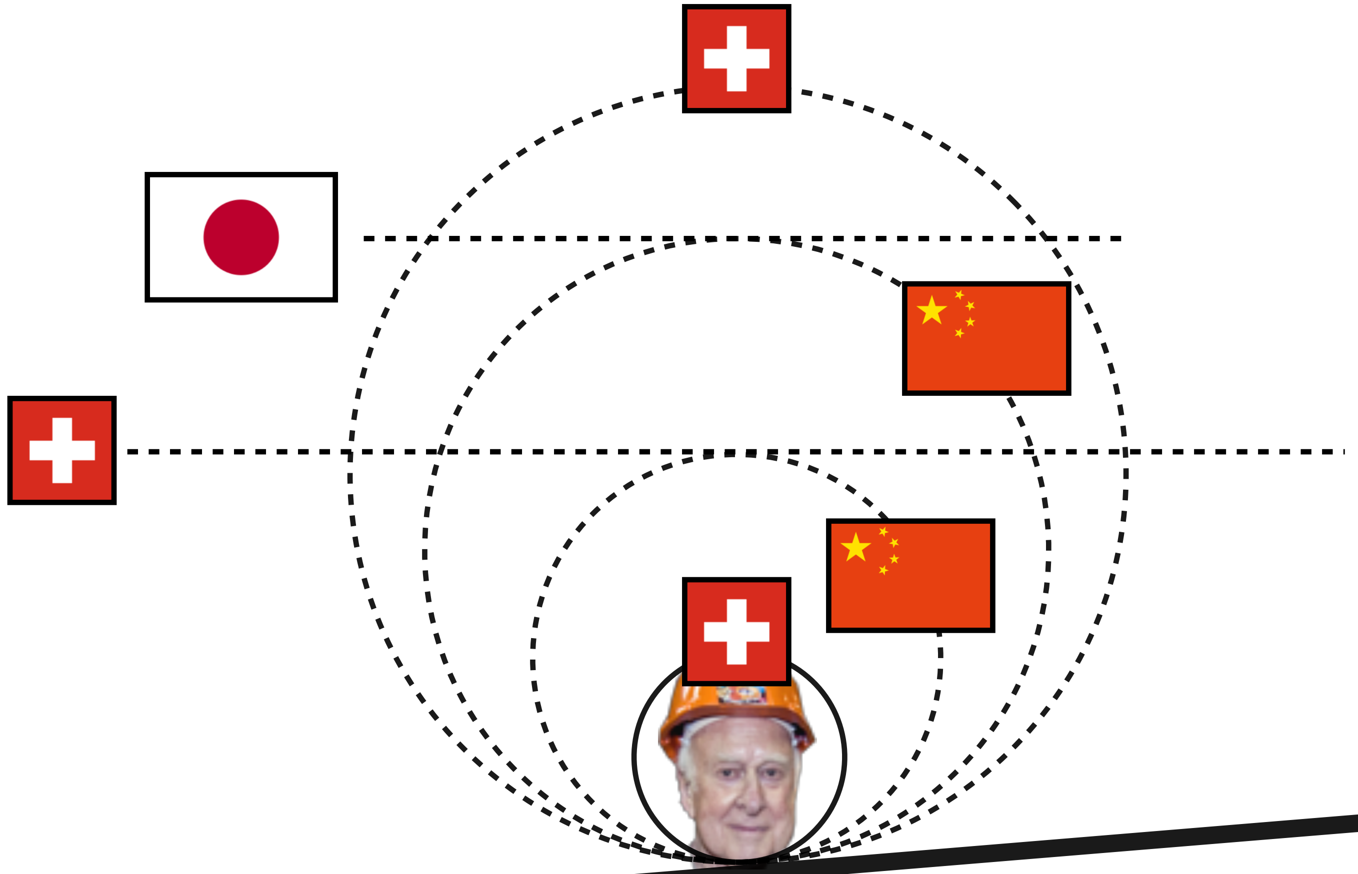
What will the Future Colliders know about the Higgs?

Quantum Universe Future Platform

DESY, May 27, 2019



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High Energy Physics with a Higgs

High Energy Physics with a Higgs

ECFA
European Committee for Future Accelerators

J. D'Hondt ECFA '18

Towards new discoveries via the Higgs sector

- No clear indication where new physics is hiding, hence experimental observations will have to guide us in our exploration.
- One of the avenues is to explore as fast as possible, and as wide as possible, the Higgs sector.
    - Yukawa couplings
    - Self-couplings (HHH and HHHH)
    - Couplings to Z/W/γ/g
    - Rare SM and BSM decays (H$\rightarrow$Meson+γ, Zγ, FCNC, $\mu e/\tau\mu/\tau e$, …)
    - CP violation in Higgs decays
    - Invisible decay
    - Mass and width
    - …
- Important progress will be made on Higgs physics with the LHC and the HL-LHC.
- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.

November 14th, 2018 Proposal on WG Higgs physics 13

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The **Higgs** boson is the **simplest Q-bit**/particle:
as far as we know, it has
no spin, no charge, no structure.
This vacancy can make its richness:
e.g., unlike other SM particle, it can easily couple to a Hidden Sector
⇗ A formidable tool to explore the deepest principles of Nature ⇖

Future of HEP

ECFA Higgs study group '19

	T_0	+5	+10	+15	+20	...	+26
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						

+ muon-collider + gamma-gamma collider + …

Future of HEP

ECFA Higgs study group '19

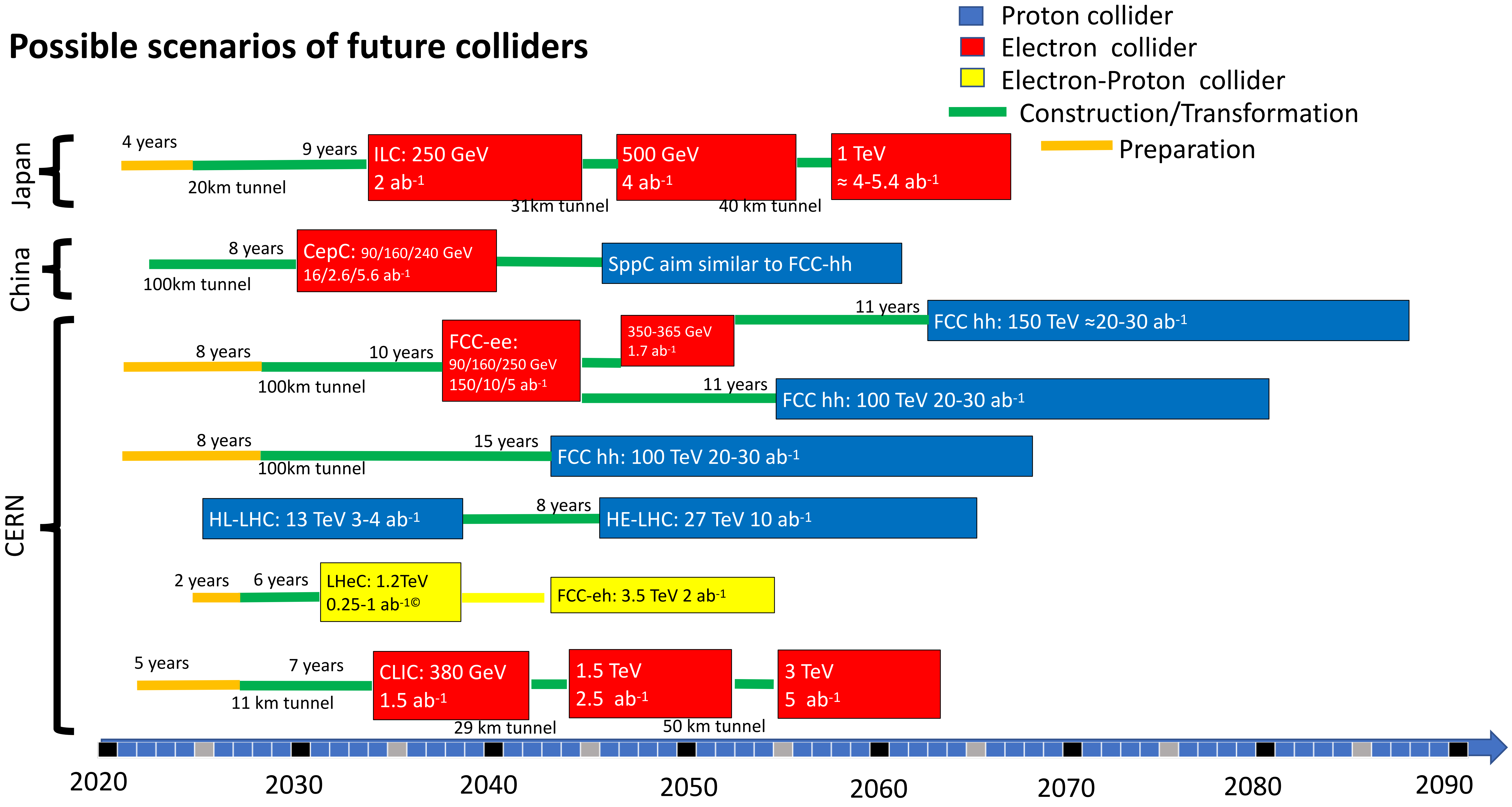
Subject to large uncertainty
1) need a scientific consensus
2) political approval

