Physics Perspective at Future Lepton Colliders

Jorge de Blas
University of Padova & INFN-Sezione di Padova

Based on the results presented in:

Higgs Boson Studies at Future Particle Colliders (arXiv:1905.03764 [hep-ph])

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

J.B., G. Durieux, C. Grojean, J. Gu, A. Paul, In preparation

and the results presented at the "Open Symposium of the European Strategy for Particle Physics, Granada, May 13-16, 2019

7th Edition of the Large Hadron Collider Physics Conference
LHCP 2019

Puebla, May 24, 2019

LHCP 2019

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare

Future Lepton Colliders

Lepton Colliders

LEP/SLC $\xrightarrow{?}$ ilc CLIC

CEPC FCC ee

Linear e+e- Colliders

	ilc	CLIC
$\sqrt{s}\,[\mathrm{GeV}]$	**250 (350/500?)**	**380/1500/3000**
(P_{e^-},P_{e^+})	**±80%/∓30%**	**±80%/0%**
$L[\mathrm{ab}^{-1}]$	**2 (0.2/4?)**	**1/2.5/5**

Circular e+e- Colliders

	CEPC	FCC ee
$\sqrt{s}\,[\mathrm{GeV}]$	**91/161/240**	**91/161/240/350/365**
(P_{e^-},P_{e^+})	**-**	**-**
$L[\mathrm{ab}^{-1}]$	**16/2.6/5.6**	**150/10/5/1.5**

Physics at Lepton Colliders

- **What kind of measurements/physics can be done at lepton colliders?**

- **What can we learn from these measurements? (What questions can be asked at lepton colliders?)**

Physics at Lepton Colliders

- **What kind of measurements/physics can be done at lepton colliders?**
  - **Precision measurements: EW/Higgs/Top**

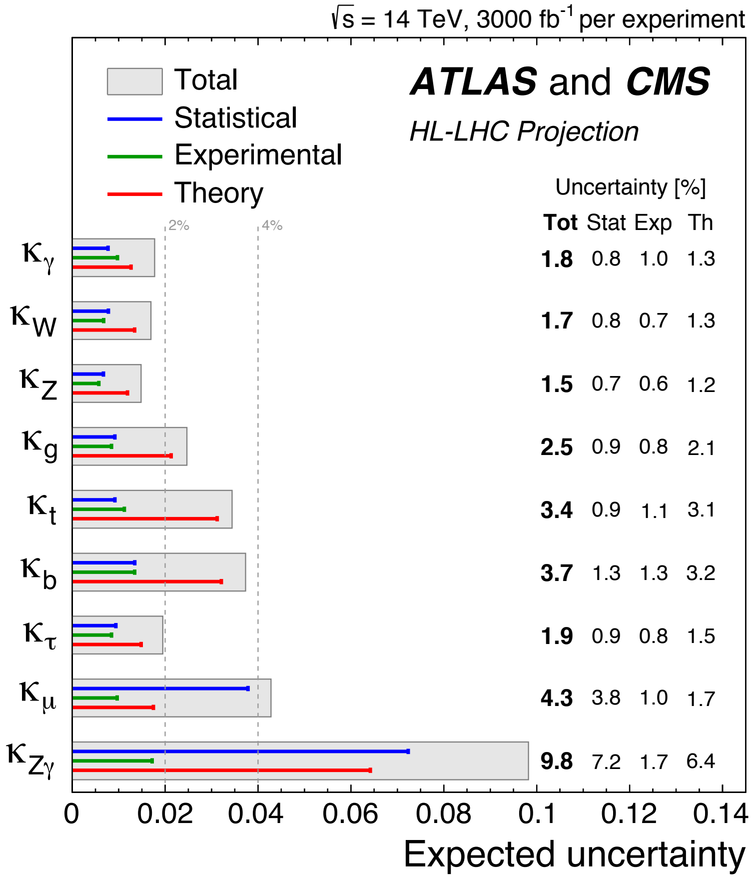
The Higgs factory option is an integral part of the physics program at all future lepton collider projects

- **What can we learn from these measurements? (What questions can be asked at lepton colliders?)**

Precision Physics at Future Lepton Colliders

Precision Higgs Physics at Lepton vs. Hadron Collider

Hadron Collider Higgs



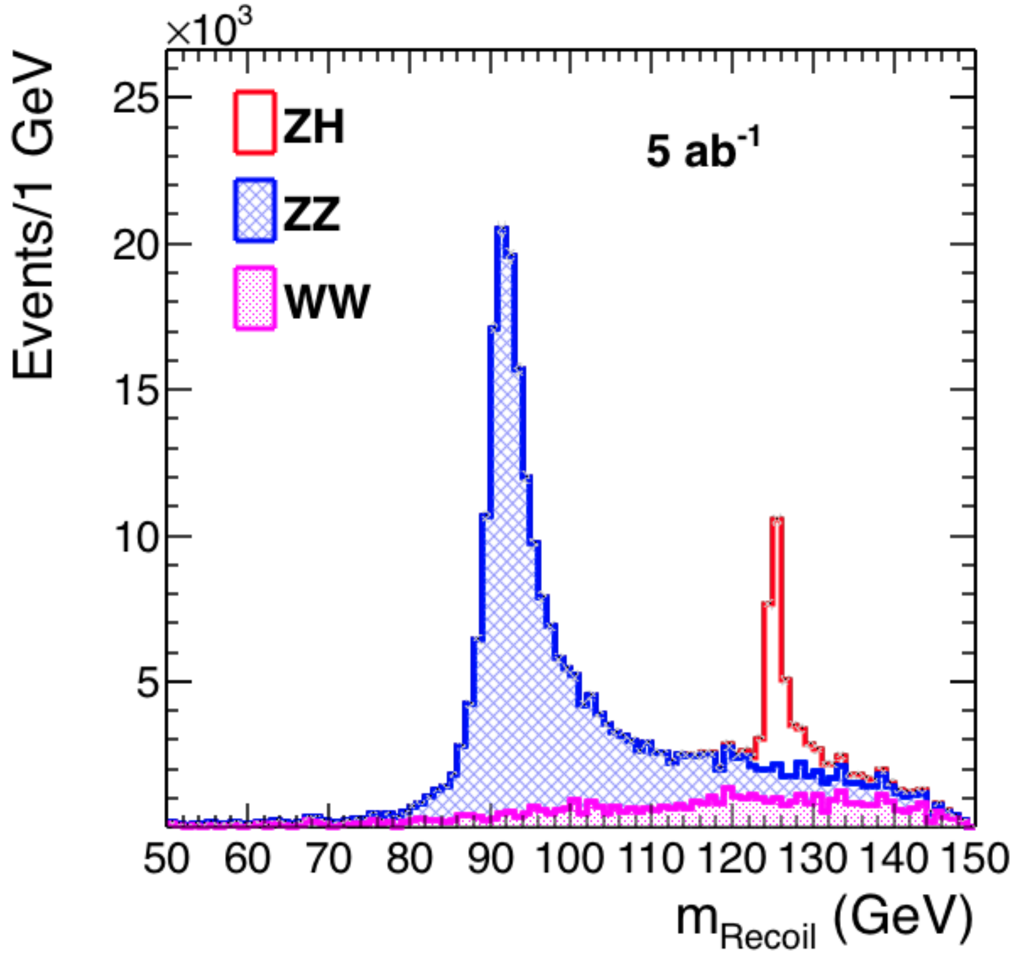
Uncertainty [%]

	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}

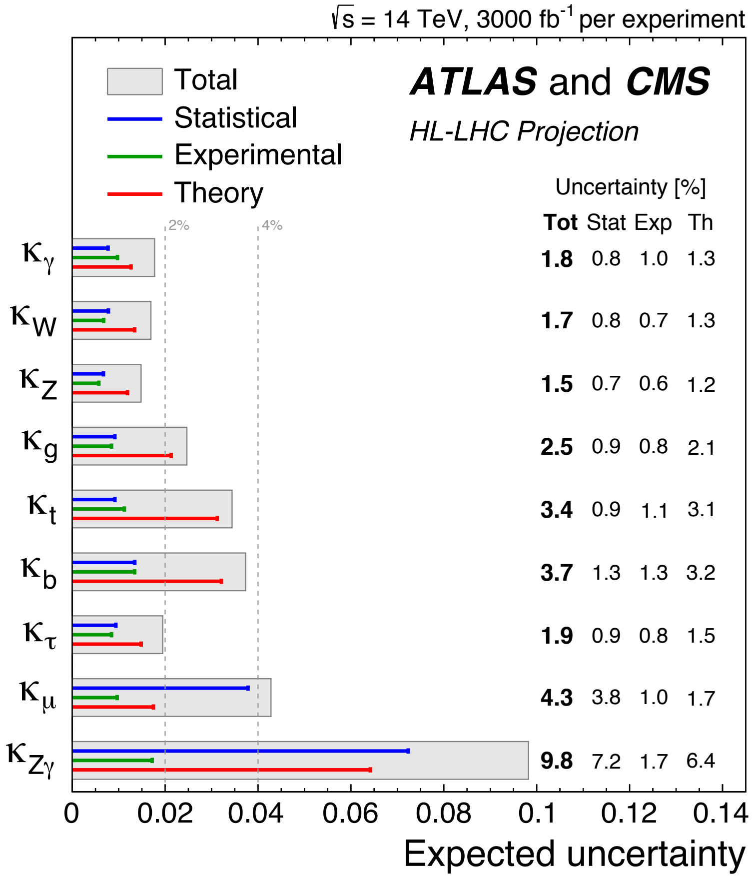
(only possible at lepton colliders)

Translates ratios into couplings

Precision Physics at Future Lepton Colliders

Precision Higgs Physics at Lepton vs. Hadron Collider

Hadron Collider Higgs



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

Ratios, no absolute couplings

Lepton Collider Higgs

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12	±10
$H \to \tau\tau$	±0.9		±1.8	±8
$H \to \gamma\gamma$	±9.0		±18	±22
$H \to \mu^+\mu^-$	±19		±40	
$H \to$ invis.	< 0.3		< 0.6	

