CERN Open Symposium on the ESU: Summary of the EW/Higgs session

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European Strategy Update

KAIST-KAIX Workshop for Future Particle Accelerators

Daejeon, July 8, 2019

Introduction

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

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

- Therefore, a key component of the physics program at future colliders has revolved around the possible improvements on the knowledge of properties Higgs and, to less extent, the EW gauge bosons…
- … including physics that will remain largely beyond the reach of the (HL-) LHC, e.g. a measurement of the Higgs self-coupling

Introduction

Future Particle Colliders

Hadron Colliders

Tevatron 1983-2011

LHC → HiLumi HL-LHC PROJECT $\xrightarrow{?}$ HE-LHC, FCC hh

⇒

Large E reach ⇒ Direct searches

“Dirty” environment

Mass reach limited by PDF

Sensitivity to NP with strong interactions

Electron-Proton Colliders

HERA $\xrightarrow{?}$ LHeC, FCC he

⇒

A mix of the two (both pros and cons)

Lepton Colliders

LEP/SLC $\xrightarrow{?}$ ilc, CLIC, CEPC, FCC ee

⇒

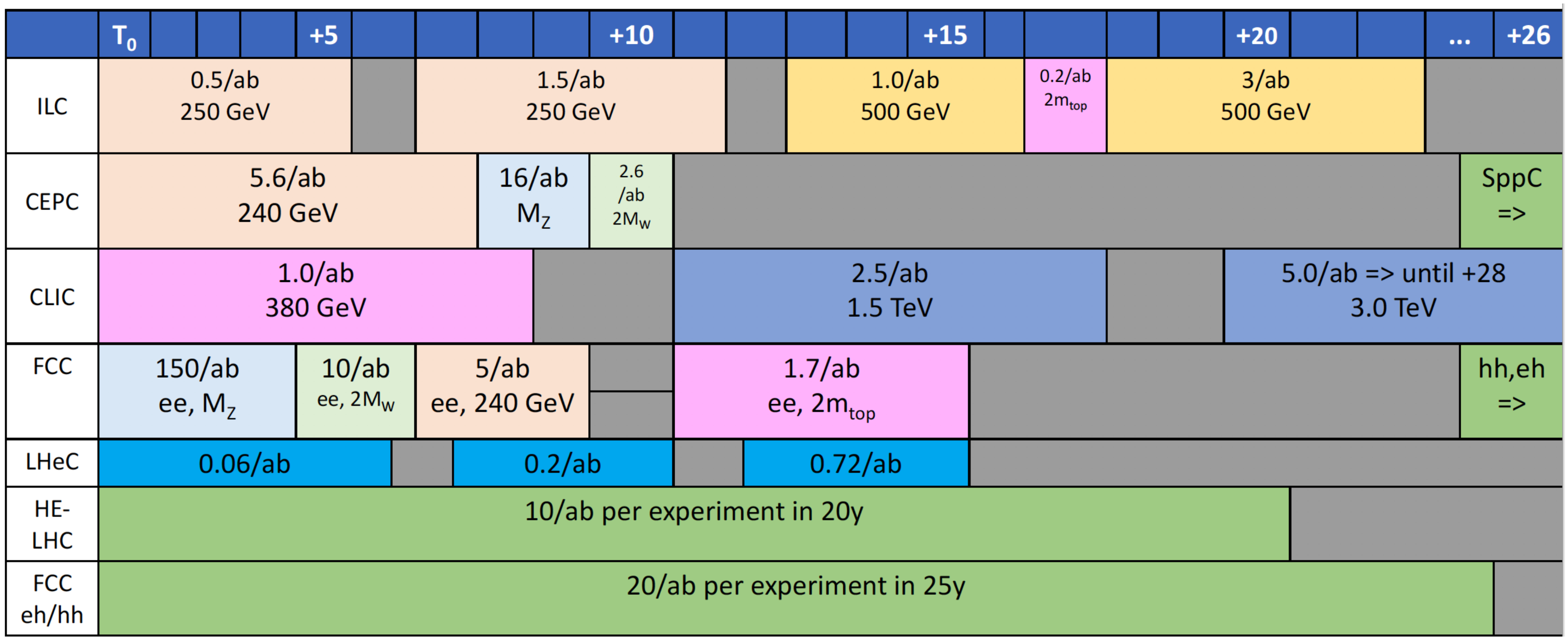
Limited E reach for direct searches

Clean environment ⇒ precision measurements

Sensitivity to NP with EW interactions

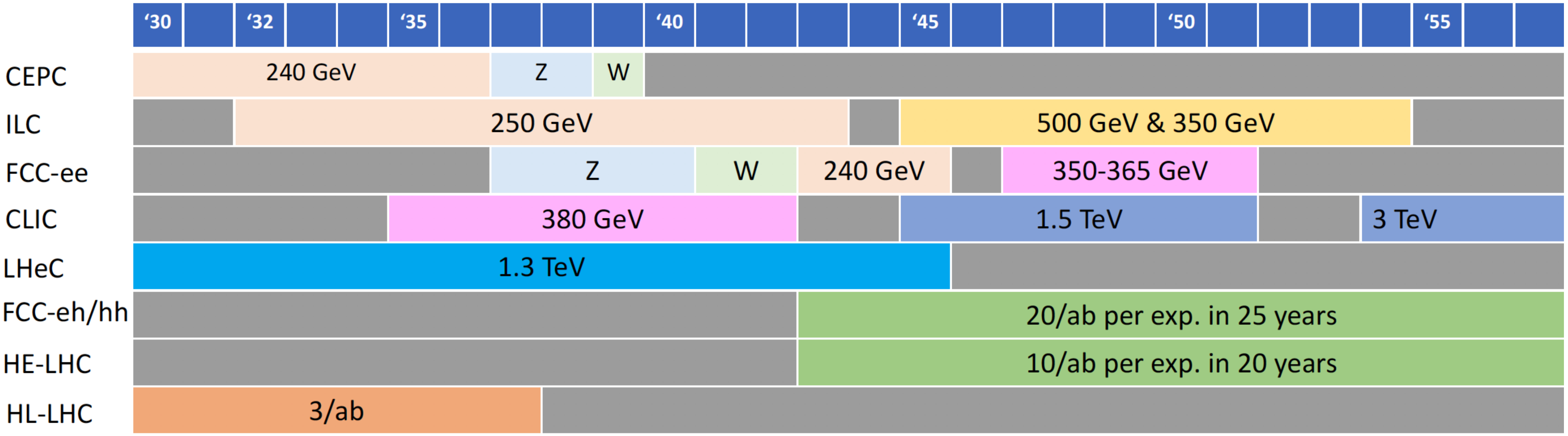
Introduction

Future Particle Colliders



ILC	0.5/ab 250 GeV	1.5/ab 250 GeV	1.0/ab 500 GeV	0.2/ab 2m$_{top}$	3/ab 500 GeV
CEPC	5.6/ab 240 GeV	16/ab M$_Z$	2.6 /ab 2M$_W$	SppC =>	
CLIC	1.0/ab 380 GeV	2.5/ab 1.5 TeV	5.0/ab => until +28 3.0 TeV		
FCC	150/ab ee, M$_Z$	10/ab ee, 2M$_W$	5/ab ee, 240 GeV	1.7/ab ee, 2m$_{top}$	hh,eh =>
LHeC	0.06/ab	0.2/ab	0.72/ab		
HE-LHC	10/ab per experiment in 20y				
FCC eh/hh	20/ab per experiment in 25y				

Starting time at T$_0$



CEPC	240 GeV	Z	W	
ILC	250 GeV	500 GeV & 350 GeV		
FCC-ee	Z	W	240 GeV	350-365 GeV
CLIC	380 GeV	1.5 TeV	3 TeV	
LHeC	1.3 TeV			
FCC-eh/hh	20/ab per exp. in 25 years			
HE-LHC	10/ab per exp. in 20 years			
HL-LHC	3/ab			

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

Introduction

The Open symposium on the ESU

- Meeting prepared to present and discuss the inputs presented by the different future experimental projects to the Update of the European Strategy for Particle Physics

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

Introduction

The Open symposium on the ESU: EW/Higgs session

Session 1:

Talk 1: Prospects for Higgs and EW measurements at HL-LHC (P. Azzi, INFN Padova)
Talk 2: QCD uncertainties on Higgs and EWK measurables (F. Caola, Oxford)
Talk 3: Theoretical Perspective on direct and indirect searches for new physics (R. Rattazzi, EPFL)

Session 2:

Talk 4: Overview and technical challenges of proposed Higgs factories (D. Schulte, CERN)
Talk 5: Capability of future machines for precision Higgs physics (M. Cepeda, CIEMAT)
Discussion

Session 3:

Talk 6: Electroweak Precision Measurements at future experiments (M. Lancaster, Manchester)
Talk 7: Precision Electroweak calculations (Giga-Z,WW, Higgs BRs, etc) (S. Dittmaier, Freiburg)
Talk 8: The Higgs potential and its cosmological histories (G. Servant, DESY)

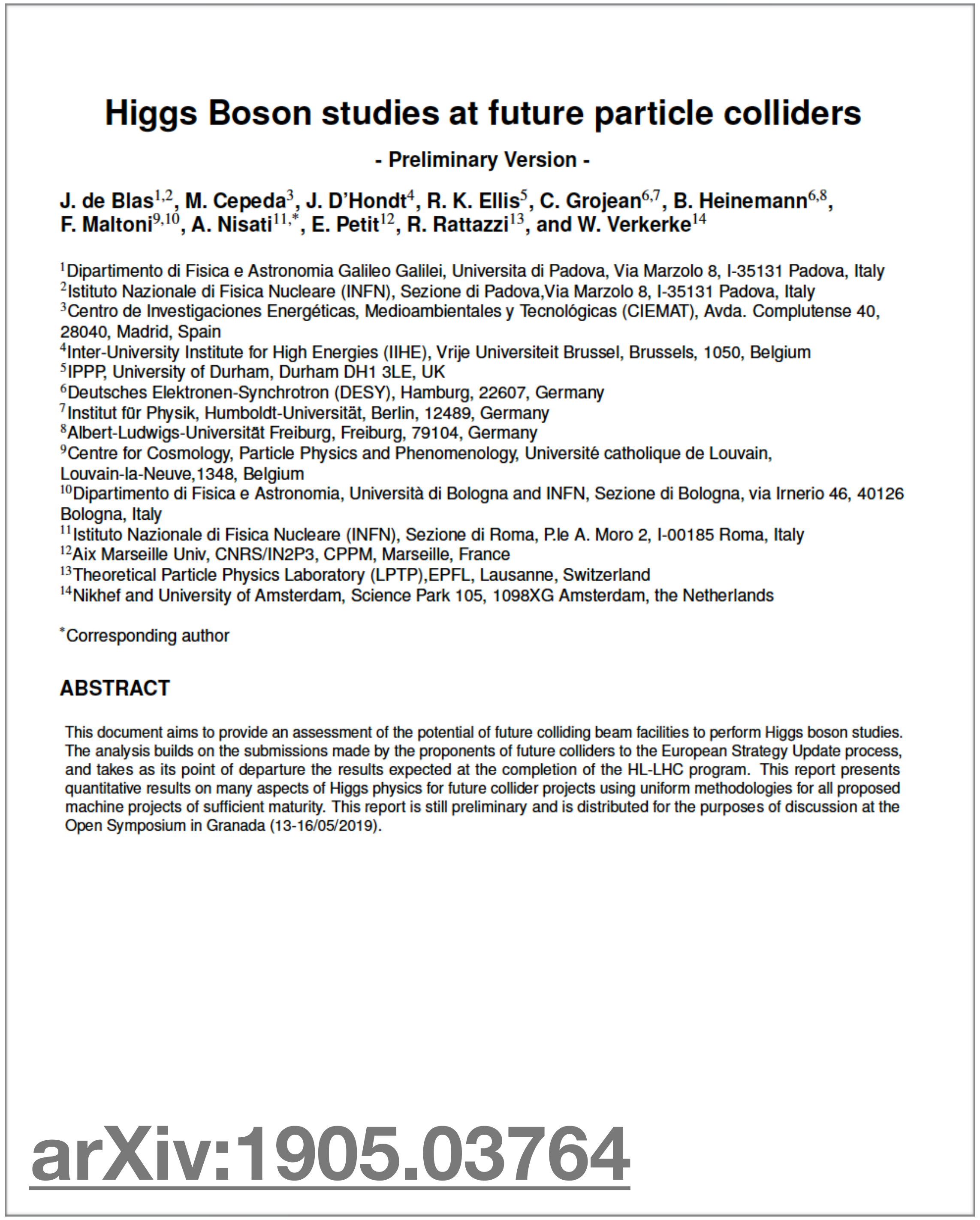
Session 4:

