Higgs coupling measurements at the HL-LHC and beyond

Shankha Banerjee

IPPP, Durham University

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Based on

Phys. Rev. D 89, 053010 (2014): with S. Mukhopadhyay, B.Mukhopadhyaya, **JHEP 1502 (2015) 128**: with G. Amar, S. Buddenbrock, A. Cornell, T.Mandal, B.Mellado, B. Mukhopadhyaya, **arXiv:1807.01796**: with R. S. Gupta, C. Englert, M. Spannowsky, **JHEP 1807 (2018) 116**: with A. Adhikary, R. K. Barman, B. Bhattacherjee, S. Niyogi, **Phys. Rev. D 95, 035009**: with B. Batell, M. Spannowsky, **Eur. Phys. J. C (2018) 78: 322**: with C. Englert, M. Mangano, M. Spannowsky

Plan of my talk

- Higgs couplings in SMEFT
- di-Higgs searches
- Exotic Higgs decays
- Summary and Conclusions

Introduction for SMEFT

- Many reasons to go beyond the SM, *viz.* gauge hierarchy, neutrino mass, dark matter, baryon asymmetry etc.
- Plethora of BSM theories
- 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 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

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

Introduction for SMEFT

- Precisely measuring the Higgs couplings → 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

  Going to higher energies in LHC is the only way
- EFT techniques show that many Higgs deformations aren't independent from cTGCs and EW precision which were already constrained at LEP → Same operators affect TGCs and Higgs deformations

HD operators

- Higher-dimensional Operators: invariant under SM gauge group
- $d = 5$: Unique operator $\rightarrow$ Majorana mass to the neutrinos: $\frac{1}{\Lambda}(\Phi^\dagger L)^T C(\Phi^\dagger L)$
- $d = 6$: $59 = 15 + 19 + 25$ independent operators. Lowest dimension (after $d = 4$) which induces HXX interactions [W. Buchmuller and D. Wyler; B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek; K.Hagiwara, D. Zeppenfeld et. al.]
- $d = 7$: Such operators appear in Higgs portal dark matter models
- $d = 8$: Lowest dimension inducing neutral TGC interactions
- To understand the EWSB sector better, we first consider a subset of $d = 6$ operators involving Φ, $\partial_\mu \Phi$, $X_{\mu\nu}$ (where $X = G, B, W$)

Gauge-invariant D6 CP^{+} operators : Higgs-Gauge sector

- The operators containing the Higgs doublet Φ and its derivatives:

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi); \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi); \quad \mathcal{O}_{\Phi,3} = \frac{1}{3} (\Phi^\dagger \Phi)^3$$

- The operators containing the Higgs doublet Φ (or its derivatives) and bosonic field strengths :

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi G^a_{\mu\nu} G^{a\,\mu\nu}; \quad \mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi; \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi); \quad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi; \quad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi),$$

$\hat{W}^{\mu\nu} = i\,\frac{g}{2} \sigma_a W^{a\,\mu\nu}$, $\hat{B}^{\mu\nu} = i\,\frac{g}{2}' B^{\mu\nu}$; $\quad g$, g' : $SU(2)_L$, $U(1)_Y$ gauge couplings

$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g \epsilon^{abc} W^b_\mu W^c_\nu$; $\quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc} G^b_\mu G^c_\nu$

Φ : Higgs doublet, $D_\mu \Phi = (\partial_\mu + \frac{i}{2} g' B_\mu + ig \frac{\sigma_a}{2} W^a_\mu)\Phi$: Covariant derivative

Properties of these operators

- $\mathcal{O}_{\Phi,1}$: Custodial symmetry violated $\rightarrow$ severely constrained by T-parameter
- $\mathcal{O}_{\Phi,2}$: Custodial symmetry preserved; modifies SM HVV couplings by multiplicative factors (same Lorentz structure)
- $\mathcal{O}_{\Phi,3}$: Modifies only the Higgs self-interaction; gives additional contribution to the Higgs potential
- $\mathcal{O}_{GG}$: Introduces HGG coupling with same Lorentz structure as in the SM; constrained from single Higgs production
- $\mathcal{O}_{BW}$: Drives tree-level $Z \leftrightarrow \gamma$ mixing $\rightarrow$ highly constrained by EWPT
- $\mathcal{O}_{WW}$, $\mathcal{O}_{W}$, $\mathcal{O}_{BB}$, $\mathcal{O}_{B}$: Modifies the HVV couplings by introducing new Lorentz structures in the Lagrangian; not all are severely constrained by the EWPT

Effective Lagrangian

$$\mathcal{L} = \beta\left(\frac{2m_W^2}{v} H W_\mu^+ W^{\mu -} + \frac{m_Z^2}{v} H Z_\mu Z^\mu\right) + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

$$\begin{aligned}\mathcal{L}_{eff} \supset & g^{(1)}_{HWW}\ (W^+_{\mu\nu} W^{-\mu}\partial^\nu H + h.c.) + g^{(2)}_{HWW}\ H W^+_{\mu\nu} W^{-\mu\nu} \\ & + g^{(1)}_{HZZ}\ Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZZ}\ H Z_{\mu\nu} Z^{\mu\nu} \\ & + g^{(1)}_{HZ\gamma}\ A_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZ\gamma}\ H A_{\mu\nu} Z^{\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu};\end{aligned}$$

$$\begin{aligned} g^{(1)}_{HWW} &= \left(\frac{gM_W}{\Lambda^2}\right)\frac{f_W}{2}; \quad g^{(2)}_{HWW} = -\left(\frac{gM_W}{\Lambda^2}\right) f_{WW} \\ g^{(1)}_{HZZ} &= \left(\frac{gM_W}{\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2}; \quad g^{(2)}_{HZZ} = -\left(\frac{gM_W}{\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \\ g^{(1)}_{HZ\gamma} &= \left(\frac{gM_W}{\Lambda^2}\right)\frac{s(f_W - f_B)}{2c}; \quad g^{(2)}_{HZ\gamma} = \left(\frac{gM_W}{\Lambda^2}\right)\frac{s(s^2 f_{BB} - c^2 f_{WW})}{c} \\ g_{H\gamma\gamma} &= -\left(\frac{gM_W}{\Lambda^2}\right)\frac{s^2(f_{BB} + f_{WW})}{2} \end{aligned}$$

Anomalous charged TGC interactions

We also consider the anomalous VVV interactions by

$$\mathcal{L}_{WWV} = -ig_{WWV}\{g_1^V \left(W^+_{\mu\nu}W^{-\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{-\mu\nu}\right) + \kappa_V W^+_{\mu}W^-_{\nu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^+_{\mu\nu}W^{-\nu\rho}V_{\rho}^{\mu}\}$$

where $g_{WWV} = g\,s$, $g_{WWZ} = g\,c$, $\kappa_V = 1 + \Delta\kappa_V$ and $g_1^Z = 1 + \Delta g_1^Z$ with

