

Improved extraction of the up- and down-quark contributions to the nucleon electromagnetic form factors

I A Qattan¹ and J Arrington²

¹ Department of Physics, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, United Arab Emirates

² Physics Division, Argonne National Laboratory, Argonne, Illinois, 60439, USA

E-mail: issam.qattan@ku.ac.ae

Abstract. The nucleon (proton and neutron) electromagnetic form factors (FFs) are fundamental quantities in nuclear and elementary particle physics as they are essential ingredients needed to parametrize the internal structure of composite particles. The spatial distribution of charge and magnetization within the nucleon is encoded in the electric $G_E^{(p,n)}$ and magnetic $G_M^{(p,n)}$ FFs. These FFs have been extensively and precisely measured using elastic electron scattering. In addition, the combination of the proton and neutron FFs allows for the separation of the up- and down-quark contributions to the nucleon FFs. In this work, we improve on and extend to low- and high- Q^2 values our original analysis and extract the up- and down-quark contributions to the nucleon electromagnetic FFs using worldwide data. In particular, we emphasize new precise data which cover the low- Q^2 region which is sensitive to the large-scale structure of the nucleon. We compare our results to previous extractions and several recent theoretical calculations and models.

1. Introduction

The electric $G_E^{(p,n)}(Q^2)$ and magnetic $G_M^{(p,n)}(Q^2)$ FFs of the nucleon are fundamental quantities in nuclear and elementary particle physics used to parametrize the internal structure of composite particles [1, 2]. They provide information on the spatial distributions of charge and magnetization within the nucleon and they are a function of the four-momentum transfer squared of the virtual photon, Q^2 . At low Q^2 , the nonrelativistic limit, $G_E^{(p,n)}$ and $G_M^{(p,n)}$ are the Fourier transform of the charge and magnetization distributions. Therefore, it is essential to isolate their flavor-separated FFs or the up- and down-quark contributions to examine spatial asymmetries in the quark distributions.

In electron scattering, there are primarily two methods used to extract the proton's FFs. The first is the Rosenbluth or (LT) separation method [3] which relies mainly on measurements of the unpolarized cross section $d\sigma/d\Omega$. The second method is the polarization transfer or (PT) method [4] which requires measurements of the spin-dependent cross section. Note that in the one-photon exchange (OPE) approximation or the Born value, $d\sigma/d\Omega$ is proportional to the “reduced” cross section $\sigma_R = [G_M^p]^2 + (\varepsilon/\tau)[G_E^p]^2$, where $\tau = Q^2/4M_p^2$, M_p is the proton's mass, ε is the virtual photon longitudinal polarization parameter defined as $\varepsilon^{-1} = [1+2(1+\tau)\tan^2(\theta_e/2)]$, and θ_e is the scattering angle of the electron. At fixed Q^2 , G_E^p and G_M^p can be separated by

measuring σ_R at several ε points. On the other hand, the PT measurements are sensitive only to the ratio $R_p = \mu_p G_E^p / G_M^p$, μ_p is the proton's magnetic dipole moment, where by simultaneously measuring the transverse P_t and longitudinal P_l components of the recoil proton, many of the systematic uncertainties in the ratio cancel allowing for precise measurements of the ratio R_p [5]. The two techniques yield significantly different results for the ratio R_p in the region $Q^2 \geq 2$ (GeV/c)² [6]. While the LT extractions show approximate FFs scaling where $\mu_p G_E^p / G_M^p \approx 1$, the PT data show a nearly linear falloff in R_p with Q^2 with some hint of flattening out for $Q^2 > 5$ (GeV/c)². To reconcile the ratios, several recent studies suggested the importance of missing higher order radiative corrections and in particular hard two-photon exchange (TPE) corrections to σ_R in order to explain the discrepancy [7, 8, 9, 10, 11, 12].

2. Extraction of the flavor-separated form factors

The first analysis attempted to separate the up- and down-quark contributions to the nucleon FFs [15], referred to as "CJRW" in this proceedings, examined the scaling behavior of the up- and down-quark contributions at large Q^2 . They combined existing world data on the ratio R_p with recent precise measurements of the neutron's electric to magnetic FFs ratio $R_n = \mu_n G_E^n / G_M^n$, μ_n is the neutron's magnetic dipole moment, up to 3.4 (GeV/c)² [14]. Their results supported the importance of the role played by diquark correlations [16]. In this work, we improve on the original CJRW analysis, and extend to low- and high- Q^2 values the flavor separation analysis [17, 18, 19, 20] where we combine cross section and polarization measurements emphasizing precise new low- Q^2 data from Ref. [21] which are sensitive to the large-scale structure of the nucleon. In addition, we apply TPE corrections in the extraction of the proton's FFs which were neglected in the CJRW analysis. We follow the approach of Ref. [22] and apply TPE corrections following the parametrization of Ref. [23]. The TPE corrections applied are linear in ε and vanish in the limit $\varepsilon \rightarrow 1$ [24]. Moreover, we include new G_M^n data from CLAS [25] and present new parametrization to G_M^n . This parametrization combined with the new R_n parametrization from Ref. [14] are then used to construct G_E^n . We also account for all FFs associated uncertainties neglected in the CJRW analysis as they only accounted for uncertainties on the ratio R_n as the dominant uncertainty for their flavor-separated results. We compare our flavor-separated results to those obtained based on a parametrization of the proton's FFs based on recent TPE hadronic calculation from Ref. [13]. Finally, we construct the flavor-separated Dirac, $F_1^{(u,d)}$, and Pauli, $F_2^{(u,d)}$, FFs and their ratios, and compare the results to previous extractions and several recent theoretical calculations and models.

