Operators Evolution and the Standard Model Scalar $\to \gamma\gamma$

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Rencontres de Moriond March 2-9, 2013

- Christophe Grojean, Elizabeth E. Jenkins, Aneesh V. Manohar and Michael Trott, "Renormalization Group Scaling of Higgs Operators and $h \to \gamma\gamma$," arXiv:1301.2588

SM Scalar

- In this talk, I will assume that the new scalar discovered at LHC with mass 126 GeV is *the* SM Scalar h.
- $m_h^2 = 2\lambda v^2 \Rightarrow \lambda$ determined experimentally for first time!
- Natural question arises: Is there any New Physics associated with the SM scalar?
- Can address question by studying higher-dimension operators added to SM Lagrangian

Already know that SM Lagrangian is an EFT Lagrangian; $d = 5$ L-violating operator necessary to generate Majorana mass matrix for light, weakly-interacting neutrinos upon spontaneous symmetry breakdown of EW gauge symmetry... Weinberg 1979

$$\mathcal{L}^{d=5} = \frac{1}{2} c^{d=5} \left(\bar{L}_L{}^c \tilde{\phi}^* \right) \left(\tilde{\phi}^\dagger L_L \right) + \text{h.c.}$$

Seesaw Mechanism — Gell-Mann, Ramond, Slansky 1979, Yanagida 1979, Mohapatra, Senjanovic 1980

New Physics in SM EFT Encoded in Higher Dimension Operators

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

$$\mathcal{L}^{d=6} = \sum_i c_i(\mu) O_i(\mu)$$

- NP operators involving the SM Scalar and gauge bosons first arise at $d = 6$
- Complete set of independent $d = 6$ operators yields 59 operators Buchmuller,Wyler 1986. Grzadkowski, Iskrzynski, Misiak, Rosiek 2010. Exact number depends on B conservation assumption.
- For arbitrary NP particles with masses $\sim \mathcal{O}(\Lambda)$, integrating out NP at this scale generates higher dimension operators with coefficients $c_i(\Lambda) \sim \mathcal{O}(1)$. For precision studies, need to compute RG evolution of these coefficients from high-energy NP scale $\Lambda^{d=6}$ to low-energy EW scale.

New RG Calculation

- In this talk, I focus on a subset of $d = 6$ operators involving SM scalar doublet H and $SU(3) \times SU(2) \times U(1)$ gauge bosons G_μ^A, W_μ^a, B_μ
- Renormalization Group (RG) running of this subset of operators from high-energy NP scale $\Lambda^{d=6}$ to low-energy EWSB scale $\sim v$ is computed for the first time.
- RG running of NP operator basis is necessary to disentangle SM physics and NP of h at precision level
- RG evolution of this subset of NP operators has implications for relationship of S parameter and $h \to \gamma\gamma,\ Z\gamma$

$d = 6$ Operators, CP even

$$\frac{1}{\Lambda^2}\,\mathcal{L}^{d=6} = \frac{1}{2\Lambda^2}\left(c_G\,\mathcal{O}_G + c_B\,\mathcal{O}_B + c_W\,\mathcal{O}_W + c_{WB}\,\mathcal{O}_{WB}\right)$$

$$\begin{aligned}
\mathcal{O}_G &= g_3^2\, H^\dagger H\, G^A_{\mu\nu} G^{A\,\mu\nu}, \\
\mathcal{O}_B &= g_1^2\, H^\dagger H\, B_{\mu\nu} B^{\mu\nu}, \\
\mathcal{O}_W &= g_2^2\, H^\dagger H\, W^a_{\mu\nu} W^{a\,\mu\nu}, \\
\mathcal{O}_{WB} &= g_1\, g_2\, H^\dagger \sigma^a H\, W^a_{\mu\nu} B^{\mu\nu}.
\end{aligned}$$

NB: These NP operators affect $h \to gg, WW, ZZ, Z\gamma, \gamma\gamma$ at tree level. In SM, $h \to gg, Z\gamma, \gamma\gamma$ first occur at one loop.

