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PHOTON-PHOTON COLLISIONS

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Warning : Space being limited, the many references to contributions to the VIIth Workshop on $\gamma\gamma$ Collisions have been noted 0) and have been omitted in the reference list at the end.

1. DISTINCTIVE FEATURES OF GAMMA-GAMMA COLLISIONS.

Photon collisions allow to produce hadrons in an efficient way without any hadron spectator. Calculations of such processes are therefore insensitive or little sensitive to non-perturbative input in most cases. Furthermore, photons couple to the hadron fermionic constituents -the quarks- in a known way which merely involves the quark electric charge. These two features make it possible to predict absolute cross sections based on first principles for many $\gamma\gamma \to$ hadron(s) processes, in contrast to hadron-hadron collision cases where some phenomenological input is usually needed and where, sometimes, uncertainties arise because of ambiguous momentum transfer scales involved in the evaluation of the strong coupling constant.

The same two features are shared by hadron production in e^+e^- annihilation via a virtual γ or a Z^0. These two kinds of annihilations ($\gamma\gamma$ and e^+e^-) are complementary since they lead to final states with different quantum numbers. In e^+e^- annihilations, $s = Q^2$ is a parameter which is precisely controlled. In $\gamma\gamma$ collisions, besides s, the squared mass of each one of the colliding photons can be controlled by appropriate tagging techniques*.

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* Such techniques further allow to study photon polarization effects - but little has been done in this respect up to now.

Photon-photon collisions therefore provide especially good grounds to study the strong force, i.e. to check QCD. This holds for both the QCD perturbative sector by measuring meson or baryon pair production, jet production, inclusive hadron production at large p_T, and the non-perturbative sector by contributing to the hadron spectroscopy program in relation with glueball or hybrid searches and also by giving an insight in the hadron distribution amplitudes related to the valence quark wave function in mesons or baryons.

The measurement of the photon partonic content in deep inelastic $e\gamma$ scattering is also of prime interest since it might lead to a determination of Λ_{QCD}.

σ_{tot} ($\gamma\gamma \to$ hadrons) is a basic cross section to be compared to $\sigma_{tot}(pp)$ and $\sigma_{elastic}(\gamma p)$, while the measurement of $\sigma_{elastic}$ ($\gamma\gamma \to \gamma\gamma$ in the continuum with real or quasi-real photons is still a challenge for experimentators.

Last general remark : for a given e^+e^- machine, the $\gamma\gamma$ collision luminosity is lower than the e^+e^- one at energies presently accessible. Data on $\gamma\gamma$ processes have therefore been collected more slowly than those on e^+e^- annihilation. Despite this handicap many precise measurements are now available in $\gamma\gamma$ physics which bear on a variety of final states.

2. RELATED PROCESSES.

One may distinguish four different groups of related processes. The first one follows from a natural extension towards other α^4 QED processes, e.g. the $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ reaction which shares some Feynman diagrams with $e^+e^- \to e^+e^-\mu^+\mu^-$, and towards α^5 processes such as $e^+e^- \to e^+e^-\mu^+\mu^-\gamma$. Since total luminosities delivered by the higher energy e^+e^- rings are of the order of 200 to 300 pb^{-1}, some α^5 events are now on tapes. A good understanding of these events is necessary as they represent a potential background in the searches for rare events which could be clues for new physics.

Compton scattering ($e\gamma \to X$) is also a related QED process. It sits at the border between $\gamma\gamma$ and e^+e^- processes and is of interest not only as a well understood reference process which may be used e.g. for luminosity measurements or detector checks (Courau[0]) but also as a potential source of new particles (e.g. excited electrons, scalar electrons, winos).

A second kind of relationship is provided by crossing, e.g. γ + hadron $\rightarrow$ γ+X, or hadron + hadron $\rightarrow$ $\gamma\gamma$+X. Such processes have been or are being investigated both theoretically and experimentally (Aurenche[0], Wormser[0]). Like in $\gamma\gamma$ collisions, the fact that two of the participating particles are photons simplifies the theoretical analyses and allows distinct QCD predictions.

Also closely related to the $\gamma\gamma$ physics program are the spectroscopic studies based on the J/ψ decays and/or hadron radiative decays of the type $\rho^{\circ} \rightarrow \gamma\eta$. Like $\gamma\gamma \rightarrow$ resonance measurements, they give an insight in the flavour content of the hadrons participating in such decays. To obtain a clear cut picture of the hadron family and to draw conclusions as to whether or not exotic particles are present in this numerous family, all of these various channels must be taken into account simultaneously.

Last but not least among the related processes are collisions between literally all kinds of electroweak gauge bosons which will take place in future multi-TeV colliders. Such colliders should be viewed as machines with mixed primary beams including γ's, $W^{\pm}$'s and Z°'s. In the case of e^+e^- colliders, the equivalent γ, W and Z beams can be calculated from first principles. Experimental (phenomenological) input bearing on the quark distributions within the nucleon is needed in the $\bar{p}p$ or pp case.

Quite naturally, the Weiszäcker-Williams method can be and has been extended (Renard[0]) to estimate collision rates to be expected in the various channels which are open by colliding any pairs of electroweak gauge bosons.

3. PHOTON-PHOTON ELASTIC SCATTERING IN THE CONTINUUM AND $\gamma\gamma \rightarrow$ gg.

Photon-photon scattering demonstrates the non linear nature of the quantized electromagnetic field. It is an α^4 process which involves virtual fermion pair production (see Fig.1).

Light scattering by an external electric field was first predicted to occur by Delbrück[1] more than 50 years ago. In the case of scatteing by the field of a nucleus, a Z^4 enhancement factor brings the cross section into the several mb range. Experimental evidence for this process was reported by R.R. Wilson in 1953[2].

Light by light scattering has been the object of a series of theoretical investigations which started with Euler's work[3] in 1936 and which have been pursued in recent years (Karplus and Neuman[4], de Tollis[5], Cheng, Tsai and Zhu[6]). Observing such an elastic process in the continuum is still a challenge for the experimentators.

At low energy ($\omega \lesssim m_e$) the cross section is given by

$$\frac{d\sigma}{d\Omega} = 139 \left(\frac{\alpha^2}{180\ \pi}\right)^2 \frac{1}{m_e^2} \left(\frac{s}{4\ m_e^2}\right)^3 (3 + \cos^2\theta).$$

It peaks around 2 nb at $s \simeq 4\ m_e^2$. At high energy, $d\sigma/d\Omega(\theta = \frac{\pi}{2}) \simeq \alpha^4/s$. The asymptotic angular distribution is given by Cheng et al[6].

The quasi-real photon beams provided by e^+e^- machines may allow to observe this process in conditions quite close to the theoretical ones. With e^+e^- beams of energy 5 GeV, assuming complete acceptance for all final state photons with a transverse momentum above 100 MeV/c each, Cahn and Gunion's calculations[7] lead one to predict a cross section close to 1 pb. It follows that a detector like the Crystal Ball could detect on the order of 50 events/year. Therefore the rate is not a major problem but, of course, the challenging question is the background subtraction.

