Constraining certain EFT coefficients using boosted Higgs-strahlung

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Based on

(with R. S. Gupta, C. Englert and M. Spannowsky)

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(with R. S. Gupta, J. Y. Reiness and M. Spannowsky)
Plan of my talk

- Motivating Higgs Effective Field Theory
- LHC versus LEP
- $hZ_L f \bar{f}$ interaction: Higgs-Strahlung at the HL-LHC
- $hZ_T Z_T$ interaction: Higgs-Strahlung at the HL-LHC
- Summary and Conclusions
SMEFT motivation

- Many reasons to go beyond the SM, *viz.* gauge hierarchy, neutrino mass, dark matter, baryon asymmetry etc.
- Plethora of BSM theories to address these issues
- Two phenomenological approaches:
  - *Model dependent:* study the signatures of each model individually
  - *Model independent:* low energy effective theory formalism – analogous to Fermi’s theory of beta decay
- The SM here is a low energy effective theory valid below a cut-off scale $\Lambda$
- A bigger theory (either weakly or strongly coupled) is assumed to supersede the SM above the scale $\Lambda$
- At the perturbative level, all heavy ($>\Lambda$) DOF are decoupled from the low energy theory (*Appelquist-Carazzone theorem*)
- Appearance of HD operators in the effective Lagrangian valid below $\Lambda$

\[ \mathcal{L} = \mathcal{L}_{SM}^{d=4} + \sum_{d \geq 5} \sum_{i} \frac{f_i}{\Lambda^{d-4}} \mathcal{O}_i^{d} \]
SMEFT motivation

- Precisely measuring the Higgs couplings → one of the most important LHC goals [See C. Zhang’s slides for a detailed discussion on Higgs EFT]
- Indirect constraints can constrain much higher scales S, T parameters being prime examples
- Q: Can LHC compete with LEP in constraining precision physics? Can LHC provide new information?
  A: From EFT correlated variables, LEP already constrained certain anomalous Higgs couplings → Z-pole measurements, TGCs
  Going to higher energies in LHC is the only way to obtain new information
- EFT techniques show that many Higgs deformations aren’t independent from cTGCs and EW precision which were already constrained at LEP → Same operators affect TGCs and Higgs deformations
Classification of anomalous Higgs interactions

- The following terms are **not constrained** by LEP. First time probed at the LHC
  
  $$\mathcal{L}_h^{\text{primary}} = g_{VV}^h h \left[ W^+ \mu W^- + \frac{1}{2c_w^2} Z^\mu Z_\mu \right] + g_3 h^3 + g_{ff}^h \left( h f_L f_R + \text{h.c.} \right)$$

  $$+ \ \kappa_{GG} \frac{h}{v} G^{\mu \nu} G_{\mu \nu}^A + \kappa_{\gamma \gamma} \frac{h}{v} A^{\mu \nu} A_{\mu \nu} + \kappa_{Z \gamma} t_\theta W h A^{\mu \nu} Z_{\mu \nu} ,$$

- In contrast, the following interactions were **constrained** by LEP

  $$\Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_w^2} h Z^\mu Z_\mu + g_{Zf}^h \frac{h}{2v} \left( Z_\mu J_\mu^N + \text{h.c.} \right) + g_{Wf}^h \frac{h}{v} \left( W^+ \mu J_\mu^C + \text{h.c.} \right)$$

  $$+ \ \kappa_{WW} \frac{h}{v} W^+ \mu W^- + \kappa_{ZZ} \frac{h}{v} Z^\mu Z_\mu ,$$
Couplings constrained by LEP

- The coefficients of the following

\[
\Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} h Z^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} (Z_\mu J^\mu_N + h.c.) + g_{Wff'}^h \frac{h}{v} (W_\mu^+ J^\mu_C + h.c.) \\
+ \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu},
\]

can be written as

\[
\delta g_{ZZ}^h = \delta g_1^Z e^2 - \delta \kappa_\gamma \frac{e^2}{c_{\theta_W}^2} \\
q_{Zff}^h = 2\delta g_{ff}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ_f s_{2\theta_W}) + 2\delta \kappa_\gamma Y_f \frac{e^2 s_{\theta_W}}{c_{\theta_W}^3}, \\
\kappa_{ZZ} = \frac{1}{2c_{\theta_W}^2} (\delta \kappa_\gamma + \kappa_{Z\gamma} c_{2\theta_W} + 2\kappa_{\gamma\gamma} c_{\theta_W}^2), \\
\kappa_{WW} = \delta \kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma},
\]

[Gupta, Pomarol, Riva, 2014]
Proof of principle

- If one of these predictions is not confirmed then either
- Our Higgs is not a part of the doublet
- $\Lambda$ may not be very high and D8 operators need to be seriously considered
Sensitivity at high-energy colliders

We have seen that there are a fewer number of $SU(2)_L \times U(1)_Y$ invariant HD operators than the number of pseudo-observables.

Hence, correlations between LEP and LHC measurements can be exploited.

LEP measurements of $Z$-pole measurements and anomalous TGCs inform the Higgs observables at the LHC.

Apart from the 8 “Higgs primaries“, all other Higgs observables can be already constrained by $Z$-pole and diboson measurements.

For processes that grow with energy

$$\frac{\delta \sigma(\hat{s})}{\sigma_{SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2},$$

one can measure the coupling deviation to per-mille level if the fractional cross-section is $\mathcal{O}(30\%)$ for $\sqrt{\hat{s}} \sim 1 \text{ TeV}$.
Higgs-Strahlung at the LHC ($hZZ^*/hZ\bar{f}f$)

- The leading effect comes from contact interaction at high energies.
- The energy growth occurs because there is no propagator.

$$\Delta \mathcal{L}_6^{hZ\bar{f}f} \supset \delta \hat{g}_{ZZ}^h \frac{2m_Z^2}{v} h \frac{Z^\mu Z^\mu}{2} + \sum_f g_{Zf}^h \frac{h}{v} Z^\mu \bar{f} \gamma^\mu f$$

$$+ \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

- There are also contributions from

$$\kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \tilde{\kappa}_{Z\gamma} \frac{h}{v} A^{\mu\nu} \tilde{Z}_{\mu\nu}$$

[SB, Englert, Gupta, Spannowsky, 2018], [SB, Gupta, Reiness, Spannowsky, 2019]
Higgs-Strahlung at the LHC ($hZZ^*/hZ\bar{f}f$)