Manohar Wise 2006

$d = 6$ Operators, CP odd

$$\frac{1}{\Lambda^2}\,\mathcal{L}^{d=6} = \frac{1}{2\Lambda^2}\left(\widetilde{c}_G\,\widetilde{\mathcal{O}}_G + \widetilde{c}_B\,\widetilde{\mathcal{O}}_B + \widetilde{c}_W\,\widetilde{\mathcal{O}}_W + \widetilde{c}_{WB}\,\widetilde{\mathcal{O}}_{WB}\right)$$

$$\widetilde{\mathcal{O}}_G = g_3^2\,H^\dagger\,H\,G^A_{\mu\,\nu}\widetilde{G}^{A\,\mu\,\nu},$$

$$\widetilde{\mathcal{O}}_B = g_1^2\,H^\dagger\,H\,B_{\mu\,\nu}\widetilde{B}^{\mu\,\nu},$$

$$\widetilde{\mathcal{O}}_W = g_2^2\,H^\dagger\,H\,W^a_{\mu\,\nu}\widetilde{W}^{a\,\mu\,\nu},$$

$$\widetilde{\mathcal{O}}_{WB} = g_1\,g_2\,H^\dagger\,\sigma^a\,H\,W^a_{\mu\,\nu}\widetilde{B}^{\mu\,\nu}.$$

$$\widetilde{F}^{\mu\nu} \quad\equiv\quad \frac{1}{2}\,\epsilon^{\mu\nu\alpha\beta}\,F_{\alpha\beta}$$

Non-Renormalization Theorems

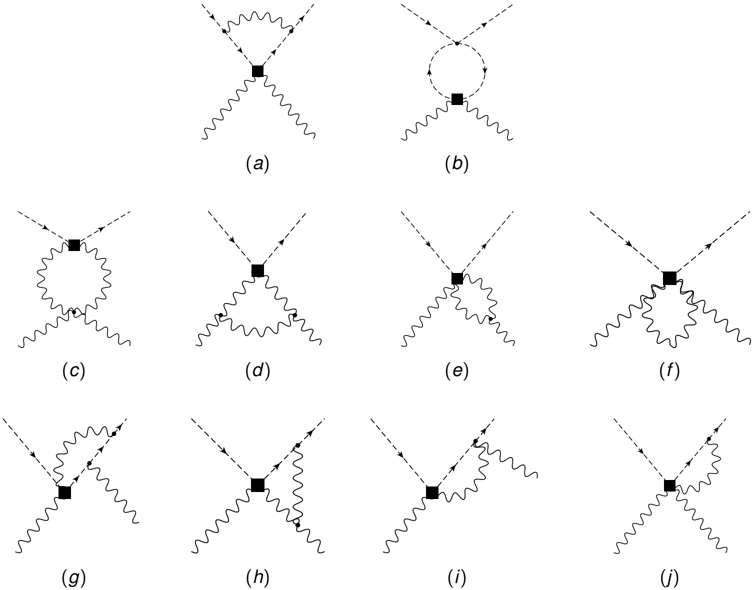
$$
\begin{aligned}
O_+ &= \frac{\beta(g)}{2g}\, F^A_{\mu\nu}\, F^{A\,\mu\nu} \\
O_- &= g^2\, F^A_{\mu\nu}\, \widetilde{F}^{A\,\mu\nu}
\end{aligned}
$$

- *CP*-even/odd operators $O_\pm$ are *not* renormalized to all orders in perturbation theory.

  O_+ is trace of conserved energy-momentum tensor.

  O_- multiplied by Lagrangian parameter θ-angle, which is periodic with periodicity 2π.
- At one-loop, O_+ non-renormalization $\Rightarrow g^2\, F^A_{\mu\nu}\, F^{A\,\mu\nu}$ not renormalized. In background field gauge, $Z_g Z_A^{1/2} = 1$.
- NB: $g_1\, g_2\, W^a_{\mu\,\nu} B^{\mu\,\nu}$ and $g_1\, g_2\, W^a_{\mu\,\nu} \widetilde{B}^{\mu\,\nu}$

1-Loop Operator Mixing



Operator Mixing

Look at 4×4 mixing matrix. (NB: Can mix with other dim 6 operators.)

