Snowmass status on Higgs + EW SMEFT Fits

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The energy frontier

- **Build large colliders $\rightarrow$ go to high energy $\rightarrow$ discover new particles!**

- Higgs and nothing else?

- What's next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!

The energy frontier

- **Build large colliders** $\rightarrow$ go to high energy $\rightarrow$ discover new particles!

  ↘ **do precision measurements** $\rightarrow$ **discover new physics indirectly!**

- Higgs and nothing else?

- What's next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!
  - **Higgs factory!** (A lepton collider at $\sqrt{s} \sim 240$-250 GeV or above.)
  - **SMEFT** (model independent approach)

Why lepton colliders?

- **Higgs (and Z, W, top) factory!**
  - Large statistics, clean environment
    $\Rightarrow$ **precise measurements!**
- EFT is good for lepton colliders.
  - A systematic parameterization of Higgs (and other) couplings.
- Lepton colliders are also good for EFT!
  - High precision $\Rightarrow$ $E \ll \Lambda$
    Ideal for EFT studies!
  - LHC is built for discovery, but ....

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  - LHC is built for discovery, but ....
- **Energy** *vs.* **Precision**
  - Poor measurements at the high energy tails lead to problems in the interpretation of EFT...

Structure of the fits

- A **global global fit** with all measurements to all operator coefficients?
  - Not there yet!

- Four parts:
  - EW + Higgs (this talk)
  - 4-fermion processes (Off Z-pole $e^+e^- \to f\bar{f}$)
  - CP-violating effects
  - Top (see Víctor Miralles's talk tomorrow)

- EW + Higgs
  - Based on [1905.03764] ECFA Higgs study, [1907.04311] de Blas, Durieux, Grojean, Gu, Paul.
  - What's new?

What's new?

- Diboson ($e^+e^- \to WW$, $pp \to WW/WZ$)
  - [1905.03764] (ECFA study):
    - LEP $e^+e^- \to WW$ + some future $e^+e^- \to WW$ (depending on official inputs)
  - [1907.04311]:
    - HL-LHC $pp \to WW/WZ$ ([1810.05149] Grojean, Montull, Riembau)
    - $e^+e^- \to WW$, semi-leptonic channel, 50% selection efficiency, optimal observable analysis
  - Now:
    - Same as [1907.04311], but
    - with all decay channels for $e^+e^- \to WW$, removed the 50% efficiency factor, and
    - applied realistic cuts on lepton/jets acceptance as well as simple detector smearing. (checked to have small impact, to be fully implemented soon)
- Z factories
  - Consistent estimations of systematic (theory) error for all colliders.
  - Previous large differences in R_b, A_b between ILC and FCC-ee are now resolved.
- Updated run scenarios / inputs.

Scenarios

- **CEPC**
  - Z-pole $[100\,\mathrm{ab}^{-1}]$, WW threshold $[6\,\mathrm{ab}^{-1}]$, 240 GeV $[20\,\mathrm{ab}^{-1}]$, 360 GeV $[1\,\mathrm{ab}^{-1}]$
- **FCC-ee**
  - Z-pole $[150\,\mathrm{ab}^{-1}]$, WW threshold $[10\,\mathrm{ab}^{-1}]$, 240 GeV $[5\,\mathrm{ab}^{-1}]$, 365 GeV $[1.5\,\mathrm{ab}^{-1}]$
- **ILC** $P(e^-, e^+) = (\mp 0.8, \pm 0.3)$ ($(\mp 0.8, \pm 0.2)$ for 1TeV)
  - 250 GeV $[2\,\mathrm{ab}^{-1}]$, 350 GeV $[0.2\,\mathrm{ab}^{-1}]$, 500 GeV $[4\,\mathrm{ab}^{-1}]$, 1 TeV $[8\,\mathrm{ab}^{-1}]$, (optional) Giga-Z
- **CLIC** $P(e^-, e^+) = (\mp 0.8, \pm 0.2)$
  - 380 GeV $[1\,\mathrm{ab}^{-1}]$, 1.5 TeV $[2.5\,\mathrm{ab}^{-1}]$, 3 TeV $[5\,\mathrm{ab}^{-1}]$,
- **Muon collider**
  - 3 TeV $[1\,\mathrm{ab}^{-1}]$ or 10 TeV $[10\,\mathrm{ab}^{-1}]$ or 10 TeV $[10\,\mathrm{ab}^{-1}]$ + 125 GeV $[20\,\mathrm{fb}^{-1}]$,

Global fit

- Global fit
  - Usually ~ 20-30 parameters (instead of 2499) if we focus on Higgs and electroweak measurements. (29 or 30 in our case)

- Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$
  - Results depend on operator bases, conventions, ...

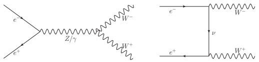
- Present the results in terms of effective couplings ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - $g(hZZ)$, $g(hWW)$ couplings have multiple contributions: $hZ^\mu Z_\mu$, $hZ^{\mu\nu} Z_{\mu\nu}$ ...
    defined as: $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}$, $g(hWW) \propto \sqrt{\Gamma(h \to WW)}$.

