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Loop Divergences in the Effective Theory of Chern–Simons Boson–Fermion Couplings

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Although the Standard Model (SM) has proven remarkably effective in accounting for a wide range of experimental data from particle colliders, it remains an incomplete framework. It does not account for several key phenomena, such as the oscillations of active neutrinos, the observed matter–antimatter imbalance in the Universe, and the nature of dark matter. Consequently, the SM requires extensions that introduce new particles and fundamental interactions.

One explanation for why these hypothetical particles have eluded detection is that they are either very massive with weak couplings to SM particles or very light but interact so feebly that their presence is difficult to observe. In the case of heavy particles, future high-energy colliders like the FCC may have sufficient reach to detect them. Conversely, if these particles are light, they could potentially be discovered at existing facilities in experiments operating at the intensity frontier—such as MATHUSLA, FACET, FASER, SHiP, and others at CERN.

Here we investigate a specific extension of the SM that introduces a new massive vector boson, known as the Chern–Simons (CS) boson, which interacts through terms analogous to the Chern–Simons structure. These interactions are encapsulated by a minimal, gauge-invariant Lagrangian constructed from dimension-six operators {1}:

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

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

In these expressions, Λ_Y and $\Lambda_{SU(2)}$ denote new energy thresholds associated with physics beyond the SM, and $C_Y, C_{SU(2)}$ are dimensionless coupling constants. The Levi-Civita symbol $\epsilon^{\mu\nu\lambda\rho}$ is defined with $\epsilon^{0123} = +1$. The vector field X_μ corresponds to the CS boson, while H is the Higgs doublet scalar field. The field strength tensors $B_{\mu\nu}$ and $F_{\mu\nu}$ describe the dynamics of the $U(1)_Y$ and $SU(2)_W$ gauge fields of the SM, respectively.

After electroweak symmetry breaking, the interactions defined by Lagrangians (1) and (2) give rise to additional terms in the effective theory, including three-particle interactions characterized by dimension-four operators:

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

Here, $A\mu$ is the photon field, while $W^\pm_\mu$ and Z_μ denote the charged and neutral weak gauge bosons, respectively. The coefficients c_z and c_γ are real-valued constants, whereas c_w may generally be complex. Importantly, in this minimal scenario, the CS boson X_μ does not couple directly to matter fields.

Effective loop interactions involving the CS boson and fermions of different flavors are well-behaved and finite. This finiteness arises because any potential divergence is tied to off-diagonal terms in the matrix product $(V^\dagger V)_{ij}$, where V represents the CKM matrix. These terms vanish, eliminating problematic contributions, as previously demonstrated in {2,3}.

However, complications emerge in the case where the CS boson interacts with fermions of the same generation. Our prior work {4} explored this scenario within the unitary gauge, using a purely four-dimensional interaction basis defined by (3). The findings revealed persistent divergences in loop diagrams, which could not be eliminated by conventional means.

In the present work {5}, we extend the investigation to the more general R_ξ gauge, allowing for arbitrary but finite values of the gauge-fixing parameters ξ_i, and concentrate on the CS boson's loop interactions with same-flavor leptons.

Our analysis shows that even when all one-loop diagrams are considered in this gauge setting, ultraviolet divergences persist. As a result, the seemingly renormalizable theory defined by (3) fails to meet renormalizability requirements in the presence of a massive vector field.

Analysing the sum of the divergent parts of all considered diagrams, we identify two divergent terms for the CS boson interacting with same-flavor fermions that are present in both the unitary and R_ξ gauge calculations.

Since the initial interaction of the CS bosons with SM fields is given by dimension-6 operators (1) and (2), we conclude that after the electroweak symmetry breaking the interaction of the CS boson with fermions of the same flavor should be considered within the framework of the effective field theory approach and can be written as

$$\mathcal{L}^{int}_{Xff} = \bar{f}\gamma^{\mu}(\alpha_f + \beta_f\gamma^5)fX_{\mu} + \frac{m_f}{v^2}\bar{f}\sigma^{\mu\nu}(\gamma_f + \delta_f\gamma^5)fX_{\mu\nu} + \mathcal{L}'_{Xff}, \quad (4)$$

where $X_{\mu\nu} = \partial_{\mu}X_{\nu} - \partial_{\nu}X_{\mu}$. Here dimensionless parameters α_f β_f, γ_f, δ_f should be considered as new 4 parameters of the effective theory and $\mathcal{L}'_{Xff}$ is a well-defined Lagrangian of interaction depending on the coupling parameters of the Lagrangian (3).

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