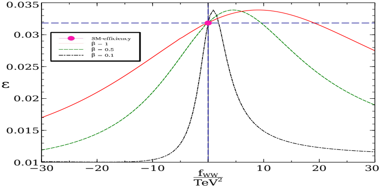
$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}\left(f_W + f_B\right); \quad \lambda_\gamma = \lambda_Z = \frac{3g^2M_W^2}{2\Lambda^2}f_{WWW}$$

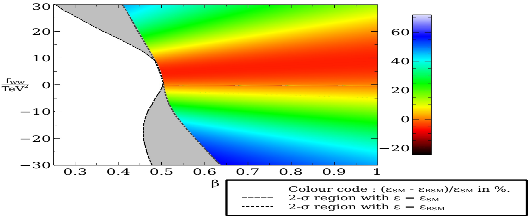
$$\Delta g_1^Z = \frac{M_W^2}{2c^2\Lambda^2}f_W; \quad \Delta\kappa_Z = \frac{M_W^2}{2c^2\Lambda^2}\left(c^2 f_W - s^2 f_B\right)$$

Modified efficiencies: Case study $(pp \to Hjj \to WW^*jj)$

- We consider the $H \to WW^* + 2j$, $WW^* \to l^+\nu l^-\bar{\nu}$ $(l = \{e, \mu\})$ channel which includes contributions from both *VBF* and *VH* production modes.

$$\epsilon_{WW^*+\geq 2-\text{jets}} = \frac{50.98\beta^4 + 121.76\beta^3 f_{WW} + 22.85\beta^2 f_{WW}^2 + 0.15\beta f_{WW}^3 + 0.01 f_{WW}^4}{1601.43\beta^4 + 3796.63\beta^3 f_{WW} + 666.79\beta^2 f_{WW}^2 - 1.98\beta f_{WW}^3 + 0.73 f_{WW}^4}.$$

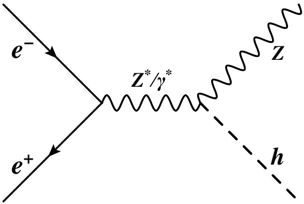


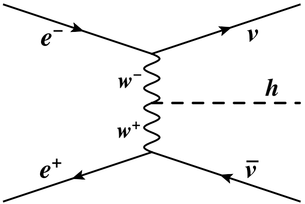


- Percentage modification of the combined efficiency of all cuts compared to the SM case. Grey region : $\epsilon_{BSM} = \epsilon_{SM}$

Phenomenology at e^+e^- colliders

Two main Higgs production processes are



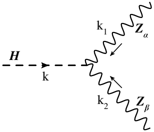


- $e^+e^- \to \nu\bar{\nu}H$ process $\to$ admixture of s and t-channel processes
- Possible to separate s and t-channel from $e^+e^- \to \nu\bar{\nu}H$ events by applying

$$E_H\text{-cut:} \quad \left| E_H - \frac{S + M_H^2 - M_Z^2}{2\sqrt{S}} \right| \leq \Delta(= 5 \text{ GeV})$$

- $\Delta \sim \Delta E_{jet}$ where $\Delta E_{jet}/E_{jet} \lesssim 0.3/\sqrt{E_{jet}}$. For two b-jets each with energy $\sim$100 GeV,$\Delta E_{jet} = \sqrt{2 \times (0.3 \times \sqrt{100})^2} \sim 4$ GeV

The amplitudes : An example



$$M = i(\frac{gM_W}{c})[\beta g^{\alpha\beta} + T^{\alpha\beta}]$$

$$T^{\alpha\beta} = \frac{1}{2\Lambda^2 c}\{4(s^4 f_{BB} + c^4 f_{WW})[g^{\alpha\beta}(k_1 \cdot k_2) - k_2^\alpha k_1^\beta] + (c^2 f_W + s^2 f_B)$$
$$\times[-g^{\alpha\beta}(k_1^2 + k_2^2 + 2k_1 \cdot k_2) + (k_1^\alpha k_1^\beta + 2k_2^\alpha k_1^\beta + k_2^\alpha k_2^\beta)]\}$$

- $\mathcal{M}_{e^+e^- \to ZH}$ is a linear combination of $x_i \in \{\beta, f_{WW}, f_W, f_{BB}, f_B\}$
- Cross-section can always be expressed as a bilinear combination

$$\sigma_{ZH}(\sqrt{S}, x_i) = \sum_{i,j=1}^{5} x_i C_{ij}(\sqrt{S}) x_j$$

Fitted cross-sections

$$\sigma(\sqrt{S}) = \mathcal{X} \cdot \mathcal{M}(\sqrt{S}) \cdot \mathcal{X}^T$$

where $\mathcal{X} = (\beta, f_{WW}, f_W, f_{BB}, f_B)$ is a row vector on parameter-space

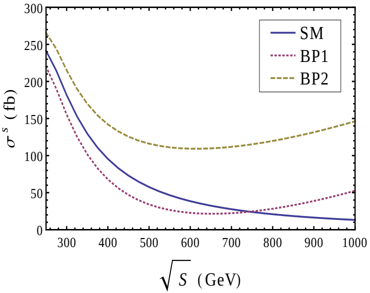
$$\mathcal{M}^s_{ZH}(300\ GeV) = \begin{pmatrix} 181.67 & -6.43 & -2.99 & -0.51 & -0.71 \\ -6.43 & 0.46 & 0.18 & -0.03 & -0.08 \\ -2.99 & 0.18 & 0.14 & -0.02 & -0.06 \\ -0.51 & -0.03 & -0.02 & 0.02 & 0.03 \\ -0.71 & -0.08 & -0.06 & 0.03 & 0.08 \end{pmatrix}$$

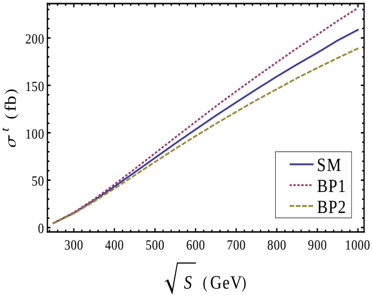
$$\mathcal{M}^t_{\nu\bar{\nu}H}(300\ GeV) = \begin{pmatrix} 15.36 & 0.04 & 0.07 \\ 0.04 & 1.2 \times 10^{-3} & -7.7 \times 10^{-4} \\ 0.07 & -7.7 \times 10^{-4} & 4.6 \times 10^{-4} \end{pmatrix}$$

- σ^s is less sensitive on $\mathcal{O}_{BB}$ and $\mathcal{O}_B$ but σ^t is almost insensitive to HDOs

σ versus $\sqrt{S}$

Benchmark points: $BP1 = \{1, 0, 5, 0, 0\}$, $BP2 = \{1, 0, -5, 0, 0\}$ (allowed by *EWPT* constraints and *LHC* data)