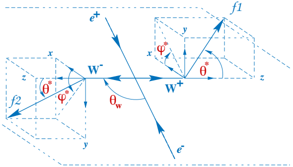
- Present the results with some fancy bar plots!

- Also provide full likelihood / χ^2 / invariance covariance matrix?
  - All bases are equal...

$e^+e^- \to WW$ with Optimal Observables

- TGCs (and additional EFT parameters) are sensitive to the differential distributions!
  - One could do a fit to the binned distributions of all angles.
  - Not the most efficient way of extracting information.
  - Correlations among angles are sometimes ignored.



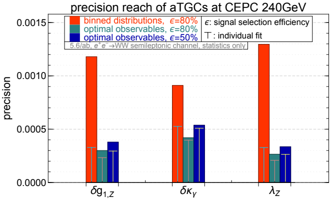


- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - In the limit of large statistics (everything is Gaussian) and small parameters (linear contribution dominates), the best possible reaches can be derived analytically!

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i\,, \qquad c_{ij}^{-1} = \int d\Omega \frac{S_{1,i} S_{1,j}}{S_0} \cdot \mathcal{L}\,,$$

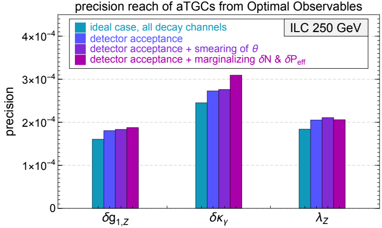
- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.

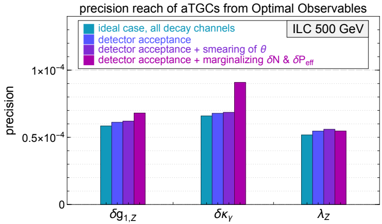


[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

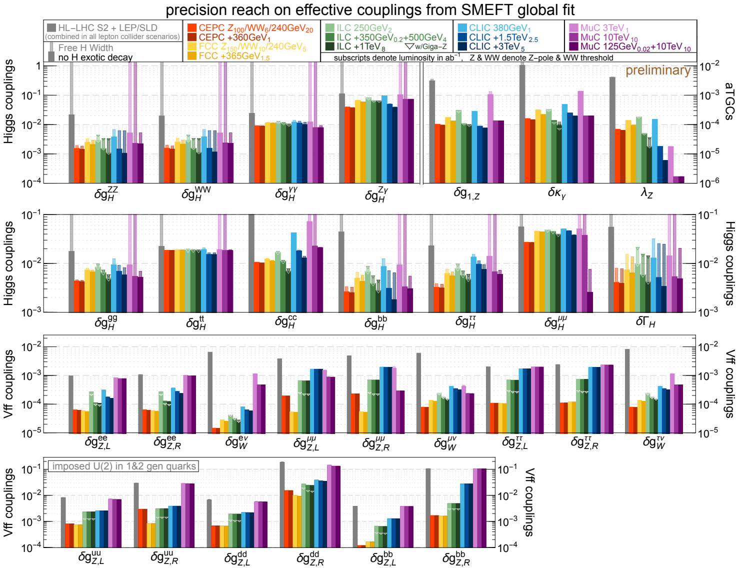
Updates on the *WW* analysis with Optimal Observables

- How well can we do it in practice?
  - detector acceptance, measurement uncertainties, ...
- What we have checked
  - detector acceptance
    ($|\cos\theta| < 0.9$ for jets, < 0.95 for leptons)
  - some smearing
    (production polar angle only, $\Delta = 0.1$)
  - ILC: marginalizing over total rate (δN) and effective beam polarization (δP_{eff})
- Constructing full EFT likelihood and feed it to the global fit. (For illustration, only showing the 3-aTGC fit results here.)
- Further verifications (by experimentalists) are needed.
- (A machine-learning analysis eventually?)





Results


precision reach on effective couplings from SMEFT global fit
HL–LHC S2 + LEP/SLD
(combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z100/WW6/240GeV20
CEPC +360GeV1
FCC Z150/WW10/240GeV5
FCC +365GeV1.5
ILC 250GeV2
ILC +350GeV0.2+500GeV4
ILC +1TeV8
w/Giga–Z
CLIC 380GeV1
CLIC +1.5TeV2.5
CLIC +3TeV5
MuC 3TeV1
MuC 10TeV10
MuC 125GeV0.02+10TeV10
subscripts denote luminosity in ab−1, Z & WW denote Z–pole & WW threshold
preliminary
Higgs couplings
aTGCs
Vff couplings
imposed U(2) in 1&2 gen quarks

What's next? (practically speaking)

- Snowmass Timeline
  - preliminary report by end of May,
  - (almost) final results by Snowmass summer meeting,
  - final report around October.

