Constraining certain EFT coefficients using boosted Higgs-strahlung

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Based on

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

arXiv:1905.02728

(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 Λ
- A bigger theory (either weakly or strongly coupled) is assumed to supersede the SM above the scale Λ
- 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 Λ

$$\mathcal{L} = \mathcal{L}_{SM}^{d=4} + \sum_{d\geq 5} \sum_i \frac{f_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

SMEFT motivation

- Precisely measuring the Higgs couplings $\rightarrow$ 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 $\rightarrow$ 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 $\rightarrow$ 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

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

- In contrast, the following interactions were constrained by LEP

$$\Delta\mathcal{L}_h = \delta g_{ZZ}^h\,\frac{v}{2c_{\theta_W}^2} hZ^\mu Z_\mu + g_{Zff}^h\,\frac{h}{2v}\left(Z_\mu J_N^\mu + h.c.\right) + g_{Wff'}^h\,\frac{h}{v}\left(W_\mu^+ J_C^\mu + h.c.\right)$$
$$+ \kappa_{WW}\,\frac{h}{v} W^{+\mu\nu}W_{\mu\nu}^- + \kappa_{ZZ}\,\frac{h}{v} Z^{\mu\nu}Z_{\mu\nu}\,,$$

Couplings constrained by LEP

- The coefficients of the following

$$
\begin{aligned}
\Delta\mathcal{L}_h &= \delta g^h_{ZZ}\,\frac{v}{2c^2_{\theta_W}} hZ^\mu Z_\mu + g^h_{Zff}\,\frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\,\frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right) \\
&+ \kappa_{WW}\,\frac{h}{v} W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{v} Z^{\mu\nu}Z_{\mu\nu}\,,
\end{aligned}
$$

can be written as

$$\delta g^h_{ZZ} = \delta g^Z_1 e^2 - \delta\kappa_\gamma \frac{e^2}{c^2_{\theta_W}}$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ_f s_{2\theta_W}) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}\,, \qquad g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}\,,$$

$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}(\delta\kappa_\gamma + \kappa_{Z\gamma} c_{2\theta_W} + 2\kappa_{\gamma\gamma} c^2_{\theta_W})\,, \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

[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
- Λ 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 $\sqrt{\hat{s}} \sim 1$ 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

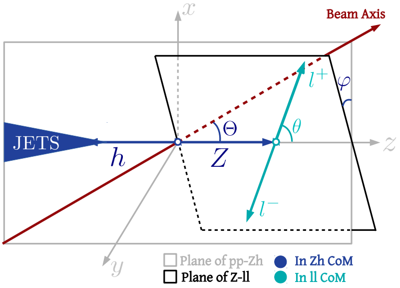
$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$
$$+ \kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

- 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 φ and Θ are defined) and the CoM frame of the Z (in which θ 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 $2 \to 2$ process $f(\sigma)\bar{f}(-\sigma) \to Zh$, the helicity amplitudes are given by

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

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

- $\lambda = \pm 1$ and $\sigma = \pm 1$ are, respectively, the helicities of the Z-boson and initial-state fermions, $g_f^Z = g(T_3^f - Q_f s_{\theta_W}^2)/c_{\theta_W}$
- Leading SM is longitudinal ($\lambda = 0$)
- Leading effect of $\kappa_{ZZ}, \tilde{\kappa}_{ZZ}$ is in the transverse-longitudinal (LT) interference
- LT term vanishes if we aren't careful

Precision measurement: LHC vs LEP (Contact term)

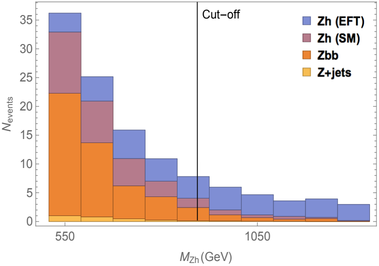
$$\mathcal{M}(ff \to Z_L h) \;=\; g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g^h_{Zff}}{g_f^Z} \frac{\hat{s}}{2m_Z^2}\right]$$

$$g^h_{Zd_Ld_L} \;=\; \frac{g}{c_{\theta_W}} \left((c^2_{\theta_W} - \frac{s^2_{\theta_W}}{3}) \delta g_1^Z + W - \frac{t^2_{\theta_W}}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$

