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DIVERGENCES IN THE EFFECTIVE INTERACTION BETWEEN CHERN–SIMONS BOSONS AND SM FERMIONS IN NON-UNITARY GAUGE[1]

A vector extension of the Standard Model (SM) involving an interaction of the Chern–Simons type is analyzed. The model introduces a new massive vector field, referred to as the Chern–Simons (CS) boson, which does not couple directly to the fermionic sector of the SM. The study focuses on the structure and renormalizability of the effective loop-induced interactions between the CS boson and SM fermions in an arbitrary gauge. It is demonstrated that the ultraviolet divergences arising in the loop calculations cannot be consistently removed for interactions involving fermions of identical flavor, while the corresponding loop-induced couplings between fermions of distinct flavors remain finite. The specific interaction operators associated with divergent coefficients are identified, and their treatment within the framework of effective field theory is proposed.

Keywords: vector extension of the Standard Model, effective field theory, Chern–Simons type interaction.

1. Introduction

Although the Standard Model (SM) [1] has been extraordinarily successful, it leaves several key observations unexplained. Among these are the presence of dark matter [2–4], the phenomenon of neutrino oscillations [5–8], and the observed matter–antimatter asymmetry of the Universe [9, 10]. These shortcomings suggest the existence of an additional (hidden) sector of particles. Such a hidden sector may contain new particles that are either too massive to be produced at current collider energies or interact only feebly with the SM degrees of freedom. Light feebly coupled particles may be found in intensity-frontier experiments at present [11–13].

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The nature of these particles remains uncertain. Depending on the underlying theory, they could manifest as new vector [14,15], scalar [16,17], or pseudoscalar bosons [18, 19], or fermions [20, 21]. In the present paper, we concentrate on an extension of the SM that introduces a massive vector boson (the CS boson), which directly interacts only with the Higgs and vector fields of the SM.

The simplest gauge-invariant realization of such interactions can be formulated in terms of dimension-six operators [11, 22]:

$$\mathcal{L}_1 = \frac{C_Y}{\Lambda_Y^2}\, X_\mu (\mathfrak{D}_\nu H)^\dagger H\, B_{\lambda\rho}\, \epsilon^{\mu\nu\lambda\rho} + \text{h.c.}, \quad (1)$$

$$\mathcal{L}_2 = \frac{C_{SU(2)}}{\Lambda_{SU(2)}^2}\, X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H\, \epsilon^{\mu\nu\lambda\rho} + \text{h.c.}, \quad (2)$$

where X_μ denotes the new vector field with mass M_X, and $\epsilon^{\mu\nu\lambda\rho}$ is the Levi–Civita tensor normalized as $\epsilon^{0123} = +1$. The Higgs doublet is denoted

[1] This work is based on the results presented at the 2025 "New Trends in High-Energy Physics" Conference.

by H, while $B_{\mu\nu}$ and $F_{\mu\nu}$ are the field strength tensors of the $U_Y(1)$ and $SU_W(2)$ gauge groups, respectively. The constants C_Y and $C_{SU(2)}$ are dimensionless coefficients, and Λ_Y, $\Lambda_{SU(2)}$ represent the heavy mass scales associated with new physics. The The Lagrangians remain gauge invariant because X_μ is the Stueckelberg field.

After electroweak symmetry breaking, the operators in Eqs. (1), (2) give rise (among other terms) to a set of three-field interactions between the physical Higgs field, the Standard Model vector bosons, and the CS boson:

$$\mathcal{L}^{(4)}_{\rm CS} = c_z\,\epsilon^{\mu\nu\lambda\rho}X_\mu Z_\nu \partial_\lambda Z_\rho + c_\gamma\,\epsilon^{\mu\nu\lambda\rho}X_\mu Z_\nu \partial_\lambda A_\rho + + \left\{c_w\,\epsilon^{\mu\nu\lambda\rho}X_\mu W^-_\nu \partial_\lambda W^+_\rho + \text{h.c.}\right\}, \tag{3}$$