3. Results and discussion

Our results on the flavor-separated FFs $F_1^{(u,d)}$ and $F_2^{(u,d)}$ are shown in Fig. 1. We compare our results to the original CJRW extractions to examine the effect of the updated FFs data set used, TPE corrections applied, as well as additional FFs uncertainties. We also compare the results to extractions from Ref. [26] ("VAMZ") and Ref. [7] ("AMT") which used an improved proton FFs parametrization assuming different treatment of the TPE corrections applied at low- Q^2 . To examine the impact of our updated G_M^n parametrization, we compare our results to a version of the "VAMZ" extraction which uses the Kelly [27] parametrization for G_M^n ("VAMZ-Kelly"). Finally, we compare our results to recent theoretical calculations and fits: a Dyson-Schwinger equation ("DSE") calculation [16], a pion-cloud relativistic constituent quark model ("PC-RCQM") [28], a relativistic constituent quark model whose hyperfine interaction is derived from Goldstone-boson exchange ("GBE-RCQM") [29], and a generalized parton distribution (GPD) calculations [30].

Our results for $F_{(1,2)}^u$ are in agreement with the CJRW analysis which reported continuous rise of both the up-quark FFs with increasing Q^2 but with our F_2^u values somewhat higher than

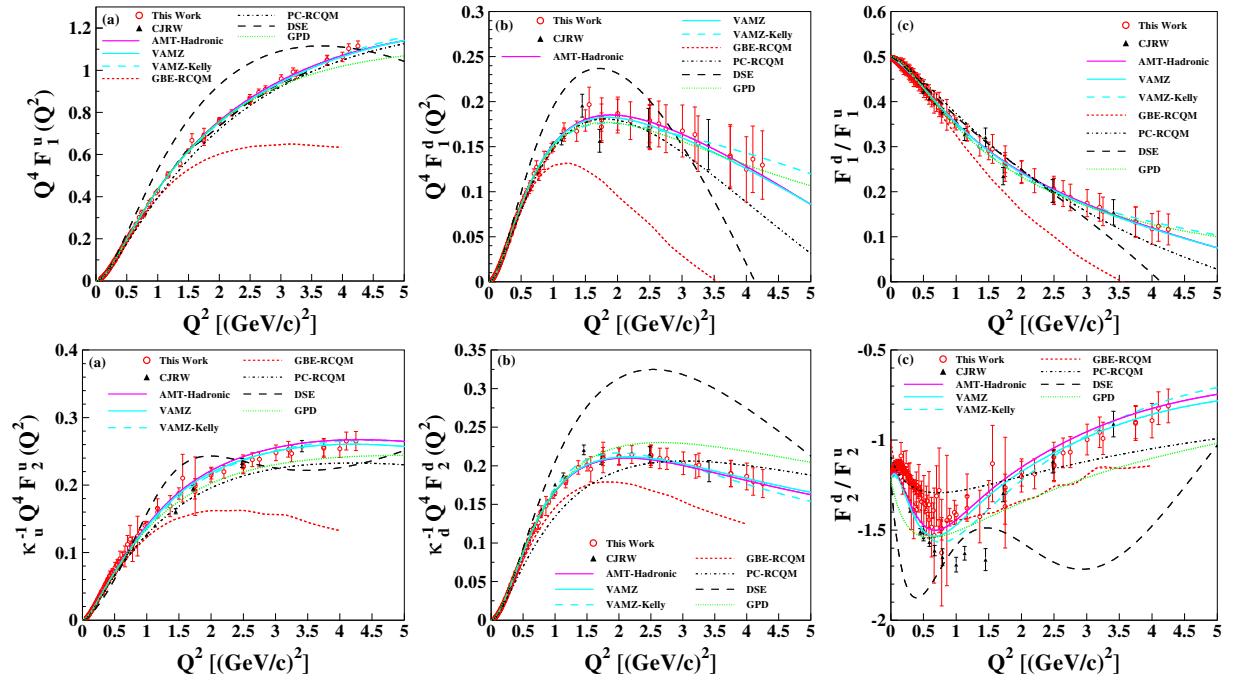


Figure 1. The flavor-separated FFs $F_1^{(u,d)}$ (top) and $F_2^{(u,d)}$ (bottom) and their ratios from this work [19]. Also shown are the CJRW extractions [15], AMT [7] and VAMZ fits [26], and theoretical calculations based on: GBE-RCQM [29], PC-RCQM [28], DSE [16], and GPD [30].

