Some (limited) perspectives on EFT phenomenology

Shankha Banerjee

IPPP, Durham University

September 20, 2019

SMEFT motivation

- Many reasons to go beyond the SM, *viz.* gauge hierarchy, neutrino mass, dark matter, baryon asymmetry etc. [See Jakub Scholtz's and Julia Stadler's slides for a concrete overview]
- Plethora of BSM theories to address these issues
- Two phenomenological approaches:
  - *Model dependent:* study the signatures of each model individually
  - *Model independent (or is it really?):* 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
- Bigger theory (either weakly or strongly coupled) assumed to supersede SM above 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

- Some of the EFT operators show energy growth $\sim (E/\Lambda)^n$ and effects can be seen in tails
- Have to take care of unitarity $\rightarrow$ take proper cut-off [More later]
- 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

  [For a detailed experimental account on Higgs EFT: $H \rightarrow \not{E}_T$, Differential Higgs p_T ($h \rightarrow \gamma\gamma/ZZ^*$), $Vh \rightarrow Vb\bar{b}$, $gg \rightarrow hh$ etc please see N. Wardle's 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

HL-LHC vs. LEP

- Question 1: *Can HL-LHC compete with LEP for precision physics?*
- Question 2: *Can we obtain new information from the HL-LHC that was not obtained from LEP?*
- Expansion of many EFT operators show that many of the Higgs anomalous couplings were already constrained at LEP
- Same operators modify both the Higgs and the EW couplings
- Can we gain anything new? Perhaps upon going to very high energies

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 being probed at the LHC
- 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 only 18 independent operators from which the aforementioned vertices ensue

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

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

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

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 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 $(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$
- 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

Classification of anomalous Higgs interactions

- The following terms are not constrained by LEP. First time probed at the LHC

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

- In contrast, the following interactions were constrained by LEP

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

[Pomarol, 2014]

Couplings constrained by LEP

- The coefficients of the following

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

can be written as

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

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

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

[Gupta, Pomarol, Riva, 2014]

Proof of principle

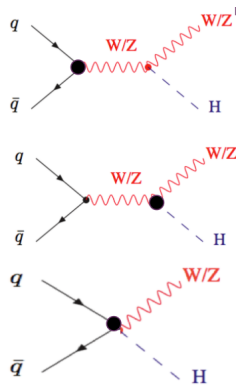
- If one of these predictions is not confirmed then either
- Our Higgs is not a part of the doublet
- Λ may not be very high and D8 operators need to be seriously considered

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

- The following interactions contribute in the unitary gauge



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

The leading effect comes from contact interaction at high energies

The energy growth occurs because there is no propagator

See J. Reiness' slides for the constraints on $\kappa_{ZZ}, \tilde{\kappa}_Z Z \to CP$-odd admixture?

$$Z_T h : g_f^Z \frac{\epsilon^* \cdot J_f}{v} \frac{2m_Z^2}{\hat{s}} \left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \kappa_{ZZ} \right) \frac{\hat{s}}{2m_Z^2} \right],$$
$$Z_L h : g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right],$$
$$W_T h : g_f^W \frac{\epsilon^* \cdot J_f}{v} \frac{2m_W^2}{\hat{s}} \left[1 + \left(\frac{g_{Wff'}^h}{g_f^W} - \kappa_{WW} \right) \frac{\hat{s}}{2m_W^2} \right],$$
$$W_L h : g_f^W \frac{q \cdot J_f}{v} \frac{2m_W}{\hat{s}} \left[1 + \frac{g_{Wff'}^h}{g_f^W} \frac{\hat{s}}{2m_W^2} \right],$$

[SB, Englert, Gupta, Spannowsky, 2018]

Higgs-Strahlung: Operators at play

SILH Basis	Warsaw Basis
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_L = (\bar{Q}_L \gamma^\mu Q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	

Precision measurement: LHC vs LEP

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

$$g_{Zd_L d_L}^h = \frac{g}{c_{\theta_W}} \left((c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$

- 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

Moral of the story

- High energies and high luminosities essential in order for LHC to compete with LEP
- Higher energy colliders will yield even better sensitivity

The EFT space directions

- δg_f^Z and $\delta g_{ZZ}^h \rightarrow$ 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

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

$$g_{\mathbf{d}}^Z = g_{Zd_L}^h + \frac{g_{d_R}^Z}{g_{d_L}^Z} g_{Zd_R}^h \qquad g_{\mathbf{p}}^Z = g_{\mathbf{u}}^Z + \frac{\mathcal{L}_d(\hat{s})}{\mathcal{L}_u(\hat{s})} g_{\mathbf{d}}^Z \qquad g_f^Z = g(T_3^f - Q_f s_{\theta_W}^2)/c_{\theta_W}$$