- Missing inputs to be completed
  - CEPC Z-pole (to be updated from the whitepaper),
  - R_s and $A_s/A^s_{\rm FB}$,
  - HL-LHC $pp \to WW/WZ$ global SMEFT analysis.

- More improvements
  - Lift the $U(2)$ constraints on 1&2 gen. quarks? ($pp \to \ell^+\ell^-$)
    [2103.12074] Bresó-Pla, Falkowski, González-Alonso
  - Implement theory errors?
  - (One-loop) triple Higgs coupling (Top loops as well?)

- Higgs+EW+Top, more loop contributions, dim-8 operators, future hadron colliders ...
  - The next snowmass, maybe...

backup slides

Higgs inputs

HL-LHC	3 ab^{-1} *ATLAS + CMS*				
Prod.	ggH	VBF	WH	ZH	ttH
σ	-	-	-	-	-
$\sigma \times BR_{bb}$	19.1	-	8.3	4.6	10.2
$\sigma \times BR_{cc}$	-	-	-	-	-
$\sigma \times BR_{gg}$	-	-	-	-	-
$\sigma \times BR_{ZZ}$	2.5	9.5	32.1	58.3	15.2
$\sigma \times BR_{WW}$	2.5	5.5	9.9	12.8	6.6
$\sigma \times BR_{\tau\tau}$	4.5	3.9	-	-	10.2
$\sigma \times BR_{\gamma\gamma}$	2.5	7.9	9.9	13.2	5.9
$\sigma \times BR_{\gamma Z}$	24.4	51.2	-	-	-
$\sigma \times BR_{\mu\mu}$	11.1	30.7	-	-	-
$\sigma \times BR_{inv.}$	-	2.5	-	-	-
Δm_H	10-20 MeV	-	-	-	-

	FCCee240 5ab^{-1}		CEPC240 20ab^{-1}	
Prod.	*ZH*	$\nu\nu H$	*ZH*	$\nu\nu H$
σ	0.5(0.537)	-	0.26	-
$\sigma \times BR_{bb}$	0.3(0.380)	3.1(2.78)	0.14	1.59
$\sigma \times BR_{cc}$	2.2(2.08)	-	2.02	-
$\sigma \times BR_{gg}$	1.9(1.75)	-	0.81	-
$\sigma \times BR_{ZZ}$	4.4(4.49)	-	4.17	-
$\sigma \times BR_{WW}$	1.2(1.16)	-	0.53	-
$\sigma \times BR_{\tau\tau}$	0.9(0.822)	-	0.42	-
$\sigma \times BR_{\gamma\gamma}$	9(8.47)	-	3.02	-
$\sigma \times BR_{\gamma Z}$	(17^*)	-	8.5	-
$\sigma \times BR_{\mu\mu}$	19(17.9)	-	6.36	-
$\sigma \times BR_{inv.}$	0.3(0.226)	-	0.07	-

ILC250	0.9ab^{-1} (-0.8,+0.3)		0.9ab^{-1} (+0.8,-0.3)	
Prod.	*ZH*	$\nu\nu H$	*ZH*	$\nu\nu H$
σ	1.07	-	1.07	-
$\sigma \times BR_{bb}$	0.714	4.27	0.714	17.4
$\sigma \times BR_{cc}$	4.38	-	4.38	-
$\sigma \times BR_{gg}$	3.69	-	3.69	-
$\sigma \times BR_{ZZ}$	9.49	-	9.49	-
$\sigma \times BR_{WW}$	2.43	-	2.43	-
$\sigma \times BR_{\tau\tau}$	1.7	-	1.7	-
$\sigma \times BR_{\gamma\gamma}$	17.9	-	17.9	-
$\sigma \times BR_{\gamma Z}$	63	-	59	-
$\sigma \times BR_{\mu\mu}$	37.9	-	37.9	-
$\sigma \times BR_{inv.}$	0.336	-	0.277	-

CLIC380	0.5 ab^{-1} (-0.8,0)		0.5 ab^{-1} (+0.8,0)	
Prod.	*ZH*	$\nu\nu H$	*ZH*	$\nu\nu H$
σ	1.5(1.43)	-	1.8(1.43)	-
$\sigma \times BR_{bb}$	0.81(1.2)	1.4(1.47)	0.92(1.2)	4.1(4.4)
$\sigma \times BR_{cc}$	13(8.7)	19(15.3)	15(8.7)	24(46)
$\sigma \times BR_{gg}$	5.7(6.6)	3.3(6.2)	6.5(6.6)	20(18.8)
$\sigma \times BR_{ZZ}$	(19.7)	(16.1)	(19.7)	(46)
$\sigma \times BR_{WW}$	5.1(4.4)	(4.6)	(4.4)	(14)
$\sigma \times BR_{\tau\tau}$	5.9(3.2)	(12.9)	6.6(3.2)	(39)
$\sigma \times BR_{\gamma\gamma}$	(31)	(36)	(31)	(108)
$\sigma \times BR_{\mu\mu}$	(69)	(129)	(69)	(129)
$\sigma \times BR_{inv.}$	0.57(0.68)	-	0.64(0.64)	-

- Some important inputs are scaled from other colliders.
- Important correlations are still missing?

