Towards v2.0 of the CEPC EFT fit

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Overview

- EFT fit **v1.0** (CEPC CDR) based on [arXiv:1704.02333] Durieux, Grojean, JG, and Wang, [arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, and Vantalon
  - **Higgs + aTGCs** (anomalous triple gauge couplings)
  - Z-pole, W mass, width and BRs all assumed to be **perfectly SM-like**.
  - Simple binned analysis to extract aTGCs from $e^+e^- \to WW$.
  - Indirect probes on the triple Higgs coupling.

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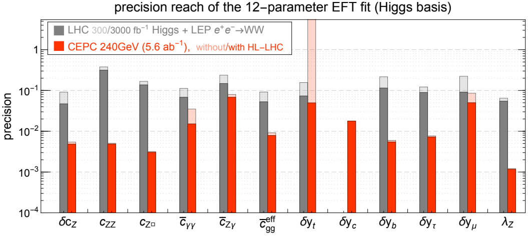
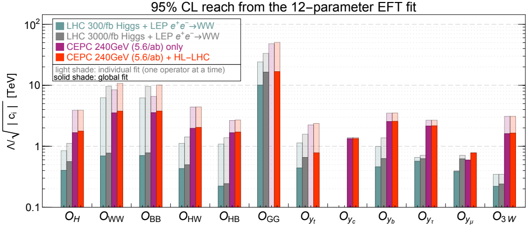
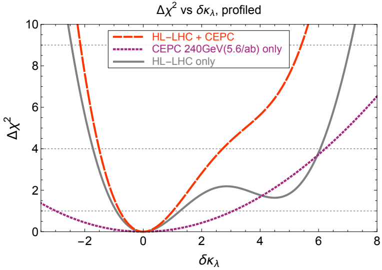
- EFT fit **v2.0?** (CEPC TDR)
  - **Higgs + EW + Top?** (see also Junping's talk)
  - 1-loop contributions: triple Higgs coupling, top couplings, others?
  - Dimension 8 operators?

EFT fit v1.0 (Results in the CDR)





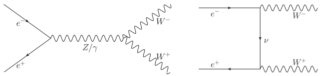
- See also the CEPC Higgs whitepaper [arXiv:1810.09037].
- ~~Now we wait for 20 years until all the data has been taken ...~~
- **Still a lot of work to be done before that!**



What's new in v1.5?

- Z-pole & W mass/width/BR:
  perfect $\Rightarrow$ realistic (CEPC)!
  - Higgs+aTGCs (12 parameters)
    $\Rightarrow$ Higgs+aTGCs**+EW** (28 parameters)
    (impose $U(2)$ on 1st and 2nd generation quarks, exclude $Zt\bar{t}$ and Wtb couplings)
  - Important for constraining the hZe^+e^- contact interactions.

- An improved diboson ($e^+e^- \to WW$) analysis.
  - Going beyond the TGC-dominance assumption.
  - Binned analysis $\Rightarrow$ optimal observables
    (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - Still an idealized theorists' analysis...
    (no background, no systematics...)



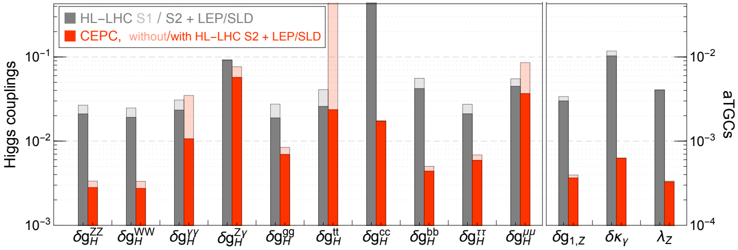
- Updated **(much better)** HL-LHC Higgs measurements.

