# Higgs coupling determination at the CEPC

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mainly based on the CEPC Snowmass report [2205.08553]

# Why CEPC?

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

- Higgs and nothing else?


LHC will definitely find new physics!

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

# Why CEPC?

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

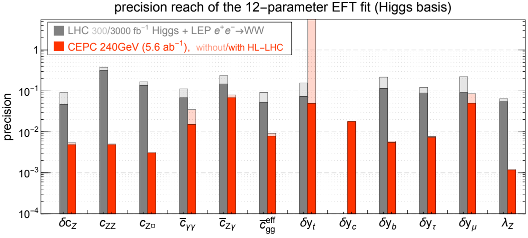
  $\searrow$ **do precision measurements $\rightarrow$ discover new physics indirectly!**

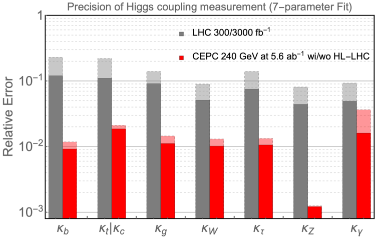
- Higgs and nothing else?

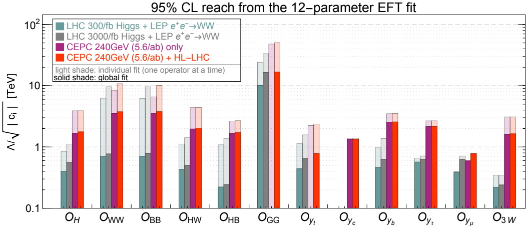

LHC will definitely find new physics!

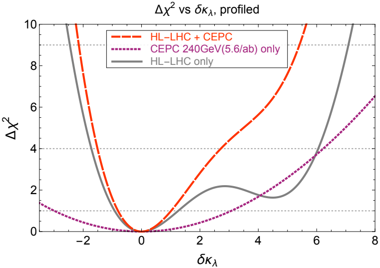
- What's next?
  - Build an even larger collider ($\sim 100$ TeV)?
  - No guaranteed discovery!
  - **Higgs factory!** (A lepton collider at $\sqrt{s} \sim 240$-$250$ GeV or above.)
  - **More than just a Higgs factory!**

# Results in the CDR



# What's new?

- 2205.08553

**The Physics potential of the CEPC**

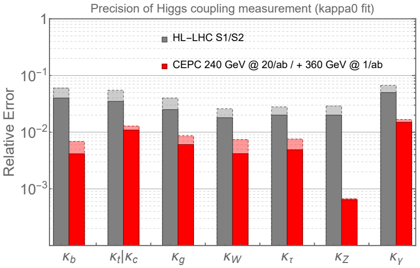
*Prepared for the US Snowmass Community Planning Exercise*

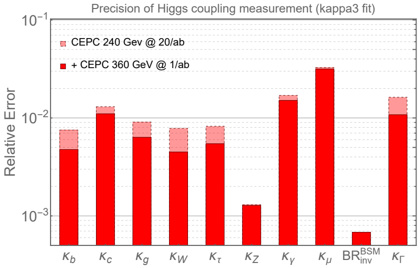
*(Snowmass 2021)*

CEPC Physics Study Group

- The run scenarios are updated!
  - 240 GeV ($5.6\,\mathrm{ab}^{-1}$) $\rightarrow$ 240 GeV ($20\,\mathrm{ab}^{-1}$) + 360 GeV ($1\,\mathrm{ab}^{-1}$)
  - Also better *Z*-pole and *WW*-threshold runs.
- The SMEFT framework is improved
  - Higgs + *WW* global fit $\rightarrow$ Higgs + *WW* + *Z*-pole global fit
  - A better *WW* analysis with optimal observables.