Closely related to $\gamma\gamma$ elastic scattering is the $\gamma\gamma \to gg$ process which has been theoretically investigated by Cahn and Gunion[7]. One might think that it could be a clean source of gluon jets. In fact, it is obscured by the $\gamma\gamma \to q\bar{q}$ production which, in typical conditions, has a yield an order of magnitude higher. Still it might be possible to demonstrate the contribution of the $\gamma\gamma \to gg$ amplitude by selecting two jet events which have about the same C of M energy (by the double tagging technique) and by studying their angular distribution in the high p_T region (B. Muryn[8]).

By crossing, one obtains the γ+g $\to$ γ+g reaction. It plays a role in direct photon experiments (γ+hadron $\to$ γ+X). The NA14 Collaboration has obtained a clear evidence (Wormser[0]) for such a direct γ production but the "box diagram" contribution does not exceed ~ 30 % in this experiment. It peaks in the lower p_T region where the background subtraction is quite important and does not allow to make precise statements yet on this $\gamma+g \rightarrow \gamma+g$ amplitude.

Crossing again leads to the $gg \rightarrow \gamma\gamma$ amplitude which contributes to the direct production of γ pairs at large p_T in hadron collisions.

Signals of direct γ pairs have been observed by the R806 and the R808 Collaborations[9-10] at the ISR and by the NA3 Collaboration[11] at the SPS but here again the box diagram contribution is relatively small, except perhaps in the π^+p case studied by NA3, and its contribution is not firmly established.

4. TOTAL $\gamma\gamma$ CROSS SECTION.

The measurement of σ_{tot} ($\gamma\gamma \rightarrow$ hadrons) is a delicate one. At low energy (W ~ 1 GeV), small multiplicities combined with substantial probabilities of having forward or backward going particles make it difficult to determine the trigger efficiency and to carry out a reliable unfolding of the W_{true} distribution from the $W_{visible}$ one. At high energy (W ~ 20 GeV), rates fall off and multihadron events from the annihilation channel become a serious background.

Ideally one would like to measure σ_{tot} in e^-e^- or e^+e^+ collisions in double ring machines* but such colliders are not available presently. To eliminate the annihilation background, simple or double tagging is usually performed. With the MD-1 set up (Telnov[0]) at Novosibirsk, double tagging can be achieved very close to 0°. In such conditions no extrapolation to $Q^2 = 0$ is needed whereas in more standard set ups like the ones of PLUTO or TPC/2γ, the squared mass of the tagged photons is of the order of $-.5\ GeV^2/c^2$ and the extrapolation to real photons involves correction factors which may reach values as high as 2. Although the Generalized Vector Dominance Model[12] seems adequate to describe the Q^2 variation, a systematic uncertainty remains ; furthermore the factorization of the Q^2 dependence is not totally guaranteed (see M.Poppe's discussion, Ref.13).

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* For instance, DCI at Orsay could provide e^-e^- (or e^+e^+) collisions.

Results on σ_{tot} presented at this Workshop (Fig.2) are of special interest since they are not affected by this kind of extrapolation uncertainty. They are based on no tag events observed by PLUTO (Feindt[0]) and on (zero degree) double tag events observed by the Novosibirsk Group (Telnov[0]). These two sets of results agree within errors with the previous PLUTO and PEP-9 results[14].

As far as the calculation of σ_{tot} is concerned, this is a particular case where one does not know how to proceed starting from first principles. Nevertheless one may try to relate this cross section to other fundamental cross sections, namely $\sigma_{tot}(pp)$ and $\sigma_{el}(\gamma p)$. A simple formula was proposed by Rosner[15] : $\sigma_{\gamma\gamma} = \sigma^2_{\gamma p}/\sigma_{pp}$, who used factorization of the Regge trajectories and duality. This prediction turns out to be a good approximation even in the low W range considered here, although it is a bit low with respect to the data. Slightly higher values are obtained by Ginzburg and Serber[16] who also based their analysis on Regge exchanges (Pomeron, f and A_2).

This t channel factorization approach has been refined at low energy by Alexander et al.[17] who take into account the proper flux factors and use consistent values of p_{CM} for the different channels to be considered. One thus obtains a good fit to the data. At this Workshop, Levy[0] has proposed another relation, also based on amplitude factorization but restricted to the forward direction by making use of the optical theorem for $\sigma_{tot}(\gamma\gamma)$. Levy's result is

$$\sigma_{tot}(\gamma\gamma) = 4\sqrt{\pi}\,\frac{d\sigma}{dt}(\gamma p\to\gamma p)\Big|_{t=0} F_{\gamma p} \Big/ \left[\frac{d\sigma}{dt}(pp\to pp)\Big|_{t=0} F_{pp}\, F_{\gamma\gamma}\right]^{1/2}$$

where $F_{\gamma p}$, F_{pp} and $F_{\gamma\gamma}$ are flux factors. This expression describes very nicely the presently available σ_{tot} values, in particular in the low energy region (see Fig.2).

Breaking σ_{tot} into contributions from various exclusive channels cannot be completely performed at present. Nevertheless, from VMD considerations, vector mesons are expected to be relatively frequent among the final state particles, at least at low energy. The next section deals with some aspects of this question.

5. $\gamma\gamma \rightarrow V_1 V_2$ (V = vector meson).

Quite a large contribution of the $\gamma\gamma \rightarrow \rho^0\rho^0$ channel to σ_{tot} ($\gamma\gamma$) was first measured by the TASSO Collaboration and subsequently by Mark II, CELLO and TPC/2γ[18]. Then a sizeable but much lower cross section for the $\gamma\gamma \rightarrow \rho^+\rho^-$ process was observed by JADE [19]. At this Workshop, the first observation of the $\omega\rho^0$ channel was reported by ARGUS (Nilsson[0]). This Collaboration studied the $\gamma\gamma \rightarrow \omega\pi^+\pi^-$ process (Fig.3) and found that the final state is compatible with pure $\omega\rho^0$ production for $W > 1.7$ GeV.

ϕ's and K^*'s have also been searched for by TASSO[20] and by TPC/2γ (Shen[0]) in the $\gamma\gamma \rightarrow \pi^+\pi^-K^+K^-$ channel. $\phi\pi^+\pi^-$ and $K^*\pi\pi$ are indeed observed but only upper limits could be put on the $\rho^0\phi$ or the $K^*\bar{K}^*$ channels. Upper limits have also been put on $\phi\phi$ production in the $2K^+2K^-$ channel. These limits are at the level of 1 nb (resp.10 nb) for the $\rho^0\phi$ and the $\phi\phi$ channels (resp. the $K^{*0}\bar{K}^{*0}$ channel).

Thus, at present, data are available on the $\gamma\gamma \rightarrow \rho^0\rho^0, \rho^+\rho^-$ and $\omega\rho^0$ channels (and one is waiting for a possible $\omega\omega$ signal from the ARGUS tapes...). Can one interpret the three measured V_1V_2 yields together with the upper limits set on the other V_1V_2 channels ? To put it in another way : can one interpret the large $\rho^0\rho^0$ yield observed near threshold without invoking some exotic states ?

A detailed discussion of this point may be found in Poppe's recent review article[13]. "Conventional" interpretations are based on t-channel exchanges (Batzis and Paschalis[21], Alexander et al.[22]). Alexander and co-authors argue that most of the $\rho^0\rho^0$ production can be interpreted in terms of the ρ^0 photoproduction data. The basic relationship deduced from amplitude factorization is simply

$\sigma(\gamma\gamma \rightarrow \rho^0\rho^0) = \sigma^2(\gamma p \rightarrow \rho^0 p)\, F^2_{\gamma p} / [\sigma(pp \rightarrow pp)\, F_{pp}\, F_{\gamma\gamma}]$, (here again the F's are flux factors) modified by Alexander, Levy and Maor[0] to take the ρ^0 width into account. Some questions about the validity of this formalism used in this context may be raised but it leads to a $\rho^0\rho^0$ yield consistent with the data.

