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QCD PROCESSES AT THE AMPLITUDE LEVEL *

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Abstract

Some of the most difficult theoretical challenges of QCD occur at the interface of the perturbative and nonperturbative regimes. Exclusive and semi-exclusive processes, the diffractive dissociation of hadrons into jets, and hard diffractive processes such as vector meson leptoproduction provide new testing grounds for QCD and essential information on the structure of light-cone wavefunctions of hadrons, particularly the pion distribution amplitude. I review the basic features of the leading-twist QCD predictions and the problems and challenges of studying QCD at the amplitude level.

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1 Introduction

An audacious claim of the Standard Model is the assertion that all of the properties of hadrons, all of their strong interactions, and even nuclear physics can be derived from just one line, the Lagrangian density of quantum chromodynamics. This assertion is even more remarkable considering that the fundamental quanta and the color charges of QCD cannot be directly observed. In addition to the set of quark masses, $\{m_f\}$ the only dynamical mass scale of QCD is $\Lambda_{QCD} \sim 200$ GeV, the momentum scale where the QCD coupling becomes large.

The traditional focus of theoretical work in QCD has been on hard inclusive processes and jet physics where perturbative methods and leading-twist factorization provide predictions up to next-to-next-to leading order. Most of these predictions appear to be validated by experiment with good precision. More recently, the domain of reliable perturbative QCD predictions has been extended to much more complex phenomena, such as the BFKL approach to the hard QCD pomeron in deep inelastic scattering at small x_{bj}, [1] virtual photon scattering,[2] and the energy dependence of hard virtual photon diffractive processes, such as $\gamma^* p \to \rho^0 p$.[3]

Now a primary goal of both high energy and nuclear physics is to unravel the nonperturbative structure and dynamics of nucleons and nuclei in terms of their fundamental quark and gluon degrees of freedom. There are many applications of QCD where the non-perturbative composition of hadrons in terms of their quark and gluon degrees of freedom play a crucial role, for example the x_{bj}-dependence of structure functions measured in deep inelastic scattering, exclusive and semi-exclusive processes such as form factors, two-photon processes, elastic scattering at fixed θ_{cm}, as well as the semi-leptonic decays of heavy hadrons. The analysis of QCD processes at the amplitude level is a challenging problem, mixing issues involving non-perturbative and perturbative dynamics.

Deep inelastic lepton-proton scattering has provided the traditional guide to the proton's structure. When the photon virtuality is of order of the quark intrinsic transverse momentum, evolution from QCD radiative processes becomes quenched, and the structure functions reveal fundamental features of the proton's composition. The data in fact indicate a nonperturbative structure of nucleons more complex than a simple three quark bound state. For example, if the sea quarks were generated solely by perturbative QCD evolution via gluon splitting, the anti-quark distributions would be approximately isospin symmetric. However, the $\overline{u}(x)$ and $\overline{d}(x)$ antiquark distributions of the proton at $Q^2 \sim 10$ GeV^2 are found to be quite different in shape [4] and thus must reflect dynamics intrinsic to the proton's structure. Evidence for a difference between the $\overline{s}(x)$ and $s(x)$ distributions has also been claimed. [5]

It is helpful to categorize the parton distributions as "intrinsic"—pertaining to the long-time scale composition of the target hadron, and "extrinsic",—reflecting the short-time substructure of the individual quarks and gluons themselves. Gluons carry a significant fraction of the proton's spin as well as its momentum. Since gluon exchange between valence quarks contributes to the $p - \Delta$ mass splitting, it follows

that the gluon distributions cannot be solely accounted for by gluon bremsstrahlung from individual quarks, the process responsible for DGLAP evolutions of the structure functions. Similarly, in the case of heavy quarks, $s\overline{s}$, $c\overline{c}$, $b\overline{b}$, the diagrams in which the sea quarks are multiply connected to the valence quarks are intrinsic to the proton structure itself. [6] The x distribution of intrinsic heavy quarks is peaked at large x reflecting the fact that higher Fock state wavefunctions containing heavy quarks are maximal when the off-shellness of the fluctuation is minimized. The evidence for intrinsic charm at large x in deep inelastic scattering is discussed by Harris *et al.*[7] Thus neither gluons nor sea quarks are solely generated by DGLAP evolution, and one cannot define a resolution scale Q_0 where the sea or gluon degrees of freedom can be neglected.

