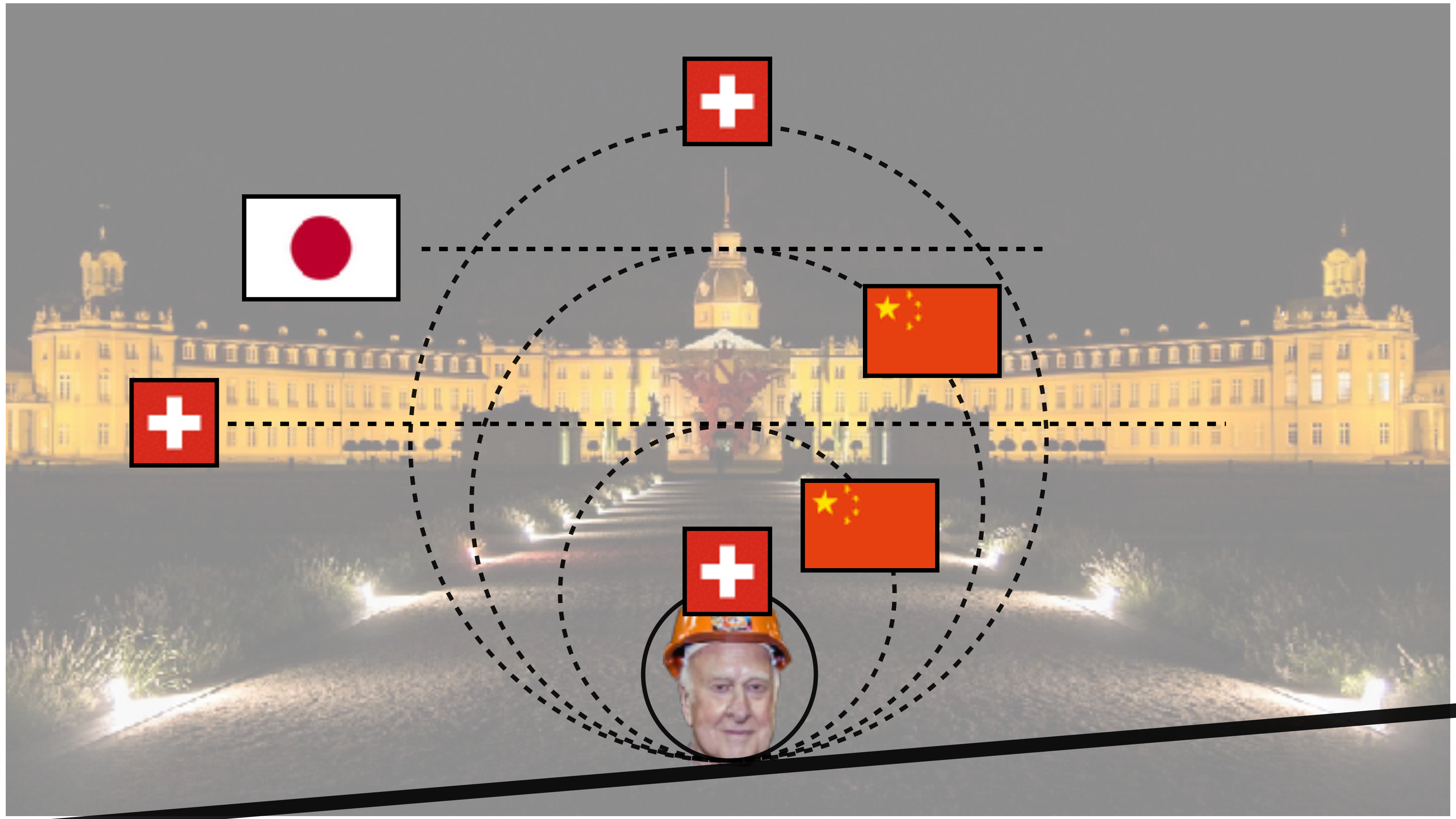
Outlook

What will the Future Colliders know about the Higgs?

"Theory Challenges in Higher-Order New Physics Calculations"

Karlsruhe, October 9, 2019



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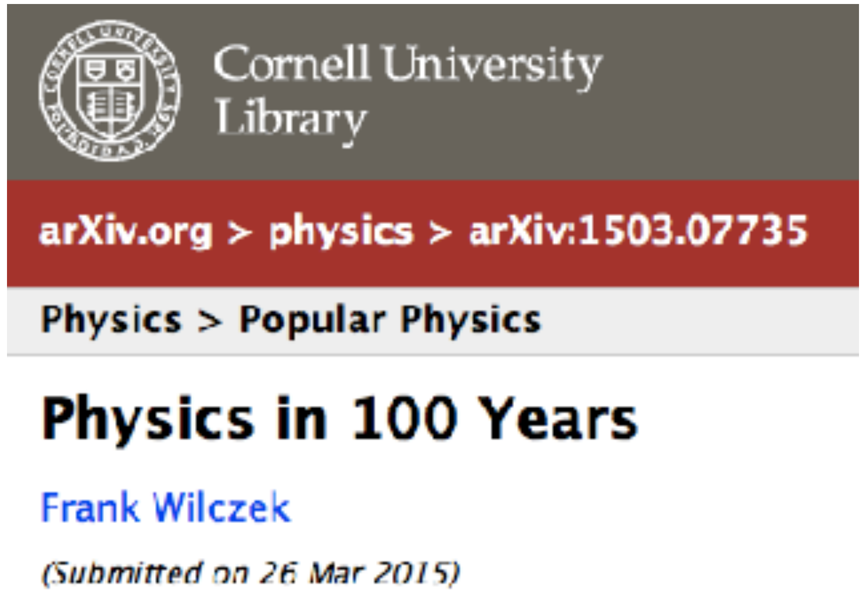
Today is a unique moment in history of science

The Higgs discovery is the triumph of XXth century physics
combination of Quantum Mechanism + Special Relativity
SM=S(R+Q)M

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)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Physics in 100 Years
Frank Wilczek
(Submitted on 26 Mar 2015)

The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

*But we do *not* understand the Matter the Universe is made from!*

The Higgs Boson is Special

The Higgs discovery has been an important milestone for HEP.
And many of us are still excited about it.
And others, especially in other fields of science, should be excited too.