	T_0 … +5 … +10 … +15 … +20 … … +26	T_0
ILC	0.5/ab 250 GeV; [gap]; 1.5/ab 250 GeV; [gap]; 1.0/ab 500 GeV; 0.2/ab $2m_{top}$; 3/ab 500 GeV; [gap]	2032
CEPC	5.6/ab 240 GeV; 16/ab M_Z; 2.6 /ab $2M_W$; [gap]; SppC =>	2030
CLIC	1.0/ab 380 GeV; [gap]; 2.5/ab 1.5 TeV; [gap]; 5.0/ab => until +28 3.0 TeV	2035
FCC	150/ab ee, M_Z; 10/ab ee, $2M_W$; 5/ab ee, 240 GeV; [gap]; 1.7/ab ee, $2m_{top}$; [gap]; hh,eh =>	2037
LHeC	0.06/ab; [gap]; 0.2/ab; [gap]; 0.72/ab; [gap]	2030
HE-LHC	10/ab per experiment in 20y; [gap]	2040
FCC eh/hh	20/ab per experiment in 25y; [gap]	2045

+ muon-collider + gamma-gamma collider + …

Future of HEP

Possible scenarios of future colliders



Colliders being considered

ECFA Higgs study group '19

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\rm inst}$ $[10^{34}]\ {\rm cm}^{-2}{\rm s}^{-1}$	$\mathscr{L}$ $[{\rm ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
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, 11]	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)	
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	[12]	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)	
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	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

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

Higgs couplings: kappa vs EFT

Complementarity between the two approaches

Kappa:

- Close connection to exp measurements
- Widely used
- Exploration tool (very much like epsilons for LEP)
- Could still valid even with light new physics
- Captures leading effects of UV motivated scenarios (SUSY, composite)
- Doesn't require BSM theoretical computations

EFT:

- Allows to put Higgs measurements in perspective with other measurements (EW, diboson, flavour…)
- Connects measurements at different scales (particularly relevant for high-energy colliders CLIC, FCC-hh)
- Fully exploits more exclusive observables (polarisation, angular distributions…)
- Can accommodate subleading effects (loops, dim-8…)
- Fully QFT consistent framework
- Assumptions about symmetries more transparent
- Valid only if heavy new physics

Kappa Framework

- Kappa fit method described in https://arxiv.org/abs/1209.0040 : *LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle.*
  - $k^2_X = \Gamma_{H\to X} / \Gamma^{SM}_{H\to X}$
  - for top coupling above the ttH threshold: $k^2_t = \sigma_{ttH} / \sigma^{SM}_{ttH}$
- Not general parametrisation of BSM, but has the advantage of simple framework, largely known in the hep community
- Scheme adopted by Higgs@FutureColliders (H@FC):
  - **10 coupling modifiers** : $k_W, k_Z, k_t, k_b, k_c, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}$
  - $k_H^2 = \Gamma_H / \Gamma_H^{SM} = \Sigma(k_j^2 \times BR^j_{SM})/(1-BR_{i,u})$ $(BR_{i,u} = BR_{inv} + BR_{unt})$
    - BR_{inv} = Higgs boson non-SM decays with invisible final states
    - Br_{unt} = Higgs boson non-SM decays difficult to separate from the background
  - **Higgs boson selfcoupling fixed to SM value**
  - **Low-energy machines don't have access to k_t**

Assumption kV<1 made for hadron collider alone (not needed for ee-colliders)

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

About κ_V<1 assumption

kappa-0	HL-LHC	HL-LHC(YR)	HL-LHC
κ_W (%)	1.2	1.7	1.9
κ_Z (%)	1.0	1.5	1.6
κ_g (%)	2.2	2.5	2.6
κ_γ (%)	1.7	1.8	2.0
$\kappa_{Z\gamma}$ (%)	10		11
κ_c (%)	—	-	
κ_t (%)	2.8	3.4	2.8
κ_b (%)	2.7	3.7	3.5
κ_μ (%)	4.4	4.3	4.6
κ_τ (%)	1.6	1.9	1.9

H@FC w/ assumption kV<1

H@FC w/o assumption kV<1

Results of kappa-2 fit

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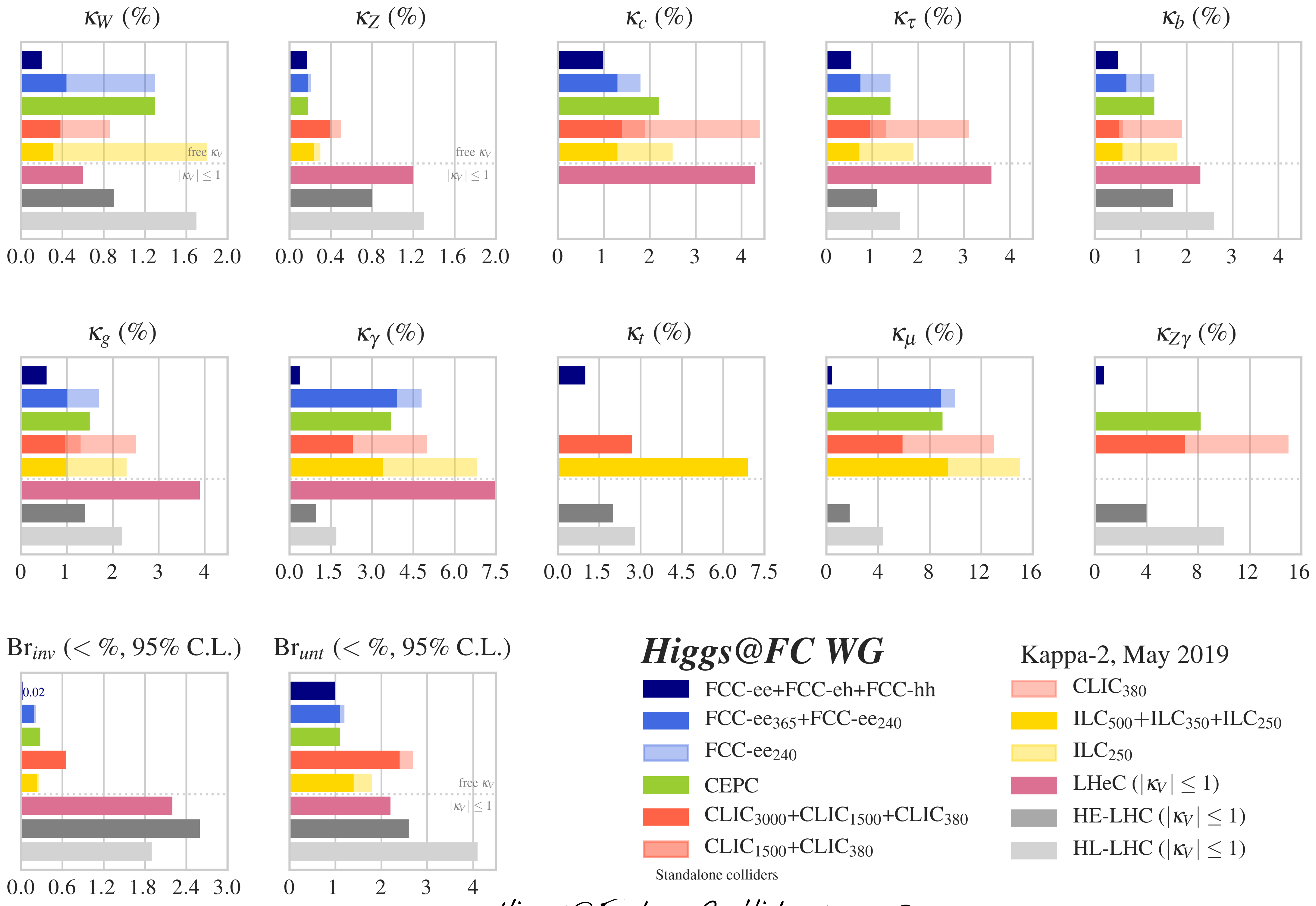

