LIBERATING HIGGS/EW OBSERVABLES AT DIMENSION 8

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Based on: Bertuzzo, Grojean & RSG (in prep)
RSG, Pomarol & Riva (2014)
SMEFT: MODEL INDEPENDENT PARAMETRISATION

Vectorlike fermions  Superpartners  Composite states

Top partners  \( W', Z' \)  Heavy Higgs bosons

\( \mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{84} \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^6 + \sum_{i=1}^{993} \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^8 \ldots \)

1 TeV

100 GeV

Mass

Deviations from SM in all possible low-energy measurements at the LHC/elsewhere
SMEFT: A PREDICTIVE FRAMEWORK

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{84} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \sum_{i=1}^{993} \frac{c_i}{\Lambda^2} \mathcal{O}_i^8 \cdots \]

• SMEFT not just a parametrisation but a predictive framework.

• At a given order in SMEFT fewer parameters than observables that it contributes to.

• These lead to predictions of some observable as a function of others
D4-PREDICTIONS

• Same SU(2)x U(1) invariant D4 operator gives rise to both LHS and RHS

• Experimentally fermion mass and Yukawa completely different measurements. So are W and Z mass.

• But actually we are probing the same effect by two different measurements.

$$m_W = m_Z \cos \theta_W$$

$$g_{ff}^h = \frac{m_f}{v}$$

$$y_f \bar{Q} H f + h.c. \rightarrow m_f \left(1 + \frac{h}{v}\right) \bar{f} f$$

$$|D_\mu H|^2 \rightarrow \left(m_{W^+W^-}^2 + \frac{m_Z^2}{2} Z^2 \right)$$
Liberating Observables at D6

\[ m_W = m_Z \cos \theta_W \]

\[ g_{ff}^n = \frac{m_f}{\nu} \]

- At D6 level another SU(2) \times U(1) invariant operator:

\[ \mathcal{O}_T = \frac{1}{2} \left( H^\dagger \bar{D}_\mu H \right)^2 \]

- Now 2 operators and 2 measurements so prediction is broken

\[ (m_W^2 - m_Z^2 c_{\theta_W}^2) = c_T \frac{v^2}{\Lambda^2} m_Z^2 \]

- At \( O(\nu^2/\Lambda^2) \), W and Z mass independent couplings. We liberated an observable/ opened a new BSM primary at D6.
BSM PRIMARIES

Up to a given order

No of independent observables = No of operators = N

The subset of N observables that are all independent and can be best measured are called BSM Primaries

RSG, Pomarol & Riva (2014)
Liberating Observables at D8

\[ m_W = m_Z \cos \theta_W \]
\[ g_{ff}^h = \frac{m_f}{v} \]

- At D6 level another SU(2)x U(1) invariant operator:

\[ \mathcal{O}_y = y_f |H|^2 \bar{F} H f \]

- Now 2 operators and 2 observables so prediction is broken.

\[ (g_{ff}^h - \frac{m_f}{v}) = c_y \frac{v^2}{\Lambda^2} \frac{m_f}{v} \]

- At \( O(v^2/\Lambda^2) \), hff coupling and mass independent couplings. We liberated an observable/opened a new BSM primary at D6.
D4 AND D6 PREDICTION EXAMPLE

• At D4 level, $Z_{ff}$, $W_{ff}$ couplings can be completely determined as a function of $(g, g', \nu)$ which can be determined by $W/Z$ mass and fine structure constant measurements.

\[
g_f^Z = \frac{g}{c_{\theta_W}} (T_3 - Qs_{\theta_W}^2), \quad g_F^W = \frac{g}{\sqrt{2}}
\]

• At D6 level following operators break these D4 predictions at $O(\nu^2/\Lambda^2)$

\[
\mathcal{O}_{e_R} = iH^+ \vec{D}_\mu H \bar{e}_R \gamma^\mu e_R, \quad \mathcal{O}_L = iH^+ \vec{D}_\mu H \bar{L} \gamma^\mu L, \quad \mathcal{O}_L^{(3)} = iH^+ \sigma^a \vec{D}_\mu H \bar{L} \sigma^a \gamma^\mu L.
\]

• But (considering only leptons) there are four couplings and only 3 operators so 1 prediction:

\[
\delta g_{e_L}^Z Z_\mu \bar{e}_L \gamma^\mu e_R + \delta g_{e_R}^Z Z_\mu \bar{e}_R \gamma^\mu e_R + \delta g_{\nu_L}^Z Z_\mu \bar{\nu}_L \gamma^\mu \nu_L + \delta g_{W_L}^W (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.)
\]

\[
\delta g_{\nu e}^W = \frac{c_{\theta_W} (\delta g_{\nu e}^Z - \delta g_{e L}^Z)}{\sqrt{2}} = 0
\]
LIBERATING OBSERVABLES AT D8