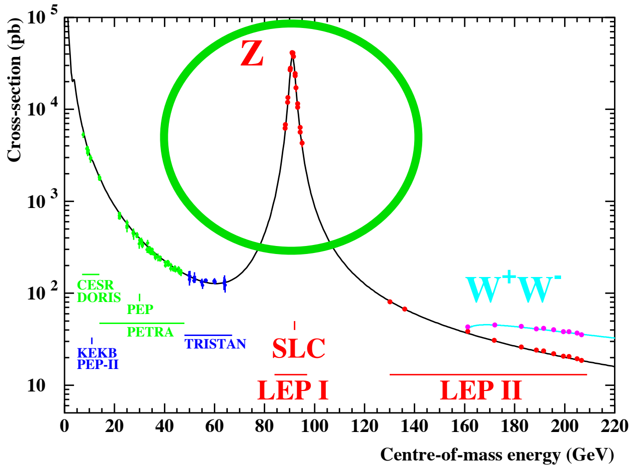
Sub-percent precision in Higgs rates

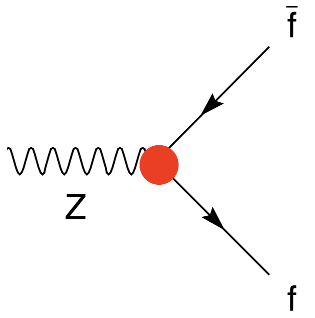
Precision Physics at Future Lepton Colliders

Precision EW Physics at Lepton Colliders

- Many other precision measurements in the EW sector

EWPO

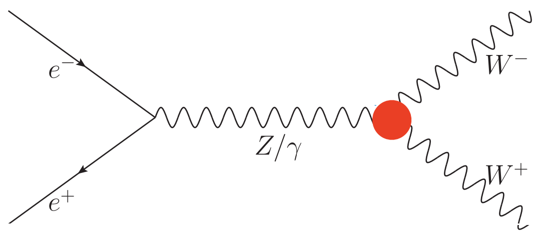




Tests of *Vff* interactions

~10-100x better than LEP

Diboson



Tests of anomalous triple gauge couplings (aTGC)

~10-100x better than LEP

- Separation of EW/Higgs (& Top/Flavor/…) is "artificial" from the BSM point of view:

EFT description of (heavy) new physics

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

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

EWSB

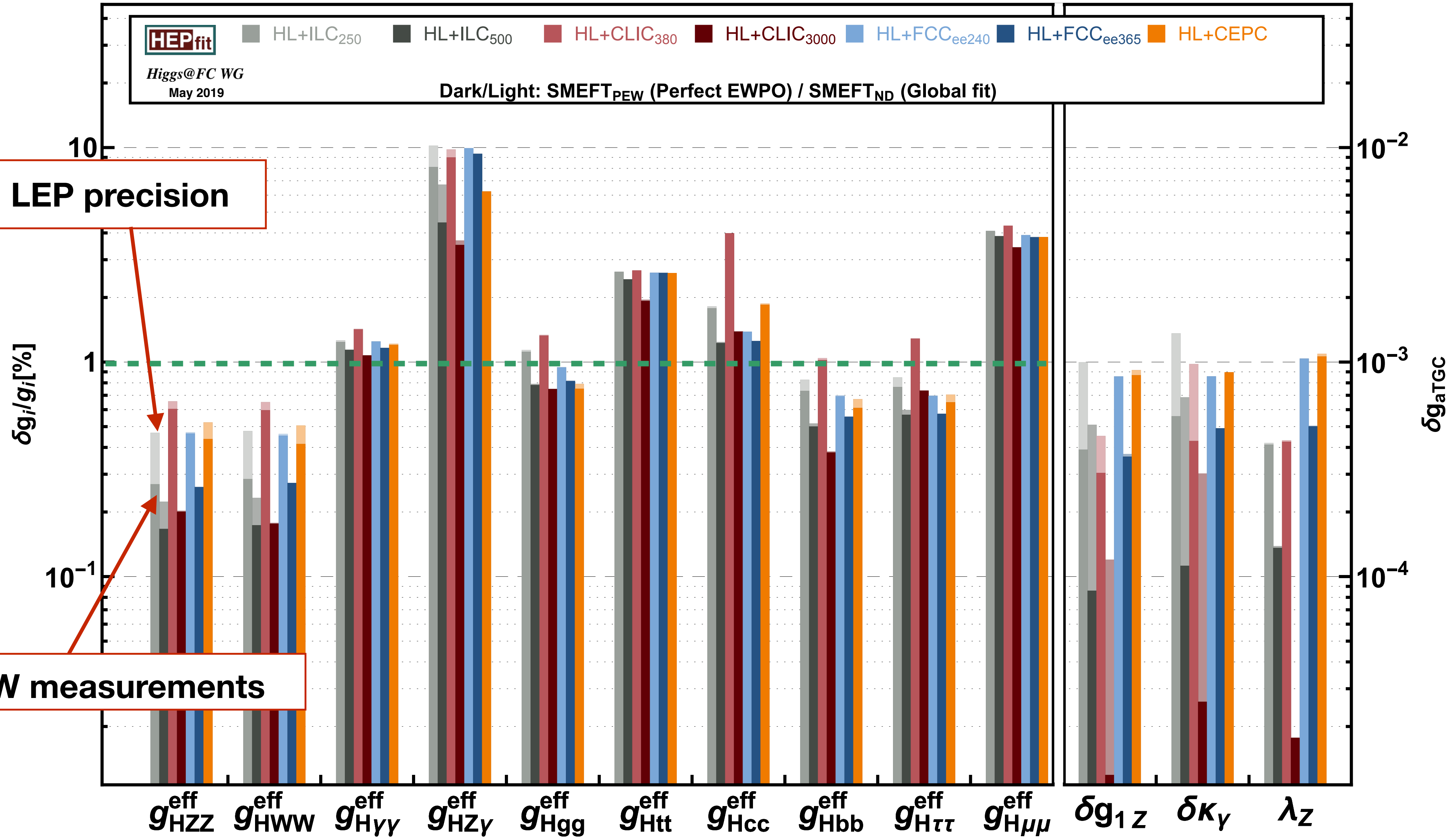
$v^2 B^{\mu\nu} W^3_{\mu\nu}$ **(dim 4)** — Modifies neutral gauge boson self-energies — **EWPO**

$vh B^{\mu\nu} W^3_{\mu\nu}$ **(dim 5)** — $h \to ZZ, \gamma\gamma$ — **Higgs phys.**

EFT studies at Future Lepton Colliders

Global EFT fit to EW/Higgs at Future Lepton Colliders

Sub-percent precision expected in main Higgs couplings



Assuming LEP precision

Perfect EW measurements

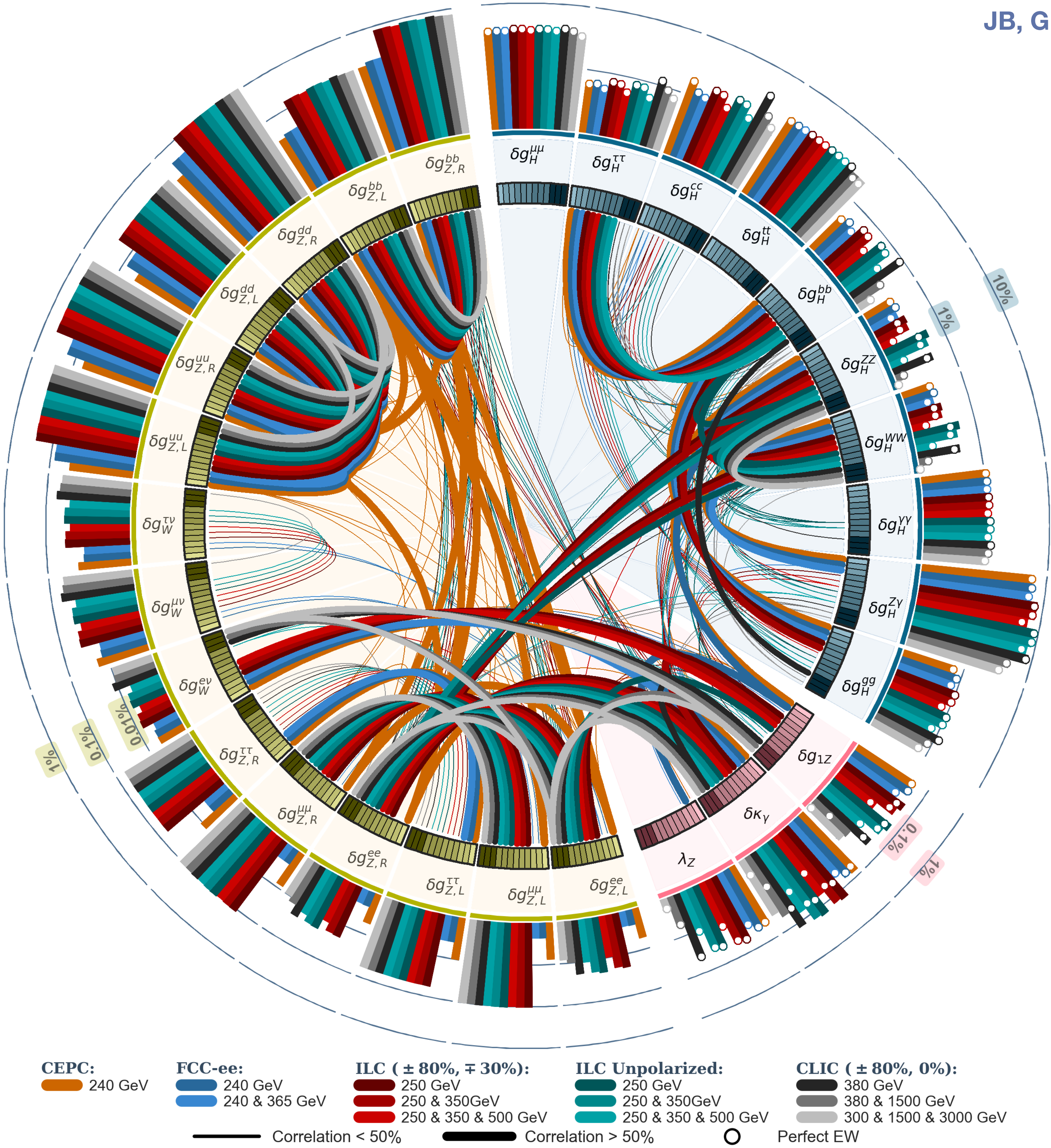
EFT results projected into effective Higgs couplings and aTGC

$$\mathcal{L}_{\rm Eff}=\sum_{d=4}^{\infty}\frac{1}{\Lambda^{d-4}}\mathcal{L}_d=\mathcal{L}_{\rm SM}+\frac{1}{\Lambda}\mathcal{L}_5+\frac{1}{\Lambda^2}\mathcal{L}_6+\cdots \quad\rightarrow\quad g_{HX}^{{\rm eff}\ 2}\equiv\frac{\Gamma_{H\to X}}{\Gamma^{\rm SM}_{H\to X}}$$