- In the SM: $\sigma_{ZH} \sim 1/S$ and $\sigma^t_{\nu\bar{\nu}H} \sim \ln(S/M_H^2)$
- In presence of HDOs, the $\sqrt{S}$-dependency is non-trivial especially for the s-channel process

Estimating D6 coefficients at the HL-LHC

- The HD operator coefficients are constrained to values of $\mathcal{O}(1)/\text{TeV}^2$
- Kinematic variables can show very little variations *w.r.t.* the *SM* for such small coefficients
- One may construct observables sensitive to even small values of the operator coefficients
- Cross-sections and decay widths are sensitive observables
- If we construct ratios, many correlated uncertainties get cancelled

The ratio $\mathcal{R}_1$

$$\mathcal{R}_1(f_i) = \frac{\sigma_{ggF} \times BR_{H\to\gamma\gamma}(f_i)}{\sigma_{ggF} \times BR_{H\to WW^*\to 2\ell 2\nu}(f_i)}$$

$$\mathcal{R}_1(f_i) = \frac{\mu^{ggF}_{\gamma\gamma}(f_i)}{\mu^{ggF}_{WW^*}(f_i)} \times \frac{(\sigma_{ggF} \times BR_{H\to\gamma\gamma})^{SM}}{(\sigma_{ggF} \times BR_{H\to WW^*\to 2\ell 2\nu})^{SM}}$$

- Strong bounds on $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$; insensitive to the other two operators $\mathcal{O}_W$ and $\mathcal{O}_B$
- $f_{WW} \approx f_{BB}$ allowed region $\approx [-2.76, -2.65] \cup [-0.06, 0.04]$ TeV^{-2}

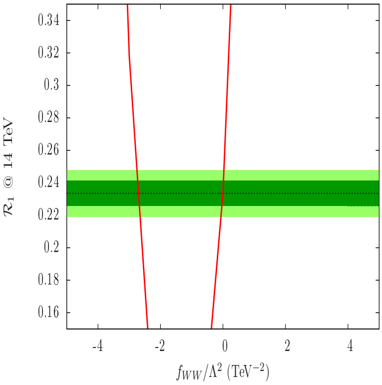


Figure : $\mathcal{R}_1$ versus f_{WW}/Λ^2 (TeV^{-2}). Red line $\to$ theoretical expectation in presence of HDOs; Dark green band $\to$ uncorrelated theoretical uncertainty; Light green band $\to$ total uncorrelated uncertainty at 14 TeV with 3000 fb^{-1} integrated luminosity; Black dotted line $\to$ central value.

Constraining TGC couplings with $pp \to ZH$ at the HL-LHC

- We have seen from LEP that measuring the oblique S, T parameters can constrain several BSM scenarios at much higher scales than the LEP running energy
- Many vertices ensuing from EFT operators are correlated and hence LEP has already constrained certain operators affecting the Higgs vertices
- We target the higher energy regions in the parameter space in order to compete with the LEP constraints

Constraining TGC couplings with $pp \to ZH$ at the HL-LHC

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

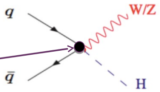
The $qq \to Vh$ amplitude can be expressed as

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

$$
g_f^Z = \frac{g}{c_{\theta_W}} (T_3 - Q_f s_{\theta_W}^2) \qquad g_f^W = \frac{g}{\sqrt{2}}.
$$

Constraining TGC couplings with $pp \to ZH$ at the HL-LHC

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



Leading effect from contact interaction at high energies.
Energy growth as there is no propagator.

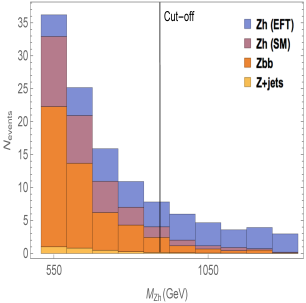
$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right]$$

At high energies, the following four directions in the EFT parameter space are isolated by ZH production

$$g_{Zu_Lu_L}^h = -\frac{g}{c_{\theta_W}} \left((c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$
$$g_{Zd_Ld_L}^h = -\frac{g}{c_{\theta_W}} \left((c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W + \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$
$$g_{Zu_Ru_R}^h = \frac{4 g s_{\theta_W}^2}{3 c_{\theta_W}^3} (\hat{S} - \delta\kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y)$$
$$g_{Zd_Rd_R}^h = -\frac{2 g s_{\theta_W}^2}{3 c_{\theta_W}^3} (\hat{S} - \delta\kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y)$$

$pp \to ZH$ at high energies

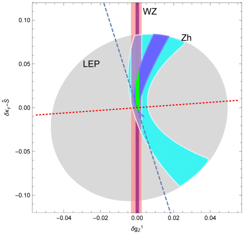
- We study the impact of constraining TGC couplings at higher energies
- We study the channel $pp \to ZH \to \ell^+\ell^- b\bar{b}$
- The backgrounds are SM $pp \to ZH$, $Zb\bar{b}$, $t\bar{t}$ and the fake $pp \to Zjj$ ($j \to b$ fake rate taken as 2%)
- Boosted substructure analysis with fat-jets of $R = 1.5$ used (Varying the filtering cone radius)



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

$pp \to Zh$ at high energies

- Next we perform a two-parameter χ^2-fit (at 300 (3000) fb^{-1}) to find the allowed region in the $\delta g_1^Z - (\delta\kappa_\gamma - \hat{S})$



	Our Projection	LEP Bound
$\delta g^Z_{u_L}$	±0.003 (±0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	±0.003 (±0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	±0.004 (±0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	±0.015 (±0.006)	0.0016 ± 0.0052
δg_1^Z	±0.004 (±0.001)	$0.009^{+0.043}_{-0.042}$
$\delta\kappa_\gamma$	±0.028 (±0.010)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	±0.028 (±0.010)	0.0004 ± 0.0007
W	±0.003 (±0.001)	0.0000 ± 0.0006
Y	±0.028 (±0.010)	0.0003 ± 0.0006

$$+ \; igc_{\theta_W}\delta g_1^Z\left[(Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu + \cdots\right]$$
$$+ \; ie\,\delta\kappa_\gamma\;\left[(A_{\mu\nu} - t_{\theta_W}Z_{\mu\nu})W^{+\mu}W^{-\nu} + \cdots\right]\,,$$

