ERC Workshop on "EFTs for Collider Physics, Flavor Phenomena and Electroweak Symmetry Breaking"

Burg Crass, Eltville (Rheingau), 12-15 September 2016

Analyzing the CP Nature of a New Scalar Particle via S→Z+h Decay

with Martin Bauer and Andrea Thamm (arXiv:1607.01016)

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ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

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Motivation

- He (750), whose name shall not be spoken …
- Spin-0 gauge singlets play an important role in many extensions of the SM, e.g. as mediators to a hidden (dark) sector or in solutions to the strong CP problem
- Determining the CP nature of such a new particle will be a top priority once it has been discovered

Motivation

- Consider a spin-0 particle S, which is a singlet under the SM gauge group
- Its only renormalizable interactions with the SM arise through the Higgs portals:

$$\mathcal{L}_{\rm portal} = -\lambda_1\, S\, \phi^\dagger \phi - \frac{\lambda_2}{2}\, S^2\, \phi^\dagger \phi$$

- First term gives rise to a mixing of S with the Higgs, with mixing angle $\alpha \sim v\lambda_1/m_S^2$ which naturally can be large
- Affects Higgs phenomenology (α must be small) and potentially the phenomenology of S decays

[Bauer, MN 2016; Dawson, Lewis 2016; …]

Motivation

- Finding ways of suppressing the coupling λ_1 is a challenge to model building (coupling λ_2 is harmless)

  [Carmona, Goertz, Papaefstathiou 2016]

- Two options:
  - dynamically, e.g. sequestering in WEDs, where λ_1 is suppressed by a small wave-function overlap or a loop factor [Bauer, Hörner, MN 2016; Csaki, Randall 2016]
  - by means of a discrete symmetry, such as CP invariance, as λ_1 is forbidden if S is a pseudoscalar boson

Motivation

- How can one probe is S if a scalar (CP even), a pseudoscalar (CP odd), or a particle with mixed CP properties?
- Traditionally (Higgs case): [Soni, Xu 1993; Chala et al. 2016; Franceschini et al. 2016]
  - study angular distributions in $S \to ZZ \to 4l$ decay
  - but method requires large statistics and fails if S only weakly couples to Z bosons

Motivation

- Our idea:
  - search for the decay $S \to Z+h$ ($\to l^+l^-b\bar{b}$), which can only be mediated via CP-odd interactions of S
  - observing a single event proves that S is a pseudo-scalar (if CP is conserved in the UV theory), or that it has pseudoscalar interactions (in case it is a mixture of CP eigenstates)

Introductory remarks

- We assume that S is heavy enough to decay into Z+h, i.e. $m_S > 216$ GeV
- For illustration we will sometimes consider the cases $m_S = 750$ GeV and $m_S = 1.5$ TeV
- An analogous discussion can be made for the Higgs decay $h \to Z+A$ involving a light pseudoscalar A with mass $m_A < 34$ GeV (work in progress) [with M. Bauer, A. Thamm]

Introductory remarks

- Besides the Higgs portals, all other interactions of S with SM particles arise from higher-dimensional operators starting at dimension 5
- The pseudoscalar couplings at D=5 order are: [too many refs.!]

$$\mathcal{L}_{\rm eff}^{\rm gauge} = \frac{\tilde{c}_{gg}}{M}\frac{\alpha_s}{4\pi}\,S\,G_{\mu\nu}^a\widetilde{G}^{\mu\nu,a} + \dots$$

$$\mathcal{L}_{\rm eff}^{\rm ferm} = -\tilde{c}_{tt}\,\frac{y_t}{M}\,S\left(i\bar{Q}_L\tilde{\phi}\,t_R + \text{h.c.}\right) + \dots$$

- They induce couplings such as gg → S, S → γγ, S → ZZ, S → $t\bar{t}$ etc.

Caveat: EFT does not really make sense if $M_{\rm NP} \sim m_S$!

Operator analysis of $S \to Z + h$ decay

(not in 2HDM, but for a SM gauge singlet!)

