi^+ + \pi^- + \pi^0$

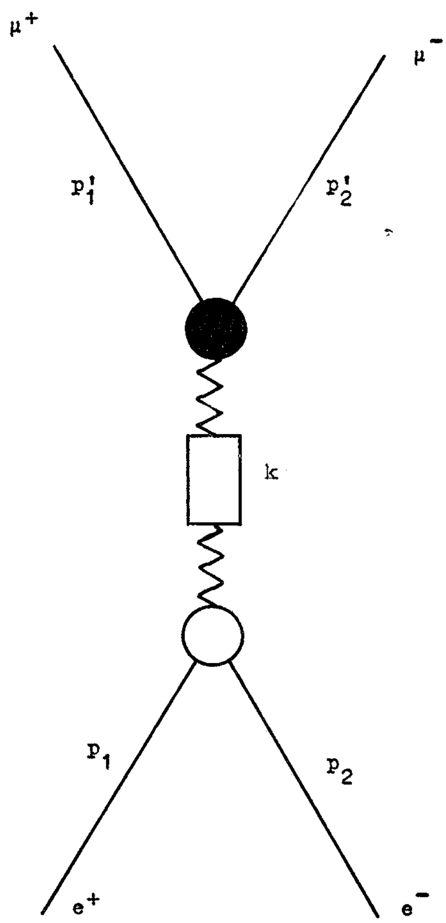

Figure 6

$$\frac{d\sigma}{d\omega_+ \, d\omega_- \, d(\cos\vartheta)} = \frac{\alpha}{(2\pi)^2}\,\frac{\lambda\!\!\!^-{}^2}{64}\,|H|^2 \sin^2\vartheta \,(\vec{p}_+ \times \vec{p}_-)^2 \qquad (6)$$

where ω_+, ω_- and $\vec{p}_+$, $\vec{p}_-$ are the energies and momenta of π^+, π^-, and ϑ is the angle between the production plane and the incident electron direction. The form factors F and H in (5) and (6) are important fot the theory of nucleon structure. Pion resonances with T = 1, J = 1 will be exhibited in F ; with T = 0, J = 1 they will be exhibited in H.

Eq (6) also applies to $e^+ + e^- \longrightarrow K^+ + K^-$ or $K^o\overline{K}^o$. From charge conjugation it follows that $K_1^o K_1^o$ or $K_2^o K_2^o$ pairs cannot be produced, but only $K_1^o K_2^o$.