- LEP constrains δg_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

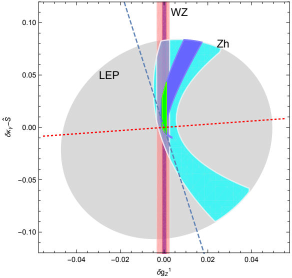


Cuts	$Zb\bar{b}$	Zh (SM)
At least 1 fat jet with 2 B-mesons with $p_T > 15$ GeV	0.23	0.41
2 OSSF isolated leptons	0.41	0.50
80 GeV $< M_{\ell\ell} <$ 100 GeV, $p_{T,\ell\ell} > 160$ GeV, $\Delta R_{\ell\ell} > 0.2$	0.83	0.89
At least 1 fat jet with 2 B-meson tracks with $p_T > 110$ GeV	0.96	0.98
2 Mass drop subjets and ≥ 2 filtered subjets	0.88	0.92
2 b-tagged subjets	0.38	0.41
115 GeV $< m_h <$ 135 GeV	0.15	0.51
$\Delta R(b_i, \ell_j) > 0.4$, $\not{E}_T < 30$ GeV, $\lvert y_h \rvert < 2.5$, $p_{T,h/Z} > 200$ GeV	0.47	0.69

[SB, Englert, Gupta, Spannowsky, 2018]

$pp \to Zh$ at high energies (Contact term)

- Next we perform a two-parameter χ^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 $\to$ 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:

	Our Projection 300 fb^{-1} (3 ab^{-1})	LEP Bound
$\delta g^Z_{u_L}$	± 0.002 (± 0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	± 0.003 (± 0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	± 0.005 (± 0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	± 0.016 (± 0.005)	0.016 ± 0.0052
δg^Z_1	± 0.005 (± 0.001)	$0.009^{+0.043}_{-0.042}$
$\delta\kappa_\gamma$	± 0.032 (± 0.009)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.003 (± 0.001)	0.0000 ± 0.0006
Y	± 0.032 (± 0.009)	0.0003 ± 0.0006

[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

$$\mathcal{A}_h(\hat{s}, \Theta, \hat{\theta}, \hat{\varphi}) = \frac{-i\sqrt{2}g_\ell^Z}{\Gamma_Z} \sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s}, \Theta) d_{\lambda,1}^{J=1}(\hat{\theta}) e^{i\lambda\hat{\varphi}},$$

- $d_{\lambda,1}^{J=1}(\hat{\theta})$ are the Wigner functions, Γ_Z is the Z-width and $g_\ell^Z = g(T_3^\ell - Q_\ell s_{\theta_W}^2)/c_{\theta_W}$
- $\hat{\varphi} \to$ 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 (θ, φ) for the positively-charged lepton

$$\sum_{L,R} |\mathcal{A}(\hat{s}, \Theta, \theta, \varphi)|^2 \quad = \quad \alpha_L |\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)|^2 + \alpha_R |\mathcal{A}_h(\hat{s}, \Theta, \pi - \theta, \pi + \varphi)|^2$$