Grey region: LEP exclusion; pink band: exclusion from WZ [Franceschini, Panico, Pomarol, Riva and Wulzer, 2017];

light (dark) blue region: exclusion from ZH at 300 (3000) fb^{-1}

Summary

- EFT framework is a powerful tool to understand Higgs coupling deviations and nature of the Higgs (part of a doublet or not?)
- Efficiencies for various acceptance cuts are altered by varying Lorentz structure
- Future e^+e^- colliders can potentially constrain EFT parameters to excellent precision
- Various ratios can be used to see the effect of small values of operator coefficients $\rightarrow$ cancellation of several uncertainties
- Possible to constrain certain EFT parameters to stronger degrees at HL-LHC than was done at LEP
- Boosted *ZH* channel helps in constraining TGC couplings

di-Higgs: Motivation

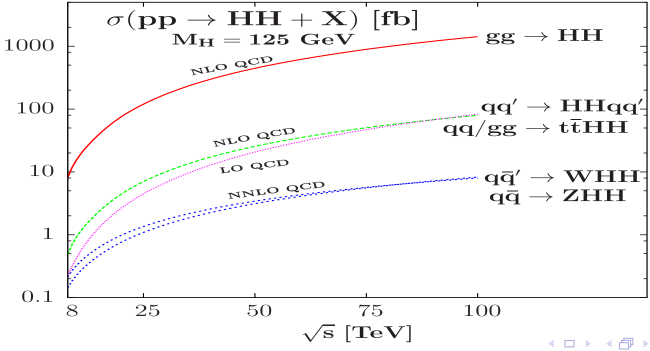
- Di-Higgs provides means to directly probe Higgs self coupling
- Indirect probe: Through radiative corrections of single Higgs productions [Goertz *et. al.*, 2013, McCullough, 2013, Degrassi *et. al.*, 2016]
- Challenging task : small di-Higgs cross-section in SM ($39.56^{+7.32\%}_{-8.38\%}$ fb at NNLO + 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: $-0.8 < \frac{\lambda}{\lambda_{\rm SM}} < 7.7$ at 95% C.L. [ATL-PHYS-PUB-2017-001]

di-Higgs: Motivation

- Enhancement of σ_{hh} → 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] → kinematics altered → requires different experimental search strategies
- Till date → major focus on BSM di-Higgs sector → enhancement in production
- New physics can affect Higgs *decays* → exotic Higgs decays now actively studied [Curtin *et. al.*, 2015]
- $\sigma_{pp \to h} \gg \sigma_{pp \to hh}$ → 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 → present bounds on variety of Higgs decays : BR very weak (10-50%)

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)]
$b\bar{b}b\bar{b}$	342	1511-47 (260-1200)	13	2000-2 (260-3000)
$b\bar{b}\gamma\gamma$	19.2	232-325 (250-900)	117	7000-4000 (275-400)
$b\bar{b}\tau^+\tau^-$	30	3120-73 (250-900)		
$\gamma\gamma WW^*$ ($\gamma\gamma\ell\nu jj$)			747	47700-24300 (260-500)
$b\bar{b}\ell\nu\ell\nu$	79	20499-803 (300-900)		

NR: Non-resonant, R: Resonant, $\sim$ 36 fb^{-1}, $\sim$ 13.3 fb^{-1} and $\sim$ 2.3-3.2 fb^{-1}

Non resonant di-Higgs production at the HL-LHC

- We choose channels based on the rate and cleanliness
- Focus on final states with leptons and/or photons
- Focus on 11 channels, *viz.*
    - $b\bar{b}\gamma\gamma$
    - $b\bar{b}\tau^+\tau^- \to b\bar{b}\ell\ell + \not{E}_T,\ b\bar{b}\ell\tau_h + \not{E}_T,\ b\bar{b}\tau_h\tau_h + \not{E}_T$
    - $b\bar{b}WW^* \to b\bar{b}\ell\ell + \not{E}_T,\ b\bar{b}\ell jj + \not{E}_T$
    - $WW^*\gamma\gamma \to \ell\ell\gamma\gamma + \not{E}_T,\ \ell jj\gamma\gamma + \not{E}_T$
    - $WW^*WW^* \to \ell^\pm\ell^\pm jjjj + \not{E}_T,\ \ell\ell\ell jj + \not{E}_T,\ \ell\ell\ell\ell + \not{E}_T$
- $4\tau,\ WW^*\tau^+\tau^-,\ ZZ^*\tau^+\tau^-,\ 4\gamma,\ ZZ^*\gamma\gamma,\ 4Z$ may be important at 100 TeV colliders
- Follow CMS and ATLAS analyses (when available) and optimise upon them

Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$

- Cleanest channel in spite of the low rate
- Major backgrounds: QCD-QED $b\bar{b}\gamma\gamma$, $hb\bar{b}$, $t\bar{t}h$, Zh
- Dominant fakes: $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$, $b\bar{b}jj$

Selection cuts
$N_j < 6$
$0.4 < \Delta R_{\gamma\gamma} < 2.0$, $0.4 < \Delta R_{bb} < 2.0$, $\Delta R_{\gamma b} > 0.4$
$100\ \mathrm{GeV} < m_{bb} < 150\ \mathrm{GeV}$
$122\ \mathrm{GeV} < m_{\gamma\gamma} < 128\ \mathrm{GeV}$
$p_{T,bb} > 80\ \mathrm{GeV},\ p_{T,\gamma\gamma} > 80\ \mathrm{GeV}$

Cut flow	Event rates with $3000\ \mathrm{fb}^{-1}$ of integrated luminosity							$\frac{S}{\sqrt{B}}$
	Signal	SM Backgrounds						
	$hh \to 2b2\gamma$	$hb\bar{b}$	$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma^*$	Fake 1	Fake 2	
Order	NNLO	NNLO (5FS) + NLO (4FS)	NLO	NNLO (QCD) + NLO EW	LO	LO	LO	
$2b + 2\gamma$	31.63	21.20	324.91	39.32	25890.31	1141.18	393.79	0.19
lepton veto	31.63	21.20	255.66	39.32	25889.94	1141.18	393.79	0.19
$N_j < 6$	31.04	21	192.05	39.23	25352.78	1064.64	167.32	0.19
ΔR cuts	22.19	7.75	38.71	23.48	4715.21	130.10	28.81	0.31
m_{bb}	12.71	1.53	13.80	1.09	862.37	22.11	6.88	0.42
$m_{\gamma\gamma}$	12.36	1.5	13.16	1.06	26.54	22.11	6.88	1.46
$p_{T,bb}, p_{T,\gamma\gamma}$	12.32	1.48	13.03	1.06	26.54	21.82	6.88	1.46

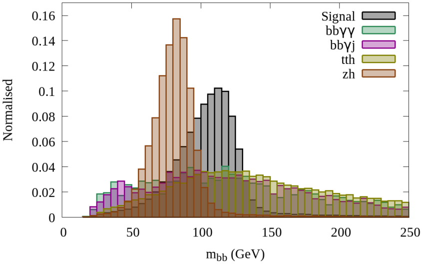
- significance: $S/B = 0.17$ and $S/\sqrt{B} = 1.46$
- With additional $\not{E}_T < 50$ GeV, $S/B = 0.19$ and $S/\sqrt{B} = 1.51$
- Changing to: 90 GeV $< m_{bb} <$ 130 GeV: $S/B = 0.19$ and $S/\sqrt{B} = 1.64$
- $b\bar{b}\gamma\gamma^* = b\bar{b}\gamma\gamma + c\bar{c}\gamma\gamma + jj\gamma\gamma$, Fake1 $= b\bar{b}j\gamma + c\bar{c}j\gamma$, Fake2 $= b\bar{b}jj$