EFT studies at Future Lepton Colliders

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, In preparation

Correlation Map at Future Lepton Colliders

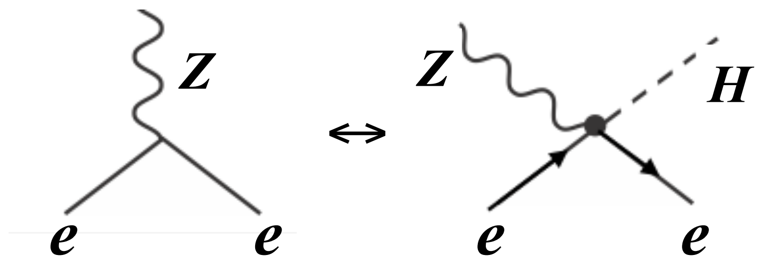


CEPC/FCC-ee: Z-pole run largely decouples EWPO and Higgs fits

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

(Could be mitigated by using rad. return EWPO, or at 500 GeV)

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



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

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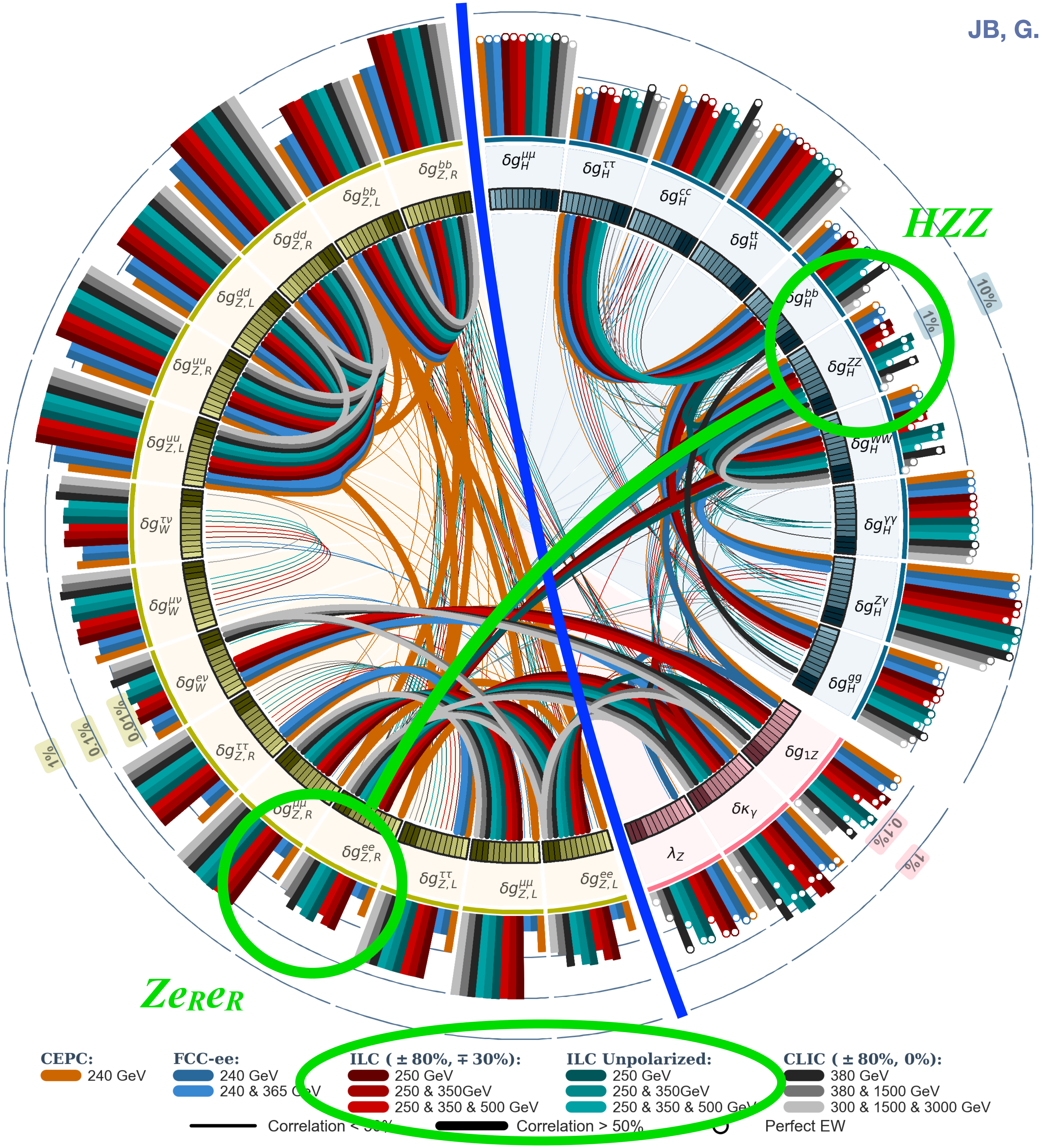

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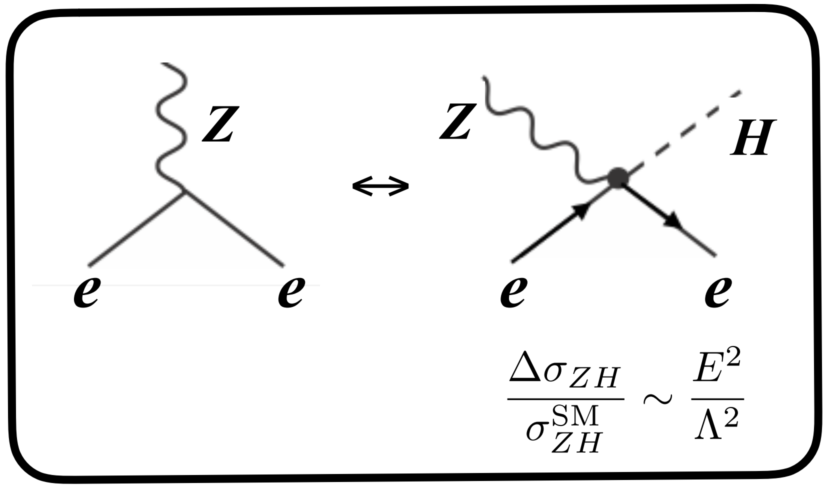
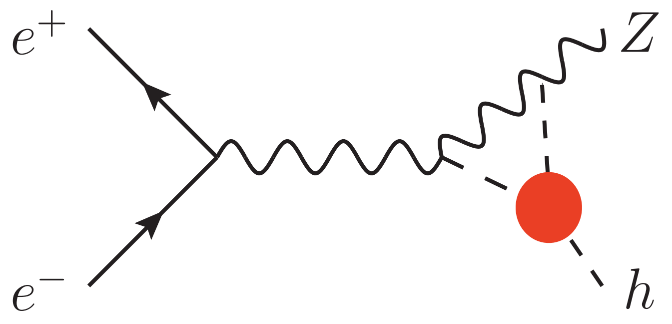


$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}^{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

