Constraining the Higgs-gauge couplings through differential SMEFT analyses

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Based on

Phys. Rev. D 98, 095012 (2018), arXiv:1807.01796
(with R. S. Gupta, C. Englert and M. Spannowsky)
Phys. Rev. D 100, 115004, arXiv:1905.02728
(with R. S. Gupta, J. Y. Reiness and M. Spannowsky)
arXiv: 1912.07628
(with R. S. Gupta, J. Y. Reiness, S. Seth and M. Spannowsky)

Motivation

- Plethora of data available/ will be available at the LHC
- Q: How do we reconstruct a TeV-Scale Lagrangian from this data?
- Q: How to extract the best observables to study the effects of a particular operator?
- New vertices ensuing from EFT can produce novel/ enhanced effects in parts of the phase space
- Q: What is the best way to extract every differential information for a particular process?
- These questions and ideas can be addressed in the regime of high energies/ luminosities

Motivation

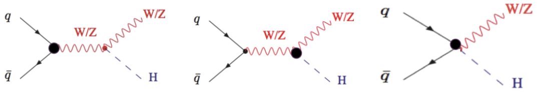
- The SM here is a low energy effective theory valid below a cut-off scale Λ
- A bigger theory (either weakly or strongly coupled) is assumed to supersede the SM above the scale Λ
- At the perturbative level, all heavy ($> \Lambda$) DOF are decoupled from the low energy theory (Appelquist-Carazzone theorem)
- 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
- 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

Case study: Higgs-Strahlung at the LHC



$$
\begin{aligned}
\Delta\mathcal{L}_6 \quad \supset \quad & \delta\hat{g}^h_{WW}\,\frac{2m_W^2}{v}hW^{+\mu}W^-_\mu + \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \delta g^W_Q\,(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.)\\
+ \quad & \delta g^W_L\,(W^+_\mu \bar{\nu}_L\gamma^\mu e_L + h.c.) + g^h_{WL}\,\frac{h}{v}(W^+_\mu \bar{\nu}_L\gamma^\mu e_L + h.c.)\\
+ \quad & g^h_{WQ}\,\frac{h}{v}(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.) + \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f + \sum_f g^h_{Zf}\,\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f\\
+ \quad & \kappa_{WW}\,\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \tilde{\kappa}_{WW}\,\frac{h}{v}W^{+\mu\nu}\tilde{W}^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}\\
+ \quad & \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu} + \kappa_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}\tilde{Z}_{\mu\nu} + \delta\hat{g}^h_{bb}\frac{\sqrt{2}m_b}{v}hb\bar{b}
\end{aligned}
$$

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

Higgs-Strahlung: Operators at play

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

Table: D6 operators in Warsaw basis contributing to anomalous $hVV^*/hV\bar{f}f$ couplings.

The EFT space directions

- δg_f^Z and $\delta \hat{g}^h_{ZZ}$ → 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^h_{Vf}
- Five directions: g^h_{Zf} with $f = u_L, u_R, d_L, d_R$ and g^h_{WQ} → only four operators in Warsaw basis → $g^h_{WQ} = c_\theta \frac{g^h_{Zu_L} - g^h_{Zd_L}}{\sqrt{2}}$
- Knowing proton polarisation is not possible and hence in reality there are two directions Also, upon only considering interference terms, we have

$$g^Z_{\mathbf{u}} = g^h_{Zu_L} + \frac{g^Z_{u_R}}{g^Z_{u_L}} g^h_{Zu_R}$$

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

$$g^Z_{\mathbf{p}} = g^h_{Zu_L} - 0.76\; g^h_{Zd_L} - 0.45\; g^h_{Zu_R} + 0.14\; g^h_{Zd_R}$$

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

$$g^Z_f = g(T_3^f - Q_f s^2_{\theta_W})/c_{\theta_W}$$

$$g^h_{Z\mathbf{p}} = 2\delta g^h_{Zu_L} - 1.52\; g^h_{Zd_L} - 0.90\; g^h_{Zu_R} + 0.28\; g^h_{Zd_R} - 0.14\;\delta\kappa_\gamma - 0.89\;\delta g_1^Z$$

