NEW PHYSICS OPERATOR EVOLUTION AND THE STANDARD MODEL SCALAR DECAY $h \to \gamma\gamma$

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The renormalization group evolution of a set of dimension-six operators involving Standard Model (SM) scalar boson fields and gauge fields is calculated. These operators parametrize the effect of new physics at an energy scale Λ on $gg \to h$, $h \to \gamma\gamma$ and $h \to Z\gamma$ in an effective field theory with renormalizable interactions given by the SM interactions. Deviations of $h \to \gamma\gamma$ from the SM rate at the $\sim 10\%$ level are possible due to renormalization group running of new physics operators contributing to the decay. Such effects are important for precision analysis of decays of the SM scalar boson.

1 Introduction

In this talk, I will assume that the new scalar discovered at the LHC with mass 126 GeV is *the* SM scalar h. The natural question arises: Is there any new physics associated with the SM scalar? One can address this question in an effective field theory (EFT) of the SM with renormalizable interactions given by the SM interactions and non-renormalizable interactions parametrized by higher-dimension operators in the SM fields. The non-renormalizable operators of the effective Lagrangian encode arbitrary new physics at a high-energy scale Λ larger than the experimentally accessible energies probed at LHC to date.

The SM EFT is of the form

$$\mathcal{L} \;=\; \mathcal{L}_{SM}^{d\leq 4} + \left(\frac{1}{\Lambda^{d=5}}\right)\mathcal{L}^{d=5} + \left(\frac{1}{\Lambda^{d=6}}\right)^2 \mathcal{L}^{d=6} + \cdots \tag{1}$$

In the EFT, higher-dimension non-renormalizable operators are suppressed by powers of $1/\Lambda$. For arbitrary new physics at scale Λ, integrating out the new physics particles with masses of order Λ generates higher dimension operators with operator coefficients $c(\Lambda)/\Lambda^{d-4}$, where $c(\Lambda)$ are of order unity.

The new physics operators involving the SM scalar and gauge boson fields first arise at dimension six. The complete set of independent $d = 6$ operators consists of 59 operators, assuming baryon number B conservation [1,2]. This talk focuses on a subset of $d = 6$ operators involving the SM scalar doublet H and the $SU(3) \times SU(2) \times U(1)$ gauge bosons G_μ^A, W_μ^a and B_μ. The $d = 6$ operators are given by

$$\begin{aligned}\frac{1}{\Lambda^2}\,\mathcal{L}^{d=6} \;=\;& \frac{1}{2\Lambda^2}\left(c_{GG}\,\mathcal{O}_{GG} + c_{WW}\,\mathcal{O}_{WW} + c_{BB}\,\mathcal{O}_{BB} + c_{WB}\,\mathcal{O}_{WB}\right)\\ &+\frac{1}{2\Lambda^2}\left(\widetilde{c}_{GG}\,\widetilde{\mathcal{O}}_{GG} + \widetilde{c}_{WW}\,\widetilde{\mathcal{O}}_{WW} + \widetilde{c}_{BB}\,\widetilde{\mathcal{O}}_{BB} + \widetilde{c}_{WB}\,\widetilde{\mathcal{O}}_{WB}\right),\end{aligned} \tag{2}$$

where

$$
\begin{aligned}
\mathcal{O}_{GG} &= g_3^2\, H^\dagger\, H\, G^A_{\mu\nu} G^{A\,\mu\nu}, & \widetilde{\mathcal{O}}_{GG} &= g_3^2\, H^\dagger\, H\, G^A_{\mu\nu} \widetilde{G}^{A\,\mu\nu}, \\
\mathcal{O}_{WW} &= g_2^2\, H^\dagger\, H\, W^a_{\mu\nu} W^{a\,\mu\nu}, & \widetilde{\mathcal{O}}_{WW} &= g_2^2\, H^\dagger\, H\, W^a_{\mu\nu} \widetilde{W}^{a\,\mu\nu}, \\
\mathcal{O}_{BB} &= g_1^2\, H^\dagger\, H\, B_{\mu\nu} B^{\mu\nu}, & \widetilde{\mathcal{O}}_{BB} &= g_1^2\, H^\dagger\, H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}, \\
\mathcal{O}_{WB} &= g_1\, g_2\, H^\dagger\, \tau^a\, H\, W^a_{\mu\nu} B^{\mu\nu}, & \widetilde{\mathcal{O}}_{WB} &= g_1\, g_2\, H^\dagger\, \tau^a\, H\, W^a_{\mu\nu} \widetilde{B}^{\mu\nu}.
\end{aligned}
\tag{3}
$$

