On the future of Higgs, electroweak and diboson measurements at lepton colliders

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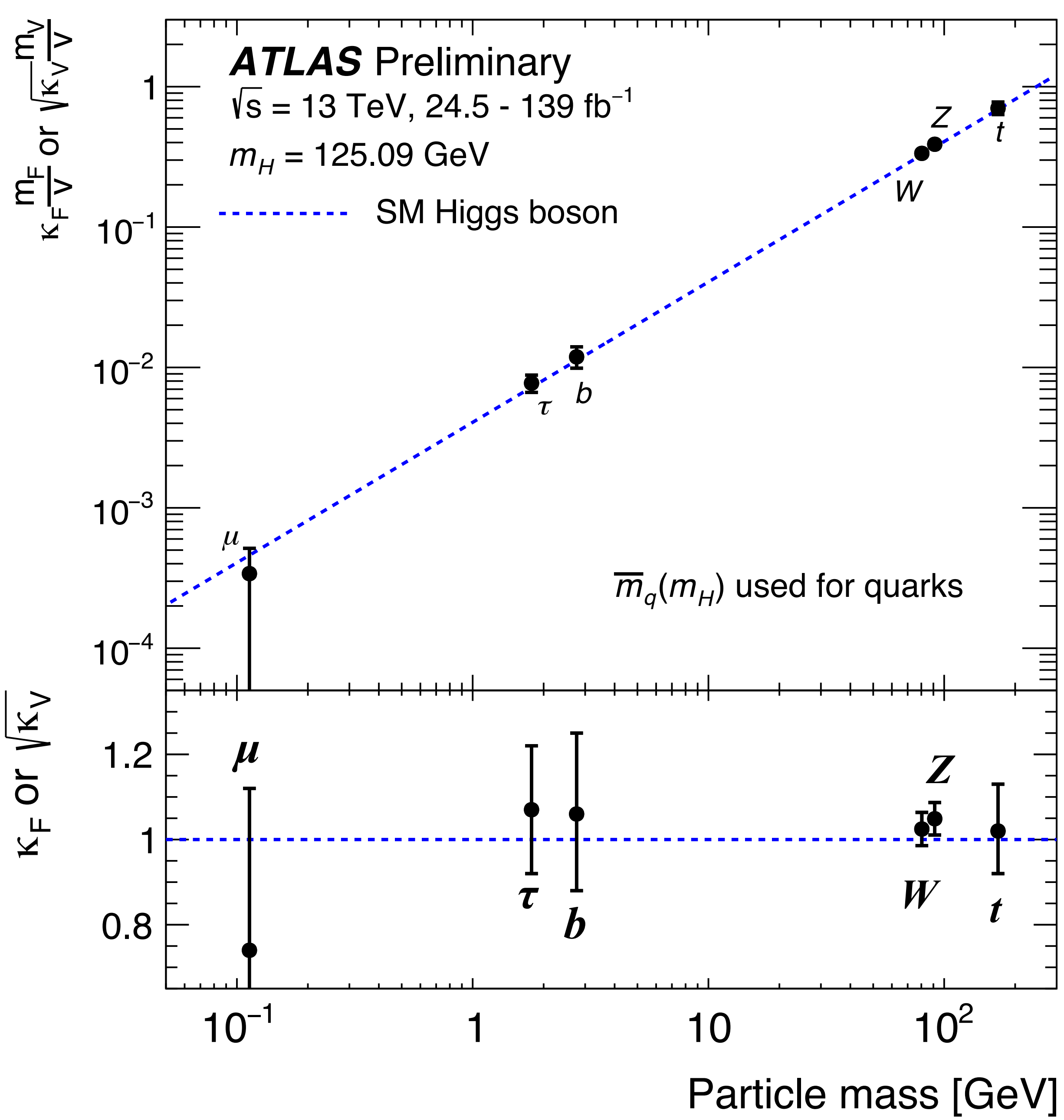
Based on *J.B., G. Durieux, C. Grojean, J. Gu and A. Paul,* JHEP12 (2019) 117
(arXiv:1907.04311 [hep-ph])

Introduction

- The discovery of a Higgs-like boson in 2012 provided experimental confirmation of the last particle predicted by the SM…



- So far, its properties also seem to be very SM-like… to ~10-20% accuracy.

- This precision, however, is still not enough to learn too much about possible sources of New Physics (NP)…

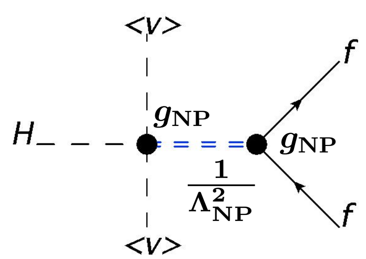
Introduction

- Indeed, the measurements of the Higgs properties have not provided much information (constraints) on New Physics yet:

$\left.\frac{\delta g_h}{g_h}\right|_{\rm LHC} \sim O(10\text{ - }20)\%$

Typical BSM deformation: $\frac{\delta g_h}{g_h} \sim \frac{g_{\rm NP}^2 v^2}{\Lambda_{\rm NP}^2} \Longrightarrow \Lambda_{\rm NP} \gtrsim 500\,\frac{g_{\rm NP}}{g_{\rm SM}}\ {\rm GeV}$

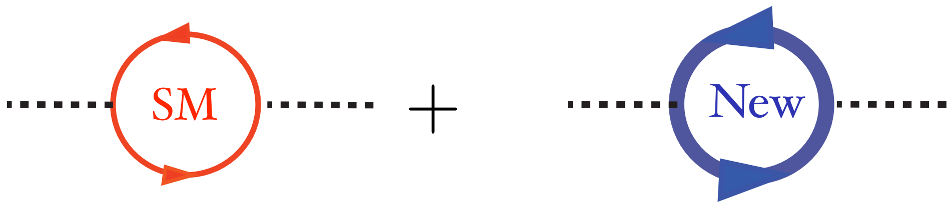
E.g.



Not better than direct searches
(unless NP is strongly coupled)

- Higgs couplings also provide information about Naturalness:

$\delta m_H^2 \;=$



$\sim\ 0$

R. Rattazzi's talk at
ESU symposium, Granada

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning}$$

⇒ Higgs precision physics is a key tool to learn from BSM

Introduction

- Therefore, a key component of the physics program at **future particle colliders** has revolved around the possible improvements on the knowledge of **properties of the Higgs** …

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- One should however not forget about improving our measurements of the properties of the other particles of the **EW sector**:

Electroweak Precision Observables (EWPO)

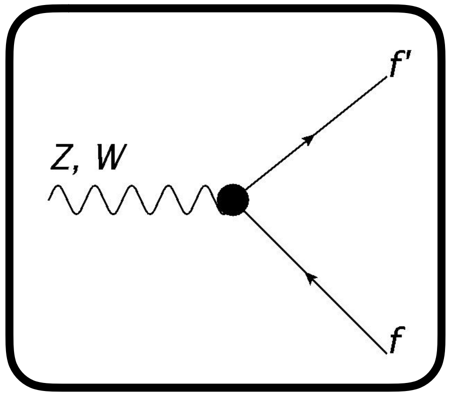
Measurements of cross sections and asymmetries, coming mostly from e^+e^- colliders (LEP/SLD)

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

Z-pole obs. (SLD/LEP)
0.002-$\mathcal{O}(1)$%

$$M_W,\ \Gamma_W$$

W obs. (LEP2, Tevatron, LHC)
0.02-$\mathcal{O}(1)$%



Provide precise measurements of properties (mass & couplings) of the W & Z bosons

Introduction

- Therefore, a key component of the physics program at **future particle colliders** has revolved around the possible improvements on the knowledge of **properties of the Higgs** …

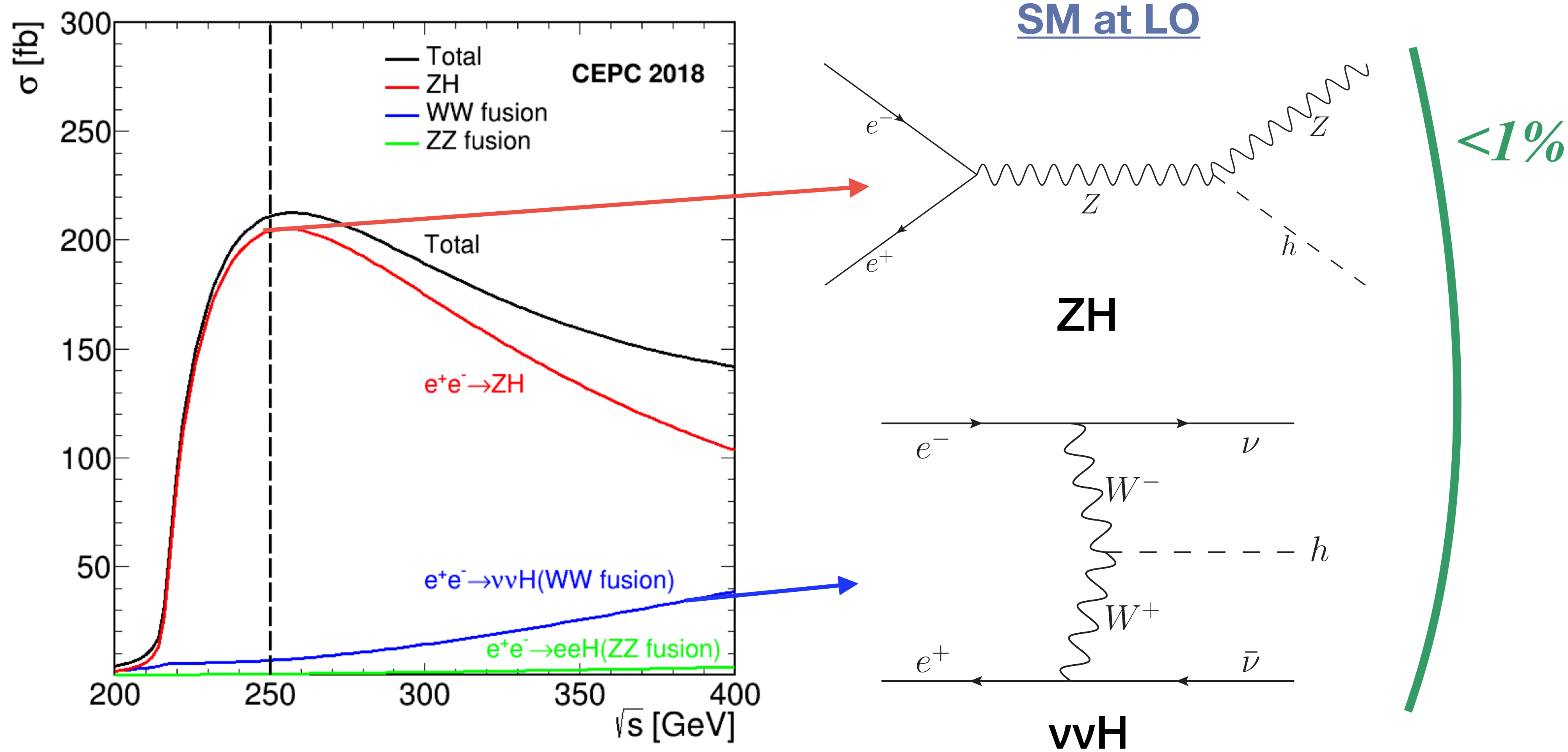
- One should however not forget about improving our measurements of the properties of the other particles of the **EW sector**:

  - …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

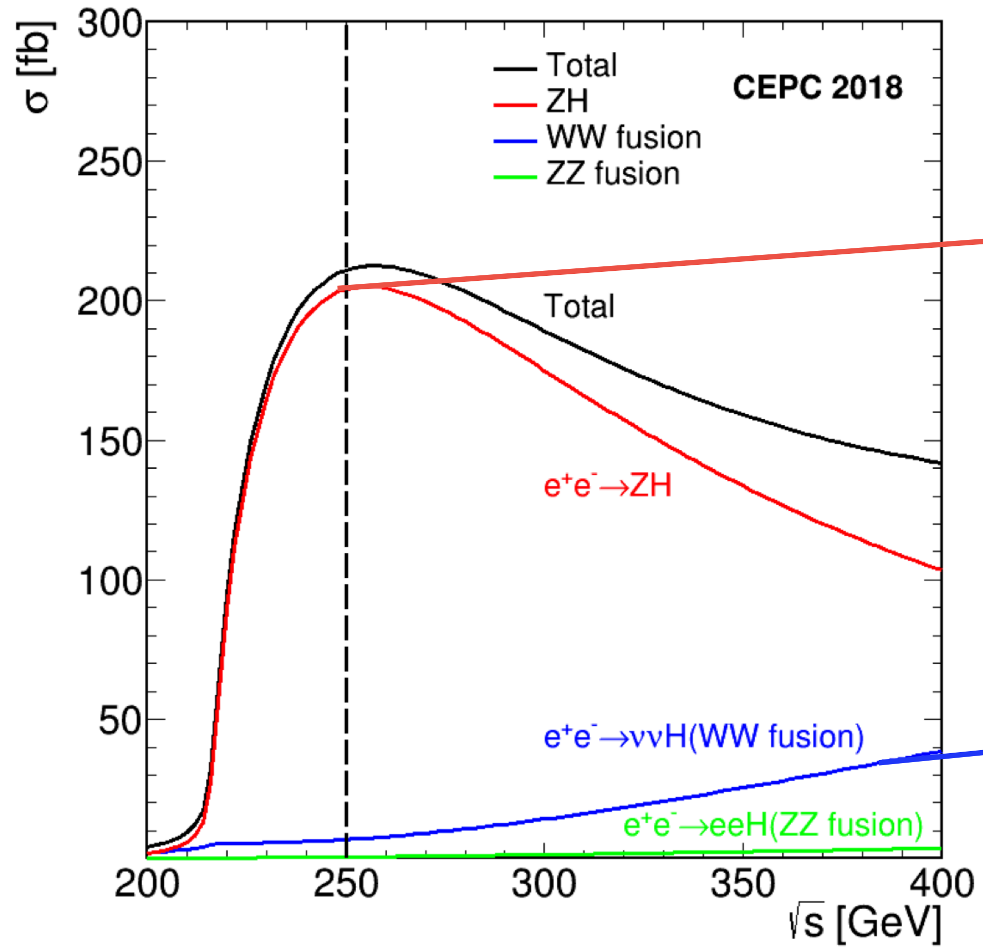
SM at LO

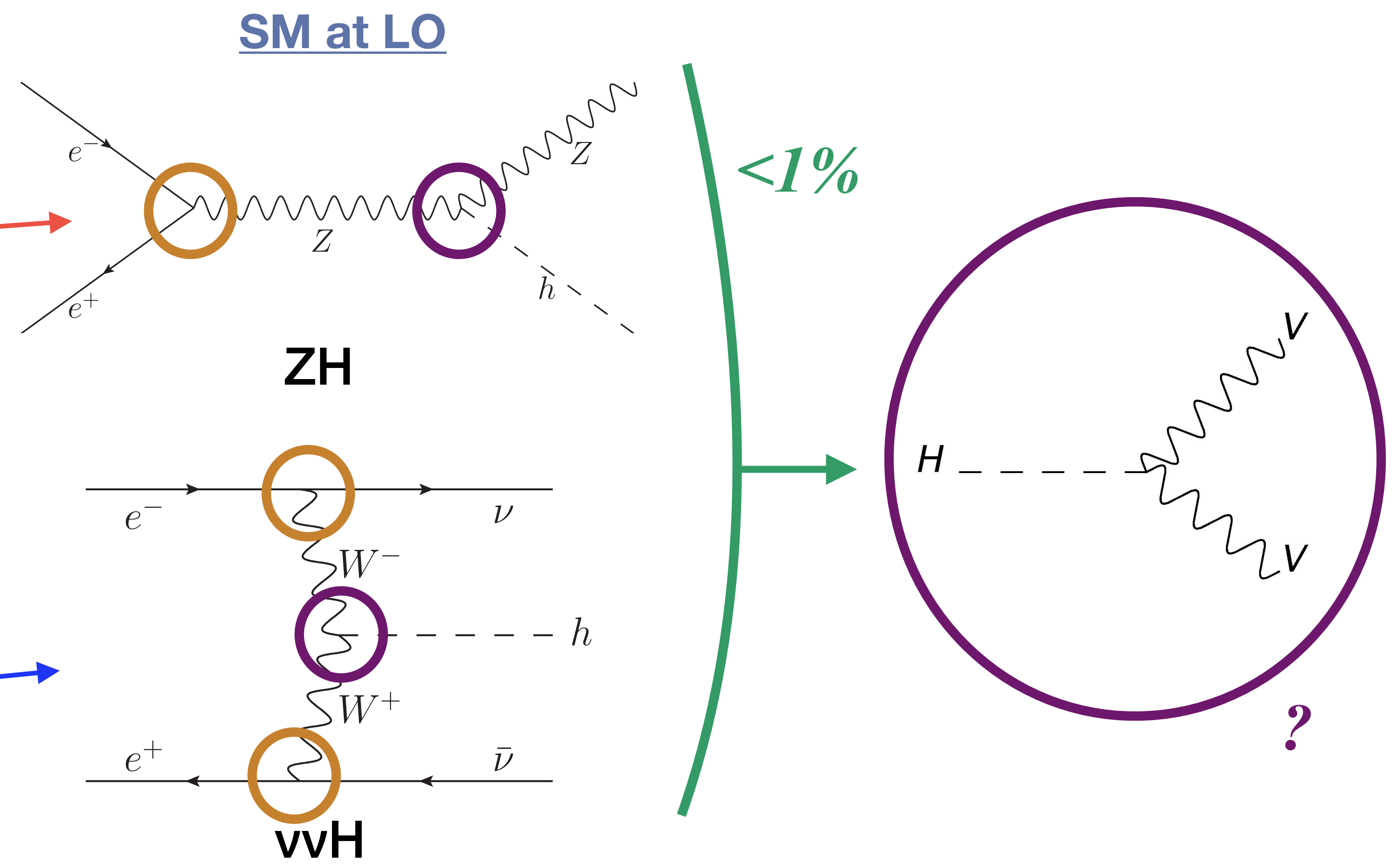


- Precision of **Higgs measurements** expected to be close to per mille level in several cases

Introduction

Higgs production at "low-energy" lepton colliders

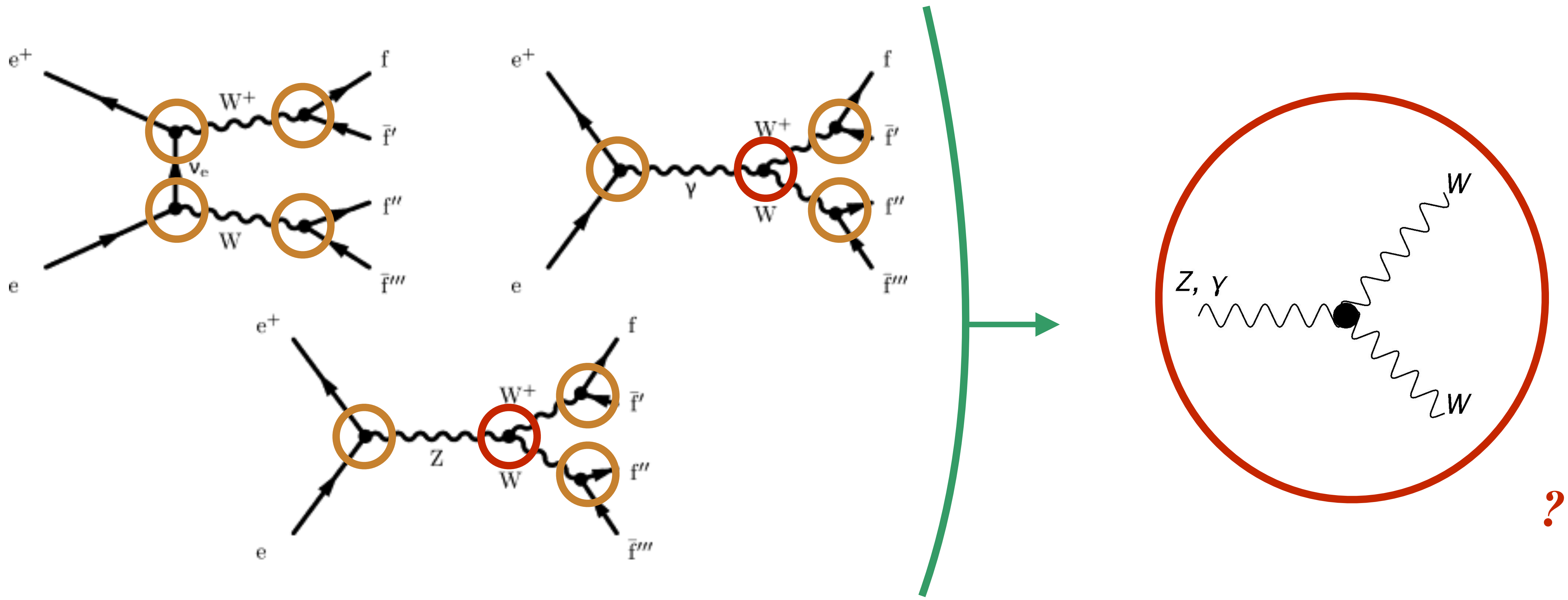




- Precision of **Higgs measurements** expected to be close to per mille level in several cases
- Is the knowledge of the **EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **Higgs properties**?
- To answer this, first we need to set the (B)SM interpretation "framework"

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

- Two possible approaches to compare **indirect sensitivity to BSM**:

Look at Specific Models:
SUSY, Composite Higgs, …

Too many models
+
No experimental indication favoring any particular scenario

Look at Model-Independent deformations of SM interactions

- We will follow the **model-independent** approach using an EFT:

Theory framework

- **The dimension 6 SMEFT:**
  - SM Particles and Symmetries at Low-energies. Assume H in SU(2) doublet
  - Expansion in canonical mass dimension

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

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

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

- Describes correlations of BSM effects in different types of observables,

Example:

$\mathcal{O}_{\phi WB} = \phi^\dagger \sigma_a \phi B^{\mu\nu} W^a_{\mu\nu}$ → EWSB →

- $v^2 B^{\mu\nu} W^3_{\mu\nu}$ (dim 4): Modifies neutral gauge boson self-energies — EWPO, aTGC
- $vh B^{\mu\nu} W^3_{\mu\nu}$ (dim 5): $h \to ZZ, \gamma\gamma$ — Higgs physics

- **We focus on EW/Higgs:** Assume CP-even. 4-Fermion and dipole operators tested better by other processes (no EW/Higgs) and are neglected.

We also restrict the analysis to flavour preserving processes/interactions

Theory framework

Dimension-6 effects in Higgs/EW physics at LO

Higgs "basis" parameterization: LHCHXSWG-INT-2015-001

HVV

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

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

aTGC

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

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

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

Dimension-6 effects in Higgs/EW physics at LO

HVV

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Only 7 independent parameters

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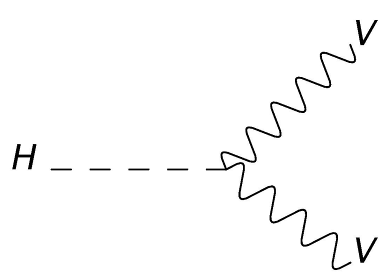
Where to test these?



$H \to VV'$ $\quad pp \to HV$

$gg \to H$ $\quad e^+e^- \to HZ$

(Tree level)

Theory framework

Dimension-6 effects in Higgs/EW physics at LO

Higgs "basis" parameteriza... SWG-INT-2015-001

HVV

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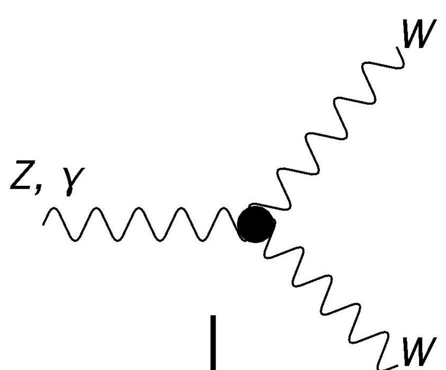
Only λ_z is independent

δg_{1Z} and $\delta\kappa_\gamma$ related to *HVV* couplings



$e^+e^- \to W^+W^-$

$pp \to W^+W^-, WZ, W\gamma$

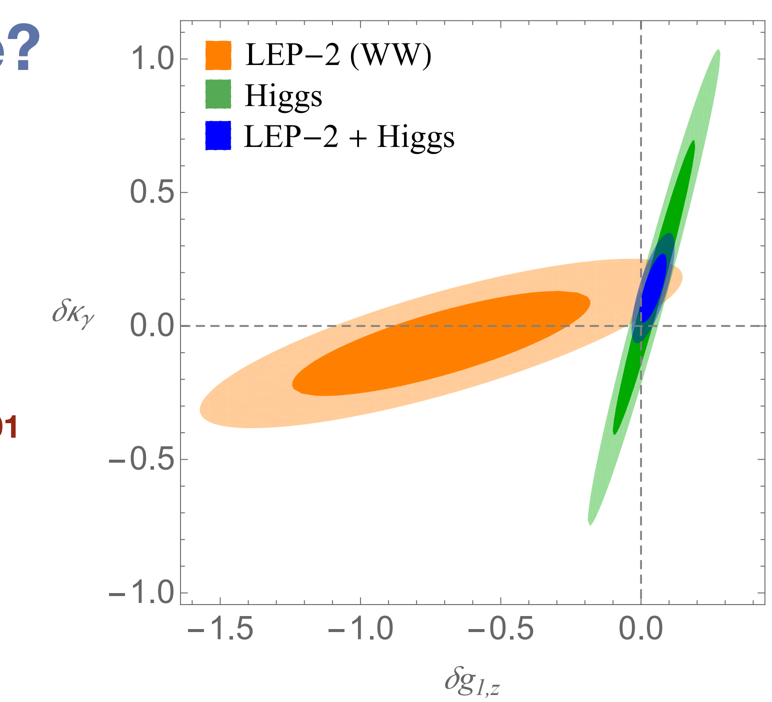
Where to test these?

Complementarity H/aTGC

→

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

(Tree level)



Theory framework

Dimension-6 effects in Higgs/EW physics at LO

Higgs “basis” parameteri... LHCHXSWG-INT-2015-001

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Hff

5 NP parameters ***(t,b,c,τ,μ)***

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

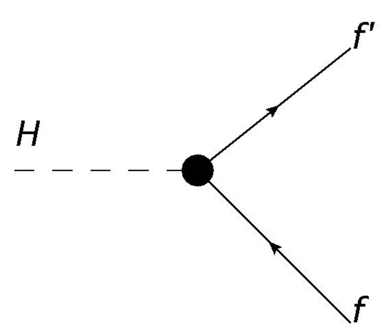
aTGC

$$+\frac{ig^2\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu} W_\nu^{-\rho} A_\rho^\mu + \cos\theta_w W_\mu^{+\nu} W_\nu^{-\rho} Z_\rho^\mu\right),$$

Vff & HVff

$\Delta\mathscr{L}$

Where to test these?



→ $H \to f f'$

$pp \to t\bar{t}H$

$e^+e^- \to t\bar{t}H$

(Tree level)

Theory framework

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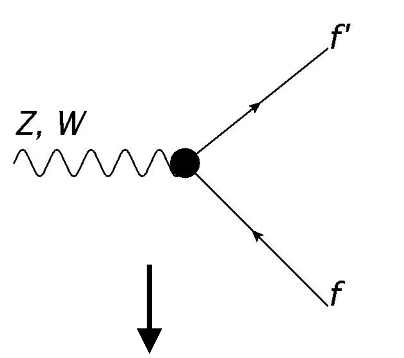
Vff & HVff

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

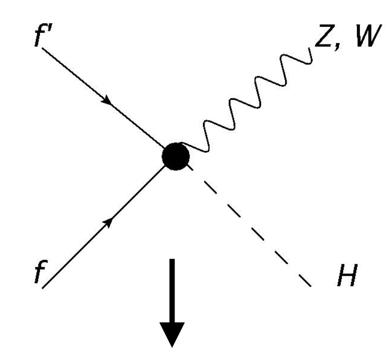
$$\hat{\delta}g_L^{W\ell} = \hat{\delta}g_L^{Z\nu} - \hat{\delta}g_L^{Ze}$$
$$\hat{\delta}g_L^{Wq} = \hat{\delta}g_L^{Zu}V_{CKM} - V_{CKM}\hat{\delta}g_L^{Zd}$$

Where to test these?



