TWO PHOTON PHYSICS

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I. INTRODUCTION

A new experimental frontier has recently been opened to the study of two photon processes. The first results of many aspects of these reactions are being presented at this conference. In contrast, the theoretical development of research into two photon processes has a much longer history. In this talk, I will review the many different theoretical ideas which provide a detailed framework for our understanding of two photon processes.

This field began with papers by Low[1] on resonance production and by Calogero and Zemach[2] on meson pair production, both published in the same volume of the Physical Review in 1960. After a dormant period, interest in two photon processes was renewed in 1970 by a number of groups[3,4,5]. The classic papers by Brodsky, Kinoshita, and Terazawa[3] emphasize the intrinsic physical interest of two photon processes in addition to their role as a background to the annihilation reactions in e^+e^- collisions. The advent of these papers was followed by a burst of theoretical activity which is largely summarized in reviews by Terazawa[6] and Budnev et al[7]. After a diversion provided by the discovery of charm, interest in two photon processes was renewed with emphasis on structure functions, jets and QCD. The progress of the field, both theoretically and experimentally, is emphasized by the creation of specialized annual workshops held at Lake Tahoe in 1979, Amiens in 1980, and in Paris in 1981. We can look forward to continuing interest as more data becomes available to challenge a variety of theoretical speculations.

After a brief discussion of the equivalent photon approximations I will review the theoretical foundation of various aspects of two photon physics. These aspects include resonance production, exclusive particle production, structure functions, and jet production.

II. EQUIVALENT PHOTON APPROXIMATION

We are primarily interested in the physics associated with the two photon reaction, $\gamma^*+\gamma^*\rightarrow X$. This reaction is not observed directly but must be inferred from e^+e^- reactions, $e^++e^-\rightarrow e^++e^-+X$. Severe technical problems are associated with the precision determination of $\gamma^*\gamma^*$ cross-sections from e^+e^- data.

At high energy, the initial e^+ and e^- beams may be approximately treated as an equivalent spectrum of collinear photons. The classical determination of this spectrum involves the equivalent photon approximation (EPA) developed by Weizsäcker and Williams and by Landau and Lifshitz in 1934. Brodsky et al[1] make use of a version of the EPA in their analysis of a number of interesting physical processes. Budnev et al[7] criticize the use of this version of EPA when precision results are needed in certain kinematic regions.

Attempts to improve the EPA have been a continuing interest. To obtain a model independent analysis of two photon processes, a complete study of their kinematic structure was made[8]. The group at College de France[9] has made an extensive study of methods for extracting two photon cross-sections in a variety of situations including various tagging possibilities. The role of standard radiative corrections has also been studied[10] and found to be small in most cases.

An alternative approach to the analysis of two photon processes involves the use of Monte Carlo studies of particular physical processes[11]. This approach requires a detailed modelling of the physical processes, such as provided by the lowest order Feynman diagrams, and then uses a Monte Carlo program to compute the observable cross-sections. This procedure is clearly more sensitive to the experimental configurations but is dependent on the validity of the physical models employed.

The effective luminosity available for various two photon processes was also critically reviewed by J. Field[12] for various machine and tagging possibilities.

These different methods of analysis are important if two photon processes are eventually to provide precision tests of QCD or other dynamical theories. With this somewhat technical introduction, I now turn to the physics of two photon processes.

III. RESONANCE PRODUCTION

In 1960, Low[1] suggested that the π^o lifetime could be determined by observing its production in e^+e^- collisions via the two photon process. He derived an expression which relates the production cross-section to the partial decay width into two photons. This expression, generalized to arbitrary spin, is given by

$$\sigma(e^+e^-\to e^+e^-R) = (2\alpha \ln(s/4M_e^2))^2 \cdot f(M_R^2/s) \cdot (2J+1) \cdot \Gamma(R\to\gamma\gamma)/M_R^3$$

where

$$f(\tau) = (1/2) \cdot (2+\tau)^2 \ln(1/\tau) - (1-\tau)(3+\tau)$$

and s the total energy squared.