• At D8 level another SU(2)x U(1) invariant operator breaks D6 prediction at $O(v^4/\Lambda^4)$

\[ O^{(3)Q}_{3L} = iH^\dagger D_\mu H (H^\dagger \sigma^a H) \bar{L} \sigma^a \gamma^\mu L \]

• So of the 4 D4 predictions 3 are broken at $O(v^2/\Lambda^2)$ and 1 at $O(v^4/\Lambda^4)$

\[ \delta^8 g_{\nu e} = \delta g_{\nu e} - \frac{c_{\theta_W} (\delta g^Z_{\nu l} - \delta g^Z_{e l})}{\sqrt{2}} = -\frac{c^{(3)}_{3L} g v^4}{2\sqrt{2} \Lambda^4} \]

• At D6 level there were 3 independent couplings, at D8 we liberate a further observable/ open a 4th BSM primary

Bertuzzo, Grojean & RSG (in prep)
So far all ‘observables’ we have considered were QCD & EM invariant vertices/anomalous couplings.

More examples:

(1) Higgs observables (20):

\[ h W_{\mu\nu}^+ W^{-\mu\nu} \]
\[ h Z_{\mu} f_{L,R} \gamma^\mu f_{L,R} \]

(2) Electroweak precision observables (9):

\[ Z_{\mu} f_{L,R} \gamma^\mu f_{L,R} \]
\[ W^+_{\mu} \bar{\nu}_L \gamma^\mu e_L \]

(3) Triple and Quartic Gauge couplings (3+4):

\[ g_1^Z c_{\theta_W} Z_{\mu} \left( W^{+\nu} \bar{W}_{\mu\nu}^- - W^{-\nu} \bar{W}_{\mu\nu}^+ \right) \]
\[ \kappa_{\gamma} s_{\theta_W} \hat{A}_{\mu\nu}^+ W_{\mu}^+ W_{\nu}^- \]
\[ \lambda_{\gamma} s_{\theta_W} \hat{A}_{\mu\nu} W_{\mu}^- \rho \bar{W}_{\rho\nu}^+ \]
**SMEFT: A PREDICTIVE FRAMEWORK**

<table>
<thead>
<tr>
<th>No of operators (No of free parameters)</th>
<th>&lt;</th>
<th>No of ‘observables’ (anomalous couplings)</th>
</tr>
</thead>
</table>

- No of SMEFT Predictions = No of observables - No of Operators

<table>
<thead>
<tr>
<th>Eg. $iH^\dagger \bar{D}<em>\mu H \bar{f} \gamma^\mu f, (H^\dagger \sigma^a H)W^a</em>\mu B^{\mu\nu}$</th>
<th>Eg. $Z_\mu \bar{f} \gamma^\mu f, hZ_\mu \bar{f} \gamma^\mu f, hZ_{\mu\nu} Z^{\mu\nu}$</th>
</tr>
</thead>
</table>

- Invariant under full electroweak group
- Smaller number
- More Symmetry
- Invariant under $U(1)_{em}$
- Larger number
- Less Symmetry
WHAT ABOUT THE HEFT?

- So far we have considered lagrangian terms in broken EW phase as they are can be thought of as ‘observables’ that can be separately measured.

- But these can be promoted to invariant terms where EW symmetry is non-linearly realised, i.e. HEFT operators.

\[
D_\mu U = U^\dagger \partial_\mu U - iU^\dagger [g W_\mu^a T_a + g' B_\mu Y] U
\]

\[
eA_\mu = 2i \text{ Tr}[X_{em} D_\mu U]
\]

\[
\frac{g}{2c_w} Z_\mu = i \text{ Tr}[X_3 D_\mu U]
\]

\[
g W_\mu^\pm = i\sqrt{2} \text{ Tr}[T^\pm D_\mu U]
\]

Unitary gauge: \( U = 1 \)

\[
\{ A, Z, W^\pm \} \rightarrow \{ A, Z, W^\pm \}
\]

Chanowitz, Holden & Georgi (1987)
WHAT ABOUT THE HEFT?

- HEFT equivalent to lagrangian of EM invariant operators.
- All anomalous couplings independent
- No predictions apart from those that test EM invariance

\[ D_\mu U = U^\dagger \partial_\mu U - iU^\dagger [g W^a_\mu T_a + g' B_\mu Y] U \]

\[ e A_\mu = 2i \text{ Tr}[X_{em} D_\mu U] \]
\[ \frac{g}{2c_w} Z_\mu = i \text{ Tr}[X_3 D_\mu U] \]
\[ g W^\pm_\mu = i\sqrt{2} \text{ Tr}[T^\pm D_\mu U] \]

Unitary gauge: \( U=1 \)

\[ \{ A, Z, W^\pm \} \rightarrow \{ A, Z, W^\pm \} \]
WHICH OBSERVABLES DO WE INCLUDE?