Talk 9: Path towards measuring the Higgs potential (E. Petit, CPPM Marseille)
Talk 10: Interpretation of Higgs and EWK data in EFT framework (J. de Blas, Padova)
Discussion

Future Collider Studies of the EW/Higgs sector

EW/Higgs studies for the ESU

- Most quantitative results from preliminary version of:



Higgs Boson studies at future particle colliders

- Preliminary Version -

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ABSTRACT

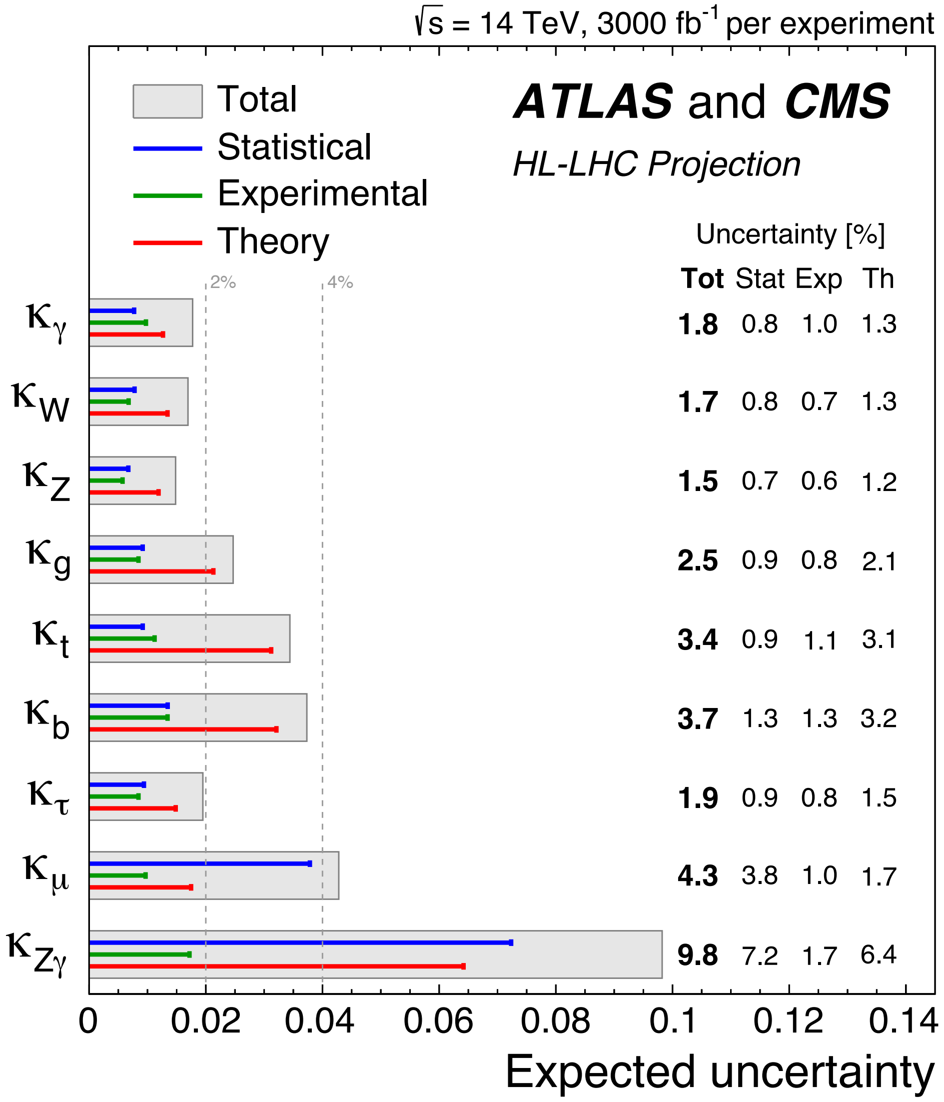
This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects using uniform methodologies for all proposed machine projects of sufficient maturity. This report is still preliminary and is distributed for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019).

arXiv:1905.03764

To be updated in the coming weeks including the input from the discussion at the Open Symposium at Granada

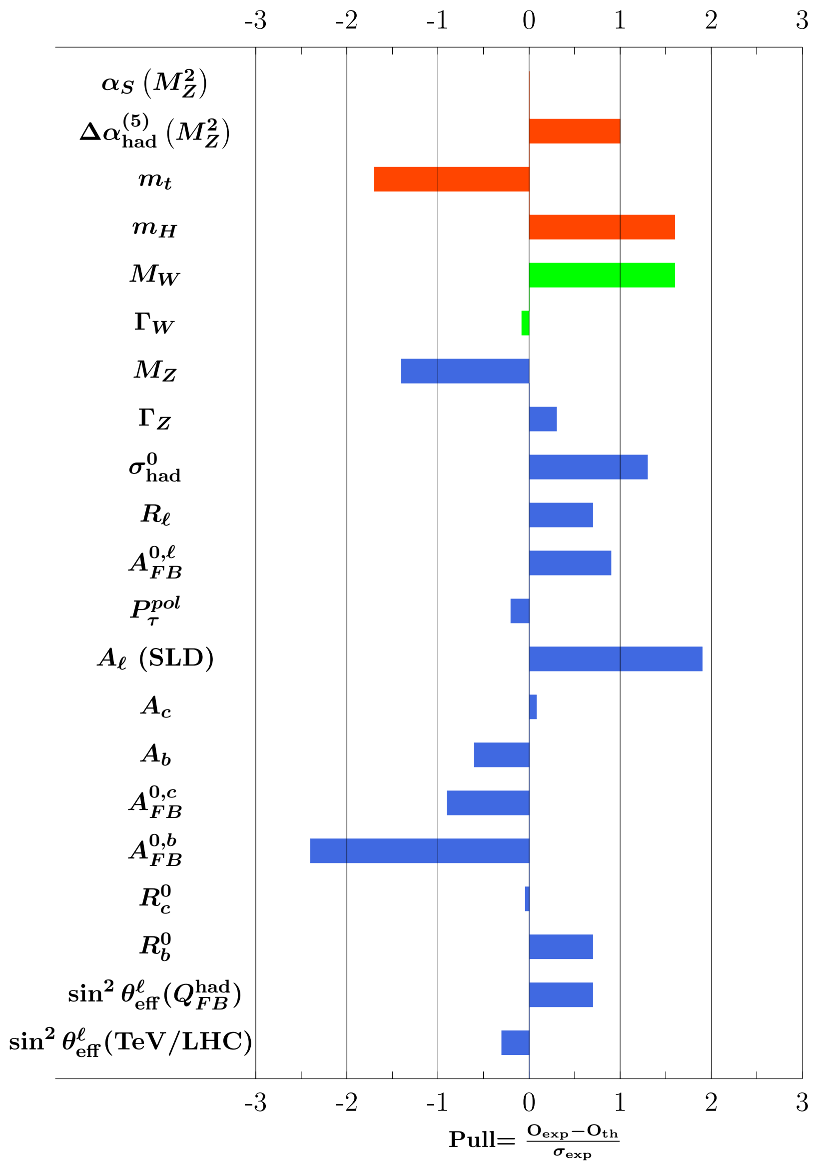
Baseline of Higgs/EW studies at Future Colliders

- **Higgs projections from HL-LHC, EWPO/WW from LEP/SLD:**



Uncertainty [%]

Tot	Stat	Exp	Th
1.8	0.8	1.0	1.3
1.7	0.8	0.7	1.3
1.5	0.7	0.6	1.2
2.5	0.9	0.8	2.1
3.4	0.9	1.1	3.1
3.7	1.3	1.3	3.2
1.9	0.9	0.8	1.5
4.3	3.8	1.0	1.7
9.8	7.2	1.7	6.4



- Precision ~few percent

- Controlled in many cases by TH and Sys (assumes ~2 better than LHC Run 2)

- Model-dependent: ratios, no couplings

- Precision in many cases at per mile level

- SM TH ≪ Exp. Uncertainties

- HL-LHC: M_W, m_t, M_H, weak mixing angle

Baseline of Higgs/EW studies at Future Colliders

- **Studies prepared using 2 frameworks:**

κ-framework

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

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

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

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

Pros

-Theoretically robust framework

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

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

Cons

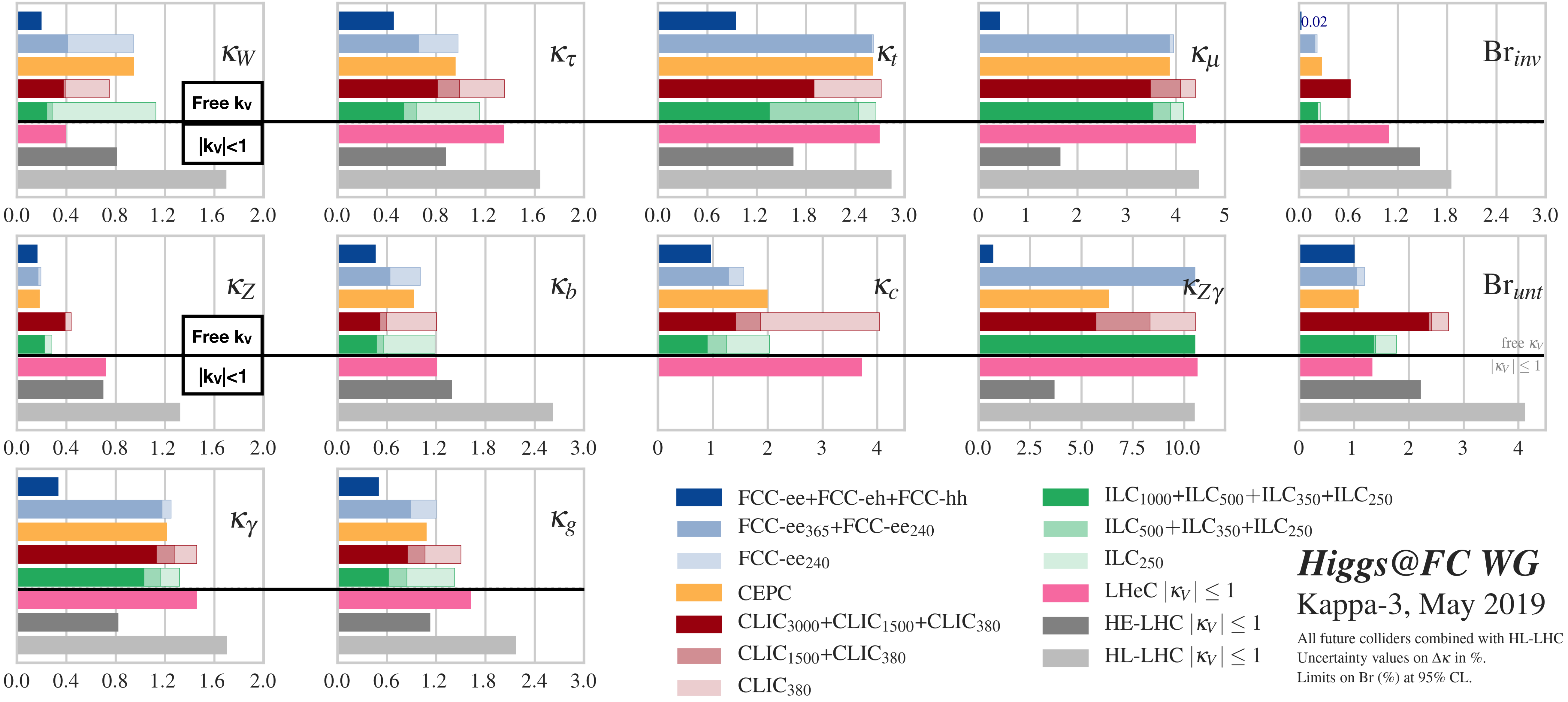
-Many parameters (2499 to dimension 6)