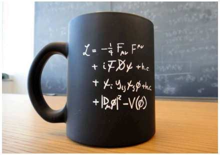
# The kappa framework (see Kaili's talk earlier)




- **Larger statistics $\Rightarrow$ better Higgs coupling determination!**

# The Standard Model Effective Field Theory




+

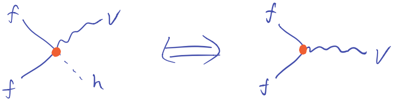
| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$ |

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$ |
| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | $B$-violating | | | |
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ | | |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ | | |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ | | |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |

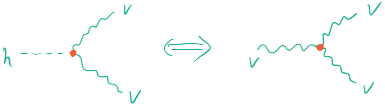
- Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
- 59 operators (76 parameters) for 1 generation, or 2499 parameters for 3 generations. [arXiv:1008.4884] Grzadkowski, Iskrzyński, Misiak, Rosiek, [arXiv:1312.2014] Alonso, Jenkins, Manohar, Trott.
- A **global global fit** with all measurements to all operator coefficients? (Not there yet!)
  - Here we focus on Higgs and electroweak measurements with $\sim 20$-$30$ parameters.

# You can't really separate Higgs from the EW gauge bosons!

- $\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D_\mu} H \bar{\ell}_L \gamma^\mu \ell_L$,
  $\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$,
  $\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D_\mu} H \bar{e}_R \gamma^\mu e_R$
  (or the ones with quarks)
  - modifies gauge couplings of fermions,
  - also generates $hVff$ type contact interaction.




- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$,
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate **aTGCs** $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates $HVV$ **anomalous couplings** such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



# You also have to measure the Higgs!

- Some operators can only be probed with the **Higgs particle**.
- $|H|^2 W_{\mu\nu} W^{\mu\nu}$ and $|H|^2 B_{\mu\nu} B^{\mu\nu}$
  - $H \to v/\sqrt{2}$, corrections to gauge couplings?
  - Can be absorbed by field redefinition! This applies to any operators in the form $|H|^2 \mathcal{O}_{\rm SM}$.

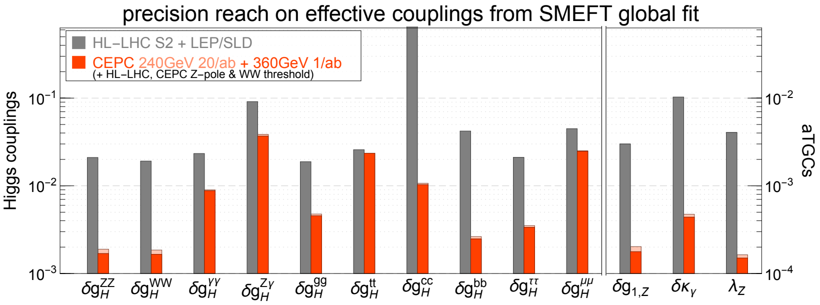
$$
\begin{aligned}
c_{\rm SM}\mathcal{O}_{\rm SM} \quad vs. \quad & c_{\rm SM}\mathcal{O}_{\rm SM} + \frac{c}{\Lambda^2}|H|^2\mathcal{O}_{\rm SM} \\
&= (c_{\rm SM} + \frac{c\,v^2}{2\,\Lambda^2})\mathcal{O}_{\rm SM} + \text{terms with } h \\
&= c'_{\rm SM}\mathcal{O}_{\rm SM} + \text{terms with } h
\end{aligned}
$$

  - probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the $hWW$ and $hZZ$ anomalous couplings.
  - or Higgs in the loop (different story...)
- Yukawa couplings, Higgs self couplings, ...