- $\alpha_{L,R} = (g^Z_{l_{L,R}})^2/[(g^Z_{l_L})^2 + (g^Z_{l_R})^2] \rightarrow$ fraction of $Z \rightarrow \ell^+\ell^-$ 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 $\rightarrow$ positive-charged lepton
- For right-handed chiralities, positive-helicity lepton $\rightarrow$ negative-charged lepton $\rightarrow$ $(\hat{\theta}, \hat{\varphi}) \rightarrow (\pi - \theta, \pi + \varphi)$

$$\begin{aligned}
&\sum_{L,R} |\mathcal{A}(\hat{s}, \Theta, \theta, \varphi)|^2 = a_{LL} \sin^2\Theta \sin^2\theta + a^1_{TT} \cos\Theta \cos\theta \\
&+ a^2_{TT}(1 + \cos^2\Theta)(1 + \cos^2\theta) + \cos\varphi \sin\Theta \sin\theta \\
&\times (a^1_{LT} + a^2_{LT} \cos\theta \cos\Theta) + \sin\varphi \sin\Theta \sin\theta \\
&\times (\tilde{a}^1_{LT} + \tilde{a}^2_{LT} \cos\theta \cos\Theta) + a_{TT'} \cos 2\varphi \sin^2\Theta \sin^2\theta \\
&+ \tilde{a}_{TT'} \sin 2\varphi \sin^2\Theta \sin^2\theta
\end{aligned}$$

Constraining the LT terms

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

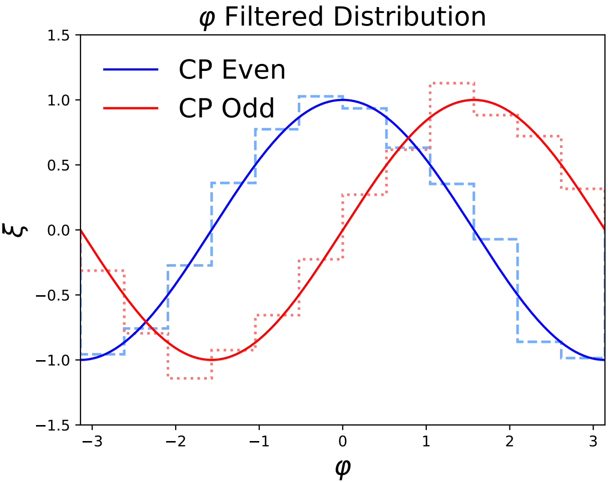
$$\frac{a_{LT}^2}{4}\cos\varphi\sin 2\theta\sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4}\sin\varphi\sin 2\theta\sin 2\Theta$$

- These terms vanish on integration of any angle
- Q: How to probe κ_{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



Constraining the LT terms

- Perform χ^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 κ_{ZZ} and $\tilde{\kappa}_{ZZ}$

Constraining the LT terms

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

$$\begin{aligned} -0.03 < \quad & \kappa_{ZZ} \quad < 0.03 \\ -0.04 < \quad & \tilde{\kappa}_{ZZ} \quad < 0.04 \end{aligned}$$

[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 infomation
- 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

Backup Slides

HD operators

- Higher-dimensional Operators: invariant under SM gauge group
- $d = 5$: Unique operator $\rightarrow$ 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

Effective Field Theory: The operators at play

- There are only 18 independent operators from which the aforementioned vertices ensue

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$
$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$

Higgs anomalous couplings: Dimension 6 effects

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

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ} \frac{v}{2c^2_{\theta_W}} h Z^\mu Z_\mu + g^h_{Zff} \frac{h}{2v} \left(Z_\mu J^\mu_N + h.c. \right) + g^h_{Wff'} \frac{h}{v} \left(W^+_\mu J^\mu_C + h.c. \right)$$
$$+ \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}\,,$$

[Pomarol, 2014]

- Higgs interactions were directly measured for the first time at the LHC

Higgs Pseudo-Observables

- Following are some of the Higgs observables (assuming flavour universality)

  $hW^{+}_{\mu\nu}W^{-\mu\nu}$

  $hZ_{\mu\nu}Z^{\mu\nu},\ hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu},\ hG_{\mu\nu}G^{\mu\nu}$

