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1. - INTRODUCTION.

Ten years after the nice papers by Low(1) and Calogero and Zemach(2), the importance of the photon processes in e^+e^- colliding beam experiments was emphasized by three independent groups(3, 4, 5), who carried out a quite detailed analysis of the most relevant leptonic and hadronic reactions. Together with the first observations(6) of $\gamma\gamma$ processes at Novosibirsk, Frascati and CEA those works stimulated a great deal of theoretical interest. Much of the work done in this field, particularly $\gamma\gamma \to$ hadrons, dates back in fact to the early seventies(7).

It is only after ten more years that we finally have detailed and quite precise measurements of the photon-photon cross sections $\sigma(\gamma\gamma \to \text{hadrons})$. Exiting data have been reported to this Conference from various experimental groups operating at SPEAR and PETRA storage rings(8, 9).

In this talk I will review the theoretical predictions for $\gamma\gamma \to$ hadrons at low c.m. energies, with special emphasis on those results which are in closer connection with the data. Because, as already said, much of the work done in this field is not very recent and has been excellently reviewed earlier(7), I will not give very many details, which can be found in the original papers.

The plan of the talk is the following. After a brief kinematical introduction, I will discuss in Sect. 3 the case of pseudoscalars production, which is by now rather well settled, on the light of the recent measurements of $\Gamma(\eta' \to \gamma\gamma)$(10, 11). Scalar and tensor resonance production is considered in Sect. 4. Estimates of $\gamma\gamma$ total cross sections are finally discussed in Sect. 5, together with the question of the validity of simple resonance $\leftrightarrow$ Regge duality in presence of non-Regge terms in the absorptive part of the $\gamma\gamma$ scattering amplitude.

The production of pion pairs, as well as the applications of current algebra and soft pion theorems to the processes $\gamma\gamma \to (2n)\pi$, $(2n+1)\pi$, which have been already discussed(7) many times in great detail, will not be included in the written version of the talk, which is centered on various aspects of resonance production and $\gamma\gamma$ total cross sections. In the same spirit we also leave out a discussion of a duality sum rule between resonances and the quark box diagram in virtual $\gamma\gamma$ scattering. The interested reader can refer to the original work[12].

2. - KINEMATICS AND NOTATION.

The absorptive part of the forward ($q_1 = q_3$, $q_2 = q_4$) current x current scattering is defined as

$$W^{\mu\nu\lambda\sigma}(q_1, q_2) = \frac{1}{2} \sum_n (2\pi)^4 \delta^4(q_1 + q_2 - P_n) T_n^{\mu\nu}(q_1, q_2) T_n^{\lambda\sigma *}(q_1, q_2) =$$

$$= \frac{1}{2} \int d^4x\, d^4y\, d^4z \exp\left[-\frac{i}{2} \left\{ (q_2 - q_1)(x - y) + (q_1 + q_2) z \right\} \right] \cdot \tag{1}$$

$$\cdot \left\langle 0 \left| \bar{T}\left[j^\lambda(\tfrac{x}{2})\, j^\sigma(-\tfrac{x}{2}) \right] T\left[j^\mu(\tfrac{y}{2} + z)\, j^\nu(-\tfrac{y}{2} + z) \right] \right| 0 \right\rangle ,$$

where the vertex function $T_n^{\mu\nu}(q_1, q_2)$ is given by

$$T_n^{\mu\nu}(q_1, q_2) = i \int d^4x \exp(iQx) \left\langle n \left| T\left[j^\mu(\tfrac{x}{2})\, j^\nu(-\tfrac{x}{2}) \right] \right| 0 \right\rangle . \tag{2}$$

We use the following notations

$$P = (q_1 + q_2), \quad Q = \frac{1}{2}(q_2 - q_1), \quad s = (q_1 + q_2)^2, \quad t = (q_1 - q_3)^2, \quad u = (q_1 - q_4)^2 .$$