$$\mathcal{L}^{(5)}_{\rm CS} = c_{\gamma h}\,\epsilon^{\mu\nu\lambda\rho}X_\mu \frac{\partial_\nu h}{v}\partial_\lambda A_\rho + + c_{zh}\,\epsilon^{\mu\nu\lambda\rho}X_\mu \frac{\partial_\nu h}{v}\partial_\lambda Z_\rho, \tag{4}$$

where Eq. (3) contains dimension-four operators, while Eq. (4) represents dimension-five contributions. The field h corresponds to the physical excitation of the Higgs doublet with vacuum expectation value v, and A_μ, $W^\pm_\mu$, and Z_μ denote the photon and the electroweak vector bosons, respectively. The coefficients $c_{\gamma h}$, c_{zh}, c_γ, and c_z are real-valued, whereas c_w may, in general, possess a complex phase. Notably, the Chern–Simons field X_μ interacts only with the bosonic sector of the Standard Model and has no direct coupling to fermions.

The renormalizability of the interactions in Eq. (3) has been the subject of several earlier analyses [23–25]. These studies established that loop interactions of the CS boson with quarks of different flavors are finite, while loop interactions with leptons or quarks of the same flavor contain ultraviolet divergences [26]. Calculations performed in the unitary gauge [27] further demonstrated that such divergences cannot be removed.

In this paper, we extend the analysis of renormalizability to the case of a general R_ξ gauge, incorporating the full set of diagrams that include both Higgs and Goldstone bosons. The purpose of this investigation is twofold: first, to determine whether the divergences persist when the gauge parameters ξ_i are finite, and second, to establish the correspondence between results obtained in the R_ξ and unitary gauges.

A rigorous treatment of loop-induced interactions between the Chern–Simons boson and Standard Model fermions is necessary for experimental searches for feebly-coupled vector extensions of the Standard Model [28]. Following the approach of Ref. [27], we will focus primarily on leptonic interactions, thereby avoiding the additional complexities associated with quark flavor mixing through the CKM matrix.

2. Interactions in the R_ξ Gauge

In a general R_ξ gauge, the Higgs doublet takes the form

$$H = \begin{pmatrix} \phi^+ \\ \dfrac{v + h + i\phi_z}{\sqrt{2}} \end{pmatrix}. \tag{5}$$

Here ϕ^+ and ϕ_z correspond to the charged and neutral Goldstone bosons, respectively, and h denotes the physical Higgs field. Within this gauge choice, the three-point Chern–Simons (CS) interactions defined by Eqs. (3) and (4) acquire additional contributions that explicitly involve the Goldstone bosons. These new vertices can be obtained directly from the higher-dimensional operators in Eqs. (1) and (2), and their explicit forms read

$$\mathcal{L}^{X\phi^\mp W^\pm} = \frac{2i}{gv}\Big(c_w\,X_\mu\,\partial_\nu\phi^-\,\partial_\lambda W^+_\rho - - c_w^*\,X_\mu\,\partial_\nu\phi^+\,\partial_\lambda W^-_\rho\Big)\epsilon^{\mu\nu\lambda\rho}, \tag{6}$$

$$\mathcal{L}^{X\phi_z Z} = \frac{c_z g}{2\cos\theta_W}X_\mu\,\frac{\partial_\nu\phi_z}{v}\,\partial_\lambda Z_\rho\,\epsilon^{\mu\nu\lambda\rho}, \tag{7}$$

$$\mathcal{L}^{X\phi_z A} = \frac{c_\gamma g}{2\cos\theta_W}X_\mu\,\frac{\partial_\nu\phi_z}{v}\,\partial_\lambda A_\rho\,\epsilon^{\mu\nu\lambda\rho}. \tag{8}$$

In what follows, we analyze the decay process of a massive Chern–Simons boson into a pair of charged leptons $X \to \ell^+\ell^-$ ($\ell = e, \mu, \tau$) within the R_ξ gauge formalism.