Higgs inputs 2

	1.5 ab^{-1} FCC-ee365		1.0 ab^{-1} CEPC360	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.9(0.84)	-	1.4(1.02)	-
$\sigma \times BR_{bb}$	0.5(0.71)	0.9(1.14)	0.90(0.86)	1.1(1.39)
$\sigma \times BR_{cc}$	6.5(5.0)	10(11.9)	8.8(6.1)	16(14.5)
$\sigma \times BR_{gg}$	3.5(3.8)	4.5(4.8)	3.4(4.7)	4.5(5.9)
$\sigma \times BR_{ZZ}$	12(11.4)	10(12.5)	20(13.9)	21(15.3)
$\sigma \times BR_{WW}$	2.6(2.55)	(3.6)	2.8(3.12)	4.4(4.4)
$\sigma \times BR_{\tau\tau}$	1.8(1.83)	8(10)	2.1(2.24)	4.2(12.2)
$\sigma \times BR_{\gamma\gamma}$	18(17.7)	22(28.1)	11(21.7)	16(34.4)
$\sigma \times BR_{\mu\mu}$	40(40)	(100)	41(48)	57(123)
$\sigma \times BR_{inv.}$	0.60(0.42)	-	(0.49)	-

ILC500	1.6 ab^{-1} (-0.8,+0.3)		1.6 ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.67	-	1.67	-
$\sigma \times BR_{bb}$	1.01	0.42	1.01	1.52
$\sigma \times BR_{cc}$	7.1	3.48	7.1	14.2
$\sigma \times BR_{gg}$	5.9	2.3	5.9	9.5
$\sigma \times BR_{ZZ}$	13.8	4.8	13.8	19
$\sigma \times BR_{WW}$	3.1	1.36	3.1	5.5
$\sigma \times BR_{\tau\tau}$	2.42	3.9	2.42	15.8
$\sigma \times BR_{\gamma\gamma}$	18.6	10.7	18.6	44
$\sigma \times BR_{\mu\mu}$	47	40	47	166
$\sigma \times BR_{inv.}$	0.83	-	0.60	-

ILC350	0.135 ab^{-1} (-0.8,+0.3)		0.045 ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	2.46	-	4.3	-
$\sigma \times BR_{bb}$	2.05	2.46	3.5	17.7
$\sigma \times BR_{cc}$	15	25.9	25.9	186
$\sigma \times BR_{gg}$	11.4	10.5	19.8	75
$\sigma \times BR_{ZZ}$	34	27.2	59	191
$\sigma \times BR_{WW}$	7.6	7.8	13.2	57
$\sigma \times BR_{\tau\tau}$	5.5	21.8	9.4	156
$\sigma \times BR_{\gamma\gamma}$	53	61	92	424
$\sigma \times BR_{\mu\mu}$	118	218	205	1580
$\sigma \times BR_{inv.}$	1.15	-	1.83	-

ILC1000	3.2 ab^{-1} (-0.8,+0.2)	3.2 ab^{-1} (+0.8,-0.2)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.32	1.0
$\sigma \times BR_{cc}$	1.7	6.4
$\sigma \times BR_{gg}$	1.3	4.7
$\sigma \times BR_{ZZ}$	2.3	8.4
$\sigma \times BR_{WW}$	0.91	3.3
$\sigma \times BR_{\tau\tau}$	1.7	6.4
$\sigma \times BR_{\gamma\gamma}$	4.8	17
$\sigma \times BR_{\mu\mu}$	17	64

Higgs inputs 3

CLIC1500	2 ab^{-1} (-0.8,0)	0.5 ab^{-1} (+0.8,0)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.25	1.5
$\sigma \times BR_{cc}$	3.9	24
$\sigma \times BR_{gg}$	3.3	20
$\sigma \times BR_{ZZ}$	3.6	22
$\sigma \times BR_{WW}$	0.67	4.0
$\sigma \times BR_{\tau\tau}$	2.8	17
$\sigma \times BR_{\gamma\gamma}$	10	60
$\sigma \times BR_{\gamma Z}$	28	170
$\sigma \times BR_{\mu\mu}$	24	150

CLIC3000	4 ab^{-1} (-0.8,0)	1 ab^{-1} (+0.8,0)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.17	1.0
$\sigma \times BR_{cc}$	3.7	22
$\sigma \times BR_{gg}$	2.3	14
$\sigma \times BR_{ZZ}$	2.1	13
$\sigma \times BR_{WW}$	0.33	2.0
$\sigma \times BR_{\tau\tau}$	2.3	14
$\sigma \times BR_{\gamma\gamma}$	5.0	30
$\sigma \times BR_{\gamma Z}$	16	95
$\sigma \times BR_{\mu\mu}$	13	80

