Constraining certain EFT couplings at the HL-LHC and beyond

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Based on

Phys. Rev. D 98, 095012 (2018), arXiv:1807.01796
(with R. S. Gupta, C. Englert, M. Spannowsky)
Eur. Phys. J. C (2018) 78: 322, arXiv:1802.01607
(with C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky)

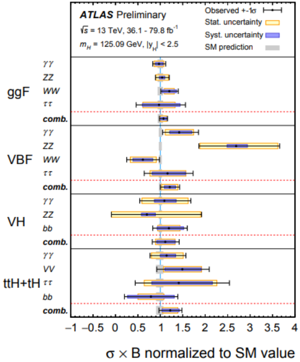
Plan of my talk

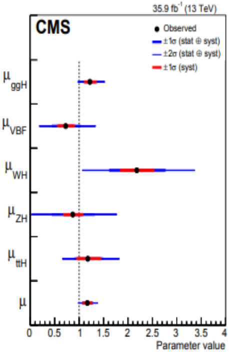
- Higgs-Strahlung at the HL-LHC and FCC-hh
- Higgs self-coupling measurement at the FCC-hh
- Summary and Conclusions

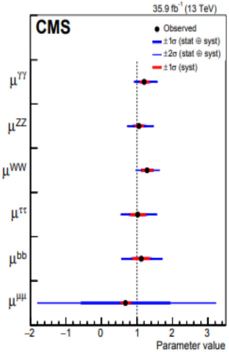
The story so far

- The nature of the discovered boson is more or less consistent with the *SM* Higgs
- Its combined (CMS + ATLAS) mass, from run-I data, is measured to be $M_h = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV in the $h \to \gamma\gamma$ and the $h \to ZZ^* \to 4\ell$ channels
- From run-II: ATLAS: $m_h = 124.97 \pm 0.24$ GeV at 36.1 fb^{-1} in $\gamma\gamma + 4\ell$ and CMS: $m_h = 125.26 \pm 0.21$ GeV at 35.9 fb^{-1} in 4ℓ
- A *CP*-even spin zero hypothesis is favoured
- If it is "the Higgs", then its mass has fixed the *SM*
- Still to be measured: $h \to Z\gamma$, $h \to \mu^+\mu^-$, λ_{hhh}
- Till a reliable measurement of self-coupling is available it is best to consider the available final states that reflect the Higgs couplings

Signal strengths @ 13 TeV







[ATLAS-CONF-2018-031, arXiv:1809.10733]

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
- 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

SMEFT motivation

- Naturalness does not provide a strict upper bound on new physics. A factor of few larger masses can lead to an exponential drop in parton luminosities
- New physics might be just lurking around outside the reach of the LHC. Upon integrating out new physics, one will encounter deviations in various couplings

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

Higgs anomalous couplings: Dimension 6 effects

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

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

[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
  $g_1^Z c_{\theta_w} Z^\mu (W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu})$
  $\kappa_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W_\mu^+ W_\nu^-$
  $\lambda_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W_\mu^{-\rho} W^+_{\rho\nu}$
- 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

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

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

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

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

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

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

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

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

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

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

[Gupta, Pomarol, Riva, 2014]

Proof of principle

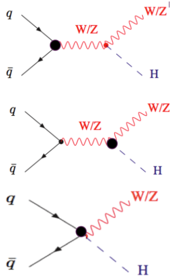
- If one of these predictions is not confirmed then either
- Our Higgs is not a part of the doublet
- Λ may not be very high and D8 operators need to be seriously considered