The operators $\mathcal{O}_{GG}$, $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$ and $\mathcal{O}_{WB}$ are CP-even, whereas the operators $\widetilde{\mathcal{O}}_{GG}$, $\widetilde{\mathcal{O}}_{WW}$, $\widetilde{\mathcal{O}}_{BB}$ and $\widetilde{\mathcal{O}}_{WB}$ are CP-odd. Each operator involves two SM scalar doublet fields and two gauge field strengths. The dual gauge field strengths are given by $\widetilde{F}^{\mu\nu} \equiv \frac{1}{2}\, \epsilon^{\mu\nu\alpha\beta}\, F_{\alpha\beta}$.

2 Operator Evolution

The new physics operators in Eq. 3 affect $gg \to h$, WW^*, ZZ^*, $Z\gamma$, $\gamma\gamma$ at tree level in the EFT. [3] In the SM, $h \to gg$, $\gamma\gamma$, $Z\gamma$ first occur at one loop, so production of h by gluon fusion and the decay modes $h \to \gamma\gamma$ and $Z\gamma$ are particularly sensitive to the effects of these new physics operators. The renormalization group running of the new physics operator basis is necessary to disentangle SM physics and new physics of h at the precision level. The renormalization group running of this subset of operators from the high-energy scale of new physics Λ to the low-energy scale $\sim v$ of electroweak symmetry breaking is calculated in the unbroken theory in Ref. [4]. The renormalization group evolution of this subset of new physics operators has implications for the relationship of the S parameter and the decay modes $h \to \gamma\gamma$ and $h \to Z\gamma$.

An important nontrivial check on the calculation of Ref. [4] is that the operators

$$
\begin{aligned}
O_+ &= \frac{\beta(g)}{2g}\, F^A_{\mu\nu}\, F^{A\,\mu\nu}\,, \\
O_- &= g^2\, F^A_{\mu\nu}\, \widetilde{F}^{A\,\mu\nu}\,,
\end{aligned}
\tag{4}
$$

are *not* renormalized to all orders in perturbation theory. The CP-even operator O_+ is not renormalized because it is the trace of the conserved energy-momentum tensor. The CP-odd operator O_- is multiplied in the Lagrangian by the θ-angle parameter, which is periodic with periodicity 2π, so it also is not renormalized. At one-loop, non-renormalization of O_+ implies that $g^2\, F^A_{\mu\nu}\, F^{A\,\mu\nu}$ is not renormalized since $\beta(g) \sim g^3$. Note that the operators $g_1 g_2 W^a_{\mu\nu} B^{\mu\nu}$ and $g_1 g_2 W^a_{\mu\nu} \widetilde{B}^{\mu\nu}$ are not constrained by non-renormalization theorems.

The one-loop Feynman diagrams producing operator mixing between the operators in Eq. (3) are shown in Fig. 1. First, consider the 4×4 mixing matrix of the CP-even operators.[a] The one-loop renormalization group equation for the CP-even operators split into two equations,

$$
\mu \frac{\mathrm{d}}{\mathrm{d}\mu} c_{GG} = \gamma_G\, c_{GG}, \tag{5}
$$

$$
\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \begin{bmatrix} c_{BB} \\ c_{WW} \\ c_{WB} \end{bmatrix} = \gamma_{WB} \begin{bmatrix} c_{BB} \\ c_{WW} \\ c_{WB} \end{bmatrix}, \tag{6}
$$

[a] Note that only operator mixing between the operators of Eq. 3 is considered in the calculation performed in Ref. [4]. There are other dimension-six operators in the operator basis of Ref. [2] which can mix with these operators. Calculation of the full anomalous dimension matrix of the dimension-six operator basis remains an important open problem.