- We focus on vertices involved in the following processes:

- Let us focus up to dimension 4 vertices, i.e. the lowest order of HEFT. These are almost all the ‘observables’ of D6 SMEFT in Higgs/EW Physics

- For these O(1) deviations from predictions in HEFT

- Dimension 6 operators with more than or equal to 2 Higgs doublets can contribute

- Dimension 8 operators with more than or equal to 4 Higgs doublets can contribute

\[
\begin{align*}
pp/ee/VV & \rightarrow VV/Vh \\
pp/VV & \rightarrow h \\
h & \rightarrow V f f / \gamma \gamma / f f \\
pp & \rightarrow hh, hhh
\end{align*}
\]

\[
\begin{align*}
O_6 &= |H|^2 O_4 \rightarrow v^2 O_4 \\
O_8 &= |H|^4 O_4 \rightarrow v^4 O_4
\end{align*}
\]
(considering only 1 generation for the purpose of counting)
Pattern of breaking of these predictions distinguishes between HEFT and SMEFT:

1. **HEFT**: $O(1)$ breaking

2. **SMEFT**: Breaking order by order in $\frac{v^2}{\Lambda^2}$

3. With sufficient no of Higgs doublets all predictions broken in SMEFT too at high $D$
COUNTING

SMEFT

- 59 vertices
- 7 SM input parameters
- 52 SM Predictions
  - 17 D6 operators
- 35 D6 Predictions
  - 23 D8 operators
- 12 D8 Predictions
59 VERTICES

7 input parameters

$\alpha_{em}, m_w^2, m_Z^2, m_u, m_d, m_e, \text{ and } m_h$

52 deformations

\[ \Delta L_{V,V} = \sum_f \delta g_f Z_{\mu} \gamma^\mu f_{L,R} + \delta g_{\gamma V} (W^+_{\mu} \gamma^\mu e_L + h.c.) L + \delta g_{V A} (W^\mu u_L \gamma^\mu d_L + h.c.) L + \delta g_{\omega A} (W^\mu \gamma^\mu e_L + h.c.) L + \delta g_{Z A} (W^\mu \gamma^\mu d_L + h.c.) L \]

\[ \Delta L_{TGC} = i g_{CW} [\delta g^2_{TGC} (W^\mu W^{\nu} - W_{\mu} W^{\nu}) + \delta \kappa^2 Z_{\mu} W^\nu W^\nu] \]

\[ + i e \delta \kappa W^\mu W^- A^{\mu \nu} + g_{\gamma v e L} Z_{\mu} D_{\nu} W^\nu Z_{\sigma} \]

\[ \Delta L_{QGC} = g^2 c_w \left[ \delta g^2_{QGC} (Z_{\mu} W^\nu W^\nu - \delta g^2_{QGC} Z_{\mu} W^{\nu} W^\nu W^\nu) + \frac{g^2}{4 e_w} h Q (Z_{\mu} Z_{\mu}) \right] \]

\[ + \frac{g^2}{2} \left[ \delta g^2_{QGC} (W^{\mu \nu} W^\mu W^\nu - \delta g^2_{QGC} W^{\mu \nu} W^\mu W^\nu) \right] \]

\[ \Delta L_h = g_{V V} h \left[ W^{\mu \nu} W^- + \frac{1}{2 c_w^2} Z_{\mu} Z_{\nu} \right] + g_{T GC} (h f_{L,R} + h.c.) + \delta g_{Z Z} h Z_{\mu} Z_{\mu} \]

\[ + \sum_f g_{Z f} h (Z_{\mu} f_{L,R} f_{L,R} + h.c.) + \delta g_{W W} h (W_{\mu} u_L e_L) + h.c. + \frac{h}{2} (W_{\mu} u_L \gamma^\mu e_L + h.c.) \]

\[ + \kappa_{Z Z} h Z_{\mu} Z_{\nu} + \kappa_{A A} h A^{\mu \nu} A_{\mu \nu} + \kappa_{Z A} h A^{\mu \nu} Z_{\mu \nu} + \kappa_{W W} h W^{\mu \nu} W_{\mu \nu} + \kappa_{G A} h G^{A \mu \nu} G_{\mu \nu} \]

\[ \Delta L_{h h} = \kappa_{G G} \left( \frac{h^2}{4 e_w^2} g_{A A} G_{\mu \nu} \right) - g_{h h} v h^3 - g_{h h} h^4 \]

\[ \Delta L_{k k} = g_{V V} h \left[ W^{\mu \nu} W^\mu + \frac{1}{2 c_w^2} Z_{\mu} Z_{\mu} \right] + g_{Z Z} h Z_{\mu} Z_{\mu} \]

\[ + \sum_f g_{Z f} h Z_{\mu} f_{L,R} f_{L,R} + h.c. + \frac{h}{2} (Z_{\mu} f_{L,R} f_{L,R} + h.c.) \]