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

- The following interactions contribute in the unitary gauge



$$\Delta\mathcal{L}_6 \supset \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f + \delta g^W_{ud}(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.)$$

$$+ g^h_{VV}\, h \left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$

$$+ \sum_f g^h_{Zf} \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{Wud}\frac{h}{v}(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.)$$

$$+\kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \kappa_{WW}\frac{h}{v}W^{+\,\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}$$

$$Z_T h:\ g^Z_f \frac{\epsilon^*\cdot J_f}{v}\frac{2m^2_Z}{\hat{s}}\left[1 + \left(\frac{g^h_{Zff}}{g^Z_f} - \kappa_{ZZ}\right)\frac{\hat{s}}{2m^2_Z}\right],$$

$$Z_L h:\ g^Z_f \frac{q\cdot J_f}{v}\frac{2m_Z}{\hat{s}}\left[1 + \frac{g^h_{Zff}}{g^Z_f}\frac{\hat{s}}{2m^2_Z}\right],$$

$$W_T h:\ g^W_f \frac{\epsilon^*\cdot J_f}{v}\frac{2m^2_W}{\hat{s}}\left[1 + \left(\frac{g^h_{Wff'}}{g^W_f} - \kappa_{WW}\right)\frac{\hat{s}}{2m^2_W}\right],$$

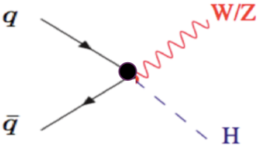
$$W_L h:\ g^W_f \frac{q\cdot J_f}{v}\frac{2m_W}{\hat{s}}\left[1 + \frac{g^h_{Wff'}}{g^W_f}\frac{\hat{s}}{2m^2_W}\right],$$

[SB, Englert, Gupta, Spannowsky, 2018]

Higgs-Strahlung at the LHC

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

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



$$
Z_L h : \; g^Z_f \frac{q \cdot J_f}{v}\frac{2m_Z}{\hat{s}} \;\; \left[1 + \frac{g^h_{Zff}}{g^Z_f}\frac{\hat{s}}{2m^2_Z}\right]
$$

[SB, Englert, Gupta, Spannowsky, 2018]

Higgs-Strahlung: Operators at play

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

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)

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}+\frac{s^2_{\theta_W}}{3})\delta g_1^Z + W + \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zd_Ld_L} &= \frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}-\frac{s^2_{\theta_W}}{3})\delta g_1^Z + W - \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zu_Ru_R} &= -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g_1^Z - Y)\\
g^h_{Zd_Rd_R} &= \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g_1^Z - Y)
\end{aligned}
$$

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

Precision measurement: LHC vs LEP

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

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

- 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

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

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

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

$$g^Z_f = g(T^f_3 - Q_f s^2_{\theta_W})/c_{\theta_W}$$

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

$$\begin{aligned} g^h_{Z\mathbf{p}} &= 2\delta g^h_{Zu_L} - 1.52\ g^h_{Zd_L} - 0.90\ g^h_{Zu_R} + 0.28\ g^h_{Zd_R} \\ &\quad -0.14\ \delta\kappa_\gamma - 0.89\ \delta g^Z_1 \end{aligned}$$

$$g^h_{Z\mathbf{p}} = -0.14\ (\delta\kappa_\gamma - \hat{S} + Y) - 0.89\ \delta g^Z_1 - 1.3\ W$$

EFT validity

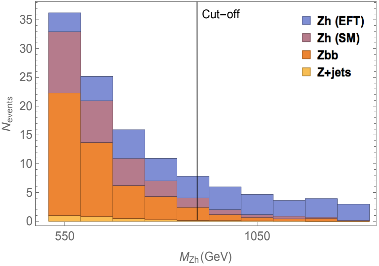
- Till now, we have dropped the $gg \to Zh$ contribution which is $\sim 15\%$ of the qq rate
- It doesn't grow with energy in presence of the anomalous couplings
- We estimate the scale of new physics for a given δg^h_{Zf}
- Example: Heavy $SU(2)_L$ triplet (singlet) vector W'^a (Z') couples to SM fermion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

$pp \to ZH$ 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]

BDRS: An aside

2

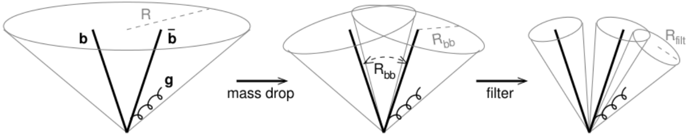


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this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

