Higgs EFT and kinematic distributions

Anke Biekoetter

RWTH Aachen

based on 1602.05202
(with Johann Brehmer and Tilman Plehn)

Higgs Hunting in Paris, September 1, 2016
Higgs effective field theory

- New physics at $\Lambda \gg E_{\text{LHC}} \sim v$? [Grzadkowski et al 1008.4884; ...]

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \mathcal{O} \left( \frac{1}{\Lambda^4} \right) \]

- Framework for indirect searches at the electroweak scale
- Reproducible and (mostly) model independent

\[ \mathcal{O}_{WW} = - \frac{g^2}{4} (\phi^\dagger \phi) W_{\mu\nu}^a W^{\mu\nu a} , \]
\[ \mathcal{O}_W = \frac{ig}{2} (D^{\mu} \phi)^\dagger \sigma^k (D^{\nu} \phi) W_{\mu\nu}^k \]
EFT cannot describe LHC Higgs physics

- LHC accuracy $\sim 10\%$ translates to new physics reach of:

  $$\left| \frac{\sigma \times BR}{(\sigma \times BR)_{SM}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 10\% \iff \Lambda < \frac{g m_h}{\sqrt{10\%}} \approx 400 \text{ GeV}$$

- scenarios with $\Lambda \gg E$ not measurable at the LHC
- D8 not sufficiently suppressed
EFT can describe LHC Higgs physics

→ answer some remaining questions
D6 can describe LHC Higgs physics

answer some remaining questions
Outline

D6 description

- To square or not to square dimension-6 amplitudes?
- Vector triplet model
- Higgs-strahlung and WBF
- Which observable to study for WBF?
D6 description - to square or not to square?

$|\mathcal{M}_{4+6}|^2 = |\mathcal{M}_4|^2 + 2 \text{Re}\mathcal{M}_4^*\mathcal{M}_6 + |\mathcal{M}_6|^2$
D6 description - to square or not to square?

\[ |\mathcal{M}_{4+6}|^2 = |\mathcal{M}_4|^2 + 2 \text{Re}\mathcal{M}_4^*\mathcal{M}_6 + |\mathcal{M}_6|^2 \]

Preferable to include D6\(^2\) when neglecting D8?

Study for vector triplet model

NOT a consistent EFT → **practical** question
Vector triplet model

Full model

\[ \mathcal{L} \supset -\frac{1}{4} V^a_{\mu \nu} V^{\mu \nu a} + \frac{M^2}{2} V^a_{\mu} V^a_{\mu} + \frac{g_s}{2} c_H V^a_{\mu} \left[ \phi^\dagger \sigma^a D^\mu \phi \right] + \frac{g_w^2}{2 g_V} V^a_{\mu} \sum_{\text{fermions}} c_F \bar{F}_L \gamma^\mu \sigma^a F_L + g_V^2 c_{VVH} V^a_{\mu} V^{\mu a} (\phi^\dagger \phi) \]

D6 approximation

\[ \mathcal{O}_{WW} = -\frac{g^2}{4} (\phi^\dagger \phi) W^a_{\mu \nu} W^{\mu \nu a} \]

\[ \mathcal{O}_W = \frac{ig}{2} (D^\mu \phi)^\dagger \sigma^k (D^\nu \phi) W^k_{\mu \nu} \]

\[ \Lambda = m_\xi \]

new \( \xi \) resonance - modification of Higgs couplings

[1510.03443; 1211.2229; 1406.7320; 1506.03631]
WBF - momentum transfer

- study parton-level process $ud \rightarrow u'd'h$
- momentum transfer $q$

[1512.06135]
WBF - parton level

- study momentum transfer $q$ ($p_{T,j_1}$)
- two benchmarks with $m_\xi = 1200$ GeV

constructive

```
g_V = 3, c_H = -0.47, c_F = -5, c_{VVHH} = 2
```

destructive

```
g_V = 3, c_H = -0.5, c_F = 3, c_{VVHH} = -0.2
```
WBF - parton level

- study momentum transfer \( q \left( p_{T,j_1} \right) \)
- two benchmarks with \( m_\xi = 1200 \text{ GeV} \)

**constructive**

\[ u \, d \rightarrow u \, d \, h, \, T1 \]

\[ g_V = 3, \, c_H = -0.47, \, c_F = -5, \, c_{V VH H} = 2 \]

**destructive**

\[ u \, d \rightarrow u \, d \, h, \, T4 \]

\[ g_V = 3, \, c_H = -0.5, \, c_F = 3, \, c_{V VH H} = -0.2 \]
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destructive