Results of kappa-3 fit

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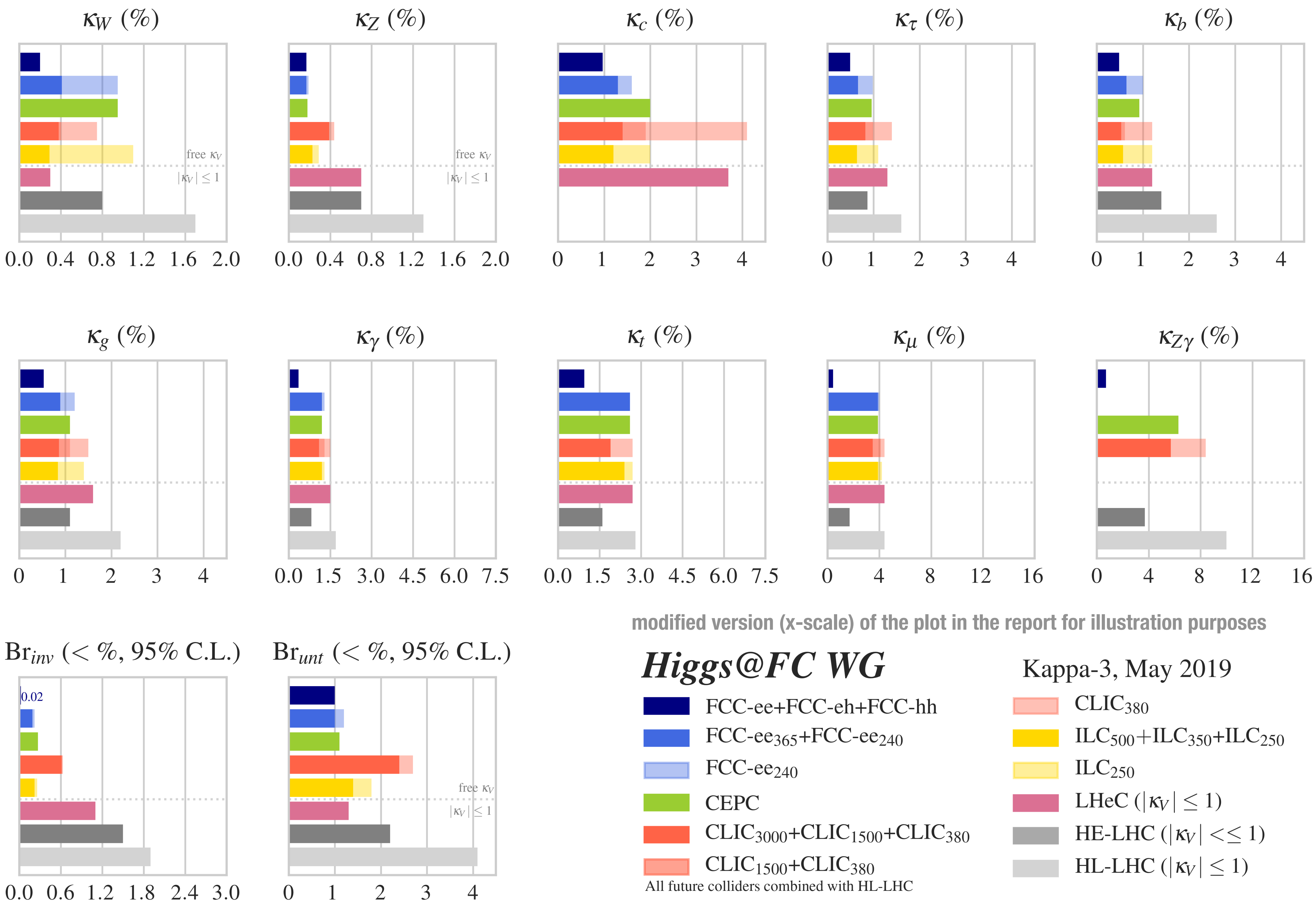

modified version (x-scale) of the plot in the report for illustration purposes

Results of kappa-3 fit

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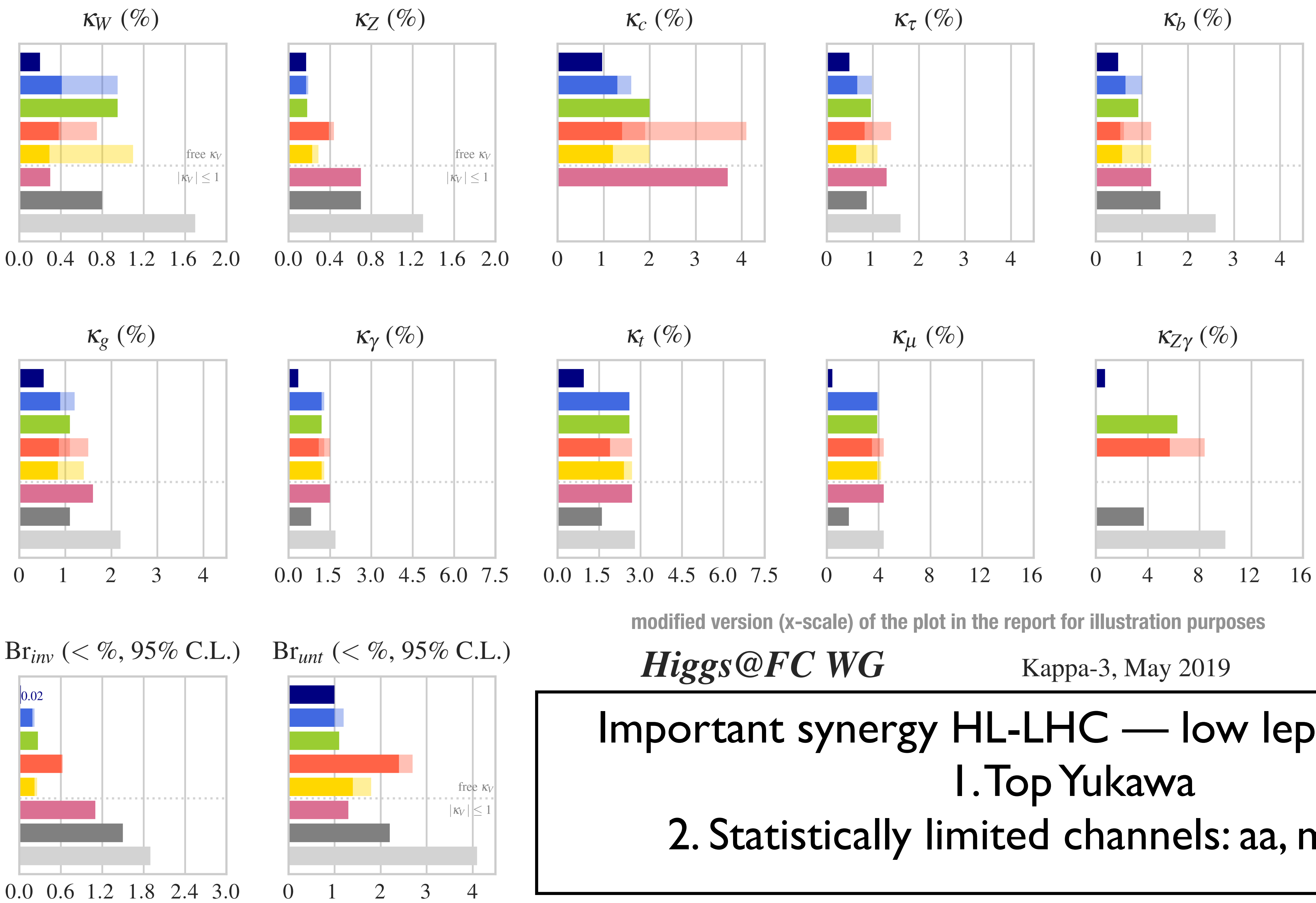

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Higgs@FC WG Kappa-3, May 2019

Important synergy HL-LHC — low lepton colliders

1. Top Yukawa
2. Statistically limited channels: aa, mumu, Za

EFT Framework

- Many advantages offered by the EFT approach
  - Among these: describes correlation of New Physics (NP) effects in different types of observables in the Higgs sector and outside
- The following scenarios are under study:
  - We limit our analysis to Dim-6 Operators; we focus on holomorphic /SU(2)-linearly realised Lagrangian
  - We don't consider BSM Higgs boson decays

Flavour "assumptions": Neutral Diagonal (ND)

