Diboson (including di-Higgs) at FCC-hh

Shankha Banerjee
CERN

January 27, 2023

FUTURE CIRCULAR COLLIDER

Why FCC-hh and why dibosons?

- To push the field of particle physics to the next energy frontier beyond HL-LHC $\rightarrow$ increasing possible mass probe of BSM particles by an order of magnitude
- To push precision by several orders of magnitude thereby constraining EFT couplings and gauging the presence of possible new physics effects
- Diboson ($W^+W^-, W^\pm Z, ZZ, W^\pm\gamma$) searches $\rightarrow$ TGC and QGC couplings
- Higgs-strahlung ($Zh, W^\pm h$) searches $\rightarrow$ TGC, VVh, and contact ($q\bar{q}^{(\prime)}Vh$) interactions [See talks by Ang Li and Giovanni Marchiori for Zh in e^+e^- colliders]
- Di-Higgs ($hh, hh+j, hh+jj, t\bar{t}hh$) searches $\rightarrow$ Higgs trilinear, Higgs quartic, $t\bar{t}hh$ couplings [See slides by Michele Selvaggi, Jorge de Blas, and Ennio Salvioni]

  [For top-Higgs interplay and global fits see talk by Eleni Vryonidou]

Cross-section growth with $\sqrt{\hat{s}}$ in VV, Vh, hh

	σ_{LO}(pb)	σ_{NLO}(pb)	$\sigma_{NLO} + \sigma_{gg}$(pb)	σ_{NNLO}(pb)
100 TeV				
$ZZ \to e^+e^-\mu^+\mu^-$	0.29	0.37	0.43	$0.460\ ^{(+4.0\%)}_{(-3.3\%)}$
$WW \to e\nu\mu\nu$	10.0	13.4	14.4	$15.8\ ^{(+3.6\%)}_{(-3.0\%)}$
$WZ \to e\nu\mu^+\mu^-$	1.1	2.2	–	$2.38 \pm 2.3\%$
27 TeV				
$ZZ \to e^+e^-\mu^+\mu^-$	0.058	0.080	0.090	$0.0952\ ^{(+2.9\%)}_{(-2.4\%)}$
$WW \to e\nu\mu\nu$	2.1	3.0	3.2	$3.46\ ^{(+2.8\%)}_{(-2.4\%)}$
$WZ \to e\nu\mu^+\mu^-$	0.23	0.42	–	$0.483 \pm 2.1\%$

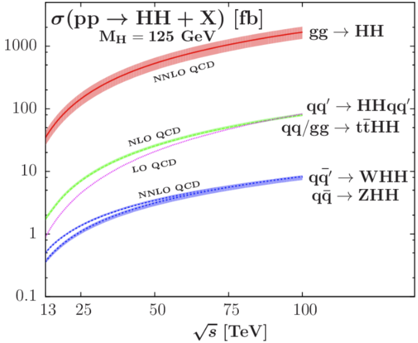
	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390
N_{27}	2.2×10^9	1.8×10^8	5.1×10^7	3.7×10^7	4.4×10^7	2.1×10^6
N_{27}/N_{14}	16	15	11	12	24	19

- For $W^+W^-(W^\pm Z)$, there is a growth of $\sim 8.7(9.5)$ when going from 14 TeV to 100 TeV in the SM. For ZZ, it is ~ 9.6.

[FCC Physics Opportunities: CDR; 2018]

Cross-section growth with $\sqrt{\hat{s}}$ in $hh + X$

	σ[100 TeV](fb)	σ[27 TeV](fb)
$gg \to HH$	$1.22 \times 10^3\,^{+0.9\%}_{-3.2\%} \pm 2.4\% \pm 4.5\%_{m_t}$	$140\,^{+1.3\%}_{-3.9\%} \pm 2.5\% \pm 3.4\%_{m_t}$
HHjj	$80.5 \pm 0.5\% \pm 1.8\%$	$1.95 \pm 2\% \pm 2.4\%$
W^+HH	$4.7 \pm 1\% \pm 1.8\%$	$0.37 \pm 0.4\% \pm 2.1\%$
W^-HH	$3.3 \pm 4\% \pm 1.9\%$	$0.20 \pm 1.3\% \pm 2.7\%$
ZHH	$8.2 \pm 5\% \pm 1.7\%$	$0.41 \pm 3\% \pm 1.8\%$
$t\bar{t}HH$	$82.1 \pm 8\% \pm 1.6\%$	$0.95\,^{+1.7\%}_{-4.5\%} \pm 3.1\%$



[FCC Physics Opportunities: CDR; 2018], [Baglio, Djouadi, Quevillon; 2015]

EFT 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
- 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 [See Dave Sutherland's slides on SMEFT versus HEFT]
- 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 and that of the FCC-hh as well
- Indirect constraints can constrain much higher scales S, T parameters being prime examples
- Q: How well does the FCC-hh compete with LEP in constraining precision physics?

