PHOTON–PHOTON COLLISIONS — PAST AND FUTURE*

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I give a brief review of the history of photon–photon physics and a survey of its potential at future electron–positron colliders. Exclusive hadron production processes in photon–photon and electron–photon collisions provide important tests of QCD at the amplitude level, particularly as measures of hadron distribution amplitudes. There are also important high energy $\gamma\gamma$ and $e\gamma$ tests of quantum chromodynamics, including the production of jets in photon–photon collisions, deeply virtual Compton scattering on a photon target, and leading-twist single-spin asymmetries for a photon polarized normal to a production plane. Since photons couple directly to all fundamental fields carrying the electromagnetic current including leptons, quarks, $W's$, and supersymmetric particles, high energy $\gamma\gamma$ collisions will provide a comprehensive laboratory for Higgs production and exploring virtually every aspect of the Standard Model and its extensions. High energy back-scattered laser beams will thus greatly extend the range of physics of the International Linear Collider.

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1. Introduction

One of the remarkable capabilities of high energy physics is the ability to collide beams of photons. The photons couple directly to the fundamental currents to produce the full spectrum of $C = +$ states with virtually no restriction on their spin J. The photons can annihilate to produce lepton pairs $\gamma\gamma \to \ell^+\ell^-$, exclusive and inclusive $C = +$ hadronic states evolving from $q\bar{q}$ and $q\bar{q}q\bar{q}$ systems, weak vector bosons $\gamma\gamma \to Z^0, W^+W^-$, neutral Higgs bosons $\gamma\gamma \to H^0$, as well as supersymmetric and other particles predicted in theories beyond the Standard Model. The collision of a photon beam with an

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electron beam allows the study of the photon structure function, the photon to hadron transition form factors, such as $\gamma\gamma^* \to \pi^0$, and other virtual $\gamma\gamma^*$ reactions. photon–photon collisions also serve as the prototypes of collisions of the other gauge fields of the Standard model: gluons, Z and W. There are also important high energy $\gamma\gamma$ and $e\gamma$ tests of quantum chromodynamics, including the production of two gluon jets in photon–photon collisions, deeply virtual Compton scattering on a photon target, and leading-twist single-spin asymmetries for a photon polarized normal to a production plane. Exclusive hadron production processes in photon–photon collisions provide important tests of QCD at the amplitude level, particularly as measures of hadron distribution amplitudes which are also important for the analysis of exclusive semi-leptonic and two-body hadronic B-decays.

Since photons couple directly to all fundamental fields carrying the electromagnetic current — leptons, quarks, $W's$, supersymmetric particles, *etc.* — high energy $\gamma\gamma$ collisions will provide a comprehensive laboratory for exploring virtually every aspect of the Standard Model and its extensions [1–7]. High energy back-scattered laser beams will thus greatly extend the range of physics of the International Linear Collider.

2. The theoretical development of photon–photon collisions

The theory of two-photon physics at e^+e^- colliders was developed independently in Paris, Novosibirsk and at Cornell University where I was visiting in 1969–1970. Tom Kinoshita, Hidezumi Terazawa, and I began our work stimulated by reports that an unexpectedly large cross section for hadron production at $\sqrt{s} \sim 3$–5 GeV was being observed by the BOLD experiment at the pioneering CEA e^+e^- storage ring [8, 9]. Richter even speculated at that time on the possibility that electrons could have strong interactions [10]. In our studies we wondered whether the hadrons observed at CEA could be produced by the annihilation of photons produced by bremsstrahlung of the beams rather than by e^+e^- annihilation. In fact, since the BOLD detector had no magnetic field, it was possible that the observed hadrons had lower total energy than the full energy of the machine. We published our first paper in *Physical Review Letters* in August, 1970 [11]: "We report on our calculation of the energy and angular dependence of the cross sections for the production of various particles by two-photon annihilation processes in e^+e^- and e^-e^- colliding beams. For beam energy E of more than 1 GeV, these cross sections $\sigma \propto \alpha^4(\ln E)^3$ become increasingly more important than the usual one-photon cross sections $\sigma \propto \alpha^2/E^2$ for hadron production." We also introduced a factorized form of the two-photon cross section with the equivalent photon distributions for photons in the incident leptons:

