SMEFT fits at Future Colliders:
Studies for the Update of the European Strategy and Beyond

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Based on

J.B., M. Cepeda, J. D'Hondt, R. K. Ellis, C. Grojean, B. Heinemann, F. Maltoni, A. Nisati, E. Petit, R. Rattazzi and W. Verkerke, *JHEP 01 (2020) 139 (1905.03764 [hep-ph])*

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

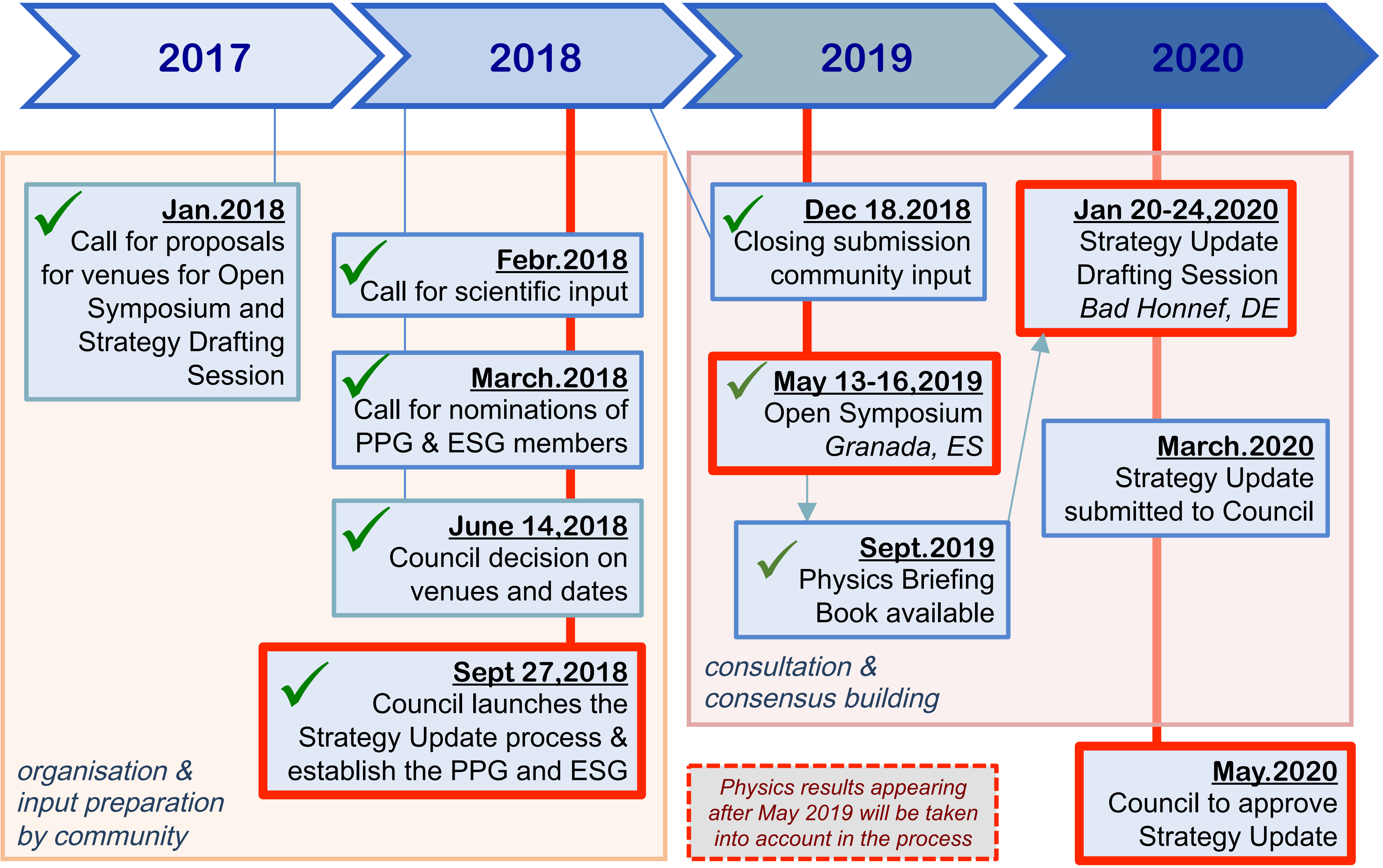
European Strategy Update

Snowmass 2021 - EF04 Topical Group Community Meeting

June 4, 2020

European Strategy Update 2020

European Strategy for Particle Physics: the cornerstone of Europe's decision-making process for the long-term future of the field



2017 · **2018** · **2019** · **2020**

organisation & input preparation by community

✓ **Jan.2018**
Call for proposals for venues for Open Symposium and Strategy Drafting Session

✓ **Febr.2018**
Call for scientific input

✓ **March.2018**
Call for nominations of PPG & ESG members

✓ **June 14,2018**
Council decision on venues and dates

✓ **Sept 27,2018**
Council launches the Strategy Update process & establish the PPG and ESG

consultation & consensus building

✓ **Dec 18.2018**
Closing submission community input

✓ **May 13-16,2019**
Open Symposium
Granada, ES

✓ **Sept.2019**
Physics Briefing Book available

Physics results appearing after May 2019 will be taken into account in the process

Jan 20-24,2020
Strategy Update Drafting Session
Bad Honnef, DE

March.2020
Strategy Update submitted to Council

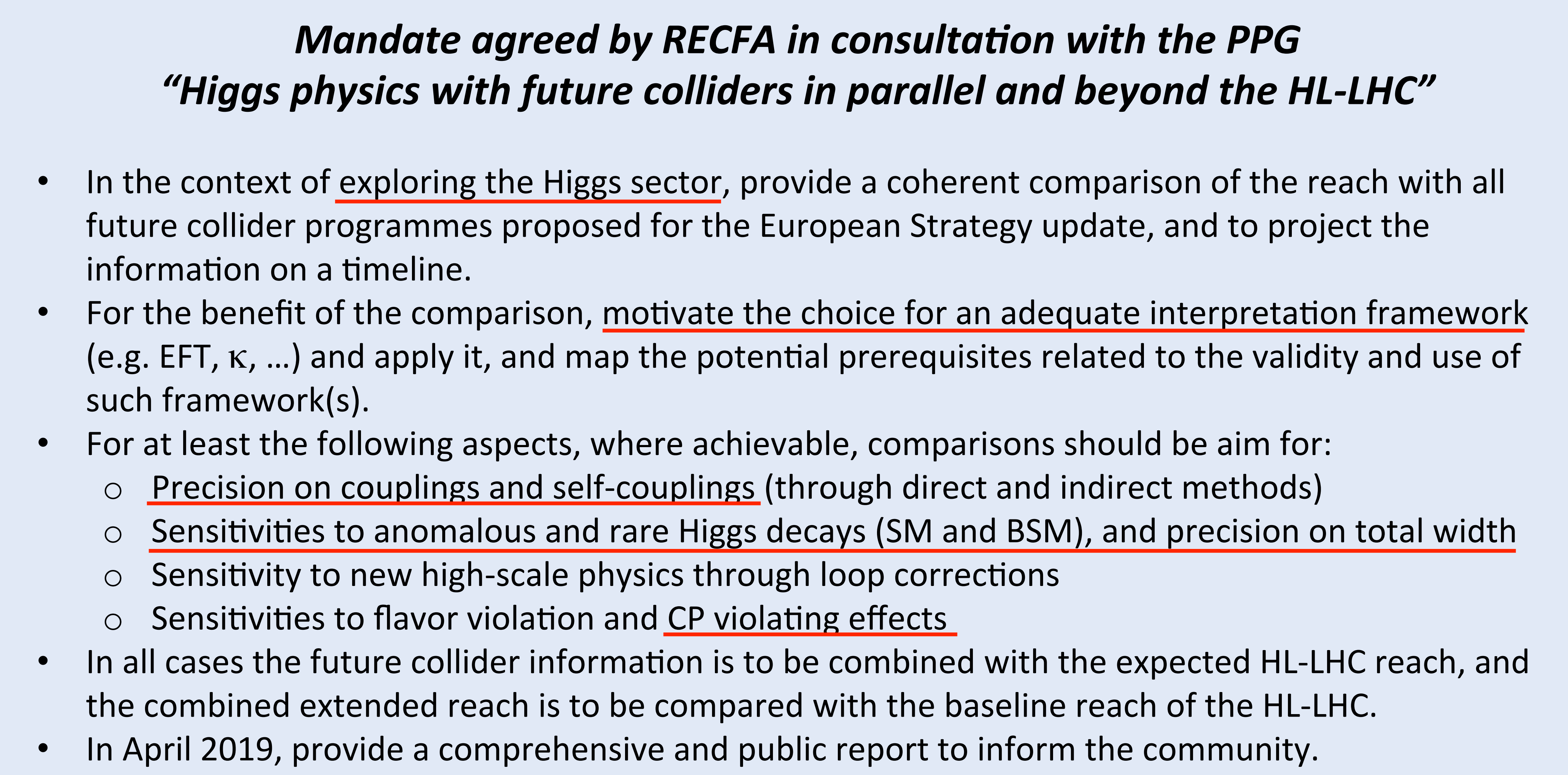
May.2020
Council to approve Strategy Update

Draft still confidential

No official timeline for release

European Strategy Update 2020

- Different Working Groups formed to assist the Physics Preparatory Group (PPG) in evaluating the physics potential of the different future experimental projects in different areas: Higgs/EW, Strong Interactions, BSM, …
- The Higgs@Future Colliders WG was formed by RECFA for this purpose, to help in areas related to Higgs physics:

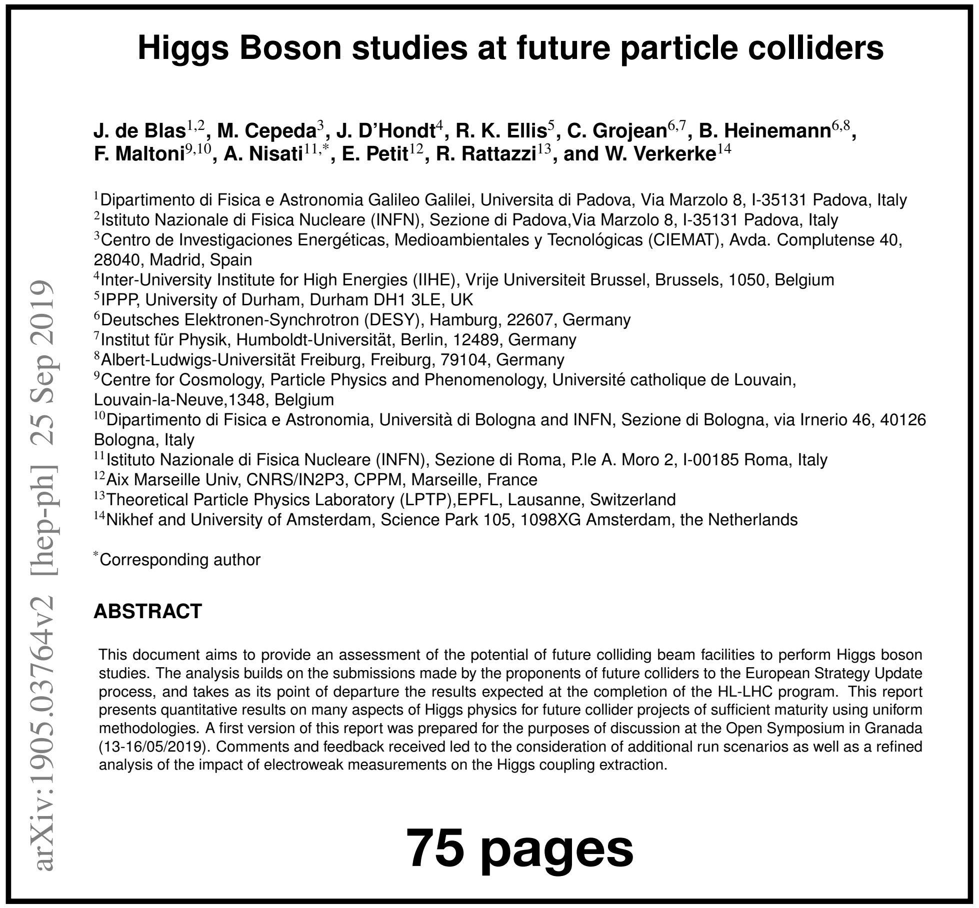


Mandate agreed by RECFA in consultation with the PPG
"Higgs physics with future colliders in parallel and beyond the HL-LHC"

- In the context of exploring the Higgs sector, provide a coherent comparison of the reach with all future collider programmes proposed for the European Strategy update, and to project the information on a timeline.
- For the benefit of the comparison, motivate the choice for an adequate interpretation framework (e.g. EFT, κ, …) and apply it, and map the potential prerequisites related to the validity and use of such framework(s).
- For at least the following aspects, where achievable, comparisons should be aim for:
  - Precision on couplings and self-couplings (through direct and indirect methods)
  - Sensitivities to anomalous and rare Higgs decays (SM and BSM), and precision on total width
  - Sensitivity to new high-scale physics through loop corrections
  - Sensitivities to flavor violation and CP violating effects
- In all cases the future collider information is to be combined with the expected HL-LHC reach, and the combined extended reach is to be compared with the baseline reach of the HL-LHC.
- In April 2019, provide a comprehensive and public report to inform the community.

EW/Higgs studies for the ESU

- The main outcome of the Higgs@FC working group studies is collected in the report in **JHEP 01 (2020) 139 (1905.03764 [hep-ph])** and some of its results are summarized in the *Electroweak Physics* chapter of the **Physics Briefing Book**



arXiv:1905.03764v2 [hep-ph] 25 Sep 2019

Higgs Boson studies at future particle colliders

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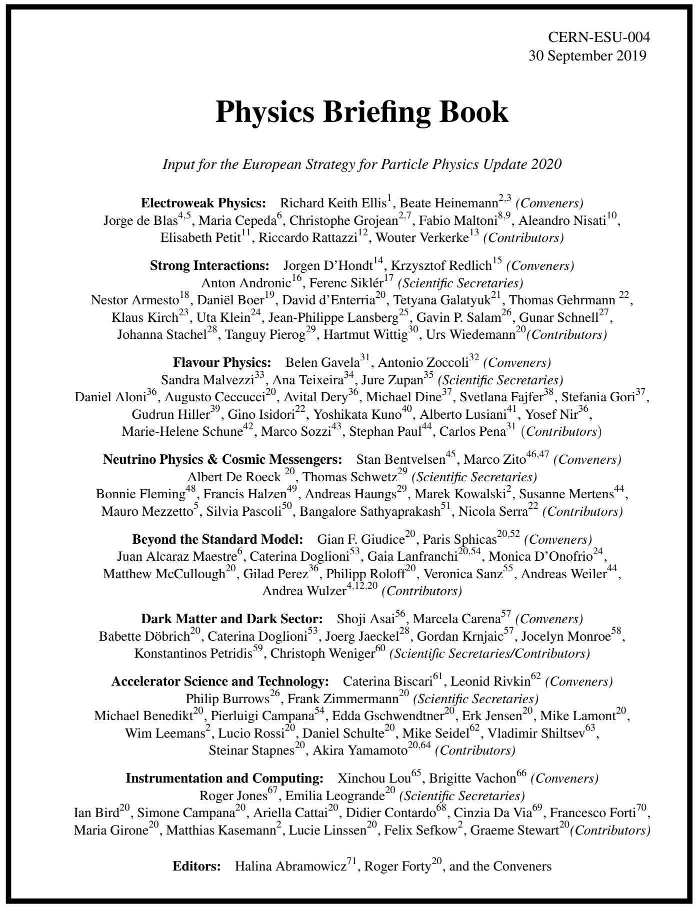
ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

75 pages



CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis[1], Beate Heinemann[2,3] *(Conveners)*
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Nestor Armesto[18], Daniël Boer[19], David d'Enterria[20], Tetyana Galatyuk[21], Thomas Gehrmann [22],
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Gudrun Hiller[39], Gino Isidori[22], Yoshikata Kuno[40], Alberto Lusiani[41], Yosef Nir[36],
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Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners

- Here I will briefly present some of the SMEFT results prepared for the Higgs@FC WG, as well as some items to go beyond the ESU studies

- For more details, see C. Grojean's talk at the EF01 kickoff meeting on May 13, 2020

Comparison framework

- **Studies prepared using 2 frameworks and different scenarios:**

κ-framework

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

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

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

Comparison framework

- **Studies prepared using 2 frameworks and different scenarios:**

κ-framework

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

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

-Also useful for validation of our procedure/code, comparing with the κ fits prepared by the different future collider projects

-Not covered in this talk. See C. Grojean's talk at EF01 kickoff meeting for results in this formalism

ys

NP scenarios (e.g. CH, MSSM)

(interpreted only as mod. of SM-like H couplings)

SMEFT-framework

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Comparison framework

- **Global SMEFT studies: Fit to Higgs/EWPO/diBoson/Top**

SMEFT assumptions

- SMEFT truncated at the dim 6 in the EFT expansion (Calculations performed in a modified version of the Warsaw basis)
- Neglect effects from 4-fermion operators other than the 4-lepton operator contributing to μ decay (and hence to G_F).
  - 4-fermion operators assumed to be constrained better in non-Higgs processes (e.g. $pp \to ff$ or $e^+e^- \to ff$ at high E)
- No dipole operators (Could be relevant for general analysis of Top processes, but are neglected in our studies)
- Two types of flavor assumptions: flavour universal (18 NP pars) and flavour diagonal (30 NP pars)

Neutral Diagonal: SMEFT$_{\rm ND}$ fit

-Hff and Vff ($HVff$) diagonal in the physical basis
-Vff ($HVff$) flavour universality respected by first 2 quark families

-Better for exploration of H & EW capabilities at future colliders
-Cumbersome from model-building point of view to avoid FCNC

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

Higgs/VVV

$$\mathrm{SMEFT}_{\rm ND} \equiv \{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\}$$
$$+\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_\ell\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}$$

Vff/hVff

5 SM + 30 New Physics Parameters

Comparison framework

- **Global SMEFT studies: Presentation of SMEFT fit results**
- Compare Future Collider sensitivity to BSM deformations in a basis-independent way:
  - **Effective Higgs couplings: Project EFT fit results from dim-6 Wilson coefficients/Higgs "basis" parameters into (pseudo) observable quantities**

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

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

Only these are described in κ-framework

  - **Not enough** to match EFT d.o.f. modifying H interactions → **Add aTGC**

  - Similarly, for EW interactions, **project results into effective *Zff* couplings** defined from EWPO, e.g.