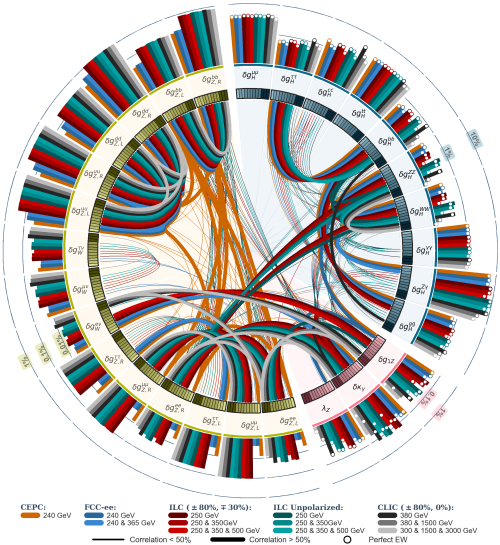
EW inputs

EWPO Uncertainties	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha_{QED}^{-1}$	0.0178*		$3.8(1.2)\times10^{-3}$	0.0178*	
Δm_W(/MeV)	2.4(0.5)		0.25(0.3)	1	
Δm_Z(/MeV)	2.1*		0.004(0.1)	0.1	2.1*
Δm_H(/MeV)	14		2.5(2)	5.9	78
$\Delta\Gamma_W$(/MeV)	2		1.2(0.3)	2.8	
$\Delta\Gamma_Z$(/MeV)	2.3*	(1)	0.025(0.004)	0.025	2.3*
$\Delta A_e(\times10^5)$	14(4.5)	1.5(8)	0.7(2)	1.5	64
$\Delta A_\mu(\times10^5)$	82(4.5)	3(8)	2.3(2.2)	45	400
$\Delta A_\tau(\times10^5)$	86(4.5)	3(8)	0.5(20)	7	570
$\Delta A_b(\times10^5)$	53(35)	9(51)	2.4(21)	22	380
$\Delta A_c(\times10^5)$	140(25)	20(50)	20(15)	200	200
$\Delta\sigma_{had}$(/pb)			4	5	37*
$\delta R_e(\times10^3)$	1.1	0.54	0.3	0.6	2.7
$\delta R_\mu(\times10^3)$	1.1	0.28	0.05	0.1	2.7
$\delta R_\tau(\times10^3)$	1.1	0.45	0.1	0.2	6
$\delta R_b(\times10^3)$	1.1	0.7	<0.3	0.2	1.8
$\delta R_c(\times10^3)$	5.0	3.0	1.5	1.1	5.6

- EWPO at future e^+e^-: statistical error (experimental systematic error). Δ (δ) stands for absolute (relative) uncertainty.
- Some CEPC inputs are still based on 1 month of data... (to be updated from the CEPC whitepaper)

Fit Results

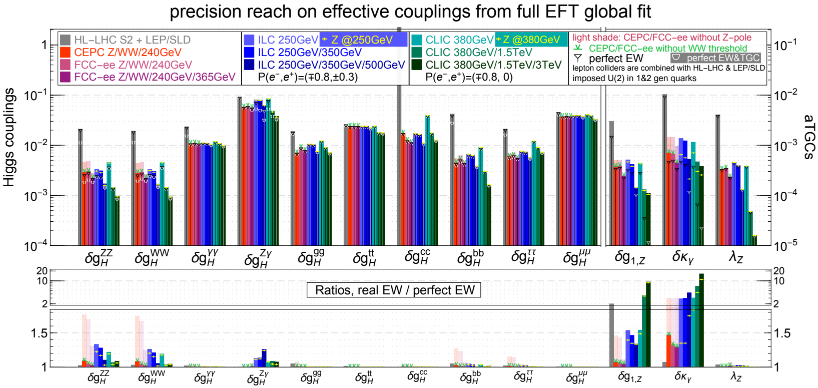
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul



- Global fit of dim-6 operators at tree-level with Higgs and electroweak measurements.
- Correlations are also important!

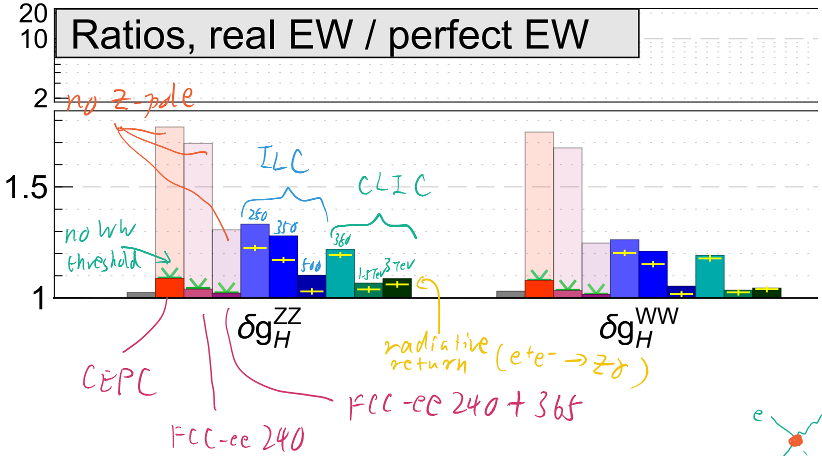
"Full fit" projected on the Higgs couplings (and aTGCs)