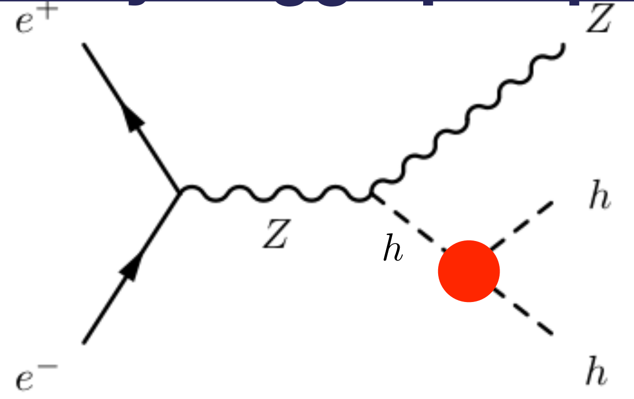
EFT studies at Future Lepton Colliders

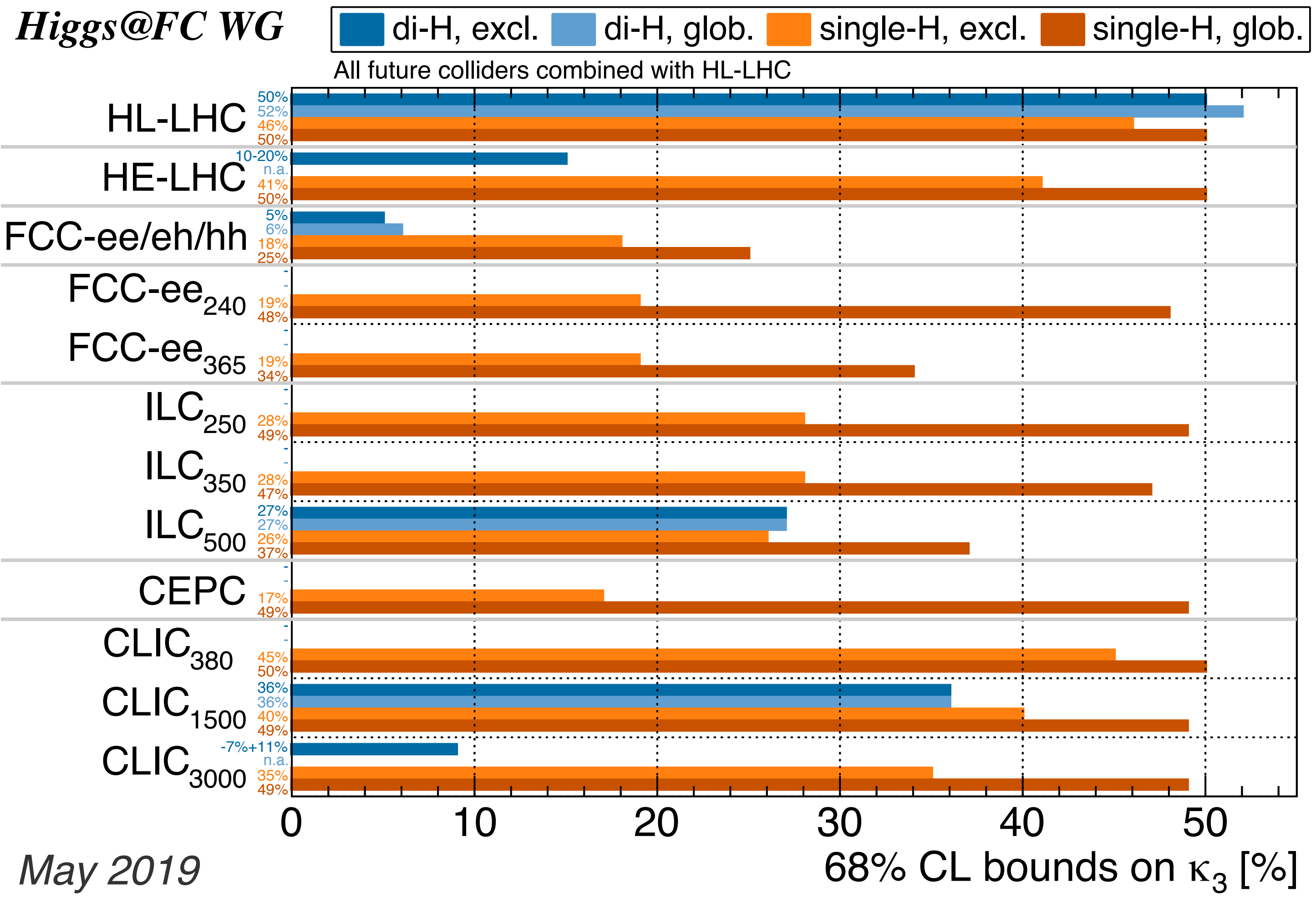
Testing the Higgs self-interaction

Indirectly: via single Higgs



Directly: Higgs-pair prod





Indirect ~34%

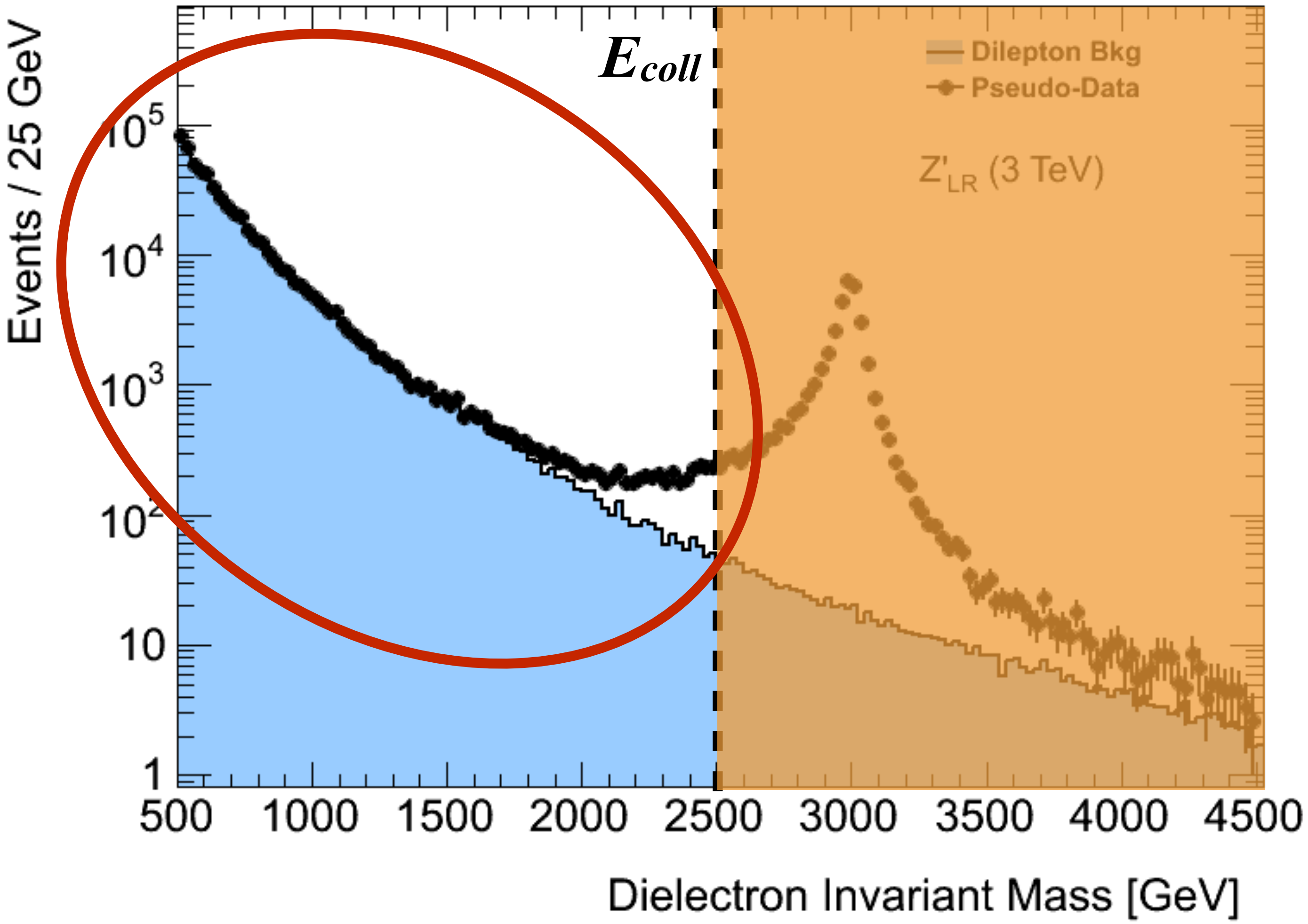
Direct ~10%

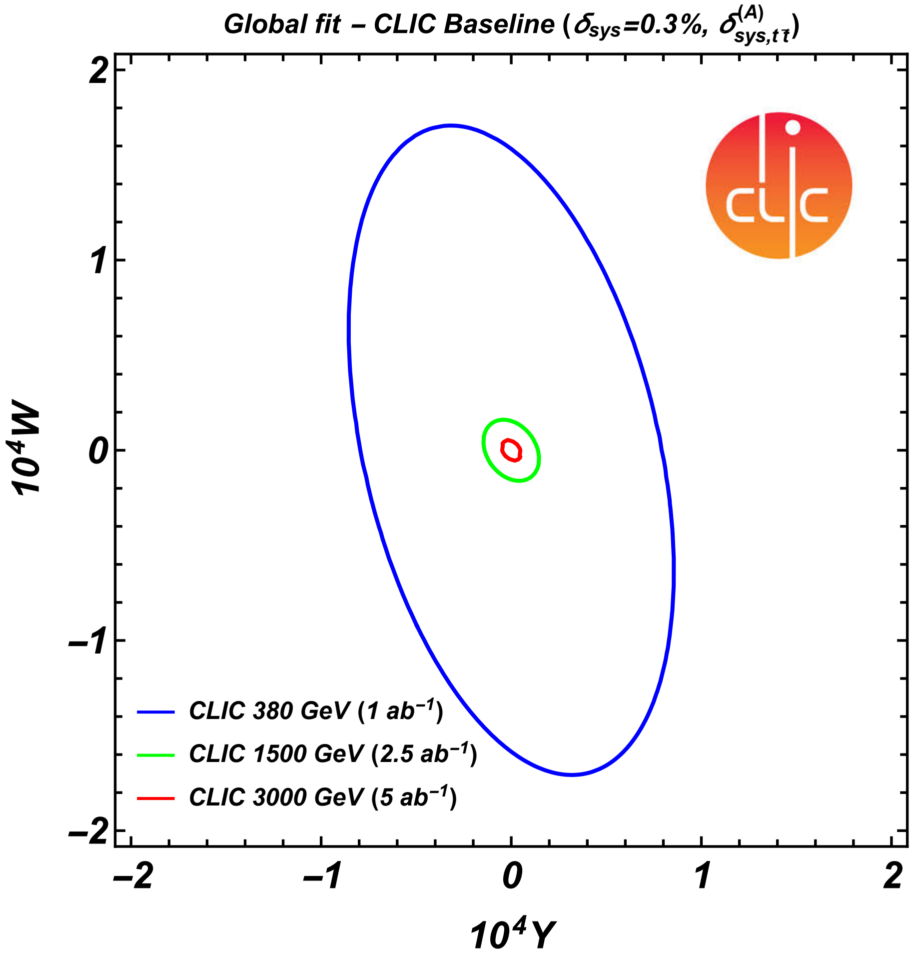
Important to test the SM structure of the Higgs potential + implications for BSM questions: EW Baryogenesis

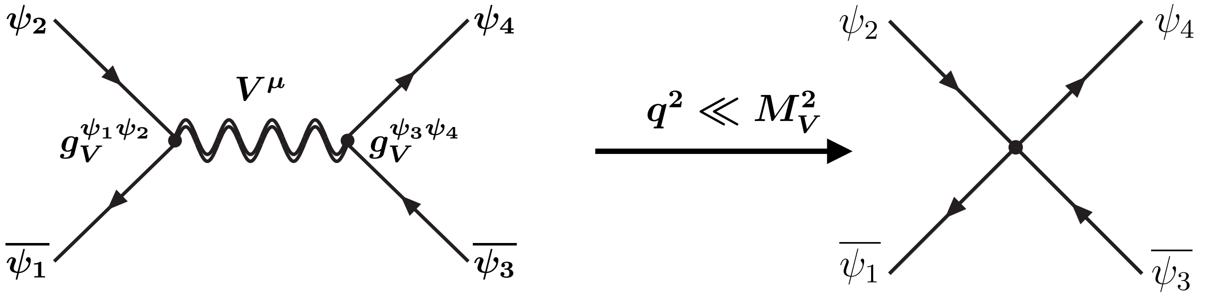
Precision Physics at Future Lepton Colliders

High Energy probes of new physics

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







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

Universal NP

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

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

Physics at Lepton Colliders

- **What kind of measurements/physics can be done at lepton colliders?**
  - **Precision measurements: EW/Higgs/Top**

The Higgs factory option is an integral part of the physics program at all future lepton collider projects

- **What can we learn from these measurements? (What questions can be asked at lepton colliders?)**

e.g. Naturalness: Is the Higgs a composite particle?

(Others: Dark Matter, extended gauge sectors, …)

See also A. Wulzer's plenary talk

Is the Higgs a composite particle?