$e^+e^- \to Z \to f\bar{f}$

“Same” EFT interaction ⟷



$pp \to HV$ $\quad e^+e^- \to HZ$

(Tree level)

Dimension-6 effects in Higgs/EW physics at LO

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

13 Higgs/VVV

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

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

15 Vff/HVff

5 SM + 28 New Physics Parameters

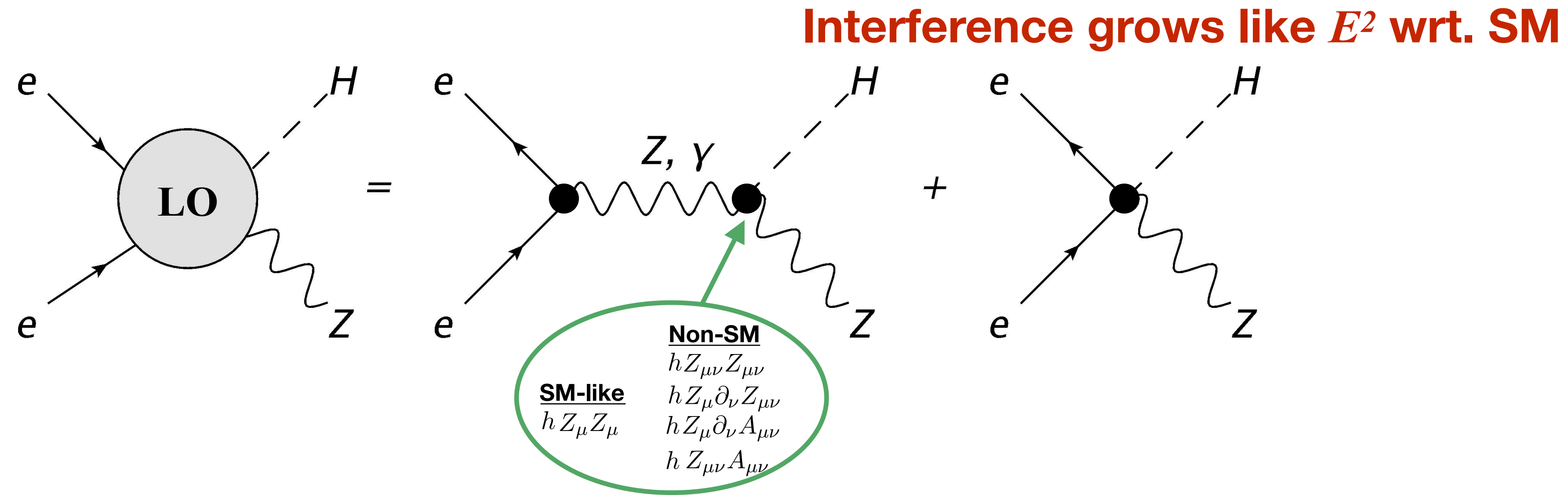
To study the impact of EW measurements in the determination of Higgs properties we will compare with an scenario with "perfect EW" data i.e. EW interactions known to be SM-like with infinite precision:

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

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



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

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

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

Presentation of SMEFT fit results

- Compare Future Collider sensitivity to BSM EW/Higgs deformations in a basis-independent way
  - **Project EFT fit** results from dim-6 Wilson coefficients into (pseudo) observable Higgs **effective couplings**, aTGC and effective *Zff/Wff* couplings defined from EWPO:

Dim 6 Wilson coeffs. **Effective couplings**

$$\frac{C_i}{\Lambda^2} \longrightarrow g_x^{\rm eff} \equiv g_x^{\rm eff}\left(\frac{C_i}{\Lambda^2}\right) = g_x^{\rm eff}\Big|_{\rm SM} + \sum \alpha_i^x \frac{C_i}{\Lambda^2} + O\left(\frac{C^2}{\Lambda^4}\right)$$

Higgs

$$g_H^{X\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\rm SM}}$$

Electroweak

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

SMEFT-fit Results presented in terms of

13 Higgs/VVV

$$\left\{\delta g_H^{ZZ},\ \delta g_H^{WW},\ \delta g_H^{\gamma\gamma},\ \delta g_H^{Z\gamma},\ \delta g_H^{gg},\ \delta g_H^{tt},\ \delta g_H^{cc},\ \delta g_H^{bb},\ \delta g_H^{\tau\tau},\ \delta g_H^{\mu\mu},\ \delta g_{1z}, \delta\kappa_\gamma,\ \lambda_z\right\}$$

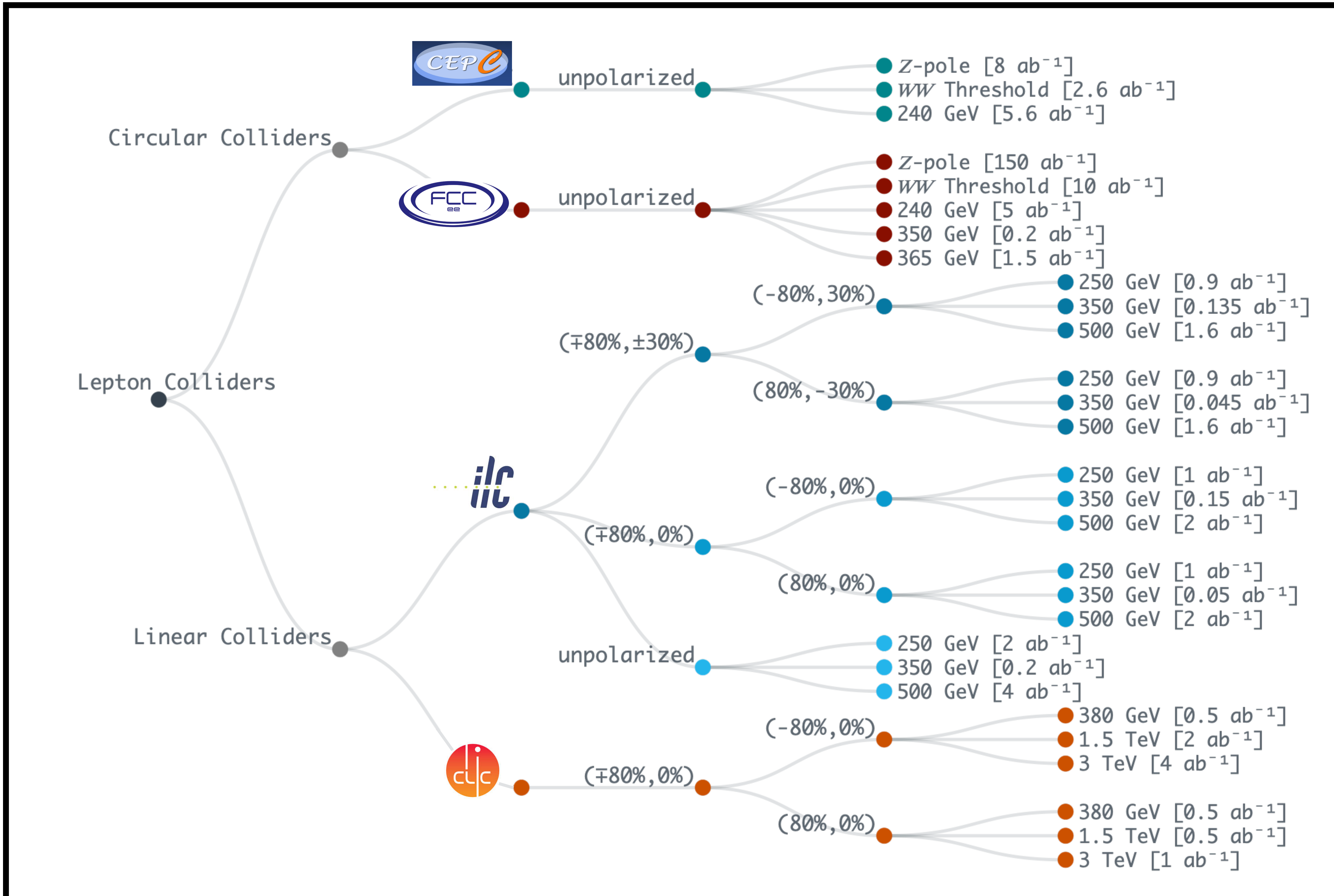
15 Vff/HVff

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

$(q_i \neq t)$

EW/WW/Higgs inputs at future lepton colliders

Future lepton colliders considered in the study



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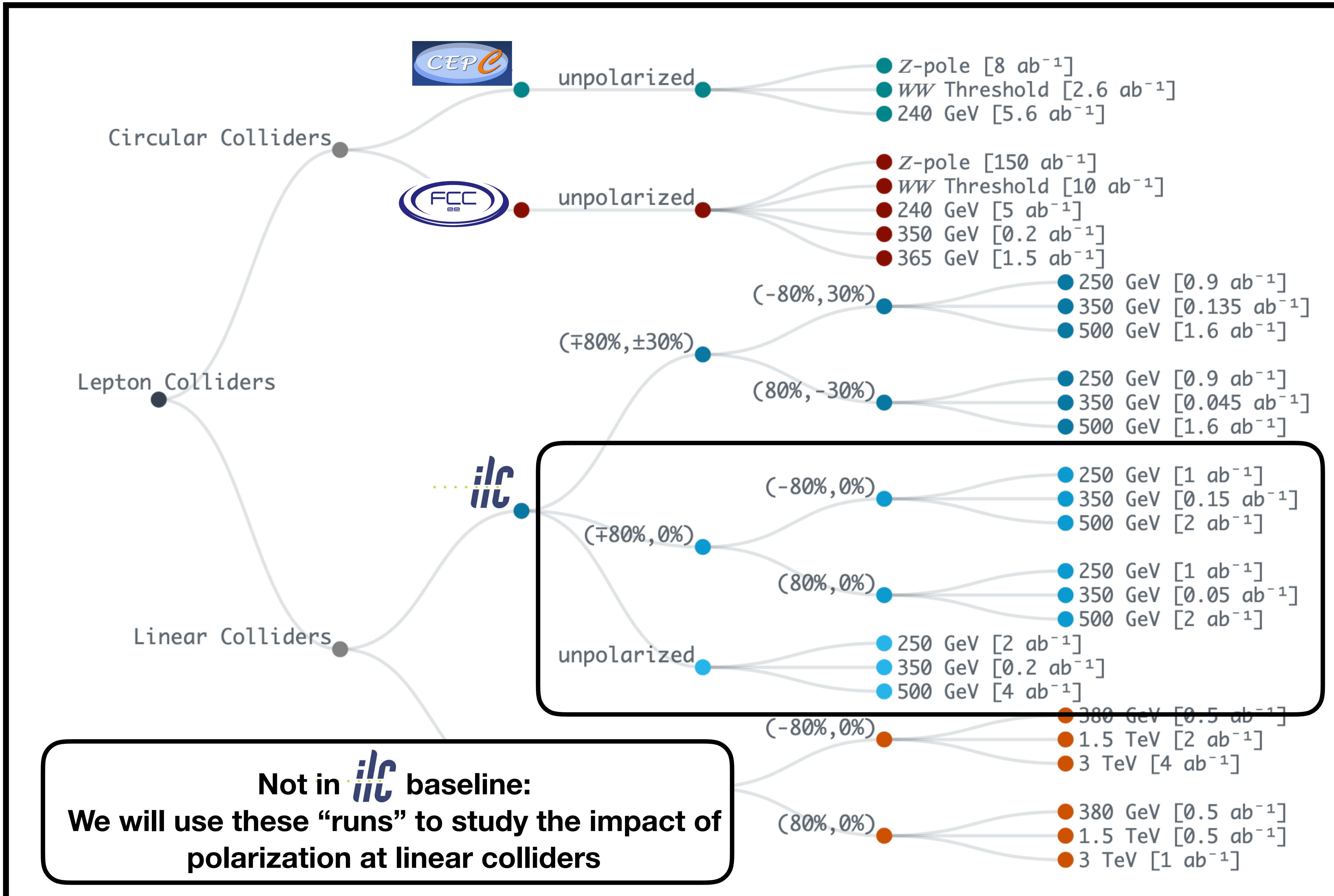

Not in ilc baseline:
We will use these "runs" to study the impact of polarization at linear colliders

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 (Z-pole run)
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 (Z-pole run)
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

Higgs

Rates (signal strength)

$$\mu \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}}}$$

(Inclusive) cross section

$$\sigma_{ZH} \equiv \sigma(e^+e^- \to ZH)$$

Only possible at lepton colliders

aTGC

$$\delta g_{1z}, \delta\kappa_\gamma, \lambda_z$$

EWPO

$$M_Z,\ \Gamma_Z,\ \Gamma_{Z\to f},\ A^f_{FB,LR},\ \ldots$$

$$M_W,\ \Gamma_W,\ \Gamma_{W\to f}$$

Z physics via Z-pole:

$$\sqrt{s} = M_Z: \quad e^+e^- \to Z \to X$$

or Rad. Return:

$$\sqrt{s} > M_Z: \quad e^+e^- \to \gamma Z \to \gamma X$$

Future lepton colliders considered in the study

Official inputs available for Higgs/WW/EW

Higgs

Rates (signal strength)

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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

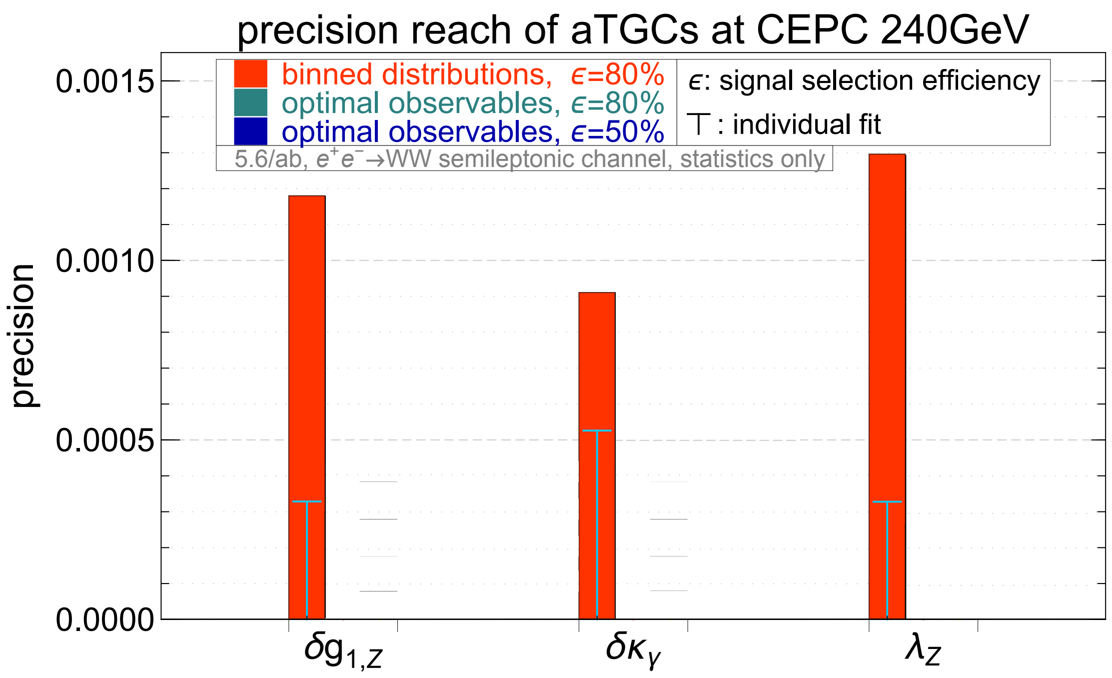
No full EFT studies available for WW processes at future lepton colliders

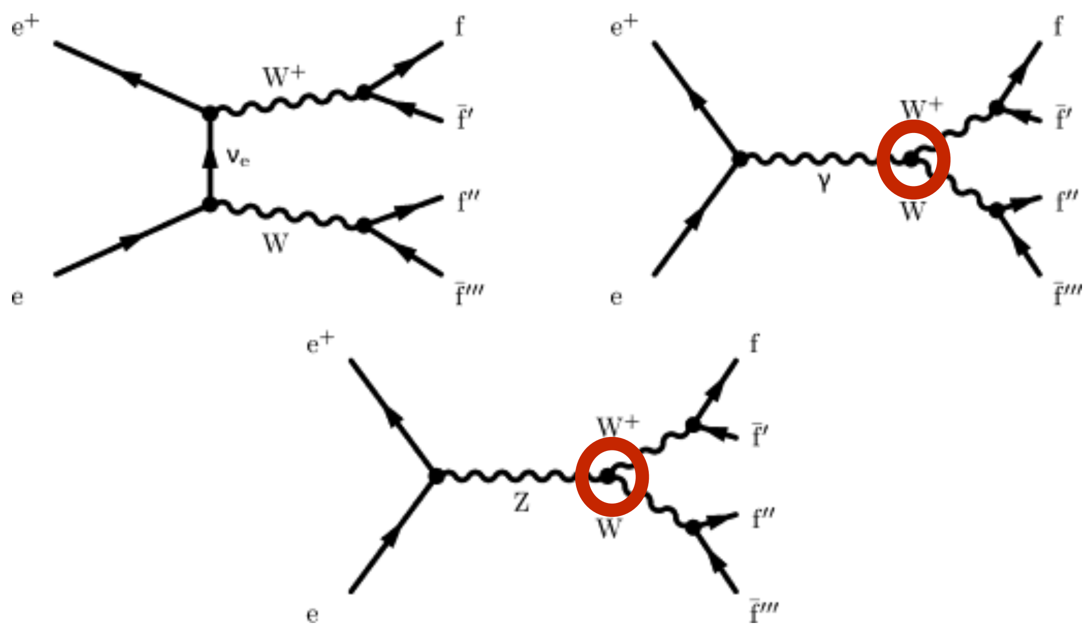
(Except for CLIC, which uses a preliminary version of this study)

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)





WW production at lepton colliders

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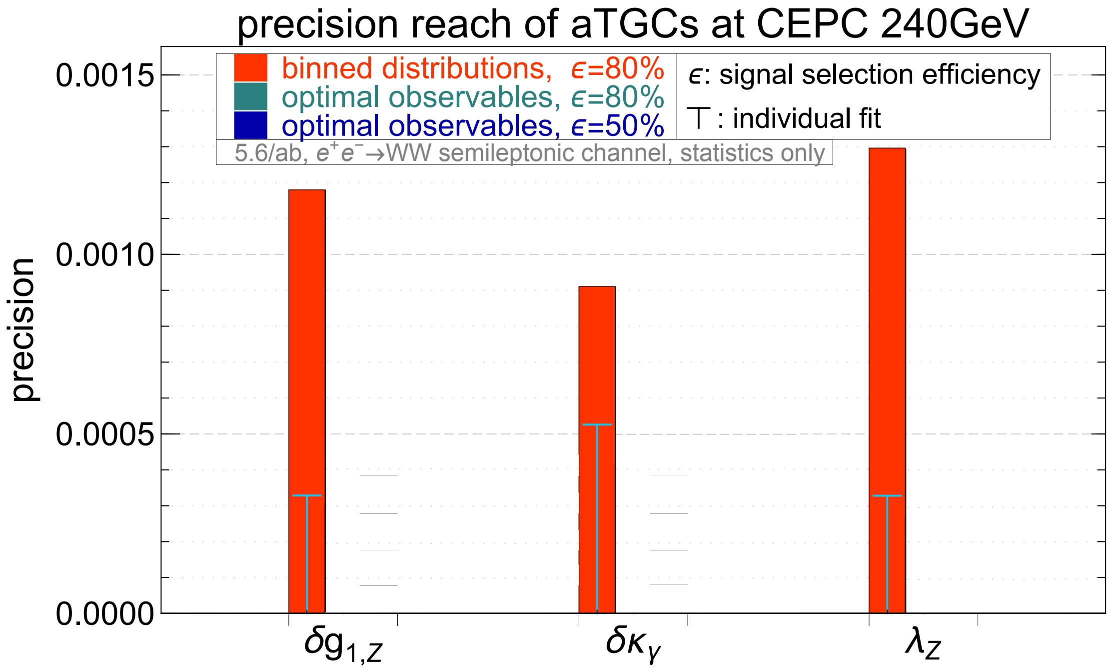
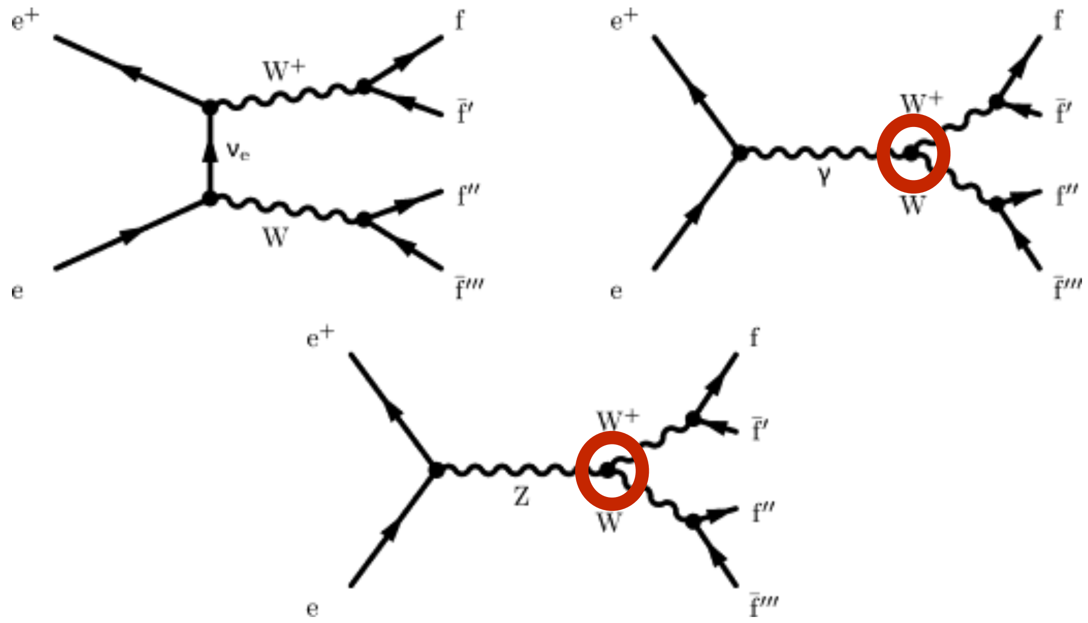




- We prepared a new sensitivity study using full information about each event in the formalism of "optimal statistical observables"

Global EFT study of WW production

Optimal Statistical Observables (OO)

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

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

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

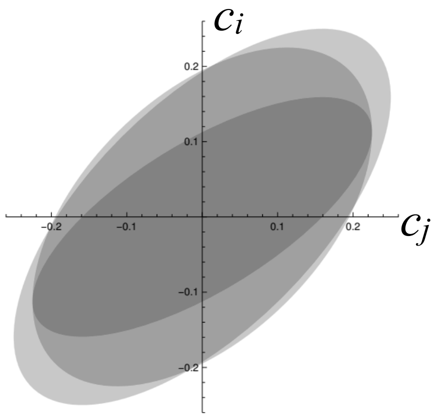
- In the limit of large statistics, the observables

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

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

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

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



OO minimize the volume of the 1-σ ellipsoid

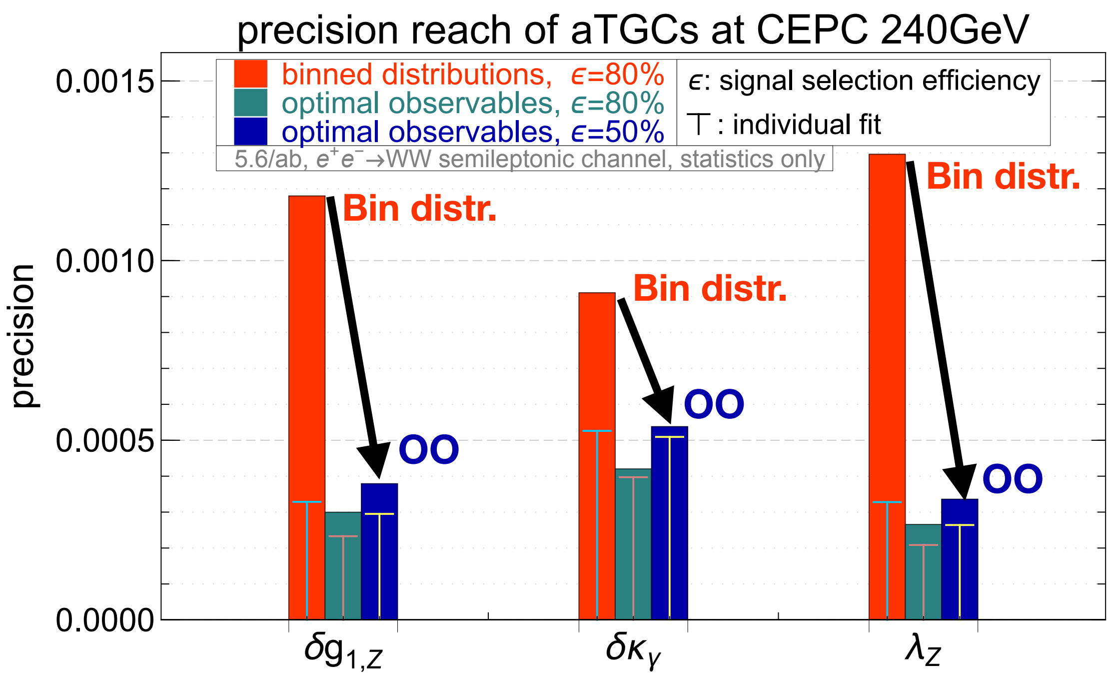
- Idealized (no systematics) ⇒ We compensate omission of systematics via conservative selection efficiency ε

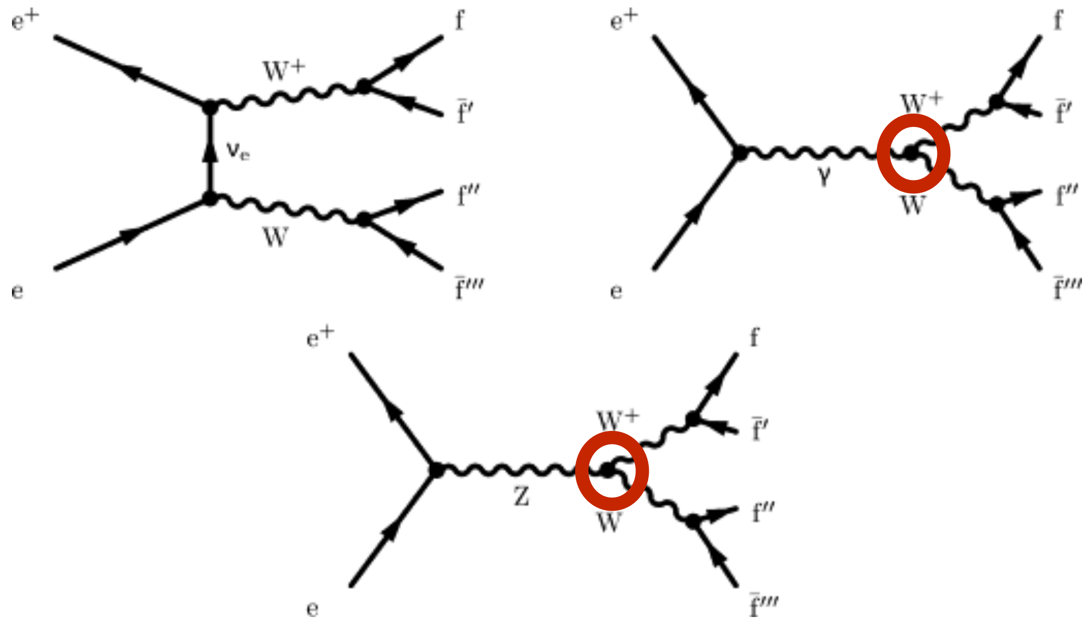
$$\mathcal{L} \longrightarrow \varepsilon \mathcal{L}$$

