Has a coupling of right-handed quarks to $W$ been observed?

Micaela Oertel

LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, 5 place Jules Janssen, 92195 Meudon, France

E-mail: micaela.oertel@obspm.fr

Abstract. Stringent tests of non-standard electroweak (EW) couplings of (light) quarks are rare because it is not easy to disentangle QCD and EW quantities. We will discuss here a recently proposed test of right-handed charged quark currents, based on $K_{l3}$ decay data and the prediction of the Callan-Treiman low energy theorem. Non-standard couplings of fermions to $W$ and $Z$ are suggested by the minimal low-energy effective electroweak theory (LEET) to be the dominant new physics effects. It is shown that coherent values for these couplings emerge from an analysis of $Z$-pole observables, too, curing in particular the long-standing $A_{FB}$ puzzle.

1. Introduction

In view of the large variety of models describing physics beyond the Standard model (SM) it is important to perform precision low-energy tests of new physics in addition to the direct searches at LHC and future colliders in order to correctly interpret the results. An effective theory framework is a very efficient way to organise the low-energy searches of small modifications of the couplings of known particles without relying on a specific model. The basis of the present work is a “not-quite decoupling” alternative to the usually applied decoupling low energy effective theory (LEET) framework. Within the former, the heavy particles adherent to an extended symmetry $S_{nat} \supset S_{ew} = SU(2)_L \times U(1)_Y$ at high energies decouple, but the symmetry becomes partly non-linearly realised and constrains the effective interactions at low energies. The classification of the different operators is thereby based on infrared power counting. The symmetry $S_{nat}$ can be inferred from the requirement that at lowest order the (higgsless) vertices of the SM are recovered and nothing else. We have worked with the minimal version of $S_{nat} = [SU(2)]^4 \times U(1)^{B-L}$ fulfilling this requirement [1, 2, 3].

This LEET predicts that a priori the most important effects beyond the SM are (universal) non-standard couplings of fermions to the gauge bosons $W$ and $Z$ appearing at next-to-leading order (NLO). In particular, a direct coupling of right-handed quarks to $W$ emerges. Charged right-handed lepton currents are forbidden by an additional discrete symmetry in the lepton sector originally designed to suppress Dirac neutrino masses. From general arguments (see Ref. [3]) these non-standard couplings are expected to be of the order of percent. We will discuss here some aspects of tests of electroweak (EW) couplings of (right-handed) quarks, which depend strongly on our understanding of the involved QCD processes. A complete NLO analysis of experimental constraints on these modified couplings can be found in Ref. [4].

1 Based on work in collaboration with V. Bernard, E. Passemar, J. Stern.
2. Couplings to W

At NLO the charged current (CC) Lagrangian is given by

$$\mathcal{L}_W = \frac{e(1 - \xi_2^2 \rho_L)}{\sqrt{2s}} \left\{ j^\mu_{\text{lepton}} + (1 + \delta) \bar{U}_L \gamma^\mu D_L + \epsilon \bar{U}_R \gamma^\mu D_R \right\} W^\mu_+ + \text{h.c.}$$

where $j^\mu_{\text{lepton}}$ denotes the charged lepton current. There are no charged right-handed lepton currents and the (universal) modification of the couplings of left-handed leptons to $W$ can be absorbed into a redefinition of $G_F$, such that at NLO there is no observable modification of lepton couplings to $W$. $U_{L/R}$ denote up-type quark fields and $D_{L/R}$ down-type quark fields for three generations. The two matrices $V_L$ and $V_R$ describe chiral quark flavor mixing. For comparison with experiment it is convenient to introduce effective vector and axial couplings as:

$$V^{\mu}_{\text{eff}} = (1 + \delta)V^{\mu}_{L} + \epsilon V^{\mu}_{R}, \quad A^{\mu}_{\text{eff}} = -(1 + \delta)V^{\mu}_{L} + \epsilon V^{\mu}_{R}.$$  