How to present the results

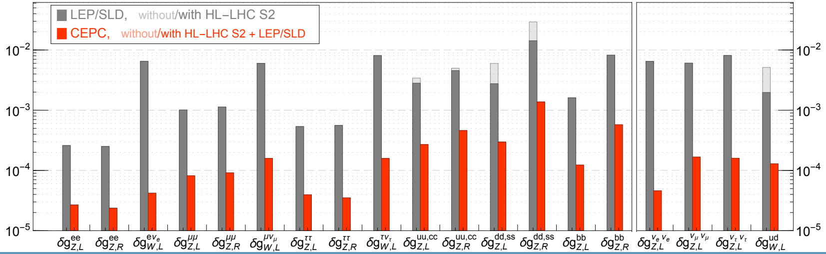
- **Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$**
  - Results depend on operator bases, conventions, ...
- **Higgs basis:** Define parameters in the broken EW phase so we can interpret them as Higgs couplings.
- **Or present the results in terms of effective couplings?**
  ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - Make your EFT look as much like "κ" as possible...
  - $g(hZZ)$, $g(hWW)$ are defined at the scale of the relavent Higgs decay.
    $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h \to WW)}\,.$
  - Intuitive, can be interpreted as "Higgs couplings."
  - Gives you the illusion that you understand the results...
- Current choices: Present the results in terms of both the **effective couplings** and the reach on $\Lambda/\sqrt{|c_i|}$ of dim-6 operators.

CEPC EFT fit v1.5

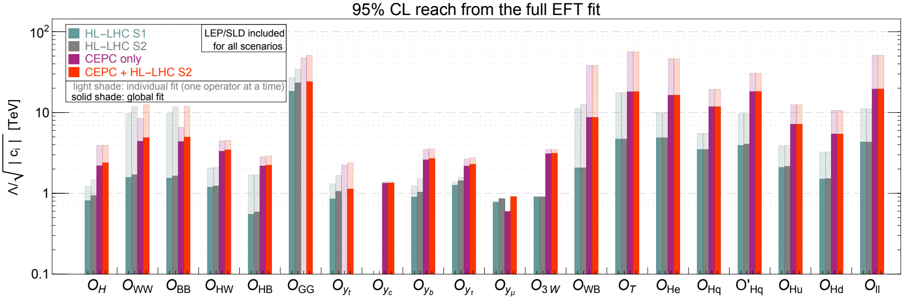
precision reach of the full EFT fit (effective couplings and aTGCs)



precision reach on the $Vf\bar{f}$ couplings from the full EFT fit



CEPC EFT fit v1.5



D6 operators

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

- 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 $\mathcal{O}_{HB}$)

Plans on a realistic $e^+e^- \to WW$ analysis

current work, JG, Lingfeng Li, Shuqi Li, Zhijun Liang, Manqi Ruan, Dan Yu, and Yudong Wang

- LOI sent to Snowmass EF04
- Impacts of systematics on the use of Optimal Observables
  - ISR, beamstrahlung effects
  - Jet energy resolution
  - Reconstruction of the neutrino momentum
- Machine learning everything in the end?

Snowmass2021 - Letter of Interest

Probing new physics with the measurements of $e^+e^- \to W^+W^-$ at CEPC with optimal observables

Thematic Areas: (check all that apply ☐/■)

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Precision Physics and constraining new physics
☐ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders

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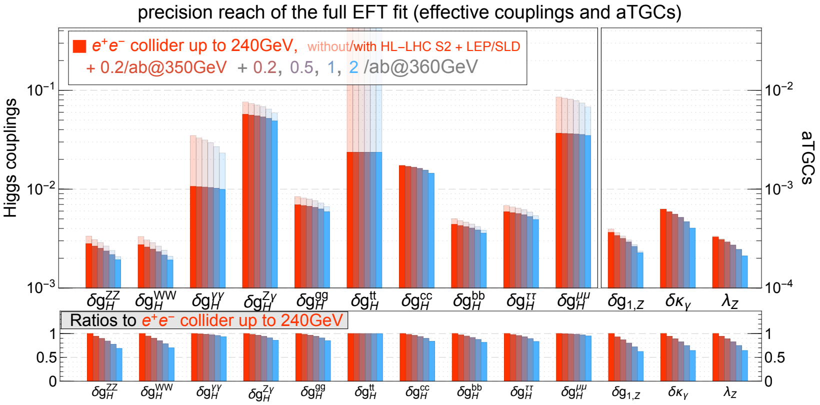
Abstract:

We propose to study the prospectives of the diboson ($e^+e^- \to W^+W^-$) measurements at the CEPC in the effective-field-theory framework. We plan to implement the method of optimal observables to extract useful information in the differential distributions and obtain the best possible reach on the coefficients of the corresponding dimension-six operators. The impact of systematic uncertainties due to detector resolutions and beamstrahlung/ISR effects will be thoroughly investigated.