# EFT Global fit

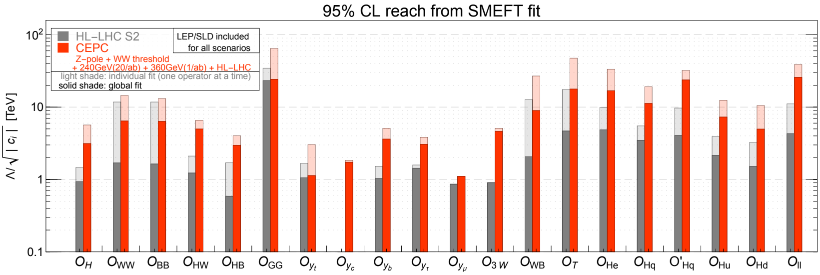
- Global fit
  - Usually $\sim 20$-$30$ parameters (instead of 2499) if we focus on Higgs and electroweak measurements.
  - The $Z$ ($Z$-pole) and $W$ ($e^+e^- \to WW$) measurements are also crucial for Higgs coupling determination!
    (See Shengdu Chai's talk on Wednesday on $e^+e^- \to WW$ with machine learning.)
- 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: $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}$, $g(hWW) \propto \sqrt{\Gamma(h \to WW)}$.
- Both forms are used.

# SMEFT global fit (effective coupling precision)




- 28-parameter fit projected on Higgs couplings and anomalous triple gauge couplings.
- $\delta g_H^{ZZ} \approx \delta g_H^{WW}$ from theoretical constraints (gauge invariance & custodial symmetry) and EW measurements.
- Non-negligible improvement from the 360 GeV run.

# SMEFT global fit (reach on new physics scale)




- 20-parameter fit (assuming flavor universality in gauge-fermion couplings).
- See next page for the operator basis.

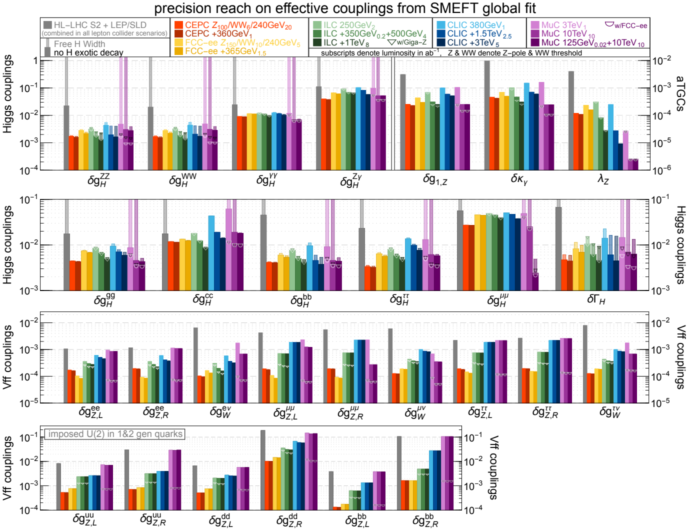
# D6 operators

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

- 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 $\mathcal{O}'_{H\ell}$) (used here)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

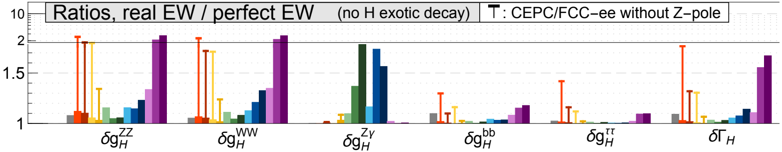
# Results from the recent snowmass study

