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CP violation from spin-1 resonances in a left-right dynamical Higgs context (postprint)

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Abstract

New physics field content in the nature, more specifically, from spin-1 resonances sourced by the extension of the SM local gauge symmetry to the larger local group SU(2)L SU(2)R U(1)B−L, may induce CP-violation signalling NP effects from higher energy regimes. In this work we completely list and study all the CP-violating operators up to the p4-order in the Lagrangian expansion, for a non-linear left-right electroweak chiral context and coupled to a light dynamical Higgs. Heavy right handed fields can be integrated out from the physical spectrum, inducing thus a physical impact in the effective gauge couplings, fermionic electric dipole moment, and CP-violation in the decay h → ZZ∗ → 4 l that are briefly analysed. The final relevant set of effective operators have also been identified at low energies.

Full Text

Preamble

New physics field content in nature, specifically spin-1 resonances arising from extending the SM local gauge symmetry to the larger group SU(2) SU(2) U(1) , may induce CP violation that signals new physics effects from higher energy regimes. In this work we provide a complete classification and study of all CP-violating operators up to p -order in the Lagrangian expansion, within a non-linear left-right electroweak chiral context coupled to a light dynamical Higgs. Heavy right-handed fields can be integrated out from the physical spectrum, thereby inducing physical effects in the effective gauge couplings, fermionic electric dipole moments, and CP violation in the decay h → ZZ* → 4 , which are briefly analyzed. The final relevant set of effective operators at low energies has also been identified.

Introduction

The Standard Model (SM) has been firmly established as a coherent and consistent picture of electroweak symmetry breaking (EWSB) following the LHC experimental confirmation of a new scalar resonance [1, 2] in nature, resembling the long-proposed Higgs boson particle [3–5]. Nevertheless, new physics (NP) effects remain to be discovered, as required by the long-standing hierarchy problem in particle physics. Among possible NP manifestations, CP-violating low-energy effects could reveal the existence of higher energy regimes accessible at the LHC and future facilities. Indeed, electroweak interactions in nature do not perfectly conserve the combined charge conjugation and parity symmetries. Moreover, the observed matter-antimatter asymmetry of our universe compels us to consider new sources of CP violation, as signaled by the extreme fine-tuning entailed by the strong CP problem.

Phenomenological analyses pursuing effective signals have been performed [6–43] to search for anomalous CP-odd fermion-Higgs and gauge-Higgs couplings. Complementary theoretical studies are essential to establish and analyze the complete set of independent CP-violating bosonic operators, as they may directly illuminate the nature of EWSB and pinpoint NP effects from higher energy regimes.

Motivated by these prospects, this work addresses the possibility of detecting non-zero CP-violating signals arising from new physics field content in nature, specifically from spin-1 resonances introduced by extending the SM local gauge symmetry U(1) to the larger local group U(1) (see [44, 45] for left-right symmetric models literature). Such an extended gauge field sector is tackled here through a systematic and model-independent effective field theory (EFT) approach. The basic strategy employs a non-linear -model to account for the strong dynamics giving rise to the Goldstone bosons (GB), namely the W± and Z longitudinal components that introduce the Goldstone scale f , together with the corresponding GB from the extended local group, i.e., the additional R and Z longitudinal degrees of freedom and the associated Goldstone scale f . This non-linear -model effective Lagrangian is then coupled a posteriori to a scalar singlet h in a general way through powers of h/f [46], with the scale suppression dictated by f , as this is the scale where h is generated as a GB prior to the extension of the SM local group.

In this work we analyze the physical picture of spin-1 resonances dictated by the larger local gauge group with an underlying strongly interacting scenario coupled to a light Higgs particle, via the non-linear EFT construction of the complete tower of pure gauge and gauge-Higgs operators up to p -order in the Lagrangian expansion, restricted to the CP non-conserving bosonic sector. The corresponding CP-conserving counterpart was recently analyzed in [47]. This work enlarges and completes the operator basis previously considered in [48, 49] (for the CP-breaking sector) in the context of left-right symmetric electroweak chiral models, completing and generalizing the work done in [50–54] (for the CP-violating sector), and extends [55] to the case of a larger local gauge symmetry in the context of non-linear electroweak interactions coupled to a light Higgs particle.

