Global fits to electroweak, diboson and Higgs observables at future lepton colliders

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Based on *J.B., G. Durieux, C. Grojean, J. Gu and A. Paul,* arXiv:1907.04311 [hep-ph]

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Introduction

- The main outcome of the LHC physics program may be the discovery of the Higgs and a first exploration of its properties.
- We have experimental evidence (Dark Matter, Neutrino masses, …) and solid arguments (e.g. Hierarchy problem) to expect the presence of new physics beyond the Standard Model:

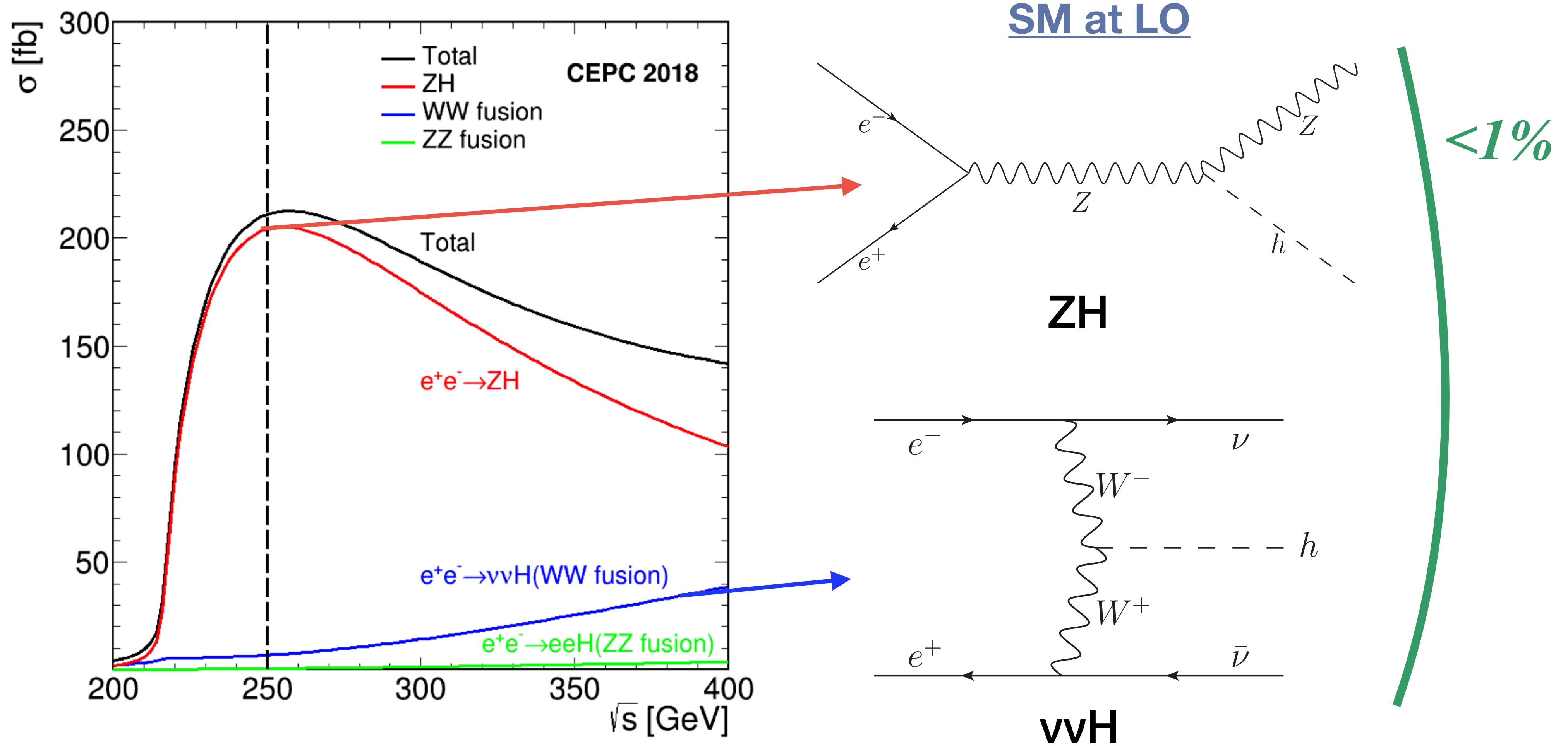
EW hierarchy/Naturalness ⇒ Solutions expected to leave imprint on the interactions of the EW/Higgs sector

- Therefore, a key component of the physics program at **future lepton colliders** has revolved around the possible improvements on the knowledge of **properties of the Higgs and (to less extent) the EW gauge bosons**…
- …even if the Higgs is the primary goal, **one cannot separate the determination of its properties from the knowledge of the properties of the other SM particles…**

Introduction

Higgs production at “low-energy” lepton colliders

SM at LO



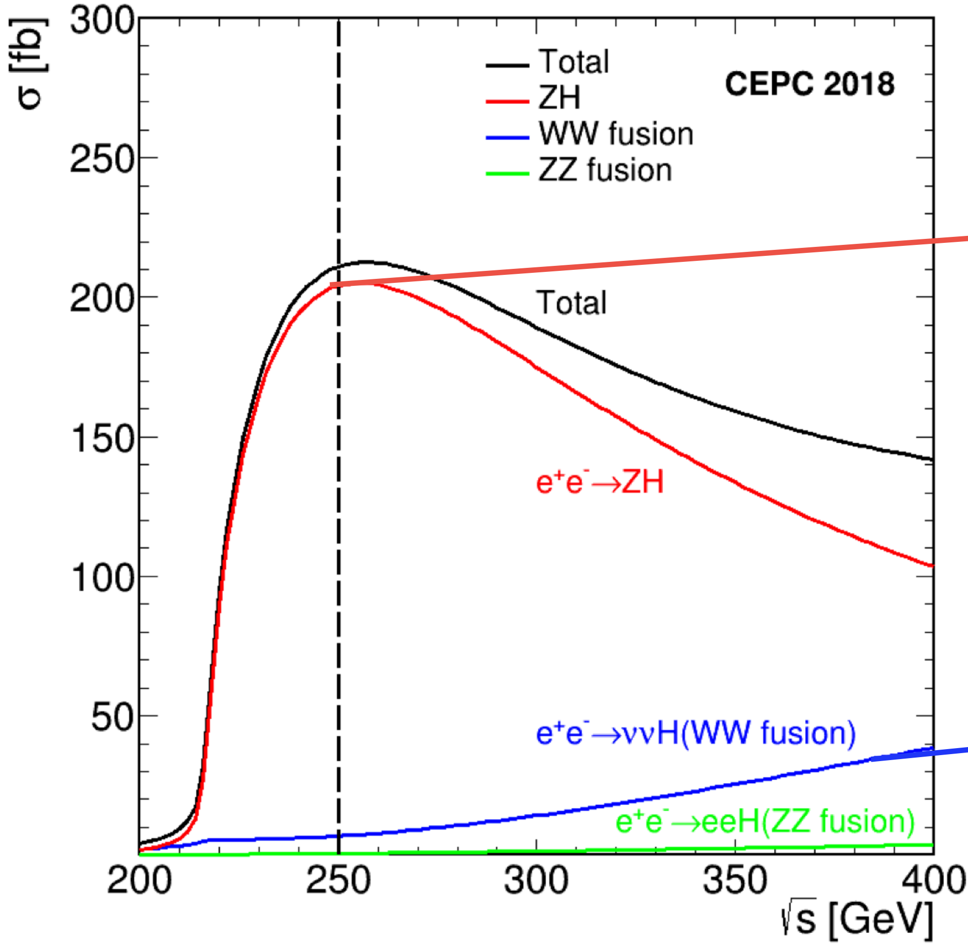
ZH

ννH

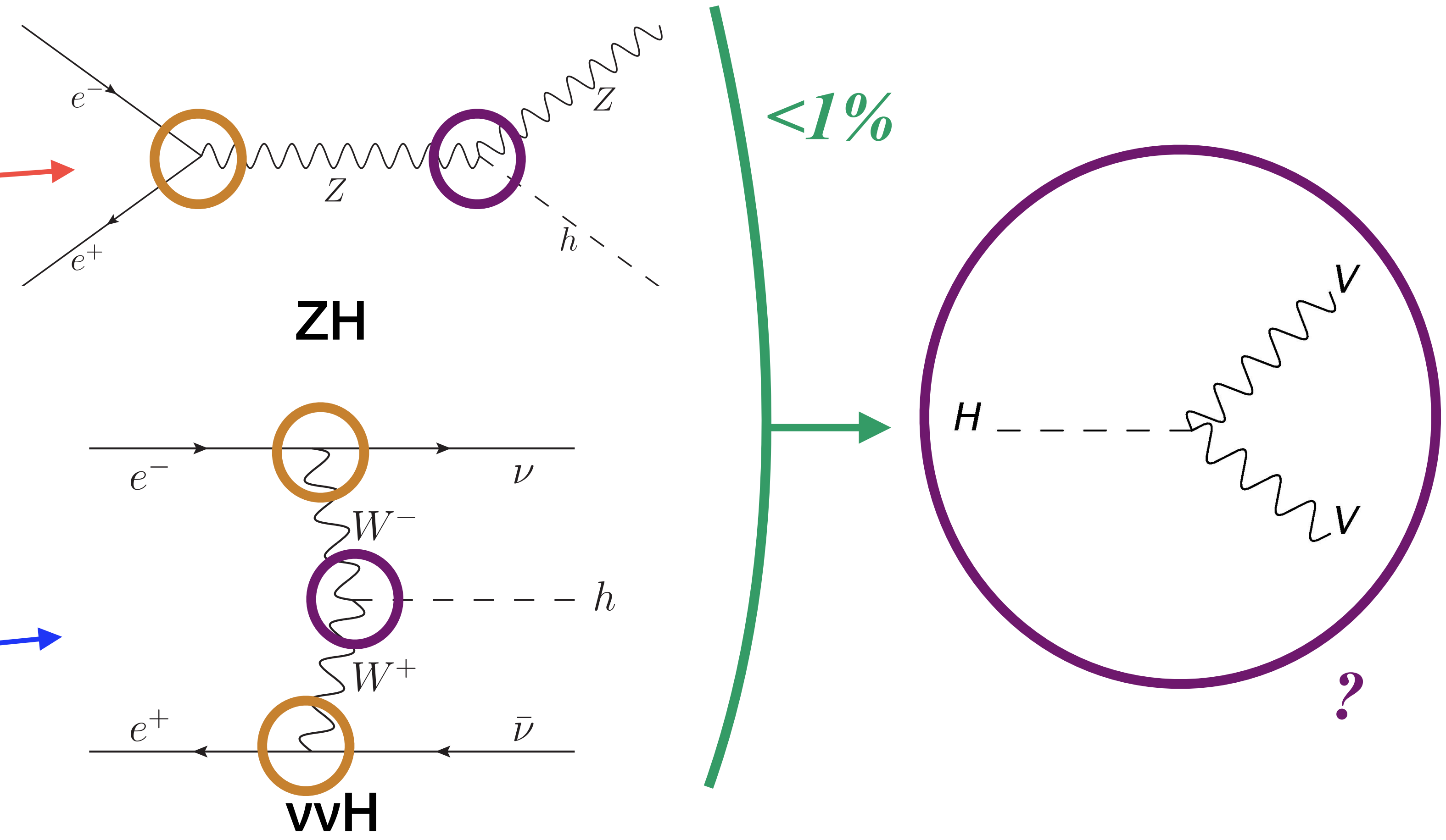
- Precision of **Higgs measurements** expected to be close to per mille level in several cases

Introduction

Higgs production at “low-energy” lepton colliders



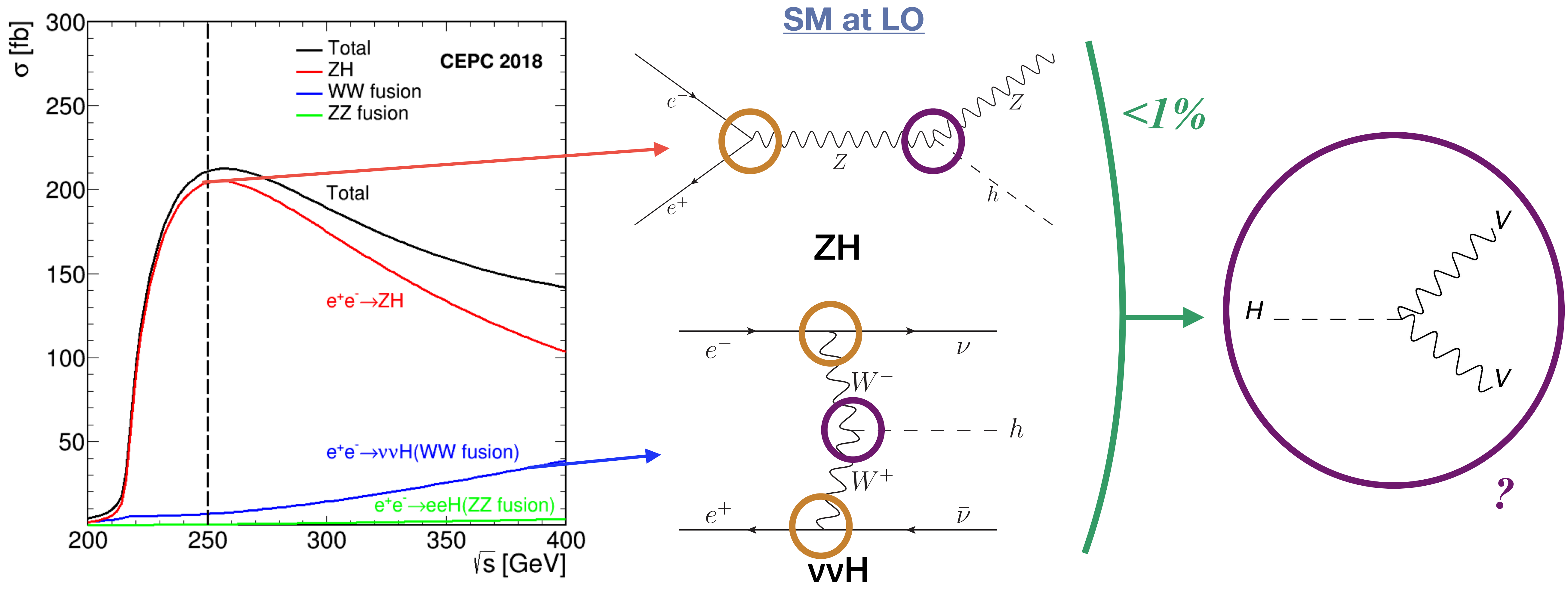
SM at LO



- Precision of **Higgs measurements** expected to be close to per mille level in several cases
- Is the knowledge of the **EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **Higgs properties**?

Introduction

Higgs production at “low-energy” lepton colliders


SM at LO

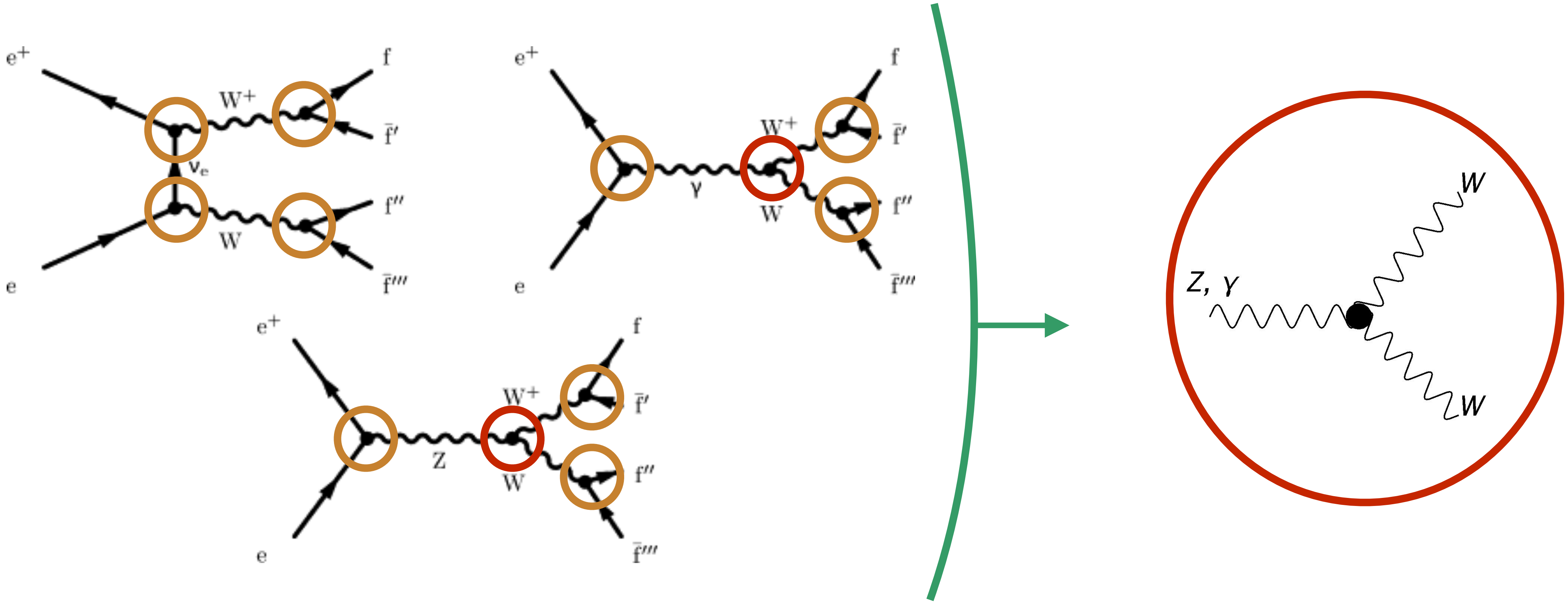
- Precision of **Higgs measurements** expected to be close to per mille level in several cases

- Is the knowledge of the **EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **Higgs properties**?

- To answer this, first we need to set the (B)SM interpretation “framework”

Introduction

Similar considerations for WW production at lepton colliders



- At LEP2 **aTGC** determination was built on the assumption that the EW Vff are SM-like. Justified by the precise LEP/SLD Z-pole constraints
- Is the knowledge of the **EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **aTGC** at future colliders?
- To answer this, first we need to set the (B)SM interpretation “framework”

The theoretical framework

Theory framework

Interpretation frameworks for Higgs measurements

κ-framework

$$(\sigma \cdot \mathrm{BR})(i \to H \to f) = \kappa_i^2 \sigma^{\mathrm{SM}}(i \to H) \frac{\kappa_f^2 \Gamma^{\mathrm{SM}}(H \to f)}{\Gamma_H}$$

$$\Gamma_H = \Gamma_H^{\mathrm{SM}} \frac{\sum_i \kappa_i^2 \mathrm{BR}_i^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{inv}} - \mathrm{BR}_{\mathrm{unt}}}$$

BSM decays

Pros

-Compact parameterization of NP in single Higgs processes

-Does not require any BSM calculation per se

-Info easily applicable to several interesting NP scenarios (e.g. CH, MSSM)

Cons

- Not usable beyond single Higgs processes

- Only for total rates, no kinematics (Energy, angular dependence), no polarization

-Does not distinguish the source of NP (interpreted only as mod. of SM-like H couplings)

SMEFT-framework

$$\mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i$$

$$[\mathcal{O}_i] = d$$

Pros

-Theoretically robust framework

-Describes correlations between EW/Higgs/VV/Top/…

-Easy to interpret within general classes of (decoupling) new physics

Cons

-Many parameters (2499 to dimension 6)

-It requires extension to apply to not-heavy new physics

Theory framework

Interpretation frameworks for Higgs measurements

κ-framework

See backup slides for some results
(from JB, et al., arXiv:1905.03764 [hep-ph])

See also Kaili Zhang's talk on the parallel Higgs session (Nov 19, 2019)

SMEFT-framework

$$\mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i$$

$$[\mathcal{O}_i] = d$$

Framework adopted for the results presented in this talk:
The dimension-6 SMEFT

Theory framework

- **The dimension 6 SMEFT:**

$$\mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

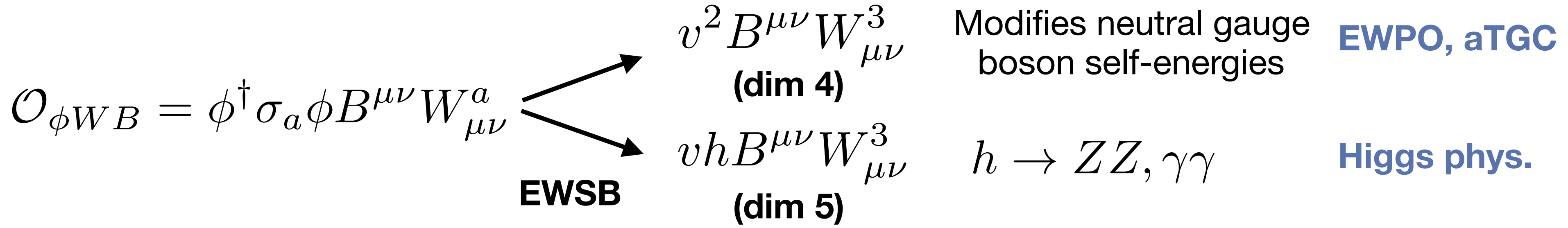
$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

Λ: Cut-off of the EFT

Effects suppressed by $q = v, E < \Lambda$

- LO new physics effects "start" at dimension 6: **59 B & L preserving operators (2499 counting flavor)**
  B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085

- SMEFT describes correlations of new physics effects in different types of observables, e.g.



$$\begin{tikzcd} & v^2 B^{\mu\nu} W^3_{\mu\nu} \\ \mathcal{O}_{\phi WB} = \phi^\dagger \sigma_a \phi B^{\mu\nu} W^a_{\mu\nu} \arrow[ru] \arrow[rd, "\text{EWSB}"'] & \\ & vh B^{\mu\nu} W^3_{\mu\nu} \end{tikzcd}$$

(dim 4) Modifies neutral gauge boson self-energies — EWPO, aTGC

(dim 5) $h \to ZZ, \gamma\gamma$ — Higgs phys.