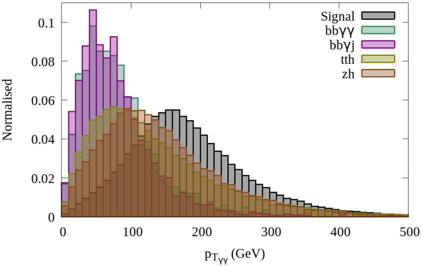
- Multivariate technique employed to further optimise search
- Boosted decision tree (BDT) algorithms chosen
- Overtaining checked using the Kolmogorov-Smirnov test
- Variables chosen (according to the best discriminatory power):

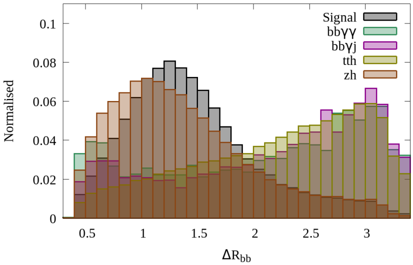
$$m_{bb},\ p_{T,\gamma\gamma},\ \Delta R_{\gamma\gamma},\ p_{T,bb},\ \Delta R_{b_1\gamma_1},\ p_{T,\gamma_1},\ \Delta R_{bb},$$
$$p_{T,\gamma_2},\ \Delta R_{b_2\gamma_1},\ \Delta R_{b_2\gamma_2},\ p_{T,b_1},\ \Delta R_{b_1\gamma_2},\ p_{T,b_2}, \not{E}_T$$

- $S/B = 0.19$ and $S/\sqrt{B} = 1.76\sigma$ CMS (ATLAS) projection: 1.6σ (1.05σ)

Non resonant di-Higgs production at the HL-LHC: $b\bar{b}\gamma\gamma$







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

Higgs invisible decays in the Higgs pair productions: Motivation

- Here we will discuss the scenario where one Higgs decays invisibly ($h \to \not{E}_T$)
- $\mathrm{BR_{inv}}$ constrained from global fits of Higgs data or from direct searches like mono-jet (hj), VBF (hjj) and Vh channels $\to$ $BR_{\rm inv} \lesssim 25 - 50\%$ $\to$ potential to bound $Br_{\rm inv} \lesssim 5\%$ at HL-LHC
- Current limit $\to$ $\mathrm{BR_{inv}} < 0.28$ (0.31) from ATLAS @ 8 TeV and < 0.24 (0.23) from CMS at 7+8+13 TeV at 95% CL [CMS-PAS-HIG-16-016]
- If any new light particles couple to Higgs even with a coupling strength comparable to b-quark Yukawa ($\sim 1/60$) $\to$ sizeable exotic BR
- Motivations $\to$ DM connection, decay to long-lived sterile neutrinos, PNGBs like axions or Majorons, LSP in SUSY, KK-states in extra-dimensional theories

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

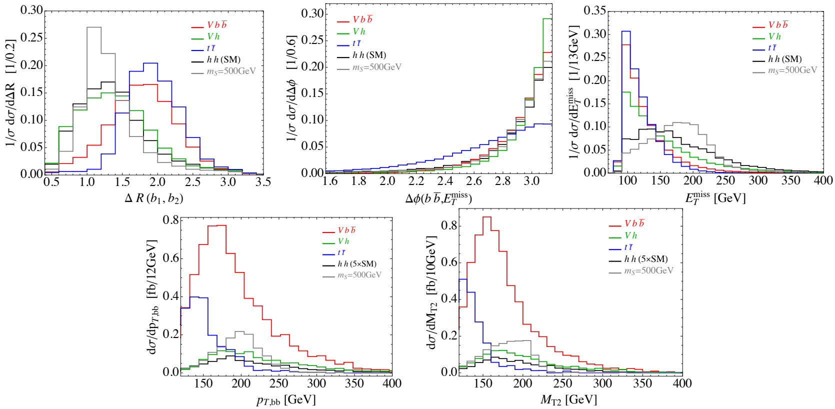
- Several other interesting channels like $2\gamma + \not{E}_T, 4\ell + \not{E}_T$ $\rightarrow$ tiny cross-section due to small BR, important for resonance scenario
- $WW^* + \not{E}_T$ has larger BR but a fully leptonic channel will give additional $\not{E}_T$ (reconstruction of both Higgs extremely challenging) and fully hadronic will have large SM backgrounds. Similarly for $\tau\tau + \not{E}_T$. However, even without being able to reconstruct either Higgs, a counting of events for such channels can be useful

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

- We will thus consider the scenario : $pp \to hh + X \to (b\bar{b})(\not{E}_T) + X \to$ largest possible signal rate
- Combining with the aforementioned channels might yield a larger sensitivity $\to$ future work
- Proposed signature similar to *mono-Higgs*, studied as a probe of certain DM scenarios $\to$ little overlap, cuts for mono-Higgs searches not optimised for di-Higgs especially the hard $\not{E}_T$ cut [Carpenter *et. al.*, 2013 *etc.*]
- Each visible Higgs BR is now scaled by $(1 - BR_{\rm inv}) \to$ rates diluted by $(1 - BR_{\rm inv})^2$ per visible Higgs decay

Higgs invisible decays in the Higgs pair productions: $b\bar{b} + \not{E}_T$ final state

- Cut-based analysis: after selection of 2 b-jets: $S/B = 0.026$, $S/\sqrt{B} = 2.82$ (Non-resonant)
- Cut-based analysis: before the final event selection ($\mathrm{BR_{inv}} = 0.2$)



Higgs invisible decays in the Higgs pair productions: BDT

- BDT with 13 kinematic variables, *viz.* $M_{b_1 b_2}$, $\Delta R(b_1, b_2)$, $p_T^{b_1}$, $p_T^{b_2}$, η^{b_1}, η^{b_2}, ϕ^{b_1}, ϕ^{b_2}, $\Delta\phi(\not{E}_T, b_1 b_2)$, $p_T^{b_1 b_2}$, M_{T2}, M_T, $\not{E}_T$
- Non-resonant: $S/B = 0.033$, $S\sqrt{B} = 4.44$
- If systematic uncertainties are controlled using data-driven techniques, then only the SM production mode can be a useful channel
- For $m_S = 500$ GeV, $\sigma_{hh} < 450$ fb $\rightarrow$ these assume SM BRs and hence for us results will be larger by $(1 - BR_{\mathrm{inv}})^{-2}$ $\rightarrow$ Boosted b-jets and larger $\not{E}_T$
- Benchmark chosen : $m_S = 500$ GeV, $\sigma(pp \rightarrow S \rightarrow hh)_{14\ \mathrm{TeV}} = 5\sigma_{SM}^{hh}$, $\Gamma_S = 5.47$ GeV
- Cut-based analysis: $S/B = 0.13$, $S/\sqrt{B} = 12$ and BDT: $S/B = 0.20$, $S/\sqrt{B} = 21.60$ for $\mathrm{BR}_{\mathrm{inv}} = 0.1$