  $hf\bar{f},\ h^2f\bar{f}$

  $hW^{+}_{\mu}W^{-\mu}$

  h^3

  $hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$

- 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 $e^+e^- \to W^+W^-$ channel at LEP
  $g_1^Z c_{\theta_w} Z^\mu (W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu})$
  $\kappa_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^+_\mu W^-_\nu$
  $\lambda_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^{-\rho}_\mu W^+_{\rho\nu}$
- 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

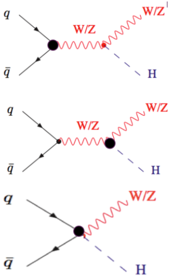
- There are 18 independent operators and many more pseudo-observables
- This implies correlations between the various pseudo-observables
- Besides, the following operators can not be constrained by LEP
  $|H|^2 G_{\mu\nu} G^{\mu\nu}, \ |H|^2 B_{\mu\nu} B^{\mu\nu}, |H|^2 W^a_{\mu\nu} W^{a,\mu\nu}$
  $|H|^2 |D_\mu H|^2, \ |H|^6$
  $|H|^2 f_L H f_R \ + \ h.c.$
- 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 $\hat{h} = v + h$ 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

Higgs-Strahlung at the LHC

- The following interactions contribute in the unitary gauge



$$
\begin{aligned}
\Delta\mathcal{L}_6 \supset & \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f + \delta g^W_{ud}(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.) \\
& + g^h_{VV}\, h \left[W^{+\,\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu \right] + \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} \\
& + \sum_f g^h_{Zf}\, \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{Wud}\, \frac{h}{v}(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.) \\
& + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW}\, \frac{h}{v} W^{+\,\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ}\, \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}
\end{aligned}
$$

[SB, Englert, Gupta, Spannowsky, 2018]

Higgs-Strahlung at the LHC ($hZZ^*/hZ\bar{f}f$)

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

$$\begin{aligned}
\delta\hat{g}^h_{ZZ} &\to \delta\hat{g}^h_{ZZ} + \delta\hat{g}^h_{b\bar{b}} + \delta\hat{g}^Z_f \\
\kappa_{ZZ} &\to \kappa_{ZZ} + \frac{Q_f e}{g^Z_f}\kappa_{Z\gamma} \\
\tilde{\kappa}_{ZZ} &\to \tilde{\kappa}_{ZZ} + \frac{Q_f e}{g^Z_f}\tilde{\kappa}_{Z\gamma}
\end{aligned}$$

- For last two replacements, we assume $\hat{s} \gg m_Z^2$
- At the $pp \to Zh$ level, last two replacements become $\kappa_{ZZ} \to \kappa_{ZZ} + 0.3\ \kappa_{Z\gamma}$, $\tilde{\kappa}_{ZZ} \to \tilde{\kappa}_{ZZ} + 0.3\ \tilde{\kappa}_{Z\gamma}$
- These degeneracies can be resolved by including LEP Z-pole data and information from other Higgs production and decay channels

The EFT space directions

- δg_f^Z and δg_{ZZ}^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 $g_{Wud}^h = c_{\theta_W} \frac{g_{Zu_L}^h - g_{Zd_L}^h}{\sqrt{2}}$
- Knowing proton polarisation is not possible and hence in reality there are two directions Also, upon only considering interference terms, we have

$$g_{\mathbf{u}}^Z = g_{Zu_L}^h + \frac{g_{u_R}^Z}{g_{u_L}^Z} g_{Zu_R}^h$$

$$g_{\mathbf{d}}^Z = g_{Zd_L}^h + \frac{g_{d_R}^Z}{g_{d_L}^Z} g_{Zd_R}^h \qquad g_{\mathbf{p}}^Z = g_{\mathbf{u}}^Z + \frac{\mathcal{L}_d(\hat{s})}{\mathcal{L}_u(\hat{s})} g_{\mathbf{d}}^Z$$

$$g_f^Z = g(T_3^f - Q_f s_{\theta_W}^2)/c_{\theta_W}$$

$$g_{\mathbf{p}}^Z = g_{Zu_L}^h - 0.76\ g_{Zd_L}^h - 0.45\ g_{Zu_R}^h + 0.14\ g_{Zd_R}^h$$