-Requires extension to apply to not-heavy new physics

Higgs interactions

Single Higgs couplings

Results in the κ-framework



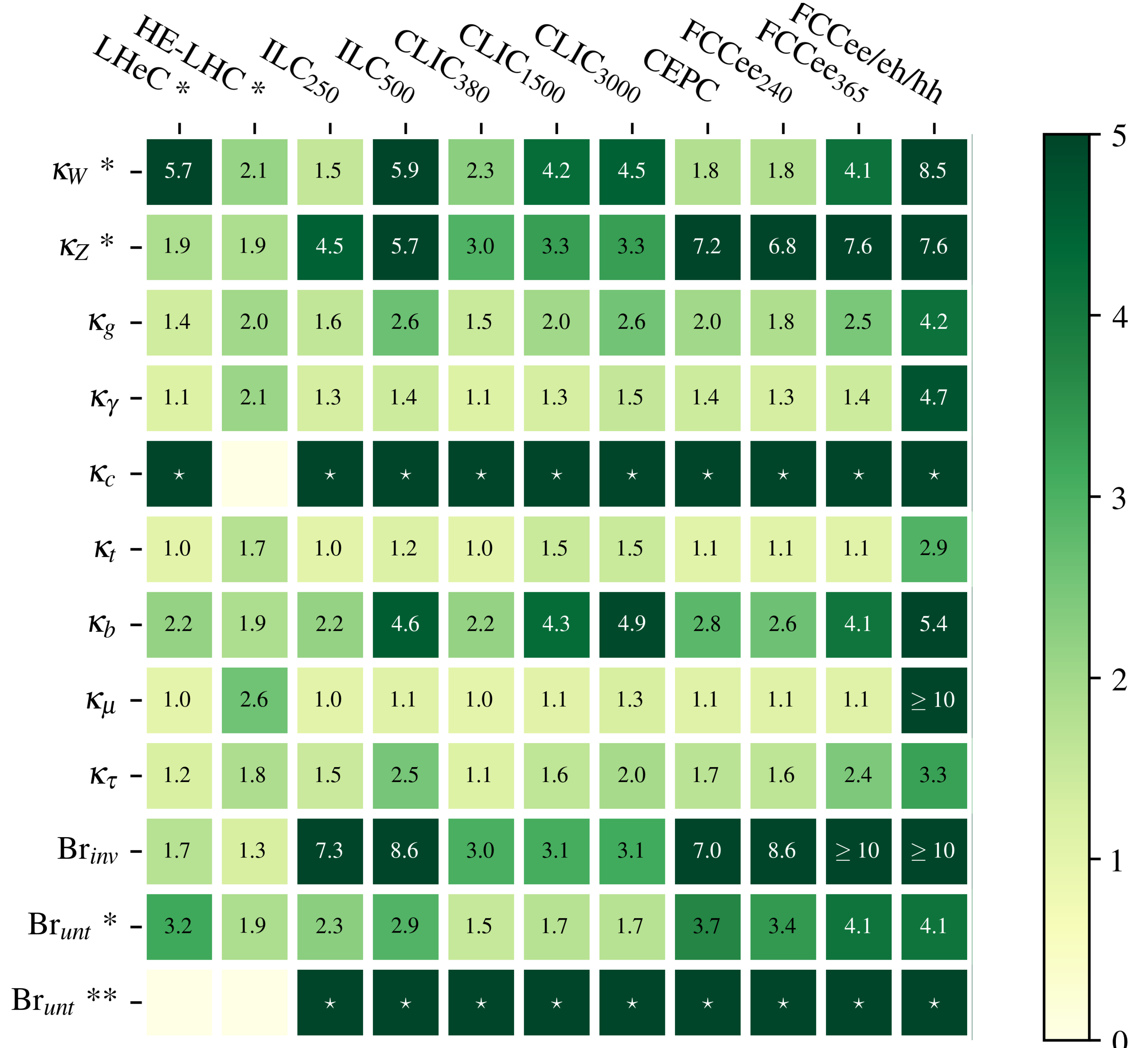
Allowing for extra invisible or other exotic (untagged) H decays

-**WARNING:** Hadron collider results assume $|k_V|<1$

No assumption needed when including a lepton collider

Single Higgs couplings

Results in κ-framework: Improvement wrt HL-LHC



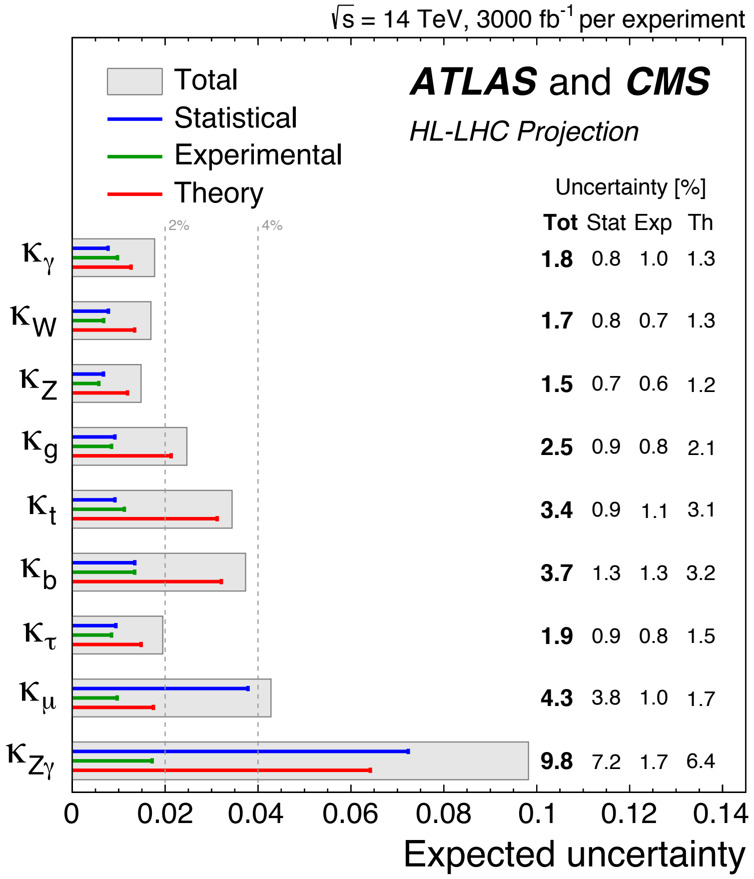
	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCCee_{240}	FCCee_{365}	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

Single Higgs couplings

Precision Higgs Physics at Lepton vs. Hadron Collider

Hadron Collider Higgs

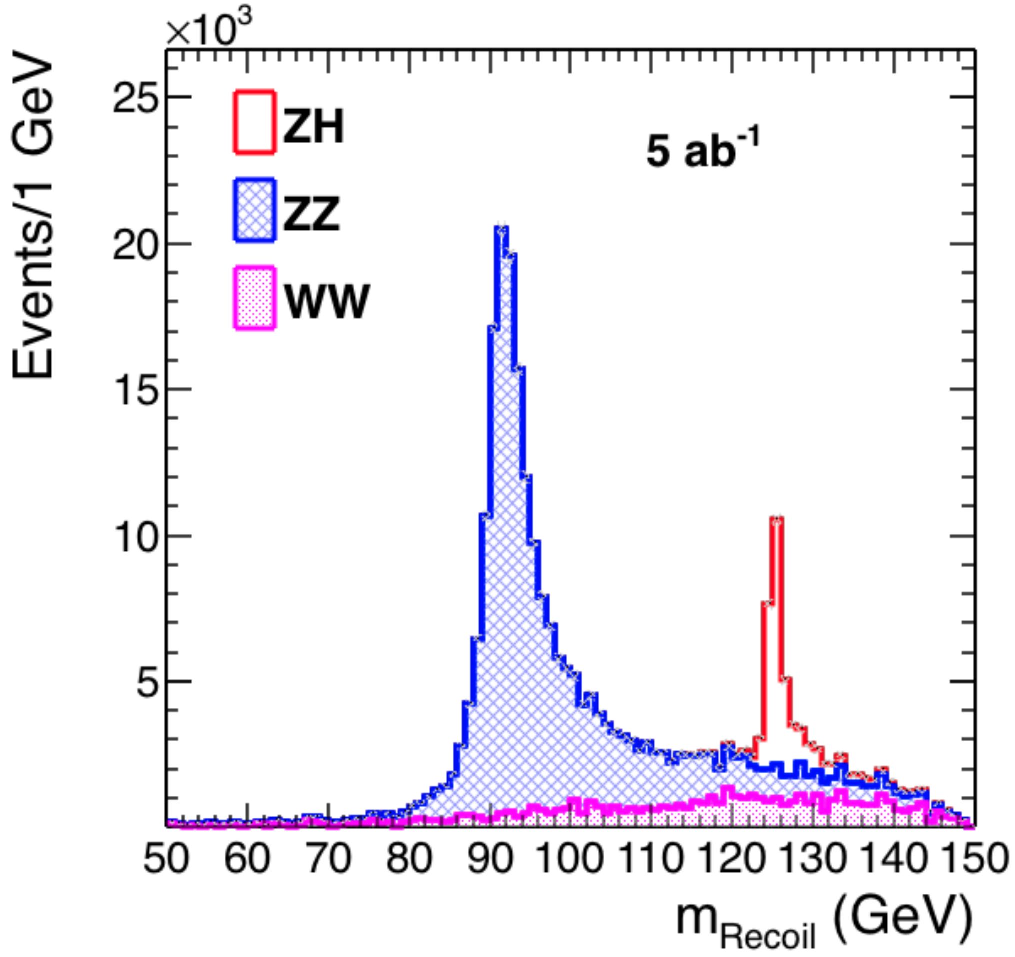


	Uncertainty [%]			
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

O(1-10%) precision but model-dependent (BR_{NP}=0)

Ratios, no absolute couplings

Lepton Collider Higgs



Recoil mass method: absolute measurement of σ_{ZH}

(only possible at lepton colliders)

Translates ratios into couplings

Single Higgs couplings

The Higgs width

- **Hadron colliders:**
  - Diphoton interference studies ~8-22 x SM
  - κ-fit requires extra constraints (e.g. $|\kappa_V|<1$)
  - HZZ on-shell vs off-shell: ~20% precision but model-dependent
- **Lepton colliders:** absolute measurement of couplings increases model independence

κ-framework

From recoil mass method →

From H rates →

$$\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)}=\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H}\simeq\left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}}\times\Gamma_H$$