3. Triangle Diagrams

An example of triangle diagrams describing lepton production in the decay of the CS boson, mediated by interactions with $W^\pm$ and Goldstone bosons, is shown in Fig. 1. In addition to the diagrams displayed, the R_ξ gauge also introduces analogous diagrams involving photons, Z bosons, the Higgs boson h, and the Goldstone fields $\phi^\pm$ and ϕ_z, as determined by the Feynman rules derived from interactions (3), (4), and (6)–(8).

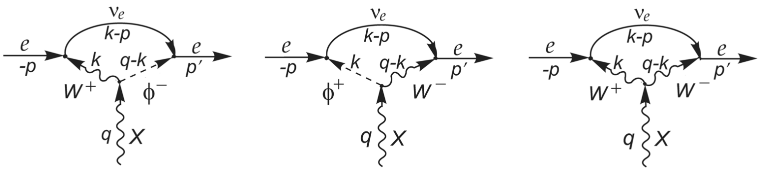

Fig. 1. Representative triangle diagrams contributing to lepton pair production in CS boson decay via interactions with two W bosons or with W and charged ϕ bosons

A direct calculation shows that the amplitudes corresponding to these triangle diagrams include both logarithmic and linear divergences, leading to the appearance of divergent (infinite) parameter

$$\Lambda_1 = \frac{\pi^2}{2(2\pi)^4} \ln\left(\frac{\Lambda^2}{M_W^2}\right) \longrightarrow \infty. \tag{9}$$

It can be shown that one-loop diagrams with two internal lines for lepton production from interactions of the CS boson with vector fields of the SM, Goldstone bosons, or Higgs bosons give zero contribution due to the properties of the Levi–Civita tensor.

4. Sum of Divergent Terms in the R_ξ Gauge

The divergent summarized contributions from all diagrams can be written as

$$\sum_{\text{diagrams}} M_{fi,\,\text{div}} = \Lambda_1\, \bar{\ell}(p') \Big[(A + A_5\gamma^5)\, \gamma_\nu \gamma_\lambda \gamma_\rho + + \frac{B + B_5\gamma^5}{v}\, q_\nu \gamma_\lambda \gamma_\rho \Big] \ell(-p)\, \varepsilon_\mu^{\lambda_X}\, \epsilon^{\mu\nu\lambda\rho}. \tag{10}$$

Here A, A_5, B, and B_5 are dimensionless coefficients given by

$$A + A_5\gamma^5 = - i\frac{g^2}{4}\Big[\Theta_{W1} + \frac{2c_z}{\cos^2\theta_W}(t_3^\ell(t_3^\ell - 2q_\ell \sin^2\theta_W) + + 2q_\ell^2 \sin^4\theta_W) + 2q_\ell c_\gamma \tan\theta_W (t_3^\ell - 2q_\ell \sin^2\theta_W)\Big] - - i\gamma^5 \frac{g^2}{4}\Big[\Theta_{W1} + \frac{2t_3^\ell c_z}{\cos^2\theta_W}(t_3^\ell - 2q_\ell \sin^2\theta_W) + + 2q_\ell t_3^\ell c_\gamma \tan\theta_W\Big], \tag{11}$$

$$B + B_5\gamma^5 = -\frac{m_\ell}{v}\Big[\Theta_{W2} - c_{zh}\frac{g(t_3^\ell - 2q_\ell \sin^2\theta_W)}{2\cos\theta_W} - - c_{\gamma h} e q_\ell\Big] - i\frac{m_\ell}{v}\gamma^5\Big[\Theta_{W1} - c_z(t_3^\ell - 2q_\ell \sin^2\theta_W) - - q_e c_\gamma \sin 2\theta_W\Big]. \tag{12}$$

The divergences vanish only when the conditions $A = A_5 = B = B_5 = 0$ are satisfied. We did not find any relation between the couplings c_z, c_γ, $c_{\gamma h}$, c_{zh}, Θ_{W1}, and Θ_{W2} for which these conditions are true. They are met only when all couplings vanish.

5. Comparison with the Unitary Gauge

Calculations carried out in the unitary gauge [27] similarly indicate that ultraviolet divergences in the effective loop coupling between the Chern–Simons (CS) boson and Standard Model leptons cannot be eliminated [2].