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

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

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

EFT validity

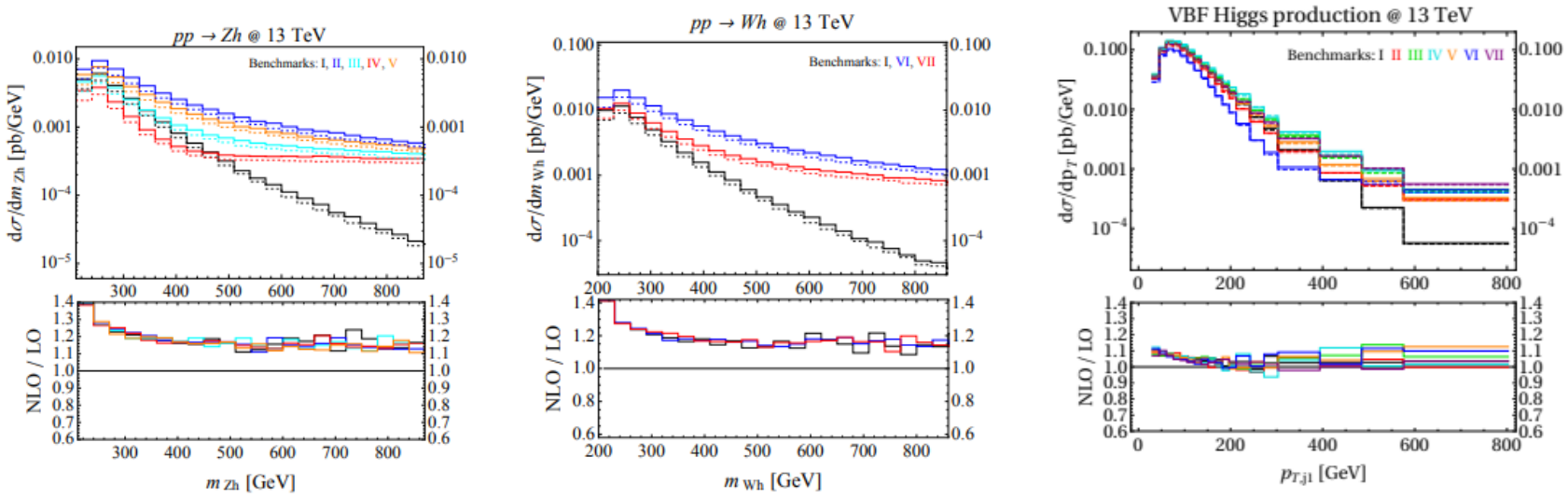
- We estimate the scale of new physics for a given δg^h_{Zf}
- Example: Heavy $SU(2)_L$ triplet (singlet) vector W'^a (Z') couples to SM fermion current $\bar{f}\sigma^a\gamma_\mu f$ ($\bar{f}\gamma_\mu f$) with g_f and to the Higgs current $iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H$ ($iH^\dagger\overleftrightarrow{D}_\mu H$) with g_H

$$g^h_{Zu_L,d_L} \sim \frac{g_H g^2 v^2}{2\Lambda^2},$$

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

- $\Lambda \rightarrow$ 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

$pp \to Zh/Wh/VBF$ at NLO QCD



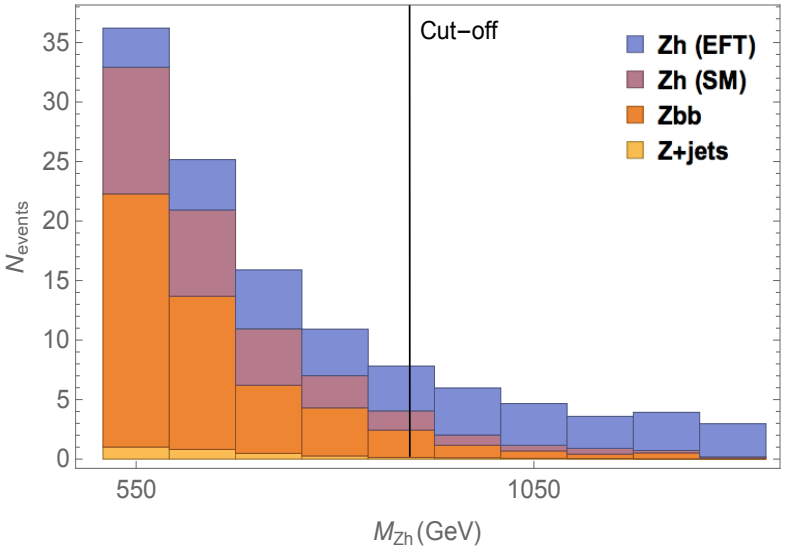
[Greljo, Isidori, Lindert, Marzocca, Zhang, 2017]

Important to consider NLO EW effects in the tails of the distributions for SMEFT studies [SB, Schönherr, Spannowsky; Upcoming]

[Also see Hannes Mildner's slides]

$pp \to Zh$ 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

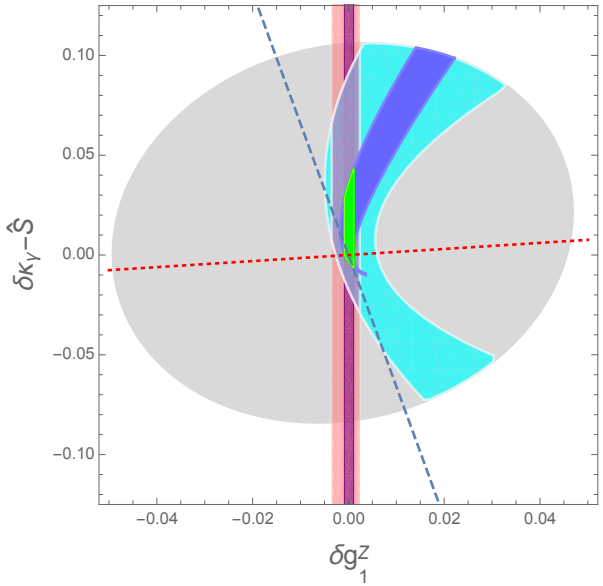


Cuts	Zbb	Zh (SM)
At least 1 fat jet with 2 B-mesons with $p_T > 15$ GeV	0.23	0.41
2 OSSF isolated leptons	0.41	0.50
80 GeV $< M_{\ell\ell} <$ 100 GeV, $p_{T,\ell\ell} > 160$ GeV, $\Delta R_{\ell\ell} > 0.2$	0.83	0.89
At least 1 fat jet with 2 B-meson tracks with $p_T > 110$ GeV	0.96	0.98
2 Mass drop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