In addition to the π^o, even charge conjugation resonances can be produced through the two photon process which are not observable through annihilation. Among these possible resonances are $\pi^o, \eta, \eta', f, f', A_2$, quarkonia $(\eta_c, \chi_c, \eta_b, \chi_b)$, gluonia, Higg's bosons, technibosons, etc. Of course these resonances are not produced with equal efficiency. A comprehensive review by Gilman[13] uses various theoretical and experimental estimates of the partial widths to predict production cross-sections. We present his estimates for an electron beam energy of 15GeV; tables for other energies can be computed directly or found in Gilman's review.

Table I

Resonance	$\Gamma(R\to 2\gamma)$ KeV	$(2\alpha\ln(s/4M_e^2))^2 f(\tau)$	$\sigma(ee\to eeR)$ nb.
π^o	7.95×10^{-3}	1.68	2.1
η	0.324	1.17	0.9
η'	5.9	0.97	2.6
A_2	1.8	0.86	1.3
f	5.0	0.87	4.2
f'	0.4	0.81	0.18
η_c	6.4	0.57	5×10^{-2}
χ_o	1	0.53	5×10^{-3}
χ_2	4/15	0.51	1×10^{-3}
η_b	0.4	0.21	4×10^{-5}

The theoretical framework for estimating $\Gamma(R\to\gamma\gamma)$ is described by Budnev et al[7] and reviewed by Gilman[13]. I will briefly present the various theoretical arguments that have been used for these predictions for the different types of resonances.

A. π^o, η, η': The rate for pseudoscalar meson production is enhanced by the triangle anomaly and can be computed using a low energy theorem following from current algebra and chiral symmetry. The rate is given by

$$\Gamma(R\to\gamma\gamma) = (\alpha^2/(2\pi)^4)\cdot(S^2/f_\pi^2)\cdot M_R^3$$

where the constant $S=tr(\lambda^R Q^2)$ includes the quark color factor and f_π is the pion decay constant. Recent measurements may be compared with the predictions in Table II.

Table II

	Theory	Experiment
$\Gamma(\pi^0\to\gamma\gamma)$	7.6 eV	7.95 eV
$\Gamma(\eta\to\gamma\gamma)$	395 eV	324 eV
$\Gamma(\eta'\to\gamma\gamma)$	6.0 KeV	5.9 KeV

This dramatic agreement seems hard to justify as the use of current algebra for such heavy states as η and η' is suspect, especially when complicated by the "U(1) problem".

B. $f, f', A_2, E, \ldots$: Predictions for the other light quark states are less firmly based and a variety of theoretical models have been used. Early models involved either vector-tensor dominance[14] or FESR and duality[15]. The nonrelativistic quark model has been developed for these states and applied to these reactions[16]. An alternative model based on S-matrix unitarization[17] has also been submitted to this conference.

Krasemann and Vermaseren[16] make an extensive analysis of resonance production observed via the $\pi^+\pi^-$ final state based on the quark model. They obtain a 2γ width of 2-4 KeV and a helicity two dominance in the production. They also find a helicity one component due to virtual photons. Their results are in rough agreement with earlier quark model results and with the FESR predictions which obtain somewhat larger widths. The observation of the $\pi^+\pi^-$ angular distributions and the Q^2 dependence in virtual production provide an important test of these models.

C. $\eta_c, \chi_c, \eta_b, \chi_b, \ldots$: The production of heavy quark states should be well described through the use of the nonrelativistic Schrödinger bound state picture[13]. The two photon widths may be simply calculated in terms of the properties of the wave functions near the origin which can be determined from other reactions. For example, the two photon width of the pseudoscalar state is simply related to the leptonic width of the vector meson through the relation,

$$\Gamma(\eta_q\to 2\gamma) = \Gamma(V_q\to e^+e^-)\cdot(e_q/e)^2$$

where (e_q/e) is the ratio of the heavy quark charge to that of the electron. In a similar manner, the two photon widths of the χ states are related to their hadronic widths by

$$\Gamma(\chi\to\gamma\gamma) = \Gamma(\chi\to GG)\cdot(\alpha/\alpha_s)^2\cdot(9e_q^4/2).$$

The model also makes definite predictions for the helicity structure of the decays. However, it is possible that some of these predictions receive large QCD corrections in higher order.