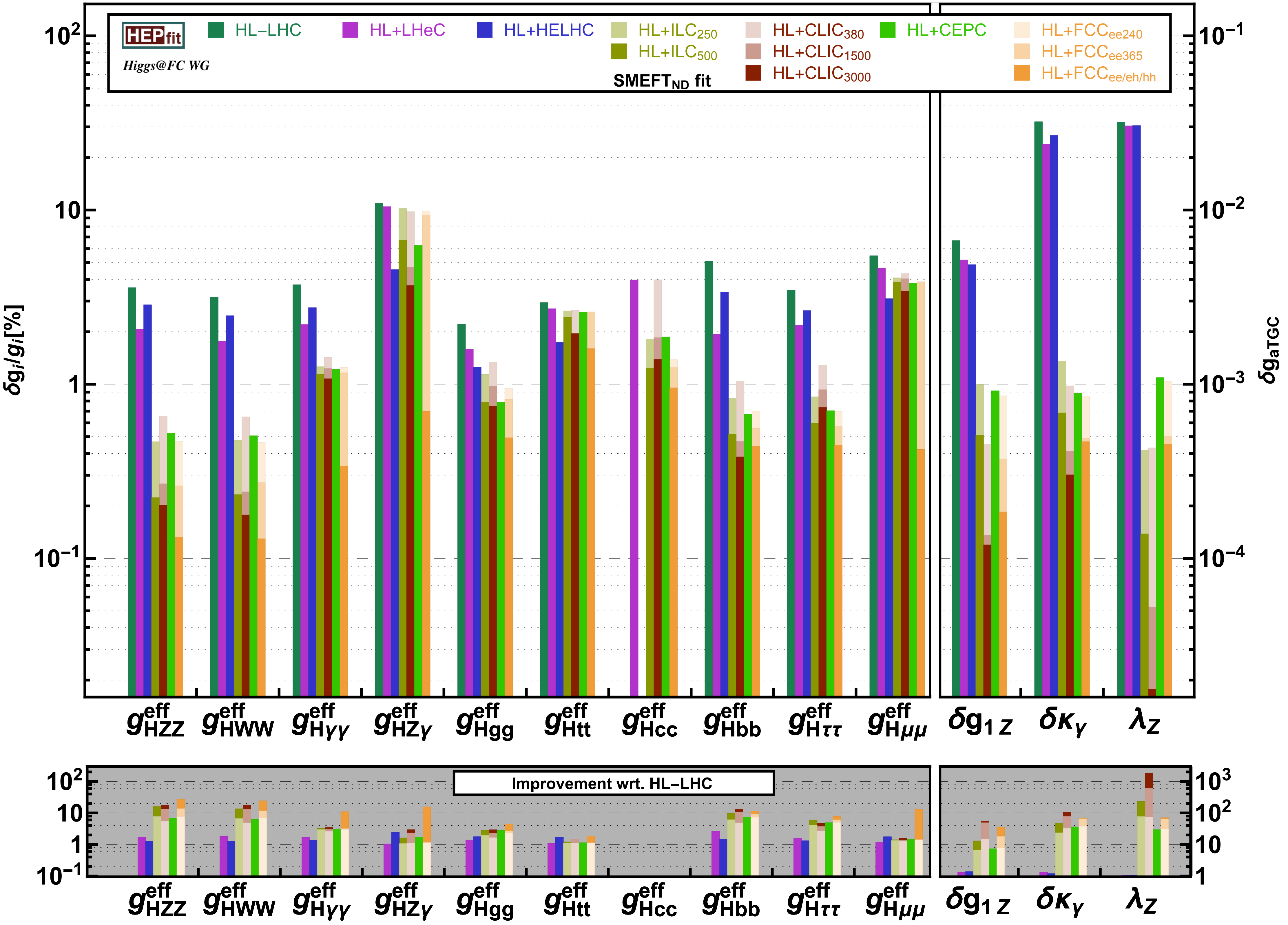
Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [80]	2.6
CLIC_{1500}	2.6	κ-framework [80]	1.7
CLIC_{3000}	2.5	κ-framework [80]	1.6
CEPC	3.1	$\sigma(ZH,\nu\bar{\nu}H)$, $\mathrm{BR}(H\to Z,b\bar{b},WW)$ [85]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

Single Higgs couplings

Results in the SMEFT-framework (Higgs/aTGC)

EFT results projected into effective Higgs couplings and aTGC

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

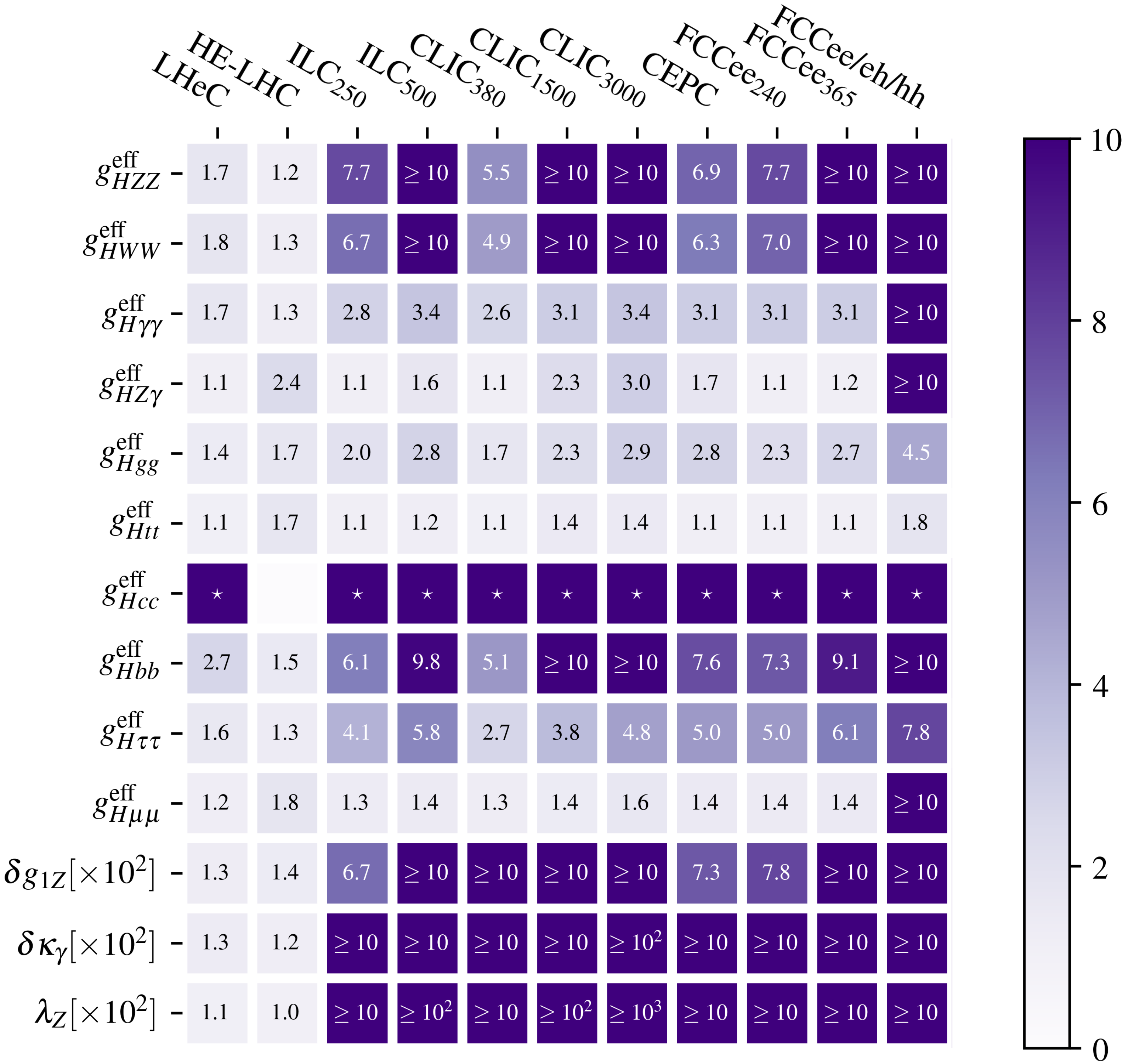


Single Higgs couplings

Results in SMEFT-framework: Improvement wrt HL-LHC

EFT results projected into effective Higgs couplings and aTGC

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

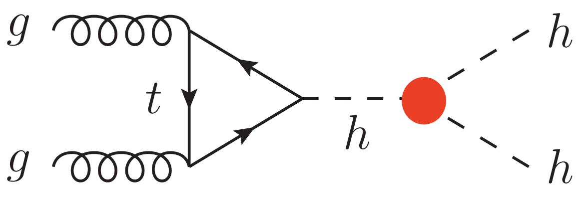
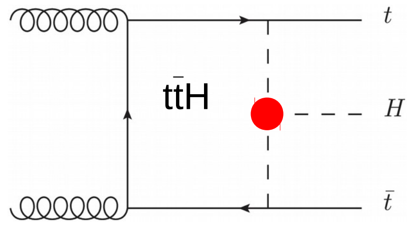
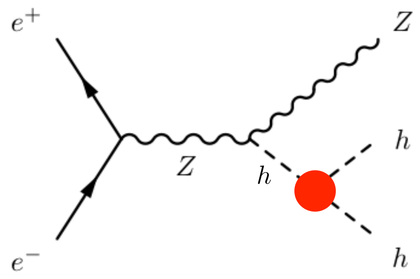
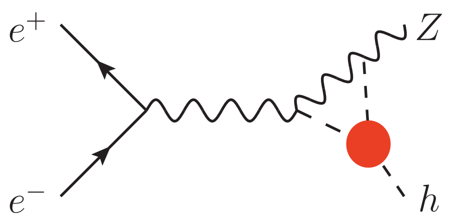


	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g_{HZZ}^{eff}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g_{HWW}^{eff}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g_{H\gamma\gamma}^{\text{eff}}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g_{HZ\gamma}^{\text{eff}}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g_{Hgg}^{eff}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g_{Htt}^{eff}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g_{Hcc}^{eff}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g_{Hbb}^{eff}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g_{H\tau\tau}^{\text{eff}}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g_{H\mu\mu}^{\text{eff}}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

The Higgs self-coupling

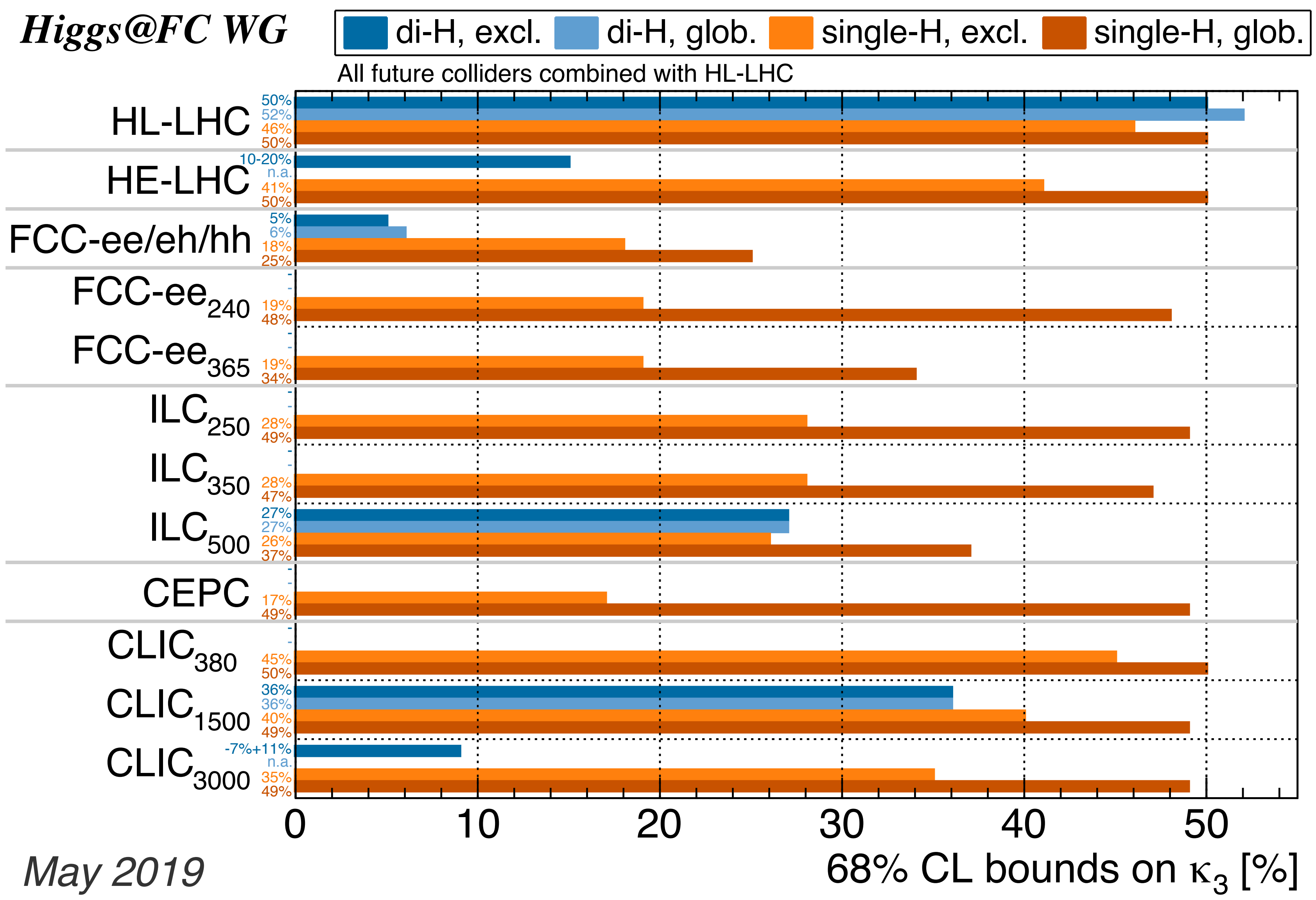
- **Comparison of capabilities to measure the H^3 coupling**

