ELFE Physics

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Abstract

This is an introductory review of central topics in hadron physics that are addressed by high intensity, continuous electron beam facilities in the multi-GeV range. Exclusive processes are a crucial tool for increasing our knowledge of hadron wave functions beyond what can be learned from studies of hard inclusive processes. Data shows precocious scaling, suggesting a simple underlying picture. Important conceptual advances in the application of PQCD is being made.

1 General Aims

The ELFE (Electron Laboratory for Europe) project aims at the construction of a high intensity, continuous electron beam with good energy resolution in the 15 …30 GeV energy range [1]. In this overview I shall give some of the physics motivations in a form that should be accessible for persons working outside this field.

A photon of virtuality $Q^2 \simeq 10$ GeV^2, typical of what can be reached in the ELFE energy range, has a wavelength $1/Q \sim 0.06$ fm. ELFE will measure hadron and nuclear wave functions with this resolution.

In view of the moderate energy scale, one might ask what new ELFE can tell us? Nucleon and nuclear structure functions are known [2] over a vastly larger range of x and Q^2 than can be covered at ELFE. Indeed, the experimental limit on the radius of the proton constituents, quarks and gluons, is better than 0.001 fm. Moreover, the data on $F_2(x, Q^2)$ is in impressive agreement with the predictions of perturbative QCD (PQCD).

The short answer is that there is a lot more to proton structure than is revealed by the quark and gluon structure functions. To illustrate this, consider the 'Fock expansion' of the proton state $|p\rangle$ in terms of its quark and gluon constituents, at equal Light-Cone (LC) time $x^+ = x^0 + x^3$,

$$\begin{aligned} |p\rangle \ &= \ \int \left[\prod_i dx_i\, d^2k_{\perp i}\right] \{\Psi_{uud}(x_i, k_{\perp i}, \lambda_i)|uud\rangle \\ &+ \ \Psi_{uudg}(\ldots)|uudg\rangle + \ldots + \Psi_{\ldots}(\ldots)|uudq\bar{q}\rangle + \ldots\} \end{aligned} \tag{1}$$

Each Fock state $|uud\ldots\rangle$ is weighted by an amplitude Ψ which depends on the LC momentum fractions x_i ($\sum_i x_i = 1$), the relative transverse momenta $k_{\perp i}$ ($\sum_i k_{\perp i} = 0$) and the helicities λ_i of its constituents. A complete description of the proton is equivalent to specifying all its Fock amplitudes.

The inclusive single parton distributions $F_{j/p}(x,Q^2)$ give the probability for finding (at resolution $1/Q$) a parton j which carries the momentum fraction x of the proton. This parton can be in any Fock state of the proton. The inclusive parton distribution can thus be schematically expressed in terms of the Fock amplitudes as

$$F_{j/p}(x,Q^2) = \sum_n \int^{k_\perp^2<Q^2} \left[\prod_i dx_i\, d^2k_{\perp i}\right] |\Psi_n(x_i,k_{\perp i})|^2 \sum_j \delta(x-x_j) \tag{2}$$

It should be clear from this grand average over Fock states that Deep Inelastic Scattering (DIS), despite its central role in advancing our understanding of hadrons and in establishing QCD as the theory of strong interactions, still only provides a limited glimpse of the structure of the proton. This fact appears sometimes to be forgotten in review talks on QCD.

Further qualitative progress in our understanding of QCD and hadron structure can and has been made by considering other processes than hard inclusive scattering, where factorization theorems allow PQCD to be rigorously applied. Such processes tend to be difficult to measure, due to small cross sections and precise specifications of the final state. This is the arena in which ELFE can make a contribution, thanks to the unique qualities of its electron beam.

In the next section I give some examples of PQCD processes which are currently under theoretical and experimental study. I then briefly describe the present options for ELFE and conclude with some general remarks.