EFT validity

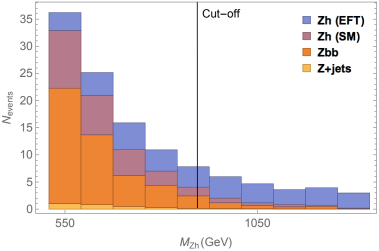
- Till now, we have dropped the $gg \to Zh$ contribution which is $\sim 15\%$ of the qq rate
- It doesn't grow with energy in presence of the anomalous couplings
- We estimate the scale of new physics for a given δg^h_{Zf}
- Example: Heavy $SU(2)_L$ triplet (singlet) vector W'^a (Z') couples to SM fermion 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

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

- $\Lambda \to$ 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

Differential in Energy: $pp \to Zh$ at high energies (Contact term)

- 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



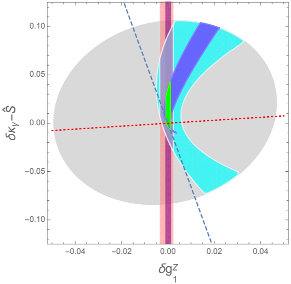
Cuts	Zbb	Zh (SM)
At least 1 fat jet with 2 B-mesons with $p_T > 15$ GeV	0.23	0.41
2 OSSF isolated leptons	0.41	0.50
80 GeV $< M_{\ell\ell} <$ 100 GeV, $p_{T,\ell\ell} >$ 160 GeV, $\Delta R_{\ell\ell} > 0.2$	0.83	0.89
At least 1 fat jet with 2 B-meson tracks with $p_T >$ 110 GeV	0.96	0.98
2 Mass drop 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

Differential in Energy: $pp \to Zh$ at high energies (Contact term)

- $\sigma_{Zh}^{SM}/\sigma_{Zb\bar{b}}$ without cuts $\sim 4.6/165$
- With the cut-based analysis $\to$ 0.26
- With MVA optimisation $\to$ 0.50 See also [Freitas, Khosa and Sanz, 2019]
- 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]

Differential in Energy: $pp \to Zh$ 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

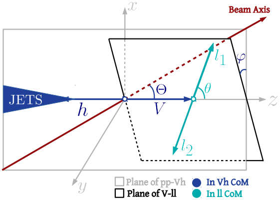
- Our bounds are derived by considering one parameter at a time and upon considering only interference (at 95% CL). The four directions in LEP are at 68% CL.

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

	Our Projection	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]

Differential in angles: $pp \to V(\ell\ell)h$ (Fat jet)



- φ, Θ and $\{x, y, z\}$ in Vh CoM frame (z identified as direction of V-boson; y identified as normal to the plane of V and beam axis; x defined to complete the right-handed set), θ in V CoM frame
- Q: How much differential information can one extract from this process?
- For three body phase space, $3 \times 3 - 4 = 5$ kinematic variables completely define final state
- Barring boost factor, the variables are $\sqrt{s}, \Theta, \theta, \varphi$
- Considering 10 bins per variable $\to$ 1000 numbers per energy bin to obtain full information $\to$ can be reduced to 9 per energy bin

Helicity Amplitudes

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

$$\mathcal{M}_\sigma^{\lambda=\pm} = \sigma \frac{1+\sigma\lambda\cos\Theta}{\sqrt{2}} G_V \frac{m_V}{\sqrt{\hat{s}}} \left[1 + \left(\frac{g^h_{Vf}}{g^V_f} + \hat{\kappa}_{VV} - i\lambda\hat{\tilde{\kappa}}_{VV}\right)\frac{\hat{s}}{2m_V^2}\right]$$

$$\mathcal{M}_\sigma^{\lambda=0} = -\frac{\sin\Theta}{2} G_V \left[1 + \delta\hat{g}^h_{VV} + 2\hat{\kappa}_{VV} + \delta g^Z_f + \frac{g^h_{Vf}}{g^V_f}\left(-\frac{1}{2} + \frac{\hat{s}}{2m_V^2}\right)\right]$$

$$\begin{aligned} \hat{\kappa}_{WW} &= \kappa_{WW} \\ \hat{\kappa}_{ZZ} &= \kappa_{ZZ} + \frac{Q_f e}{g^Z_f}\kappa_{Z\gamma}, \\ \hat{\tilde{\kappa}}_{ZZ} &= \tilde{\kappa}_{ZZ} + \frac{Q_f e}{g^Z_f}\tilde{\kappa}_{Z\gamma} \end{aligned}$$