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WBF - parton level

- study momentum transfer \( q (p_{T,j1}) \)
- two benchmarks with \( m_\xi = 1200 \text{ GeV} \)

**constructive**

\[ \sigma \text{ [fb/bin]} \]

**destructive**

\[ \sigma \text{ [fb/bin]} \]

Reality check

- □ Valid for larger parameter range?
- □ Valid for full, hadron level process?

\[ g_V = 3, c_H = -0.47, c_F = -5, c_{VVHH} = 2 \]

\[ g_V = 3, c_H = -0.5, c_F = 3, c_{VVHH} = -0.2 \]
WBF - Comparison of expected exclusion limits

- choose universal coupling rescaling $c$
  \[ g_V = 1, \quad c_H = c, \quad c_F = \frac{g_V^2}{2g^2} c, \quad c_{HHVV} = c^2 \]

- $m_\xi$ mass of the new heavy vector

![Graph](image)

150 GeV < $p_{T,j1}$ < 300 GeV

$10 \text{ fb}^{-1}$ (dashed: 100 fb$^{-1}$)

$m_\xi \ [\text{GeV}]$

$m_\xi \[\text{GeV}\]$
WBF - Comparison of expected exclusion limits

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![Graph showing exclusion limits]

Reality check

☑ Valid for larger parameter range?
☐ Valid for full, hadron level process?
WBF - getting realistic

- hadron level analysis $pp \rightarrow hjj (+j)$ using PYTHIA6 and FastJet
- apply WBF cuts

$$p_{T,j} > 20 \text{ GeV}, \quad m_{jj} > 500 \text{ GeV}, \quad \Delta \eta_{jj} > 3.6$$

![Graph showing $\sigma$ vs. $p_{T,j}$ with different curves labeled as SM, full, D6, D6². The graph is labeled with dotted: WBF diagrams only, without $\Delta \eta_{jj}$ cut.](image-url)
WBF - getting realistic

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Reality check

- ✔ Valid for larger parameter range?
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[dotted: WBF diagrams only, without $\Delta \eta_{jj}$ cut]
Conclusions

- Including $D6^2$ terms improves agreement with full model and avoids negative cross sections.
- Leading tagging jet $p_T$ highly correlated with momentum transfer $q$ for WBF.
- Results survive in a realistic environment.
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- Including $D_6^2$ terms improves agreement with full model and avoids negative cross sections.
- Leading tagging jet $p_T$ highly correlated with momentum transfer $q$ for WBF.
- Results survive in a realistic environment.

Thank you for your attention!
Any questions?
## D6 operators

**Table:** Bosonic CP-conserving Higgs operators in the HISZ basis.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{\phi_1}$</td>
<td>$(D_\mu \phi)^\dagger (\phi \phi^\dagger) (D^\mu \phi)$</td>
</tr>
<tr>
<td>$O_{\phi_2}$</td>
<td>$\frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi)$</td>
</tr>
<tr>
<td>$O_{\phi_3}$</td>
<td>$\frac{1}{3} (\phi^\dagger \phi)^3$</td>
</tr>
<tr>
<td>$O_{GG}$</td>
<td>$(\phi^\dagger \phi) G^A_{\mu\nu} G^{\mu\nu \ A}$</td>
</tr>
<tr>
<td>$O_{BW}$</td>
<td>$-\frac{gg'}{4} (\phi^\dagger \sigma^k \phi) B_{\mu\nu} W^{\mu\nu \ k}$</td>
</tr>
<tr>
<td>$O_{BB}$</td>
<td>$-\frac{g'^2}{4} (\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>$O_{WW}$</td>
<td>$-\frac{g^2}{4} (\phi^\dagger \phi) W^k_{\mu\nu} W^{\mu\nu \ k}$</td>
</tr>
<tr>
<td>$O_B$</td>
<td>$\frac{ig}{2} (D_\mu \phi)^\dagger (D^\nu \phi) B_{\mu\nu}$</td>
</tr>
<tr>
<td>$O_W$</td>
<td>$\frac{ig}{2} (D_\mu \phi)^\dagger \sigma^k (D^\nu \phi) W^k_{\mu\nu}$</td>
</tr>
</tbody>
</table>
Wilson coefficients

\[ f_{\phi 2} = \frac{3}{4} \left( -2 c_F g^2 + c_H g_V^2 \right), \]
\[ f_{\phi 3} = -3 \lambda \left( -2 c_F g^2 + c_H g_V^2 \right), \]
\[ f_{\phi\phi} = -\frac{1}{4} y_f c_H \left( -2 c_F g^2 + c_H g_V^2 \right), \]
\[ f_{WW} = c_F c_H \]
\[ f_{BW} = c_F c_H \equiv f_{WW} \]
\[ f_W = -2 c_F c_H. \]
WBF - Which observable to study?