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

Fitting framework

General strategy for calculation of future sensitivities

- Fit to new physics effects parameterized by the dimension 6 SMEFT:
  - Bayesian fit using HEPfit
    Eur.Phys.J.C 80 (2020) 5, 456 (arXiv:1910.14012 [hep-ph])
    http://hepfit.roma1.infn.it
  - **Future sensitivity** from posterior info (NP-parameters/Observables errors/ limits)

- **Assumptions:**
  - **Likelihood:** SM predictions as central values for future "experimental" measurements. Errors given by projected experimental uncertainties.
  - **New physics effects:** Working at the linear-level in the EFT effects (interference with SM amplitudes)

$$O = O_{\rm SM} + \delta O_{\rm NP}\frac{1}{\Lambda^2}$$

  - **SM theory uncertainties:** SM intrinsic and parametric uncertainties reduced according to future projections. Included in the analysis when available via nuisance parameters + marginalization

Main results presented with SM parametric uncertainties

(Impact of different TH uncertainties also discussed)

Inputs of the SMEFT fits

Future Collider projects included in the study

Future Particle Colliders

	Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
pp	HL-LHC	*pp*	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
	HE-LHC	*pp*	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
	FCC-hh$^{(*)}$	*pp*	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
e^+e^-	FCC-ee	*ee*	M_Z	0/0	2	100/200	150	4	[1]	
			$2M_W$	0/0	2	25	10	1-2		
			240 GeV	0/0	2	7	5	3		FCC-ee_{240}
			$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
								(+1)		(1y SD before $2m_{top}$ run)
	ILC	*ee*	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC_{250}
			350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
			500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
								(+1)		(1y SD after 250 GeV run)
			1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC_{1000}
								(+1-2)		(1-2y SD after 500 GeV run)
	CEPC	*ee*	M_Z	0/0	2	17/32	16	2	[2]	CEPC
			$2M_W$	0/0	2	10	2.6	1		
			240 GeV	0/0	2	3	5.6	7		
	CLIC	*ee*	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC_{380}
			1.5 TeV	±80/0	1	3.7	2.5	7		CLIC_{1500}
			3.0 TeV	±80/0	1	6.0	5.0	8		CLIC_{3000}
								(+4)		(2y SDs between energy stages)
ep	LHeC	*ep*	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
	HE-LHeC	*ep*	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
	FCC-eh	*ep*	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

Note: Different definitions of “Year”: ILC 1.6 x 10^7 sec, FCC-ee/CLIC: 1.2 x 10^7 sec, CEPC: 1.3 x 10^7 sec

Higgs and EW physics at Future Colliders

- Inputs included in the fits (from ESU documents and refs. therein):

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**	**Top EW**
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return, Giga-Z)	Yes
HE-LHC	Extrapolated from HL-LHC	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_w$)	-
FCC-hh	Yes (μ, BR_i/BR_j) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_w$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

Higgs and EW physics at Future Colliders

- Inputs included in the fits (from ESU documents and refs. therein):

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

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

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

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

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

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

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes (μ, σ_{ZH})	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_w$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

Results always presented in combination with the expected knowledge of H/EW interactions at the end of the HL-LHC era

As part of the Higgs@FC mandate, we restrict our main results to using the inputs of the different future collider projects <u>as provided</u> in the corresponding reports

(Note that in some cases there is different level of sophistication, e.g. fast vs full simulation)

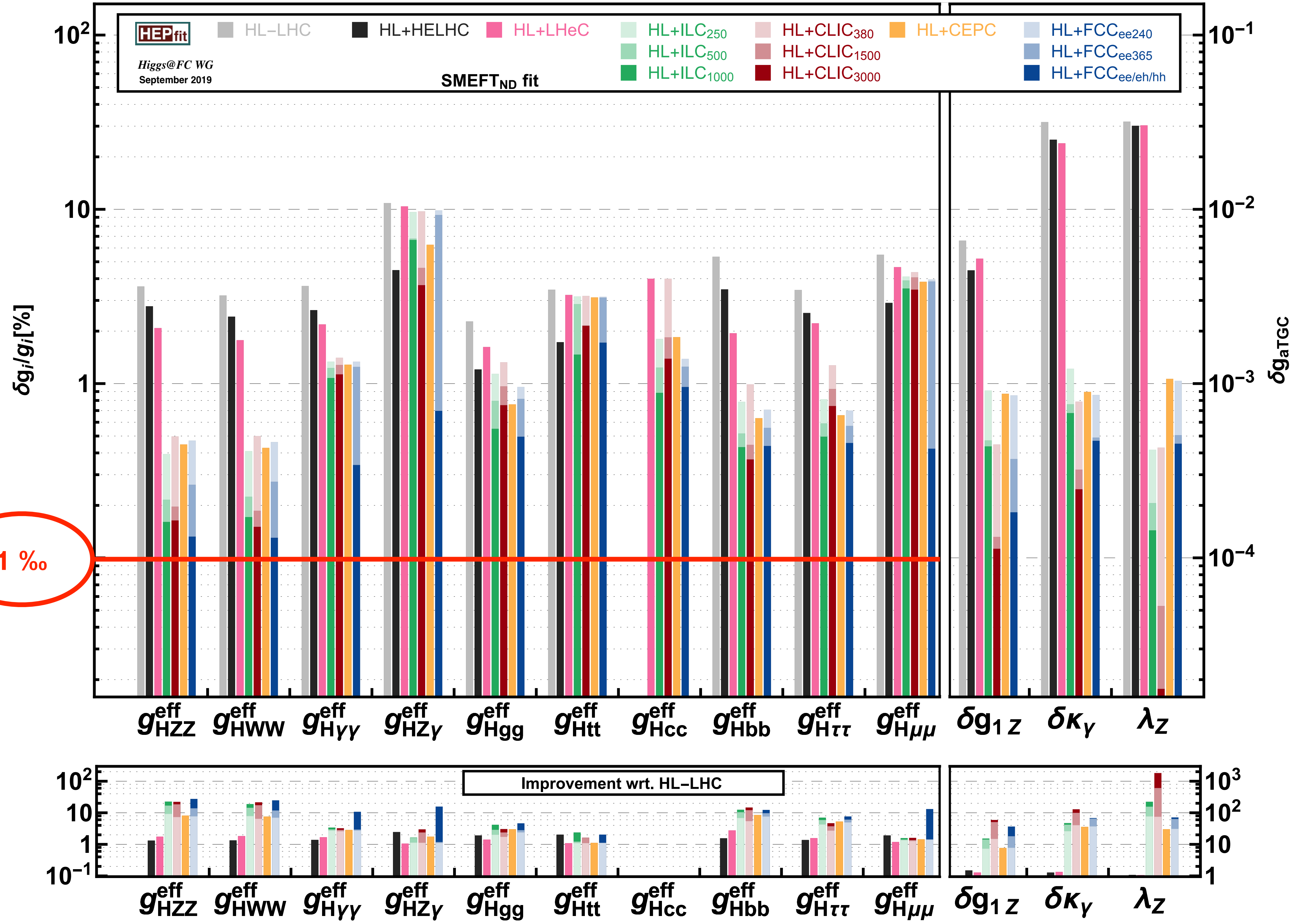
SMEFT fit results

Single Higgs couplings

Results in the SMEFT-framework (Higgs/aTGC)

EFT results projected into effective Higgs couplings and aTGC

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



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Single Higgs couplings

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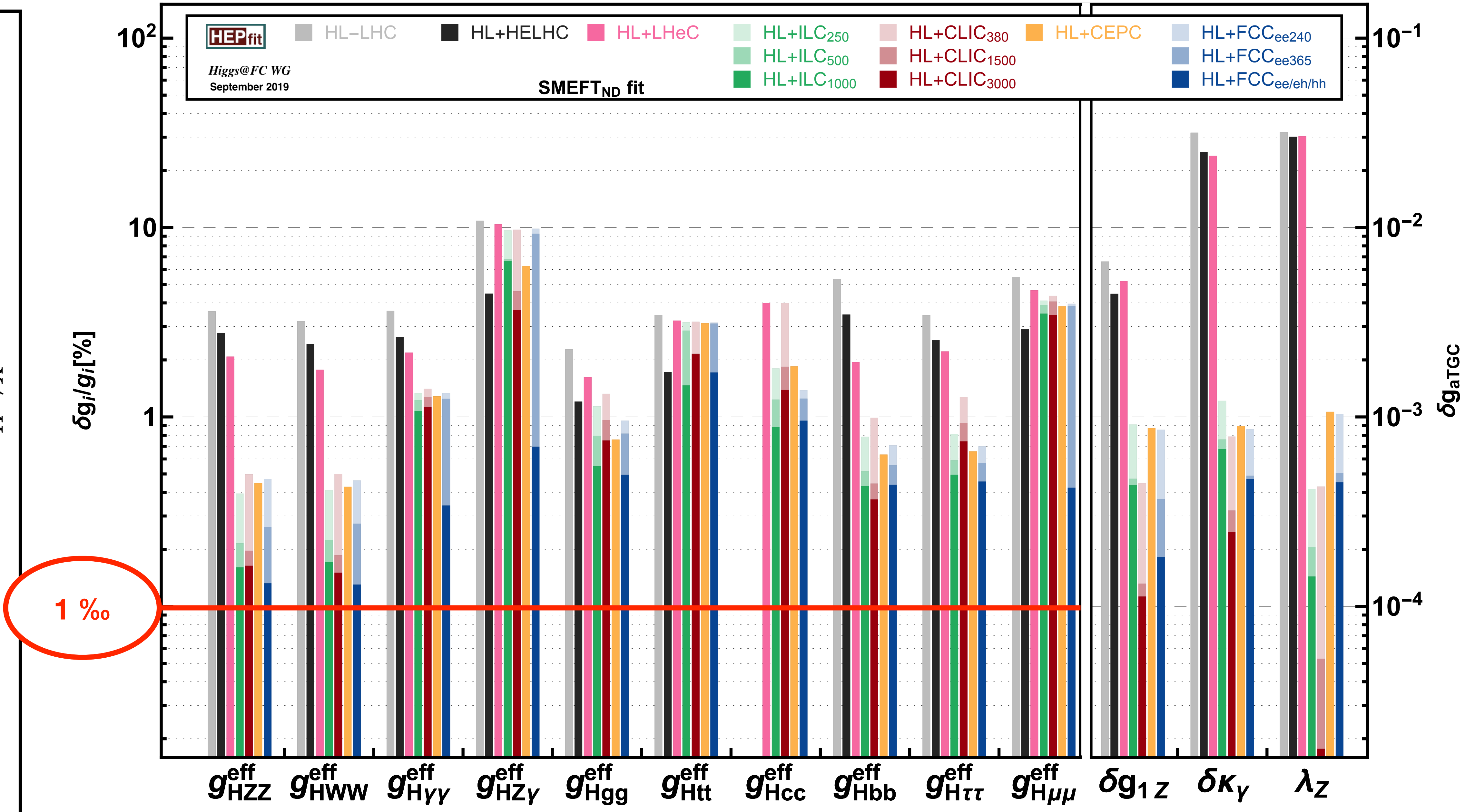
EFT results projected into effective Higgs couplings and aTGC

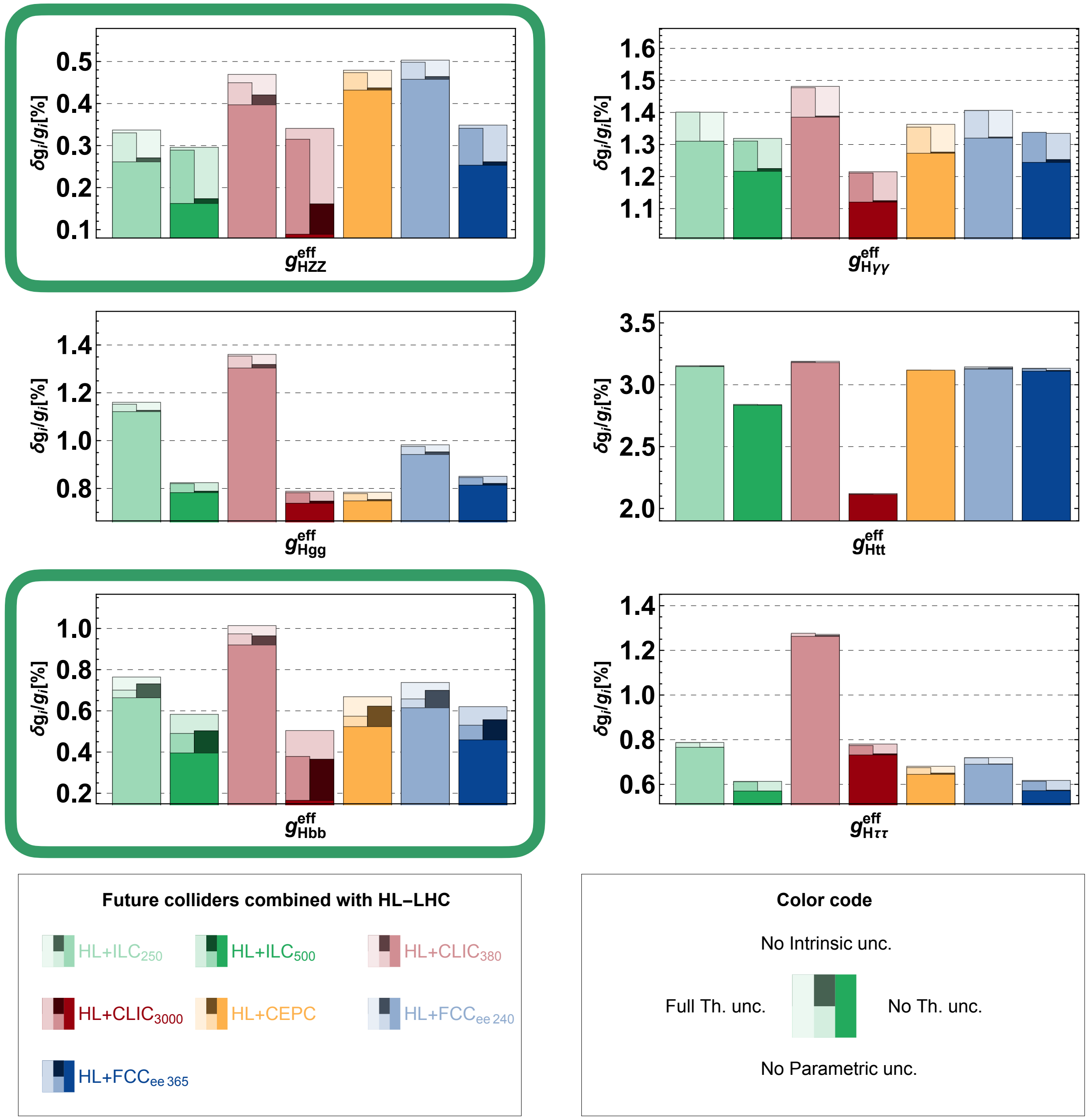
$$g^{\text{eff}\;2}_{HX} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}$$



See C. Grojean's talk during EF-01 kickoff meeting or backup slides for more details on the results for Higgs couplings/aTGC (including H self-coupling)

Will SM theory calculations be enough?

Impact of SM Theory uncertainties in Higgs calculations



Largest effect on HVV couplings

Differences in other couplings mainly due to unc. in production

TH unc. in decays

Decay	future unc. $\Delta\Gamma/\Gamma$ [%]			
	Th_{Intr}	$\text{Th}_{\text{Par}}(m_q)$	$\text{Th}_{\text{Par}}(\alpha_s)$	$\text{Th}_{\text{Par}}(m_H)$
$H \to b\bar{b}$	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	< 0.1	–	–	–
$H \to c\bar{c}$	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	< 0.1	–	–	–
$H \to W^+W^-$	0.4	–	–	0.1
$H \to gg$	1.0	–	0.5	–
$H \to ZZ$	0.3	–	–	0.1
$H \to \gamma\gamma$	< 1.0	–	–	–
$H \to Z\gamma$	1.0	–	–	0.1

Intrinsic TH unc. in production

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

Missing 2-loop: O(1%)

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

In any case, reducible with necessary effort from theory side

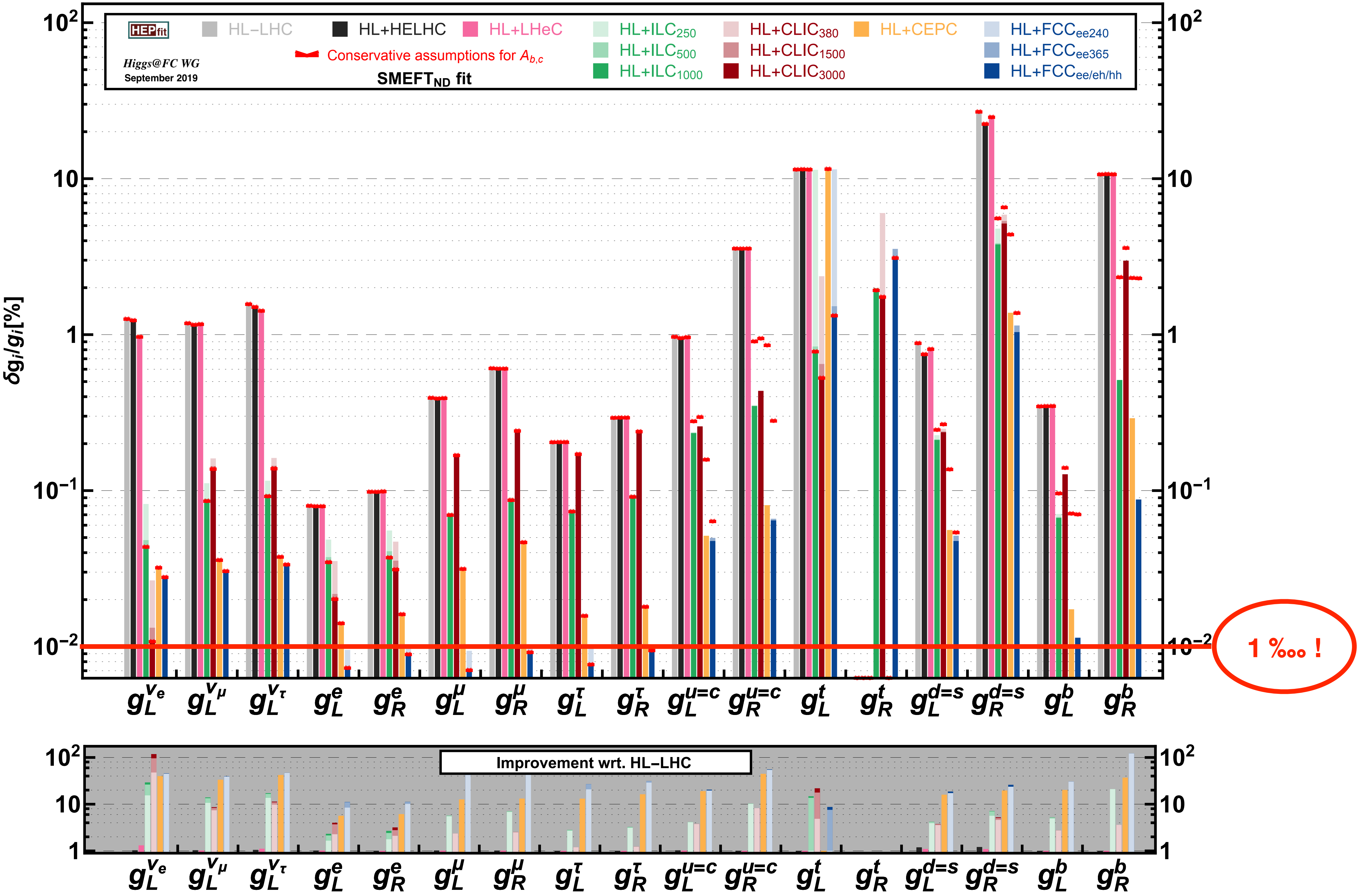
Hence the choice of presenting main results with parametrics only

See C. Grojean's talk during EF-01 kickoff meeting or backup slides for more details on the results for Higgs couplings/aTGC (including H self-coupling)

Sensitivity to NP in EW interactions

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

EFT results projected into effective Zff couplings



1 ‱ !

