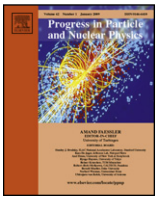
Progress in Particle and Nuclear Physics 71 (2013) 93–118

Contents lists available at SciVerse ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp



Review

Beta decays and non-standard interactions in the LHC era

Vincenzo Cirigliano[a,*], Susan Gardner[b], Barry R. Holstein[c]

[a] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[b] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA*
[c] *Department of Physics-LGRT, University of Massachusetts, Amherst, MA 01003, USA*

ARTICLE INFO

Keywords:
Beta decays
Symmetry tests
Physics beyond the Standard Model

ABSTRACT

We consider the role of precision measurements of beta decays and light meson semi-leptonic decays in probing physics beyond the Standard Model in the LHC era. We describe all low-energy charged-current processes within and beyond the Standard Model using an effective field theory framework. We first discuss the theoretical hadronic input which in these precision tests plays a crucial role in setting the baseline for new physics searches. We then review the current and upcoming constraints on the various non-standard operators from the study of decay rates, spectra, and correlations in a broad array of light-quark systems. We finally discuss the interplay with LHC searches, both within models and in an effective theory approach. Our discussion illustrates the independent yet complementary nature of precision beta decay measurements as probes of new physics, showing them to be of continuing importance throughout the LHC era.

1. Introduction

Beta decays played a central role in determining the $V - A$ structure of the weak interactions and in shaping what we now call the Standard Model (SM) [1–3]. We focus here on the set of semi-leptonic "charged current" (CC) processes that are mediated in the SM by tree-level W exchange, up to radiative corrections. In the SM the CC weak processes are characterized by two main features: (i) the hadronic and leptonic bilinear densities involved in the process have a dominant $V - A$ component, with other types of couplings – $V + A$, S, P, T – arising at higher order in radiative corrections or in recoil momentum; (ii) the effective Fermi constants extracted in beta decays obey lepton universality as well as quark–lepton, or Cabibbo, universality, which is equivalent in the SM to the unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix. Universality relations can only emerge once the process-dependent radiative corrections are removed. Currently precision beta-decay measurements involving neutrons, nuclei, and mesons are used to probe the existence of non-SM interactions which effectively induce violations of the universality relations and/or novel non-($V - A$) structures or corrections to the dominant vector and axial–vector couplings.[1] The low-energy charged-current-interaction Hamiltonian is sensitive to many classes of SM extensions. In this sense, beta decay measurements can be considered as "broad band" probes of physics beyond the Standard Model (BSM): while by themselves they do not allow us to reconstruct the ultraviolet dynamics, they provide, at 0.1%-level precision, powerful boundary conditions and diagnostics on virtually any TeV-scale SM extension.

Considerable experimental progress is ongoing or expected in a few-year time scale on several fronts, using both cold and ultracold neutrons [4–20], trapped nuclei [21,22], and rare pion and kaon decays [23–26]. Some of the measurements plan

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* Corresponding author.
E-mail address: vincenzo.cirigliano@gmail.com (V. Cirigliano).

[1] In this review we consider the decays involving the light quarks u, d, and s exclusively.

0146-6410/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ppnp.2013.03.005

to reach sensitivities between 10^{-3} and 10^{-4}; this makes such observables very interesting probes of new physics effects originating at the TeV scale, because such effects are expected to have size $\mathcal{O}((v/\Lambda_{\rm BSM})^2)$, where $v = (2\sqrt{2}G_F)^{-1/2} \approx 174$ GeV and $\Lambda_{\rm BSM}$ denotes the mass scale where BSM physics appears.

As in previous reviews [27–30], the overall goal of this article is to discuss the discovery potential and discriminating power of planned precision beta-decay measurements with neutrons, nuclei, and mesons, in light of other existing precision electroweak tests and high-energy collider searches, such as at the Tevatron and the LHC. In order to achieve our goal, we work within an effective field theory (EFT) framework, in which the dynamical effects of new heavy BSM degrees of freedom are parameterized by local operators of dimension higher than four built with SM fields.[2] All model-specific analyses of beta decays can be cast in the EFT language and the limits on the effective operators we derive can be readily converted into constraints on the parameters of any SM extension. In the absence of an emerging picture of new dynamics from collider searches, the EFT analysis is the first necessary step to establish the motivation and significance of this set of low-energy probes. Subsequently, we will also discuss well-motivated models such as the Left–Right Symmetric Model and supersymmetric extensions of the SM in order to show the discriminating power that combinations of beta decay measurements can have on explicit models.