-*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

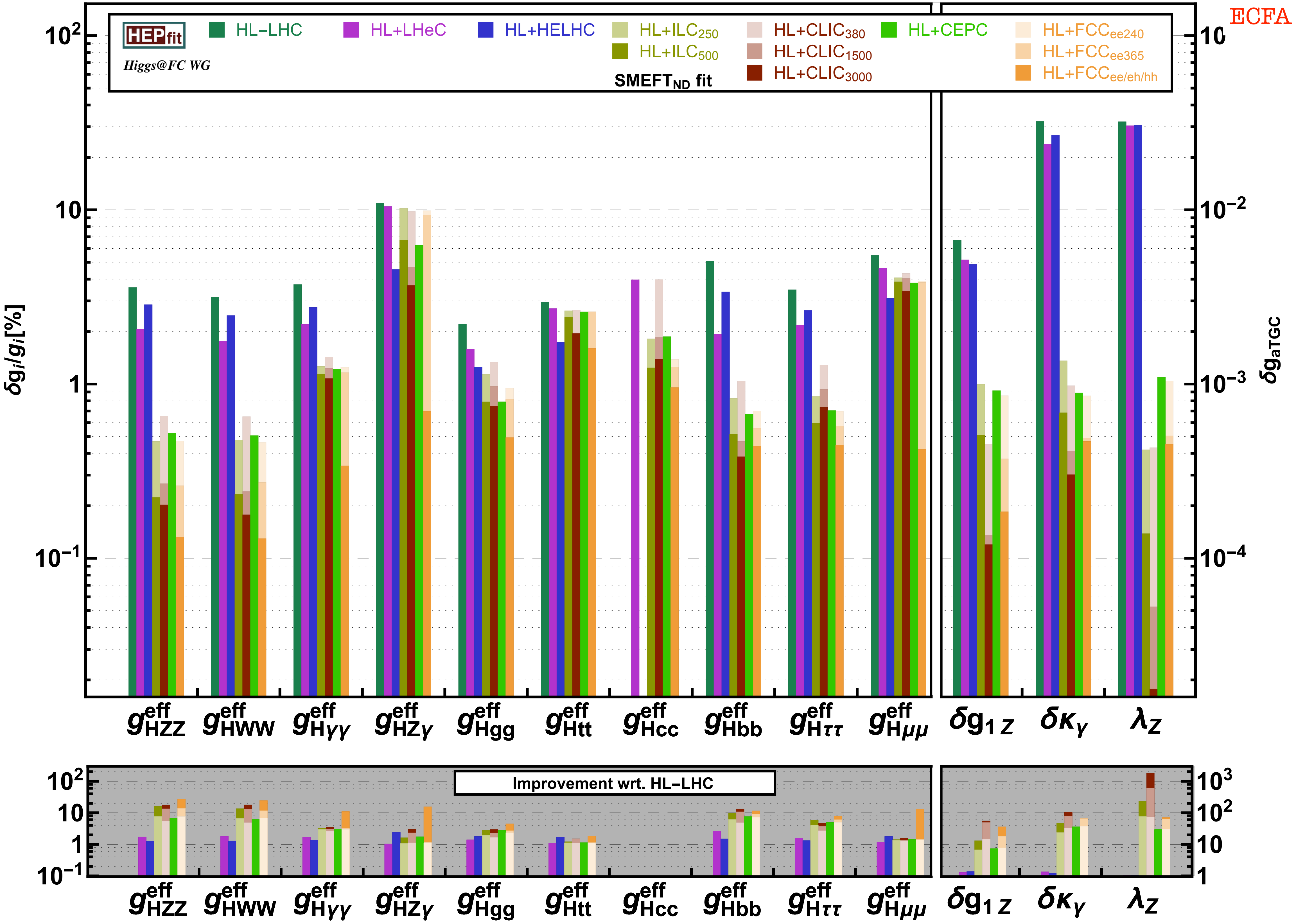
$$\mathrm{SMEFT_{ND}} \equiv \{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\} + \left\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell,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

5 SM + 30 New Physics Parameters

Experimental Inputs

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.) Warning	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit) Warning	LEP/SLD (Z-pole) + HL-LHC + W (ILC)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom) Warning	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	LEP/SLD (Z-pole) + HL-LHC + W (CLIC)	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	-

Global EFT fit



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Figures of Merit with Respects to HL-LHC

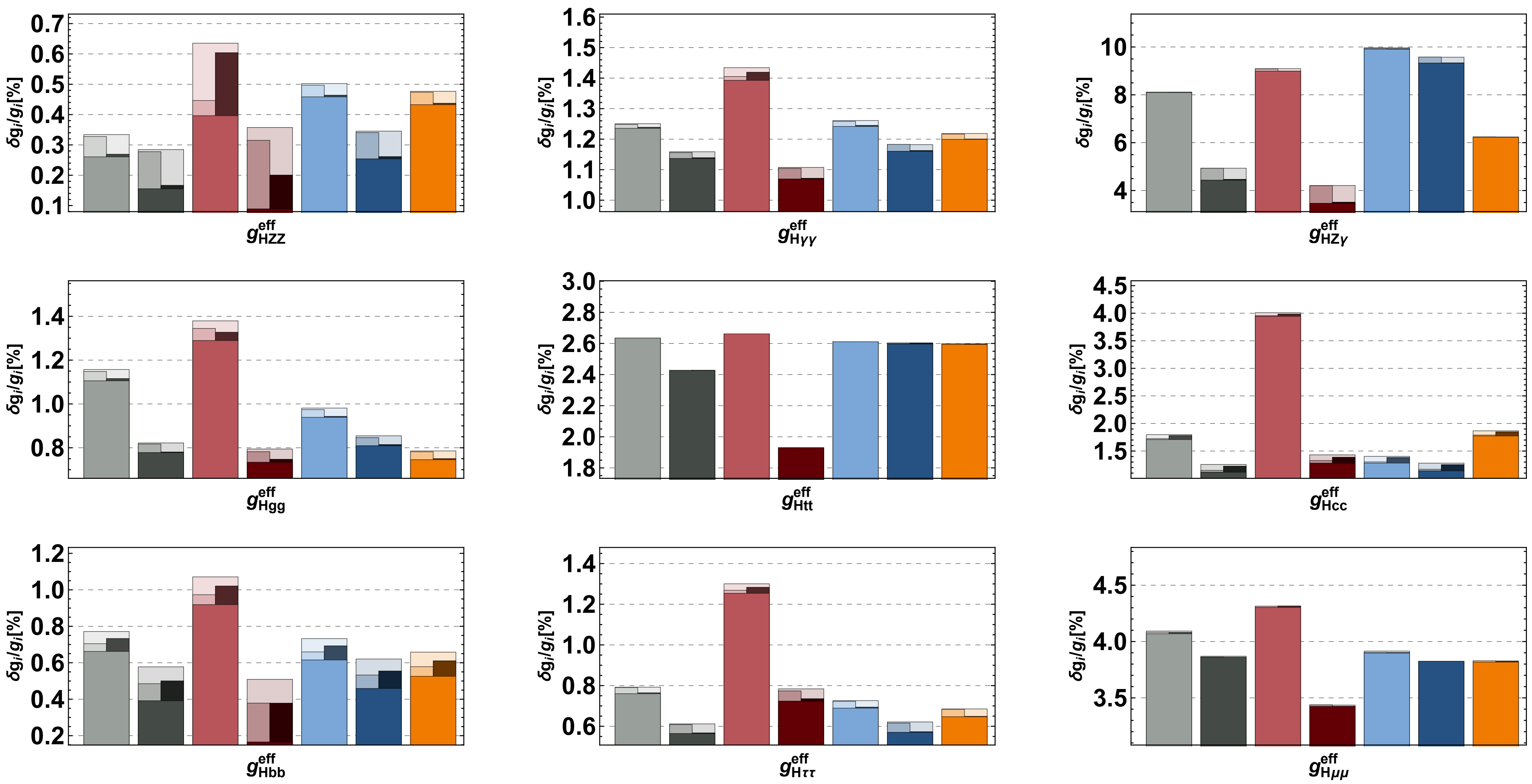
M. Cepeda for Higgs@FC WG

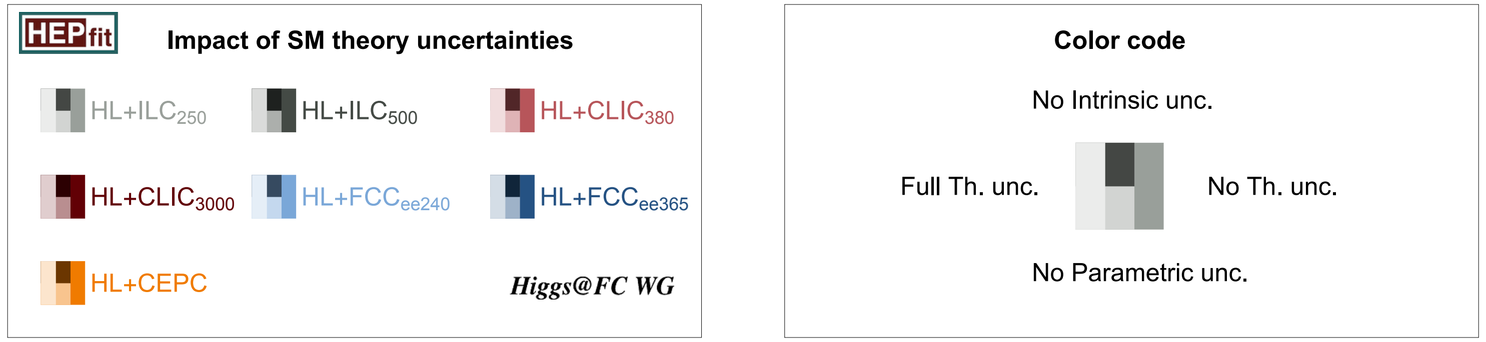
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCCee_{240}	FCCee_{365}	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{\text{eff}}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1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