Sensitivity to NP in EW interactions

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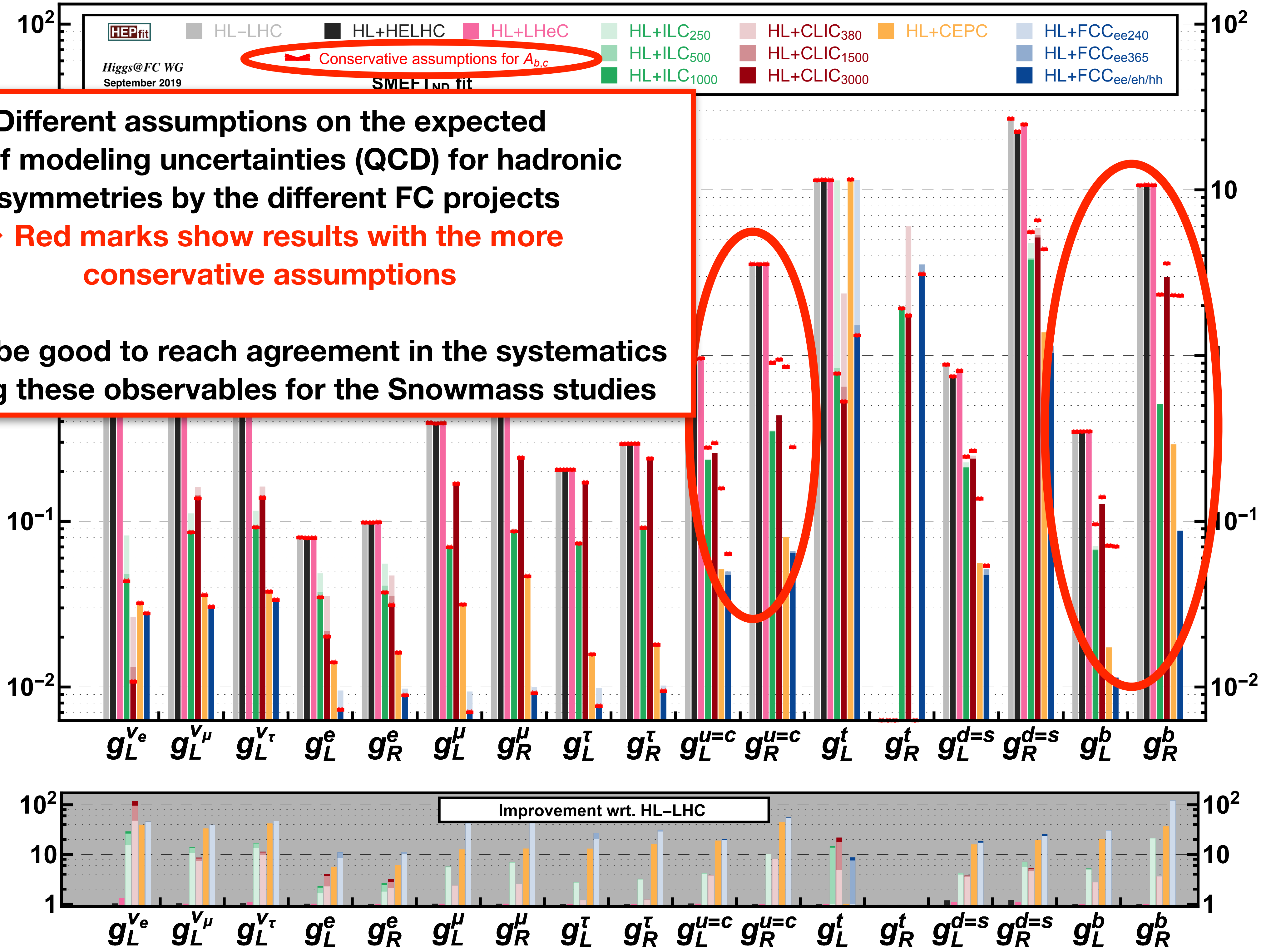


Different assumptions on the expected size of modeling uncertainties (QCD) for hadronic asymmetries by the different FC projects

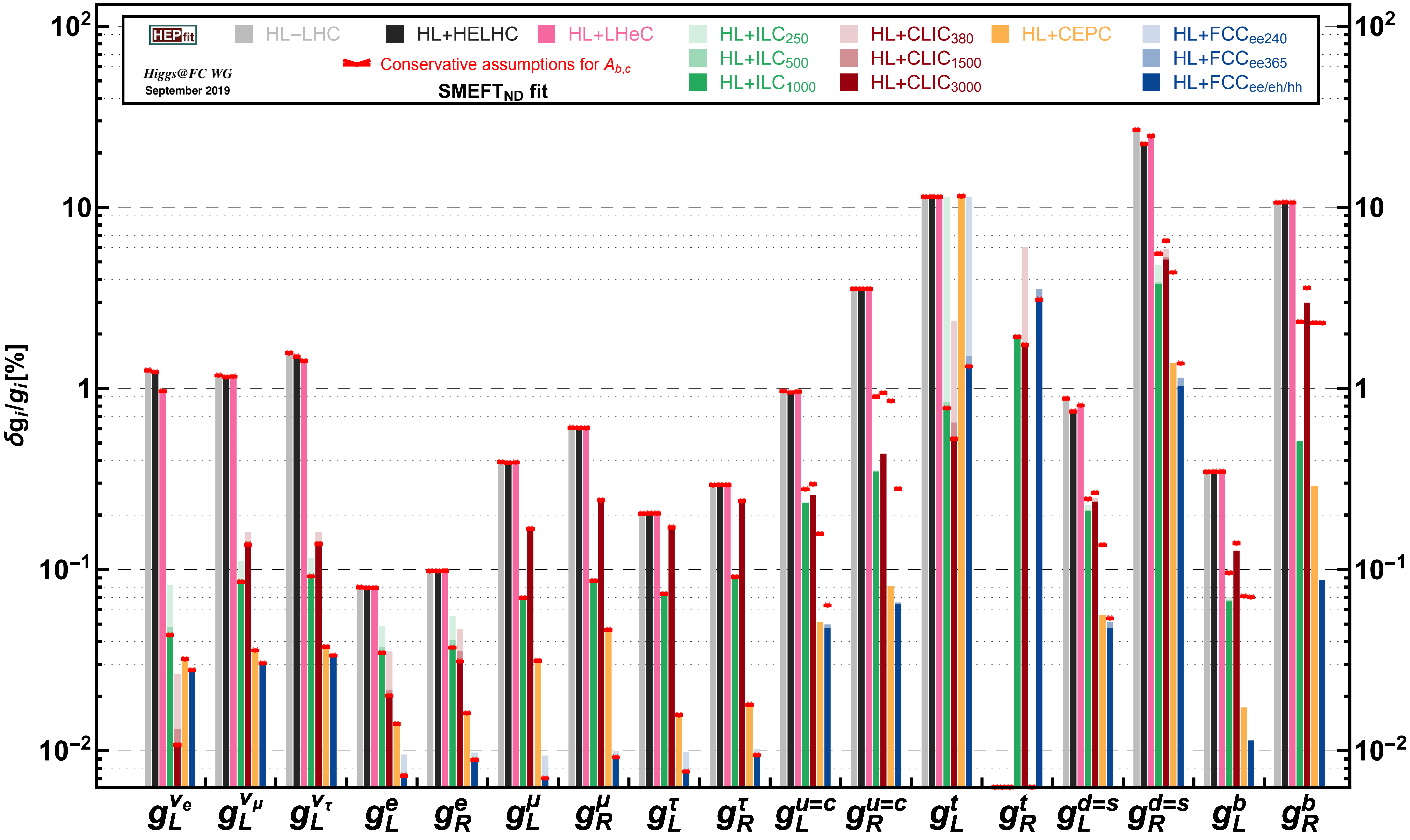
→ Red marks show results with the more conservative assumptions

It would be good to reach agreement in the systematics affecting these observables for the Snowmass studies

Sensitivity to NP in EW interactions

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

EFT results projected into effective Zff couplings



Results including the Giga-Z option at linear colliders also available in Appendix F of the Higgs@FC WG report

Will SM theory calculations be enough?

Theory requirements for EWPO

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_Z[\mathrm{MeV}]$	2.1	–	0.1			
$\Delta\Gamma_Z[\mathrm{MeV}]$	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta\sin^2\theta^\ell_{\mathrm{eff}}[10^{-5}]$	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

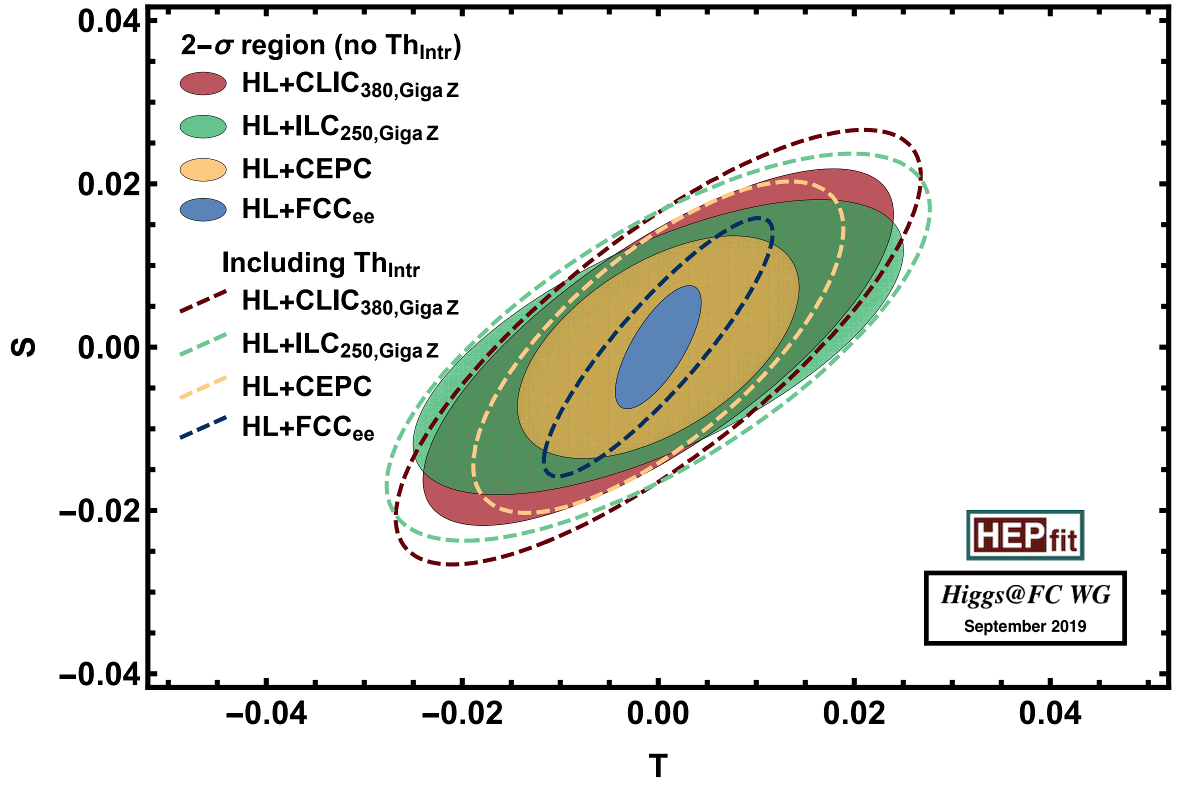
Oblique parameters:

NP modifying gauge boson self-energies

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

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

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



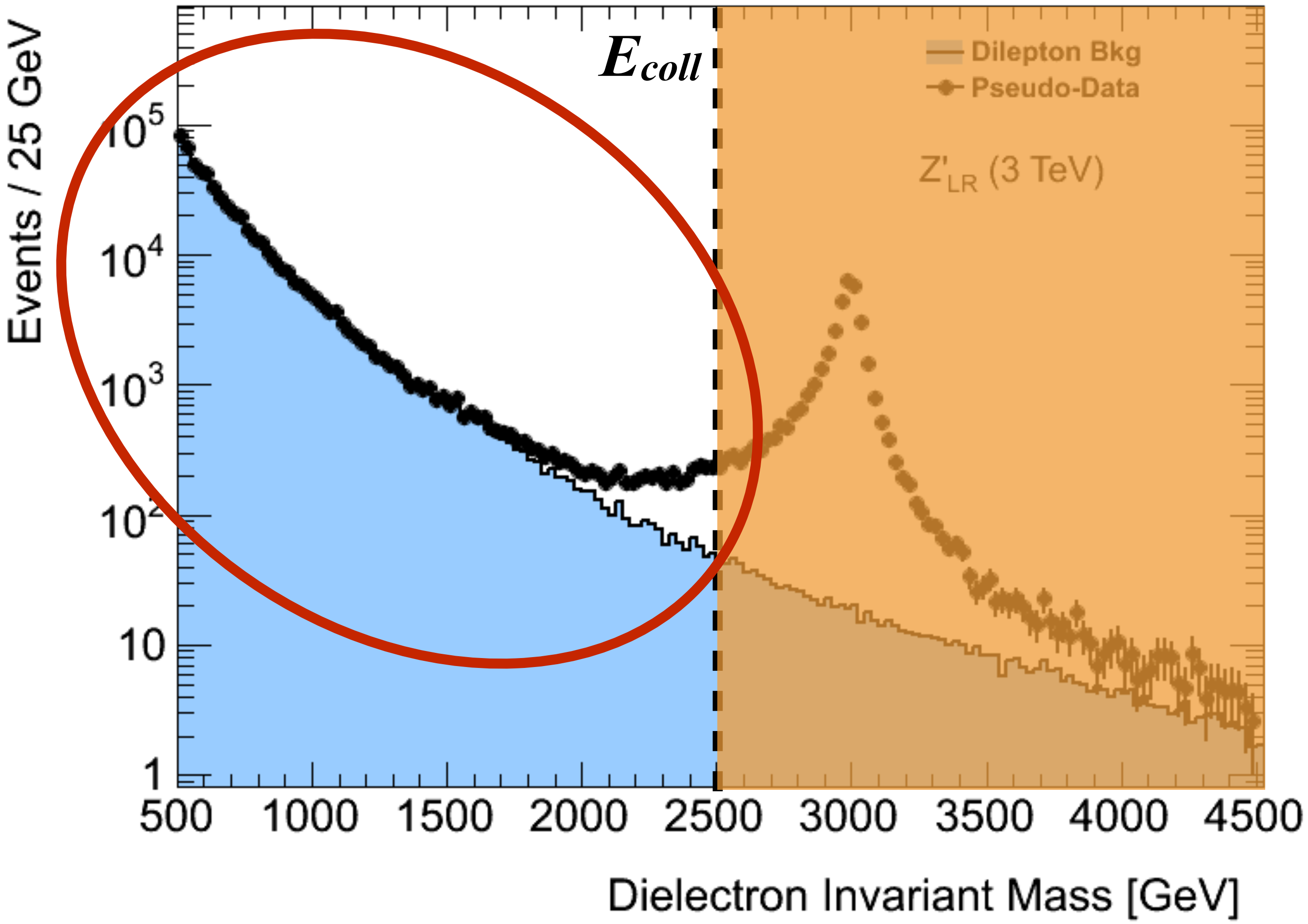
High-E probes of Electroweak/Higgs physics

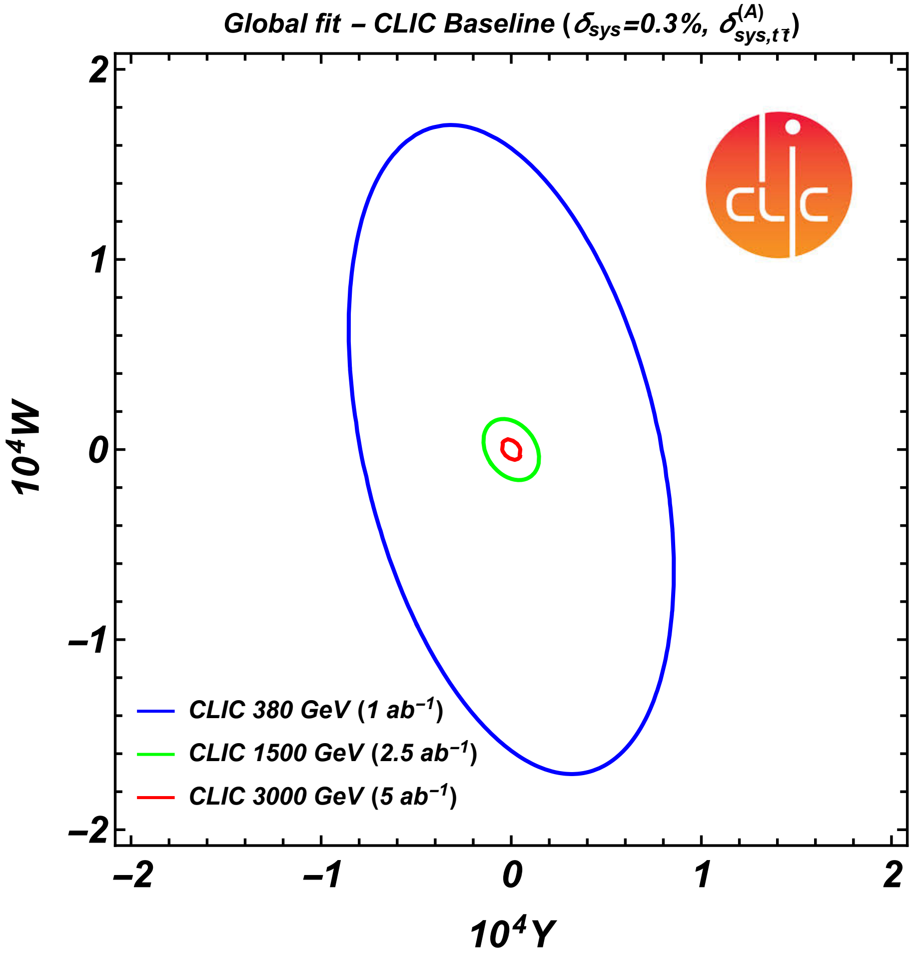
Electroweak/Higgs physics in high-E tails

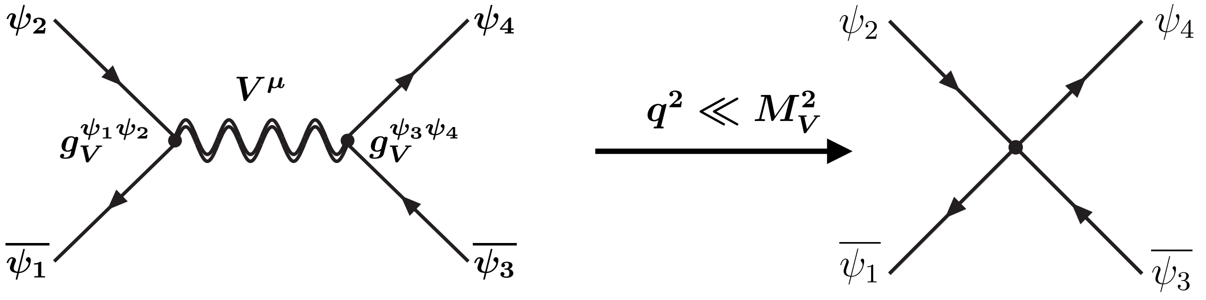
- Electroweak interactions beyond the Z-pole: precision via high E

High Energy probes of new physics:

e.g. growing with energy-effects in 2 → 2 fermion processes







$$\frac{\Delta O}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

Universal NP

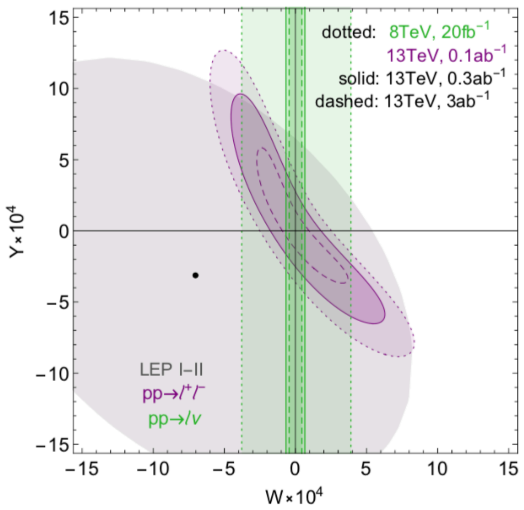
***W* & *Y* parameters**

CLIC~25x better than HL-LHC
Similar to 100 TeV FCC-hh

Electroweak/Higgs physics in high-E tails

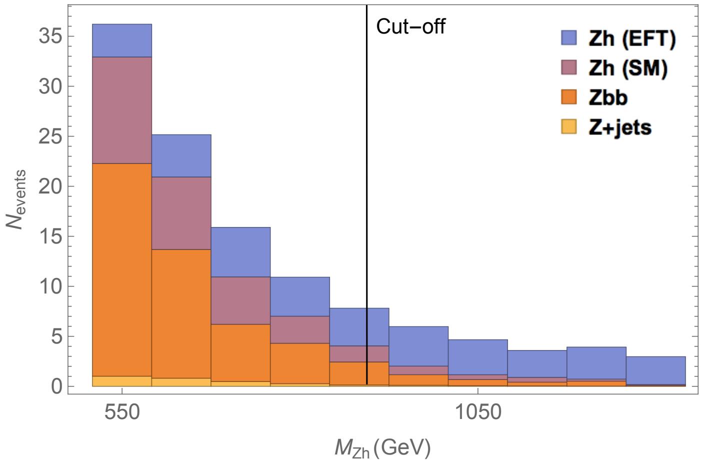
- High-E processes included in the study (when available in the literature)