  A: From EFT correlated variables, LEP already constrained certain anomalous Higgs couplings $\rightarrow$ Z-pole measurements, TGCs

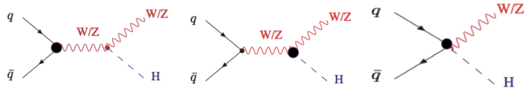
  Going to higher energies in FCC-hh is the only way to obtain newer information after the HL-LHC
- EFT techniques show that many Higgs deformations aren't independent from cTGCs and EW precision which were already constrained at LEP $\rightarrow$ Same operators affect TGCs and Higgs deformations

Diboson and Higgs-strahlung in SMEFT

$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{HL}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{L}\sigma^a\gamma^\mu L$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{HB} = \|H\|^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{d}_R\gamma^\mu d_R$	$\mathcal{O}_{HW} = \|H\|^2 W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{e}_R\gamma^\mu e_R$	$\mathcal{O}_{H\tilde{B}} = \|H\|^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{Q}\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}B} = H^\dagger\sigma^a H W^a_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{Q}\sigma^a\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}} = \|H\|^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
$\mathcal{O}_{HL}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{L}\gamma^\mu L$	$\mathcal{O}_{y_b} = \|H\|^2(\bar{Q}_3 H b_R + h.c.)$

Operators in the Warsaw basis contributing to anomalous $q\bar{q}^{(\prime)} \to WV, Vh$ processes

Diboson and Higgs-strahlung in SMEFT



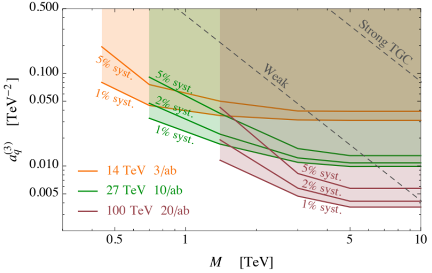
[Franceschini, Panico, Pomarol, Riva, Wulzer; 2017], [SB, Gupta, Reiness, Seth, Spannowsky; 2020]

$$
\begin{aligned}
\Delta\mathcal{L}_6 \quad \supset \quad & \delta\hat{g}^h_{WW}\,\frac{2m_W^2}{v}\,hW^{+\mu}W^-_\mu + \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}\,h\frac{Z^\mu Z_\mu}{2} + \delta g^W_Q\,(W^+_\mu\bar{u}_L\gamma^\mu d_L + h.c.)\\
+ \quad & \delta g^W_L\,(W^+_\mu\bar{\nu}_L\gamma^\mu e_L + h.c.) + g^h_{WL}\,\frac{h}{v}(W^+_\mu\bar{\nu}_L\gamma^\mu e_L + h.c.)\\
+ \quad & g^h_{WQ}\,\frac{h}{v}(W^+_\mu\bar{u}_L\gamma^\mu d_L + h.c.) + \sum_f \delta g^Z_f Z_\mu\bar{f}\gamma^\mu f + \sum_f g^h_{Zf}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f\\
+ \quad & \kappa_{WW}\,\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \tilde{\kappa}_{WW}\,\frac{h}{v}W^{+\mu\nu}\tilde{W}^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}\\
+ \quad & \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu} + \kappa_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\\
+ \quad & \tilde{\kappa}_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}\tilde{Z}_{\mu\nu} + \delta\hat{g}^h_{bb}\,\frac{\sqrt{2}m_b}{v}\,hb\bar{b}\\
+ \quad & igc_{\theta_W}\delta g^Z_1[Z^\mu(W^{+\nu}W^-{}_{\mu\nu} - h.c.) + Z^{\mu\nu}(W^+_\mu W^-_\nu) + \ldots)]\\
+ \quad & ie\delta\kappa_\gamma[(A^{\mu\nu} - c_{\theta_W}Z^{\mu\nu})W^+_\mu W^-{}_\mu + \ldots]
\end{aligned}
$$

Diboson example: $W^{\pm}Z$

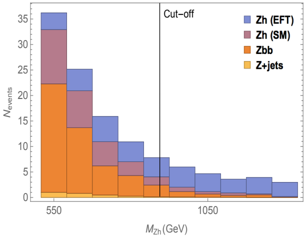
[Franceschini, Panico, Pomarol, Riva, Wulzer; 2017]

- Process: $pp \to W^{\pm}Z\ +\ \text{jets} \to \ell\nu\ell'\bar{\ell}'\ +\ jets$ with $\ell, \ell' = e, \mu$
- Low reducible background. Systematic uncertainty of 5% considered
- LO matched with one extra jet
- Sensitivity of high-energy primary $a_q^{(3)} = 4\frac{C_{HL}^{(3)}}{M^2}$ ("Weak" "non-universal" theories) is studied at various energies
- Result: HL-LHC, 3 ab^{-1}: $a_q^{(3)} \in [-4.9, 3.9]10^{-2}$ TeV^{-2} and FCC-hh, 20 ab^{-1}: $a_q^{(3)} \in [-7.3, 5.7]10^{-3}$ TeV^{-2}



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

- We study the impact of constraining TGC couplings at higher energies
- We study the channel $pp \to Zh \to \ell^+\ell^- b\bar{b}$
- The backgrounds are SM $pp \to Zh$, $Zb\bar{b}$, $t\bar{t}$ and the fake $pp \to Zjj$ ($j \to b$ fake rate taken as 2%)
- Major background $Zb\bar{b}$ (b-tagging efficiency taken to be 70%)
- Boosted substructure analysis with fat-jets of $R = 1.2$ used



Cuts	$Zb\bar{b}$	Zh (SM)
At least 1 fat jet with 2 B-mesons with $p_T > 15$ GeV	0.52	0.79
2 OSSF isolated leptons	0.44	0.48
80 GeV $< M_{\ell\ell} <$ 100 GeV, $p_{T,\ell\ell} > 260$ GeV, $\Delta R_{\ell\ell} > 0.2$	0.83	0.84
At least 1 fat jet with 2 B-meson tracks with $p_T > 220$ GeV	0.85	0.94
2 Mass drop subjets and ≥ 2 filtered subjets	0.88	0.92
2 b-tagged subjets	0.35	0.40
115 GeV $< m_h <$ 135 GeV	0.180	0.50
$\Delta R(b_i, \ell_j) > 0.4$, $\not{E}_T < 30$ GeV, $\lvert y_h \rvert < 2.5$, $p_{T,h/Z} > 300$ GeV	0.31	0.55