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

Theoretical Uncertainties





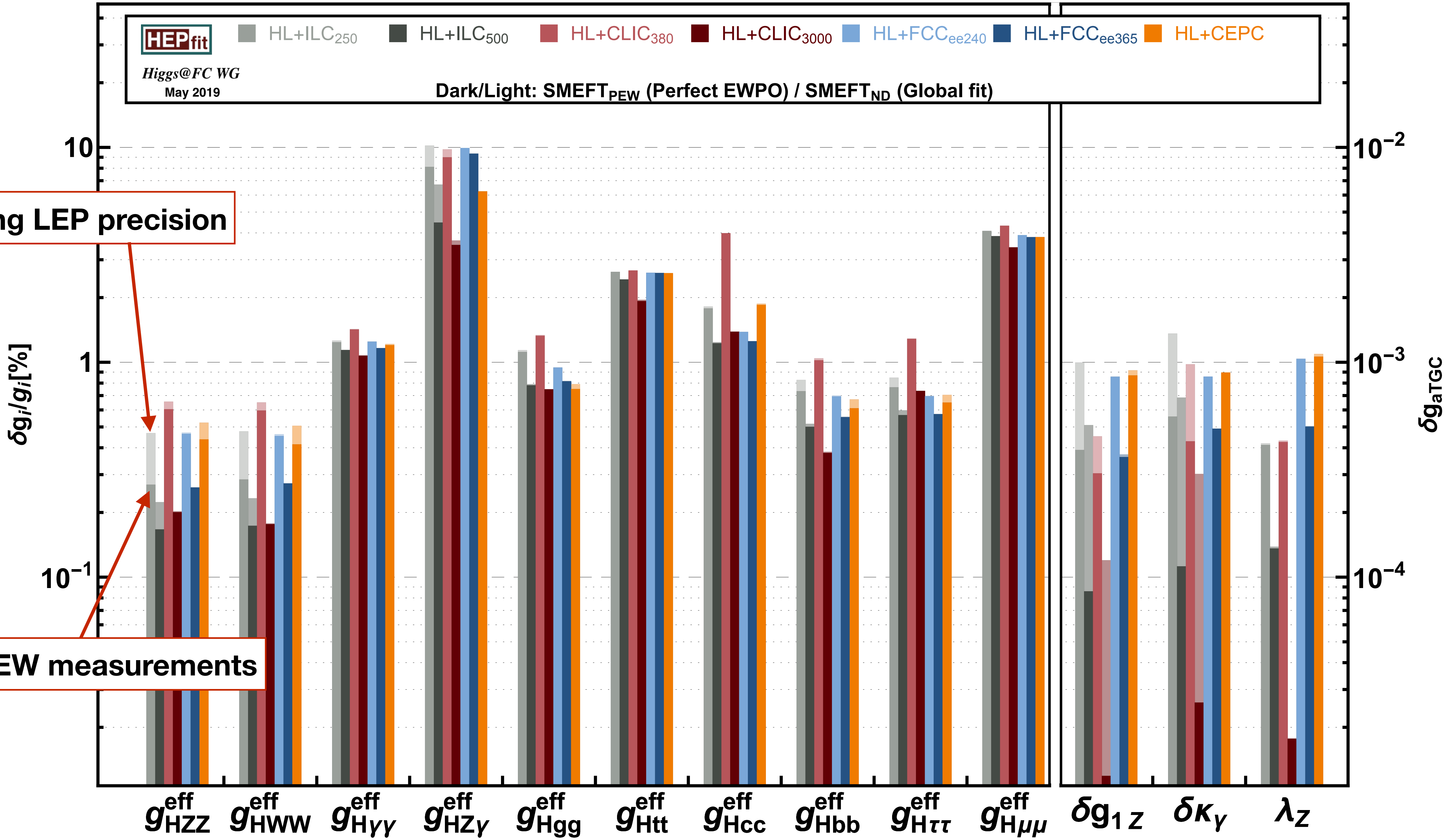
- **Parametric theory uncertainties:** For an observable O, this is the error associated to the propagation of the experimental error of the SM input parameters to the prediction O_{SM} .
- **Intrinsic theory uncertainties:** Estimate of the net size associated with the contributions to O_{SM} from missing higher-order corrections in perturbation theory.

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul to appear

Assuming LEP precision

Perfect EW measurements



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

Can be mitigated by using: (1) High-energies (2) EWPO from radiative return

Impact of Z-pole measurements

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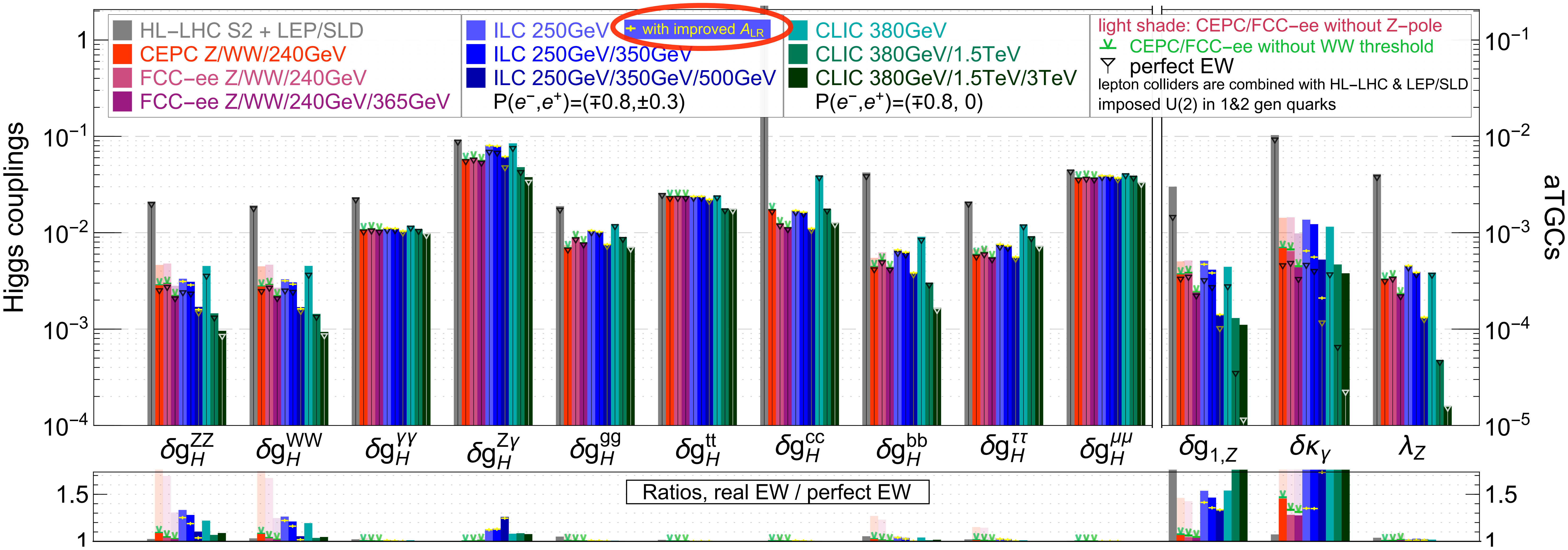