- $\lambda = \pm 1$ and $\sigma = \pm 1$ are, respectively, the helicities of the Z-boson and initial-state fermions, $g^Z_f = g(T^f_3 - Q_f s^2_{\theta_W})/c_{\theta_W}$
- Leading SM is longitudinal ($\lambda = 0$), Leading effect of $\kappa_{WW}, \kappa_{ZZ}, \tilde{\kappa}_{ZZ}$ is in the transverse-longitudinal (LT) interference, LT term vanishes if we aren't careful

Helicity Amplitudes

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

$$\mathcal{A}(\hat{s},\Theta,\theta,\varphi) = \frac{-ig_\ell^V + \delta g_\ell^V}{\Gamma_V} \sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s},\Theta) d_{\lambda,1}^{J=1}(\theta) e^{i\lambda\hat{\varphi}}$$

- $d_{\pm1,1}^{J=1} = \tau\frac{1\pm\tau\cos\theta}{\sqrt{2}}$, $d_{0,1}^{J=1} = \sin\theta$ are the Wigner functions, τ is lepton helicity, Γ_V is the V-width and $g_f^Z = g(T_3^f - Q_f s_{\theta_W}^2)/c_{\theta_W}$ and $g_f^W = g/\sqrt{2}$
- $\hat{\varphi} \to$ azimuthal angle of positive helicity lepton, $\hat{\theta} \to$ its polar angle in Z-rest frame
- Polarisation of lepton is experimentally not accessible

$$\mathcal{A}_0 \sim \sin\Theta\sin\theta$$
$$\mathcal{A}_+ \sim (1+\cos\Theta)(1+\cos\theta)e^{i\varphi}$$
$$\mathcal{A}_- \sim (1-\cos\Theta)(1-\cos\theta)e^{-i\varphi}$$

Helicity Amplitudes: Angular Moments

- 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 $\rightarrow$ $(\hat{\theta}, \hat{\varphi}) \rightarrow (\pi - \theta, \pi + \varphi) \rightarrow$ Following 9 coefficients are 9 angular moments for $pp \rightarrow Z(\ell\ell)h$

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

See also [Azatov, Elias-Miro, Reyimuaji, Venturini; 2017]

Differential in angles: Method of moments

- An analog of Fourier analysis utilised to extract the aforementioned angular moments
- Our squared amplitude can be parametrised as, $|\mathcal{A}|^2 = \sum_i a_i(E) f_i(\Theta, \theta, \varphi)$
- We look for weight functions, $w_i(\Theta, \theta, \varphi)$, such that $< w_i | f_i >= \int d(\Theta, \theta, \varphi) w_i f_j = \delta_{ij}$
- One can then pick out the angular moments, a_i as $a_i = \int d(\Theta, \theta, \varphi) |\mathcal{A}|^2 w_i$

Differential in angles: Method of moments

- For the set of basis functions, we get the following matrix

$$M = \begin{pmatrix} \frac{512\pi}{225} & 0 & \frac{128\pi}{25} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{8\pi}{9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{128\pi}{25} & 0 & \frac{6272\pi}{225} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{16\pi}{9} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{16\pi}{225} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{16\pi}{9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{16\pi}{225} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{256\pi}{225} \end{pmatrix}$$

- $w_i \propto f_i$ except for $i = 1, 3$
- We rotate the (1,3) system to an orthogonal basis
- Using discrete method, we find: $a_i(M) = \frac{\hat{N}}{N} \sum_{n=1}^{N} w_i(\Theta_n, \theta_n, \varphi_n)$
- Events divided in bins of final state invariant mass ($M \to$ central value of bin), $N(M)(N(\hat{M})) \to$ number of MC (actual) events in that bin for a fixed integrated luminosity

Differential in angles: Constraining the LT terms

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

Table: Contribution of the different anomalous couplings to the angular coefficients up to linear order. Contributions subdominant in $\gamma=\sqrt{\hat{s}}/(2m_V)$ are neglected, with the exception of the next-to-leading EFT contribution to a_{LL}, which we retain in order to keep the leading effect of the $\delta\hat{g}^h_{VV}$ term. $\mathcal{G}=gg^Z_f\sqrt{(g^Z_{l_L})^2+(g^Z_{l_R})^2}/(c_{\theta_W}\Gamma_Z)$.