[SB, Englert, Gupta, Spannowsky, 2018]

$pp \to Zh$ at high energies

- Performed a two-parameter χ^2-fit (at 300 fb^{-1})



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

[SB, Englert, Gupta, Spannowsky, 2018]

The four di-bosonic channels

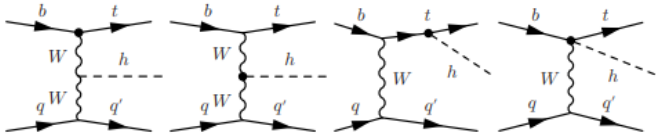
- The four directions, *viz.*, Zh, Wh, W^+W^- and $W^\pm Z$ can be expressed (at high energies) respectively as $G^0 h$, $G^+ h$, $G^+ G^-$ and $G^\pm G^0$ and the Higgs field can be written as
$$\begin{pmatrix} G^+ \\ \frac{h+iG^0}{2} \end{pmatrix}$$
- These four final states are intrinsically connected
- 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]

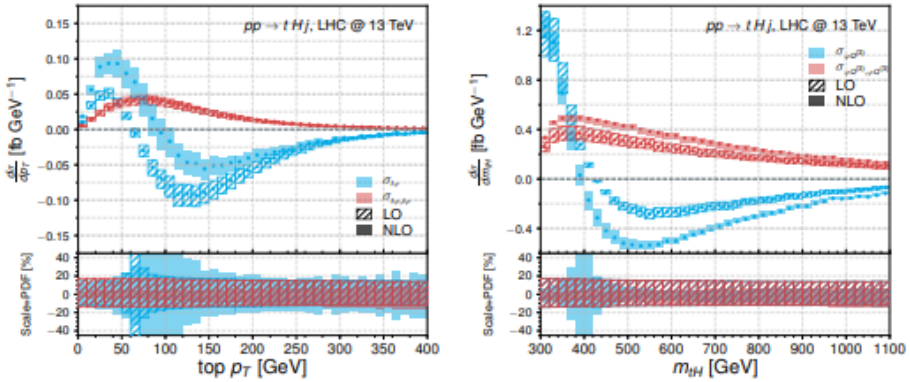
EFT in the top sector

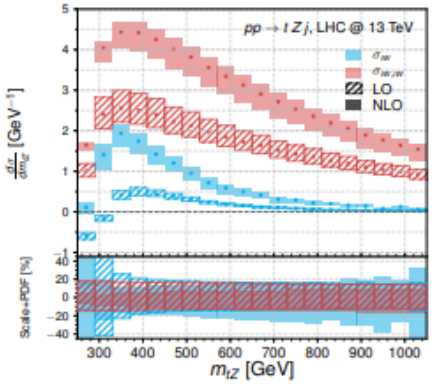
- Channels include: *tZj*, *thj* [Degrande, Maltoni, Mimasu, Vryonidou, Zhang, 2018]. Constrain couplings like $tbW, hW^+W^-, t\bar{t}h, t\bar{b}W^-h$

$\mathcal{O}_W$	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu \varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_i) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}_i \gamma^\mu \tau^I q_i) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t)\tilde{\varphi} W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_i) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$(\bar{q}_i \gamma_\mu \tau_I q_i)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{tG}$	$i(\bar{Q}\sigma^{\mu\nu} T_A t)\tilde{\varphi} G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$(\bar{q}_i \gamma_\mu \tau_I T_A q_i)(\bar{Q}\gamma^\mu \tau^I T^A Q)$

Table 1: Dim-6 operators relevant for the tZj and tHj processes in the Warsaw basis. The first set corresponds to bosonic operators, then two-fermion ones, and, finally, four fermion operators.







EFT in the top sector

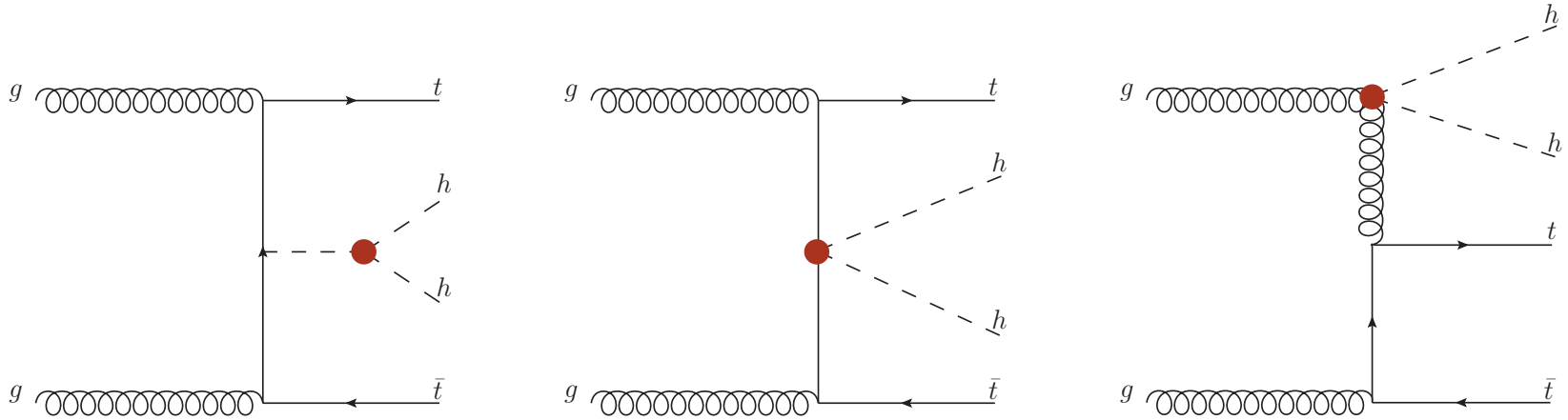
- Other channels include $t\bar{t}Z, t\bar{t}\gamma, t\bar{t}\mu^+\mu^-$ [Bylund, Maltoni, Tsinikos, Vryonidou, Zhang, 2016]
  [See Tom Stevenson's slides for more details on the $t\bar{t}Z$ production in SMEFT]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