$$\sigma(ee \to eeX) = \frac{\alpha^2}{\pi} \ln^2 \frac{E^2}{m_e^2} \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} \frac{(E^2 + (E-\omega_1)^2)(E^2 + (E-\omega_2)^2)}{4E^4} \times d\sigma(\gamma(k_1)\gamma(k_2) \to X)$$

which is the prototype for factorized hard inclusive reactions in QCD. This formula was first proposed in 1960 in a remarkable paper by Francis Low [12] in $e^+e^- \to \pi^0 e^+e^-$ as a way to measure the $\pi^0\gamma\gamma$ coupling. We later published a comprehensive study of hadronic two-photon processes in a Physical Review paper [13]. We found a significant $\gamma\gamma$ rate, but it could not explain the BOLD data [14,15]. In fact as discovered by Richter and collaborators at the SPEAR storage ring at SLAC, the large cross section reported by BOLD was actually due to the onset of charm production [16]. We subsequently learned that Kessler *et al.* [17] in Paris, and Balakin, Budnev, Ginzburg, Meledin, Serbo [18, 19] and Baier and Fadin [20] in Novosibirsk had independently developed the theory of two-photon processes. We also learned that Calegero and Zemach [21] had written a prescient paper in 1960 on the possibility of studying pion pair production in $ee \to ee\pi^+\pi^-$. The work in Russia, utilizing a helicity amplitude decomposition, is reviewed in Ref. [22]. The theoretical developments in Novosibirsk were stimulated by the first observations of lepton pair processes at the e^+e^- collider VEPP-2 [23].

Kinoshita, Terazawa and I [24] and Walsh [25] at DESY also realized that it was possible to probe the structure functions of the photon in $e\gamma \to e'X$ in deep inelastic electron quasi-real photon collisions, in analogy to the probes of the structure functions of the proton. In our analysis, we used vector meson dominance to estimate of the magnitude of the photon structure function. Zerwas and Walsh [26, 27], however, realized that the pointlike couplings of the real photon to quarks would lead to an additional point-like term in the photon structure function rising as $\ln Q^2/m_q^2$. In a remarkable paper, Witten [28] derived the evolution of the photon structure function from first principles, extending DGLAP evolution to allow for an inhomogeneous term from the direct pointlike coupling of the photon to the quark current.

3. Photon–photon collisions at low energy

Quasi-real photon beams are radiated in e^+e^- or e^-e^- colliders, as described by the double equivalent photon approximation $ee \to e'e'\gamma\gamma \to e'e'X$ [13, 22, 29, 30], thus creating a broad bremsstrahlung spectrum of virtual photon energies. By tagging the final state electrons, one can create effective beams of photons with controllable energy, space-like virtuality, and polarization — the photon's linear polarization is transverse to the electron's scattering plane. A large number of studies have been performed at LEP, at CESR, BaBar, Belle, VEPP-4, VEPP-2, and Adone. The QED processes $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\tau^+\tau^-$ have been studied at the L3 detector at LEP at 161 GeV $< \sqrt{s} <$ 209 GeV. The muon pair invariant mass was measured in the range 3 GeV $< W_{\gamma\gamma} <$ 40 GeV. Good agreement was found with $\mathcal{O}(\alpha^4)$ QED expectations. In addition, limits on the anomalous magnetic and electric dipole moments of the tau lepton have been obtained [31].