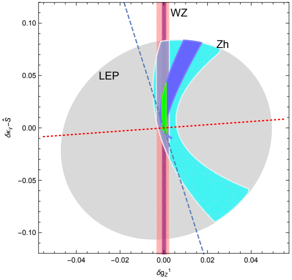
- $\sigma^{SM}_{Zh}/\sigma_{Zb\bar{b}}$ without cuts $\sim 4.6/165$
- With the cut-based analysis $\to$ 0.26
- With MVA optimisation $\to$ 0.50 [See also the recent study by Freitas, Khosa and Sanz]
- S/B changes from $1/40$ to $\mathcal{O}(1)$ $\to$ Close to 35 SM $Zh(b\bar{b}\ell^+\ell^-)$ events left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

  [SB, Englert, Gupta, Spannowsky, 2018]

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

$pp \to Zh$ at high energies

- 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.

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

	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]

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]

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)]

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
- Orders of magnitude over LEP seen at HL-LHC and FCC-hh studies
- Combining FCC-ee and FCC-he will be very important

di-Higgs: Motivation

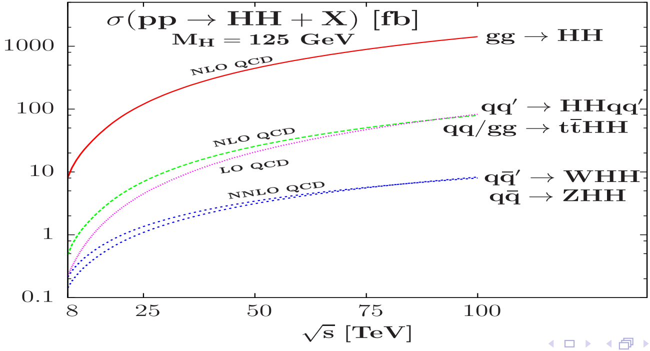
- Di-Higgs provides means to directly probe Higgs self coupling
- Indirect probe: Through radiative corrections of single Higgs productions [Goertz *et. al.*, 2013, McCullough, 2013, Degrassi *et. al.*, 2016]
- Challenging task : small di-Higgs cross-section in SM ($39.56^{+7.32\%}_{-8.38\%}$ fb at NNLO + NNLL at 14 TeV with the exact top-quark mass dependence at NLO [deFlorian *et. al.*, 2013, Borowka *et. al.*, 2016]) $\leftarrow$ partial cancellation of triangle and box diagram contributions
- LHC or 100 TeV colliders : self-coupling measurement at 10-50% precision possible $\rightarrow$ size of dataset, beam energy, control over systematics
- Assuming SM couplings, HL-LHC prediction: $-0.8 < \frac{\lambda}{\lambda_{\mathrm{SM}}} < 7.7$ at 95% C.L. [ATL-PHYS-PUB-2017-001]

di-Higgs: Motivation

- Enhancement of σ_{hh} $\rightarrow$ s-channel heavy di-Higgs resonance [xSM models *etc.*] [Mühlleitner *et. al.*, 2015; Ramsey-Musolf *et. al.*, 2016 *etc.*], new coloured particles in loops [Kribs *et. al.*, 2012, Nakamura *et. al.*, 2017] or HD operators [Nishiwaki *et. al.*, 2013] $\rightarrow$ kinematics altered $\rightarrow$ requires different experimental search strategies
- Till date $\rightarrow$ major focus on BSM di-Higgs sector $\rightarrow$ enhancement in production
- New physics can affect Higgs *decays* $\rightarrow$ exotic Higgs decays now actively studied [Curtin *et. al.*, 2015]
- $\sigma_{pp\rightarrow h} \gg \sigma_{pp\rightarrow hh}$ $\rightarrow$ expect exotic Higgs decays to show up in single Higgs channels first unless di-Higgs is enhanced considerably
- Worthwhile to consider exotic decays for di-Higgs $\rightarrow$ present bounds on variety of Higgs decays : BR very weak (10-50%) [SB, Batell, Spannowsky, 2016]