- Four fermion operators constrain interactions like $t\bar{t}b\bar{b}, t\bar{t}t\bar{t}$
  [DHondt, Mariotti, Mimasu, Moortgat, Zhang, 2018]

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at 100 TeV

- Feynman diagrams showing the impact of the three effective vertices, *viz.*, hhh, $t\bar{t}hh$ and $gghh$



Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at 100 TeV

[SB, F. Krauss, M. Spannowsky; 2019]

- Upon taking $\kappa_{t\bar{t}hh} = 0$, one obtains (using the CLs method) at 68% CL

$$-3.09 < \kappa_\lambda < 2.44 \quad 3/\mathrm{ab}$$

$$-2.56 < \kappa_\lambda < 1.64 \quad 30/\mathrm{ab}$$

- Upon taking $\kappa_\lambda = 1$, one obtains (using the CLs method) at 68% CL

$$-0.53\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.89\ \mathrm{TeV}^{-1} \quad 3/\mathrm{ab}$$

$$-0.25\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.61\ \mathrm{TeV}^{-1} \quad 30/\mathrm{ab}$$

- Ultimate goal is to perform a global fit using the $pp \to hh$, $pp \to hhj$, $pp \to hhjj$ and $pp \to t\bar{t}hh$ with all these couplings to find correlated bounds

Neutral triple gauge couplings

- nTGCs first arise at dimension-8 in the SMEFT [Hagiwara, Peccei, Zeppenfeld, Hikasa, 1986; Gounaris, Layssac, Renard, 2000]

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,P) = \frac{i(s-m_V^2)}{m_Z^2}\left[f_4^V(P^\alpha g^{\mu\beta}+P^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right] ,$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = \frac{i(s-m_V^2)}{m_Z^2}\Big\{h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2}P^\alpha[(Pq_2)g^{\mu\beta}-q_2^\mu P^\beta] - h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\Big\} ,$$

- The operators [Degrande, 2013]

$$\mathcal{O}_{BW} = i\,H^\dagger B_{\mu\nu}W^{\mu\rho}\{D_\rho,D^\nu\}\,H, \qquad \mathcal{O}_{\widetilde{B}W} = i\,H^\dagger \widetilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho,D^\nu\}\,H,$$

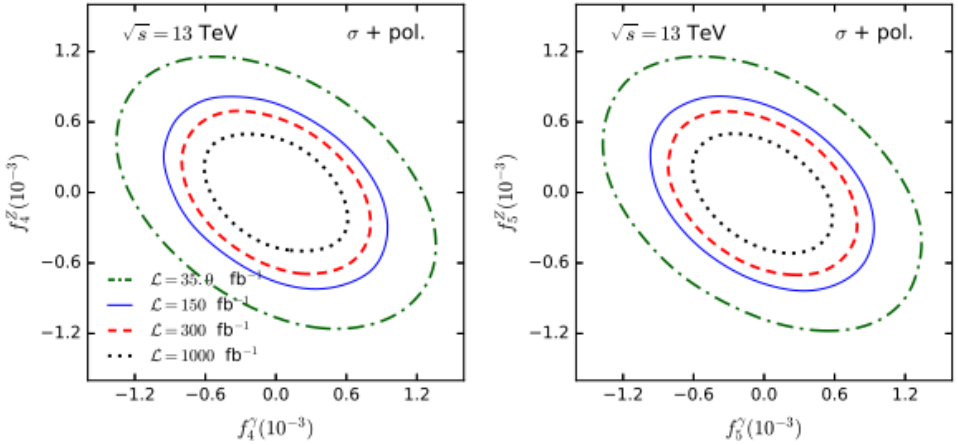
$$\mathcal{O}_{WW} = i\,H^\dagger W_{\mu\nu}W^{\mu\rho}\{D_\rho,D^\nu\}\,H, \qquad \mathcal{O}_{B\widetilde{W}} = i\,H^\dagger B^{\mu\nu}\widetilde{W}_{\mu\rho}\{D_\rho,D^\nu\}\,H,$$

$$\mathcal{O}_{BB} = i\,H^\dagger B_{\mu\nu}B^{\mu\rho}\{D_\rho,D^\nu\}\,H. \qquad \mathcal{O}_{\widetilde{W}W} = i\,H^\dagger \widetilde{W}_{\mu\nu}W^{\mu\rho}\{D_\rho,D^\nu\}\,H,$$

$$\mathcal{O}_{\widetilde{B}B} = i\,H^\dagger \widetilde{B}_{\mu\nu}B^{\mu\rho}\{D_\rho,D^\nu\}\,H.$$

Neutral triple gauge couplings

- Constraints derived by studying the $ZZ/Z\gamma$ channels [Rahaman, Singh, 2019]