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)



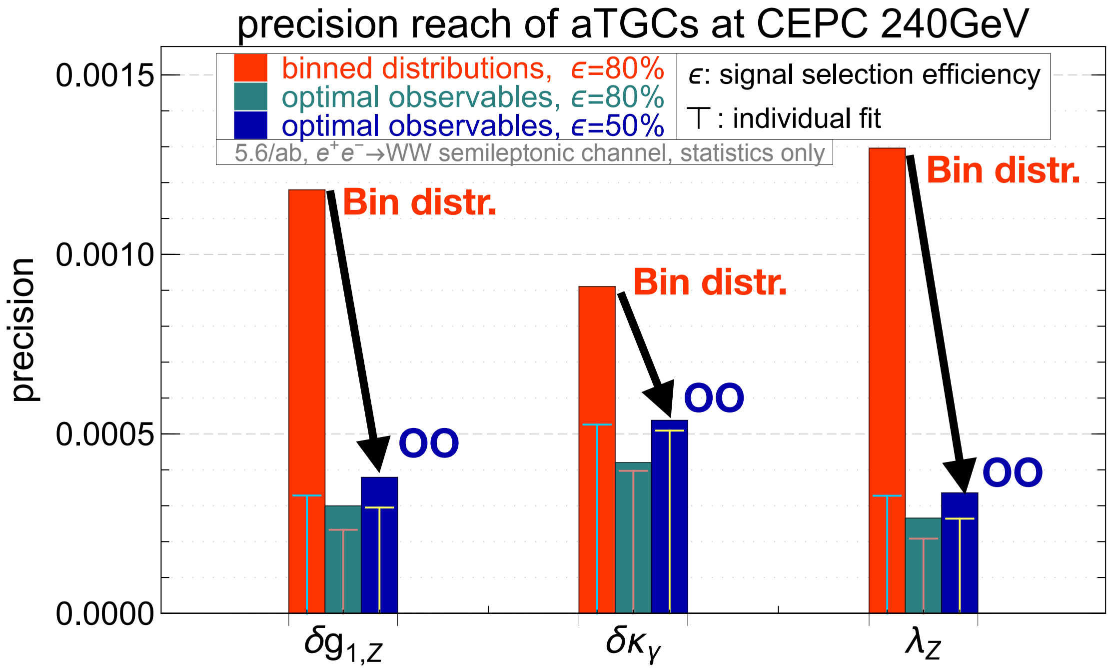


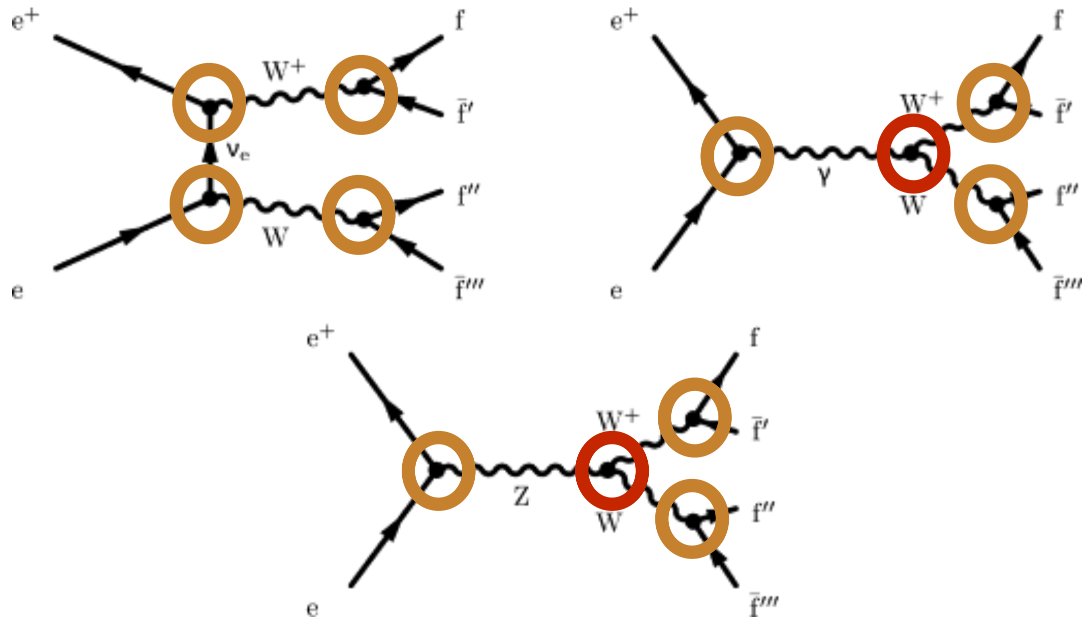
- We prepared a new sensitivity study using full information about each event in the formalism of “optimal statistical observables”
  - Default method only accounts for statistical sensitivity ⇒ Compensate omission of systematics via conservative selection efficiency ε

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)





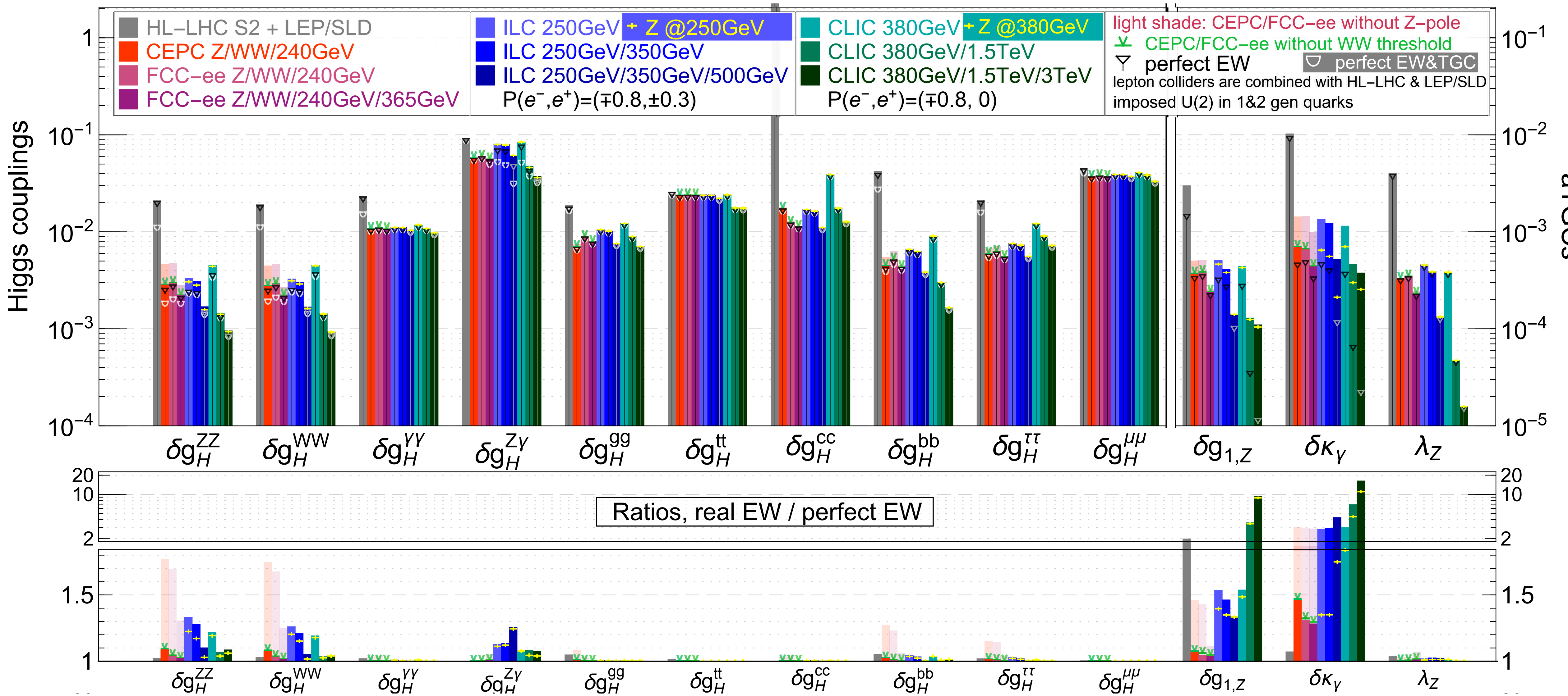
- We prepared a new sensitivity study using full information about each event in the formalism of "optimal statistical observables":
    - We also consider all possible BSM deformations within the dim-6 SMEFT framework

Global EW/Higgs fits at future colliders

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC

precision reach on effective couplings from full EFT global fit

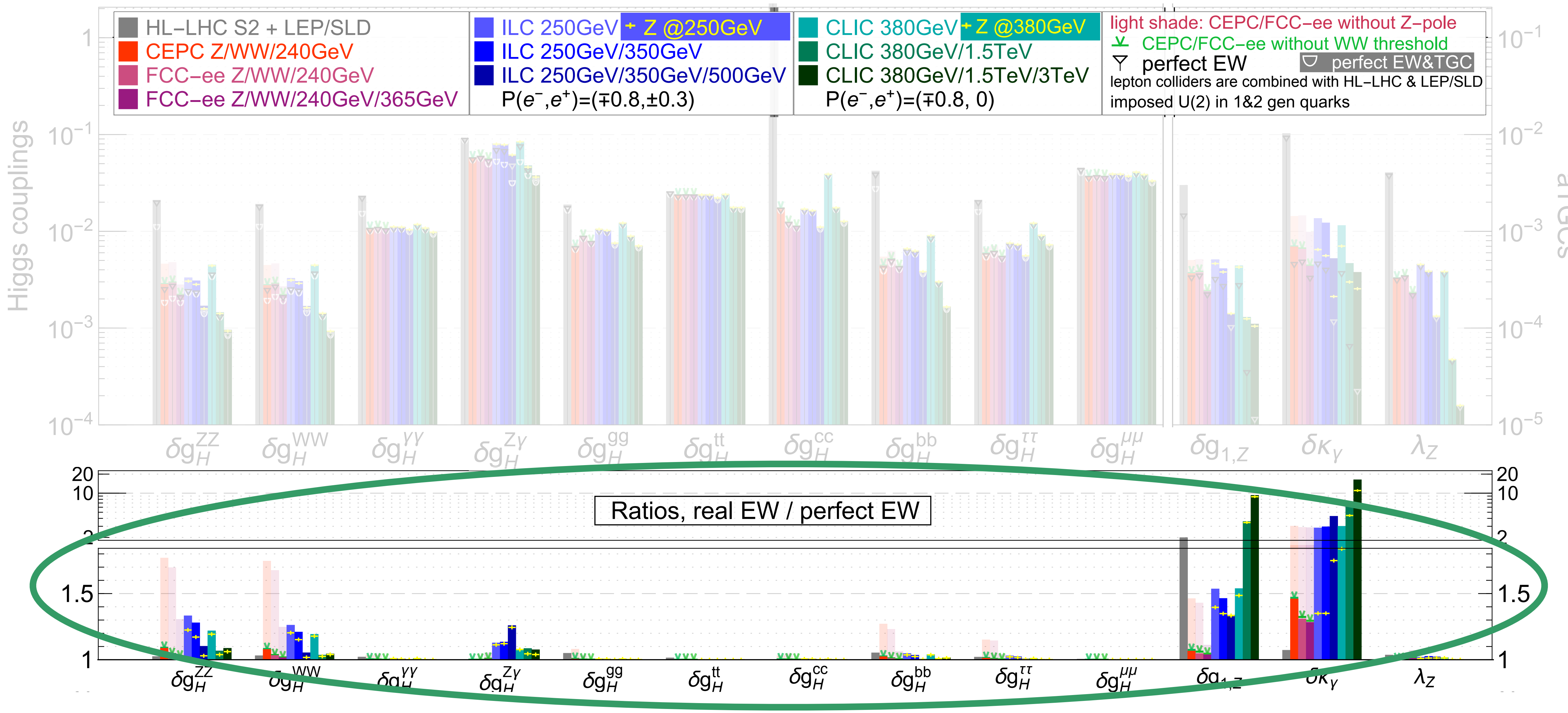


- All future lepton colliders can reach near per-mile level precision on hVV
- Rare decays ($H\to Z\gamma$, $H\to\mu\mu$) statistically limited ← **Better at pp coll., e.g. FCC-hh**

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC

precision reach on effective couplings from full EFT global fit

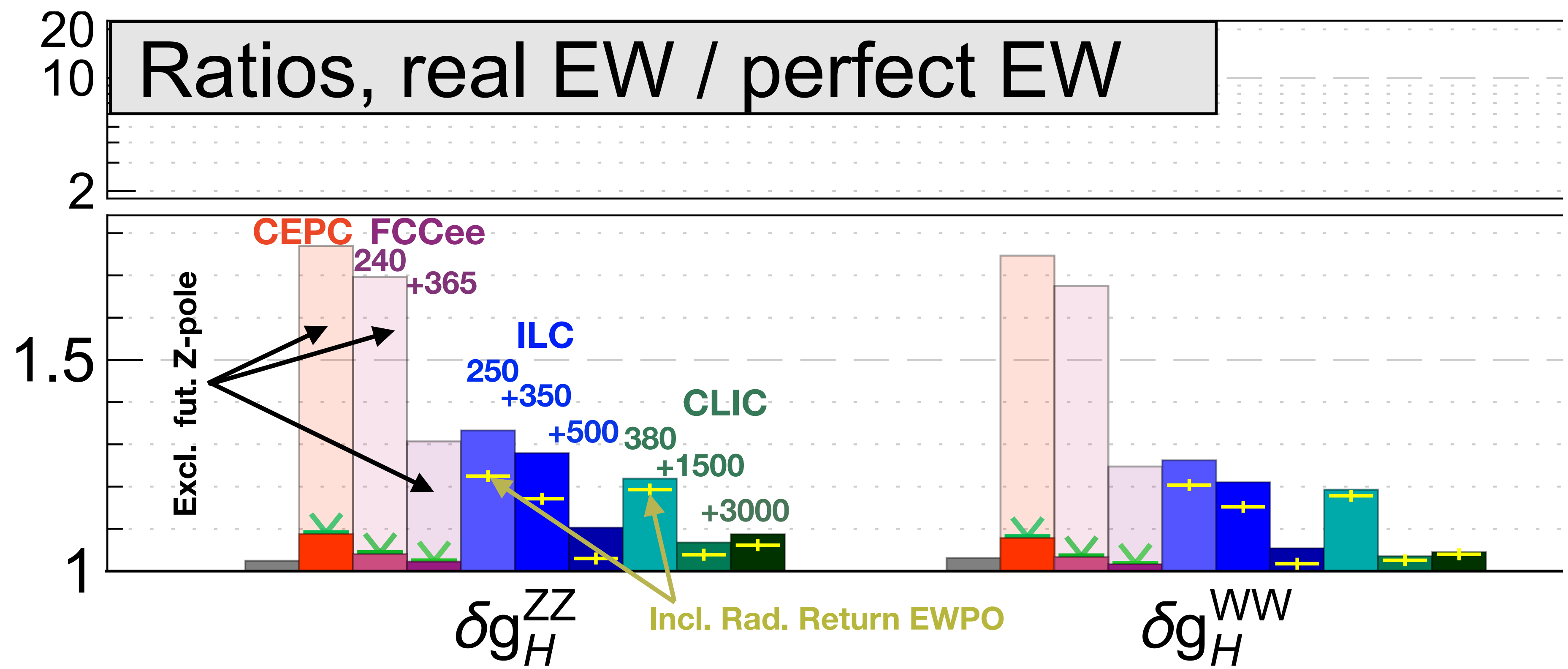


- All future ... on hVV
- Rare dec... e.g. FCC-hh

Are LEP/SLD EW precision measurements enough?

Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC

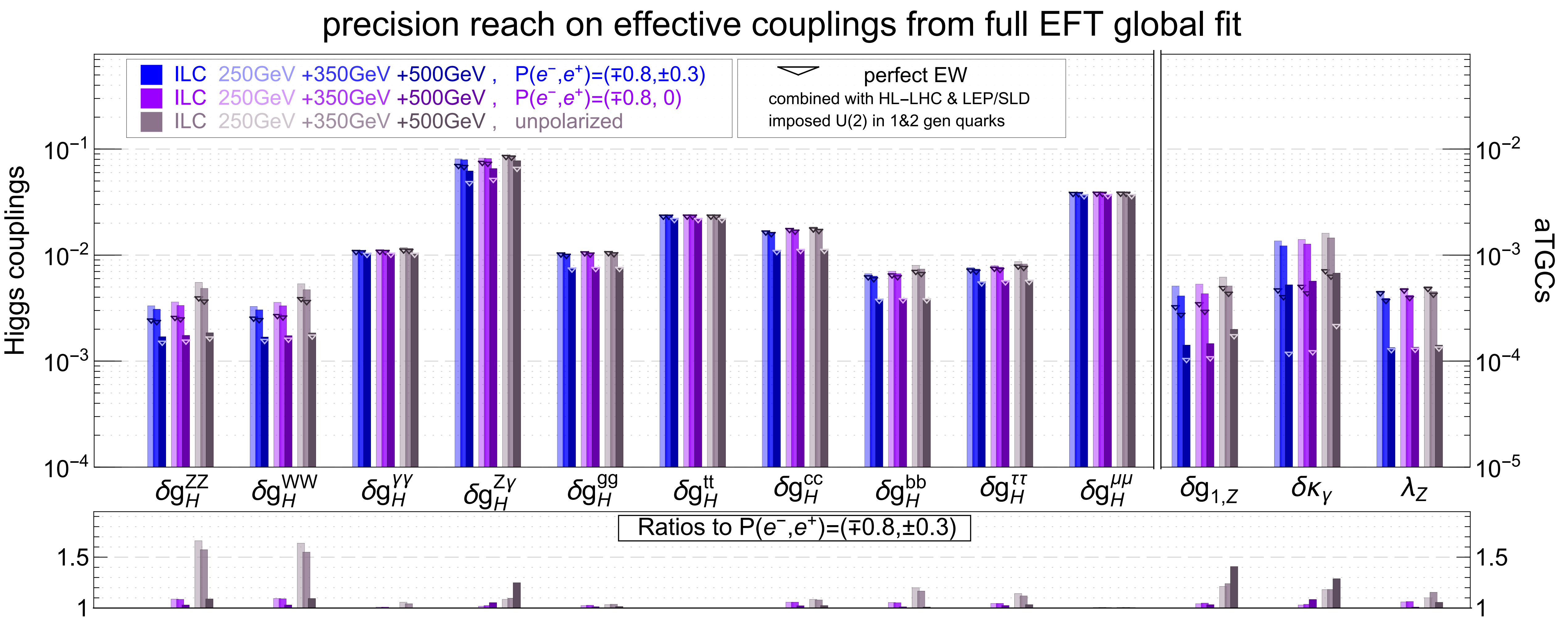


- **Note:** polarization partially compensates the absence of Z-pole at linear colliders

- All future ... on hVV
- Rare dec... ...oll., e.g. FCC-hh

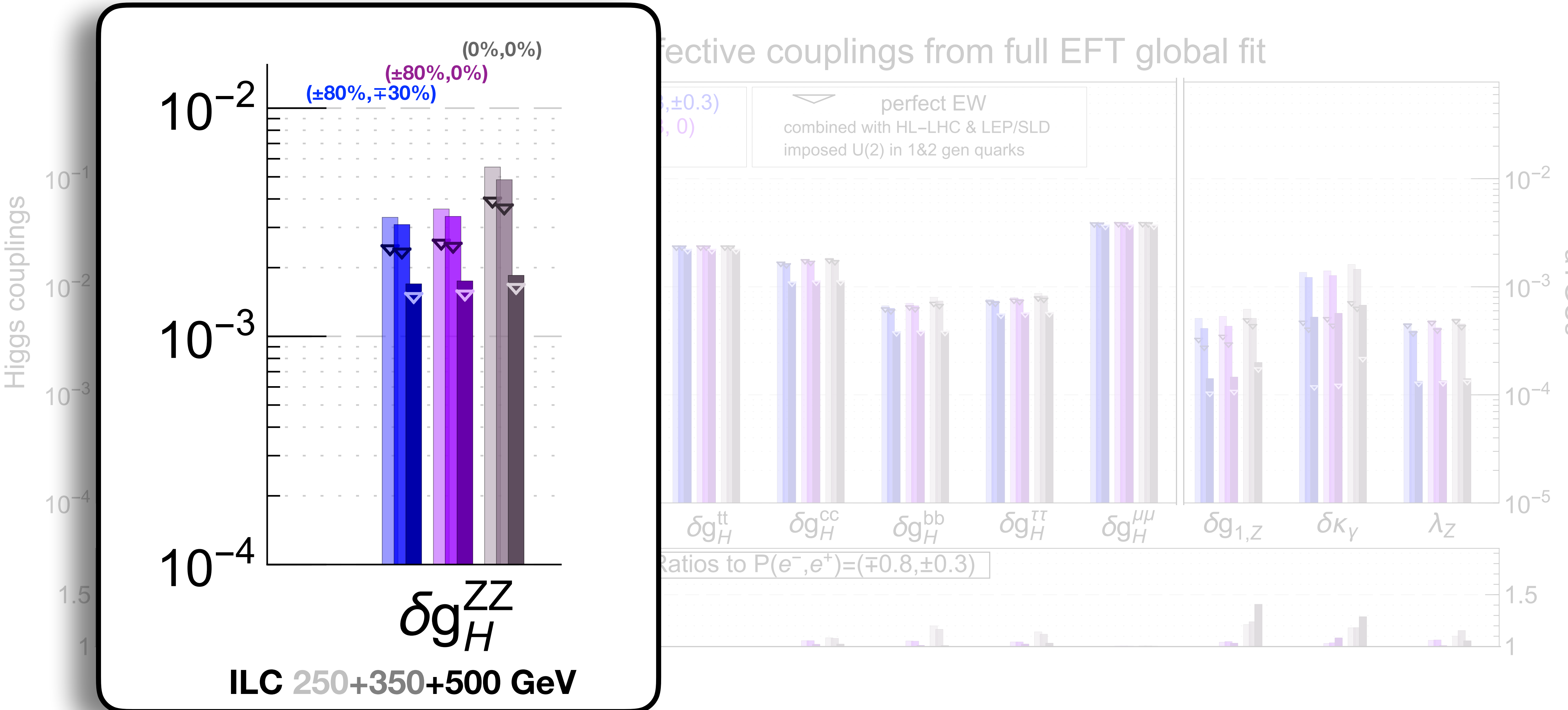
Are LEP/SLD EW precision measurements enough?

Impact of polarization in Higgs coupling sensitivity



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

Impact of polarization in Higgs coupling sensitivity



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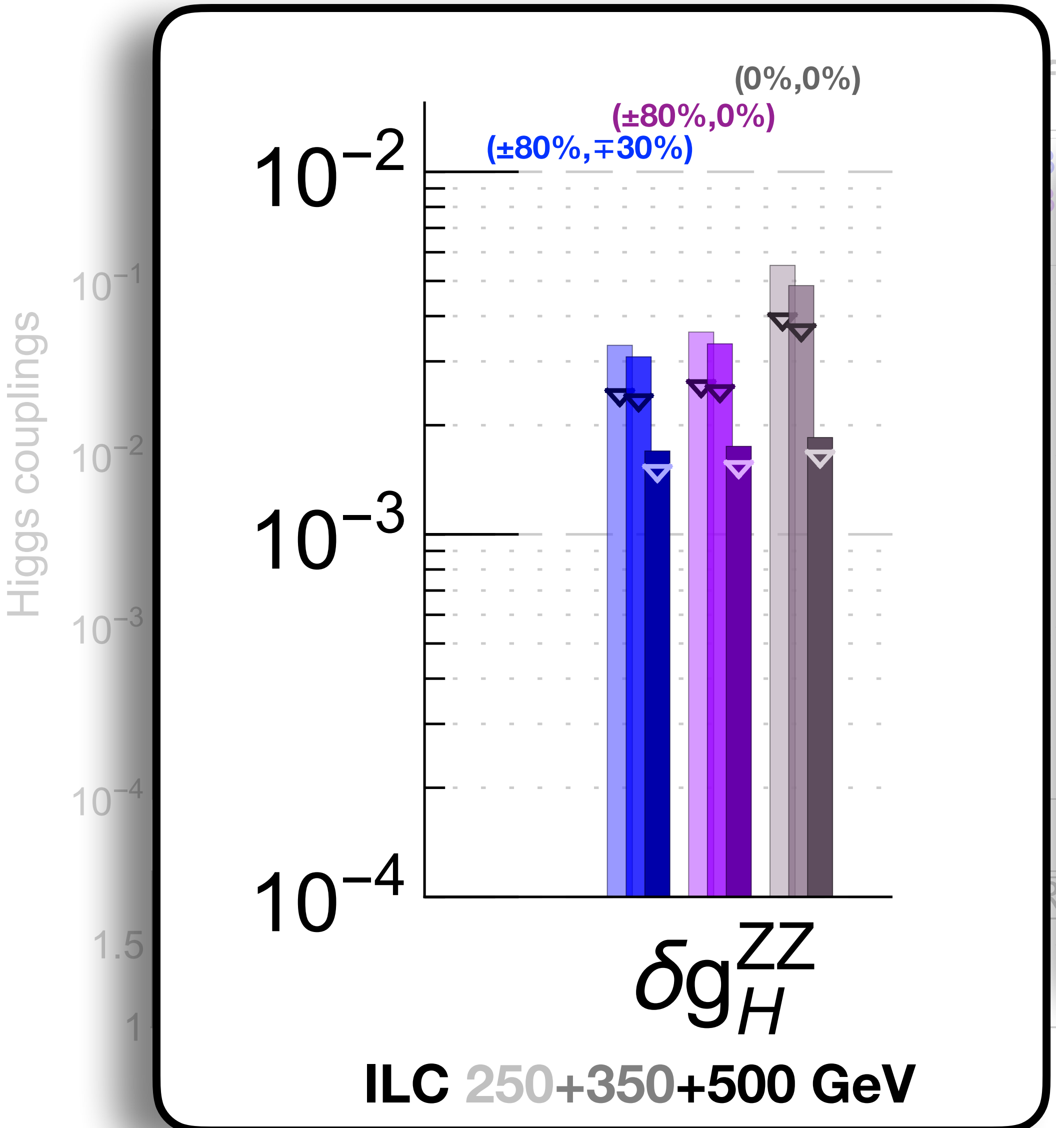
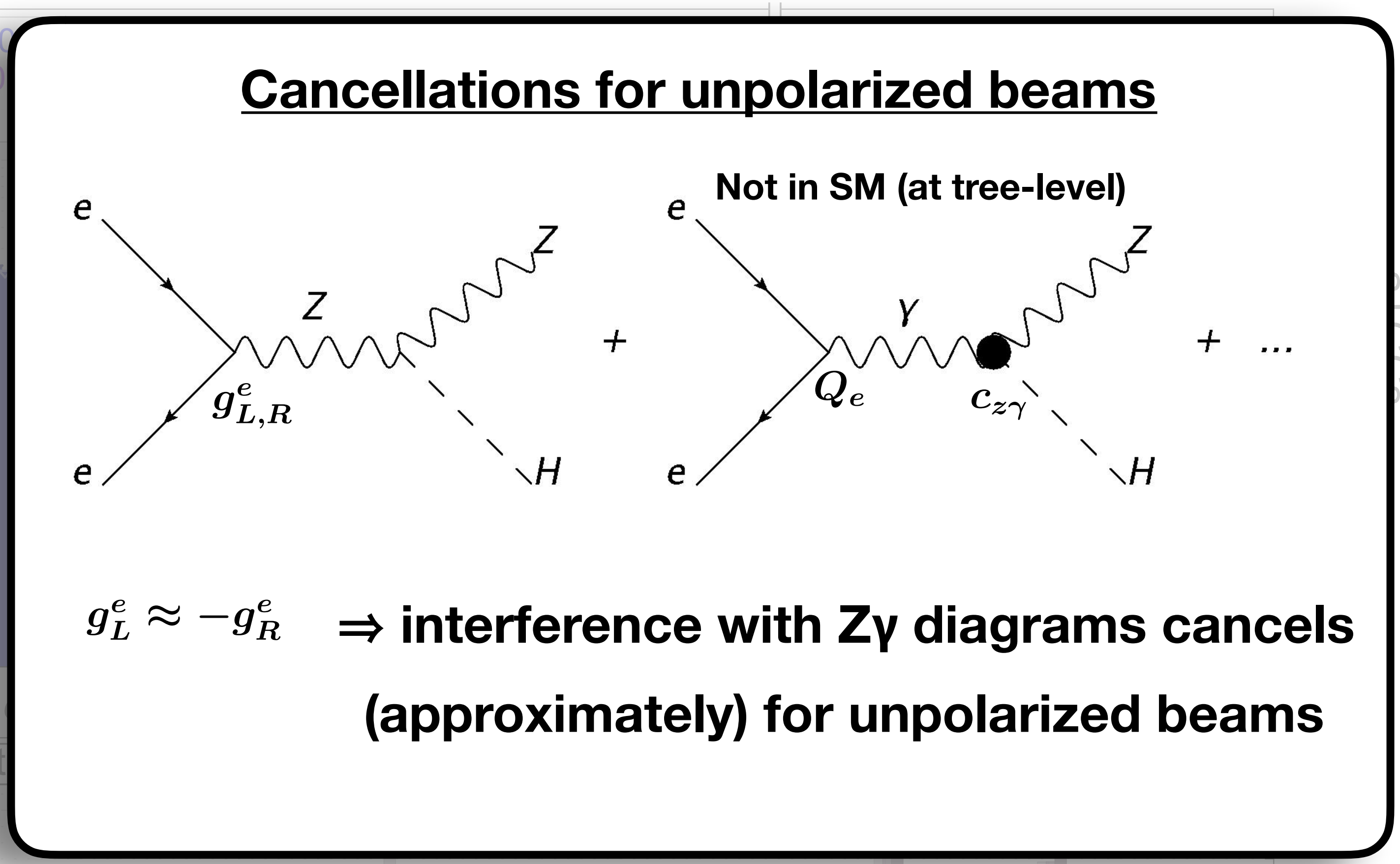
On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity





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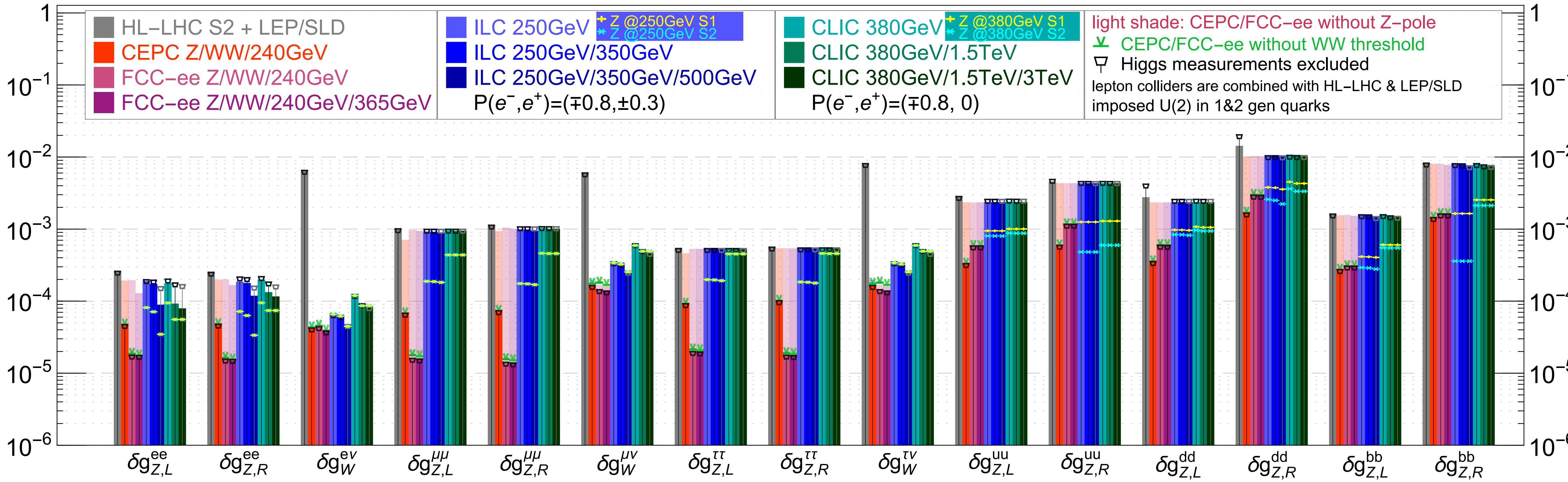
Global fit to EW/Higgs projections

The other “half” of the EFT fit: EW couplings

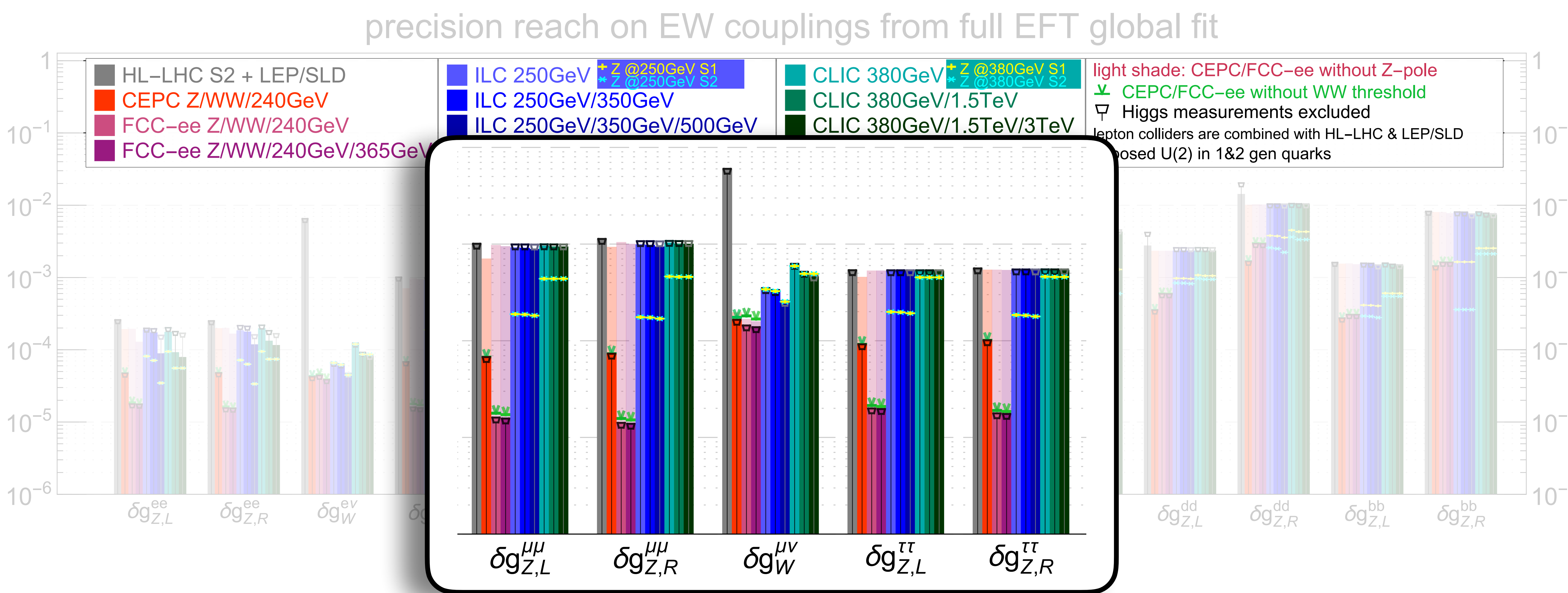
precision reach on EW couplings from full EFT global fit



- 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

Global fit to EW/Higgs projections

The other "half" of the EFT fit: EW couplings



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Global fit to EW/Higgs projections

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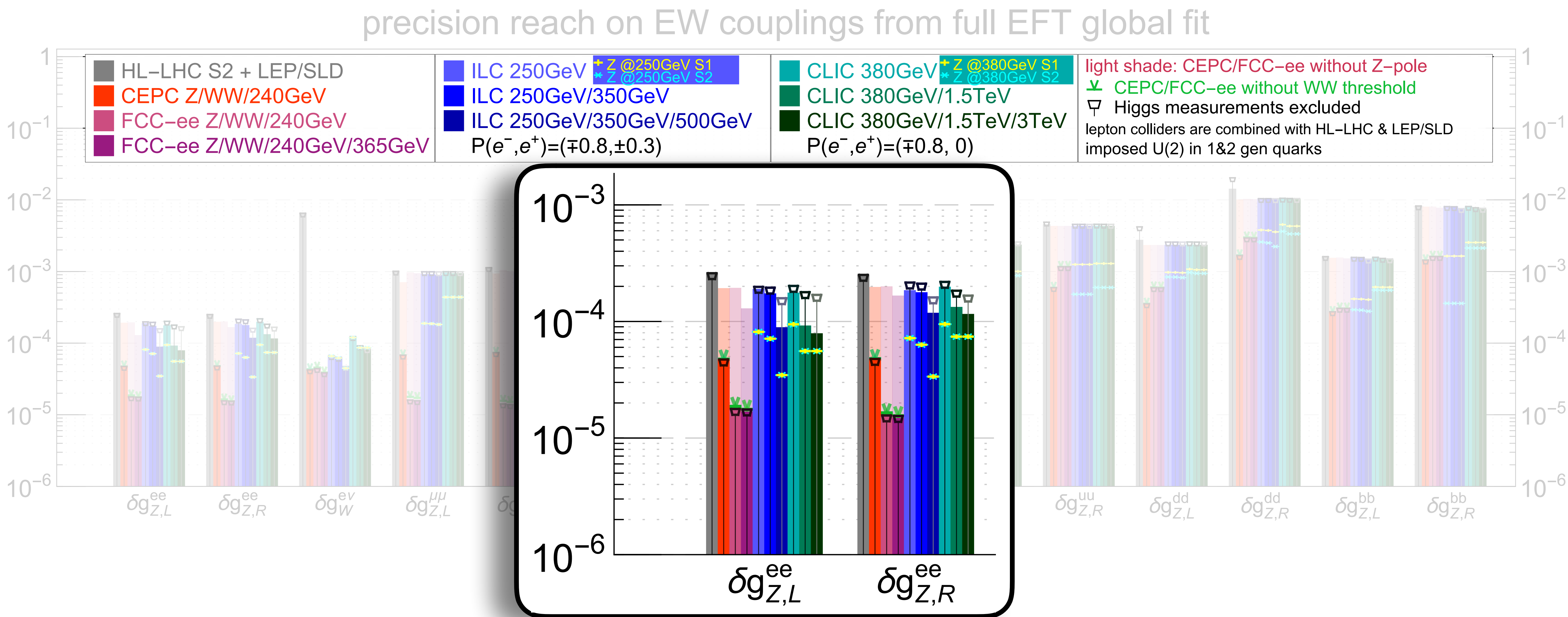

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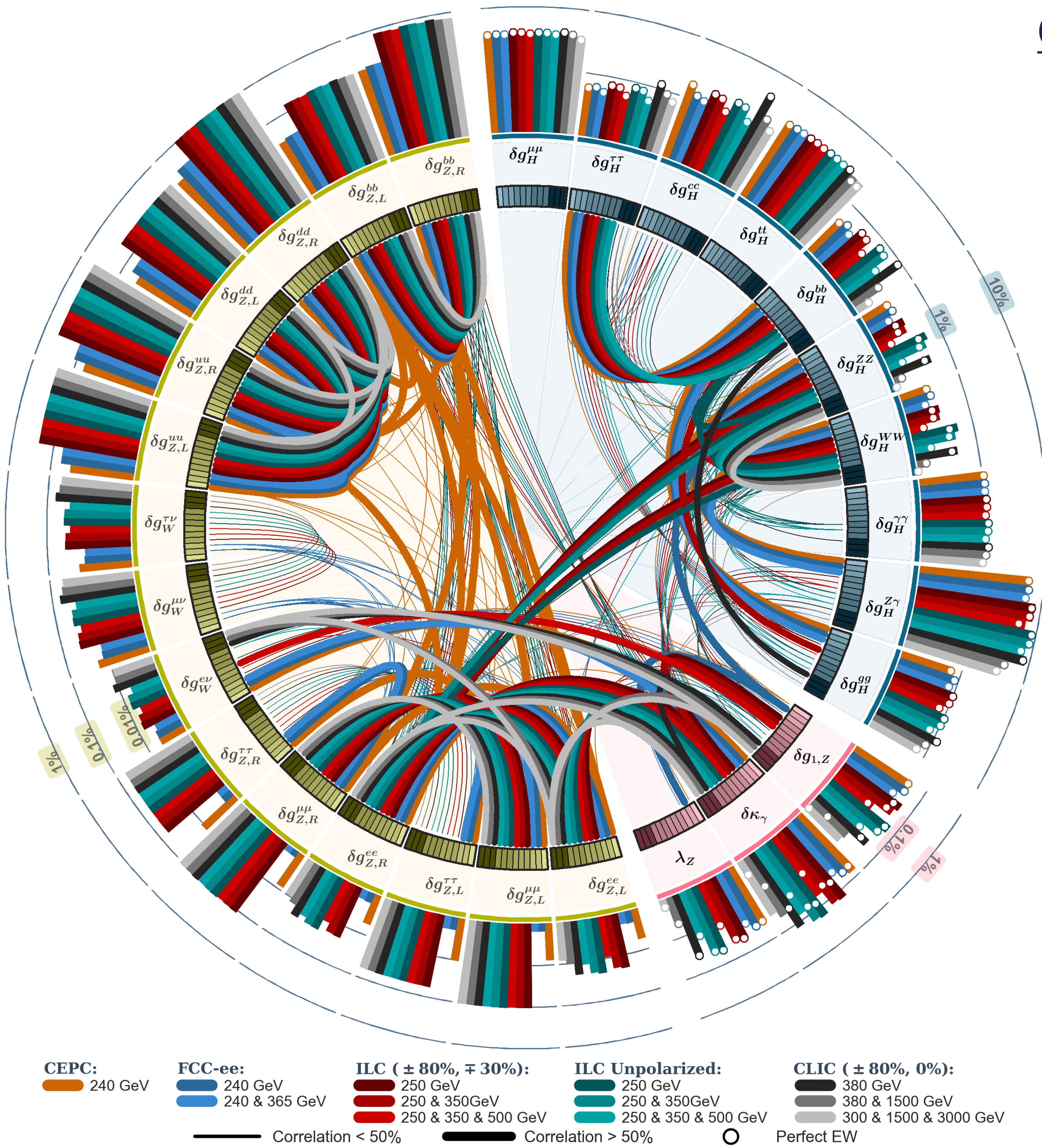
Interplay EW/Higgs at future colliders

Correlation Map at Future Lepton Colliders



Couplings and correlations

How to read "this"?

Interplay EW/Higgs at future colliders

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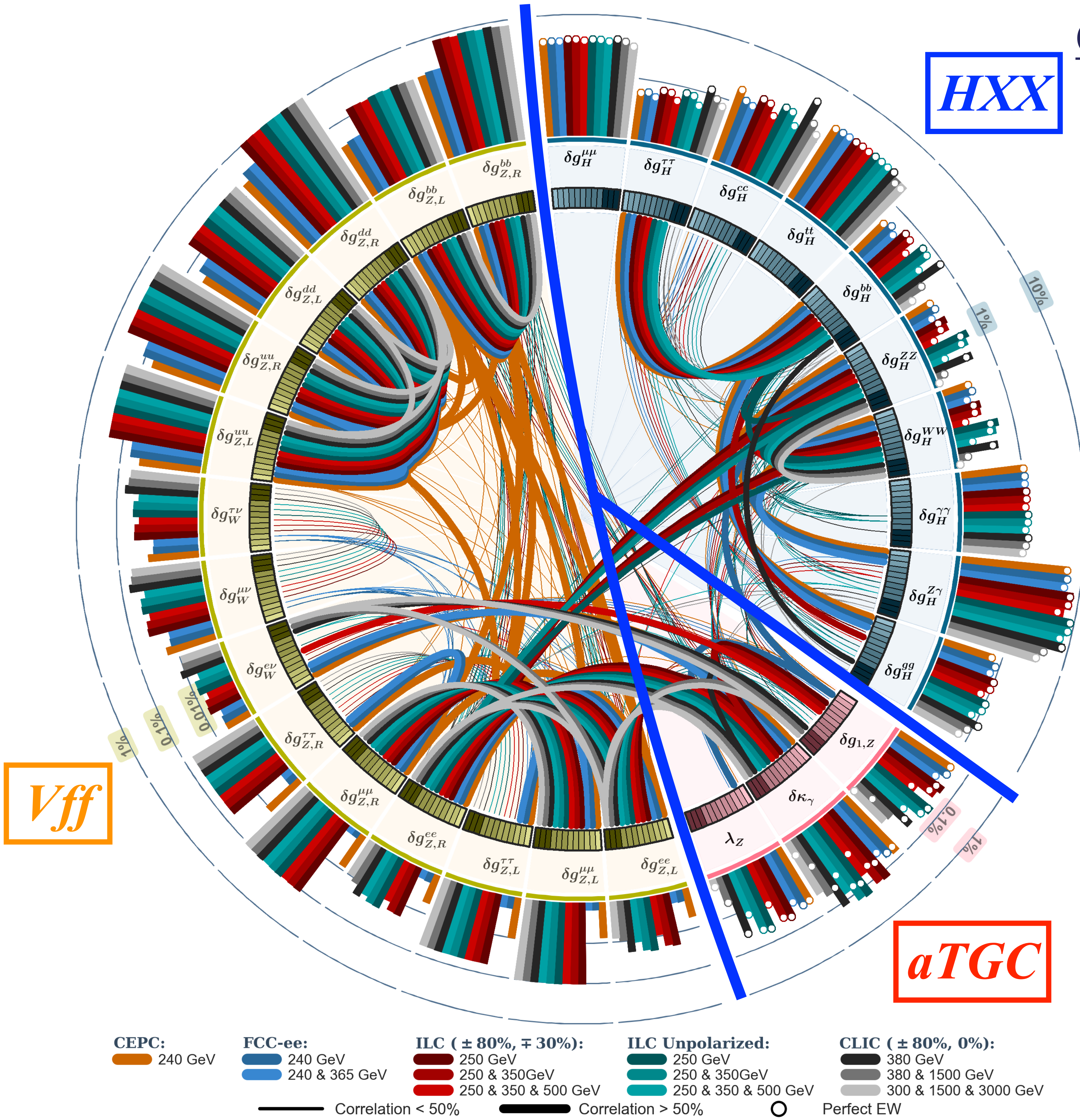


Couplings and correlations

How to read "this"?

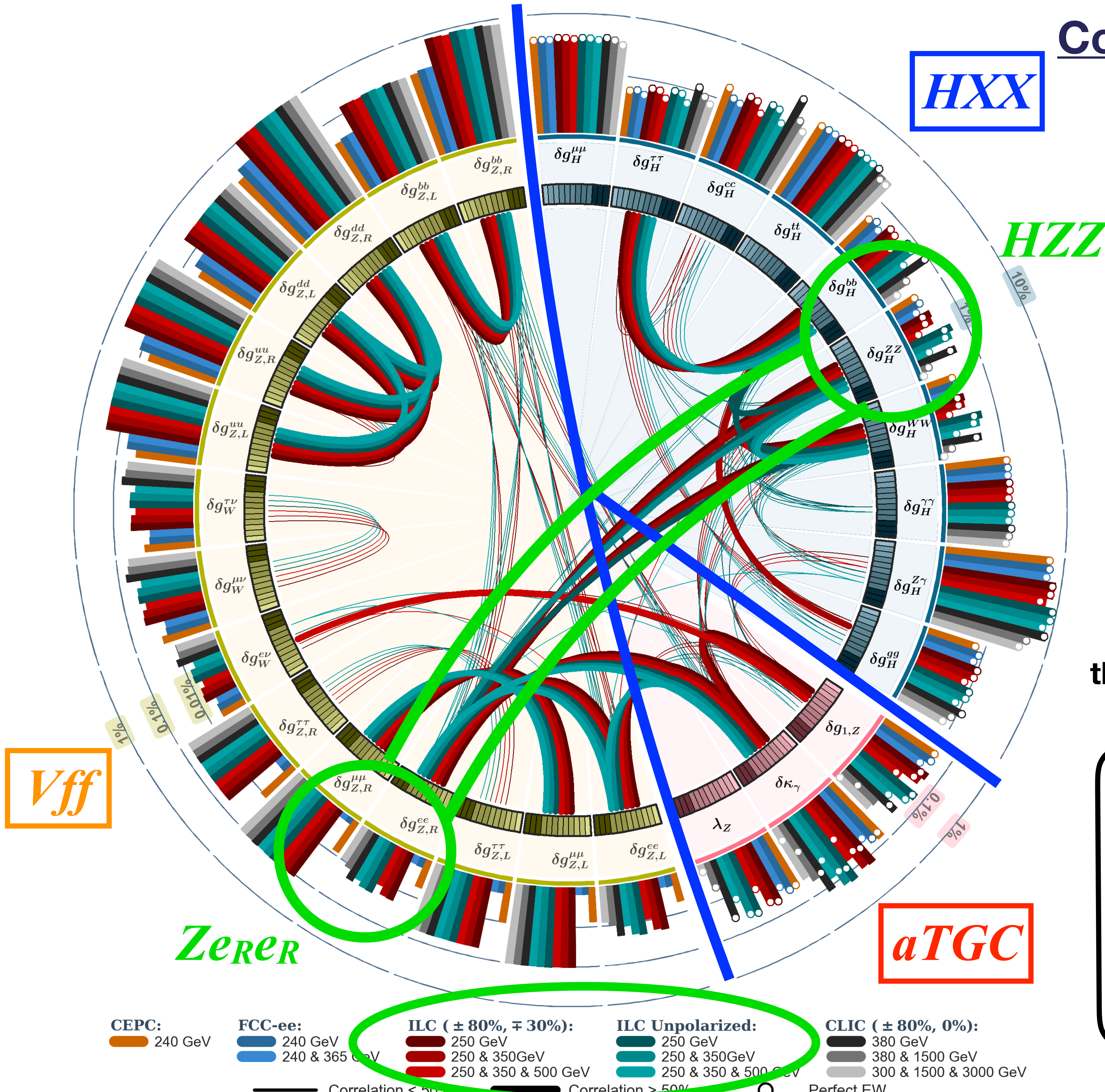
On the outside: 1σ uncertainty on the different interactions

(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



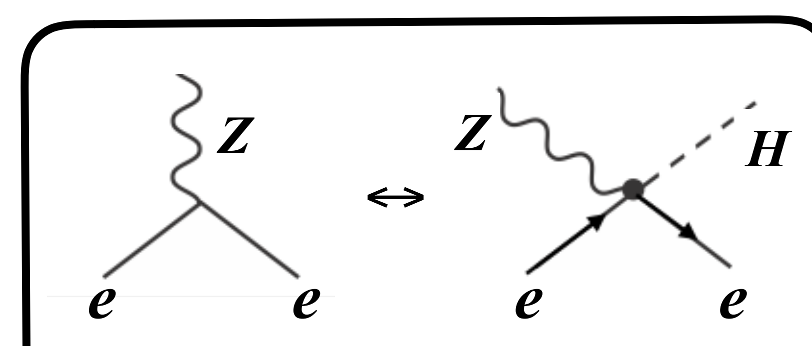
Couplings and correlations

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)

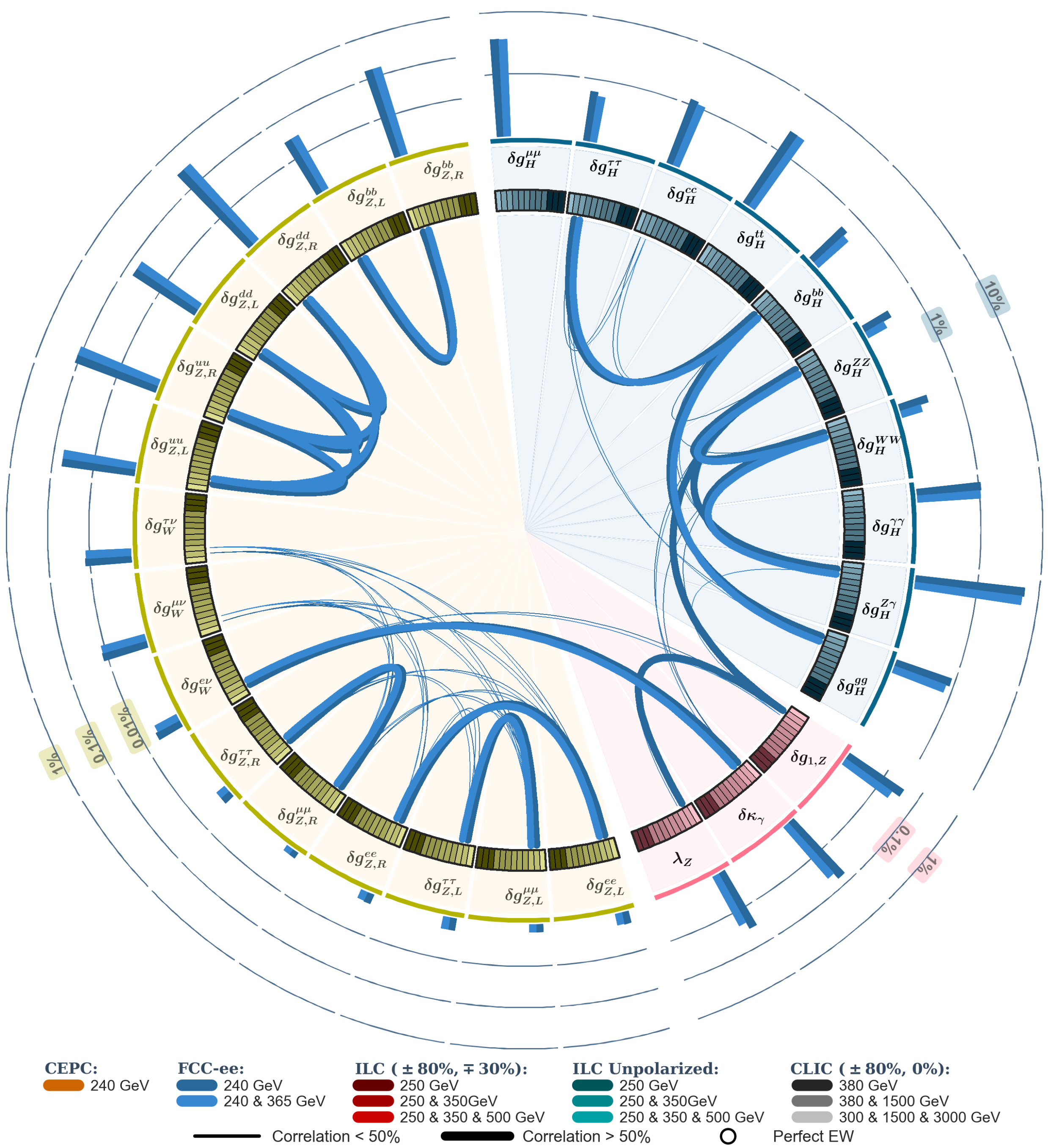


$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}^{\mathrm{SM}}} \sim \frac{E^2}{\Lambda^2}$$