2 PQCD Processes

2.1 Factorization in exclusive reactions

As an example of the kind of question about proton structure that is not addressed by data on inclusive scattering, consider the following:

> *What is the probability that the proton contains only its three valence quarks uud, in a configuration of transverse size* ~ 0.1 *fm?*

This probability is given by the square of the proton 'distribution amplitude' φ_p,

$$\varphi_p(x_i,Q^2) = \int^{k_{i\perp}^2<Q^2} \prod_i d^2\vec{k}_{i\perp} \Psi_{uud}(x_i,k_{i\perp}) \tag{3}$$

which is just the valence Fock amplitude of Eq. (1), integrated over the relative transverse momenta up to $Q \sim 2$ GeV at fixed LC momentum fractions x_i.

In order to study compact proton Fock states we need to measure hard *exclusive* scattering [3], where coherence is required over the whole proton rather than just over a single quark constituent. For example, the proton electromagnetic form factor $F_p(Q^2)$, measured in elastic $ep \to ep$ scattering at high momentum transfer Q^2, is determined by the distribution amplitude (3),

$$A(ep\to ep) = \int_0^1 \left[\prod_{i=1}^3 dx_i dy_i\right] \varphi_p(x_i,Q^2)\, T_H\, \varphi_p(y_i,Q^2)\{1+\mathcal{O}(1/Q^2)\} \tag{4}$$

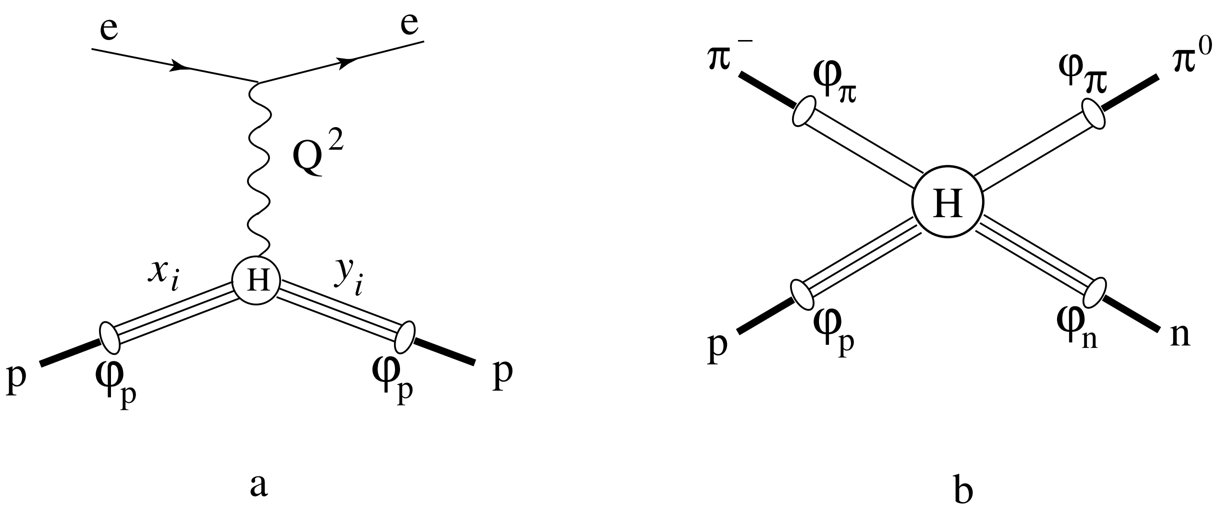

Figure 1: a. Elastic $ep \to ep$ scattering at large Q^2 factorizes into a product of proton distribution amplitudes φ_p and a hard electron scattering from the compact valence Fock state $|uud\rangle$. b. An analogous factorization is illustrated for the large angle process $\pi^- p \to \pi^0 n$.

where T_H is a hard scattering amplitude calculable in PQCD (Fig. 1 a).

