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Model-dependence of the γZ-dispersion correction to the proton's weak charge

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We analyze the dispersion correction to elastic parity violating electron-proton scattering due to γZ exchange and theoretical uncertainties associated with this correction. The new Standard Model prediction for the weak charge of the proton in the kinematics of the Q-Weak experiment, $Q_W^p = (0.0767 \pm 0.0008 \pm 0.0020_{\gamma Z})$, the latter error being dominated by the uncertainty in the isospin structure of the inclusive cross-section. To reduce this uncertainty we propose to analyze the VDM sum rule at JLab energy. Another possibility is to perform the measurement of Q_W^p at a lower energy, and such an experiment is planned in Mainz.

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1. Introduction

Standard Model of particle physics and fundamental interactions (SM) has established itself as a unified picture that summarizes all phenomena that were observed in the low-energy world. The last missing piece that completes the SM puzzle, the Higgs boson has recently been observed at the LHC independently by ATLAS and CMS collaborations. Nonetheless, there persist a number of serious problems that Standard Model has no answer to and that suggest that Standard Model is only a low-energy realization of a more fundamental theory that is yet to be found. Popular extensions, as e.g. SuperSymmetry operate with a number of extra particles that are bound to be heavy (few hundred GeV and up) and extra interactions. Searches for the extensions of the SM are ongoing in collider experiments, in astrophysics and within the low-energy precision tests. This latter framework aims at precise measurements of low-energy observables and from comparison to the SM predictions one is able to constrain the size of the signal of the unknown New Physics. The precision of such low energy tests is in a direct correspondence with the mass of new particles, and modern low energy experiments are sensitive to the masses from few hundred GeV to tens TeV, thus being complementary to astrophysical and collider searches.

2. Weak charge of the proton

Precise measurements of parity-violating (PV) observables in atomic physics and electron scattering (PVES) have provided important tests of the neutral weak current sector of the SM and of its possible extensions [1]. In PVES, the weak charge is defined through the limit of the PV asymmetry $A_{PV} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ at small negative four-momentum transfer t, that including corrections $\sim \alpha_{em} G_F$ reads

$$\frac{A^{PV}}{t}\bigg|_{t\to 0} = \frac{G_F}{4\sqrt{2}\pi\alpha_{em}}\left[(1+\Delta\rho+\Delta e)(\hat{Q}_W^p+\Delta e') + \mathrm{Re}\Delta_{WW} + \mathrm{Re}\Delta_{ZZ} + \mathrm{Re}\Delta_{\gamma Z}\right], \tag{2.1}$$

with α_{em} the fine strucutre constant, G_F the Fermi constant and $\hat{Q}_W^p = 1 - 4\sin^2\hat{\theta}_W(0) \approx 0.05$ the proton's weak charge in SM at tree-level, and $\hat{\theta}_W(0)$ the running weak mixing angle in the $\overline{MS}$ scheme at zero momentum transfer. A precise $\sim 2\%$ measurement of A^{PV} at $t = 0.03$ GeV^2 and electron lab energy $E_e = 1.16$ GeV is currently being analyzed at Jefferson Laboratory within the QWEAK experiment [2]. Translated in $\hat{\theta}_W(0)$, this precision corresponds to an unprecedental 0.4% determination of the weak mixing angle. To match the experimental precision, correction terms in Eq. (2.1) were considered in [3, 4] where it was found that $\Delta\rho$, Δe, $\Delta e'$, Δ_{WW}, Δ_{ZZ} are dominated by the electroweak physics, while $\Delta_{\gamma Z}$ that is due to γZ-exchange can have sizeable uncertainty due to hadronic structure [5]. In a recent PRL [6], this uncertainty was found to be bigger than it was anticipated before, and subsequently this conclusion was confirmed by [7, 8, 9].

3. Dispersion γZ correction from forward dispersion relations

The dispersion correction $\Delta_{\gamma Z}$ can be represented as the sum $\Delta_{\gamma Z} = \Delta_{\gamma Z_V} + \Delta_{\gamma Z_A}$ that obey dispersion relations of two different forms,

$$\mathrm{Re}\Delta_{\gamma Z_V}(\nu) = \frac{2\nu}{\pi}\int_{\nu_\pi}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}\mathrm{Im}\Delta_{\gamma Z_V}(\nu'), \quad \mathrm{Re}\Delta_{\gamma Z_A}(\nu) = \frac{2}{\pi}\int_{\nu_\pi}^{\infty}\frac{\nu' d\nu'}{\nu'^2-\nu^2}\mathrm{Im}\Delta_{\gamma Z_A}(\nu'). \tag{3.1}$$

The correction $\mathrm{Re}\Delta_{\gamma Z_A}$ obtains most of its value due to hard kinematics inside the loop and is largely energy-independent [4, 5, 10]. In the rest of this paper we concentrate on $\mathrm{Re}\Delta_{\gamma Z_V}$. Its imaginary part is given in terms of the PV DIS structure functions $\tilde{F}_i(x,Q^2)$,

$$\mathrm{Im}\Delta_{\gamma Z_V}(\nu) = \frac{\alpha_{em}}{(s-M^2)^2}\int_{W_\pi^2}^{s} dW^2\int_0^{Q^2_{max}}\frac{dQ^2}{1+(Q^2/M_Z^2)}\left[\tilde{F}_1+A\tilde{F}_2\right] \tag{3.2}$$

with $W_\pi^2 = (M+m_\pi)^2$ the pion production threshold, and $Q^2_{max} = \frac{(s-M^2)(s-W^2)}{s}$, and A a known kinematical factor [9].