It is obvious that at NLO, due to the direct coupling of right-handed quarks to $W$, we have $V^{\mu}_{\text{eff}} \neq -A^{\mu}_{\text{eff}}$. Focussing on light quarks, we have to determine three parameters, $\epsilon_{ns} = \epsilon \text{ Re}(V^{ud}_{\text{eff}}/V^{ud}), \epsilon_s = \epsilon \text{ Re}(V^{us}_{\text{eff}}/V^{us})$, parametrising non-strange and strange charged right-handed quark currents and $\delta$, describing a (universal) modification of couplings of left-handed quarks.

2.1. $K_{\mu3}^L$ decays

In Ref. [5] it has been shown that a stringent test involving the EW coupling $\epsilon_s - \epsilon_{ns}$ can be devised in $K_{\mu3}^L$ decay. Indeed, it is possible to measure the ratio $\xi = F_{K^+}/(F_{\pi^+} + f_{K^0}M_{K^0}(0))$ in two independent ways.

First, one can combine the branching ratios $Br K_{l2(\tau)/\pi_{l2(\tau)}}^\pm$ [9], the inclusive decay rate $K_{e3(\gamma)}^L$ [10], and the value of $|V_{ud}^{\text{eff}}|$ known from superallowed $0^+ \to 0^+$ nuclear $\beta$-decays [11] to determine $(1 + 2(\epsilon_s - \epsilon_{ns}))\xi$. Second, the Callan-Treiman low-energy theorem (CT) [6] fixes the value of the normalised scalar $K\pi$ form factor, $f(t)$, at the point $t = \Delta_{K\pi} = m_{K^0}^2 - m_{\pi^0}^2$, as $f(\Delta_{K\pi}) = \xi + \Delta_{\text{CT}}$, where the CT discrepancy $\Delta_{\text{CT}}$ is expected to be small and calculable in ChPT. It is proportional to $m_u$ and/or $m_d$. In the limit $m_d = m_u$ at NLO in ChPT one has $\Delta_{\text{CT}} = -3.5 \times 10^{-3}$ [7]. We will focus the discussion on the neutral kaon mode since the analysis of the charged mode is subject to larger uncertainties related, in particular, to $\pi^0\eta$ mixing [5] which could easily enhance the CT discrepancy by one order of magnitude.

There is a $5\sigma$ deviation between the SM prediction via the measured branching ratios and the recent measurement of $f(\Delta_{K\pi})$ in $K_{\mu3}^L$ decays by the NA48 collaboration [8]. This is clearly shown in the left panel of Fig. 1 which displays $f(t)$. The upper black curve corresponds to the SM prediction, i.e. $\epsilon_s = \epsilon_{ns} = 0$. The assigned error is purely experimental. The dotted blue curve correspond to the NA48 value using the dispersive representation. Of course, this
result should be confirmed by other independent measurements of the scalar $K\pi$ form factor based on the dispersive representation which are underway. From the KLOE collaboration, a preliminary value for $\ln C$ is available [12]. The corresponding form factor is shown by the pink dashed curve.

Since the decay rate for $K_{e3}$ depends only on the vector form factor and the $K_{\mu3}$ decay rate depends on the vector and the scalar form factor, the ratio $R_{\mu/e} = \Gamma(K_{\mu3}(\gamma))/\Gamma(K_{e3}(\gamma))$ is a particularly sensitive probe of $\ln C$ where the dependence on the vector form factor partially cancels out. In the right panel of Fig. 1 we show the constraints on $\ln C$ and $\Lambda_\gamma$, the corresponding parameter of the dispersive representation of the vector form factor [13], imposed by the different recent measurements of $R_{\mu/e}$ for neutral kaons. We show the direct determinations via $K_{\mu3}^{L}$ decays, too. Before any firm conclusion can be drawn, further experimental results have to be awaited. For more discussion see Refs. [5, 13].