The theoretical framework undertaken here may be considered a generic UV completion of the low-energy non-linear approaches of [50–54] and [55].

Theoretical Framework

The transformation properties of the longitudinal degrees of freedom of the electroweak gauge bosons are parametrized at low energies via dimensionless unitary matrices U(x), specifically through U (x) and U (x) for the symmetry group SU(2) SU(2) , defined as

U ( )(x) = exp(i ( )(x)/f ( ))

with being Pauli matrices and ( )(x) the corresponding Goldstone boson fields suppressed by their associated non-linear sigma model scales f ( ), where the scale f comes from the additional Goldstone boson dynamics introduced by the SU(2) group.

It is customary to introduce the corresponding covariant derivative objects for both Goldstone matrices U ( )(x) as

D U ( ) U ( ) + ig ( )W ( )(/2)U ( ) + ig' B U ( )(³/2)

with the SU(2) , SU(2) and U(1) gauge fields denoted by W ( ) and B respectively, and the associated gauge couplings g , g and g' respectively. Additionally, it is straightforward to introduce in the framework the adjoint SU(2) ( )-covariant vectorial V ( ) and the covariant scalar T ( ) objects as

V ( ) (D U ( ))U ( )†, T ( ) U ( ) ³U ( )†

all transforming covariantly under local transformations of the larger group.

Notice that the local gauge invariance of the theory allows building operators made from traces depending on products of purely left-handed or right-handed covariant objects. When operators mixing left- and right-handed structures are considered, new covariant objects emerge to guarantee their construction. In fact, considering for instance the simple trace mixing left- and right-handed covariant objects, gauge invariance no longer holds. Proper insertions of the Goldstone matrices U and U make it invariant, motivating the introduction of the following objects:

T̃ ( ) U ( )†T ( )U ( ), Ṽ ( ) U ( )†V ( )U ( )

that are required hereafter for constructing operators from mixed SU(2) and SU(2) covariant structures. Notice that under local transformations L(x), R(x) and (x) (space-time dependent variables with parametrizing local rotations), the newly defined objects transform covariantly.

The corresponding definitions for the covariant vectorial V ( ) and scalar T ( ) objects are:

V̄ ( ) U ( )†(D U ( ))U ( )†U ( ), T̄ ( ) U ( )†U ( ) ^{3}U ( )†U ( )

where the unitary property of the Goldstone matrices U ( ) has been employed. Similar definitions for the strength gauge fields W ( ) are straightforward:

W̄ ( ) U ( )†U ( )W ( )U ( )†U ( )

It is therefore mandatory to introduce the covariant objects V̄ ( ) and T̄ ( ) to construct any operator mixing left- and right-handed operators. As realized in [47], covariant quantities made from products of purely left- or right-handed covariant quantities can also be constructed via the objects T̄ ( ) defined above. Henceforth, the set {V ( ), T ( ), V̄ ( ), T̄ ( )} (together with W ( )) makes up the building blocks for constructing the effective electroweak non-linear left-right CP-violating approach undertaken in this work, whose CP-conserving counterpart was already explored in Ref. [47].

This construction will be enlarged after accounting for all possible gauge-Higgs couplings arising in this scenario via the generic polynomial light singlet Higgs function F(h) [56], defined through the expansion

F (h) = 1 + 2a (h/f) + ⋯

with dots standing for higher powers in h/f [46], not considered below. The scale suppression for each h-insertion is dictated by f , as this is the scale where h is generated as a GB prior to the extension of the SM local group. Gauge-Higgs interactions arise by letting the non-linear operators be coupled either directly to F(h) or through its derivative couplings, e.g., via F(h) and F(h). Thus the building block set is complemented by accounting for all possible interactions with F(h) and its derivative couplings, under the assumption of CP-even behavior for h.

The local gauge symmetry GSM = SU(2) U(1) has been demanded throughout the non-linear effective approach considered up to now. Another relevant symmetry emerges once the initial SM local group is extended: the discrete parity symmetry P , related to the exchange of left- and right-handed components of the group SU(2) SU(2) . This symmetry is useful for protecting the Zb̄b coupling from large corrections in composite Higgs models [57] and brings additional effective operators to the scenario, as will be realized when listing the operators.