- These operators assume 3 gauge boson vertex modification $\rightarrow$ s-channel modification $\rightarrow$ only $J = 1$ amplitude modified $\rightarrow$ Only LT di-boson final state possible $\rightarrow$ Suppressed by m_Z/E or smaller
- How about $\pm\mp$ ($J = 2$) di-boson production? [Bellazzini, Riva, 2018]

$$\mathcal{O}^{(8)}_{\psi B} = -\frac{1}{4}\left(i\bar{\psi}\gamma^{\{\rho}D^{\nu\}}\psi + \text{h.c.}\right) B_{\mu\nu}B^{\mu}{}_{\rho}$$

$$\mathcal{O}^{(8)}_{\psi W} = -\frac{1}{4}\left(i\bar{\psi}\gamma^{\{\rho}D^{\nu\}}\psi + \text{h.c.}\right) W^{a}_{\mu\nu}W^{a\,\mu}_{\rho} \qquad \hat{\mathcal{O}}^{(8)}_{QH} = \frac{1}{2}\left(i\bar{Q}\sigma^{a}\gamma^{\{\mu}D^{\nu\}}Q + \text{h.c.}\right) D_{\mu}H^{\dagger}\sigma^{a}D_{\nu}H$$

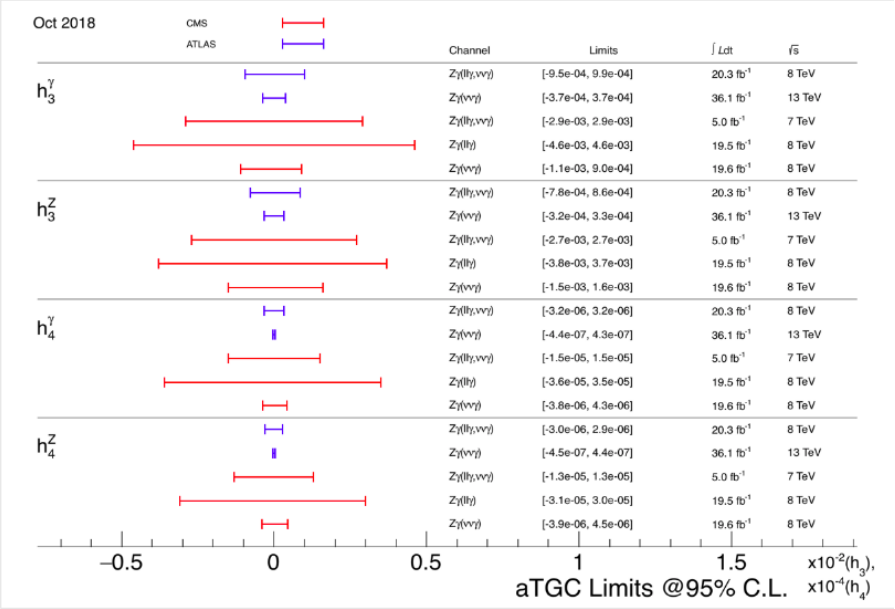
$$\mathcal{O}^{(8)}_{\psi H} = \frac{1}{2}\left(i\bar{\psi}\gamma^{\{\mu}D^{\nu\}}\psi + \text{h.c.}\right) D_{\mu}H^{\dagger}D_{\nu}H \qquad \hat{\mathcal{O}}^{(8)}_{QBW} = -\frac{1}{4}\left(i\bar{Q}\sigma^{a}\gamma^{\{\rho}D^{\nu\}}Q + \text{h.c.}\right) B_{\mu\nu}W^{a\,\mu}_{\rho}$$

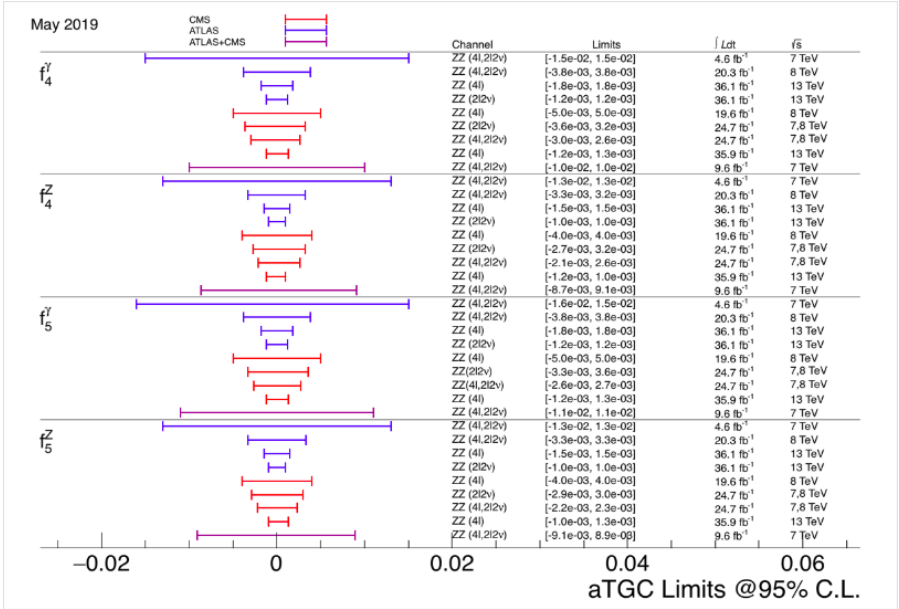
Invokes $Z_T Z_T$ and $Z_L Z_L$ and some have energy growth as well

Neutral triple gauge couplings

- Experimental bounds:

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC





- Q: Some of the D8 operators modifying nTGCs also affect cTGCs. Why not study these two sets in conjunction to provide better constraints?