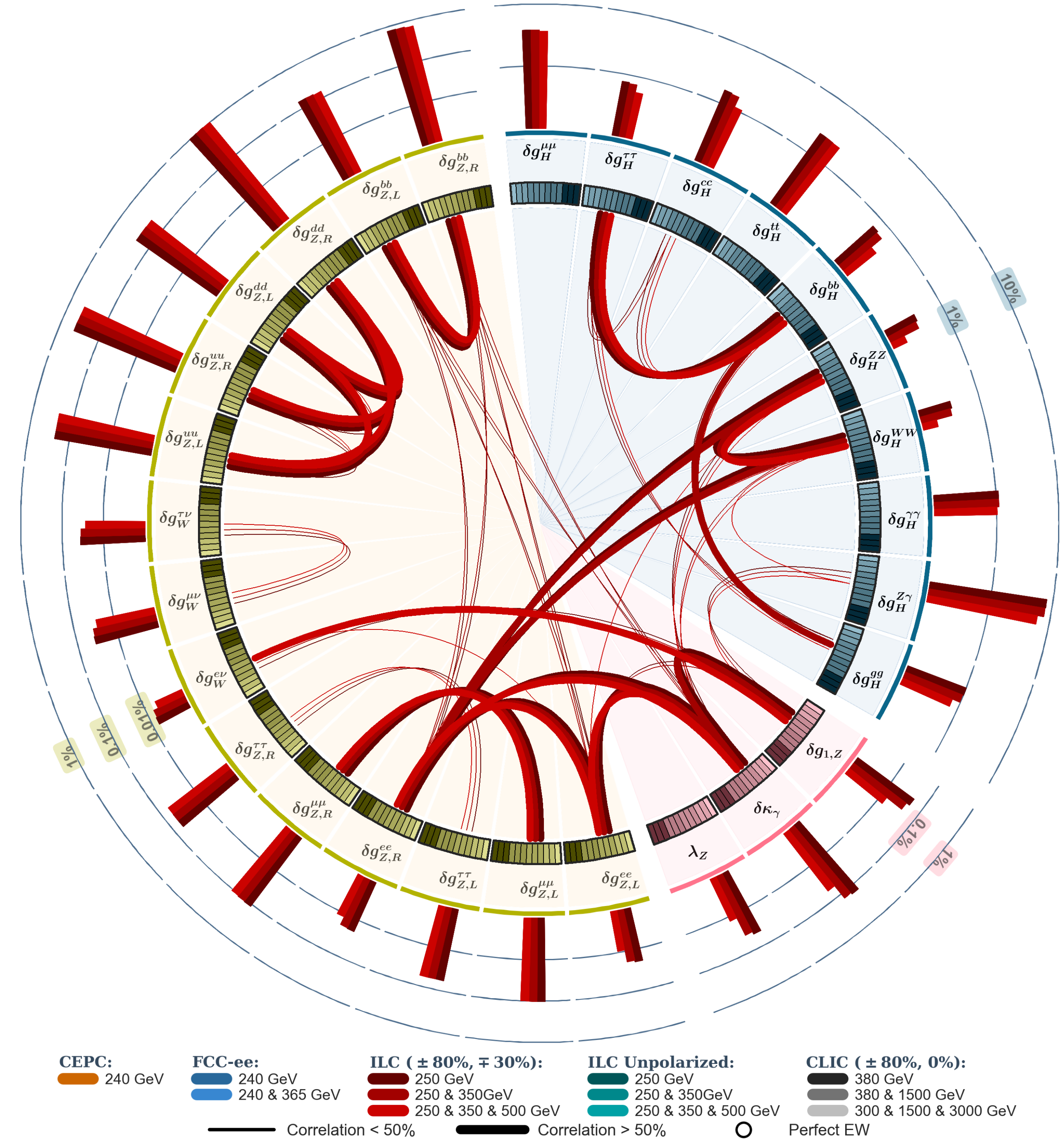
Interplay EW/Higgs at future colliders

Couplings and correlations

FCCee



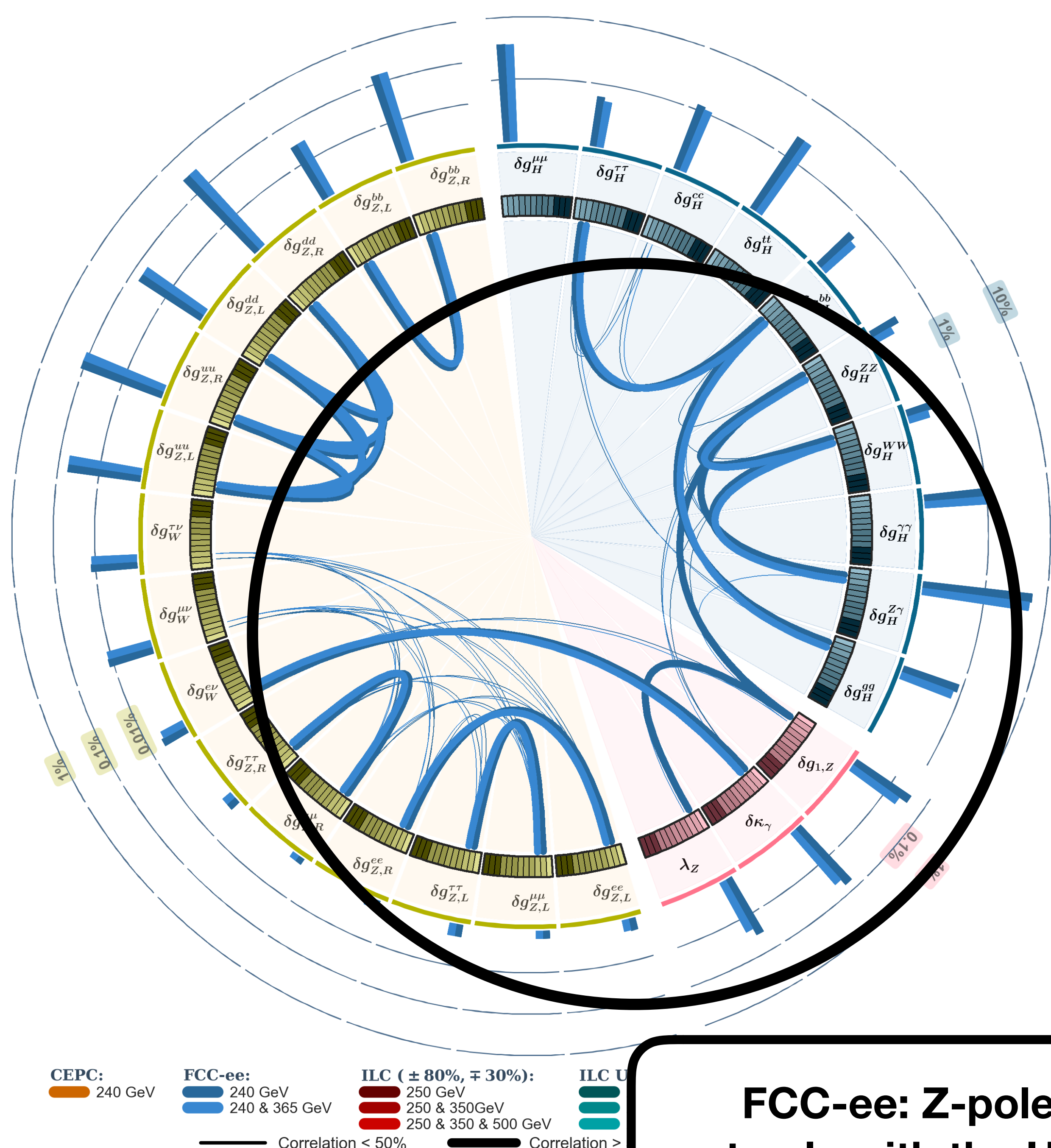
ILC



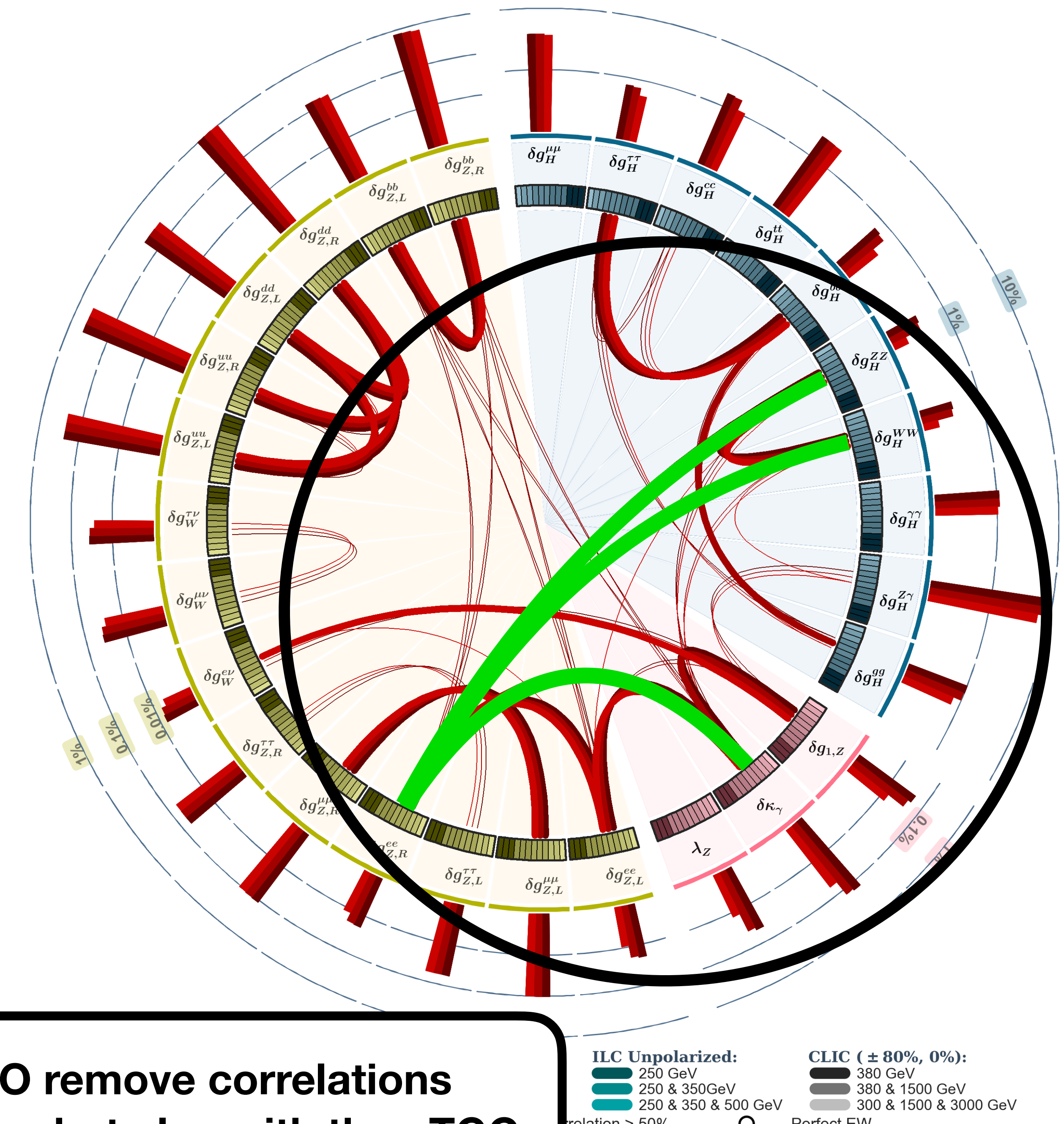
Interplay EW/Higgs at future colliders

Couplings and correlations

FCCee



ILC



FCC-ee: Z-pole EWPO remove correlations not only with the H sector, but also with the aTGC

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 (unlike the HL-LHC)
  - Near **per-mille level** precision in some H couplings.
  - But **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 fully global EFT study of WW at future lepton colliders**

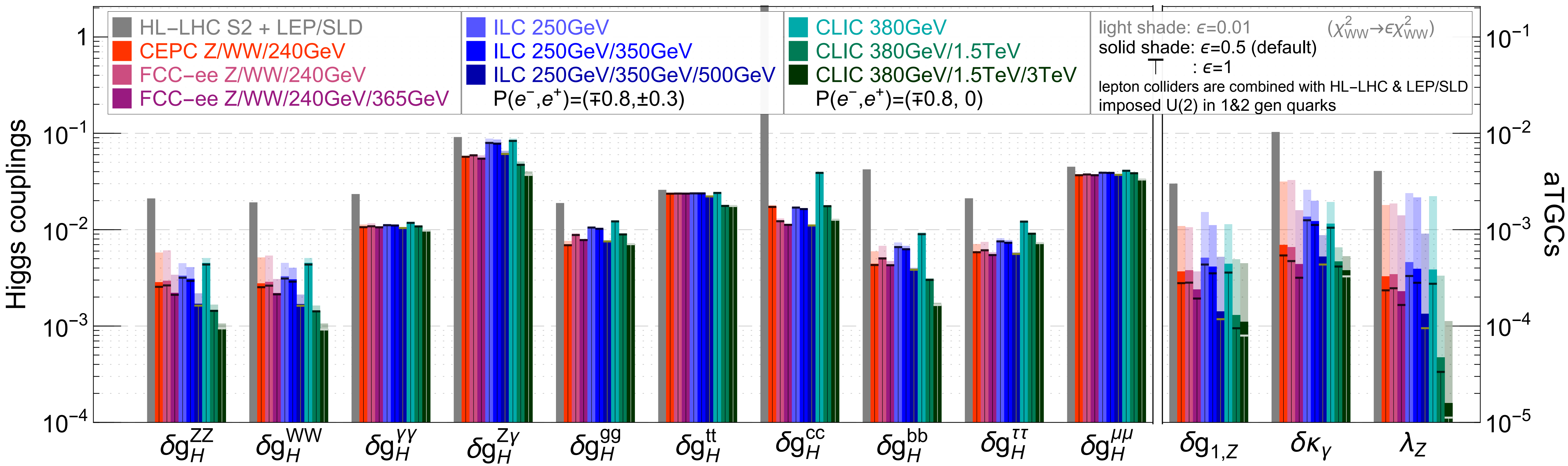
- Polarization and higher energies at LC can partially mitigate the impact of the absence of Z-pole run in some couplings (*HZZ*), but cannot the replace the net added value of the EW precision measurements.

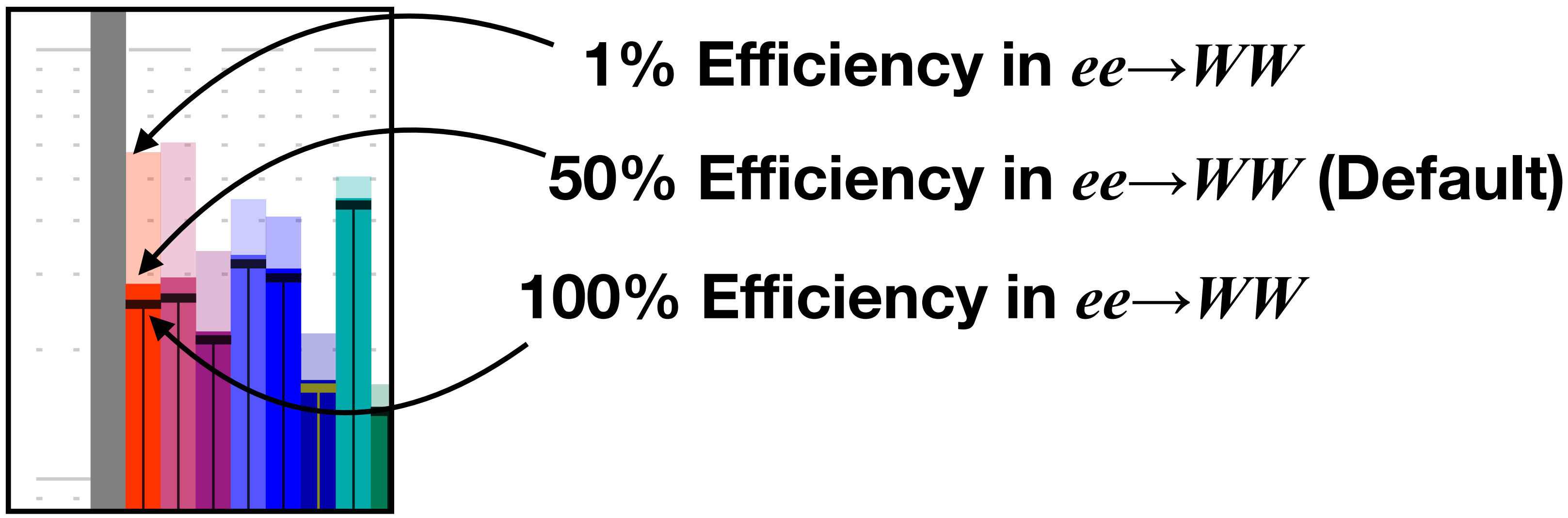
Backup slides

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





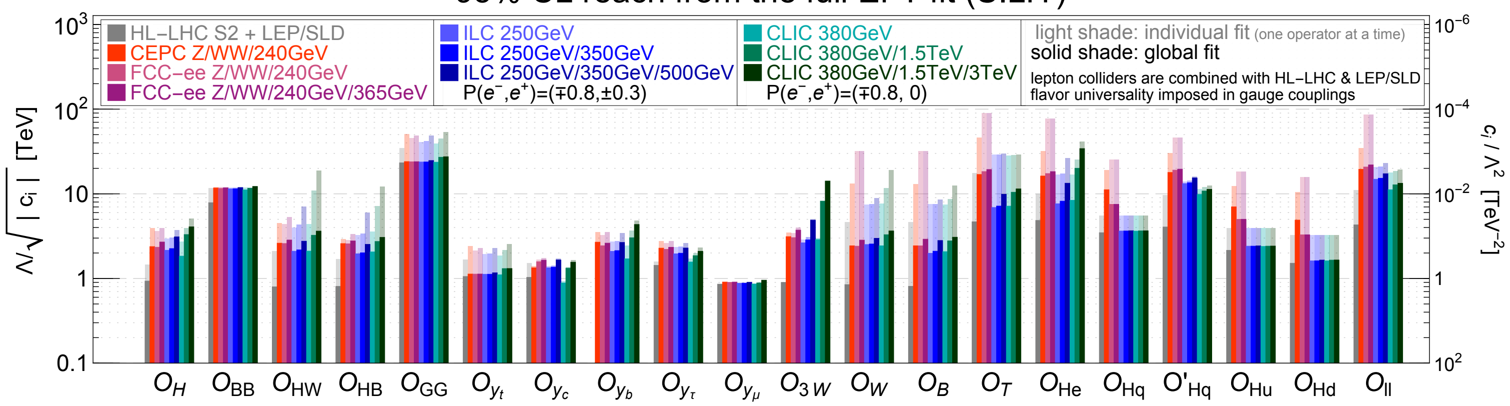
Influence of the assumptions in the *OO* study of *WW* production in the extraction of *H* couplings

Other EFT results

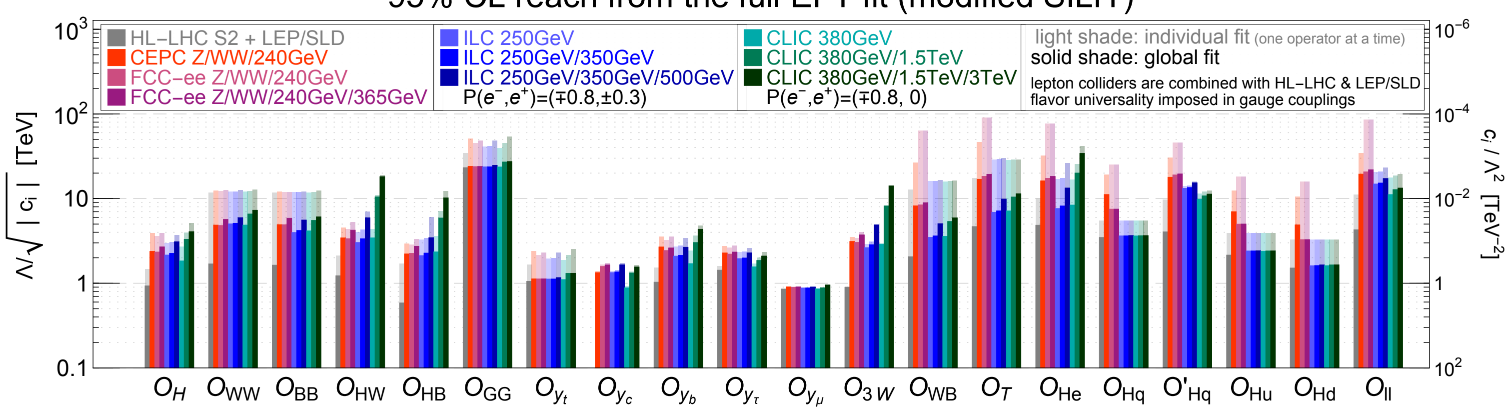
Other EFT results

Results in manifestly gauge-invariant dim-6 bases

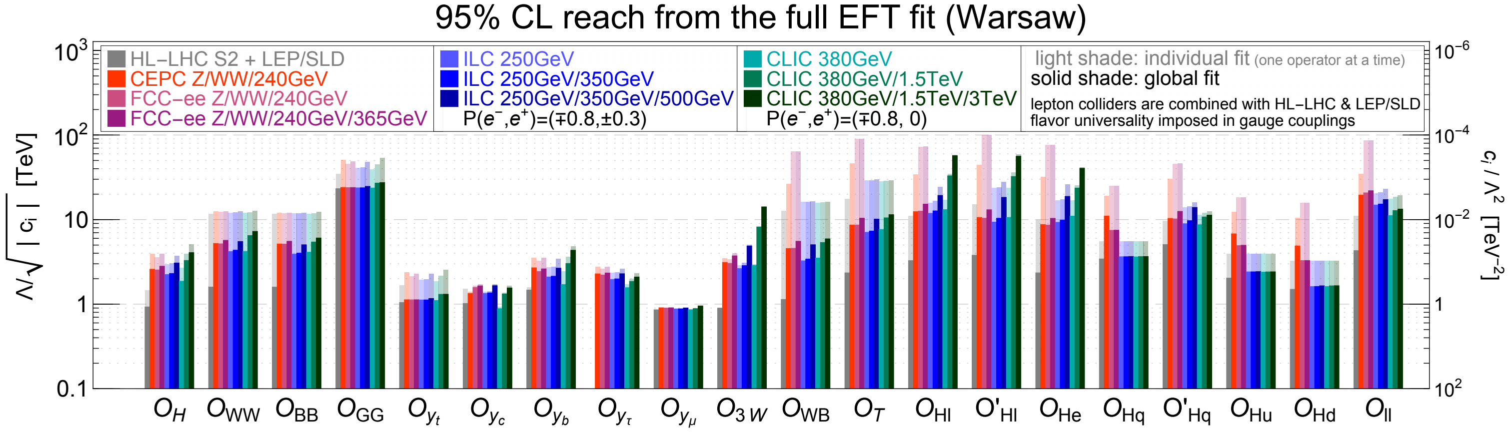
95% CL reach from the full EFT fit (SILH')



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



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



Notation

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

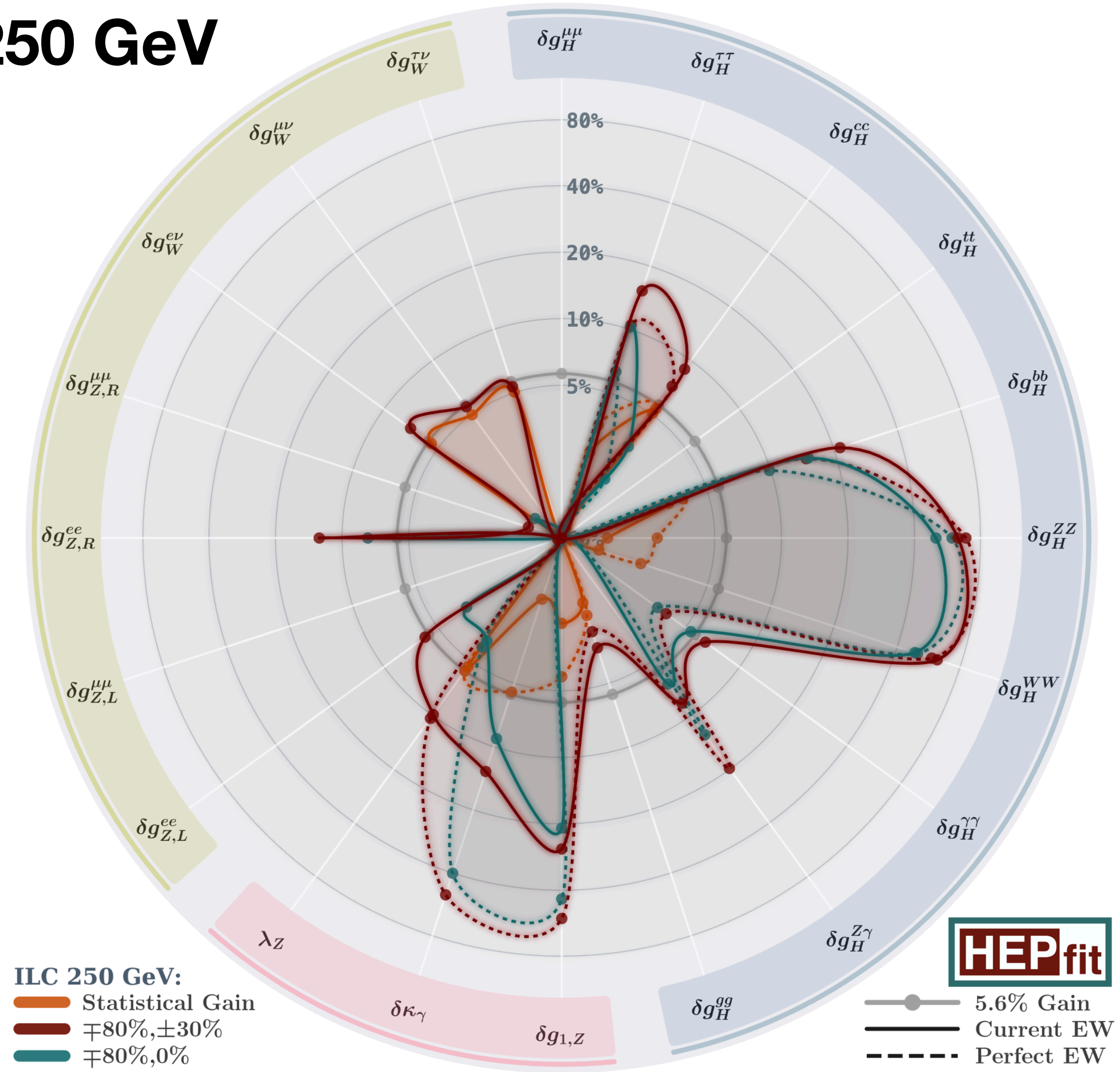
Fits assuming flavour universality in O_{Hf} and O'_{Hf}

A bit more on polarization

On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity

ILC 250 GeV



How to read "this"?