Differential in angles: Constraining the LT terms

- As anticipated, 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 $\tilde{\kappa}_{ZZ}$?

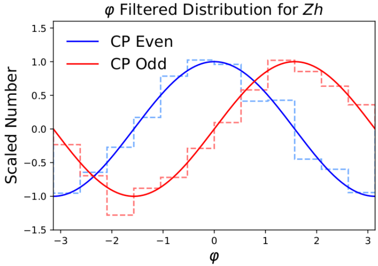
  A: Simplified approach $\rightarrow$ Flip sign in regions to maintain positive $\sin 2\theta \sin 2\Theta$

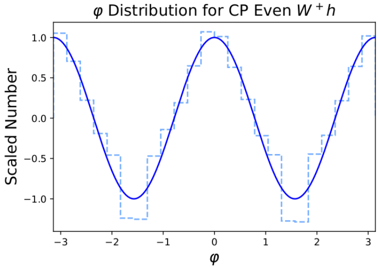
  A: Sophisticated approach $\rightarrow$ Use method of moments
- Expect $\cos\varphi$ distribution for CP-even and $\sin\varphi$ distribution for CP-odd

Differential in angles: Constraining the LT terms

Q: Are the LO theoretical shapes preserved upon the inclusion of NLO effects, radiations, showering, experimental cuts, etc.?

A: For the azimuthal angles, they are.

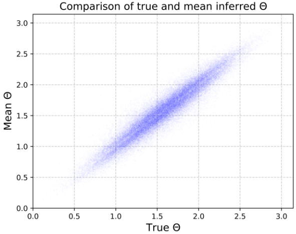


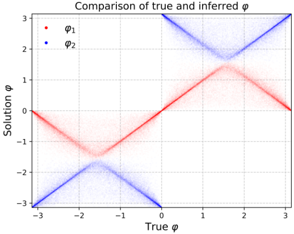


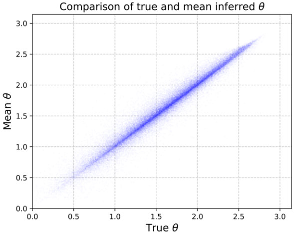
[SB, Gupta, Reiness, Spannowsky; 2019], [SB, Gupta, Reiness, Seth, Spannowsky; 2019]

Differential in angles: Reconstruction of angles for *Wh*

- Ambiguity in neutrino p_z





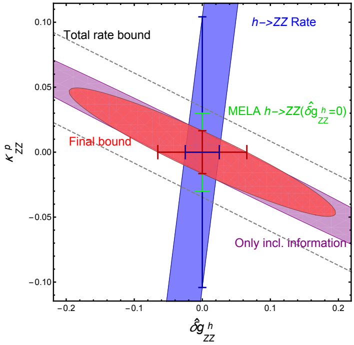


Results: Contact terms

- We have limited our calculations to include only the interference terms
- The four-point contact vertex is constrained upon using the E^2 dependent terms
- The a_{LL} term dominates at high energies $\rightarrow |g^h_{WQ}| < 6 \times 10^{-4}$ and $\rightarrow |g^h_{Zf}| < 4 \times 10^{-4}$ at $\mathcal{L} = 3$ ab^{-1}

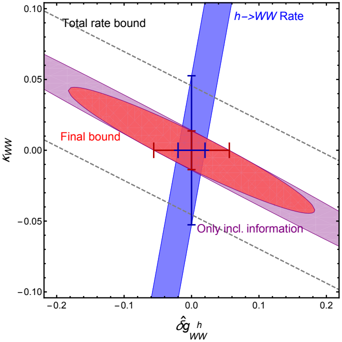
Results: *Zh*

- Method of moments used to constrain the other couplings
- We obtain percent level bounds on κ_{ZZ} and in the $(\kappa_{ZZ}, \delta g^h_{ZZ})$ plane
- Competitive and complementary bounds to previous analyses
- Independent bound on the *CP*-odd coupling, $|\tilde{\kappa}^{\mathbf{p}}_{ZZ}| < 0.03$