Operator analysis at D=5

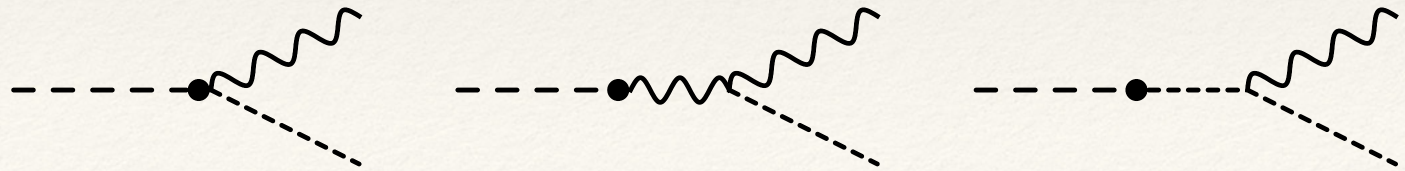
- There does not exist a dimension-5 operator giving rise to a tree-level S → Z+h matrix element!
- The obvious candidate

$$(\partial^\mu S)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \to -\frac{g}{2c_w}\,(\partial^\mu S)\, Z_\mu\, (v+h)^2$$

can be eliminated using the equations of motion:

$$\partial^\mu\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right) \to -\left(1+\frac{h}{v}\right)\sum_f 2T_3^f m_f \bar{f}\, i\gamma_5 f$$

- The corresponding S → Zh(h) matrix elements vanish!

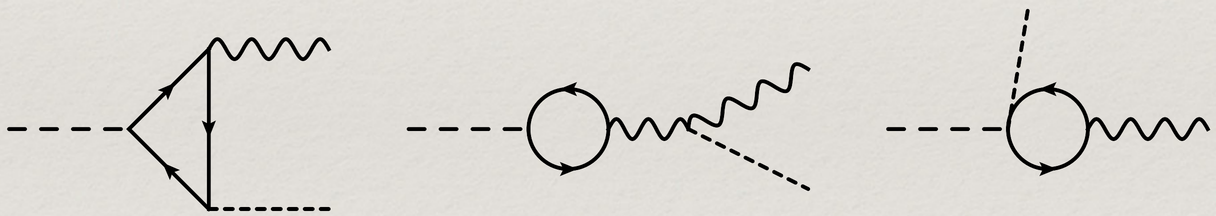


Operator analysis at D=5

- The unique operator giving rise to a one-loop S → Z+h matrix element is:

$$\mathcal{L}_{\rm eff}^{D=5} = -\tilde{c}_{tt}\,\frac{y_t}{M}\,S\left(i\bar{Q}_L\tilde{\phi}\,t_R + \text{h.c.}\right)$$

- Evaluating the resulting diagrams



we obtain:

$$i\mathcal{A}(S\to Zh) = -\frac{2m_Z\,\epsilon_Z^*\cdot p_h}{M}\,C_5^{\rm top}\,, \quad \text{with} \quad C_5^{\rm top} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

Operator analysis at D=5

- We obtain:

$$i\mathcal{A}(S \to Zh) = -\frac{2m_Z\,\epsilon_Z^* \cdot p_h}{M}\,C_5^{\rm top}\,, \quad \text{with} \quad C_5^{\rm top} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

- Z boson is longitudinally polarized ($\epsilon_Z^\mu \approx p_Z^\mu / m_Z$)
- Loop integral scales like:

$$F = -\frac{m_t^2}{m_S^2}\left(\ln\frac{m_S^2}{m_t^2} - i\pi\right)^2 + \mathcal{O}\left(\frac{m_t^4}{m_S^4}\right)$$

- Numerically, $F \approx -0.01 + 0.67i$ for $m_S = 750$ GeV, and $F \approx -0.09 + 0.23i$ for $m_S = 1.5$ TeV

Operator analysis at D=5

- We find

$$\Gamma(S \to Zh)_{D=5} = \frac{m_S^3}{16\pi M^2} \left|C_5^{\text{top}}\right|^2 \lambda^{3/2}(1, x_h, x_Z)$$

$$\approx 0.6\,\text{MeV}\,\tilde{c}_{tt}^2\,(\text{TeV}/M)^2$$

in both cases, which is a very small decay rate

- If the decay into top-quark pairs is kinematically allowed, one obtains

$$\frac{\Gamma(S \to Zh)_{D=5}}{\Gamma(S \to t\bar{t})} = \frac{3y_t^2}{16\pi^2} \left(\frac{m_S}{4\pi v}\right)^2 |F|^2 \frac{\lambda^{3/2}(1, x_h, x_Z)}{\sqrt{1 - 4x_t}}$$

yielding $3.6 \cdot 10^{-4}$ ($1.8 \cdot 10^{-4}$) for $m_S = 750$ GeV (1.5 TeV)

Operator analysis at D=5

- Under the assumption of S production in gluon fusion, the current experimental bounds on $pp \to S \to t\bar{t}$ then imply $pp \to S \to Zh$ rates less than 1.1 fb and 0.1 fb (at D=5), respectively, which is two orders of magnitude smaller than the experimental upper bounds of 123 fb and 40 fb [ATLAS-CONF-2016-015]

- However, it is by no means guaranteed that the D=5 contributions to the S → Z+h decay rates are the dominant ones!