Higgs invisible decays in the Higgs pair productions: Complementing VBF

- We demand 90% exclusion for $\mathrm{BR}_{\mathrm{inv}} = 5\%$, with a heavy scalar of $m_H = 500$ GeV
- Assuming zero systematics, after BDT cut, we have 27 (58) signal (background) events. We need $\mathcal{L} = 54\ \mathrm{fb}^{-1}$
- Assuming 5% systematics, after BDT cut, we have 237 (513) signal (background) events. We require $\mathcal{L} = 120\ \mathrm{fb}^{-1}$
- This channel has the potential to give a stiff competition to the VBF channel having the potential to exclude invisible BR of 5% at 90% CL and at the same time also has potential to study di-Higgs signatures
- With a BDT multi-variate analysis @ 13 TeV with $\mathcal{L} = 10\ \mathrm{fb}^{-1}$, reach on $\mathrm{BR}_{\mathrm{inv}}$ improves from 47% to 28% at 95% CL. For the HL-LHC at 3 ab^{-1}, one can have a final reach of $\mathrm{BR}_{\mathrm{inv}} = 3.5\%$ [Bernaciak *et. al.*, 2014]

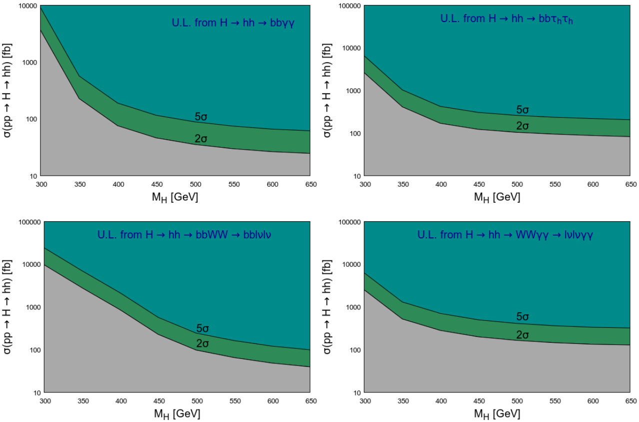
Contaminations to the Higgs pair producing channels

- SM di-Higgs signal events are rather small for most final states
- BSM physics may distort or contaminate the signal $\rightarrow$ if statistically significant $\rightarrow$ new physics
- May be due to y_t or λ_{hhh}
- May be some totally different new physics scenarios mimicking some or all SM di-Higgs final states
- Q: How much contamination possible once BDT performed to maximise SM di-Higgs?
- A: If new physics kinematic variables overlap with SM counterpart or If overlap is not significant but overall rate is large
- Correlations possible: Some non-resonant channels will incur contamination from more new physics scenarios than others

Contaminations to the Higgs pair producing channels: $hh(+X)$

- Extended Higgs sectors like 2HDM, complex scalar extension, MSSM allow for a heavy resonant Higgs decaying to an SM-like Higgs pair
- Requirement: alignment limit and low $\tan\beta$ for large di-Higgs cross-section for $m_{H(A)} \sim$ few 100 GeV
- Require narrow width assumption (GeV range)
- Cross-section upper limit defined as: $S_{\rm NP}^{\rm UL}/\sqrt{B_{\rm SM}} > N\sigma$
- Green (blue) region indicate upper limit on cross-section to contaminate SM yield at $2\sigma(5\sigma)$: $B_{\rm SM}$ contains SM di-Higgs

Contaminations to the Higgs pair producing channels: $hh(+X)$



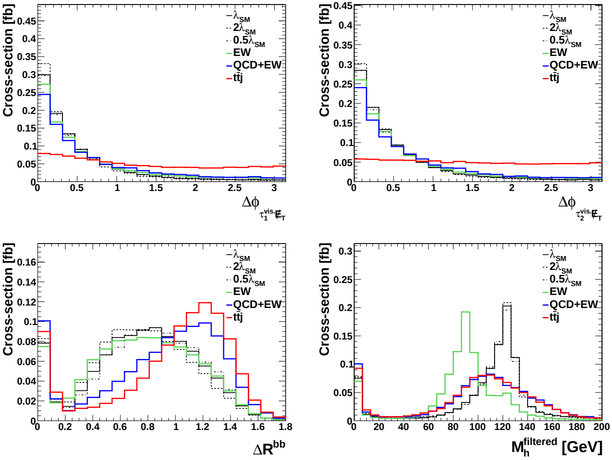
- Order 100 fb cross-section for resonant Higgs mass $\gtrsim$ 400 GeV $\rightarrow$ Contaminates SM di-Higgs expectation to at least 2σ

Di-Higgs + jet at a 100 TeV collider

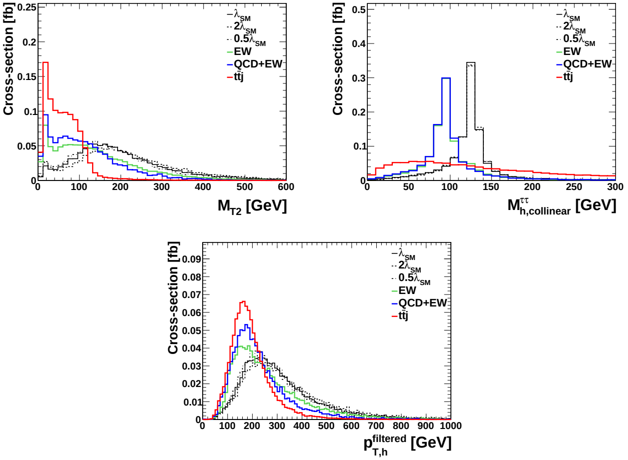
- Observing the Higgs self-coupling at the HL-LHC seem far fetched
- Di-Higgs cross-section increases by 39 times going from 14 TeV $\to$ 100 TeV
- Extra jet emission becomes significantly less suppressed: 77 times enhancement from 14 TeV $\to$ 100 TeV collider $\to$ extra handle
- Recoiling a collimated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

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

- $R = 1.5$, $p_T^j > 110$ 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 ($jb\bar{b}\tau^+\tau^-$)



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

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
$M_{\tau\tau}^{\rm col}$	collinear approximation of $h \to \tau\tau$ mass
$M^{\rm filt}$	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
$N_{\rm jets}$	number of anti-k_T jets with $R = 0.4$