There have also been surprises associated with the chirality distributions $\Delta q = q_{\uparrow/\uparrow} - q_{\downarrow/\uparrow}$ of the valence quarks which show that a simple valence quark approximation to nucleon spin structure functions is far from the actual dynamical situation.[8]

Part of the complexity of hadronic physics is related to the fact that a relativistic bound state of a quantum field theory fluctuates not only in momentum space and helicity, but also in particle number. For example, the heavy quark sea is associated with higher particle number states. Fortunately we can use the light-cone Fock expansion to provide a frame-independent representation of a hadron in terms of a set of wavefunctions $\{\psi_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)\}$ describing its composition into relativistic quark and gluon constituents. The light-cone Fock representation of QCD obtained by quantizing the theory at fixed "light-cone" time $\tau = t + z/c$.[9] This representation is the extension of Schrödinger many-body theory to the relativistic domain. For example, the proton state has the Fock expansion

$$\begin{aligned} |\, p\rangle &= \sum_n \langle n \,|\, p\rangle \;|\, n\rangle \\ &= \psi^{(\Lambda)}_{3q/p}(x_i, \vec{k}_{\perp i}, \lambda_i) \,|\, uud\rangle \\ &\quad + \psi^{(\Lambda)}_{3qg/p}(x_i, \vec{k}_{\perp i}, \lambda_i) \,|\, uudg\rangle + \cdots \end{aligned} \tag{1}$$

representing the expansion of the exact QCD eigenstate on a non-interacting quark and gluon basis. The probability amplitude for each such n-particle state of on-mass shell quarks and gluons in a hadron is given by a light-cone Fock state wavefunction $\psi_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)$, where the constituents have longitudinal light-cone momentum fractions $x_i = k_i^+/p^+ = (k_i^0 + k_i^z)/(p^0 + p^z)$, $\sum_{i=1}^n x_i = 1$, relative transverse momentum $\vec{k}_{\perp i}$, $\sum_{i=1}^n \vec{k}_{\perp i} = \vec{0}_\perp$, and helicities λ_i. The effective lifetime of each configuration in the laboratory frame is $2P_{lab}/(\mathcal{M}_n^2 - M_p^2)$ where $\mathcal{M}_n^2 = \sum_{i=1}^n (k_{\perp i}^2 + m_i^2)/x_i < \Lambda^2$ is the off-shell invariant mass and Λ is a global ultraviolet regulator.

A crucial feature of the light-cone formalism is the fact that the form of the $\psi^{(\Lambda)}_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)$ is invariant under longitudinal boosts; *i.e.*, the light-cone wavefunctions expressed in the relative coordinates x_i and $k_{\perp i}$ are independent of the total momentum P^+, $\vec{P}_\perp$ of the hadron. The ensemble $\{\psi_{n/H}\}$ of such light-cone Fock wavefunctions is a key concept for hadronic physics, providing a conceptual basis for

representing physical hadrons (and also nuclei) in terms of their fundamental quark and gluon degrees of freedom. Each Fock state interacts distinctly; *e.g.*, Fock states with small particle number and small impact separation have small color dipole moments and can traverse a nucleus with minimal interactions. This is the basis for the predictions for "color transparency". [10]

Given the $\psi^{(\Lambda)}_{n/H}$, we can construct any spacelike electromagnetic or electroweak form factor from the diagonal overlap of the LC wavefunctions.[11] The natural formalism for describing the hadronic wavefunctions which enter exclusive and diffractive amplitudes is the light-cone expansion. Similarly, the matrix elements of the currents that define quark and gluon structure functions can be computed from the integrated squares of the LC wavefunctions.[12]

Can we ever hope to predict the light-cone wavefunctions from first principles in QCD? In the Discretized Light-Cone Quantization (DLCQ) method,[13] periodic boundary conditions are introduced in order to render the set of light-cone momenta $k_i^+, k_{\perp i}$ discrete. Solving QCD then becomes reduced to diagonalizing the mass operator of the theory. Virtually any $1+1$ quantum field theory, including "reduced QCD" (which has both quark and gluonic degrees of freedom) can be completely solved using DLCQ.[14, 15] The method yields not only the bound-state and continuum spectrum, but also the light-cone wavefunction for each eigensolution. The method is particularly elegant in the case of supersymmetric theories. [16] The solutions for the model 1+1 theories can provide an important theoretical laboratory for testing approximations and QCD-based models. Recent progress in DLCQ has been obtained for $3+1$ theories utilizing Pauli-Villars ghost fields to provide a covariant regularization. Broken supersymmetry may be the key method for regulating non-Abelian theories. Light-cone gauge allows one to utilize only the physical degrees of freedom of the gluon field. However, light-cone quantization in Feynman gauge has a number of attractive features, including manifest covariance and a straightforward passage to the Coulomb limit in the case of static quarks.[17]

Exclusive hard-scattering reactions and hard diffractive reactions are now providing an invaluable window into the structure and dynamics of hadronic amplitudes. Recent measurements of the photon-to-pion transition form factor at CLEO,[18] the diffractive dissociation of pions into jets at Fermilab,[19] diffractive vector meson leptoproduction at Fermilab and HERA, and the new program of experiments on exclusive proton and deuteron processes at Jefferson Laboratory are now yielding fundamental information on hadronic wavefunctions, particularly the distribution amplitude of mesons. There is now strong evidence for color transparency from such processes. Such information is also critical for interpreting exclusive heavy hadron decays and the matrix elements and amplitudes entering CP-violating processes at the B factories.