The CP-violating setup described in the next section follows the dynamical Higgs scenario of [55, 56, 58, 59] (see also [61, 62] and the summary [63]), as well as the left-right bosonic CP-conserving picture of [47].

The Effective Lagrangian

The effective CP-violating new physics contributions from the strong dynamics assumed here will lead to non-zero departures from the SM Lagrangian L and will be encoded in the Lagrangian L_chiral through

L_chiral = L + L ,   + ΔL_CP + ΔL_CP,

Concerning only the bosonic interacting sector, the first piece in L_chiral reads as

L = -¼B B   - ¼W , W   ,   - ¼G , G ,   + ½(h)(h) - V(h) + (f ²/4)Tr(V , V   ) + (1/32 ²)   G   G

providing the SM strength gauge kinetic terms canonically normalized in the first line, while the second line contains h kinetic terms and the effective scalar potential V(h) triggering EWSB, plus the W± and Z masses and their couplings to the scalar h together with the GB-fermion kinetic terms. The last term corresponds to the well-known total derivative CP-odd gluonic coupling. Notice that the SU(2) kinetic term and custodial-conserving p^2-operator Tr(V , V   ) have been properly labeled to maintain clear notation according to the assumed local symmetry group. GB kinetic terms are already canonically normalized from the scale factor of Tr(V , V   ), consistent with the U definition.

Non-zero new physics departures from L play a role once the symmetric counterpart sourced by the corresponding local SU(2) extension is included, encoded through the remaining pieces of L_chiral, focusing only on CP-violating operators:

- L , : accounts for all possible p^2 operators mixing left- and right-handed covariant objects
- ΔL_CP: encodes all operators up to p contributions made from purely left- or right-handed covariant objects
- ΔL_CP, : parametrizes any possible mixing interactions between SU(2) and SU(2) covariant objects up to p operators permitted by the underlying left-right symmetry

It is worth noting that at leading p^2-order, the corresponding CP-violating SU(2) strength gauge kinetic term (which would be encoded in L ,) turns out to be proportional to a total divergence and is thus disregarded from L_chiral. However, once light Higgs couplings are switched on through F(h), such SU(2) kinetic terms must be retained in the effective approach, as will be done later.

A. SU(2) —SU(2) p^2-interplay: L ,

The leading-order p^2 Lagrangian for the SU(2) extension brings operators made of mixed products of left- and right-handed objects via the covariant objects T ( ) and V   ( ) defined previously, specifically from T ( ), V   ( ), and W   ( ) defined in the building block section.

The p²-interplaying Lagrangian for these contributions is parametrized by

L , = (/4) Tr(V V)

Contrary to the case of pure left- or right-handed strength gauge kinetic terms, this operator must be maintained in the effective Lagrangian, as it cannot be expressed as a total divergence due to the mixed fields involved.

At higher orders in the momentum expansion, more interactions are sourced by the local symmetry group, with some accounted for by the third piece of L_chiral, ΔL_CP, described below.

B. G-extension of L + L , : ΔL_CP

ΔL_CP describes deviations from the leading-order Lagrangian L + L , , encoding all possible CP-violating gauge-Higgs interactions up to p operators. It is split as

ΔL_CP = ΔL_CP, + ΔL_CP,

with the suffix L(R) labeling operators built from the SU(2) ( ) building blocks.

In the context of purely electroweak chiral effective theories coupled to a light Higgs, the first contribution ΔL_CP, has been provided in Ref. [55], while parts of ΔL_CP, and ΔL_CP, were analyzed for left-right symmetric frameworks in Refs. [48, 49].

