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EXCLUSIVE TWO-PHOTON PROCESSES: TESTS OF QCD AT THE AMPLITUDE LEVEL*

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ABSTRACT

Exclusive two-photon processes at large momentum transfer, particularly Compton scattering $\gamma p \to \gamma p$ and its crossed-channel reactions $\gamma\gamma \to \overline{p}p$ and $\overline{p}p \to \gamma\gamma$, can provide definitive information on the bound-state distributions of quarks in hadrons at the amplitude level. Recent theoretical work has shown that QCD predictions based on the factorization of long and short distance physics are already applicable at momentum transfers of order of a few GeV.

1. Introduction

Among the most challenging tests of quantum chromodynamics are exclusive reactions at large momentum transfer. The dynamics of such reactions reflect not only the behavior of quark-gluon scattering processes at the amplitude level, but also the fundamental structure of the hadron wavefunctions themselves [1].

Exclusive reactions involving two real or virtual photons provide an important testing ground for QCD because of the relative simplicity of the couplings of the photons to the underlying quark currents and the absence of significant initial state interactions – any remnant of vector-meson dominance contributions is suppressed at large momentum transfer. The angular distributions for the hadron pair production processes $\gamma\gamma \to H\overline{H}$ are particularly interesting because of their sensitivity to the shapes of the hadron wavefunctions [2]. We can anticipate high statistics, systematic measurements of exclusive two-photon reactions due to the increased luminosity capabilities of the electron-positron storage rings, such as CESR and the proposed B-factories.

The traditional method for examining the structure of a system is to scatter photons on it; *i.e.* Compton scattering. In high energy physics, one can study not only the proton Compton amplitude $\gamma p \to \gamma p$, but also its annihilation cross channels $\gamma\gamma \to p\overline{p}$ and $p\overline{p} \to \gamma\gamma$ by utilizing anti-proton collisions as in the $E760$ experiment at the FermiLab accumulator. One can also envision detailed studies of two-photon annihilation processes for polarized photons utilizing back-scattered laser beams.

Because of asymptotic freedom, the nominal power-law fall-off $\mathcal{M} \sim Q^{4-n}$ of an exclusive amplitude at large momentum transfer reflects the elementary scaling of the lowest-order connected quark and gluon tree graphs obtained by replacing each of the external hadrons by its respective collinear quarks. Here n is the total

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number of initial state and final state lepton, photon, or quark fields entering or leaving the hard scattering subprocess. The empirical success of the dimensional counting rules for the power-law fall-off of form factors and general fixed center-of-mass angle scattering amplitudes has given important evidence for scale-invariant quark and gluon interactions at short distances [3]. QCD also predicts calculable corrections to the nominal dimensional counting power-law behavior due to the running of the strong coupling constant, higher order corrections to the hard scattering amplitude, Sudakov effects, pinch singularities, as well as the evolution of the hadron distribution amplitudes, $\phi_H(x_i, Q)$, the basic factorizable non-perturbative wavefunctions needed to compute exclusive amplitudes [1,4].

In a relativistic quantum field theory, a bound state cannot be described in terms of a fixed number of constituents. However, in the case of exclusive reactions, there is an enormous simplification: only the lowest valence-quark Fock state of each hadron contributes to a high momentum transfer exclusive scattering process. It is easy to show that in the light-cone gauge, $A^+ = 0$, higher Fock state contributions involving extra gluons are always suppressed by powers of the momentum transfer Q. Furthermore, the absence of gluon radiation into the final state demands that the valence quarks in the hadron wavefunction must be at relative transverse separation $b^i_\perp$ of order $1/Q$; thus small color-dipole configurations of the hadron wavefunction control large momentum transfer exclusive processes [5,1].

The fundamental non-perturbative quantities which control large momentum transfer exclusive reactions in quantum chromodynamics are the hadron distribution amplitudes [6]: $\phi_B(x_i, \lambda_i, Q)$, for the baryons with $x_1 + x_2 + x_3 = 1$, and $\phi_M(x_i, \lambda_i, Q)$, for the mesons with $x_1 + x_2 = 1$. The distribution amplitudes are the hadron wavefunctions which interpolate between the QCD bound state and their valence quarks. The constituents have longitudinal light-cone momentum fractions $x_i = (k^0 + k^z)_i/(p^0 + p^z)$, helicities λ_i, and transverse separation $b_\perp \simeq 1/Q$. [Formally, the distribution amplitudes are boost-invariant, gauge-invariant vacuum-to-hadron Bethe-Salpeter matrix elements of the valence quark field operators, evaluated at fixed light-cone time.] If one can calculate the distribution amplitude at an initial scale Q_0, then one can determine $\phi(x_i, Q)$ at higher momentum scales via evolution equations in $\log Q^2$ or equivalently, the operator product expansion. The basic framework used for representing the hadrons in terms of their quark and gluon degrees of freedom is the light-cone Fock state expansion, which provides boost invariant wavefunctions and a consistent basis for deriving hadron amplitudes and parton distributions. A review of these analyses is given in Ref. [1].