Note that in fact two different frames of reference are represented: the CoM frame of the $Zh$ system (in which $\varphi$ and $\Theta$ are defined) and the CoM frame of the $Z$ (in which $\theta$ is defined). We define the Cartesian axes $\{x, y, z\}$ in the $Zh$ centre-of-mass frame, with $z$ identified as the direction of the $Z$-boson; $y$ identified as the normal to the plane of the $Z$-boson and the beam axis; finally $x$ is defined such that it completes the right-handed set.
Higgs-Strahlung at the LHC \((hZZ^*/hZ\bar{f}f)\)

- For a \(2 \rightarrow 2\) process \(f(\sigma)\bar{f}(\sigma) \rightarrow Zh\), the helicity amplitudes are given by

\[
\mathcal{M}_{\lambda=\pm} = \sigma \frac{1 + \sigma \lambda \cos \Theta}{\sqrt{2}} \frac{g g_f^Z}{c_{\theta_W}} \frac{m_Z}{\sqrt{\hat{s}}} \left[ 1 + \left( \frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} - i\lambda \bar{\kappa}_{ZZ} \right) \frac{\hat{s}}{2m_Z^2} \right]
\]

\[
\mathcal{M}_{\lambda=0} = -\sin \Theta \frac{g g_f^Z}{2c_{\theta_W}} \left[ 1 + \delta \hat{g}_{ZZ}^h + 2\kappa_{ZZ} + \frac{g_{Zf}^h}{g_f^Z} \left( -\frac{1}{2} + \frac{\hat{s}}{2m_Z^2} \right) \right]
\]

- \(\lambda = \pm 1\) and \(\sigma = \pm 1\) are, respectively, the helicities of the \(Z\)-boson and initial-state fermions, \(g_f^Z = g(T_f^3 - Q_f s_{\theta_W}^2)/c_{\theta_W}\)

- Leading SM is longitudinal \((\lambda = 0)\)

- Leading effect of \(\kappa_{ZZ}, \bar{\kappa}_{ZZ}\) is in the transverse-longitudinal (LT) interference

- LT term vanishes if we aren’t careful
Precision measurement: LHC vs LEP (Contact term)

\[ M(f f \rightarrow Z_L h) = g_f^Z q \cdot J_f 2m_Z \left[ 1 + \frac{g_{Zff}^h}{g_f^Z} \frac{s}{2m_Z^2} \right] \]

\[ g_{ZdLdL}^h = \frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 - s_{\theta_W}^2) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (s - \delta \kappa \gamma - Y) \right) \]

- LEP constrains \( \delta g_1^Z \) and \( \delta \kappa \gamma \) at 5-10% and \( \hat{S} \) at the per-mille level
- In order to match LEP sensitivity, LHC has to measure cross-section deviations at \( \sim 30\% \) precision
$pp \to ZH$ at high energies

- We study the impact of constraining TGC couplings at higher energies
- We study the channel $pp \to ZH \to \ell^+\ell^- b\bar{b}$
- The backgrounds are SM $pp \to ZH, Zb\bar{b}, t\bar{t}$ and the fake $pp \to Zjj$ ($j \to b$ fake rate taken as 2%)
- Major background $Zb\bar{b}$ ($b$-tagging efficiency taken to be 70%)
- Boosted substructure analysis with fat-jets of $R = 1.2$ used

![Graph showing cuts-off in $M_{Zh}$ (GeV) vs. number of events]

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$Zb\bar{b}$</th>
<th>$Zh$ (SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least 1 fat jet with 2 $B$-mesons with $p_T &gt; 15$ GeV</td>
<td>0.23</td>
<td>0.41</td>
</tr>
<tr>
<td>2 OSSF isolated leptons</td>
<td>0.41</td>
<td>0.50</td>
</tr>
<tr>
<td>80 GeV &lt; $M_{\ell\ell}$ &lt; 100 GeV, $p_T,\ell\ell &gt; 160$ GeV, $\Delta R_{\ell\ell} &gt; 0.2$</td>
<td>0.83</td>
<td>0.89</td>
</tr>
<tr>
<td>At least 1 fat jet with 2 $B$-meson tracks with $p_T &gt; 110$ GeV</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>2 Mass drop subjets and $\geq 2$ filtered subjets</td>
<td>0.88</td>
<td>0.92</td>
</tr>
<tr>
<td>2 $b$-tagged subjets</td>
<td>0.38</td>
<td>0.41</td>
</tr>
<tr>
<td>115 GeV &lt; $m_h &lt; 135$ GeV</td>
<td>0.15</td>
<td>0.51</td>
</tr>
<tr>
<td>$\Delta R(b_i, \ell_j) &gt; 0.4$, $\not{E}_T &lt; 30$ GeV, $</td>
<td>y_h</td>
<td>&lt; 2.5$, $p_{T,h,Z}$ &gt; 200 GeV</td>
</tr>
</tbody>
</table>

[SB, Englert, Gupta, Spannowsky, 2018]
Next we perform a two-parameter $\chi^2$-fit (at 300 fb$^{-1}$) to find the allowed region in the $\delta g_1^Z - (\delta \kappa_\gamma - \hat{S})$.

Blue dashed line $\rightarrow$ direction of accidental cancellation of interference term; Gray region: LEP exclusion; pink band: exclusion from WZ [Franceschini, Panico, Pomarol, Riva and Wulzer, 2017]; Blue region: exclusion from ZH Dark (light) shade represents bounds at 3 ab$^{-1}$ (300 fb$^{-1}$) luminosity; Green region: Combined bound from Zh and WZ [SB, Englert, Gupta, Spannowsky, 2018].
Bounds on Pseudo-observables at HL-LHC