- **Indirect sensitivity to Composite Higgs (CH) via SILH Lagrangian:**

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

- Not a general EFT/basis, but contains the most relevant effective interactions expected in composite Higgs scenarios

- Expected dependence of the different Wilson coefficients, up to O(1) factors:

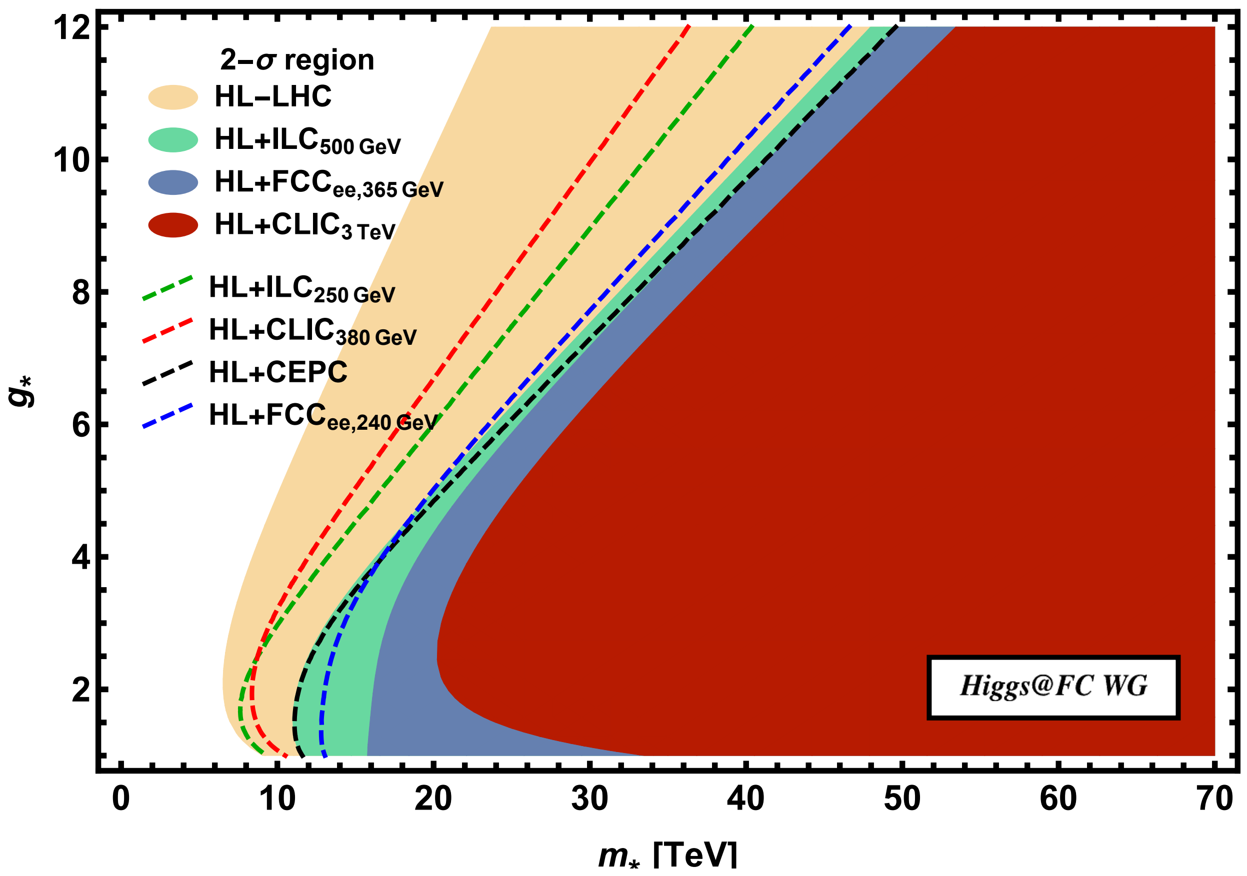
$$\frac{c_{\phi,6,y_f}}{\Lambda^2} = \frac{g_\star^2}{m_\star^2}, \qquad \frac{c_{W,B}}{\Lambda^2} = \frac{1}{m_\star^2}, \qquad \frac{c_{2W,2B,2G}}{\Lambda^2} = \frac{1}{g_\star^2}\frac{1}{m_\star^2},$$

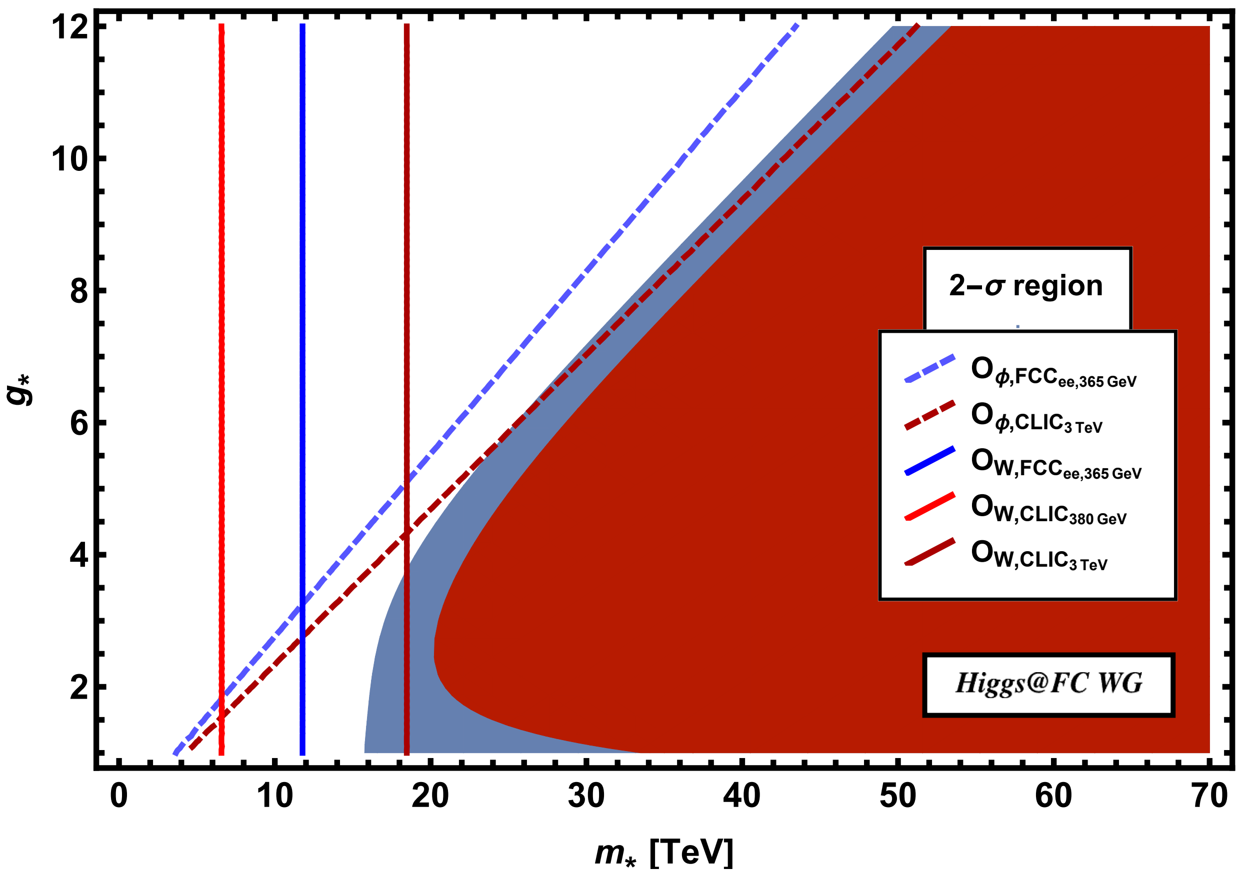
$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \qquad \frac{c_{3W,3G}}{\Lambda^2} = \frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

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

Is the Higgs a composite particle?

Indirect constraints in CH models





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

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

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

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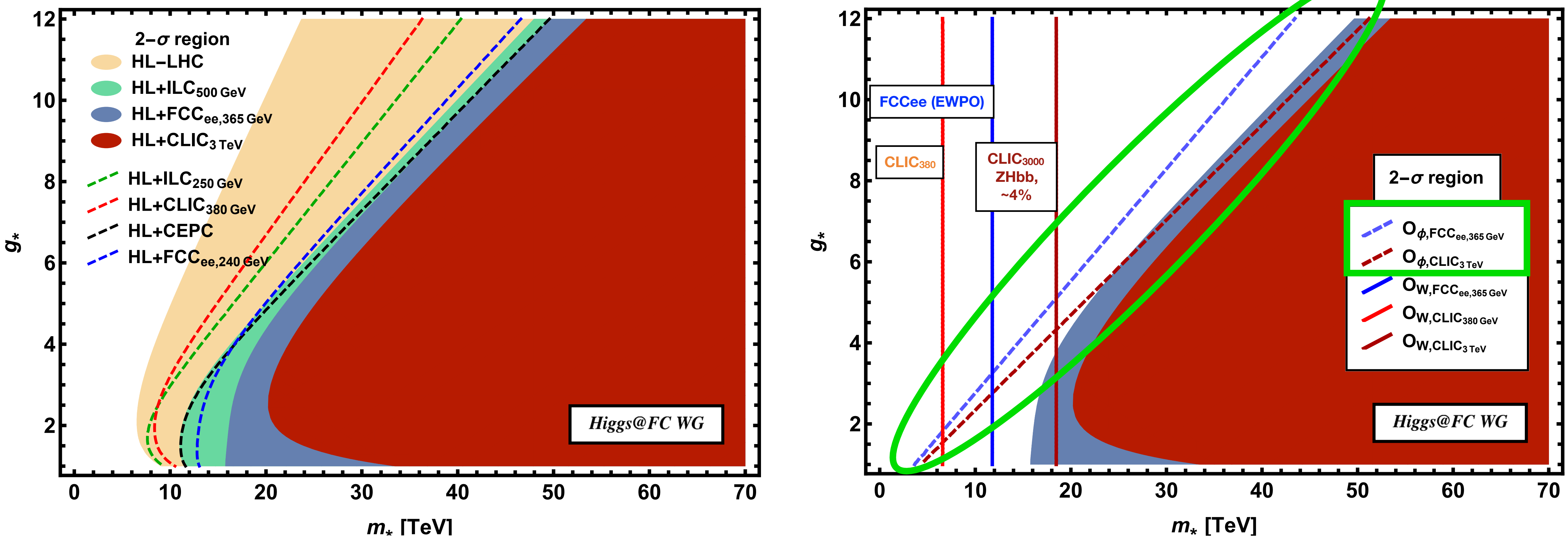

Simplified CH benchmark: 1 coupling (g*) - 1 scale (m*)