D. Exotic Particles: Two photon production of the Higgs boson[18] is expected to be quite small due to the small couplings to known fermions and the extremely small induced couplings. It may be possible to see light charged Higgs bosons but they are much more easily seen in annihilation. Similar conclusions must be reached for the production of possible technicolor bosons[19]. Goldberg[20] suggests substantial production of glueball states despite their suppressed two photon couplings.

E. The large cross section observed in $\gamma\gamma\to\rho^0\rho^0$ has motivated a number of speculations on resonant structures. These speculations must be consistant with the lack of similar signal in $\pi^+\pi^-$, etc., final states. Suggestions for resonance explanations range from standard $\bar{q}q$ resonances to glueballs[21]. Nonresonant threshold enhancements are also possible explanations[22]. The quark composite structure of the ρ^0 is one such mechanism that has been advocated by Biswal and Misra[23]. Further clarification of this interesting effect is clearly needed both experimentally and theoretically.

IV. EXCLUSIVE PRODUCTION

In their pioneering paper, Calogero and Zemach[2] studied the exclusive production of muon pairs and pion pairs in two photon reactions. Brodsky et al[3] made extensive numerical studies of these processes and provided the initial framework for understanding details of exclusive production. A vast amount of early research on exclusive reactions is summarized in the reviews of Terazawa[6] and Budnev et al[7]. I will briefly review some aspects of exclusive production by two photons.

A. QED processes: Lepton pair production provides a test not only of QED but also the EPA and other aspects of two photon production[24].

B. Meson production at low energy: Low energy theorems which follow from chiral symmetry and current algebra provide a systematic procedure for analysing the production of soft pions. The normal parity production is determined from the Born terms and current algebra while the abnormal parity production is enhanced by contributions from the Adler anomaly[25]. While these results are clean theoretically, they have limited applicability due to the importance of resonance structure. A recent attempt to incorporate resonance structure through a proper unitarization procedure is discussed by Mennessier[17]. The anomalously large $\rho^0\rho^0$ production discussed in the previous section may be due to resonance structure or, more likely, due to subtle threshold enhancements.

C. Charm production: The photon production of open charm states is quite interesting but is expected to be highly suppressed at current accelerator energies due to the large mass thresholds in the production. Some detailed quark model estimates of the production of $D\bar{D}$, $\bar{D}D^*$, $\bar{D}^*D^*$ have been made by Suaya et al[26].

D. Meson production at high energy: The exclusive production of mesons at high transverse momentum provides a unique test of QCD. Brodsky and Lepage[27] have recently argued that these reactions may be factorized into a contribution coming from the hard scattering of the two photons which is calculable in QCD and a contribution which depends on the meson wavefunction in a minimal $Q\bar{Q}$ Fock state. Simplifications occur from the suppression of vector meson dominance effects because of dimensional counting and Sudakov effects.

Similar techniques can also be applied to the meson-photon transition formfactors, $\gamma^*+\gamma\to M$. The factorization properties can again be applied to give the matrix elements in terms of a perturbatively calculable component and a minimal wavefunction component. These effects are related to the results of meson production in the massive quark model mentioned previously[16].

V. STRUCTURE FUNCTIONS

Two photon processes in the deep inelastic configuration provide a unique probe of the structure of the photon and a sensitive test of QCD. Because of the direct coupling of the photon to quarks, the photon is expected to have a pointlike component in addition to the hadronic component usually described using vector meson dominance (VMD).