Both contributions can be written as

ΔL_CP, = c_GS_G(h) + c_BS_B(h) + Σ_{i={W,2D}}c_i, S_i, (h) + Σ_i c_i, S_i, (h)

ΔL_CP, = Σ_{i={W,2D}}c_i, S_i, (h) + Σ_i c_i, S_i, (h)

where the coefficients c_B, c_G and c_i, (with = L, R) are model-dependent constants, while the first three terms of ΔL_CP, and the first term of ΔL_CP, can be jointly expressed as

S_G(h) = (g_s²/32 ²) G G F_G(h) S_B(h) = (g'²/16 ²) B B_ F_B(h)
S_W, (h) = (g_ ²/16 ²) Tr[W , W_ ,]F_W, (h) S_2D, (h) = i Tr[V , V , V_ , V_ ,]F_2D, (h)

with suffix = L, R, and the F_i(h) functions of the scalar singlet h defined generically as in Eq. (10). The Higgs-independent terms are physically irrelevant for operators S_B(h) and S_2D(h), as the first two can be written as total divergences and the latter vanishes after integration by parts.

The covariant derivative D of a field transforming in the adjoint representation of SU(2) is defined as

D V , = V , + ig_ [V , , V ,], = L, R

The complete linearly independent set of 16 CP-violating pure gauge and gauge-Higgs non-linear invariant operators up to p -order in the effective Lagrangian expansion are encoded by S_i, (h) (the fourth term in ΔL_CP,) and have been completely listed in Ref. [55].

The symmetric counterpart extending this set, accounting for all possible CP-violating pure gauge and gauge-Higgs interactions up to p operators, is described by the complete linearly independent set of 16 operators S_i, (h) (the second term in ΔL_CP,). In total one has 32 non-linear operators, of which 20 (10 S_i, (h) + 10 S_i, (h)) had already been listed in Refs. [48, 49].

Here, 12 additional operators have been found (6 S_i, (h) + 6 S_i, (h)) and are naturally promoted by the symmetries of the model (together with the P symmetry), such that the complete operator basis S_i, (h) + S_i, (h) is given by:

S , (h) = g_ g' B Tr[T_ W_ ,]F , (h) S , (h) = ig' B Tr[T_ V_ ,]F , (h)
S , (h) = ig_ Tr[V , T_ W_ ,]F , (h) S , (h) = g_ Tr[T_ V , V ,] F , (h)
S , (h) = iTr[T_ V , V ,] F , (h) S , (h) = iTr[T_ V , V , V_ ,] F , (h) S , (h)
= g_ Tr[T_ W , V_ ,] F , (h) S , (h) = g_ ² Tr[T_ W ,]Tr[T_ W_ ,]F , (h)
S , (h) = ig_ Tr[T_ D V , D V_ ,]F , (h) S , (h) = iTr[T_ V , V , W ,]F , (h)
S , (h) = iTr[T_ V , V ,] F (h) S , (h) = iTr[T_ V , V , V , V ,] F , (h)
S , (h) = iTr[T_ V , V , V , V ,] F , (h) S , (h) = iTr[T_ V , V , V , V ,]F , (h)
S , (h) = iTr[T_ V , V , V , V ,] F , (h) S , (h) = iTr[T_ V , V , V , V ,]F , (h)

with W , = W , /2. Operators already listed in the context of CP-violating electroweak chiral effective theories coupled to a light Higgs in Ref. [55] are highlighted in red. Notice that operators S , (h) and S , (h) containing double derivatives of F(h) are not present in Refs. [48, 49], and are additional ones arising from extending the SM local symmetry through SU(2) , naturally allowed by the local symmetries of the model. The entire basis S_i, (h) in Eq. (19) (for = R) emerges from the straightforward parity action of P on the operator tower S_i, from Ref. [55] (concerning the Goldstone boson part only, i.e., before gauging the scenario).

The number of independent operators in the non-linear expansion turns out to be larger than for the analogous basis in the linear expansion, a generic feature when comparing both types of effective Lagrangians [58, 66]. The basis is also larger than those for chiral expansions developed for a very heavy Higgs particle (i.e., absent at low energies) [50–52, 54], because: (i) terms that were equivalent via total derivatives in the absence of F_i(h) functions are now independent, and (ii) new terms including derivatives of h appear.