II. 3 - $e^+ + e^- \longrightarrow \pi^o + \gamma$ [10] and $e^+ + e^- \longrightarrow e^+ + e^- + \pi^o$ [11].

The cross section for

$$e^+ + e^- \longrightarrow \pi^o + \gamma$$

can be written in the form

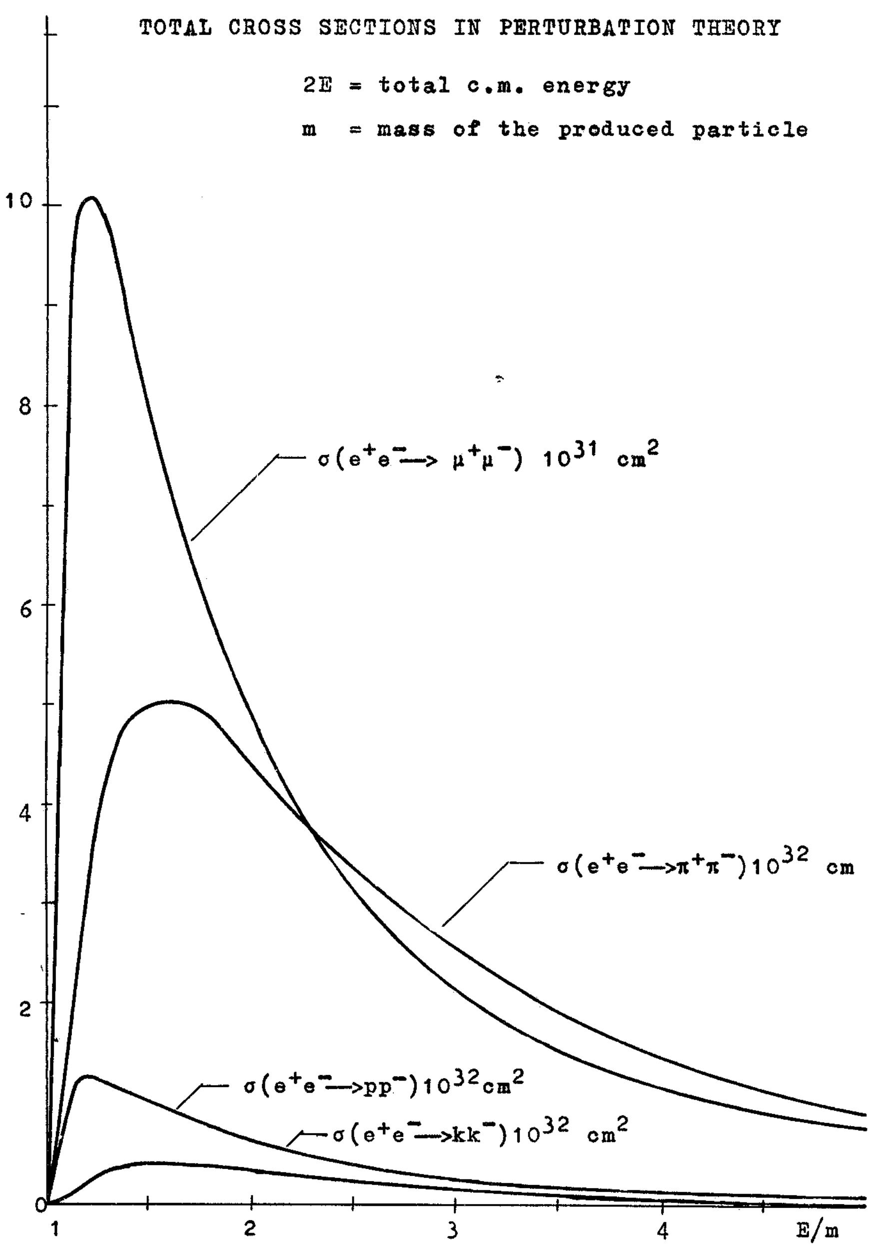

Figure 7

$$\frac{d\sigma}{d(\cos\vartheta)} = \frac{\pi\alpha}{m_\pi^3}\,\frac{1}{\tau}\,\beta_\pi^3\,(1+\cos^2\vartheta)\left|\frac{G(-K^2)}{G(O)}\right|^2 \qquad (7)$$

where $G(-K^2)$ is the form factor for $\pi^\circ \longrightarrow \gamma + \gamma$; τ is the π° lifetime and β_π is the π° velocity. The form factor G for $K^2 = 0$ determines the π° decay rate ; for $K^2 > 0$ (spacelike) it determines the rate of the Primakoff effect [12] ; for $-m_\pi^2 < K^2 < 0$ it gives the rate for Dalitz pairs ($\pi^\circ \longrightarrow \gamma + e^+ + e^-$) ; and for $K^2 < -m_\pi^2$ it determines the cross section (7). With G = 1 the total cross-section from (7) rises from zero to a small constant value of 2.75×10^{-35} cm^2. However if

