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Two-Photon Exclusive Processes in QCD*

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Abstract

Exclusive two-photon reactions such as Compton scattering at large angles, deeply virtual Compton scattering, and hadron production in photon-photon collisions provide important tests of QCD at the amplitude level, particularly as measures of hadron distribution amplitudes and skewed parton distributions.

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1 Introduction

A central focus of study in QCD are the wavefunctions which describe hadrons in terms of their quark and gluon degrees of freedom at the amplitude level. Of particular interest are the gauge- and process-independent meson and baryon valence-quark distribution amplitudes $\phi_M(x, Q)$, and $\phi_B(x_i, Q)$ which control exclusive processes involving a hard scale Q; for example, meson distribution amplitudes play a key role in the analysis of exclusive semi-leptonic and two-body hadronic B-decays[1, 2, 3, 4, 5, 6]. There has recently been considerable progress both in calculating hadron wavefunctions from first principles in QCD and in measuring them using diffractive di-jet dissociation.

Two-photon processes such as $\gamma^*\gamma \to$ hadrons, Compton scattering $\gamma p \to \gamma p$ at large momentum transfer, and $\gamma\gamma \to$ hadron pairs at high momentum transfer and fixed θ_{cm}, can play a crucial role in understanding the perturbative and non-perturbative structure of QCD, first by testing the validity and empirical applicability of leading-twist factorization theorems, second by verifying the structure of the underlying perturbative QCD subprocesses, and third, through measurements of angular distributions and ratios which are sensitive to the shape of the distribution amplitudes. In effect, Compton scattering and photon-photon collisions are microscopes for testing fundamental scaling laws of PQCD and for measuring distribution amplitudes. In addition, as I shall discuss in the next section, deeply virtual Compton scattering $\gamma^* p \to \gamma p$ for far off-shell initial photons has emerged as one of the most important and interesting exclusive QCD reactions.

2 Deeply Virtual Compton Scattering

The virtual Compton scattering amplitude $\frac{d\sigma}{dt}(\gamma^* p \to \gamma p)$ has extraordinary sensitivity to fundamental features of proton structure[7, 8, 9, 10, 11, 12, 13, 14]. Even though the final state photon is on-shell, the deeply virtual Compton process probes the elementary quark structure of the proton near the light cone as an effective local current. In contrast to deep inelastic scattering, which measures only the absorptive part of the $t = 0$ forward virtual Compton amplitude, deeply virtual Compton scattering allows the measurement of the phase and spin structure of proton matrix elements for general momentum transfer t. The scaling, Regge behavior, and phase structure of deeply virtual Compton scattering have been discussed in the context of the covariant parton model in Ref. [15]. The interference of Compton and

bremsstrahlung amplitudes gives an electron-positron asymmetry in the $e^{\pm}p \to e^{\pm}\gamma p$ cross section which is proportional to the real part of the Compton amplitude[15].

To leading order in $1/Q$, the deeply virtual Compton scattering amplitude factorizes as the convolution in x of the amplitude $t^{\mu\nu}$ for hard Compton scattering on a quark line with the generalized Compton form factors $H(x,t,\zeta)$, $E(x,t,\zeta)$, $\tilde{H}(x,t,\zeta)$, and $\tilde{E}(x,t,\zeta)$ of the target proton. Here x is the light-cone momentum fraction of the struck quark, and $\zeta = Q^2/2P\cdot q$ plays the role of the Bjorken variable. The form factor $H(x,t,\zeta)$ describes the proton response when the helicity of the proton is unchanged, and $E(x,t,\zeta)$ is for the case when the proton helicity is flipped. Two additional functions $\tilde{H}(x,t,\zeta)$, and $\tilde{E}(x,t,\zeta)$ appear, corresponding to the dependence of the Compton amplitude on quark helicity. These "skewed" parton distributions involve non-zero momentum transfer, so that a probabalistic interpretation is not possible. However, there are remarkable sum rules connecting the chiral-conserving and chiral-flip form factors $H(x,t,\zeta)$ and $E(x,t,\zeta)$ with the corresponding spin-conserving and spin-flip electromagnetic form factors $F_1(t)$ and $F_2(t)$ and gravitational form factors $A_{\rm q}(t)$ and $B_{\rm q}(t)$ for each quark and anti-quark constituent[7]. Thus deeply virtual Compton scattering is related to the quark contribution to the form factors of a proton scattering in a gravitational field.