⇒ Use global EW/Higgs fits to estimate sensitivity to NP effects

- **Focus on EW/Higgs:** Assume CP-even. 4-fermion and dipole operators tested better by other processes and are neglected.

We also restrict the analysis to flavour preserving processes/interactions

Theory framework

Operators and their direct contributions to Higgs/EW interactions

		Operator	Notation	Operator	Notation
Class 1	ϕ^6	$(\phi^\dagger\phi)^3$	$\mathcal{O}_\phi$		
	$\phi^4 D^2$	$(\phi^\dagger\phi)\,\Box\,(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger D_\mu\phi)\left((D^\mu\phi)^\dagger\phi\right)$	$\mathcal{O}_{\phi D}$
	$X^2\phi^2$	$\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$
		$\phi^\dagger\sigma_a\phi W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$\phi^\dagger\phi G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$
	X^3	$\varepsilon_{abc}W_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_W$		
Class 2	$\psi^2\phi^2$	$(\phi^\dagger\phi)\,(\bar{l}^i_L\phi e^j_R)$	$(\mathcal{O}_{e\phi})_{ij}$		
		$(\phi^\dagger\phi)\,(\bar{q}^i_L\phi d^j_R)$	$(\mathcal{O}_{d\phi})_{ij}$	$(\phi^\dagger\phi)\,(\bar{q}^i_L\tilde{\phi}u^j_R)$	$(\mathcal{O}_{u\phi})_{ij}$
Class 3	$\psi^2\phi^2 D$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}^i_L\gamma^\mu l^j_L)$	$\left(\mathcal{O}^{(1)}_{\phi l}\right)_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}^i_L\gamma^\mu\sigma_a l^j_L)$	$(\mathcal{O}^{(3)}_{\phi l})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}^i_R\gamma^\mu e^j_R)$	$(\mathcal{O}_{\phi e})_{ij}$		
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}^i_L\gamma^\mu q^j_L)$	$(\mathcal{O}^{(1)}_{\phi q})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}^i_L\gamma^\mu\sigma_a q^j_L)$	$(\mathcal{O}^{(3)}_{\phi q})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}^i_R\gamma^\mu u^j_R)$	$(\mathcal{O}_{\phi u})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}^i_R\gamma^\mu d^j_R)$	$(\mathcal{O}_{\phi d})_{ij}$
		$(\tilde{\phi}^\dagger iD_\mu\phi)(\bar{u}^i_R\gamma^\mu d^j_R)$	$(\mathcal{O}_{\phi ud})_{ij}$		
G_F	ψ^4	$(\bar{l}_1\gamma_\mu l_2)\,(\bar{l}_2\gamma^\mu l_1)$	$(\mathcal{O}_{ll})_{1221}$		

Theory framework

Parameterization of dim-6 contributions to Higgs/EW interactions

LHCHXSWG-INT-2015-001

HVV

$$\begin{aligned}\Delta\mathcal{L}_6^{\rm hVV} &= \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{w\Box}\, g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + c_{z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}\, g g' Z_\mu \partial_\nu A_{\mu\nu} \\ &\quad + c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu}\Big]\end{aligned}$$

Only 7 independent parameters

$$\begin{aligned}\delta c_w &= \delta c_z + 4\delta m, \\ c_{ww} &= c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma}, \\ c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\sin^2\theta_w c_{\gamma\gamma} - (g^2-g'^2)\sin^2\theta_w c_{z\gamma}\right] \\ c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)c_{zz} - e^2 c_{\gamma\gamma} - (g^2-g'^2)c_{z\gamma}\right],\end{aligned}$$

aTGC

$$\begin{aligned}\Delta\mathcal{L}^{\rm aTGC} &= ie\,\delta\kappa_\gamma A^{\mu\nu}W_\mu^+W_\nu^- + ig\cos\theta_w\left[\delta g_{1Z}\left(W_{\mu\nu}^+W^{-\mu} - W_{\mu\nu}^-W^{+\mu}\right)Z^\nu + \left(\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma\right)Z^{\mu\nu}W_\mu^+W_\nu^-\right] \\ &\quad + \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu}W_\nu^{-\rho}A_\rho^\mu + \cos\theta_w W_\mu^{+\nu}W_\nu^{-\rho}Z_\rho^\mu\right),\end{aligned}$$

δg_{1Z} and $\delta\kappa_\gamma$ given by *HVV* couplings

Hff

$$\Delta\mathcal{L}_6^{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\hat{\delta}y_f\, m_f \bar{f}f + \text{h.c.}$$

Vff & HVff

$$\begin{aligned}\Delta\mathcal{L}_6^{vff,hvff} &= \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left(\hat{\delta}g_L^{W\ell}\bar{\nu}\gamma_\mu e + \hat{\delta}g_L^{Wq}\bar{u}\gamma_\mu d + \hat{\delta}g_R^{Wq}\bar{u}\gamma_\mu d + \text{h.c.}\right) \\ &+ \sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\delta}g_L^{Zf}\bar{f}\gamma_\mu f + \sum_{f=u,d,e}\hat{\delta}g_R^{Zf}\bar{f}\gamma_\mu f\right]\end{aligned}$$

Theory framework

Parameterization of dim-6 contributions to Higgs/EW interactions

$$\Delta\mathcal{L}_6^{\rm hVV} = \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}$$

SMEFT fit

-*Hff* and *Vff* (*HVff*) diagonal in the physical basis

-*Vff* (*HVff*) flavour universality respected by first 2 quark families

-For H & EW exploration purposes only

-Cumbersome from model-building point of view to avoid FCNC

Parameter counting in the parameterization of LHCHXSWG-INT-2015-001

Higgs/VVV

$$\{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\} +$$

$$\left\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{W\ell\nu})_\ell, (\delta g_L^{Ze})_\ell, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_\ell\right\}_{q_1=q_2,\ \ell=e,\mu,\tau}$$

Vff/HVff

5 SM + 28 New Physics Parameters

To study the impact of EW measurements we will compare with an scenario with "perfect EW" data i.e. EW interactions known to be SM-like with infinite precision:

"Perfect EW" → $\left\{\delta m, (\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{W\ell\nu})_\ell, (\delta g_L^{Ze})_\ell, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_\ell\right\} \equiv 0$

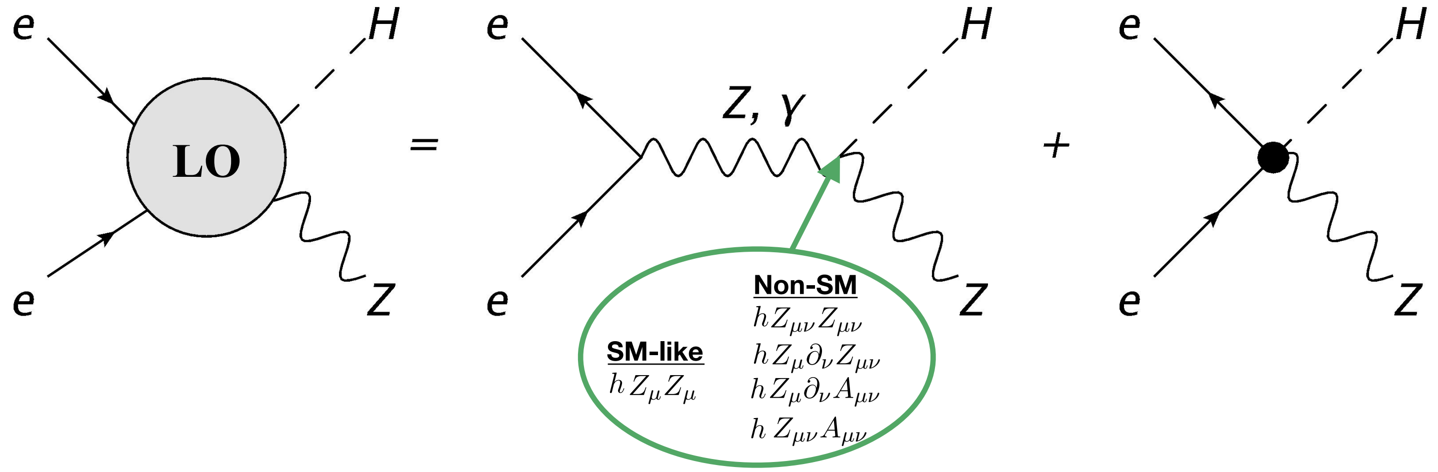
$f=u,d,e,\nu$ $f=u,d,e$

Theory framework

Higgs production in the EFT framework

- New type of contributions: apart from new *HVV'* tensor structures, virtual exchange of BSM particles can generate contact interactions

Interference grows like E^2 wrt. SM



- These *HZff* terms are connected to modifications of *Zff* couplings, e.g.

$$\phi^\dagger i\overleftrightarrow{D}_\mu\phi\,\overline{e_R}\gamma^\mu e_R \sim \frac{ev^2}{2sc}Z_\mu\overline{e_R}\gamma^\mu e_R + \frac{ev}{sc}HZ_\mu\overline{e_R}\gamma^\mu e_R + \dots$$

Uncertainty on *(H)Zee* introduces growing-with-*E* "contamination" in the extraction of *HZZ* interactions from *ZH* processes

⇒ Use future EWPO (Z-pole data) to constrain *Zee* → *HZee*

Theory framework

Interplay Higgs/aTGC in the EFT framework

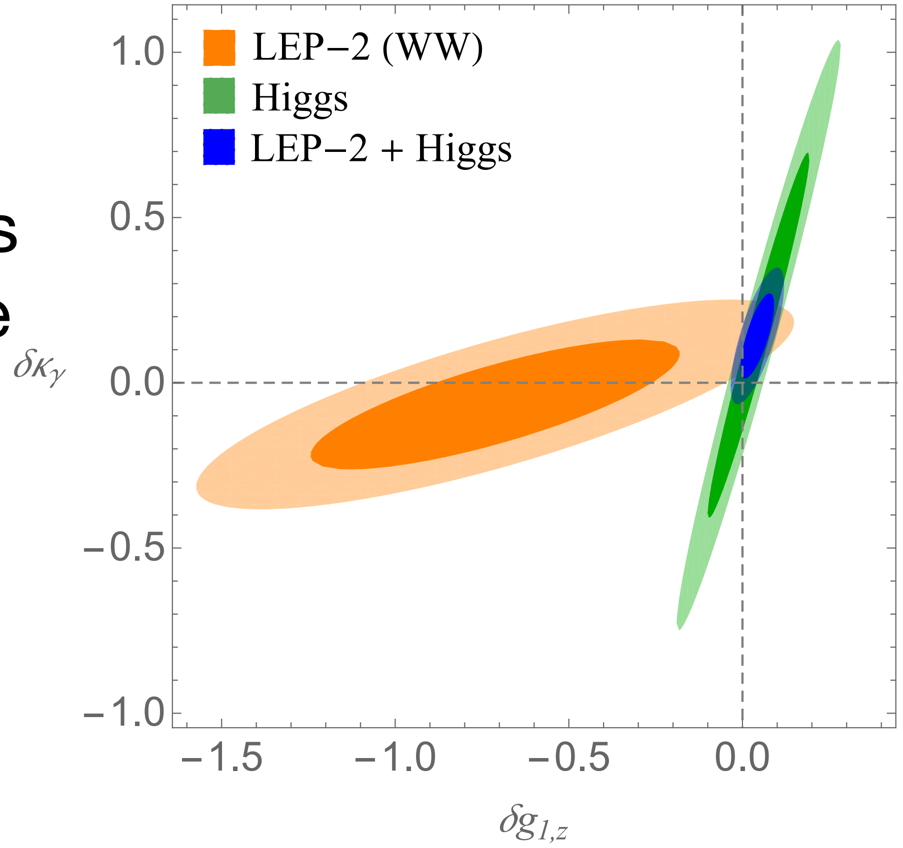
- To dimension 6, 2 aTGC are generated by the same interactions modifying HVV couplings

$$\begin{aligned}\Delta\mathscr{L}^{\mathrm{aTGC}} &= ie\delta\kappa_\gamma A^{\mu\nu}W^+_\mu W^-_\nu + ig\cos\theta_w\left[\delta g_{1Z}(W^+_{\mu\nu}W^{-\mu}-W^-_{\mu\nu}W^{+\mu})Z^\nu + (\delta g_{1Z}-\frac{g'^2}{g^2}\delta\kappa_\gamma)Z^{\mu\nu}W^+_\mu W^-_\nu\right]\\ &+\frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W^{+\nu}_\mu W^{-\rho}_\nu A^\mu_\rho + \cos\theta_w W^{+\nu}_\mu W^{-\rho}_\nu Z^\mu_\rho\right),\end{aligned}$$

$$\begin{aligned}\delta g_{1,z} &= \tfrac{1}{2}(g^2-g'^2)\left[c_{\gamma\gamma}e^2g'^2 + c_{z\gamma}(g^2-g'^2)g'^2 - c_{zz}(g^2+g'^2)g'^2 - c_{z\Box}(g^2+g'^2)g^2\right],\\ \delta\kappa_\gamma &= -\tfrac{g^2}{2}\left(c_{\gamma\gamma}\tfrac{e^2}{g^2+g'^2} + c_{z\gamma}\tfrac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right),\end{aligned}$$

- Technically not needed to break degeneracies but provides “orthogonal" handle to the same BSM interactions entering in Higgs:

A. Falkowski et al., PRL 116 (2016) 011801



Theory framework

Presentation of SMEFT fit results

- Compare Future Collider sensitivity to deformations of Higgs couplings in a basis-independent way
  - **Project EFT fit results into (pseudo) observable quantities**

$$g_{HX}^{\text{eff}\;2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}$$

Effective Higgs couplings

Similar definition as κ modifiers, but different interpretation, e.g.

$$\frac{\Gamma_{ZZ^*}}{\Gamma^{\text{SM}}_{ZZ^*}} \simeq \underline{1 + 2\,\delta c_Z} - 0.15\,c_{ZZ} + 0.41\,c_{Z\Box} + \ldots\ (\text{EW } Vff,\ hVff)$$

Only these are described in κ-framework

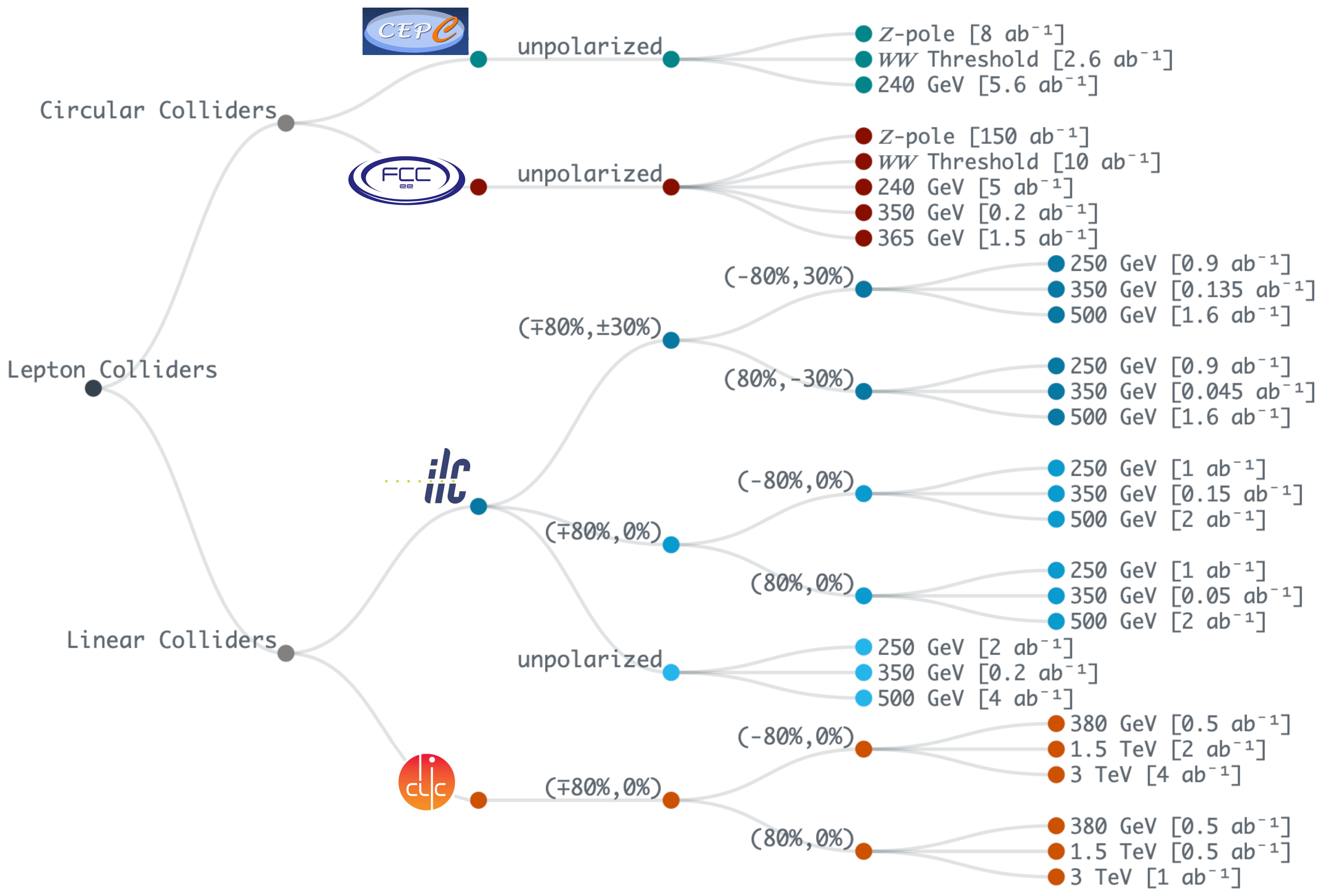
  - **Not enough to match EFT d.o.f : Add also aTGC**
- Similarly, for EW interactions, one could **project results into effective *Zff* couplings** defined from EWPO, e.g.