Important non-perturbative constraints on the shape of the meson and baryon distribution amplitudes have been obtained from both lattice gauge theory [7] and QCD sum rules [4]. Unfortunately, it is difficult to judge the accuracy or convergence of these predictions, and in some cases, the predictions of the various methods have been contradictory. In the case of QCD in one-space and one time the distribution amplitudes for all of the hadronic bound states can be obtained explicitly by direct diagonalization of the light-cone Hamiltonian using the discretized light-cone quantization (DLCQ) method [8]. Thus far the most important experimental constraints on the hadron distribution amplitudes has come from the normalization and scaling of form factors at large momentum transfer.

It should be emphasized that knowledge of hadron distribution amplitudes is necessary not only for predicting large momentum transfer exclusive amplitudes in QCD, but also for calculating weak decay transitions, structure functions at $x \sim 1$, fragmentation distributions at large z, and higher twist correlations. In each of these applications, one can use factorization theorems to separate the perturbative quark and gluon dynamics which involves momentum transfers higher than Q from the non-perturbative long-distance physics contained in $\phi(x_i, Q)$. These analyses parallel the developments in inclusive reactions, where one factorizes hard-scattering quark-gluon subprocess cross sections from the long-distance physics contained in the hadron structure functions. However, in the case of exclusive processes at large momentum transfer, the scale-separation and factorization are done at the amplitude level. Detailed predictions for meson pair production in two photon collisions using this formalism are given in Ref. [2] and [4].

Isgur and Llewellyn Smith [9] and also Radyshkin [10] have raised the concern that important contributions to exclusive processes could arise from non-factorizing end-point contributions of the hadron wavefunctions with $x \sim 1$ even at very large momentum transfer. However, recent work by Li and Sterman [11] has now shown that such soft physics contributions are effectively eliminated due to Sudakov suppression. I will briefly review this work in Section 3. In addition, as I discuss in the following section, Kronfeld and Nizic [12] have shown how one can consistently integrate over on-shell singularities in the hard-scattering amplitude for Compton processes involving baryons. Thus the QCD predictions based on the factorization of long and short distance physics are reliable and should be valid for momentum transfers in the experimentally accessible domain beyond a few GeV. It is clearly important to test these predictions as precisely as possible.

The simplest example of two-photon exclusive reactions is the $\gamma^*(q)\gamma \to M^0$ process which is measurable in tagged $ee \to eeM^0$ reactions. The photon to neutral meson transition form factor $F_{\gamma \to M^0}(Q^2)$ is predicted to fall as $1/Q^2$ – modulo calculable logarithmic corrections from the evolution of the meson distribution amplitude. The QCD prediction reflects the scale invariance of the quark propagator at high momentum transfer, the same scale-invariance which gives Bjorken scaling of the deep inelastic lepton-nucleon cross sections. The existing data from the TPC/$\gamma\gamma$ experiment are consistent with the predicted scaling and normalization of the transition form factors for the π^0, η_0, and η'. The Mark II and TPC/$\gamma\gamma$ measurements of $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$. reactions are also consistent with PQCD expectations. A review of this work is given in Ref. [13].

2. Compton Scattering in Perturbative QCD

Compton scattering $\gamma p \to \gamma p$ at large momentum transfer and its s-channel crossed reactions $\gamma\gamma \to \bar{p}p$ and $\bar{p}p \to \gamma\gamma$ are classic tests of the perturbative QCD formalism for exclusive reactions. At leading twist, each helicity amplitude has the factorized form [1], (see Fig. 1)

$$\mathcal{M}^{\lambda\lambda'}_{hh'}(s,t) = \sum_{d,i} \int [dx][dy]\phi_i(x_1,x_2,x_3,\widetilde{Q})T^{(d)}_i(x,h,\lambda;y,h',\lambda';s,t)\phi_i(y_1,y_2,y_3;\widetilde{Q}) \ .$$

The index i labels the three contributing valence Fock amplitudes at the renormalization scale $\widetilde{Q}$. The index d labels the 378 connected Feynman diagrams which contribute to the eight-point hard scattering amplitude $qqq\gamma \to qqq\gamma$ at the tree level; *i.e.* at order $\alpha\alpha_s^2(\widehat{Q})$. The arguments $\widehat{Q}$ of the QCD running coupling constant can be evaluated amplitude by amplitude using the method of Ref. [14]. The evaluation of the hard scattering amplitudes $T^{(d)}_i(x,h,\lambda;y,h',\lambda';s,t)$ has now been done by several groups [15,16,12,17].