Di-Higgs production cross-sections at 14 TeV

- Di-Higgs cross-section largest in the *ggF* mode
- In *VBF* @ NLO : $2.01^{+7.6\%}_{-5.1\%}$ fb
- In *Whh* @ NNLO : $0.57^{+3.7\%}_{-3.3\%}$ fb
- In *Zhh* @ NNLO : $0.42^{+7.0\%}_{-5.5\%}$ fb
- In $qq'(gg) \to t\bar{t}hh$ @ LO : 1.02 fb [Baglio *et. al.*, 2012]



Status of the di-Higgs searches

Channel	CMS (NR) ($\times$SM)	CMS (R) [fb, (GeV)]	ATLAS (NR) ($\times$SM)	ATLAS (R) [fb, (GeV)]
$b\bar{b}b\bar{b}$	75	1500-45	13	2000-2
$b\bar{b}\gamma\gamma$	24	240-290	22	1100-120
$b\bar{b}\tau^+\tau^-$	30	3110-70 (250-900)	12.7	1780-100 (260-1000)
$\gamma\gamma WW^*$ ($\gamma\gamma\ell\nu jj$)			200	40000-6100 (260-500)
$b\bar{b}\ell\nu\ell\nu$	79	20500-800 (300-900)	300	6000-170 (500-3000)
WW^*WW^*			160	9300-2800 (260-500)

Table : Bounds on di-Higgs cross-sections (in fb) from CMS and ATLAS for non-resonant (NR) and resonant (R) double Higgs production. The numbers in brackets show the range of the heavy scalar mass considered in that particular study.

Non resonant di-Higgs production at the HL-LHC: Summary

- Bleak prospects for discovering SM non-resonant di-Higgs channel at HL-LHC with 3 ab^{-1} data
- $b\bar{b}\gamma\gamma$ is the cleanest $(S/B \sim 0.19)$ but suffers from small rate
- Combined significance $\sim 2.1\sigma$ from the aforementioned channels
- Combination to other (hadronic) channels will not drastically improve this: Still to be optimised and seen
- Purely leptonic case for $b\bar{b}WW^*$ shows promise but needs better handle over backgrounds $\rightarrow$ data driven backgrounds
- Both semi-leptonic and leptonic channels for $\gamma\gamma WW^*$ show excellent $S/B \rightarrow$ need larger luminosity (considering CMS and ATLAS datasets separately to form 6 ab^{-1}) or higher energy colliders [Adhikary, SB, Barman, Bhattacherjee, Niyogi, 2017]