	Directly: Higgs-pair prod	**Indirectly: via single Higgs**
Hadron Colliders		
Lepton Colliders		

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

The Higgs self-coupling

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



ee: Indirect ~34%

hh: Direct ~5-10%

Little indirect reach w/o 365 GeV run

Direct ~10%

Direct ~27%

Assuming upgrade to 500 GeV

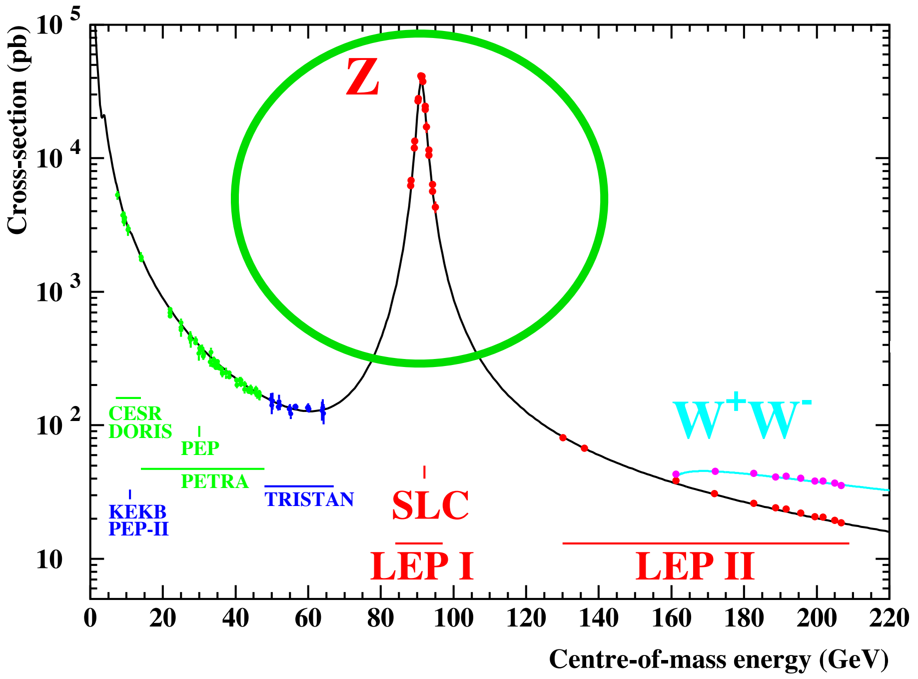
Electroweak interactions

Sensitivity to NP in EW interactions

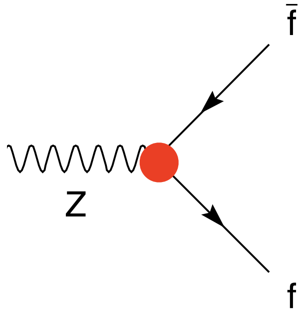
Electroweak precision measurements

- Very precise measurements of the Z and W boson properties

Running at the Z-pole



Tests of *Vff* interactions:



Tera Z (10^{12} Z): EWPO (sys dominated)~10-100x better than LEP/SLD

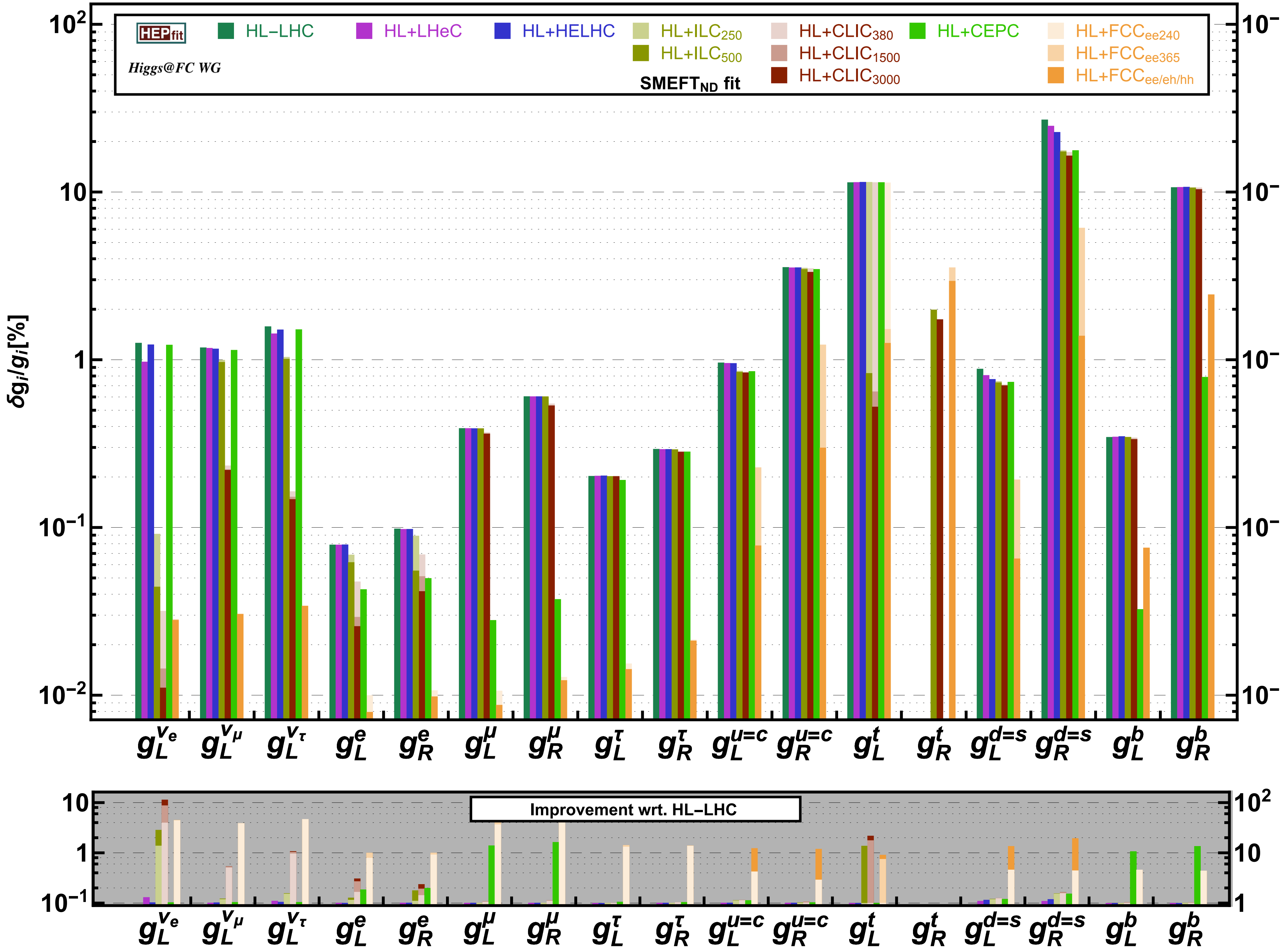
Giga Z (10^9 Z): Z-pole run not in baseline (but possible)

- Studies of EWPO included in the global EFT fits prepared for PPG:
  - 17 extra EFT directions considered (no fermion universality)
  - Studied interplay between Higgs/EW constraints based on inputs to the ESU

Sensitivity to NP in EW interactions

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

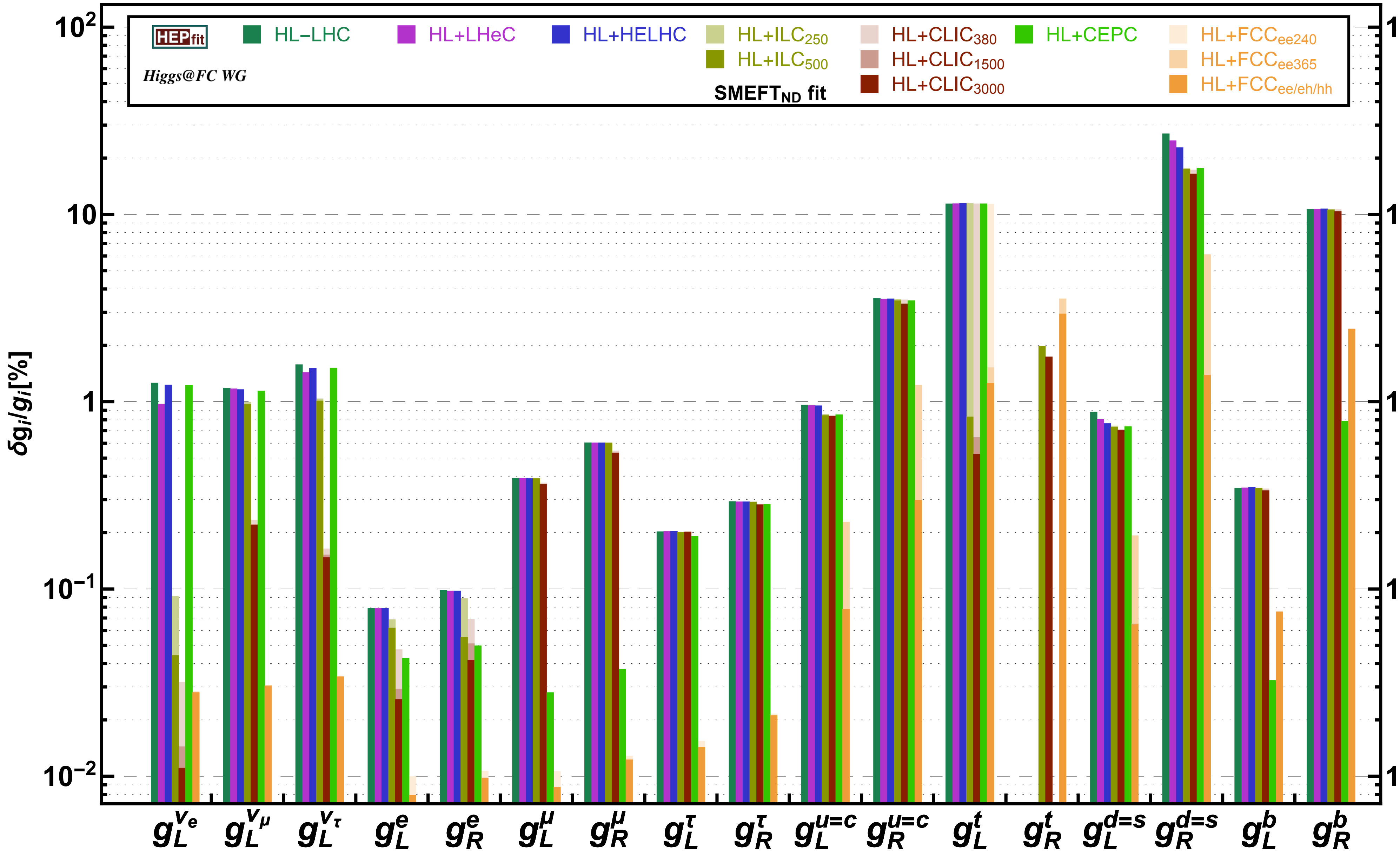
EFT results projected into effective Zff couplings