[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou

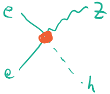


# Impacts of (lack of) the Z-pole run

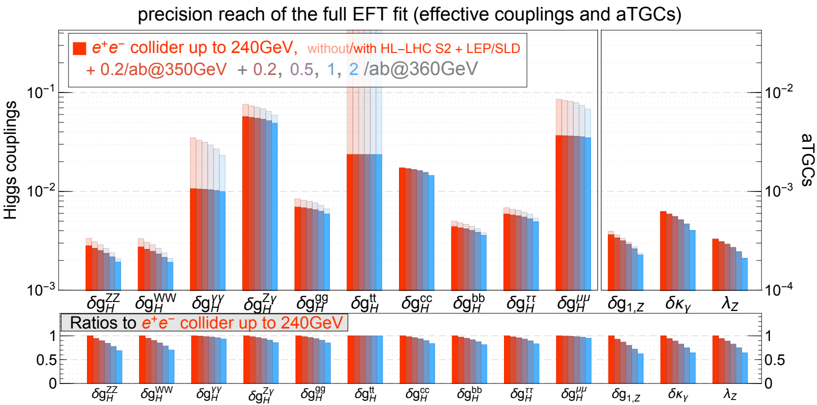
[2206.08326] de Blas, Du, Grojean, JG, Miralles, Peskin, Tian, Vos, Vryonidou




- Without good $Z$-pole measurements, the *eeZh* contact interaction may have a significant impact on the Higgs coupling determination.
- Current (LEP) $Z$-pole measurements are not good enough for CEPC Higgs measurements!
- **The CEPC *Z*-pole measurements are!**



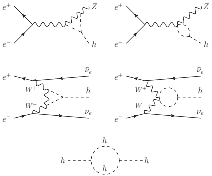
# Impact of a 350/360 GeV run

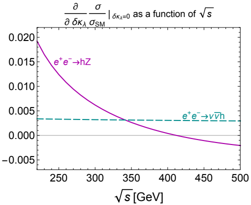


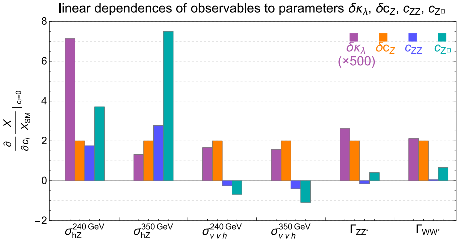

- $5.6\,\mathrm{ab}^{-1}$ at 240 GeV assumed.
- Measurements at 350/360 GeV provides additional handles on the anomalous couplings (*e.g.* $hZ^{\mu}Z_{\mu}$ *vs.* $hZ^{\mu\nu}Z_{\mu\nu}$ ).
- Also improves the measurements of aTGCs.

# Triple Higgs coupling at one-loop order

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

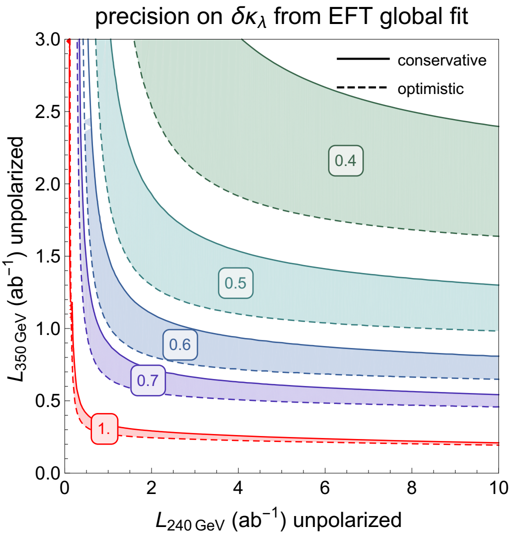





- $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$,
  $\delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2}c_H$,
  with $\mathcal{L} \supset -\frac{c_6\,\lambda}{v^2}(H^\dagger H)^3$.
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: $hZ$ near 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!

# Conclusion

- **The CEPC is a Higgs factory!**
  - and also a factory of $Z$, $W$ and top.
- **In the SMEFT framework,**
  - good electroweak measurements are crucial for the Higgs coupling determination,
  - the 360 GeV run also helps.
- **More things to do in the future?**
  - CP-odd operators (see Qiyu Sha's talk).
  - Loop contributions, both SM and BSM.
  - Dimension-8 operators?
- **What's the optimal run scenario?**
  - 240 GeV: $5.6\,\mathrm{ab}^{-1}$? $20\,\mathrm{ab}^{-1}$? $40\,\mathrm{ab}^{-1}$?