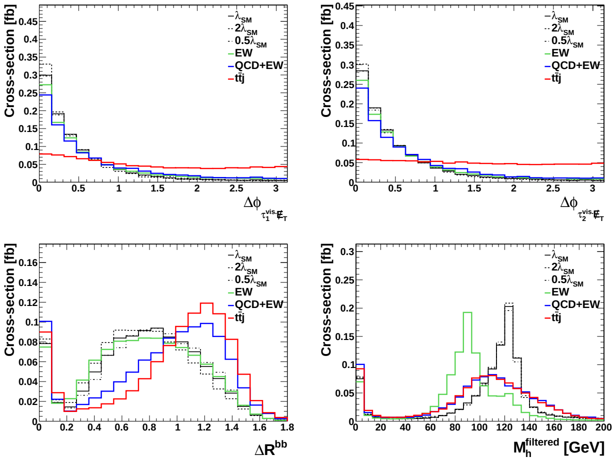
Di-Higgs + jet at a 100 TeV collider

- Observing the Higgs self-coupling at the HL-LHC seem far fetched
- Di-Higgs cross-section increases by 39 times going from 14 TeV $\rightarrow$ 100 TeV
- Extra jet emission becomes significantly less suppressed: 77 times enhancement from 14 TeV $\rightarrow$ 100 TeV collider $\rightarrow$ extra handle
- Recoiling a collimated Higgs pair against a jet exhibits more sensitivity to λ_{hhh} as compared to $pp \rightarrow hh$ $\rightarrow$ statistically limited at the LHC
- Study $hhj \rightarrow b\bar{b}\tau^+\tau^- j \rightarrow b\bar{b}\tau_h(\tau_\ell)\tau_\ell j$ and $hhj \rightarrow b\bar{b}b\bar{b}j$
- Use substructure technique: BDRS [Butterworth, *et. al.*, 2008] with mass drop and filtering

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

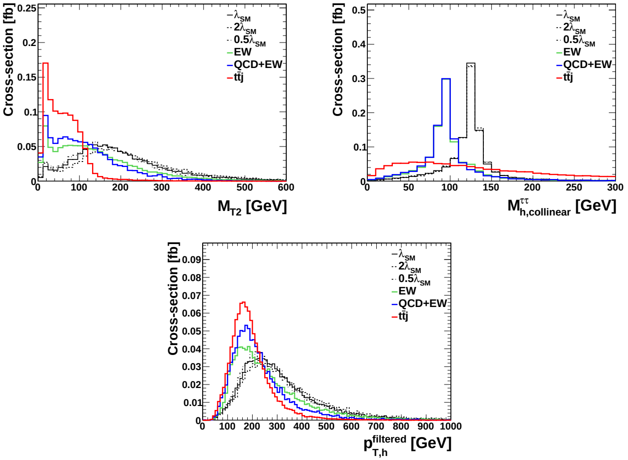
[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky, 2018]

- $R = 1.5$, $p_T^j > 110$ GeV, τ-tag efficiency 70%, b-tag efficiency 70%, b-mistag rate 2%; Combined $\tau_h\tau_h$ and $\tau_h\tau_\ell$



Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky, 2018]



Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky, 2018]

observable	reconstructed object
p_T	2 hardest filtered subjets 2 visible τ objects (τ_ℓ or τ_h) hardest non b, τ-tagged jet reconstructed Higgs from filtered jets reconstructed Higgs from visible τ final states
p_T ratios	2 hardest filtered jets 2 visible τ final state objects
m_{T2}	described before
ΔR	two hardest filtered subjets two visible τ objects ($\tau_\ell \tau_\ell$ or $\tau_\ell \tau_h$) b-tagged jets and lepton or τ_h b-tagged jets and jet j_1 lepton or τ_h with jet j_1
$M_{\tau\tau}^{\text{col}}$	collinear approximation of $h \to \tau\tau$ mass
M^{filt}	filtered j_1 and j_2 (and j_3 if present)
$M_{hh}^{vis.}$	filtered jets and leptons (or lepton and τ_h)
$\not{E}_T$	reduce sub-leading backgrounds
$\Delta\phi$	between visible τ final state objects and $\not{E}_T$ between filtered jets system and $\ell\ell$ (or ℓ τ_h) systems
N_{jets}	number of anti-k_T jets with $R = 0.4$

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}\tau^+\tau^-$)

[SB, C. Englert, M. Mangano, M. Selvaggi, M. Spannowsky, 2018]

	signal	QCD+QED	QED	$t\bar{t}j$	tot. background	S/B	$S/\sqrt{B}$, 3/ab
$\kappa_\lambda = 0.5$	0.444					0.126	12.47
$\kappa_\lambda = 1$	0.363	0.949	0.270	2.311	3.530	0.103	10.57
$\kappa_\lambda = 2$	0.264					0.075	7.69

$$0.76 < \kappa_\lambda < 1.28 \quad 3/\text{ab}$$

$$0.92 < \kappa_\lambda < 1.08 \quad 30/\text{ab}$$

at 68% confidence level using the CLs method.