In addition to the light-cone expansion, a number of theoretical tools are available:

1. Factorization theorems for hard exclusive, semi-exclusive, and diffractive processes allow a rigorous separation of soft non-perturbative dynamics of the bound state

hadrons from the hard dynamics of a perturbatively-calculable quark-gluon scattering amplitude. The key non-perturbative input is the gauge and frame independent hadron distribution amplitude [12] defined as the integral over transverse momenta of the valence (lowest particle number) Fock wavefunction; *e.g.* for the pion

$$\phi_\pi(x_i, Q) \equiv \int d^2k_\perp \, \psi^{(Q)}_{q\overline{q}/\pi}(x_i, \vec{k}_{\perp i}, \lambda) \tag{2}$$

where the global cutoff Λ is identified with the resolution Q. The distribution amplitude controls leading-twist exclusive amplitudes at high momentum transfer, and it can be related to the gauge-invariant Bethe-Salpeter wavefunction at equal light-cone time $\tau = x^+$.

2. The logarithmic evolution of hadron distribution amplitudes $\phi_H(x_i, Q)$ can be derived from the perturbatively-computable tail of the valence light-cone wavefunction in the high transverse momentum regime.[12]

3. Conformal symmetry provides a template for QCD predictions, leading to relations between observables which are present even in a theory which is not scale invariant. For example, the natural representation of distribution amplitudes is in terms of an expansion of orthonormal conformal functions multiplied by anomalous dimensions determined by QCD evolution equations.[20, 21] Thus an important guide in QCD analyses is to identify the underlying conformal relations of QCD which are manifest if we drop quark masses and effects due to the running of the QCD couplings. In fact, if QCD has an infrared fixed point (vanishing of the Gell Mann-Low function at low momenta), the theory will closely resemble a scale-free conformally symmetric theory in many applications.

4. Commensurate scale relations[22] are perturbative QCD predictions which relate observable to observable at fixed relative scale, such as the "generalized Crewther relation",[23] which connects the Bjorken and Gross-Llewellyn Smith deep inelastic scattering sum rules to measurements of the e^+e^- annihilation cross section. The relations have no renormalization scale or scheme ambiguity. The coefficients in the perturbative series for commensurate scale relations are identical to those of conformal QCD; thus no infrared renormalons are present.[24] One can identify the required conformal coefficients at any finite order by expanding the coefficients of the usual PQCD expansion around a formal infrared fixed point, as in the Banks-Zak method.[25] All non-conformal effects are absorbed by fixing the ratio of the respective momentum transfer and energy scales. In the case of fixed-point theories, commensurate scale relations relate both the ratio of couplings and the ratio of scales as the fixed point is approached.[24]

5. α_V Scheme. A natural scheme for defining the QCD coupling in exclusive and other processes is the $\alpha_V(Q^2)$ scheme defined from the potential of static heavy quarks. Heavy-quark lattice gauge theory can provide highly precise values for the coupling. All vacuum polarization corrections due to fermion pairs are then automatically and analytically incorporated into the Gell Mann-Low function, thus avoiding the problem of explicitly computing and resumming quark mass corrections related to the running

of the coupling. The use of a finite effective charge such as α_V as the expansion parameter also provides a basis for regulating the infrared nonperturbative domain of the QCD coupling.

6. The Abelian Correspondence Principle. One can consider QCD predictions as analytic functions of the number of colors N_C and flavors N_F. In particular, one can show at all orders of perturbation theory that PQCD predictions reduce to those of an Abelian theory at $N_C \to 0$ with $\widehat{\alpha} = C_F \alpha_s$ and $\widehat{N}_F = N_F/TC_F$ held fixed.[26] There is thus a deep connection between QCD processes and their corresponding QED analogs.

2 Electoweak Decays and the Light-Cone Fock Expansion

Exclusive semi-leptonic B-decay amplitudes, such as $B \to A\ell\overline{\nu}$ can be evaluated exactly in the light-cone formalism.[27] These timelike decay matrix elements require the computation of the diagonal matrix element $n \to n$ where parton number is conserved, and the off-diagonal $n+1 \to n-1$ convolution where the current operator annihilates a $q\overline{q'}$ pair in the initial B wavefunction. (See Fig. 1.) This term is a consequence of the fact that the time-like decay $q^2 = (p_\ell + p_{\overline{\nu}})^2 > 0$ requires a positive light-cone momentum fraction $q^+ > 0$. Conversely for space-like currents, one can choose $q^+ = 0$, as in the Drell-Yan-West representation of the space-like electromagnetic form factors.[28, 11, 29] However, the off-diagonal convolution can yield a nonzero q^+/q^+ limiting form as $q^+ \to 0$. This extra term appears specifically in the case of "bad" currents such as J^- in which the coupling to $q\overline{q}$ fluctuations in the light-cone wavefunctions are favored. In effect, the $q^+ \to 0$ limit generates $\delta(x)$ contributions as residues of the $n+1 \to n-1$ contributions. The necessity for zero mode $\delta(x)$ terms has been noted by Chang, Root and Yan,[30] and Burkardt.[31]