The factorization of hard exclusive scattering amplitudes into long distance parts that depend on the hadron wave functions (φ_h) and a hard calculable subprocess (T_H) is quite general [3]. As an example, the factorization of $A(\pi^- p \to \pi^0 n)$ at large CM energy and fixed scattering angle is illustrated in Fig. 1b. The same distribution amplitudes occur in many hard exclusive processes, allowing cross checks of the PQCD factorization. The (logarithmic) dependence on the hardness scale Q^2 is predicted, *e.g.*,

$$\varphi_p(x_i, Q^2) = 120 x_1 x_2 x_3 \delta(1 - x_1 - x_2 - x_3) \sum_{n=0} \left[\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}\right]^{\lambda_n} C_n P_n(x_i) \tag{5}$$

The anomalous dimensions form an increasing series

$$\lambda_0 = \frac{2}{27} < \lambda_1 = \frac{20}{81} < \lambda_2 = \frac{24}{81} < \ldots \tag{6}$$

implying that each successive term in Eq. (5) decreases faster with Q^2 than the previous one. The P_n are Appell polynomials, $P_0 = 1$, $P_1 = x_1 - x_3$, $P_2 = 1 - 3x_2$, ... and the C_n are constants which characterize the proton wave function and have to be determined from experiment.

The PQCD framework for exclusive processes is in many ways analogous to that of inclusive reactions. The distribution amplitude takes the place of parton distributions, with the 'scaling violations' specified by Eq. (5). The good news is that the asymptotic shape of the distribution amplitude in the $Q^2 \to \infty$ limit is predicted, *e.g.*, $\varphi_p^{as}(x_i) \propto x_1 x_2 x_3 \delta(1 - x_1 - x_2 - x_3)$. The bad news is that an exclusive process typically measures only the absolute square of the convolution of several distribution amplitudes with a perturbative subprocess amplitude T_H, *cf.* Eq. (4). Moreover, exclusive cross sections are small and difficult to measure – this is why facilities like ELFE are called for.

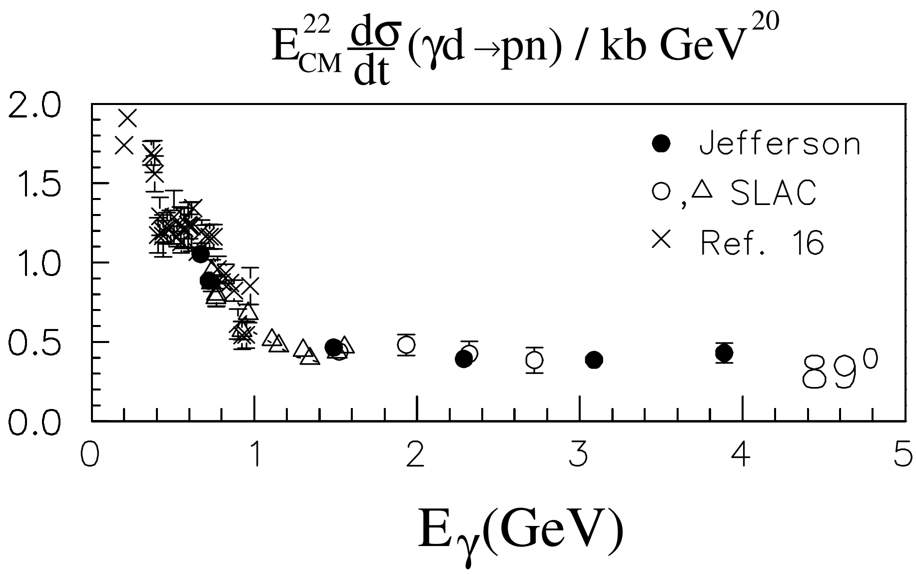

Figure 2: The $\gamma d \to pn$ cross section at 89° multiplied by E^{22}_{CM} as a function of the photon beam energy [9].

2.2 Tests of scaling

A basic test of the PQCD factorization of exclusive processes is that the cross section has the predicted power dependence on the hardness scale Q^2. The power is independent of the shape of the distribution amplitude(s), and is for two-body scattering given by the dimensional scaling rule [4]

$$\frac{d\sigma}{dt}(2 \to 2) \propto \frac{f(t/s)}{t^{n-2}} \tag{7}$$

where n is the total number of elementary fields (quarks, gluons, photons) that are involved in the scattering. It should be kept in mind that the logarithmic scaling violations (5) of the distribution amplitude(s) as well as the running of $\alpha_s(Q^2)$ induces further Q^2-dependence which at low scales can be appreciable.