\[ + \frac{h}{2} (W_{\mu} u_L \gamma^\mu e_L + h.c.) + g_{Z W} h W^{\mu \nu} W_{\mu \nu} + \kappa_{Z Z} h Z_{\mu} Z_{\nu} \]

\[ \Delta L_{A V} = i g_{CW} h \left[ g_{A A} (W_{\mu} W^{\nu} - W_{\mu} W^{\nu}) + \kappa h Z_{\mu} (W_{\mu} W^{\nu} - W_{\mu} W^{\nu}) \right] \]

\[ + i e \kappa_{h h} h W_{\mu} W_{\mu} A^{\mu \nu} + g_{A \gamma v e L} Z_{\mu} \]

\[ + g_{Z W} h W^{\mu \nu} W_{\mu \nu} + \kappa_{Z Z} h Z_{\mu} Z_{\nu}. \]

Bertuzzo, Grojean & RSG (in prep)
COUNTING

59 vertices

52 SM Predictions

35 D6 Predictions

12 D8 Predictions

SMEFT

7 SM input parameters

17 D6 operators

23 D8 operators
### $H^2$-operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_{H^2}$</td>
<td>$</td>
</tr>
<tr>
<td>$\mathcal{O}_{HD}$</td>
<td>$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$</td>
</tr>
<tr>
<td>$\mathcal{O}_6$</td>
<td>$\lambda</td>
</tr>
<tr>
<td>$\mathcal{O}_y$</td>
<td>$</td>
</tr>
<tr>
<td>$\mathcal{O}_f$</td>
<td>$i H^\dagger D_\mu H \bar{f} \gamma^\mu f$</td>
</tr>
<tr>
<td>$\mathcal{O}_L$</td>
<td>$i H^\dagger D_\mu H \bar{F} \gamma^\mu F$</td>
</tr>
<tr>
<td>$\mathcal{O}_L^{(3)}$</td>
<td>$i H^\dagger \sigma^a \bar{D}_\mu H \bar{F} \sigma^a \gamma^\mu F$</td>
</tr>
<tr>
<td>$\mathcal{O}_{BB}$</td>
<td>$g'^2</td>
</tr>
<tr>
<td>$\mathcal{O}_{WB}$</td>
<td>$g g' H^\dagger \sigma^a H W^a_{\mu \nu} B^{\mu \nu}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{WW}$</td>
<td>$g^2</td>
</tr>
<tr>
<td>$\mathcal{O}_{GG}$</td>
<td>$g_s^2</td>
</tr>
</tbody>
</table>

### $H^0$-operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_{3W}$</td>
<td>$\varepsilon_{abc} \frac{3!}{\lambda} W^a_{\mu \nu} W^b_{\mu \rho} W^c_{\nu \rho}$</td>
</tr>
</tbody>
</table>
COUNTING

SMEFT

- 59 vertices
- 52 SM Predictions
- 35 D6 Predictions
- 12 D8 Predictions
- 7 SM input parameters
- 17 D6 operators
- 23 D8 operators
35 Dependant couplings as a function of 17 best measured ‘observables’ called BSM Primaries