Amplitude factorization applied to $\gamma\gamma \rightarrow V_1V_2$ was further discussed at this Workshop by Brodsky and Meshkov[0] who attempt to understand the flat angular distribution observed for the $\rho^0\rho^0$ production on the basis of ρ° electro-production features. The point here is that the slope parameter b which appears in the amplitude M ($M = Ae^{bt}$) is observed[23] to approach zero when the kinematic factor $1/(E_\rho - E_\gamma)_{labo} \simeq 2\gamma/(Q^2 + m_\rho^2)$ (see Fig.4) becomes small. Applying this "shrinking (from VMD to point-like) photon" concept to the $\gamma\gamma \to V_1V_2$ process with proper kinematics taken into account leads to arguments as to why the $\rho^\circ\rho^\circ$ flat angular distribution should not surprise us.

An "exotic" interpretation of the $\rho^\circ\rho^\circ$ and $\rho^+\rho^-$ relative yields was proposed by Achasov et al[27] who, in fact, anticipated the main features of the experimental results bearing on these two channels by assuming the existence of two interfering 4 quark states. A similar approach has been followed by Li and Liu[25] whose further predictions concerning the $\omega\rho^\circ$ channel look roughly compatible with the ARGUS preliminary values.

Clearly more precise experimental data is required to conclude on this controversial question. Further theoretical investigations of the dynamics of 4q states are also needed (cf. Barnes review talk[0]).

6. RADIATIVE WIDTH MEASUREMENTS AND LIGHT MESON SPECTROCOPY.

The number of radiative width measurements done by using $\gamma\gamma$ collisions has become impressive : in total, including preliminary values reported at this Workshop, one has in hand 4 values for the η, 14 for the η', 12 for the f and 8 for the A_2.

Of particular interest is the first measurement of $\Gamma(\eta_c \to \gamma\gamma).B(\eta_c \to K_S^\circ K^\pm\pi^\mp)$ presented by PLUTO at this Workshop. TASSO has shown preliminary results on this channel too which, taken at their face value, confirm the $\gamma\gamma \to K_S^\circ K\pi$ signal on top of some background which appears delicate to delineate.

In view of the upper limit put by Baglin et al.[26] at the ISR on $\Gamma(\eta_c \to \gamma\gamma).B(\eta_c \to p\bar{p})$ at 8 10^{-3} keV and of the DM2 analysis (Falvard[0]) of the $J/\psi \to \gamma\gamma\gamma$ decay, more data on this channel width are needed.

Another highlight of this Workshop is the TPC/2γ upper limit set on $\Gamma(\iota \to \gamma\gamma).B(\iota \to K\pi\pi)$ in no tag conditions (Bauer[0]). This upper limit seems difficult to reconcile* (cf.Meshkov[0]) with the value of 10^{-4}

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* It may turn out that the interpretation of the $\iota \to \gamma\rho^\circ$ signal has to be revised since it has peculiar features[27,28] (mass and width).

obtained for the product $B(J/\psi \to \gamma\iota).B(\iota \to \gamma\rho^0)$ by the Crystal Ball[27], the Mark III[27] and the DM2 (Falvard[0] and Ref.28) Collaborations.

Quite intriguing is the hint for a signal observed in single tag events by PTC/2γ (Bauer[0]) at 1450 MeV of an object which, like the ι, decays into $K^0_S K\pi$. Could this be a J = 1 resonance (E?) with a mass close to m_ι ?

Finding or not finding glueballs is a key issue of QCD, and this requires an overall understanding of the light meson spectroscopy. In view of the many mass "bumps" seen by DM2 and Mark III (Falvard[0], Seiden[0]) in the J/ψ decays and of the ι/E puzzle, it would be premature to draw hard conclusions from the data at hand - nevertheless it is tempting to try and put everything together and see what comes out. What is important here is (i) to make use of all information available, i.e. combine the purely radiative widths with many other radiative or strong transitions which constrain the meson flavour content, and (ii) to relax as much as possible restrictive hypotheses implicitly or explicitly included in many models which attempt to determine the flavour and glueball content of light mesons.

It has become customary to write down for any meson M content :

$$|M\rangle = a_1^M \, |u\bar{u}\rangle + a_2^M \, |d\bar{d}\rangle + a_3^M \, |s\bar{s}\rangle + |z_M| G\rangle \qquad (1)$$

which, in the case of an I = 0 state, takes the form

$$|M, I = 0\rangle = x_M \, |N\rangle + y_M \, |S\rangle + z_M \, |G\rangle, \qquad (2)$$

where $|N\rangle = (|u\bar{u}\rangle + |d\bar{d}\rangle)/\sqrt{2}$, $S = |s\bar{s}\rangle$ and $|G\rangle$ represents pure glue or whatever basis state which does not couple to photons. Already at this stage, the above expressions raise several questions which may point to unjustified prejudices : (i) may one take x, y and z real ? (ii) what about radial excitations ? (iii) what about $q\bar{q}$ g hybrid states ? Having in view, in particular, the analysis of the 0^- mesons, the ι could a priori be interpreted as a radial excitation of the η or as a hybrid state (Barnes[0]). We will discard these two hypotheses in the following. The first one* on the basis of the high value of the ratio $B(J/\psi \rightarrow \gamma\iota)/B\ (J/\psi \rightarrow \gamma\eta) \approx 8$, and the second one** because of the low value of $\Gamma(\iota \rightarrow \gamma\gamma)$.

Keeping in mind these restrictions implied by (1) or (2), we proceed by considering a series of transitions and look at their implications as far as the a_i^M or the x_M, y_M, z_M coefficients are concerned. In such an analysis, the vector meson nonet serves somehow as a reference : it is assumed to be ideally mixed, without glue.

A first ingredient to the meson flavour content analysis consists in the $V \rightarrow P\gamma$ or $P \rightarrow V\gamma$ transitions ($P = 0^{-+}$ mesons, $V = 1^{--}$ mesons, $T = 2^{++}$ mesons). They are caused by a single quark spin flip. What is being measured there is

$$\Gamma_{V \rightarrow P\gamma} \propto |\vec{p}^{\,*}|^3 \ \left|\sum_i a_i^V a_i^P \mu_i I_i\right|^2 \tag{3}$$

where μ_i represents a magnetic moment ($\propto q/m$) and I_i are overlap integrals which are assumed to cancel out when taking such ratios as $\Gamma(\phi \rightarrow \gamma\eta)/\Gamma(\omega \rightarrow \gamma\pi^0)$.

A second ingredient is provided by the $J/\psi \rightarrow VP$ decay widths. The overall analysis made by Mark III[31] introduces 4 parameters to characterize the 3 g and 1 γ transitions and takes into account the $P = \pi^0, \eta, \eta', K$ and $V = \rho, \omega, \phi, K^*$ cases. Doubly disconnected diagrams are neglected. There are good reasons to do so for $J/\psi \rightarrow VT$ transitions since e.g. $\Gamma(J/\psi \rightarrow \omega f) >> \Gamma(J/\mu \rightarrow \omega f')$; however this approximation could be not so valid in the $J/\psi \rightarrow VP$ case.