Photons can scatter elastically at any energy via the light-by-light scattering loop. The contribution of the box graphs $\sigma(\gamma\gamma \to \gamma\gamma) \sim \alpha^4 s^3/m_\ell^8$ has a very small rate in the optical regime at $s \ll 4m_\ell^2$ due to the effective Euler–Heisenberg Lagrangian [32]. However, the light-by-light scattering amplitude is observed indirectly from its contributions of order α^3/π^3 and $\frac{\alpha^3}{\pi^3} \times \ln \frac{m_\mu^2}{m_e^2}$ in the measured anomalous electron and muon anomalous moments. In principle one can observe elastic photon–photon scattering at the positronium and true muonium resonances. The production of lepton pairs in $\gamma\gamma$ scattering $\sigma(\gamma\gamma \to \ell^+\ell^-)$ was first observed in pioneering experiments in Novosibirsk [33] and Frascati [35]. At high energies $s \gg m_\ell^2$, the leading contributions in QED come from double lepton pair production $\sigma(\gamma\gamma \to \ell^+\ell^-\ell^+\ell^-) \sim \frac{\alpha^4}{m_\ell^2}$ where the energy dependence reflects spin-1 photon exchange [34].

One can also study key features of QCD such as hard exclusive hadron pair production $\gamma\gamma \to H\bar{H}$, such as the time-like Compton process $\gamma\gamma \to p\bar{p}$, hard inclusive reactions such as $\sigma(\gamma\gamma \to c\bar{c})$ (proportional to e_c^4, the high energy cross section $\gamma\gamma \to X$ and $\gamma\gamma \to V^0V^0$ which are fundamental of the QCD pomeron BFKL dynamics. The comparison of resonance production in $\gamma\gamma$ and gg channels such as $J/\psi \to \gamma gg$ allows the identification of glueballs using Chanowitz's "stickiness criterion" [36]. The radial extension of the η_c, the $\eta_c'(2^1S_0)$, originally observed in B decays by Belle, has recently been confirmed in $\gamma\gamma \to K_sK\pi$ at 3642.9 ± 3.4 GeV by CLEO. Belle has also reported the discovery of the $Z(3931)$, a candidate for the charmonium state $\chi_2'(2^3P_2)$. A recent review is given in Ref. [37].

4. High energy photon–photon collisions

The advent of back-scattered laser beams for $e^\pm e^-$ colliders will allow the efficient conversion of a substantial fraction of the incident lepton energy into high energy photons [38, 39]. When a polarized laser beam Compton-scatters on a polarized electron beam, each electron is effectively converted into a polarized photon with a high fraction of its energy. The effective luminosity and energy of photon–photon collisions from back-scattered laser beams is expected to be comparable to that of the primary electron–positron collisions. Polarized electron–photon collisions are also an important by-product of this program. The high energy luminosity, and polarization of back-scattered laser beams thus has the potential to make photon–photon collisions a key component of the physics program of the next linear collider [1,2]. This capability will allow detailed studies of a large array of high energy $\gamma\gamma$ and γe collision processes, including polarized beams. The physics program includes tests of electroweak theory in photon–photon annihilation such as $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to$ neutral and charged Higgs bosons, and higher-order loop processes, such as $\gamma\gamma \to \gamma\gamma, Z\gamma, H^0Z^0$ and Z. Since each photon can be resolved into a W^+W^- pair, high energy photon–photon collisions can also provide a remarkably background-free laboratory for studying WW collisions and annihilation. Some of these processes are illustrated in Fig. 1.

High energy photon–photon collisions can be classified as follows: (A) The photons can annihilate into a charged pair such as $\gamma\gamma \to W^+W^-, q\bar{q}$, lepton pairs or charged Higgs; (B) the photons can produce neutral pairs via loop diagrams such as $\gamma\gamma \to Z^0Z^0, \gamma Z^0$ and $\gamma\gamma \to gg$; or (C) the photons can each couple to separate charged pairs which scatter by a gauge particle exchange: $\gamma\gamma \to q_1\bar{q}_1q_2\bar{q}_2$; (D) the photons can fuse to produce a single $C = +$ resonance such as a neutral Higgs, an η_b, or χ_b higher orbital state. Exclusive hadronic final states such as meson or baryon pairs can be formed. In each case, a state of even charge conjugation C is produced in a general partial wave. A recent survey of the physics potential of ee $e\gamma$ and $\gamma\gamma$ colliders has been given by De Roeck [3]. A detailed study of Higgs production in the Standard Model and the Minimal Supersymmetric Standard Model (MSSM) has been summarized by Krawczyk [4] and Asner [40]. Probes of the physics of alternative models, such as the "little Higgs" model [41] is discussed by Asner *et al.* [2]. A review of recent experimental results in two-photon interactions is given by Urner [5].