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g_L^e|^2 + |g_R^e|^2\right), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

Similar to LHCHXSWG-INT-2015-001 parameterization of EW interactions, e.g. $\delta g_{Z,L}^{ee}$

EW/WW/Higgs inputs at future lepton colliders

Future lepton colliders considered in the study



- Lepton Colliders
  - Circular Colliders
    - CEPC
      - unpolarized
        - Z-pole [8 ab^{-1}]
        - WW Threshold [2.6 ab^{-1}]
        - 240 GeV [5.6 ab^{-1}]
    - FCC ee
      - unpolarized
        - Z-pole [150 ab^{-1}]
        - WW Threshold [10 ab^{-1}]
        - 240 GeV [5 ab^{-1}]
        - 350 GeV [0.2 ab^{-1}]
        - 365 GeV [1.5 ab^{-1}]
  - Linear Colliders
    - ilc
      - (∓80%,±30%)
        - (-80%,30%)
          - 250 GeV [0.9 ab^{-1}]
          - 350 GeV [0.135 ab^{-1}]
          - 500 GeV [1.6 ab^{-1}]
        - (80%,-30%)
          - 250 GeV [0.9 ab^{-1}]
          - 350 GeV [0.045 ab^{-1}]
          - 500 GeV [1.6 ab^{-1}]
      - (∓80%,0%)
        - (-80%,0%)
          - 250 GeV [1 ab^{-1}]
          - 350 GeV [0.15 ab^{-1}]
          - 500 GeV [2 ab^{-1}]
        - (80%,0%)
          - 250 GeV [1 ab^{-1}]
          - 350 GeV [0.05 ab^{-1}]
          - 500 GeV [2 ab^{-1}]
      - unpolarized
        - 250 GeV [2 ab^{-1}]
        - 350 GeV [0.2 ab^{-1}]
        - 500 GeV [4 ab^{-1}]
    - CLIC
      - (∓80%,0%)
        - (-80%,0%)
          - 380 GeV [0.5 ab^{-1}]
          - 1.5 TeV [2 ab^{-1}]
          - 3 TeV [4 ab^{-1}]
        - (80%,0%)
          - 380 GeV [0.5 ab^{-1}]
          - 1.5 TeV [0.5 ab^{-1}]
          - 3 TeV [1 ab^{-1}]

Future lepton colliders considered in the study

Official inputs available for Higgs/WW/EW

	Higgs	aTGC	EWPO
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return) (Giga-Z? Not in baseline)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return) (Giga-Z? Not in baseline)

We will always combine with the info expected at the end of the (HL-)LHC era

Future lepton colliders considered in the study

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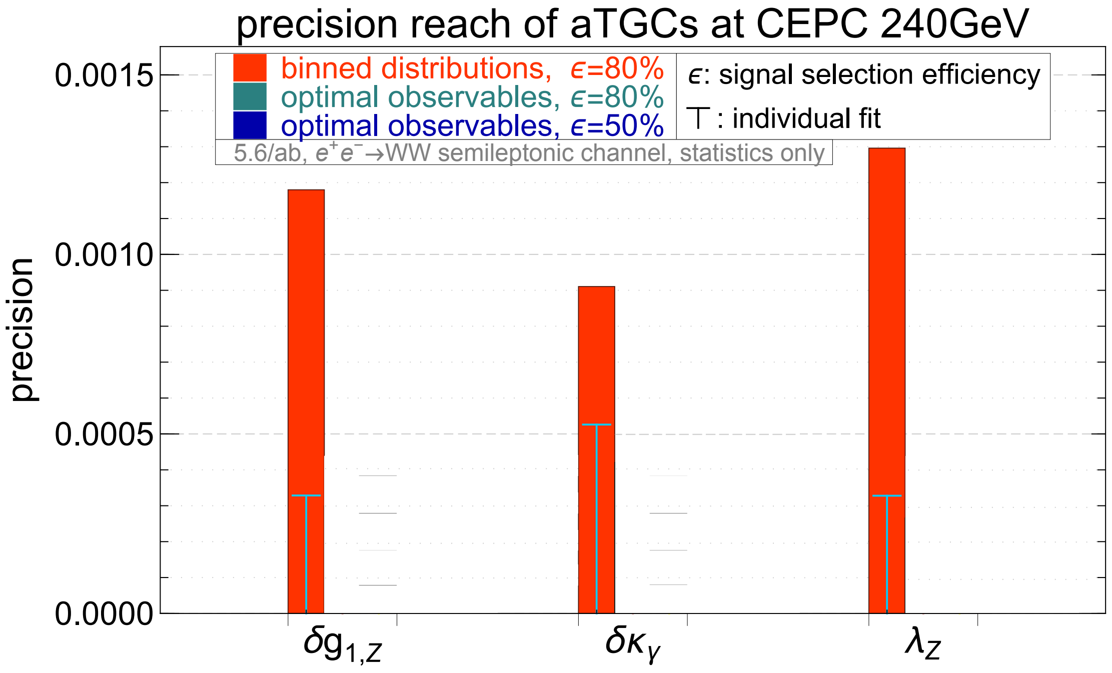
We will always combine with the info expected at the end of the (HL-)LHC era

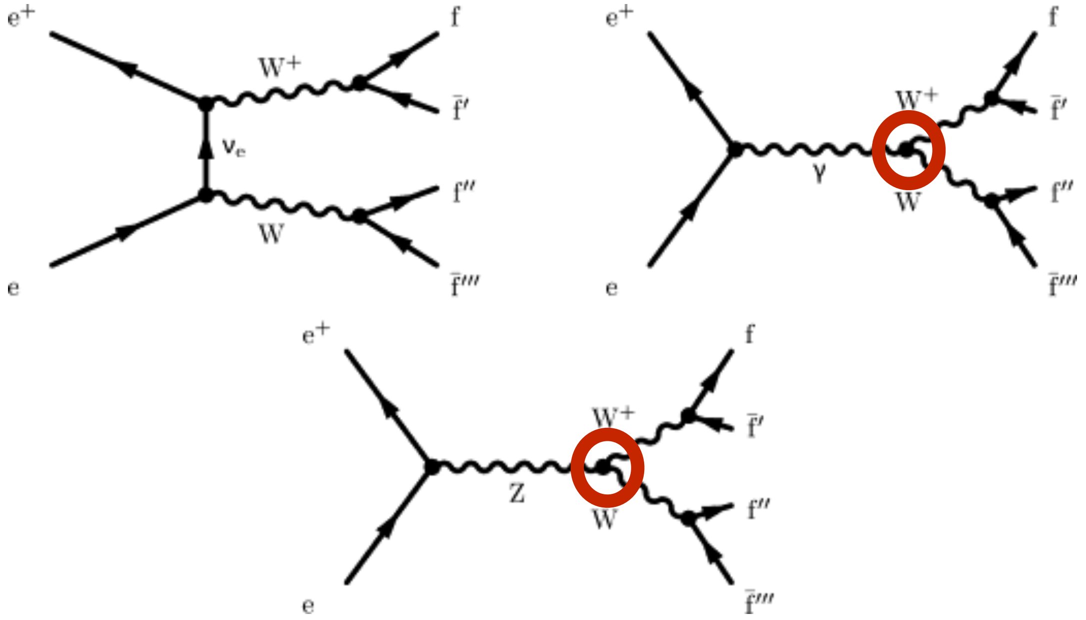
No full EFT studies available for WW processes at future lepton colliders

Global EFT study of WW production

WW production at lepton colliders

- Current projections based on sensitivity to aTGC ONLY in differential angular distributions (ignoring correlations between bins)





Global EFT study of WW production

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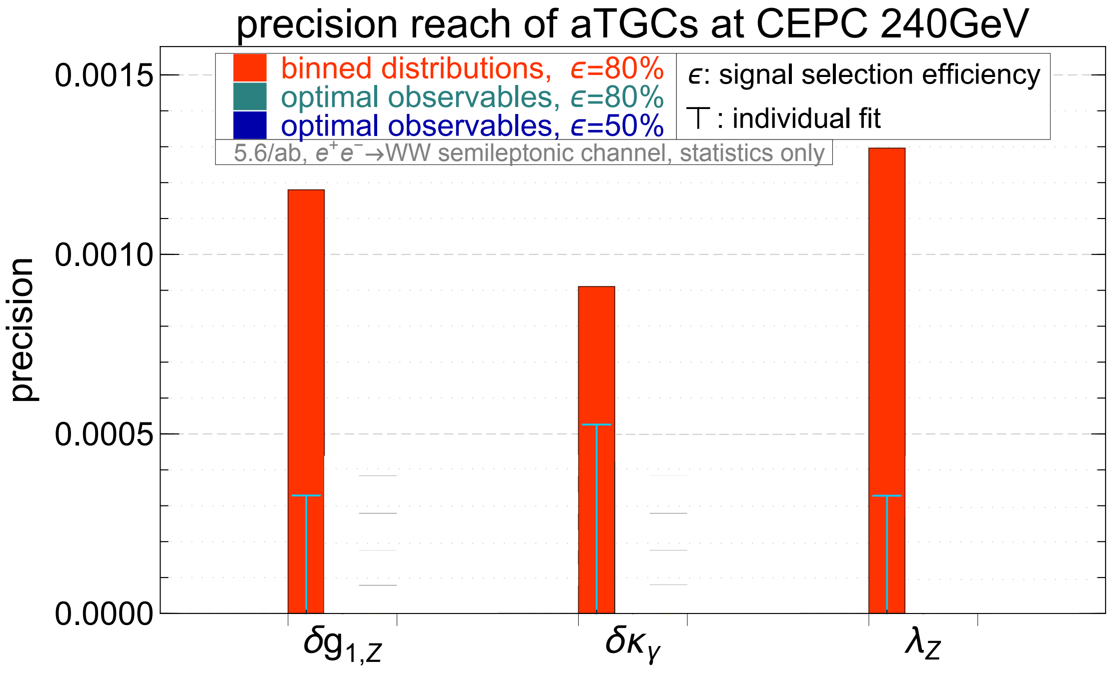
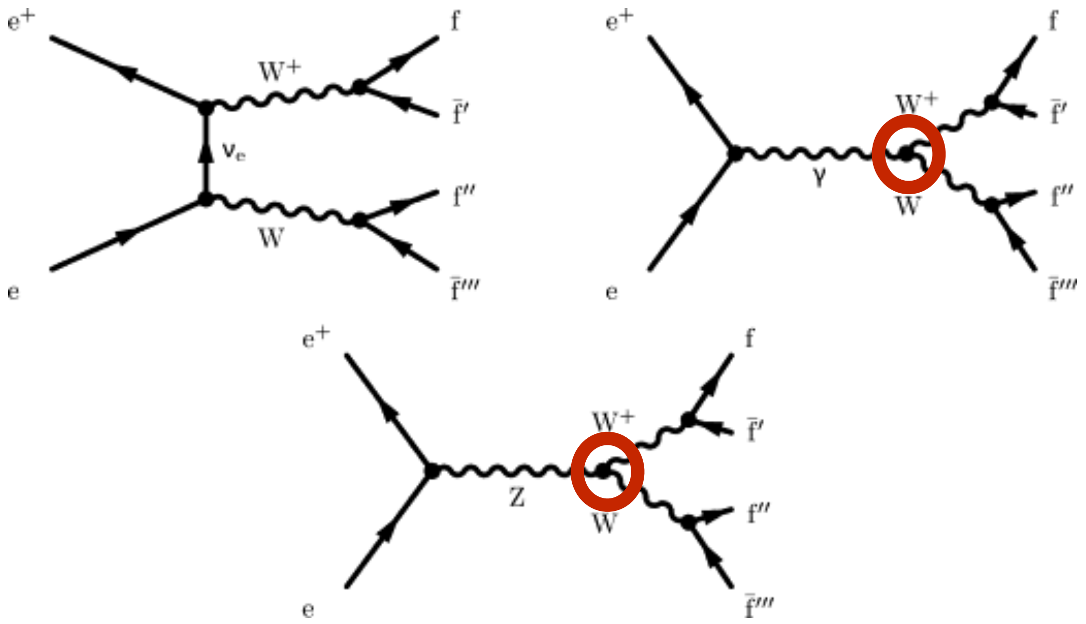




- We prepared a new sensitivity study using full information about each event in the formalism of “optimal statistical observables”

Global EFT study of WW production

Optimal Statistical Observables

- Consider a Phase-space distribution linear in some coefficients c_i:

$$\boldsymbol{S(\Phi) = S_0(\Phi) + \sum_i c_i S_i(\Phi)}$$

SMEFT: $S(\Phi) = \frac{d\sigma}{d\Phi}$ $S_0(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\text{SM}}$ $c_i S_i(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\text{Interf. SM}-\text{NP}}$

- In the limit of large statistics, the observables

(See e.g., Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

$$\boldsymbol{O_i = \sum_{k \in \text{events}} \frac{S_i(\Phi_k)}{S_0(\Phi_k)}}$$

provide the most precise statistical information about the coefficients c_i around the point $c_i=0$, $\forall i$

$$\boldsymbol{\text{cov}(c_i, c_j) = \left(\mathcal{L} \int d\Phi \frac{S_i(\Phi) S_j(\Phi)}{S_0(\Phi)}\right)^{-1} + \mathcal{O}(c_k)}$$

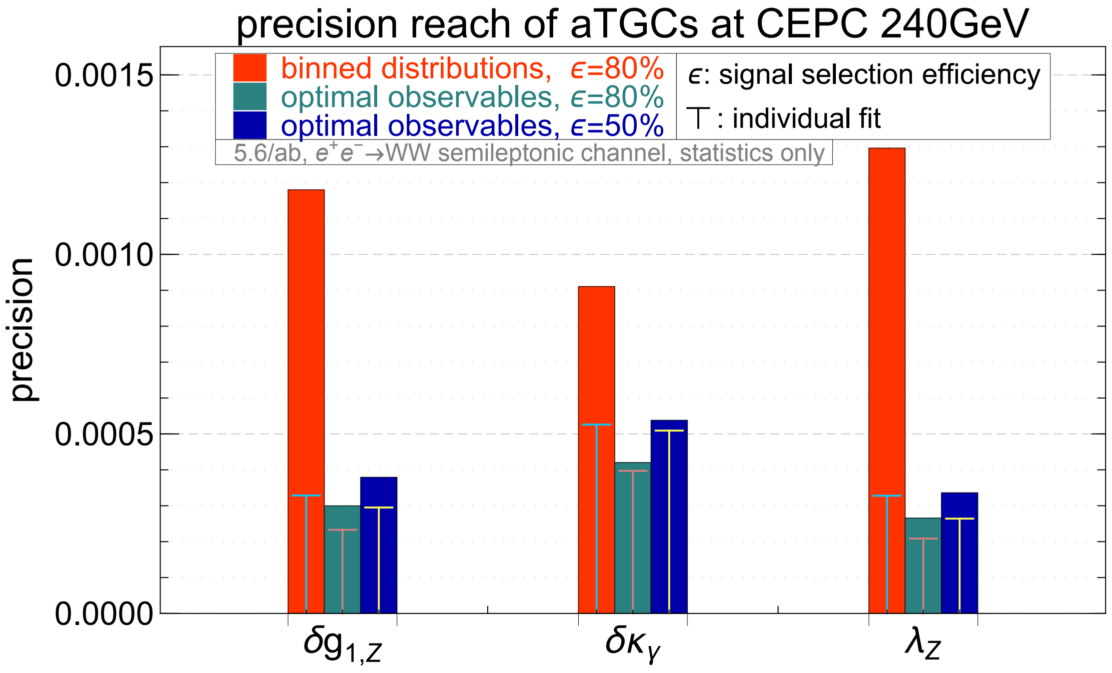
- Idealized (no systematics) ⇒ We compensate omission of systematics via conservative selection efficiency ε

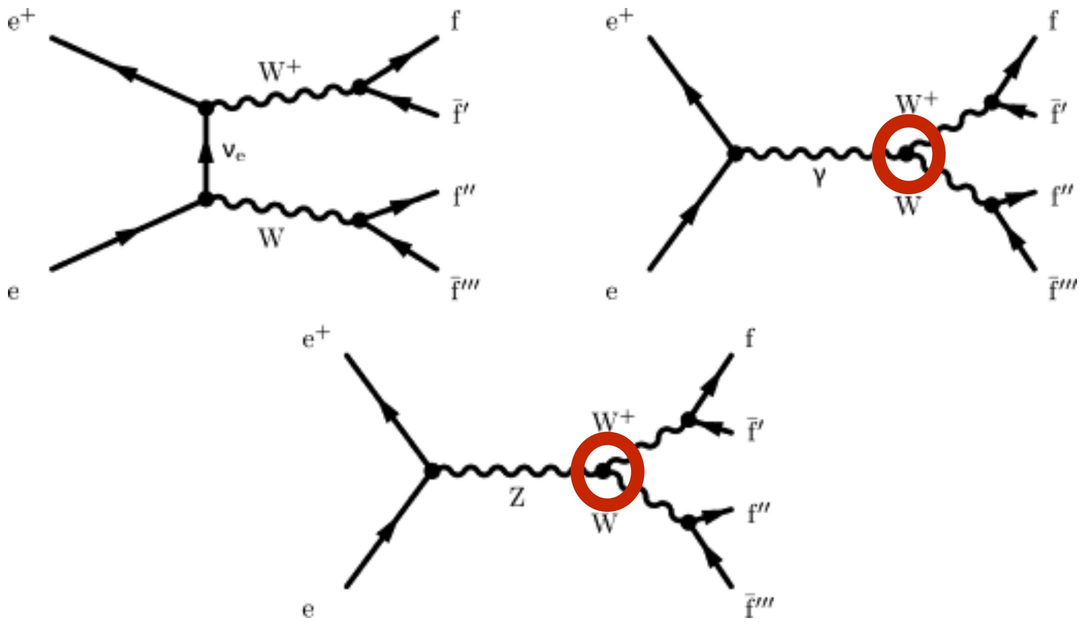
$$\boldsymbol{\mathcal{L} \longrightarrow \varepsilon \mathcal{L}}$$

Global EFT study of WW production

WW production at lepton colliders

- Current projections based on sensitivity to aTGC ONLY in differential angular distributions (ignoring correlations between bins)



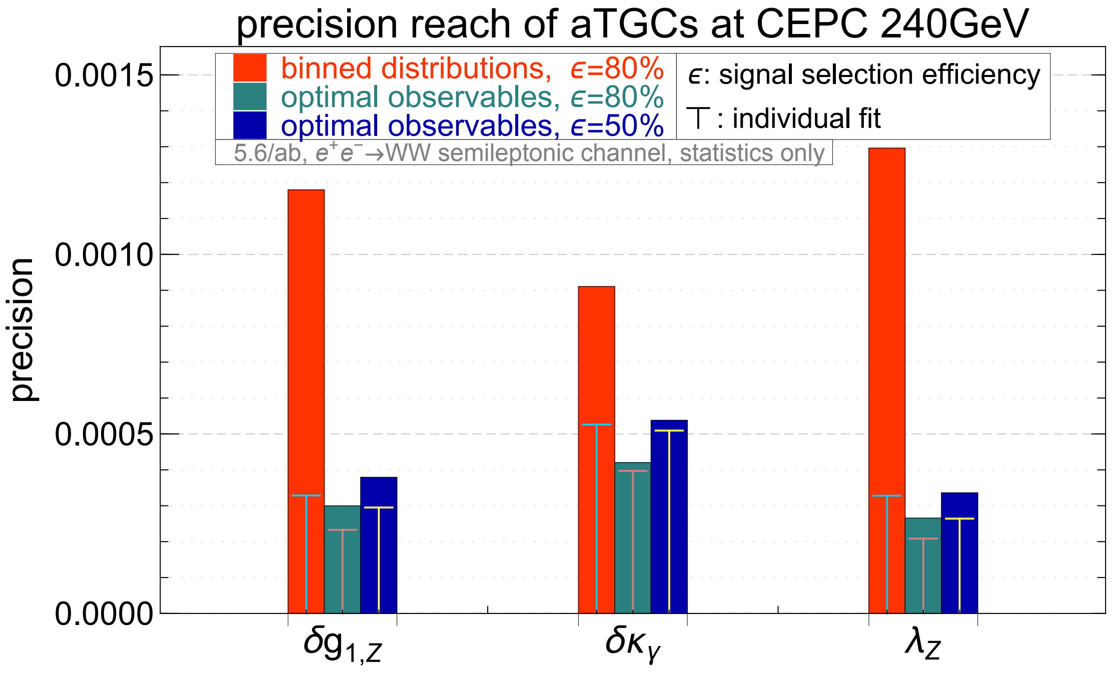


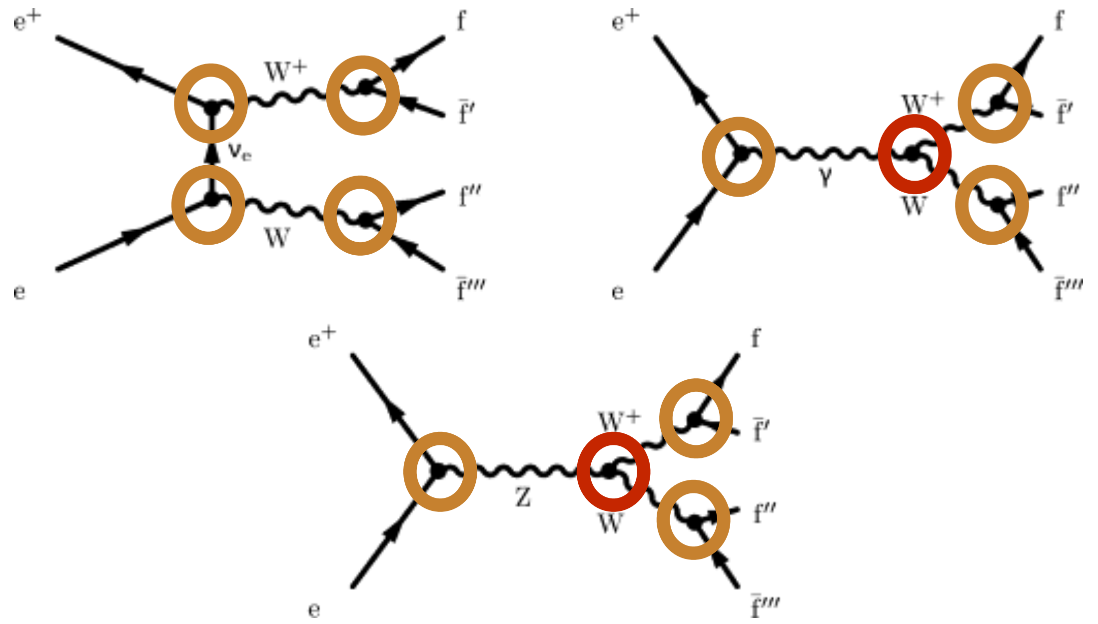
- We prepared a new sensitivity study using full information about each event in the formalism of “optimal statistical observables”
  - Default method only accounts for statistical sensitivity ⇒ Compensate omission of systematics via conservative selection efficiency ε

