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The effective neutrino charge radius in the presence of fermion masses

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Abstract

We show how the crucial gauge cancellations leading to a physical definition of an effective neutrino charge radius persist in the presence of non-vanishing fermion masses. An explicit one-loop calculation demonstrates that, as happens in the massless case, the pinch technique rearrangement of the Feynman amplitudes, together with the judicious exploitation of the fundamental current relation $J_\alpha^{(3)} = 2(J_Z + \sin\theta_{\mathrm{w}}^2 J_\gamma)_\alpha$, leads to a completely gauge independent definition of the effective neutrino charge radius. Using the formalism of the Nielsen identities it is further proved that the same cancellation mechanism operates unaltered to all orders in perturbation theory.

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1. Introduction

It is well known that, even though within the Standard Model (SM) the photon (A) does not interact with the neutrino (ν) at tree-level, an effective photon-neutrino vertex $\Gamma^{\mu}_{A\nu\bar{\nu}}$ is generated through one-loop radiative corrections, giving rise to a non-zero neutrino charge radius (NCR) [1]. Traditionally (and, of course, rather heuristically) the NCR

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has been interpreted as a measure of the "size" of the neutrino ν when probed electromagnetically, owing to its classical definition[1] (in the static limit) as the second moment of the spatial neutrino charge density $\rho_\nu(\mathbf{r})$, i.e., $\langle r_\nu^2\rangle = \int d\mathbf{r}\, r^2 \rho_\nu(\mathbf{r})$. However, the direct calculation of this quantity has been faced with serious complications [2] which, in turn, can be traced back to the fact that in non-Abelian gauge theories off-shell Green's functions depend in general explicitly on the gauge-fixing parameter. In the popular renormalizable (R_ξ) gauges, for example, the electromagnetic form-factor F_1 depends explicitly on gauge-fixing parameter ξ in a prohibiting way. Specifically, even though in the static limit of zero momentum transfer, $q^2 \to 0$, the form-factor $F(q^2, \xi)$ becomes independent of ξ, its first derivative with respect to q^2, which corresponds to the definition of the NCR, namely, $\langle r_\nu^2\rangle = -6(dF/dq^2)_{q^2=0}$, continues to depend on it. Similar (and some times worse) problems occur in the context of other gauges (e.g., the unitary gauge).

One way out of this difficulty is to identify a *modified* vertex-like amplitude, which could lead to a consistent definition of an effective electromagnetic form factor and the corresponding effective neutrino charge radius (eNCR). The basic idea is to exploit the fact that the *full* one-loop S-matrix element describing the interaction between a neutrino with a charged particle is gauge-independent, and try to rearrange the Feynman graphs contributing to this scattering amplitude in such a way as to find a vertex-like combination that would satisfy all desirable properties. What became gradually clear over the years was that, for reaching a physical definition for the NCR, in addition to gauge-independence, a plethora of important physical constraints need be satisfied. For example, one should not enforce gauge-independence at the expense of introducing target-dependence. Therefore, a definite guiding-principle is needed, allowing for the systematic construction of physical sub-amplitudes with definite kinematic structure (i.e., self-energies, vertices, boxes).

The field-theoretical methodology allowing this meaningful rearrangement of the perturbative expansion is that of the pinch technique (PT) [3]. The PT is a diagrammatic method which exploits the underlying symmetries encoded in a *physical* amplitude, such as an S-matrix element, in order to construct effective Green's functions with special properties. In the context of the NCR, the basic observation [4] is that the gauge-dependent parts of the conventional $A^*\nu\nu$, to which one would naively associate the (gauge-dependent) NCR, communicate and eventually cancel *algebraically* against analogous contributions concealed inside the $Z^*\nu\nu$ vertex, the self-energy graphs, and the box-diagrams (if there are boxes in the process), *before* any integration over the virtual momenta is carried out. For example, due to rearrangements produced through the systematic triggering of elementary Ward identities, the gauge-dependent contributions coming from boxes are not box-like, but self-energy-like or vertex-like; it is only those latter contributions that need be included in the definition of the new, effective $\hat{A}^*\nu\nu$ vertex.

The new one-loop proper three-point function satisfies the following properties [5–7]: (i) is independent of the gauge-fixing parameter (ξ); (ii) is ultraviolet finite; (iii) satisfies a QED-like Ward-identity; (iv) captures all that is coupled to a genuine $(1/q^2)$ photon

[1] Of course, the covariant generalization of this definition, just as that of a static charge distribution, is ambiguous.