Higgs = **new forces** of different nature than the gauge interactions known so far

- No underlying local symmetry
- No quantised charges
- Deeply connected to the space-time vacuum structure

The knowledge of the values of the **Higgs couplings**
is essential to our understanding of the deep structure of matter

- Up- and Down-quark Yukawa's decide if $m_{proton} < m_{neutron}$ i.e. stability of nuclei
- Electron Yukawa controls the size of the atoms (and thus the size of the Universe?)
- Top quark Yukawa decides (in part) of the stability of the EW vacuum
- The Higgs self-coupling controls the (thermo)dynamics of the EW phase transition ($t \sim 10^{-10}$s)

(and therefore might be responsible of the dominance of matter over antimatter in the Universe)

High Energy Physics with a Higgs

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda^2_{\rm BSM}}$

current (and future) LHC sensitivity
O(10-20)% ⇔ $\Lambda_{\rm BSM}$ > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

1% is also a magic number to probe naturalness of EW sector

An incredibly rich program

Zanderighi @ Higgs Hunting 2019

H

Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width interferometry
- differential distributions

Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu$, τe, $e\mu$
- $H \to J/\Psi\gamma$, $\Upsilon\gamma$, …

Tool for discovery
- portal to BSM
- portal to hidden sector
- portal to DM

… and much more
- Higgs potential
- di-Higgs
- other FCNC decays
- …

SM minimal or not?
- 2HDM
- MSSM, NMSSM
- extra Higgs states, doubly-charged Higgs

An incredibly rich program

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

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Which Machine(s)?

The challenges of big colliders:

- energy: 10^{13} larger than everyday life batteries

- magnetic field: 10^{4} larger than everyday life magnets

Cannot use permanent magnets:

currents needed in 16T magnets ~ intramolecular fields (100 MV/m).

Going higher will imply a reorganisation of matter!

→ Plasma wakefield acceleration

Exercise: with 2 magnets of 1T, can you build a magnet of 2T?

Which Machine(s)?

Choice between different options: delicate balance between
physics return, technological challenges and feasibility,
time scales for completion and exploitation, financial and political realities

Exploration machines are at the heart of HEP
Current consensus towards European Strategy Update:
the best way to go to energy frontier is to start with a **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Dedicated Z-pole run

Three relevant questions to address to help taking a decision:
1) Impact of Z pole measurements?
2) Benefit of beam polarisation?
3) Is low energy a limitation?

Future of HEP

ECFA Higgs study group ‘19

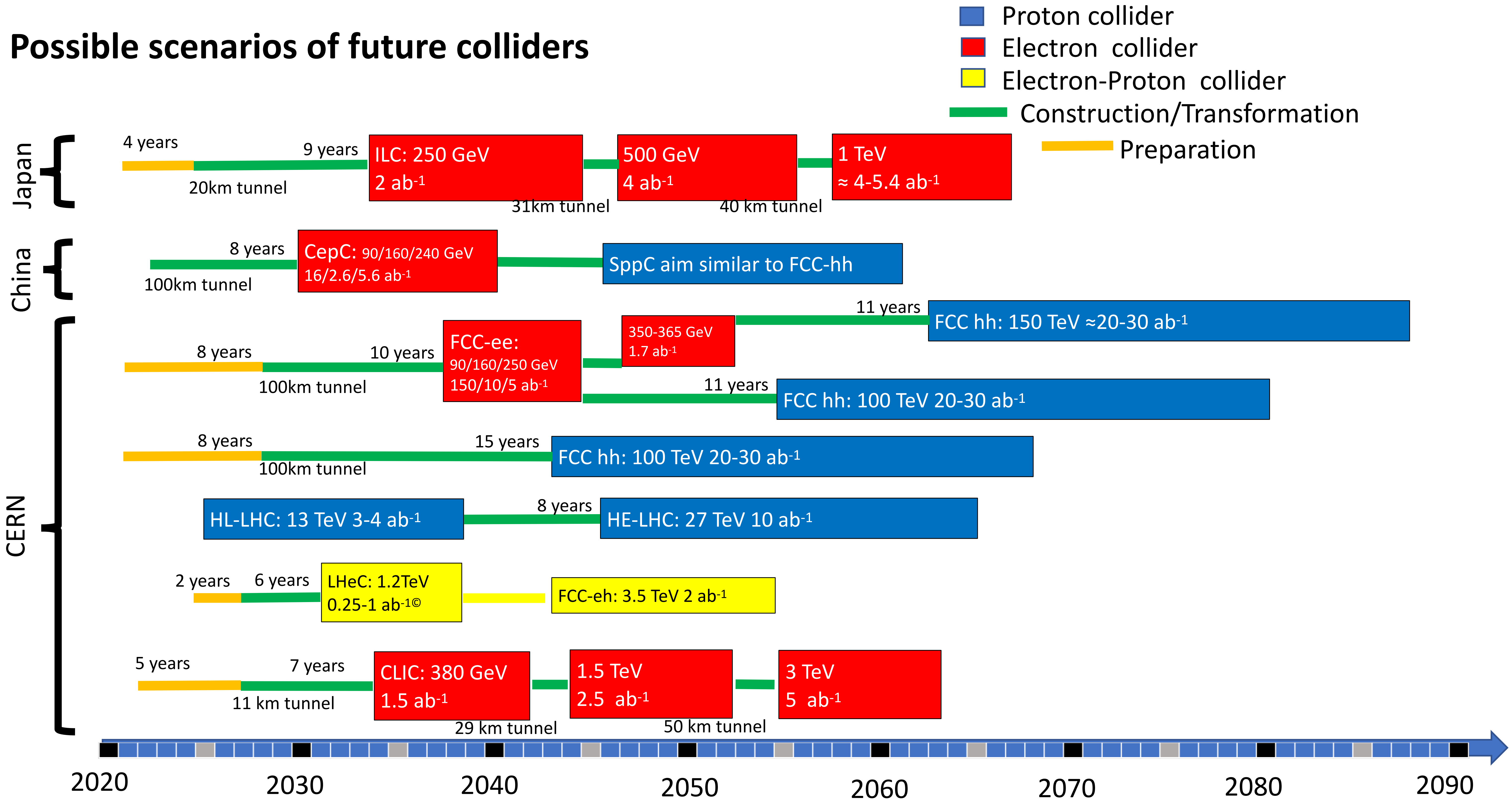
Subject to large uncertainty
1) need a scientific consensus
2) political approval