- Our bounds are derived by considering one parameter at a time and upon considering only interference (at 95% CL). The 68% CL bounds are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Our Projection</th>
<th>LEP Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{uL}^Z$</td>
<td>$\pm 0.002 \pm 0.0007$</td>
<td>$-0.0026 \pm 0.0016$</td>
</tr>
<tr>
<td>$\delta g_{dL}^Z$</td>
<td>$\pm 0.003 \pm 0.001$</td>
<td>$0.0023 \pm 0.001$</td>
</tr>
<tr>
<td>$\delta g_{uR}^Z$</td>
<td>$\pm 0.005 \pm 0.001$</td>
<td>$-0.0036 \pm 0.0035$</td>
</tr>
<tr>
<td>$\delta g_{dR}^Z$</td>
<td>$\pm 0.016 \pm 0.005$</td>
<td>$0.016 \pm 0.0052$</td>
</tr>
<tr>
<td>$\delta g_1^Z$</td>
<td>$\pm 0.005 \pm 0.001$</td>
<td>$0.009_{-0.042}^{+0.043}$</td>
</tr>
<tr>
<td>$\delta \kappa$</td>
<td>$\pm 0.032 \pm 0.009$</td>
<td>$0.016_{-0.096}^{+0.085}$</td>
</tr>
<tr>
<td>$\hat{S}$</td>
<td>$\pm 0.032 \pm 0.009$</td>
<td>$0.0004 \pm 0.0007$</td>
</tr>
<tr>
<td>$W$</td>
<td>$\pm 0.003 \pm 0.001$</td>
<td>$0.0000 \pm 0.0006$</td>
</tr>
<tr>
<td>$Y$</td>
<td>$\pm 0.032 \pm 0.009$</td>
<td>$0.0003 \pm 0.0006$</td>
</tr>
</tbody>
</table>

[SB, Englert, Gupta, Spannowsky, 2018]
Constraining the LT terms

- The differential cross-section for the process $pp \to Z(\ell^+ \ell^-) h(b\bar{b})$ is a differential in four variables, viz., $\frac{d\sigma}{dE d\Theta d\theta d\varphi}$
- The amplitude at the decay level can be written as

$$A_h(\hat{s}, \Theta, \hat{\theta}, \hat{\phi}) = \frac{-i\sqrt{2}g_{Z\ell}}{\Gamma_Z} \sum_{\lambda} M_\lambda^1(\hat{s}, \Theta) d_{\lambda,1}^{J=1}(\hat{\theta}) e^{i\lambda \hat{\phi}},$$

- $d_{\lambda,1}^{J=1}(\hat{\theta})$ are the Wigner functions, $\Gamma_Z$ is the $Z$-width and $g_{Z\ell}^Z = g(T_3^\ell - Q_\ell s_{\theta_W}^2) / c_{\theta_W}$
- $\hat{\phi} \to$ azimuthal angle of positive helicity lepton, $\hat{\theta} \to$ its polar angle in $Z$-rest frame
- Polarisation of lepton is experimentally not accessible

[SB, Gupta, Reiness, Spannowsky, 2019]
Constraining the LT terms

- We sum over lepton polarisations and express the analogous angles \((\theta, \varphi)\) for the positively-charged lepton
  \[
  \sum_{L,R} |A(\hat{s}, \Theta, \theta, \varphi)|^2 = \alpha_L |A_h(\hat{s}, \Theta, \theta, \varphi)|^2 + \alpha_R |A_h(\hat{s}, \Theta, \pi - \theta, \pi + \varphi)|^2
  \]

- \(\alpha_{L,R} = (g_{ZL,R}^Z)^2 / [(g_{L}^Z)^2 + (g_{R}^Z)^2]\) \(\to\) fraction of \(Z \to \ell^+ \ell^-\) decays to leptons with left-handed (right-handed) chiralities \(\epsilon_{LR} = \alpha_L - \alpha_R \approx 0.16\)

- For left-handed chiralities, positive-helicity lepton \(\to\) positive-charged lepton
- For right-handed chiralities, positive-helicity lepton \(\to\) negative-charged lepton \(\to\) \((\hat{\theta}, \hat{\varphi}) \to (\pi - \theta, \pi + \varphi)\)

\[
\sum_{L,R} |A(\hat{s}, \Theta, \theta, \varphi)|^2 = a_{LL} \sin^2 \Theta \sin^2 \theta + a_{TT}^1 \cos \Theta \cos \theta \\
+ a_{TT}^2 (1 + \cos^2 \Theta)(1 + \cos^2 \theta) + \cos \varphi \sin \Theta \sin \theta \\
\times (a_{LT}^1 + a_{LT}^2 \cos \theta \cos \Theta) + \sin \varphi \sin \Theta \sin \theta \\
\times (\tilde{a}_{LT}^1 + \tilde{a}_{LT}^2 \cos \theta \cos \Theta) + a_{TT'} \cos 2\varphi \sin^2 \Theta \sin^2 \theta \\
+ \tilde{a}_{TT'} \sin 2\varphi \sin^2 \Theta \sin^2 \theta
\]
Constraining the LT terms

- The parametrically-largest contribution is to the LT interference terms

\[
\frac{a_{LT}^2}{4} \cos \varphi \sin 2\theta \sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4} \sin \varphi \sin 2\theta \sin 2\Theta
\]

- These terms vanish on integration of any angle

- Q: How to probe $\kappa_{ZZ}$ and $\tilde{\kappa}_{ZZ}$?
  A: Flip sign in regions to maintain positive $\sin 2\theta \sin 2\Theta$

- Expect $\cos \varphi$ distribution for CP-even and $\sin \varphi$ distribution for CP-odd

[SB, Gupta, Reiness, Spannowsky, 2019]
Constraining the LT terms

\[ \varphi \text{ Filtered Distribution} \]

- Blue line: CP Even
- Red line: CP Odd

\[ \omega \]

\[ \varphi \]

Shankha Banerjee (IPPP, Durham)

Higgs Hunting 2019, Orsay-Paris
Constraining the LT terms

- Perform $\chi^2$ tests
- Look at high $M_{Zh}$ range to constrain $g^h_{Zf}$
- Look at low $M_{Zh}$ range to constrain $\delta \hat{g}_{ZZ} \rightarrow$ Total rate
- Split into bins across all three angles ($\varphi, \theta, \Theta$) to resurrect interference LT terms
- Use constraint on $g^h_{Zf}$, $\delta \hat{g}_{ZZ}$ and the aforementioned split to constrain $\kappa_{ZZ}$ and $\tilde{\kappa}_{ZZ}$
Constraining the LT terms