The general structure of a hard scattering reaction is normally described by a factor representing the hard scattering off the pointlike constituents of the target and a factor representing the distribution of these constituents in the target. In contrast to the hadronic situation, the target photon can participate directly in the hard scattering process and must, in some sense, be considered its own constituent. If quarks and gluons are considered as possible pointlike constituents, then the general hard scattering cross-section may be represented by a convolution of the constituent cross-sections with the appropriate constituent distribution functions. For a photon target, we have

$$\sigma_\gamma = \tilde{\sigma}_Q \otimes Q + \tilde{\sigma}_G \otimes G + \tilde{\sigma}_\gamma$$

where the VMD (or hadronic) components contribute only to Q and G and the pointlike component generating $\tilde{\sigma}_\gamma$ as well as possible additional contributions to Q and G.

In the parton model the pointlike component in deep inelastic scattering off a photon target has been identified with the 'box' diagram where a quark, or parton, is exchanged between the real and virtual photons[28]. The box diagram gives the contribution

$$F_2^{Box}(x,Q^2) = \sum_Q e_Q^4 \cdot P(x) \cdot \ln(Q^2/m^2)$$

and the full structure function has the form

$$F_2(x,Q^2) = F_2^{Box}(x,Q^2) + F_2^{VMD}(x).$$

The noted features of box contribution are its sensitivity to the fourth power of the quark charge, the stiff x distribution, P(x), and the dominance of the pointlike component at sufficiently high Q^2 over the scaling VMD component.

In QCD, the quarks and gluons are not free constituents but also have pointlike interactions with each other. The first consistent treatment of the photon structure function was made by Witten[29] using the operator product formalism. In this procedure, the asymptotic freedom of QCD permits the calculation of the hard scattering cross-sections as an expansion in the running coupling constant, α_s, and the calculation of the Q^2 evolution of the constituent distributions. This calculation implies the existence of a dominant pointlike component in addition to the normal hadronic terms which reflects the behavior of the box diagram contribution modified by the QCD interactions.

The predictions for the theory are most simply stated in terms of moments of the structure functions,

$$M_n(Q^2) \equiv \int_0^1 dx\, x^{n-2}\, F_2(x,Q^2)$$

$$\rightarrow a_n/\alpha_s(Q^2) + b_n(\text{pointlike}) + \sum_i (\alpha_s(Q^2))^{d_{ni}}(1 + \cdots)C_{ni}(\text{hadronic})$$

where a_n and b_n are calculable coefficients and the exponents, $d_{ni}=\gamma_{ni}^{o}\geq 0$ are the logarithmic anomalous dimensions of the relevant hadronic operators. The pointlike terms dominate at high Q^2 as the asymptotic freedom implies a vanishing of the running coupling constant,

$$\alpha_s(Q^2) \rightarrow 16\pi^2/\beta_o \ln(Q^2/\Lambda^2) \rightarrow 0$$

as $Q^2 \rightarrow \infty$. The asymptotic behavior of the moments becomes

$$M_n(Q^2) \rightarrow A_N \cdot \ln(Q^2/\Lambda^2) + B_N + O(1/\ln Q^2)$$

or for the structure function

$$F_2(x,Q^2) \rightarrow A_2(x) \cdot \ln(Q^2/\Lambda^2) + B_2(x) + O(1/\ln Q^2).$$

The asymptotic structure function has the same Q^2 behavior as the lowest order box diagram, but the shape of the x distribution has been modified to reflect the pointlike dynamics of the quarks and gluons (see Figure 1). Similar leading order (in $\alpha_s(Q^2)$) results have been obtained using many different procedures[30].