Global EFT study of WW production

WW production at lepton colliders

- Current projections based on sensitivity to aTGC ONLY in differential angular distributions (ignoring correlations between bins)



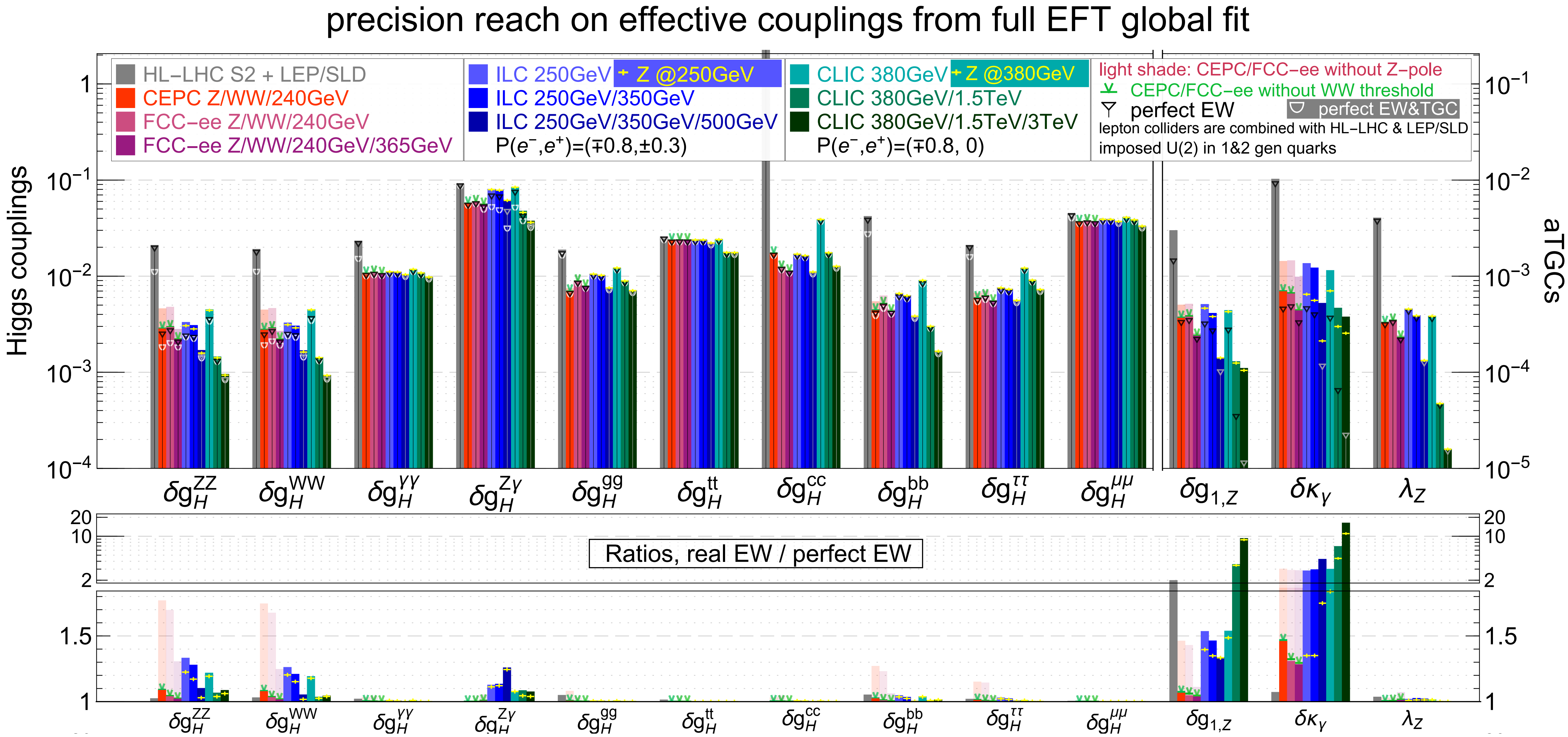


- We prepared a new sensitivity study using full information about each event in the formalism of “optimal statistical observables”:
  - We also consider all possible BSM deformations within the SMEFT framework

Global EW/Higgs fits at future lepton colliders

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC

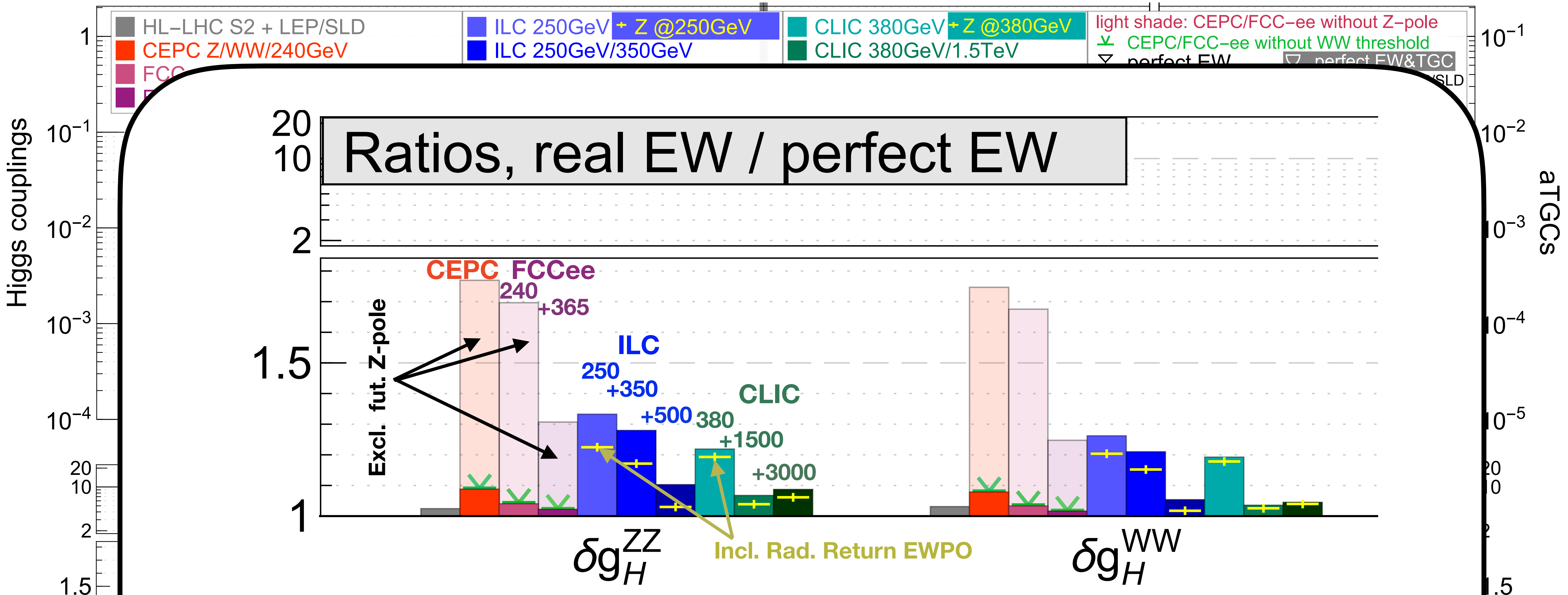


- All future lepton colliders can reach near per-mile level precision on hVV
- Rare decays ($H \to Z\gamma$, $H \to \mu\mu$) statistically limited

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC

precision reach on effective couplings from full EFT global fit



- Note: polarization partially compensates the absence of Z-pole at linear colliders

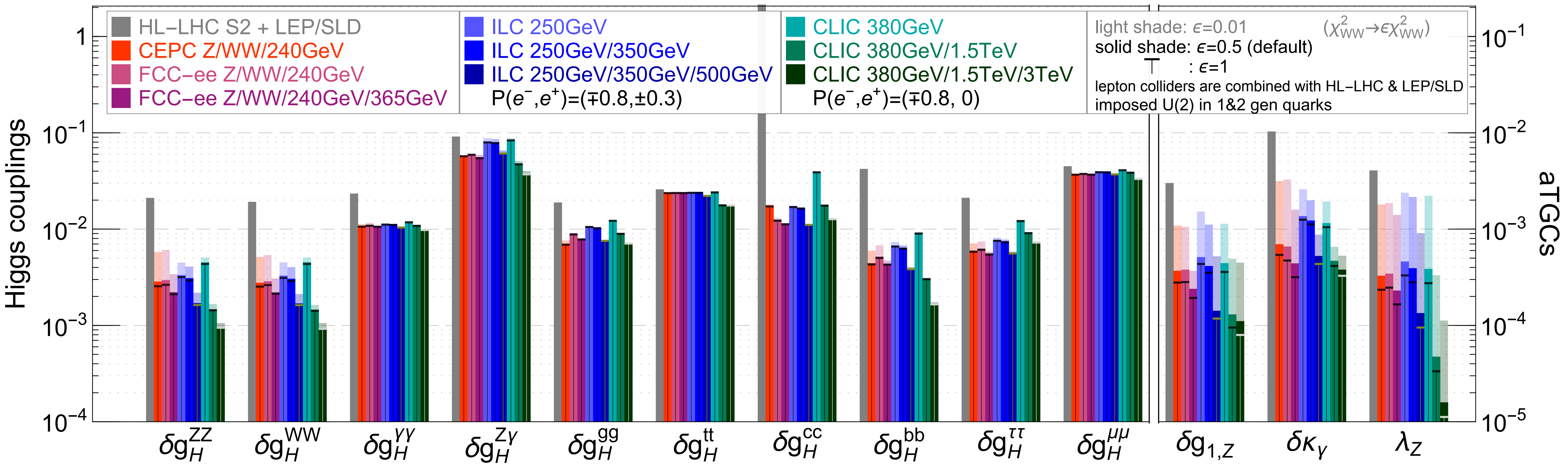
- A

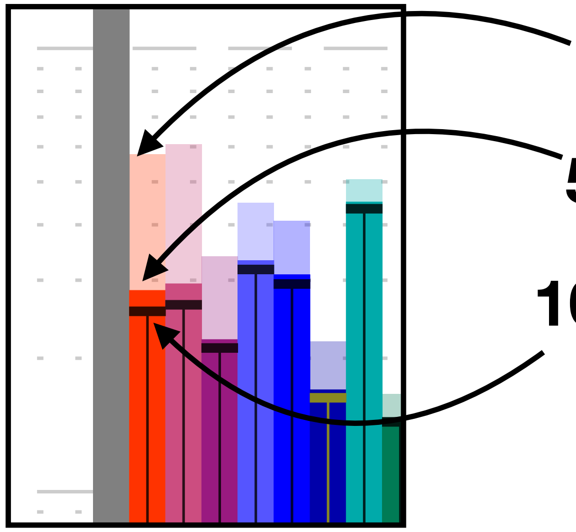
- Rare decays ($H \to Z\gamma$, $H \to \mu\mu$) statistically limited

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC: dependence on WW projections

precision reach with different assumptions on $e^+e^- \to WW$ measurements





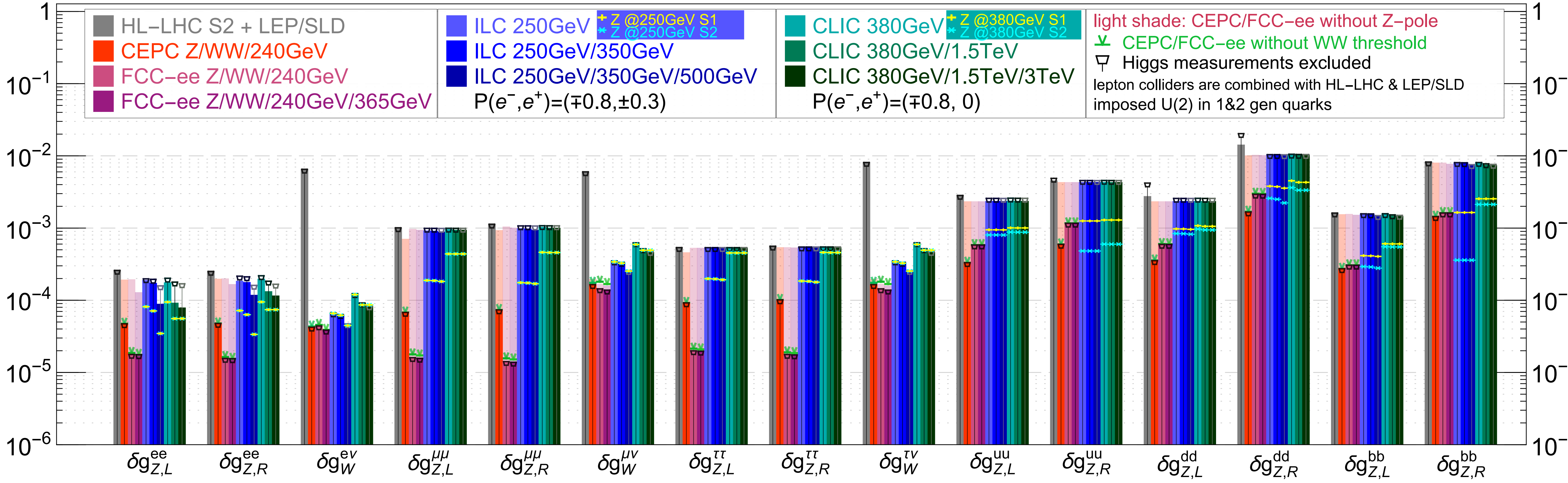
1% Efficiency in *ee→WW*

50% Efficiency in *ee→WW* (Default)

100% Efficiency in *ee→WW*

Global fit to EW/Higgs projections

EFT EW couplings



precision reach on EW couplings from full EFT global fit

- EW Vff couplings (and therefore $HVff$) better determined at circular colliders due to the Tera-Z factory run vs. the use of rad. return measurements at linear colliders

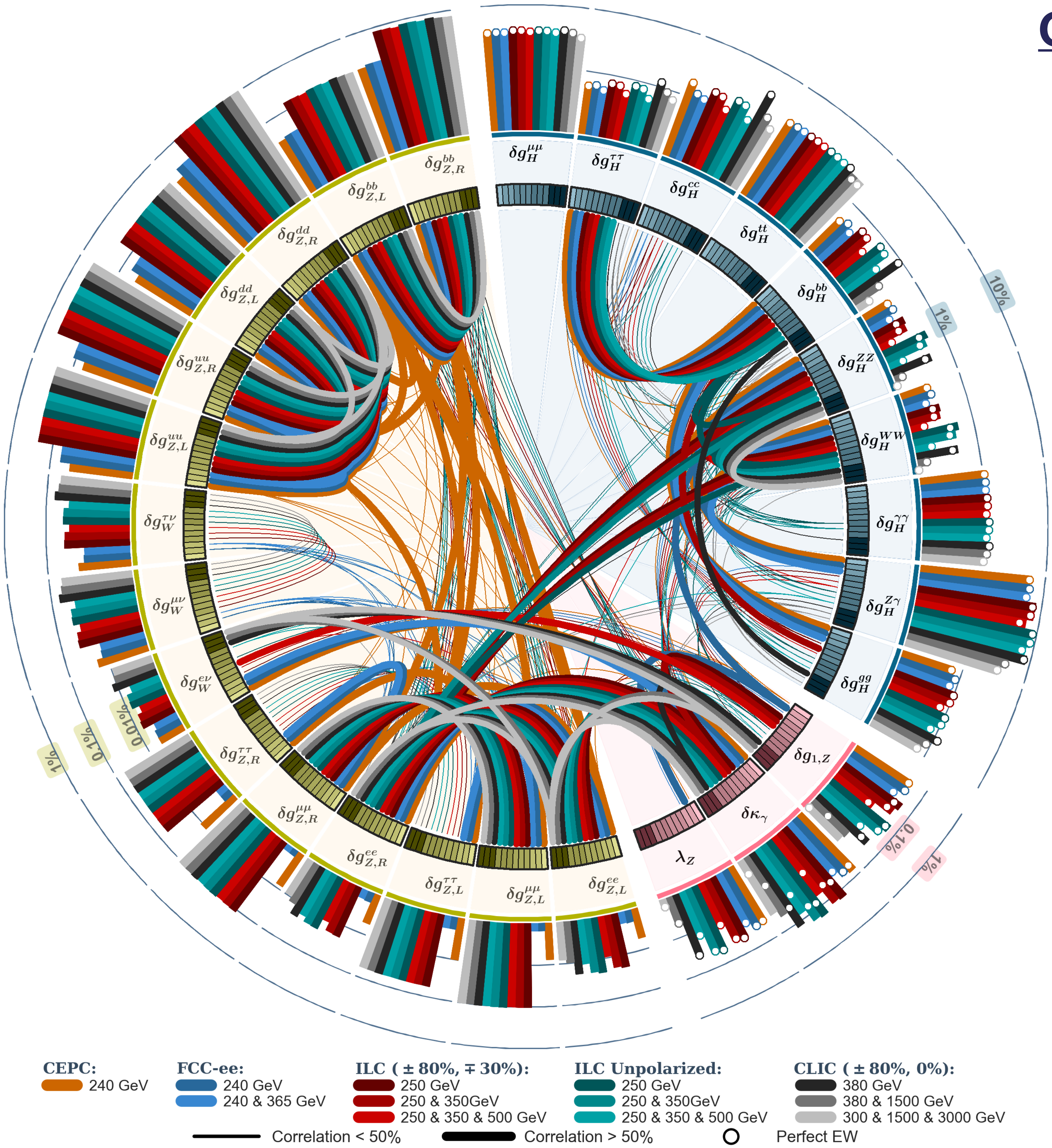
- Conversely, high-energy runs at linear colliders can measure $HZee$ (and therefore Zee) via Higgs, but only in combination with other HZZ interactions