For an integrated luminosity of $3 \text{ ab}^{-1}$, we obtain

$$-0.03 < \kappa_{ZZ} < 0.03$$
$$-0.04 < \tilde{\kappa}_{ZZ} < 0.04$$

[SB, Gupta, Reiness, Spannowsky, 2019]
Summary and conclusions

- LHC can thus compete with LEP and can be considered a good precision machine at the moment.
- EFT’s essence shows that many anomalous Higgs couplings were already constrained by LEP through $Z$-pole and di-boson measurements.
- It is essential to go to higher energies and luminosities in order to compete with LEP’s precision.
- The full $hZZ$ tensor structure can be disentangled by using fully differential information.
- $ZH$, $WH$, $WW$ and $WZ$ are important channels to disentangle various directions in the EFT space. They are intrinsically correlated.
- Orders of magnitude over LEP seen at HL-LHC and FCC-hh studies.
- Combining FCC-ee and FCC-he will be very important.
HD operators

- Higher-dimensional Operators: invariant under SM gauge group
- $d = 5$: Unique operator → Majorana mass to the neutrinos: $\frac{1}{\Lambda} (\Phi^\dagger L)^T C (\Phi^\dagger L)$
- $d = 6$: $59 = 15$ (bosonic) + 19 (single fermionic) + 25 (four fermion) independent $B$-conserving operators. Lowest dimension (after $d = 4$) which induces $HXY, HXYZ$ interactions, charged TGCs [W. Buchmuller and D. Wyler; B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek; K. Hagiwara, D. Zeppenfeld et. al., Azatov, et. al., Falkowski, et. al.]
- $d = 7$: Such operators appear in Higgs portal dark matter models
- $d = 8$: Lowest dimension inducing neutral TGC interactions
There are only **18 independent operators** from which the aforementioned vertices ensue.

\[
\begin{align*}
\mathcal{O}_H &= \frac{1}{2} (\partial^\mu |H|^2)^2 \\
\mathcal{O}_T &= \frac{1}{2} \left( H^\dagger \bar{D}_\mu H \right)^2 \\
\mathcal{O}_6 &= \lambda |H|^6 \\
\mathcal{O}_W &= \frac{ig}{2} \left( H^\dagger \sigma^a \bar{D}^\mu H \right) D^\nu W^a_{\mu\nu} \\
\mathcal{O}_B &= \frac{ig'}{2} \left( H^\dagger \bar{D}^\mu H \right) \partial^\nu B_{\mu\nu} \\
\mathcal{O}_{BB} &= g^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu} \\
\mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \\
\mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
\mathcal{O}_{3W} &= \frac{1}{3!} g \epsilon_{abc} W^a_{\mu} W^b_{\nu\rho} W^c_{\rho\mu}
\end{align*}
\]
Higgs anomalous couplings: Dimension 6 effects

\[ \mathcal{L}_{h}^{\text{primary}} = g_{VV}^h h \left[ W^+\mu W^-_\mu + \frac{1}{2 c^2_{\theta_W}} Z^\mu Z_\mu \right] + g_{3h} h^3 + g_{ff}^h (h \bar{f}_L f_R + h.c.) + \kappa_{GG} \frac{h}{v} G^A_{\mu\nu} G_{\mu\nu}^A + \kappa_{\gamma\gamma} \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma t} \theta_W \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}, \]

\[ \Delta \mathcal{L}_h = \frac{\delta g_{ZZ}^h}{2 c^2_{\theta_W}} \frac{v}{h} Z^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} \left( Z_\mu J_{N}^\mu + h.c. \right) + g_{Wff}^h \frac{h}{v} \left( W^{+\mu} J_{C}^\mu + h.c. \right) + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}, \]

[Pomarol, 2014]

- Higgs interactions were directly measured for the first time at the LHC
Following are some of the Higgs observables (assuming flavour universality)

\[ hW^+_{\mu\nu} W^{-\mu\nu} \]
\[ hZ_{\mu\nu} Z^{\mu\nu}, \ hA_{\mu\nu} A^{\mu\nu}, \ hA_{\mu\nu} Z^{\mu\nu}, \ hG_{\mu\nu} G^{\mu\nu} \]
\[ hf\bar{f}, \ h^2 f\bar{f} \]
\[ hW^+_{\mu} W^{-\mu} \]
\[ h^3 \]
\[ hZ_{\mu} f_{L,R} \gamma^{\mu} f_{L,R} \]

These anomalous Higgs couplings are first probed at the LHC
Electroweak Pseudo-Observables

- Following are the 9 EW precision observables (assuming flavour universality)
  \[ Z_\mu \bar{f}_{L,R} \gamma^{\mu} f_{L,R} \ W_{\mu}^+ \bar{u}_L \gamma^{\mu} d_R \]
  - These couplings were measured very precisely by the $Z/W$-pole measurements through the $Z/W$ decays

- Following are the 3 TGCs which were measured by the $e^+e^- \rightarrow W^+W^-$ channel at LEP
  \[
  g_1^Z c_{\theta_w} Z^{\mu} ( W^{+\nu} \hat{W}^{\mu\nu}_{\mu\nu} - W^{-\nu} \hat{W}^{\mu+}_{\mu\nu} )
  \]
  \[
  \kappa_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^+_{\mu} W^-_{\nu}
  \]
  \[
  \lambda_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^-_{\mu} W^+_{\nu}
  \]

- Finally, following are the QGCs
  \[
  Z^{\mu} Z^{\nu} W^-_{\mu} W^+_{\nu}
  \]
  \[
  W^{-\mu} W^{+\nu} W^-_{\mu} W^+_{\nu}
  \]
Effective Field Theory: The operators at play

- There are **18 independent operators** and many more pseudo-observables.

- This implies correlations between the various pseudo-observables.

- Besides, the following operators can not be constrained by LEP:
  \[
  |H|^2 G_{\mu\nu} G^{\mu\nu}, \quad |H|^2 B_{\mu\nu} B^{\mu\nu}, \quad |H|^2 W^a_{\mu\nu} W^{a,\mu\nu},
  \]
  \[
  |H|^2 |D_\mu H|^2, \quad |H|^6
  \]
  \[
  |H|^2 f_L H f_R + h.c.
  \]

- It is thus necessary to redefine many parameters, *viz.*, $e(\hat{h}), s_{\theta_w}(\hat{h}), g_s(\hat{h}), \lambda_h(\hat{h}), Z_h(\hat{h}), Y_f(\hat{h})$, where $\hat{h} = v + h$. 
Many deformations from a single operator: Correlated interactions