Compare deviations from the full model

\[
\Delta_{\text{theo}}(x_{\text{min}, \text{max}}) = \left| \frac{\sigma_{D6} - \sigma_{\text{full}}}{\sigma_{\text{full}}} \right|, \ x \in \{q, \ p_{T,j_1}, \ p_{T,j_2}, \ p_{T,h}\}
\]

to statistics-driven and systematics-driven significances

\[
\frac{S}{B}(x_{\text{min}, \text{max}}) = \left| \frac{\sigma_{\text{full}} - \sigma_{\text{SM}}}{\sigma_{\text{SM}}} \right| \quad \text{and} \quad \frac{S}{\sqrt{B}}(x_{\text{min}, \text{max}}) = \sqrt{L} \left| \frac{\sigma_{\text{full}} - \sigma_{\text{SM}}}{\sqrt{\sigma_{\text{SM}}}} \right|
\]
Higgs-strahlung

- study distribution of $m_{Vh} (p_T, V)$
- two benchmarks with $m_\xi = 1200$ GeV

**destructive**

\[
\begin{align*}
\sigma_{pp \to Vh, T1} & \quad \text{[fb/bin]} \\
& \quad \text{[GeV]} \\
& \quad \text{m}_{Vh} \quad \text{[GeV]} \\
& \quad g_V = 3, c_H = -0.47, c_F = -5, c_{VVHH} = 2
\end{align*}
\]

**constructive**

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\begin{align*}
\sigma_{pp \to Vh, T4} & \quad \text{[fb/bin]} \\
& \quad \text{[GeV]} \\
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Higgs-strahlung

- study distribution of $m_{Vh}$ ($p_{T,V}$)
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Destructive

$g_V = 3$, $c_H = -0.47$, $c_F = -5$, $c_{VVHH} = 2$

Constructive

$g_V = 3$, $c_H = -0.5$, $c_F = 3$, $c_{VVHH} = -0.2$
Only WBF diagrams, $\Delta \eta_{jj}$

$p p \rightarrow h j j (j), T1$

$\sigma$ [fb/bin]

$\Delta \eta_{jj}$

solid: $p_{T,j1} < 200$ GeV

$D6^2$

$D6$

$SM$

full
Normalized distribution

$0.002 \quad 0.004 \quad 0.006 \quad 0.008$

interference dashed

$u \ d \rightarrow u \ d \ h, \ T_1$

$\xi$

$SM$

$D_6$

$16/10$
Normalized distribution

$\Delta \phi_{ji}$

Normalized distribution

$\Delta \eta_{ji}$

$u d \rightarrow u d h, T1$

interference dashed

ξ

SM

D6

$\xi$

$\Delta \phi_{ji}$

$\Delta \eta_{ji}$
$u \ d \rightarrow u \ d \ h, \ T1$

**Normalized distribution**

- **$p_{T,h}$ [GeV]**
- **$p_{T,j1}$ [GeV]**

- **Interference dashed**

Legend:
- **SM**
- **$S$**
- **$\xi$**
Scalar splitting function

\[ |\mathcal{M}(q \to q'S)|^2 = g_F^2 \frac{x^2 m_q^2}{1 - x} + g_F^2 \frac{p_T^2}{1 - x} + \mathcal{O}\left(\frac{m_q^2 p_T^2}{E^2}, \frac{m_q^4}{E^2}, \frac{p_T^4}{E^2}\right) \]

\[ \sigma(qX \to q'Y) = \int dx \, dp_T \, F_S(x, p_T) \sigma(SX \to Y) \]

with the splitting function

\[ F_S(x, p_T) = \frac{g_F^2}{16\pi^2} x \frac{p_T^3}{(m_S^2 (1 - x) + p_T^2)^2} \]

\[ F_T(x, p_T) = \frac{g^2}{16\pi^2} \frac{1 + (1 - x)^2}{x} \frac{p_T^3}{(m_W^2 (1 - x) + p_T^2)^2} \]

\[ F_L(x, p_T) = \frac{g^2}{16\pi^2} \frac{(1 - x)^2}{x} \frac{2m_W^2 p_T}{(m_W^2 (1 - x) + p_T^2)^2} \]

[9712400; S. Dawson (1985); G. L. Kane, W. W. Repko, W. B. Rolnick (1684); 0706.0536; 1202.1904]