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

+ muon-collider + gamma-gamma collider + …

Future of HEP

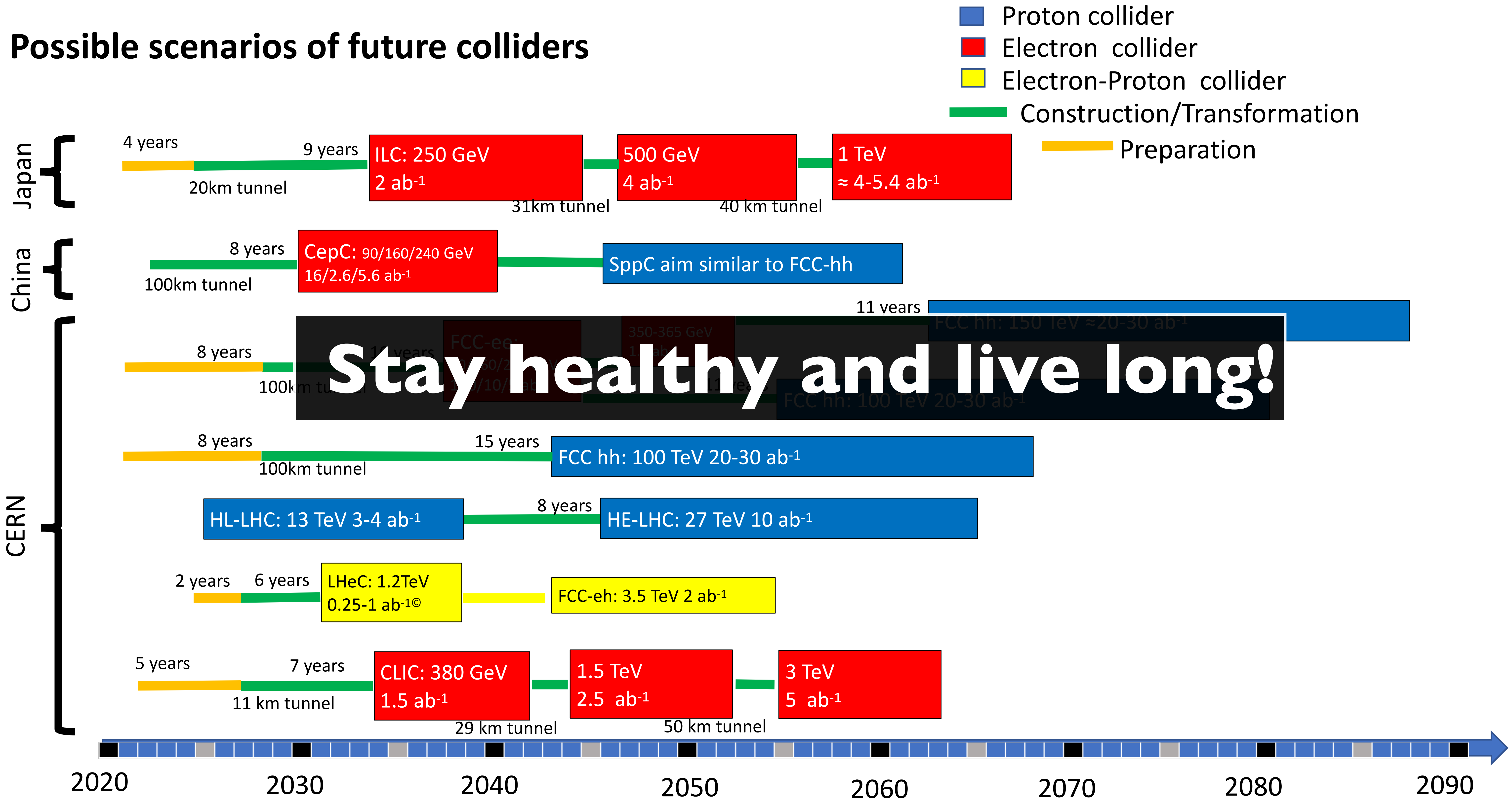
Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

Future of HEP

Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

The LHC Legacy (so far)