The higher order corrections to the pointlike contribution have also been calculated[31]. These corrections involve both the modification of the evolution of $\alpha_s(Q^2)$ and the computation of the coefficient, b_n. These calculations are

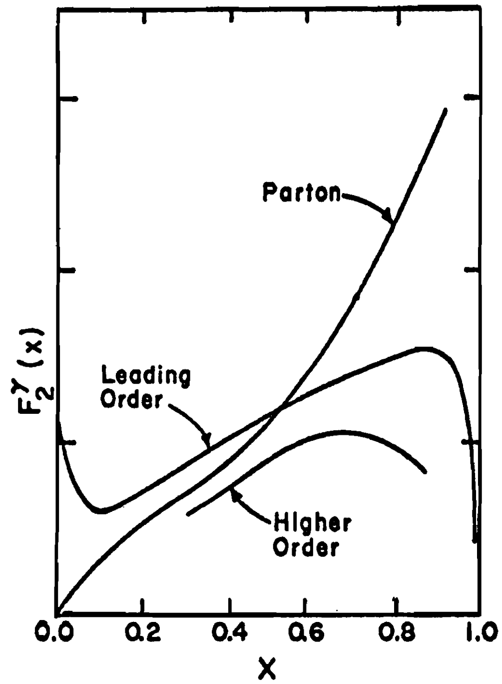

Figure 1. The photon structure function.

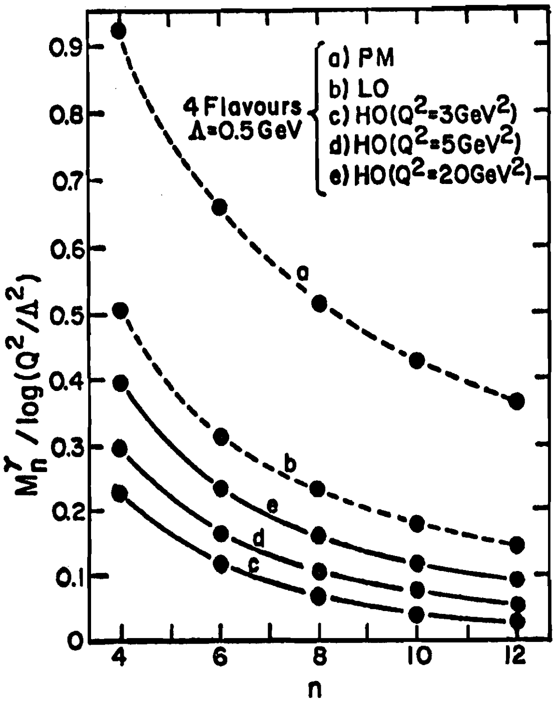

Figure 2. Higher order moments.

necessary if the scale parameter Λ^2 in the definition of $\alpha_s(Q^2)$ is to have significance. These contributions continue to dominate the hadronic contributions asymptotically since all the hadronic anomalous dimensions are positive except for the singlet operators where $d_n \to o$ as $n\to 2$. The effect of these pointlike corrections on the structure functions is shown in Figure 1 and, in more detail, for the moments in Figure 2. The prediction is seen to be perturbative for moderate x. An additional suppression of the structure function at large x beyond that found in leading order is evident.

Duke and Owens[31] emphasize the existence of a strong negative component at small x which forces the structure function negative for sufficiently small values of x. To examine this pathology, they separate the structure function into its valence and sea components,

$$F^\gamma(x,Q^2) = \underset{\text{(Valence)}}{\langle e^4\rangle \cdot F_V^\gamma} + \underset{\text{(Sea)}}{\langle e^2\rangle^2 \cdot F_S^\gamma} \quad .$$

In the valence component, both photons interact with the same quark while the sea component contains all the quark-gluon mixing. The small x singularity occurs only in the sea distribution. This pointlike component mixes strongly with hadronic sea distribution because the anomalous dimensions, d_{n-}, vanishes as $n\to 2, (x\to 0)$. Duke and Owens include a standard vector dominance estimate for the hadronic component which leaves the small x behavior singular as seen in Figure 4.

I conclude that the simple higher order analysis should be valid at moderate x, $.4<x<.9$, where the perturbative approach seems to converge well. However, the perturbative treatment seems to break down for both small x and large x. A realistic analysis at moderate energies will also require the proper treatment of mass effects for the heavy quarks such as charm[32].