Sensitivity to NP in EW interactions

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

EFT results projected into effective Zff couplings



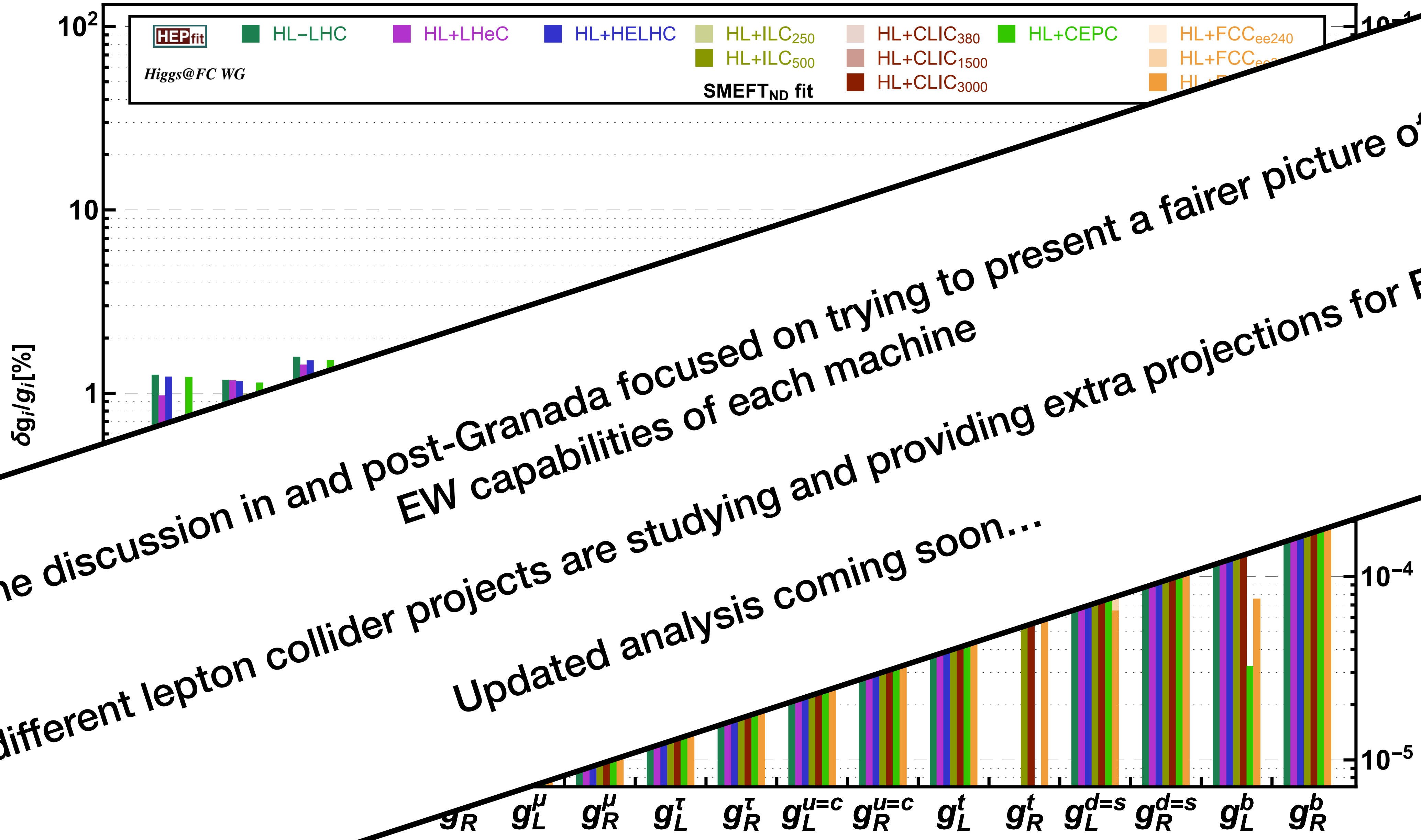
-WARNING: CEPC EWPO ~ FCCee EWPO (except 365 GeV: top).
Difference due to current status of EWPO projections (Flav. Non-univ, sys,…)

- **Linear colliders (w/o Z-pole): Improv. in electron couplings from H/VV processes**
- **Circular colliders (w Z pole): precise *Zff* without trading precision with other processes**

Sensitivity to NP in EW interactions

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

EFT results proje
to effective Zff couplings



Part of the discussion in and post-Granada focused on trying to present a fairer picture of the EW capabilities of each machine

The different lepton collider projects are studying and providing extra projections for EWPO

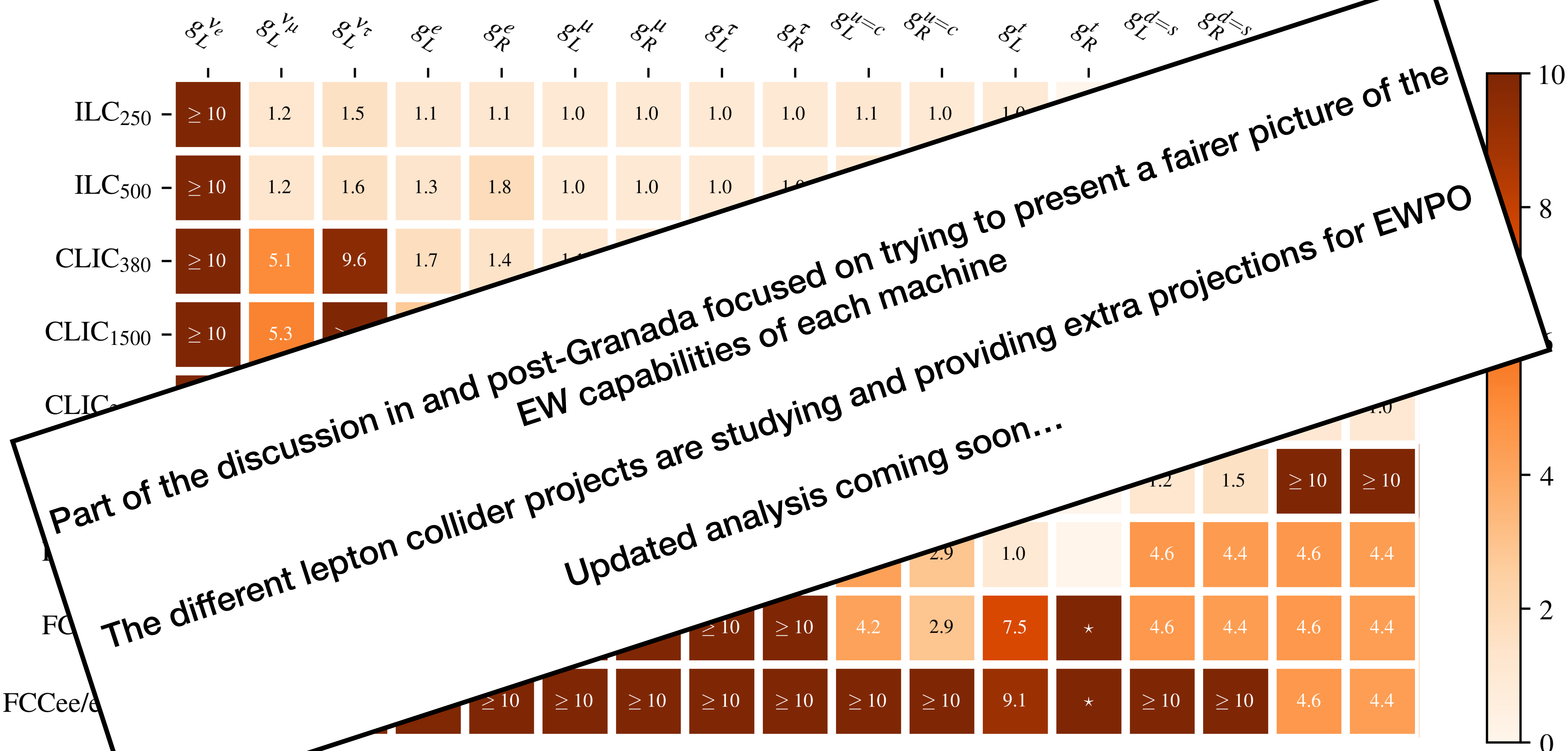
Updated analysis coming soon…

WARNING: CEPC EWPO ~ FCCee EWPO (except 365 GeV: top). Difference due to current status of EWPO projections (Flav. Non-univ, sys,…)

- Linear colliders (w/o Z-pole): Improv. in electron couplings from H/VV processes
- Circular colliders (w Z pole): precise Zff without trading precision with other processes

Sensitivity to NP in EW interactions

Improvement with respect to HL-LHC



Part of the discussion in and post-Granada focused on trying to present a fairer picture of the EW capabilities of each machine

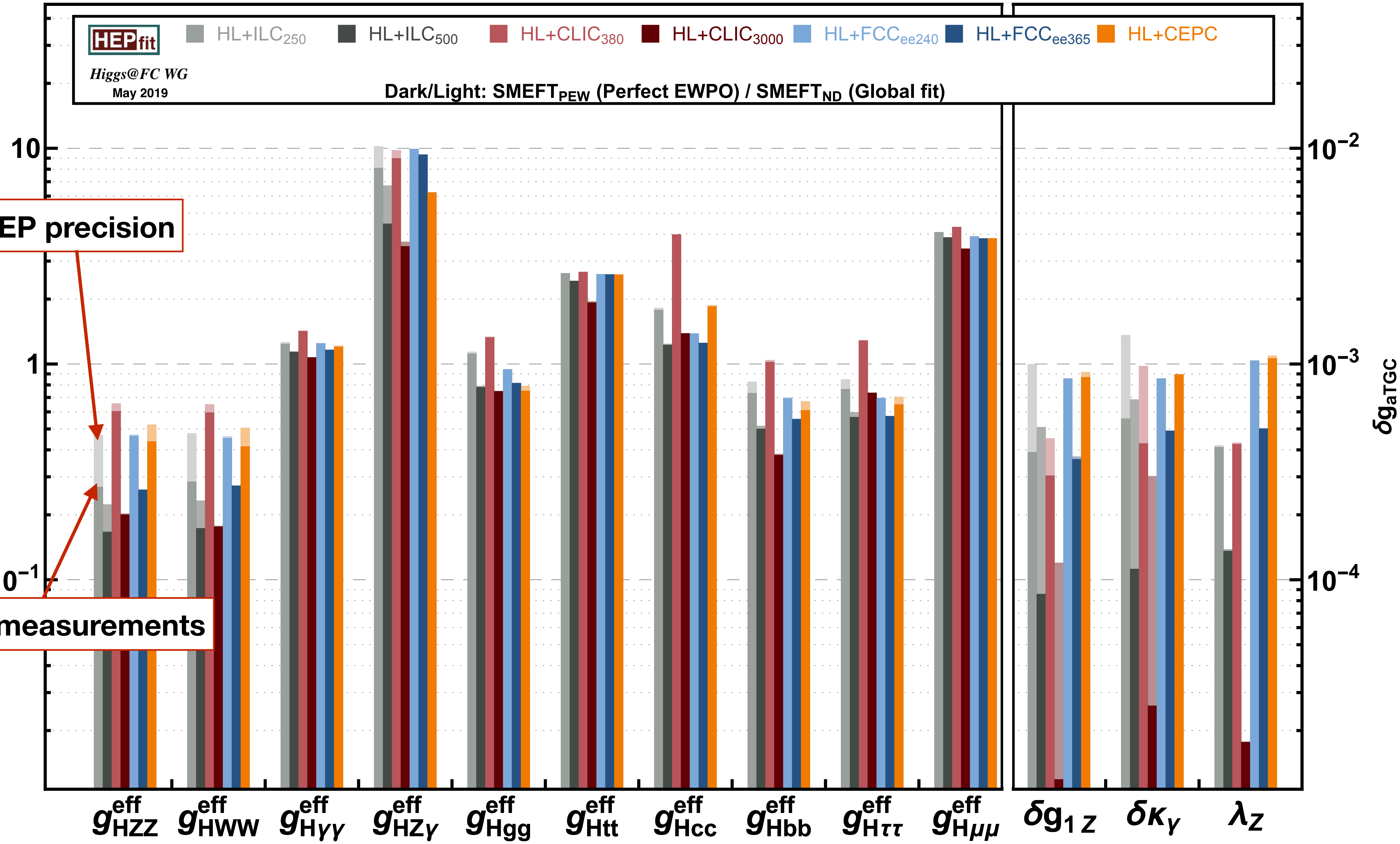
The different lepton collider projects are studying and providing extra projections for EWPO