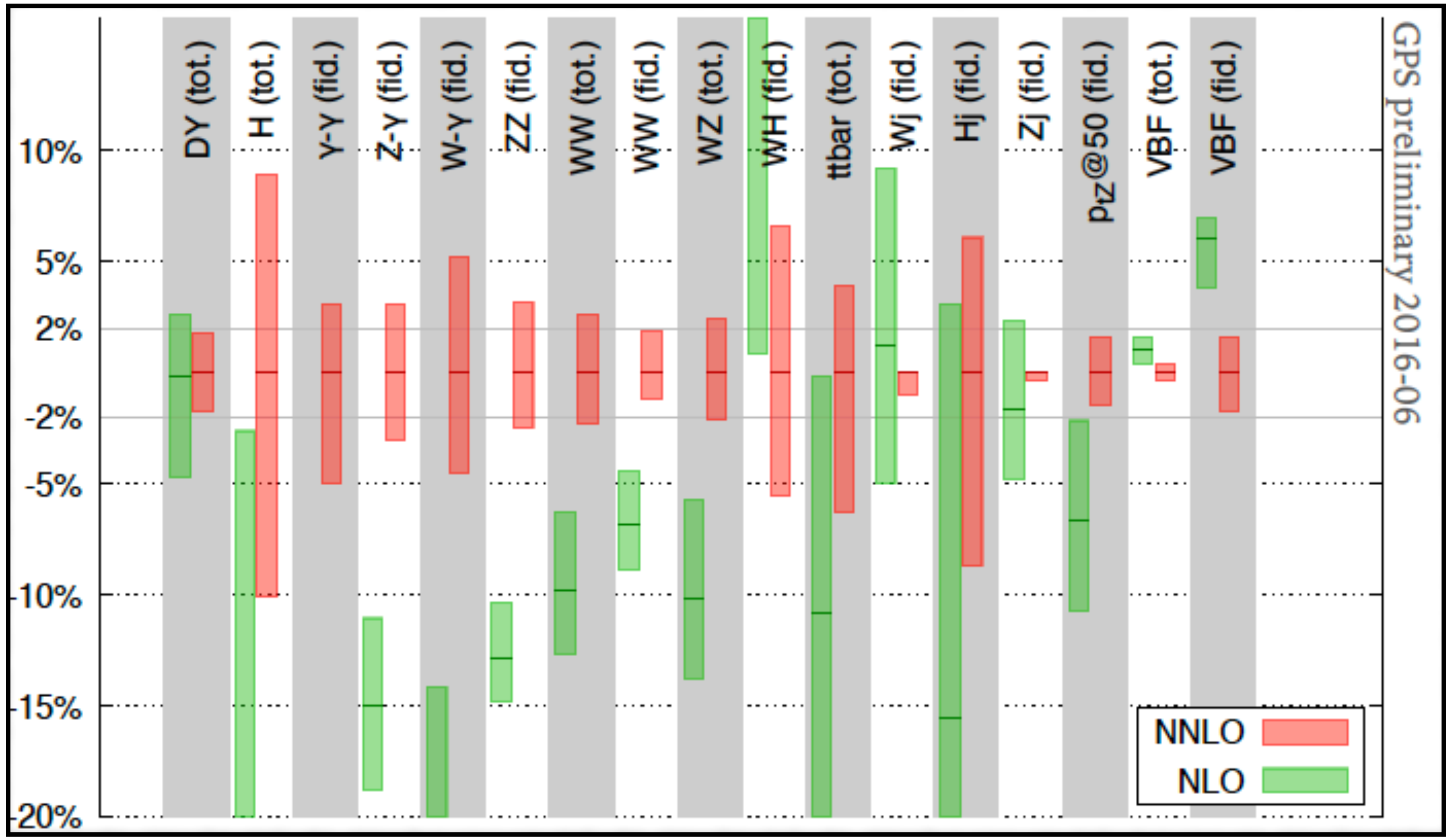
- **SM confirmed to high accuracy up to energies of several TeV**
- **Higgs boson discovered**
- **Absence of new physics** → { Traditional models are under siege; New approaches: relaxion, Nnaturalness, clockwork… }

The SM challenges

Statistical uncertainty will become less and less important ↔ Systematics wall will be faced

— So progress requires —

- Better control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
- Higher order theoretical computations, e.g. N…NLO
- Access to phase-space limited regions
- Understand correlations among different bins in diff. distributions



Don't think future HEP is only EXP-business. Theorists have to work harder too!

The QCD frontiers

- NNLO 2 → 3 processes, e.g.
  - Production of 3 vector bosons (VVV) [quartic couplings]
  - Higgs plus di-jet production [background to VBF Higgs production]
  - VBF W/Z production
  - Productions of 3 jets [strong coupling, PDFs, …]
- Internal masses ☀ Major result for HH (Borowska et al.'16, Baglio et al '18)
  - Higgs at large transverse momentum, currently described only at LO accuracy ☀ Lot of progress in the last 2 years (Lindert et al.)
  - Mixed QCD+EW corrections (short term: assess ambiguity in how they are combined; long term: compute genuine mixed corrections) ☀ Nice progress in the last 2 years (Bonetti et al.)
- NNLO production and decay, e.g.
  - NNLO top production and decay
- Off-shell effects/interferences
- Merging of NNLO to parton showers for complicated processes
- Improve logarithmic accuracy of parton showers

Zanderighi @ HL/HE-LHC kick-off '17

The e+e- Frontiers

The greatest challenges: (+ many more very demanding tasks)

- Z:
  - ◇ full EW 2-loop calculation for off-shell $\mathrm{e}^+\mathrm{e}^- \to f\bar{f}$ $+$ theoretically sound concept of pseudo-obervables
  - ◇ massive 3-loop calculations for $1 \to 2$ decays and μ decay
- WW:
  - ◇ NNLO threshold EFT calculation for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW}$
- Higgs:
  - ◇ full EW 2-loop calculation for off-shell $\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZH}$
  - ◇ massless 4-/5-loop QCD calculations for $1 \to 2$ decays

$\hookrightarrow$ Certainly takes another generation of bright minds!

Dittmaier @ ESU Granada '19

Which Higgs couplings?