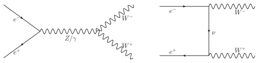
# Conclusion

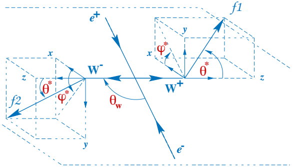
**Waiting for the CEPC to be built…**

# backup slides

# $e^+e^- \to WW$ 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.



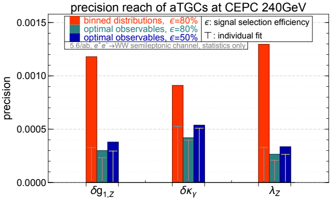



- What are optimal observables?

(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.

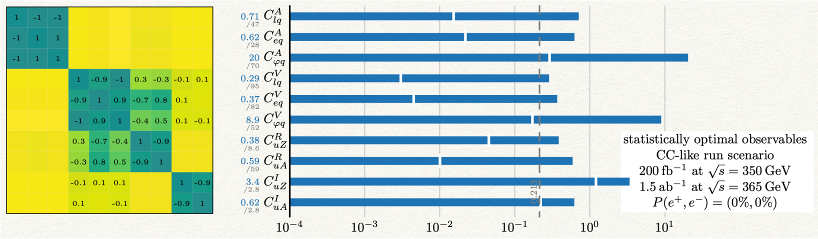
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

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

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

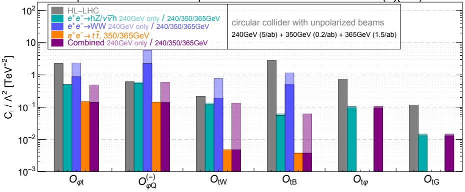
$$
\begin{aligned}
O^1_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu q\ \ \bar{l}\gamma^\mu l,\\
O^3_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\tau^I\gamma_\mu q\ \ \bar{l}\tau^I\gamma^\mu l,\\
O_{lu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_\mu u\ \ \bar{l}\gamma^\mu l,\\
O_{eq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_\mu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

- 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?

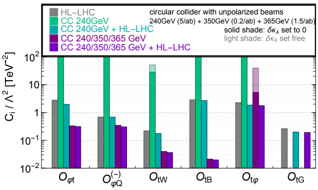


# Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

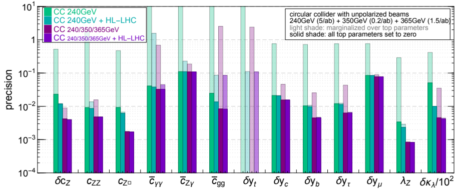
precision of individual operator coefficients at LHC and CC ($\Delta\chi^2$=1)



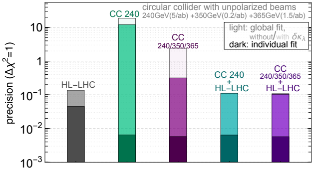

precision of top operator coefficients (global fit, $\Delta\chi^2$=1)




precision of the Higgs parameters at CC (global fit, $\Delta\chi^2$=1)



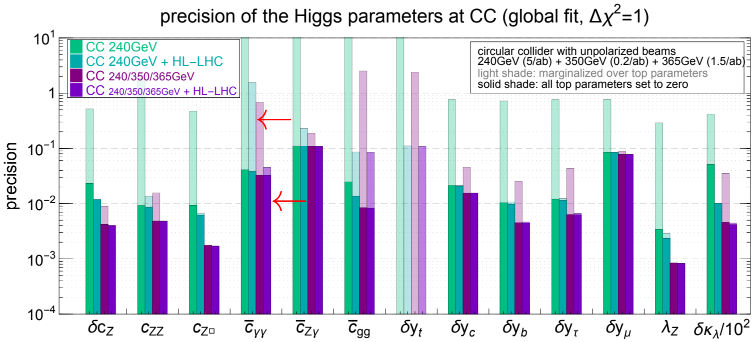

precision reach on the top Yukawa coupling



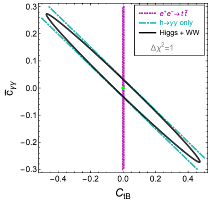

- Higgs precision measurements have sensitivity to the top operators in the loops.
  - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