The connection between the non-linear framework analyzed here and effective linear scenarios explicitly implementing the SM Higgs doublet has been established for the CP-conserving Lagrangian L_chiral = L + ΔL_CP, in [56, 58], where all corresponding non-linear CP-conserving operators were weighted by powers of = v^2/f^2 to track their operator siblings in the linear side. Likewise, a similar connection was made in [55] for the CP-violating non-linear Lagrangian L_chiral = L + ΔL_CP, , where each operator in the tower of Eq. (19) (for = L) was weighted by corresponding powers of = v^2/f^2. For the complete

CP-violating Lagrangian in Eq. (11) assumed in this work, such linking between both EFT sides would require accounting for the left-right symmetric extension of the effective linear approaches, which is beyond the scope of this work.

Concerning the symmetry P mentioned in Section II, in the context of a general effective SO(5)/SO(4) composite Higgs model scenario [67], the discrete parity P was shown to be an accidental symmetry up to p^2-order and broken by several p operators. Exactly the same properties are shared by the non-linear electroweak bosonic SU(2) SU(2) SO(4) invariant scenario studied recently in [47]. As suspected from the fact that SU(2) SU(2) SO(4), the corresponding leading-order p^2 Lagrangian analyzed in [47] explicitly exhibited P as an accidental symmetry (before gauging). At higher momentum order, the p operators encoded in ΔL_CP did not break P either. Only when p operators made of mixed left- and right-handed covariant structures were included did non-zero contributions appear that trigger the breaking of P (see [47] for details).

All possible CP non-invariant pure gauge and gauge-Higgs interactions allowed by the local symmetry have been encoded up to p non-linear operators in the first three pieces of L_chiral, i.e., in L + L , + ΔL_CP through Eqs. (12)-(19). In the following section, the SU(2) −SU(2) interplay is addressed by accounting for all possible left-right symmetric CP-breaking interactions up to p -order in the chiral Lagrangian L_chiral, parametrized by the remaining piece in Eq. (11), ΔL_CP, .

C. SU(2) −SU(2) interplay: ΔL_CP,

The implementation of the covariant objects V ( ), T ( ) and W ( ) allows building the complete basis of independent CP-violating operators accounting for mixing between SU(2) and SU(2) covariant structures, encoded as

ΔL_CP, = c_W, S_W, (h) + Σ_{i=3, i 13,14}^{16}Σ_j c_i(j), S_i(j), (h)

where index j spans all possible operators S_i, (h) in Eq. (19) that can be built from each, here labeled as S_i(j), (h) (with coefficients c_i(j),), while the first term encodes the operator

S_W, (h) = g g Tr[W W_]F_W, (h)

The complete set of operators S_i(j), (h) in the second term of ΔL_CP, are listed as:

S ( )(h) = ig Tr[V , V , W_]F ( )(h) S ( )(h) = ig Tr[V , V , W_]F ( )(h)
S ( )(h) = g Tr[T V , V ,] F ( )(h) S ( )(h) = g Tr[T V , V ,] F ( )(h)
S ( )(h) = g Tr[T V , V ,] F ( )(h) S ( )(h) = g Tr[T V , V ,] F ( )(h)
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S ( )(h) = iTr[T V , V , V ,] F ( )(h) S ( )(h) = g Tr[T W V ,] F ( )(h)
S ( )(h) = g Tr[T W V ,] F ( )(h) S ( )(h) = g g Tr[T W]Tr[T W_]F ( )(h)
S ( )(h) = ig Tr[T D V , D V ,]F ( )(h) S ( )(h) = ig Tr[T D V , D V ,]F ( )(h)
S ( )(h) = iTr[T V , V , W]F ( )(h) S ( )(h) = iTr[T V , V , W]F ( )(h)
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S ( )(h) = iTr[T V , V , V , V ,] F ( )(h) S ( )(h) = iTr[T V , V , V , V ,] F ( )(h)
S ( )(h) = iTr[T V , V , V , V ,]F ( )(h) S ( )(h) = iTr[T V , V , V , V ,]F ( )(h)
S ( )(h) = iTr[T V , V , V , V ,]F ( )(h) S ( )(h) = iTr[T V , V , V , V ,]F ( )(h)

where the suffix LR in all S_i(j), (h) and their corresponding F_i(j), (h) has been omitted. Among the total 43 operators S_i(j), (h) listed, 16 operators (highlighted in red) are missing in the left-right symmetric electroweak chiral treatment of Refs. [48, 49].