Interplay EW/Higgs at future colliders

Couplings and correlations

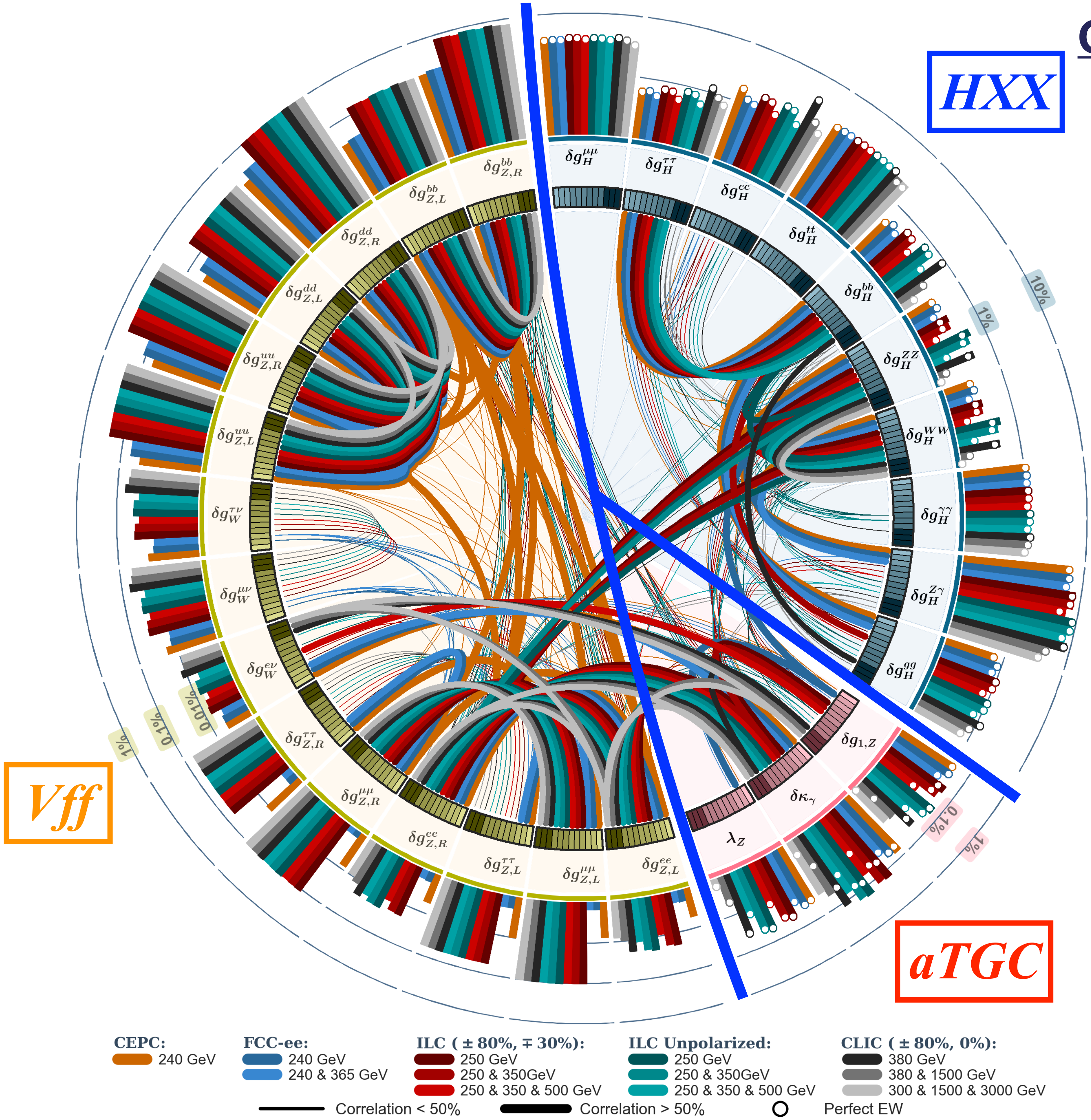
How to read “this”?

Correlation Map at Future Lepton Colliders



Interplay EW/Higgs at future colliders

Correlation Map at Future Lepton Colliders



Couplings and correlations

How to read "this"?

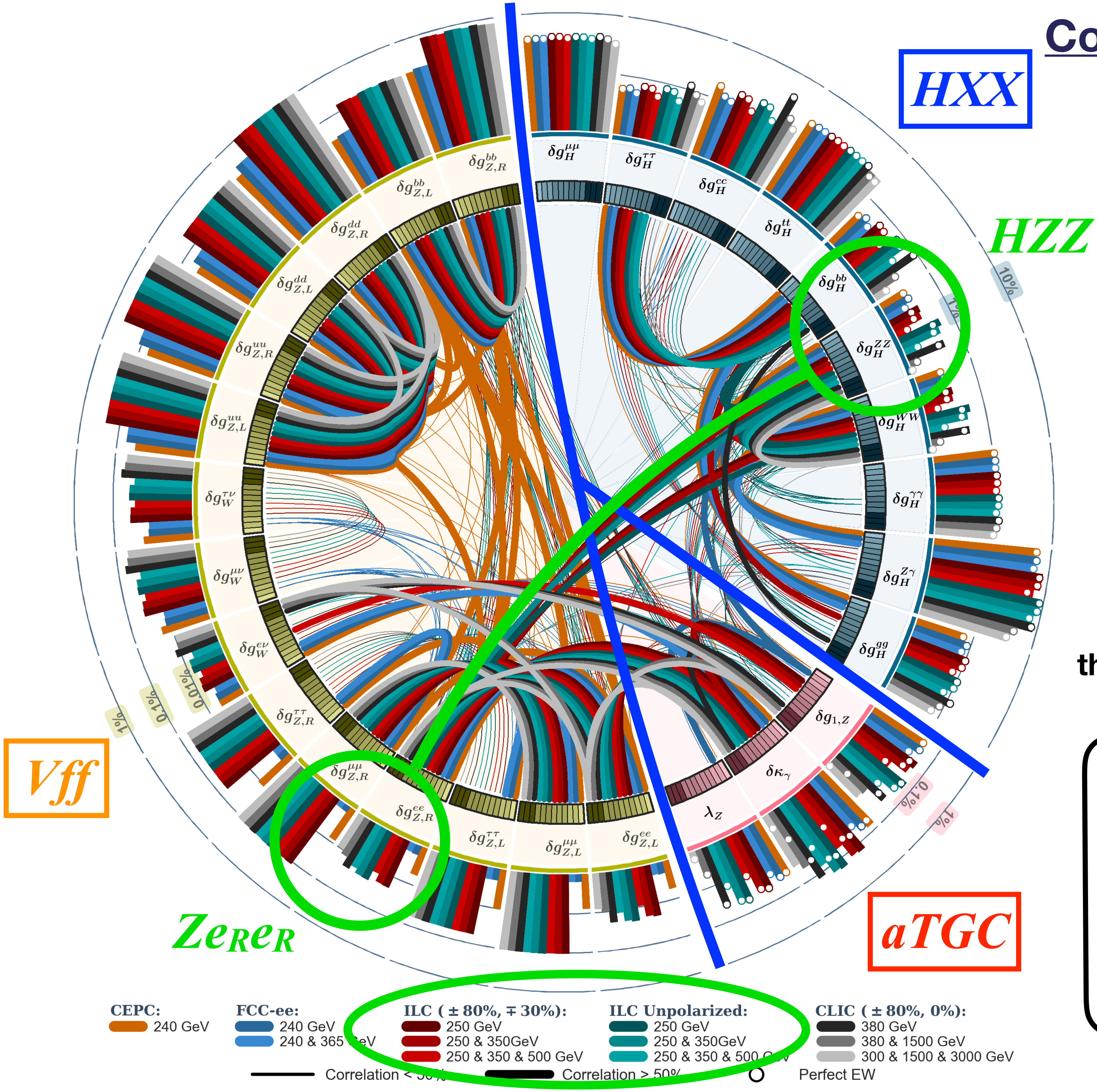
On the outside: 1σ uncertainty on the different interactions

(Interactions grouped as: Eff. H couplings, $aTGC$ and Vff)

Correlations indicated by lines linking the different couplings

Interplay EW/Higgs at future colliders

Correlation Map at Future Lepton Colliders



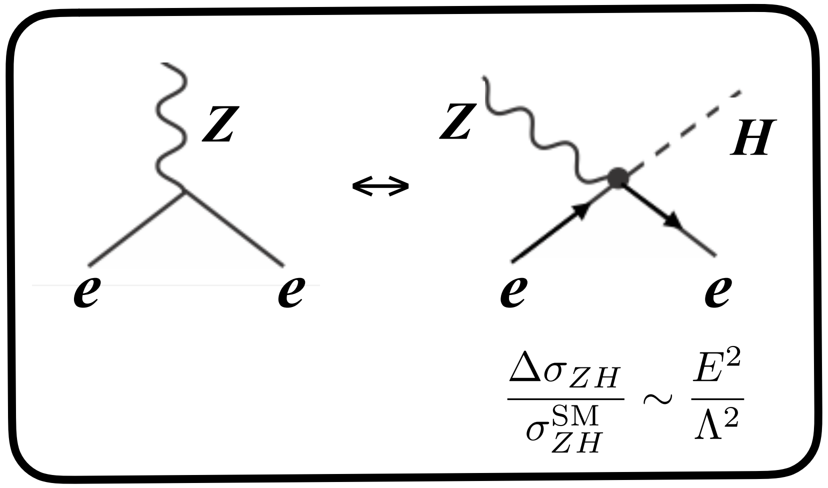
Couplings and correlations

CEPC/FCC-ee: Z-pole run largely decouples EWPO and Higgs fits

ILC: precision of HZZ limited by absence of Z-pole run

(Less pronounced at 500 GeV)

CLIC: High-E run compensate the absence of Z-pole run (for HZZ)

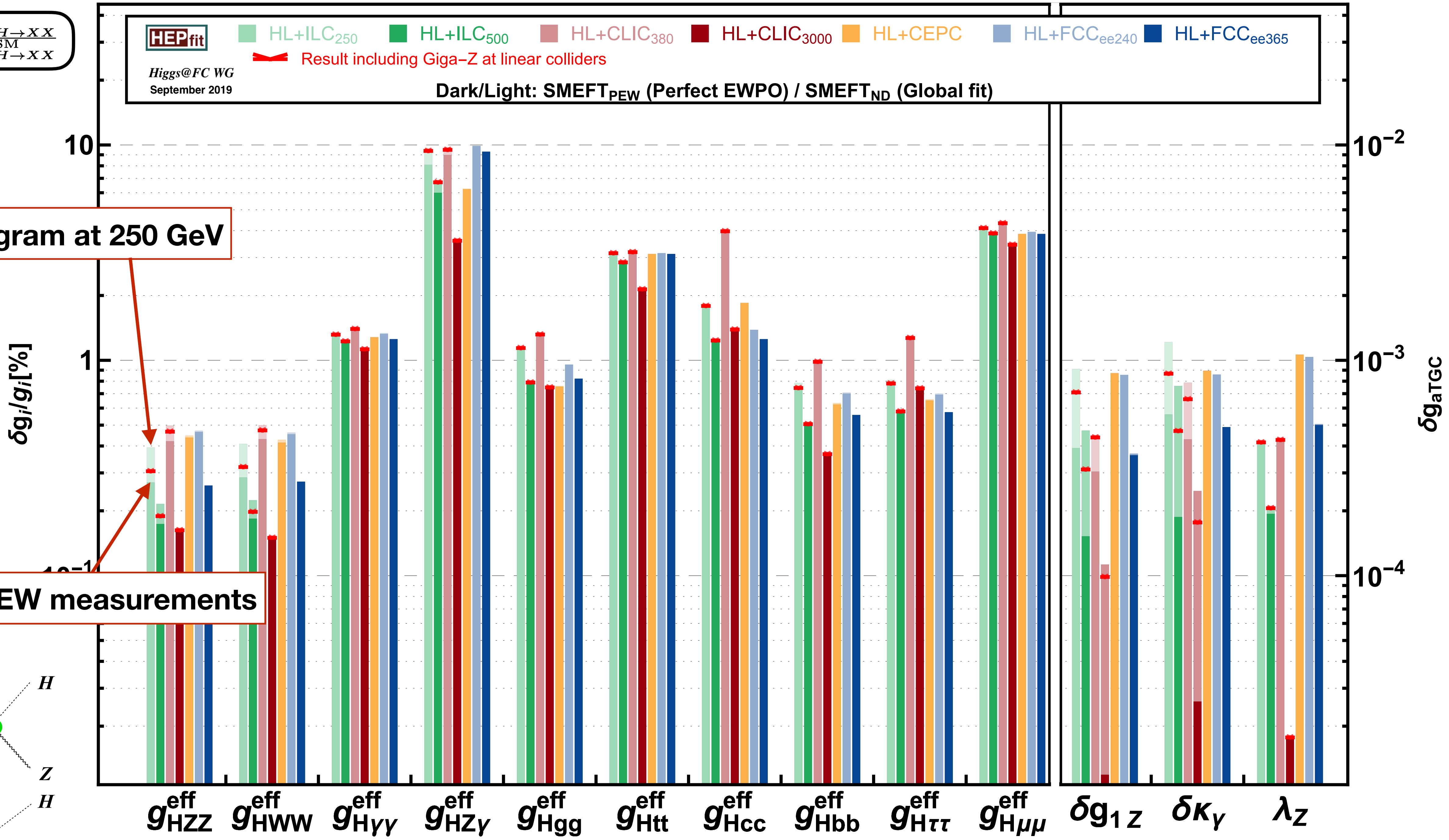


$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}^{SM}} \sim \frac{E^2}{\Lambda^2}$$

Interplay EW/Higgs at future colliders

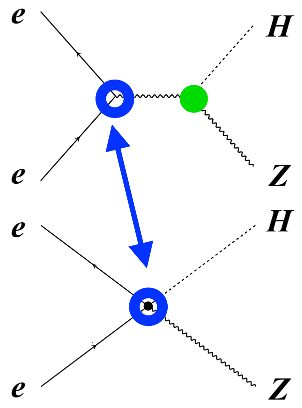
Impact of EWPO (Z pole measurements) in Higgs coupling sensitivity

$$g^{\text{eff}\ 2}_{hXX} = \frac{\Gamma_{H\to XX}}{\Gamma^{\text{SM}}_{H\to XX}}$$



EW program at 250 GeV

Perfect EW measurements



Difference due to absence of precise enough EWPO at LC (no Z pole run)

Can be mitigated by using: (1) High-energies (2) EWPO from Giga-Z run?

JB, et al., arXiv:1905.03764 [hep-ph]

Interplay EW/Higgs at future colliders

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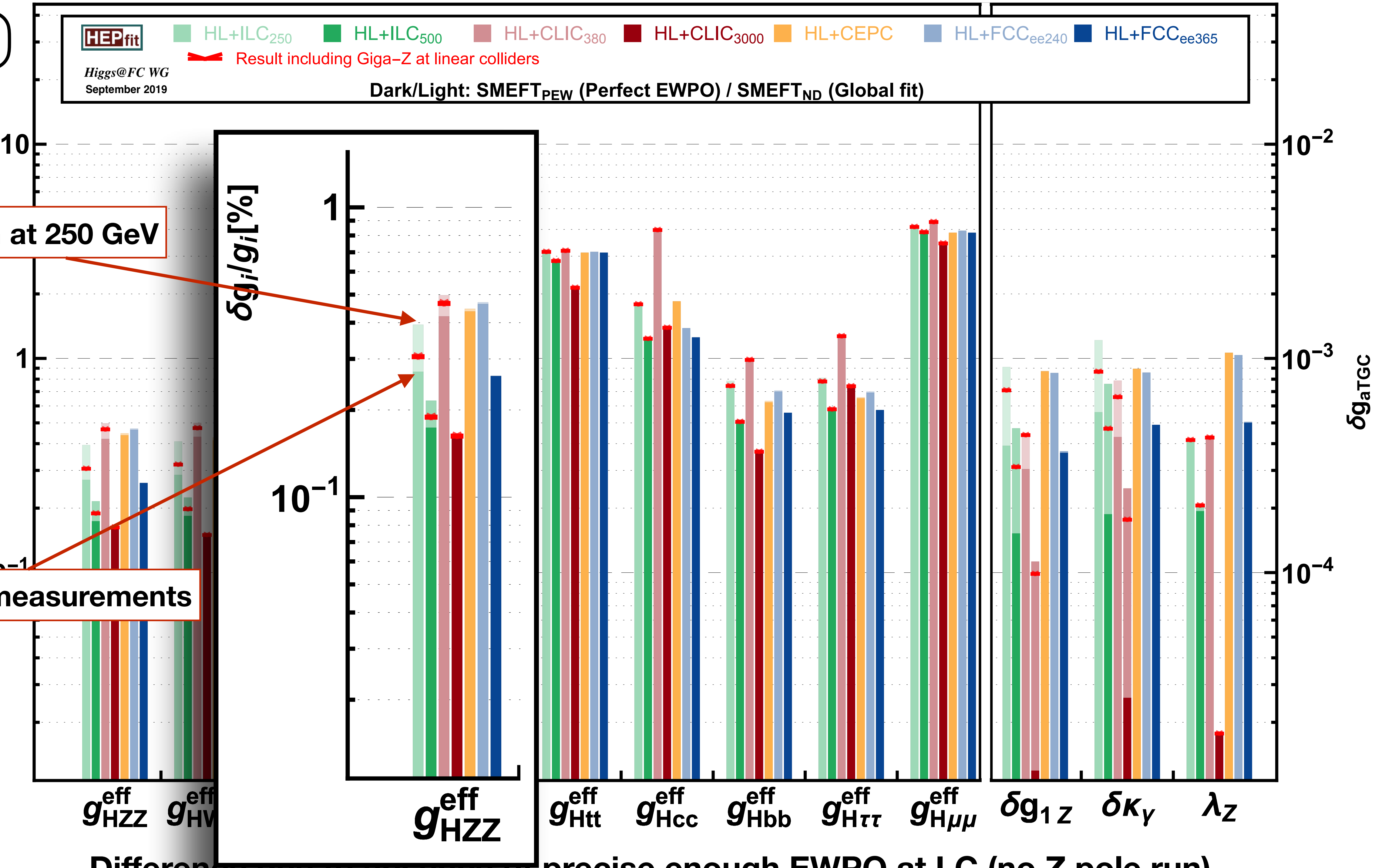
$$g_{hXX}^{\text{eff }2} = \frac{\Gamma_{H\to XX}}{\Gamma_{H\to XX}^{\text{SM}}}$$



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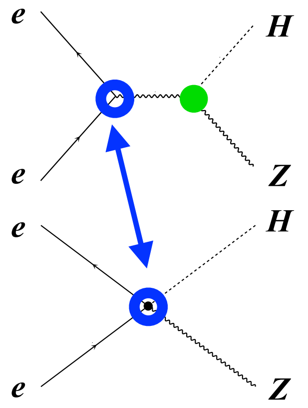

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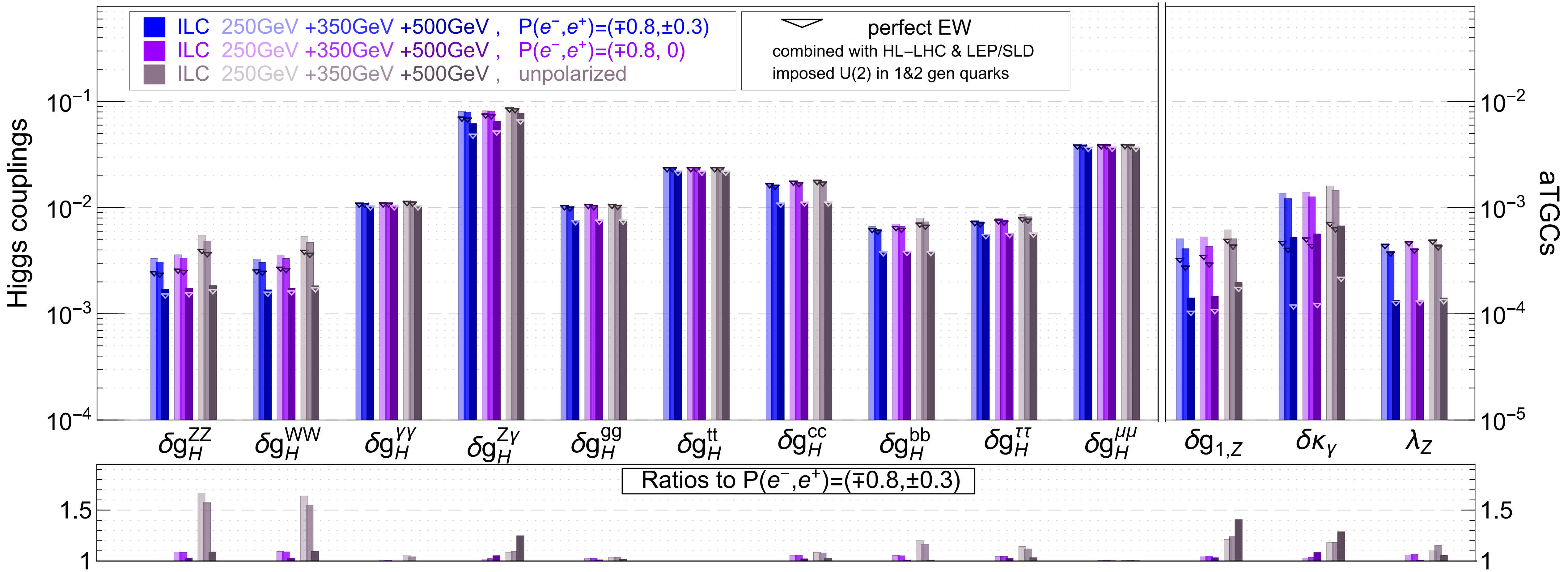
On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity