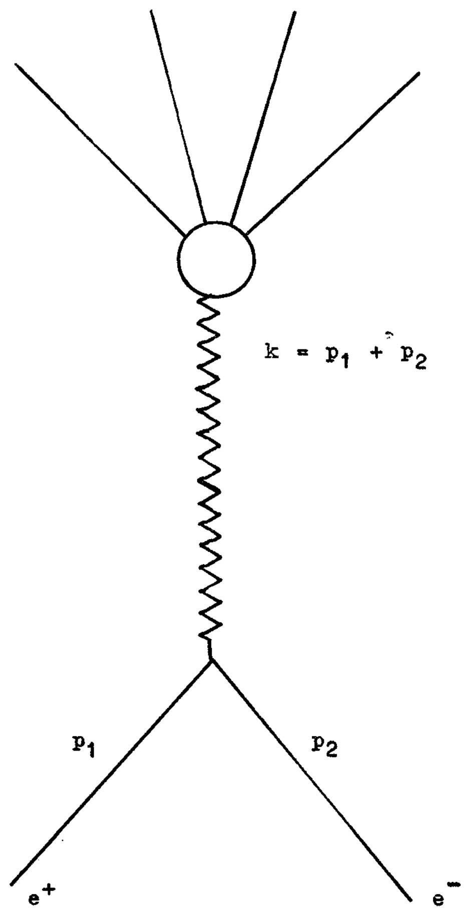

Figure 8

there is a vector meson with T = 0, J = 1 decaying predominantly into $\pi^\circ + \gamma$ [13] the cross-section rises to a sharp peak at a total c.m. energy equal to the mass M of the vector meson. If we use a Breit-Wigner formula, assume $M \leqslant 3\ m_\pi$ and a branching ratio $\sim 10^{-3}$ for decay of this meson into $e^+ + e^-$, we find for the cross-section, over the experimental energy resolution ΔE, a value $\bar{\sigma} = 1.3 \times 10^{-28} (\Gamma/2\Delta E)^2\ cm^2$ where Γ is the decay rate of the vector meson. With $\Gamma \sim 10^{20}$ sec^{-1}, $\bar{\sigma} = 0.8 \times 10^{-29} (2\Delta E \text{ in MeV})^{-1}\ cm^2$ (a value 10^{-5} larger than perturbation theory, for $\Delta E \sim 10$ MeV).

In general both T = 1 and T = 0 pion resonances with J = 1 will produce peaks in the cross-section (7). A phenomenological theory of the form factor G can be developed using as imput data the π° lifetime, the values of the derivative of G for $K^2 = 0$ (measured by Samios from $\pi^\circ \longrightarrow e^+ + e^- + \gamma$ [14]) and the positions and widths of a 2π resonance and a 3π resonance. With the presently ava able data [14] [15] we find big enhancements of factors of the order 10^2, or even larger, over perturbation theory.

The cross section for $e^+ + e^- \longrightarrow e^+ + e^- + \pi^\circ$ is $\sim 2.2 \times 10^{-35} cm^2 (E/m_\pi)$ with $\tau = 2.2 \times 10^{-16} sec$.

II.4 - It can readily be shown by an application of charge conjugation and angular momentum selection rules, and by estimates of the order of magnitudes involved, that $e^+ - e^-$ collisions will in general be very sensitive to intermediate resonant states with J = 1 and C = - 1 (and, of course, with zero nucleonic number and zero strangeness). Resonances with other quantum numbers will generally escape detection.

II. 5 - $e^+ + e^- \longrightarrow$ (baryon) + (antibaryon) [10].

The cross-section can be written as

$$\frac{d\sigma}{d(\cos\vartheta)} = \frac{\pi}{8}\,\alpha^2 \bar{\lambda}^2 \beta \left[\left| F_1(K^2) + \mu\, F_2(K^2) \right|^2 (1+\cos^2\vartheta) + \left| \frac{m}{E} F_1(K^2) + \frac{E}{m}\mu\, F_2(K) \right|^2 \sin^2\vartheta \right] \qquad (8)$$

where m is the baryon mass ; $F_1(K^2)$ and $F_2(K^2)$ are analytic continuations of the electric and magnetic form factors of the baryon for $K^2 < -4m^2$; μ is the static anomalous magnetic moment of the baryon. The normalization is $eF_1(0)$ = charge of the baryon, $F_2(0) = 1$. The total cross-section for F = 1 is reported in figure 7. The form factors are complex in the physical region for the process. This leads to a polarization of the produced baryons normal to the production plane [10]. The final baryons are produced in $3S_1$ and $3D_1$. In the reaction $e^+ + e^- \longrightarrow \Sigma^\circ + \overline{\Lambda}^\circ$ the two final baryons are in $3S_1$ and $3D_1$ for relative Σ-Λ parity even ; in $1P_1$ and $3P_3$, for parity odd. This could allow a determination of the relative parity.