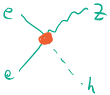
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul, see also Higgs@FutureColliders WG report



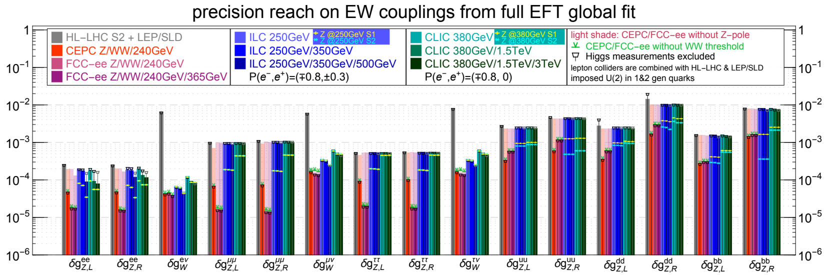
- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- Lepton colliders are combined with HL-LHC & LEP/SLD.
- The *hZZ* and *hWW* couplings are not independent!

Z-pole run is also important for Higgs couplings!





Reach on the (h)Vff couplings



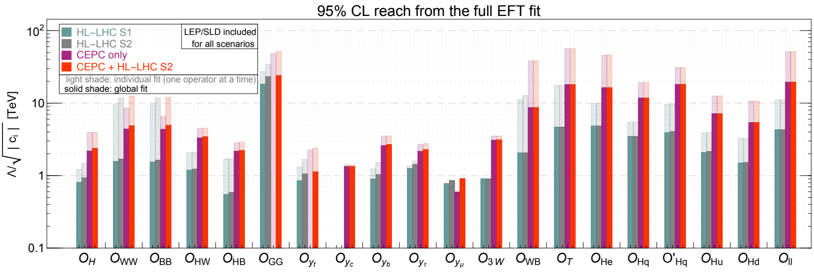
- $(h)Zff$ couplings are still best probed by future Z-pole runs.
- Higgs and diboson measurements at high energy (at linear colliders) are also sensitive to the $(h)Zee$ couplings, but can not resolve them from other parameters.
- Linear colliders: Using radiative return ($e^+e^- \to Z\gamma$) to measure Z observables at high energy?

D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{q}_L H u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- SILH’ basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH’ basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

Reach on the scale of new physics



- Reach on the scale of new physics Λ.
- Note: reach depends on the couplings c_i!

$e^+e^- \to WW$ parameterization

- "~~Higgs~~ effective coupling basis"
  (+ deviations in W BR. δ_{m_W} is constrained very well by W mass measurements.)

$$\delta g_{1,Z},\ \ \delta\kappa_\gamma,\ \ \lambda_Z,\ \ \delta g^{ee}_{Z,L},\ \ \delta g^{ee}_{Z,R},\ \ \delta g^{e\nu}_{W},\ \ \delta_{m_W}$$

- ILC parameterization (projective map to any EFT basis)

$$e,\ \ g_L,\ \ g_R,\ \ g_Z,\ \ g_W,\ \ \kappa_A,\ \ \kappa_Z,\ \ \lambda_A,\ \ \lambda_Z,\ \ BR$$

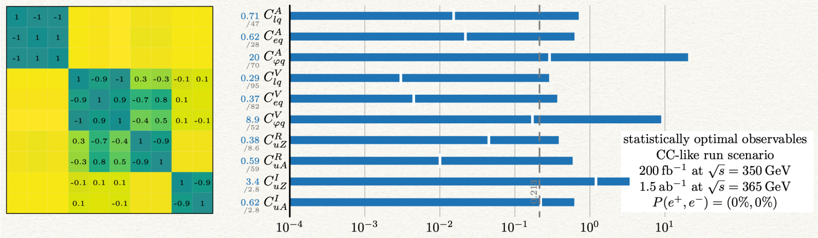
- 2 nuisance variables δN, δP_{eff} for ILC
  - $e^+e^- \to WW$ is also used to determine the effective luminosity and polarization.