The off-diagonal $n+1 \to n-1$ contributions provide a new perspective for the physics of B-decays. A semi-leptonic decay involves not only matrix elements where a quark changes flavor, but also a contribution where the leptonic pair is created from the annihilation of a $q\overline{q'}$ pair within the Fock states of the initial B wavefunction. The semi-leptonic decay thus can occur from the annihilation of a nonvalence quark-antiquark pair in the initial hadron. This feature will carry over to exclusive hadronic B-decays, such as $B^0 \to \pi^- D^+$. In this case the pion can be produced from the coalescence of a $d\overline{u}$ pair emerging from the initial higher particle number Fock wavefunction of the B. The D meson is then formed from the remaining quarks after the internal exchange of a W boson.

In principle, a precise evaluation of the hadronic matrix elements needed for B-decays and other exclusive electroweak decay amplitudes requires knowledge of all of the light-cone Fock wavefunctions of the initial and final state hadrons. In the case of model gauge theories such as QCD(1+1) [32] or collinear QCD [15] in one-space and one-time dimensions, the complete evaluation of the light-cone wavefunction is

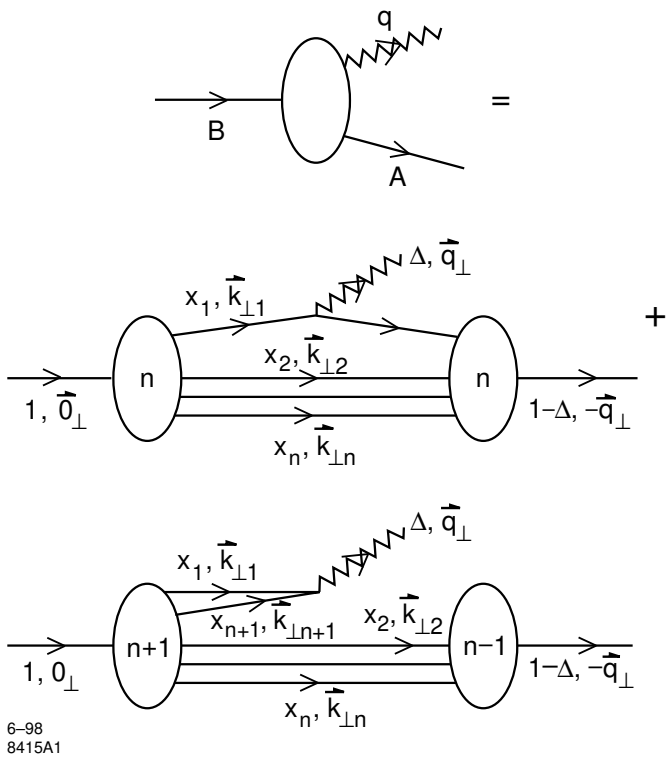

Figure 1: Exact representation of electroweak decays and time-like form factors in the light-cone Fock representation.

possible for each baryon or meson bound-state using the DLCQ method.[13, 15] It would be interesting to use such solutions as a model for physical B-decays.

3 Exclusive Processes in QCD

Exclusive and diffractive reactions are highly challenging to analyze in QCD since they require knowledge of the hadron wavefunctions at the amplitude level. There has been much progress analyzing exclusive and diffractive reactions at large momentum transfer from first principles in QCD. Rigorous statements can be made on the basis of asymptotic freedom and factorization theorems which separate the underlying hard quark and gluon subprocess amplitude from the nonperturbative physics incorporated into the process-independent hadron distribution amplitudes $\phi_H(x_i, Q)$,[12] the valence light-cone wavefunctions integrated over $k_\perp^2 < Q^2$.

In general, hard exclusive hadronic amplitudes such as quarkonium decay, heavy hadron decay, and scattering amplitudes where hadrons are scattered with large momentum transfer can be factorized at leading power as a convolution of distribution

amplitudes and hard-scattering quark/gluon matrix elements[12]

$$\mathcal{M}_{\rm Hadron} = \prod_H \sum_n \int \prod_{i=1}^n d^2k_\perp \prod_{i=1}^n dx\, \delta\left(1-\sum_{i=1}^n x_i\right)\, \delta\left(\sum_{i=1}^n \vec{k}_{\perp i}\right)$$
$$\times \psi^{(\lambda)}_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)\, T_H^{(\Lambda)} \ . \tag{3}$$