- Let’s consider the operator \((H^\dagger \sigma^a H) W^{a}_{\mu\nu} B^{\mu\nu}\)
- Upon expanding, we get terms like:
  \[\hat{h}^2[\hat{W}^3_{\mu\nu} B^{\mu\nu} + 2igc_{\theta_w} W^-_{\mu} W^+_{\nu}(A^{\mu\nu} - t_{\theta_w} Z^{\mu\nu})]\]
- Considering \(\hat{h} = \nu + h\) and expanding further, we get the following deformations:
  - \(hA_{\mu\nu} A^{\mu\nu}, hA_{\mu\nu} Z^{\mu\nu}, hZ_{\mu\nu} Z^{\mu\nu}, hW^+_{\mu\nu} W^-_{\mu\nu} \rightarrow \) Higgs deformations
  - \(2igc_{\theta_w} W^-_{\mu} W^+_{\nu}(A^{\mu\nu} - t_{\theta_w} Z^{\mu\nu}) \rightarrow \delta_{\kappa\gamma}, \delta_{\kappa Z} \) (TGCs)
  - \(\hat{W}_{\mu\nu} B^{\mu\nu} \rightarrow S\)-parameter
- Hence, we obtain 7 deformations from a single operator
The following interactions contribute in the unitary gauge

\[ \Delta L_6 \supset \sum_f \delta g_f^Z Z_\mu \bar{f} \gamma^\mu f + \delta g_u^W (W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.) + g_{V}^h h \left[ W^+\mu W^-_\mu + \frac{1}{2c_w^2} Z^\mu Z_\mu \right] + \delta g_Z^h h \frac{Z^\mu Z_\mu}{2c_w^2} + \sum_f g_{Zf}^h \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f + g_{W}^h \frac{h}{v} (W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.) + \kappa_Z \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_W \frac{h}{v} W^+\mu W^-_{\mu\nu} + \kappa_Z \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} \]

[SB, Englert, Gupta, Spannowsky, 2018]
Higgs-Strahlung at the LHC ($hZZ^*/hZ\bar{f}f$)

- $pp \rightarrow Z(\ell^+\ell^-)h(b\bar{b})$ also gets contributions from operators that rescale $hb\bar{b}$ and $Z\bar{f}f$ couplings ($\delta\hat{g}^h_{bb}$ and $\delta\hat{g}^Z_f$ respectively) and from the vertices

$$
\delta\hat{g}^h_{ZZ} \rightarrow \delta\hat{g}^h_{ZZ} + \delta\hat{g}^h_{bb} + \delta\hat{g}^Z_f,
$$

$$
\kappa_{ZZ} \rightarrow \kappa_{ZZ} + \frac{Q_f e}{g^Z_f} \kappa_{Z\gamma},
$$

$$
\tilde{\kappa}_{ZZ} \rightarrow \tilde{\kappa}_{ZZ} + \frac{Q_f e}{g^Z_f} \tilde{\kappa}_{Z\gamma}.
$$

- For last two replacements, we assume $\hat{s} \gg m_Z^2$

- At the $pp \rightarrow Zh$ level, last two replacements become $\kappa_{ZZ} \rightarrow \kappa_{ZZ} + 0.3 \kappa_{Z\gamma}$, $\tilde{\kappa}_{ZZ} \rightarrow \tilde{\kappa}_{ZZ} + 0.3 \tilde{\kappa}_{Z\gamma}$

- These degeneracies can be resolved by including LEP $Z$-pole data and information from other Higgs production and decay channels
The EFT space directions

- $\delta g_f^Z$ and $\delta g_Z^h \rightarrow$ deviations in SM amplitude
- These do not grow with energy and are suppressed by $\mathcal{O}(m_Z^2/\hat{s})$ w.r.t. $g_{Vf}^h$
- Five directions: $g_{Zf}^h$ with $f = u_L, u_R, d_L, d_R$ and $g_{Wud}^h \rightarrow$ only four operators in Warsaw basis

Knowing proton polarisation is not possible and hence in reality there are two directions. Also, upon only considering interference terms, we have

$$g_{Zu}^h = g_{ZuL}^h + \frac{g_{ZuR}^h}{g_{uL}^h} g_{ZuR}^h$$
$$g_{Zd}^h = g_{ZdL}^h + \frac{g_{ZdR}^h}{g_{dL}^h} g_{ZdR}^h$$
$$g_{ZP}^h = g_{ZuL}^h - 0.76 g_{ZdL}^h - 0.45 g_{ZuR}^h + 0.14 g_{ZdR}^h$$
$$g_{ZP}^h = -0.14 (\delta \kappa_\gamma - \hat{S} + Y) - 0.89 \delta g_1^Z - 1.3 W$$
EFT validity

- Till now, we have dropped the $gg \rightarrow Zh$ contribution which is $\sim 15\%$ of the $qq$ rate.
- It doesn’t grow with energy in presence of the anomalous couplings.
- We estimate the scale of new physics for a given $\delta g_{Zf}^h$.
- Example: Heavy $SU(2)_L$ triplet (singlet) vector $W'^a (Z')$ couples to SM fermion current $\bar{f}\sigma^a\gamma_\mu f$ ($\bar{f}\gamma_\mu f$) with $g_f$ and to the Higgs current $iH^\dagger \sigma^aD_\mu H$ ($iH^\dagger D_\mu H$) with $g_H$.

$$
\begin{align*}
\Lambda \rightarrow \text{mass scale of vector and thus cut-off for low energy EFT}
\end{align*}
$$

$$
\begin{align*}
g_{Zu_L,d_L}^h & \sim \frac{g_H g_f v^2}{2\Lambda^2}, \\
g_{Zf}^h & \sim \frac{g_H g_f v^2}{\Lambda^2}, \\
g_{Zu_R,d_R}^h & \sim \frac{g_H g'_f Y_{u_R,d_R} v^2}{\Lambda^2}
\end{align*}
$$