The Higgs production cross section is

$$\sigma(\gamma\gamma \to H^0) = \frac{8\pi^2 \mathit{\Gamma}_{(H\to\gamma\gamma)}}{M_H} \frac{m_H \mathit{\Gamma}_{\rm tot}/\pi}{(s-m_H^2)^2 + (m_H \mathit{\Gamma}_{\rm tot})^2} \,,$$

where the coupling of the Higgs to the photons can proceed through quark, lepton, and vector boson triangle graphs. One can use the transverse polarization of the colliding photons to distinguish the parity of the resonance: the coupling for a scalar resonance is $\epsilon_1 \cdot \epsilon_2$ *versus* $\epsilon_1 \times k_1 \cdot \epsilon_2$ for the pseudoscalar. More generally, one can use polarized photon–photon scattering to study CP violation in the fundamental Higgs to two-photon couplings [42–44]. In the case of electron–photon collisions, one can use the transverse momentum fall-off of the recoil electron in $e\gamma \to eH^0$ to measure the fall-off of the

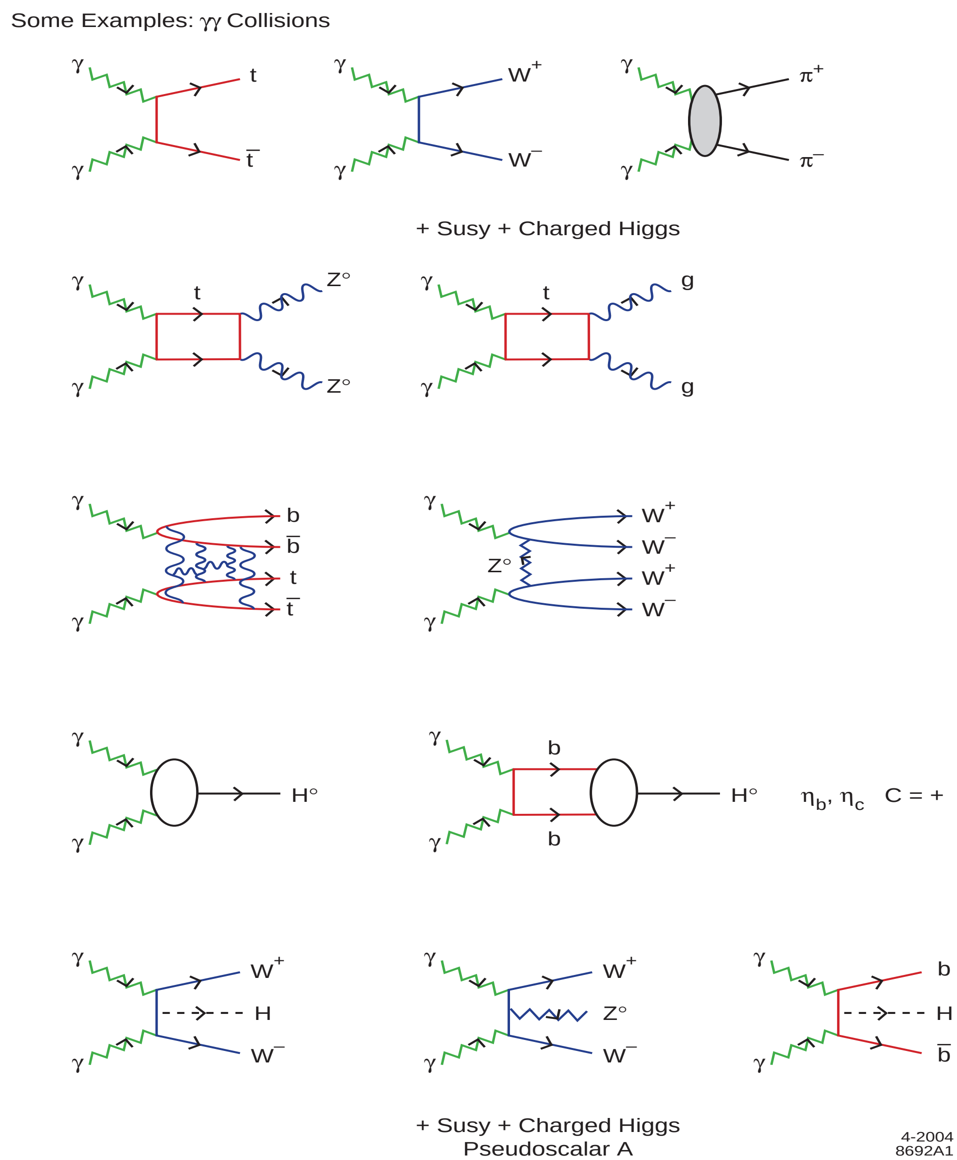

Fig. 1. Representative $\gamma\gamma$ processes accessible at a high energy photon–photon collider.

$\gamma \rightarrow$ Higgs transition form factor and thus check the mass scale of the internal massive quark and W loops coupling to the Higgs. The cross sections for pairs of scalars, fermions or vectors particles are all significantly larger (by about one order of magnitude) in $\gamma\gamma$ collisions than in e^+e^- collisions.

One of the most important applications of two-photon physics is the direct production of $W^{\pm}$ pairs. By using polarized back-scattered laser beams, one can in principle study $\gamma\gamma \to W^+W^-$ production as a function of initial photon helicities as well as resolve the W helicities through their decays. The study of $\gamma\gamma \to W^+W^-$ is complimentary to the corresponding $e^+e^- \to W^+W^-$ channel, but it also can check for the presence of anomalous four-point $\gamma\gamma \to WW$ interactions not already constrained by electromagnetic gauge invariance, such as the effects due to W^* exchange. The cross sections of many Standard Model processes are illustrated in Fig. 2. Reviews of this physics are given in the Refs. [45–49].