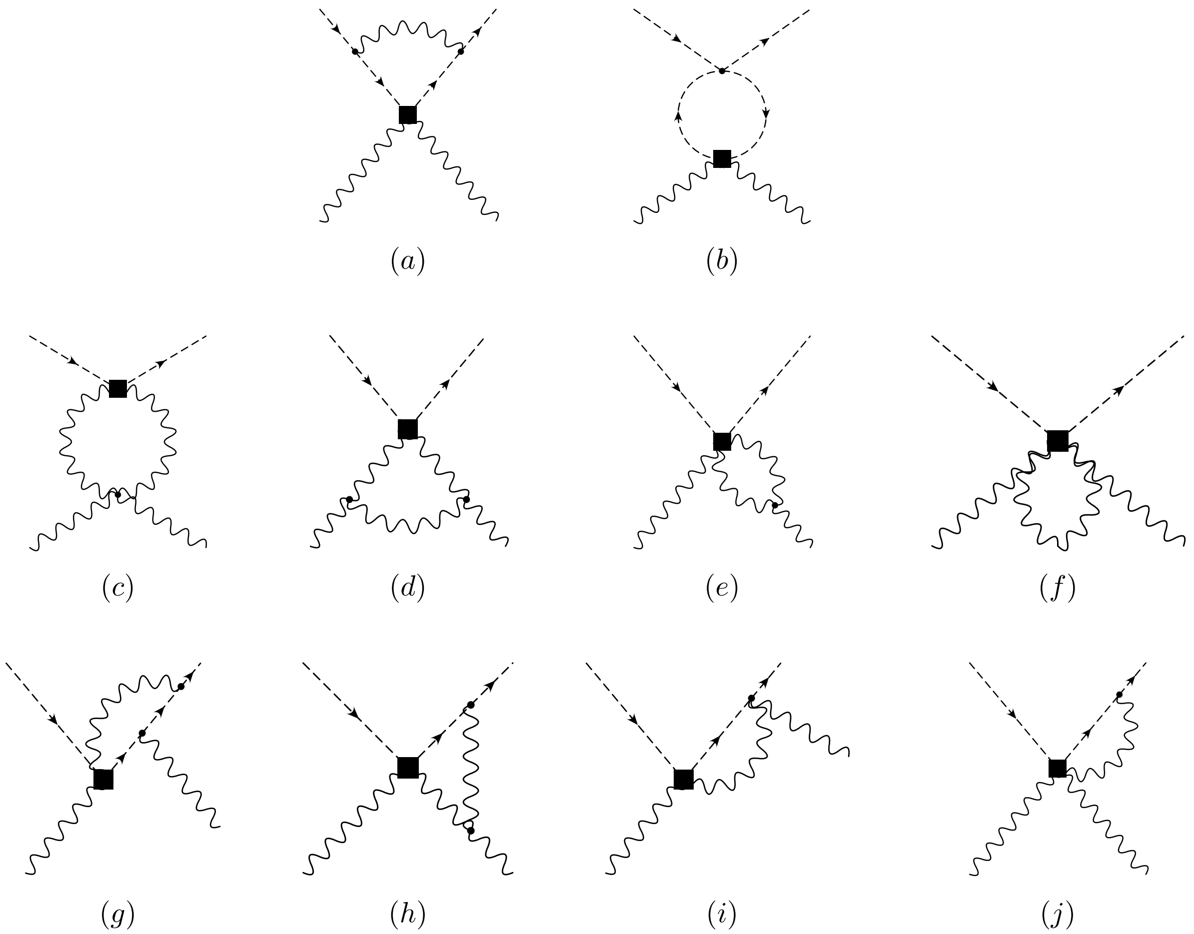

Figure 1: One-loop diagrams for the renormalization of the operators in Eq. 3. Graph (e) has a partner graph where the loop is on the other gauge boson line. Graphs (g,h,i,j) have partner graphs where the gauge bosons couple to the incoming scalar line. Wavefunction graphs have not been shown. Here, the complex scalar field is shown as a dashed line, while the gauge fields are shown as wavy lines; in each diagram, the gauge fields are the B, W^a or G^A fields depending on the operator considered.

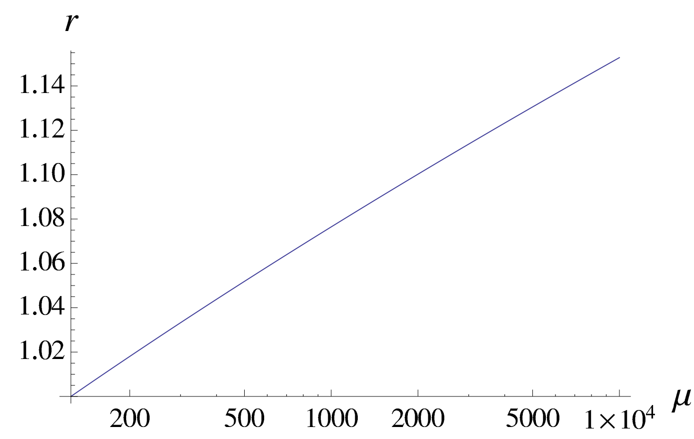

Figure 2: The function $r(\mu)$.