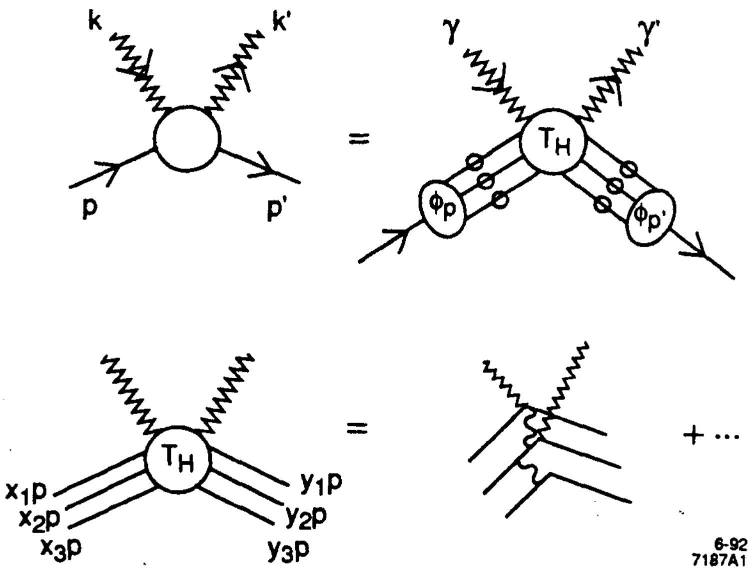

Figure 1. Factorization of the Compton amplitude in QCD.

An important simplification of Compton scattering in PQCD is the fact that pinch singularities are readily integrable and do not change the nominal power-law behavior of the basic amplitudes [12]. Physically, the pinch singularities correspond to the existence of potentially on-shell intermediate states in the hard scattering amplitudes, leading to a non-trivial phase structure of the Compton amplitudes. Such phases can in principle be measured by interfering the virtual Compton process in $e^{\pm}p \rightarrow e^{\pm}p\gamma$ with the purely real Bethe-Heitler bremmstrahlung amplitude [19]. A careful analytic treatment of the integration over the on-shell intermediate states is given by Kronfeld and Nizic [12], and I shall report their results here.

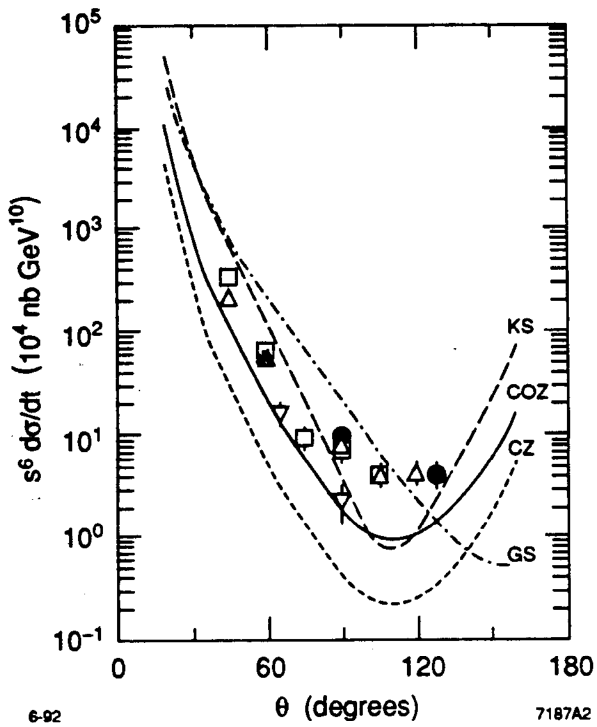

Figure 2. Comparison of the QCD prediction for the scaled unpolarized proton Compton scattering differential cross section $s^6 d\sigma/dt(\gamma p \rightarrow \gamma p)$ with experiment. The experimental data [20] are at $s = 4.63$ GeV (circles) $s = 6.51$ GeV (triangles), $s = 8.38$ GeV (squares) and $s = 10.26$ GeV (asterisk). The QCD prediction is from the calculation of Kronfeld and Nizic [12]. The QCD sum rule distribution amplitudes are listed in Ref. [4].