The decomposition of $W^{\mu\nu\lambda\sigma}$ for virtual photons in terms of the eight helicity amplitudes may be found in ref. (13). When $q_1^2 = q_2^2 = 0$ only five helicity amplitudes survive and one can define the amplitudes $F_i^s(s,t,u)$ $(i = 1, \dots, 5)$:

$$\begin{aligned}
F_1^s &\equiv f^s_{++,++} + f^s_{++,--} \sim \sum_{J=0}^{\text{even},\, P=+1} F_{1J} , \\
F_2^s &\equiv f^s_{+-,++} + f^s_{+-,--} \sim \sum_{J=2}^{\text{even},\, P=+1} F_{2J} , \\
F_3^s &\equiv f^s_{+-,+-} + f^s_{+-,-+} \sim \sum_{J=2}^{P=+1} F_{3J} , \\
F_4^s &\equiv f^s_{++,++} - f^s_{++,--} \sim \sum_{J=0}^{\text{even},\, P=-1} F_{4J} , \\
F_5^s &\equiv f^s_{+-,+-} - f^s_{+-,-+} \sim \sum_{J=2}^{P=+1} F_{5J} ,
\end{aligned} \tag{3}$$

where $f^{s}_{\lambda_1\lambda_2,\lambda_3\lambda_4}$ stand for the s-channel helicity amplitudes ($\lambda_i = \pm 1$) and the spin parity of the intermediate states which contribute in the s-channel are indicated in the r.h.s. of eq. (3).

By using the crossing properties of the amplitudes (3) and their partial wave expansion a new set of amplitudes can be found(12, 13) which are free of kinematical singularities and have appropriate Regge expansion.

The contribution of a given resonances of mass m_R, width Γ_R and spin J_R to the total cross section for a given helicity amplitude is

$$\sigma_{\lambda_1\lambda_2}(s) = \frac{1}{s}\,\mathrm{Im}\, f^{s}_{\lambda_1\lambda_2,\lambda_1\lambda_2}(s, t=0) \simeq 16\pi^2(2J_R+1)\,\frac{\Gamma^{R}_{\lambda_1\lambda_2}}{m_R}\,\delta(s-m_R^2)\,, \tag{4}$$

which leads, in the equivalent photon approximation, to

$$\sigma(ee \to eeR) \simeq 8\alpha^2(2J_R+1)\,\frac{\Gamma(R\to\gamma\gamma)}{m_R^3}\,\ln^2\left(\frac{E}{m}\right) f\left(\frac{m_R^2}{4E^2}\right)\,, \tag{5}$$

with $f(y) = -(2+y)^2 \ln y - 2(1-y)(3+y)$.

3. - PSEUDOSCALAR MESON PRODUCTION.

The simplest example of hadron production by e-e collisions is the production of a single π^o, η, η'. The $P\gamma\gamma$ vertex function $T_P^{\mu\nu}$ of eq. (2) can be written in terms of one form factor as

$$T_P^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} q_{1\rho}\, q_{2\sigma}\, F_P(q_1^2, q_2^2)\,. \tag{6}$$

The normalization of F_{π^o} is given by the PCAC triangle anomaly(14)

$$F_{\pi^o}(q_1^2 = q_2^2 = 0)\Big|_{P^2=0} = -\frac{S_\pi}{2\pi^2 f_\pi} \simeq g_{\pi^o\gamma\gamma}\,, \tag{7}$$

where $S_\pi = \frac{1}{2}$ for fractionally charged quarks, $f_\pi \simeq 95$ MeV and the approximate equality refers to the extrapolation from $P^2 = 0$ to $P^2 = m_\pi^2$. As well known, eq. (7) predicts

$$\Gamma(\pi^o \to \gamma\gamma) = \frac{e^4}{64\pi}\, g^2_{\pi^o\gamma\gamma}\, m_\pi^3 \simeq 7.3\ \text{eV}\,, \tag{8}$$

in excellent agreement with the experimental value $\Gamma(\pi^o \to \gamma\gamma) = (7.95 \pm 0.55)$ eV.

According to the Bjorken-Johnson-Low theorem(15), the asymptotic limit of

$F_\pi(q_1^2, q_2^2)$, when $q_1^2 \to \infty$ with $q_1^2/q_2^2 \to 1$ is determined by the commutator of the currents and is given by

$$F_\pi(q_1^2, q_2^2) \to \frac{2 f_\pi}{q_1^2} . \qquad (9)$$

It would be very interesting to check this type of predictions, particularly for the case $P = \eta, \eta'$ discussed below, which seems more easily experimentally accessible.