Here $T_H^{(\Lambda)}$ is the underlying quark-gluon subprocess scattering amplitude in which the (incident and final) hadrons are replaced by their respective quarks and gluons with momenta $x_i p^+$, $x_i \vec{p}_\perp + \vec{k}_{\perp i}$ and invariant mass above the separation scale $\mathcal{M}_n^2 > \Lambda^2$. At large Q^2 one can integrate over the transverse momenta. The leading power behavior of the hard quark-gluon scattering amplitude $T_H(\vec{k}_{\perp i} = 0)$, defined for the case where the quarks are effectively collinear with their respective parent hadron's momentum, provides the basic scaling and helicity features of the hadronic amplitude. The essential part of the hadron wavefunction is the hadronic distribution amplitudes, [12] defined as the integral over transverse momenta of the valence (lowest particle number) Fock wavefunction, as defined in Eq. 2 where the global cutoff Λ is identified with the resolution Q. The distribution amplitude controls leading-twist exclusive amplitudes at high momentum transfer, and it can be related to the gauge-invariant Bethe-Salpeter wavefunction at equal light-cone time $\tau = x^+$.

The $\log Q$ evolution of the hadron distribution amplitudes $\phi_H(x_i, Q)$ can be derived from the perturbatively-computable tail of the valence light-cone wavefunction in the high transverse momentum regime. The LC ultraviolet regulators provide a factorization scheme for elastic and inelastic scattering, separating the hard dynamical contributions with invariant mass squared $\mathcal{M}^2 > \Lambda^2_{\rm global}$ from the soft physics with $\mathcal{M}^2 \leq \Lambda^2_{\rm global}$ which is incorporated in the nonperturbative LC wavefunctions. The DGLAP evolution of quark and gluon distributions can also be derived in an analogous way by computing the variation of the Fock expansion with respect to Λ^2. The renormalization scale ambiguities in hard-scattering amplitudes via commensurate scale relations[22, 23, 24] which connect the couplings entering exclusive amplitudes to the α_V coupling which controls the QCD heavy quark potential.[33]

The features of exclusive processes to leading power in the transferred momenta are well known:

(1) The leading power fall-off is given by dimensional counting rules for the hard-scattering amplitude: $T_H \sim 1/Q^{n-1}$, where n is the total number of fields (quarks, leptons, or gauge fields) participating in the hard scattering.[34, 35] Thus the reaction is dominated by subprocesses and Fock states involving the minimum number of interacting fields. The hadronic amplitude follows this fall-off modulo logarithmic corrections from the running of the QCD coupling, and the evolution of the hadron distribution amplitudes. In some cases, such as large angle $pp \to pp$ scattering, pinch contributions from multiple hard-scattering processes must also be included.[36] The general success of dimensional counting rules implies that the effective coupling $\alpha_V(Q^*)$ controlling the gluon exchange propagators in T_H are frozen in the infrared,

i.e., have an infrared fixed point, since the effective momentum transfers Q^* exchanged by the gluons are often a small fraction of the overall momentum transfer.[33] The pinch contributions are then suppressed by a factor decreasing faster than a fixed power.[34]

(2) The leading power dependence is given by hard-scattering amplitudes T_H which conserve quark helicity.[37, 38] Since the convolution of T_H with the light-cone wavefunctions projects out states with $L_z = 0$, the leading hadron amplitudes conserve hadron helicity; *i.e.*, the sum of initial and final hadron helicities are conserved. Hadron helicity conservation thus follows from the underlying chiral structure of QCD.

(3) Since the convolution of the hard scattering amplitude T_H with the light-cone wavefunctions projects out the valence states with small impact parameter, the essential part of the hadron wavefunction entering a hard exclusive amplitude has a small color dipole moment. This leads to the absence of initial or final state interactions among the scattering hadrons as well as the color transparency of quasi-elastic interactions in a nuclear target.[10, 39] Color transparency reflects the underlying gauge theoretic basis of the strong interactions. For example, the amplitude for diffractive vector meson photoproduction $\gamma^*(Q^2)p \to \rho p$, can be written as convolution of the virtual photon and the vector meson Fock state light-cone wavefunctions the $gp \to gp$ near-forward matrix element.[40] One can easily show that only small transverse size $b_\perp \sim 1/Q$ of the vector meson distribution amplitude is involved. The sum over the interactions of the exchanged gluons tend to cancel reflecting its small color dipole moment. Since the hadronic interactions are minimal, the $\gamma^*(Q^2)N \to \rho N$ reaction at large Q^2 can occur coherently throughout a nuclear target in reactions without absorption or final state interactions. The $\gamma^* A \to VA$ process thus provides a natural framework for testing QCD color transparency. Evidence for color transparency in such reactions has been found by Fermilab experiment E665.[41]

(4) The evolution equations for distribution amplitudes which incorporate the operator product expansion, renormalization group invariance, and conformal symmetry; [12, 20, 21, 42, 43]

(5) Hidden color degrees of freedom in nuclear wavefunctions reflects the complex color structure of hadron and nuclear wavefunctions.[44] The hidden color increases the normalization of nuclear amplitudes such as the deuteron form factor at large momentum transfer.