As a third ingredient, we use the $P \rightarrow \gamma\gamma$ or $T \rightarrow \gamma\gamma$ partial widths. Usually, these data are analyzed either by extending the current algebra expression obtained for $\Gamma(\pi^0 \rightarrow 2\gamma)$ to other 2γ decays, or within the framework of quarkonium annihilation models. The first approach leads, in particular, to the following relations :

$$\left(\frac{m_{\pi^0}}{m_\eta}\right)^3 \frac{\Gamma(\eta\rightarrow\gamma\gamma)}{\Gamma(\pi^0\rightarrow\gamma\gamma)} = \left(\frac{\cos\theta - \sqrt{2}\, r \sin\theta}{\sqrt{3}}\right)^2 = \frac{25}{9} \left|x_\eta + \frac{\sqrt{2}}{5} y_\eta\right|^2 , \tag{4}$$

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* Arguments supporting the possible importance of radial excitations may be found e.g. in Frank and O'Donnel's analysis[29].

** One has to keep in mind, though, the discussion presented by Barnes[6] at this Workshop, based on Lacaze and Navelet's results[30].

and similar ones for the η' with $\cos\theta$ and $\sin\theta$ replaced by $\sin\theta$ and $-\cos\theta$ respectively. Such expressions have clear short-comings : the one which contains the mixing angle θ and the free parameter $r = F_8/F_1$ (F_i are the PCAC constants) assumes no glue content ; the one which contains the non-strange (x) and strange (y) content assumes "nonet symmetry", i.e. $F_1 = F_8$ which, a priori, is not well founded in the P nonet case.

Several versions of quarkonium annihilation formulae have been proposed (Barnes[0], see also Ref.32). The following one given by Godfrey and Isgur[33] may be considered as representative of this approach :

$$\Gamma_{P\to\gamma\gamma} = 24\,\frac{\alpha^4}{m_q^2}\left|\sum_i a_i Q_i^2\right|^2 \left|\int p^2 dp\,\phi(p)\,\frac{m_q}{E_p}\right|^2 \left(\frac{M_P}{\tilde{M}_P}\right)^3 \tag{5}$$

where $\phi(p)$ is the Fourier transform of the meson wave function and the $(M_P/\tilde{M}_P)^3$ factor takes into account kinematical effects linked to binding energy when the latter is large. Formulae (3), (4) or (5), or the Mark III fit to the J/ψ decays lead to allowed domains in the x_M versus y_M plots first studied by Rosner[34].

These allowed regions (see Fig.5) fit roughly together without being totally compatible, but this is not surprising in view of the underlying questionable assumptions.

A related though different approach (Rosner[34], Rosner and Tuan[35], Field[36], Kawai[37], Eremyan and Nazaryan[38]), consists in using the $|N\rangle$, $|S\rangle$ and $|G\rangle$ states as a basis for the η, η' and ι mesons (resp. f, f' and ϕ). Of course, in so doing, glue content is assumed from the start : the idea here is to check whether or not this assumption leads to predictions which are in conflict with experimental data. The mass matrix between these three states contains 6 parameters when some SU(3)-breaking mass effects are allowed for. The masses of the three 0^- (resp 2^+) mesons are then used together with M_{π^0} (resp.M_{A_2}) for the mass of the non-strange state. Complementary inputs depend upon the authors[34-38]. Table 1 illustrates the kind of mixtures thus found for the 0^- and the 2^+ mesons. One then has to confront the various transition rates implied by such mixtures with experimental values including not only all the processes discussed above but also such decays as $J/\psi \to P\gamma$ (resp. $J/\psi \to T\gamma$) or the forward production of η or

η' mesons in $\pi^- p$ scattering. The number of results which can be accommodated this way is rather impressive (see e.g. Field's analysis[36]). Nevertheless the ι radiative width thus predicted (~ 5 keV) is well above the lowest upper limit reported by Bauer at this Meeting.

To conclude this section : radiative widths obtained by studying $\gamma\gamma$ collisions combine with other radiative or strong transition rate measurements to form a large body of data bearing on the meson flavour content. Still some points remain to be clarified (like E/ι) and some additional measurements would be particularly useful (like $\Gamma(\phi \rightarrow \gamma\eta')$ or $\sigma(\pi^- p \rightarrow \iota n)$). Although no analysis yet fully accounts for all these data -probably because of some oversimplifying assumptions here and there- one has gone a long way towards this goal.

7. EXCLUSIVE CHANNELS AT LARGE $|t|$.

Since the pioneering work of Brodsky and Lepage[39], the way the $\gamma\gamma \rightarrow M\bar{M}$, $B\bar{B}$ amplitudes (M=meson, B=Baryon) can be factorized* in QCD is by now a familiar topic. In the $\gamma\gamma \rightarrow \pi^+\pi^-$ case for example, this well established factorization leads one to fold in two kinds of amplitudes :

$$M_{\lambda\lambda'}(W,\theta^*) = T_{\lambda\lambda'}(x_j,W,\theta^*) \times \prod_{\pi^+,\pi^-} \phi_\pi(x_j,\tilde{Q}).$$

T is the $\gamma\gamma \rightarrow q\bar{q}\ q\bar{q}$ amplitude for the two photons of total energy W and helicities λ,λ' to produce the pion valence quarks collinear with each meson and carrying the fractionnal momentum x_j ($0< x_j <1$). The meson are produced back-to-back at an angle θ^* in the C of M system.

ϕ_π is the probability amplitude to find valence quarks in the pion wave function collinear up to the scale $\tilde{Q}$, i.e. with transverse momentum $k_\perp \lesssim \tilde{Q}$. The scale $\tilde{Q}$ is given by $Q \times \min(x, 2-x)$ where Q is the momentum transfer scale of the process : $Q = W\sin\theta^*$. $T_{\lambda\lambda'}$ is calculable perturbative QCD (see graphs of Fig.6). The Born amplitude is of order α_s^2 in the case of $M\bar{M}$ production, α_s^4 for $B\bar{B}$ production. In the latter case, the Born approximation includes several hundreds of diagrams.

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* This factorization applies to other exclusive processes too.

ϕ is a non-perturbative amplitude which is process independent. The same amplitude enters e.g. in hadron electromagnetic form factors, photo-production and Compton scattering. The relationship thus established between several classes of processes is one of the interesting features of these QCD calculations. This line of attack of exclusive processes is quite predictive. It leads to definite statements on :

(i) the cross section variation as a function of s : $d\sigma/dt \propto s^{2-n}$, where n is the minimum number of elementary fields involved in the process (n = 6 (resp. 8) for $\gamma\gamma \to M\bar{M}$ (resp. $B\bar{B}$) production),

(ii) the angular distribution in some cases, e.g. :

$$\frac{d\sigma/dt(\gamma\gamma\to\pi^+\pi^-)}{d\sigma/dt(\gamma\gamma\to\mu^+\mu^-)} \sim 4\left|F_\pi(s)\right|^2 / (1-\cos^4\theta^*) \Rightarrow dt/d\Omega^* \propto 1 / \sin^4\theta^*$$

where F_π is the pion EM form factor,

(iii) relations between channels, e.g. :

$d\sigma/dt(\gamma\gamma \to K^+K^-)/d\sigma/dt(\gamma\gamma \to \pi^+\pi^-) = (f_K/f_\pi)^4 \approx 2$,

or $\sigma(\gamma\gamma \to \rho^+\rho^-) >> \sigma(\gamma\gamma \to \rho^0\rho^0)$,

(iv) the final state helicity structure : for example, M and $\bar{M}$ are expected to be produced with opposite helicities in leading order in $1/Q^2$ and at all orders in α_s,

(v) the Q_i^2 dependence of $d\sigma/dt$ (absolute normalization and angular dependence) where $Q_{1,2}^2$ = -(colliding photon mass)^2.