In the simplest quark model, expressing the quark content of the photon as the usual mixture of $\varrho - \omega - \varphi$ mesons one obtains the following relations

$$g_{\eta\gamma\gamma} = \frac{1}{\sqrt{3}} g_{\pi^o\gamma\gamma}(\cos\theta_p - 2\sqrt{2}\sin\theta_p) , \qquad g_{\eta'\gamma\gamma} = -\frac{1}{\sqrt{3}} g_{\pi^o\gamma\gamma}(\sin\theta_p + 2\sqrt{2}\cos\theta_p) \qquad (10)$$

where θ_p is the usual $\eta - \eta'$ mixing angle. This is also equivalent to the statement that the $\eta - \eta'$ couplings are also determined by the quark charges, with the additional assumption of pure nonet symmetry

$$f_{\eta_1} = f_{\eta_8} = f_\pi . \qquad (11)$$

Eqs. (10), using $\theta_p = -11^o$ from the naive mass formula, predict[16] $\Gamma(\eta \to \gamma\gamma) = 0.39$ keV, $\Gamma(\eta' \to \gamma\gamma) = 6.3$ keV in very good agreement with the experimental values $\Gamma(\eta \to \gamma\gamma) = (0.32 \pm 0.05)$ keV and $\Gamma(\eta' \to \gamma\gamma) = (5.9 \pm 1.6)$ keV[10]. These results definitively favour the fractionally-charged quark model with respect the integral-charged quark model, which predicts for $\eta' \to \gamma\gamma$ a decay rate four times larger. A possible violation of the condition (11), as recently discussed by Chanowitz[17], can however be checked by studying the large q^2 dependence of the $\eta - \eta'$ form factors, in analogy to eq. (9). Furthermore the value of the mixing angle $\theta_p = -11^o$ is also in agreement with all other SU(3) radiative decays/involving the $\eta - \eta'$ mesons[18].

Finally, for later purposes, let us observe that the sum

$$\sum_{\pi^o, \eta, \eta'} \frac{\Gamma(P_i \to \gamma\gamma)}{m_i^3} = \frac{4\,\Gamma(\pi^o \to \gamma\gamma)}{m_{\pi^o}^3} = \frac{e^4}{16\pi} g_{\pi^o\gamma\gamma}^2 \qquad (12)$$

is independent both of the pseudoscalar masses and the mixing angle θ_p.

4. - SCALAR AND TENSOR MESONS PRODUCTION.

The physics of $\gamma\gamma \to \pi\pi$ has been discussed in many places in the literature[7]. We shall only study here the strong interaction modifications due to the production of scalar and tensor resonances, also in order to estimate the resonant contribution to the total $\gamma\gamma$ cross section.

Let us consider first the $\sigma\gamma\gamma$ vertex, where σ indicates a scalar SU(3) singlet. Defining

$$T_\sigma^{\mu\nu}(q_1, q_2) = i A^{\mu\nu} F_\sigma(q_1^2, q_2^2) + i A'^{\mu\nu} F'_\sigma(q_1^2, q_2^2) \quad , \tag{13}$$

with

$$\begin{aligned} A_{\mu\nu} &= Q^2 P_\mu P_\nu + P^2 Q_\mu Q_\nu - (P\cdot Q)(P_\mu Q_\nu + P_\nu Q_\mu) + \left[(P\cdot Q)^2 - Q^2 P^2\right] g_{\mu\nu} \, , \\ A'_{\mu\nu} &= -\frac{1}{4} P_\mu P_\nu + Q_\mu Q_\nu + \frac{1}{2}(P_\mu Q_\nu - P_\nu Q_\mu) - (Q^2 - \frac{1}{4}P^2) g_{\mu\nu} \, , \end{aligned} \tag{14}$$

the two form factors $F_\sigma(q_1^2, q_2^2)$ and $F'_\sigma(q_1^2, q_2^2)$ are related to the two independent helicity amplitudes as

$$T_\sigma^{++} = i(\nu^2 - m^2 Q^2) F_\sigma - i(Q^2 - \frac{1}{4} m_\sigma^2) F'_\sigma \, , \qquad T_\sigma^{oo} = i \sqrt{(Q^2 + \frac{1}{4} m_\sigma^2)^2 - \nu^2} \; F'_\sigma \quad , \tag{15}$$

with $\nu = P\cdot Q$. The coupling constant $g_{\sigma\gamma\gamma}$ for the $\sigma \to \gamma\gamma$ decay is given by

$$g_{\sigma\gamma\gamma} = \frac{1}{4} \left[m_\sigma^2 F_\sigma(0,0) + 2 F'_\sigma(0,0)\right] \quad , \tag{16}$$

with

$$\Gamma(\sigma \to \gamma\gamma) = \frac{e^4}{16\pi} g_{\sigma\gamma\gamma}^2 m_\sigma^3 \quad . \tag{17}$$