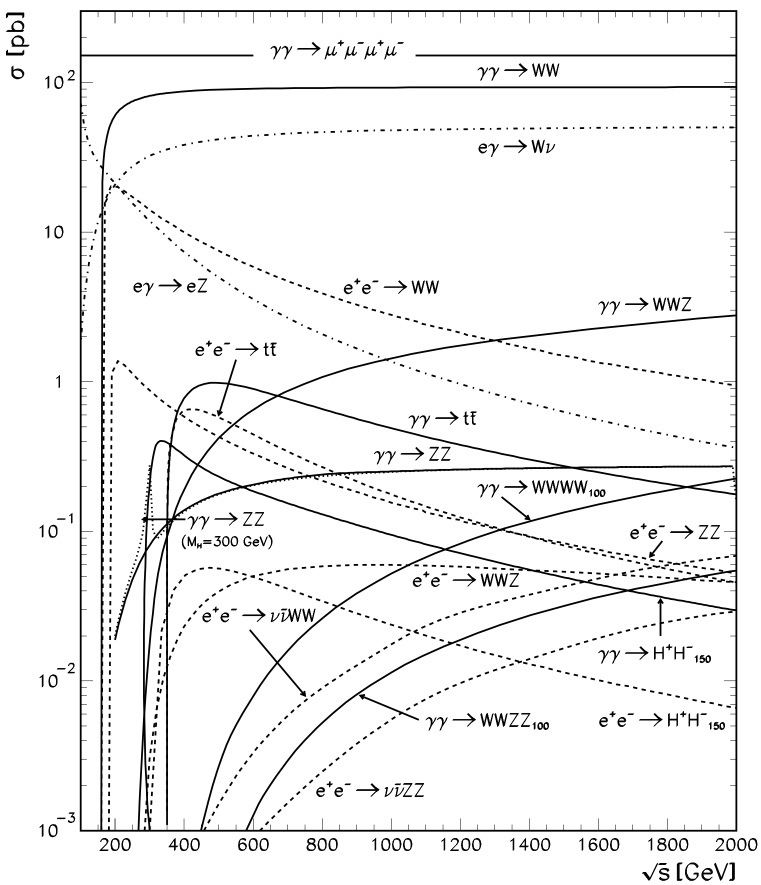

Fig. 2. Typical (unpolarized) cross sections in $\gamma\gamma$, γe and e^+e^- collisions. Solid, dash-dotted and dashed curves correspond to $\gamma\gamma$, γe and e^+e^- modes, respectively. Unless indicated otherwise the neutral Higgs mass was taken to be 100 GeV. For charged Higgs pair production, $M_{H^{\pm}} = 150$ GeV was assumed. From Boos *et al.* [45].

5. Tests for anomalous couplings

Schmidt, Rizzo, and I [50, 51] have shown that one can use the sign change of the integrand of the DHG sum rule to test the canonical couplings of the Standard Model and to isolate the higher order radiative corrections. For example, consider the reactions $\gamma\gamma \to q\overline{q}$, $\gamma e \to W\nu$ and $\gamma e \to Ze$ which can be studied with back-scattered laser beams. In contrast to the time-like process $e^+e^- \to W^+W^-$, the $\gamma\gamma$ and γe reactions are sensitive to the anomalous moments of the gauge bosons at $q^2 = 0$. The vanishing of the logarithmic integral of $\Delta\sigma$ in the Born approximation implies that there must be a center-of-mass energy, $\sqrt{s_0}$, where the polarization asymmetry $A = \Delta\sigma/\sigma$ possesses a zero, *i.e.*, where $\Delta\sigma(\gamma e \to W\nu)$ reverses sign. The cancellation of the positive and negative contributions of $\Delta\sigma(\gamma e \to W\nu)$ to the DHG integral is evident in Fig. 3. We find strong sensitivity of the position of this zero or "crossing point" (which occurs at $\sqrt{s_{\gamma e}} = 3.1583\ldots M_W \simeq 254$ GeV in the SM) to modifications of the SM trilinear γWW coupling and thus can lead to high precision constraints. In addition to the fact that only a limited range of energy is required, the polarization asymmetry measurements have the advantage that many of the systematic errors cancel in taking cross section ratios. This technique can clearly be generalized to other higher order tree-graph processes in the Standard Model and supersymmetric gauge theory. The position of the zero in the photoabsorption asymmetry thus provides an additional weapon in the arsenal used to probe anomalous trilinear gauge couplings.

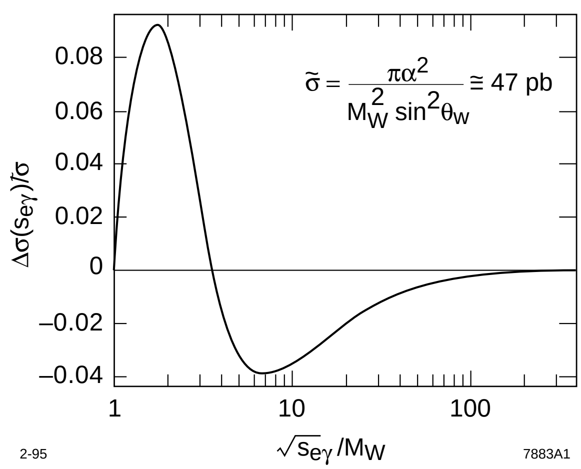

Fig. 3. The Born cross section difference $\Delta\sigma$ for the Standard Model process $\gamma e \to W\nu$ for parallel minus antiparallel electron/photon helicities as a function of $\log \sqrt{s_{e\gamma}}/M_W$. The logarithmic integral of $\Delta\sigma$ vanishes in the classical limit [50].