A possible resolution of the $x\to 0$ behavior is suggested by the work of Uematsu and Walsh[33]. They study the structure of a virtual photon target. The structure functions are now completely calculable as QCD can be used to evaluate the previously unknown hadronic component. The principal effect they find is the

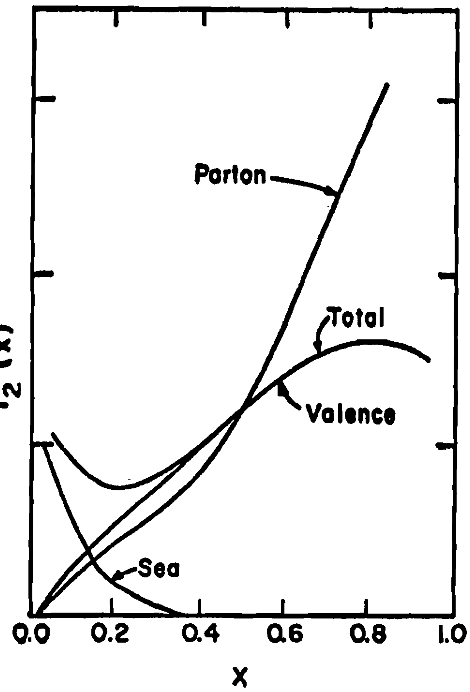

Figure 3. Leading order valence-sea distributions.

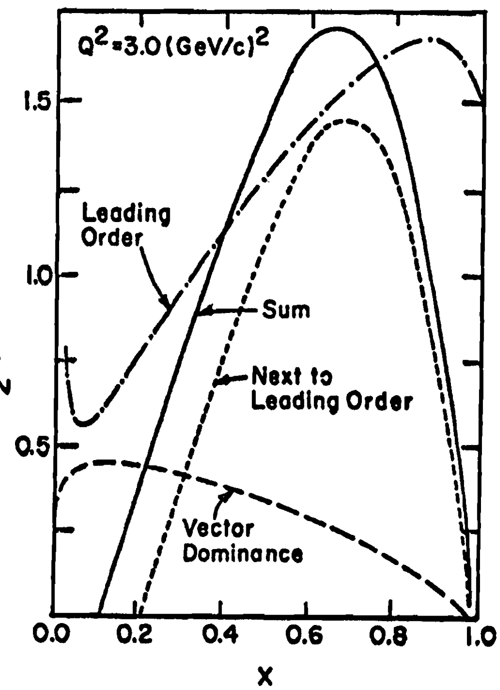

Figure 4. Higher order structure function.

suppression of the QCD corrections particularly those associated with the hadronic operators related to d_{n-}. The negative pointlike contribution of Duke and Owens can be traced to a singular term contained in b_n,

$$b_n \to -1/d_{n-} + \cdots$$

This singularity is compensated by a similar singularity in the hadronic component,

$$c_{n-} \to +(\alpha_s(P^2))^{-d_{n-}}/d_{n-} \quad .$$

Together the contribution to the moment is given by

$$M_n(Q^2) \sim -\frac{1}{d_{n\_}} + \frac{1}{d_{n\_}}(\alpha_s(Q^2)/\alpha_s(P^2))^{d_{n\_}}$$

where P^2 is the mass of the virtual photon target. This combination is nonsingular even when $d_{n-}\to 0$ which occurs as $n\to 2$. Hence the asymptotic behavior as $Q^2\to\infty$ is not uniform in near n=2 or equivalently, small x. While this cancellation is explicit for a virtual photon target, the same cancellation must occur for a real photon target where $\alpha_s(P^2)$ is replaced by an effective scale which can depend on n but whose precise value is not relevant when d_{n-} is small. Since the entire sea contribution is small except for the singularity, once we have determined that the singularity is cancelled by the hadronic sea contribution we should expect the remaining sea contribution will be quite small. The calculable, nonsingular valence contribution will dominate the higher order corrections for small x as well as for moderate values of x.