$\delta g_{unpol.}/\delta g_{unpol.(Lx1.12)}$ **-1 : Increased stats.**

$\delta g_{unpol.}/\delta g_{(\pm 80\%,0\%)}$ **-1 : Increased stats. + resolving degeneracies**

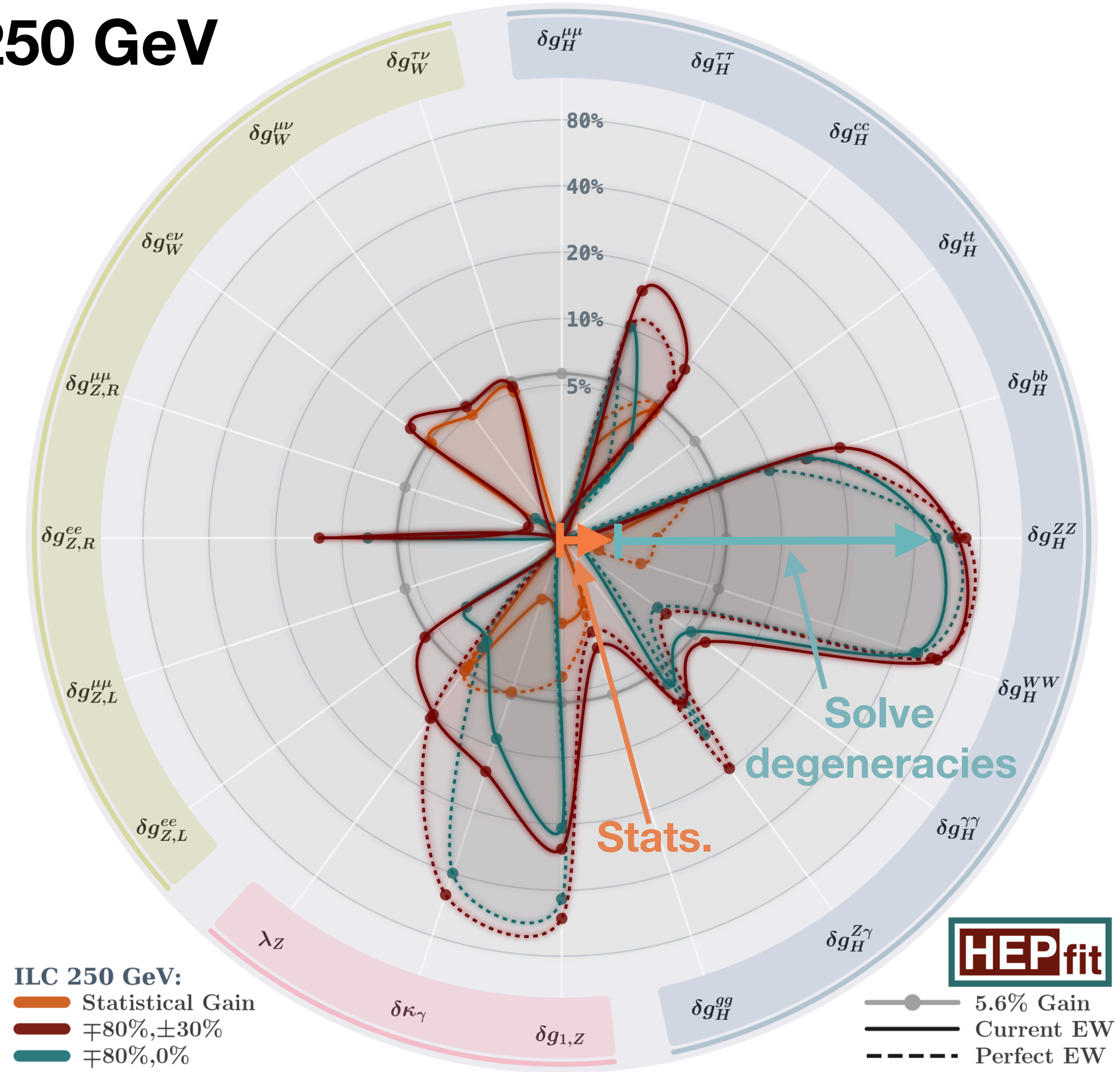
$\delta g_{unpol.}/\delta g_{(\pm 80\%,\mp 30\%)}$ **-1 : Increased stats. + resolving degeneracies**

- 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

On the beam polarization at linear colliders

Impact of polarization in Higgs coupling sensitivity

ILC 250 GeV



How to read "this"?

$\delta g_{unpol.}/\delta g_{unpol.(Lx1.12)}$ -1 : Increased stats.

$\delta g_{unpol.}/\delta g_{(\pm 80\%,0\%)}$ -1 : Increased stats. + resolving degeneracies

$\delta g_{unpol.}/\delta g_{(\pm 80\%,\mp 30\%)}$ -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

Combinations with FCC-hh

Future colliders considered in the study

Official inputs available for Higgs/WW/EW

Higgs

Rates (signal strength)

$$\mu \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}}}$$

(Inclusive) cross section

$$\sigma_{ZH} \equiv \sigma(e^+e^- \to ZH)$$

Only possible at lepton colliders

aTGC

$$\delta g_{1z}, \delta\kappa_\gamma, \lambda_z$$

EWPO

$$M_Z,\ \Gamma_Z,\ \Gamma_{Z\to f},\ A^f_{FB,LR},\ \ldots$$

$$M_W,\ \Gamma_W,\ \Gamma_{W\to f}$$

Z physics via Z-pole:

$$\sqrt{s} = M_Z: \quad e^+e^- \to Z \to X$$

or Rad. Return:

$$\sqrt{s} > M_Z: \quad e^+e^- \to \gamma Z \to \gamma X$$

	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)
FCC-hh	Yes (μ, BR_i/BR_j for rare decays)	From Lepton Coll.	From Lepton Coll.

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

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	Higg[...]		
FCC-ee	Yes (μ, [...] (Complete wit[...]		
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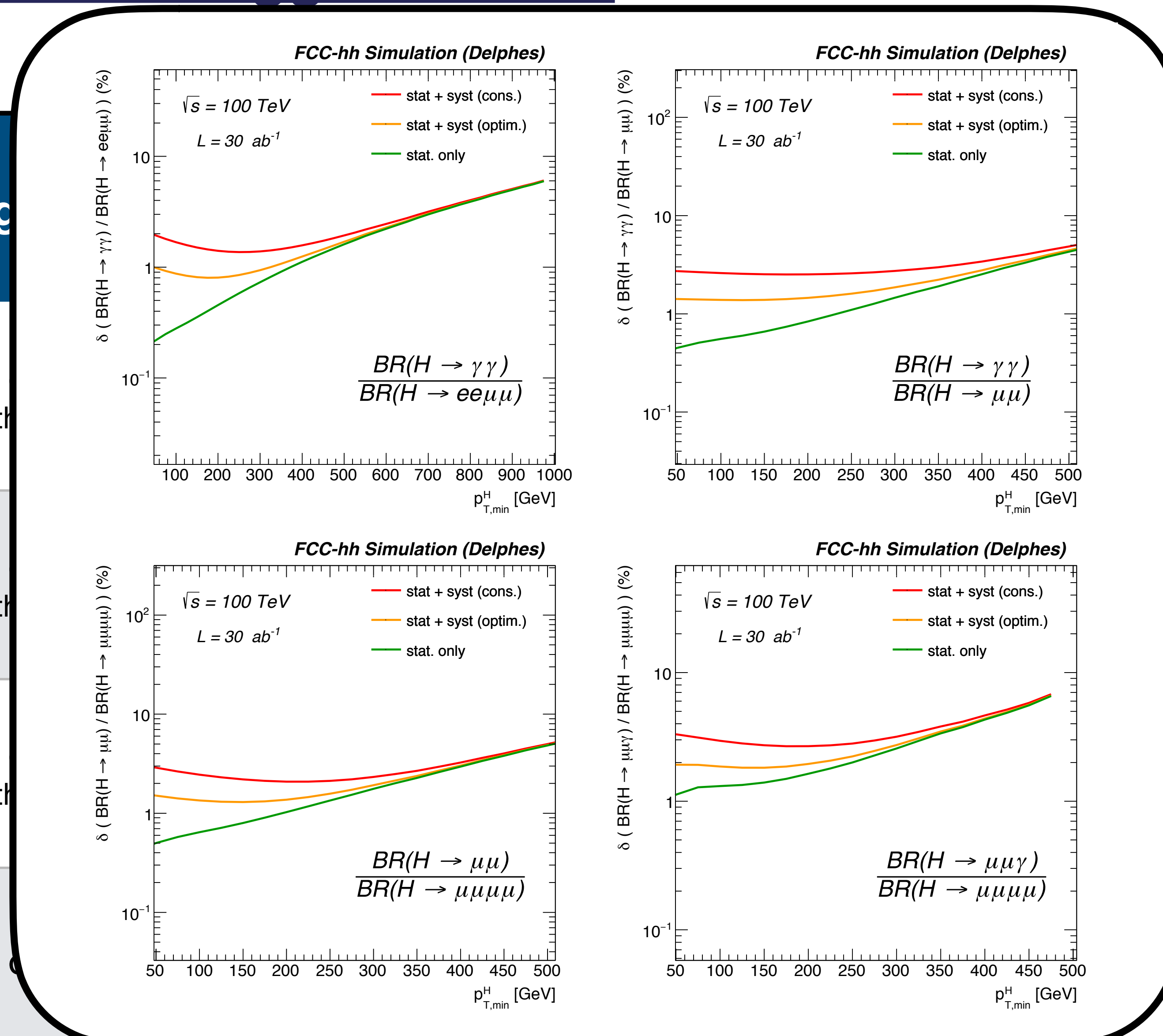

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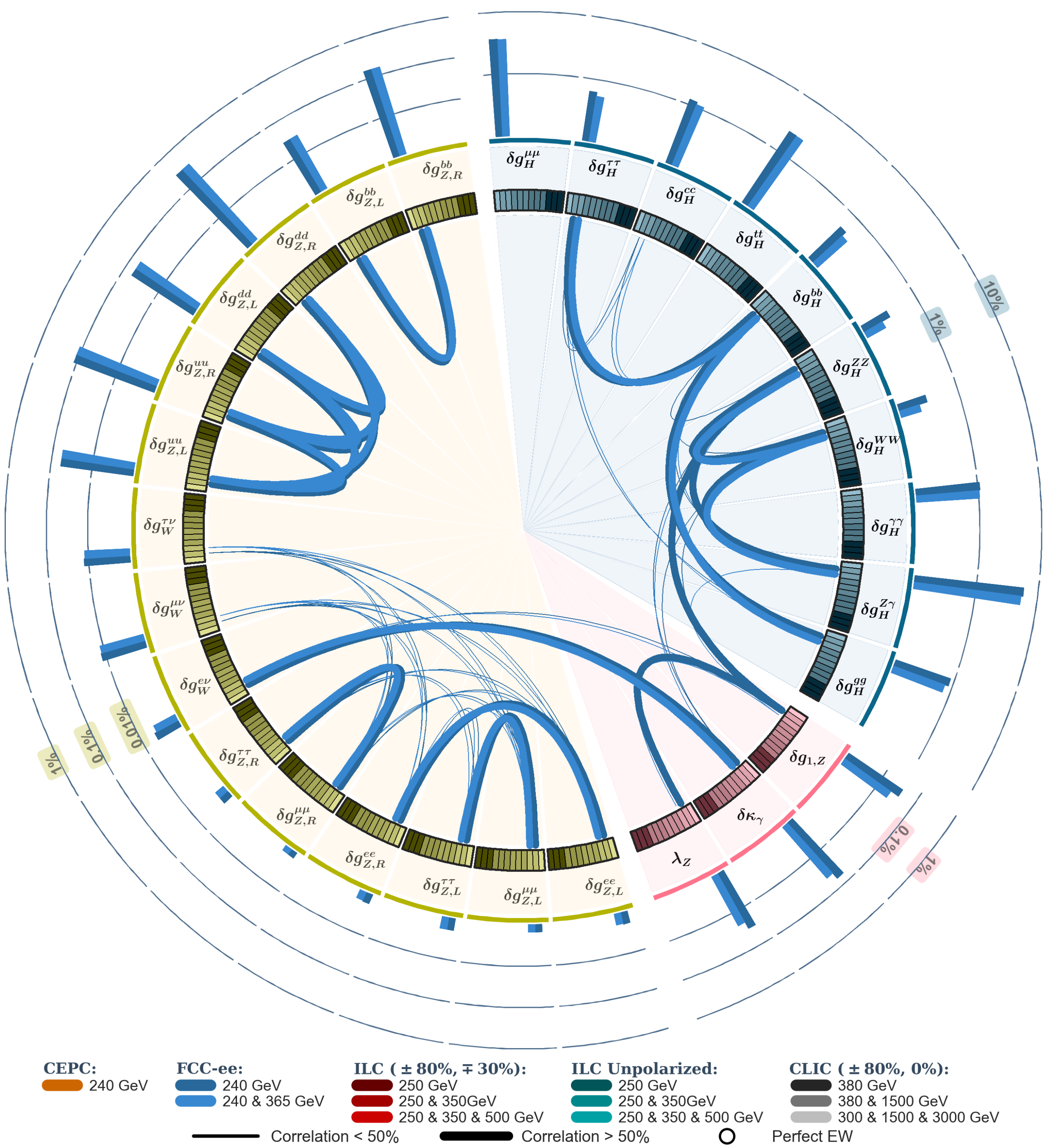
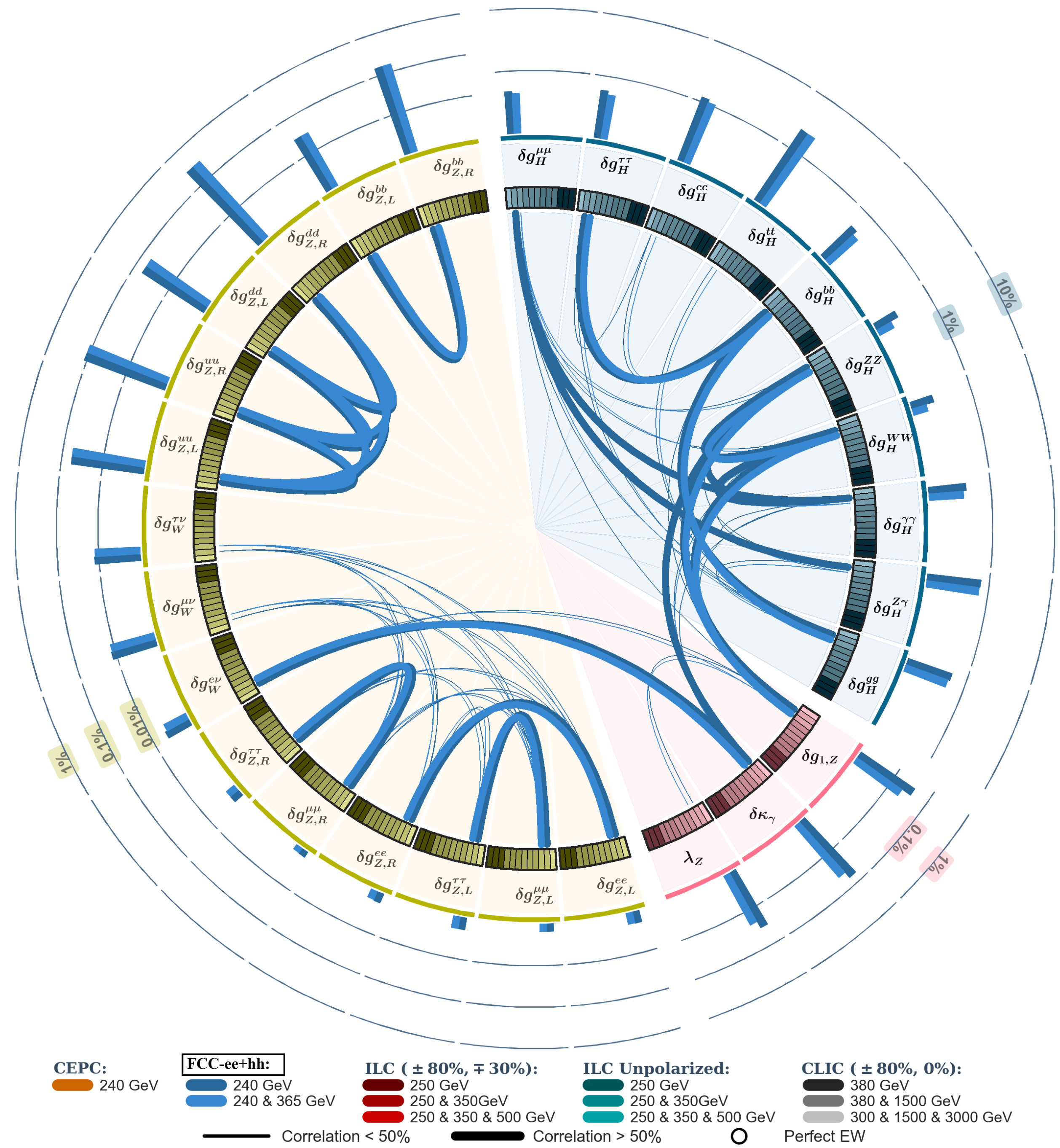
Interplay EW/Higgs at future colliders

Couplings and correlations

FCCee



FCCee+hh

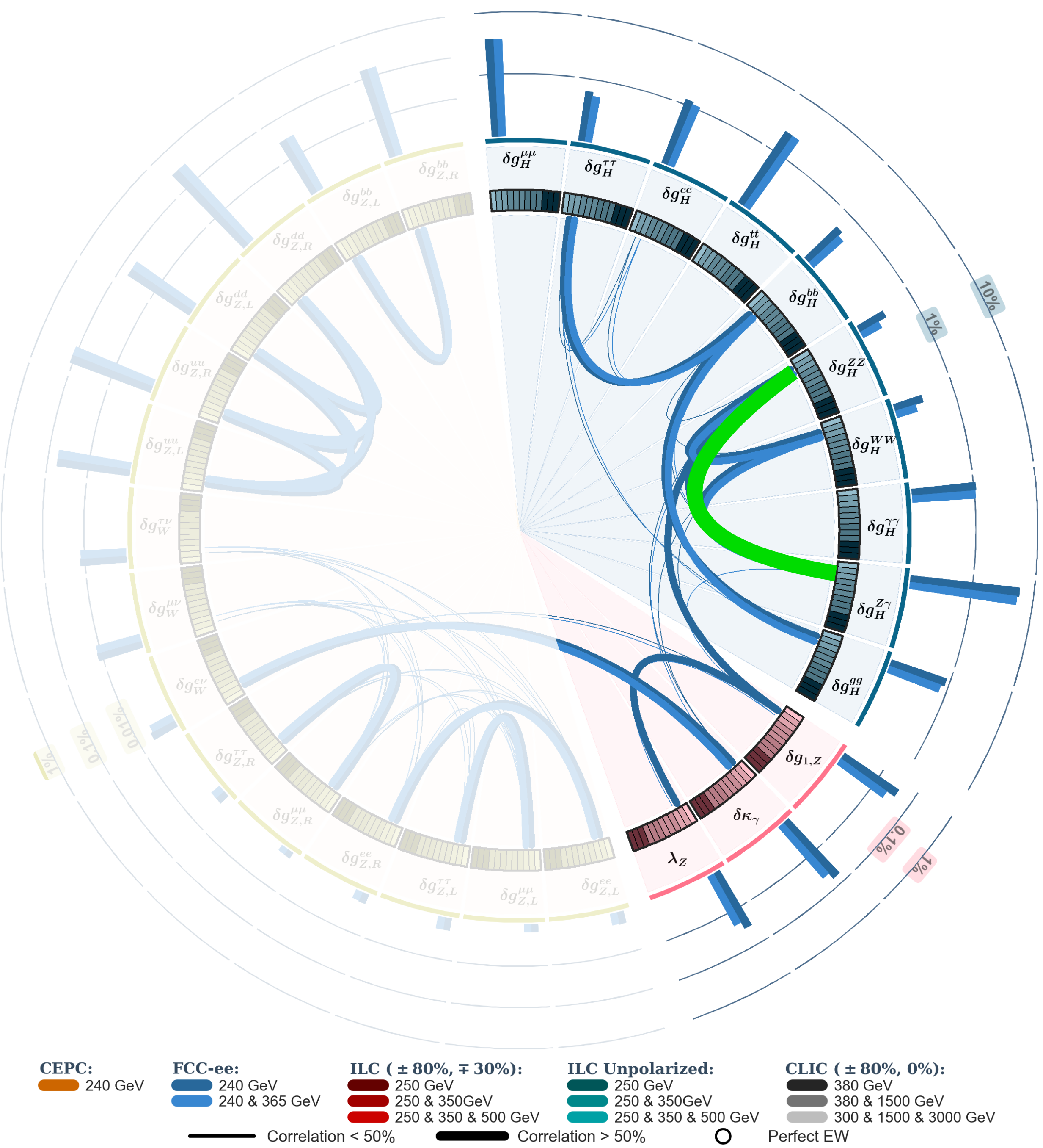


PRELIMINARY

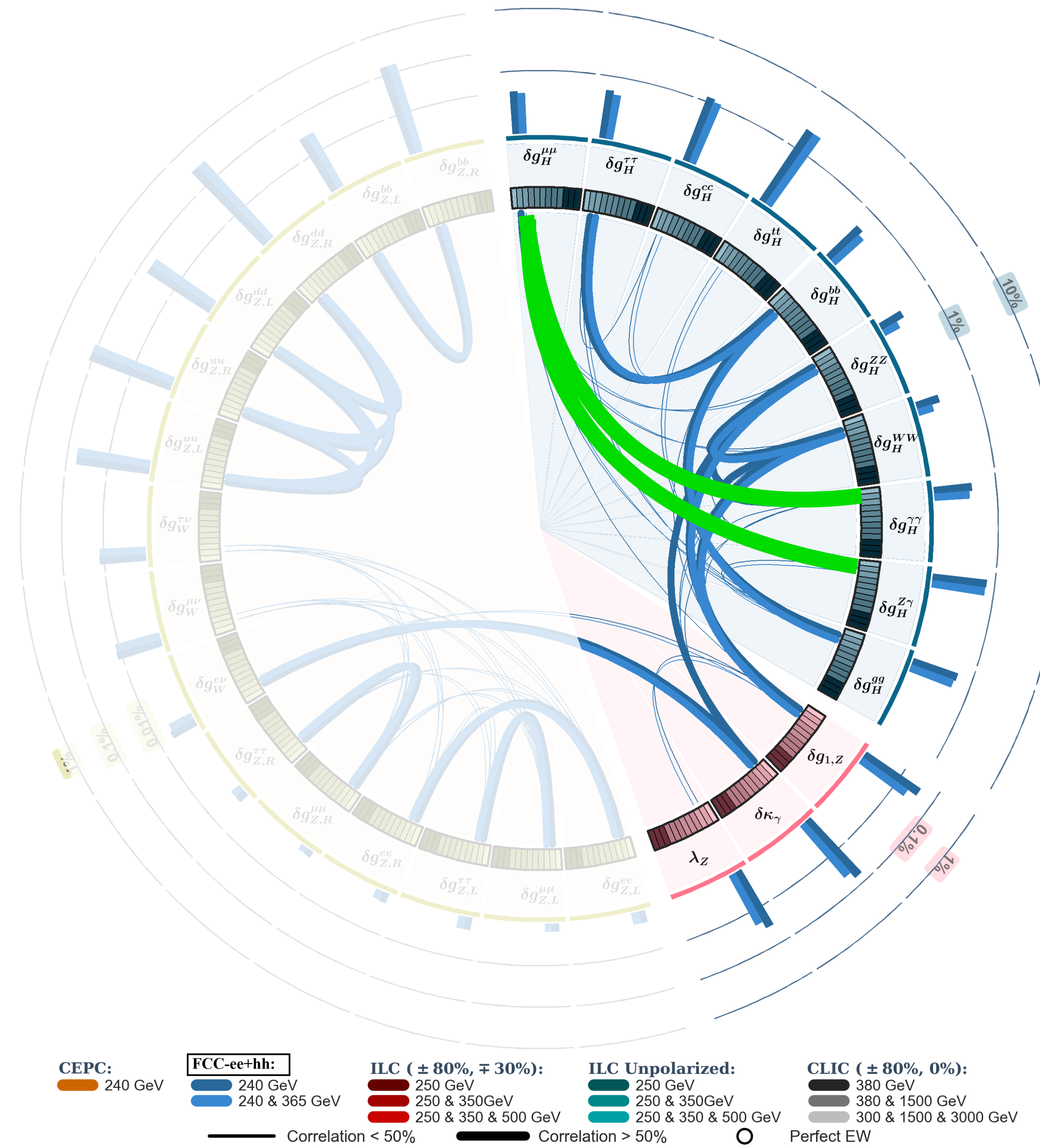
Interplay EW/Higgs at future colliders

Couplings and correlations

FCCee



FCCee+hh



PRELIMINARY

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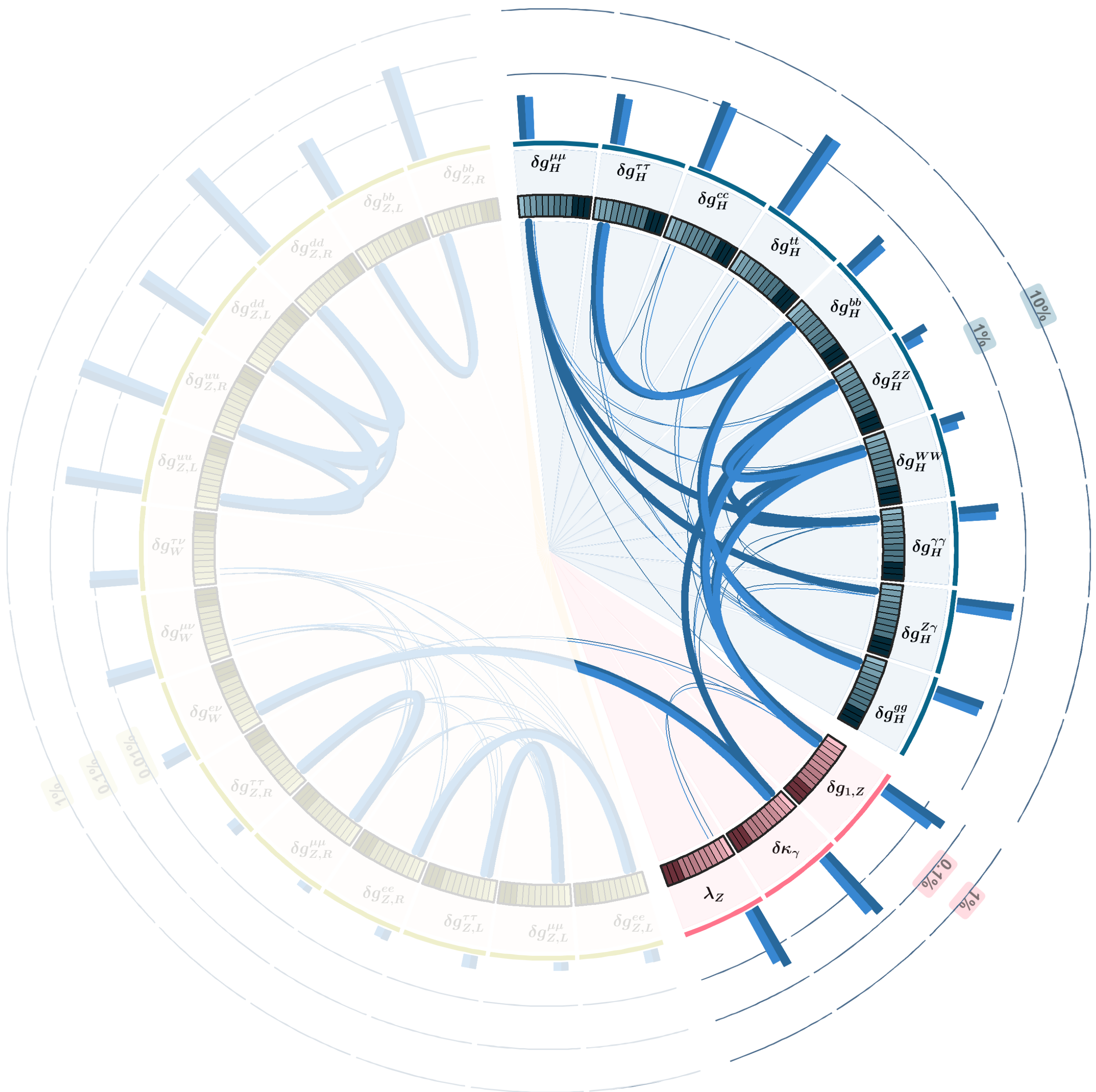
FCC-hh	Yes (μ, $\mathrm{BR}_i/\mathrm{BR}_j$ for rare decays)	From Lepton Coll.	From Lepton Coll.
FCC-eh	Yes (μ: CC & NC DIS $\to HVV$)	From Lepton Coll.	From Lepton Coll.