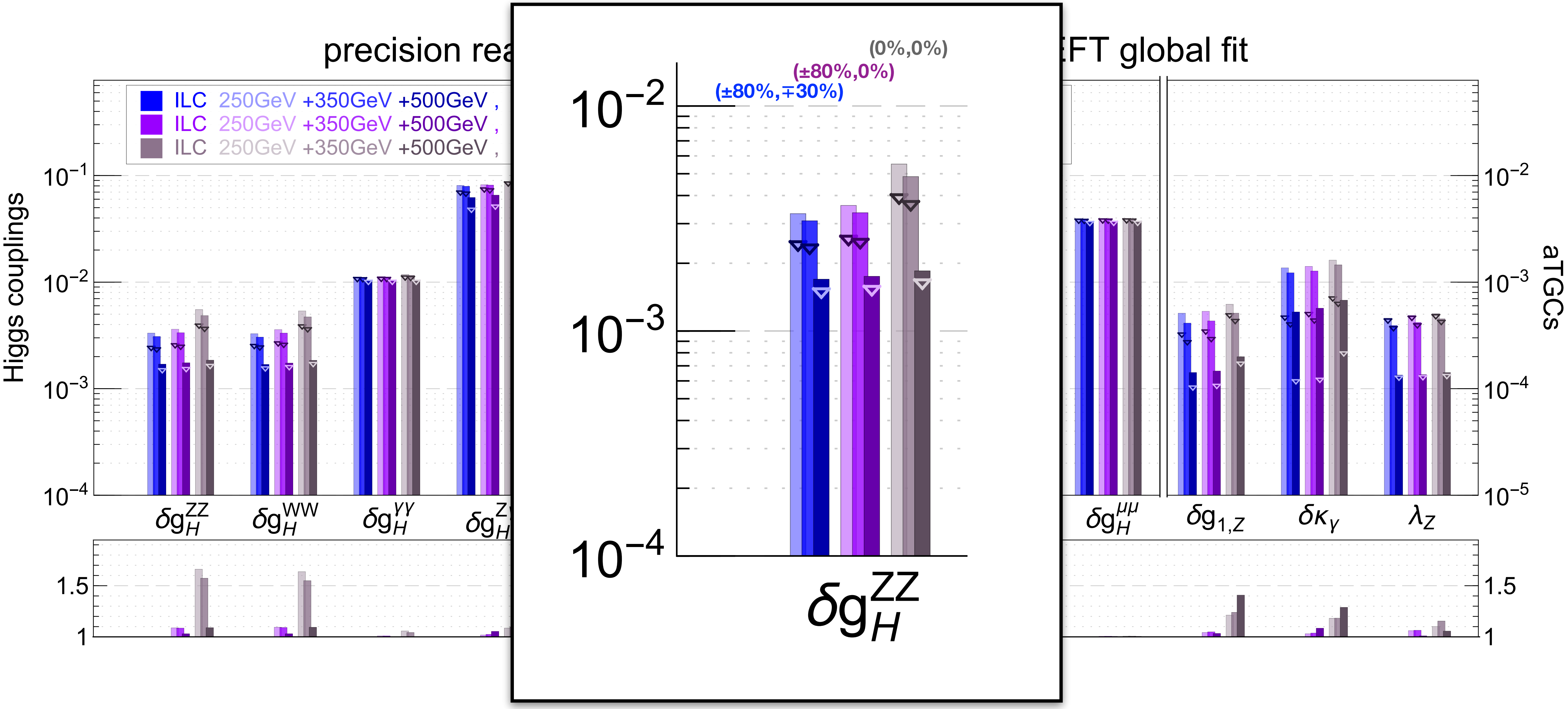
precision reach on effective couplings from full EFT global fit



- Polarization can resolve degeneracies in the ZH rate appearing in the unpolarized case.

On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity



- Polarization can resolve degeneracies in the ZH rate appearing in the unpolarized case.

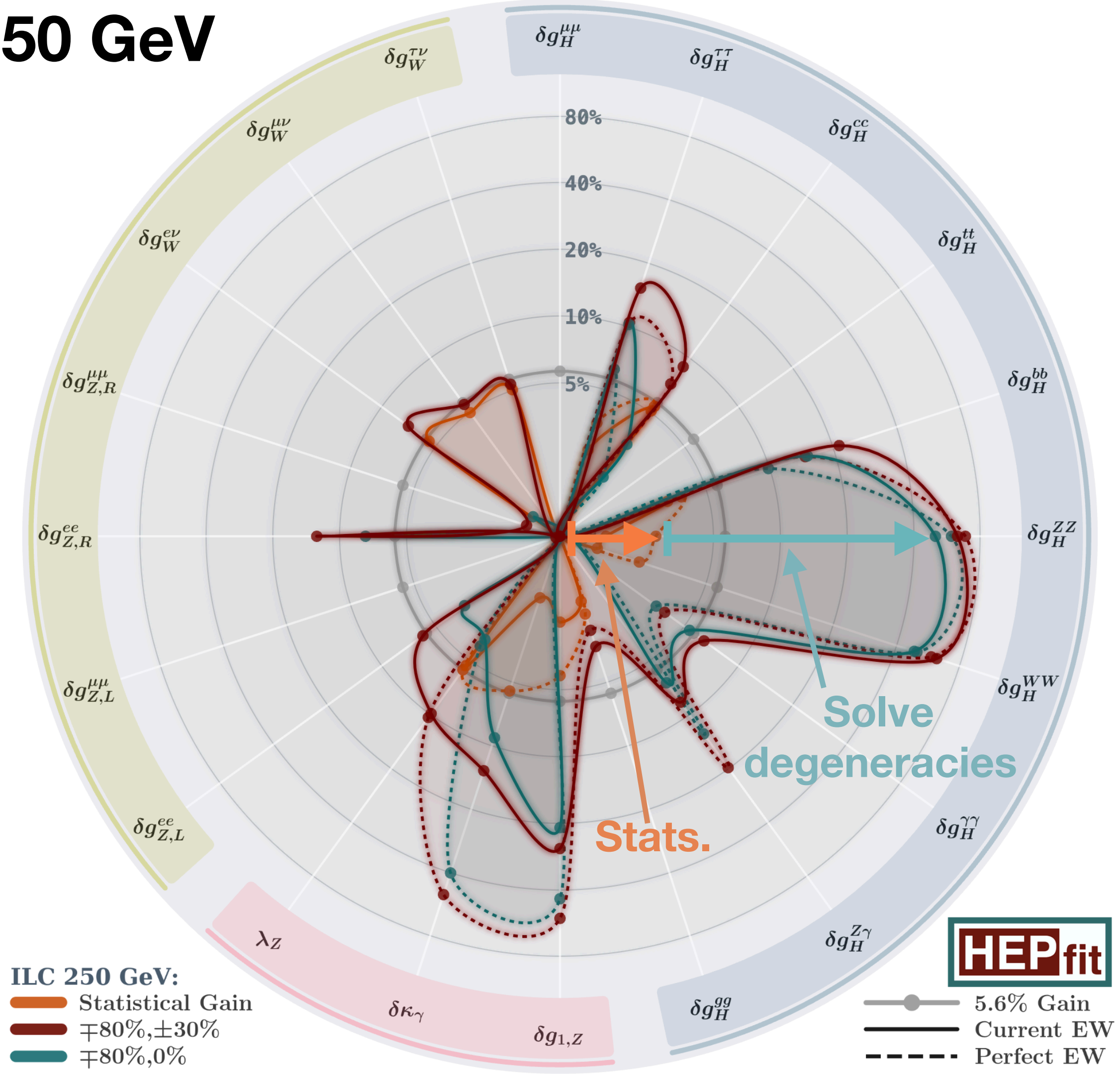
- The same can be resolved using data at different energies

  ⇒ negligible influence of polarization in the results at 500 GeV

On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity

ILC 250 GeV



Solve degeneracies

Stats.

How to read "this"?

$\delta g_{\text{unpol.}}/\delta g_{\text{unpol.}(L\times1.12)}$ -1 : Increased stats.

$\delta g_{\text{unpol.}}/\delta g_{(\pm80\%,0\%)}$ -1 : Increased stats. + resolving degeneracies

$\delta g_{\text{unpol.}}/\delta g_{(\pm80\%,\mp30\%)}$ -1 : Increased stats. + resolving degeneracies

- Polarization can resolve degeneracies in the ZH rate appearing in the unpolarized case.
- The same can be resolved using data at different energies

  ⇒ negligible influence of polarization in the results at 500 GeV

Conclusions

Conclusions

- **Motivated by the Higgs factory option**, there seems to be a consensus that a future lepton collider must be the next step in particle collider experiments:
  - “Model-independent” determination of H couplings (as opposed to HL-LHC)
  - Near per-mille level precision in some H couplings…
  - … still, rare channels limited by stats (⇒ need Hadron collider afterwards)

- **But future lepton colliders are more than Higgs factories:** possibility of improving the knowledge of ALL EW interactions

- In fact, **a precise determination of Higgs properties requires to keep under control uncertainties associated to other EW parameters!**
  - We studied the impact of the EW uncertainties adding to the global Higgs + EW fit a global EFT study of WW at future lepton colliders

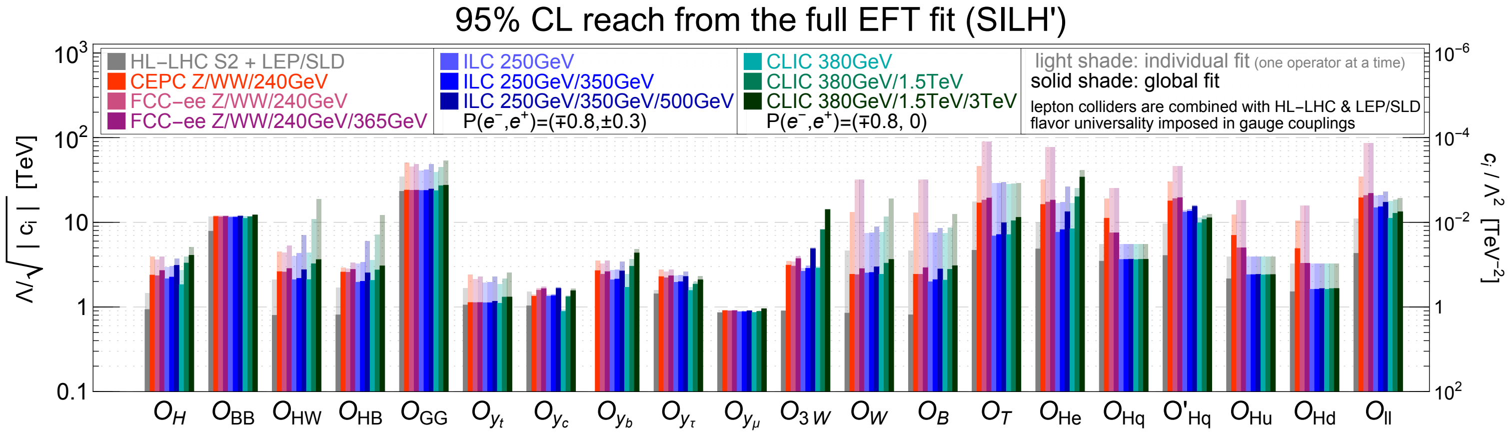
- **Next step:** Fully global Higgs + EW+ Diboson + Top fit

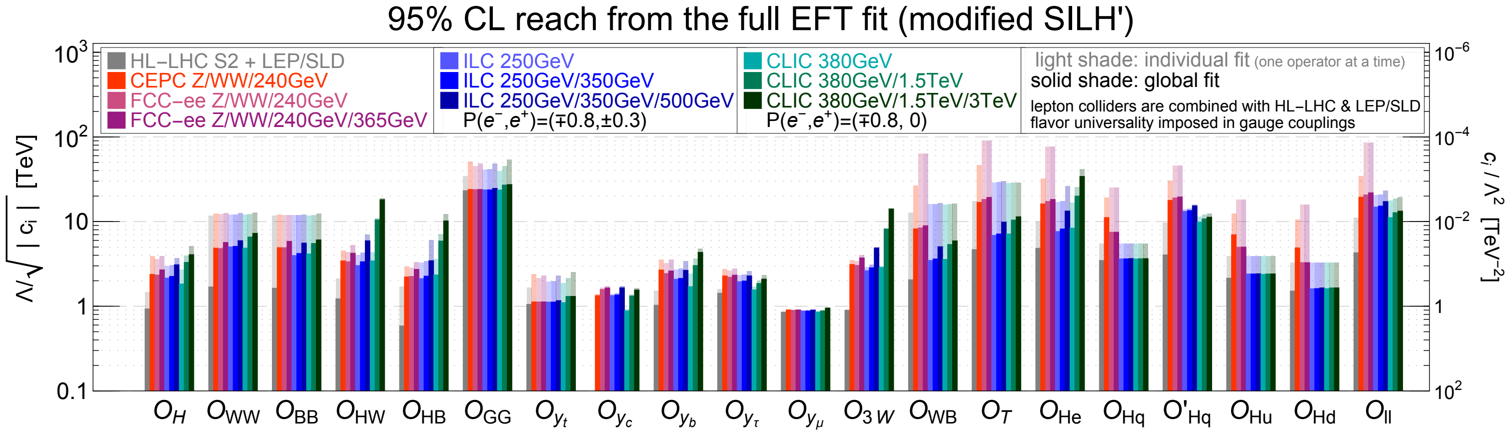
Backup slides

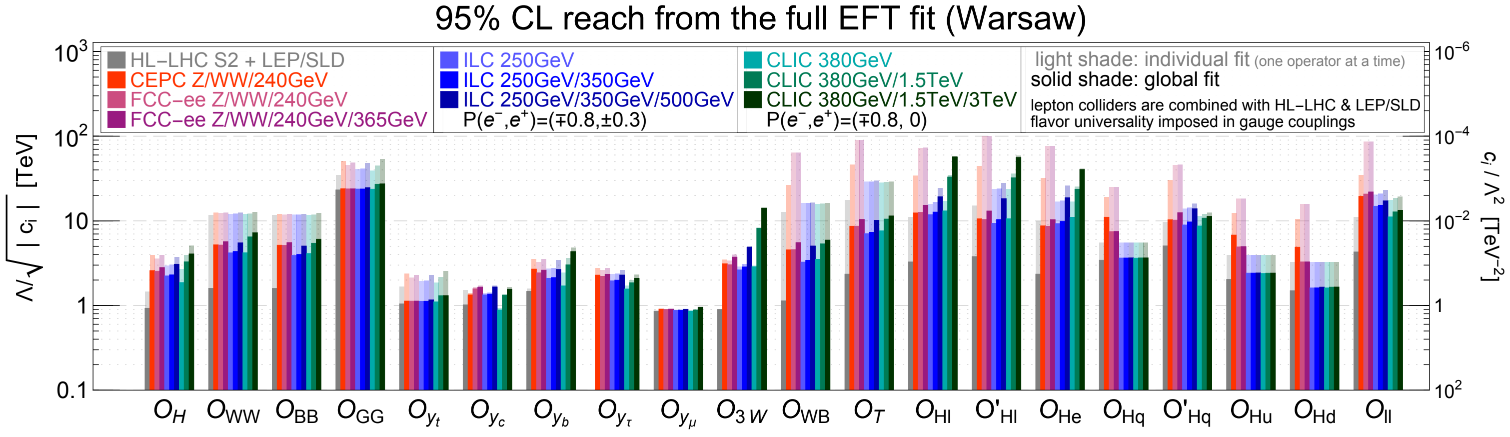
Other EFT results

Other EFT results

Results in manifestly gauge-invariant dim-6 bases


95% CL reach from the full EFT fit (SILH')


95% CL reach from the full EFT fit (modified SILH')


95% CL reach from the full EFT fit (Warsaw)

Notation

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

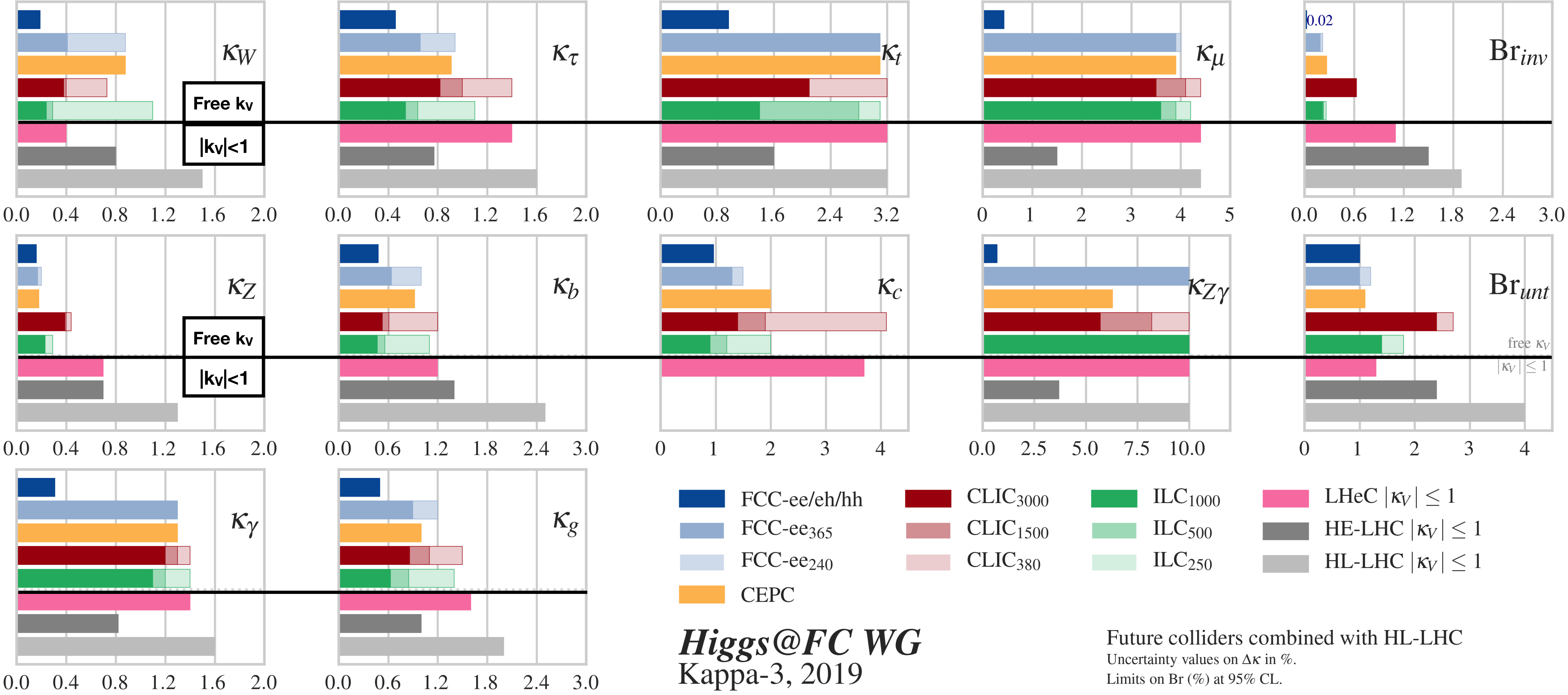
Fits assuming flavour universality in O_{Hf} and O'_{Hf}

