Precision Measurement of the Charged Pion Form Factor

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Abstract. Hadronic form factors are objects that contribute significantly to our understanding of the structure of matter. The simplest hadronic system is the pion, whose electromagnetic structure is given by a single form factor (F_π). In this talk the results from the most recent F_π at Jefferson Lab are presented.

One of the fundamental issues in nuclear physics remains to construct a quantitative description of hadrons in terms of the constituents of the underlying theory of strong interactions, quarks and gluons. Properties such as the total charge and magnetic moments are well described in a constituent quark framework, which effectively takes into account quark-gluon interactions. However, charge and current distributions, which are more sensitive to the underlying dynamic processes, are not well described. By definition a description of such dynamic properties is non-perturbative and is therefore quite challenging theoretically.

One of the systems available for study of hadronic structure is the pion, the lightest $q\bar{q}$ object. Its electromagnetic structure is parameterized by a single form factor. The pion charge form factor, F_π , can be calculated in perturbative Quantum Chromo-Dynamics (pQCD) at large four momentum transfer, Q^2 . In the asymptotic limit the lowest order term dominates and one obtains the well known form[1]:

$$F_\pi(Q^2) = 8\pi \frac{\alpha_s f_\pi^2}{Q^2} \quad (Q^2 \rightarrow \infty), \quad (1)$$

where α_s is the strong coupling constant. The normalization is fixed by the pion decay constant, f_π , which is determined from the weak decay of the pion ($\pi \rightarrow \mu + \nu_\mu$). At low values of Q^2 , Vector Meson Dominance models provide a reasonable description of F_π . Due to the pion's simple $\bar{q}q$ valence structure, the transition from “soft” (nonperturbative) to “hard” (perturbative) physics is expected to occur at significantly lower values of Q^2 for F_π than for the nucleon form factors [2] and thus is more likely to be observable experimentally.

The form factor of the pion is well determined up to $Q^2=0.28 \text{ GeV}^2$ by elastic $\pi - e$ scattering experiments [3], from which the charge radius has been extracted. Extending the measurement of F_π to larger values of Q^2 requires the use of pion electroproduction from a nucleon target. The pion exchange (t -pole) process, in which a virtual photon couples to a virtual pion inside the nucleon, dominates the longitudinal pion electroproduction cross section, σ_L , at small values of the Mandelstam variable t .

There σ_L exhibits a characteristic t -dependence and is proportional to F_π^2 .

The unpolarized pion electroproduction cross section can be written as the product of a virtual photon flux factor and a virtual photon cross section,

$$\frac{d^5\sigma}{d\Omega_e dE'_e d\Omega_\pi} = J(t, \phi \rightarrow \Omega_\pi) \Gamma_\nu \frac{d^2\sigma}{dt d\phi}, \quad (2)$$

where $J(t, \phi \rightarrow \Omega_\pi)$ is the Jacobian of the transformation from $dt d\phi$ to $d\Omega_\pi$, ϕ is the azimuthal angle between the scattering and the reaction plane, and $\Gamma_\nu = \frac{\alpha}{2\pi^2} \frac{E'_e}{E_e} \frac{1}{Q^2} \frac{1}{1-\varepsilon} \frac{W^2 - M^2}{2M}$ is the virtual photon flux factor. The virtual photon cross section can be expressed in terms of contributions from transversely and longitudinally polarized photons,

$$2\pi \frac{d^2\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(1+\varepsilon)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi. \quad (3)$$

Here, $\varepsilon = \left(1 + 2 \frac{|\mathbf{q}^2|}{Q^2} \tan^2 \frac{\theta}{2}\right)^{-1}$ is the virtual photon polarization, where $\mathbf{q}^2$ is the square of the three-momentum transferred to the nucleon and θ is the electron scattering angle. Measuring the cross sections at two different values of the virtual photon polarization, ε , at a fixed value of Q^2 allows for a separation of the longitudinal (σ_L) and transverse (σ_T) components of the cross section.

In order to determine F_π , the experimental results for σ_L are compared to a Regge model calculation by Vanderhaeghen, Guidal and Laget (VGL) [7]. Since most model parameters are fixed by pion photoproduction data, F_π can be determined in a one parameter fit from a comparison of the longitudinal experimental cross section to the one predicted from the Regge model.

In Figure 1, our results [8] are shown along with results from CERN, DESY, earlier Jefferson Lab data, and some representative calculations. Comparing the result at $Q^2 = 1.60 \text{ GeV}^2$ to the earlier Jefferson Lab data point at a lower value of W allows for a direct test of the theoretical model dependence. A higher value of W allows for a measurement at smaller values of $-t$, at closer proximity to the pion pole. The data are consistent with the previous Jefferson Lab F_π measurement at a value of $Q^2 = 1.60 \text{ GeV}^2$ and suggest a small model uncertainty due to fitting the VGL model to the data. The data indicate a one sigma deviation from a monopole form factor that yields the measured charge radius. That form factor is up to $Q^2 = 2.5 \text{ GeV}^2$ indistinguishable from the solid curve in Figure 1. Various models provide a good description of the measured values for F_π up to $Q^2 = 1.60 \text{ GeV}^2$. Representative examples are the calculation of Nesterenko and Radyushkin [9], in which a QCD sum rule framework for the soft contribution to F_π as well as an asymptotically dominant hard gluon exchange term is used, the dispersion relation calculation by Geshkenbein [10], and the Dyson-Schwinger calculation by Maris and Tandy, which is based on the Bethe-Salpeter equation with dressed quark and gluon propagators [11]. The 12-GeV upgrade at Jefferson Lab will provide the kinematic reach where one might begin to approach QCD expectations and distinguish between QCD model calculations.

FIGURE 1. *The charged pion form factor. Shown are $e - \pi$ elastic data from CERN, and earlier pion electroproduction data from DESY and Jefferson Lab. The earlier Jefferson Lab data are taken from reference [5]. The data point at $Q^2 = 1.60 \text{ GeV}^2$ from [5] has been shifted from its central value for visual representation. The curves are from a Dyson-Schwinger equation (solid, [11]), QCD sum rules (dotted, [9]), dispersion relations with QCD constraint (dashed, [10]), and from a pQCD calculation (dashed-dotted, [12])*

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