W & Y in $pp, e^+e^- \to ff$



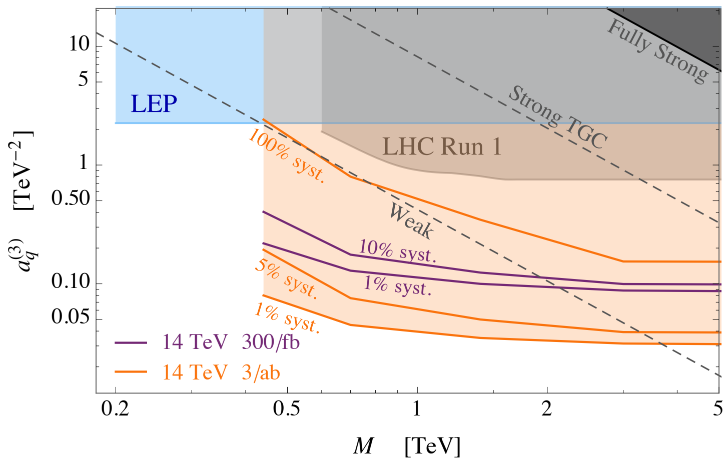
arXiv: 1902.00134 [hep-ph],
CERN YRM Vol. 3 (2018),
arXiv: 1908.11299 [hep-ex]

M_{ZH} in $pp \to ZH \to Zbb$



arXiv: 1807.01796 [hep-ph]

p_{TV} in $pp \to WZ$



JHEP 1802 (2018) 111

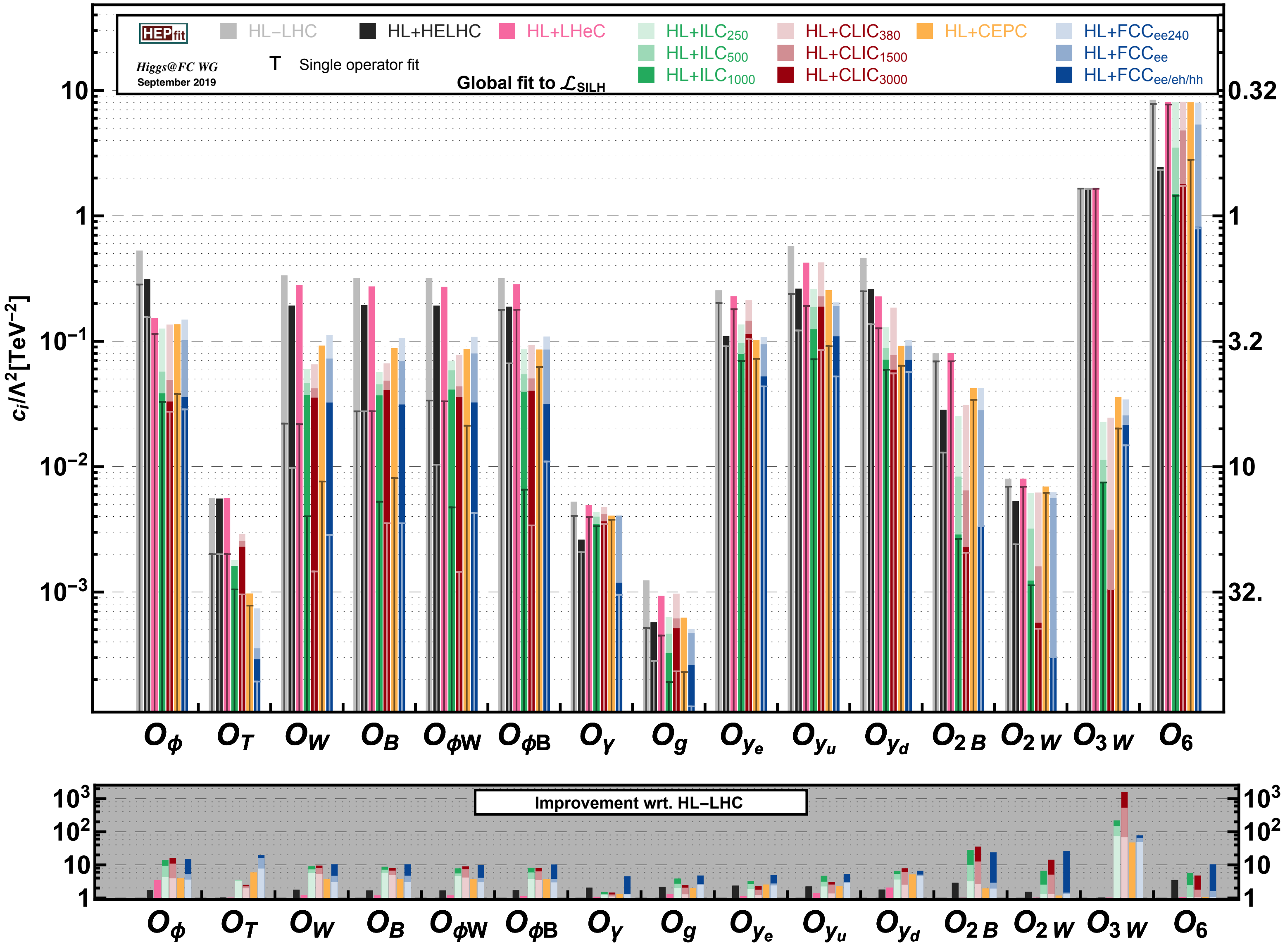
- Studied using a SILH-like effective Lagrangian (applied to CH models):

$$
\begin{aligned}
\mathscr{L}_{\text{SILH}} = & \frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{c_T}{\Lambda^2}\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\phi^\dagger \overleftrightarrow{D}^\mu \phi) - \frac{c_6}{\Lambda^2}\lambda(\phi^\dagger\phi)^3 + \left(\frac{c_{y_f}}{\Lambda^2} y_{ij}^f \phi^\dagger\phi\bar\psi_{Li}\phi\psi_{Rj} + \text{h.c.}\right) \\
& + \frac{c_W}{\Lambda^2}\frac{ig}{2}\left(\phi^\dagger \overleftrightarrow{D}^a_\mu \phi\right) D_\nu W^{a\,\mu\nu} + \frac{c_B}{\Lambda^2}\frac{ig'}{2}\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\partial_\nu B^{\mu\nu} + \frac{c_{\phi W}}{\Lambda^2} igD_\mu\phi^\dagger\sigma_a D_\nu\phi W^{a\,\mu\nu} + \frac{c_{\phi B}}{\Lambda^2} ig' D_\mu\phi^\dagger\sigma_a D_\nu\phi B^{\mu\nu} \\
& + \frac{c_\gamma}{\Lambda^2} g'^{\,2}\phi^\dagger\phi B^{\mu\nu}B_{\mu\nu} + \frac{c_g}{\Lambda^2} g_s^2\phi^\dagger\phi G^{A\,\mu\nu}G^A_{\mu\nu} \\
& - \frac{c_{2W}}{\Lambda^2}\frac{g^2}{2}(D^\mu W^a_{\mu\nu})(D_\rho W^{a\,\rho\nu}) - \frac{c_{2B}}{\Lambda^2}\frac{g'^{\,2}}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{c_{2G}}{\Lambda^2}\frac{g_S^2}{2}(D^\mu G^A_{\mu\nu})(D_\rho G^{A\,\rho\nu}) \\
& + \frac{c_{3W}}{\Lambda^2} g^3\epsilon_{abc}W_\mu^{a\ \nu}W_\nu^{b\ \rho}W_\rho^{c\ \mu} + \frac{c_{3G}}{\Lambda^2} g_S^3 f_{ABC}G_\mu^{A\ \nu}G_\nu^{B\ \rho}G_\rho^{C\ \mu},
\end{aligned}
$$

Electroweak/Higgs physics in high-E tails

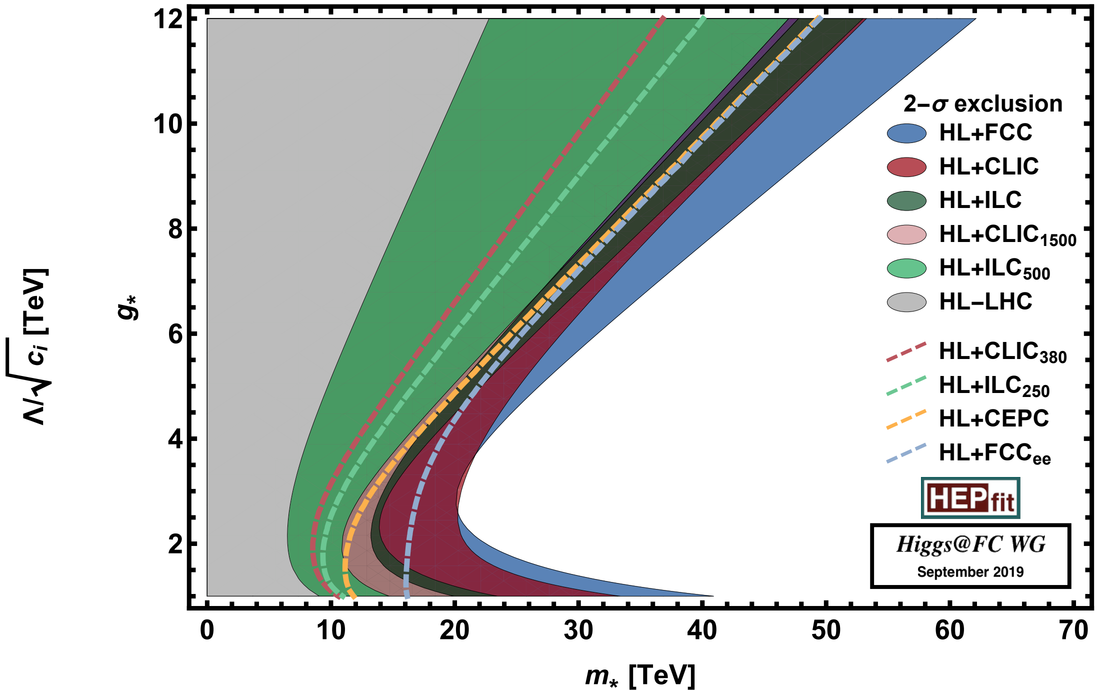
- Studied using a SILH-like effective Lagrangian (applied to CH models):

Indirect constraints on SILH Lagrangian



Input for several of the limits in the BSM chapter of the Physics Briefing Book

Indirect constraints on Composite Higgs models



Simplified CH benchmark: 1 coupling (g*) - 1 scale (m*)

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

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

$$\frac{c_{3W,3G}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

Beyond the ESG SMEFT studies

Higgs and EW physics at Future Colliders

- Inputs included in the fits (from ESU documents and refs. therein):

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	Top EW
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return, Giga-Z)	Yes
	HL-LHC		HC (M_W, $\sin^2\theta_W$)	
FCC-hh	Yes (μ, $\mathrm{BR}_i/\mathrm{BR}_j$) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_W$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

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

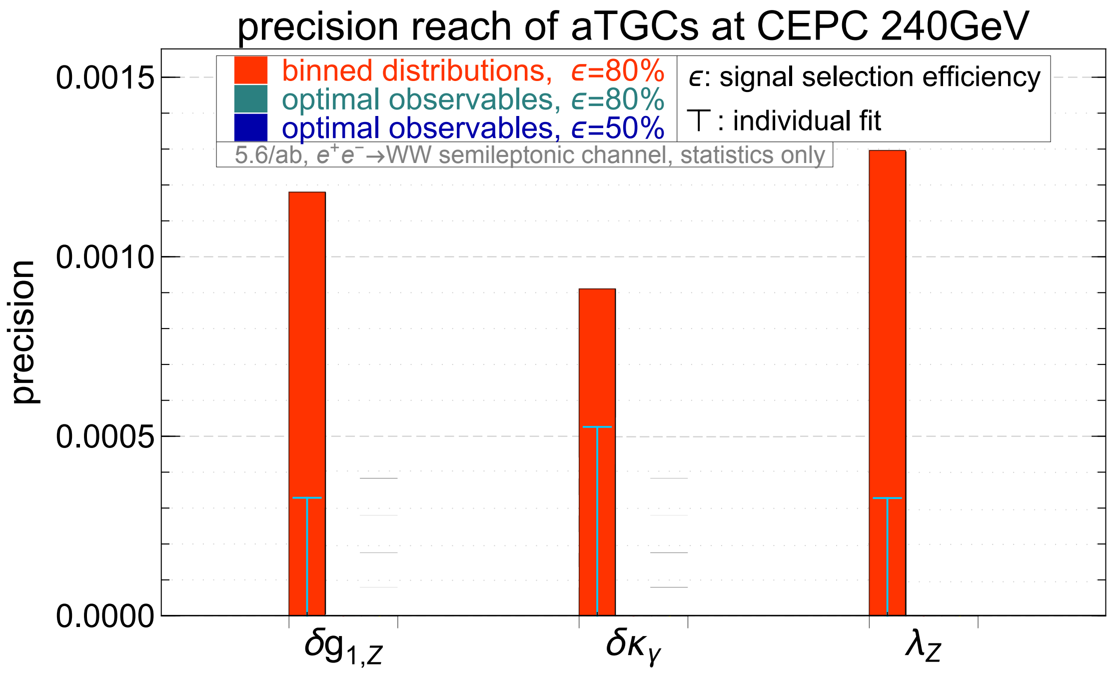
(Except for CLIC)

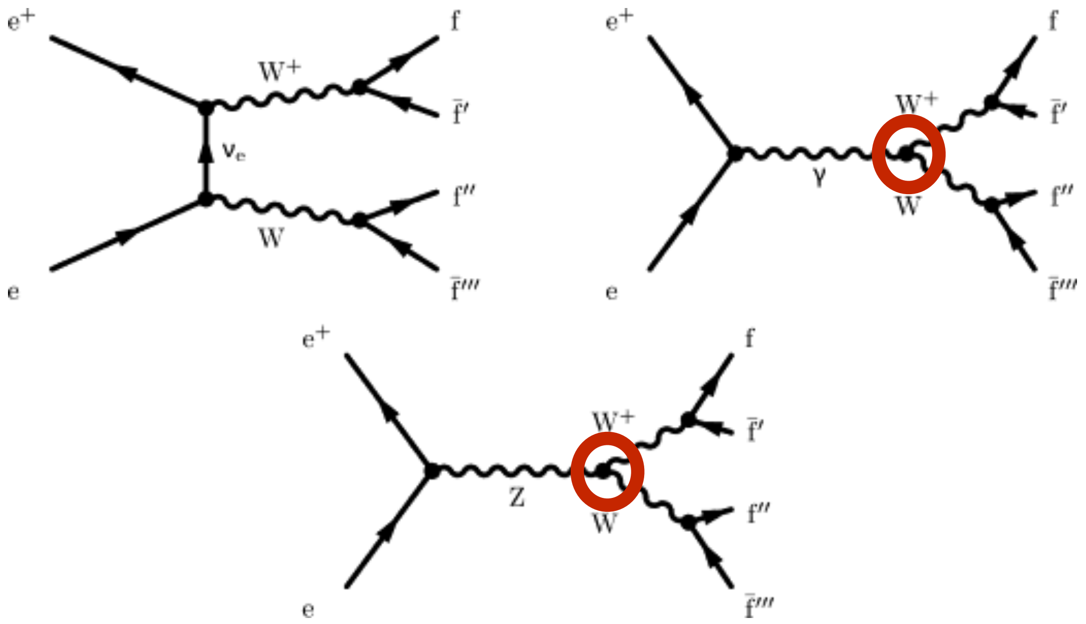
Global EFT study of WW production

WW production at lepton colliders

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

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





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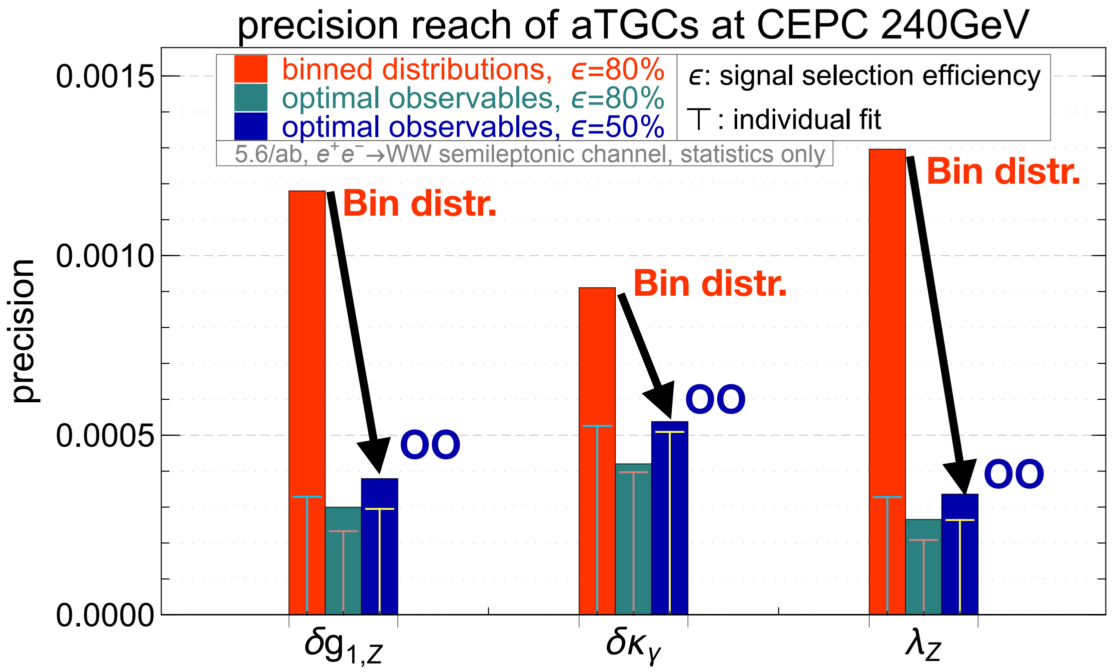
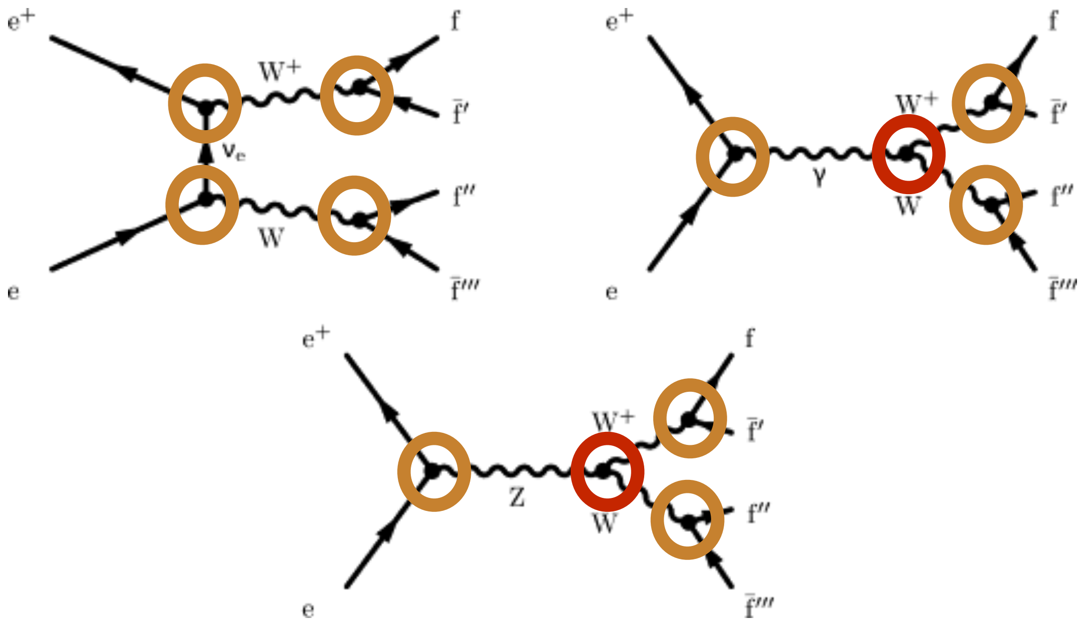