III - ANNIHILATION INTO PAIRS OF VECTOR MESONS -

There have recently been proposals of vector mesons in the theory of strong interactions [16] and also in the theory of weak interactions [17]. The cross-section for

$$e^+ + e^- \longrightarrow B + \overline{B}$$

where B is a vector meson can be written in the form

$$\frac{d\sigma}{d(\cos\vartheta)} = \frac{\pi}{16}\alpha^2 \bar{\lambda}^2 \beta^3 \Big\{ 2\left(\frac{E}{m_B}\right)^2 |G_1(K^2) + \mu\, G_2(K^2) + \varepsilon\, G_3(K^2)|^2 (1+\cos^2\vartheta) + \sin^2\vartheta\ [2\,|G_1(K^2) +$$

$$+ 2\left(\frac{E}{m_B}\right)^2 \varepsilon\, G_3(K^2)|^2 + |G_1(K^2) + 2\left(\frac{E}{m_B}\right)^2 \mu\, G_2(K^2)|^2 \Big\} \qquad (9)$$

where G_1, G_2 and G_3 are form factors, and $\mu + \varepsilon$ and 2ε are the possible static anomalous magnetic moment and quadrupole moment of B. The normalization is $eG_1(0)$ = charge of B, $G_2(0) = G_3(0) = 1$. Eq (9) results from the general expression for the electromagnetic vertex for spin one bosons

$$J_\mu = \frac{e}{(4\,\omega_1\omega_2)^{\frac{1}{2}}} \Big\{ (\varepsilon_1\varepsilon_2)\, p_\mu\, G_1 + [(\varepsilon_1 K)\varepsilon_{2\mu} - (\varepsilon_2 K)\varepsilon_{1\mu}]\ [G_1 + \mu G_2 + \varepsilon G_3] + [(K\varepsilon_1)(K\varepsilon_2) - \frac{1}{2}K^2(\varepsilon_1\varepsilon_2)]\,\varepsilon G_3\, m_B^{-2}\, p_\mu \Big\}$$

where ω_1 and ω_2 are the c.m. energies of B and $\overline{B}$, whose momenta and polarization vectors are respectively p_1, ε_1 and p_2, ε_2 ; and $K = p_1 + p_2$, $p = p_1 - p_2$. With $G_1 = 1$ and $G_2 = G_3 = 0$ the total cross-section is

$$\sigma = m_B^{-1}\,(2.1 \times 10^{-32}\ \mathrm{cm}^2)\,\frac{3}{4}\left(1 - \frac{1}{x^2}\right)^{\frac{3}{2}}\left(\frac{4}{3} + \frac{1}{x^2}\right) \qquad (10)$$

with m_B in BeV and $x = E/m_B$. In figure 9 we have reported σ for various m_B. The angular distributions are reported in figure 10. In figure 11 we report σ as derived from (9) with $G_1 = 1$, $G_2 = 1$, $G_3 = 0$ and $\mu = 1$. The corresponding angular distributions are in figure 12. One finds that both the total cross-sections and the differential cross-sections are generally very sensitive to anomalous moments. When B decays the decay products exhibit correlations reminiscent of the polarization state of B [4]. The cross-section 10 violates unitarity at high energy. One can show that for the one-photon channel that we are discussing, unitarity puts an upper limit of $(3/4)\,\pi\bar{\lambda}^2$ to the total reaction cross-section [4]. Instead the cross-section (10) tends to a constant value when $E \longrightarrow \infty$. However with (10) the violation of unitarity only occurs at energies of the order of $10^2\, m_B$ (or $x = 10^2$).