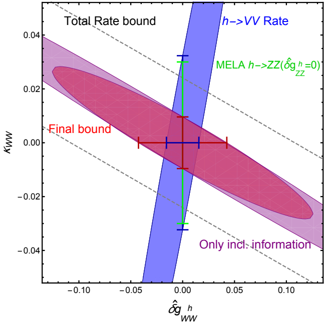
Results: *Wh*

- We obtain percent level bounds on κ_{WW} and in the $(\kappa_{WW}, \delta g^h_{WW})$ plane
- Competitive and complementary bounds to previous analyses
- Independent bound on the *CP*-odd coupling, $|\tilde{\kappa}^{\mathbf{p}}_{WW}| < 0.04$



Results: Combination

- Upon assuming a linearly realised electroweak symmetry and correlations, we can combine the above bounds



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 $G^0 h$, $G^+ h$, $G^+ G^-$ 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]

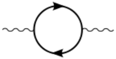
Summary and conclusions

- 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 and sophisticated techniques like the Method of moments
- Zh, Wh, WW and WZ are important channels to disentangle various directions in the EFT space. They are intrinsically correlated
- Studying complementary directions like the *WBF* is also important [Araz, SB, Gupta, Spannowsky; (in final stages)]
- Orders of magnitude over LEP seen at HL-LHC and FCC-hh studies
- Combining FCC-ee and FCC-he will be very important

¡Muchas gracias! Stay safe, stay positive and stay healthy.

Backup Slides

STU oblique parameters



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

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

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.

VH: Relations to the Warsaw Basis

$$
\begin{aligned}
g^h_{Wf} &= \sqrt{2}g\frac{v^2}{\Lambda^2}c^{(3)}_{HF}, \quad \delta\hat{g}^h_{WW} = \frac{v^2}{\Lambda^2}\left(c_{H\Box} - \frac{c_{HD}}{4}\right) \\
\kappa_{WW} &= \frac{2v^2}{\Lambda^2}c_{HW}, \quad \tilde{\kappa}_{WW} = \frac{2v^2}{\Lambda^2}c_{H\tilde{W}} \\
\delta g^Z_f &= -\frac{g' Y_f}{c_{\theta_W}}c_{WB}\frac{v^2}{\Lambda^2} - \frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T^f_3|c^{(1)}_{HF} - T^f_3 c^{(3)}_{HF} + (1/2 - |T^f_3|)c_{Hf})c_{\theta_W} \\
&+ \frac{\delta m^2_Z}{m^2_Z}\frac{g}{2c_{\theta_W}s^2_{\theta_W}}(T_3 c^2_{\theta_W} + Y_f s^2_{\theta_W}) \\
\delta\hat{g}^h_{ZZ} &= \frac{v^2}{\Lambda^2}\left(c_{H\Box} + \frac{c_{HD}}{4}\right), \quad g^h_{Zf} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T^f_3|c^{(1)}_{HF} - T^f_3 c^{(3)}_{HF} + (1/2 - |T^f_3|)c_{Hf}) \\
\kappa_{ZZ} &= \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{HW} + s^2_{\theta_W}c_{HB} + s_{\theta_W}c_{\theta_W}c_{HWB}) \\
\tilde{\kappa}_{ZZ} &= \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{H\tilde{W}} + s^2_{\theta_W}c_{H\tilde{B}} + s_{\theta_W}c_{\theta_W}c_{H\tilde{W}B}), \quad \delta\hat{g}^h_{bb} = yyyc_{y_b}
\end{aligned}
$$

BDRS: An aside

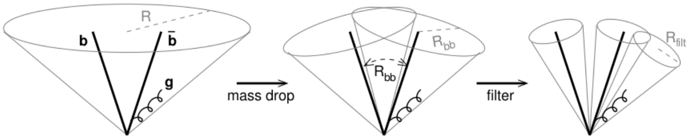


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to $R_{\rm filt}$ 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 $y_{\rm cut}$:

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, $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2}\Delta R_{j_1,j_2}^2 > y_{\rm cut}$, 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), $R_{b\bar{b}} \gtrsim 2m_H/p_T$ 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, $R_{\rm filt} < R_{b\bar{b}}$, 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 $R_{\rm filt} = \min(0.3, R_{b\bar{b}}/2)$ to be rather effective. We also require the two hardest of the subjets to have the b tags.

ZH: Four directions in the EFT space (SILH Basis)

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

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)]

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)]