Interpreting SMEFT Results in Extended Scalar Sectors

Based on

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In collaboration with
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Higgs Physics in the Age of the SMEFT

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d=6,8,\ldots} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-2}} \mathcal{O}_i^{(d)} \]

Ellis, Madigan, Mimasu, Sanz, You [2012.02779]

ATLAS-DRAFT

ATLAS-CONF-2021-053

(See Alessandro Calandrini’s Talk from Monday)
Start model building! Focussed searches, make sure we understand the SM, …
Alas...

But we are still learning a lot about the Standard Model!
What are we learning about New Physics?

SMEFT allows for a robust, precision program at the LHC, but ultimately these operators arise from some underlying UV model.

Lots of interesting / challenging methodological questions:

- At what order do we truncate the amplitude / Lagrangian?
- What assumptions about flavor should we make to get a manageable set of operators?
- How should we account for EFT validity issues?

Also “higher-order” effects to consider:

- RG Evolution of Wilson Coefficients
- One-Loop Matching Effects
- Importance of Dimension-8 Operators
- Higher Order QCD / EW Corrections in the EFT

These questions are best studied in examples!
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These questions are best studied in examples!

Focus on the impacts of these today
Example 1: The Singlet Model

arXiv:2102.02823, Dawson, Giardino, SH
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Simplest extension to the SM — only one additional state

Ideal test case for investigating details of matching procedure
- theoretical constraints well understood
- one-loop matching results are known
  (Jiang et al., 1811.08878, Haisch et al., 2003.05936)

\[ C_i(\mu_R) = c_i(M) + \frac{1}{16\pi^2} d_i(M) + \frac{1}{32\pi^2} \gamma_{ij} c_j(M) \log \left( \frac{\mu_R^2}{M^2} \right) \]

Goal: understand numerical importance of RGEs + 1-loop matching effects in the context of the singlet model
The Singlet Model

\[ V(\Phi, S) = -\mu_H^2 \Phi^\dagger \Phi + \lambda_H (\Phi^\dagger \Phi)^2 + \frac{1}{2} m_\xi \Phi^\dagger \Phi S + \frac{1}{2} \kappa \Phi^\dagger \Phi S^2 \]

\[ + t_S S + \frac{1}{2} M^2 S^2 + \frac{1}{3} m_\zeta S^3 + \frac{1}{4} \lambda_S S^4 \]

In \( Z_2 \) non-symmetric case, use shift symmetry to set \( v_S \to 0 \)

Physical states:

\[ h = \cos \theta \, \Phi_0 + \sin \theta \, S \]
\[ H = -\sin \theta \, \Phi_0 + \cos \theta \, S \]

Masses \( m_h = 125 \text{ GeV}, \quad M_H \)

Other physical parameters:

\( \sin \theta, \quad \kappa, \quad m_\zeta, \quad \lambda_S \)

Higgs couplings universally suppressed by \( \cos \theta \)
Singlet Matching to SMEFT

Two coefficients are generated at tree-level:

\[
CH^\Box = - \frac{m_\xi^2}{8M^2}
\]

\[
CH = \frac{m_\xi^2}{8M^2} \left( \frac{m_\xi m_\zeta}{3M^2} - \kappa \right)
\]

Perform matching at the scale \( M \), related to the physical mass via

\[
M^2 = m_h^2 \sin^2 \theta + M_H^2 \cos^2 \theta - \frac{\kappa}{2} v^2
\]
Singlet Matching to SMEFT

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\begin{align*}
    c_{H\Box} &= -\frac{m_\xi^2}{8M^2} \\
    c_H &= \frac{m_\xi^2}{8M^2} \left( \frac{m_\xi m_\zeta}{3M^2} - \kappa \right)
\end{align*}
\]

Perform matching at the scale \( M \), related to the physical mass via

\[
M^2 = m_h \sin^2 \theta + M_H^2 \cos^2 \theta - \frac{\kappa}{2} v^2
\]