There are still open questions raised by this formalism such as : What is the minimal value of $|t|$ which insures the validity of these calculations ? One often assumes $|t| \gtrsim 5$ GeV^2/c^2 as a "safe" domain but there is no clear answer yet to this question. What value should be taken for the running coupling constant α_s ? Is it clear that these perturbative QCD calculations are valid in the whole phase space region -including the $x_j \to 0$ end points- in the $B\bar{B}$ production case ? How important are the higher twist correction terms ? What should one take for the non-perturbative ϕ amplitudes ?

Concerning the last two questions and the Q_i^2 dependence mentionned above, Brodsky has shown in his rapporteur's talk at this Workshop that good progress is being made. Gunion et al.[10] have studied the $\gamma^*\gamma \to \pi^+\pi^-$ process showing that, although the scale of the Q^2 variation is given by s (rather than m_ρ^2 for example), this variation might be rapid. Higher order graphs (α_s^4) have been computed by B. Nižic[41] in the $\gamma\gamma \to K^+K^-$ case, assuming $\phi = \delta(x-\frac{1}{2})$, and these corrections have been found to be important.

Of particular interest are the new developments reported by Brodsky concerning the calculations of the ϕ amplitudes. While one had to be content with mere ansatz a few years ago, several ways of actually computing these non-perturbative amplitudes are now being investigated. One of these approaches is based on QCD sum rules and the results of Cernyak and Zhitnitsky's[42] calculations concerning the proton distribution amplitude had an important impact on the predictions bearing on $\sigma(\gamma\gamma \to p\bar{p})$ (see Maiana[0], Farrar et al.[43]).

I would also like to mention the recent results concerning the pion distribution amplitude which indicate that the latter favors unbalanced sharing of the momentum among the two valence quarks -in contrast with what is expected either in the non-relativistic limit or in the QCD asymptotic limit. In some cases, these amplitude shapes could be checked, in principle, by studying the angular distributions.

Good progress has also been made as far as experimental results are concerned in this field (cf. Ronan's review talk). The $\pi^+\pi^-$ and K^+K^- yields have been untangled by the TPC/2γ Collaboration and data are available at energies up to $W \approx 3.5$ GeV (see Fig.7).

The K^+K^- data agree with the QCD calculations, while the $\pi^+\pi^-$ ones are above the theoretical prediction by a factor 3 to 4 at $W \approx 1.5$-2 GeV where resonances may still play some role ; the general trend as a function of W points to a better agreement at high W values.

As far as baryon pairs are concerned, $p\bar{p}$ yields have been measured at W values up to 2 GeV ; only upper limits are available for the $\Delta^{++}\bar{\Delta}^{++}$ production which is expected to have the highest yield among baryons.

At energies where data on $p\bar{p}$ and $\Delta^+\Delta^-$ are available so far, the observed yields are about one order of magnitude above the QCD values, but one may doubt the validity of the QCD calculations in this energy range which is quite close to threshold. Furthermore, 0^+ resonances may still play some role at such energies.

Clearly, to be on better grounds to test these QCD calculations one would like to have data in a significantly higher $|t|$ range. Because of the rapid fall off of the cross sections, this is a challenge for the experimentators but such a step is not excluded, at least at PEP since this machine should deliver quite high luminosities in the coming years.

8. JETS AND INCLUSIVE PARTICLE DISTRIBUTION IN $\gamma\gamma$ COLLISIONS.

The main features of jet production in $\gamma\gamma$ collisions have been known for some time. In the single tag case, the background coming from the annihilation channel is much easier to control, making it possible to explore a higher W range and therefore to analyze the p_T^2 tail of the two jet production up to higher values ($\sim$ 20 GeV^2/c^2) than in the no tag measurements. In the latter case, a W_{max} cut is usually introduced to eliminate potential contamination by annihilation events. As shown by JADE and PLUTO at this Workshop, this high p_T^2 tail is well described by the simple $\gamma\gamma \rightarrow q\bar{q}$ process calculated in the Born approximation, i.e. according to the naive quark parton model.

In the low p_T region, jet production has a completely different behaviour which is roughly accounted for by VMD, i.e. $\rho\rho$ type scattering, or by generalized VMD models. One may recall that the TASSO[44] results indicating a large p_T inclusive hadron yield gave some new momentum to the integrally charged quark models. The results of the NA14 experiment reported at this Workshop by Wormser[0] clearly rule out such models. On the other hand, calculations at the parton level (Arteaga-Romero et al.[0], Grayson[0], Kapusta[0]) lead one to expect a substantial contribution to jet production from higher order graphs. To progress in this domain one has to study in great detail the intermediate p_T^2 region, for events with $Q_{1,2}^2 \lesssim 0.3$ GeV^2/c^2 where calculable QCD corrections are expected to be sizeable. Trying to pin down these corrections appears to be a priority goal in this field.

Evidence for an excess of low thrust events has been presented at this Workshop by the CELLO and by the PLUTO Collaborations. In both cases these events belong to a low Q_i^2 sample and correspond to intermediate p_T values (p_T = 2-3.5 GeV/c). PLUTO has found that these events in excess could be simulated by such a higher order process as $\gamma\gamma \rightarrow qq\bar{q}\bar{q}$ which implies a virtual gluon exchange between two of the four quarks.

On general grounds one may write σ_{tot} = Born term (QPM) + VMD (~ ρ-ρ scattering) + QCD corrections, where the VMD contribution is non-perturbative and therefore non-calculable...yet. It is an essentially soft piece of the form A $\exp(-Bp_T)$ with some power tail (~ p_T^{-n}). The various QCD corrections have been described in detail by Stirling at this Workshop. These higher order perturbative QCD amplitudes imply a "K factor" by which the Born cross section has to be multiplied* and are at the origin of 3 and 4 jet events. These corrections have been computed by Aurenche et al.[45] for inclusive hadron production $\sigma(\gamma\gamma \to h^{\pm}X)$, and the very small higher twist contributions to this process have also been calculated. More particle spectra ($d\sigma/dp_T^2$) "à la TASSO[44]" are needed to be compared to these complete QCD predictions (see Gidal[0] for preliminary results from Mark II).

As mentioned above, three and four jet production in $\gamma\gamma$ collisions has also been computed. In these calculations, "jets" are identified with energetic primary partons. QCD higher order corrections to these cross sections are more delicate to compute than in the $h^{\pm}X$ case because they require explicit prescriptions as to the definition of a jet (Stirling[0]).

While the underlying QCD processes are well understood and the corresponding cross section calculations available, a difficulty remains which comes from the VMD contribution to be subtracted. No standard model exists for this, i.e. a parton generator combined with a fragmentation scheme, or just a hadron generator, with an absolute normalization, all of this reliable enough for all experimental groups to adopt it.