Bounds on Pseudo-observables at HL-LHC and FCC-hh

HL-LHC: @ 95% CL

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

Directions: $(\xi = v^2/\Lambda^2)$ [Araz, SB, Gupta, Spannowsky, 2020]

$$|(-0.04\ c^1_Q + 1.4\ c^{(3)}_Q + 0.1\ c_{uR} - 0.03\ c_{dR})\xi| < 0.003 \qquad [VBF]$$
$$|(-0.18\ c^1_Q + 1.3\ c^{(3)}_Q + 0.3\ c_{uR} - 0.1\ c_{dR})\xi| < 0.0005 \qquad [Zh]$$
$$|c^{(3)}_Q \xi| < 0.0004 \qquad [Wh]$$
$$-0.0004 < c^{(3)}_Q \xi < 0.0003 \qquad [WZ]$$

FCC-hh: @ 95% CL

$g^{h,\ell\ell b\bar{b}}_{Z\mathbf{p}} \in$ $[-0.00051, 0.00054]$ ($[-0.00021, 0.00023]$) with 5% systematic uncertainty.

$\in$ $[-0.00047, 0.00049]$ ($[-0.00016, 0.00017]$) with 1% systematic uncertainty.

$g^{h,\ell\ell\gamma\gamma}_{Z\mathbf{p}} \in$ $[-0.001, 0.001]$ ($[-0.0004, 0.0004]$) with 1% systematic uncertainty at 3 (30) ab^{-1}.

	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 ± 0.0032
$\delta g^Z_{d_L}$	± 0.0003 (± 0.0001)	± 0.003 (± 0.001)	0.0023 ± 0.002
$\delta g^Z_{u_R}$	± 0.0005 (± 0.0002)	± 0.005 (± 0.001)	-0.0036 ± 0.0070
$\delta g^Z_{d_R}$	± 0.0015 (± 0.0006)	± 0.016 (± 0.005)	0.016 ± 0.0104
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)	-0.0003 ± 0.0006
Y	± 0.0035 (± 0.0015)	± 0.032 (± 0.009)	0.0000 ± 0.0006

[SB, Englert, Gupta, Spannowsky, 2018] LEP bounds: [Falkowski, Riva, 2014], [Baak *et al.*, 2012], [Barbieri, Pomarol, Rattazzi, Strumia, 2004]

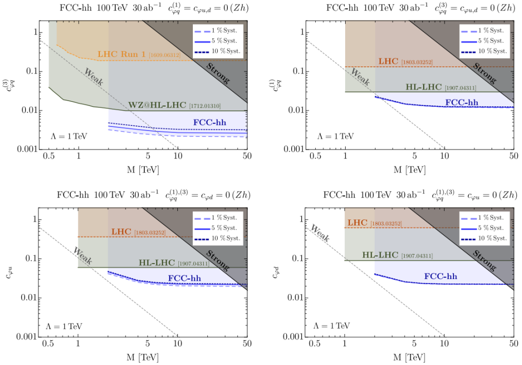
Map between bases: Zh case contact interaction h^h_{Zf}

	EFT directions probed by high energy $ff \to Vh$ production
Warsaw basis [1]	$-\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(\lvert T_3^f\rvert c_L^1 - T_3^f c_L^3 + (1/2 - \lvert T_3^f\rvert)c_f)$
BSM primaries [2]	$\frac{2g}{c_{\theta_W}} Y_f t_{\theta_W}^2 \delta\kappa_\gamma + 2\delta g_f^Z - \frac{2g}{c_{\theta_W}}(T_3^f c_{\theta_W}^2 + Y_f s_{\theta_W}^2)\delta g_1^Z$
SILH Lagrangian [26]	$\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}(2T_3^f \hat{c}_W - 2t_{\theta_W}^2 Y_f \hat{c}_B)$
Universal observables	$\frac{2g}{c_{\theta_W}} Y_f t_{\theta_W}^2(\delta\kappa_\gamma - \hat{S} + Y) - \frac{2g}{c_{\theta_W}}(T_3^f c_{\theta_W}^2 + Y_f s_{\theta_W}^2)\delta g_1^Z - \frac{2g}{c_{\theta_W}} T_3^f W$
High energy primaries [20]	$-\frac{2m_W^2}{g c_{\theta_W}}(\lvert T_3^f\rvert a_q^{(1)} - T_3^f a_q^{(3)} + (1/2 - \lvert T_3^f\rvert)a_f)$

Here $\hat{c}_W = c_W + c_{HW} - c_{2W}$ and $\hat{c}_B = c_B + c_{HB} - c_{2B}$.

[SB, Englert, Gupta, Spannowsky, 2018]

$Zh \to \ell^+\ell^-(\nu\bar{\nu})\gamma\gamma$ at FCC-hh



Single-operator analysis (growth $\hat{s}$)

$$c_{\varphi q}^{(3)} = +\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} - \delta g_L^{Zd} - c_{\mathrm{W}}^2\, \delta g_{1z}\right)$$

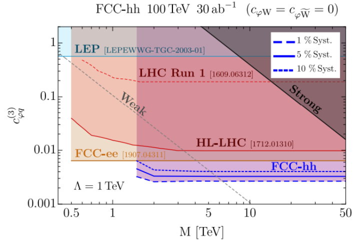
$$c_{\varphi q}^{(1)} = -\frac{\Lambda^2}{4m_W^2} g^2 \left(\delta g_L^{Zu} + \delta g_L^{Zd} + \frac{1}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

$$c_{\varphi u} = -\frac{\Lambda^2}{2m_W^2} g^2 \left(\delta g_R^{Zu} + \frac{2}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