One can construct space-like electromagnetic, electroweak, gravitational couplings, or any local operator product matrix element from the diagonal overlap of the LC wavefunctions [16]. In the case of the generalized form factors of deeply virtual Compton scattering, the computation[17, 18] requires not only the diagonal matrix element $n \to n$ for $\zeta < x < 1$, where parton number is conserved, but also an off-diagonal $n+1 \to n-1$ convolution for $0 < x < \zeta$. This second domain occurs since the current operator of the final-state photon with positive light-cone momentum fraction ζ can annihilate a $q\overline{q'}$ pair in the initial proton wavefunction. The off-diagonal terms are referred to in the literature as the "ERBL" contributions, since they resemble virtual Compton scattering on an exchanged mesonic system $\gamma^* q\overline{q'} \to \gamma$ and thus obey the same evolution equations in $\log q^2$ as the meson distribution amplitudes [19, 20, 21, 22]. In fact, the light cone Fock representation shows that there are underlying relations between the Fock states of different particle number which interrelate the two domains.

3 Non-Perturbative Calculations of the Pion Distribution Amplitude

The distribution amplitude $\phi(x, \widetilde{Q})$ can be computed from the integral over transverse momenta of the renormalized hadron valence wavefunction in the light-cone gauge at fixed light-cone time [23]:

$$\phi(x, \widetilde{Q}) = \int d^2\vec{k_\perp}\, \theta\left(\widetilde{Q}^2 - \frac{\vec{k_\perp}^{\,2}}{x(1-x)}\right) \psi^{(\widetilde{Q})}(x, \vec{k_\perp}), \tag{1}$$

where a global cutoff in invariant mass is identified with the resolution $\tilde{Q}$. The distribution amplitude $\phi(x, \tilde{Q})$ is boost and gauge invariant and evolves in $\ln \tilde{Q}$ through an evolution equation[24, 19, 21]. Since it is formed from the same product of operators as the non-singlet structure function, the anomalous dimensions controlling $\phi(x, Q)$ dependence in the ultraviolet $\log Q$ scale are the same as those which appear in the DGLAP evolution of structure functions[25]. The decay $\pi \to \mu\nu$ normalizes the wave function at the origin: $a_0/6 = \int_0^1 dx \phi(x, Q) = f_\pi/(2\sqrt{3})$. One can also compute the distribution amplitude from the gauge invariant Bethe-Salpeter wavefunction at equal light-cone time. This also allows contact with both QCD sum rules[26] and lattice gauge theory; for example, moments of the pion distribution amplitudes have been computed in lattice gauge theory [27, 28, 29]. Conformal symmetry can be used as a template to organize the renormalization scales and evolution of QCD predictions [25, 30]. For example, Braun and collaborators have shown how one can use conformal symmetry to classify the eigensolutions of the baryon distribution amplitude[31].

Dalley[32] has recently calculated the pion distribution amplitude from QCD using a combination of the discretized light-cone quantization[33] method for the x^- and x^+ light-cone coordinates with the transverse lattice method [34, 35] in the transverse directions, A finite lattice spacing a can be used by choosing the parameters of the effective theory in a region of renormalization group stability to respect the required gauge, Poincaré, chiral, and continuum symmetries. The overall normalization gives $f_\pi = 101$ MeV compared with the experimental value of 93 MeV. Figure 1 (a) compares the resulting DLCQ/transverse lattice pion wavefunction with the best fit to the diffractive di-jet data (see the next section) after corrections for hadronization and experimental acceptance [36]. The theoretical curve is somewhat broader than the experimental result. However, there are experimental uncertainties from hadronization and theoretical errors introduced from finite DLCQ resolution, using a nearly massless pion, ambiguities in setting the factorization scale Q^2, as well as