The lack of such a model makes it difficult if not impossible to compare the results from different experiments and to measure unambiguously the "QCD correction terms" contribution. Hopefully this difficulty will be overcome in the near future.

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* In contrast to the "K factor" in the Drell-Yan process which involves a time-like transfer, here the "K factor" is close to unity.

9. THE PHOTON STRUCTURE FUNCTION F_2^γ.

The interpretation of the F_2^γ measurements is the most controversial but also the most fascinating topic in $\gamma\gamma$ physics. Different authors come to opposite conclusions as to whether this line of research leads to a reliable measurement of Λ_{QCD}.

The mere fact that one can observe hard collisions between an electron and a photon and thus probe the photon content, i.e. its leptonic and hadronic quantum fluctuations, is quite a remarkable result in itself, related, of course, to the possibility of achieving light by light scattering.

Let x and y be the usual scaling variables ($x = -q^2/2k.q$, $y = k.q/k.p$ (see Fig.8)). In usual experimental conditions y is small ($\langle y\rangle \simeq 0.2$) and what is being measured is essentially $d^2\sigma/dxdQ^2 \propto F_2^\gamma(x,Q^2)/(Q^4x)$ where $Q^2 = -(\text{probe photon mass})^2$.

One may first check that one has a good understanding of the underlying physics by analyzing the leptonic quantum fluctuations, i.e. the process $e + \gamma \to e + \mu^+ + \mu^-$. Fig. 8a shows PEP4/9 results[46] on this process. They point to a mass scale of about 100 MeV/c^2 which is, of course, the muon mass. But to conclude that the mass of the fermions into which the target photon can virtually transform is effectively 100 MeV/c^2, three conditions must be met :

(i) all final state muon pairs -or at least most of them- must be detected. Let p_T^* be the muon transverse momentum in the $\gamma\gamma^*$ center of mass frame ; if the detector acceptance introduces some p_T^* cut, then the scale which dominates this process is p_{Tmin}^{*2} and not m_μ^2 (assuming $p_{Tmin}^* > m_\mu$).

(ii) no other mass scale (larger than m_μ) should come in the process. In particular, the photon target mass has to be kept small by some anti-tagging condition. If anti-tagging is achieved for $\theta > \theta_{max}$, then

$$\langle -(\text{target } \gamma \text{ mass})^2\rangle \equiv \langle P^2\rangle \simeq \frac{\omega\,(E-\omega)\,\theta_{max}^2}{2\ell n\,[\gamma(E-\omega)\,\theta_{max}]}$$

where $E = \gamma m_e$ is the $e^\pm$ beam energy, and ω is the target photon energy. In typical conditions $\langle P^2\rangle \simeq (100\text{ MeV}/c^2)^2$ and cannot be altogether neglected with respect to m_μ^2, $m_{u,d}^2$ or Λ_{QCD}^2.

(iii) sub-leading terms should be taken into account in the expression of F_2^γ :

$$F_2^\gamma/x \propto [x^2+(1-x)^2]\ \ell n\ \frac{Q^2}{m^2} + [x^2+(1-x)^2]\ \ell n\ \frac{1-x}{x} + 8x(1-x) - 1.$$

At $x \simeq 0.5$, neglecting the sub-leading terms is equivalent to replacing m by m/e !

Let us now consider the hadronic quantum fluctuations within the target photon. New at this Workshop was a very interesting detailed analysis of the final state done by TPC/2γ (Mc Neil[0]) at low Q^2, and a measurement of F_2^γ at Q^2 from 7 to 70 $(GeV/c)^2$ reported Karshon[0] from TASSO. The TASSO Collaboration has unfolded the F_2^γ values. The results are shown in Fig. 8b. They point to some mass scale and the question is : what is the physical parameter which is behind this mass scale ?

There are several mass scales which, a priori, may enter into the F_2^γ analysis. The first one which should be considered in this hadronic case and which is to be treated apart from the others, is the hadronic resonance mass scale : W values less than about 2 GeV/c^2 (here W represents the total hadronic invariant mass) do not belong to the deep inelastic scattering domain. As a consequence, in the TASSO experiment taken as an example, we leave aside the $x > 0.85$ region. Then comes a series of other mass scales : (i) the photon target mass for which corrections have to be applied, (ii) the quark constituent masses which, in the case of the charmed quark, gives the mass scale for $c\bar{c}$ virtual pairs at the presently available Q^2 values ; that is why the $c\bar{c}$ contribution to F_2^γ is subtracted (see Fig.8b) to remain with light quarks only, with the u quark dominating by far because of the electric charge factor which enters with a fourth power, (iii) the QCD scale Λ, (iv) a possible p_{Tcut} below which binding effects become predominant so that perturbative QCD does not apply anymore (p_T is the transverse momomentum of each member of the $q\bar{q}$ pair into which the target photon splits in the $\gamma\gamma^*$ CM frame).

In a contribution to this Workshop, J. Field et al. have presented new calculations of F_2^γ. These calculations are valid in the non-asymptotic Q^2 region. They are based on the leading contributions to the splitting functions $\gamma \to q\bar{q}$, $q \to gq$, $g \to q\bar{q}$. Care is being taken to perform the Feymann graph calculations in the phase space region where

α_s does not become too large, i.e. where perturbative calculations are valid. Since the value of α_s depends on $|t|$, the squared mass of the off-shell quark produced at the $\gamma_{target} \to q\bar{q}$ vertex, these considerations lead to put a lower bound, p_{Tcut}, to the transverse momentum (with respect to the $\gamma\gamma^*$ direction in the $\gamma\gamma^*$ CM system) of the on-shell quark.

As far as the contribution of the $p_T < p_{Tcut}$ phase space region is concerned, Field et al. assume that this contribution is accounted for by $(F_2^\gamma)_{hadronic}$ with its usual expression : $\simeq 0.2\ \alpha\ (1-x)$. The authors then argue that p_{Tcut} is certainly larger than Λ_{QCD} (a typical value for p_{Tcut} is ~ 1 GeV/c) and therefore it obscures the Λ_{QCD} dependence of F_2^γ. Indeed the leading order term thus obtained is $\ln Q^2/p_{Tcut}^2)$ and the sensitivity to Λ_{QCD} is very small. These conclusions are similar to the ones of Glück, Grassie and Reya[47].

Quite an opposite conclusion was reached by Grunberg in his rapporteur's talk. Basing his analysis on the structure function moments and their developments in power series* of α_s, he discussed in detail the singularities which appear in the terms that remain in the asymptotic limit, i.e. in the limit $Q^2 \to \infty$. The origin of these singularities is well understood by now : they come from mixing effects between the so-called "point-like" part and "hadronic" part of F_2^γ. Concerning these spurious singularities which are present in the truncated series, they must be removed to get sensible predictions. One can do so at the expense of introducing new parameters besides Λ_{QCD}. This procedure first worked out for one of the most preeminent singularity by Antoniadis and Grunberg[48] raises two questions : (i) how large is the x range affected by these unknown parameters ? (ii) how large is the remaining (presumably regular) hadronic piece of F_2^γ ? Antoniadis and Marleau[49] have recently addressed both questions. In particular, they have studied the regularization of several of the low n singularities (see Fig.9). They conclude that only the small x region ($x \lesssim 0.4$) is affected by the singularities. Furthermore, by performing this regularization one takes into account part of the hadronic component of the photon structure function. The authors present some argument

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* The powers that enter in these series are integers and hadronic anomalous dimensions.

indicating that what remains of these non-calculable terms is likely to be unimportant at high Q^2, and conclude that F_2^γ provides good grounds for measuring Λ_{QCD}.