- Assumed $g_f$ to be a combination of $g_B = g' Y_f$ and $g_W = g/2$ for universal case.
Higgs-Strahlung: Operators at play

| \( \mathcal{O}_{H□} = (H^\dagger H)□(H^\dagger H) \) |
| \( \mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H) \) |
| \( \mathcal{O}_{Hu} = iH^\dagger \leftrightarrow D_\mu H\bar{u}_R\gamma^\mu u_R \) |
| \( \mathcal{O}_{Hd} = iH^\dagger \leftrightarrow D_\mu H\bar{d}_R\gamma^\mu d_R \) |
| \( \mathcal{O}_{He} = iH^\dagger \leftrightarrow D_\mu H\bar{e}_R\gamma^\mu e_R \) |
| \( \mathcal{O}^{(1)}_{HQ} = iH^\dagger \leftrightarrow D_\mu H\bar{Q}\gamma^\mu Q \) |
| \( \mathcal{O}^{(3)}_{HQ} = iH^\dagger \sigma^a \leftrightarrow D_\mu H\bar{Q}\sigma^a\gamma^\mu Q \) |
| \( \mathcal{O}^{(1)}_{HL} = iH^\dagger \leftrightarrow D_\mu H\bar{L}\gamma^\mu L \) |
| \( \mathcal{O}^{(3)}_{HL} = iH^\dagger \sigma^a \leftrightarrow D_\mu H\bar{L}\sigma^a\gamma^\mu L \) |
| \( \mathcal{O}_{HB} = |H|^2 B_{\mu\nu} B^{\mu\nu} \) |
| \( \mathcal{O}_{HWB} = H^\dagger \sigma^a HW_{\mu\nu} B^{\mu\nu} \) |
| \( \mathcal{O}_{HW} = |H|^2 W_{\mu\nu} W^{\mu\nu} \) |
| \( \mathcal{O}_{HB} = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \) |
| \( \mathcal{O}_{H\tilde{W}B} = H^\dagger \sigma^a HW_{\mu\nu} \tilde{B}^{\mu\nu} \) |
| \( \mathcal{O}_{H\tilde{W}} = |H|^2 W_{\mu\nu} \tilde{W}^{a\mu\nu} \) |

Shankha Banerjee (IPPP, Durham)  Higgs Hunting 2019, Orsay-Paris 13 / 25
$ZH$: Relations to the Warsaw Basis

\[
\delta \hat{g}^h_{Z\bar{Z}} = \frac{v^2}{\Lambda^2} \left( c_{H\Box} + \frac{3c_{HD}}{4} \right)
\]

\[
g^h_{Zf} = -\frac{2g}{c_{\theta_W}} \frac{v^2}{\Lambda^2} (|T^f_3| c_{Hf}^{(1)} - T^f_3 c_{Hf}^{(3)} + (1/2 - |T^f_3|) c_{Hf})
\]

\[
\kappa_{Z\bar{Z}} = \frac{2v^2}{\Lambda^2} (c_{\theta_W}^2 c_{HW} + s_{\theta_W}^2 c_{HB} + s_{\theta_W} c_{\theta_W} c_{HWB})
\]

\[
\tilde{\kappa}_{Z\bar{Z}} = \frac{2v^2}{\Lambda^2} (c_{\theta_W}^2 c_{H\bar{W}} + s_{\theta_W}^2 c_{H\bar{B}} + s_{\theta_W} c_{\theta_W} c_{H\bar{W}B})
\]
Bounds on Pseudo-observables at HL-LHC

- Our bounds are derived by considering one parameter at a time and upon considering only interference (at 95% CL). The four directions in LEP are at 68% CL.

\[
g_{Zp}^b \in [-0.004, 0.004] \quad (300 \text{ fb}^{-1})
\]
\[
g_{Zp}^b \in [-0.001, 0.001] \quad (3000 \text{ fb}^{-1})
\]

<table>
<thead>
<tr>
<th></th>
<th>Our Projection 300 fb(^{-1}) (3 ab(^{-1}))</th>
<th>LEP Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta g_{uL}^Z)</td>
<td>(\pm 0.002 \ (\pm 0.0007))</td>
<td>(-0.0026 \pm 0.0016)</td>
</tr>
<tr>
<td>(\delta g_{dL}^Z)</td>
<td>(\pm 0.003 \ (\pm 0.001))</td>
<td>(0.0023 \pm 0.001)</td>
</tr>
<tr>
<td>(\delta g_{uR}^Z)</td>
<td>(\pm 0.005 \ (\pm 0.001))</td>
<td>(-0.0036 \pm 0.0035)</td>
</tr>
<tr>
<td>(\delta g_{dR}^Z)</td>
<td>(\pm 0.016 \ (\pm 0.005))</td>
<td>(0.016 \pm 0.0052)</td>
</tr>
<tr>
<td>(\delta g_{1}^Z)</td>
<td>(\pm 0.005 \ (\pm 0.001))</td>
<td>(0.009+0.043_{-0.042})</td>
</tr>
<tr>
<td>(\delta \kappa_{\gamma})</td>
<td>(\pm 0.032 \ (\pm 0.009))</td>
<td>(0.016+0.085_{-0.096})</td>
</tr>
<tr>
<td>(\hat{S})</td>
<td>(\pm 0.032 \ (\pm 0.009))</td>
<td>(0.0004 \pm 0.0007)</td>
</tr>
<tr>
<td>(W)</td>
<td>(\pm 0.003 \ (\pm 0.001))</td>
<td>(0.0000 \pm 0.0006)</td>
</tr>
<tr>
<td>(Y)</td>
<td>(\pm 0.032 \ (\pm 0.009))</td>
<td>(0.0003 \pm 0.0006)</td>
</tr>
</tbody>
</table>

[SB, Englert, Gupta, Spannowsky, 2018]
BDRS: An aside

FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale $R$, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to $R_{bb}$ and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

Given a hard jet $j$, obtained with some radius $R$, we then use the following new iterative decomposition procedure to search for a generic boosted heavy-particle decay. It involves two dimensionless parameters, $\mu$ and $y_{cut}$:

1. Break the jet $j$ into two subjets by undoing its last stage of clustering. Label the two subjets $j_1, j_2$ such that $m_{j_1} > m_{j_2}$.

2. If there was a significant mass drop (MD), $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \min(R_{bb}^2, \frac{p_{T,j_1}}{p_{T,j_2}}) > y_{cut}$, then deem $j$ to be the heavy-particle neighbourhood and exit the loop. Note that $y \approx \min(p_{T,j_1}, p_{T,j_2}) / \max(p_{T,j_1}, p_{T,j_2})$.