The field of analyzable exclusive processes has recently been expanded to a new range of QCD processes, such as the highly virtual diffractive processes $\gamma^* p \to \rho p$,[40, 45] and semi-exclusive processes such as $\gamma^* p \to \pi^+ X$ [46, 47, 48] where the π^+ is produced in isolation at large p_T. An important new application of the perturbative QCD analysis of exclusive processes is the recent analysis of hard B decays such as $B \to \pi\pi$ by Beneke, *et al.*[49]

4 The Transition from Soft to Hard Physics

The existence of an exact formalism provides a basis for systematic approximations and a control over neglected terms. For example, one can analyze exclusive semi-leptonic B-decays which involve hard internal momentum transfer using a perturbative QCD formalism[50, 49] patterned after the analysis of form factors at large momentum transfer.[12] The hard-scattering analysis proceeds by writing each hadronic wavefunction as a sum of soft and hard contributions

$$\psi_n = \psi_n^{\rm soft}(\mathcal{M}_n^2 < \Lambda^2) + \psi_n^{\rm hard}(\mathcal{M}_n^2 > \Lambda^2), \tag{4}$$

where $\mathcal{M}_n^2$ is the invariant mass of the partons in the n-particle Fock state and Λ is the separation scale. The high internal momentum contributions to the wavefunction $\psi_n^{\rm hard}$ can be calculated systematically from QCD perturbation theory by iterating the gluon exchange kernel. The contributions from high momentum transfer exchange to the B-decay amplitude can then be written as a convolution of a hard-scattering quark-gluon scattering amplitude T_H with the distribution amplitudes $\phi(x_i, \Lambda)$, the valence wavefunctions obtained by integrating the constituent momenta up to the separation scale $\mathcal{M}_n < \Lambda < Q$. This is the basis for the perturbative hard-scattering analyses.[50, 51, 52, 49] In the exact analysis, one can identify the hard PQCD contribution as well as the soft contribution from the convolution of the light-cone wavefunctions. Furthermore, the hard-scattering contribution can be systematically improved.

5 Measurement of Light-cone Wavefunctions and Tests of Color Transparency via Diffractive Dissociation.

Diffractive multi-jet production in heavy nuclei provides a novel way to measure the shape of the LC Fock state wavefunctions and test color transparency. For example, consider the reaction [53, 54, 55] $\pi A \to \text{Jet}_1 + \text{Jet}_2 + A'$ at high energy where the nucleus A' is left intact in its ground state. The transverse momenta of the jets have to balance so that $\vec{k}_{\perp i} + \vec{k}_{\perp 2} = \vec{q}_\perp < R^{-1}{}_A$, and the light-cone longitudinal momentum fractions have 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, *i.e.*, the cancelation of color interactions in a small-size color-singlet hadron, the valence wavefunction of the pion with small impact separation will penetrate the nucleus with minimal interactions, diffracting into jet pairs.[53] The two-gluon exchange process in effect differentiates the transverse momentum dependence of the hadron's wavefunction twice. Thus the $x_1 = x$, $x_2 = 1 - x$ dependence of the di-jet distributions will reflect the shape of the pion distribution amplitude; the $\vec{k}_{\perp 1} - \vec{k}_{\perp 2}$ relative transverse momenta of the jets also gives key information on the underlying shape of the valence pion wavefunction.[54, 55] The QCD analysis can be confirmed by the observation

that the diffractive nuclear amplitude extrapolated to $t = 0$ is linear in nuclear number A, as predicted by QCD color transparency. The integrated diffractive rate should scale as $A^2/R_A^2 \sim A^{4/3}$. A diffractive dissociation experiment of this type, E791, is now in progress at Fermilab using 500 GeV incident pions on nuclear targets.[19] The preliminary results from E791 appear to be consistent with color transparency. The momentum fraction distribution of the jets is consistent with a valence light-cone wavefunction of the pion consistent with the shape of the asymptotic distribution amplitude, $\phi_\pi^{\rm asympt}(x) = \sqrt{3} f_\pi x(1-x)$. Data from CLEO[18] for the $\gamma\gamma^* \to \pi^0$ transition form factor also favor a form for the pion distribution amplitude close to the asymptotic solution[12] to the perturbative QCD evolution equation.[56, 57, 33, 58, 59] It is also possible that the distribution amplitude of the $\Delta(1232)$ for $J_z = 1/2, 3/2$ is close to the asymptotic form $x_1 x_2 x_3$, but that the proton distribution amplitude is more complex. This would explain why the $p \to \Delta$ transition form factor appears to fall faster at large Q^2 than the elastic $p \to p$ and the other $p \to N^*$ transition form factors.[60] It will thus be very interesting to study diffractive tri-jet production using proton beams dissociating into three jets on a nuclear target. $pA \to \text{Jet}_1 + \text{Jet}_2 + \text{Jet}_3 + A'$ to determine the fundamental shape of the 3-quark structure of the valence light-cone wavefunction of the nucleon at small transverse separation.[54]