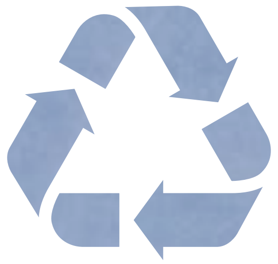
Within the SM, all the Higgs couplings are uniquely fixed by known quantities
(G_F, m_W, m_Z, m_{quark}, m_{lepton})

This is a **curse** (nothing more to learn) and a **blessing** (can asses the inconsistency of the SM)

M. Mangano

Two approaches to go BSM

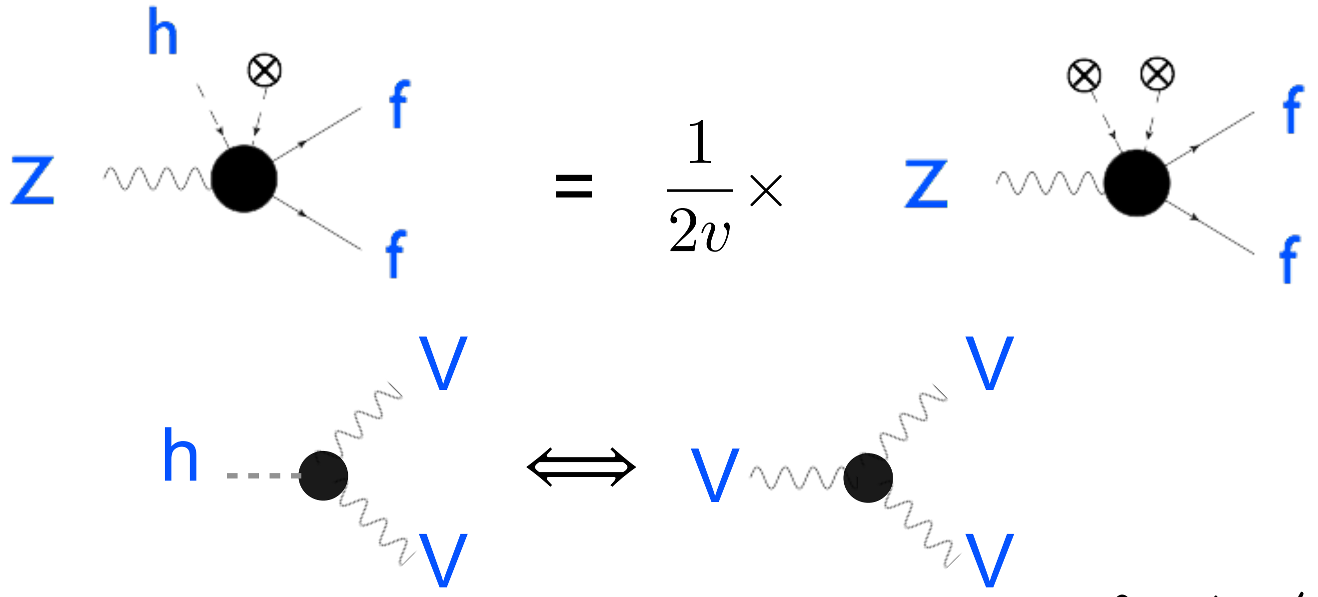
Study
specific models



Try to introduce
continuous deformations of the SM

Higgs & the rest of the world

Assuming h is part of
a SU(2) doublet



At LHC: EW/VV precision strong enough not
to interfere with Higgs measurements
(at least if Higgs part of EW doublet)

Not necessarily true at future colliders
Need a more global strategy

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)
- Doesn't require BSM theoretical computations
- Could still be valid even with light new physics, i.e. exotic decays
- Captures leading effects of UV motivated scenarios (SUSY, composite)

$$g_{hXX} = \kappa_X \, g_{hXX}^{\rm SM}$$

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?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d,i} \frac{c_i \, \mathcal{O}_d^i}{\Lambda^{d-4}}$$

Results of kappa-2 fit

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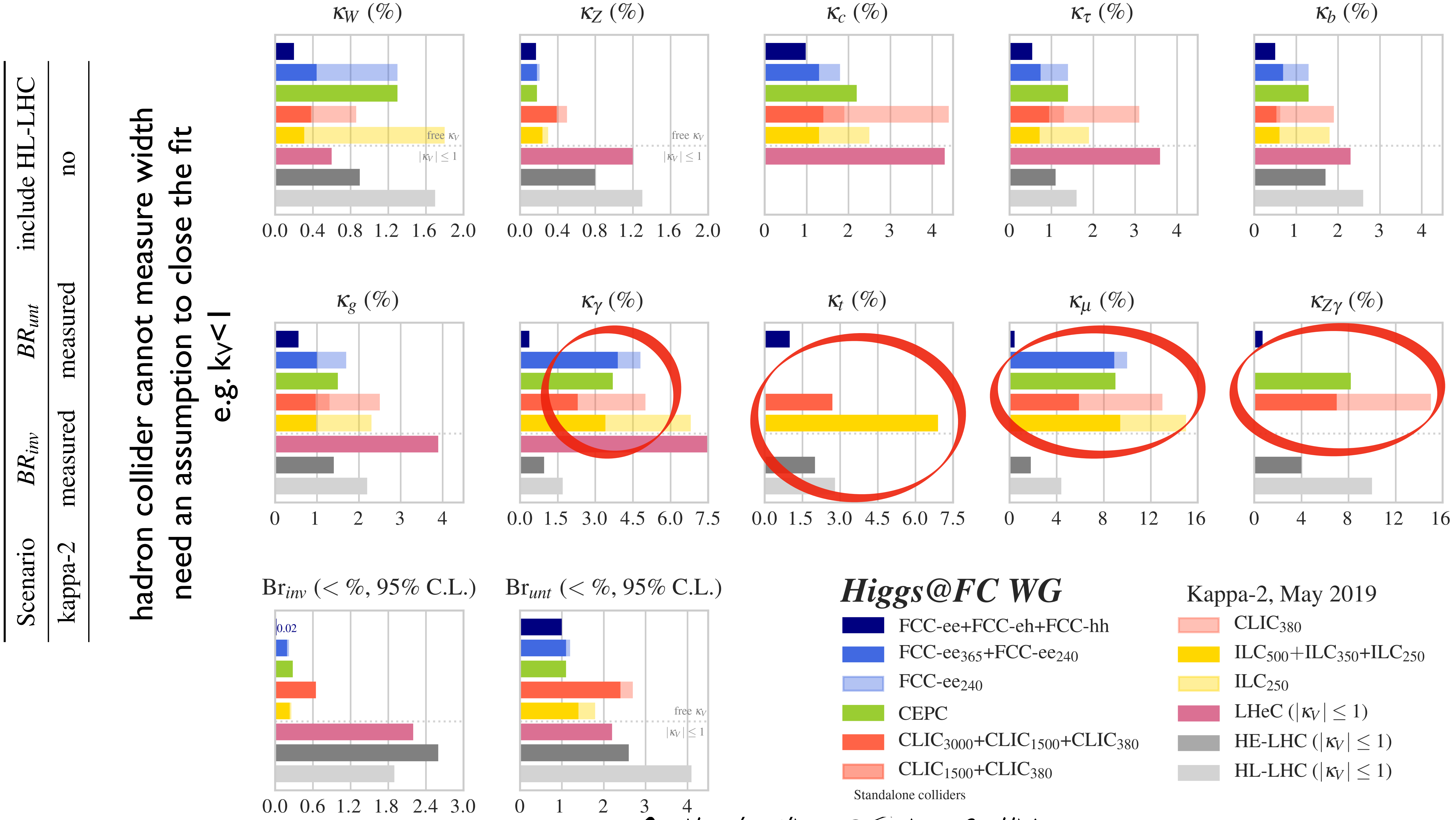
hadron collider cannot measure width
need an assumption to close the fit
e.g. $\kappa_V<1$