By use of the canonical trace anomaly of the energy momentum tensor Crewther and Chanowitz and Ellis[19] have obtained the low energy theorem

$$F'_\sigma(0,0) = \frac{R}{6\pi^2 f_\sigma} \quad , \tag{18}$$

with the usual definition of $R \equiv \sigma(e\bar{e} \to \text{hadrons})/\sigma(e\bar{e} \to \mu\bar{\mu})$. In deriving eq. (18) it has been assumed that the scalar meson σ dominates the trace of the energy momentum tensor, which define f_σ as

$$\langle \sigma(P) | \theta_{\mu\nu}(0) | 0 \rangle = \frac{i}{3} f_\sigma (m_\sigma^2 g_{\mu\nu} - P_\mu P_\nu) \; . \tag{19}$$

Assuming a smooth extrapolation to $q^2 = 0$ of the asymptotic relation $m_\sigma^2 F_\sigma = F'_\sigma$, obtained[20] for $q_1^2 = q_2^2 \to \infty$ one finally has

$$g_{\sigma\gamma\gamma} = \frac{R}{8\pi^2 f_\sigma} , \tag{20}$$

in exact analogy to the π^0 case (eq. (7)). The estimates for f_σ are in the range $f_\sigma \sim 150$ MeV, for $\Gamma(\epsilon = \sigma \to \pi\pi) \sim 400$ MeV, and $f_\sigma \sim f_\pi \sim 100$ MeV, for $\Gamma(\epsilon \to \pi\pi) \sim$ ~ 700 MeV. Using $R \simeq 2.5$, $f_\sigma \sim 100$ MeV and, for comparison with the FESR estimates given below, $m_\sigma \sim 700$ MeV, one gets $\Gamma(\sigma \to \gamma\gamma) \sim 6$ keV. It is obvious that this result strongly depends on m_σ. However the ratio $\Gamma(\sigma \to \gamma\gamma)/m_\sigma^3$, on which we will come back later. should be rather stable, within a factor of two.

Previous estimates of $\Gamma(\sigma \to \gamma\gamma)$ have been obtained by using finite energy sum rules (FESR) and duality. More in detail the product $g_{\sigma\gamma\gamma} g_{\sigma\pi\pi}$ of coupling constants has been estimated from various authors[21], the results depending however on the way the sum rules are saturated. Then using $m_\sigma \sim 700$ MeV, $\Gamma(\sigma \to \pi\pi) \sim$ ~ 200-400 MeV one finds $\Gamma(\sigma \to \gamma\gamma) \sim 6$-$22$ keV.

More recently non-relativistic quark models have also been applied[22] to light mesons decaying into two photons. The results however are rather questionable for the strong assumption of the non-relativistic treatment of bound states of n, d quarks. Values $\Gamma(\sigma \to \gamma\gamma) \sim 8.4$ GkeV and $\Gamma(S^* \to \gamma\gamma) \sim 13$ B keV are found[2, 3].

The experimental verification of the above predictions through the direct measurement of the $\pi\pi$ production cross section seems hardly feasible since the ϵ is a very broad resonance. A similar conclusion applies also to the S^*-resonance in the reaction $\gamma\gamma \to K\bar{K}$, because the S^* is too much close to the $K\bar{K}$ threshold.

The situation is much neater in the case of tensor mesons. Nice evidence for f production has been in fact reported to this Conference by the PLUTO and TASSO Collaborations[9] at PETRA and Mark II[8] at SPEAR. Various theoretical estimates for $f \to \gamma\gamma$ are also quite consistent each other.

Assuming tensor meson dominance for the energy momentum tensor, together with vector meson dominance for the electromagnetic current, Renner[24] has estimated $\Gamma(f \to \gamma\gamma) \simeq 8$ keV.

A similar value, $\Gamma(f \to \gamma\gamma) \sim 6$ keV has been found by Schrempp-Otto, Schremmp and Walsh[21] by use of FESR. They also predict $|T_{+-}|^2 \gg |T_{++}|^2$, namely the f couples mainly to two photons of opposite helicity. This can be simply tested by measuring the angular distribution of the two pions produced in the f decay, which is expected $\propto \sin^4\theta$. The same conclusion has been drawn by Grassberger and Kögerler[25] on the basis of various sum rules of the type discussed below. A value $\Gamma(f \to \gamma\gamma) \sim 12$ keV, with $|T_{+-}|^2 : |T_{++}| = 6 : 1$, has been also more recently predicted in refs. (26).