with anomalous dimensions

$$\gamma_G = \tfrac{1}{16\pi^2}\left[-\tfrac{3}{2}g_1^2 - \tfrac{9}{2}g_2^2 + 12\lambda + 2Y\right],$$
$$\gamma_{WB} = \tfrac{1}{16\pi^2}\begin{bmatrix} \tfrac{1}{2}g_1^2 - \tfrac{9}{2}g_2^2 + 12\lambda + 2Y & 0 & 3g_2^2 \\ 0 & -\tfrac{3}{2}g_1^2 - \tfrac{5}{2}g_2^2 + 12\lambda + 2Y & g_1^2 \\ 2g_1^2 & 2g_2^2 & -\tfrac{1}{2}g_1^2 + \tfrac{9}{2}g_2^2 + 4\lambda + 2Y \end{bmatrix}, \tag{7}$$

where

$$Y = \mathrm{Tr}\left[3Y_u^\dagger Y_u + 3Y_d^\dagger Y_d + Y_e^\dagger Y_e\right] \approx 3y_t^2 \tag{8}$$

is dominated by the top quark Yukawa coupling. The renormalization of these operators depends on the λ coupling constant of the SM scalar potential as well as on the top quark Yukawa coupling y_t. Both of these effects were not obtained by previous calculations in the literature [5,6]. The one-loop renormalization group equations for the CP-odd operators are given by

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\widetilde{c}_{GG} = \gamma_G\,\widetilde{c}_{GG}, \tag{9}$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\begin{bmatrix}\widetilde{c}_{BB}\\ \widetilde{c}_{WW}\\ \widetilde{c}_{WB}\end{bmatrix} = \gamma_{WB}\begin{bmatrix}\widetilde{c}_{BB}\\ \widetilde{c}_{WW}\\ \widetilde{c}_{WB}\end{bmatrix}, \tag{10}$$

with the *same* anomalous dimensions as for the CP-even operators.

The largest contribution to renormalization group running is the universal contribution $\propto Y$. One can integrate this contribution exactly by defining a function $r(\mu)$ which satisfies

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}r(\mu) = \tfrac{3y_t^2(\mu)}{8\pi^2}r(\mu)\,. \tag{11}$$

The function $r(\mu)$ is graphed in Fig. 2. For $\Lambda = 1$ TeV, $r(\mu)$ gives an approximately 8% correction to the operator coefficients c_i. The rest of the anomalous dimension matrix running is treated in leading log approximation, so the operator coefficients at the low-energy electroweak scale M_h are related to the coefficients at the high-energy scale of new physics Λ by

$$c(M_h) = \frac{r(M_h)}{r(\Lambda)}\left[1 - \gamma_{WB}(Y\to 0)\ \log\frac{\Lambda}{M_h}\right]c(\Lambda)\,. \tag{12}$$

3 The S Parameter and $h \to \gamma\gamma$

SM scalar decay modes and electroweak precision observables are both affected by the new physics operators. Comparison to the data at the precision level requires inclusion of renormalization group mixing effects of new physics operators. Present experimental measurements are not at the precision level, but the future experimental Higgs program will be sensitive to renormalization group mixing effects.

Earlier work in the literature [5] found the contribution of the new physics operators Eq. 3 to be

$$S \;=\; -\frac{8\,\pi\,v^2}{\Lambda^2}\left(c_{WB}(\Lambda) - \frac{1}{8\,\pi^2}\,\left[g_2^2\,c_{WW}(\Lambda) + g_1^2\,c_{BB}(\Lambda)\right]\,\log\frac{\Lambda}{M_h}\right). \tag{13}$$

Ref. [4] finds instead

$$S \;=\; -\frac{8\,\pi\,v^2}{\Lambda^2}c_{WB}(M_h)\,, \tag{14}$$

with

$$\begin{aligned} c_{WB}(M_h) \;&=\; \frac{r(M_h)}{r(\Lambda)}\,c_{WB}(\Lambda)\,\left[1 + \frac{g_1^2 - 9\,g_2^2 - 8\lambda}{32\,\pi^2}\;\log\frac{\Lambda}{M_h}\right] \\ &\quad -\frac{r(M_h)}{r(\Lambda)}\,\frac{1}{8\,\pi^2}\,\left[g_2^2\,c_{WW}(\Lambda) + g_1^2\,c_{BB}(\Lambda)\right]\,\log\frac{\Lambda}{M_h}. \end{aligned} \tag{15}$$

The contribution to the renormalization group running from the top quark Yukawa coupling through the function $r(\mu)$ is missing in the earlier formula. In addition, there is a modification of the term proportional to $c_{WB}(\Lambda)$ from wave function renormalization of the SM scalar doublet H depending on λ and the weak gauge coupling constants times a log factor.