[See H. Mildner's talk for more details on TGCs with EFT]

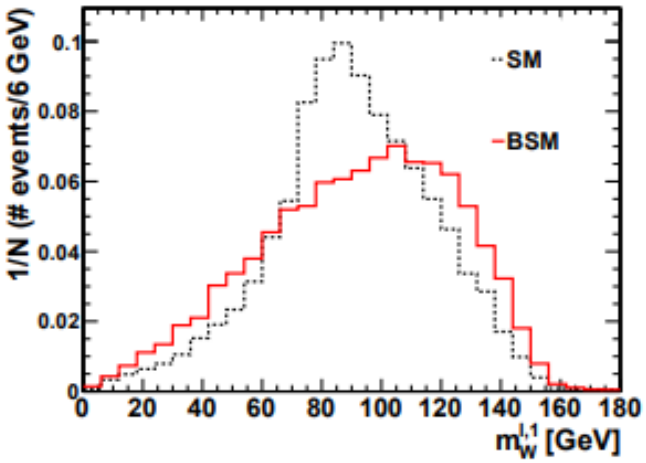
Beyond SMEFT: νSMEFT

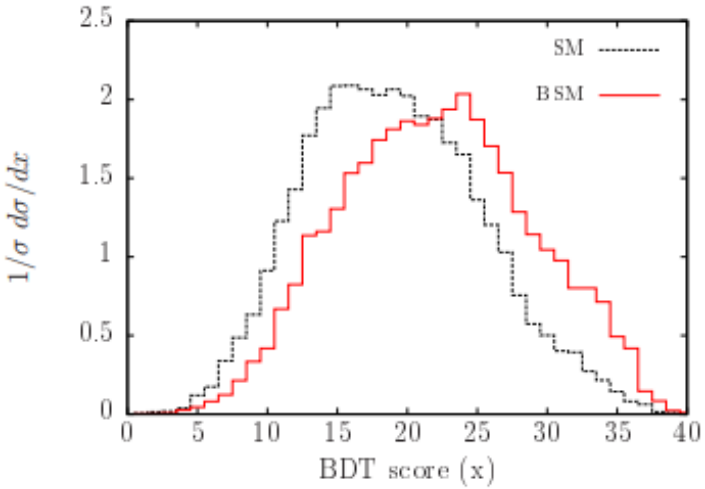
- SMEFT at dimension 5, the Weinberg operator $\frac{1}{\Lambda}(LH)^c(LH)$ gives mass to Majorana neutrinos [More details in Jakub Scholtz's slides]
- For Dirac neutrinos, SMEFT needs to be modified with a right-handed neutrino, N

	Operator	Notation	Operator	Notation
SF	$(\overline{l_L}N)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{lNH}$ (+h.c.)		
	$(\overline{N}\gamma^\mu N)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HN}$	$(\overline{N}\gamma^\mu e_R)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{HNe}$ (+h.c.)
	$(\overline{l_L}\sigma_{\mu\nu}N)\tilde{H}B^{\mu\nu}$	$\mathcal{O}_{NB}$ (+h.c.)	$(\overline{l_L}\sigma_{\mu\nu}N)\sigma_I\tilde{H}W^{I\mu\nu}$	$\mathcal{O}_{NW}$ (+h.c.)
RRRR	$(\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{NN}$		
	$(\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{eN}$	$(\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN}$
	$(\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu e_R)$	$\mathcal{O}_{duNe}$ (+h.c.)
LLRR	$(\overline{l_L}\gamma_\mu l_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{lN}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{qN}$
LRRL	$(\overline{l_L}N)\epsilon(\overline{l_L}e_R)$	$\mathcal{O}_{lNle}$ (+h.c.)	$(\overline{l_L}N)\epsilon(\overline{q_L}d_R)$	$\mathcal{O}_{lNqd}$ (+h.c.)
	$(\overline{l_L}d_R)\epsilon(\overline{q_L}N)$	$\mathcal{O}_{ldqN}$ (+h.c.)	$(\overline{q_L}u_R)(\overline{N}l_L)$	$\mathcal{O}_{quNl}$ (+h.c.)

- Many of these operators can be constrained via: $\ell + \not{E}_T$ searches, monojet searches, pion decays, τ decays, rare top decays