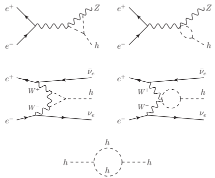
1

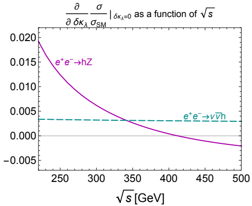
Impact of a hypothetical 350/360 GeV run

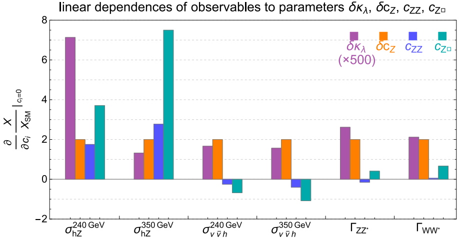


- Measurements at 350/360 GeV provides additional handles on the anomalous couplings (*e.g.* $hZ^\mu Z_\mu$ *vs.* $hZ^{\mu\nu}Z_{\mu\nu}$).
- Also improves the measurements of aTGCs.

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

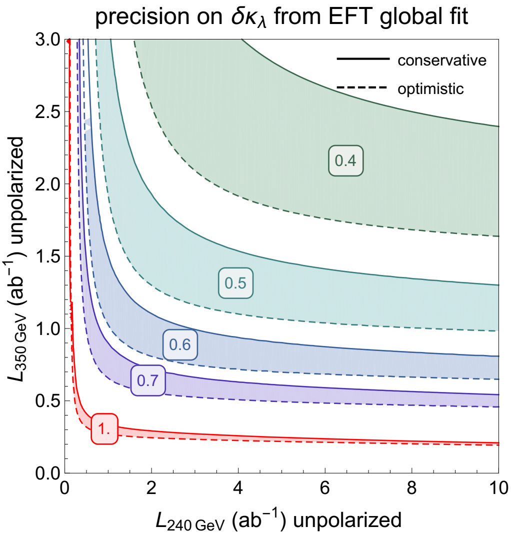






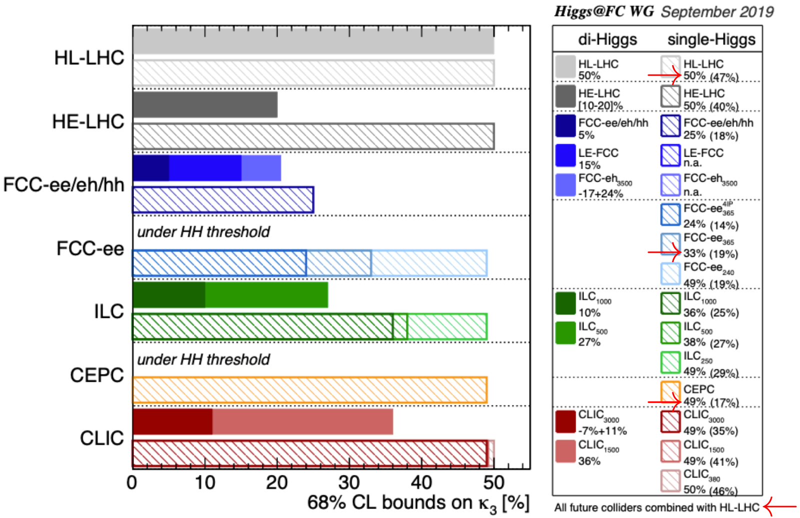
- λ_3 contributes to 1H processes at **1-loop**.
- 35% precision on λ_3 from inclusive $\sigma(hZ)$ at **240 GeV**, assuming all other couplings are SM-like (CEPC CDR).
- Measuring *hZ* at a different energy (*e.g.* **365 GeV**) is very helpful in a global fit!

Triple Higgs coupling at circular colliders [arXiv:1711.03978]



- Runs at two different energies (240 GeV and 350/360 GeV) are needed to obtain good constraints on the triple Higgs coupling (in a global fit)!