Results of kappa-3 fit

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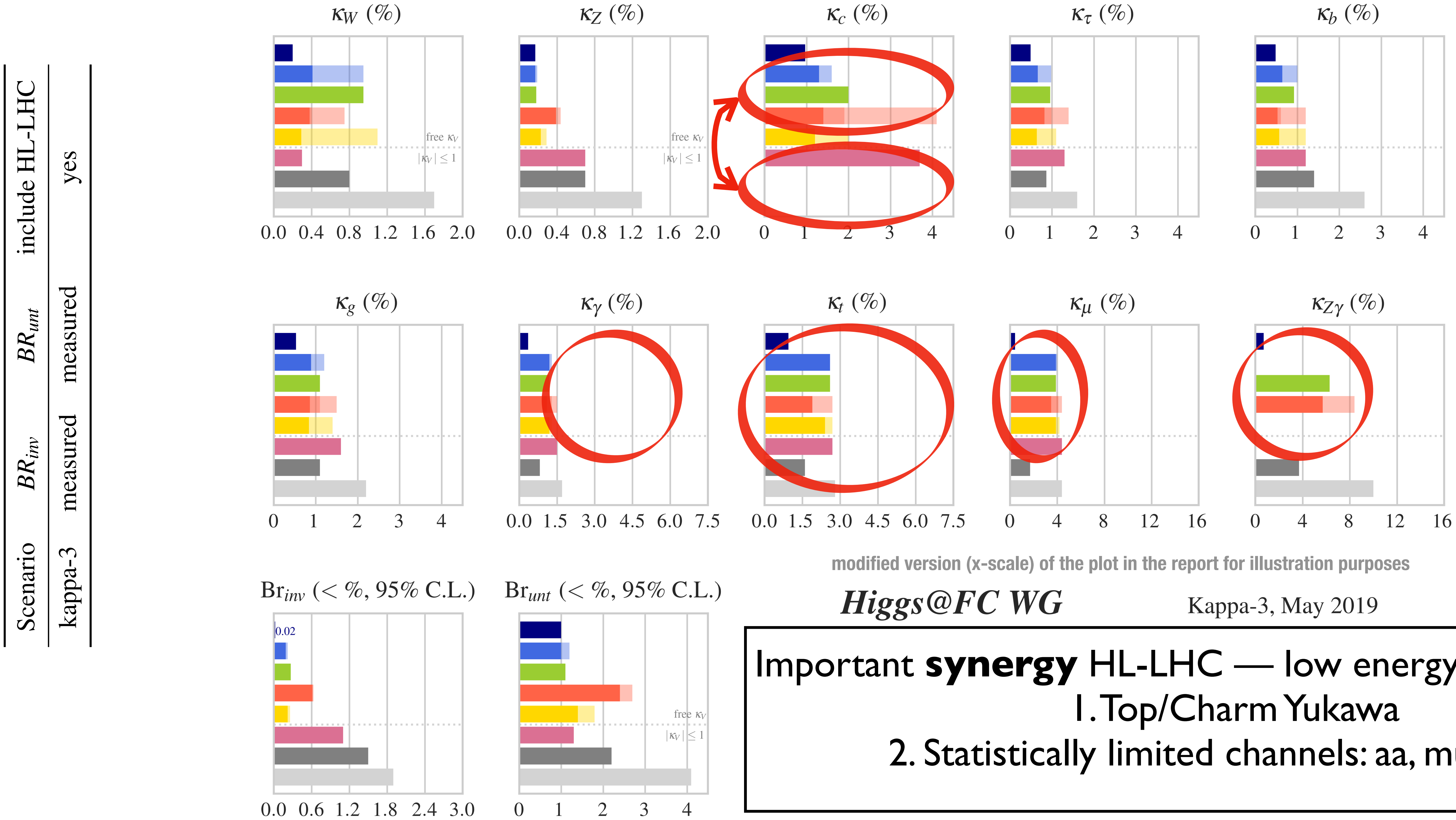


modified version (x-scale) of the plot in the report for illustration purposes

Higgs@FC WG Kappa-3, May 2019

Important **synergy** HL-LHC — low energy lepton colliders
1. Top/Charm Yukawa
2. Statistically limited channels: aa, mumu, Za

Experimental Inputs

A circular ee Higgs factory starts as a Z/EW factory (**TeraZ**)

A linear ee Higgs factory operating above Z-pole can also preform EW measurements via **Z-radiative** return

A linear ee Higgs factory could also operate on the Z-pole though at lower lumi (**GigaZ**)

	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	-

EFT and Higgs couplings

EFT fits can be performed in different bases (difficult to compare results among different analyses) and seldom the meaning on the sensitivity on the various Wilson coefficients is transparent

— Practical approach —

perform the fit in any basis you like and project the results on **effective/pseudo couplings**

(need a special care for top coupling and self-coupling)

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

Similar definition as κ modifiers, but different interpretation, e.g.