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} c_G = \gamma_G \, c_G,$$

$$\gamma_G = \frac{1}{16\pi^2}\left[-\frac{3}{2}g_1^2 - \frac{9}{2}g_2^2 + 12\lambda + 2Y\right]$$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu}\begin{bmatrix} c_B \\ c_W \\ c_{WB} \end{bmatrix} = \gamma_{WB}\begin{bmatrix} c_B \\ c_W \\ c_{WB} \end{bmatrix},$$

$$\gamma_{WB} = \frac{1}{16\pi^2}\begin{bmatrix} \frac{1}{2}g_1^2 - \frac{9}{2}g_2^2 + 12\lambda + 2Y & 0 & 3g_2^2 \\ 0 & -\frac{3}{2}g_1^2 - \frac{5}{2}g_2^2 + 12\lambda + 2Y & g_1^2 \\ 2g_1^2 & 2g_2^2 & -\frac{1}{2}g_1^2 + \frac{9}{2}g_2^2 + 4\lambda + 2Y \end{bmatrix},$$

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

Operator Mixing

Same anomalous dimension matrix For *CP*-odd ops

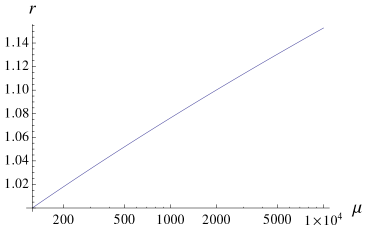
$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \begin{bmatrix} \widetilde{c}_B \\ \widetilde{c}_W \\ \widetilde{c}_{WB} \end{bmatrix} = \gamma_{WB} \begin{bmatrix} \widetilde{c}_B \\ \widetilde{c}_W \\ \widetilde{c}_{WB} \end{bmatrix},$$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \widetilde{c}_G = \gamma_G \, \widetilde{c}_G,$$

Integration of RG Equations

The largest contribution to RG running is $\propto Y$, dominated by top quark Yukawa coupling. Can integrate this contribution exactly by defining $r(\mu)$

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



Rest of anomalous dim matrix running in leading log approximation

$$c(M_h) = \frac{r(M_h)}{r(\Lambda)} \left[1 - \gamma_{WB}(Y \to 0) \ \ln \frac{\Lambda}{M_h} \right] c(\Lambda)$$

Comparison to Data

- SM scalar decay modes and EW precision observables are both affected by NP operators
- Fit to data at precision level will require inclusion of RG running/mixing effects of NP operators
- Early days... Need to look at many observables to overdetermine the many NP operators

S Parameter

$$S = -\frac{8\,\pi\,v^2}{\Lambda^2}\left(c_{WB}(\Lambda) - \frac{1}{8\,\pi^2}\,\left[g_2^2\,c_W(\Lambda) + g_1^2\,c_B(\Lambda)\right]\,\log\frac{\Lambda}{M_h}\right),$$

Grinstein, Wise 1991, Hagiwara, Ishihara, Szalapski, Zeppenfeld 1993,

Alam, Dawson, Szalapski 1998, Han,Skiba 2005

Find instead

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

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

c_i must cancel in S. $c_{WB}(\Lambda) = 0$ is not good enough.

$h \to \gamma\gamma$ and S

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

$$c_{\gamma\gamma} = c_W + c_B - c_{WB}, \qquad \tilde{c}_{\gamma\gamma} = \tilde{c}_W + \tilde{c}_B - \tilde{c}_{WB}\,.$$

When neglecting RG running, coefficients $c_{\gamma\gamma}(\Lambda)$ at renormalization scale $\mu = \Lambda$.
For RG Improved calculation, use $c_{\gamma\gamma}(M_h)$.

$$c_{\gamma\gamma}(M_h) = \frac{r(M_h)}{r(\Lambda)}\left\{\left[1 + \frac{3}{32\pi^2}\left(g_1^2 + 3g_2^2 - 8\lambda\right)\log\frac{\Lambda}{M_h}\right]c_{\gamma\gamma}(\Lambda) + \frac{1}{8\pi^2}\left(3g_2^2 - 4\lambda\right)\log\frac{\Lambda}{M_h}c_{WB}(\Lambda)\right\},$$

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

Hard to get large $\mu_{\gamma\gamma}$ given $|S| < 0.1$.
Analogous expressions for $\mu_{Z\gamma}$.

Summary

- Beginning to measure couplings of SM scalar h in a variety of channels
- NP effects parmetrized by $\sim$ 59 operators at dimension $d = 6$
- RG running of subset of NP operators basis computed for first time
- RG effects of enhanced importance for $h \to \gamma\gamma$, which arises in SM at one loop, but at tree-level in NP operators
- Connection of S parameter and $\mu_{\gamma\gamma}$, $\mu_{Z\gamma}$