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



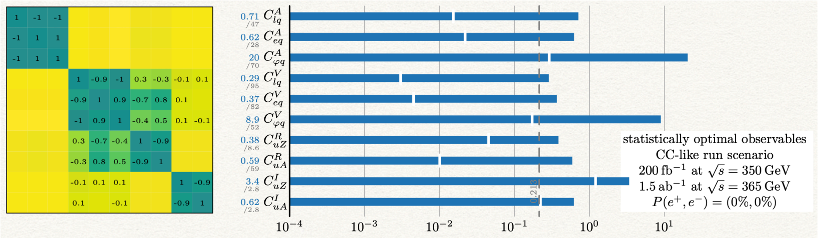
Top EFT

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

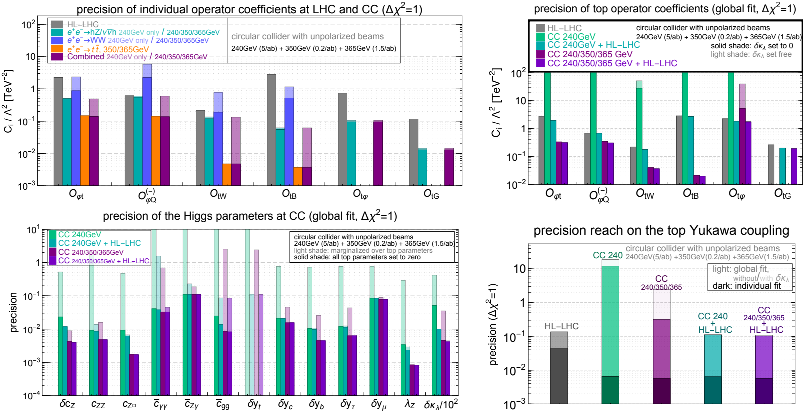
$$
\begin{aligned}
O^1_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, & O_{uG} &\equiv y_t g_s\ \bar{q}T^A\sigma^{\mu\nu}u\ \epsilon\varphi^* G^A_{\mu\nu},\\
O^3_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\tau^I\gamma^\mu q \quad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

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

- 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 $e^+e^- \to Z' \to t\bar{t}$.

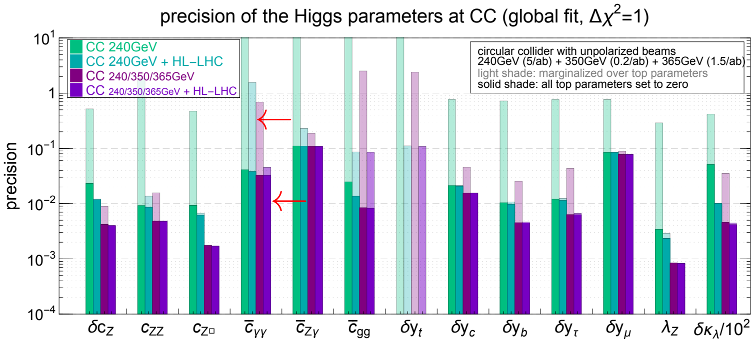


Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

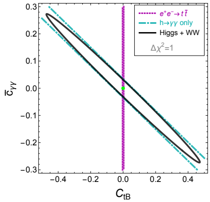


- Higgs precision measurements have sensitivity to the top operators in the loops.
  - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

Top operators in loops



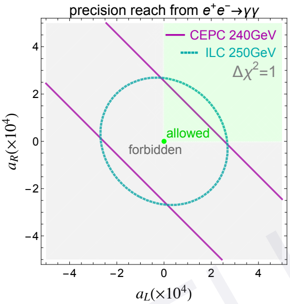
- $O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi} B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling $\Rightarrow$ run at ~ 365 GeV to confirm?

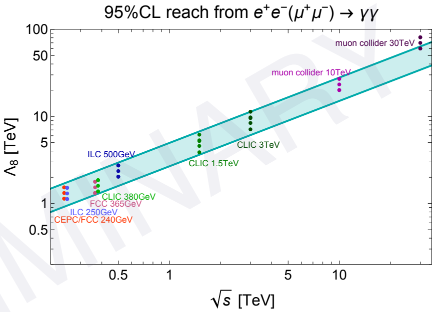


Dimension 8 operators?

- **Neutral TGCs in $Z\gamma/ZZ$** [arXiv:1902.06631, 2008.04298], Ellis et al.
  - See R.-Q. Xiao's talk earlier today.
- **Think beyond TGC:** Dim-8 operators also generate contact interactions with $+-$ final state helicities!
- **"Golden channel": $e^+e^- \to \gamma\gamma$**
  - (current work, JG, C. Zhang and L.-T. Wang)
  - SM$\times$d6, d6^2, 1-loop SM$\times$d6 are either vanishing or suppressed...
  - **Interference with d8 is the leading contribution!**
- **Positivity bounds** on d8 operators that generates forward elastic amplitudes $\propto E^4$.
  - $\sigma(e^+e^- \to \gamma\gamma) > \sigma_{\rm SM}(e^+e^- \to \gamma\gamma)$
    (Note: LEP measurement was $\sim 1.5\sigma$ below SM.)
- See also [arXiv:2009.02212] Fuks, Liu, Zhang, Zhou for d8 contributions to the 4e process and the associated positivity bounds.