the CJRW extractions at low Q^2 as can be seen clearly in the ratio F_2^d/F_2^u . For the down-quark FFs, and while the CJRW analysis reported strikingly the $1/Q^4$ scaling behavior above $Q^2 = 1.0$ (GeV/c) 2 for both FFs in agreement with the moments of the generalized parton distributions predictions [31], our results suggest that both FFs are falling more rapidly than the up-quark contributions at high Q^2 with respect to the $1/Q^4$ behavior. Such behavior is more apparent for F_2^d and the ratio F_2^d/F_2^u in agreement with recent global parametrizations and theoretical calculations which predict faster falloff than the apparent $1/Q^4$ scaling behavior. Such differences in the results can be attributed mainly to the TPE corrections applied, G_E^n parametrization for $Q^2 > 2$ (GeV/c) 2 [14], and to lesser extent the updated G_M^n parametrization. Note however that, and while the G_E^n uncertainties have the largest impact, the additional uncertainties from the proton and G_M^n yield a non-negligible increase in the total uncertainties.

The ratios $\kappa_u^{-1} F_2^u/F_1^u$ and $\kappa_d^{-1} F_2^d/F_1^d$ are shown in Fig. 2 with $\kappa_{(u,d)}$ being the $Q^2 = 0$ limits of $F_2^{(u,d)}$ such as $\kappa_u = \mu_u - 2 = 1.67$ and $\kappa_d = \mu_d - 1 = -2.03$. Note that when the ratios are scaled by $\kappa_{(u,d)}^{-1}$ and normalized to $1/F_1^{(u,d)}$ they yield 0.5(1) for the up(down)-quark contribution. The ratio F_2^u/F_1^u falls off rapidly at low Q^2 up to $Q^2 \simeq 1$ (GeV/c) 2 where the decrease is significantly slower. For the range $Q^2 < 1.5$ (GeV/c) 2 , our values for the ratio are somewhat higher than those obtained by the CJRW extractions due to the difference in the F_2^u values. However, our results are consistent with both FFs fits and calculations. For the ratio $\kappa_d^{-1} F_2^d/F_1^d$, our results are consistent with the CJRW extractions and fits to the FFs with slight increase in the ratio at low Q^2 and nearly constant value for $Q^2 > 1$ (GeV/c) 2 . On the other hand, our results disagree strongly with all theoretical calculations as the predicted F_1^d falls off more rapidly than F_2^d at large Q^2 leading to a rapid increase in the ratio. Finally, measurements of G_E^n planned for higher Q^2 values at Jefferson Lab [32] are clearly critical in pinning down the behavior of this ratio and examining the theoretical calculations and models.

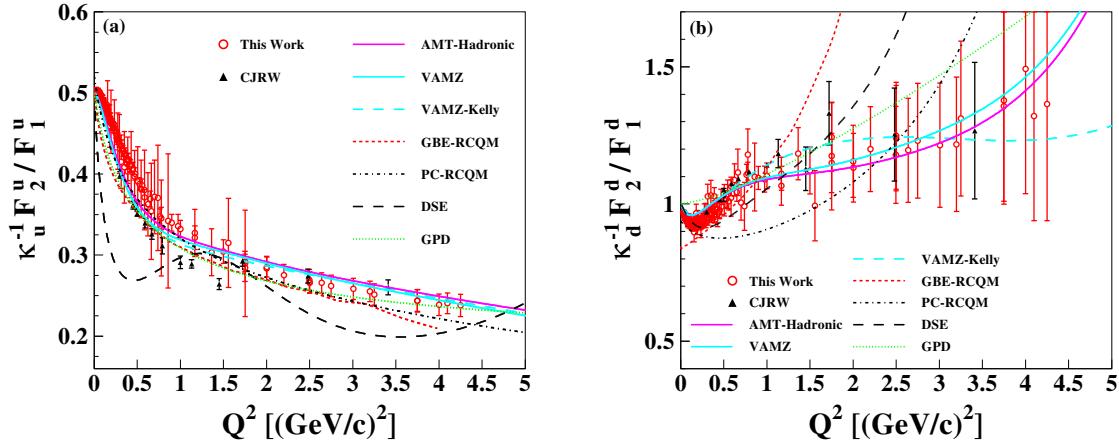


Figure 2. The ratios $\kappa_u^{-1} F_2^u / F_1^u$ and $\kappa_d^{-1} F_2^d / F_1^d$. Points and curves are the same as in Fig. 1.

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