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

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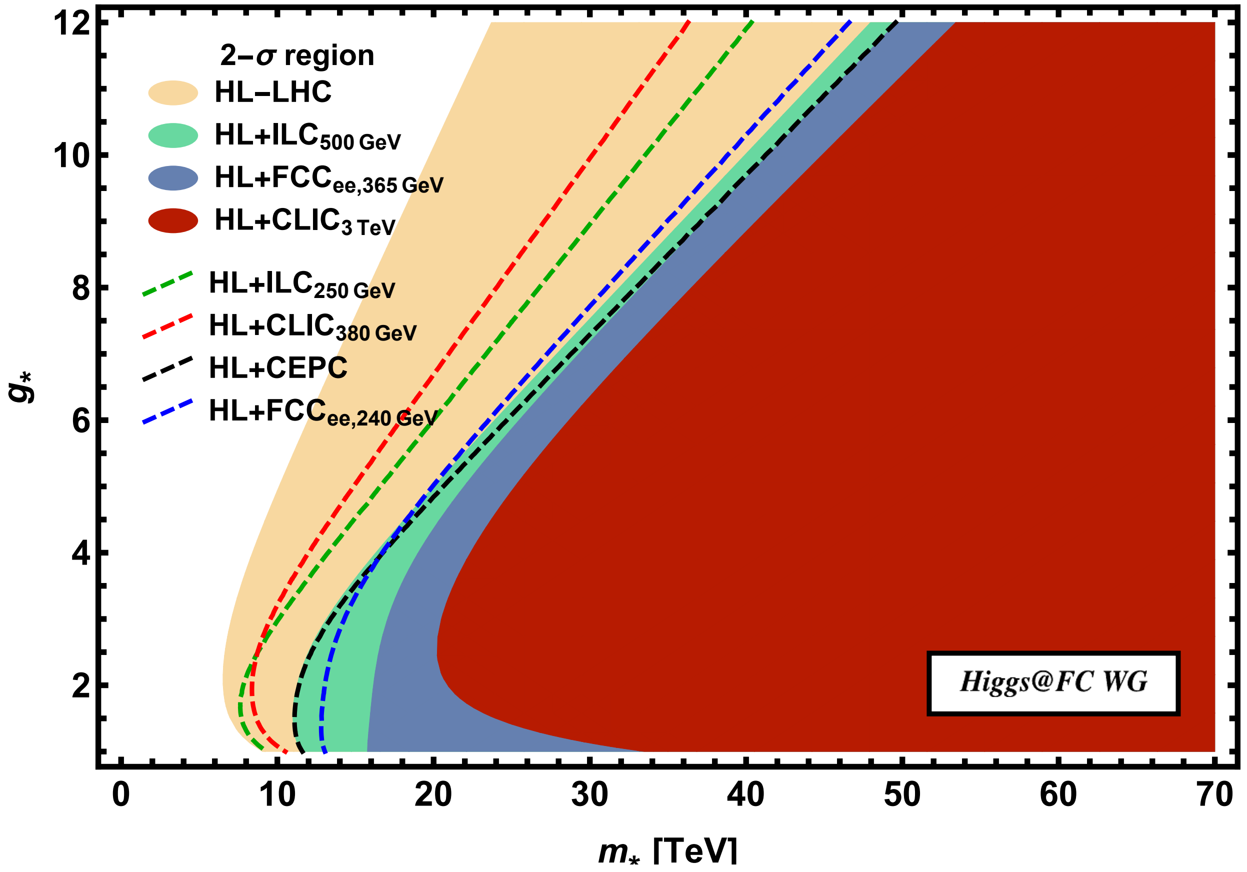
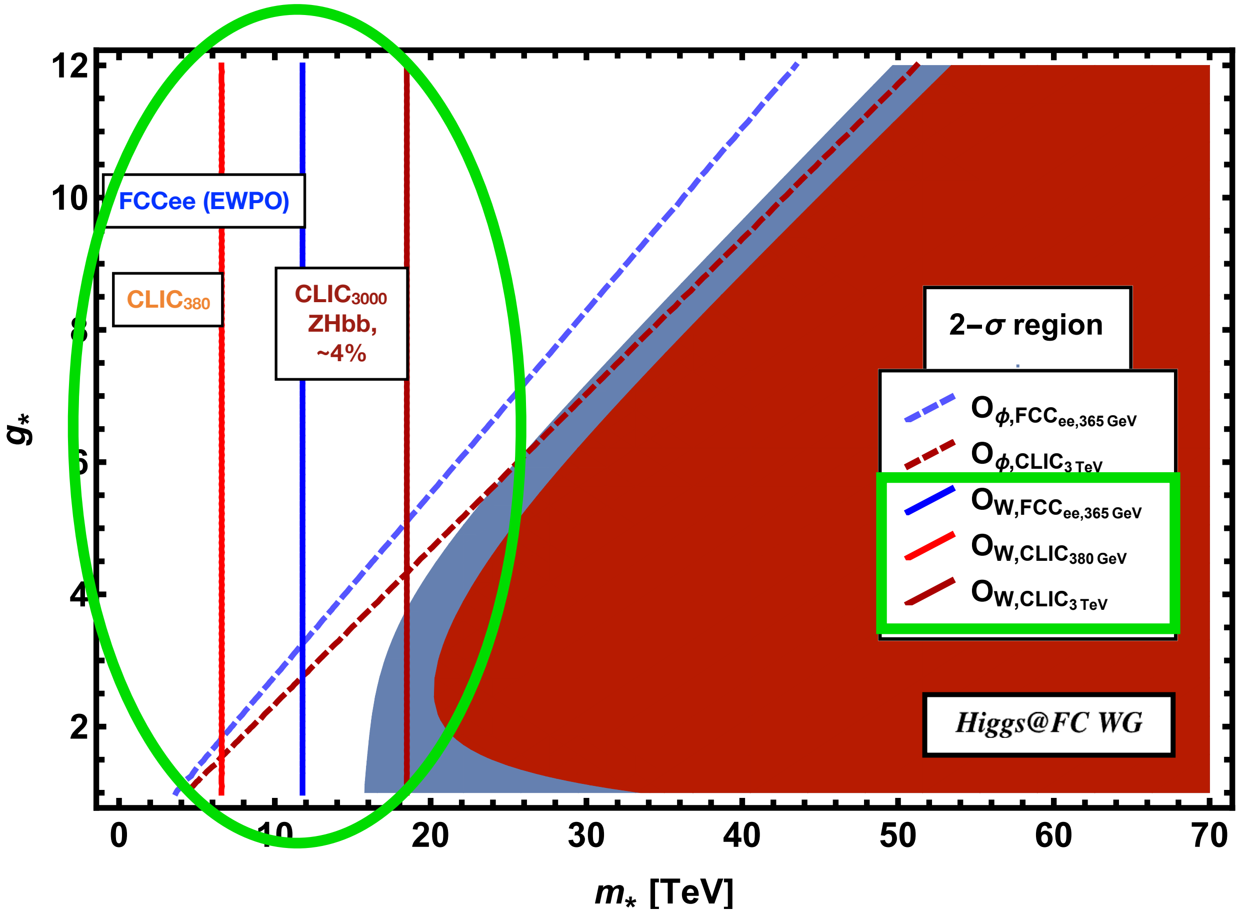
Higgs couplings provide the dominant constraint for strongly coupled CH models

Is the Higgs a composite particle?

Indirect constraints in CH models





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

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

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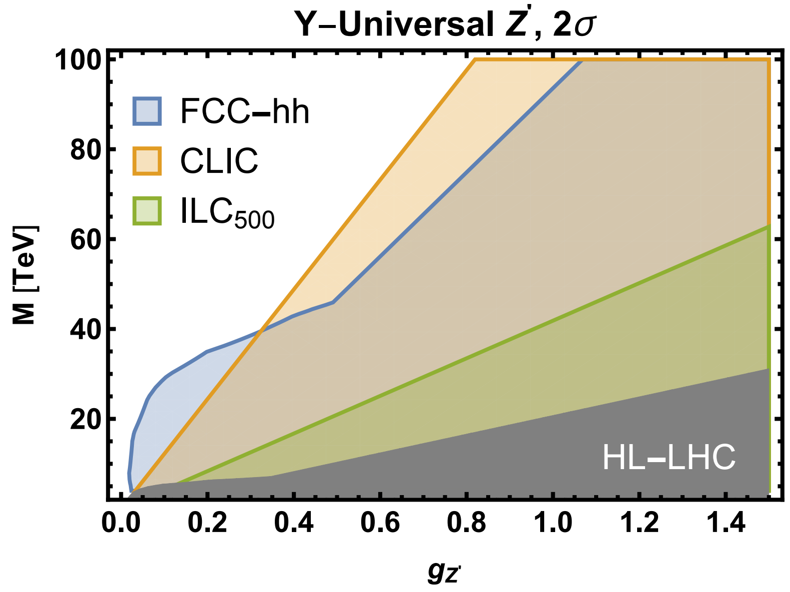
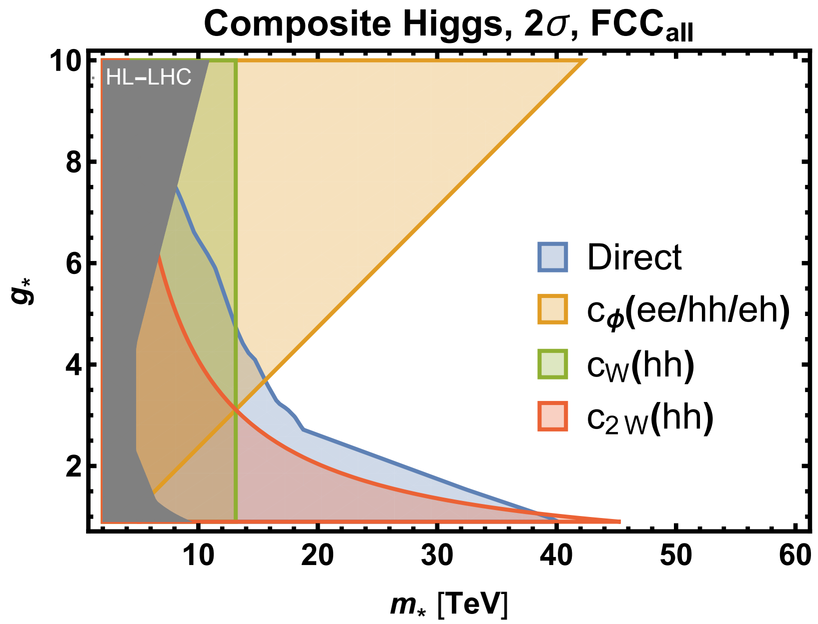
Different ways of testing the compositeness scale (via $O_{W,B}$):
Low-Energy precision (FCCee) vs High-Energy (CLIC)