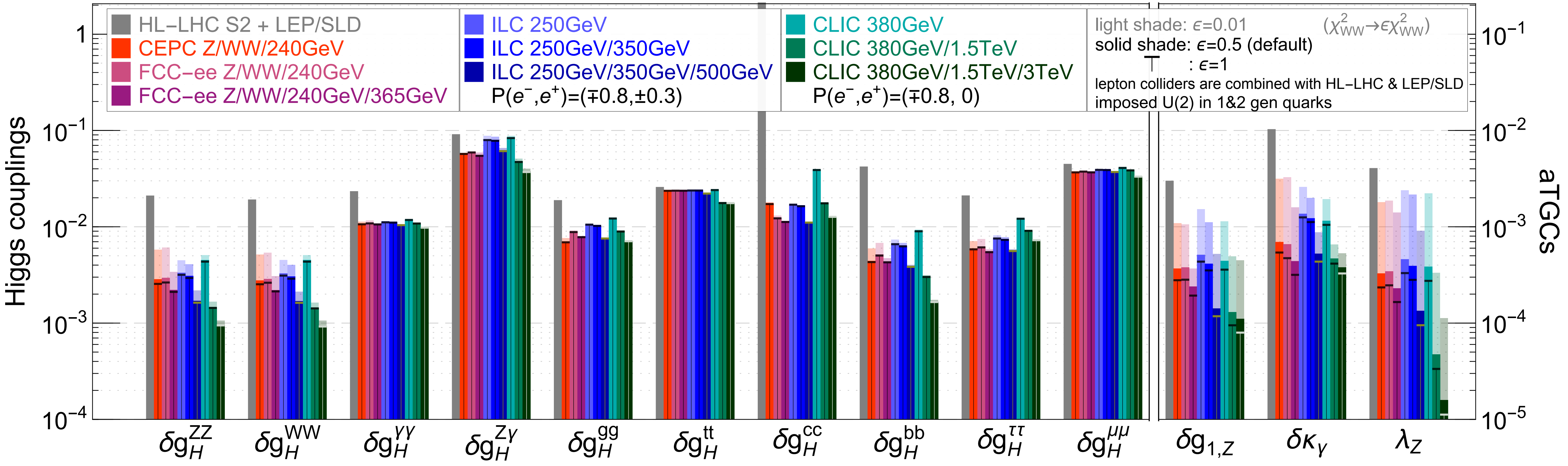


- In **JHEP12 (2019) 117** we prepared a new sensitivity study using full info about each event in the formalism of “optimal statistical observables” (OO):
  - We consider all possible BSM deformations within the dim-6 SMEFT framework
  - Default method only accounts for statistical sensitivity ⇒ Compensate omission of systematics via conservative selection efficiency ε

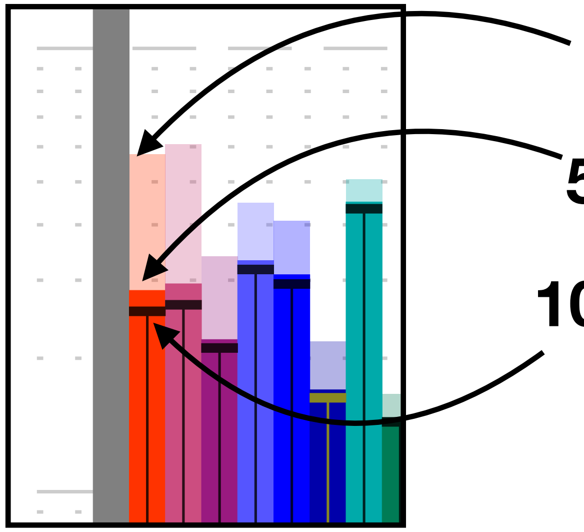
Global fit to EW/Higgs projections

EFT Higgs couplings and aTGC: dependence on WW projections

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



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



1% Efficiency in $ee \to WW$

50% Efficiency in $ee \to WW$ (Default)

100% Efficiency in $ee \to WW$

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

Future directions

- The previous study of $ee \to WW$ uses a full EFT parameterization and is "optimal" from the point of view of statistical uncertainties only. Assessing the potential of the method in a more realistic way would require:
  - Proper treatment of exp. systematics ☛ **Experimental input would be great here**
  - Including the effect of theory uncertainties

Contact us if you are interested in helping with this

Other areas to go beyond the SMEFT studies prepared for the ESU

- **Differential observables:** ESU studies focused mostly on inclusive H observables. Cannot exploit all info of the kinematical distributions available at future colliders
  - STXS, Boosted H + j, …
  - **High-E probes of EFT** effects that grow with the energy:
    - No full EFT parameterization in ESU studies (only the leading growing-with-E effects)
- **Impact of SMEFT uncertainties:** NLO, $(\text{dim-6})^2$ vs. dim 8, … ☛ **See talk by W. Shepherd**
- **Vector boson scattering:** not included in ESU studies
- **CP-violating observables:** not explored in the ESU SMEFT fits

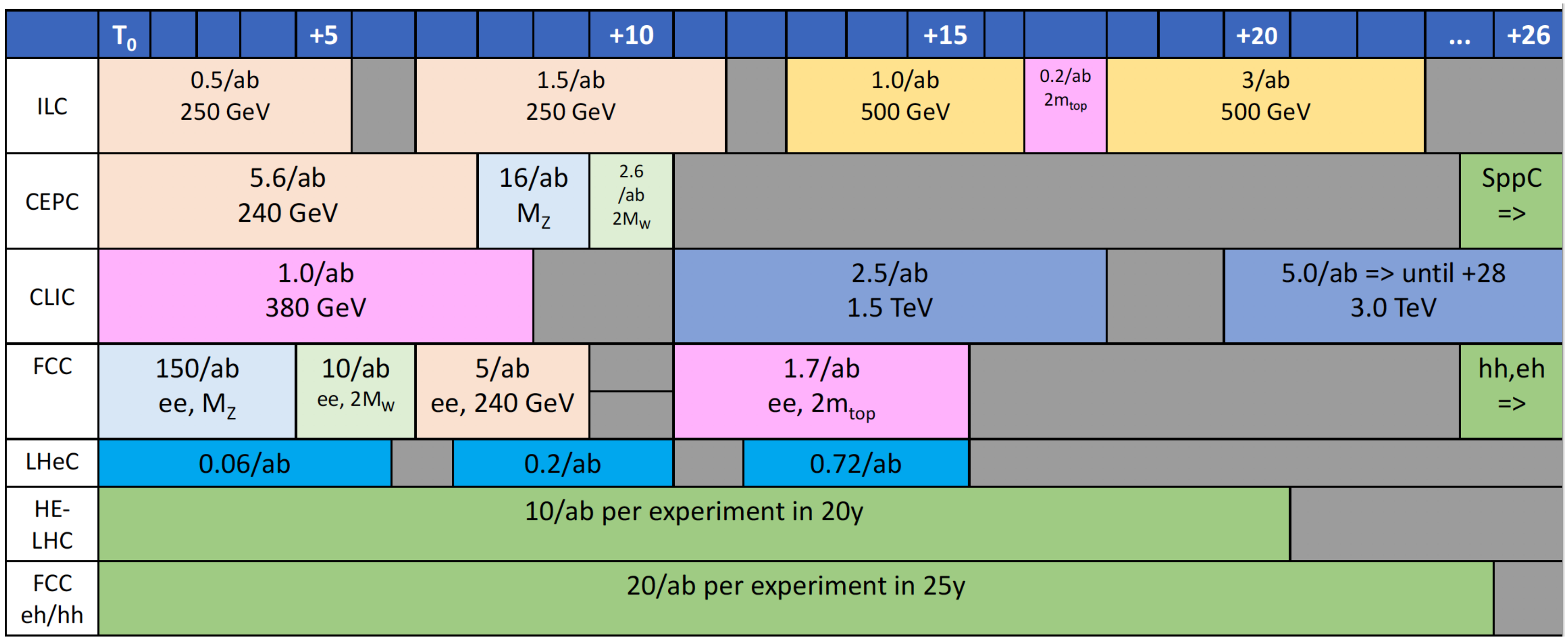
Future directions

- **EW precision observables:**
    - Clarify systematics for heavy flavor observables (A_q, R_q)
    - Exploit EW measurements outside the Z-pole (low and high energy): requires adding 4-fermion operators into the global fit
    - Non-universality: combine with flavor data to explore more flavor scenarios consistently
- **Top sector only explored superficially:**
    - Consider effects from 4-fermion operators or top dipole operators
    - Exploit NLO effects of Top EW couplings in H/diBoson
- **BSM interpretation of SMEFT limits:**
    - ESU: done for several simple scenarios and mostly taking the SMEFT limits assuming only 1 operator at a time
    - Explore more BSM interpretations (matching SMEFT/UV), and in particular those related to important physics questions, e.g. baryogenesis
    - Pay attention to SMEFT fit correlations ☛ **Not reported in ESU reports but crucial for BSM interpretation**
- Study other future collider facilities, e.g. **High-E muon collider**?

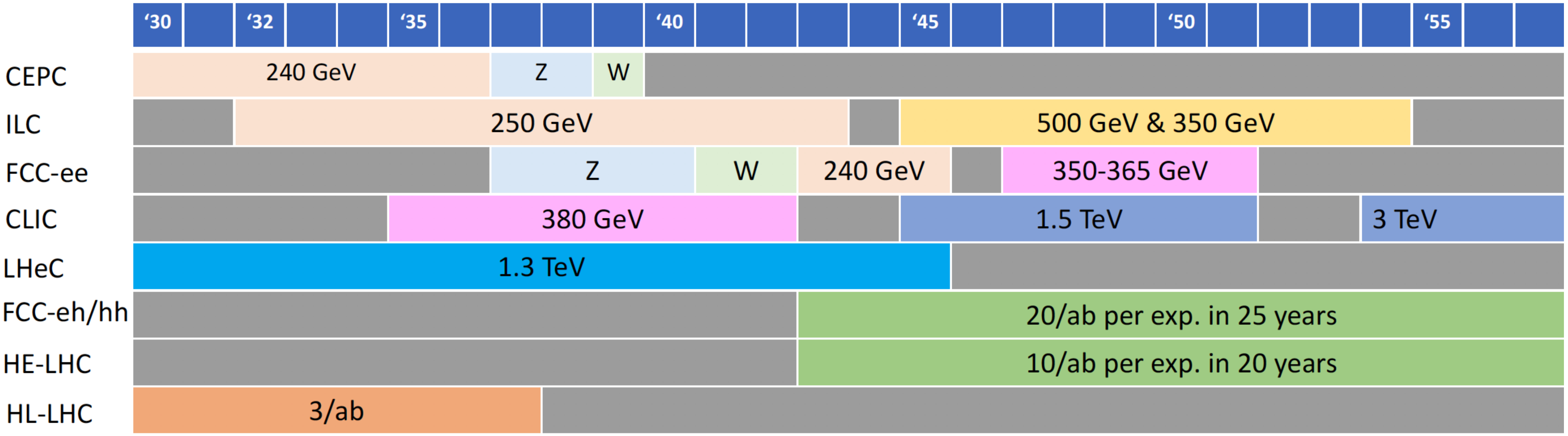
Backup slides

Introduction

Future Particle Colliders



Starting time at T_0



Earliest start time in ESU documents

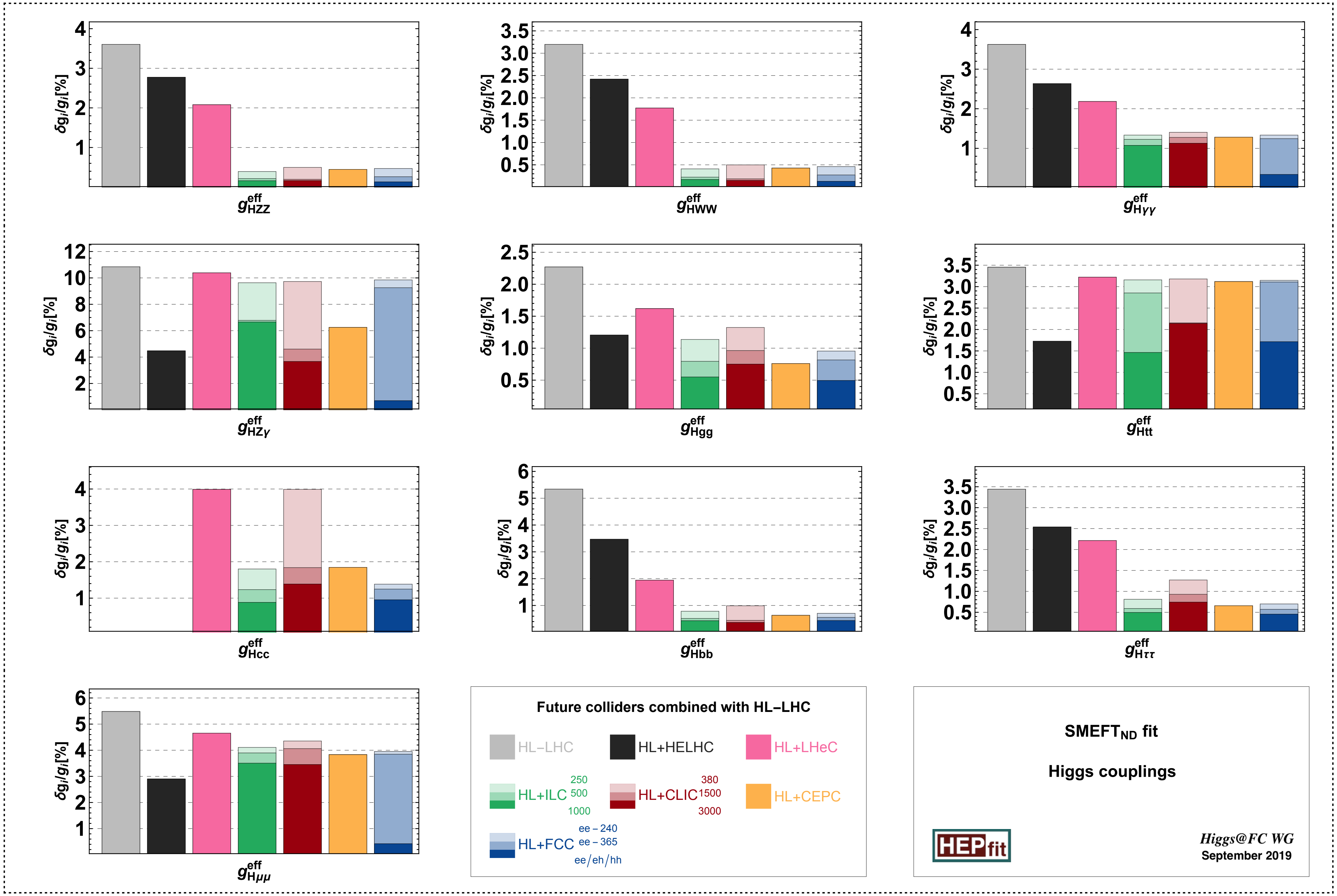
Note: Different definitions of "Year": ILC 1.6 x 10^7 sec, FCC-ee/CLIC: 1.2 x 10^7 sec, CEPC: 1.3 x 10^7 sec

Single Higgs couplings

Results in the SMEFT-framework (Higgs)

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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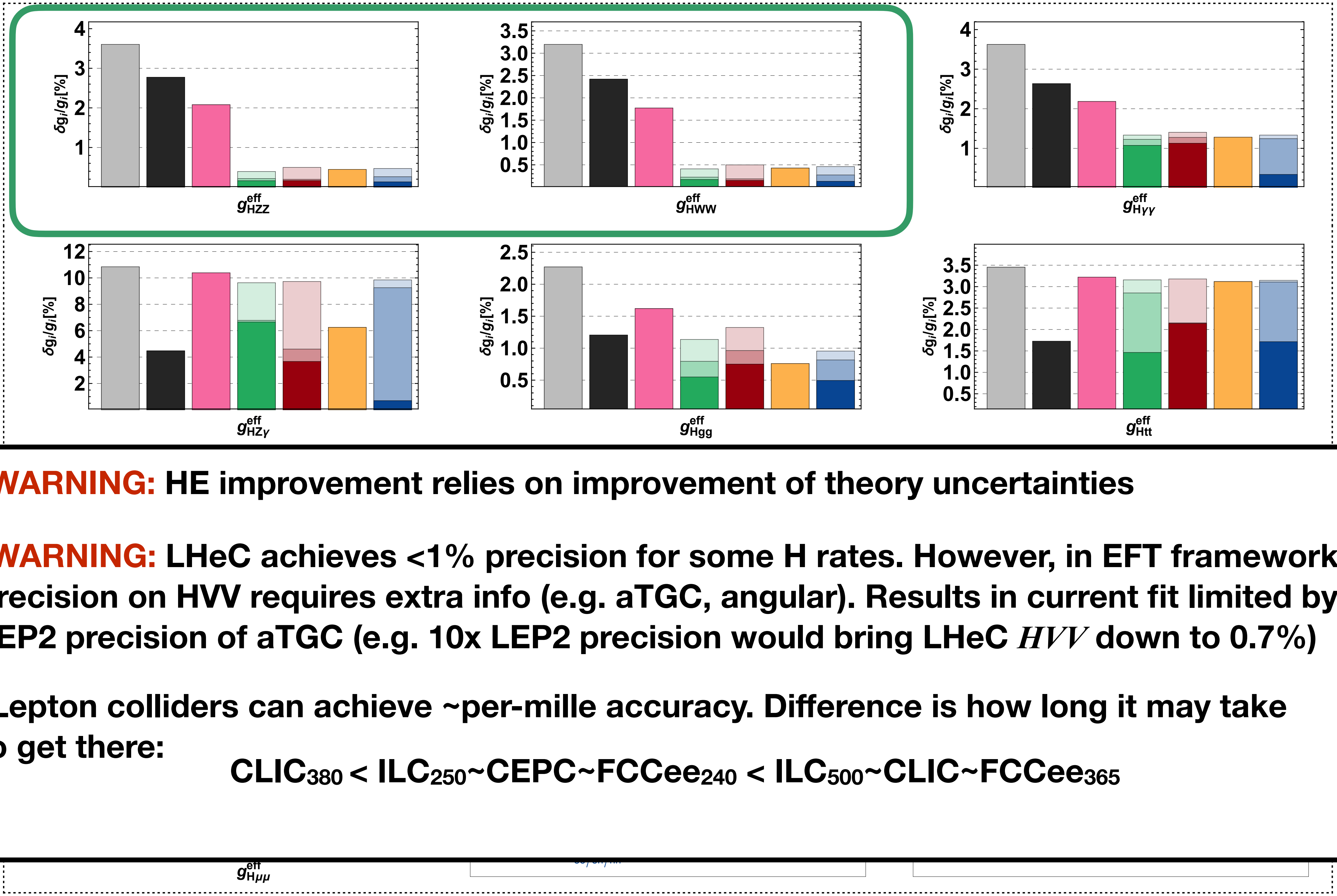


-**WARNING:** HE improvement relies on improvement of theory uncertainties

-**WARNING:** LHeC achieves <1% precision for some H rates. However, in EFT framework precision on HVV requires extra info (e.g. aTGC, angular). Results in current fit limited by LEP2 precision of aTGC (e.g. 10x LEP2 precision would bring LHeC HVV down to 0.7%)

-Lepton colliders can achieve ~per-mille accuracy. Difference is how long it may take to get there:

$\text{CLIC}_{380} < \text{ILC}_{250} \sim \text{CEPC} \sim \text{FCCee}_{240} < \text{ILC}_{500} \sim \text{CLIC} \sim \text{FCCee}_{365}$

Single Higgs couplings

Results in the SMEFT-framework (Higgs)

EFT results projected into effective Higgs couplings and aTGC

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

- **e$^+$e$^-$ coll: Tau and Bottom Yukawa (0.5% - 1%)**

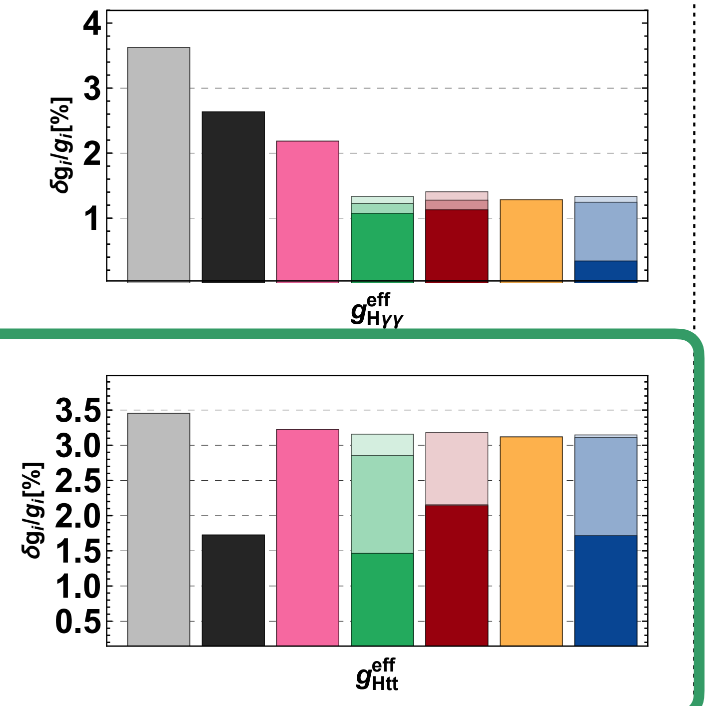
-Top Yukawa not directly accessible to low-E lepton colliders.