The most characteristic feature of the PQCD predictions is the scaling of the differential Compton cross section at fixed t/s or θ_{CM}.

$$s^6 \frac{d\sigma}{dt}(\gamma p \rightarrow \gamma p) = F(t/s).$$

The power s^6 reflects the fact that 8 elementary fields enter or leave the hard scattering subprocess [3]. The scaling of the existing data [20] as shown in Fig. 2 is remarkably consistent with the PQCD power-law prediction, but measurements at higher energies and momentum transfer are needed to test the predicted logarithmic corrections to this scaling behavior and determine the angular distribution of the scaled cross section over as large a range as possible.

The predictions for the normalization of the Compton cross section and the shape of its angular distribution are sensitive to the shape of the proton distribution amplitude $\phi_p(x_i, Q)$.

The forms predicted for the proton distribution amplitude by QCD sum-rules by Chernyak, Oglobin, and Zhitnitskii, and also King and Sachrajda, appear to give a reasonable representation of the existing data. These distributions, which predict that 65% of the proton's momentum is carried by the u quark with helicity parallel to the proton's helicity also provide reasonable predictions for the normalization of the proton's form factor and the $J/\psi \to p\overline{p}$ decay rate. Kronfeld and Nizic have also given detailed predictions for the helicity and phase structure of the PQCD predictions for both proton and neutrons. The crossing behavior from the Compton scattering to the annihilation channels will also provide important tests and constraints on the PQCD formalism and the shape of the proton distribution amplitudes. Predictions for the timelike processes have been made by Farrar *et al.* [15], Millers and Gunion [16], and Hyer [17].

It should be emphasized that the theoretical uncertainties from finite nucleon mass corrections, the magnitude of the QCD running coupling constant, and the normalization of the proton distribution amplitude largely cancel out in the ratio of differential cross sections

$$R_{\overline{p}p}(s, \theta_{cm}) = \frac{\frac{d\sigma}{dt}(\overline{p}p \to \gamma\gamma)}{\frac{d\sigma}{dt}(\overline{p}p \to e^+e^-)},$$

which is predicted by QCD to be essentially independent of s at large momentum transfer. If this scaling is confirmed, then the center-of-mass angular dependence of $R_{\overline{p}p}(s, \theta_{cm})$ will be one of the best ways to determine the shape of $\phi_p(x_i, Q)$ [18]. The measurement of this ratio appears to well-suited to the Fermilab antiproton accumulator experiment $E760$ and SuperLear,

Another important characteristic of the leading-twist QCD predictions for exclusive processes is hadron-helicity conservation [21]. Because of chiral invariance, the hard-scattering amplitude is non-zero only for amplitudes that conserve quark helicity. Since the distribution amplitude projects only $L_z = 0$, this implies that the proton helicity is conserved in $\gamma p \to \gamma p$. Similarly, the baryon and x antibaryon helicities must be opposite in the crossed reactions $\gamma\gamma \to \overline{BB}$ and $\overline{p}p \to \gamma\gamma$ at large momentum transfer. Detailed predictions for each of the leading power Compton scattering helicity amplitudes are also given by Kronfeld and Nizic [12].

3. The Domain of Validity of the Perturbative QCD Predictions

The factorized predictions for the Compton amplitude are rigorous predictions of QCD at large momentum transfer. However, it is important to understand the kinematic domain where the leading twist predictions become valid. As emphasized by Isgur and Llewellyn Smith [9], this question is non-trivial because of the possibility of significant contributions to the scattering amplitude at the endpoint regions $x_i \to 1$ where the PQCD factorization could break down. Because of the denominator structure of the hard scattering amplitudes, *e.g.*, $T_H \propto \alpha_s/[(1-x)(1-y)Q^2]$ for the meson form factor, the endpoint integration region at $x \sim 1$ and $y \sim 1$ will be enhanced. Of more concern is the fact that such endpoint regions are even further emphasized when one assumes the strongly asymmetric forms for the nucleon distribution amplitude derived from QCD sum rules.

It is important to note that the end-point regime corresponds to scattering processes where one quark carries nearly all of the proton's momentum and is at a fixed transverse separation $b_\perp$ from the spectator quarks. However, if a quark which is isolated in space receives a large momentum transfer $x_i Q$, it will normally strongly radiate gluons into the final state due to the displacement of both its initial and final self-field, contrary to the requirements of exclusive scattering [11]. For example, in QED. the radiation from the initial and final state charged lines is controlled by the coherent sum

$$\sum_i \frac{\epsilon \cdot p_i}{k \cdot p_i} \eta_i q_i$$

where q_i and p_i are the charges four-momenta of the charged lines, ϵ and k are polarization and four-momentum of the radiation, and $\eta_i = \pm 1$ for initial and final state particles, respectively. Radiation will occur for any finite momentum transfer scattering as long as the photon's wavelength is less than the size of the initial and final neutral bound states. The radiation from the colored lines in QCD have similar coherence properties [22]: because of the destructive color interference of the radiators, the momentum of the radiated gluon in a QCD hard scattering process only ranges from k of order $1/b_\perp$, where color screening occurs, up to the momentum transfer $x_i Q$ of the scattered quarks.