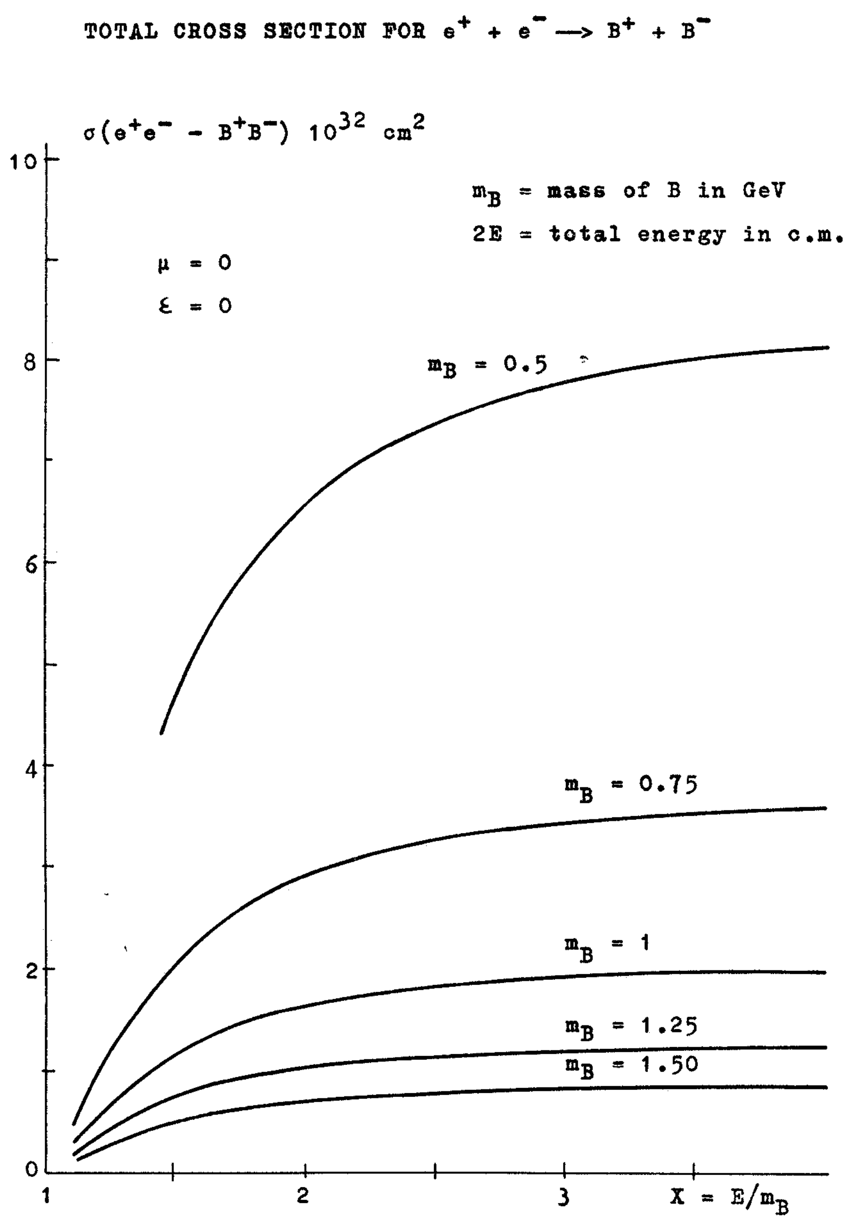

Figure 9

IV - FURTHER REMARKS -

IV. 1 - Weak interactions.

The considerations of the last section can be applied in particular to the production of the semiweak-interacting vector mesons, that have been proposed in the theory of weak interactions. Actually the production of such mesons from e^+ - e^- clashing beams is perhaps one of the best ways for producing vector mesons. A semiweak-interacting neutral vector meson B° cannot be coupled to leptons if it is also coupled to a neutral strangeness non-conserving current. If it exists and is coupled to leptons one would have a resonant contribution from $e^+ + e^- \longrightarrow B^\circ \longrightarrow \mu^+ + \mu^-$, that might be very big. We have estimated, with reasonable values of the parameters, that it could