6. The photon structure functions

One can also utilize electron–photon collisions at a linear collider to test the shape and growth of the photon structure functions [24, 25, 28, 52, 53]. The back-scattered laser beam provides a high energy polarized target photon, and the neutral current probe is obtained by tagging the scattered electron at momentum transfer squared Q^2. One can also reconstruct the charged current contributions where the electron scatters into a neutrino from calorimetric measurements of the recoiling system. It also should be possible to identify the separate charm, bottom, top and W contributions to the photon structure functions.

The photon structure functions receive hadron-like contributions from the photon's resolved Fock components as well as its direct component derived from the $\gamma^*\gamma \to q\bar{q}$ time-like QCD Compton amplitude. Because of the direct contributions, the photon structure functions obey an inhomogeneous evolution equation. The result, as first shown by Witten [28], is that the leading order QCD structure functions of the photon have a unique scaling behavior: $F_1(x,Q^2) = h(x)\ln Q^2/\Lambda^2$, $F_2(x,Q^2) = f_2(x)$, and $F_3(x,Q^2) = f_3^{\rm Box}(x)$.

The most characteristic behavior of the photon structure function $F_2^\gamma(x,Q^2)$ in QCD is its continuous linear rise of with $\log Q^2$ at fixed x. As emphasized by Peterson, Walsh and Zerwas [54], the fact that this tree graph behavior is preserved to all orders in perturbation theory is due to the balance in QCD between the increase of the phase space for gluon emission in the scattering processes *versus* the decreasing strength of the gluon coupling due to asymptotic freedom. Although the logarithmic rise of the Born approximation result is preserved, the shape of $h(x)$ is modified by the QCD radiation. If the running coupling constant were to freeze to a constant value at large momentum transfer, the photon structure function stops rising at high Q^2 due to the increased phase space for gluon radiation. Thus probing the QCD photon structure functions at the high momentum transfers available at the ILC will provide a valuable test of asymptotic freedom.

Hoyer, Marchal, Peigne, Sannino and I [55] have challenged the common view that structure functions measured in deep inelastic lepton scattering are determined by the probability of finding quarks and gluons in the target hadron. We show that this is not correct in gauge theory. Gluon exchange between the fast, outgoing partons and target spectators, which is usually assumed to be an irrelevant gauge artifact, affects the leading twist structure functions in a profound way. This observation removes the apparent contradiction between the projectile (eikonal) and target (parton model) views of diffractive and small $x_{\rm Bjorken}$ phenomena. The diffractive scattering of the fast outgoing quarks on spectators in the target in turn causes shadowing in the DIS cross section. Thus the depletion of the nuclear structure functions is not intrinsic to the wave function of the nucleus, but is a coherent effect arising from the destructive interference of diffractive channels induced by final-state interactions. This is consistent with the Glauber–Gribov interpretation of shadowing as a rescattering effect. Similar effects can be present in the photon structure function; *i.e.*, the photon structure function will be modified by rescattering of the struck quark with the photon's spectator system.

Final state interactions will lead to new types of single spin asymmetries in photon–photon collisions. For example, in $\gamma^* \gamma \to \pi X$ and $\gamma^* \gamma \to \mathrm{jet} X$ we expect T-odd correlations of the type $\vec{S}_\gamma \cdot \vec{q} \times \vec{p}$ where $\vec{S}_\gamma$ is the polarization of the real photon, $\vec{q}$ is the beam direction of an incident virtual photon, and $\vec{p}$ is the direction of a produced quark or hadron. The resulting asymmetry of the photon polarized normal to the production plane will be leading twist. As in the proton target case, the single-spin asymmetry will be sensitive to orbital angular momentum in the photon wavefunction and details of the photon structure at the amplitude level.