\[
\begin{align*}
\delta g^W_{\gamma} &= \frac{c_{\theta_W} (\delta g^Z_{\gamma} - \delta g^Z_{\gamma})}{\sqrt{2}} \\
\delta \kappa_{\gamma} &= \delta g^Z_{\gamma} - t_{\theta_W} \delta \kappa_{\gamma} \\
g^h_{\gamma f} &= \delta g^Z_{\gamma} - 2 \delta g^Z_{\gamma} (g^Z_{\gamma} c_{\theta_W} + eQ_{\gamma 2 e_W}) + 2 \delta \kappa_{\gamma} g^Y_{\gamma} \frac{g_W}{c^2_{\theta_W}} \\
g^h_{\gamma f} &= \sqrt{2} c_{\theta_W} (\delta g^Z_{\gamma} - \delta g^Z_{\gamma}) - 2 \delta g^Z_{\gamma} g^W_{\gamma} c_{\theta_W} \\
\kappa^W_{\gamma W} &= 5 \kappa_{\gamma} + \kappa_{Z \gamma} + 2 \kappa_{\gamma \gamma} \\
\delta g^Z_{\gamma Z} &= \delta g^Z_{\gamma} e^2 - \delta \kappa_{\gamma} g^Z_{\gamma} \\
\kappa^Z_{\gamma ZZ} &= \frac{\delta \kappa_{\gamma}}{2 c_{\theta_W}^2} + \frac{\kappa_{Z \gamma}}{2 c_{\theta_W}^2} + \kappa_{\gamma \gamma} \\
\kappa^Z_{W W} &= 5 \kappa_{\gamma} + \kappa_{Z \gamma} + 2 \kappa_{\gamma \gamma} \\
\kappa^Z_{Z Z} &= \frac{\delta \kappa_{\gamma}}{2 c_{\theta_W}^2} + \frac{\kappa_{Z \gamma}}{2 c_{\theta_W}^2} + \kappa_{\gamma \gamma} \\
\delta g^W_{h h 1} &= \frac{5 \delta g^W_{W W}}{4v} \\
\delta g^W_{h 1} &= \frac{5 \delta g^W_{V V}}{4v} \\
\delta g^W_{1 W} &= 2 c_{\theta_W} \delta g^Z_{1} \\
\delta g^W_{2 W} &= 2 c_{\theta_W} \delta g^Z_{1} \\
\delta g^Z_{1 Z} &= 2 \delta g^Z_{1} \\
\delta g^Z_{2 Z} &= 2 \delta g^Z_{1} \\
g^h_{2 1} &= \frac{-2 \kappa_{Z \gamma} g_{\theta_W}}{c_{\theta_W}^2} - \frac{2 \delta \kappa_{\gamma}}{c_{\theta_W}^2} - \frac{2 \kappa_{\gamma \gamma}}{c_{\theta_W}^2} \\
\kappa^h_{1} &= \frac{-2 \kappa_{Z \gamma}}{t_{\theta_W}} - \frac{2 \kappa_{\gamma \gamma}}{t_{\theta_W}} \\
\kappa^h_{2} &= \frac{-2 \delta \kappa_{\gamma}}{c_{\theta_W}^2} - \frac{2 \kappa_{Z \gamma}}{c_{\theta_W}^2} - \frac{2 \kappa_{\gamma \gamma}}{c_{\theta_W}^2}
\end{align*}
\]
<table>
<thead>
<tr>
<th>Higgs Physics (8)</th>
<th>Process</th>
<th>Vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h \rightarrow \gamma\gamma$, $h \rightarrow \gamma Z$, $h \rightarrow gg$</td>
<td>$hA_{\mu\nu}A^{\mu\nu}$, $hA_{\mu\nu}Z^{\mu\nu}$, $hG_{\mu\nu}G^{\mu\nu}$</td>
</tr>
<tr>
<td></td>
<td>$h \rightarrow VV$, $h \rightarrow f f$, $p p \rightarrow h^* \rightarrow h h$</td>
<td>$hW^{+\mu}W_\mu^-$, $h f f$, $h^3$</td>
</tr>
<tr>
<td>Z-pole(7)</td>
<td>$Z \rightarrow f f$</td>
<td>$Z_{\mu}f_{L,R}\gamma_{\mu}f_{L,R}$</td>
</tr>
<tr>
<td>(2 can be traded for $S,T$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triple Gauge</td>
<td>$ee \rightarrow WW$</td>
<td>$g_1^Z c_{\theta_w} Z^\mu \left( W^{+\nu} \hat{W}<em>{\mu\nu}^- - W^{-\nu} \hat{W}</em>{\mu\nu}^+ \right)$</td>
</tr>
<tr>
<td>Couplings(2)</td>
<td></td>
<td>$\kappa_{\gamma S_{\theta_w}} A^{\mu\nu} W_\mu^+ W_\nu^-$</td>
</tr>
</tbody>
</table>
Do these 17 best measurements make the rest of the 52-17=35 ‘observables’ irrelevant?
EXAMPLE OF D6 PREDICTION: \( h > V_{ff} \)

Slide Courtesy: F. Riva
D8 opens 23 new primaries liberates 23 observables!
### D8 Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^8$</td>
<td>$O_8 = H^8$</td>
</tr>
<tr>
<td>$D^8H^6$</td>
<td>$O_{D8} = H^8$</td>
</tr>
</tbody>
</table>

**$H^2D^2X^2$: 9**

- $O_{DHH1} = g^2D_{\mu}H^I D^\mu H^{\mu\nu}$
- $O_{DHW1} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu}$
- $O_{DHW2} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda}$
- $O_{DHW3} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW4} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW5} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW6} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW7} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW8} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$
- $O_{DHW9} = g^2D_{\mu}H^I D^\mu H^{\mu\nu} W_{\mu\lambda}^{\nu} W_{\nu\mu}^{\lambda} W_{\nu\mu}^{\lambda}$

**$X^2$: 10**

- $O_{DH1} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH2} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH3} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH4} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH5} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH6} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH7} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH8} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH9} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DH10} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$

**$JH^2DX$: 32**

- $O_{DP1} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP2} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP3} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP4} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP5} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP6} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP7} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP8} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP9} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$
- $O_{DP10} = g^2B_{\mu\nu}B^{\mu\nu} B_{\mu\rho}^{\rho}$

