Physics Letters B 752 (2016) 135–145

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

How strange is pion electroproduction?

Mikhail Gorchtein [a,*], Hubert Spiesberger [b,c], Xilin Zhang [d]

[a] PRISMA Cluster of Excellence, Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany
[b] PRISMA Cluster of Excellence, Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany
[c] Centre for Theoretical and Mathematical Physics and Department of Physics, University of Cape Town, Rondebosch 7700, South Africa
[d] Department of Physcs, University of Washington, Seattle, WA, USA

ARTICLE INFO

Article history:
Received 12 October 2015
Accepted 13 November 2015
Available online 18 November 2015
Editor: W. Haxton

ABSTRACT

We consider pion production in parity-violating electron scattering (PVES) in the presence of nucleon strangeness in the framework of partial wave analysis with unitarity. Using the experimental bounds on the strange form factors obtained in elastic PVES, we study the sensitivity of the parity-violating asymmetry to strange nucleon form factors. For forward kinematics and electron energies above 1 GeV, we observe that this sensitivity may reach about 20% in the threshold region. With parity-violating asymmetries being as large as tens p.p.m., this study suggests that threshold pion production in PVES can be used as a promising way to better constrain strangeness contributions. Using this model for the neutral current pion production, we update the estimate for the dispersive γZ-box correction to the weak charge of the proton. In the kinematics of the Qweak experiment, our new prediction reads $\mathrm{Re}\,\Box^V_{\gamma Z}(E = 1.165\ \mathrm{GeV}) = (5.58 \pm 1.41) \times 10^{-3}$, an improvement over the previous uncertainty estimate of $\pm 2.0 \times 10^{-3}$. Our new prediction in the kinematics of the upcoming MESA/P2 experiment reads $\mathrm{Re}\,\Box^V_{\gamma Z}(E = 0.155\ \mathrm{GeV}) = (1.1 \pm 0.2) \times 10^{-3}$.

1. Introduction

The discovery of weak neutral current interactions in parity-violating electron scattering (PVES) [1,2] and in atomic parity violation (APV) [3] provided an important proof for the structure of the Standard Model (SM). The accuracy of modern experiments provides access to physics beyond the Standard Model (BSM) in a mass range which is comparable or complementary to searches at colliders and in astrophysics [4,5]. Two experiments designed to test the SM running of the weak mixing angle at low energies, Qweak at the Jefferson Laboratory in the U.S. [6] and P2@MESA at Mainz University, Germany [7] will constrain SM extensions with mass scales in the 30–50 TeV range.

The interpretation of these high-precision experiments in terms of the fundamental SM parameters is based on a similarly precise calculation of electroweak radiative corrections [4,8]. At the one-loop level, γZ-box graph corrections constitute a numerically important contribution. Their evaluation requires knowledge of the hadron structure at low energies, i.e. in a region where perturbation theory cannot be applied. Recently, the vector part of these corrections was re-evaluated in the framework of forward dispersion relations [9], and its value and uncertainty was found to be considerably larger than previously anticipated. Subsequent work allowed to constrain its central value [9–13], but the size of its uncertainty is still an open question. For the kinematics of the Qweak and P2 experiments, the dispersion representation of the γZ-box graph correction involves the inclusive inelastic interference structure functions $F^{\gamma Z}_{1,2}$ integrated over the full kinematical range with a strong emphasis on the low-energy range, $Q^2 \leq 1\ \mathrm{GeV}^2$ and $W \leq 4$ GeV (Q^2 is the virtuality of the space-like photon or Z-boson originating from electron scattering, and W the invariant mass of the hadronic final state X resulting from the process $\gamma^* + N \to X$ with $X = \pi N$, $2\pi N$, etc.).[1]

The approach of Refs. [9–13], in the absence of any detailed interference data in the required kinematical range, was based on a purely phenomenological fit to the electromagnetic inelastic total cross section data [14], complemented with an isospin-rotation to

* Corresponding author.
E-mail addresses: gorshtey@kph.uni-mainz.de (M. Gorchtein), spiesber@uni-mainz.de (H. Spiesberger), xilinz@uw.edu (X. Zhang).