errors in the evolution of the distribution amplitude from 1 to 10 GeV^2. Instanton models also predict a pion distribution amplitude close to the asymptotic form[37]. In contrast, recent lattice results from Del Debbio *et al.*[29] predict a much narrower shape for the pion distribution amplitude than the distribution predicted by the transverse lattice. A new result for the proton distribution amplitude treating nucleons as chiral solitons has recently been derived by Diakonov and Petrov[38]. Dyson-Schwinger models[39] of hadronic Bethe-Salpeter wavefunctions can also be used to predict light-cone wavefunctions and hadron distribution amplitudes by integrating over the relative k^- momentum. There is also the possibility of deriving Bethe-Salpeter wavefunctions within light-cone gauge quantized QCD[40] in order to properly match to the light-cone gauge Fock state decomposition.

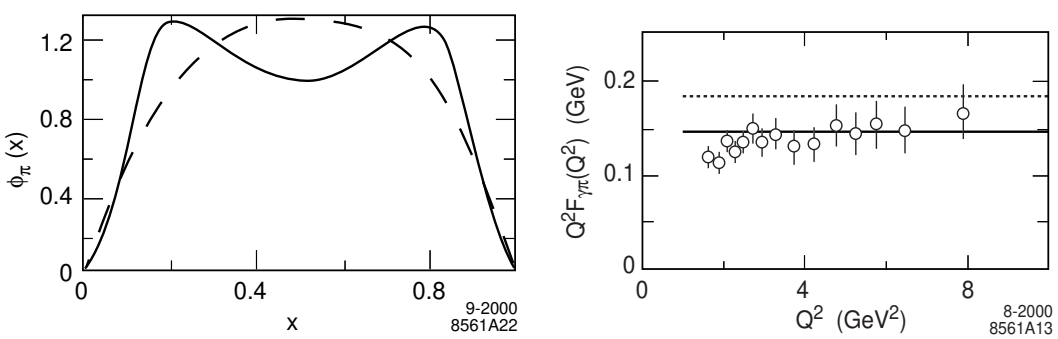

Figure 1: (a) Preliminary transverse lattice results for the pion distribution amplitude at $Q^2 \sim 10\text{GeV}^2$. The solid curve is the theoretical prediction from the combined DLCQ/transverse lattice method[32]; the chain line is the experimental result obtained from jet diffractive dissociation[36]. Both are normalized to the same area for comparison. (b) Scaling of the transition photon to pion transition form factor $Q^2F_{\gamma\pi^0}(Q^2)$. The dotted and solid theoretical curves are the perturbative QCD prediction at leading and next-to-leading order, respectively, assuming the asymptotic pion distribution The data are from the CLEO collaboration[41].

4 Measurements of the Pion Distribution Amplitude by Di-jet Diffractive Dissociation

The shape of hadron distribution amplitudes can be measured in the diffractive dissociation of high energy hadrons into jets on a nucleus. For example, consider the reaction[42, 43, 44] $\pi A \to \text{Jet}_1 + \text{Jet}_2 + A'$ at high energy where the nucleus A' is left intact in its ground state. The transverse momenta of the jets balance so that $\vec{k}_{\perp i} + \vec{k}_{\perp 2} = \vec{q}_\perp < R^{-1}{}_A$. The light-cone longitudinal momentum fractions also need to add to $x_1 + x_2 \sim 1$ so that $\Delta p_L < R_A^{-1}$. The process can then occur coherently in the nucleus. Because of color transparency and the long coherence length, a valence $q\overline{q}$ fluctuation of the pion with small impact separation will penetrate the nucleus with minimal interactions, diffracting into jet pairs[42]. The $x_1 = x$, $x_2 = 1 - x$ dependence of the di-jet distributions will thus reflect the shape of the pion valence light-cone wavefunction in x; similarly, the $\vec{k}_{\perp 1} - \vec{k}_{\perp 2}$ relative transverse momenta of the jets gives key information on the second derivative of the underlying shape of the valence pion wavefunction[43, 44, 45]. The diffractive nuclear amplitude extrapolated to $t = 0$ should be linear in nuclear number A if color transparency is correct. The integrated diffractive rate should then scale as $A^2/R_A^2 \sim A^{4/3}$.