4. Isospin rotation of the inclusive electromagnetic data

The dispersion representation of Eq. (3.1) itself is model-independent; however, in absence of detailed inclusive PV data, the input in $\tilde{F}_{1,2}$ will depend on a model. In Ref. [9] it was found that the dominant contribution to $\mathrm{Re}\Delta_{\gamma Z_V}$ comes from $W \leq 5-10$ GeV, $Q^2 \leq 3$ GeV^2 kinematics, which means that the input should realistically account for the resonance region and high energy scattering below the DIS region. We thus choose the framework of resonances plus non-resonant background, $\sigma = \sum_R \sigma_R + \sigma_{NR}$. The latter is matched onto Regge-behaved low-x DIS structure functions, and its low-Q^2 behavior is correctly reproduced by the generalized vector dominance model (GVDM) [11].

We proceed applying this model to the electromagnetic data accounting for 7 resonances in the spirit of [12] but use the non-resonant background that has correct high-energy behavior [9]. Consequently, we isospin-rotate the individual contributions to obtain respective contributions into the interference cross sections.

For the $N \to N^*(I=1/2)$ transition, the isospin decomposition resembles that for the elastic form factors, $\langle N^*|J^\mu_{NC,V}|p\rangle = (1-4s^2\hat{\theta}_W)\langle N^*|J^\mu_{em}|p\rangle - \langle N^*|J^\mu_{em}|n\rangle$ It is then straightforward to relate the contribution of a resonance R with isospin $1/2$ to the interference transverse γZ "cross section", to its contribution to the electromagnetic one,

$$\sigma^{\gamma Z,p}_{T,R}(W^2,Q^2) = \left[1-4s^2\theta_W - \frac{A^p_{R,1/2}A^{n*}_{R,1/2}+A^p_{R,3/2}A^{n*}_{R,3/2}}{|A^p_{R,1/2}|^2+|A^p_{R,3/2}|^2}\right]\sigma^{\gamma\gamma p}_{T,R}(W^2,Q^2) \tag{4.1}$$

Above, $A^{p(n)}_{R,1/2(3/2)}$ are the transition helicity amplitudes for exciting the resonance R on the proton (neutron), respectively. The values of the helicity amplitudes and uncertainties thereof are taken from PDG [13]. Thus, Eq. (4.1) allows us to estimate the contribution of $I=1/2$ resonances to the interference cross section and the respective uncertainty. Contribution of isovector transitions $N \to \Delta(\Delta^*)$ to the cross section rescales as $\sigma^{\gamma Z,p}_{T,\Delta} = (2-4\sin^2\theta_W)\sigma^{\gamma\gamma p}_{T,\Delta}$.

Vector Meson Dominance Model (VDM) capitalizes on the fact that the photon (Z-boson) has the same quantum numbers as vector mesons and can be represented as a superposition of a few vector mesons, $|\gamma\rangle = \sum_{V=\rho,\omega,\phi,\ldots}(e/f_V)|V\rangle$, f_V denoting the vector mesons' decay constants. This assumption leads to the VDM sum rule [14]

$$\sigma_{tot}(\gamma p) = \sum_{V=\rho,\omega,\phi} \sqrt{16\pi \frac{4\pi\alpha}{f_V^2} \frac{d\sigma^{\gamma p \to Vp}}{dt}(t=0)}, \tag{4.2}$$

that was measured by ZEUS collaboration [15], and a missing strength of 21% was observed. This missing strength can then be phenomenologically taken into account by adding a new, "continuum" piece to the decomposition of the photon hadronic wave function (and thus the inclusive cross section), $\sigma_{NR} = \sigma_{NR}^{\rho} + \sigma_{NR}^{\omega} + \sigma_{NR}^{\phi} + \sigma_{NR}^{C}$. Supplementing an appropriate Q^2 dependence to the continuum part [11] one obtains a very good description of inclusive virtual photabsorption data in the resonance region and above [9]. To obtain the non-resonant background contribution to the interference cross sections we substitute $\sum_{q\in V} e_q^2 \to \sum_{q\in V} 2g_V^q e_q$ for the isovector ($V=\rho$), isoscalar ($V=\omega$) and strange ($V=\phi$) channel. Above, $e_q(g_V^q)$ stand for the electric (weak) charges of quarks. The drawback of this procedure is that the flavor structure of the continuum contribution is unknown, being purely phenomenological, and has to be assigned a 100% uncertainty.