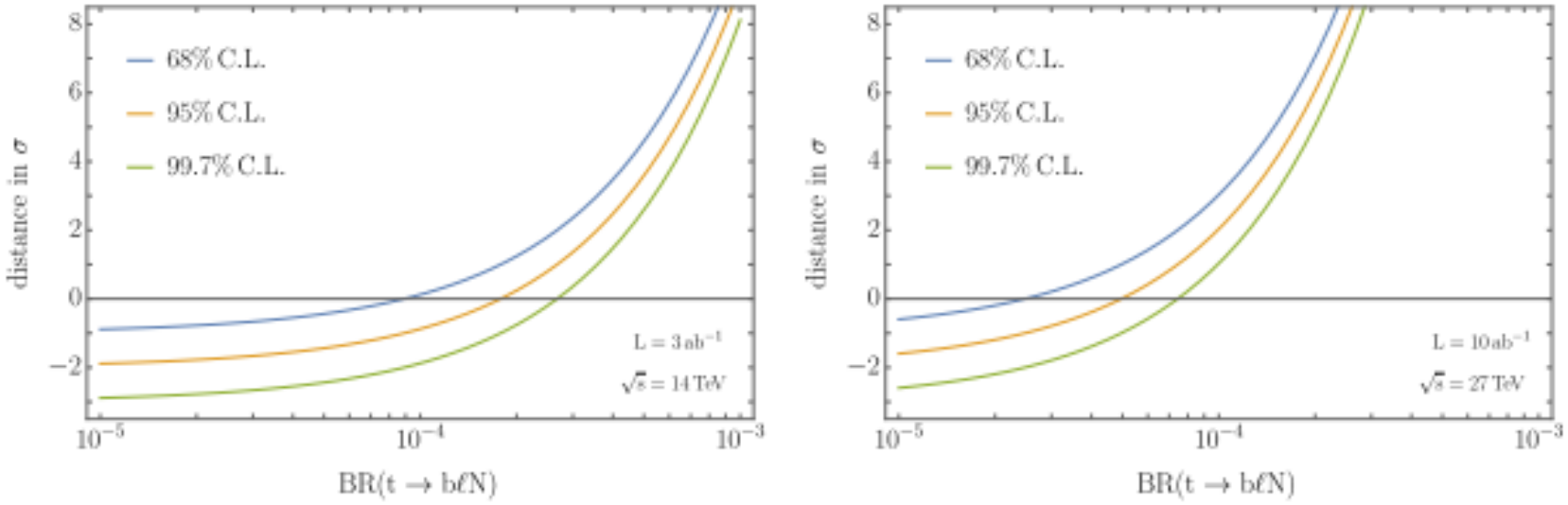
Beyond SMEFT: νSMEFT (Example: $t \to b\ell N$)





- The reconstructed invariant masses $m_{b\ell N}$ for the two solutions to the W-mass become the input to the MVA
- We construct an asymmetry using the BDT score. Several systematic uncertainties cancel in this ratio.

Beyond SMEFT: νSMEFT (Example: $t \to b\ell N$)



- Branching ratio as low as 2×10^{-4} (5×10^{-5}) can be tested at the 14 TeV (27 TeV) at 95% CL with 3 (10) ab^{-1} luminosity
- The limit on the scale is ~ 1 TeV upon assuming 3 generations of N and when $\ell = e, \mu$

  [Alcaide, SB, Chala, Titov, 2019]

Beyond SMEFT: νSMEFT (bounds on operators for 1 right handed N)

Operator	$\alpha_{\max}$ for $\Lambda = 1$ TeV	$\Lambda_{\min}$ [TeV] for $\alpha = 1$	Observable
$\mathcal{O}_{eN}^{i3}$	3.0 (2.9)	0.58 (0.59)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{dN}^{11}$	0.72	1.2	monojet
$\mathcal{O}_{uN}^{11}$	0.48	1.4	monojet
$\mathcal{O}_{duNe}^{11i}$	0.11 (0.16)	3.0 (2.5)	$\ell + \not{E}_T$
$\mathcal{O}_{duNe}^{113}$	0.15	2.6	$\tau + \not{E}_T$
$\mathcal{O}_{duNe}^{33i}$	**9.2 (9.2)**	**0.33 (0.33)**	$\boldsymbol{t \to b\ell + \text{inv}}$

Operator	$\alpha_{\max}$ for $\Lambda = 1$ TeV	$\Lambda_{\min}$ [TeV] for $\alpha = 1$	Observable
$\mathcal{O}_{lN}^{i3}$	3.0 (2.9)	0.58 (0.59)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{qN}^{11}$	0.40	1.6	monojet

Operator	$\alpha_{\max}$ for $\Lambda = 1$ TeV	$\Lambda_{\min}$ [TeV] for $\alpha = 1$	Observable
$\mathcal{O}_{lNle}^{i3}$	6.0 (5.9)	0.41 (0.41)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{lNle}^{i3i}$	6.8 (6.8)	0.38 (0.38)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{lNle}^{i33}$	6.8 (6.8)	0.38 (0.38)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{lNle}^{3ii}$	6.8 (6.8)	0.38 (0.38)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{lNle}^{3i3}$	6.8 (6.8)	0.38 (0.38)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{lNle}^{33i}$	6.0 (5.9)	0.41 (0.41)	$\tau \to \ell + \text{inv}$
$\mathcal{O}_{ldqN}^{i11}$	0.46 (0.66)	1.5 (1.2)	$\ell + \not{E}_T$
$\mathcal{O}_{ldqN}^{i33}$	**21 (21)**	**0.22 (0.22)**	$\boldsymbol{t \to b\ell + \text{inv}}$
$\mathcal{O}_{ldqN}^{311}$	0.67	1.2	$\tau + \not{E}_T$
$\mathcal{O}_{lNqd}^{i11}$	0.25 (0.36)	2.0 (1.7)	$\pi \to \ell + \text{inv}$
$\mathcal{O}_{lNqd}^{i33}$	**21 (21)**	**0.22 (0.22)**	$\boldsymbol{t \to b\ell + \text{inv}}$
$\mathcal{O}_{lNqd}^{311}$	0.35	1.7	$\tau + \not{E}_T$
$\mathcal{O}_{quNl}^{11i}$	0.13 (0.19)	2.8 (2.3)	$\ell + \not{E}_T$
$\mathcal{O}_{quNl}^{113}$	0.19	2.3	$\tau + \not{E}_T$
$\mathcal{O}_{quNl}^{33i}$	**18 (18)**	**0.23 (0.23)**	$\boldsymbol{t \to b\ell + \text{inv}}$

νSMEFT in the $h \to \gamma(\gamma\gamma) + \not{E}_T$ has also been studied [Butterworth, Chala, Englert, Spannowsky, Titov, 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
- Zh, Wh, WW and WZ are important channels to disentangle various directions in the EFT space. They are intrinsically correlated
- Top production constrains several other SMEFT operators
- D8 operators required to probe nTGCs
- νSMEFT required to address Dirac neutrinos in the theory and provides a rich phenomenology