The E791 collaboration at Fermilab has recently measured the diffractive di-jet dissociation of 500 GeV incident pions on nuclear targets[36]. The results are consistent with color transparency, and the momentum partition of the jets conforms closely with the shape of the asymptotic distribution amplitude, $\phi_\pi^{\text{asympt}}(x) = \sqrt{3} f_\pi x(1-x)$, corresponding to the leading anomalous dimension solution[19, 21] to the perturbative QCD evolution equation.

5 The Photon-to-Pion Transition Form Factor and the Pion Distribution Amplitude

The simplest and perhaps most elegant illustration of an exclusive reaction in QCD is the evaluation of the photon-to-pion transition form factor $F_{\gamma\to\pi}(Q^2)$ which is measurable in single-tagged two-photon $ee \to ee\pi^0$ reactions. The form factor is defined via the invariant amplitude $\Gamma^\mu = -ie^2 F_{\pi\gamma}(Q^2)\epsilon^{\mu\nu\rho\sigma} p^\pi_\nu \epsilon_\rho q_\sigma$. As in inclusive reactions, one must specify a factorization scheme which divides the integration regions of the loop integrals into hard and soft momenta, compared to the resolution scale $\tilde{Q}$. At leading twist, the transition form factor then factorizes as a convolution of the $\gamma^*\gamma \to q\overline{q}$

amplitude (where the quarks are collinear with the final state pion) with the valence light-cone wavefunction of the pion:

$$F_{\gamma M}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \phi_M(x, \tilde{Q}) T^H_{\gamma \to M}(x, Q^2). \tag{2}$$

The hard scattering amplitude for $\gamma\gamma^* \to q\overline{q}$ is $T^H_{\gamma M}(x, Q^2) = [(1-x)Q^2]^{-1} (1 + \mathcal{O}(\alpha_s))$. The leading QCD corrections have been computed by Braaten [46]. The evaluation of the next-to-leading corrections in the physical α_V scheme is given in Ref. [47]. For the asymptotic distribution amplitude $\phi_\pi^{\rm asympt}(x) = \sqrt{3} f_\pi x(1-x)$ one predicts $Q^2 F_{\gamma\pi}(Q^2) = 2 f_\pi \left(1 - \frac{5}{3}\frac{\alpha_V(Q^*)}{\pi}\right)$ where $Q^* = e^{-3/2} Q$ is the BLM scale for the pion form factor. The PQCD predictions have been tested in measurements of $e\gamma \to e\pi^0$ by the CLEO collaboration[41]. See Fig. 1 (b). The flat scaling of the $Q^2 F_{\gamma\pi}(Q^2)$ data from $Q^2 = 2$ to $Q^2 = 8$ GeV^2 provides an important confirmation of the applicability of leading twist QCD to this process. The magnitude of $Q^2 F_{\gamma\pi}(Q^2)$ is remarkably consistent with the predicted form, assuming the asymptotic distribution amplitude and including the LO QCD radiative correction with $\alpha_V(e^{-3/2}Q)/\pi \simeq 0.12$. One could allow for some broadening of the distribution amplitude with a corresponding increase in the value of α_V at small scales. Radyushkin [48], Ong [49] and Kroll [50] have also noted that the scaling and normalization of the photon-to-pion transition form factor tends to favor the asymptotic form for the pion distribution amplitude and rules out broader distributions such as the two-humped form suggested by QCD sum rules [51].