The higher order calculation also gives large corrections as $x\to 1$. Brodsky and Lepage[34] interpret this behavior as a kinematic effect due to the use of improper phase space limits for the $K_\perp$ integration in leading order. This interpretation is certainly valid in leading order but there are discrepancies[35] in the next order which need clarification. Fortunately these effects are well treated by the higher order perturbative calculation except for x very close to 1.

I have only discussed problems associated with the F_2 structure function. Deep inelastic scattering off a photon target involves four structure functions. The QCD corrections to the longitudinal structure function, F_L, were also computed by Witten[29]. He found that this structure function scales but is modified slightly from the parton model result.

The polarized structure function F_3 and F_4 have been studied by many groups[36]. The F_3 structure function was found to be given correctly by the parton model result. The F_4 structure function behaves in a manner similar to the F_2 structure function with a nonscaling, leading pointlike component. I note that the F_4 structure function involves a "new" set of leading twist hadronic operators which have no proton matrix elements because of the large intrinsic spin required.

Another approach to two photon structure functions outside the context of QCD is that of a massive quark model developed by Preparata[37].

Kripfganz and Schiller[38] argue that many of the problems associated with determining the photon structure functions in e^+e^- reactions could be avoided by directly measuring the electron structure function. They argue that the electron structure function is "calculable" in a manner similar to the photon structure function. However Caldwell and DeGrand[39] argue that the electron structure function is not measurable in the physically interesting region, $x_e \to 0$.

VI. JETS

Quark and gluon jets are produced by the hard scattering subprocesses. The pointlike component of the photon provides a unique mechanism for jet production. The special features of jets produced in two photon processes were emphasized by Brodsky et al[40] and were discussed by Kajantie and Raitio[41] from the context of leading log QCD.

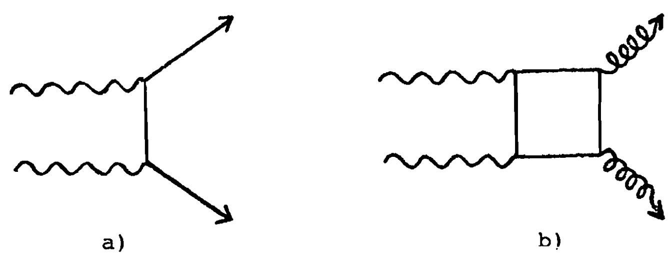

Figure 5. a) two quark jet and b) two gluon jet production.

An example of these predictions is the expected production of two quark jets via the box diagram in the reaction $e^+e^- \to e^+e^- + q\bar{q}$. The jets can be produced cleanly as shown in Figure 5 in contrast to hadronic production where beam fragmentation plays an essential role. The pointlike contribution is expected to dominate the VMD component and provides a good test of QCD[42]. This process is sensitive to the propagator of the exchanged quark and to the quark charges. The two jet cross-section may be directly compared to the equivalent muon pair cross-section through the ratio,

$$R_{\gamma\gamma} = d\sigma(\gamma\gamma \to q\bar{q})/d\sigma(\gamma\gamma \to \mu\bar{\mu}) = \Sigma Q_q^4 = 34/27$$

for u, d, s, c quarks. Two clean gluon jets can also be produced through the virtual box diagrams and represent a nontrivial contribution to the two jet cross-section at current energies.

Three and four jet reactions are also interesting as they are produced by more complex QCD mechanisms. Gluonic corrections, VMD contributions, and higher twist effects all play important roles as indicated by Figures 6 and 7. The pointlike terms dominate and the differential cross-section is expected to scale,