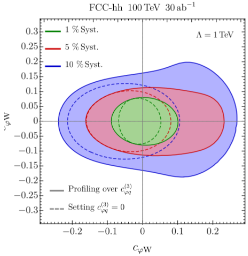
$$c_{\varphi d} = -\frac{\Lambda^2}{2m_W^2} g^2 \left(\delta g_R^{Zd} - \frac{1}{3}\left(t_{\mathrm{W}}^2 \delta\kappa_\gamma - s_{\mathrm{W}}^2 \delta g_{1z}\right)\right)$$

[Bishara, De Curtis, Rose, Englert, Grojean, Montull, Panico, Rossia; 2021]

$Wh \to \ell\nu\gamma\gamma$ at FCC-hh



Single-operator analysis (growth $\hat{s}$, longitudinal) [Bishara, Englert, Grojean, Montull, Panico, Rossia; 2020]



(growth $\sqrt{\hat{s}}$, profiled over $\mathcal{O}^{(3)}_{HQ}$, transverse)

Top interaction with Higgs and EW bosons (FCC-hh)

- $Zt_R\bar{t}_R$, $hZt_R\bar{t}_R$ poorly constrained from LEP via Z-boson decays
- Understanding top couplings to EW bosons is well-motivated as top and its partners can play crucial role in EWSB by radiatively contributing to the Higgs potential
- $\Lambda_{\text{top partners}} \sim \mathcal{O}(\text{TeV})$ from naturalness considerations $\rightarrow$ Sizeable indirect effects
- In composite models, integrating out top partners can lead to the following operators

$$\mathcal{O}^{(1)}_{HQ_L} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{Q}_L \gamma^\mu Q_L \quad \mathcal{O}^{(3)}_{HQ_L} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{Q}_L \sigma^a \gamma^\mu Q_L \quad \mathcal{O}_{Ht_R} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

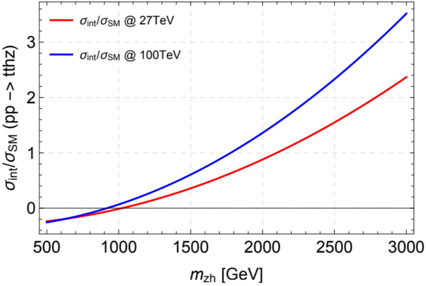
- Operators involving left-chiral fermions deform both $Zb\bar{b}$ and $Zt\bar{t}$ $\rightarrow$ constrained by $Z-$pole and TGCs
- $\mathcal{O}_{Ht_R}$ is unconstrained. Expanding in unitary gauge

$$\frac{\mathcal{O}_{Ht_R}}{\Lambda^2} = -\frac{gv^2}{2c_{\theta_W}\Lambda^2}(1 + \frac{2h}{v} + \frac{h^2}{v^2}) Z_\mu \bar{t}_R \gamma^\mu t_R$$

[SB, Gupta, Jain, Mangano, Venturini; in preparation], Les Houches 2019 WG report

Top interaction with Higgs and EW bosons (FCC-hh)

- In SM, $\sigma_{gg\to t\bar{t}hZ} \sim 1.5(130)$ fb at 14 TeV (100 TeV). With $m_{Zh} > 1.5$ TeV $\sigma_{gg\to t\bar{t}hZ} \sim 3.6$ fb at 100 TeV $\to$ Potential to study fully leptonic final state
- Final state: 4 b-tagged jets, 3 leptons, 2 light jets and $\not{E}_T$
- Backgrounds, *viz.*, $t\bar{t}h+$ jets, $t\bar{t}Z+$ jets, $t\bar{t}hb\bar{b}$, $t\bar{t}Zb\bar{b}$, $t\bar{t}hh$, $t\bar{t}WZ+$ jets, $VVV+$ jets, $WZb\bar{b}+$ jets
- Treating SM $t\bar{t}hZ$ as signal, $S/B \sim 0.20$ and preliminary bound on $|g_{hZt_R}| \sim \mathcal{O}(10^{-3})$



[SB, Gupta, Jain, Mangano, Venturini; in preparation], Les Houches 2019 WG report

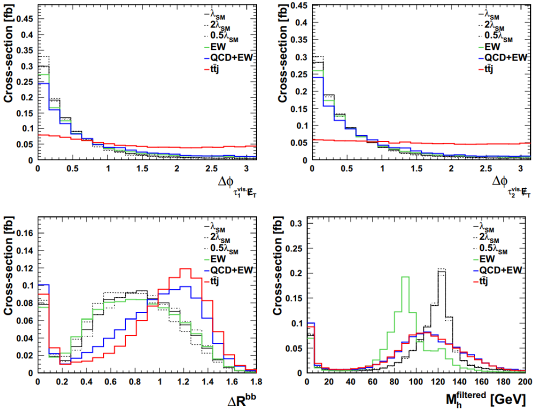
Di-Higgs + jet at FCC-hh

- Observing the Higgs self-coupling at the HL-LHC seem difficult at the moment
- 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 extra sensitivity (decorrelates $p_{T,h}$ and m_{hh}) to λ_{hhh}
- Use substructure technique: BDRS [Butterworth, *et. al.*; 2008] with mass drop and filtering