It is also interesting to consider the Coulomb dissociation of hadrons as a means to resolve their light-cone wavefunctions.[61] In the case of photon exchange, the transverse momentum dependence of the light-cone wavefunction is differentiated only once. For example, consider the process $ep \to e'\text{Jet}_1 + \text{Jet}_2 + \text{Jet}_3$ in which the proton dissociates into three distinct jets at large transverse momentum by scattering on an electron. In the case of an ep collider such as HERA, one can require all of the hadrons to be produced outside a forward annular exclusion zone, $\theta_H > \theta_{\rm min}$, thus ensuring a minimum transverse momentum of each produced final state particle. The distribution of hadron longitudinal momentum in each azimuthal sector can be used to determine the underlying x_1, x_2, x_3 dependence of the proton's valence three-quark wavefunction. Such a procedure will allow the proton to self-resolve its fundamental structure.

One can use incident real and virtual photons: $\gamma^* A \to \text{Jet}_1 + \text{Jet}_2 + A'$ to confirm the shape of the calculable light-cone wavefunction for transversely-polarized and longitudinally-polarized virtual photons. At low transverse momentum, one expects interesting nonperturbative modifications. Such experiments will open up a direct window on the amplitude structure of hadrons at short distances.

6 Leading Power Dominance in Exclusive QCD Processes

As a rule, exclusive reactions at large momentum transfer appear to approach the empirical power law fall-off predicted by dimensional counting. The PQCD pre-

dictions appear to be accurate over a large range of momentum transfer, consistent with the small mass scale of QCD. These include processes such as the proton form factor, time-like meson pair production in e^+e^- and $\gamma\gamma$ annihilation, large-angle scattering processes such as pion photoproduction $\gamma p \to \pi^+ p$, and nuclear processes such as the deuteron form factor at large momentum transfer and deuteron photodisintegration.[62] A spectacular example is the recent measurements at CESR of the photon to pion transition form factor in the reaction $e\gamma \to e\pi^0$.[18] As predicted by leading twist QCD[12] $Q^2 F_{\gamma\pi^0}(Q^2)$ is essentially constant for 1 GeV$^2 < Q^2 <$ 10 GeV^2. Furthermore, the normalization is consistent with QCD at NLO if one assumes that the pion distribution amplitude takes on the form $\phi_\pi^{\rm asympt}(x) = \sqrt{3} f_\pi x(1-x)$ which is the asymptotic solution[12] to the evolution equation for the pion distribution amplitude.[56, 57, 33, 59]

The measured deuteron form factor and the deuteron photodisintegration cross section appear to follow the leading-twist QCD predictions at large momentum transfers in the few GeV region.[63, 64] The normalization of the measured deuteron form factor is large compared to model calculations [65] assuming that the deuteron's six-quark wavefunction can be represented at short distances with the color structure of two color singlet baryons. This provides indirect evidence for the presence of hidden color components as required by PQCD.[44]

There are, however, experimental exceptions to the general success of the leading twist PQCD approach, such as (a) the dominance of the $J/\psi \to \rho\pi$ decay which is forbidden by hadron helicity conservation and (b) the strong normal-normal spin asymmetry A_{NN} observed in polarized elastic $pp \to pp$ scattering and an apparent breakdown of color transparency at large CM angles and $E_{CM} \sim 5$ GeV. These conflicts with leading-twist PQCD predictions can be used to identify the presence of new physical effects. For example, It is usually assumed that a heavy quarkonium state such as the J/ψ always decays to light hadrons via the annihilation of its heavy quark constituents to gluons. However, the transition $J/\psi \to \rho\pi$ can also occur by the rearrangement of the $c\overline{c}$ from the J/ψ into the $|\, q\overline{q}c\overline{c}\rangle$ intrinsic charm Fock state of the ρ or π.[66] On the other hand, the overlap rearrangement integral in the decay $\psi' \to \rho\pi$ will be suppressed since the intrinsic charm Fock state radial wavefunction of the light hadrons will evidently not have nodes in its radial wavefunction. This observation provides a natural explanation of the long-standing puzzle why the J/ψ decays prominently to two-body pseudoscalar-vector final states, whereas the ψ' does not. The unusual effects seen in elastic proton-proton scattering at $E_{CM} \sim 5$ GeV and large angles could be related to the charm threshold and the effect of a $|\, uuduudc\overline{c}\rangle$ resonance which would appear as in the $J = L = S = 1$ pp partial wave.[67]

If the pion distribution amplitude is close to its asymptotic form, then one can predict the normalization of exclusive amplitudes such as the spacelike pion form factor $Q^2 F_\pi(Q^2)$. Next-to-leading order predictions are available which incorporate higher order corrections to the pion distribution amplitude as well as the hard scattering amplitude.[21, 68, 69] However, the normalization of the PQCD prediction for the pion form factor depends directly on the value of the effective coupling $\alpha_V(Q^*)$

at momenta $Q^{*2} \simeq Q^2/20$. Assuming $\alpha_V(Q^*) \simeq 0.4$, the QCD LO prediction appears to be smaller by approximately a factor of 2 compared to the presently available data extracted from the original pion electroproduction experiments from CEA.[70] A definitive comparison will require a careful extrapolation to the pion pole and extraction of the longitudinally polarized photon contribution of the $ep \to \pi^+ n$ data.