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

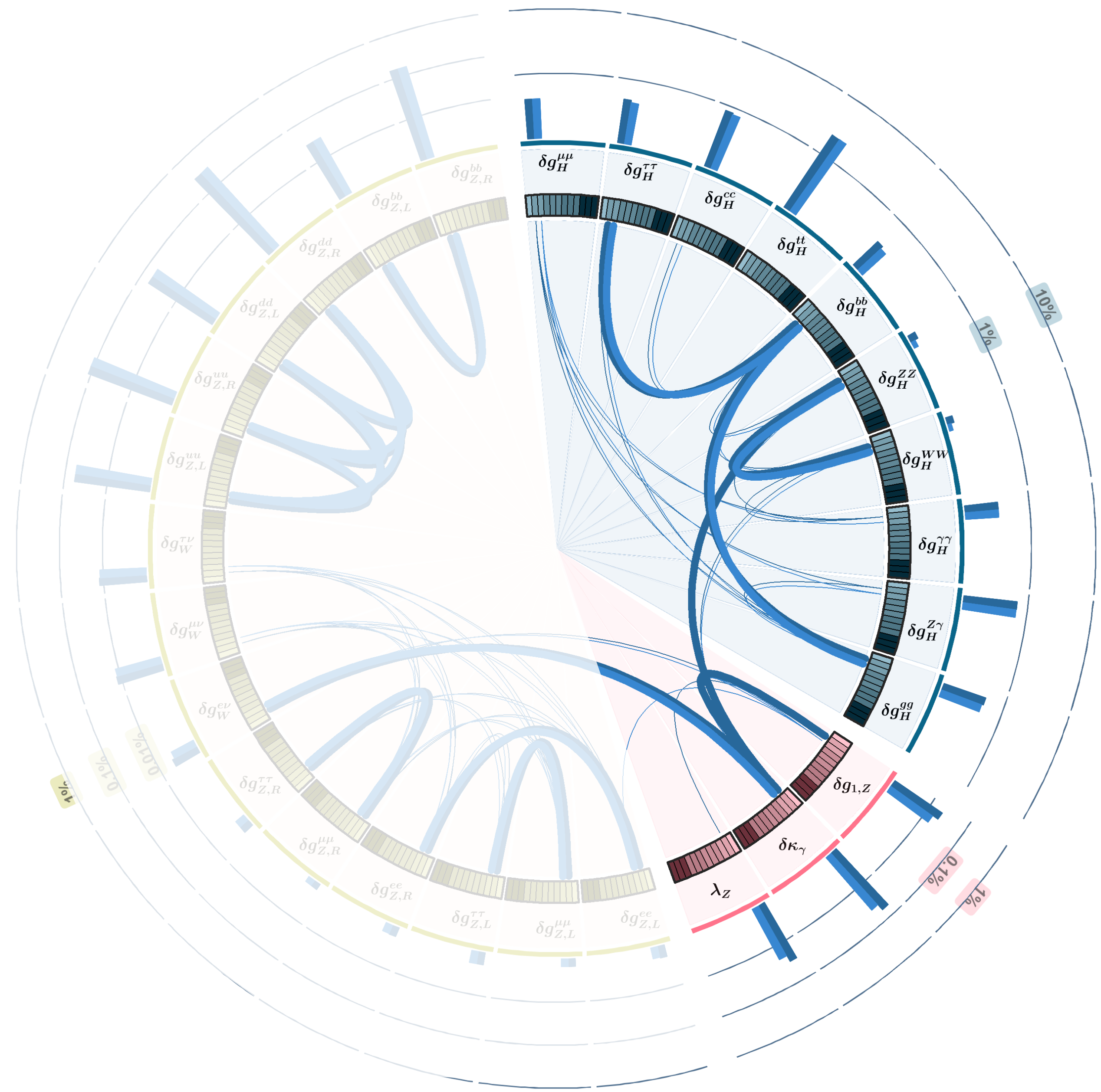
Couplings and correlations

FCCee+hh



CEPC: 240 GeV
FCC-ee+hh: 240 GeV; 240 & 365 GeV
ILC (± 80%, ∓ 30%): 250 GeV; 250 & 350GeV; 250 & 350 & 500 GeV
ILC Unpolarized: 250 GeV; 250 & 350GeV; 250 & 350 & 500 GeV
CLIC (± 80%, 0%): 380 GeV; 380 & 1500 GeV; 300 & 1500 & 3000 GeV
Correlation < 50% — Correlation > 50% — Perfect EW

FCCee+eh+hh



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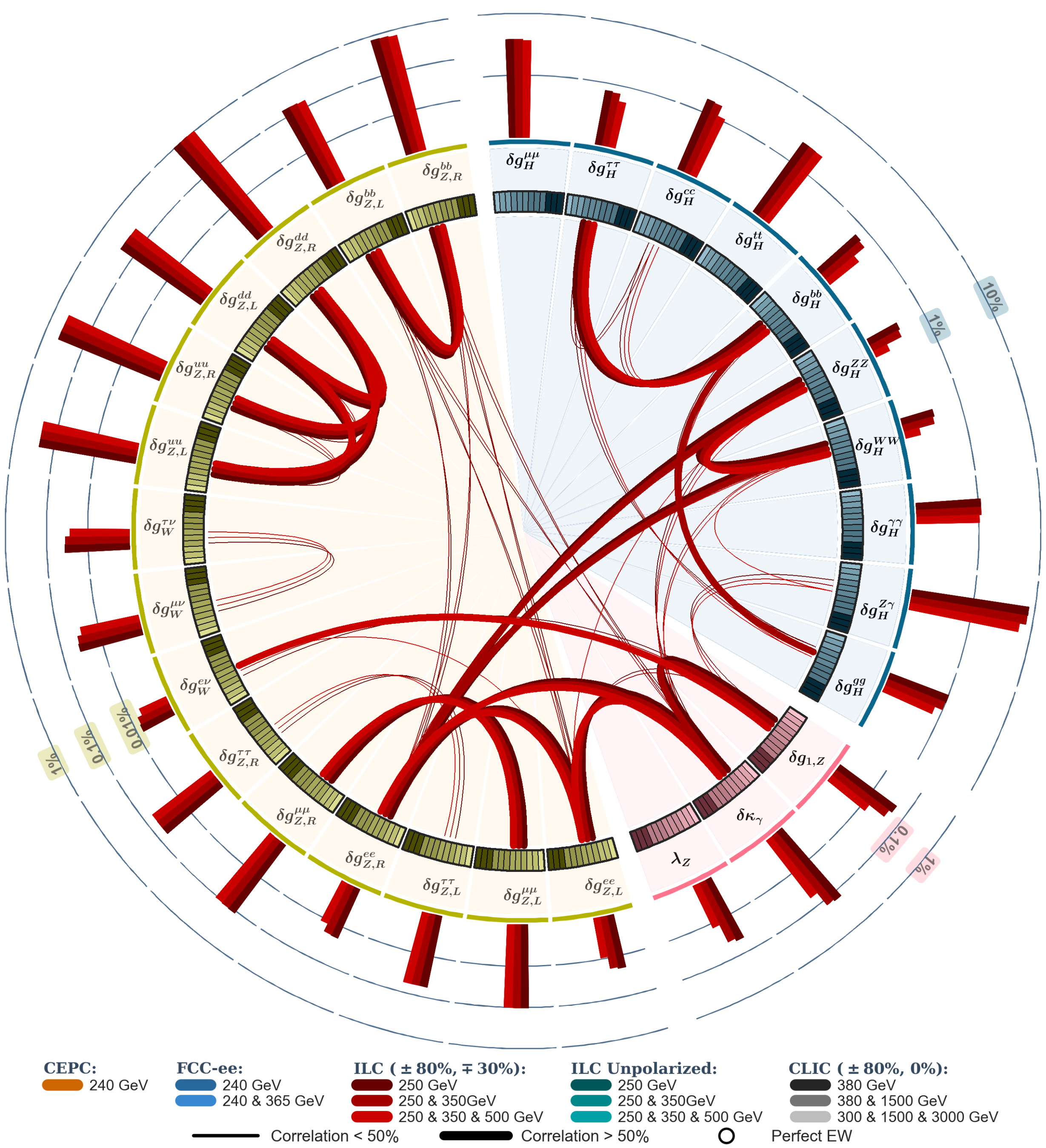
PRELIMINARY

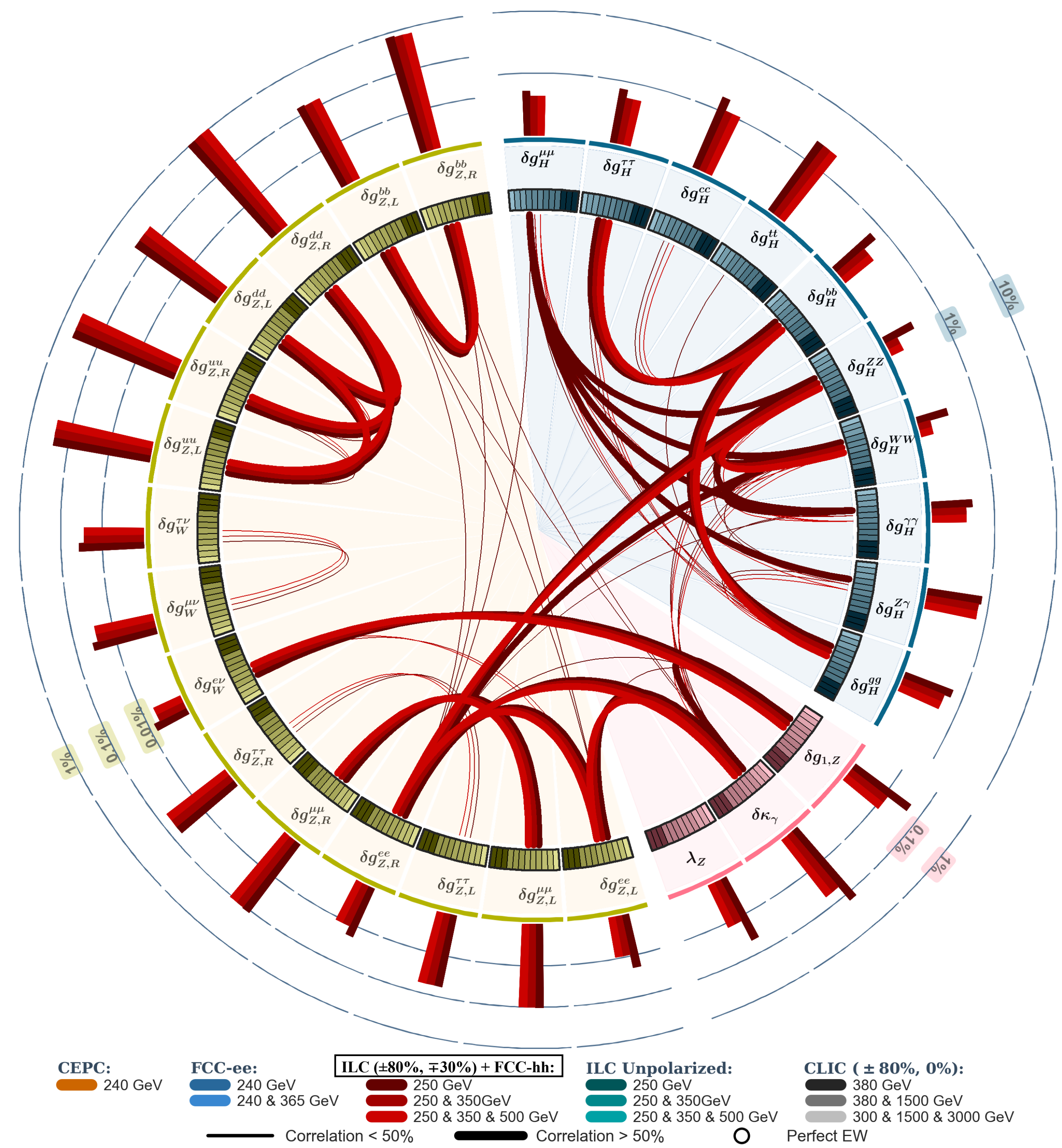
Interplay EW/Higgs at future colliders

Couplings and correlations (ILC+FCChh)

ILC



ILC+FCChh



PRELIMINARY: To be updated with FCCeh soon...

Results from Higgs@Future Colliders WG (ESPP)

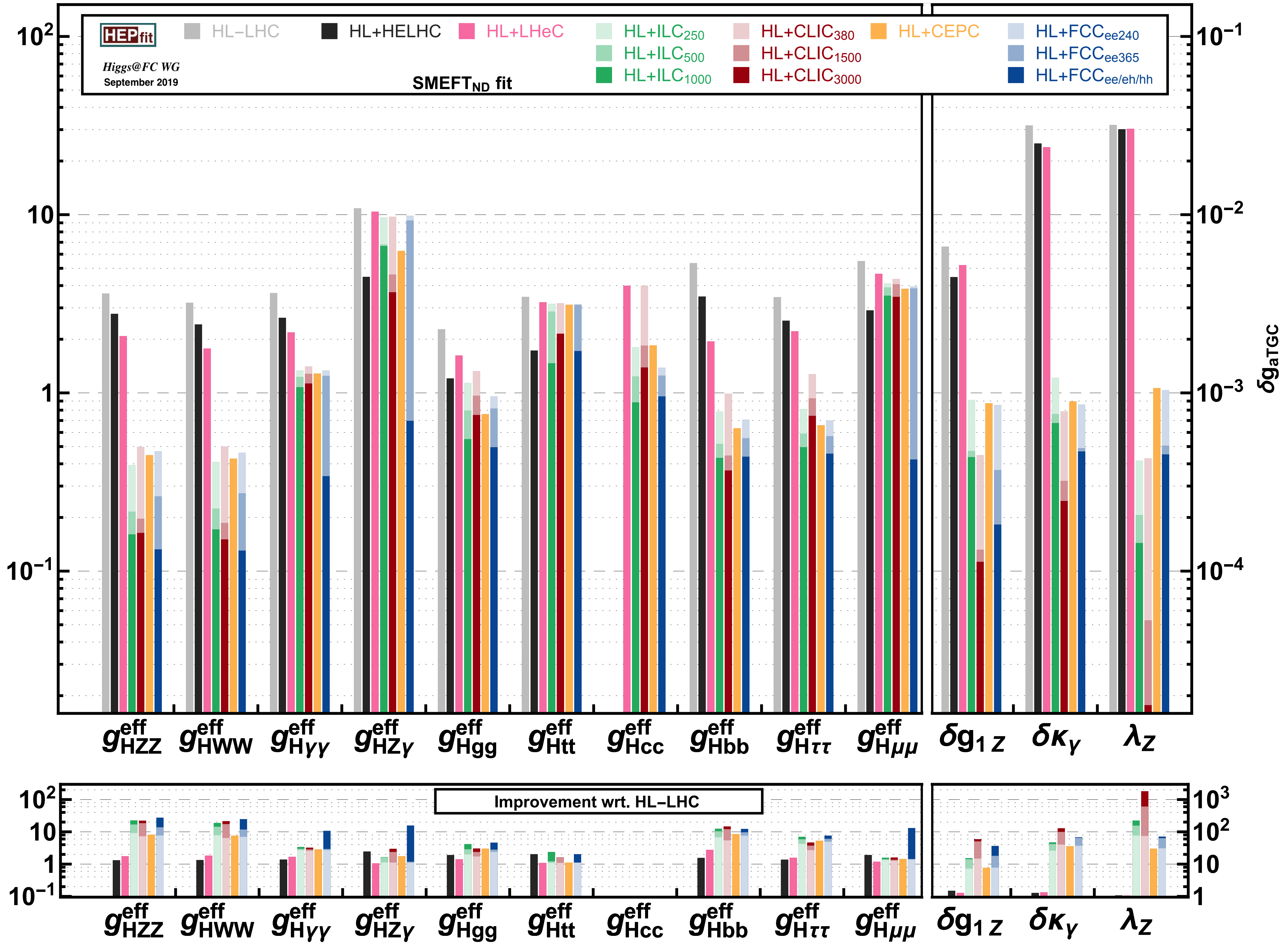
JB, et al., arXiv:1905.03764 [hep-ph]

Single Higgs couplings

Results in the SMEFT-framework (Higgs/aTGC)

EFT results projected into effective Higgs couplings and aTGC

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



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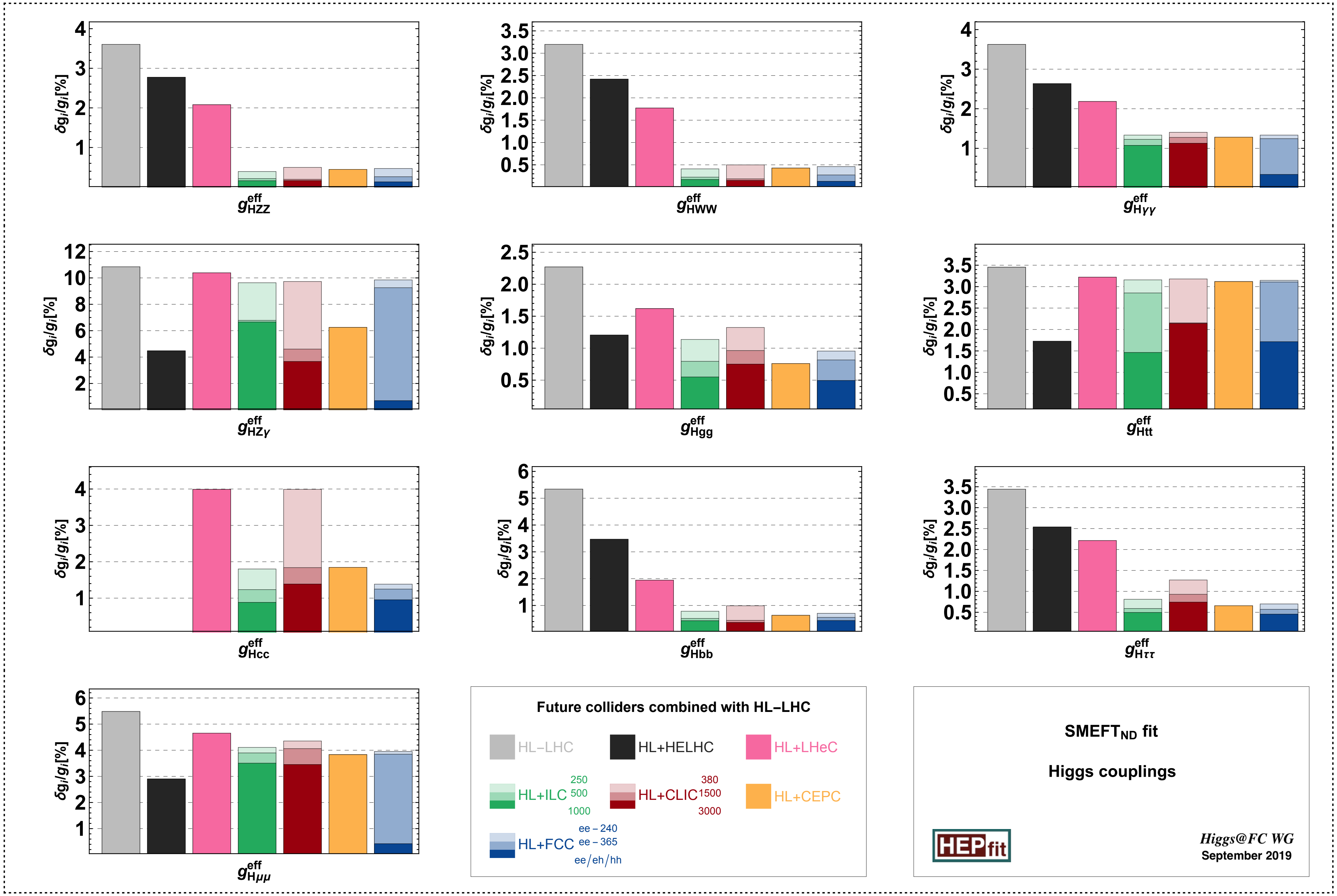
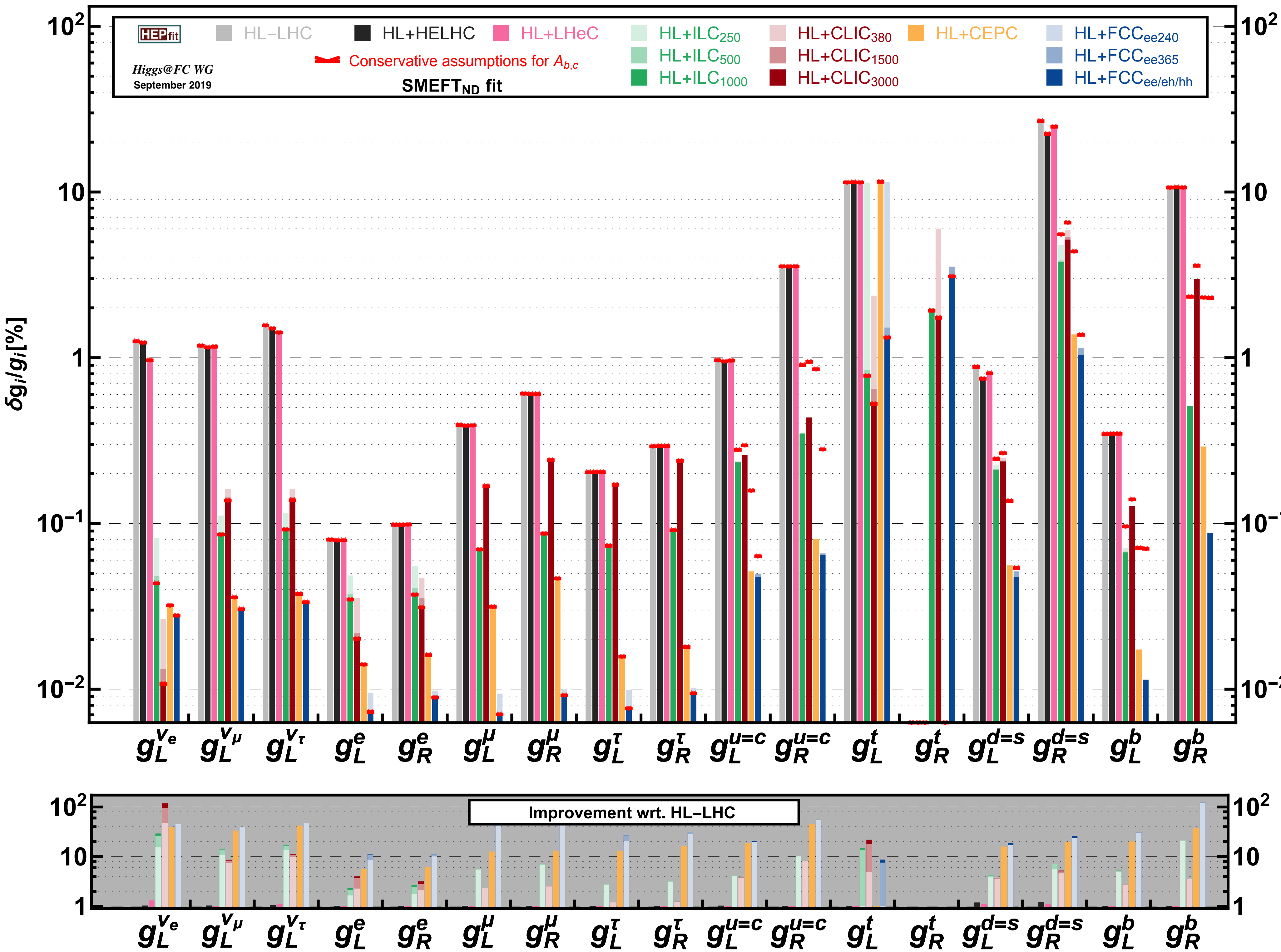


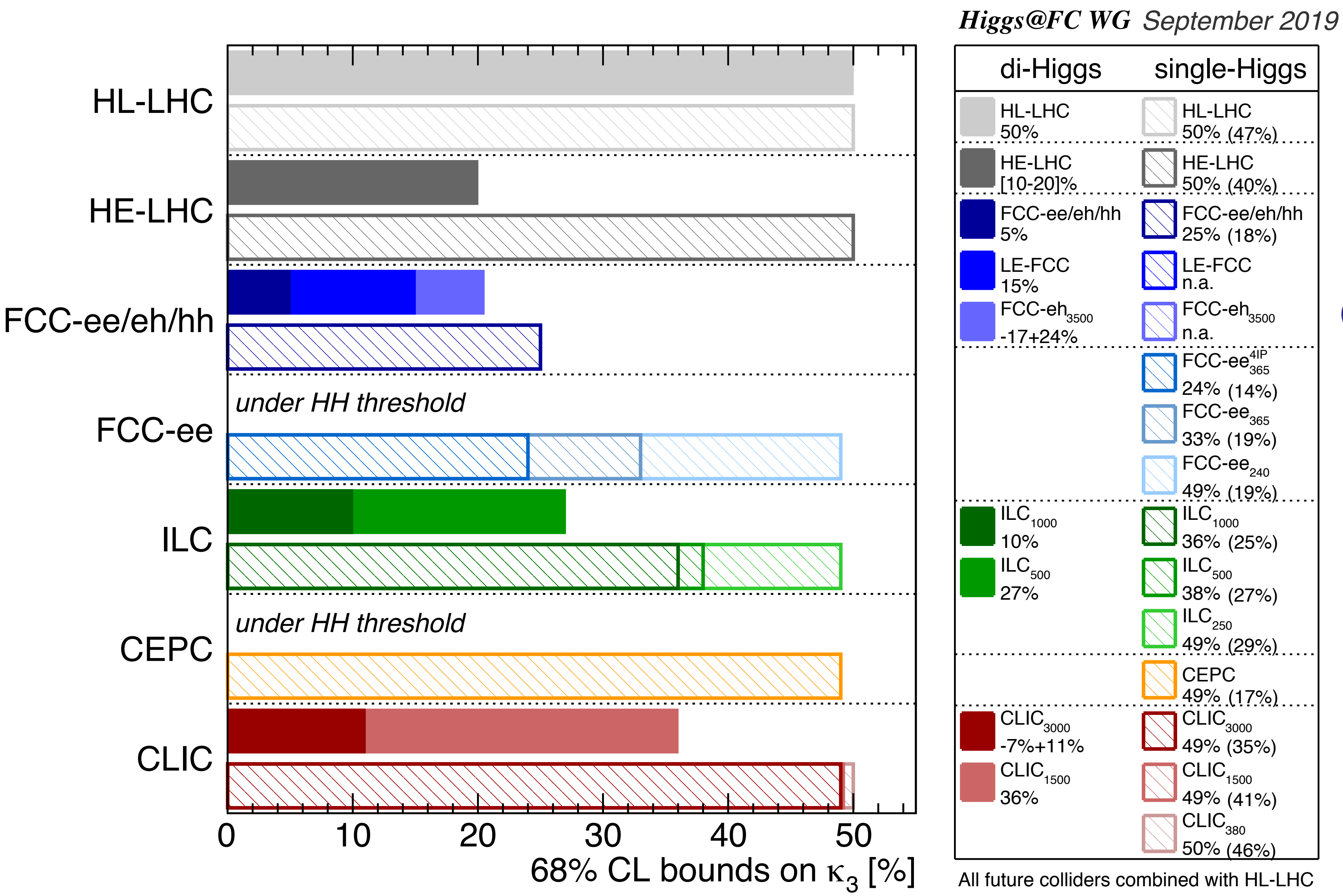
The other “half” of the SMEFT fit: EW Zff couplings