Dimension 8 operators? (current work, JG, C. Zhang and L.-T. Wang)





- Positivity bounds resolve the flat direction between a_L and a_R for unpolarized beams.
- Best reach still from high energy colliders.

$$\mathcal{O}^{(8)}_{\ell B} = -\frac{1}{4}(i\bar{\ell}_L\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})B_{\mu\nu}B^{\mu}{}_{\rho}\,,$$
$$\mathcal{O}^{(8)}_{eB} = -\frac{1}{4}(i\bar{e}_R\gamma^{\{\rho}D^{\nu\}}e_R + \text{h.c.})B_{\mu\nu}B^{\mu}{}_{\rho}\,,$$
$$\mathcal{O}^{(8)}_{\ell W} = -\frac{1}{4}(i\bar{\ell}_L\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})W^a_{\mu\nu}W^{a\mu}{}_{\rho}\,,$$
$$\mathcal{O}^{(8)}_{eW} = -\frac{1}{4}(i\bar{e}_R\gamma^{\{\rho}D^{\nu\}}e_R + \text{h.c.})W^a_{\mu\nu}W^{a\mu}{}_{\rho}\,,$$
$$\mathcal{O}^{(8)}_{\ell BW} = -\frac{1}{4}(i\bar{\ell}_L\sigma^a\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})B_{\mu\nu}W^{a\mu}{}_{\rho}\,,$$

$$a_L = \frac{v^4}{\Lambda^4}\left(\cos^2\theta_W\, c^{(8)}_{\ell B} - \cos\theta_W\sin\theta_W\, c^{(8)}_{\ell BW} + \sin^2\theta_W\, c^{(8)}_{\ell W}\right)\,,$$
$$a_R = \frac{v^4}{\Lambda^4}\left(\cos^2\theta_W\, c^{(8)}_{eB} + \sin^2\theta_W\, c^{(8)}_{eW}\right)\,,$$

Conclusion

- **Higgs + EW fit!**
  - Interplay among Higgs, Z pole and diboson measurements are important.
- **Beyond tree level?**
  - Triple Higgs coupling, top operators.
  - Include more contributions?
- **Higgs + EW + top?**
  - Hard to resolve the 1-loop contributions of top operators without the 350/360/365 GeV run.
  - Hard to resolve the *eett* contact interactions even with the 350/360/365 GeV run.
  - Not being able to resolve different contributions doesn't mean we don't learn anything...
  - Complementarity between *circular* and *linear* colliders!
- **Beyond dim-6?**
  - We have sensitivities to some dim-8 operators!
  - Global fit impossible?

Conclusion

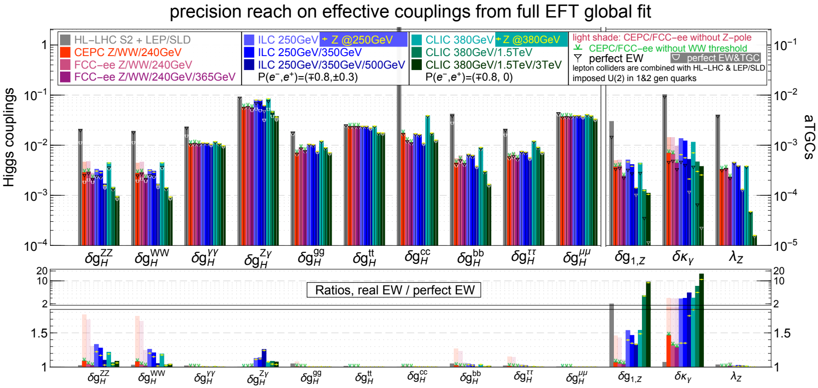
Conclusion

Note: Obviously EFT is not the only tool to probe new physics at future lepton colliders.