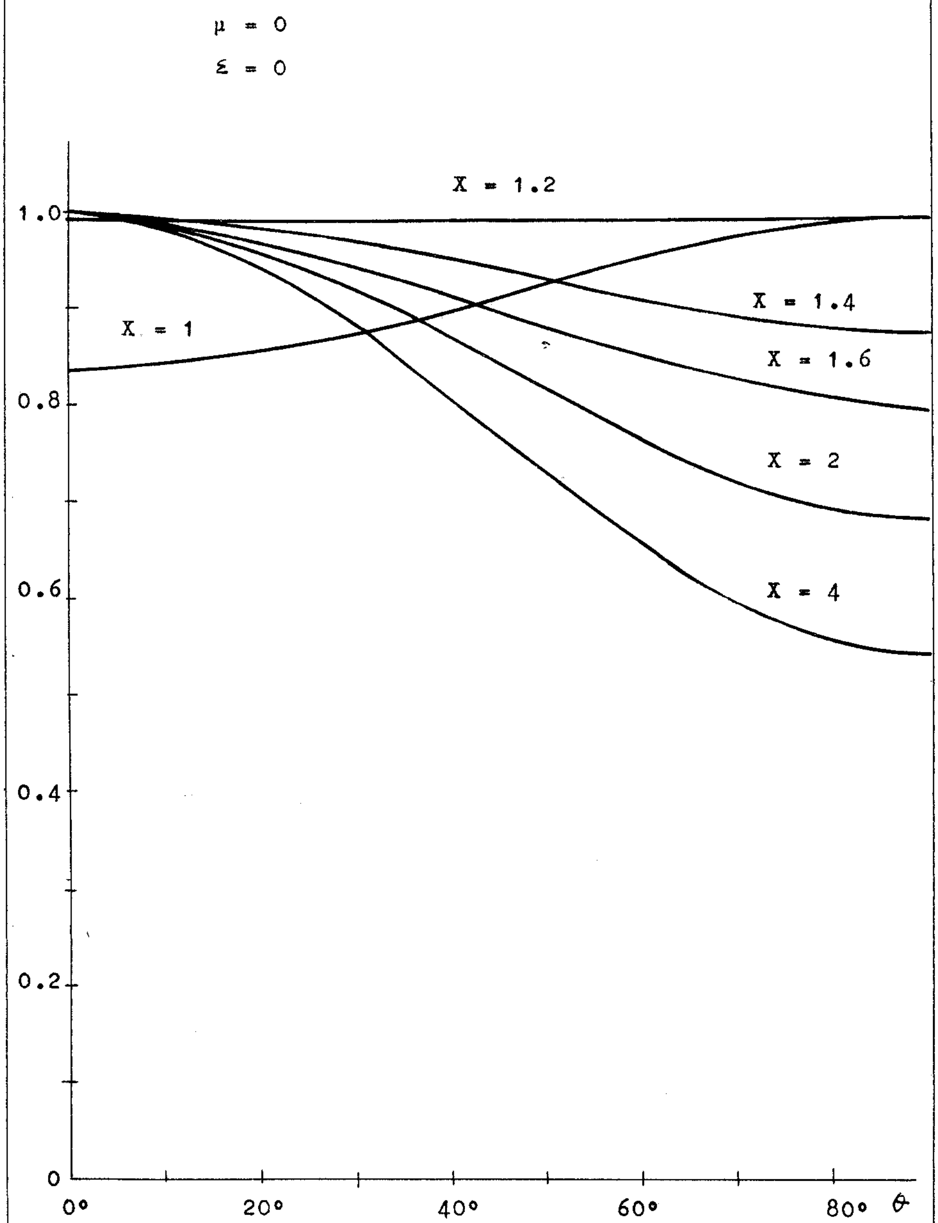

Figure 10

favorably compete (even within the limited experimental energy resolution) with the electromagnetic cross-section for $e^+ + e^- \longrightarrow \mu^+ + \mu^-$ at the appropriate energy [4]. From local weak interactions we donot expect significant effects unless the clashing beam energy is above 10 BeV. One could then find, for instance, a longitudinal polarization of the muons in $e^+ + e^- \longrightarrow \mu^+ + \mu^-$ from the interference between the e.m. amplitude and a parity non-conserving weak (charge-retention) amplitude. With a typical weak coupling strength we expect a polarization [4]

$$P \cong 6.2 \times 10^{-4} \left(\frac{E}{m_N}\right)^2 \frac{(1 + \cos\vartheta)^2}{1 + \cos^2\vartheta}$$

where m_N is the nucleon mass.