Impact of Beam Polarisation

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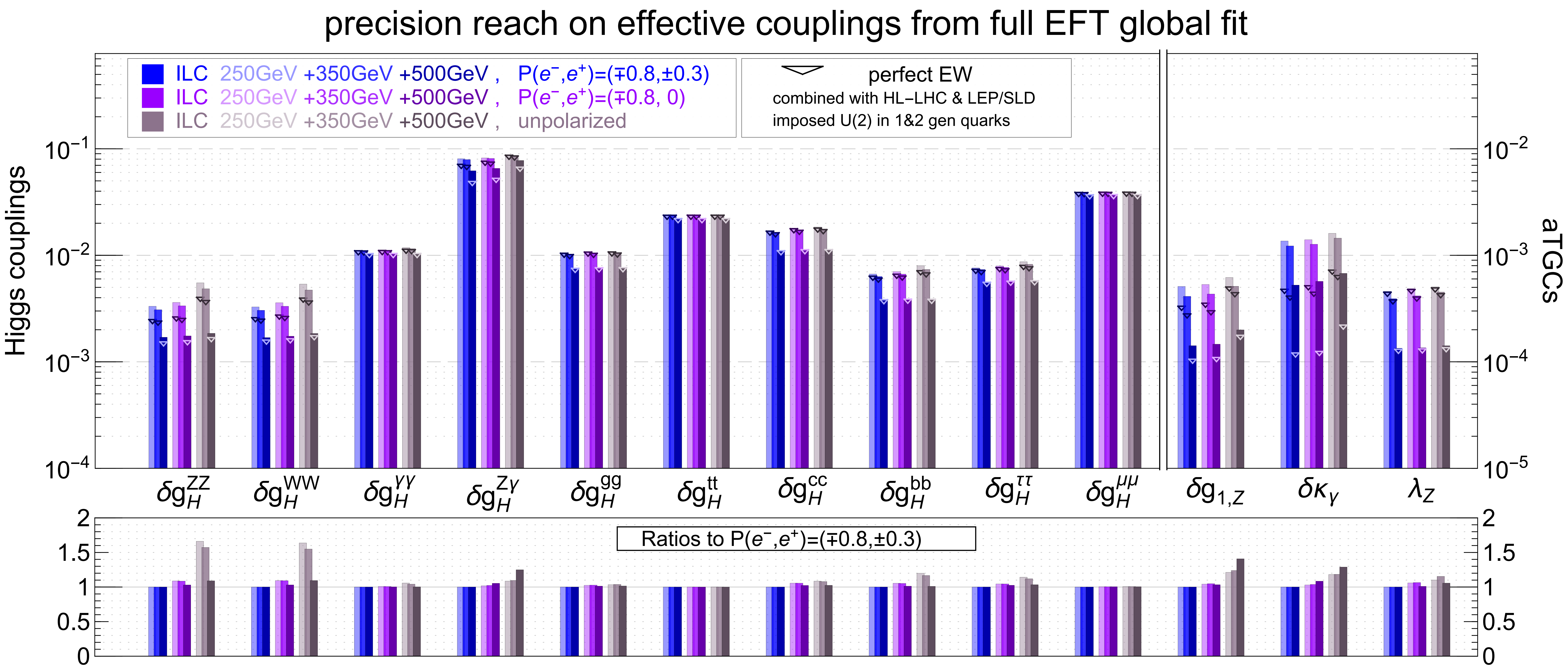

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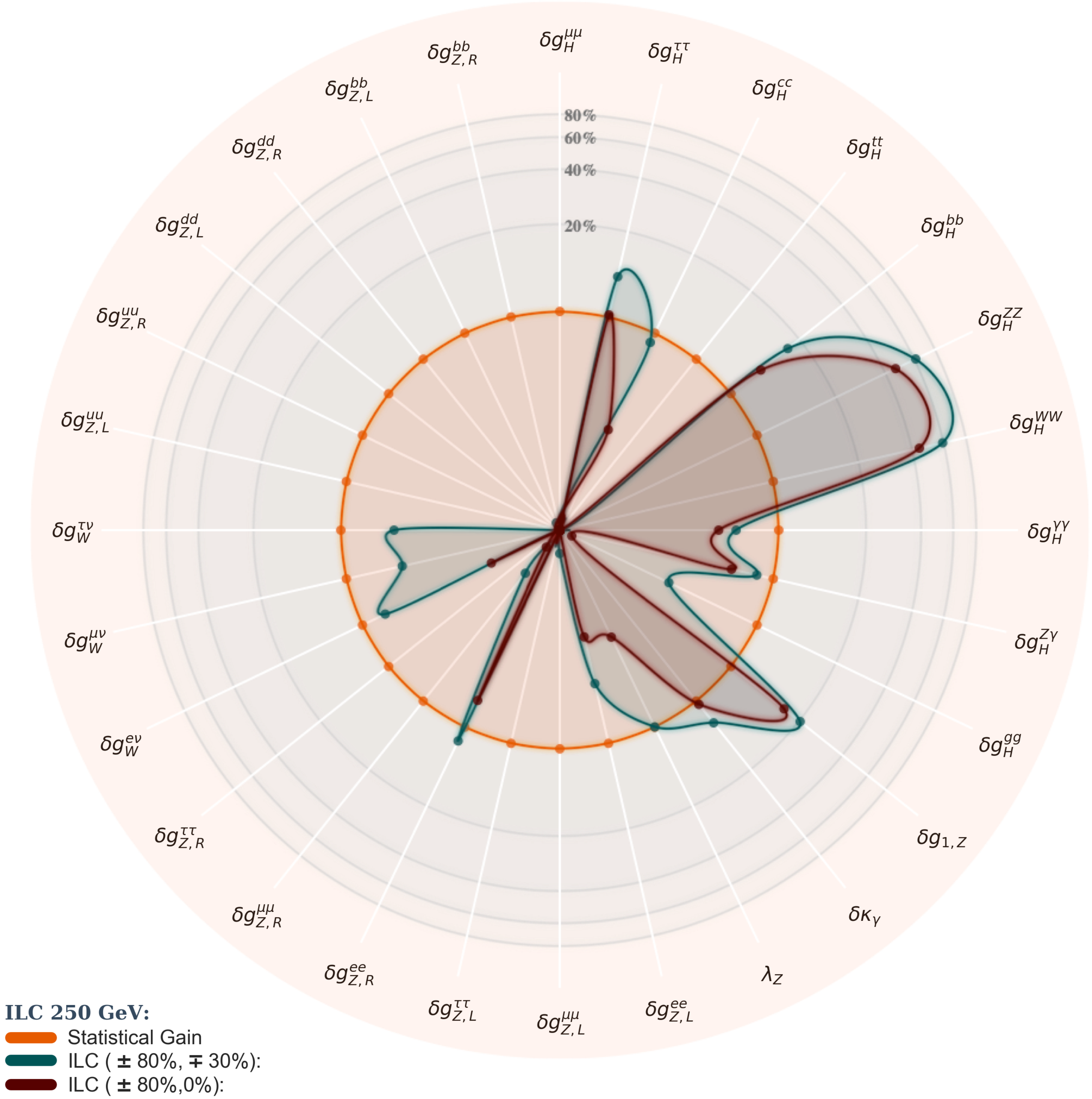

Statistical gain from increased rates

$$\sigma_{P_{e^+}P_{e^-}} = \sigma_0(1 - P_{e^+}P_{e^-})\left[1 - A_{LR}\frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}\right]$$

From ee→Zh, A_{LR}~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

overall, one could expect
~10-15% increased coupling sensitivity

Gain in higher in global EFT fit
since polarisation removes
degeneracies among operators

Polarisation benefit diminishes when other runs
at higher energies are added

Higgs self-coupling

Higgs self-couplings is very interesting for a multitude of reasons
(vacuum stability, hierarchy, baryogenesis, GW, EFT probe…).

How much different from the SM can it be given the tight constraints on other Higgs couplings?

Sensitivity on Higgs cubic self-coupling is often obtained in many different ways:

1. an exclusive analysis of HH production, i.e., a fit of the double Higgs cross section considering only deformation of the Higgs cubic coupling;
2. a global analysis of HH production, i.e., a fit of of the double Higgs cross section considering also all possible deformations of the single Higgs couplings that are already constrained by single Higgs processes;
   (a) the global fit does not consider the effects at higher order of the modified Higgs cubic coupling to single Higgs production and to Higgs decays;
   (b) these higher order effects are included;
3. an exclusive analysis of single Higgs processes at higher order, i.e., considering only deformation of the Higgs cubic coupling;
4. a global analysis of single Higgs processes at higher order, i.e., considering also all possible deformations of the single Higgs couplings.