Probing short-distance BSM couplings through precision phenomenology of beta decays requires knowing the relevant hadronic and nuclear matrix elements to a precision comparable to the size of the new physics effects one could expect to appear. This means that one needs to know the hadronic matrix elements of the SM operators, that is, of the V and A currents, to the level of $\mathcal{O}((v/\Lambda_{\rm BSM})^2)$, i.e. of 10^{-3} or better. This is a necessary condition for beta decays to function as competitive probes: we are in search of a small BSM signal, and hence we need to know the SM “background” to a level comparable to that of the signal for which we are looking. One also needs to know the matrix elements of the BSM operators, such as the S, T, P densities, because all the observables are sensitive to the product of the short-distance BSM coupling with the appropriate hadronic/nuclear matrix element. Consequently if a certain matrix element is suppressed, the sensitivity to the corresponding BSM coupling is also suppressed. Moreover, were such an anomalous suppression absent, the fractional uncertainty on the BSM matrix element still determines how well we can constrain that BSM coupling. For BSM operators, the precision required of the relevant hadronic matrix element is much less severe; an uncertainty at the $\mathcal{O}(10\%)$ level is acceptable. Motivated by these considerations, we pay special attention to the hadronic and nuclear uncertainties which appear.

This paper is organized as follows. In Section 2 we set up the theoretical framework for the analysis of all low-energy CC processes within and beyond the SM. In Section 3 we discuss the status of Cabibbo universality tests (Section 3.1) and lepton universality tests (Section 3.2) and explore the implications for BSM physics. In Section 4 we focus on differential decay distributions in beta decays and discuss the implications for non-$(V-A)$ couplings. In Section 5 we explore the constraints on non-standard CC couplings that can be obtained from LHC data. In Section 6 we illustrate how the precision tests can be used to probe the parameter space of models such as the Left–Right Symmetric Model and the Minimal Supersymmetric Standard Model (MSSM), and we present our concluding remarks in Section 7.

2. Theoretical framework

2.1. Effective Lagrangian

In this review we take the point of view that the Standard Model emerges as the low-energy limit of a more fundamental theory characterized by the scale Λ at which new particles appear. Consequently, at energies scales below Λ, namely, $\Lambda > E > M_{Z,W}$, the new degrees of freedom are no longer present; they have been “integrated out”, yielding an effective Lagrangian comprised of the SM Lagrangian augmented by a string of $d > 4$ operators constructed with the low-energy SM fields, suppressed by Λ^{d-4} [31], that respect the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry of the SM. Flavor physics observables constrain the appearance of non-SM invariant operators to energies far beyond the weak scale [32–34]. The building blocks of the gauge-invariant local operators are: the gauge fields $G^A_\mu,\ W^a_\mu,\ B_\mu$, corresponding to $SU(3)_C \times SU(2)_L \times U(1)_Y$, respectively, the six fermionic gauge multiplets, including a singlet right-handed neutrino state,

$$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \qquad u^i = u^i_R \qquad d^i = d^i_R \qquad l^i = \begin{pmatrix} \nu^i_L \\ e^i_L \end{pmatrix} \qquad e^i = e^i_R \qquad \nu^i = \nu^i_R, \tag{2.1}$$

where $i = 1, 2, 3$ is the family index, the Higgs doublet φ

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}, \tag{2.2}$$

and the covariant derivative

$$D_\mu = I\,\partial_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu - ig\frac{\sigma^a}{2} W^a_\mu - ig' Y B_\mu. \tag{2.3}$$

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[2] The EFT analysis can be applied to all low-energy probes of CC interactions. It is also valid for collider searches as long as the particles which mediate the new interactions are above particle-production threshold at the operating center-of-mass energy. In this case, a direct comparison of low-energy and collider constraints can be performed, as we discuss in Section 5.