5. Results and discussion

We summarize the results of the procedure described above in Eq. (5.1) for the kinematics of the QWEAK experiment ($E_1 = 1.165$ GeV) and for a measurement of the weak charge of the proton at lower energy ($E_2 = 0.180$ GeV) proposed at Mainz [16]

$$\begin{aligned} \mathrm{Re}\Delta_{\gamma Z_V}(E_1) &= \left[5.39 \pm 0.27_{(mod.)} \pm 1.88_{(NR)}{}^{+0.58}_{-0.49}{}_{(Res.)}\right] \times 10^{-3}, \\ \mathrm{Re}\Delta_{\gamma Z_V}(E_2) &= \left[1.32 \pm 0.05_{(mod.)} \pm 0.27_{(NR)}{}^{+0.11}_{-0.08}{}_{(Res.)}\right] \times 10^{-3}. \end{aligned} \tag{5.1}$$

The first uncertainty is due to averaging over two different models of the inclusive electromagnetic cross sections [9], the second one due to the uncertainty in the isospin structure of the non-resonant background, and the third one due to the uncertainty in isospin-rotating the resonance contributions. We conclude that the main uncertainty to the dispersion correction comes from the isospin decomposition of the electromagnetic data, most notably from high energy background. Putting together this new evaluation of $\mathrm{Re}\Delta_{\gamma Z_V}$ with other electroweak corrections in Eq. (1), we obtain the new SM prediction for the proton's weak charge for the QWEAK kinematics, and in Mainz kinematics,

$$\begin{aligned} Q_W^p(E_1) &= 0.0767 \pm 0.0008_{EW} \pm 0.0020_{\gamma Z}, \\ Q_W^p(E_2) &= 0.0726 \pm 0.0008_{EW} \pm 0.0003_{\gamma Z}, \end{aligned} \tag{5.2}$$

the first uncertainty being due to other electroweak corrections. In Mainz kinematics, the impact of $\mathrm{Re}\Delta_{\gamma Z_V}$ (represented by the second error) on the overall uncertainty is much smaller.

Our result suggests that in order to provide a new determination of the weak mixing angle with the precision of 0.4% at the kinematics of the QWEAK experiment, the uncertainty due to $\mathrm{Re}\Delta_{\gamma Z_V}$ has to be further reduced. This includes improving the precision of extracting the transition helicity amplitudes for the excitation of the $S_{11}(1535)$ and $S_{11}(1650)$ on the neutron and the identification of the $F_{37}(1950)$ resonance. Still, the main source is the isospin structure of the non-resonant background. At present, it is assessed by means of the VDM sum rule measured at $W \approx 80$ GeV, however it is not warranted that its evaluation at lower energy gives the same result. To this end, a re-evaluation of the VDM sum rule at JLab energies would be beneficial. There exist considerable amount of data on vector meson photoproduction, and it seems to be feasible technically.

An alternative strategy would be to measure the proton's weak charge at a lower energy where the contribution of the background is suppressed, and so is the respective uncertainty. A measurement at $E_2 = 180$ MeV is planned at Mainz.

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References

[1] J. Erler and M. J. Ramsey-Musolf, Prog. Part. Nucl. Phys. 54, 351 (2005).

[2] W. T. H. Van Oers [QWEAK Collaboration], Nucl. Phys. **A 790** (2007), 81.

[3] J. Erler, M.J. Ramsey-Musolf, Phys. Rev. **D 72** (2005), 073003.

[4] W.J. Marciano, A. Sirlin, Phys. Rev. **D 27** (1983), 552; *ibid.* **D 29** (1984), 75; *ibid.* **D 31** (1985), 213.

[5] M.J. Ramsey-Musolf, Phys. Rev. **C 60** (1999), 015501.

[6] M. Gorchtein, C.J. Horowitz, Phys. Rev. Lett. **102** (2009), 091806.

[7] A. Sibirtsev, P. G. Blunden, W. Melnitchouk, A. W. Thomas, Phys. Rev. D**82** (2010), 013011.

[8] B. C. Rislow, C. E. Carlson, Phys. Rev. D**32** (2011), 113007.

[9] M. Gorchtein, M.J. Ramsey-Musolf, C.J. Horowitz, Phys. Rev. C**84** (2011), 015502.

[10] P.G. Blunden, W. Melnitchouk, A.W. Thomas, Phys. Rev. Lett. **107** (2011), 081801.

[11] J. Alwall, G. Ingelman, Phys. Lett. **B 596** (2004), 77.

[12] M.E. Christy, P.E. Bosted, Phys. Rev. C**81** (2010), 055213.

[13] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D**86**, 010001 (2012).

[14] L. Stodolsky, Phys. Rev. Lett. 18 (1967), 135.

[15] S. Chekanov *et al.* [ZEUS Collaboration], Nucl. Phys. **B 627** (2002), 3.

[16] F. E. Maas, K. Kumar, spokespersons.