Top EFT [arXiv:1807.02121] Durieux, Perelló, Vos, Zhang

$$
\begin{aligned}
O^1_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, &
O_{uG} &\equiv y_t g_s\ \ \bar{q}T^A\sigma^{\mu\nu}u\ \ \epsilon\varphi^* G^A_{\mu\nu},\\
O^3_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\tau^I\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi, &
O_{uW} &\equiv y_t g_W\ \ \bar{q}\tau^I\sigma^{\mu\nu}u\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi u} &\equiv \tfrac{y_t^2}{2}\ \bar{u}\gamma^\mu u\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, &
O_{dW} &\equiv y_t g_W\ \ \bar{q}\tau^I\sigma^{\mu\nu}d\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi ud} &\equiv \tfrac{y_t^2}{2}\ \bar{u}\gamma^\mu d\ \ \varphi^T\epsilon\, iD_\mu\varphi, &
O_{uB} &\equiv y_t g_Y\ \ \bar{q}\sigma^{\mu\nu}u\ \ \epsilon\varphi^* B_{\mu\nu},
\end{aligned}
$$

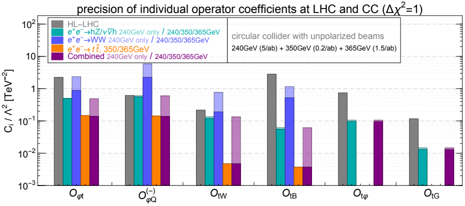
$$
\begin{aligned}
O^1_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu q\ \ \bar{l}\gamma^\mu l,\\
O^3_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\tau^I\gamma_\mu q\ \ \bar{l}\tau^I\gamma^\mu l,\\
O_{lu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_\mu u\ \ \bar{l}\gamma^\mu l,\\
O_{eq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu q\ \ \bar{e}\gamma^\mu e,\\
O_{eu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_\mu u\ \ \bar{e}\gamma^\mu e,
\end{aligned}
$$

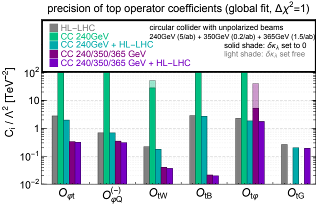
- Also need to include **top dipole** interactions and *eett* contact interactions!
- Hard to resolve the top couplings from $4f$ interactions with just the 365 GeV run.
  - Can't really separate $e^+e^- \to Z/\gamma \to t\bar{t}$ from $e^+e^- \to Z' \to t\bar{t}$.
  - Is that a big deal?

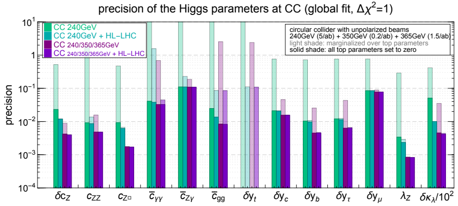


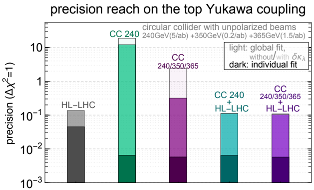
Top operators in loops

[arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang





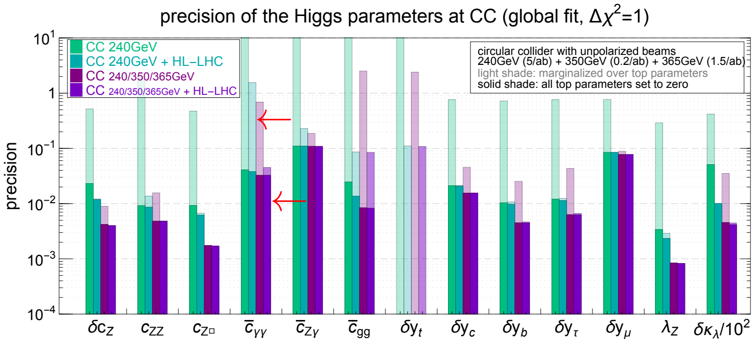




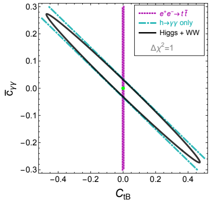
- Higgs precision measurements have sensitivity to the top operators in the loops.
  - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

Top operators in loops

[arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

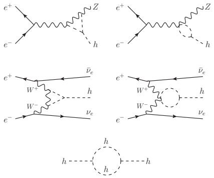


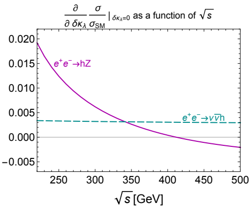
- $O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi} B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling $\Rightarrow$ run at ~ 365 GeV to confirm?