Backup slides

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

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L - c^3_L) \\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L + c^3_L) \\
g^h_{Zu_Ru_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^u_R \\
g^h_{Zd_Rd_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^d_R
\end{aligned}
$$

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]

$pp \to Zh$ 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]

BDRS: An aside

2

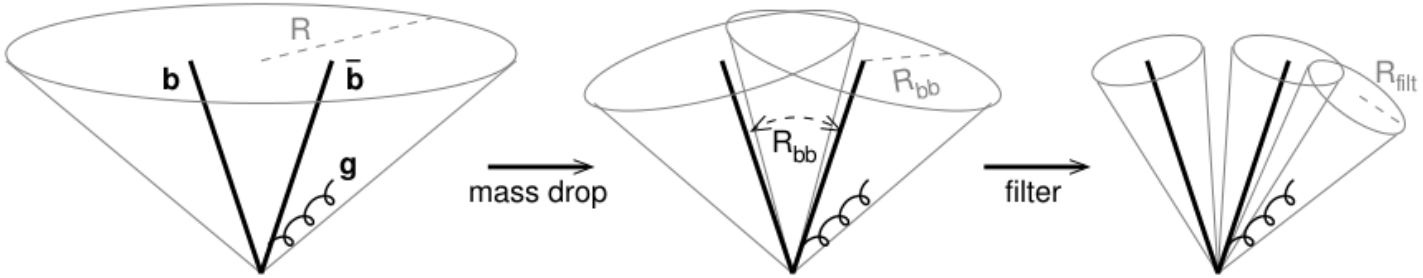


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this 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, $y = \frac{\min(p^2_{tj_1}, p^2_{tj_2})}{m_j^2} \Delta R^2_{j_1,j_2} > y_{\rm cut}$, 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, $p_T \sim 200 - 300\,$GeV because, from eq. (1), $R_{b\bar{b}} \gtrsim 2m_{\rm H}/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R^4_{b\bar{b}}$ [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.

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
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\frac{g^h_{Z d_L d_L} - g^h_{Z u_L u_L}}{\sqrt{2}}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$g^h_{Z d_L d_L}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$g^h_{Z u_L u_L}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	$g^h_{Z f_R f_R}$

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]

Non-linear EFT realisation

- Many popular BSM extensions which give rise to modification of Higgs interactions
- Composite Higgs models assume that the Higgs is a pNGB of a strongly coupled UV completion
- The electroweak chiral Lagrangian best describes the low-energy effects of a strongly-coupled embedding of the SM

$$\begin{aligned}\mathcal{L}^{\mathrm{ew}\chi} \supset \quad & - \quad V(h) + \frac{g_s^2}{48\pi^2} G^a_{\mu\nu} G_a^{\mu\nu} \left(k_g \frac{h}{v} + \frac{1}{2} k_{2g} \frac{h^2}{v^2} + \cdots \right) \\ & - \quad \frac{v}{\sqrt{2}} (\bar{u}^i_L \ \bar{d}^i_L) \Sigma \left[1 + c \frac{h}{v} + c_2 \frac{h^2}{v^2} + \cdots \right] \begin{pmatrix} y^u_{ij} u^j_R \\ y^d_{ij} d^j_R \end{pmatrix} + \mathrm{h.c.},\end{aligned}$$

with

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{m_h^2}{2v} h^3 + d_4 \frac{m_h^2}{8v^2} h^4 + \cdots \ .$$

- Here the $SU(2) \times U(1)$ symmetry is non-linearly realised $\Sigma(x) = e^{i\sigma^a \phi^a(x)/v}$ with the Goldstone bosons ϕ^a (a=1,2,3) and the Pauli matrices σ^a

Non-linear EFT realisation

- 5 vertices are of imminent importance, *viz.*, k_g, k_{2g}, c, c_2, d_3 in the top-Higgs sector
- k_g and c $\rightarrow$ can be constrained from gluon-fusion, VBF, $t\bar{t}h$ production
- k_{2g}, c_2 and d_3 $\rightarrow$ can be constrained at LO from double-Higgs processes
- To over-constrain the parameter space of $\mathcal{L}^{\mathrm{ew}\chi}$ it is necessary to access as many di-Higgs processes as possible, *viz.*, $pp \rightarrow hh, hhj, hhjj, t\bar{t}hh$
- $t\bar{t}hh$ is the only process with appreciable cross-section that has the ability to constrain c_2 at tree-level
- Here however, we will discuss in terms of the following simplified Lagrangian

$$\mathcal{L}^{\mathrm{simp}} = \mathcal{L}^{SM} + (1-\kappa_\lambda)\lambda_{\mathrm{SM}} h^3 + \kappa_{t\bar{t}hh}(\bar{t}_L t_R h^2 + \mathrm{h.c.}) - \frac{1}{8}\kappa_{\mathrm{gghh}} \mathrm{G}^{\mathrm{a}}_{\mu\nu}\mathrm{G}^{\mu\nu}_{\mathrm{a}}\mathrm{h}^2,$$

where $\lambda_{\mathrm{SM}} = \lambda v = \frac{m_h^2}{2v}$ and $\kappa_\lambda = \lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}}$

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at 100 TeV

- σ/σ_{SM} with respect to $\kappa_\lambda, \kappa_{t\bar{t}hh}, \kappa_{gghh}$
- First row shows σ/σ_{SM} at 100 TeV and at 14 TeV [Frederix *et. al.*; 2014]