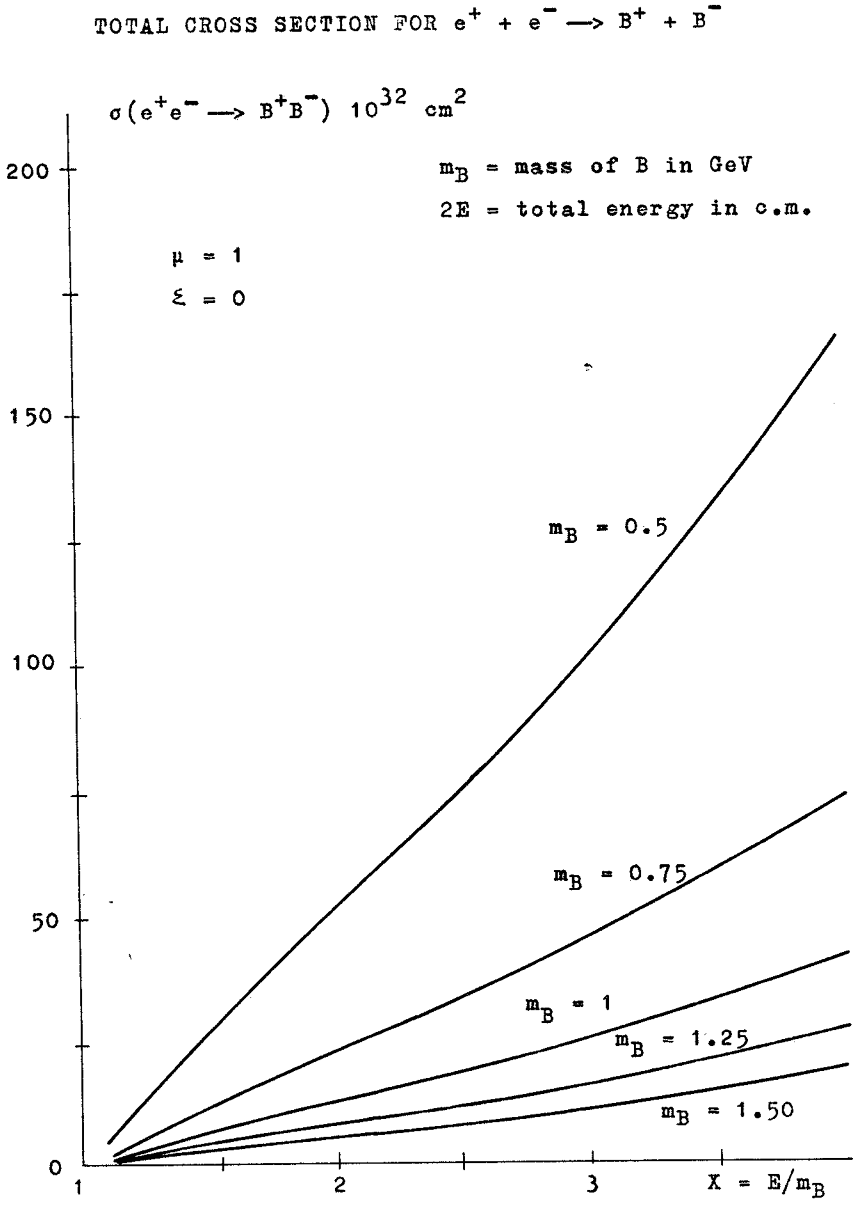

Figure 11

IV. 2 - Possible measurement of the role of virtual strong interacting particles in electromagnetic interactions.

Experimental investigations about the limits of validity of quantum electrodynamics may eventually run into the difficulty of having to deal with effects of the same order as the effects originating from virtual strong interacting particles. These effects are hard to estimate accurately. It may then be relevant to note that direct measurements of the production of strong interacting particles in e^+ - e^- collisions can directly be related to quantities that express the effect of virtual strong interacting particles on the electrodynamic parameters. The modification to the photon propagator can be expressed through the function $\Pi\,(K^2)$, which is additive with respect to the contributions from the various virtual states [18]. Consider a set F of such states (for instance