$$\begin{aligned} g_{Z\mathbf{p}}^h &= 2\delta g_{Zu_L}^h - 1.52\ g_{Zd_L}^h - 0.90\ g_{Zu_R}^h + 0.28\ g_{Zd_R}^h \\ &\quad -0.14\ \delta\kappa_\gamma - 0.89\ \delta g_1^Z \end{aligned}$$

$$g_{Z\mathbf{p}}^h = -0.14\ (\delta\kappa_\gamma - \hat{S} + Y) - 0.89\ \delta g_1^Z - 1.3\ W$$

EFT validity

- Till now, we have dropped the $gg \to Zh$ 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 δg^h_{Zf}
- 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 $iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H$ ($iH^\dagger \overleftrightarrow{D}_\mu H$) with g_H

$$g^h_{Zf} \sim \frac{g_H g g_f v^2}{\Lambda^2} \qquad g^h_{Zu_L,d_L} \sim \frac{g_H g^2 v^2}{2\Lambda^2}, \qquad g^h_{Zu_R,d_R} \sim \frac{g_H g g' Y_{u_R,d_R} v^2}{\Lambda^2}$$

- $\Lambda \to$ mass scale of vector and thus cut-off for low energy EFT
- 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

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

ZH: Relations to the Warsaw Basis

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

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

$$\kappa_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{HW} + s^2_{\theta_W}c_{HB} + s_{\theta_W}c_{\theta_W}c_{HWB})$$

$$\tilde{\kappa}_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{H\tilde{W}} + s^2_{\theta_W}c_{H\tilde{B}} + s_{\theta_W}c_{\theta_W}c_{H\tilde{W}B})$$

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.

$$g^h_{Z\mathbf{p}} \in [-0.004, 0.004] \quad (300 \text{ fb}^{-1})$$
$$g^h_{Z\mathbf{p}} \in [-0.001, 0.001] \quad (3000 \text{ fb}^{-1})$$

	Our Projection 300 fb^{-1} (3 ab^{-1})	LEP Bound
$\delta g^Z_{u_L}$	± 0.002 (± 0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	± 0.003 (± 0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	± 0.005 (± 0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	± 0.016 (± 0.005)	0.016 ± 0.0052
δg^Z_1	± 0.005 (± 0.001)	$0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	± 0.032 (± 0.009)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.003 (± 0.001)	0.0000 ± 0.0006
Y	± 0.032 (± 0.009)	0.0003 ± 0.0006

[SB, Englert, Gupta, Spannowsky, 2018]

BDRS: An aside

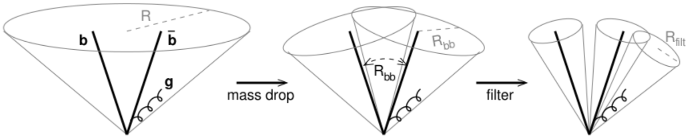


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to R_{filt} 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, μ 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, $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2}\Delta R_{j_1,j_2}^2 > y_{\text{cut}}$, then deem j to be the heavy-particle neighbourhood and exit the loop. Note that $y \simeq \min(p_{tj_1}, p_{tj_2})/\max(p_{tj_1}, p_{tj_2})$.[1]

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 $R_{b\bar{b}}$ 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, $p_T \sim 200 - 300\,\text{GeV}$ because, from eq. (1), $R_{b\bar{b}} \gtrsim 2m_{\text{H}}/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{b\bar{b}}^4$ [15]. A second novel element of our analysis is to *filter* the Higgs neighbourhood. This involves resolving it on a finer angular scale, $R_{\text{filt}} < R_{b\bar{b}}$, and taking the three hardest objects (subjets) that appear — thus one captures the dominant $\mathcal{O}(\alpha_s)$ radiation from the Higgs decay, while eliminating much of the UE contamination. We find $R_{\text{filt}} = \min(0.3, R_{b\bar{b}}/2)$ to be rather effective. We also require the two hardest of the subjets to have the b tags.