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

	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 $\sim 2.1\sigma$
- New search strategy proposed $pp \to hh \to b\bar{b} + \not{E}_T$ with a non-SM decay mode $\to$ promising: may compete with VBF to constrain $h \to$ invisible BR
- Contaminations to SM non-resonant di-Higgs channels from resonance Higgs, squark pair production, $A \to Zh$, chargino-neutralino pair production, $H \to t\bar{t}$, charged Higgs production, stop pair production etc. possible
- 100 TeV collider studies show promise for di-Higgs + jet
- Systematic uncertainties need to be understood better in the future in order to make strong claims about these channels
- Other exotic decay modes like $\gamma\gamma + \not{E}_T$, $4b + 2\ell + \not{E}_T$ etc. need to be studied

Backup Slides

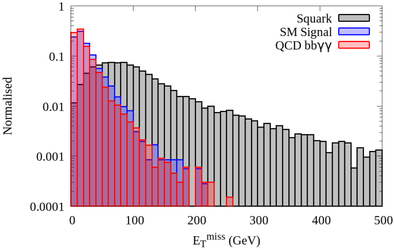
Contaminations to the Higgs pair producing channels: BPs

$M_A = 1000$ GeV, $\tan\beta = 10$, $A_t = 2500$ GeV, $m_{\tilde{Q}_{3\ell}} = m_{\tilde{b}_R} = 3000$ GeV, $A_b = A_\tau = 0$, $M_3 = 3000$ GeV

Benchmark Points	Parameters (GeV)	Mass (GeV)	Processes	Branching Fraction
BP1 $pp \to \tilde{q}_L^{(*)}\tilde{q}_L^{(*)}$ (Cross-section: 128.5 fb) $\tilde{q}_L = \tilde{u}_L, \tilde{d}_L, \tilde{c}_L, \tilde{s}_L$	$M_1 = 700$, $M_2 = 840$ $\mu = 3000$, $m_{\tilde{t}_R} = 3000$	$m_{\tilde{u}_L} = 850.1$ $m_{\tilde{d}_L} = 850.1$ $m_{\tilde{c}_L} = 850.1$ $m_{\tilde{s}_L} = 850.1$ $m_H = 1000.0$ $m_{H^\pm} = 1003.0$ $m_{\chi_2^0} = 836.0$ $m_{\chi_1^0} = 700.0$	$\tilde{u}_L \to \chi_2^0 u_L$ $\tilde{d}_L \to \chi_2^0 d_L$ $\tilde{c}_L \to \chi_2^0 c_L$ $\tilde{s}_L \to \chi_2^0 s_L$ $\chi_2^0 \to \chi_1^0 h$	13.8% 15.4% 13.8% 15.4% 98.7%
BP2 $pp \to \chi_1^\pm \chi_2^0$ (Cross-section: 420 fb)	$M_1 = 150$, $M_2 = 300$ $\mu = 1000$, $m_{\tilde{t}_R} = 3000$	$m_{\chi_2^0} = 296.7$ $m_{\chi_1^\pm} = 296.7$ $m_{\chi_1^0} = 149.3$ $m_h = 125.0$ $m_{H^\pm} = 1003.0$ $m_H = 1000.0$	$\chi_1^\pm \to \chi_1^0 W^\pm$ $\chi_2^0 \to \chi_1^0 h$	100% 93.5%
BP3 $pp \to \tilde{t}_1\tilde{t}_1^*$ (Cross-section: 200 fb)	$M_1 = 500$, $M_2 = 1000$ $\mu = 1000$, $m_{\tilde{t}_R} = 625$	$m_{\tilde{t}_1} = 609.3$ $m_{\chi_1^0} = 498.1$ $m_h = 125.0$ $m_{H^\pm} = 1003.0$ $m_H = 1000.0$	$\tilde{t}_1 \to \chi_1^0 b W^+$	99.9%

Contaminations to the Higgs pair producing channels: $hh(+X)$

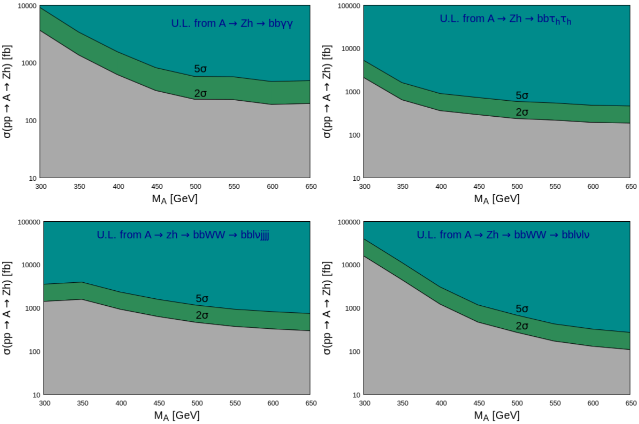
- LHC already imposed strong constraints on first and second generation squark masses ($\gtrsim \mathcal{O}(\mathrm{TeV})$)
- Squark pair production $\tilde{q}_L\tilde{q}_L$, $\tilde{q}_L\tilde{q}_L^*$, $\tilde{q}_L^*\tilde{q}_L^*$ (BP1)
- Final state: $hh + \not{E}_T +$ jets; From BP1, cross-section ~ 10.8 fb $\rightarrow$ one-third of SM-expectation; Large $\not{E}_T$; Only 0.60 events $\rightarrow$ not significant



Contaminations to the Higgs pair producing channels: $h(+X)$

- The $hh(+X)$ modes may contaminate all SM non-resonant di-Higgs channels
- The $h(+X)$ modes may contaminate some (or all) the SM non-resonant di-Higgs channels
- Looking at excesses in some channels and not others may help us narrow down on the new physics searches
- In 2HDMs, we have $pp \to A \to Zh$ and this may contaminate when $M_A < 2M_t$ and $\tan\beta$ is small
- Upper limits on cross-sections contaminating the SM non-resonant di-Higgs signals are weaker

Contaminations to the Higgs pair producing channels: $h(+X)$



- $A \rightarrow Zh$ contaminates the SM signals to a lesser degree; Possible reason: Reconstructed Z-peak is shifted from the reconstructed Higgs peak and m_{bb} is an important discriminatory variable for all such searches involving a b-jet pair

Contaminations to the Higgs pair producing channels: $h(+X)$

- Observation of SUSY will depend on its electroweak sector ($\chi_i^\pm$ and χ_j^0s)
- With decoupled Higgs sector, chargino-neutralino production mediated through W propagator
- $W^\pm \chi^\mp \chi_1^0$ coupling contains both wino and higgsino components $\rightarrow$ wino components dominate
- CMS and ATLAS searched in the $3\ell + \not{E}_T$ and SFOS $2\ell + \not{E}_T$ for non-generic scenarios with $\chi_1^\pm$, χ_2^0 dominantly wino-like and degenerate
- Choose BP2 with $M_2 \ll \mu \rightarrow \chi_1^\pm$ and χ_2^0 wino-like $\rightarrow$ $\sigma(pp \rightarrow \chi_1^\pm \chi_2^0) \gg \sigma(pp \rightarrow \chi_2^0 \chi_2^0)$
- BP2 marginally outside projected exclusion from ATLAS HL-LHC study