The experimental bounds on S are very restrictive. From the above equations, one finds that the combination of coefficients contributing to $c_{WB}(M_h)$ must cancel to high precision. Imposing $c_{WB}(\Lambda) = 0$ is not sufficient, since $c_{WB}(M_h)$ is generated by operator mixing between $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$ and $\mathcal{O}_{WB}$ from the high-energy scale Λ to the electroweak scale M_h.

The new physics operators also contribute to the decay mode $h \to \gamma\gamma$,

$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(h\to\gamma\gamma)}{\Gamma^{\rm SM}(h\to\gamma\gamma)} \simeq \left|1 - \frac{4\pi^2 v^2 c_{\gamma\gamma}}{\Lambda^2 I^\gamma}\right|^2 + \left|\frac{4\pi^2 v^2 \tilde{c}_{\gamma\gamma}}{\Lambda^2 I^\gamma}\right|^2, \tag{16}$$

where

$$c_{\gamma\gamma} \;=\; c_{WW} + c_{BB} - c_{WB}, \qquad \tilde{c}_{\gamma\gamma} = \tilde{c}_{WW} + \tilde{c}_{BB} - \tilde{c}_{WB}\,, \tag{17}$$

and the integral I^γ can be found in Ref. [3]. Neglecting the CP-odd contribution $\tilde{c}_{\gamma\gamma}$, and using the renormalization group improved value

$$\begin{aligned} c_{\gamma\gamma}(M_h) \;&=\; \frac{r(M_h)}{r(\Lambda)}\left\{\left[1 + \frac{3}{32\pi^2}\left(g_1^2 + 3g_2^2 - 8\lambda\right)\log\frac{\Lambda}{M_h}\right]c_{\gamma\gamma}(\Lambda)\right. \\ &\qquad \left. + \frac{1}{8\pi^2}\left(3g_2^2 - 4\lambda\right)\log\frac{\Lambda}{M_h}c_{WB}(\Lambda)\right\}, \end{aligned} \tag{18}$$

rather than $c_{\gamma\gamma}(\Lambda)$, yields a numerical version for Eq. 16 of

$$\mu_{\gamma\gamma} \;\simeq\; 1 - 0.02\,S\,\log\frac{\Lambda}{M_h} + 0.02\left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^2\left(16\pi^2 c_{\gamma\gamma}(\Lambda)\right). \tag{19}$$

Note that, in Eq. 19, the S parameter includes the $1/\Lambda^2$ suppression of the new physics operators. From Eq. 19, one sees that it is hard to get large $\mu_{\gamma\gamma}$ given the present experimental bound $|S| < 0.1$ and that the quantity $(16\pi^2 c_{\gamma\gamma}(\Lambda))$ obtained at the new physics scale is expected to be order unity for weakly coupled new physics. Expressions for $\mu_{Z\gamma}$ analogous to the ones quoted here for $\mu_{\gamma\gamma}$ appear in Ref. [4].

4 Conclusions

In summary, the couplings of the SM scalar h are beginning to be measured in a variety of channels. New physics effects can change the predicted properties of the SM scalar boson. The effect of arbitrary new physics at a high-energy scale Λ can be taken into account by considering an effective field theory of the SM. The effects of new physics on the SM scalar h first arise from higher dimension operators at $d = 6$ in the EFT. The complete set of independent $d = 6$ operators in SM fields consists of 59 operators when baryon number conservation is assumed. The one-loop renormalization group running of this full set of $d = 6$ operators needs to be performed. In Ref. [4], the one-loop renormalization group running of a subset of $d = 6$ operators [3] was calculated. The eight operators considered are of particular relevance since they affect the SM scalar couplings $gg \to h$, $h \to \gamma\gamma$ and $h \to Z\gamma$ at tree level in the EFT. These couplings arise only at one-loop in the renormalizable SM interaction Lagrangian. New renormalization group contributions to the operator running of these new physics operators are obtained in Ref. [4]. In particular, the renormalization group running of the new physics operators considered is affected by the SM scalar coupling constant λ of the scalar potential and by the top quark Yukawa coupling y_t. The calculation of Ref. [4] shows that it is important to include operator mixing of the new physics operators for precision analysis of SM scalar decays. Deviations of $h \to \gamma\gamma$ from the SM rate at the $\sim 10\%$ level are possible due to renormalization group running of the new physics operators contributing to the decay.

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