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

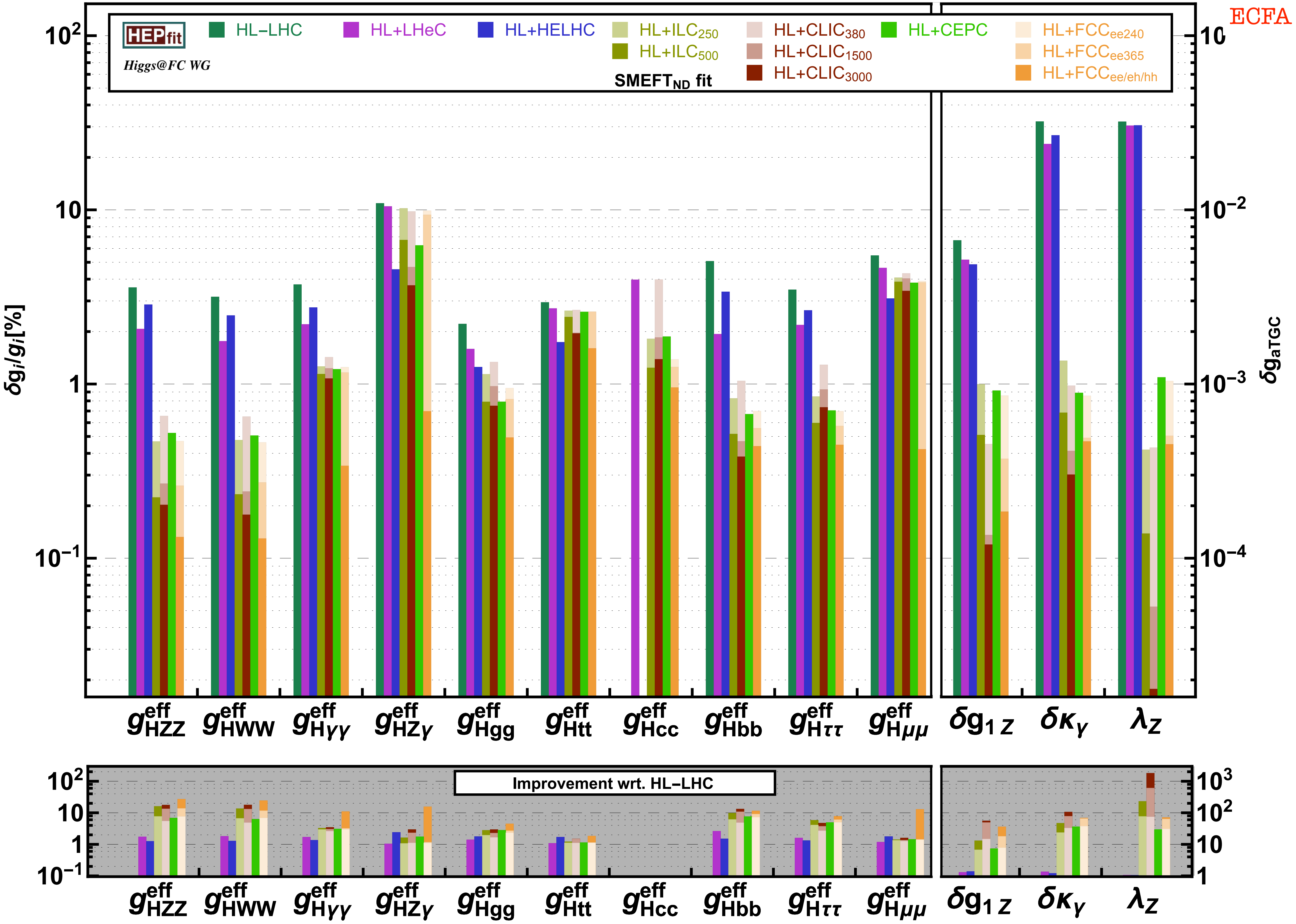
Only these are described in κ-framework

Not enough to match EFT d.o.f : Add also aTGC

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

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

Global EFT fit



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There is life beyond HL-LHC

Figures of Merit with Respects to HL-LHC

M. Cepeda for Higgs@FC WG

Factor of improvement in different channels viz. HL-LHC

	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
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	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}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	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 (⋆) not measured at HL-LHC

Colour scale: 0, 2, 4, 5, 6, 8, 10

Stat. limited → $g^{eff}_{H\gamma\gamma}$, $g^{eff}_{HZ\gamma}$, $g^{eff}_{H\mu\mu}$

Top quark channels (LHC is a top factory and it is not so easy to outperform) → g^{eff}_{Hgg}, g^{eff}_{Htt}

5 — If no deviation seen at HL-LHC 5σ discovery still possible at Future Collider

Possible at all colliders (often in their initial stage) and in most of the channels with a few exceptions