**$\phi^2DX^2$: 18**

- $O_{TP1} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP2} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP3} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP4} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP5} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP6} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP7} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP8} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP9} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
- $O_{TP10} = T_{\mu\nu}^{\rho\sigma} B_{\mu\nu}^{\rho\sigma}$
23 Dimension 8 operators with more than or equal to 4 Higgs doublets
### VIOLATION OF D6 PREDICTION/NEW D8 PRIMARY

<table>
<thead>
<tr>
<th>Pure D8 observable</th>
<th>D8 Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{2} (g_T^W - c_W^2) (\delta g_T^W - \delta g_T^F)$</td>
<td>$\frac{\sqrt{2}}{2} (c_H^W + 2 c_{HWH})$</td>
</tr>
<tr>
<td>$g_5$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\delta g_T^W - 2 c_W^2 \delta g_T^F$</td>
<td>$-\frac{\sqrt{2}}{2} (c_H^W + 2 c_{HWH} + c_{DH2} + c_{DH3})$</td>
</tr>
<tr>
<td>$\delta g_T^Z - 2 \delta g_T^F$</td>
<td>$\frac{\sqrt{2}}{4} (2 c_{HWH} + 4 c_{HWH} - c_{DH1} - 2 c_{DH2} + 2 c_{DH3})$</td>
</tr>
<tr>
<td>$\delta g_T^{WW} - 2 c_W^2 \delta g_T^F$</td>
<td>$\frac{\sqrt{2}}{4} c_{DH2}$</td>
</tr>
<tr>
<td>$\delta g_T^{ZZ} - 2 \delta g_T^F$</td>
<td>$-\frac{\sqrt{2}}{4} c_{DH1}$</td>
</tr>
<tr>
<td>$h_T^{ZZ}$</td>
<td>$\frac{\sqrt{2}}{16} (c_{DH2} + 4 c_{DH3})$</td>
</tr>
<tr>
<td>$\delta g_T^F \equiv \delta g_T^F (e^2 - \delta g_T^F)$</td>
<td>$\frac{\sqrt{2}}{16} (6 c_{BB} - 2 c_{HWH} - 8 c_{HWH} + (c_h^3 + 2 (c_H^W + 2 c_{HWH})$</td>
</tr>
<tr>
<td>$\kappa_{WW} - \delta \kappa_T - c_{WW} \kappa_{ZZ} - \kappa_{YY}$</td>
<td>$-\frac{\sqrt{2}}{4} (c_{BB} + c_{WW} - 2 c_{HWW} - c_{HWW})$</td>
</tr>
<tr>
<td>$\kappa_{ZZ} - \frac{1}{2} \delta \kappa_T - c_{WW} \kappa_{ZZ} - \kappa_{YY}$</td>
<td>$\frac{\sqrt{2}}{4} (c_{BB} - 5 c_{WW} - 10 c_{HWW} - 2 c_{HWW} - c_{HWW})$</td>
</tr>
<tr>
<td>$g_{WW}^F \equiv \frac{2 c_{BB}}{2 c_{BB} (\delta g_T^F - \delta g_T^F - c_{WW} \delta g_T^F)}$</td>
<td>$\frac{\sqrt{2}}{4} c_{DH2}$</td>
</tr>
<tr>
<td>$g_{WW}^F \equiv \frac{2 c_{BB}}{(1 - 16 c_{WW} + 5 c_{WW} + 2 c_{HWW} + c_{HWW}) (\delta g_T^F - \delta g_T^F - c_{WW} \delta g_T^F)}$</td>
<td>$\frac{\sqrt{2}}{4} c_{DH1}$</td>
</tr>
<tr>
<td>$g_{BB}^F \equiv \frac{2 c_{BB}}{16 c_{WW}}$</td>
<td>$\frac{\sqrt{2}}{4} c_{DH3}$</td>
</tr>
<tr>
<td>$g_{BB}^F \equiv \frac{2 c_{BB}}{(10 c_{WW} - 18 c_{HWW} - 2 c_{HWW} + c_{HWW}) (\delta g_T^F - \delta g_T^F - c_{WW} \delta g_T^F)}$</td>
<td>$\frac{\sqrt{2}}{4} (c_{BB} + c_{WW} - 3 c_{HWH} + 8 c_{HWH} - 2 c_{HWH})$</td>
</tr>
</tbody>
</table>