Contaminations to the Higgs pair producing channels: $h(+X)$

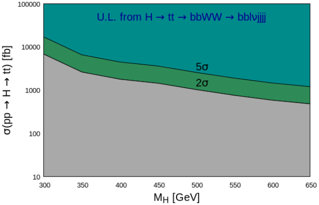
- We get a $Wh + \not{E}_T$ final state with cross-section ~ 400 fb
- Contaminations possible to: $b\bar{b}WW^* \to b\bar{b}\ell jj + \not{E}_T$, $\gamma\gamma WW^* \to \gamma\gamma\ell jj + \not{E}_T$, $4W \to \ell^\pm\ell^\pm jjjj + \not{E}_T$, $3\ell jj + \not{E}_T$

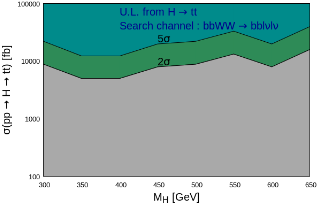
Channel	SM background	SM *hh* production	BP2 contamination
$bb\ell jj + \not{E}_T$	1103017.13	134.34	382.88
$SS2\ell jj + \not{E}_T$	12378.49	11.96	270.31
$3\ell jj + \not{E}_T$	5389.46	15.01	291.91

- Large contaminations $\to$ calling for carefully treating these channels in the future in case of observance of large number of events $\to$ potential new physics contributions

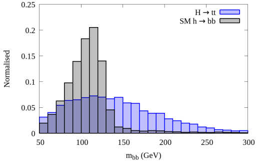
Contaminations to the Higgs pair producing channels: Null Higgs

- $H(A) \to t\bar{t}$ for $m_{H(A)} > 2m_t$ may contaminate $b\bar{b}\tau^+\tau^-$ and $b\bar{b}WW^*$



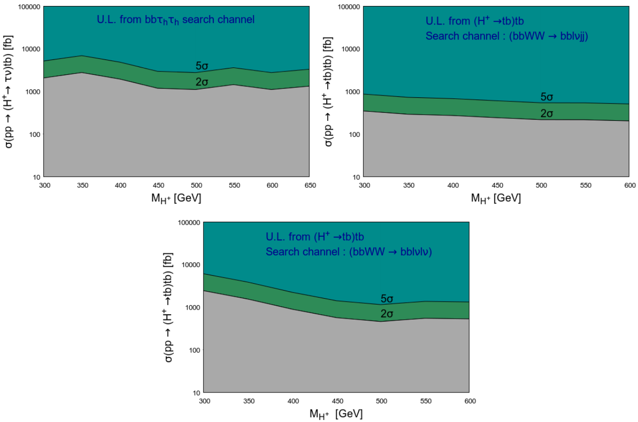


- Weaker bounds because m_{bb} is different for $t\bar{t}$; Require a large production cross-section for heavy resonant scalar in order to contaminate appreciably



Contaminations to the Higgs pair producing channels: Null Higgs

- Charged Higgs production: $\bar{t}bH^+ / t\bar{b}H^-$ with charged Higgs decaying to $\tau\nu$ or $t\bar{b}$ depending on mass of m_{H^+} (Affects low tan β regions)



Contaminations to the Higgs pair producing channels: Null Higgs

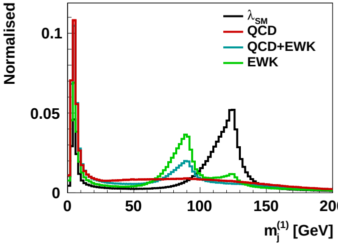
- For stop masses of $\mathcal{O}$(several hundreds of GeVs), $pp \to \tilde{t}_1 \tilde{t}_1^*$ may be large
- From BP3, BR($\tilde{t}_1 \to b\chi_1^+ \to bW^+\chi_1^0$ may be dominant $\to 2b + 2W + \not{E}_T$
- Potentially contaminate $b\bar{b}\tau^+\tau^-$ and $b\bar{b}WW^*$ channels

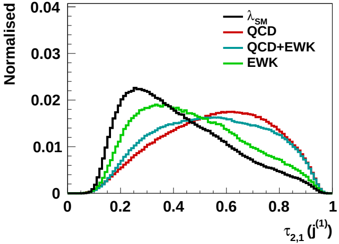
SM background	SM *hh* production	BP3 contamination
1103017.13	134.34	101.83

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
- Requre: $\tau_{2,1} < 0.35$ 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





Other exotic Higgs decays

- $\gamma\gamma + \not{E}_T$: good potential for a resonance scenario $\rightarrow$ clean channel, expect ~ 135 events before selection cuts at $\mathcal{L} = 3$ ab^{-1} for the aforementioned benchmark scenario
- Focus on scenarios where the Higgs decays to a pair of light (pseudo)scalars which in turn decay to fermions or gluons/photons
- Such signatures can be seen in models like 2HDM+S [Peccei, Quinn, 1977], extensions of SM with hidden light gauge bosons [Gopalakrishna *et. al.*, 2008], R-symmetry limit of NMSSM [Cao *et. al.*, 2013], Little Higgs models [Surujon *et. al.*, 2010] to name a few

Other exotic Higgs decays

- Following [Curtin *et. al.*] some interesting exotic decay modes like $h \to XX \to 4b$: potential final state $4b + 2\ell + \not{E}_T$ with the other Higgs decaying leptonically $(WW^*, ZZ^*, \tau\tau) \to \mathcal{O}(100)$ events before selection cuts (but including a b-tagging efficiency of 0.7) for $\text{BR}(h \to XX \to 4b) = 0.1$
- Decays like $h \to aa \to 2b2\tau$ and the other Higgs decaying to $b\bar{b}$: interesting $4b2\tau$ final state
- Decays like $h \to aa \to 4j$: both jet pairs reconstructable. The other Higgs may decay to $b\bar{b}$ or leptonically
- Another potential channel : $h \to aa \to 2\gamma 2j$ and a final signature of $2b2\gamma 2j$

Other exotic Higgs decays

- With $\mathrm{BR}_{h\to 2\gamma+\not{E}_T} = 4\%$, one can expect $\mathcal{O}(1000)$ events before the selection cuts (with 70% b-tagging efficiency) in the $2b2\gamma + \not{E}_T$ final state at $\mathcal{L} = 3$ ab^{-1}
- There are other interesting exotic decay modes which might face strong backgrounds from single Higgs production but may have very less background in di-Higgs
- We leave these for a comprehensive future work