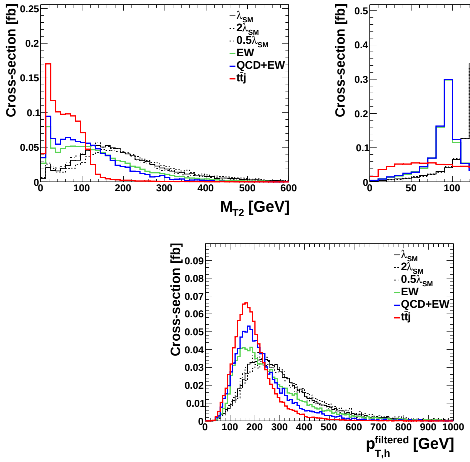
[SB, Englert, Mangano, Selvaggi, Spannowsky; 2018]

Di-Higgs + jet at FCC-hh ($jb\bar{b}\tau^+\tau^-$)

- $R = 1.5$, $p_T^j > 110$ GeV, τ-tag efficiency 70%, b-tag efficiency 70%, b-mistag rate 2%; Combined $\tau_h\tau_h$ and $\tau_h\tau_\ell$
- Backgrounds: EW (example: $HZ/\gamma^* +$ jet), QCD+EW (Example: $b\bar{b}Z/\gamma^* +$ jet), $t\bar{t}+$ jet



Di-Higgs + jet at FCC-hh ($jb\bar{b}\tau^+\tau^-$)



Di-Higgs + jet at FCC-hh ($jb\bar{b}\tau^+\tau^-$)

	signal [fb]	QCD+QED [fb]	QED [fb]	$t\bar{t}j$ [fb]	tot. background [fb]	S/B	$S/\sqrt{B}$, 30/ab
$\kappa_\lambda = 0.5$	0.428					0.121	39.44
$\kappa_\lambda = 1$	0.363	0.95	0.27	2.31	3.53	0.103	33.44
$\kappa_\lambda = 2$	0.264					0.075	24.31

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

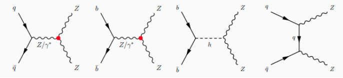
$$0.92 < \kappa_\lambda < 1.08 \quad 30/\text{ab}$$

at 68% confidence level using the CLs method.

[SB, Englert, Mangano, Selvaggi, Spannowsky; 2018]

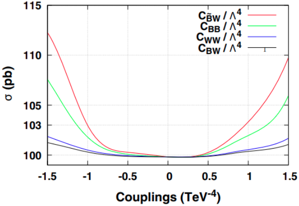
Diboson example: ZZ

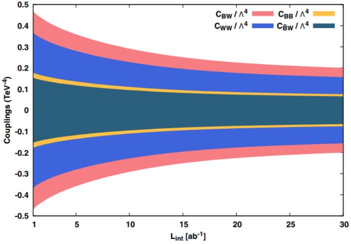
- $ZZ, Z\gamma$ channels let us constrain the neutral anomalous TGCs which appear from D8 operators
- For ZZ, relevant operators are $\mathcal{O}_{\tilde{B}W} = iH^\dagger \tilde{B}_{\mu\nu} W^{\mu\rho} D_\rho D^\nu H$ (CP-conserving), $\mathcal{O}_{BW} = iH^\dagger B_{\mu\nu} W^{\mu\rho} D_\rho D^\nu H$, $\mathcal{O}_{WW} = iH^\dagger W_{\mu\nu} W^{\mu\rho} D_\rho D^\nu H$, and



$\mathcal{O}_{BB} = iH^\dagger B_{\mu\nu} B^{\mu\rho} D_\rho D^\nu H$ (Last three CP-violating)

- Studying one coupling at a time in the 4ℓ channel, the bounds are an order stronger than HL-LHC results in the 4ℓ channel





[Yilmaz1, Senol, Denizli, Cakir, Cakir; 2019]

Summary and conclusions

- FCC-hh will be an extremely fertile ground to search for new physics including precision physics in the diboson, Higgs-strahlung, and di-Higgs sectors.
- For WZ production, the improvement on $C_{HL}^{(3)}$ is $\sim 85\%$ in the fully leptonic channel.
- Detailed studies need to be performed for W^+W^-, and $W^\pm\gamma$ at FCC-hh.
- For Zh, the contact interactions gain improvements between 80% and 90% ($\sim 50\%$) in the $b\bar{b}\ell^+\ell^-$ ($\gamma\gamma\ell^+\ell^-$) channel.
- For $hh+$ jet, κ_λ is constrained to 8%. Marginalising over all other relevant EFT couplings necessary.
- One operator at a time study of aNTGCs puts constraints of an order stronger. Necessary to do a global analysis including contact interactions with fermions.

Backup Slides

Higgs Pseudo-Observables

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

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

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

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

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

  h^3

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

- These anomalous Higgs couplings are first probed at the LHC

Electroweak Pseudo-Observables

- Following are the 9 EW precision observables (assuming flavour universality)
  $Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$ $W^+_\mu \bar{u}_L \gamma^\mu d_R$
- These couplings were measured very precisely by the Z/W-pole measurements through the Z/W decays
- Following are the 3 TGCs which were measured by the $e^+e^- \to W^+W^-$ channel at LEP
  $g_1^Z c_{\theta_w} Z^\mu (W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu})$
  $\kappa_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^+_\mu W^-_\nu$
  $\lambda_\gamma s_{\theta_w} \hat{A}^{\mu\nu} W^{-\rho}_\mu W^+_{\rho\nu}$
- Finally, following are the QGCs
  $Z^\mu Z^\nu W^-_\mu W^+_\nu$
  $W^{-\mu} W^{+\nu} W^-_\mu W^+_\nu$

Effective Field Theory: The operators at play

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

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

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

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

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 $\hat{h} = v + h$

Higgs anomalous couplings: Dimension 6 effects

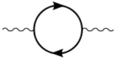
$$\mathcal{L}_h^{\text{primary}} = g_{VV}^h\, h\left[W^{+\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2}Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g_{ff}^h\, \left(h\bar{f}_L f_R + h.c.\right)$$
$$+ \quad \kappa_{GG}\,\frac{h}{v}G^{A\,\mu\nu}G_{\mu\nu}^A + \kappa_{\gamma\gamma}\,\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,$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