[1] The situation is different for the axial-vector part of γZ-box graph corrections which involve $F^{\gamma Z}_3$. In this case, loop momenta $\sim M_Z$ are dominating and the calculation can be performed in a reliable way within perturbation theory [8].

http://dx.doi.org/10.1016/j.physletb.2015.11.038

predict $F_{1,2}^{\gamma Z}$. Unfortunately, this procedure is essentially *ad hoc*, and leads to model-dependent uncertainty estimates, reflected by the spread of the uncertainties given in Refs. [11–13].

In the present work we try to construct the input to the dispersion relations, starting at threshold for pion production, in a more controlled way. In this range, approximately determined by $M + m_\pi \le W \le 2$ GeV and $Q^2 \le 2$ GeV^2, one can rely on very detailed experimental data for pion photo- and electroproduction that allow for partial wave analyses as implemented in MAID [15, 16] and SAID [17]. In this approach it is also possible to explicitly take account of constraints due to unitarity and symmetries and include dynamical effects of strong rescattering.

In the literature, the weak pion production amplitudes have been constructed from the electromagnetic ones, and observables have been studied upon neglecting strangeness contributions [18, 19]. The main distinction of the present work is in avoiding this assumption. This leads to a natural uncertainty estimate due to strangeness contributions which, firstly, is driven by experimental data on strange form factors from elastic PVES [20], and, secondly, brings this uncertainty estimate in direct correspondence with that of inelastic PVES data. Such data above the pion production threshold and reaching into the Δ-resonance region have been taken by the G0 Collaboration at JLab [21] and by the A4 Collaboration at MAMI, Mainz [22]. Our formalism can also serve as a basis for extracting the strange form factors from threshold pion production in PVES experiments. The advantage of this method lies in the fact that PV asymmetries are large, in the range of several tens of p.p.m. as opposed to a few p.p.m. for asymmetries in elastic PVES, which were traditionally used to access strangeness contributions.

Another closely related topic concerns hadronic parity violation that leads to induced PV contributions in electromagnetic interactions and may be seen in PVES as well as in parity violation in nuclei [23,24]. In elastic PVES, these contributions manifest themselves in a similar way as effects from the axial-vector coupling of the Z boson at the hadronic side, but can be disentangled from the Z-exchange contribution in PV pion electroproduction due to a different Q^2-dependence. Ref. [25] used the "DDH best value" of the PV πNN coupling constant h_π^1 [26], and showed that PV threshold π^+ electroproduction at low energies and forward angles is very sensitive to this coupling. On the other hand, there are indications that the actual value of h_π^1 is at least four times smaller [27]. Having in mind such contributions, we will focus on electron energy range ~ 1 GeV and not too forward angles. We postpone the detailed discussion of the interplay of hadronic PV effects with the strangeness to the upcoming work.

The article is organized as follows. In Section 2 we lay out the formalism and define the kinematics, in Section 3 we explicitly construct the multipoles with the weak vector current and incorporate strangeness contributions. Section 4 deals with the sensitivity of the PV asymmetry in inelastic PVES to strange form factors; in Section 5 we apply the model for weak pion production developed in the previous sections to the calculation of the dispersion γZ-correction to the proton's weak charge. Section 6 contains our concluding remarks.

2. Kinematics and definitions

In this work we consider pion electroproduction off a nucleon of mass M, $e^-(\ell) + N(p) \to e^-(\ell') + \pi(q) + N'(p')$, as shown in Fig. 1. The interaction is described by diagrams with the exchange of one boson which carries the four-momentum $k = \ell - \ell'$,

$$T = \frac{e^2}{Q^2}\bar{u}(\ell')\gamma^\mu u(\ell)\langle N, \pi | J_\mu^{EM} | N\rangle \tag{1}$$

for the contribution of the electromagnetic interaction, and

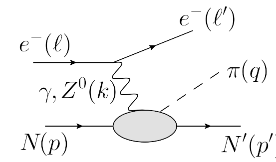

Fig. 1. Pion electroproduction via a neutral-current interaction described by the exchange of a virtual photon or a Z boson.