A clear difference between the approach of Field et al. and the more standard approach using the F_2^γ moments lies in the breaking of F_2^γ into a calculable piece (point-like) and a non-calculable one (hadronic). In the latter approach each separate piece contains singularities while neither the point-like piece nor the hadronic one defined by Field et al. have singularities : the boundary between the two pieces is therefore set differently - this might explain the difference in the Λ_{QCD} sensitivity.

Needless to say, a clarification of the two following questions is urgently needed : does F_2^γ depend in a sensitive way upon Λ_{QCD} in the Q^2 range now accessible experimentally ? Is there an x range where reliable QCD calculations can be made with no parameter other than Λ_{QCD} entering ? This clarification is the more important as there are good prospects for extending the F_2^γ measurements at LEP (Cordier[0]).

10. CONCLUSION.

In closing, I would like to emphasize again some of the topics which have been at the center of our discussions during this Workshop, namely flavour content of the light mesons and glueball searches, perturbative QCD tests, distribution amplitudes of valence quarks within mesons and baryons, measurement of the photon structure function and possibility to extract a precise value of Λ_{QCD} from this measurement.

These are key issues of particle physics. They belong to the strong interaction investigation program and we know that this program is a difficult one. $\gamma\gamma$ collisions provide favorable grounds to attack these questions. Even though no decisive breakthrough has been made yet, one only has to compare the contributions made to the successive $\gamma\gamma$ Workshops to see that much progress has been made both experimentally and theoretically : all qualitative features have been checked and many quantitative results are in hand. To proceed much further, one needs more luminosity in some cases, more energy in others. Both increases are expected in the coming years. No doubt, we will then witness very interesting developments.

ACKNOWLEDGEMENTS

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		x	y	z
η	(a)	0.67 ± 0.03	- 0.73 ± 0.03	- 0.135 ± 0.008
	(b)	0.72 ± 0.21	- 0.69 ± 0.23	- 0.09 ± 0.62
η′	(a)	0.50 ± 0.04	- 0.61 ± 0.05	- 0.62 ± 0.08
	(b)	0.57 ± 0.18	- 0.67 ± 0.23	- 0.49 ± 0.59
ι	(a)	0.53 ± 0.05	0.45 ± 0.06	0.72 ± 0.07
	(b)	0.40 ± 0.17	0.30 ± 0.14	0.87 ± 0.47
f	(c)	0.95	0.07	0.3
	(a)	0.99	0.067	- 0.155
f′	(c)	- 0.09	0.98	0.1
	(a)	- 0.08	0.99	0.09
θ	(c)	- 0.3	- 0.13	0.95
	(a)	- 0.15	- 0.10	0.98

Table 1 : Flavor mixing (x = non-strange, y = strange, z = glue) for η, η′, ι and for f, f′, θ. (a) are J. Field's values[36], (b) are Sh.S. Eremyan and A.E. Nazaryan's values[38] and (c) are J.L. Rosner and S.F. Tuan's values[35].

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FIGURE CAPTIONS.

Fig. 1. Feynmann graphs for elastic photon-photon scattering (a1, a2), and for gluon pair production (b). f represents a fermion, i.e. a lepton or a quark (there are six different diagrams of the "a" type per fermion). q represents a quark.

Fig. 2. Total cross section for the $\gamma\gamma \to$ hadrons process. The solid curve follows from Levy's formula while the dotted one shows Rosner's prediction (see text).

Fig. 3 Preliminary results of the ARGUS Collaboration on $\omega \pi^+\pi^-$ production in $\gamma\gamma$ collisions.

Fig. 4 Electroproduction of ρ^0 meson in the VMD model.

Fig. 5 Contraints on non-strange (x) and strange (y) quarkonium mixing coefficients from radiative transitions and from $J/\psi \to VP$ decays.

Fig. 6 Examples of graphs contributing at the Born level to exclusive meson pair production (a), and to baryon pair production (b) in $\gamma\gamma$ collisions. Several hundreds of such graphs have to be summed in the baryon case.

Fig. 7 The cross section for the process $\gamma\gamma \to \pi^+\pi^-$ (a), and $\gamma\gamma \to K^+K^-$ (b) measured by the TPC/2γ Collaboration (UCR-TPC-86-01).

Fig. 8 (a) The leptonic component of the photon structure function F_2^γ measured by the PEP4/9 Collaboration[46].
(b) The hadronic component of the photon structure function F_2^γ at $Q^2 = 23$ (GeV/c)^2 measured by the TASSO Collaboration. The triangles represent the full structure function. The circles represent F_2^γ for the light quarks after subtraction of the theoretical c quark contribution.

Fig. 9 Regularization of three of the singularities of $(F_2^\gamma)_{asymptotic}$ which occur at low n values (n is the moment order). This regularization is done by adding a piece of the form $\frac{-b}{n-n_0}(\lambda\alpha_s)^{d_i^n}$ where n_0 is the pole, b is a calculable residue, and λ is an adjustable parameter (cf. Refs. 48 and 49).

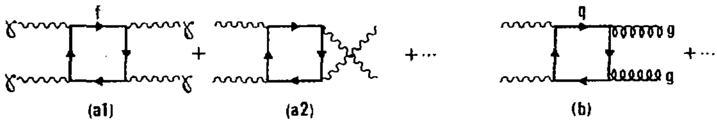


Fig. 1

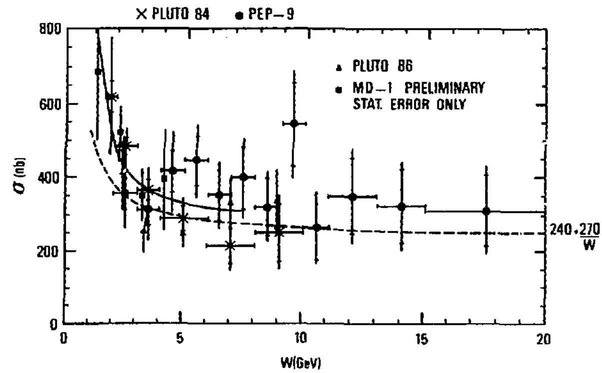


Fig. 2

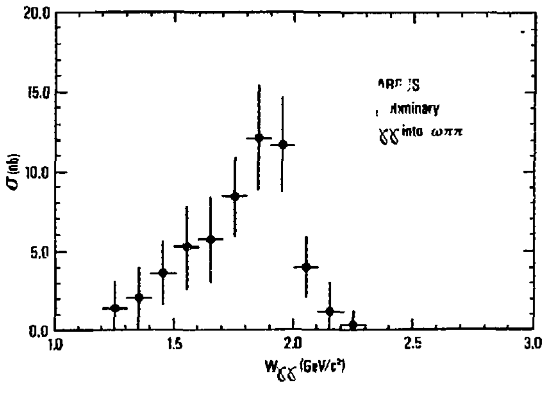
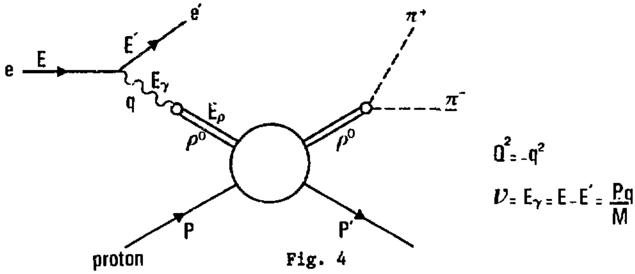