The two-photon annihilation process $\gamma^*\gamma \to$ hadrons, which is measurable in single-tagged $e^+e^- \to e^+e^-$hadrons events, provides a semi-local probe of $C = +$ hadron systems $\pi^0, \eta^0, \eta', \eta_c, \pi^+\pi^-$, etc. The $\gamma^*\gamma \to \pi^+\pi^-$ hadron pair process is related to virtual Compton scattering on a pion target by crossing. The leading twist amplitude is sensitive to the $1/x - 1/(1-x)$ moment of the two-pion distribution amplitude coupled to two valence quarks[52, 53].

6 Exclusive Two-Photon Annihilation into Hadron Pairs

Two-photon reactions, $\gamma\gamma \to H\overline{H}$ at large s $= (k_1 + k_2)^2$ and fixed $\theta_{\rm cm}$, provide a particularly important laboratory for testing QCD since these cross-channel "Compton" processes are the simplest calculable large-angle exclusive hadronic scattering reactions. The helicity structure, and often even the absolute normalization can be

rigorously computed for each two-photon channel[54]. In the case of meson pairs, dimensional counting predicts that for large s, $s^4 d\sigma/dt(\gamma\gamma \to M\overline{M}$ scales at fixed t/s or $\theta_{\rm c.m.}$ up to factors of $\ln s/\Lambda^2$. The angular dependence of the $\gamma\gamma \to H\overline{H}$ amplitudes can be used to determine the shape of the process-independent distribution amplitudes, $\phi_H(x,Q)$. An important feature of the $\gamma\gamma \to M\overline{M}$ amplitude for meson pairs is that the contributions of Landshoff pitch singularities are power-law suppressed at the Born level – even before taking into account Sudakov form factor suppression. There are also no anomalous contributions from the $x \to 1$ endpoint integration region. Thus, as in the calculation of the meson form factors, each fixed-angle helicity amplitude can be written to leading order in $1/Q$ in the factorized form $[Q^2 = p_T^2 = tu/s; \tilde{Q}_x = \min(xQ, (l-x)Q)]$:

$$\mathcal{M}_{\gamma\gamma\to M\overline{M}} = \int_0^1 dx \int_0^1 dy \phi_{\overline{M}}(y, \tilde{Q}_y) T_H(x, y, s, \theta_{\rm c.m.} \phi_M(x, \tilde{Q}_x), \tag{3}$$

where T_H is the hard-scattering amplitude $\gamma\gamma \to (q\overline{q})(q\overline{q})$ for the production of the valence quarks collinear with each meson, and $\phi_M(x,\tilde{Q})$ is the amplitude for finding the valence q and $\overline{q}$ with light-cone fractions of the meson's momentum, integrated over transverse momenta $k_\perp < \tilde{Q}$. The contribution of non-valence Fock states are power-law suppressed. Furthermore, the helicity-selection rules[55] of perturbative QCD predict that vector mesons are produced with opposite helicities to leading order in $1/Q$ and all orders in α_s. The dependence in x and y of several terms in $T_{\lambda,\lambda'}$ is quite similar to that appearing in the meson's electromagnetic form factor. Thus much of the dependence on $\phi_M(x,Q)$ can be eliminated by expressing it in terms of the meson form factor. In fact, the ratio of the $\gamma\gamma \to \pi^+\pi^-$ and $e^+e^- \to \mu^+\mu^-$ amplitudes at large s and fixed θ_{CM} is nearly insensitive to the running coupling and the shape of the pion distribution amplitude:

$$\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} \sim \frac{4|F_\pi(s)|^2}{1-\cos^2\theta_{\rm c.m.}}. \tag{4}$$

The comparison of the PQCD prediction for the sum of $\pi^+\pi^-$ plus K^+K^- channels with recent CLEO data[56] is shown in Fig. 2. The CLEO data for charged pion and kaon pairs show a clear transition to the scaling and angular distribution predicted by PQCD[54] for $W = \sqrt{(s_{\gamma\gamma}} > 2$ GeV. It is clearly important to measure the magnitude and angular dependence of the two-photon production of neutral pions and $\rho^+\rho^-$ cross sections in view of the strong sensitivity of these channels to the shape of meson distribution amplitudes. QCD also predicts that the production cross section for charged ρ-pairs (with any helicity) is much larger that for that of neutral

ρ pairs, particularly at large $\theta_{\rm c.m.}$ angles. Similar predictions are possible for other helicity-zero mesons.