Updated analysis coming soon…

-**WARNING:** CEPC EWPO ~ FCCee EWPO (except 365 GeV: top).
Difference due to current status of EWPO projections (Flav. Non-univ, sys,…)

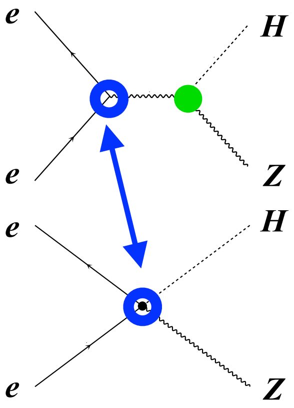
Interplay between EW and Higgs

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



Assuming LEP precision

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 radiative return

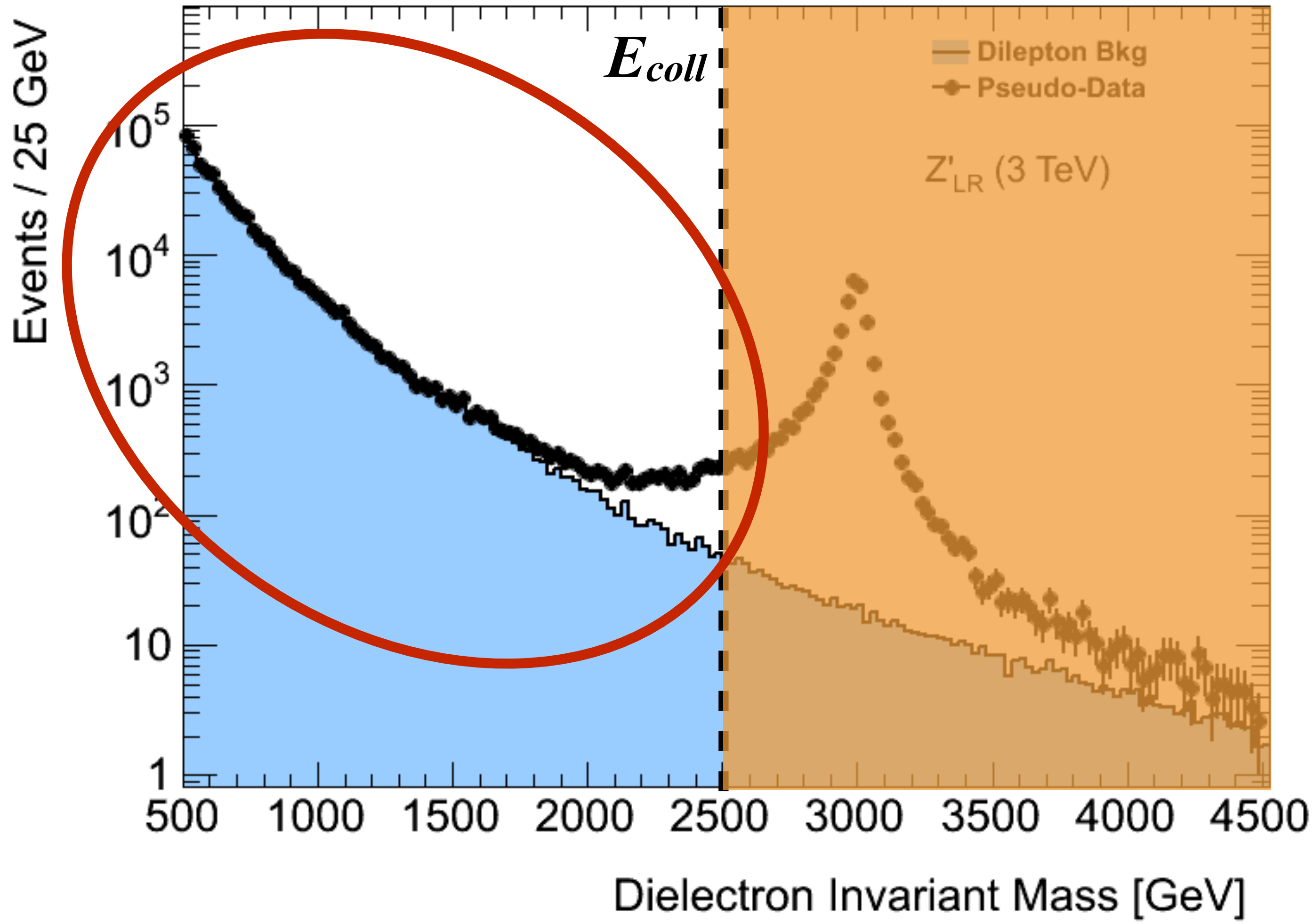
More in Jiayin Gu's talk on Wednesday

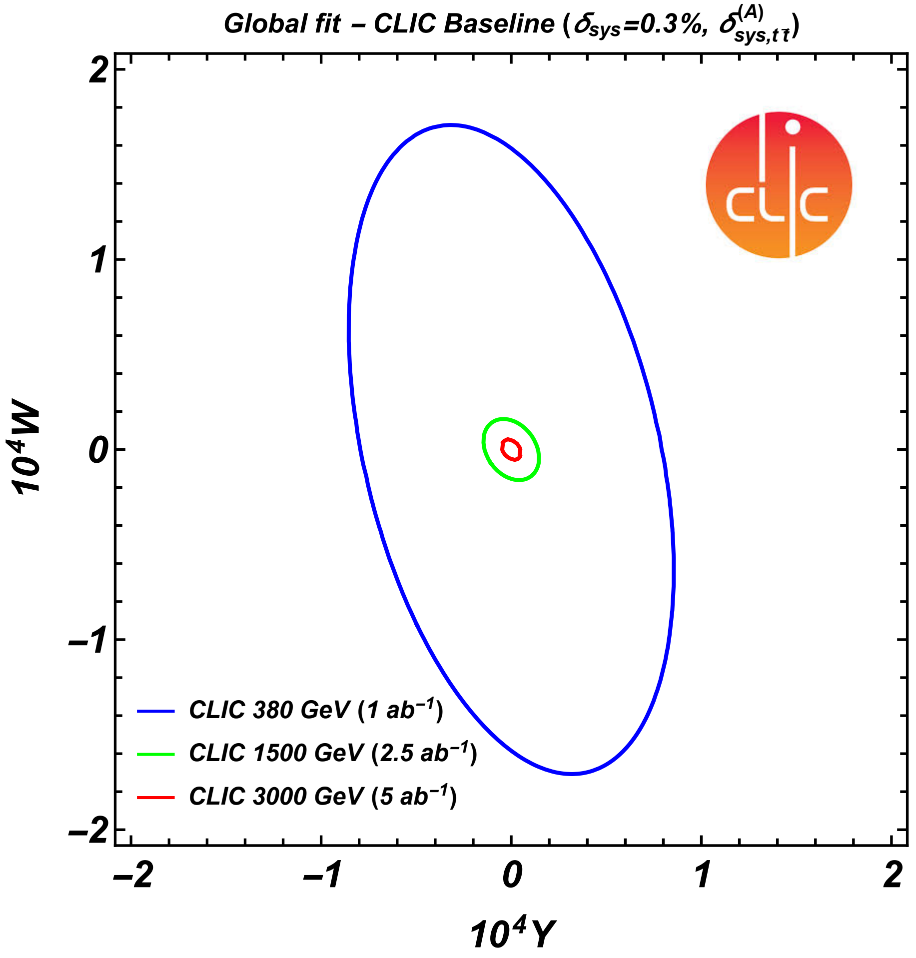
Electroweak at high-E

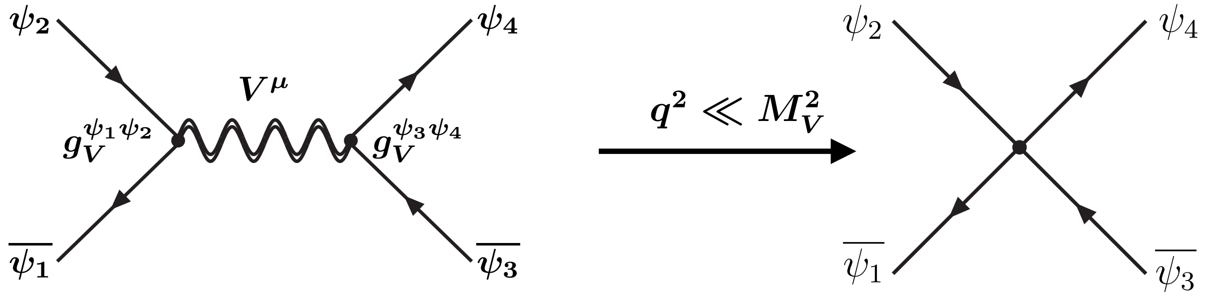
- Electroweak interactions beyond the Z-pole: precision via high E

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

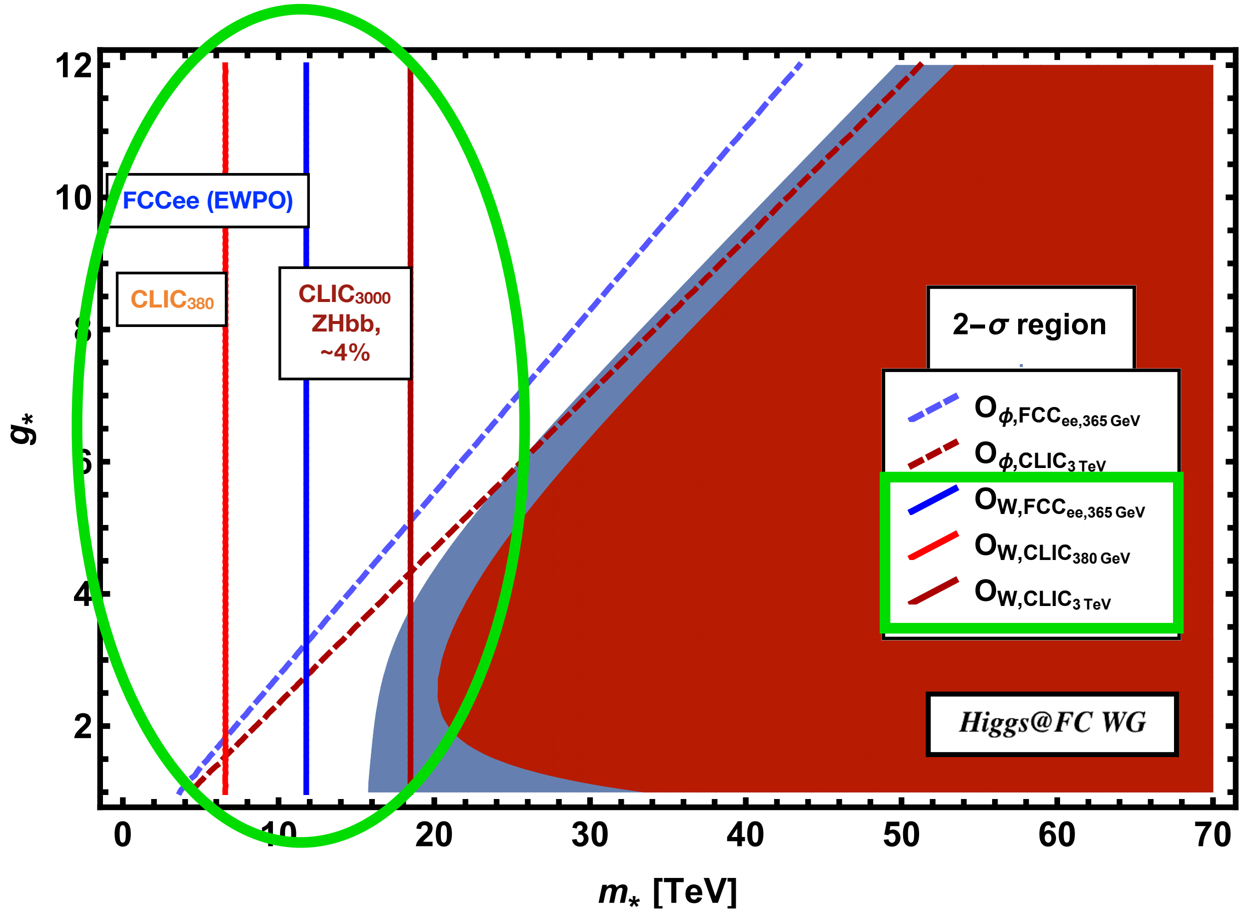
CLIC~25x better than HL-LHC

Similar to 100 TeV FCC-hh

Electroweak/Higgs: low E vs. high-E

- Example:

Indirect constraints in Composite Higgs models



Similar sensitivity to same operators via:

(1) Low-E high precision (EWPO)

(2) High-E moderate precision (ZH)

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

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

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

Different ways of testing the compositeness scale (via $O_{W,B}$):
Low-Energy precision (FCCee) vs High-Energy (CLIC)

The role of theory

Will SM theory calculations be enough?