Recent experiments at Jefferson laboratory utilizing a new polarization transfer technique indicate that $G_E(Q^2)/G_M(Q^2)$ falls with increasing momentum transfer $-t = Q^2$ in the measured domain $1 < Q^2 < 3$ GeV^2.[71] This observation implies that the helicity-changing Pauli form factor $F_2(Q^2)$ is comparable to the helicity conserving form factor $F_2(Q^2)$ in this domain. If such a trend continues to larger Q^2 it would be in severe conflict with the hadron-helicity conserving principle of perturbative QCD. If F_2 were comparable to F_1 at large Q^2 in the case of timelike processes, such as $p\overline{p} \to e^+e^-$, where $G_E = F_1 + \frac{Q^2}{4M_N^2}F_2$, one would see strong deviations from the usual $1 + \cos^2\theta$ dependence of the differential cross section as well as PQCD scaling.[72] This seems to be in conflict with the available data from the $E835$ $\overline{p}p \to e^+e^-$ experiment at Fermilab.[73]

A debate has continued 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 transfers.[74, 75, 76] For example, 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, the above form of $\psi_{\rm soft}(x, k_\perp)$ 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 soft QCD contributions. Furthermore, such endpoint contributions will be suppressed by the QCD Sudakov form factor, reflecting the fact that a near-on-shell quark must radiate if it absorbs large momentum. If the endpoint contribution dominates proton Compton scattering, then both photons will interact on the same quark line in a local fashion, and the amplitude is predicted to be real, in strong contrast to the complex phase structure of the PQCD predictions. It should be noted that there is no apparent endpoint contribution which could explain the success of dimensional counting (s^{-7} scaling at fixed θ_{cm}) in large-angle pion photoproduction.

The perturbative QCD predictions[77] for the Compton amplitude phase can be tested in virtual Compton scattering by interference with Bethe-Heitler processes.[78] One can also measure the interference of deeply virtual Compton amplitudes with the timelike form factors by studying reactions in e^+e^- colliders such as $e^+e^- \to \pi^+\pi^-\gamma$. The asymmetry with respect to the electron or positron beam measures the interference of the Compton diagrams with the amplitude in which the photon is emitted from the lepton line.

It is interesting to compare the corresponding calculations of form factors of bound states in QED. The soft wavefunction is the Schrödinger-Coulomb solution

$\psi_{1s}(\vec{k}) \propto (1+\vec{p}^2/(\alpha m_{\rm red})^2)^{-2}$, and the full wavefunction, which incorporates transversely polarized photon exchange, only differs by a factor $(1+\vec{p}^2/m_{\rm red}^2)$. Thus the leading twist dominance of form factors in QED occurs at relativistic scales $Q^2 > m_{\rm red}^2$.[79] Furthermore, there are no extra relative factors of α in the hard-scattering contribution. If the QCD coupling α_V has an infrared fixed-point, then the fall-off of the valence wavefunctions of hadrons will have analogous power-law forms, consistent with the Abelian correspondence principle.[26] If such power-law wavefunctions are indeed applicable to the soft domain of QCD then, the transition to leading-twist power law behavior will occur in the nominal hard perturbative QCD domain where $Q^2 \gg \langle k_\perp^2 \rangle, m_q^2$.

Outlook

It many ways the study of quantum chromodynamics is just beginning. The most important features of the theory remain to be solved, such as the problem of confinement in QCD, the behavior of the QCD coupling in the infrared, the phase and vacuum structure/zero mode structure of QCD, the fundamental understanding of hadronization and parton coalescence at the amplitude level, and the nonperturbative structure of hadron wavefunctions. There are also still many outstanding phenomenological puzzles in QCD. The precise interpretation of CP violation and the weak interaction parameters in exclusive B decays will require a full understanding of the QCD physics of hadrons.

Light-cone quantization methods appear to be especially well suited for progress in understanding the relevant nonperturbative structure of the theory. Since the Hamiltonian approach is formulated in Minkowski space, predictions for the hadronic phases needed for CP violation studies can be obtained. Commensurate scale relations promise a new level of precision in perturbative QCD predictions which are devoid of renormalization scale and renormalon ambiguities. However, progress in QCD is driven by experiment, and we are fortunate that there are new experimental facilities such as Jefferson laboratory, the upcoming QCD studies of exclusive processes e^+e^- and $\gamma\gamma$ processes at the high luminosity B factories, as well as the new accelerators and colliders now being planned to further advance the study of QCD phenomena.

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