The definition for D V , ( ) follows similarly to Eq. (4):

D V , ( ) U ( )†U ( )D V , ( )U ( )†U ( )

where D has been defined in Eq. (18). Notice that operators S ( )(h), S ( )(h), S ( )(h), and S ( )(h) containing the contraction D V , ( ) are not present in [48, 49], and are additional ones allowed by the SU(2) −SU(2) interplay of ΔL_CP, together with the P symmetry.

The interplaying CP-breaking non-linear operators can be catalogued as:

- S ( )(h), S ( )(h), S ( )(h), S ( )(h), S ( )(h), S ( )(h) coming from a direct extension of the original Appelquist-Longhitano chiral Higgsless basis considered in [50–54] (for the CP-breaking sector), coupled to light Higgs insertions, and after applying the discrete parity P .
- S ( )(h), S ( )(h), and S ( )(h) containing D V , ( ) and no derivative couplings.
- S ( )(h), S ( )(h), S ( )(h), and S ( )(h) with derivative coupling from V , .
- S ( )(h), S ( )(h) with one derivative coupling from W , .

Finally, the transformation properties under the parity symmetry P for some operators from ΔL_CP, are exhibited in Table I. Operators not listed there transform as P -even. Compact notation S_i(j,k,l), (h) S_i(m,n,p), (h) stands for operators S_i(j), (h), S_i(k), (h), S_i(l), (h) (or vice versa) being mapped to S_i(m), (h), S_i(n), (h), S_i(p), (h) respectively. As can be seen, P remains an accidental symmetry up to p contributions in the Lagrangian expansion. Conversely, some non-linear CP-conserving p operators trigger its explicit breaking [47], as expected from general composite Higgs model considerations [67, 68].

Some CP non-conserving bosonic operators can be directly translated into pure bosonic operators plus fermionic-bosonic ones. In fact, some operators in Eq. (19) (for = L) had not been explored but were instead traded for fermionic ones via equations of motion [61]. This connection can be established through the covariant derivative D V , and the corresponding equation of motion for the light Higgs field, as described in the non-linear left-right CP-conserving treatment of Ref. [47]. Following the same reasoning, it is inferred that for the massless fermion case, operators {S , (h), S , (h)} containing the contraction D V , can be traded for pure bosonic operators in ΔL_CP (Eq. (19)), some with structure D V , , and therefore can be disregarded from the final operator basis in ΔL_CP. A similar feature applies to ΔL_CP, (Eqs. (22)-(23)). For the massive fermion case, all previous operators must be retained in the final basis.

In general, for the vanishing fermion case, operator S , (h) with double derivatives of F(h) in Eq. (19) is rewritable in terms of bosonic operators, some contained in ΔL_CP and others in ΔL_CP, , and thus can be disregarded from the final operator basis. No operators from ΔL_CP, are tradeable to bosonic operators as there are no double derivative couplings of F(h) in ΔL_CP, . When fermion masses are switched on, S , (h) becomes physical and must be included in the final basis.

Integrating-out heavy right-handed fields

It is possible to integrate out the right-handed gauge fields from the physical spectrum via the equations of motion for the strength gauge fields W , , as done for the CP-conserving case in [47, 69]. A non-trivial equation of motion for the CP-violating case is obtained by including the analogous right-handed counterparts for the strength kinetic and custodial-conserving terms of L in (12), together with mixing effects from the term c_C, P_C, (h), where c_C, is the coefficient for the CP-conserving left-right operator P_C, (h) = (f f /2)Tr[V̄ , V̄ ,]F_C, (h). Accounting for these contributions yields

D V̄ , -(f /f)c_C, V̄ ,

This relation can be translated into unitary gauge as

W³ , - W³ , W± , - W± , B (1+)B - W³ ,

with -(f /f)c_C, .