The following superconvergence relation for real photons has been discussed extensively in the literature[27]:

$$\int_0^{\infty} \frac{d\nu}{\nu} \left[\sigma_{++}(\nu) - \sigma_{+-}(\nu) \right] = 0 . \tag{21}$$

Furthermore it has been checked[12] that the box diagram, considered as a possible source of non-Regge terms, as discussed in detail in the next section, does not affect the validity of (21). Then resonance saturation of the sum rule with low lying pseudoscalar, scalar and tensor mesons leads to

$$\sum_P \frac{\Gamma(P_i \to \gamma\gamma)}{m_i^3} + \sum_S \frac{\Gamma(S_i \to \gamma\gamma)}{m_i^3} + 5 \sum_T \frac{\Gamma(T_i \to ++)}{m_i^3} \simeq 5 \sum_T \frac{\Gamma(T_i \to +-)}{m_i^3} . \tag{22}$$

Then eqs. (12), (17), (20) and the naive quark model lead to the values $\Gamma(f \to \gamma\gamma) \simeq 9$ keV, for $|T_{++}|^2 \ll |T_{+-}|^2$. Notice that the pseudoscalar and scalar contributions are in the ratio 4 : 6. Therefore if only pseudoscalars are taken into account in eq. (22) one gets the lower bound $\Gamma(f \to \gamma\gamma) \gtrsim 3.6$ keV.

In the light of the above argument the value $\Gamma(f \to \gamma\gamma) = (2.3 \pm 0.5)$ keV, obtained by the PLUTO collaboration[9], seems rather low, and should be therefore confirmed by the other experiments at PETRA and SPEAR before definite conclusions can be drawn. It should be pointed out however that a value $\Gamma(f \to \gamma\gamma) \sim 2.6$ keV is predicted[22] by the non-relativistic quark models mentioned above, in connection with the ϵ resonance. The same kind of criticism of course applies also here.

5. - TOTAL CROSS SECTION.

Very exciting data from PLUTO and TASSO collaborations have been presented to this Conference. They show a rather large hadronic production at low c.m. energies which fall rapidly down to a constant value of about 0.25 μb, in excellent agreement with the prediction[3, 4, 5] of factorization of the cross section at high energy (universal Pomeron coupling)

$$\sigma_{\gamma\gamma}(s) \to \sigma_0 = \frac{\left[\sigma_T(\gamma N)\right]^2}{\left[\sigma_T(NN)\right]} \sim 0.24\ \mu b . \tag{23}$$

Early predictions of the energy dependent component of $\sigma_{\gamma\gamma}(s)$ are also based on the usual tools of hadronic physics, specifically, resonance-Regge duality and factorization. This leads[28] to

$$\sigma_{\gamma\gamma}(s) = \sigma_0 + \sigma_1(s) \simeq 0.24\ \mu b + \frac{0.27}{\sqrt{s}}\ \mu b\ \mathrm{GeV}\ . \tag{24}$$

However if one compares the integrated yield of $\sigma_1(s)$ in the low energy domain with the resonance estimates of the preceding sections, in particular the scalar and tensor contributions to $\sigma^{Res}_{\gamma\gamma}$, one finds[12] a large discrepancy by more than a factor of 3 :

$$\int_{\sim m_\varrho^2}^{\sim 3\ \mathrm{GeV}^2} \frac{ds}{s}\ \sigma_1(s) \lesssim \frac{1}{3} \sum_{0^+, 2^+} \int \frac{ds}{s}\ \sigma^{Res}_{\gamma\gamma}(s)\ . \tag{25}$$

This result suggest that simple resonance $\leftrightarrow$ Regge duality might not be valid in $\gamma\gamma$ scattering. A good reason for that is the plausible presence of non-Regge terms (fixed poles, Knönecker delta singularities, ...) in the absorptive part of the current current elastic amplitude, in contrast to the case of current scattering off a hadron where only the real part of the amplitude is affected by these non-Regge terms.

The box diagram (one quark loop) has been suggested[12] as a simple model for non-Regge terms in $\gamma\gamma$ scattering, on the basis of an explicit calculation of forward scattering of charged SU(2) currents where it has been found to consistently satisfy the appropriate Ward identities.