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

[Pomarol, 2014]

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

STU oblique parameters



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

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

1. Any BSM correction which is indistinguishable from a redefinition of e, G_F and M_Z (or equivalently, g_1, g_2 and v) in the Standard Model proper at the tree level does not contribute to S, T or U.
2. Assuming that the Higgs sector consists of electroweak doublet(s) H, the effective action term $\left|H^\dagger D_\mu H\right|^2/\Lambda^2$ only contributes to T and not to S or U. This term violates custodial symmetry.
3. Assuming that the Higgs sector consists of electroweak doublet(s) H, the effective action term $H^\dagger W^{\mu\nu} B_{\mu\nu} H/\Lambda^2$ only contributes to S and not to T or U. (The contribution of $H^\dagger B^{\mu\nu} B_{\mu\nu} H/\Lambda^2$ can be absorbed into g_1 and the contribution of $H^\dagger W^{\mu\nu} W_{\mu\nu} H/\Lambda^2$ can be absorbed into g_2).
4. Assuming that the Higgs sector consists of electroweak doublet(s) H, the effective action term $\left(H^\dagger W^{\mu\nu} H\right)\left(H^\dagger W_{\mu\nu} H\right)/\Lambda^4$ contributes to U.

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

$$g^h_{Zu_Lu_L} = \frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B}))$$

$$g^h_{Zd_Ld_L} = -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B}))$$

$$g^h_{Zu_Ru_R} = -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})$$

$$g^h_{Zd_Rd_R} = \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})$$

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

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

[Gupta, Pomarol, Riva, 2014]

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

$$g^h_{Zu_Lu_L} = -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}+\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W + \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)$$

$$g^h_{Zd_Ld_L} = \frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}-\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W - \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)$$

$$g^h_{Zu_Ru_R} = -\frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)$$

$$g^h_{Zd_Rd_R} = \frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)$$

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

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)]

BDRS: An aside

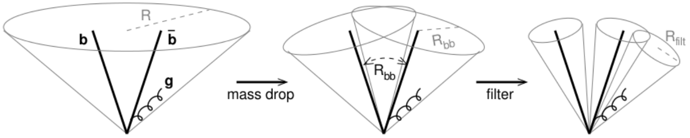


FIG. 1: The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighbourhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region one then further reduces the radius to R_{filt} and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

Given a hard jet j, obtained with some radius R, we then use the following new iterative decomposition procedure to search for a generic boosted heavy-particle decay. It involves two dimensionless parameters, μ and y_{cut}:

1. Break the jet j into two subjets by undoing its last stage of clustering. Label the two subjets j_1, j_2 such that $m_{j_1} > m_{j_2}$.
2. If there was a significant mass drop (MD), $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\text{cut}}$, then deem j to be the heavy-particle neighbourhood and exit the loop. Note that $y \simeq \min(p_{tj_1}, p_{tj_2}) / \max(p_{tj_1}, p_{tj_2})$.[1]
3. Otherwise redefine j to be equal to j_1 and go back to step 1.

The final jet j is to be considered as the candidate Higgs boson if both j_1 and j_2 have b tags. One can then identify $R_{b\bar{b}}$ with $\Delta R_{j_1 j_2}$. The effective size of jet j will thus be just sufficient to contain the QCD radiation from the

In practice the above procedure is not yet optimal for LHC at the transverse momenta of interest, $p_T \sim 200-300$ GeV because, from eq. (1), $R_{b\bar{b}} \gtrsim 2m_H/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{b\bar{b}}^4$ [15]. A second novel element of our analysis is to *filter* the Higgs neighbourhood. This involves resolving it on a finer angular scale, $R_{\text{filt}} < R_{b\bar{b}}$, 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.

Relevant operators

- Dimension 6 operators which modify the Higgs self-interactions

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

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3 \quad \mathcal{O}_{\Phi,4} = (D_\mu\Phi^\dagger)(D^\mu\Phi)\Phi^\dagger\Phi \quad \mathcal{O}_{GG} = G^a_{\mu\nu}G^{a,\mu\nu}\Phi^\dagger\Phi$$

- $\mathcal{O}_{\Phi,2/3}$ only modify Higgs self-couplings but $\mathcal{O}_{\Phi,1/4}$ also modify HVV couplings and V masses
- $\mathcal{O}_{\Phi,1}$ contributes to m_Z and not to m_W $\rightarrow$ Violates Custodial symmetry $\rightarrow$ Strongly constrained by T-parameter $\rightarrow$ Neglected for collider studies
- Redundancy amongst operators upon using EOMs $\rightarrow$ $\mathcal{O}_{\Phi,2}$, $\mathcal{O}_{\Phi,3}$ and $\mathcal{O}_{\Phi,4}$ are not independent
- Including SM Yukawa, the operator $\mathcal{O}_{\Phi,f} = (\Phi^\dagger\Phi)\bar{L}\Phi f_R + \mathrm{h.c.}$, where $L = (f_L^u, f_L^d)^T$ becomes relevant
- One can remove $\mathcal{O}_{\Phi,4}$ using EOMs $\rightarrow$ Left with $(\mathcal{O}_{\Phi,2}, \mathcal{O}_{\Phi,3}, \mathcal{O}_{\Phi,f}, \mathcal{O}_{GG})$

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 $\kappa_\lambda = \lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}}$

Bases translations

[Giudice, Grojean, Pomarol, Rattazzi; 2007, Feruglio; 1993]