By substituting Eq. (25) into (16)-(19) (for = R) and (20)-(23), all right-handed and left-right operators collapse onto left-handed ones, affecting the global coefficients c_i, generically as

c̃_i, = c_i, + c_i, + Σ_j c_i(j), + Σ_m c_l(m), where the functions encode linear combinations of coefficients c_i, , c_i(j), and additional mixing left-right operators via c_l(m), . The number of fields V , through each right- and left-right operator determines the f /f suppression for contributions induced onto left-handed operators.

Consequently, in the limiting case f f at low energies, the set of non-linear operators {S_B(h), S_2D, (h), S_2, (h)} is sensitive to contributions up to order from right-handed operators {S_W, (h), S_1, (h), S_8, (h)} and mixing left-right sets {S_2D, (h), S_9( )(h)}. It can also be seen that CP-violating self-couplings of electroweak gauge bosons are sensitive only to left-handed operators at low energies.

Following Ref. [70], the CP-odd sector of the Lagrangian describing triple gauge boson vertices (TGVs) can be parametrized as

L_WWV^eff,CP = ig_WWV[g ^VW† W (V + V) - ĩ_VW† W Ṽ + (ĩ_V/6) W† W V_ + g ^V(W† W - W W†)V + g ^V (W† _ W - W _ W†)V_ + (ĩ_V/2) (W† _ W + W _ W†)V_]

with g_WWZ e/s_Wc_W and g_WW e, where W± and V stand for the kinetic parts of the implied gauge field strengths. The dual field tensor of any field strength V is defined as Ṽ ½ V_ , with c_W cos _W and s_W sin _W (_W being the Weinberg angle). In writing this we introduced coefficients g̃ ^V, g̃_V, and ˜_V associated with operators containing the contraction V ; its part vanishes only for on-shell gauge bosons. In general, V insertions could only be disregarded when fermion masses are neglected.

In the SM all couplings vanish. Electromagnetic gauge invariance requires g̃ ^ = 0, g̃_ = 0, and ˜_ = 0. All other effective couplings are given by

g̃ ^Z = (c ²/4e²s_W²)(c , + 2c ,) ˜_ = c , ˜_Z = (c ²/4e²s_W²)(c , - 2c ,) ˜_Z = (c ²/4e²s_W²)(c , + c ,)

An additional contribution to the ZZZ vertex arises from operators S , (h) and S , (h) as

L_ZZZ^eff,CP = g̃ ^Z Z Z Z

with g̃ ^Z = (c ²/4e²s_W²)(c , + c , + 2c ,), which, like the phenomenological couplings g̃ ^V and g̃_V in the TGV parametrization, vanishes for on-shell Z bosons and can generally be disregarded when fermion masses coupling to the Z are neglected.

The coupling ˜_ induces one-loop contributions to fermion electric dipole moments (EDMs), which are generically the best probes of beyond-SM CP violation due to stringent experimental bounds and minimal SM background contributions. The amplitude for the one-loop fermionic EDM can be parametrized as

A_f -id_f ū(p) q u(p)

where d_f denotes the fermionic EDM strength. The one-loop integral diverges logarithmically; assuming a physical cutoff Λ_s for the high-energy BSM theory, following the generic computation in Ref. [72] and implementing ˜_ from (32), we obtain the EDM coefficient

d_f = (e³G_FT /√2 ²s_W²)(c , + 2c ,)log(Λ_s²/m_W²)

where T is the fermion weak isospin and G_F is the Fermi coupling constant. The present experimental bound on the electron EDM [73], |d_e| < 8.7×10 ² cm at 90% CL, and the neutron EDM [74], |d_n| < 2.9×10 ² cm at 90% CL, entail limits

|c , + 2c , | < 5.2×10 (electron) |c , + 2c , | < 2.8×10 (neutron)

Direct constraints on CP-violating effects in the WWZ vertex can be imposed by combining LEP collaboration studies on angular distributions of W bosons and their decay products in WW production at LEP2 [76–78]. This combination yields the 1 (68% CL) constraints [55]

c , -0.50 c , - c , -0.35

Effective CP-violating hVV couplings are also affected in this framework. In particular, the hZZ vertex can be parametrized as