Then writing

$$\sigma^{tot}_{\gamma\gamma}(s) \simeq \sigma^{Regge}_{\gamma\gamma}(s) + \sigma^{box}_{\gamma\gamma}(s) \tag{26}$$

with $\sigma^{Regge}_{\gamma\gamma}(s)$ given by eq. (24) and

$$\sigma^{box}_{\gamma\gamma}(s) \sim \frac{4\pi\alpha^2}{s} \sum_i Q_i^4 \ln\left(\frac{s}{m^2_{q_i}}\right), \qquad (s \gg m^2_{q_i}) \tag{27}$$

one obtains a rough estimate for $\sigma^{tot}_{\gamma\gamma}$, which however approximates quite well the experimental results. This is shown in Fig. 1, where the data from PLUTO are compared with eqs. (26-27) with $\Sigma Q_i^4 = 2/3$ and $m_q \simeq 300$ MeV.

Notice that, in contrast to what happens in e^+e^- annihilation in the one photon channel, the charm contribution to $\sigma^{tot}_{\gamma\gamma}(s)$ through eq. (27) is strongly depressed relatively to the flat background, because of the $(1/s)$ factor.

A careful theoretical reanalysis of the resonant-Regge terms in eq. (24), as

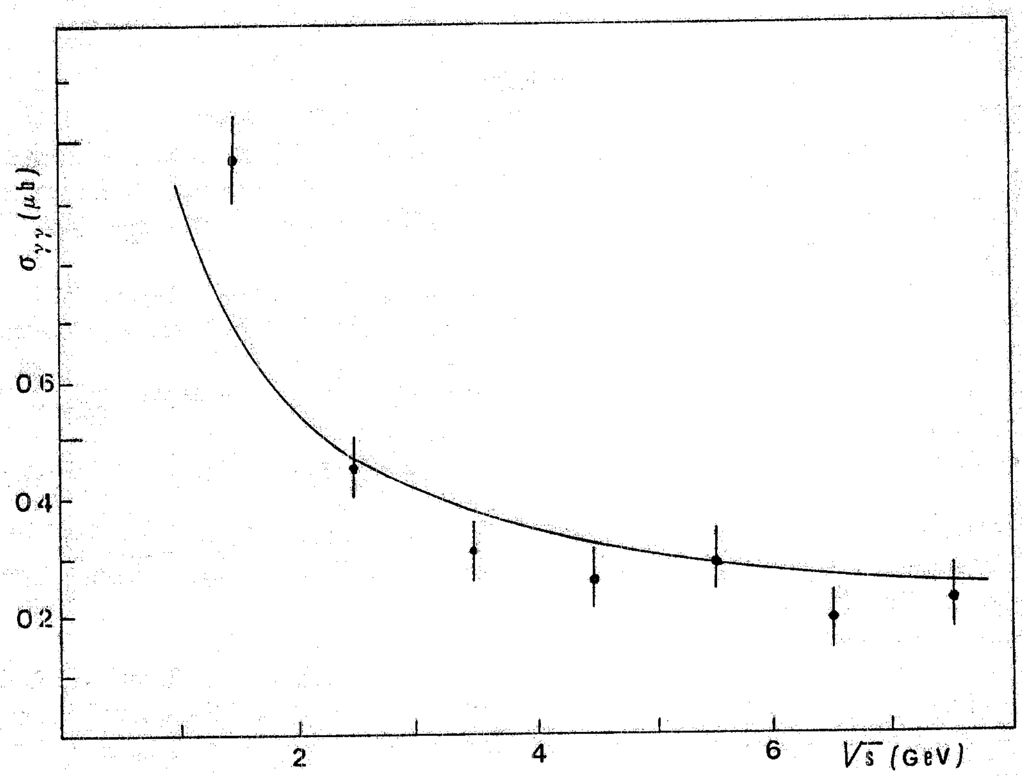

FIG. 1

well as a more detailed study of the energy dependence of the measured $\sigma_{\gamma\gamma}^{tot}$ are highly desirable in order to draw more quantitative conclusions on the relative importance of the various components of the total cross section. Nevertheless, we can conclude that the agreement obtained so far between theory and experiments is very encouraging and hope that this new generation of data will stimulate fresh theoretical ideas in $\gamma\gamma$ physics.

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