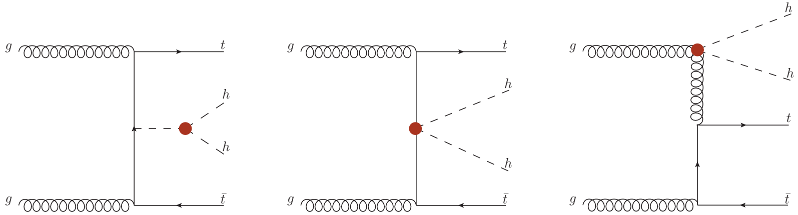
Coupling	Non-linear EFT	Simplified Lagrangian	SILH
hhh	d_3	κ_λ	$1 + (c_6 - c_T/4 - 3c_H/2)\xi$
$t\bar{t}hh$	c_2	$-\frac{\sqrt{2}v}{y_t}\kappa_{t\bar{t}hh}$	$-(c_H + 3c_y + c_T/4)\xi/2$
$gghh$	k_{2g}	$-\frac{12\pi^2 v^2}{g_s^2}\kappa_{gghh}$	$3c_g\left(\frac{y_t^2}{g_\rho^2}\right)\xi$

Table: Relationship between the hhh, $t\bar{t}hh$ and $gghh$ vertices in three different bases, where $\xi \equiv (v/f)^2$.

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = {} & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{\bar{c}_T}{2v^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] - \frac{\bar{c}_6\lambda}{v^2}\left[\Phi^\dagger\Phi\right]^3 \\
& - \left[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger\Phi\ \Phi^\dagger \cdot \bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger\Phi\ \Phi \bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell\ \Phi^\dagger\Phi\ \Phi \bar{L}_L e_R + \text{h.c.}\right] \\
& + \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\right] D^\nu W_{\mu\nu}^k + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right]\partial^\nu B_{\mu\nu} \\
& + \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu \Phi\right] W_{\mu\nu}^k + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right] B_{\mu\nu}
\end{aligned}$$

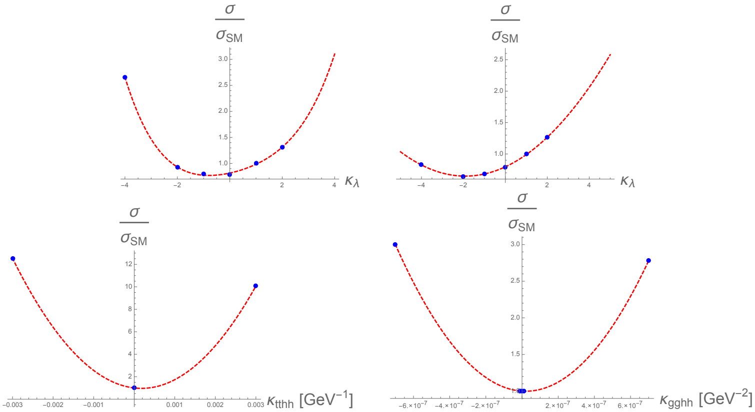
Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at 100 TeV

- 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 FCC-hh

- 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]



Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- Unlike many di-Higgs processes, in $t\bar{t}hh$ cross-section increases with $\lambda > \lambda_{\rm SM}$
- For κ_λ, growth of cross-section for $\lambda < 0$ has different features at 14 TeV and 100 TeV machines
- In linear EFT scenarios, the coupling modifying ggh and $gghh$ are correlated
  $\rightarrow$ In non-linear EFT they are uncorrelated
- We vary κ_λ and $\kappa_{t\bar{t}hh}$ to obtain bounds on these couplings

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

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

- For $\kappa_\lambda = 1$, $\sigma_{t\bar{t}hh}^{100\text{ TeV}}/\sigma_{t\bar{t}hh}^{14\text{ TeV}} \sim 75$
- 14 TeV study yields $\sim$ 13 signal events and $\kappa_\lambda \lesssim 2.5$ at 95% CL [Englert *et. al.*; 2014]
- For the 100 TeV analysis, we consider final state with 6 *b*-tagged jets, 1 isolated lepton, at least 2 light jets and $\not{E}_T$
- Several backgrounds at play, *viz.*, QCD processes: $t\bar{t}b\bar{b}b\bar{b}, t\bar{t}hb\bar{b}, t\bar{t}Zb\bar{b}$ and EW processes $t\bar{t}hZ, t\bar{t}ZZ$
- Fake backgrounds: $t\bar{t}b\bar{b}+$ jets, $t\bar{t}h+$ jets, $t\bar{t}Z+$ jets, $W^\pm b\bar{b}b\bar{b}+$ jet, $W^\pm c\bar{c}c\bar{c}+$ jets, $W^\pm b\bar{b}+$ jets, $t\bar{t}c\bar{c}c\bar{c}$, misidentifying c or light jets as *b*-tagged jets
- We assume *b*-tagging efficiency of 80%, 10% (1%) mistagging efficiency for *c*-jets (light jets)

$t\bar{t}hh$ Scale choices

Process category	μ_F^2	μ_R^2
$t\bar{t}HH$, $t\bar{t}ZZ$, $t\bar{t}HZ$	$\frac{1}{4}\,H_T^2 + 2m_t^2 + \{2m_H^2, 2m_Z^2, m_H^2 + m_Z^2\}$	$\frac{1}{4}\,H_T^2 + 2m_t^2$
$t\bar{t}Hb\bar{b}$, $t\bar{t}Zb\bar{b}$	$\frac{1}{4}\,H_T^2 + m_{H,Z}^2 + 2m_t^2$	$\frac{1}{4}\,H_T^2 + 2m_t^2$
$t\bar{t}$ + b's, c's or light jets	$\frac{1}{4}\,H_T^2 + 2m_t^2$	$\frac{1}{4}\,H_T^2 + 2m_t^2$
W + b's, c's or light jets	$\frac{1}{4}\,H_T^2 + m_W^2$	$\frac{1}{4}\,H_T^2$