From unitarity, the probability that no radiation occurs during the hard scattering is given by a rapidly-falling exponentiated Sudakov form factor $S = S(x_i Q, b_\perp, \Lambda_{QCD})$; thus at large Q and fixed impact separation, the Sudakov factor strongly suppresses the endpoint contribution. On the other hand, when $b_\perp = \mathcal{O}(x_i Q)^{-1}$, the Sudakov form factor is of order 1, and the radiation leads to logarithmic evolution and contributions of higher order in $\alpha_s(Q^2)$ corrections already contained in the PQCD predictions [6,23,24)]. This is the starting point of the detailed analysis of the suppression of endpoint contributions to meson and baryon form factors and its quantitative effect on the PQCD predictions recently presented by Li and Sterman [11].

It should be emphasized that the standard PQCD contributions to large momentum transfer exclusive reactions derive from wavefunction configurations where the valence quarks are at small transverse separation $b_\perp = \mathcal{O}(1/Q)$, the regime where there is no Sudakov suppression. However, as noted by Li and Sterman, the hard scattering amplitude loses its singular end-point structure if one retains the valence quark transverse momenta in the denominators. For example, in the case of the pion form factor, the hard scattering amplitude is effectively modified to the form

$$T_H \propto \frac{\alpha_s}{(1-x)(1-y)Q^2 + (\mathbf{k}_1^\perp + \mathbf{k}_2^\perp)^2}.$$

Li and Sterman thus find that the pion form factor becomes relatively insensitive to soft gluon exchange at momentum transfers beyond 20 Λ_{QCD}. In the case of the proton Dirac form factor, the corresponding analysis by Li [11] is in good agreement with experiment at momentum transfers greater than 3 GeV.

The Li and Sterman analysis of the Sudakov suppression of endpoint contributions makes it understandable why PQCD factorization and its predictions for exclusive processes are already applicable at momentum transfers of a few GeV, thus accounting for the empirical success of quark counting rules in exclusive process phenomenology. The Sudakov effect suppression also enhances "color transparency" phenomena, since only small color singlet wavefunction configurations can scatter at large momentum transfer [5]. Color transparency in Compton scattering can be tested by checking for the absence of final state absorption in quasi-elastic $\gamma p \to \gamma p$ scattering in heavy nuclei. Similarly, QCD color transparency implies that there will be diminished initial state absorption of the antiproton for large-angle quasi-elastic $\overline{p}p \to \gamma\gamma$ annihilation in heavy nuclear targets.

In the case of large angle proton-proton scattering, the perturbative predictions for color transparency and the spin-spin correlation A_{NN} appear to fail at $E_{CM} \sim 5$ GeV; this effect has been attributed to the effect of the threshold for charm production in intermediate states [25]. A similar breakdown of the perturbative predictions may also occur at the corresponding energy threshold in $\overline{p}p \to \gamma\gamma$ and $\overline{p}p \to \gamma\gamma$ at large angles due to charmed hadron intermediate states.

Recently Luke, Manohar, and Savage [26] have shown that the QCD trace anomaly leads to a strong, attractive, scalar potential which dominates the interaction of heavy quarkonium states with ordinary matter at low relative velocity. The scalar attraction is sufficiently strong to produce nuclear-bound quarkonium [27]. Thus it will be interesting to look for strong threshold enhancements for charm production near threshold in two-photon reactions, particularly in exclusive channels such as $\rho^0 J/\psi$ as well as $D\overline{D}$. Predictions for the threshold production of charmed mesons has also been given in Ref. [28.] Evidence for excess inclusive production of charmed mesons in photon-photon collisions has been reported by the JADE collaboration [29].

Exclusive processes, particularly two-photon reactions, provide one of the most important, but least explored frontiers in particle physics. The recent analyses by Li and Sterman and by Kronfeld and Nizic have shown that the predictions based on QCD factorization theorems are applicable to measurements at present-day accelerators. It is clearly crucial for a fundamental understanding of both the perturbative and non-perturbative aspects of QCD that the predictions for exclusive amplitudes be tested as carefully as possible.

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