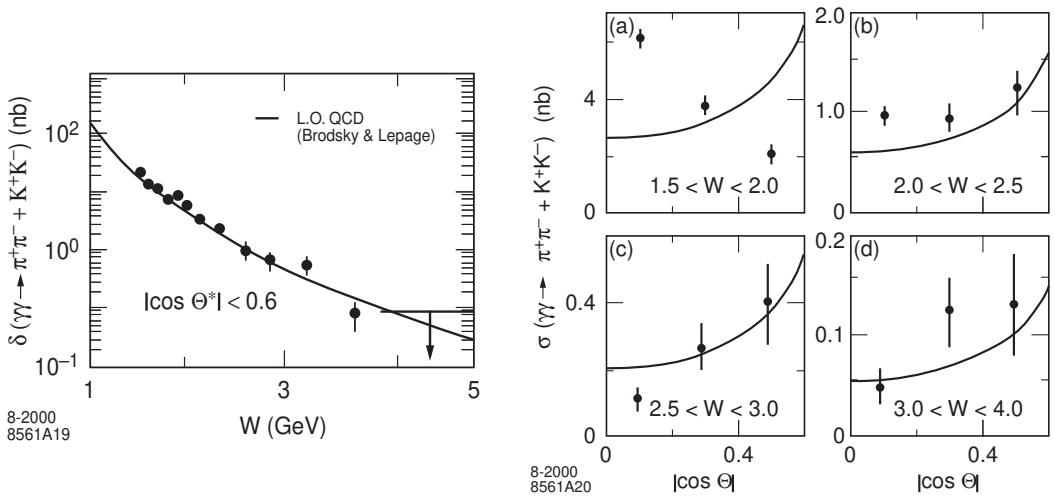

Figure 2: Comparison of the sum of $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ meson pair production cross sections with the scaling and angular distribution of the perturbative QCD prediction[54]. The data are from the CLEO collaboration[56].

Baryon pair production in two-photon annihilation is also an important testing ground for QCD. The only available data is the cross channel reaction, $\gamma p \to \gamma p$. The calculation of T_H for Compton scattering requires the evaluation of 368 helicity-conserving tree diagrams which contribute to $\gamma(qqq) \to \gamma'(qqq)'$ at the Born level and a careful integration over singular intermediate energy denominators [57, 58, 9]. Brooks and Dixon[59] have recently completed a recalculation of the Compton process at leading order in PQCD, extending and correcting earlier work. It is useful to consider the ratio $s^6 d\sigma/dt(\gamma p \to \gamma p)/t^4 F_1^2(ep \to ep)$ where $F_1(t)$ is the elastic helicity-conserving Dirac form factor since the power-law fall-off, the normalization of the valence wavefunctions, and much of the uncertainty from the scale of the QCD coupling cancel. The scaling and angular dependence of this ratio is sensitive to the shape of the proton distribution amplitudes and appears to be consistent with the distribution amplitudes motivated by QCD sum rules. The normalization of the ratio at leading order is not predicted correctly by perturbative QCD. However, it is conceivable that the QCD loop corrections to the hard scattering amplitude are

significantly larger than those of the elastic form factors in view of the much greater number of Feynman diagrams contributing to the Compton amplitude relative to the proton form factor. The perturbative QCD predictions for the phase of the Compton amplitude phase can be tested in virtual Compton scattering by interference with Bethe-Heitler processes[60].