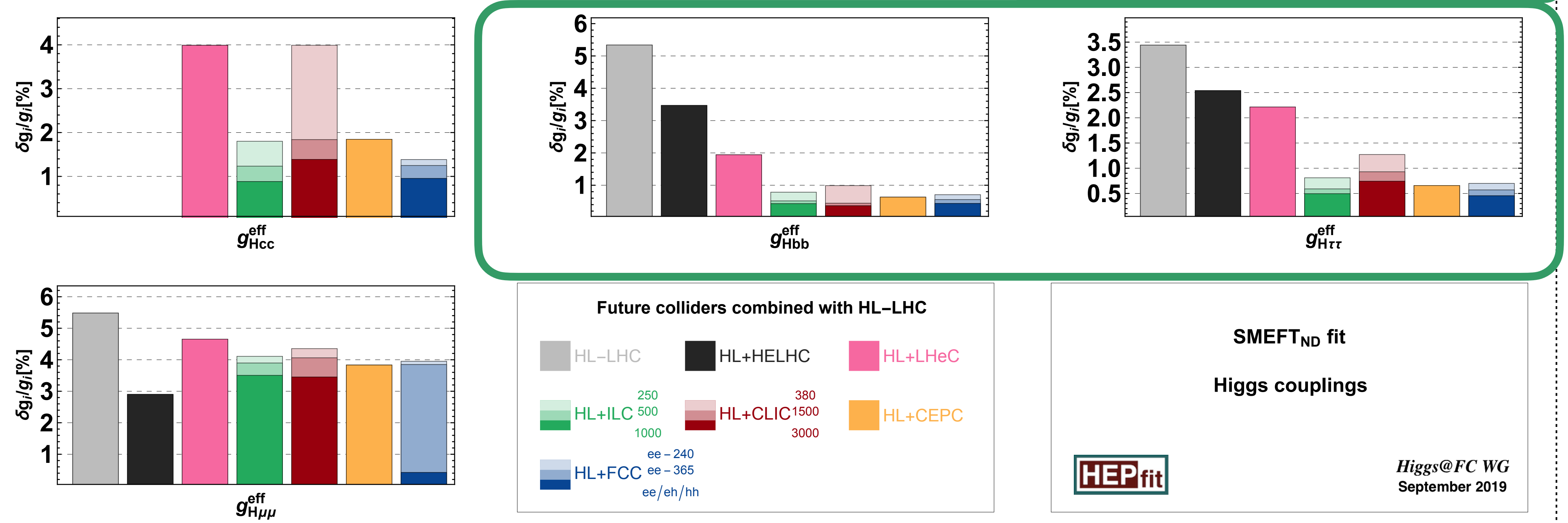
-Accessible above 500 GeV (ILC, CLIC). Precision similar to HL-LHC.

-1% precision possible at FCC-hh

WARNING: In all cases, ttH requires knowledge of, at least, other Top interactions

Model-Independent Top: Advantage for CLIC





Single Higgs couplings

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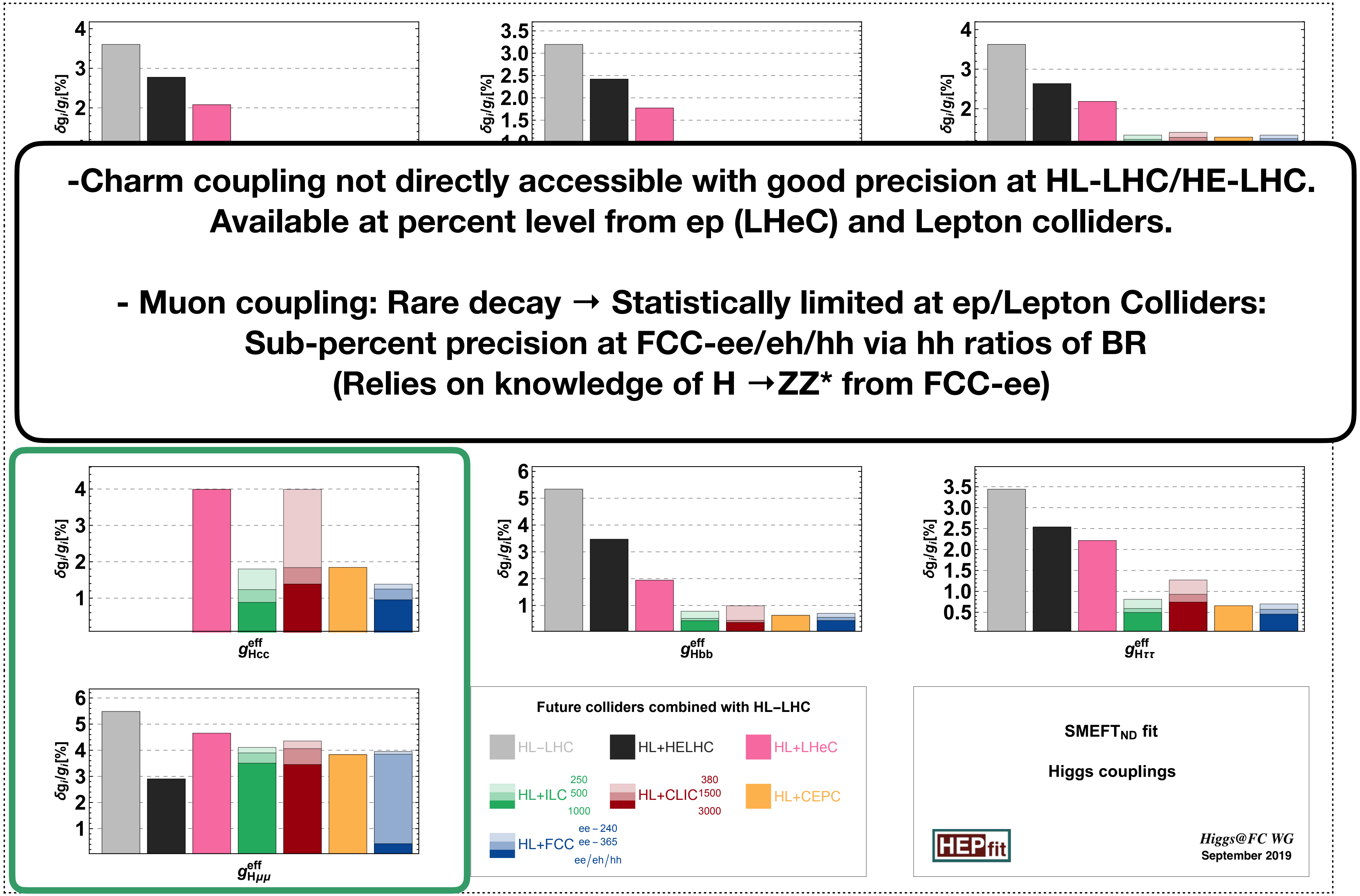

-Charm coupling not directly accessible with good precision at HL-LHC/HE-LHC. Available at percent level from ep (LHeC) and Lepton colliders.

- Muon coupling: Rare decay → Statistically limited at ep/Lepton Colliders: Sub-percent precision at FCC-ee/eh/hh via hh ratios of BR (Relies on knowledge of H →ZZ* from FCC-ee)

Single Higgs couplings

Results in the SMEFT-framework (Higgs)

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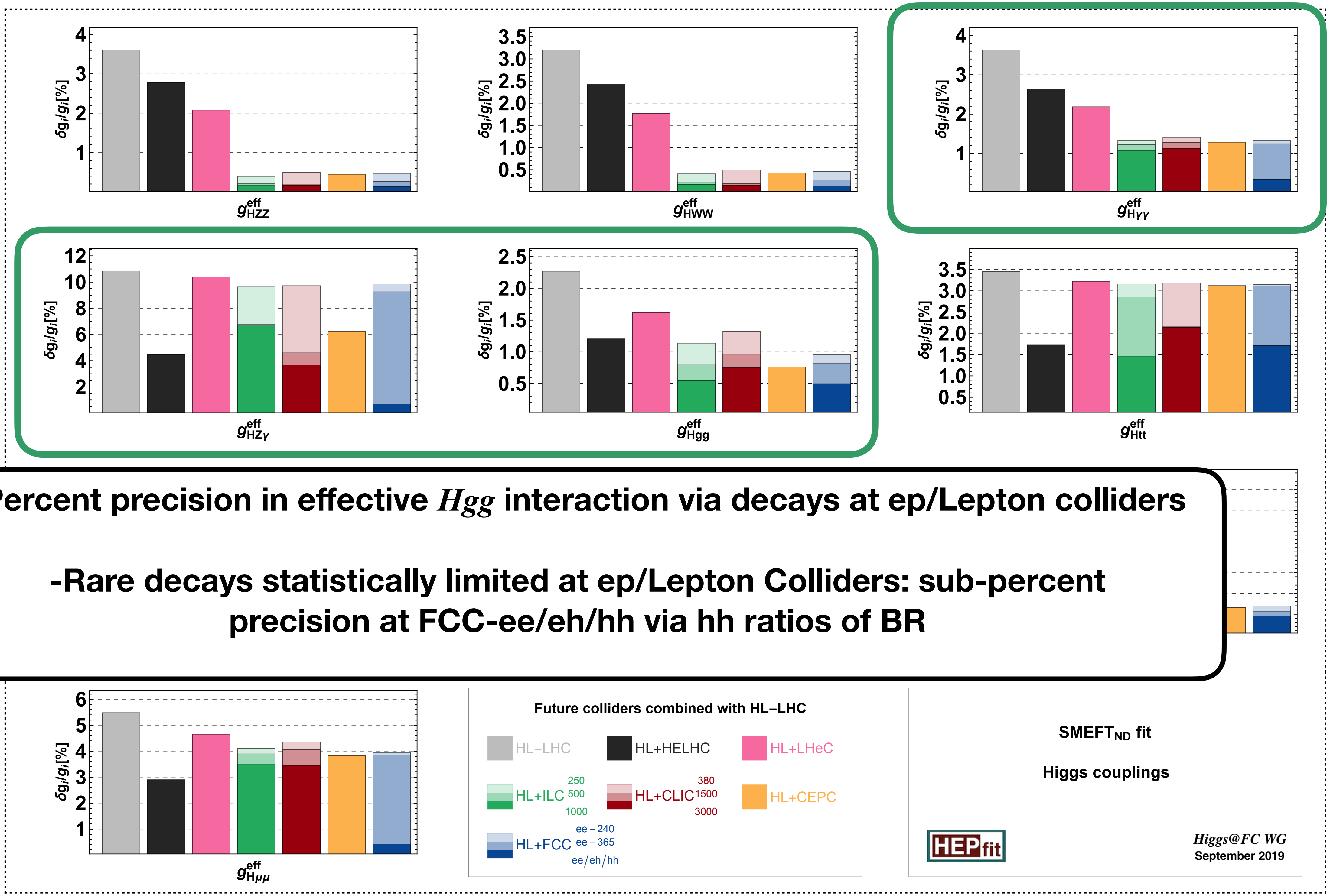
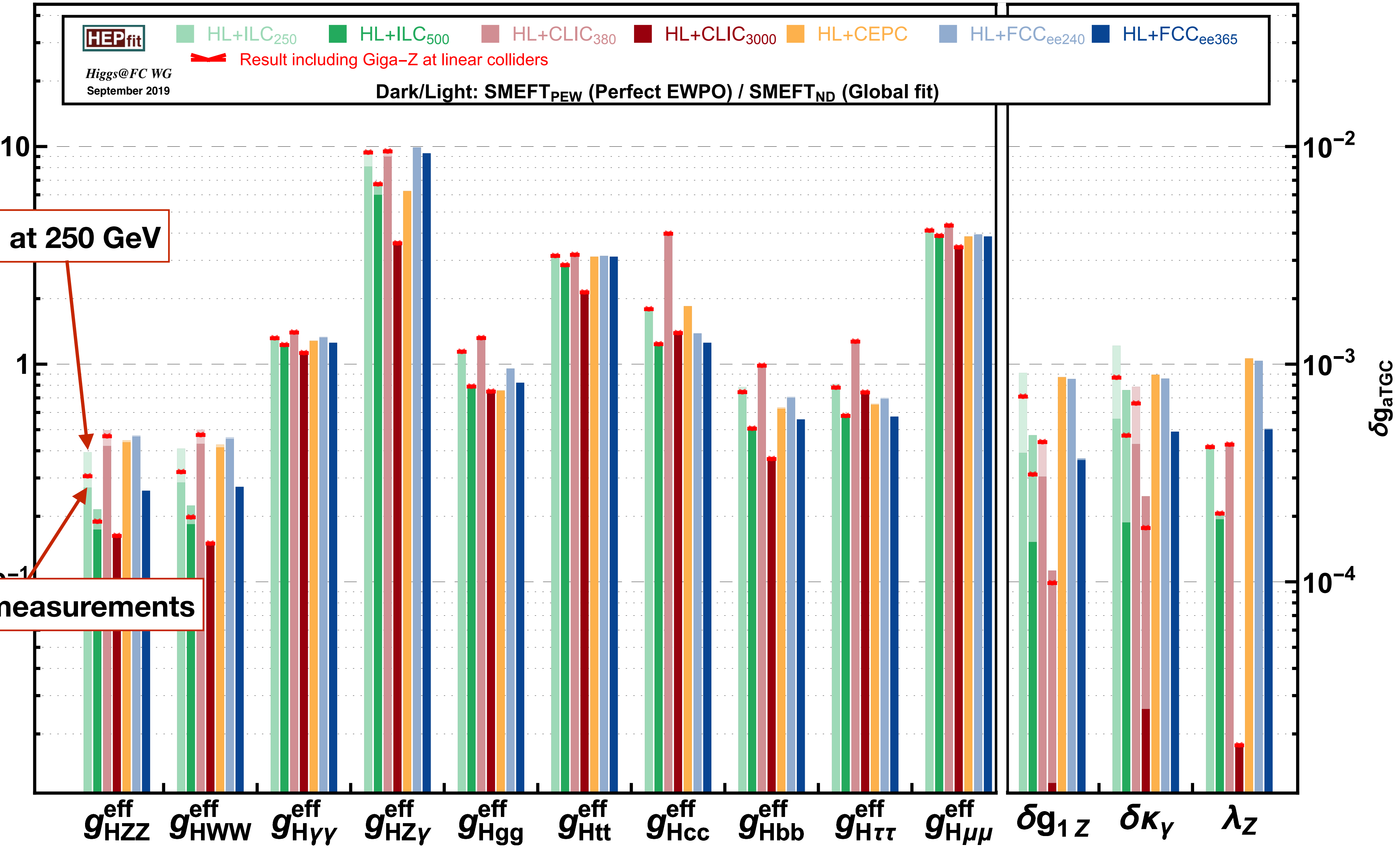


-Percent precision in effective Hgg interaction via decays at ep/Lepton colliders

-Rare decays statistically limited at ep/Lepton Colliders: sub-percent precision at FCC-ee/eh/hh via hh ratios of BR

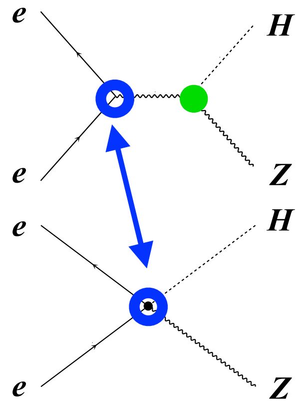
Interplay between EW and Higgs

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



EW program at 250 GeV

Perfect EW measurements

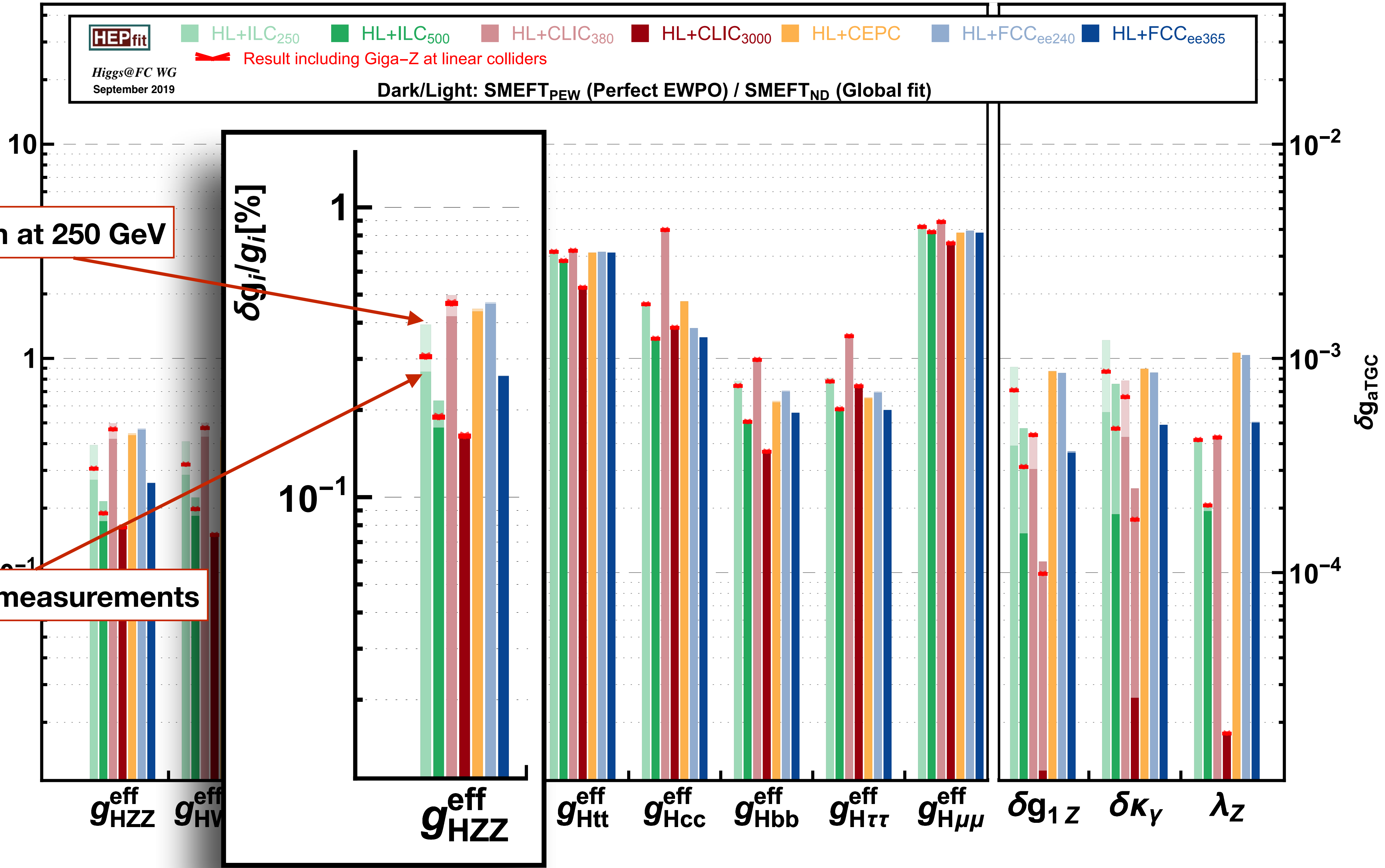


Difference due to absence of precise enough EWPO at LC (no Z pole run)