3. Couplings to $Z$

For the neutral current interaction, there are many accurate measurements available, in particular around the $Z$ resonance and even above. These data are parametrized in terms of effective observables (couplings, masses) including QED and QCD radiative effects, see Ref. [14].

At NLO within the LEET, altogether six unknown parameters describing non-standard couplings to $Z$ appear: $\epsilon^e$, $\epsilon^\mu$, $\epsilon^\nu$, $\epsilon^d$, concerning right-handed fermions, and $\delta^{ue}$ and $\delta$ for left-handed fermions. In contrast to the charged current where the additional $Z_2$ symmetry of the LEET in the neutrino sector forbids a coupling of right-handed leptons to $W$, we have to consider here non-standard leptonic as well as non-standard quark couplings. At this order there are only very weak constraints on the parameter $\epsilon^e$ because it appears only quadratically in the invisible width of $Z$ and is thus additionally suppressed [3, 4] and we will not consider it here.

A fit of the remaining five parameters to the data at the $Z$-resonance gives $(\epsilon^e)_{\text{NLO}} = -0.0024(5), (\epsilon^\mu)_{\text{NLO}} = -0.02(1), (\epsilon^\nu)_{\text{NLO}} = -0.03(1), (\delta)_{\text{NLO}} = -0.004(2), (\delta^{ue})_{\text{NLO}} = 0.2307(2)$. We obtain a good agreement with the $Z$-pole data. In particular, we can solve the long-standing $A^B_{\mu\beta}$ puzzle without introducing non-universal effects in the couplings, see Ref. [4]. The important point here is the NLO modification of the right-handed couplings. Also low-energy data such as atomic parity violation are well reproduced. There are only exceptional cases, when the LO + NLO contribution is accidentally small, where we fail to reproduce the data. One such example is the $e^-e^-$ Møller scattering. For these cases it is particularly important to extend the analysis to higher orders. More details about the analysis and further results concerning the couplings to $Z$ can be found in Ref. [4].

References

[1] Hirn J and Stern J 2004, Eur. Phys. J. C 34 447 (preprint arXiv:hep-ph/0401032).
[2] Hirn J and Stern J 2004, JHEP 0409 058 (preprint arXiv:hep-ph/0403017).
[3] Hirn J and Stern J 2006, Phys. Rev. D 73 056001 (preprint arXiv:hep-ph/0504277).
[4] Bernard V, Oertel M, Passemar E and Stern J, preprint arXiv:0707.4194 [hep-ph].
[5] Bernard V, Oertel M, Passemar E and Stern J 2006, Phys. Lett. B 638 480 (preprint arXiv:hep-ph/0606202).
[6] Dashen R F and Weinstein M 1969, Phys. Rev. Lett. 22 1337.
[7] Gasser J and Leutwyler H 1985, Nucl. Phys. B 250 517.
[8] Lai A et al. [NA48 collaboration] 2007, Phys. Lett. B 647 341 (preprint arXiv:hep-ex/0703002).
[9] Bächer E and Marciano W in Yao W M et al. [Particle Data Group] 2006, J. Phys. C 33 1.
[10] Alexopoulos T et al. [KTeV Collaboration] 2004, Phys. Rev. Lett. 93 181802; Ambrosino F et al. [KLOE Collaboration] 2006, Phys. Lett. B 632 43; Lai A et al. [NA48 Collaboration] 2004, Phys. Lett. B 602 41.
[11] Marciano W J and Sirlin A 2006, Phys. Rev. Lett. 96 032002 [arXiv:hep-ph/0510099].
[12] Ambrosino F et al. [KLOE Collaboration], preprint arXiv:0707.4631 [hep-ex].
[13] Bernard V, Oertel M, Passemar E, Stern J, in preparation; Passemar E, preprint arXiv:0708.1235 [hep-ph].
[14] [ALEPH Collaboration et al.] 2006, Phys. Rept. 427 257 (preprint arXiv:hep-ex/0509008).