Results from Higgs@Future Colliders WG (ESPP)

JB, et al., arXiv:1905.03764 [hep-ph]

Single Higgs couplings

Results in the κ-framework

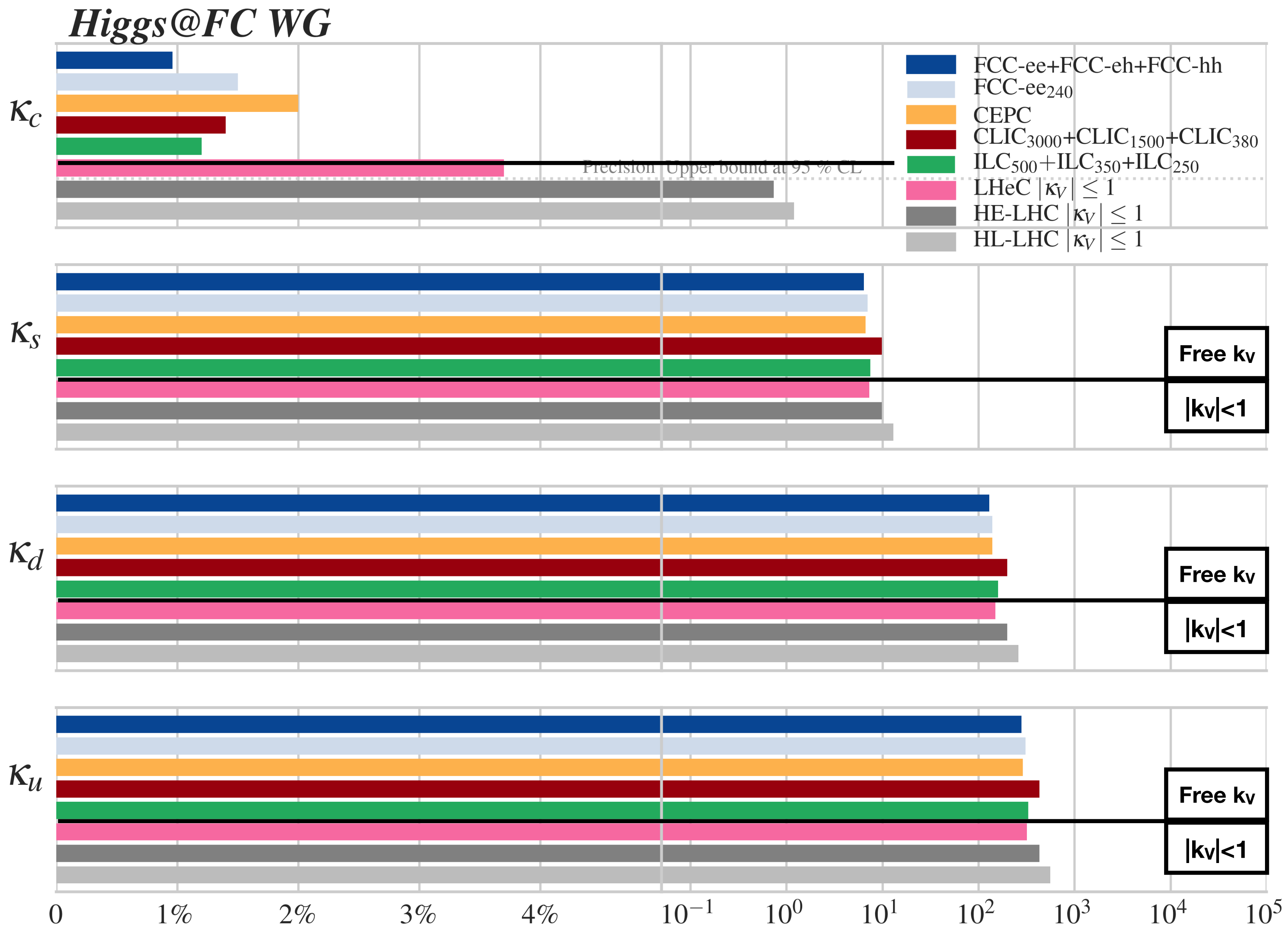


Allowing for extra invisible or other exotic (untagged) H decays

-**WARNING:** Hadron collider results assume $|k_V|<1$
<u>No assumption needed when including a lepton collider</u>

Single Higgs couplings

Results in the κ-framework: Rare decays - Light quark Yukawa couplings



Limits extracted from the bound on BR$_{\text{unt}}$ in the Kappa-3 fit

-WARNING: Hadron collider results assume |kV|<1

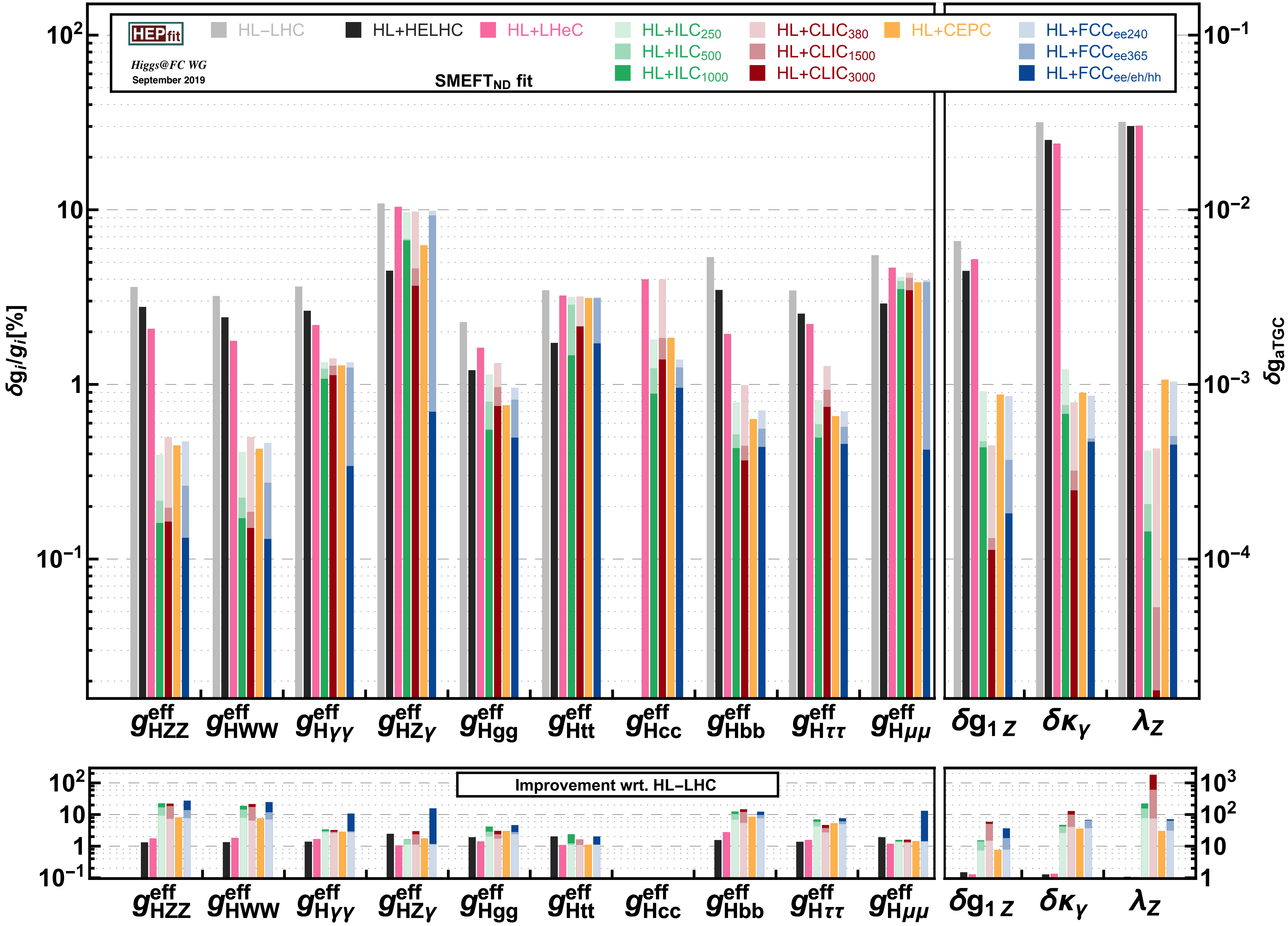
No assumption needed when including a lepton collider

Single Higgs couplings

Results in the SMEFT-framework (Higgs/aTGC)

EFT results projected into effective Higgs couplings and aTGC

$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}$$



Single Higgs couplings

Results in the SMEFT-framework (Higgs)

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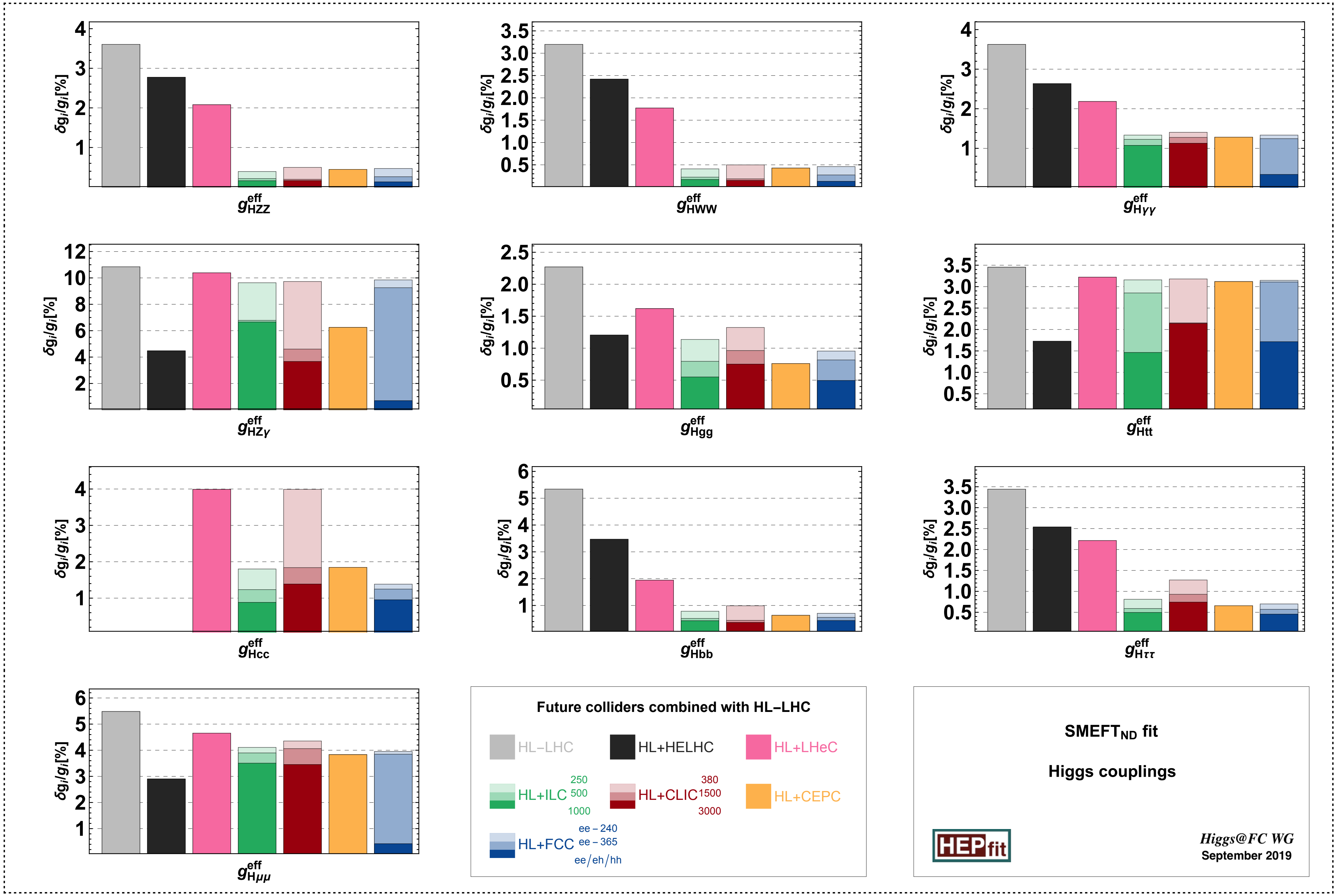
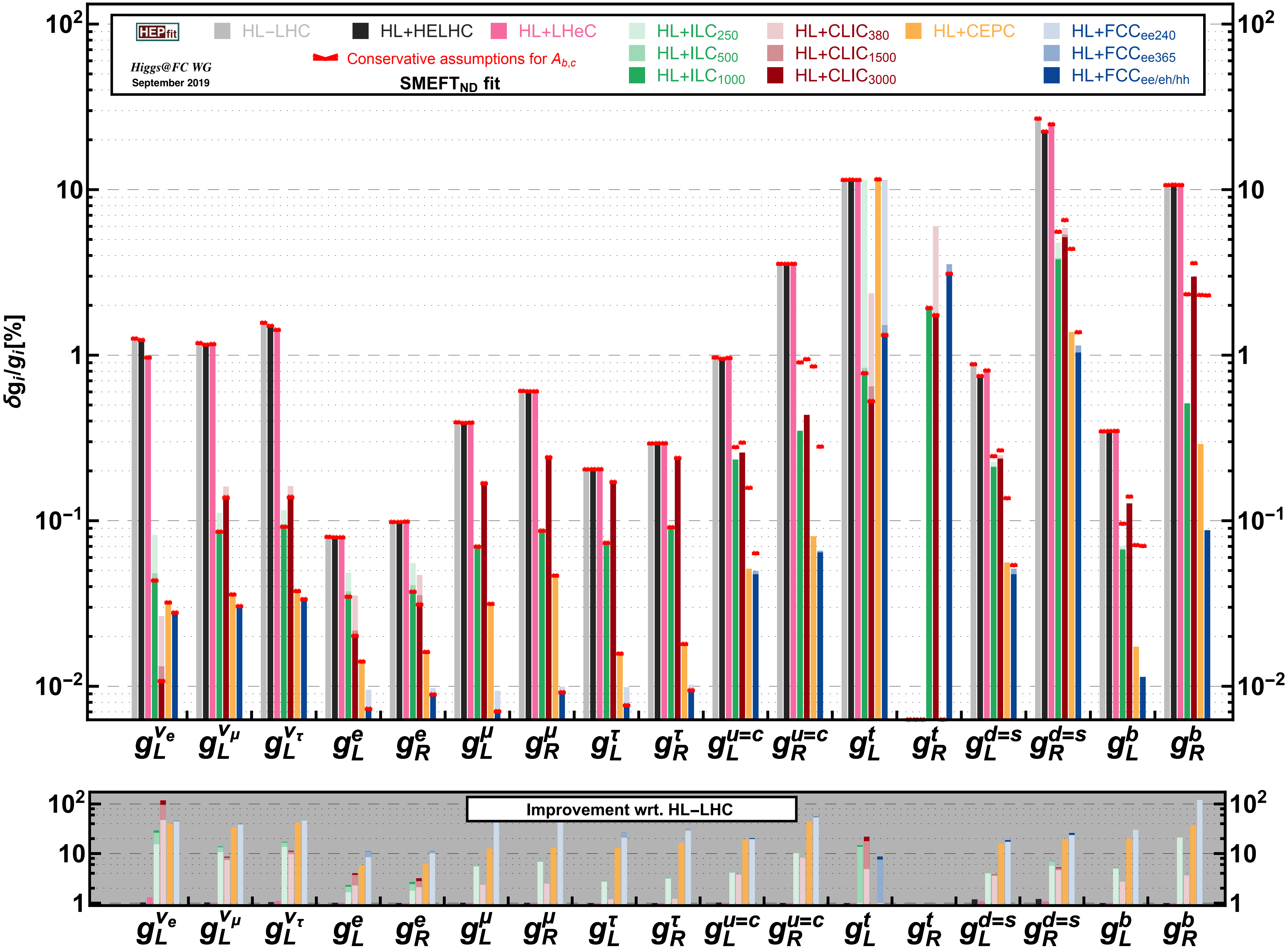


Sensitivity to NP in EW interactions

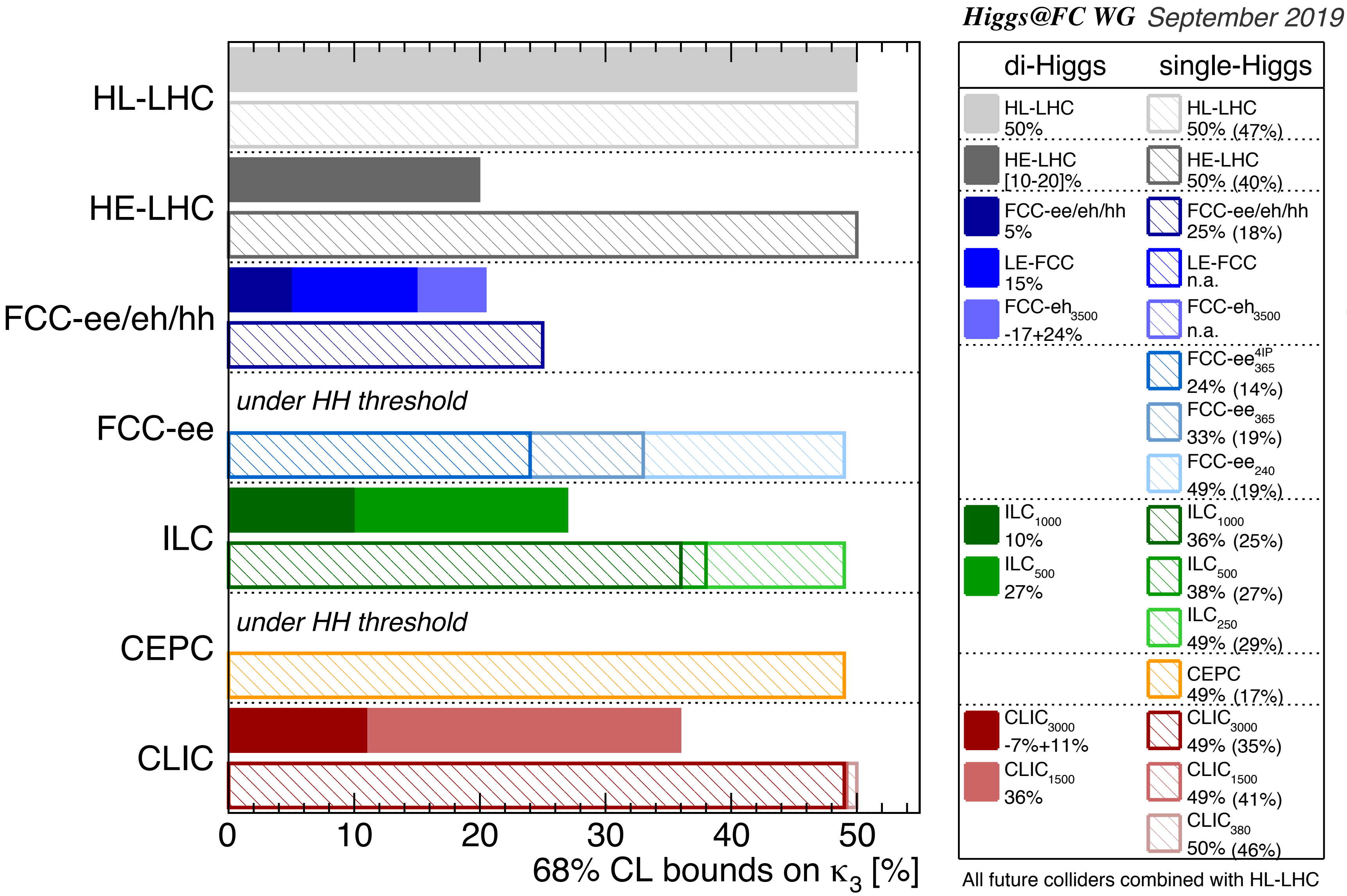
The other "half" of the SMEFT fit: EW Zff couplings