Summary

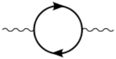
- Search for Higgs pair production is an important enterprise to understand the Higgs cubic coupling
- Non-resonant di-Higgs searches at the HL-LHC yields a significance of $\sim 2.1\sigma$
- 100 TeV collider studies show promise for di-Higgs + jet
- $t\bar{t}hh$ at FCC-hh shows excellent promise and can constrain λ_{hhh} as well as the anomalous $t\bar{t}hh$ coupling [SB, Krauss, Kuttimalai, Spannowsky (in preparation)]
- Systematic uncertainties need to be understood better in the future in order to make strong claims about these channels

Other works

- Constraining Higgs couplings with (SM Effective Field Theory) and without Lorentz structure modifications at the LHC and future e^+e^- colliders and lepton flavour violation in the Higgs sector [SB, S. Mukhopadhyay, B. Mukhopadhyaya, 2012, 2013], [G. Amar, SB, S. von Buddenbrock, A. S. Cornell, T. Mandal, B. Mellado, B. Mukhopadhyaya, 2014], [SB, T. Mandal, B. Mellado, B. Mukhopadhyaya, 2015], [SB, B. Bhattacherjee, M. Mitra, M. Spannowsky, 2016], [SB, F. Krauss, R.S. Gupta, O. Ochoa-Valeriano, M. Spannowsky, in preparation]
- Double Higgs production and Higgs invisible decays [SB, B. Batell, M. Spannowsky, 2016], [A. Adhikary, SB, B. Bhattacherjee, R. K. Barman, S. Niyogi, 2017], [A. Adhikary, SB, B. Bhattacherjee, R. K. Barman, 2018], [SB, F. Krauss, S. Kuttimalai, M. Spannowsky, in preparation]
- Studies pertaining to dark matter [SB, P.S.B. Dev, S. Mondal, B. Mukhopadhyaya, S. Roy, 2013], [SB, S. Matsumoto, K. Mukaidi, Y. S. Tsai, 2016], [SB, D. Barducci, G. Bélanger, B. Fuks, A. Goudelis, B. Zaldivar, 2016]
- Electroweak correction in dark matter sector [SB, N. Chakrabarty, 2016], [SB, F. Boudjema, N. Chakrabarty, G. Chalons, S. Hao, in preparation]
- Studies pertaining to long-lived particles [SB, G. Bélanger, B. Bhattacherjee, F. Boudjema, R. M. Godbole, S. Mukherjee, 2017], [SB, G. Bélanger, B. Mukhopadhyaya, P. Serpico, 2016], [SB, G. Bélanger, A. Ghosh, B. Mukhopahdyaya, 2018]
- Extended scalar and/or fermionic sectors [SB, M. Frank, S.K. Rai, 2013], [SB, M. Mitra, B. Bhattacherjee, M. Spannowsky, 2015], [SB, D. Barducci, C. Delaunay, G. Bélanger, 2016], [SB, M. Chala, M. Spannowsky, 2018], [J. Y. Araz, SB, M. Frank, B. Fuks, A. Goudelis, 2018]

Backup Slides

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.

Di-Higgs + jet at a 100 TeV collider ($jb\bar{b}b\bar{b}$)

- Major background: pure QCD: $g \to b\bar{b}$ (soft and collinear splittings $\to$ Resulting fat jets (R = 0.8) are one-pronged.
- Signal: $H \to b\bar{b}$; clear two prongs
- Require: $\tau_{2,1} < 0.35$ and $100\ \mathrm{GeV} < m_{SD} < 130\ \mathrm{GeV}$

	signal	QCD	QCD+EW	EW	tot. background	$S/B \times 10^3$	$S/\sqrt{B}$, 30/ab
$\kappa_\lambda = 0.5$	0.094					20.8	7.67
$\kappa_\lambda = 1$	0.085	4.3	0.1	0.003	4.4	19.1	6.61
$\kappa_\lambda = 2$	0.071					16.2	5.85