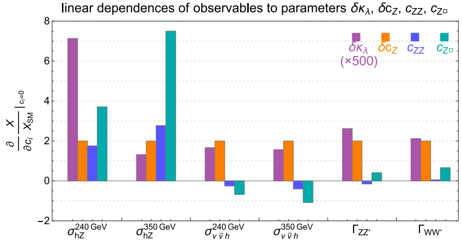


Triple Higgs coupling at one-loop order

[arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, Vantalon

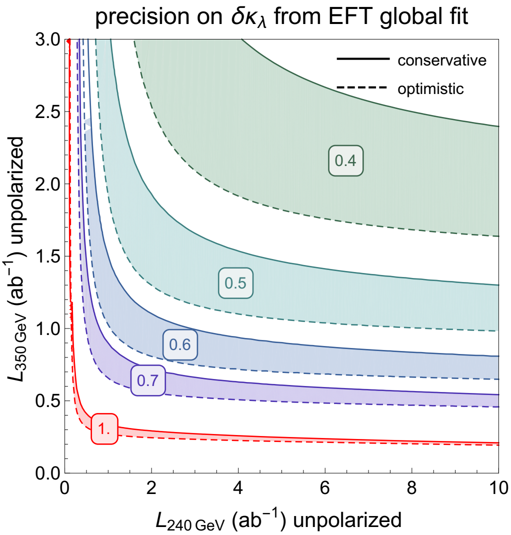






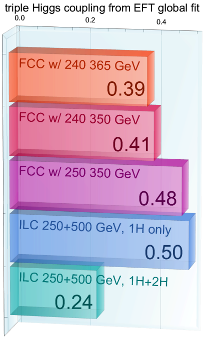
- $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$,
  $\delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2}c_H$,
  with $\mathcal{L} \supset -\frac{c_6\,\lambda}{v^2}(H^\dagger H)^3$.
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: hZ near threshold (more sensitive to $\delta\kappa_\lambda$)
- at 350-365 GeV:
  - WW fusion
  - hZ at a different energy
- $h \to WW^* / ZZ^*$ also have some discriminating power (but turned out to be not enough).

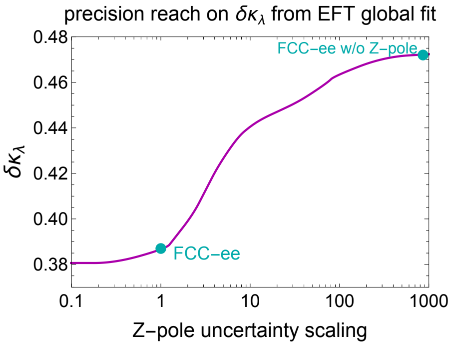
Triple Higgs coupling from EFT global fits



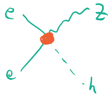
- Runs at two different energies (240 GeV and 350/365 GeV) are needed to obtain good constraints on the triple Higgs coupling in a global fit!

Updates on the triple Higgs coupling determination from EFT global fits

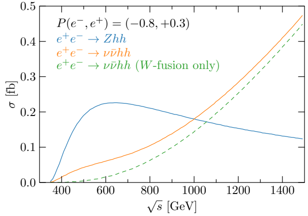


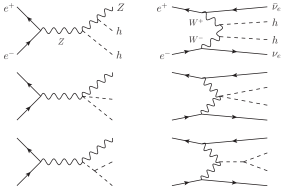


- 240, 365 GeV are better than 250, 350 GeV.
- Impacts of Z-pole measurements are not negligible. ($eeZ(h)$ contact interaction enters $e^+e^- \to hZ$.)

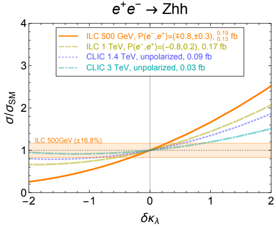


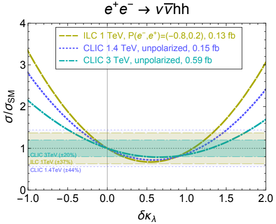
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$) [arXiv:1711.03978]

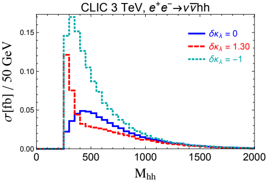




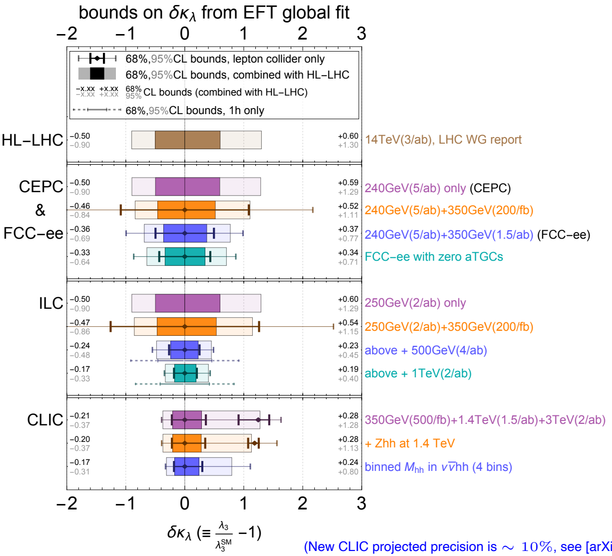
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the "2nd solution."







Triple Higgs coupling from global fits [arXiv:1711.03978]



(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

Triple Higgs coupling (Higgs@FutureColliders WG, [arXiv:1905.03764])