7. Single and double diffraction in photon–photon collisions

The high energies of a photon–photon collider will make the study of double diffractive $\gamma\gamma \to V^0 V^0$ and semi-inclusive single diffractive processes $\gamma\gamma \to V^0 X$ in the Regge regime $s \gg |t|$ interesting. Here $V^0 = \rho, \omega\phi, J/\psi, \cdots$ If $|t|$ is taken larger than the QCD confinement scale, then one has the potential for a detailed study of fundamental Pomeron processes and its gluonic composition. As in the case of large angle exclusive $\gamma\gamma$ processes, the scattering amplitude is computed by convoluting the hard scattering pQCD amplitude for $\gamma\gamma \to q\bar{q}q\bar{q}$ with the vector meson distribution amplitudes. The two gluon exchange contribution dominates in the Regge regime [56], giving a characteristic exclusive process scaling law of order $d\sigma/dt\ (\gamma\gamma \to V^0 V^0) \sim \alpha_{\mathrm{s}}^4(t)/t^6$. Ginzburg, Ivanov and Serbo [57] have emphasized that the corresponding $\gamma\gamma \to$ pseudoscalar and tensor meson channels can be used to isolate the Odderon exchange contribution, contributions related at a fundamental level to three gluon exchange.

In addition, the photon can diffractively dissociate into quark pairs $\gamma e \to q\bar{q}e'$ by Coulomb scattering on the incoming electron. This measures the transverse derivative of the photon wavefunction $\partial/\partial k_\perp \psi_{q\bar{q}}(x, k_\perp, \lambda_i)$. This is the analog of the E791 experiment at Fermilab [58] which resolved the pion light-front wavefunction by diffractive dissociation $\pi A \to q\bar{q}A'$ on a nuclear target. The results of the diffractive pion experiment are consistent with color transparency, and the momentum partition of the jets conforms closely with the shape of the asymptotic distribution amplitude,

$\phi_\pi^{\mathrm{asympt}}(x) = \sqrt{3} f_\pi x(1-x)$, corresponding to the leading anomalous dimension solution [59–62] to the perturbative QCD evolution equation.

8. Other QCD tests in photon–photon collisions

Two-photon annihilation $\gamma^*(q_1)\gamma^*(q_2) \to$ hadrons for real and virtual photons can thus provide some of the most detailed and incisive tests of QCD. Among the processes of special interest are:

1. The production of four jets such as $\gamma\gamma \to c\bar{c}c\bar{c}$ can test Fermi-color statistics for charm quarks by checking for the interference effects of like sign quarks.

2. The total two-photon annihilation hadronic cross section $\sigma(s, q_1^2, q_2^2)$, which is related to the light-by-light hadronic contribution to the muon anomalous moment.

3. The formation of $C = +$ hadronic resonances, which can reveal exotic states such as $q\bar{q}g$ hybrids and discriminate gluonium formation [63, 64]. The production of the η_B and χ_B states are essentially unexplored in QCD [65].

4. Single-hadron processes such as $\gamma^*\gamma^* \to \pi^0$, which test the transition from the anomaly-dominated pion decay constant to the short-distance structure of currents dictated by the operator-product expansion and perturbative QCD factorization theorems.

5. Hadron pair production processes such as $\gamma^*\gamma \to \pi^+\pi^-, K^+K^-, p\bar{p}$, which at fixed invariant pair mass measures the $s \to t$ crossing of the virtual Compton amplitude [61]. When one photon is highly virtual, these exclusive hadron production channels are dual to the photon structure function $F_2^\gamma(x, Q^2)$ in the endpoint $x \to 1$ region at fixed invariant pair mass. The leading twist-amplitude for $\gamma^*\gamma \to \pi^+\pi^-$ is sensitive to the $1/x - 1/(1-x)$ moment of the $q\bar{q}$ distribution amplitude $\Phi_{\pi^+\pi^-}(x, Q^2)$ of the two-pion system [66, 67], the time-like extension of skewed parton distributions. In addition one can measure the pion charge asymmetry in $e^+e^- \to \pi^+\pi^-e^+e^-$ arising from the interference of the $\gamma\gamma \to \pi^+\pi^-$ Compton amplitude with the time-like pion form factor [13].

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