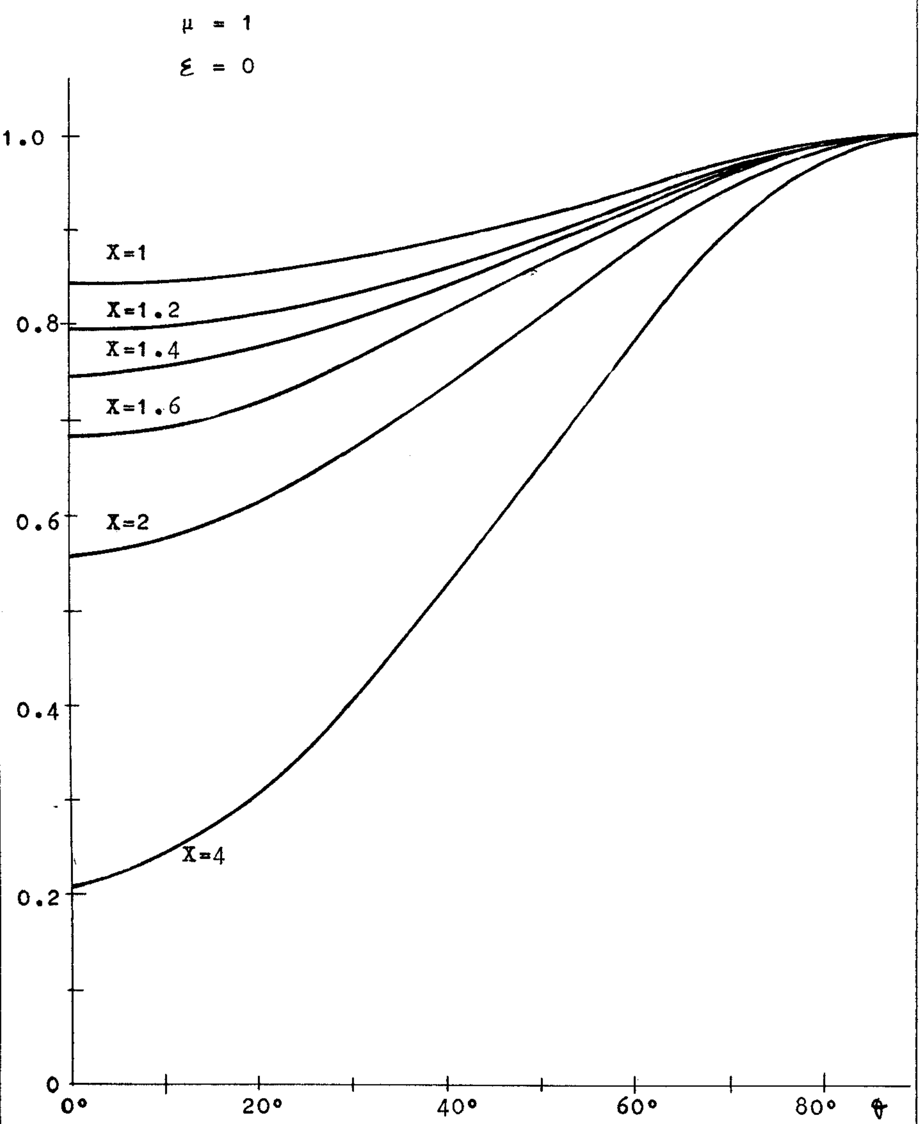

Figure 12

all the two-pion states, etc.) and call Π_F that part of Π due to F. One can than easily show [4] that excluding higher order reactions

$$\Pi_F(-4E^2) = \frac{E^2}{\pi^2 \alpha} \sigma_F(E)$$

where $\sigma_F(E)$ is the total cross-section into the set F from $e^+ - e^-$ clashing beams at energy E.

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