---

Bertuzzo, Grojean & RSG (in prep)
COUNTING

59 vertices

52 SM Predictions

35 D6 Predictions

12 D8 Predictions

7 SM input parameters

17 D6 operators

23 D8 operators
12 D8 PREDICTIONS

\[
g^5 = 0 \\
\delta^8 \kappa_{WW} - c_{\theta_w}^2 \delta^8 \kappa_{ZZ} - 2c_{\theta_w}^2 \delta^8 \kappa_Z = 0 \\
\frac{\delta^8 g_{Wud}^h}{\sqrt{2}} - \frac{c_{\theta_w}(\delta^8 g_{Zu_1}^h - \delta^8 g_{Zd_1}^h)}{\sqrt{2}} - (4\delta^8 g_{ud}^W - \sqrt{2}g_{\theta_w}^2 \delta^8 \kappa_Z) = 0 \\
\frac{\delta^8 g_{W\nu e}^h}{\sqrt{2}} - \frac{c_{\theta_w}(\delta^8 g_{Z\nu_1}^h - \delta^8 g_{Z\nu_2}^h)}{\sqrt{2}} - (4\delta^8 g_{\nu e}^W - \sqrt{2}g_{\theta_w}^2 \delta^8 \kappa_Z) = 0.
\]

\[
\delta^8 g_{Q_2}^{W W} - \delta^8 g_{Q_1}^{W W} - 2c_{\theta_w}^2 (\delta^8 g_{Q_2}^{ZZ} - \delta^8 g_{Q_1}^{ZZ}) = 0 \\
h_Q^{ZZ} + c_{\theta_w}^4 (\delta^8 g_{Q_2}^{ZZ} - \delta^8 g_{Q_1}^{ZZ}) = 0 \\
g_{hh_2}^W - 4(\delta^8 g_{Q_1}^{W W} - 2c_{\theta_w}^2 \delta^8 \kappa_Z) = 0 \\
g_{h_3}^W + 4(\delta^8 g_{Q_1}^{W W} - 2c_{\theta_w}^2 \delta^8 \kappa_Z + c_{\theta_w}^4 (\delta^8 g_{Q_2}^{ZZ} - \delta^8 g_{Q_1}^{ZZ})) = 0 \\
g_{hh_2}^W - 4c_{\theta_w}^4 \delta^8 \kappa_Z^Z = 0 \\
g_{h_3}^W + 4c_{\theta_w}^4 \delta^8 \kappa_Z^Z = 0 \\
\delta^8 \kappa_{h^Z} - \frac{1}{3} \left( \frac{9\delta^8 g_{hV}^h v - \delta^8 g_{hZ}^{h^2}}{g^2} + 3\delta^8 g_{hZ}^1 - 3s_{\theta_w}^2 (2\delta^8 g_{Q_1}^{W W} + \delta^8 \kappa_{WW}^h + g_{hZ}^h) \\
+ 6\delta^8 \kappa_Z + s_{\theta_w}^2 (32\delta^8 \kappa_Z + 15\delta^8 \kappa_{ZZ} + 6\delta^8 g_{Q_1}^{ZZ} c_{\theta_w}^2) \right) = 0 \\
\delta^8 \kappa_{h^\gamma} + \frac{1}{3s_{\theta_w}^2} \left( \frac{9\delta^8 g_{hV}^{h^2} v - \delta^8 g_{hZ}^{h^2} c_{\theta_w}^2}{g^2} + 3\delta^8 g_{hZ}^{h^2} - 3s_{\theta_w}^2 (2\delta^8 g_{Q_1}^{W W} + \delta^8 \kappa_{WW}^h + g_{hZ}^h) \\
- 6\delta^8 \kappa_Z c_{\theta_w}^4 + s_{\theta_w}^2 c_{\theta_w}^2 (26\delta^8 \kappa_Z + 15\delta^8 \kappa_{ZZ} + 6\delta^8 g_{Q_1}^{ZZ} c_{\theta_w}^2) \right) = 0
\]
OTHER D8 OPERATORS

85 Dimension 8 operators with less than 4 Higgs doublets don't contribute to D4 vertices
PHENOMENOLOGICAL EXAMPLES

(1) Shape of Higgs potential
(2) Transverse Gauge boson couplings
(3) High energy primaries
EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

Higgs potential:

\[
V(h) = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4 \\
\Delta V(h) = \delta_3 v h^3 + \frac{\delta_4}{4} h^4
\]

2 D4 Predictions:

\[
\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}
\]

D6 opens \(\delta_3\) (due to operator \(H^6\)) but one Prediction:

\[
\delta_4 = 6 \delta_3, \quad \text{(SMEFT at dim = 6)}
\]
EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

• D8 breaks D6 Prediction (due to operator $H^8$):
  \[ \delta_4 - 6\delta_3 \sim c_8 \frac{v^4}{\Lambda^4} \]

• Should not deform only one coupling but both simultaneously

• Deviations from this line probe D8 effect
EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

- D8 breaks D6 Prediction (due to operator $H^8$):
  $$\delta_4-6\delta_3 \sim c_8 \frac{v^4}{\Lambda^4}$$

- Should not deform only one coupling but both simultaneously

- Deviations from this line probe D8 effect

Chiesaa, Maltoni, Mantani, Melee, Piccinini & Zhao (2020)
EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