# Top operators in loops

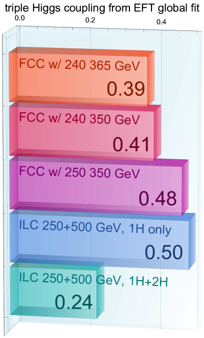
[arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

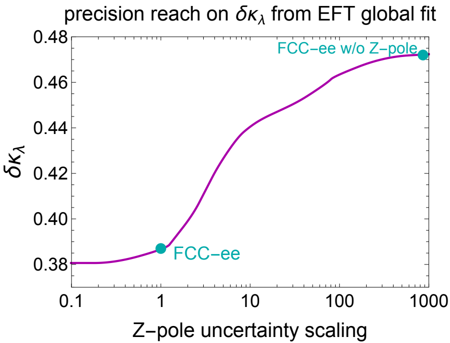



- $O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\, \tilde{\varphi} B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling $\Rightarrow$ run at $\sim 365$ GeV to confirm?

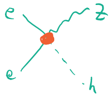


# Updates on the triple Higgs coupling determination from EFT global fits

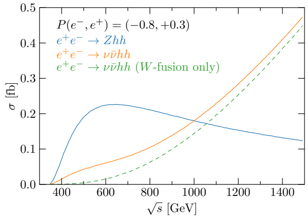


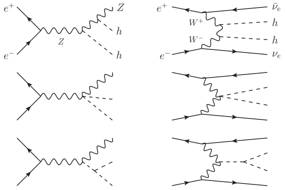




- 240, 365 GeV are better than 250, 350 GeV.
- Impacts of $Z$-pole measurements are not negligible.
  ($eeZ(h)$ contact interaction enters $e^+e^- \to hZ$.)

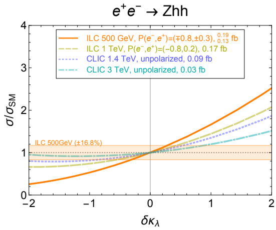


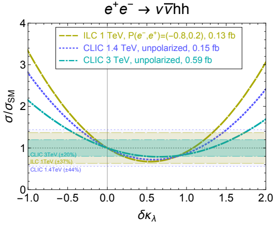
# Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$) [arXiv:1711.03978]

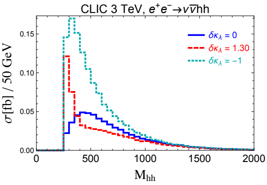


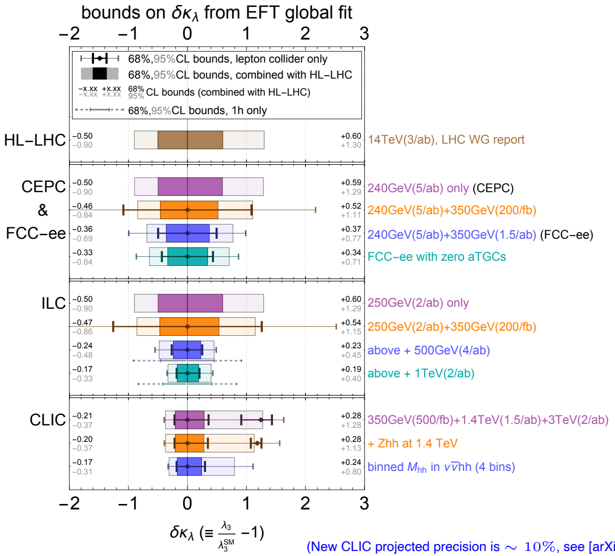

- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the “2nd solution.”



# 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])