The proton elastic and $p \to N^*$ transition form factors are in remarkably good agreement with the scaling behavior of Eq. (7) [5] (with the notable exception of $p \to \Delta(1232)$ [6]). Dimensional scaling is seen also in the $\gamma p \to \pi^+ n$ 90° cross section [7] and in the deuteron elastic form factor [8]. Remarkably precocious scaling is evidenced by $\sigma(\gamma d \to pn) \propto E_{CM}^{-22}$ at 89° for $E_\gamma = 1 \ldots 4$ GeV [9] (see Fig. 2).

The early scaling observed in many exclusive processes is a pleasant surprise. The overall momentum transfer is shared by many exchanges in the hard subprocess T_H, implying that typical parton virtualities are quite low [5]. Moreover, the cross sections involve high powers of α_s, suggesting considerable Q^2 dependence from a running coupling. This has been interpreted [10] as evidence that α_s 'freezes' at low scales, allowing PQCD to be applied and avoiding extra dependence on Q^2. On the other hand, it has also been suggested that the scaling is only apparent, and does not yet represent the true asymptotic behavior [11].

A quantitative test of the exclusive PQCD formalism is provided by measurements of the pion transition form factor $F_{\pi\gamma}$ in the process $\gamma^*\gamma \to \pi^0$. Using the asymptotic form [3] $\varphi^{as}_\pi(x) = \sqrt{3} f_\pi x(1-x)$ one predicts $F_{\pi\gamma} = \sqrt{2} f_\pi/Q^2$ at large Q^2, where f_π is the pion

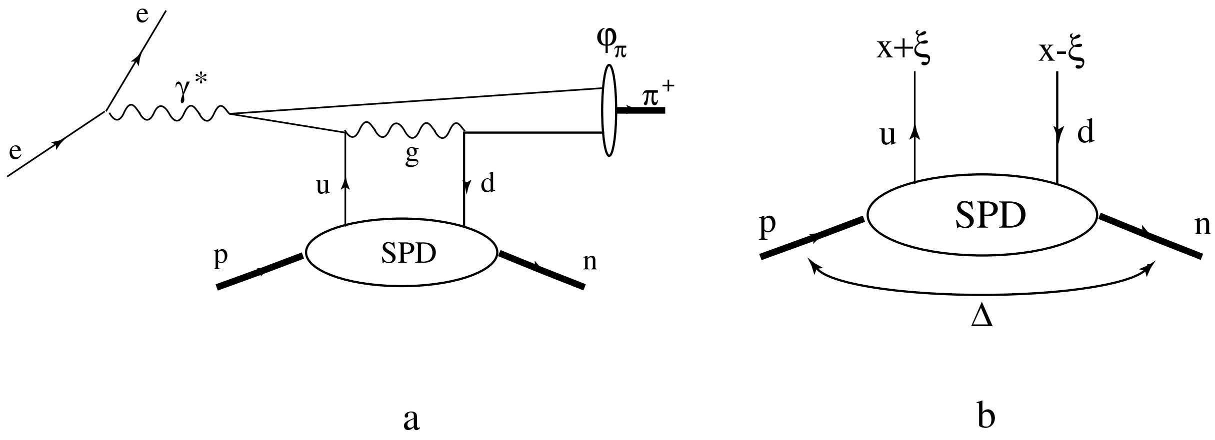

Figure 3: a. Lowest order contribution to the process $ep \to e\pi^+ n$, in the limit of large photon energy ν and virtuality Q^2 but a fixed momentum transfer between the nucleons. b. A skewed parton distribution, with the momentum fractions $x \pm \xi$ of the quarks and the momentum transfer Δ between the nucleons indicated.

decay constant. This prediction is in good agreement with the data [5].