Operator analysis at D=7

- At dimension 7, there is a unique operator mediating the decay S → Z+h at tree level: [see also: Gripaios, Sutherland 2016]

$$O_7 = (\partial^\mu S)\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\phi^\dagger\phi \;\hat{=}\; -S\left(\phi^\dagger i D_\mu \phi + \text{h.c.}\right)\partial^\mu(\phi^\dagger\phi)$$
$$\to \frac{g}{2c_w}\, S\, Z_\mu\, (v+h)^3\, \partial^\mu h$$

- It yields the decay rate:

$$\Gamma(S \to Zh) \approx \frac{m_S^3}{16\pi M^2}\left|C_5^{\rm top} + \frac{v^2}{2M^2}\, C_7\right|^2 \lambda^{3/2}(1, x_h, x_Z)$$

- With $C_7 = 1$ and M = 1 TeV this rate is 7 MeV for $m_S = 750$ GeV and 60 MeV for $m_S = 1.5$ TeV

- If S is produced in gluon fusion and dominantly decays into dijets, these rates are close to the current experimental upper bounds!

Operator analysis at D=7

- Beyond tree level, there are several fermionic operators contributing to the S → Z+h decay rate at dimension 7; those mixing under renormalization are:

$$\mathcal{L}_{\rm eff}^{D=7} = \frac{C_7}{M^3}\,O_7 + \frac{c_6^t}{M^2}\,\bar{t}_R\,\tilde{\phi}^\dagger i\not{D}\,\tilde{\phi}\,t_R + \frac{c_{7a}^t}{M^3}\left[iS\,\bar{Q}_L i\not{D}\,i\not{D}\,\tilde{\phi}\,t_R + \text{h.c.}\right] + \frac{c_{7b}^t}{M^3}\,(\partial^\mu S)\,\bar{t}_R\,\tilde{\phi}^\dagger\gamma^\mu\tilde{\phi}\,t_R$$

- Only the sum of these contributions is scale invariant at one-loop order

Heavy vector-like fermions

Heavy vector-like quarks

- To illustrate our results, we have considered a heavy, $SU(2)_L$ doublet $\psi = (T\ \ B)^T$ of vector-like quarks, which mix with the SM quarks

- The most general renormalizable Lagrangian reads:

$$\begin{aligned}\mathcal{L} = \bar{\psi}\,(i\not{D} - M)\,\psi + \bar{Q}_L\, i\not{D}\, Q_L + \bar{t}_R\, i\not{D}\, t_R + \bar{b}_R\, i\not{D}\, b_R \\ - y_t\big(\bar{Q}_L\tilde{\phi}\, t_R + \text{h.c.}\big) - \big(g_t\bar{\psi}\,\tilde{\phi}\, t_R + g_b\bar{\psi}\,\phi\, b_R + \text{h.c.}\big) \\ - c_1 S\,\bar{\psi}\, i\gamma_5\,\psi - ic_2 S\big(\bar{Q}_L\psi - \bar{\psi}\, Q_L\big)\end{aligned}$$

- Tree-level matching gives:

$$\tilde{c}_{tt} = -c_2\, g_t/y_t \qquad c_6^f = g_f^2 \qquad c_{7a}^f = c_2\, g_f \qquad c_{7b}^f = c_1\, g_f^2$$

Heavy vector-like quarks

- The coefficient c_6^b is constrained by precision measurements of the Z-boson couplings at LEP:

$$c_6^b = g_b^2 = (0.76 \pm 0.27) \left(\frac{M}{\mathrm{TeV}} \right)^2$$

- The pull away from 0 is driven by the b-quark forward-backward asymmetry, which is 2.8σ below its SM value
- Our model can easily account for this effect