$$T = -\frac{G_F}{2\sqrt{2}}\bar{u}(\ell')\gamma^\mu(g_V^e + g_A^e\gamma_5)u(\ell)\langle N, \pi | J_\mu^{NC} - J_{\mu 5}^{NC} | N\rangle \tag{2}$$

for the weak neutral current (NC) interaction. We have defined $Q^2 = -k_\mu k^\mu > 0$. The kinematics of the reaction $(\gamma/Z)(k) + N(p) \to \pi(q) + N'(p')$ in the πN center of mass frame is completely fixed in terms of three Lorentz scalars for which we take the invariant mass of the hadronic final state W, $W^2 = (p' + q)^2 = (p + k)^2$, the virtuality Q^2 of the initial boson, and the four-momentum transfer to the nucleon $t = (p' - p)^2 < 0$. In the following, we will use the center-of-mass frame of the initial nucleon–photon pair (or, equivalently, of the final nucleon–pion pair) defined by $\vec{k} + \vec{p} = \vec{q} + \vec{p}\,' = 0$. In this reference frame, the kinematics can be specified by the energy of the photon, ω, its virtuality Q^2, and the pion scattering angle θ. We parametrize the momentum 4-vectors by

$$\begin{aligned} k^\mu &= (k^0, 0, 0, k)\,, \quad p^\mu = (E_1, 0, 0, -k)\,, \\ q^\mu &= (E_\pi, q\sin\theta, 0, q\cos\theta)\,, \quad p'^\mu = (E_2, -\vec{q}\,)\,. \end{aligned} \tag{3}$$

with

$$\begin{aligned} k^0 &= \frac{W^2 - M^2 - Q^2}{2W}\,, \quad E_1 = \frac{W^2 + M^2 + Q^2}{2W}\,, \\ E_\pi &= \frac{W^2 - M^2 + m_\pi^2}{2W}\,, \quad E_2 = \frac{W^2 + M^2 - m_\pi^2}{2W}\,, \\ |\vec{k}| \equiv k &= \frac{\sqrt{[(W-M)^2 + Q^2][(W+M)^2 + Q^2]}}{2W}\,, \\ |\vec{q}| \equiv q &= \frac{\sqrt{[W^2 - (M + m_\pi)^2][W^2 - (M - m_\pi)^2]}}{2W}\,, \\ \cos\theta &= \frac{2k^0 E_\pi + t + Q^2 - m_\pi^2}{2kq}\,. \end{aligned} \tag{4}$$

2.1. Invariant amplitudes

The invariant amplitudes with the vector current were introduced, e.g., in Ref. [28] as

$$\langle N, \pi | J_\mu^{EM,\,NC} | N\rangle = \sum_{i=1}^{6} V_i^{\gamma,Z}(W^2, Q^2, t)\bar{U}_f O_{V_i}^\mu U_i\,, \tag{5}$$

with

$$\begin{aligned} O_{V_1}^\mu &= \frac{i}{2}\left(\gamma^\mu \not{k} - \not{k}\gamma^\mu\right)\gamma_5\,, \\ O_{V_2}^\mu &= -2i\left(P^\mu(q\cdot k) - q^\mu(P\cdot k)\right)\gamma_5\,, \\ O_{V_3}^\mu &= \left(\gamma^\mu(q\cdot k) - q^\mu \not{k}\right)\gamma_5\,, \\ O_{V_4}^\mu &= 2\left(\gamma^\mu(P\cdot k) - P^\mu \not{k}\right)\gamma_5 - 2MO_{V_1}^\mu\,, \\ O_{V_5}^\mu &= -i\left(k^\mu(q\cdot k) - q^\mu k^2\right)\gamma_5\,, \\ O_{V_6}^\mu &= \left(k^\mu \not{k} - \gamma^\mu k^2\right)\gamma_5\,, \end{aligned} \tag{6}$$