At first sight, the divergent terms obtained in [27] appear to be structurally more complex than those arising in non-unitary gauge, Eq. (10). Nevertheless, once the lepton equations of motion are applied,

$$\bar{\ell}(p')\, \not{p}' = m_\ell \bar{\ell}(p'), \quad -\not{p}\, \ell(-p) = m_\ell \ell(-p), \tag{13}$$

the divergent parts in both gauge choices are found to be equivalent, confirming the gauge independence of the divergence structure.

6. Discussion

In this paper, we study a vector extension of the SM with a Chern–Simons-type interaction. It contains a new massive vector boson that does not directly couple to SM fermions.

It is well established that loop-induced interactions of the CS boson with fermions of different flavors remain finite because the divergent contributions are proportional to the off-diagonal elements

[2] All expressions in this paper follow the corrected arXiv version of [27], which resolves several typographical errors present in the published text.

of the unit matrix $(V^\dagger V)_{ij}$, where V denotes the CKM matrix [23–25]. The situation changes for interactions involving fermions of identical flavor: earlier computations performed in the unitary gauge [27], based only on the Lagrangian (3), demonstrated that the divergent terms cannot be canceled or renormalized away.

In the present paper, we extend this analysis to the general R_ξ gauge, allowing arbitrary, finite values of the gauge parameters ξ_i. Our calculations show that the ultraviolet divergences persist in the effective loop-induced CS-fermion interaction even after the inclusion of all relevant diagrams derived from the Lagrangians Eqs. (3), (4), and (6)–(8). This divergence cannot be canceled by counterterms for the CS boson–fermion interaction, since such terms are absent in the original Lagrangians of the theory. Consequently, the Lagrangian (3), although composed of operators of dimension four, is a Lagrangian describing a nonrenormalizable interaction.

Two terms in the effective CS-fermion interaction (10) are found to contain divergences, which are consistent across both the unitary and R_ξ gauges.

Therefore, the interactions of the CS boson with fermions of the same flavor after electroweak symmetry breaking should be considered only within the framework of effective field theory [29–31]. These interactions can be parameterized as

$$\mathcal{L}^{\rm int}_{Xff} = \bar f\gamma^\mu(\alpha_f + \beta_f\gamma^5) f X_\mu + \\ + \frac{m_f}{v^2}\bar f\sigma^{\mu\nu}(\gamma_f + \delta_f\gamma^5) f X_{\mu\nu} + \mathcal{L}'_{Xff}, \qquad (14)$$

where α_f, β_f, γ_f, and δ_f are dimensionless new couplings of the theory, and $\mathcal{L}'_{Xff}$ denotes the finite, well-defined interaction Lagrangian.

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АНАЛІЗ РОЗБІЖНОСТЕЙ В ЕФЕКТИВНІЙ ВЗАЄМОДІЇ МІЖ БОЗОНАМИ ЧЕРНА–САЙМОНСА ТА ФЕРМІОНАМИ СТАНДАРТНОЇ МОДЕЛІ В НЕУНІТАРНОМУ КАЛІБРУВАННІ

Розглянуто векторне розширення Стандартної моделі (СМ) зі взаємодією типу Черна–Саймонса. В даній моделі вводиться нове масивне векторне поле, квантами якого є бозони Черна–Саймонса (ЧС-бозони). Нове векторне поле не взаємодіє напряму з ферміонним сектором СМ. Досліджується питання структури і перенормовності ефективних петльових взаємодій між ЧС-бозоном і СМ-ферміонами в довільному калібруванні. Показано, що ультрафіолетові розбіжності, які виникають при розрахунках петльових взаємодій, не можна усунути для взаємодій з ферміонами однакового аромату, тоді як відповідні петльові взаємодії з ферміонами різних ароматів позбавлені розбіжностей. Визначено явний вигляд операторів взаємодії, що містять розбіжні коефіцієнти, та запропоновано їх розгляд у підході ефективної теорії поля.

Ключові слова: векторне розширення Стандартної Моделі, ефективна теорія поля, взаємодія типу Черна–Саймонса.