Summary

- **Lepton colliders:** direct searches reach is limited compared to future hadron colliders, BUT they provide the best environment for precision measurements:
    - **Higgs:** sub-percent accuracy for several Higgs couplings + measurements not possible at hadron colliders. **Self-coupling:** 10-30% accuracy (direct/indirect).
    - **EW:** advantage for machines running at the Z-pole (EWPO)
    - **Top** (not in this talk): better with runs at 2 energies above tt threshold
    - **High Energy** lepton colliders ⇒ Precision constraints on growing with energy effects.
- All these measurements can be used as indirect tests of new physics

Complementary information to that from direct searches at hadron colliders





Figs. by A. Wulzer

Backup slides

Future 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

Future Colliders Summary

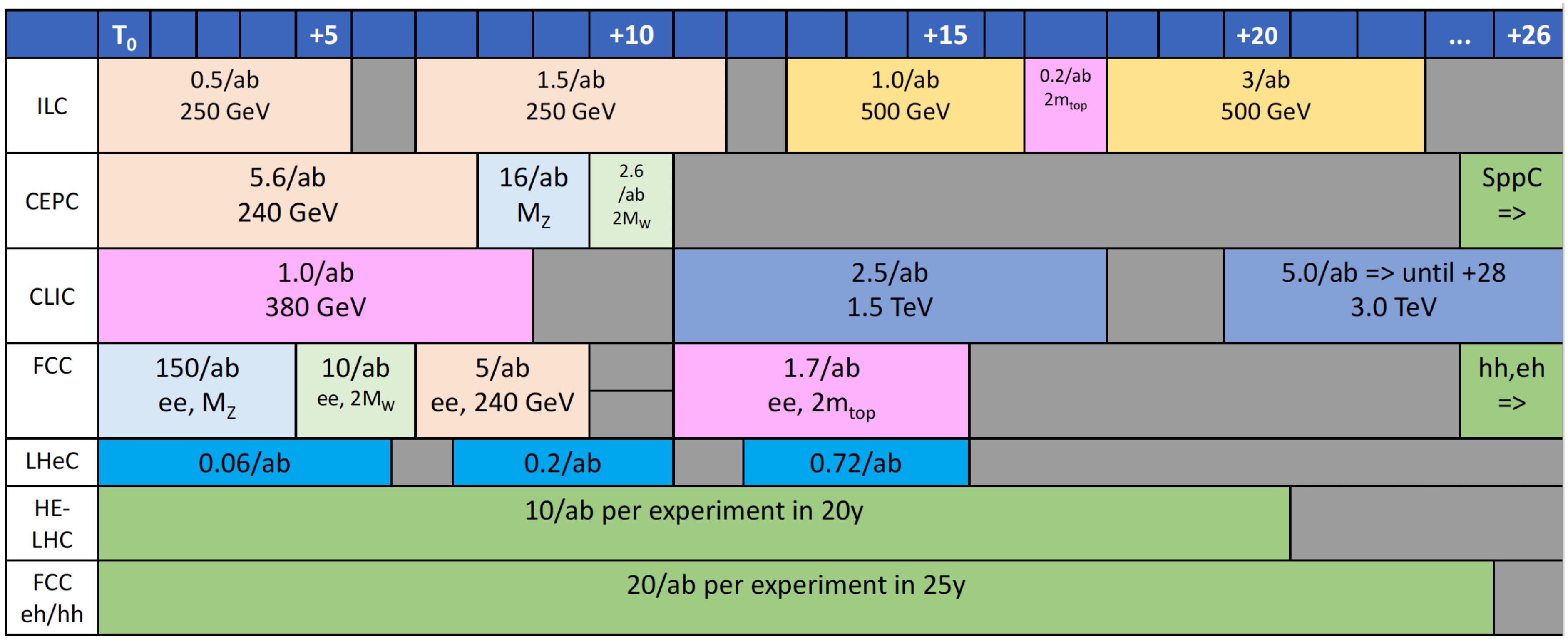
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N(Det.)	$\mathscr{L}_{\rm inst}$ [10^{34}] cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee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

All results presented in combination with HL-LHC

Each collider stage used in combination with the previous ones

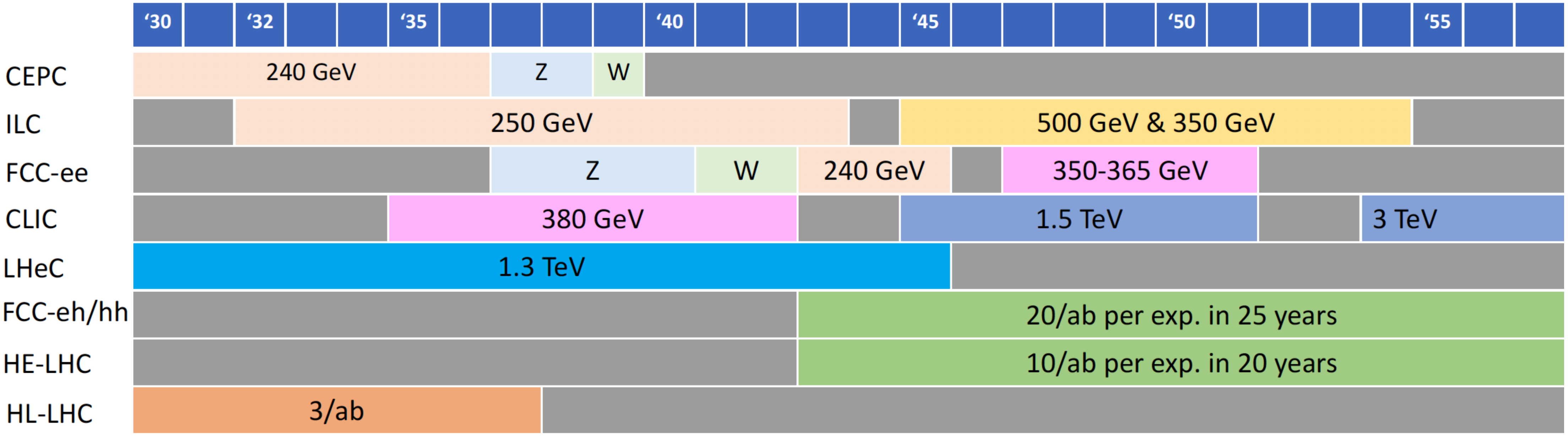
FCCeh/hh running together. Used in combination with FCCee