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	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

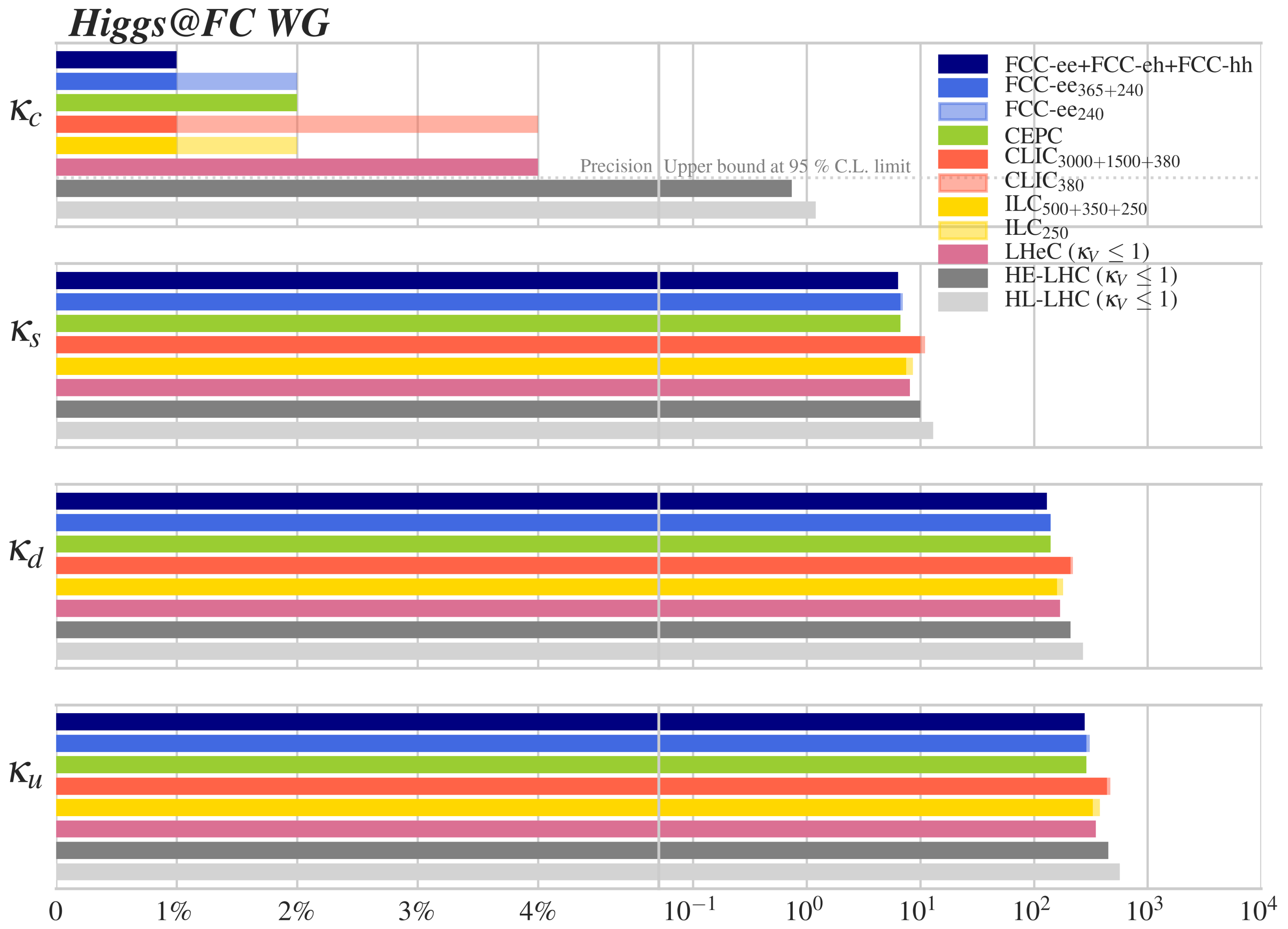
Don't take one bound and use it for a model where it doesn't apply!

Higgs self-coupling

collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl.	(4) single-H glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	46%	50%
HE-LHC	10-20% (n.a.)	n.a.	41%	50%
ILC_{250}	–	–	28%	49%
ILC_{350}	–	–	28%	47%
ILC_{500}	27% (27%)	27%	26%	37%
CLIC_{380}	–	–	45%	50%
CLIC_{1500}	36% (36%)	36%	40%	49%
CLIC_{3000}	$^{+11}_{-7}$% (n.a.)	n.a.	35%	49%
FCC-ee_{240}	–	–	19%	48%
FCC-ee_{365}	–	–	19%	34%
FCC-ee/eh/hh	5% (5%)	6%	18%	25%
CEPC	–	–	17%	49%

Light Yukawas

	HL-LHC	+LHeC	+HE-LHC	+ILC$_{500}$	+CLIC$_{3000}$	+CEPC	+FCC-ee$_{240}$	+FCC-ee/eh/hh
κ_u	570.	320.	420.	330.	430.	290.	310.	280.
κ_d	270.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.4	7.5	9.9	6.6	7.	6.4
κ_c	1.2		0.87	measured directly				



Conclusions

All future colliders have a rich potential to outperform (HL-)LHC in Higgs physics:

* Legacy measurements that will go into textbook
* Reach in BSM discoveries
* Refinements in our understanding of Nature

Uncertainty on the uncertainties is probably larger than the differences in the different projections

B. Heinemann for Higgs@FC WG

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P. Heinemann for Higgs@FC WG

		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
2nd/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

Banker accounting:
Very important to get money

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	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
2nd/3rd Run ee	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

Banker accounting:
Very important to get money

Specific BSM models
will care maybe even more
about correlations

Conclusions

All future colliders have a rich potential to outperform (HL-)LHC in Higgs physics:

$*$ Legacy measurements that will go into textbook

$*$ Reach in BSM discoveries

$*$ Refinements in our understanding of Nature

Uncertainty on the uncertainties is probably larger than the differences in the different projections

B. Heinemann for Higgs@FC WG

		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
	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
hh	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

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Specific BSM models
will care maybe even more
about correlations