A debate has continued[61, 62, 63, 64] on whether processes such as the pion and proton form factors and elastic Compton scattering $\gamma p \to \gamma p$ might be dominated by higher-twist mechanisms until very large momentum transfer. If one assumes that the light-cone wavefunction of the pion has the form $\psi_{\rm soft}(x, k_\perp) = A \exp(-b \frac{k_\perp^2}{x(1-x)})$, then the Feynman endpoint contribution to the overlap integral at small $k_\perp$ and $x \simeq 1$ will dominate the form factor compared to the hard-scattering contribution until very large Q^2. However, this ansatz for $\psi_{\rm soft}(x, k_\perp)$ has no suppression at $k_\perp = 0$ for any x; *i.e.*, the wavefunction in the hadron rest frame does not fall-off at all for $k_\perp = 0$ and $k_z \to -\infty$. Thus such wavefunctions do not represent well soft QCD contributions. Endpoint contributions are also suppressed by the QCD Sudakov form factor, reflecting the fact that a near-on-shell quark must radiate if it absorbs large momentum. One can show [21] that the leading power dependence of the two-particle light-cone Fock wavefunction in the endpoint region is $1-x$, giving a meson structure function which falls as $(1-x)^2$ and thus by duality a non-leading contribution to the meson form factor $F(Q^2) \propto 1/Q^3$. Thus the dominant contribution to meson form factors comes from the hard-scattering regime. Radyushkin [62] has argued that the Compton amplitude is dominated by soft end-point contributions of the proton wavefunctions where the two photons both interact on a quark line carrying nearly all of the proton's momentum. This description appears to agree with the Compton data at least at forward angles where $-t < 10$ GeV^2. From this viewpoint, the dominance of the factorizable PQCD leading twist contributions requires momentum transfers much higher than those currently available. However, the endpoint model cannot explain the empirical success of the perturbative QCD scaling $s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim$ const at relatively low momentum transfer in pion photoproduction [65].

7 Conclusions

The leading-twist QCD predictions for exclusive two-photon processes such as the photon-to-pion transition form factor and $\gamma\gamma \to$ hadron pairs are based on rigorous factorization theorems. The recent data from the CLEO collaboration on $F_{\gamma\pi}(Q^2)$

and the sum of $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ channels are in excellent agreement with the QCD predictions. It is particularly compelling to see a transition in angular dependence between the low energy chiral and PQCD regimes. The success of leading-twist perturbative QCD scaling for exclusive processes at presently experimentally accessible momentum transfer can be understood if the effective coupling $\alpha_V(Q^*)$ is approximately constant at the relatively small scales Q^* relevant to the hard scattering amplitudes[47]. The evolution of the quark distribution amplitudes in the low-Q^* domain at also needs to be minimal. Sudakov suppression of the endpoint contributions is also strengthened if the coupling is frozen because of the exponentiation of a double logarithmic series.

One of the formidable challenges in QCD is the calculation of non-perturbative wavefunctions of hadrons from first principles. The recent calculation of the pion distribution amplitude by Dalley[32] using light-cone and transverse lattice methods is particularly encouraging. The predicted form of $\phi_\pi(x, Q)$ is somewhat broader than but not inconsistent with the asymptotic form favored by the measured normalization of $Q^2 F_{\gamma\pi^0}(Q^2)$ and the pion wavefunction inferred from diffractive di-jet production.

Clearly much more experimental input on hadron wavefunctions is needed, particularly from measurements of two-photon exclusive reactions into meson and baryon pairs at the high luminosity B factories. For example, the ratio

$$\frac{d\sigma}{dt}(\gamma\gamma \to \pi^0\pi^0)/\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)$$

is particularly sensitive to the shape of pion distribution amplitude. Baryon pair production in two-photon reactions at threshold may reveal physics associated with the soliton structure of baryons in QCD[66]. In addition, fixed target experiments can provide much more information on fundamental QCD processes such as deeply virtual Compton scattering and large angle Compton scattering.

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