A direct measurement of the shape of hadron distribution amplitudes is possible in diffractive processes. For example, in $\pi^- A \to jet_1(xp_\pi, k_\perp) + jet_2((1-x)p_\pi, -k_\perp) + A$ one expects the longitudinal momentum sharing of the jets to reflect that of the pion valence quark amplitude at a transverse scale $r_\perp \sim 1/k_\perp$ [12]. Preliminary data from the E791 experiment [13] using a 500 GeV π^- beam on C and Pt targets indicates a nearly asymptotic shape $\varphi_\pi(x, Q^2 \sim 10\ \mathrm{GeV}^2) \sim x(1-x)$. The nuclear target dependence of the cross section (integrated over the diffractive peak), $\sigma \propto A^{1.6\pm0.1}$, shows that the nucleus is nearly transparent to the pion, which therefore must be in a configuration of small transverse size.

2.3 Skewed parton distributions

Among more recent theoretical PQCD developments I would like to mention the concept of Skewed Parton Distributions (SPD) [14]. These generalized distributions incorporate properties of both the ordinary DIS parton distributions and of the exclusive distribution amplitudes. For example, the scattering amplitude of the process $\gamma^* p \to \pi^+ n$ (Fig. 3a) factorizes in the standard Bjorken limit ($Q^2, \nu \to \infty$ with $x_B = Q^2/2m\nu$ fixed for the virtual photon) into a hard (PQCD calculable) upper vertex and an SPD (Fig. 3b).

The SPD differs from the standard forward distributions in that there is a non-vanishing momentum transfer Δ from the initial to the final nucleon. While the scattering can proceed with vanishing transverse exchange, $\Delta_\perp = 0$, the inelastic kinematics fixes a longitudinal momentum fraction $2\xi \simeq x_B/(1-x_B/2)$. The longitudinal fraction x of Fig. 3b is integrated over in the scattering amplitude of Fig. 3a. In the region $x < \xi$ the d-quark of Fig. 3b should be thought of as an outgoing $\bar{d}$ antiquark, *i.e.*, the scattering occurs off a compact $q\bar{q}$ pair as in the pion distribution amplitude.

Lorentz invariance allows 4 independent SPD's which depend on three kinematic variables (in addition to the scale Q^2), often denoted $H(x, \xi, \Delta^2)$, $\tilde{H}$, E and $\tilde{E}$ (precise definitions may be found in Ref. [15]). In the forward direction the diagonal SPD's (for which d, u in Fig. 3b are identical quarks q) are related to the standard DIS quark structure functions,

$$\begin{aligned} H^q(x,0,0) &= q(x) \\ \tilde{H}^q(x,0,0) &= \Delta q(x) \end{aligned} \tag{8}$$

where $\Delta q(x)$ is the helicity distribution. Furthermore, there are sum rules relating the SPD's to the nucleon elastic form factors (and hence, via Eq. (4), to the nucleon distribution amplitude),

$$\begin{aligned} \int_{-1}^{+1} dx\, H^q(x,\xi,\Delta^2) &= F_1^q(\Delta^2) \\ \int_{-1}^{+1} dx\, E^q(x,\xi,\Delta^2) &= F_2^q(\Delta^2) \end{aligned} \tag{9}$$

where it may be noted that the integral is predicted to be independent of ξ.

The first moment of the quark SPD's at $\Delta^2 = 0$ gives the total angular momentum carried by the quark,

$$J^q = \int_{-1}^{+1} dx\, [H^q(x,\xi,0) + E^q(x,\xi,0)] = \frac{1}{2}\Delta\Sigma + L^q \tag{10}$$

Since the quark spin $\Delta\Sigma/2$ is measured in polarized DIS, this allows the contribution of the orbital angular momentum L^q to be determined. The total angular momentum carried by gluons can analogously be determined from a relation like Eq. (10) for H^g, E^g. The nucleon angular momentum can then be expressed as $J^q + J^g = 1/2$. It should be noted, however, that $\Delta^2 = 0$ lies outside the physical region. Thus an extrapolation is needed to use measured data in the sum rule (10).

It should be clear from the above that the skewed parton distributions offer qualitatively new information on hadron structure. They are difficult to measure due to the integral over x in the expression for the scattering amplitude (which must be squared to give a measured cross section). Their phenomenology is at its infancy – only the future and dedicated facilities like ELFE can tell what they look like.

