Low Energy Tests of the Standard Model
from $\beta$-Decay and Muon Capture

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Abstract

Two recent low energy precision experiments are considered, in order to illustrate how limits set by these measurements for couplings beyond the Standard Model are complementary to high energy constraints.
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1 Introduction

Low energy precision experiments are complementary to high energy ones, both in the diversity of available experimental techniques as well as in the probed range of the parameter spaces of different model extensions of the Standard Model (SM).

It is the purpose of the present contribution to highlight such complementarity with the example of two recent precision measurements, one in nuclear $\beta$-decay, and the other in nuclear muon capture on $^3$He. The latter measurement constrains different hadronic corrections to the charged electroweak current within the SM, while both measurements constrain a variety of model extensions of the SM. Some of these constraints appear to be new, or to be competitive with existing ones derived from high energy measurements [6].

2 Nuclear $\beta$-decay

The polarisation-asymmetry correlation in $\beta$-decay presents an increased sensitivity to any deviation from the $(V-A)$ structure of the charged electroweak interaction [2]. Such experiments consist in the measurement of the longitudinal polarisation of the $\beta$ particle emitted in a direction either antiparallel or parallel to the polarisation of an oriented nucleus. The ratio of these two polarisations—a relative measurement less prone to systematic corrections—is of the form

\[ R(J) = R_0(J) \left[ 1 - k(J) \Delta \right], \]

where $J$ is the degree of nuclear polarisation, while $R_0(J)$ and $k(J)$ are known functions of the $\beta$ energy and asymmetry, quantities which are experimentally accessible. Finally, $\Delta$ is a vanishing quantity in the SM, which may be expressed in terms of the underlying effective charged current interaction [3]. In particular, for $J$ close to unity, the factor $k(J)$ can become appreciable, thus enhancing the sensitivity to a possible deviation $\Delta \neq 0$.

Two such experiments have been performed, one using polarised $^{12}$N [4, 5], the other polarised $^{107}$In [6]. The combined data result in the pre-
cision value \[5\],
\[\Delta = 0.0004 \pm 0.0026 , \]
thus in perfect agreement with the SM prediction. Prospects are to perform a similar measurement for $^{17}$F at ISOLDE/CERN, as well as for $\mu^+$ decay at PSI, with at least a 50-fold improvement in the precision of the Michel parameter $\xi''$.

3 Nuclear muon capture

The statistical muon capture rate on $^3$He to the triton channel was measured in a recent experiment to a precision of 0.3%. The experimental result is \[6\],
\[\lambda_{\text{exp}} = 1496 \pm 4 \text{ s}^{-1} , \]
to be compared to the prediction \[7\]
\[\lambda_{\text{theor}} = 1497 \pm 12 \text{ s}^{-1} . \]
Prospects are to perform at PSI a similar measurement for muon capture on the proton to better than 1%, with as by-product a 2-fold improvement in the precision of Fermis’ coupling constant $G_F$.

4 Tests within the SM

The result (2) allows for tests of QCD chiral symmetry predictions, namely tests of PCAC and of second-class currents. \[8\] The vector and axial current matrix elements are parametrised in terms of six nuclear form factors. These include the pseudoscalar one $F_P$ whose value is related to that of the axial one $F_A$ through PCAC, as well as the second-class ones, namely the scalar and tensor form factors $F_S$ and $F_T$, which vanish in the limit of exact isospin and charge conjugation invariance. Using CVC and the $^3$H $\beta$-decay rate, the values of the remaining form factors may be determined with sufficient reliability \[8\].

On that basis, ignoring first the contributions of $F_S$ and $F_T$, the result (2) leads to a value for $F_P$ which, when compared to the PCAC prediction, is in a ratio of \[9\] $1.004 \pm 0.076$. At the level of the nucleon, the same ratio is then \[10\] $1.05 \pm 0.19$. Consequently, the value (2) provides the most precise test of nuclear PCAC available, a situation to be contrasted with the recent result \[11\] from radiative muon capture on the proton which deviates by more than a factor of 1.5 from the PCAC prediction.

On the other hand, assuming the PCAC value for $F_P$, (2) may be used to set a value either for $F_S$ or for $F_T$, ignoring in each case the contribution of the other second-class form factor. One then obtains \[12\]
\[F_S = -0.062 \pm 1.18 \text{ or } F_T = 0.075 \pm 1.43 , \]
values which agree of course with expectations \[12\], and do improve on the existing situation \[13\].

5 Tests beyond the SM

Physics beyond the SM may be parametrised in terms of 4-fermion effective interactions at the quark-lepton level. For muon decay, a representation in the charge exchange form has

\footnote{The normalisation of these form factors is relative to $q^\mu/(2M)$, $M$ being the average $^3$He-$^3$H mass.}
become standard in terms of effective couplings \( g_{\eta_1 \eta_2}^{S,V,T} \), where the lower indices indicate the chiralities of the electron and muon, respectively \(^3\).

Similarly, \( \beta \)-decay is parametrised in terms of coupling coefficients \( f_{\eta_1 \eta_2}^{S,V,T} \), with the index \( \eta_1 \) being the chirality of the down quark, while muon capture is parametrised in terms of coefficients \( h_{\eta_1 \eta_2}^{S,V,T} \), \( \eta_2 \) (resp. \( \eta_2 \)) being the muon (resp. \( \bar{d} \) quark) chirality.