Future Collider Timeline



	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					

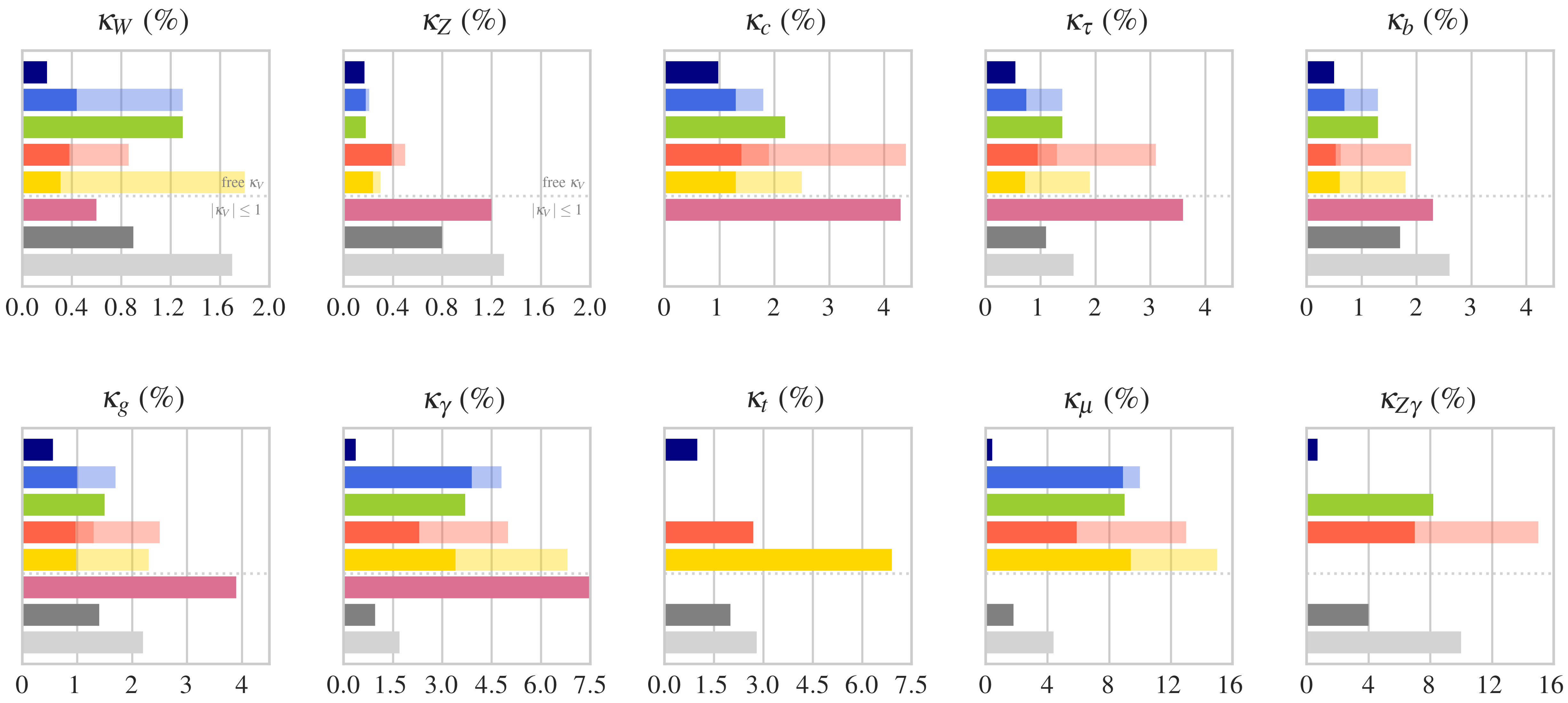
Starting time at T$_0$



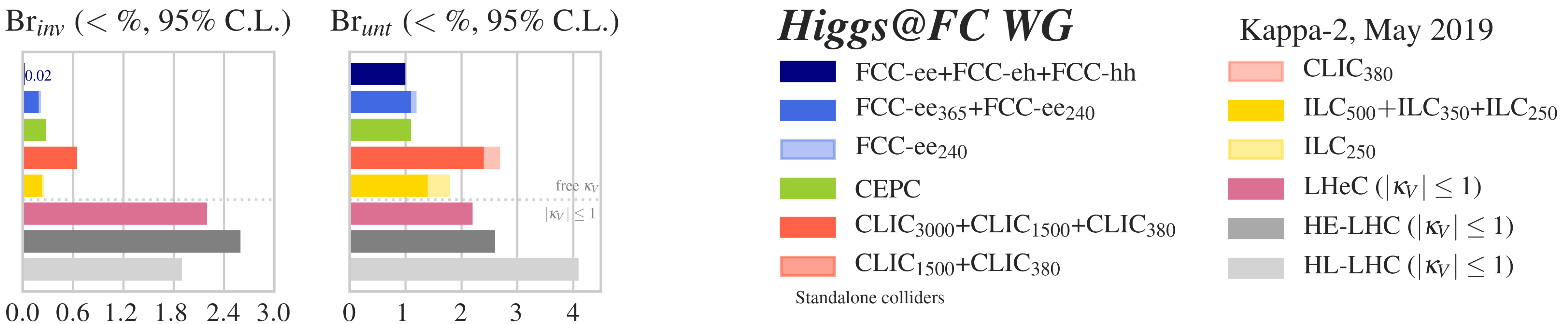
	'30 '32 '35 '40 '45 '50 '55					
CEPC	240 GeV	Z	W			
ILC	250 GeV	500 GeV & 350 GeV				
FCC-ee	Z	W	240 GeV	350-365 GeV		
CLIC	380 GeV	1.5 TeV	3 TeV			
LHeC	1.3 TeV					
FCC-eh/hh	20/ab per exp. in 25 years					
HE-LHC	10/ab per exp. in 20 years					
HL-LHC	3/ab					

Earliest start time in ESU documents

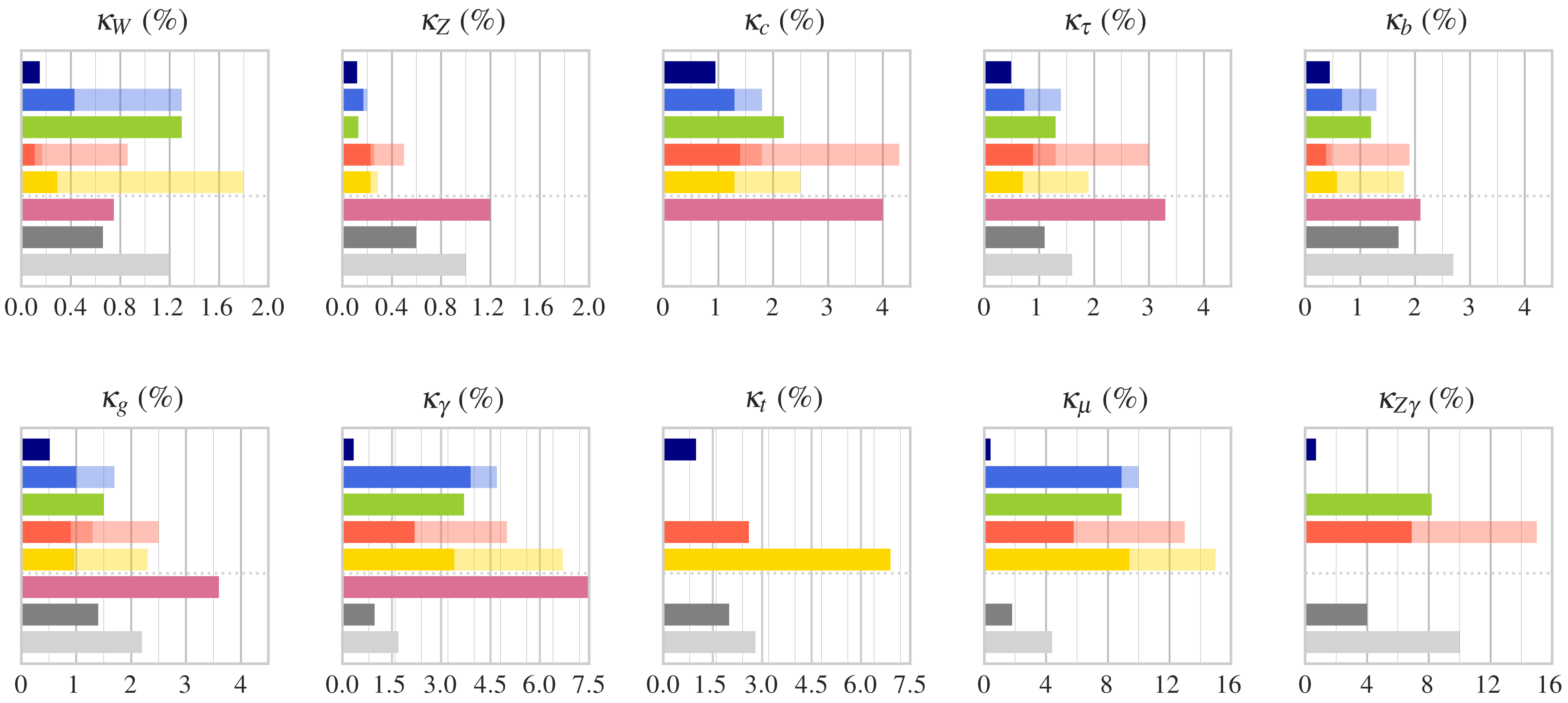
κ fit results: Higgs couplings



κ fit: Allowing extra Higgs decays



κ fit results: Higgs couplings

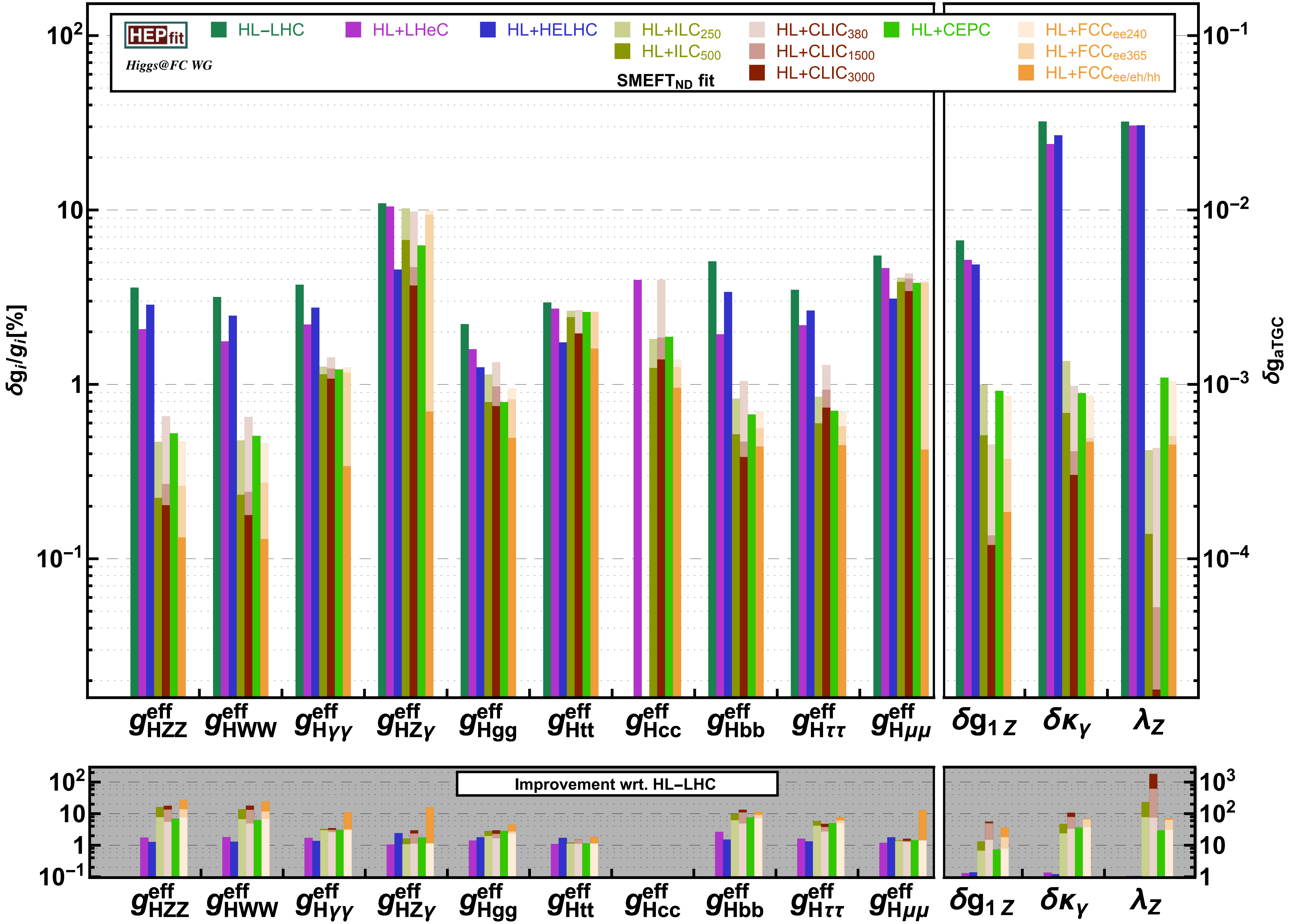


κ fit: No extra Higgs decays

Higgs@FC WG
Kappa-0
May 2019

- 🟦 FCC-ee+FCC-eh+FCC-hh
- 🟦 FCC-ee$_{365}$+FCC-ee$_{240}$
- 🟦 FCC-ee$_{240}$
- 🟩 CEPC
- 🟥 CLIC$_{3000}$+CLIC$_{1500}$+CLIC$_{380}$
- 🟥 CLIC$_{380}$+CLIC$_{1500}$
- 🟥 CLIC$_{380}$
- 🟨 ILC$_{500}$+ILC$_{350}$+ILC$_{250}$
- 🟨 ILC$_{250}$
- 🟪 LHeC
- ⬛ HE-LHC
- ⬜ HL-LHC

Global EFT fit results: Higgs couplings



BSM-motivated Effective Lagrangians

- **68% prob. bounds on SILH Lagrangian interactions:**