backup slides

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

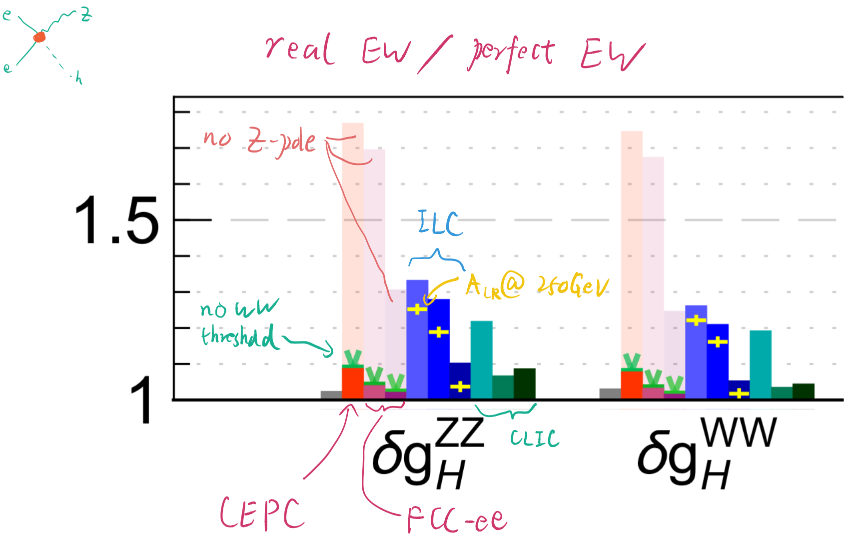
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul, see also Higgs@FutureColliders WG report



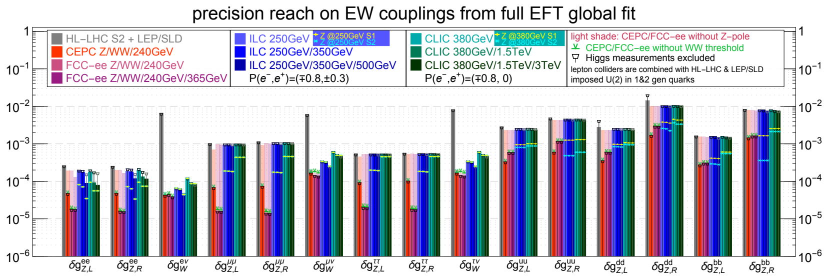
- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- Lepton colliders are combined with HL-LHC & LEP/SLD.
- The *hZZ* and *hWW* couplings are not independent!

Z-pole run is also important for Higgs couplings!

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

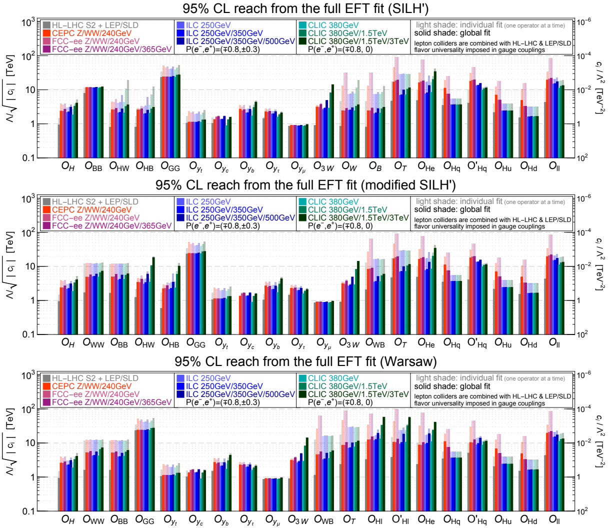


Reach on the (h)Vff couplings



- $(h)Zff$ couplings are still best probed by future Z-pole runs.

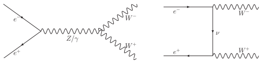
Pick your favorite basis!

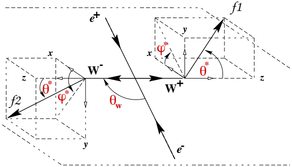


- Modified-SILH’ is most convenient in the limit of perfect EW (Z-pole, W mass/width/BR).
- Now we can choose any of them...

A refined *WW* analysis using Optimal Observables (OO)

- 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.



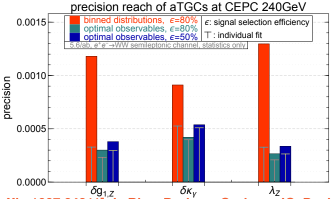


- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper limit" can be derived analytically!

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i \,,$$

- 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

How to do a practical OO analysis?

- In reality, we cannot just simply derive the results!
  - ISR effects, jet resolutions, reconstruction of the neutrino momentum, ...
  - The $\frac{d\sigma}{d\Omega}$ that we actually measure can be a bit different from the ideal "parton level" one.