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

Interplay between EW and Higgs

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



EW program at 250 GeV

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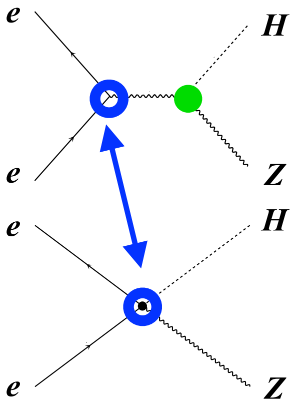

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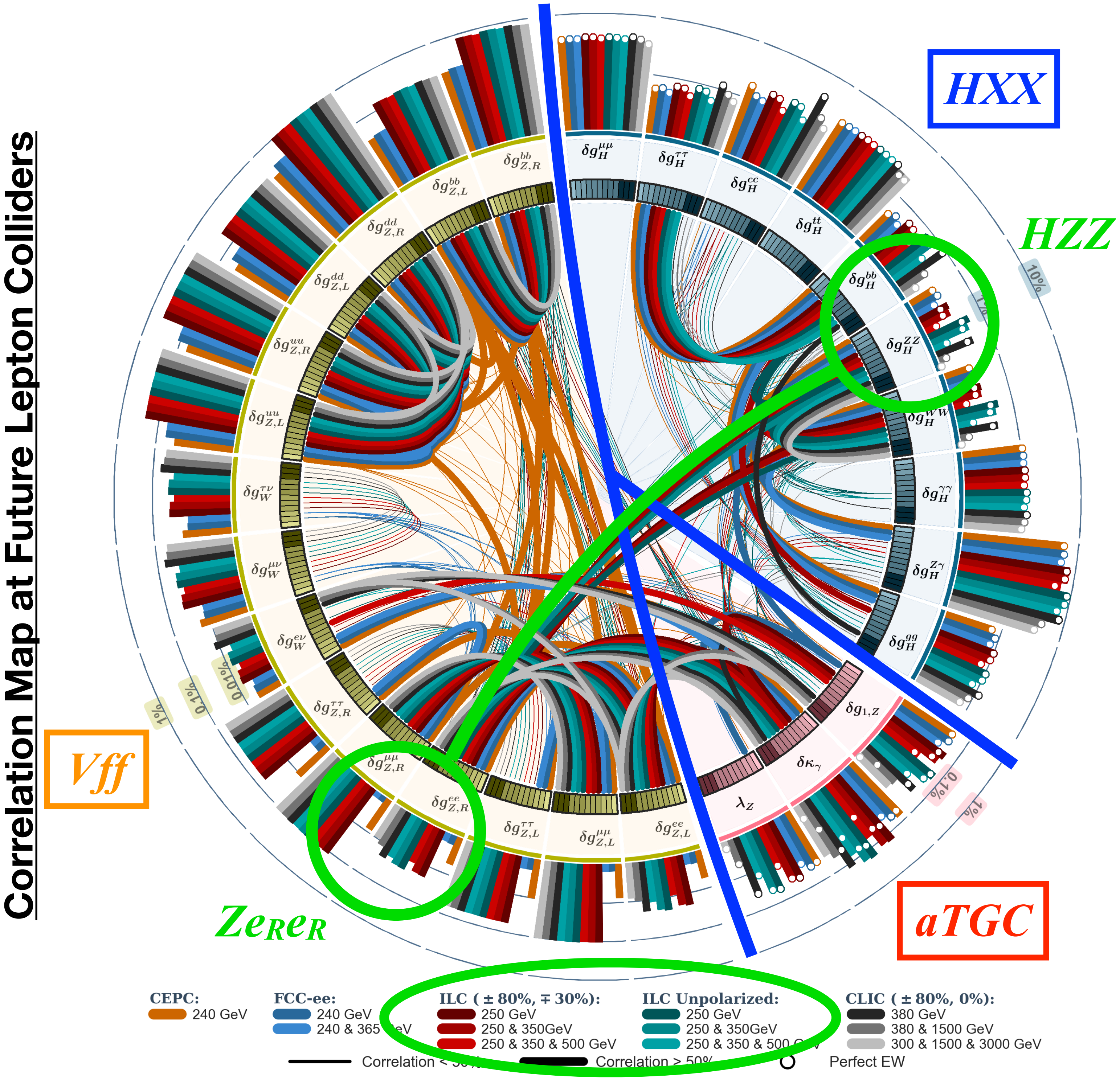
Interplay between EW and Higgs

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



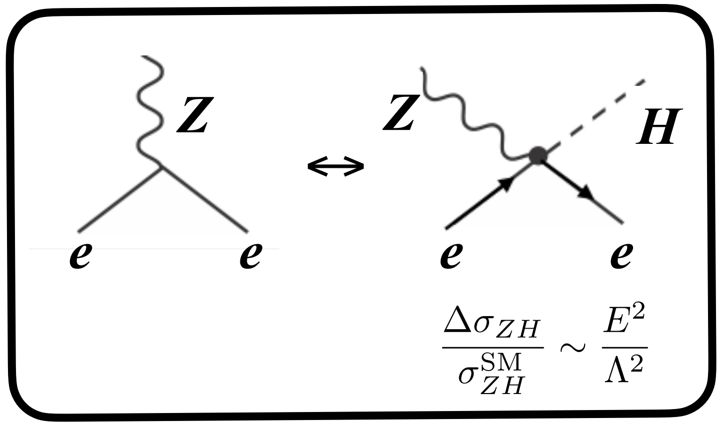
Couplings and correlations

"Contamination" EW/aTGC/H can be understood by looking at correlations

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

ILC: Large correlation HZZ-Zee: precision of HZZ limited by absence of Z-pole run (Less pronounced at 500 GeV)

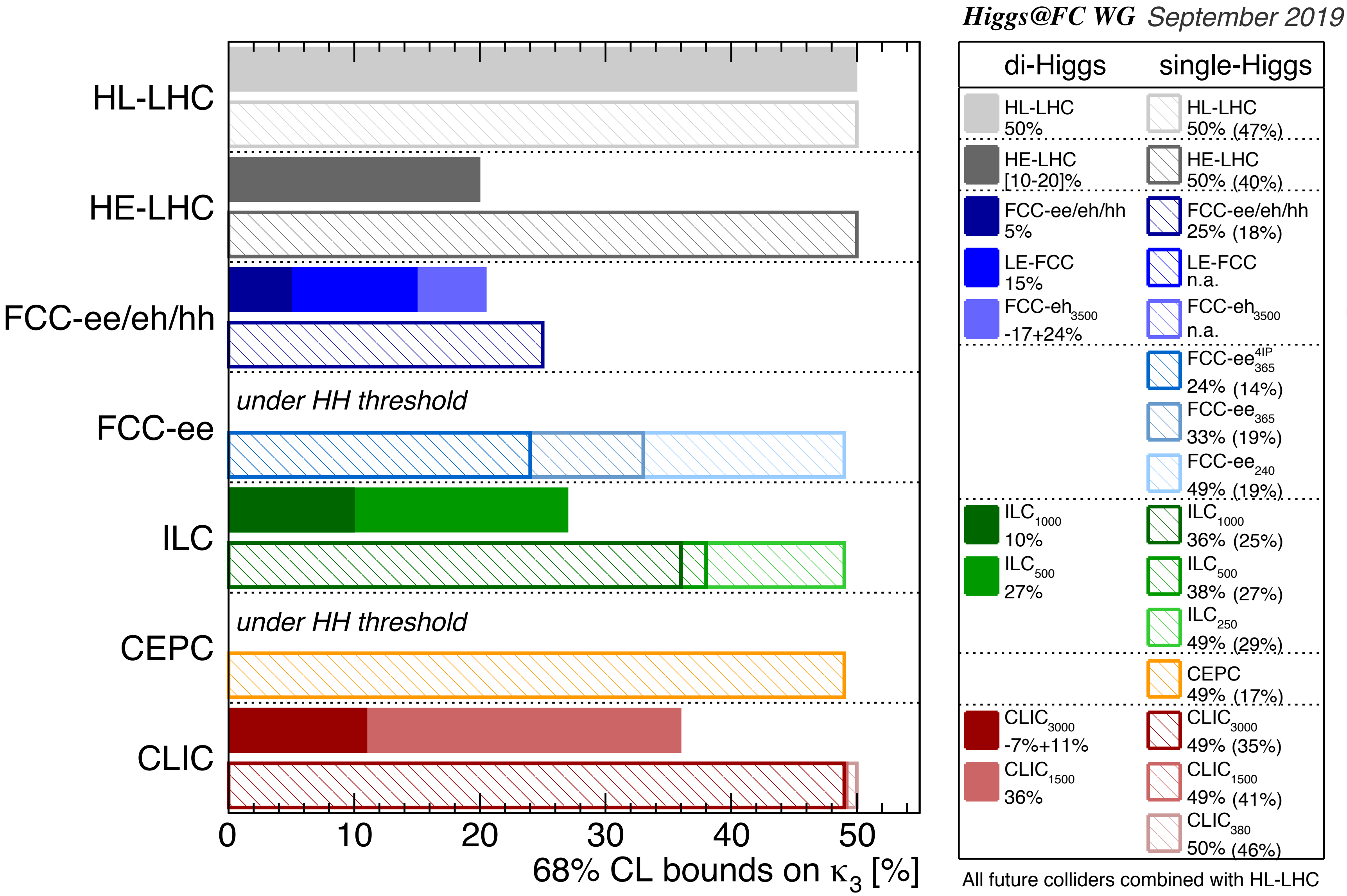
CLIC: High-E run compensate the absence of Z-pole run (for HZZ)



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

The Higgs self-coupling

- **Comparison of capabilities to measure the H³ coupling (via single or multi Higgs processes)**



All future colliders combined with HL-LHC

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%)

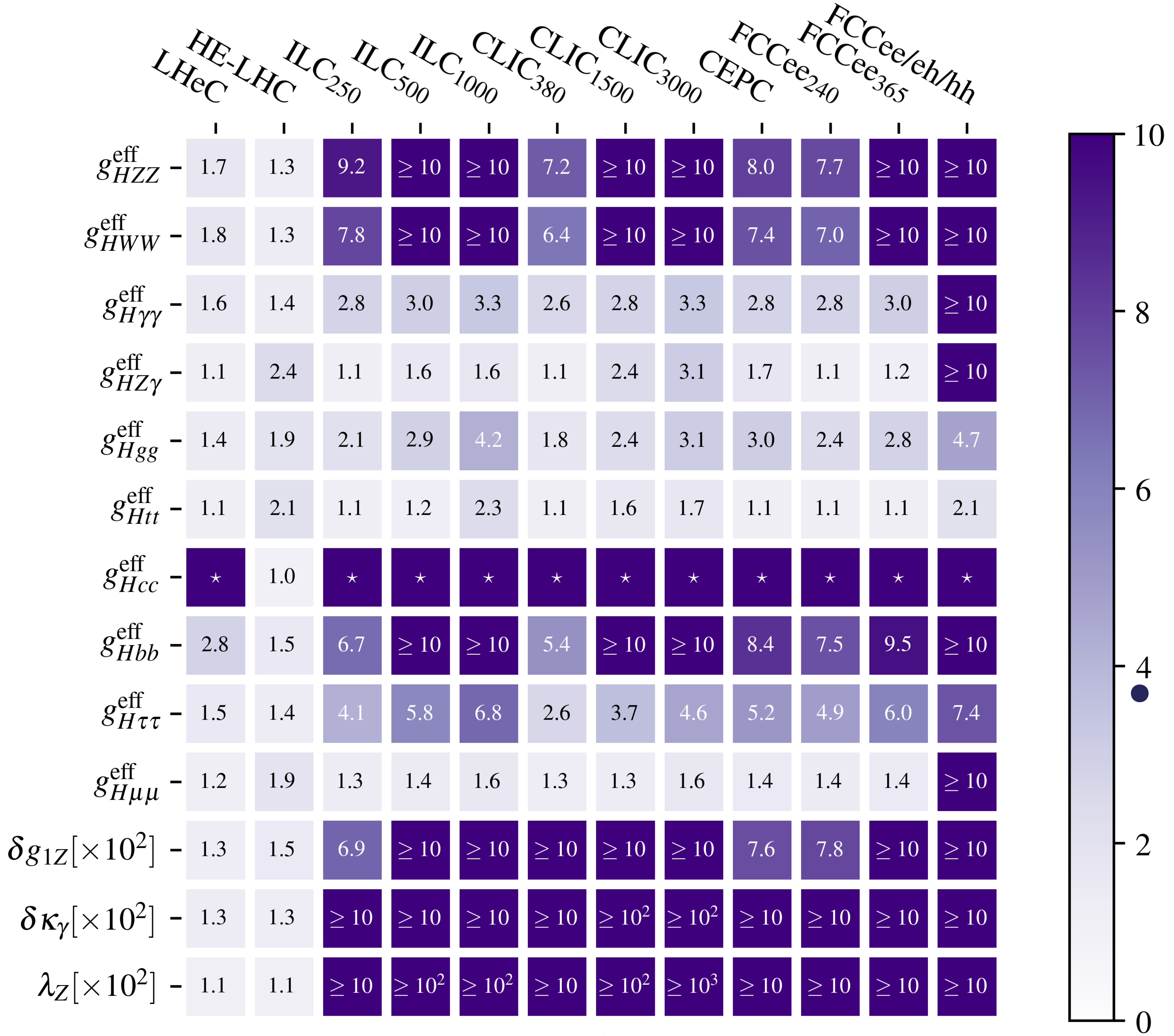
Assuming upgrade to 500 GeV (1000 GeV)

Summary

Single H couplings in the SMEFT-framework: Improvement wrt HL-LHC

EFT results projected into effective Higgs couplings and aTGC

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



	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCCee_{240}	FCCee_{365}	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{\text{eff}}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{\text{eff}}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	$\star$	1.0	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{\text{eff}}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{\text{eff}}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND

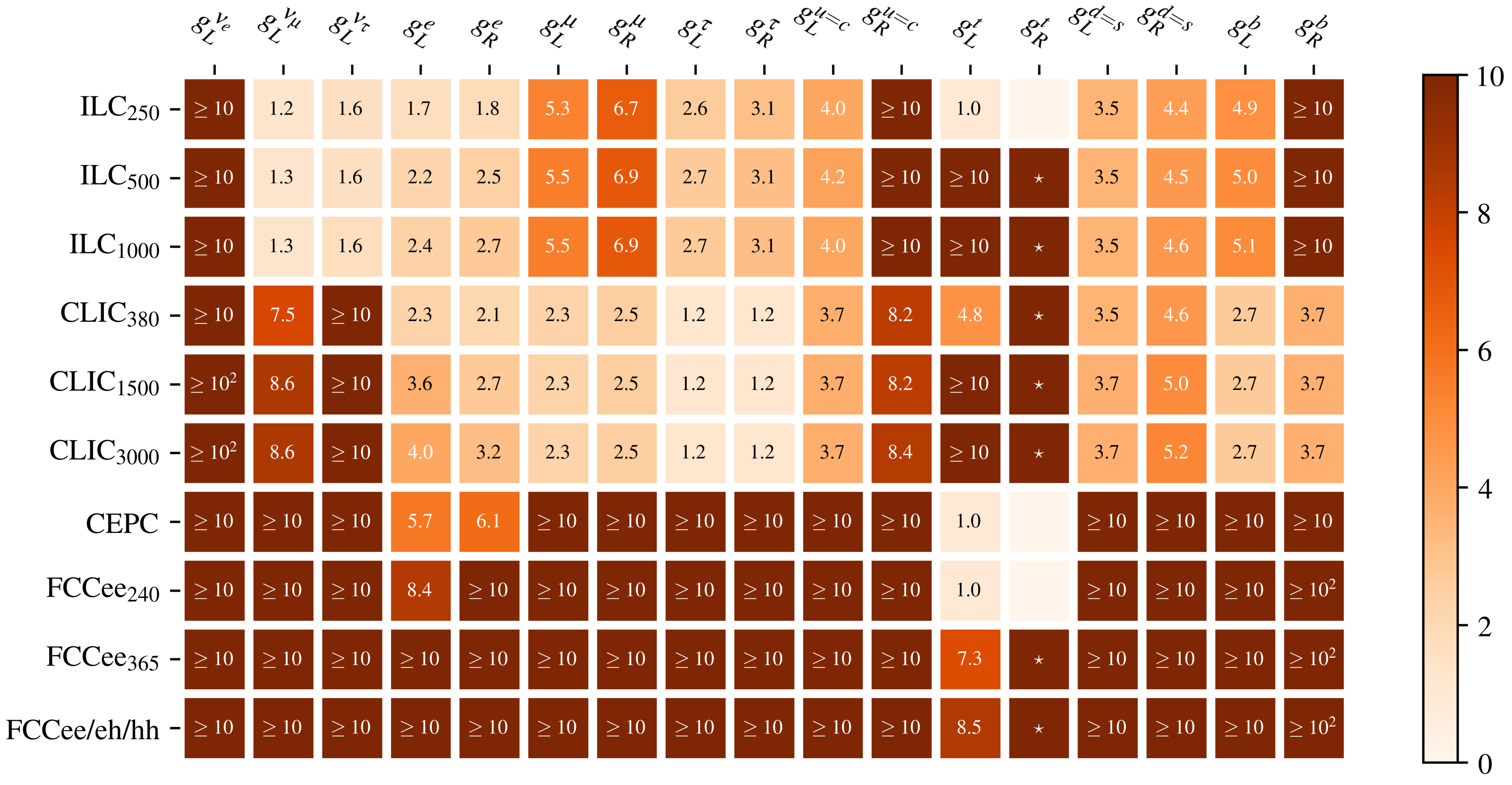
($\star$) not measured at HL-LHC

Factor 10 improvement in many parameters

Summary

EW Zff couplings in the SMEFT-framework: Improvement wrt LEP/HL-LHC

EFT results projected into effective Zff couplings



	$g_L^{\nu_e}$	$g_L^{\nu_\mu}$	$g_L^{\nu_\tau}$	g_L^e	g_R^e	g_L^μ	g_R^μ	g_L^τ	g_R^τ	$g_L^{u=c}$	$g_R^{u=c}$	g_L^t	g_R^t	$g_L^{d=s}$	$g_R^{d=s}$	g_L^b	g_R^b
ILC_{250}	≥ 10	1.2	1.6	1.7	1.8	5.3	6.7	2.6	3.1	4.0	≥ 10	1.0		3.5	4.4	4.9	≥ 10
ILC_{500}	≥ 10	1.3	1.6	2.2	2.5	5.5	6.9	2.7	3.1	4.2	≥ 10	≥ 10	$\star$	3.5	4.5	5.0	≥ 10
ILC_{1000}	≥ 10	1.3	1.6	2.4	2.7	5.5	6.9	2.7	3.1	4.0	≥ 10	≥ 10	$\star$	3.5	4.6	5.1	≥ 10
CLIC_{380}	≥ 10	7.5	≥ 10	2.3	2.1	2.3	2.5	1.2	1.2	3.7	8.2	4.8	$\star$	3.5	4.6	2.7	3.7
CLIC_{1500}	$\geq 10^2$	8.6	≥ 10	3.6	2.7	2.3	2.5	1.2	1.2	3.7	8.2	≥ 10	$\star$	3.7	5.0	2.7	3.7
CLIC_{3000}	$\geq 10^2$	8.6	≥ 10	4.0	3.2	2.3	2.5	1.2	1.2	3.7	8.4	≥ 10	$\star$	3.7	5.2	2.7	3.7
CEPC	≥ 10	≥ 10	≥ 10	5.7	6.1	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	1.0		≥ 10	≥ 10	≥ 10	≥ 10
FCCee_{240}	≥ 10	≥ 10	≥ 10	8.4	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	1.0		≥ 10	≥ 10	≥ 10	$\geq 10^2$
FCCee_{365}	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.3	$\star$	≥ 10	≥ 10	≥ 10	$\geq 10^2$
FCCee/eh/hh	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	8.5	$\star$	≥ 10	≥ 10	≥ 10	$\geq 10^2$