Assuming only vector and axial couplings \( f_{\eta_1 \eta_2}^{V} \), the result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) implies \( |f_{\eta_1 \eta_2}^{V} - f_{\eta_1 \eta_2}^{V}|^2 = 0.0004 \pm 0.0026 \). The quantity \( \Delta \) also involves scalar and tensor contributions, but the ensuing limits do not improve existing constraints \(^1\).

Under different assumptions, the result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) sets new constraints \(^2\). L-handed vector couplings only imply \( |h_{\eta_1 \eta_2}^{V} / f_{\eta_1 \eta_2}^{V}|^2 = 0.9996 \pm 0.0083 \), namely a universality test which at present does not improve the usual such test from pion decay \(^3\). For both L- and R-handed vector couplings, one finds \( h_{\eta_1 \eta_2}^{V} = 0.0065 \pm 0.0102 \). Scalar (resp. pseudoscalar) couplings are such that \( (h_{\eta_1 \eta_2}^{S} + h_{\eta_1 \eta_2}^{S})G_S = -0.0012 \pm 0.022 \), (resp. \( (h_{\eta_1 \eta_2}^{S} - h_{\eta_1 \eta_2}^{S})G_P = -0.078 \pm 1.49 \)), \( G_S, G_P \) being the nuclear matrix elements for the scalar and pseudoscalar quark densities. And for tensor couplings, one has \( h_{\eta_1 \eta_2}^{T} G_T / 2 = -0.00008 \pm 0.00143 \) (\( G_T \) being the tensor nuclear matrix element). The scalar constraint is quite stringent, but the tensor one is especially restrictive.

Within specific model extensions of the SM, these results translate into constraints on the parameters of such models. The involved observables being different from those accessible usually from high energy experiments, the probed regions of these parameter spaces are complementary to one another. Here, only a few such instances are indicated \(^4\).

Within left-right symmetric models not manifestly symmetric between their two chiral sectors, as a function of the heavier charged gauge boson mass \( M_2 \), the result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) probes regions in the right-handed mixing matrix element \( V_{R}^{2} \) or in the ratio \( g_R / g_L \) of gauge couplings constants which are inaccessible \(^4\) \(^5\) \(^6\) to the collider experiments \(^16\). In particular, the latter are totally insensitive to a mass \( M_2 \) close to the \( W \) mass provided for example the \( V_{R}^{2} \) quark mixing is sufficiently small, while the ratio \( V_{ud}^{R} / V_{ud}^{L} \) is much constrained in that mass region by the result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \). Such a possibility is thus still worth exploring also at high energies. The result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) only constrains the charged gauge boson mixing angle, to a level comparable to existing limits \(^1\).

Contact interactions are analysed similarly, replacing the coupling coefficients by \( \pm 4\pi / f_{\eta_1 \eta_2}^{V} \). The result \( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) translates into \( A_{R_1 \eta_2}^{V} > 2.5 \text{ TeV (90\% CL)} \) for charged vector interactions within the first generation. Note that these limits as such are not directly accessible to unpolarised high energy measurements, Eq.\( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) and \( h_{\eta_1 \eta_2}^{V} \) imply \( A_{R_1 \eta_2}^{V} > 4.9 \text{ TeV (90\% CL)} \) for charged vector interactions between the first quark generation and the second lepton generation. Eq.\( \frac{\Lambda}{f_{\eta_1 \eta_2}^{V}} \) also sets limits for such scales associated to scalar or tensor interactions. For \( G_T = 1 \), one has \( A_{R_1 \eta_2}^{T} > 9.3 \text{ TeV (90\% CL)} \). These limits on contact interactions

\(^3\) Precise to better than 0.4%.
for charged currents interactions within the first or the first two generations are certainly comparable to existing ones, if not better or altogether new in some cases. Most analyses of contact interactions based on the excess of large $Q^2$ events at HERA have concentrated on neutral current interactions, for which the limits are in the $2.5 - 3.0$ TeV range [1].

When extending the by-now standard approach of Ref. [17] for leptoquarks with a right-handed neutrino for each generation, a new scalar and a new vector leptoquark is possible, with three new coupling coefficients for each. The result (1) sets a limit on the coupling of the $S_0$ or $V_0$ leptoquarks (in the notation of Ref. [18]) to $(\nu e)_R$, namely $|\lambda^R_{S_0} \lambda^{\mu\nu}_{V_0}/M^2(S_0)|$ and $2|\lambda^L_{S_0} \lambda^{\mu\nu}_{V_0}/M^2(V_0)|$ each less than 4.1 TeV$^{-2}$ (90% CL), limits which obviously are not available so far from high energy measurements. The result (2) sets stringent limits on couplings and masses for interactions between the first two generations, some of which improve existing limits [18]. This is especially true for the effective tensor interactions induced by the $S_0$ and $S_{1/2}(Q = -2/3)$ leptoquarks, leading to $|\lambda^L_{S_0} \lambda^{R\mu}_S/\sqrt{M^2(S_0)}||G_T|$ and $|\lambda^{L\mu}_{S_{1/2}} \lambda^R_{S_{1/2}}/\sqrt{M^2(S_{1/2})}||G_T|$ both being less than 0.29 TeV$^{-2}$ (90% CL).

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