Nobody knows
what BSM is

Conclusions

De Blas, Durieux, Grojean, Gu, Paul 'in progress

Conclusions

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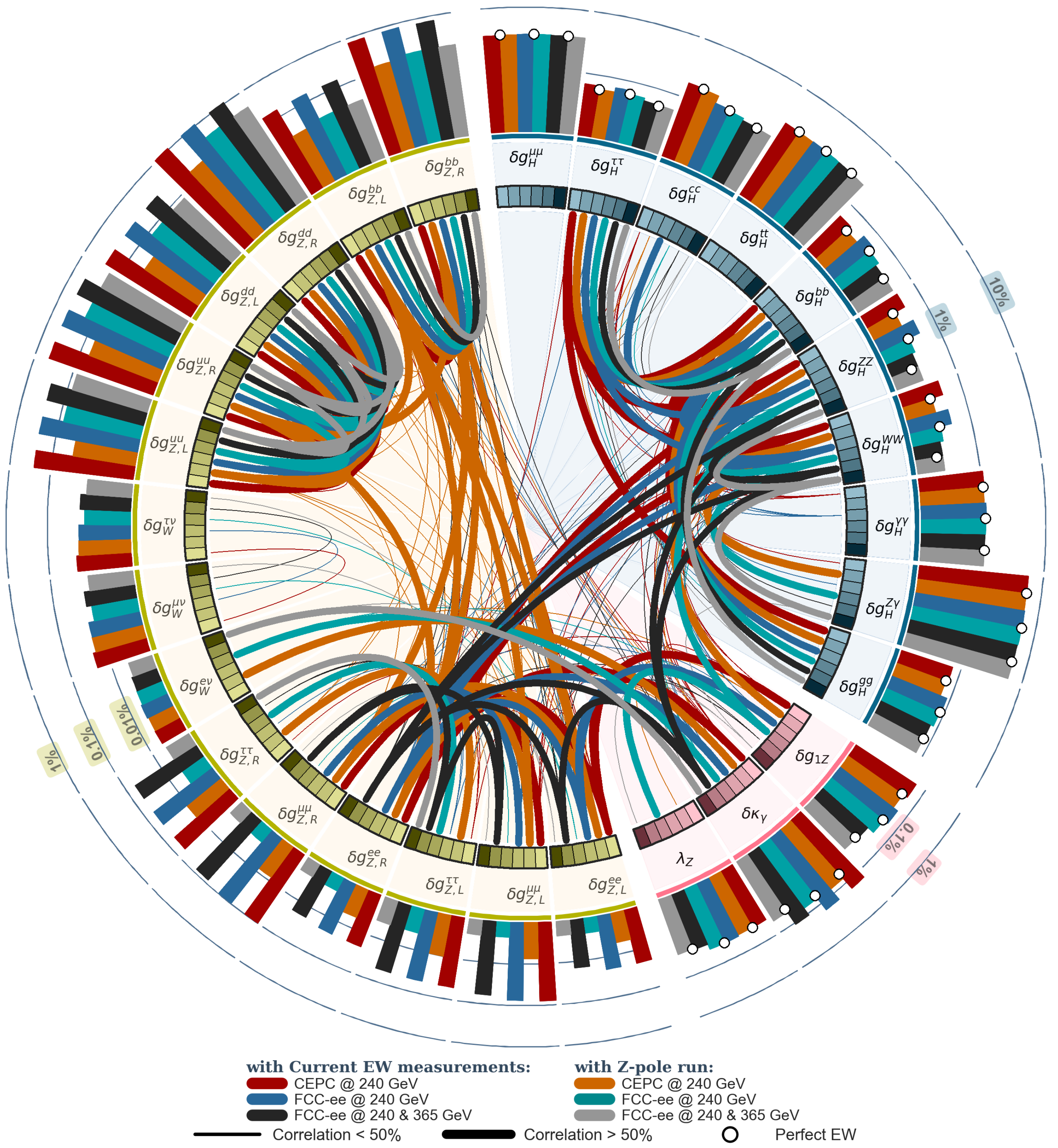
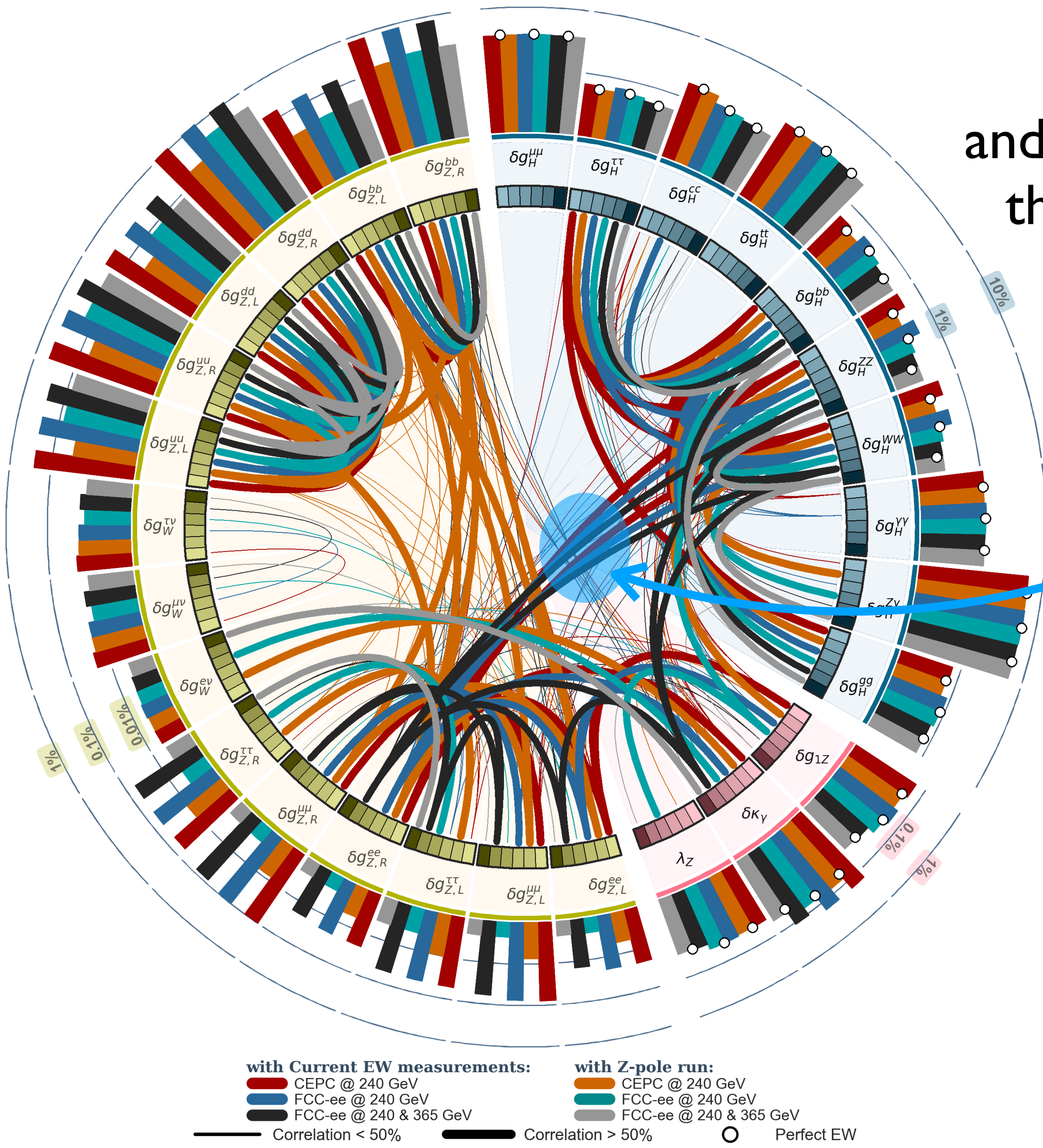


Conclusions

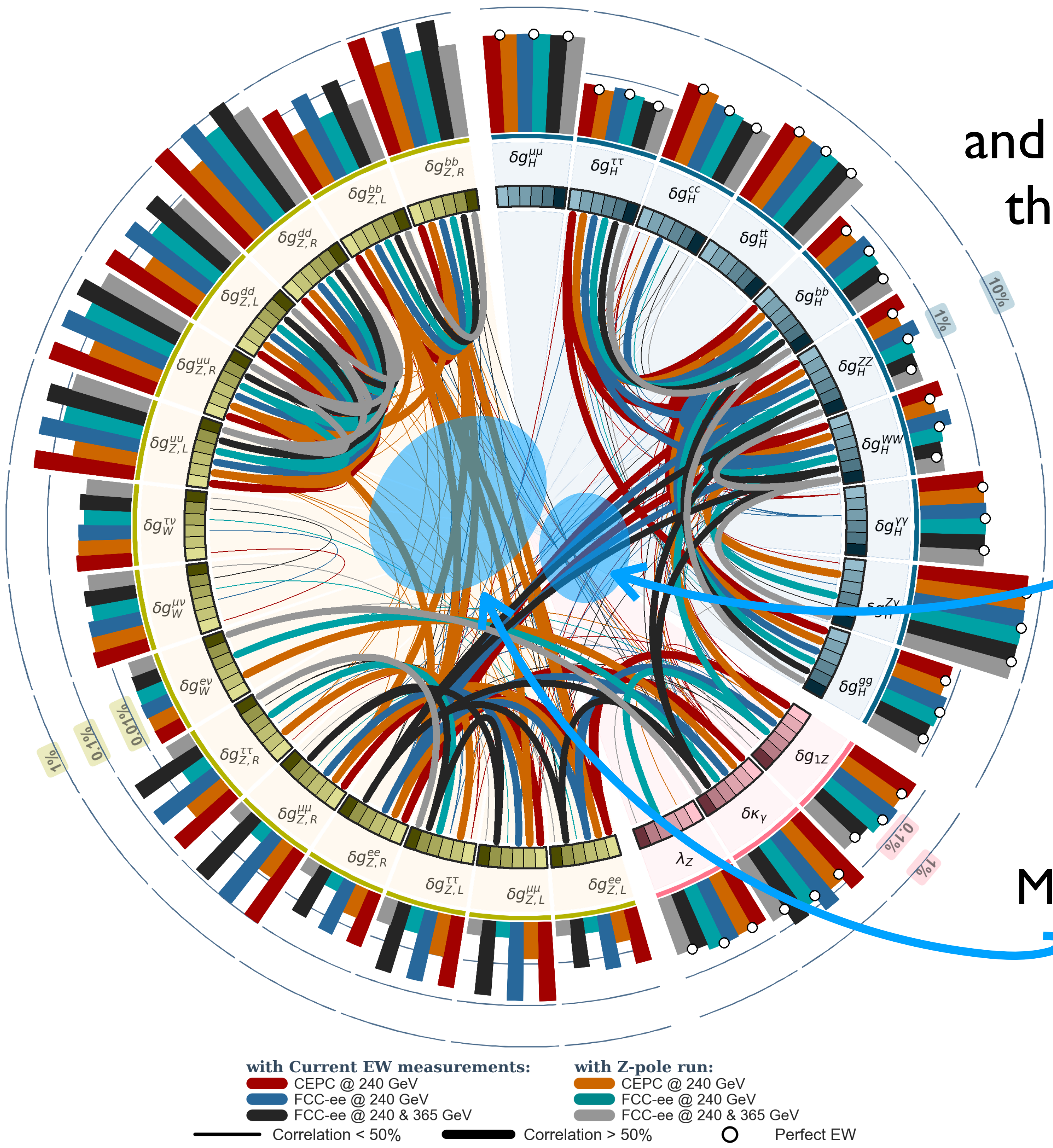
De Blas, Durieux, Grojean, Gu, Paul 'in progress



Look carefully at the plot and you'll see that, with a dedicated Z-pole, the correlations between Higgs and EW observables go away

Conclusions

De Blas, Durieux, Grojean, Gu, Paul 'in progress



Look carefully at the plot and you'll see that, with a dedicated Z-pole, the correlations between Higgs and EW observables go away

More correlations among EW observables at CEPC240 than at FCC240. Why?