$\delta \kappaZZ W^+ W^- A^{\mu\nu}$

$k_{ZZ} \frac{h}{2v} Z_{\mu\nu} Z_{\mu\nu} + \kappa_{\gamma\gamma} \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}$

D6 Prediction:

$k_{ZZ} = \frac{1}{c_{\theta_W}^2} \delta \kappa_{\gamma} + \frac{c_{2\theta_W}}{c_{\theta_W} s_{\theta_W}} \kappa_{Z\gamma} + \kappa_{\gamma\gamma}$

- **Per-cent level** constraint at HL LHC in WW production
  (Grojean, Montul & Riembau 2018)
- **Per-mille level** constraint from Higgs decays

- $k_{ZZ}$ is **already constrained at percent level** due to this correlation. Is there any point in trying to measure this separately?
EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

- $κ_{ZZ}$ is already constrained at percent level due to this correlation. Is there any point in trying to measure this separately?

YES!

- In HEFT this correlation broken at $O(1)$, i.e. there is no correlation.
- In SMEFT this correlation broken at $O(v^2/Λ^2)$ (that is at D8).
Using our technique and combining with $h > ZZ$ rate $\kappa_{ZZ}$ can be measured at 1% level at HL-LHC

See Shankha’s Talk

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS
EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

In HEFT this correlation broken at $O(1)$, i.e. there is no correlation. We need to measure LHS and RHS at same level so Banerjee et al bound essential.

\[ \kappa_{ZZ} = \frac{1}{c_{\theta W}^2} \delta \kappa_\gamma + \frac{c_{2\theta W}}{c_{\theta W} s_{\theta W}} \kappa_{Z\gamma} + \kappa_{\gamma\gamma} \]
EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

First 2 terms: $O(v^2/\Lambda^2) = 10\%$

$O(v^4/\Lambda^4) = 1\%$

\[
\kappa_{ZZ} - \frac{1}{c_{\theta W}^2} \delta\kappa_{\gamma} - \frac{c_{\theta W}^2 s_{\theta W}}{c_{\theta W}} \kappa_{Z\gamma} - \kappa_{\gamma\gamma} = -\frac{g^2 v^4}{4 c_{\theta W}^2 \Lambda^4} (c_{\theta B} + c_{\theta W} - 2 c_{H^2 W B'} + c_{HW}^3 + c_{HW H})
\]

- In SMEFT this correlation broken at $O(v^4/\Lambda^4)$
- Maximum size of each term on LHS: present bounds $<10\% = O(v^2/\Lambda^2)$
- $O(v^4/\Lambda^4) = 1\% = \text{Required future sensitivity}$ for measuring the full combination.
- Again Banerjee et al result can be used to measure this D8 effect.
EXAMPLE 3: HIGH ENERGY PRIMARIES

- Can be understood by Goldstone Boson Equivalence

- D6 Prediction for WZ—Wh case:

\[ g_{WF}^h = \sqrt{2}c_{\theta W} (\delta g_f^Z - \delta g_{f'}^Z) - 2\delta g_1^Z g_f^W c_{\theta W}^2 \]

- D6 prediction

- Z-pole, TGCs

- \( hVff \)

Franceschini, Panico, Pomarol, Riva & Wulzer (2017)
EXAMPLE 3: HIGH ENERGY PRIMARIES

D6 prediction broken at D8 level:

\[
g^h_{WF} - \sqrt{2}c_{\theta W} (\delta g^Z_f - \delta g^Z_{f'} - c_{\theta W} \delta g^Z_1) = -\frac{g^2v^4}{4c^2_{\theta W}\Lambda^4} (c_{\theta B} + c_{\theta W} - 2c_{H^2 WB'} + c^3_{H W} + c_{H W H})
\]

First and last term can be 10 % = \(O(v^2/\Lambda^2)\)

\(O(v^4/\Lambda^4) = 1\%\)

Future precision per mille level

so this D8 effect may be easily seen

Banerjee, RSG, Reines, Seth & Spannowsky (2019)
Bishara, Englert, Grojean, Montull, Panico & Rossia (2020)
CONCLUSIONS

- At any order in SMEFT more observables than operators. This leads to predictions of observables as a function of others.

- Predictions broken as we go to higher order in EFT expansions for e.g. D6 to D8, i.e. order by order in $v^2/\Lambda^2$.

- More and more observables liberated. Our work motivates more measurements.

- Probing these violations of predictions only way to probe a certain class of D8 operators.

- Predictions broken also in HEFT but all at once.
OTHER D8 OPERATORS

- These give rise to vertices with more derivatives mostly not present in D6 lagrangian. Can give rise to new final states (neutral diboson production), new kinematic signatures. For e.g. they can contribute to new helicity amplitudes, faster energy growth.

- The strategy required to probe these is very different as a careful differential study needs to be carried out to truly isolate their effect which is beyond the scope of our work.