3. Otherwise redefine $j$ to be equal to $j_1$ and go back to step 1.

The final jet $j$ is to be considered as the candidate Higgs boson if both $j_1$ and $j_2$ have $b$ tags. One can then identify $R_{bb}$ with $\Delta R_{j_1,j_2}$. The effective size of jet $j$ will thus be just sufficient to contain the QCD radiation from the

In practice the above procedure is not yet optimal for LHC at the transverse momenta of interest, $p_T \sim 200 - 300$ GeV because, from eq. (1), $R_{bb} \gtrsim 2m_H/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{bb}^4$. A second novel element of our analysis is to filter the Higgs neighbourhood. This involves resolving it on a finer angular scale, $R_{bb} < R_{bb}$, and taking the three hardest objects (subjets) that appear — thus one captures the dominant $O(\alpha_s)$ radiation from the Higgs decay, while eliminating much of the UE contamination. We find $R_{bb} = \min(0.3, R_{bb}/2)$ to be rather effective. We also require the two hardest of the subjets to have the $b$ tags.
$pp \rightarrow ZH$ at high energies

- $\sigma_{SM}^{Zh}/\sigma_{Zb\bar{b}}$ without cuts $\sim 4.6/165$
- With the cut-based analysis $\rightarrow 0.26$
- With MVA optimisation $\rightarrow 0.50$ [See also the recent study by Freitas, Khosa and Sanz]
- $S/B$ changes from 1/40 to $O(1)$ $\rightarrow$ Close to 35 SM $Zh(b\bar{b}\ell^+\ell^-)$ events left at 300 fb$^{-1}$

[SB, Englert, Gupta, Spannowsky, 2018]

Differential NLO corrections from [Greljo, Isidori, Lindert, Marzocca, Zhang, 2017]
Constraining the LT terms

\begin{table}
\begin{tabular}{|c|c|}
\hline
$a_{LL}$ & $\frac{G^2}{4} \left[ 1 + 2 \delta h_{ZZ} + 4 \kappa ZZ + \frac{g_Z^2}{g_f^2} \left( -1 + 4 \gamma^2 \right) \right]$ \\
$a_{1TT}$ & $\frac{G^2 \sigma e_{LR}}{2 \gamma^2} \left[ 1 + 4 \left( \frac{g_Z^2}{g_f^2} + \kappa ZZ \right) \gamma^2 \right]$ \\
$a_{2TT}$ & $\frac{G^2}{8 \gamma^2} \left[ 1 + 4 \left( \frac{g_Z^2}{g_f^2} + \kappa ZZ \right) \gamma^2 \right]$ \\
$a_{1LT}$ & $- \frac{G^2 \sigma e_{LR}}{2 \gamma} \left[ 1 + 2 \left( \frac{2g_Z^2}{g_f^2} + \kappa ZZ \right) \gamma^2 \right]$ \\
$a_{2LT}$ & $- \frac{G^2}{2 \gamma} \left[ 1 + 2 \left( \frac{2g_Z^2}{g_f^2} + \kappa ZZ \right) \gamma^2 \right]$ \\
$\tilde{a}_{1LT}$ & $- \frac{G^2 \sigma e_{LR}}{2 \gamma^2} \kappa ZZ \gamma$ \\
$\tilde{a}_{2LT}$ & $- \frac{G^2}{2 \gamma} \kappa ZZ \gamma$ \\
$a_{TT'}$ & $\frac{G^2}{8 \gamma^2} \left[ 1 + 4 \left( \frac{g_Z^2}{g_f^2} + \kappa ZZ \right) \gamma^2 \right]$ \\
$\tilde{a}_{TT'}$ & $\frac{G^2}{2 \gamma} \kappa ZZ$ \\
\hline
\end{tabular}
\end{table}

**Table:** Contribution of the different anomalous couplings to the angular coefficients up to linear order. We have neglected subdominant contributions in $\gamma = \sqrt{s}/(2m_Z)$, with the exception of the next-to-leading EFT contribution to $a_{LL}$, that we retain in order to keep the leading effect of the $\delta h_{ZZ}^2$ term. Here $\epsilon_{LR} = \alpha_L - \alpha_R$, $G = g g_f^2 \sqrt{(g_{lL}^Z)^2 + (g_{lR}^Z)^2}/(c_{\theta_W} \Gamma_Z)$ and $\Gamma_Z$ is the $Z$-width.
STU oblique parameters

\[ \Pi_{\gamma\gamma}(q^2) = q^2 \Pi'_{\gamma\gamma}(0) + \ldots \]
\[ \Pi_{Z\gamma}(q^2) = q^2 \Pi'_{Z\gamma}(0) + \ldots \]
\[ \Pi_{ZZ}(q^2) = \Pi_{ZZ}(0) + q^2 \Pi'_{ZZ}(0) + \ldots \]
\[ \Pi_{WW}(q^2) = \Pi_{WW}(0) + q^2 \Pi'_{WW}(0) + \ldots \]

\[ \alpha S = 4s_w^2 c_w^2 \left[ \Pi'_Z (0) - \frac{c_w^2 - s_w^2}{s_w c_w} \Pi'_{\gamma\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right] \]
\[ \alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \]
\[ \alpha U = 4s_w^2 \left[ \Pi'_{WW}(0) - c_w^2 \Pi'_{ZZ}(0) - 2s_w c_w \Pi'_{Z\gamma}(0) - s_w^2 \Pi'_{\gamma\gamma}(0) \right] \]

1. Any BSM correction which is indistinguishable from a redefinition of \( e, G_F \) and \( M_Z \) (or equivalently, \( g_1, g_2 \) and \( v \)) in the Standard Model proper at the tree level does not contribute to \( S, T \) or \( U \).

2. Assuming that the Higgs sector consists of electroweak doublet(s) \( H \), the effective action term \( \left| H^\dagger D_\mu H \right|^2 / \Lambda^2 \) only contributes to \( T \) and not to \( S \) or \( U \). This term violates custodial symmetry.

3. Assuming that the Higgs sector consists of electroweak doublet(s) \( H \), the effective action term \( H^\dagger W^{\mu\nu} B_{\mu\nu} H / \Lambda^2 \) only contributes to \( S \) and not to \( T \) or \( U \). (The contribution of \( H^\dagger B^{\mu\nu} B_{\mu\nu} H / \Lambda^2 \) can be absorbed into \( g_1 \) and the contribution of \( H^\dagger W^{\mu\nu} W_{\mu\nu} H / \Lambda^2 \) can be absorbed into \( g_2 \).)