3 ELFE Options

The exclusive processes to be measured by ELFE have cross sections that decrease rapidly with the photon virtuality Q^2 and hadron momentum transfer t. For example, $d\sigma/dQ^2(ep \to ep) \propto Q^{-12}$. This puts stringent demands on the performance of the accelerator.

- **High luminosity.** Detectors with an open (4π) geometry are estimated to be able to handle $\mathcal{L} \sim 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, while $\mathcal{L} \sim 10^{38}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ should be available for spectrometers. This will allow measurements in the range $Q^2, |t| \lesssim 20$ GeV^2.

- **Energy 10. . . 30 GeV.** Higher energies would not significantly extend the momentum transfer range due to limitations in luminosity. ELFE will be a high x_B machine, which can reach into the cumulative $x_B > 1$ region of nuclei.

- **Good energy resolution.** A beam energy spread $\Delta E/E \lesssim 10^{-3}$ is required to signal particles that escape direct detection.

- **Continuous beam.** Reconstruction of multi-particle final states requires that consequtive events are separated in time. The duty factor of the beam should be in excess of 50%.

- **Polarization.** Measurements of helicity amplitudes and tests of helicity conservation as predicted by PQCD require a polarized beam ($P_e > 60\%$).

The first ELFE design was based on a recirculating beam [16]. Later it was realized [17] that ELFE could be built in conjunction with the TESLA e^+e^- linear collider project at DESY, by using the HERA ring as a stretcher for achieving a high duty factor. This ELFE@DESY option is contingent upon an approval of TESLA. The time-scale is rather long, with operation not foreseeable before 2010.

Recently, the possibility of using the RF cavities which are becoming available at CERN at the closure of LEP has been considered. A conceptual design report for ELFE@CERN is being prepared [18], which features a recirculating accelerator in the North Area with 7 passes that could achieve electron energies up to 25 GeV. The construction time would be on the order of 6 years after approval.

Should the European options not be realized, there is on a longer time scale (ca. 2015) the possibility that the CEBAF accelerator at Jefferson Lab is upgraded to 24 GeV. This would require a major reconstruction of the machine. The long range plans of Jlab depend on the results of the present upgrade program, which aims at achieving 12 GeV electron beams by 2006.

4 Concluding Remarks

Many particle physicists believe that the frontier of fundamental physics is synonymous with the frontier of energy, and concerns physics beyond the Standard Model. Here I have advocated a frontier related to the structure of hadrons and the physics of QCD. Basic questions which are addressed at the QCD frontier include the treatment of relativistic bound states and the physics of confinement.

Hadron physics is a largely blank page in our QCD book. The proton structure functions (*i.e.*, single parton distributions) only give a first glimpse at proton structure. Fortunately, important progress is being made in widening our understanding. The properties of perturbative QCD allow factorization to be established for a variety of exclusive and semi-exclusive processes. This makes new aspects of hadron wave functions accessible to measurement. Experimental results show precocious scaling, hinting at a simple underlying picture. The situation is reminiscent of the SLAC DIS measurements 30 years ago.

The surprising simplicity of experimental results, both inclusive and exclusive, is leading to a *faith transition* in QCD [19]: The theory appears to be weakly coupled at long distance! There may be no transition from a perturbative to a non-perturbative regime. As $Q^2 \to 0$, the strong coupling freezes at a moderate value $\alpha_s(0)/\pi = 0.14 \ldots 0.17$. While this is still speculative, the mere possibility that we can use the powerful tools of PQCD in the confinement regime is daunting. By taking into account the 'condensates' of quarks and gluons in the QCD ground state one generates a PQCD series which is formally equivalent to the standard one, but which may be able to describe the long-distance dynamics of QCD [20].

Hadron physics is privileged in addressing fundamental questions through an interplay between experiment and theory. The experiments are demanding, but there seems little doubt that we have the technology to construct a facility like ELFE. The importance of accurate data on exclusive processes for a variety of beams and targets should also be kept in mind. Just as for hard inclusive scattering, one can only trust QCD factorization provided all measurements of hadron wave functions are self-consistent. New experimental results will stimulate theoretical studies and *vice versa*. The door is opening for progress in our experimental, theoretical and conceptual understanding of hadrons.

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