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

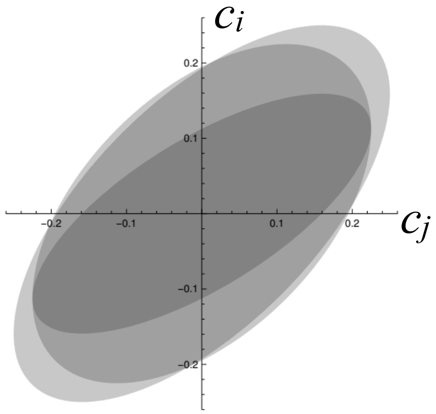
- In the limit of large statistics, the observables

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

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

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

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



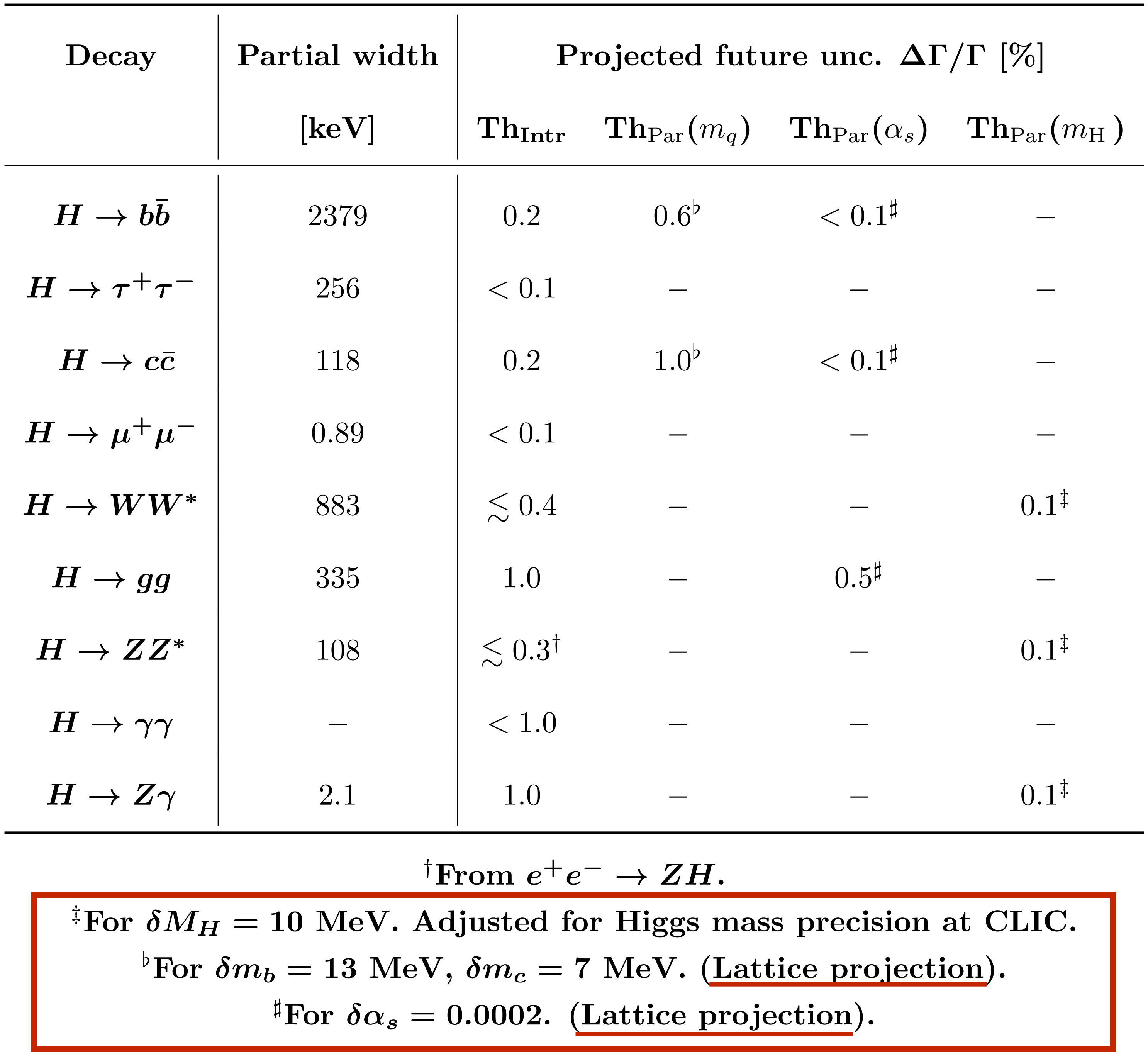
OO minimize the volume of the 1-σ ellipsoid

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

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

Will SM theory calculations be enough?

Estimates for SM theory uncertainties used in the ESU studies



Decay	Partial width [keV]	Projected future unc. $\Delta\Gamma/\Gamma$ [%] Th$_{\text{Intr}}$	Th$_{\text{Par}}(m_q)$	Th$_{\text{Par}}(\alpha_s)$	Th$_{\text{Par}}(m_H)$
$H \to b\bar{b}$	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. $e^+e^- \to Z\,H$

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

Experimental projections

Electroweak precision measurements

Quantity	Current	HL-LHC	FCC-ee	CEPC	ILC		CLIC	
					Giga-Z	250 GeV	Giga-Z	380 GeV
δm_{top} [MeV]	$\sim 500^{\,a)}$	$\sim 400^{\,a)}$	$20^{\,b)}$	–	–	$17^{\,b)}$	–	$20\text{-}22^{\,b)}$
δM_Z [MeV]	2.1	–	0.1	0.5	–	–	–	–
$\delta \Gamma_Z$ [MeV]	2.3	–	0.1	0.5	1	–	1	–
$\delta \Gamma_{Z\to\text{had}}$ [MeV]	2.0	–	–	–	0.7	–	0.7	–
$\delta \sigma^0_{\text{had}}$ [pb]	37	–	4	5	–	–	–	–
δM_W [MeV]	12	7	0.7	$1.0\ (2\text{-}3)^{\,c)}$	–	$2.4^{\,d)}$	–	2.5
$\delta \Gamma_W$ [MeV]	42	–	1.5	3	–	–	–	–
$\delta \text{BR}_{W\to e\nu}[10^{-4}]$	150	–	3	3	–	4.2	–	11
$\delta \text{BR}_{W\to \mu\nu}[10^{-4}]$	140	–	3	3	–	4.1	–	11
$\delta \text{BR}_{W\to \tau\nu}[10^{-4}]$	190	–	4	4	–	5.2	–	11
$\delta \text{BR}_{W\to \text{had}}[10^{-4}]$	40	–	1	1	–	–	–	–
δA_e $[10^{-4}]$	140	–	$1.1^{\,e)}$	$3.2^{\,e)}$	5.1	10	10	42
δA_μ $[10^{-4}]$	1060	–	–	–	5.4	54	13	270
δA_τ $[10^{-4}]$	300	–	$3.1^{\,e)}$	$5.2^{\,e)}$	5.4	57	17	370
δA_b $[10^{-4}]$	220	–	–	–	5.1	6.4	9.9	40
δA_c $[10^{-4}]$	400	–	–	–	5.8	21	10	30
δA^μ_{FB} $[10^{-4}]$	770	–	0.54	4.6	–	–	–	–
δA^b_{FB} $[10^{-4}]$	160	–	$30^{\,f)}$	$10^{\,f)}$	–	–	–	–
δA^c_{FB} $[10^{-4}]$	500	–	$80^{\,f)}$	$30^{\,f)}$	–	–	–	–
δR_e $[10^{-4}]$	24	–	3	2.4	5.4	11	4.2	27
δR_μ $[10^{-4}]$	16	–	0.5	1	2.8	11	2.2	27
δR_τ $[10^{-4}]$	22	–	1	1.5	4.5	12	4.3	60
δR_b $[10^{-4}]$	31	–	2	2	7	11	7	18
δR_c $[10^{-4}]$	170	–	10	10	30	50	23	56
δR_ν $[10^{-3}]^{\,g)}$	–	–	–	–	–	–	–	9.4
δR_{inv} $[10^{-3}]^{\,g)}$	–	–	0.27	0.5	–	–	–	–

Experimental projections

Higgs measurements: Circular lepton colliders

	FCC-ee$_{240}$	FCC-ee$_{365}$	CEPC
$\delta\sigma_{ZH}$	0.005	0.009	0.005
$\delta\mu_{ZH,bb}$	0.003	0.005	0.0031
$\delta\mu_{ZH,cc}$	0.022	0.065	0.033
$\delta\mu_{ZH,gg}$	0.019	0.035	0.013
$\delta\mu_{ZH,WW}$	0.012	0.026	0.0098
$\delta\mu_{ZH,ZZ}$	0.044	0.12	0.051
$\delta\mu_{ZH,\tau\tau}$	0.009	0.018	0.0082
$\delta\mu_{ZH,\gamma\gamma}$	0.09	0.18	0.068
$\delta\mu_{ZH,\mu\mu}$	0.19	0.40	0.17
$\delta\mu_{ZH,Z\gamma}$	–	–	0.16
$\delta\mu_{\nu\nu H,bb}$	0.031	0.009	0.030
$\delta\mu_{\nu\nu H,cc}$	–	0.10	–
$\delta\mu_{\nu\nu H,gg}$	–	0.045	–
$\delta\mu_{\nu\nu H,ZZ}$	–	0.10	–
$\delta\mu_{\nu\nu H,\tau\tau}$	–	0.08	–
$\delta\mu_{\nu\nu H,\gamma\gamma}$	–	0.22	–
BR$_{\text{inv}}$	<0.0015	<0.003	<0.0015

Experimental projections

Higgs measurements: Linear lepton colliders (ILC)

	ILC$_{250}$	
Polarization:	e^-: -80% e^+: +30%	e^-: +80% e^+: -30%
$\delta\sigma_{ZH}/\sigma_{ZH}$	0.011	0.011
$\delta\mu_{ZH,bb}$	0.0072	0.0072
$\delta\mu_{ZH,cc}$	0.044	0.044
$\delta\mu_{ZH,gg}$	0.037	0.037
$\delta\mu_{ZH,ZZ}$	0.095	0.095
$\delta\mu_{ZH,WW}$	0.024	0.024
$\delta\mu_{ZH,\tau\tau}$	0.017	0.017
$\delta\mu_{ZH,\gamma\gamma}$	0.18	0.18
$\delta\mu_{ZH,\mu\mu}$	0.38	0.38
$\delta\mu_{\nu\nu H,bb}$	0.043	0.17
$\mathrm{BR}_{\mathrm{inv}}$	<0.0027	<0.0021

	ILC$_{350}$	
Polarization:	e^-: -80% e^+: +30%	e^-: +80% e^+: -30%
$\delta\sigma_{ZH}/\sigma_{ZH}$	0.025	0.042
$\delta\mu_{ZH,bb}$	0.021	0.036
$\delta\mu_{ZH,cc}$	0.15	0.26
$\delta\mu_{ZH,gg}$	0.11	0.20
$\delta\mu_{ZH,ZZ}$	0.34	0.59
$\delta\mu_{ZH,WW}$	0.076	0.13
$\delta\mu_{ZH,\tau\tau}$	0.054	0.094
$\delta\mu_{ZH,\gamma\gamma}$	0.53	0.92
$\delta\mu_{ZH,\mu\mu}$	1.2	2.1
$\delta\mu_{\nu\nu H,bb}$	0.025	0.18
$\delta\mu_{\nu\nu H,cc}$	0.26	1.9
$\delta\mu_{\nu\nu H,gg}$	0.10	0.75
$\delta\mu_{\nu\nu H,ZZ}$	0.27	1.9
$\delta\mu_{\nu\nu H,WW}$	0.078	0.57
$\delta\mu_{\nu\nu H,\tau\tau}$	0.22	1.6
$\delta\mu_{\nu\nu H,\gamma\gamma}$	0.61	4.2
$\delta\mu_{\nu\nu H,\mu\mu}$	2.2	16
$\mathrm{BR}_{\mathrm{inv}}$	<0.0096	<0.015

	ILC$_{500}$	
Polarization:	e^-: -80% e^+: +30%	e^-: +80% e^+: -30%
$\delta\sigma_{ZH}/\sigma_{ZH}$	0.017	0.017
$\delta\mu_{ZH,bb}$	0.010	0.010
$\delta\mu_{ZH,cc}$	0.071	0.071
$\delta\mu_{ZH,gg}$	0.059	0.059
$\delta\mu_{ZH,ZZ}$	0.14	0.14
$\delta\mu_{ZH,WW}$	0.030	0.030
$\delta\mu_{ZH,\tau\tau}$	0.024	0.024
$\delta\mu_{ZH,\gamma\gamma}$	0.19	0.19
$\delta\mu_{ZH,\mu\mu}$	0.47	0.47
$\delta\mu_{\nu\nu H,bb}$	0.0041	0.015
$\delta\mu_{\nu\nu H,cc}$	0.035	0.14
$\delta\mu_{\nu\nu H,gg}$	0.023	0.095
$\delta\mu_{\nu\nu H,ZZ}$	0.047	0.19
$\delta\mu_{\nu\nu H,WW}$	0.014	0.055
$\delta\mu_{\nu\nu H,\tau\tau}$	0.039	0.16
$\delta\mu_{\nu\nu H,\gamma\gamma}$	0.11	0.43
$\delta\mu_{\nu\nu H,\mu\mu}$	0.4	1.7
$\delta\mu_{ttH,bb}$	0.20	0.20
$\mathrm{BR}_{\mathrm{inv}}$	<0.0069	<0.0050
Direct constraint on Higgs self-interaction		
$\delta\kappa_3$	0.27	

	ILC$_{1000}$	
Polarization:	e^-: -80% e^+: +20%	e^-: +80% e^+: -20%
$\delta\mu_{\nu\nu H,bb}$	0.0032	0.010
$\delta\mu_{\nu\nu H,cc}$	0.017	0.064
$\delta\mu_{\nu\nu H,gg}$	0.013	0.047
$\delta\mu_{\nu\nu H,ZZ}$	0.023	0.084
$\delta\mu_{\nu\nu H,WW}$	0.0091	0.033
$\delta\mu_{\nu\nu H,\tau\tau}$	0.017	0.064
$\delta\mu_{\nu\nu H,\gamma\gamma}$	0.048	0.17
$\delta\mu_{\nu\nu H,\mu\mu}$	0.17	0.64
$\delta\mu_{ttH,bb}$	0.045	0.045
Direct constraint on Higgs self-interaction		
$\delta\kappa_3$	0.10	

Experimental projections

Higgs measurements: Linear lepton colliders (CLIC)

	CLIC_{380}	
Polarization:	e^-: -80% e^+: 0%	e^-: +80% e^+: 0%
$\delta\sigma_{ZH,Z\to ll}/\sigma_{ZH,Z\to ll}$	0.036	0.041
$\delta\sigma_{ZH,Z\to qq}/\sigma_{ZH,Z\to qq}$	0.017	0.020
$\delta\mu_{ZH,bb}$	0.0081	0.0092
$\delta\mu_{ZH,cc}$	0.13	0.15
$\delta\mu_{ZH,gg}$	0.057	0.065
$\delta\mu_{ZH,WW}$	0.051	0.057
$\delta\mu_{ZH,\tau\tau}$	0.059	0.066
$\delta\mu_{\nu\nu H,bb}$	0.014	0.041
$\delta\mu_{\nu\nu H,cc}$	0.19	0.57
$\delta\mu_{\nu\nu H,gg}$	0.076	0.23
BR_{inv}	<0.0027	<0.003

	CLIC_{1500}	
Polarization:	e^-: -80% e^+: 0%	e^-: +80% e^+: 0%
$\delta\mu_{ZH,bb}$	0.028	0.062
$\delta\mu_{\nu\nu H,bb}$	0.0025	0.015
$\delta\mu_{\nu\nu H,cc}$	0.039	0.24
$\delta\mu_{\nu\nu H,gg}$	0.033	0.20
$\delta\mu_{\nu\nu H,WW}$	0.0067	0.04
$\delta\mu_{\nu\nu H,ZZ}$	0.036	0.22
$\delta\mu_{\nu\nu H,\gamma\gamma}$	0.1	0.6
$\delta\mu_{\nu\nu H,Z\gamma}$	0.28	1.7
$\delta\mu_{\nu\nu H,\tau\tau}$	0.028	0.17
$\delta\mu_{\nu\nu H,\mu\mu}$	0.24	1.5
$\delta\mu_{eeH,bb}$	0.015	0.033
$\delta\mu_{ttH,bb}$	0.056	0.15

	CLIC_{3000}	
Polarization:	e^-: -80% e^+: 0%	e^-: +80% e^+: 0%
$\delta\mu_{ZH,bb}$	0.045	0.10
$\delta\mu_{\nu\nu H,bb}$	0.0017	0.01
$\delta\mu_{\nu\nu H,cc}$	0.037	0.22
$\delta\mu_{\nu\nu H,gg}$	0.023	0.14
$\delta\mu_{\nu\nu H,WW}$	0.0033	0.02
$\delta\mu_{\nu\nu H,ZZ}$	0.021	0.13
$\delta\mu_{\nu\nu H,\gamma\gamma}$	0.05	0.3
$\delta\mu_{\nu\nu H,Z\gamma}$	0.16	0.95
$\delta\mu_{\nu\nu H,\tau\tau}$	0.023	0.14
$\delta\mu_{\nu\nu H,\mu\mu}$	0.13	0.8
$\delta\mu_{eeH,bb}$	0.016	0.036
Direct constraint on Higgs self-interaction		
$\delta\kappa_3$	0.11	

Experimental projections

Higgs measurements: electron-proton colliders

Observable	LHeC	FCC-eh
$\delta\mu_{WBF,bb}$	0.008	0.0025
$\delta\mu_{WBF,cc}$	0.071	0.022
$\delta\mu_{WBF,gg}$	0.058	0.018
$\delta\mu_{ZBF,bb}$	0.023	0.0065
$\delta\mu_{WBF,WW}$	0.062	0.019
$\delta\mu_{WBF,ZZ}$	0.120	0.038
$\delta\mu_{WBF,\tau\tau}$	0.052	0.016
$\delta\mu_{WBF,\gamma\gamma}$	0.15	0.046
$\delta\mu_{ZBF,cc}$	0.200	0.058
$\delta\mu_{ZBF,gg}$	0.160	0.047
$\delta\mu_{ZBF,WW}$	0.170	0.050
$\delta\mu_{ZBF,ZZ}$	0.350	0.100
$\delta\mu_{ZBF,\tau\tau}$	0.15	0.042
$\delta\mu_{ZBF,\gamma\gamma}$	0.42	0.120

Experimental projections

Higgs measurements: proton-proton colliders

FCC-hh
100 TeV

FCC-hh	
$\delta\mu_{ggF,4\mu}$	0.019
$\delta\mu_{ggF,\gamma\gamma}$	0.015
$\delta\mu_{ggF,Z\gamma}$	0.016
$\delta\mu_{ggF,\mu\mu}$	0.012
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.013
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.008
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.014
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.018
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.019
Invisible decays	
$\mathrm{BR}_{\mathrm{inv}}$	<0.00013
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.05

FCC-hh (Extra inputs used in κ fits)	
$\delta(\sigma^{H\to\gamma\gamma}_{WH}/\sigma^{Z\to e^+e^-}_{WZ})$	0.014
$\delta(\sigma^{H\to\tau\tau}_{WH}/\sigma^{Z\to\tau\tau}_{WZ})$	0.016
$\delta(\sigma^{H\to bb}_{WH}/\sigma^{Z\to bb}_{WZ})$	0.011
$\delta(\sigma^{H\to WW}_{WH}/\sigma^{H\to\gamma\gamma}_{WH})$	0.015

LE-FCC-hh
37.5 TeV

LE-FCC	
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.029
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.015
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.028
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.06
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.04-0.06
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.15