Estimates for SM theory uncertainties used in the ESU studies

Decay	Partial width	Projected future unc. $\Delta\Gamma/\Gamma$ [%]			
	[keV]	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_{\mathrm{H}})$
$H \to b\bar{b}$	2379	0.2	$0.6^\flat$	$< 0.1^\sharp$	–
$H \to \tau^+\tau^-$	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).

S. Heinemeyer et al., arXiv: 1906.05379 [hep-ph]

Intrinsic TH unc in production

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

LO to NLO: 5-10%

Missing 2-loop: O(1%)

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

Z width effects relevant
at this level of precision?

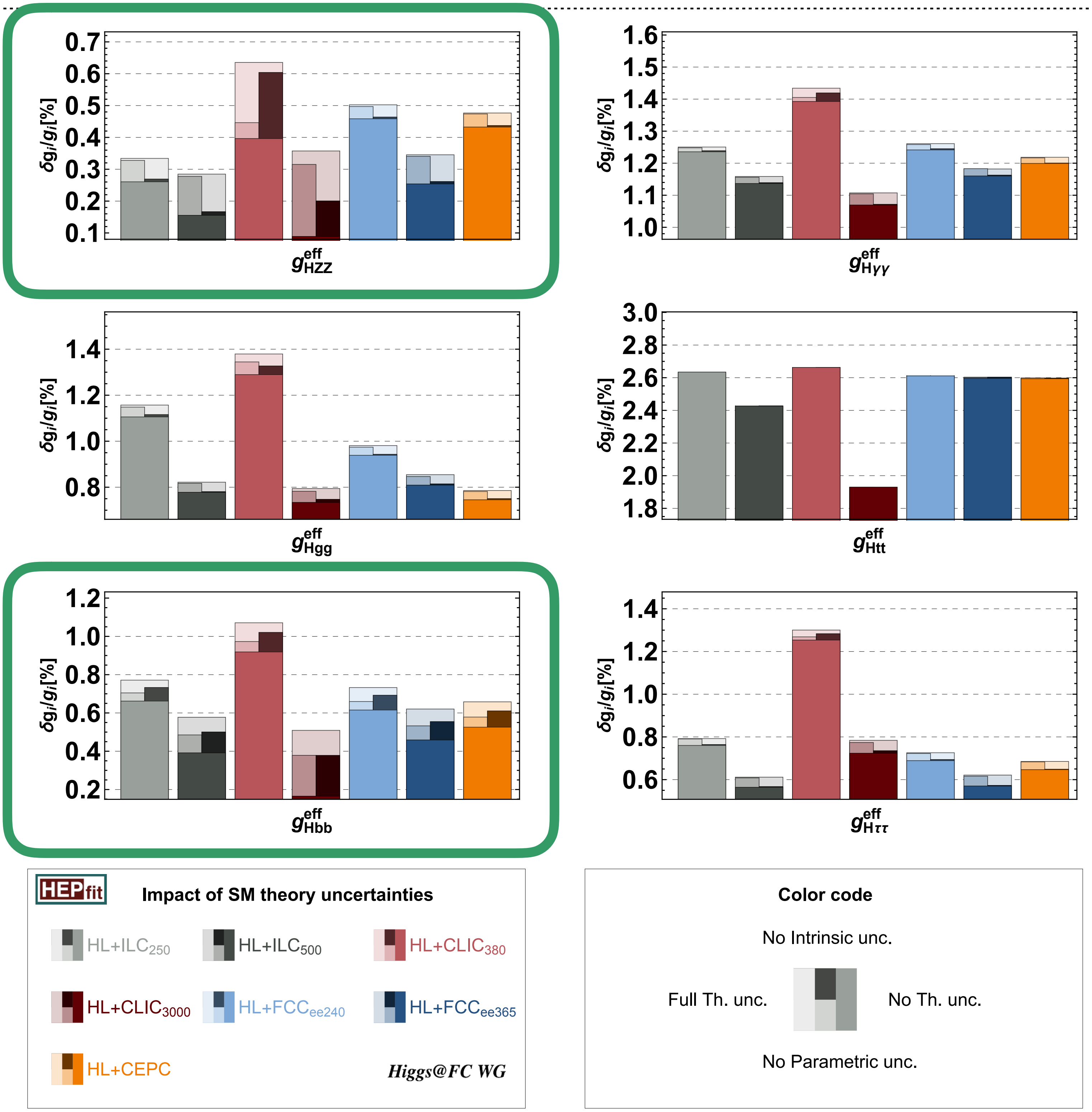
Assessment of TH uncertainty
may require full 2->3 NNLO

In any case, reducible with
necessary effort from theory side

Hence the choice of presenting
main results with parametrics only

Will SM theory calculations be enough?

Comparison of SM Theory uncertainties in Higgs calculations



Largest effect on HVV couplings

Differences in other couplings mainly due to unc. in production

Exception: Hbb

Will SM theory calculations be enough?

Theory requirements for EWPO

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

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)

Summary

Comparison of κ-framework results

Number of largely improved H couplings (κ-framework): 12 quantities total

Initial Run ee

2nd/3rd Run ee

eh or hh

ee,eh & hh

	Factor ≥2	Factor ≥4	Factor ≥7	Years from T_0
CLIC380	5	2	2	7
FCC-ee240	6	4	3	9
CEPC	7	4	4	10
ILC250	6	4	3	11
LHeC	4	2	0	15
FCC-ee365	9	7	4	15
CLIC1500	7	4	2	17
HE-LHC	4	0	0	20
ILC500	9	6	3	22
CLIC3000	8	4	2	28
FCC-ee/eh/hh	12	10	6	>50

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

Comparison of EFT results

Number of largely improved H couplings (EFT): 13 quantities total

		Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
Initial run	CLIC380	9	6	4	7
	FCC-ee240	10	8	3	9
	CEPC	10	8	3	10
	ILC250	10	7	3	11
2nd/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

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

Conclusions

General considerations from discussion at Granada

- 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
    - Near per-mille level precision in some H couplings. O(10-30%) in H^3
    - But rare channels limited by stats ⇒ need Hadron collider afterwards
    - Beyond Higgs: possibility of improving knowledge in EW interactions
- Which lepton collider? Not so clear. From the point of view of CERN experiments:
    - **Option 1:** build lepton collider (FCC-ee/CLIC) and, later, a high-E pp machine
    - **Option 2:** lepton collider somewhere else (CEPC/ILC) and focus on high-E pp

Low Energy FCC?

6 T Magnets in 100 Km tunnel ⇒ 37.5 TeV pp collider ?

(To be extended later on to 100 TeV)

- **Other options?**

Conclusions

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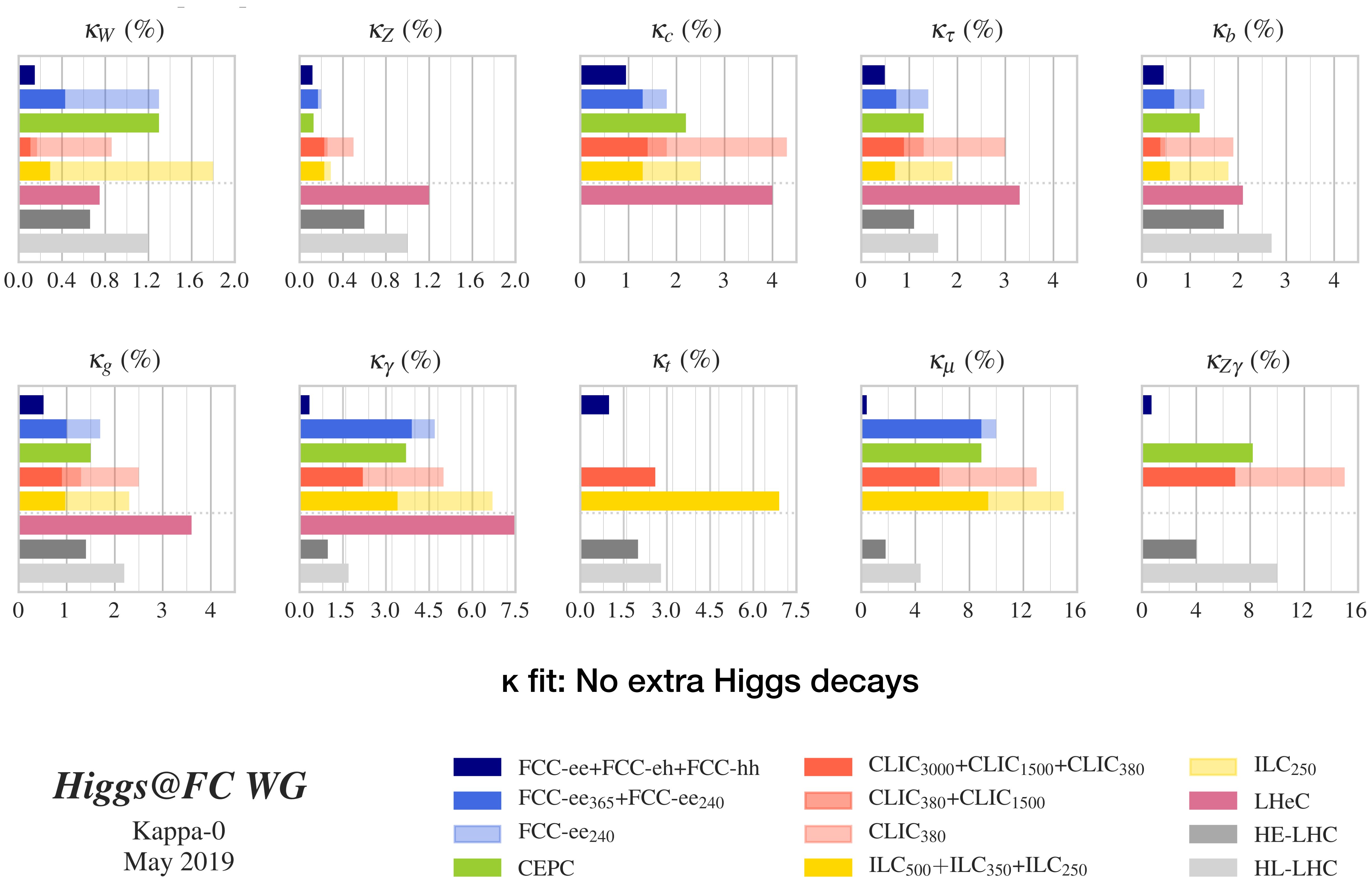
Updated studies including the input from discussion at Granada coming soon…

Low Energy FCC?
6 T Magnets in 100 Km tunnel ⇒ 37.5 TeV pp collider ?
(To be extended later on to 100 TeV)

- **Other options?**

Backup slides

Single Higgs couplings



κ fit: No extra Higgs decays

SMEFT: Bottom-Up approach

- **The dimension 6 SMEFT:**

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

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

Λ: Cut-off of the EFT

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

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

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

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

(dim 4) Modifies neutral gauge boson self-energies — EWPT

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

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

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

We also restrict the analysis to flavour preserving processes/interactions