EFT results projected into effective Zff couplings



The Higgs self-coupling

- **Comparison of capabilities to measure the H³ coupling**



HL-LHC di-Higgs ~50%

HE-LHC di-Higgs ~15%

ee: single-Higgs ~34%
hh: di-Higgs ~5-10%

Little sensitivity via single-Higgs w/o 365 GeV run

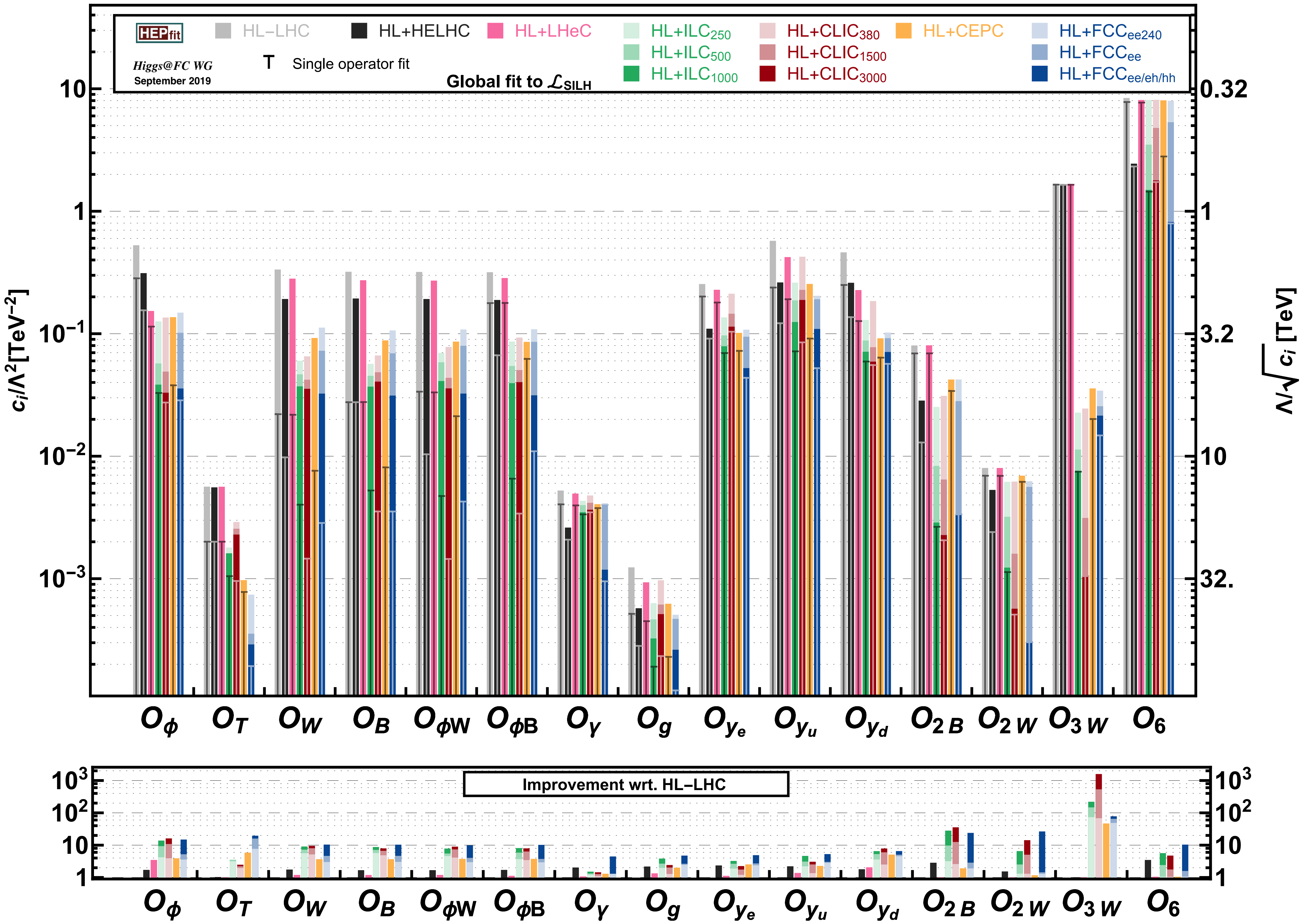
di-Higgs ~10%

di-Higgs ~27% (10%)
Assuming upgrade to 500 GeV (1000 GeV)

Indirect constraints on Composite Higgs

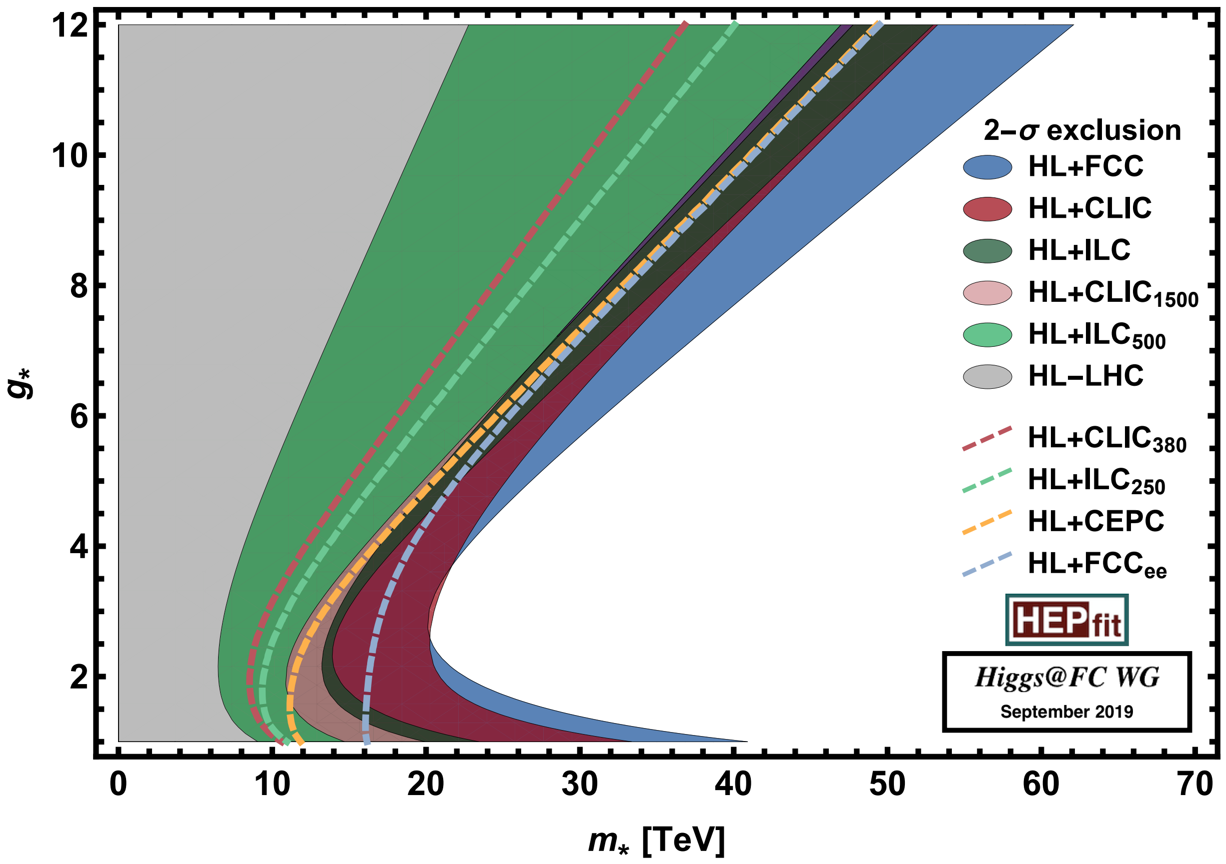
Constraints on SILH effective Lagrangian

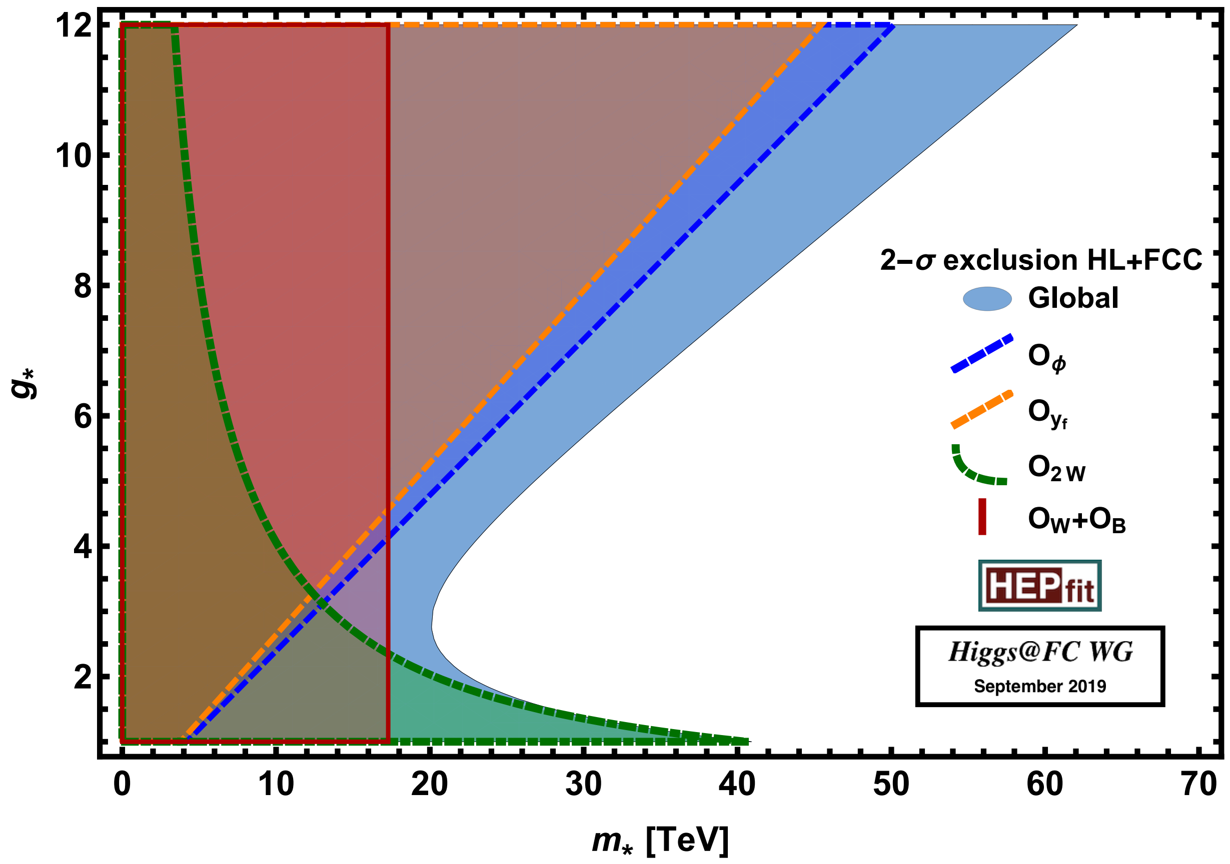
Including extra fit inputs: High-E probes of new physics



Indirect constraints on Composite Higgs

Projecting into simple Composite Higgs scenarios





Simplified CH benchmark: 1 coupling (g_*) - 1 scale (m_*)

$$\frac{c_{\phi,6,y_f}}{\Lambda^2} = \frac{g_\star^2}{m_\star^2}, \qquad \frac{c_{W,B}}{\Lambda^2} = \frac{1}{m_\star^2}, \qquad \frac{c_{2W,2B,2G}}{\Lambda^2} = \frac{1}{g_\star^2}\frac{1}{m_\star^2},$$

$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{3W,3G}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

The role of theory

Will SM theory calculations be enough?

Estimates for SM theory uncertainties used in the ESU studies

Decay	Partial width [keV]	Projected future unc. $\Delta\Gamma/\Gamma$ [%]			
		$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_{\mathrm{H}})$
$H \to b\bar{b}$	2379	0.2	0.6[♭]	< 0.1[♯]	–
$H \to \tau^+\tau^-$	256	< 0.1	–	–	–
$H \to c\bar{c}$	118	0.2	1.0[♭]	< 0.1[♯]	–
$H \to \mu^+\mu^-$	0.89	< 0.1	–	–	–
$H \to WW^*$	883	$\lesssim 0.4$	–	–	0.1[‡]
$H \to gg$	335	1.0	–	0.5[♯]	–
$H \to ZZ^*$	108	$\lesssim 0.3$[†]	–	–	0.1[‡]
$H \to \gamma\gamma$	–	< 1.0	–	–	–
$H \to Z\gamma$	2.1	1.0	–	–	0.1[‡]

[†] From $e^+e^- \to ZH$.

[‡] For $\delta M_H = 10$ MeV. Adjusted for Higgs mass precision at CLIC.

[♭] For $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV. (Lattice projection).

[♯] For $\delta\alpha_s = 0.0002$. (Lattice projection).

A. Freitas et al., arXiv: 1906.05379 [hep-ph]

Intrinsic TH unc in production

e.g. $e^+ e^- \to Z\, H$

LO to NLO: 5-10%

Missing 2-loop: O(1%)

Full 2-loop should reduce uncertainty to O(0.1%)

Z width effects relevant at this level of precision?

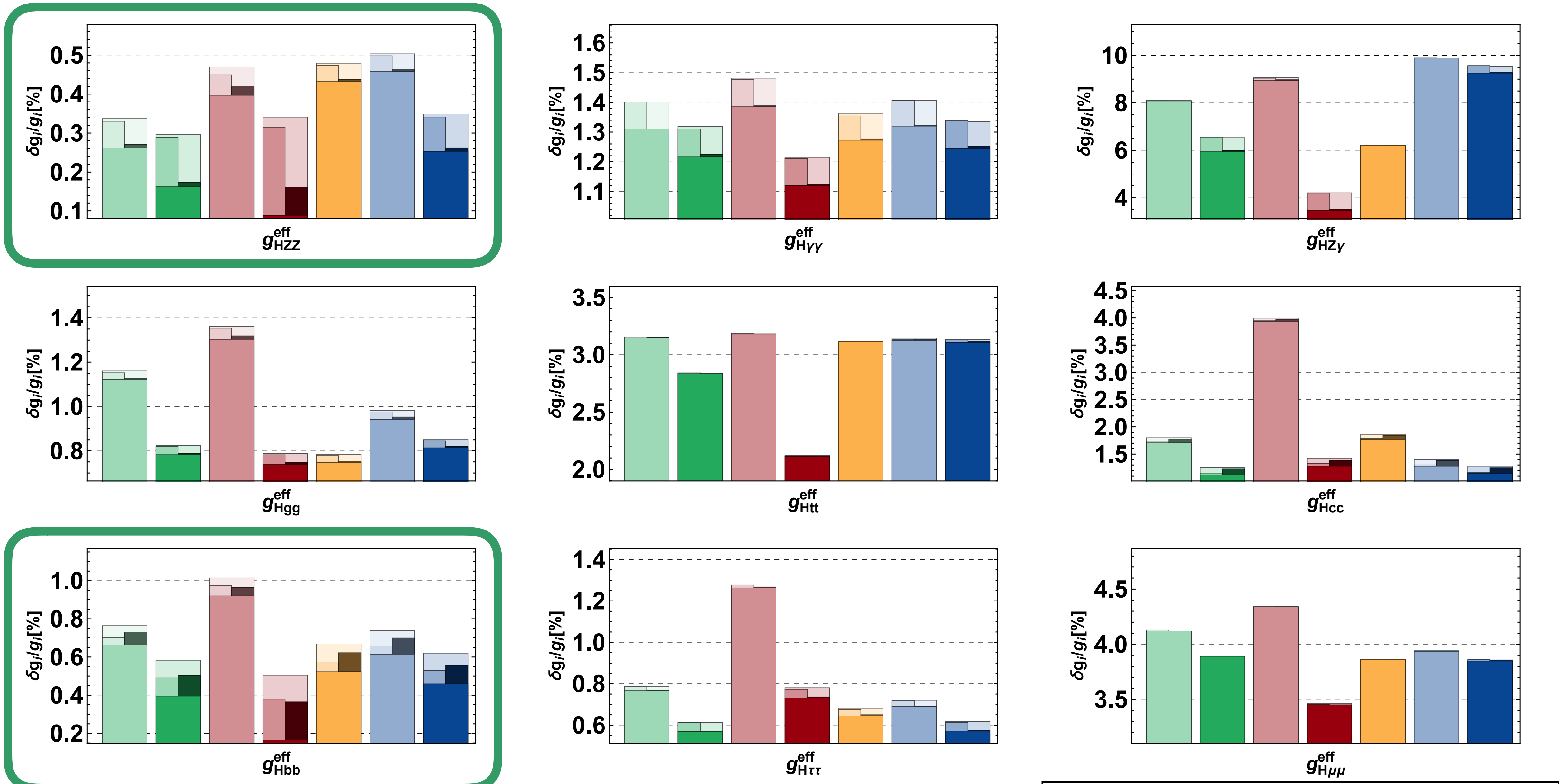
Assessment of TH uncertainty may require full 2->3 NNLO

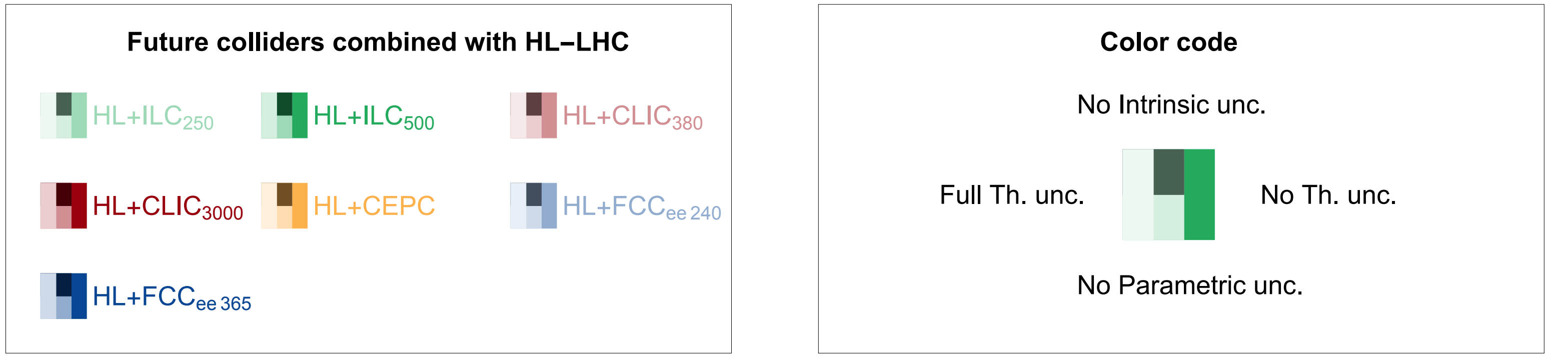
In any case, reducible with necessary effort from theory side

Hence the choice of presenting main results with parametrics only

Will SM theory calculations be enough?

Comparison of SM Theory uncertainties in Higgs calculations





Largest effect on HVV couplings

Differences in other couplings mainly due to unc. in production

Exception: Hbb

Will SM theory calculations be enough?

Theory requirements for EWPO

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	–	0.1			
$\Delta \Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta_{\rm eff}^{\ell}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

A. Freitas et al., arXiv: 1906.05379 [hep-ph]

Current: Full 2-loop corrections
(Not enough for future Exp. precision)

⇩

Prospects: Extrapolation assuming EW & QCD 3-loop corrections are known

Technically challenging
but feasible (with enough support)

Still a limiting factor… Example: Reach on oblique parameters S & T

Oblique parameters:

NP modifying gauge boson self-energies

$$\alpha S = 4e^2\left[\Pi_{33}^{\rm NP\,\prime}(0) - \Pi_{3Q}^{\rm NP\,\prime}(0)\right]$$

$$\alpha T = \frac{e^2}{s_W^2 c_W^2 M_Z^2}\left[\Pi_{11}^{\rm NP}(0) - \Pi_{33}^{\rm NP}(0)\right]$$

+ W & Y at LO in heavy NP expansion (arXiv: hep-ph/0405040)
(Assumed to be ~0 here)