Table: Renormalisation and factorisation scales used for the various processes

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- For the $t\bar{t}Z/h+$ jets, we consider a merged sample, where additional jets ensue from QCD radiation including the $g \to b\bar{b}$ splitting
- We ensure that the additional jets do not contain > 1 B-mesons by requiring that the B-hadron closest to the jet axis satisfies $x_B = \frac{|\vec{p}_B|}{|\vec{p}_j|} \times \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_B||\vec{p}_j|} > 0.7$
- Reflects b-quark fragmentation $\to$ Allows to suppress "doubly-tagged" b-jets
- We first reconstruct the two Higgs bosons by minimising the following χ^2

$$\chi^2_{HH} = \frac{(m_{b_i,b_j} - m_h)^2}{\Delta_h^2} + \frac{(m_{b_k,b_l} - m_h)^2}{\Delta_h^2},$$

$i \neq j \neq k \neq l$ run over all the 6 b-tagged jets, $m_h = 120$ GeV taking into account invisible decays of B-mesons and $\Delta_h = 20$ GeV

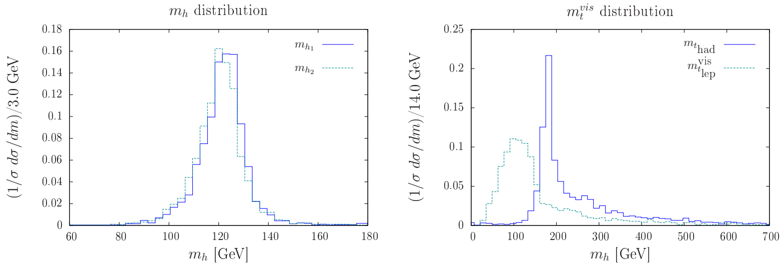
- We then require require $|m_{b_i,b_j} - m_h| < \Delta_h$ and $|m_{b_k,b_l} - m_h| < \Delta_h$

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

- Then we take the 2 remaining b-jets and minimise the following χ^2

$$\chi^2_{t_h} = \frac{(m_{b_i,j_k,j_l} - m_t)^2}{\Delta_t^2},$$

$k \neq l$ and $\Delta_t = 40$ GeV We then require $|m_{b_i,j_k,j_l} - m_t| < \Delta_t$



- Finally we require $m^{vis}_{t_{lep}} < m_t$

Constraining κ_λ and $\kappa_{t\bar{t}hh}$ from $t\bar{t}hh$ at FCC-hh

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

- At the design luminosity of 30 ab^{-1}, we expect $\sim$ 260 signal events for $\kappa_\lambda = 1$ and $\sim$ 1900 background events, with $S/B \sim 0.14$ and statistical significance of $S/\sqrt{B} \sim 5.9$
- Upon taking $\kappa_{t\bar{t}hh} = 0$, one obtains (using the CLs method) at 68% CL with 5% (10%) systematic uncertainty

$$-3.20 < \kappa_\lambda < 2.60 \; (-3.43 < \kappa_\lambda < 2.92) \quad 3/\text{ab}$$
$$-2.89 < \kappa_\lambda < 2.15 \; (-3.27 < \kappa_\lambda < 2.70) \quad 30/\text{ab}$$

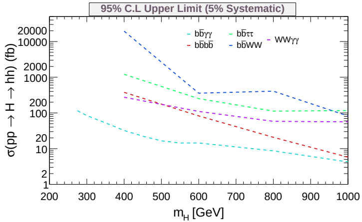
- Upon taking $\kappa_\lambda = 1$, one obtains (using the CLs method) at 68% CL with 5% (10%) systematic uncertainty

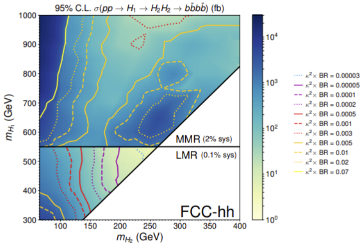
$$-0.59 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.95 \text{ TeV}^{-1} \; (-0.71 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 1.07 \text{ TeV}^{-1}) \quad 3/\text{ab}$$
$$-0.43 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.78 \text{ TeV}^{-1} \; (-0.63 \text{ TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.99 \text{ TeV}^{-1}) \quad 30/\text{ab}$$

- 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

Resonant di-Higgs at HL-LHC and FCC-hh

- Bounds on $\sigma(pp \to H \to hh)$ at HL-LHC (left) from various channels and at FCC-hh (right) from $b\bar{b}b\bar{b}$
  [A. Adhikary, SB, R. K. Barman and B. Bhattacherjee; 2018, D. Barducci, K. Mimasu, J. M. No, C. Vernieri and J. Zurita; 2019]





- Right plot: isocontours of sensitivity on $\kappa^2 \times \mathrm{BR}$ ($\kappa^2 \times \mathrm{BR}$ is defined by $\sigma\left(pp \to H_1 \to H_2 H_2 \to b\bar{b}b\bar{b}\right) = \hat{\sigma}_{H_1} \times \kappa^2 \times \mathrm{BR}$ and $\hat{\sigma}_{H_1}$ is production of SM-like Higgs with mass m_{H_1})
- FCC-hh can set stringent limit on $\kappa \times \mathrm{BR} \to$ factor $\sim$ 40 improvement with respect to HL-LHC