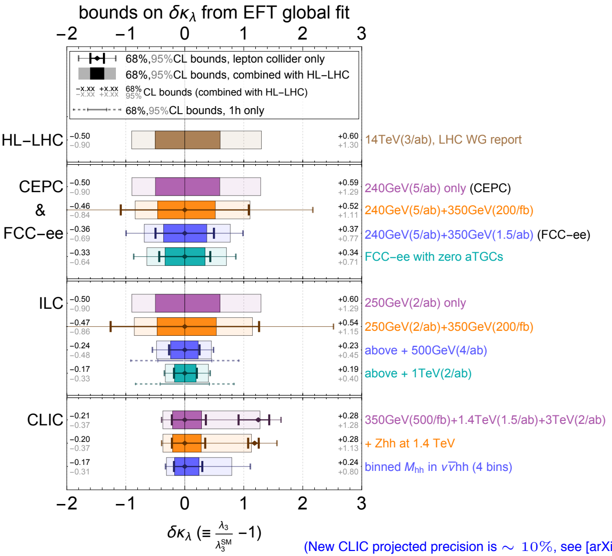
- Apply parton level OO to real events
  - The results can be biased, and the bias may take some effort to estimate.

- Directly construct "detector-level" OOs with numerical methods?
  - may require a lot of MC simulation...
  - End up with machine learning in the end?

- Full EFT parameterization: flat directions exist in the *WW* measurements, which needs the *Z*-pole measurements to be lifted.

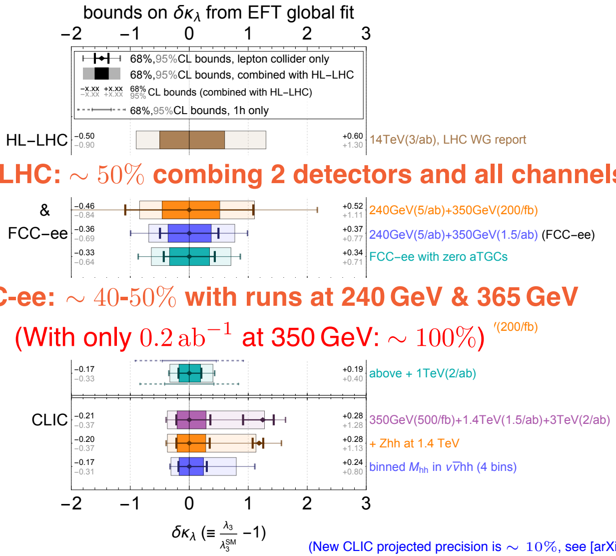
$$\delta g_{1,Z}, \quad \delta\kappa_\gamma, \quad \lambda_Z, \quad \delta g^{ee}_{Z,L}, \quad \delta g^{ee}_{Z,R}, \quad \delta g^{e\nu}_{W}, \quad \delta m_W$$

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 from global fits [arXiv:1711.03978]



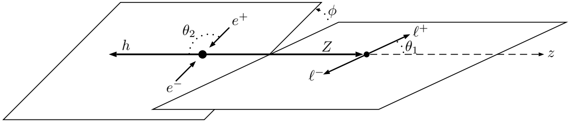
HL-LHC: $\sim 50\%$ combing 2 detectors and all channels

FCC-ee: ~ 40-50% with runs at 240 GeV & 365 GeV

(With only $0.2\,\mathrm{ab}^{-1}$ at 350 GeV: $\sim 100\%$)

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

angular observables in $e^+e^- \to hZ$



- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

$$\mathcal{A}_{\theta_1}\,,\quad \mathcal{A}_{\phi}^{(1)}\,,\quad \mathcal{A}_{\phi}^{(2)}\,,\quad \mathcal{A}_{\phi}^{(3)}\,,\quad \mathcal{A}_{\phi}^{(4)}\,,\quad \mathcal{A}_{c\theta_1,c\theta_2}\,.$$

- Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).
- Optimal observables can further improve the sensitivity.

EFT fit v1.0

- Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

- The Higgs basis is defined in the broken electroweak phase.
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}.$
- Couplings of h to W are written in terms of couplings of h to Z and γ.
- 3 aTGC parameters ($\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_Z), 2 written in terms of Higgs parameters.
- It can be easily mapped to the following basis with D6 operators.

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$