$pp \to ZH$ at high energies

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

  [SB, Englert, Gupta, Spannowsky, 2018]

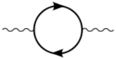
  Differential NLO corrections from [Greljo, Isidori, Lindert, Marzocca, Zhang, 2017]

Constraining the LT terms

a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1+2\delta\hat{g}^h_{ZZ}+4\kappa_{ZZ}+\frac{g^h_{Zf}}{g^Z_f}(-1+4\gamma^2)\right]$
a^1_{TT}	$\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^2_{TT}	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^1_{LT}	$-\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^2_{LT}	$-\frac{\mathcal{G}^2}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}^1_{LT}$	$-\mathcal{G}^2\sigma\epsilon_{LR}\tilde{\kappa}_{ZZ}\gamma$
$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{ZZ}\gamma$
$a_{TT'}$	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}_{TT'}$	$\frac{\mathcal{G}^2}{2}\tilde{\kappa}_{ZZ}$

Table: Contribution of the different anomalous couplings to the angular coefficients up to linear order. We have neglected subdominant contributions in $\gamma=\sqrt{\hat{s}}/(2m_Z)$, 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 $\delta\hat{g}^h_{ZZ}$ term. Here $\epsilon_{LR}=\alpha_L-\alpha_R$, $\mathcal{G}=gg^Z_f\sqrt{(g^Z_{l_L})^2+(g^Z_{l_R})^2}/(c_{\theta_W}\Gamma_Z)$ and Γ_Z is the Z-width.

STU oblique parameters



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

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

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)

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= \frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right)\\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right)\\
g^h_{Zu_Ru_R} &= -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})\\
g^h_{Zd_Rd_R} &= \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})
\end{aligned}
$$

ZH: Four directions in the EFT space (Higgs Primaries Basis)

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= 2\delta g^Z_{Zu_Lu_L} - 2\delta g^Z_1(g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zd_Ld_L} &= 2\delta g^Z_{Zd_Ld_L} - 2\delta g^Z_1(g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zu_Ru_R} &= 2\delta g^Z_{Zu_Ru_R} - 2\delta g^Z_1(g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zd_Rd_R} &= 2\delta g^Z_{Zd_Rd_R} - 2\delta g^Z_1(g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}
\end{aligned}
$$

[Gupta, Pomarol, Riva, 2014]

ZH: Four directions in the EFT space (Universal model Basis)

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}+\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W + \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zd_Ld_L} &= \frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}-\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W - \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zu_Ru_R} &= -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)\\
g^h_{Zd_Rd_R} &= \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)
\end{aligned}
$$

[Franceschini, Panico, Pomarol, Riva, Wulzer, 2017]

The four dibosonic channels

Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f

Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\dfrac{g^h_{Zd_Ld_L} - g^h_{Zu_Lu_L}}{\sqrt{2}}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$g^h_{Zd_Ld_L}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$g^h_{Zu_Lu_L}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	$g^h_{Zf_Rf_R}$

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

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

- 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

	Our 100 TeV Projection	Our 14 TeV projection	LEP Bound
$\delta g^Z_{u_L}$	± 0.0003 (± 0.0001)	± 0.002 (± 0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	± 0.0003 (± 0.0001)	± 0.003 (± 0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	± 0.0005 (± 0.0002)	± 0.005 (± 0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	± 0.0015 (± 0.0006)	± 0.016 (± 0.005)	0.0016 ± 0.0052
δg^Z_1	± 0.0005 (± 0.0002)	± 0.005 (± 0.001)	$0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.0004 (± 0.0002)	± 0.003 (± 0.001)	0.0000 ± 0.0006
Y	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	0.0003 ± 0.0006

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