Fig. 3


e
E
E'
e'
q
Eγ
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π+
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proton
Q2 = -q2
ν = Eγ = E - E' = Pq/M

Fig. 4

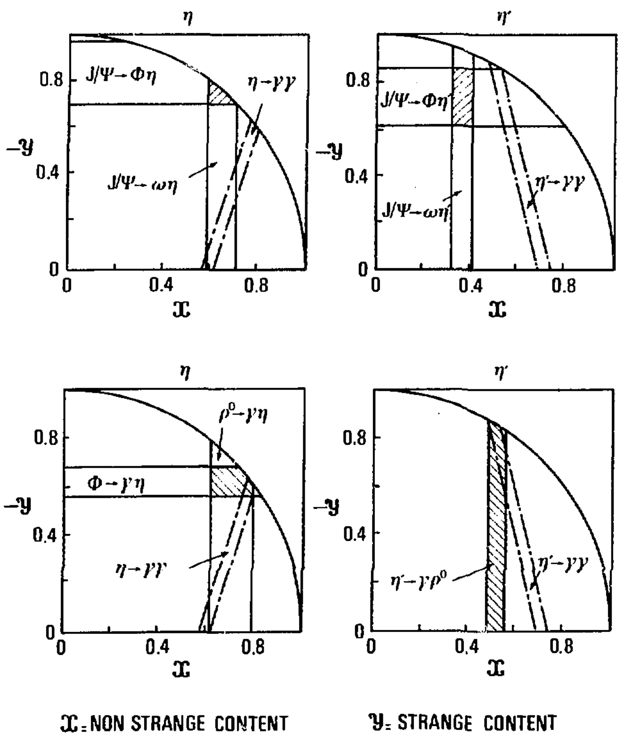
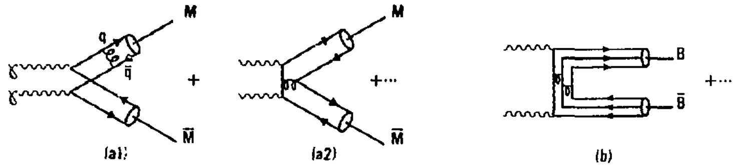

η
η'
J/Ψ→Φη
η→γγ
J/Ψ→ωη
J/Ψ→Φη'
η'→γγ
J/Ψ→ωη'
ρ0→γη
Φ→γη
η→γγ
η'→γρ0
η'→γγ
-y
x
0
0.4
0.8
x = NON STRANGE CONTENT
y = STRANGE CONTENT

Fig. 5


M
q
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+···

Fig. 6

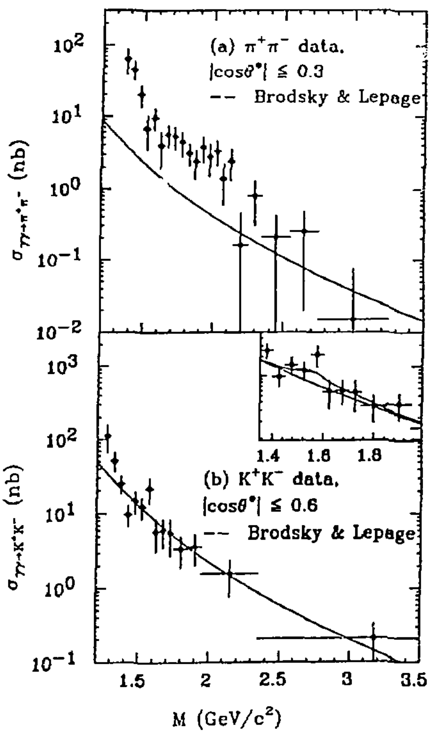

(a) π⁺π⁻ data,
|cosθ*| ≤ 0.3
-- Brodsky & Lepage
$\sigma_{\gamma\gamma\to\pi^+\pi^-}$ (nb)
(b) K⁺K⁻ data,
|cosθ*| ≤ 0.6
-- Brodsky & Lepage
$\sigma_{\gamma\gamma\to K^+K^-}$ (nb)
M (GeV/c²)

Fig. 7

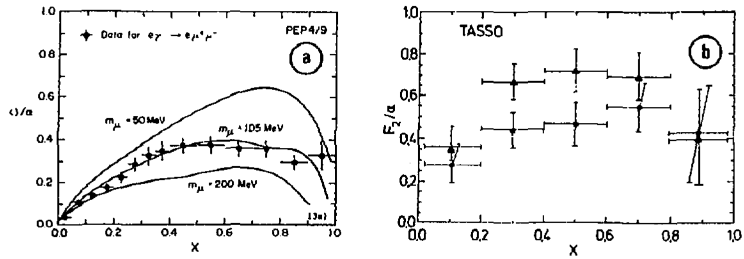

Data for eγ → eμ⁺μ⁻
PEP4/9
a
m_μ = 50 MeV
m_μ = 105 MeV
m_μ = 200 MeV
x
TASSO
b
F₂/α
x

Fig. 8

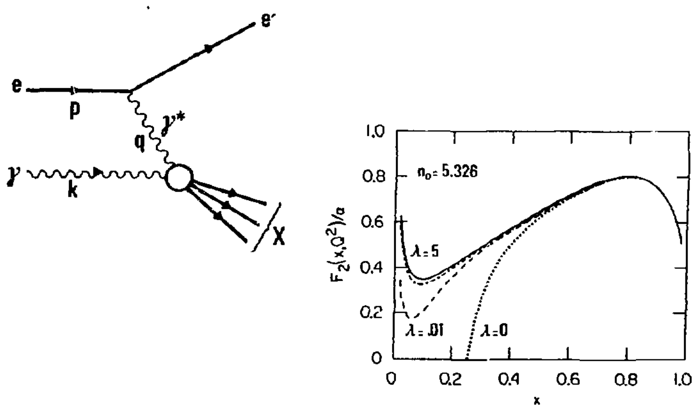
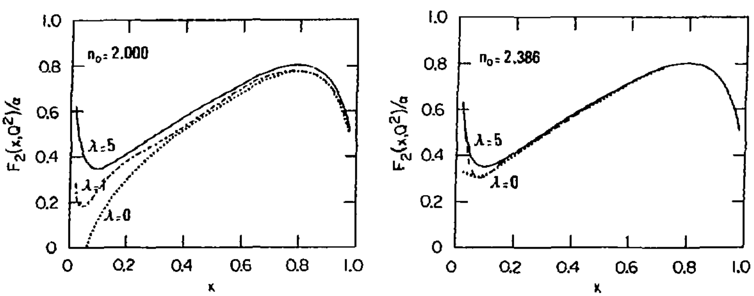

e
p
e'
γ*
q
γ
k
X
n₀ = 5.326
λ = 5
λ = .01
λ = 0
F₂(x,Q²)/α
x

Fig. 9


n₀ = 2.000
λ = 5
λ = 1
λ = 0
F₂(x,Q²)/α
x
n₀ = 2.386
λ = 5
λ = 0
F₂(x,Q²)/α
x