Heavy vector-like quarks

- Performing the matching at one-loop order, we find

$$\frac{v^2}{2} C_7 = c_1 \sum_{f=t,b} \frac{N_c\, g_f^2}{16\pi^2} \left\{ 2T_3^f \left[m_f^2 \left(L - \frac{3}{2} \right) - \frac{m_h^2}{12} + \frac{m_Z^2}{36} + \frac{g_f^2\, v^2}{4} \right] - \frac{2}{3} Q_f s_w^2 m_Z^2 \left(L - \frac{3}{2} \right) \right\}$$
$$+ \tilde{c}_{tt} \frac{N_c\, y_t^2}{16\pi^2} \left\{ 2T_3^t \left[3m_t^2 \left(L - \frac{3}{2} \right) - \frac{m_h^2}{2} \left(L - \frac{7}{6} \right) - \frac{m_Z^2}{6} \left(L + \frac{19}{6} \right) - g_t^2 v^2 \left(L - \frac{9}{4} \right) \right] + Q_t s_w^2 m_Z^2 \right\}$$

  where $L = \ln(M^2/\mu^2)$

- This can naturally lead to sizable values, e.g. with $g_t = 2$ and $\mu = m_Z$:

$$C_7 \approx \Big[c_1 \left(5.30\, g_t^2 + 0.95\, g_t^4 + 0.16\, g_b^2 - 0.95\, g_b^4 \right)$$
$$+ \tilde{c}_{tt} \left(10.18 - 6.90\, g_t^2 \right) \Big] \cdot 10^{-2}$$
$$\approx (0.36\, c_1 - 0.17\, \tilde{c}_{tt})$$

Searching in the dark …

Operator analysis at D=5

- Recall the result from the top-loop amplitude arising at dimension 5:

$$i\mathcal{A}(S \to Zh) = -\frac{2m_Z\,\epsilon_Z^* \cdot p_h}{M}\,C_5^{\text{top}}\,, \quad \text{with} \quad C_5^{\text{top}} = -\frac{N_c\,y_t^2}{8\pi^2}\,T_3^t\,\tilde{c}_{tt}\,F$$

$$F = \int_0^1 d[xyz]\,\frac{2m_t^2 - xm_h^2 - zm_Z^2}{m_t^2 - xzm_S^2 - xym_h^2 - yzm_Z^2 - i0}$$

- Consider the fictitious limit where $m_t \gg m_S$, in which case $F = 1 + \mathcal{O}(m_S^2/m_t^2)$
- The top quark is then a very heavy particle, which should be integrated out

Operator analysis at D=5

- This yields a short-distance, D=5 matching contribution!
- However, we found that no corresponding dimension-5 operator exists on the effective Lagrangian!?!
- What's going on?

Land of confusion

- One finds that the result for the top-quark loop graphs depends on the treatment of γ_5
- Our result was obtained using the NDA scheme; in the 't Hooft-Veltman (HV) scheme we find an extra term (in unitary gauge) $\delta F_{\mathrm{HV}} = -1$, which precisely cancels the asymptotic value of F and hence turns the amplitude into a D=7 contribution!
- Is this the solution to the puzzle?

Land of confusion

- No, since there is no corresponding D=7 operator whose matrix element is proportional to $m_S{}^2/M^2$! [Gripaios, Sutherland 2016]
- Also, the result of the calculation is gauge dependent:

$$\delta F_{\rm HV} = -1 - \frac{2}{3}\,\frac{6m_t^2 - m_S^2}{m_S^2 - \xi m_Z^2}$$

- The HV scheme breaks the Ward identities of chiral gauge theories, in our case: [Bonneau 1981]

$$k_\mu \Gamma^\mu(k) = -i m_Z\, \Gamma(k)$$

- When these are restored by finite counter-terms, one recovers the previous result found in the NDA scheme!

Non-polynomial operators

- When one integrates out particles whose mass arises from electroweak symmetry breaking, then non-polynomial operators in the Higgs field can arise in the effective Lagrangian! [Pierce, Thaler, Wang 2006]

- In our case, the relevant operator is:

$$O_5 = (\partial^\mu S)\left(\phi^\dagger iD_\mu\,\phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2} \;\;\hat{=}\; -\,S\left(\phi^\dagger iD_\mu\,\phi + \text{h.c.}\right)\frac{\partial^\mu(\phi^\dagger\phi)}{\phi^\dagger\phi}$$

- This operator gives the dominant contribution to the decay h → Z+A in the heavy-top limit! [Bauer, MN, Thamm (in prep.)]

Conclusions

- Novel way for probing the CP properties of a new, heavy, SM-singlet spin-0 boson
- Interesting and non-trivial application of effective field theory, with some subtleties
- Motivates continued experimental searches for $S \to Z+h$ decay in LHC Run-2