These operators introduce

\[
C_{HD}, \quad C_{tH}, \quad C_{bH}, \quad C_{\tau H}, \quad C_{Hl}^{(3)}, \quad C_{Hq}^{(3)}, \quad C_{Htb}
\]

at the weak scale from RG running.
Tree Level (+RGE) Results

Limits on the singlet from EWPO and LHC competitive — but most allowed coefficients cannot be generated in the model.
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One-Loop Matching

Jiang, Craig, Li, Sutherland [1811.08878],
Haisch, Ruhdorfer, Salvioni, Venturini, Weiler [2003.05936]

New contributions to $C_H$, $C_{H\Box}$ at the matching scale...

$$d_{H\Box} = -\frac{9}{2} \lambda c_{H\Box} + \frac{31}{36} (3g^2 + g'^2) c_{H\Box} + \frac{3}{2} c_H + \delta d_H + \delta d_{H\Box}^{\text{shift}}$$

$$d_H = \lambda \left[ \frac{1}{9} (62g^2 - 336\lambda) c_{H\Box} + 6c_H \right] + \delta d_H + \delta d_H^{\text{shift}}$$

...as well as many operators that don’t appear at tree-level

$$C_{HD}, \ C_{HW}, \ C_{HB}, \ C_{HWB}, \ C_{Hu}, \ C_{Hd},$$

$$C_{Hq}^{(1)}, \ C_{Hq}^{(3)}, \ C_{Hl}^{(3)}, \ C_{tH}$$

In principle of comparable size to RGE-induced contribution!
One-Loop Matching

SMEFT Limit of Singlet Model
\[ \cos \theta = 0.98, \kappa = 0.5, m_\chi = M/4, \lambda_\phi = 0.03 \]

One-loop matching changes operators by \(~10\text{-}20\%\) as measured at the weak scale

Include only one-loop RGEs
(two loops unavailable, but necessary to run one-loop induced operators)
Effects on the Fit

Effects mostly $O(10\%)$, except for large values of portal coupling
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Example 2: The 2HDM

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan
Example 2: The 2HDM

Four “standard” types of 2HDMs (I, II, L and F) distinguished by $Z_2$ symmetry acting on $\Phi_2$ and the fermions.

Higgs coupling deviations can be written in terms of $\tan \beta, \cos(\beta - \alpha)$.

E.g., for Type-II:

$$\kappa_u = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta} \quad \implies \quad \text{all approach 1 as } \cos(\beta - \alpha) \to 0$$

$$\kappa_d = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)$$

$$\kappa_\ell = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)$$

$$\kappa_V = \sin(\beta - \alpha)$$

Alignment parameter tells us how “SM-like” the 125-GeV Higgs is.
Matching to Dimension-6

Ignoring light flavor, there are four operators generated:

\[ \mathcal{O}_H = (H^\dagger H)^3, \]

\[ \frac{v^2}{\Lambda^2} C_H = \frac{\Lambda^2}{v^2} \cos^2(\beta - \alpha) \]

\[ \mathcal{O}_{bH} = (H^\dagger H)(\bar{Q}_3 b_R H), \]

\[ \frac{v^2}{\Lambda^2} C_{bH} = -y_b \eta_b \frac{\cos(\beta - \alpha)}{\tan \beta} \]

\[ \mathcal{O}_{tH} = (H^\dagger H)(\bar{Q}_3 t_R \tilde{H}), \]

\[ \frac{v^2}{\Lambda^2} C_{tH} = -y_t \eta_t \frac{\cos(\beta - \alpha)}{\tan \beta} \]

\[ \mathcal{O}_{\tau H} = (H^\dagger H)(\bar{L}_3 \tau_R \tilde{H}), \]

\[ \frac{v^2}{\Lambda^2} C_{\tau H} = -y_\tau \eta_\tau \frac{\cos(\beta - \alpha)}{\tan \beta} \]

<table>
<thead>
<tr>
<th></th>
<th>( \eta_t )</th>
<th>( \eta_b )</th>
<th>( \eta_\tau )</th>
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<tbody>
<tr>
<td>Type-I</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Type-II</td>
<td>1</td>
<td>( -\tan^2 \beta )</td>
<td>( -\tan^2 \beta )</td>
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<tr>
<td>Lepton-specific</td>
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<td>( -\tan^2 \beta )</td>
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<tr>
<td>Flipped</td>
<td>1</td>
<td>( -\tan^2 \beta )</td>
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Requiring all the additional states to lie at a common high scale enforces the "decoupling limit":

\[ \cos(\beta - \alpha) \sim \frac{v^2}{\Lambda^2} \ll 1 \]
Different types of 2HDM sweep out different ranges of allowed coefficients
Matching to Dimension-6