L_hZZ^eff,CP g̃_HZZ h Z Z̃

with tree-level contribution

g̃_HZZ = (c ²/4e²s_W²)[ã + ã_W, - ã , - ã , + ã , - ã , + ã ,]

where coefficients ã_i are defined as ã_i c_i a_i, with a_i from the F(h) definition in (10). This coupling is useful for parametrizing CP violation in the decay h → ZZ* → 4 [16, 79]. In Ref. [79] a measure of CP violation was defined as

f_d = |d |²/(|d |² + |d |²)

with d = 2i and d = i(f ²/4e²s_W²)g̃_HZZ, where f is the electroweak scale and ( ) is the cross section for the process h → ZZ* → 4 when d = 1, d = 0 (and vice versa). For M_h = 125.6 GeV, = 6.36 fb.

In Ref. [79], f_d was fitted as one parameter of a multivariable analysis, obtaining the measured value f_d = 0.00 .¹ . , implying |d | < 0.51 at 95% CL, which translates to |d |/|d | < 2.57. These bounds can be directly translated to 68% (95%) CL constraints on the coefficients of relevant CP-violating operators through the coupling in (41) as

|g̃_HZZ| 10.3 (23.3)

None of the involved coefficients receive contributions at low energies from right-handed or left-right operators. For a high-energy scale f not far above the electroweak scale f , additional operators would contribute to left-handed ones as the ratio f /f would be non-negligible. Nonetheless, these additional contributions are small because the allowed range -0.02 < c_C,   < 0.02 [69] suppresses the scale ratio and therefore the parameter   in (25). For the hypothetical case c_C,   1 and f   f , right- and left-right operator contributions are enhanced, and all coefficients through the couplings become modified by terms involving c_i, and c_i(j), .

Counting the number of right-handed and left-right operators appearing through the coefficients leads to a final effective set of 40 operators total = 20 left ops. (set in Eq. (17)+Eq. (19)) + 5 right ops. (in Eq. (45)) + 15 left-right ops (in Eq. (45)). A right-handed gauge sector far above the electroweak scale implies a hierarchical case with NP effects parametrized via a much smaller operator basis, as the f /f suppression leaves 25 operators total = 20 left ops. + 3 right ops. (in Eq. (29)) + 2 left-right ops (in Eq. (30)).

Conclusions

Electroweak interactions in nature exhibit non-exact charge conjugation-parity symmetry. Moreover, the observed matter-antimatter asymmetry compels us to consider new sources of CP violation, as signaled by the strong CP problem.

Low-energy effects from a CP-violating sector may be sourced by new physics field content playing a role at high-energy regimes reachable at the LHC and future colliders. An effective approach is thus needed to parametrize these effects. This paper, concerning only the bosonic gauge sector, assumes the NP field content is dictated by spin-1 resonances from extending the SM local gauge symmetry U(1) to the larger group U(1)   , described via a non-linear electroweak scenario with a light dynamical Higgs, up to p contributions in the Lagrangian expansion, focusing on the CP-violating sector.

This work completes the CP-violating pure gauge and gauge-Higgs operator basis given in Refs. [48, 49] for left-right symmetric electroweak chiral models, generalizing the work of Refs. [50–54] for the CP-violating sector with a heavy Higgs chiral scenario, and extending Ref. [55] for the CP-violating light Higgs dynamical framework to a larger local gauge symmetry in the context of non-linear electroweak interactions coupled to a light Higgs.

The framework may be considered a generic UV completion of low-energy non-linear approaches [50–54, 55], assuming the extended gauge field sector arises from an energy regime above the electroweak scale. The physical effects from integrating out right-handed fields are analyzed, particularly impacts on CP-violating gauge couplings (Eqs. (31)-(34), (37), (39)), EDM observables (Eqs. (36), (38)), effective hZZ coupling, and CP violation in h $\to$ 4 (Eqs. (40)-(41)). The relevant operator set at low energies contains 25 operators total = 20 left ops. + 3 right ops. (in Eq. (29)) + 2 left-right ops (in Eq. (30)).

Further low-energy effects from a higher-energy gauge sector [69, 80] could illuminate the underlying new physics in nature and aid in understanding the origin of electroweak symmetry breaking.

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