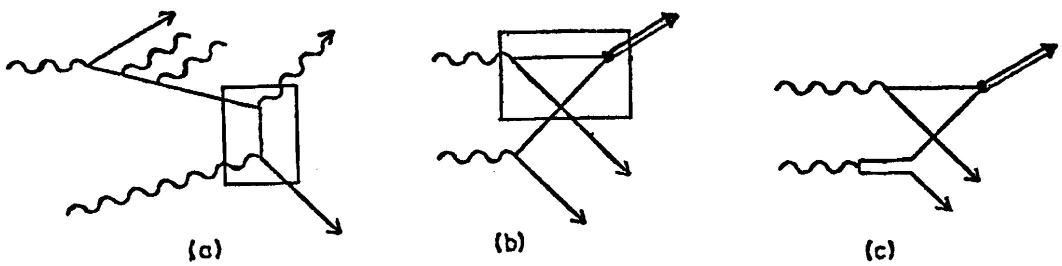

Figure 6. Three jet processes: a) contributions to QCD modification of the structure function b) and c) higher twist contributions.

$$E\frac{d\sigma^{JET}}{d^3P_\perp} \sim (P_\perp)^{-4} F\,(X_J,Q_J)\ .$$

The dependence on the running coupling constant, α_s, cancels as the explicit factor of α_s in the hard scattering amplitude is cancelled by the $(\alpha_s)^{-1}$ factor in the structure function. These reactions are more sensitive to details such as the spin structure, etc., which can enhance the QCD effects[43].

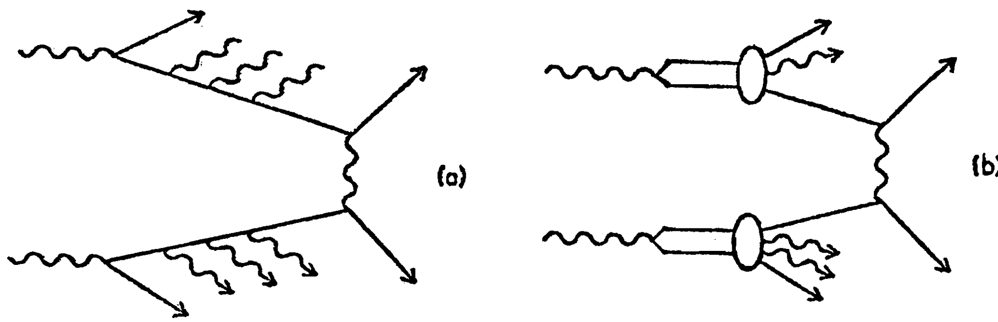

Figure 7. Four jet processes: a) pointlike and b) VMD contributions to quark-quark scattering.

An alternative analysis[44] suggests the use of energy flow, or antenna patterns, to study the implications of QCD for inclusive reactions in two photon processes.

VII. CONCLUSIONS

I have briefly reviewed the many facets of theory which relate to the physics of two photon processes. These range from the variety of mechanisms for resonance production to the detailed QCD calculations for structure functions and jet cross-sections. The experiments are now beginning to provide the precision tests needed to confront these theoretical speculations and to lead to possible new directions in two photon physics.

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Discussion

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I have a comment on "dramatic agreement" between experimental and theoretical values of $\Gamma(\eta \to \gamma\gamma)$. The latter is based on the η-η' mixing angle $\Theta_p = -10°$, which, in fact, is in "dramatic disagreement" with the value $\Theta_p \simeq -18°$, obtained in η/η' production experiments (Sov. J. Nucl. Phys. 30, 189, (1979)). This gives $\Gamma(\eta \to \gamma\gamma)$ which is twice as large as the value quoted by P.D.G., and based on only one Primakoff-type experiment (P.R.L. 32, 1057 (1974)). The earlier measurement gave the value which is larger by a factor of three (Phys. Lett. 25B, 380 (1967)). The angle $\Theta_p \simeq -19°$ was predicted theoretically (Sov. J. Nucl. Phys. 29, 534 (1979)) and is in good agreement with all other available data on radiative decays of vector and pseudoscalar mesons (JETP Lett. 32, 60 (1980), and contributed paper 242). Obviously, a new measurement of $\Gamma(\eta \to \gamma\gamma)$, preferably in 2γ processes in e^+e^- annihilation is extremely desirable.