EFT results projected into effective Zff couplings



The Higgs self-coupling

- **Comparison of capabilities to measure the H^3 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

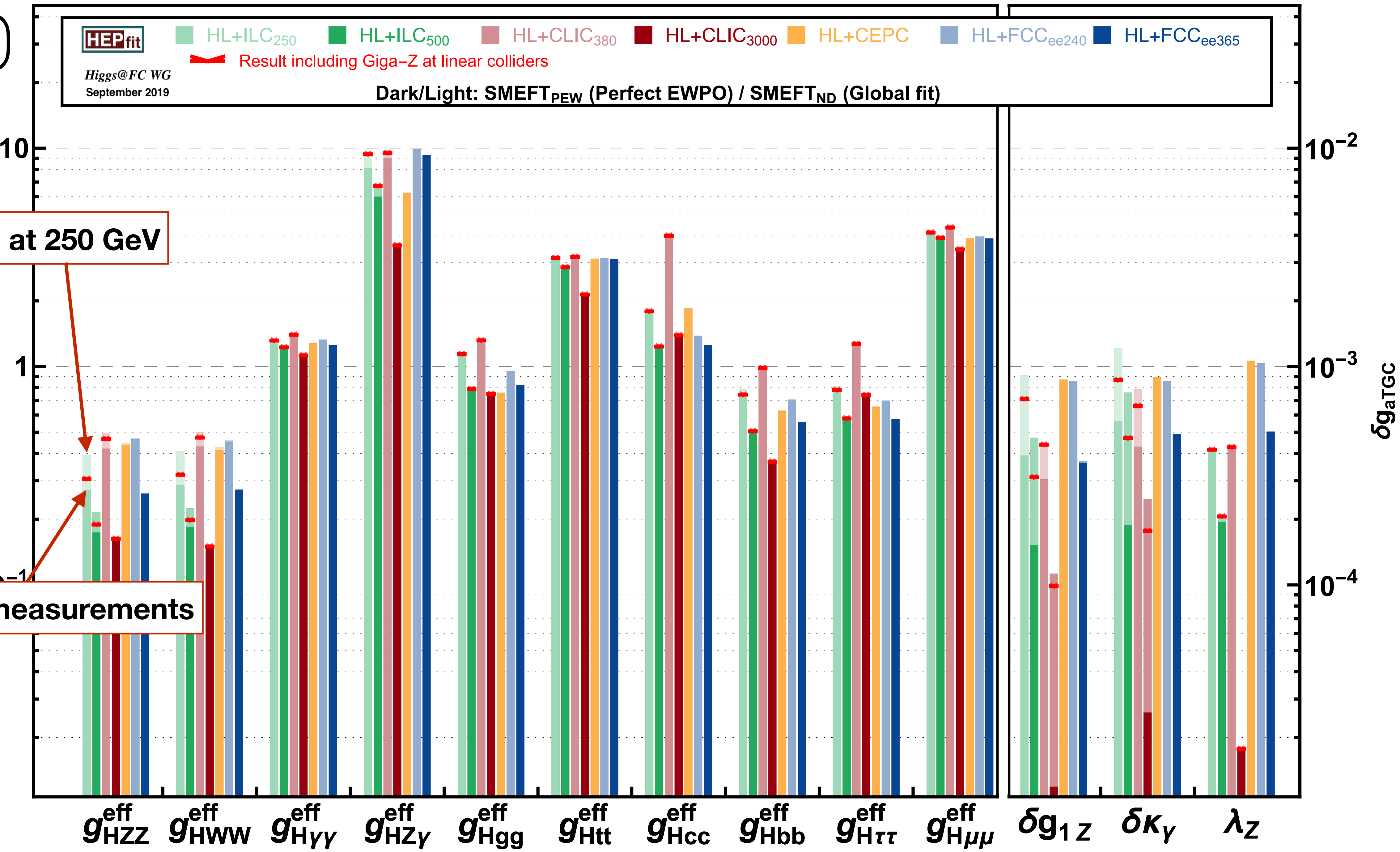
di-Higgs ~10%

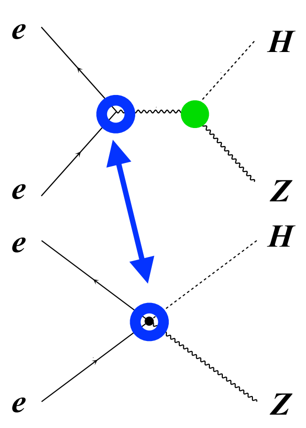
di-Higgs ~27% (10%)
Assuming upgrade to 500 GeV (1000 GeV)

Interplay EW/Higgs at future colliders

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

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





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]

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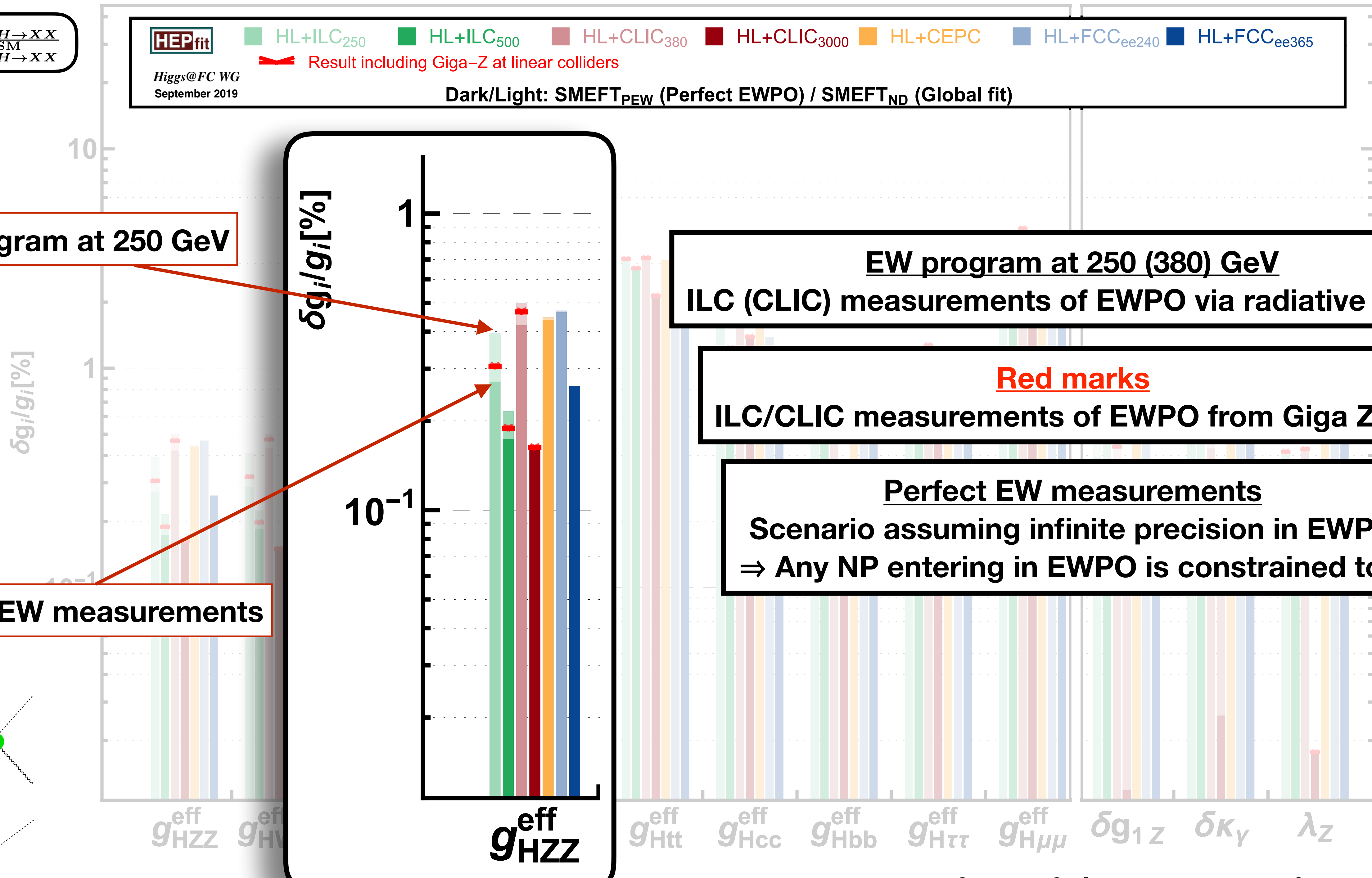


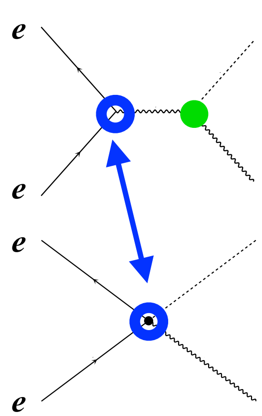
EW program at 250 GeV

Perfect EW measurements

EW program at 250 (380) GeV
ILC (CLIC) measurements of EWPO via radiative return

Red marks
ILC/CLIC measurements of EWPO from Giga Z run

Perfect EW measurements
Scenario assuming infinite precision in EWPO
⇒ Any NP entering in EWPO is constrained to 0



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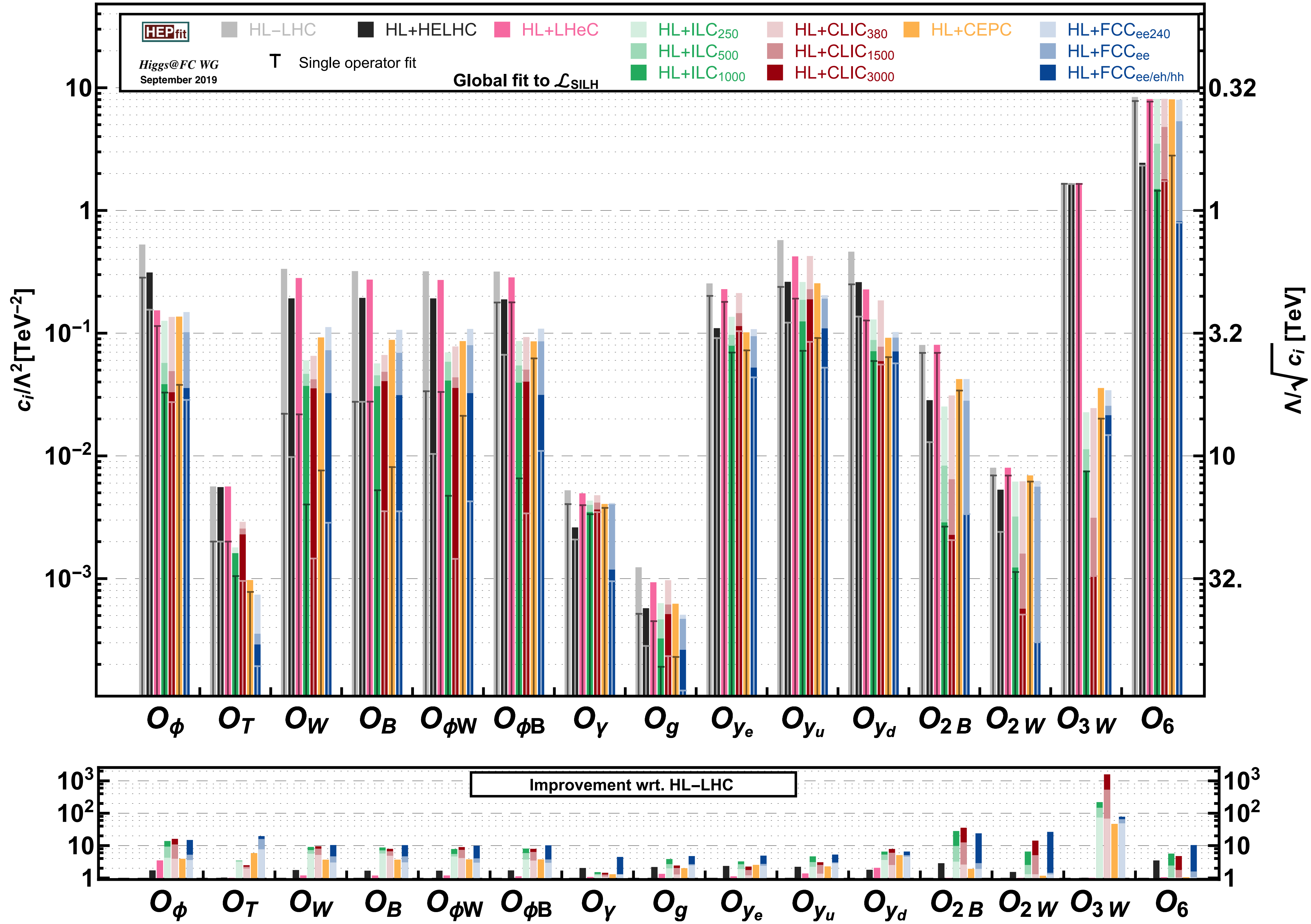
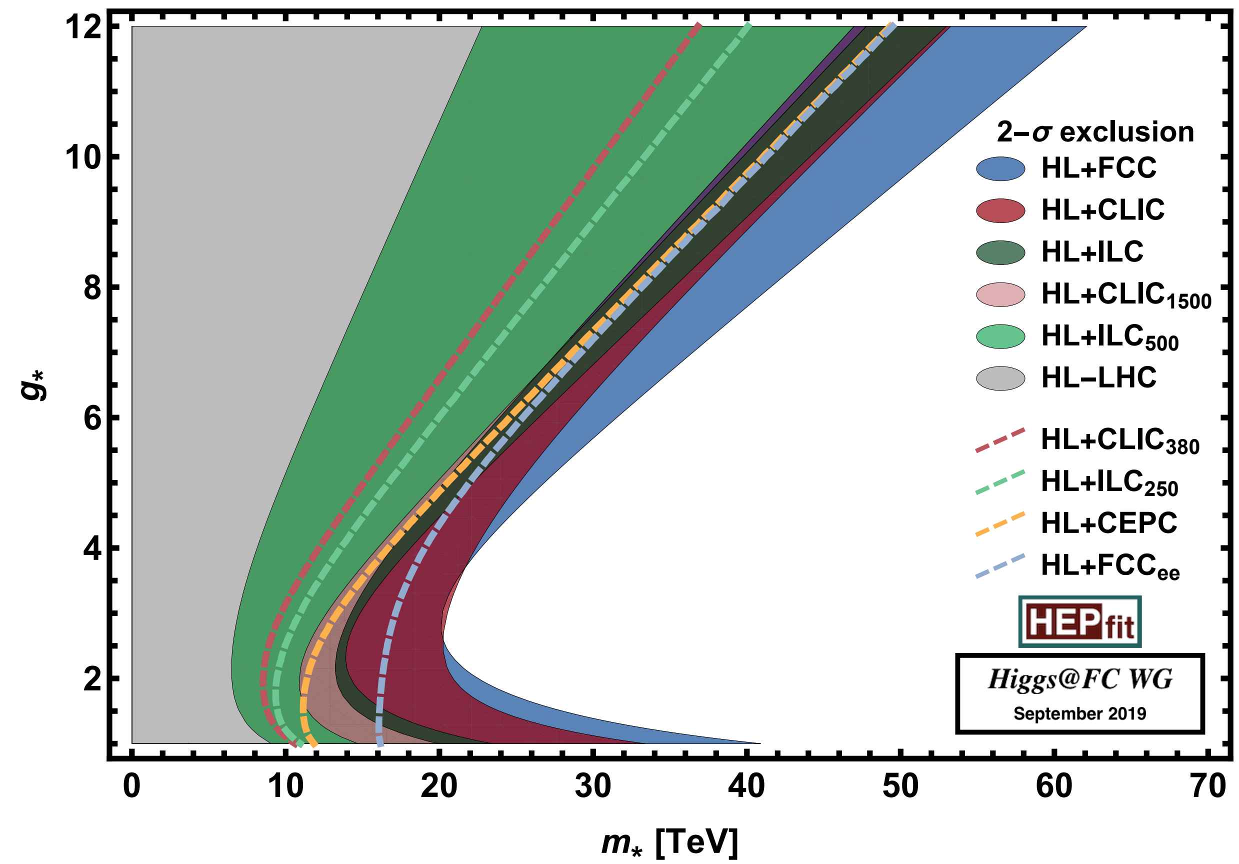
Indirect constraints on Composite Higgs

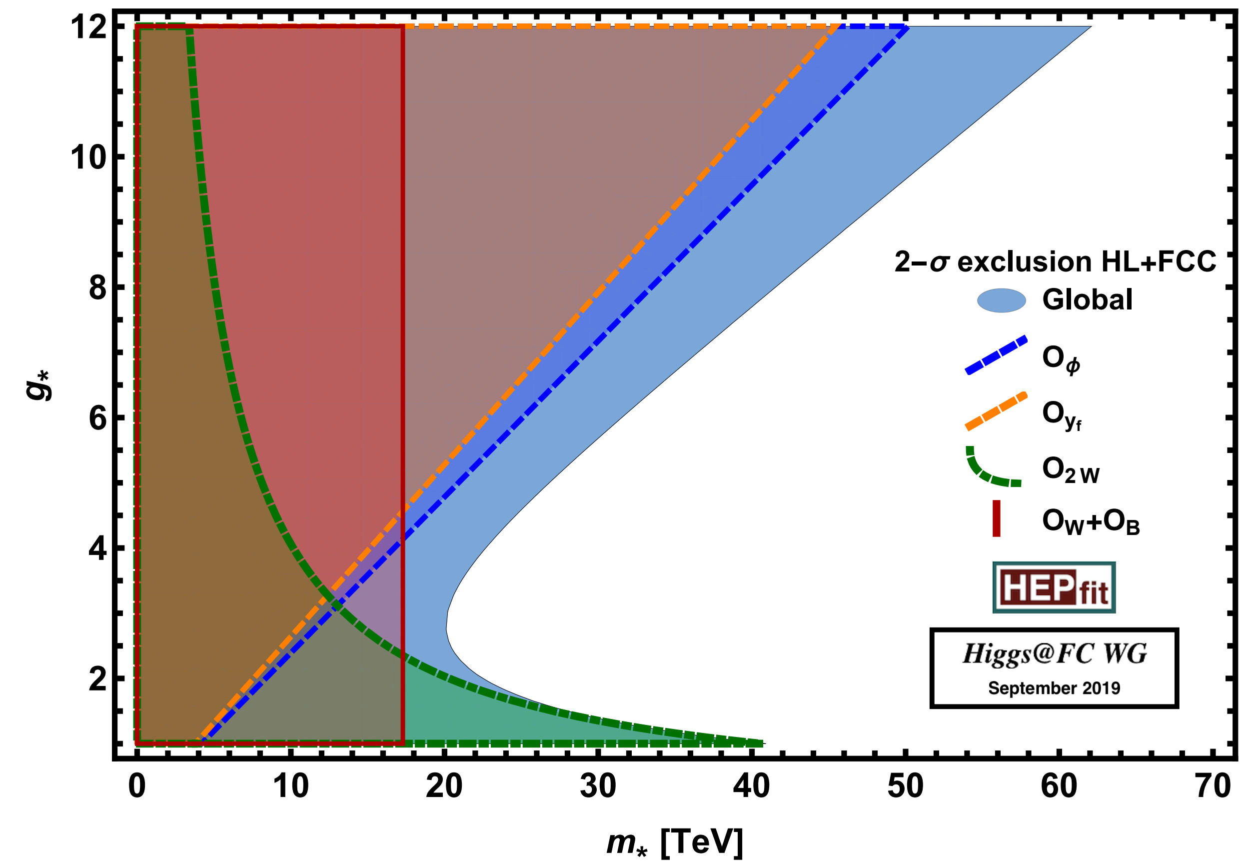
Constraints on SILH effective Lagrangian

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



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. $\Delta\Gamma/\Gamma$ [%] $\mathrm{Th_{Intr}}$	$\mathrm{Th_{Par}}(m_q)$	$\mathrm{Th_{Par}}(\alpha_s)$	$\mathrm{Th_{Par}}(m_H)$
$H \to b\bar{b}$	2379	0.2	$0.6^\flat$	$< 0.1^\sharp$	–
$H \to \tau^+\tau^-$	256	< 0.1	–	–	–
$H \to c\bar{c}$	118	0.2	$1.0^\flat$	$< 0.1^\sharp$	–
$H \to \mu^+\mu^-$	0.89	< 0.1	–	–	–
$H \to WW^*$	883	$\lesssim 0.4$	–	–	$0.1^\ddagger$
$H \to gg$	335	1.0	–	$0.5^\sharp$	–
$H \to ZZ^*$	108	$\lesssim 0.3^\dagger$	–	–	$0.1^\ddagger$
$H \to \gamma\gamma$	–	< 1.0	–	–	–
$H \to Z\gamma$	2.1	1.0	–	–	$0.1^\ddagger$

†From $e^+e^- \to ZH$.

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

$^\flat$For $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV. (Lattice projection).

$^\sharp$For $\delta\alpha_s = 0.0002$. (Lattice projection).

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

Intrinsic TH unc in production

e.g. $e^+e^- \to ZH$

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?

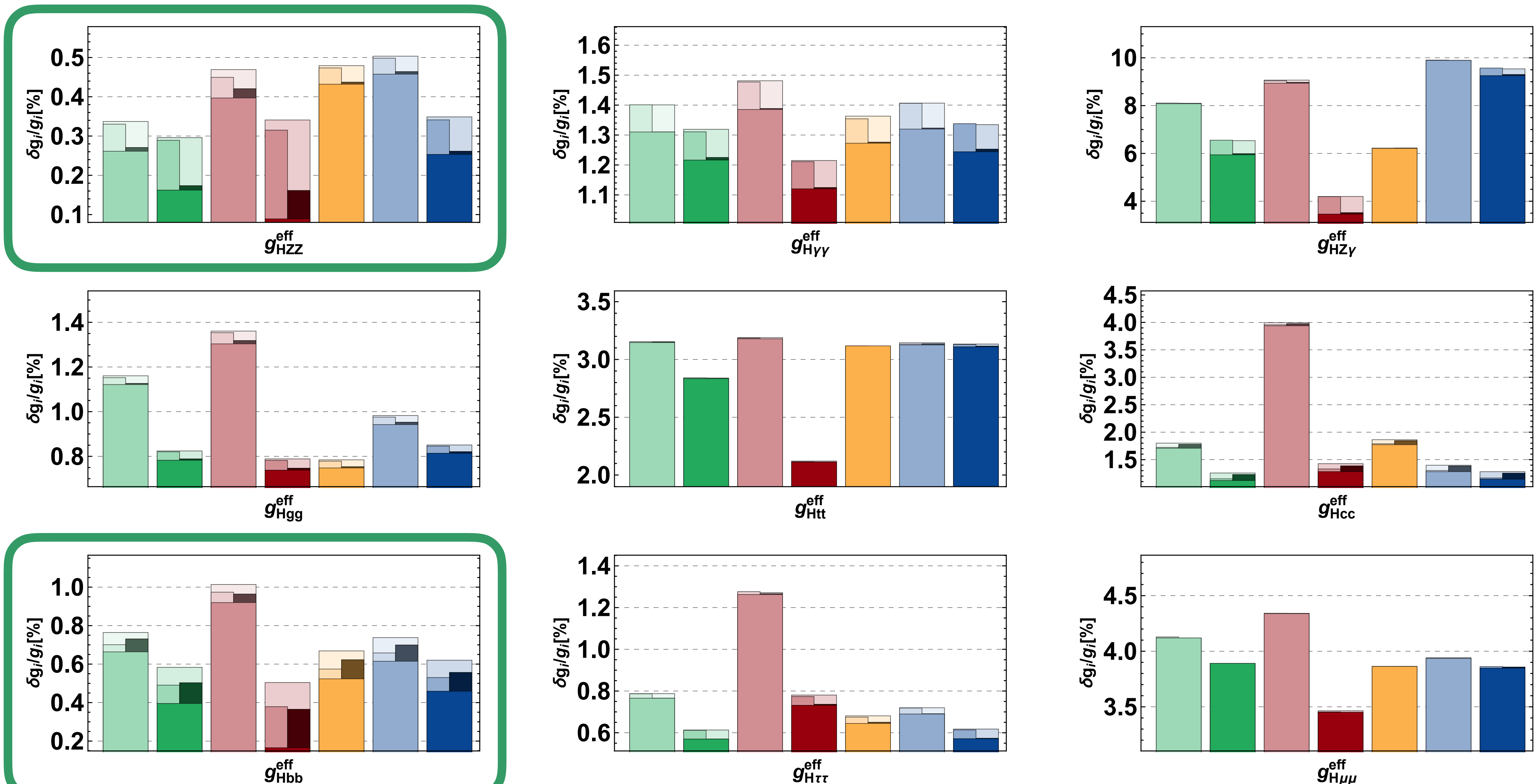
Assessment of TH uncertainty may require full 2->3 NNLO

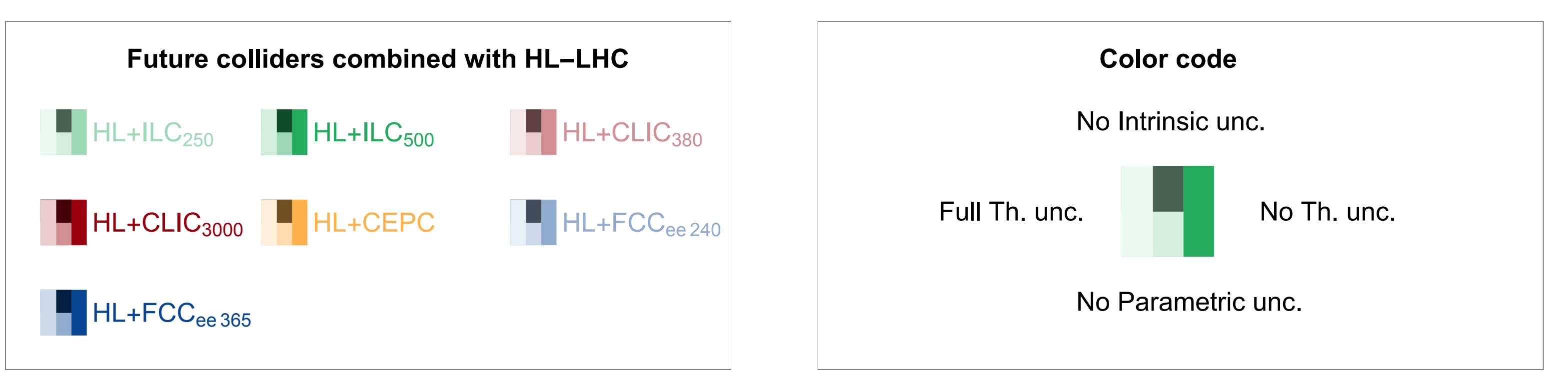
In any case, reducible with necessary effort from theory side

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
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	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

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

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

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