4. Assuming that the Higgs sector consists of electroweak doublet(s) \( H \), the effective action term \( \left( H^\dagger W^{\mu\nu} H \right) \left( H^\dagger W_{\mu\nu} H \right) / \Lambda^4 \) contributes to \( U \).
ZH: Four directions in the EFT space (SILH Basis)

\[
\begin{align*}
g_{ZuL uL}^h &= \frac{g}{c_{\theta_W}} \frac{m_W^2}{\Lambda^2} \left( c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3} (c_B + c_{HB} - c_{2B}) \right) \\
g_{ZdL dL}^h &= -\frac{g}{c_{\theta_W}} \frac{m_W^2}{\Lambda^2} \left( c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3} (c_B + c_{HB} - c_{2B}) \right) \\
g_{ZuR uR}^h &= \frac{4 g s_{\theta_W}^2}{3 c_{\theta_W}^3} \frac{m_W^2}{\Lambda^2} (c_B + c_{HB} - c_{2B}) \\
g_{ZdR dR}^h &= \frac{2 g s_{\theta_W}^2}{3 c_{\theta_W}^3} \frac{m_W^2}{\Lambda^2} (c_B + c_{HB} - c_{2B})
\end{align*}
\]
ZH: Four directions in the EFT space (Higgs Primaries Basis)

\[
\begin{align*}
 g_{Z_{uL}u_L}^h &= 2\delta g_{Z_{uL}u_L}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}^2} \\
 g_{Z_{dL}d_L}^h &= 2\delta g_{Z_{dL}d_L}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}^2} \\
 g_{Z_{uR}u_R}^h &= 2\delta g_{Z_{uR}u_R}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}^2} \\
 g_{Z_{dR}d_R}^h &= 2\delta g_{Z_{dR}d_R}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}^2}
\end{align*}
\]

[Gupta, Pomarol, Riva, 2014]
ZH: Four directions in the EFT space (Universal model Basis)

\[
\begin{align*}
    g_{Zu_L u_L}^h &= -\frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W + \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_{\gamma} - Y) \right) \\
    g_{Zd_L d_L}^h &= \frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_{\gamma} - Y) \right) \\
    g_{Zu_R u_R}^h &= -\frac{4g s_{\theta_W}^2}{3 c_{\theta_W}^3} (\hat{S} - \delta \kappa_{\gamma} + c_{\theta_W}^2 \delta g_1^Z - Y) \\
    g_{Zd_R d_R}^h &= \frac{2g s_{\theta_W}^2}{3 c_{\theta_W}^3} (\hat{S} - \delta \kappa_{\gamma} + c_{\theta_W}^2 \delta g_1^Z - Y)
\end{align*}
\]

[Franceschini, Panico, Pomarol, Riva, Wulzer, 2017]
The four dibosonic channels

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>High-energy primaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{u}_Ld_L \rightarrow W_LZ_L, W_Lh$</td>
<td>$\sqrt{2}a_q^{(3)}$</td>
</tr>
<tr>
<td>$\bar{u}_Lu_L \rightarrow W_LW_L$</td>
<td>$a_q^{(1)} + a_q^{(3)}$</td>
</tr>
<tr>
<td>$\bar{d}_Ld_L \rightarrow Z_Lh$</td>
<td>$a_q^{(1)} - a_q^{(3)}$</td>
</tr>
<tr>
<td>$\bar{u}_Lu_L \rightarrow Z_Lh$</td>
<td>$a_f$</td>
</tr>
</tbody>
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<td>$g_{Zu_Lu_L}^h$</td>
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<tr>
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<td>$g_{Zd_Ld_L}^h$</td>
</tr>
<tr>
<td>$\bar{u}_Lu_L \rightarrow Z_Lh$</td>
<td>$g_{Zu_Lu_L}^h$</td>
</tr>
<tr>
<td>$\bar{f}_Rf_R \rightarrow W_LW_L, Z_Lh$</td>
<td>$g_{Zf_Rf_R}^h$</td>
</tr>
</tbody>
</table>

*VH* and *VV* channels are entwined by symmetry and they constrain the same set of observables at High energies but may have different directions [Franceschini, Panico, Pomarol, Riva, Wulzer, 2017 & SB, Gupta, Reiness, Seth (in progress)]
The four di-bosonic channels

- The four directions, viz., $ZH$, $Wh$, $W^+W^-$ and $W^\pm Z$ can be expressed (at high energies) respectively as $G^0H$, $G^+H$, $G^+G^-$ and $G^\pm G^0$ and the Higgs field can be written as

$$\begin{pmatrix} G^+ \\ H+iG^0/2 \end{pmatrix}$$

- These four final states are intrinsically connected

- At high energies $W/Z$ production dominates

- With the Goldstone boson equivalence it is possible to compute amplitudes for various components of the Higgs in the unbroken phase

- Full SU(2) theory is manifest [Franceschini, Panico, Pomarol, Riva, Wulzer, 2017]
Higgs-Strahlung at FCC-hh

- With a similar analysis, we obtain much stronger bounds with the 100 TeV collider

<table>
<thead>
<tr>
<th>Our 100 TeV Projection</th>
<th>Our 14 TeV projection</th>
<th>LEP Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta g^Z_{uL} )</td>
<td>±0.0003 (±0.0001)</td>
<td>±0.002 (±0.0007)</td>
</tr>
<tr>
<td>( \delta g^Z_{dL} )</td>
<td>±0.0003 (±0.0001)</td>
<td>±0.003 (±0.001)</td>
</tr>
<tr>
<td>( \delta g^Z_{uR} )</td>
<td>±0.0005 (±0.0002)</td>
<td>±0.005 (±0.001)</td>
</tr>
<tr>
<td>( \delta g^Z_{dR} )</td>
<td>±0.0015 (±0.0006)</td>
<td>±0.016 (±0.005)</td>
</tr>
<tr>
<td>( \delta g^Z_{1} )</td>
<td>±0.0005 (±0.0002)</td>
<td>±0.005 (±0.001)</td>
</tr>
<tr>
<td>( \delta \kappa_{\gamma} )</td>
<td>±0.0035 (±0.0015)</td>
<td>±0.032 (±0.009)</td>
</tr>
<tr>
<td>( \hat{S} )</td>
<td>±0.0035 (±0.0015)</td>
<td>±0.032 (±0.009)</td>
</tr>
<tr>
<td>( W )</td>
<td>±0.0004 (±0.0002)</td>
<td>±0.003 (±0.001)</td>
</tr>
<tr>
<td>( Y )</td>
<td>±0.0035 (±0.0015)</td>
<td>±0.032 (±0.009)</td>
</tr>
</tbody>
</table>

[SB, Englert, Gupta, Spannowsky (in progress)]