For a given type of 2HDM, easy to translate into the $\tan \beta, \cos(\beta - \alpha)$ plane

Effects of RGE are relatively small
(logarithmic effects on Higgs couplings)
Effects at Large $\tan \beta$

There is a second minimum where the bottom Yukawa has the opposite sign.

The well-known “wrong-sign” region of the Type-II 2HDM.
Effects at Large $\tan\beta$

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The well-known “wrong-sign” region of the Type-II 2HDM

Actually ruled out for Type-II by latest Higgs data, but appears still in e.g., Type-L:

But only if we include $\mathcal{O}(\Lambda^{-4})$ terms!
Effects at Large $\tan \beta$

In the type-I 2HDM, all of the fermionic operators scale like:

$$\frac{v^2}{\Lambda^2} C_f H = -y_f \frac{\cos(\beta - \alpha)}{\tan \beta}$$

For large $\tan \beta$, approaches the SM!
Effects at Large $\tan \beta$

In the type-I 2HDM, all of the fermionic operators scale like:

$$\frac{v^2}{\Lambda^2} C_{fH} = -y_f \frac{\cos(\beta - \alpha)}{\tan \beta}$$

Ignoring the constraints on $C_H$, we see the dimension-6 description fails (see e.g., [1611.01112])

$\implies$ need to include gauge couplings! (Dimension-8)

For large $\tan \beta$, approaches the SM!
Constraints are Important!

At dimension-6, the leading constraints for large $\tan \beta$ come from information about the Higgs self coupling encoded in $C_H$

Use indirect bounds from single-Higgs measurements based on [arXiv:1607.04251]
(Degrassi, Di Micco, Giardino, Rossi).
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$$\frac{v^2}{\Lambda^2} C_H = \cos(\beta - \alpha)^2 \frac{(\Lambda^2 - 4m_h^2)}{v^2}$$

Extra factor of $\Lambda$ increases importance for larger scales
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Extra factor of $\Lambda$ increases importance for larger scales.
Matching the 2HDM to Dimension-8

Gauge coupling modifications make it clear matching to dimension-8 is important.

Perform complete matching of the 2HDM to dimension-8, and write operators in terms of “Murphy basis” in [2005.00059]

\[
\mathcal{O}^{(1)}_{H^6} = (H^\dagger H)^2 (D_\mu H)^\dagger (D^\mu H), \quad C^{(1)}_{H^6} = -\frac{\Lambda^4}{v^4} \cos(\beta - \alpha)^2
\]
Fit Results Including Dimension-8

Type-I 2HDM

Type-II 2HDM
Fit Results Including Dimension-8

Type–L 2HDM

- Exact 2HDM
- Dim–6, $\Lambda^{-2}$
- Dim–6, $\Lambda^{-4}$
- Dim–8

Type–F 2HDM

- Exact 2HDM
- Dim–6, $\Lambda^{-2}$
- Dim–6, $\Lambda^{-4}$
- Dim–8
Rich structure of the 2HDM leads to interesting effects when interpreting SMEFT results:

- SMEFT formally valid only in the “alignment-limit”, requires light scales for large mixing angles
- “Wrong-sign” regions require going beyond $\mathcal{O}(\Lambda^{-2})$
- Gauge couplings only appear at dimension-8
- Self-coupling effects introduce a dependence on the heavy scale
Conclusions

• SMEFT Fits may be the “legacy” measurements of the LHC, but important to keep UV models in mind!

• Tree level interpretations of SMEFT Fits aren’t the whole story! 
  \textit{RG evolution of coefficients is extremely important.}

• Considering explicit models lets us assess the importance of higher-order matching effects (1 loop, dim-8) in a concrete way.

• Higher order effects can change phenomenology / interpretation — what happens in even more complicated models?

Thanks for your attention!