Theoretical Uncertainties

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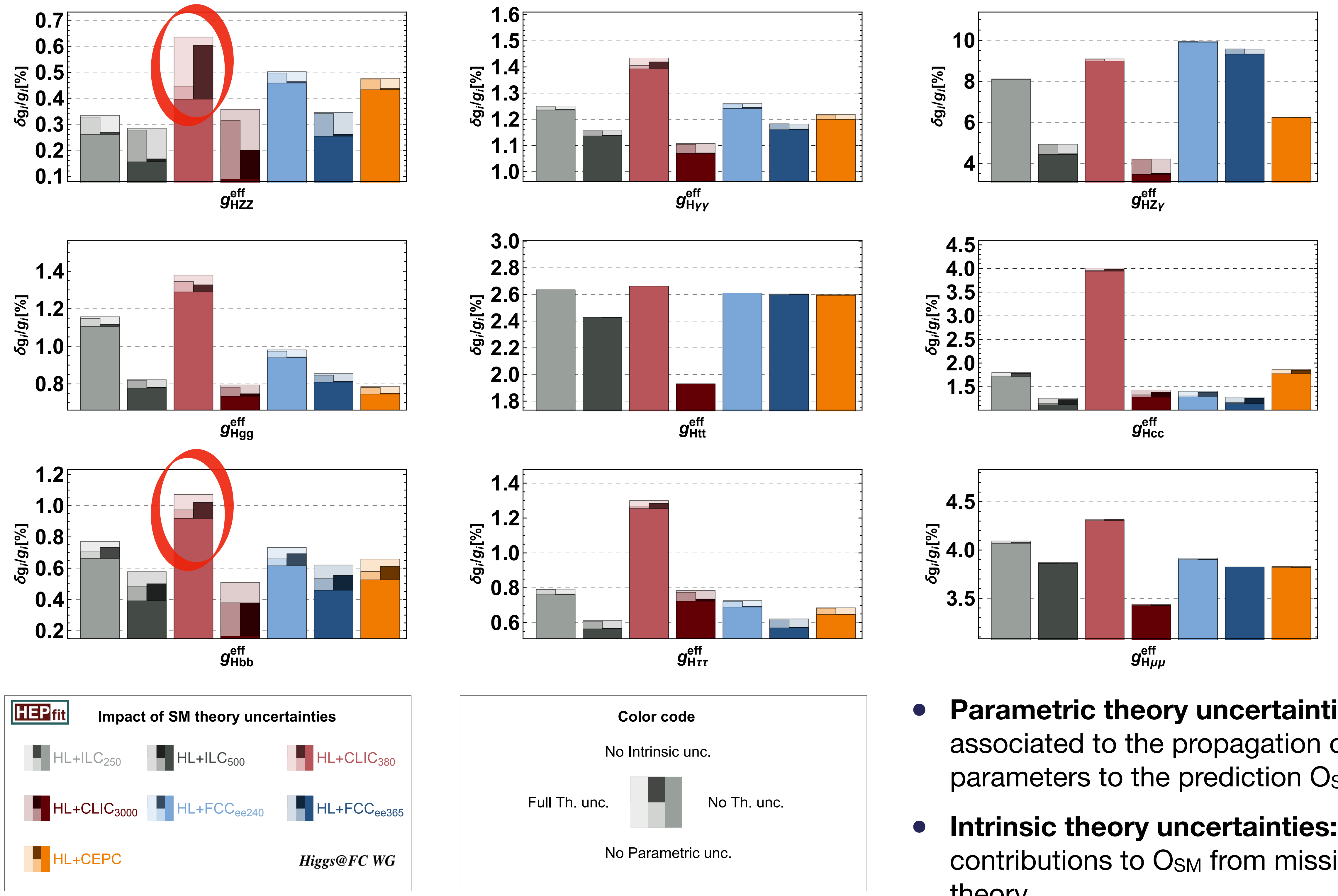

Theorists can do better in few channels (hZZ, hbb…)

- **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.

Theoretical Uncertainties

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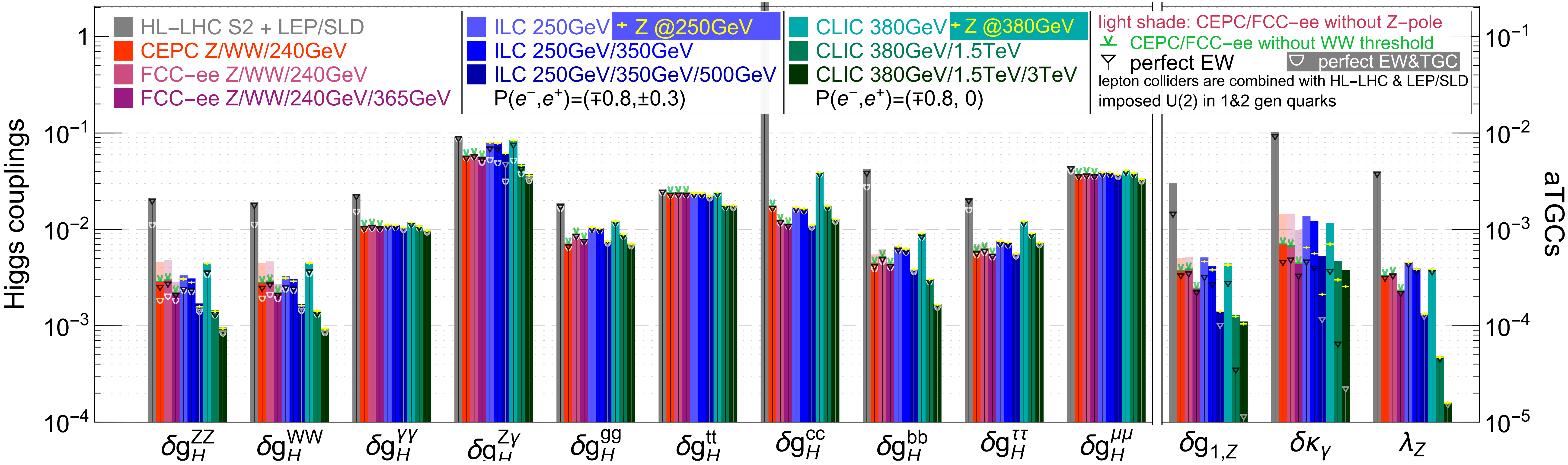
More theory work needed to match EXP uncertainties

	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

Impact of Z-pole measurements

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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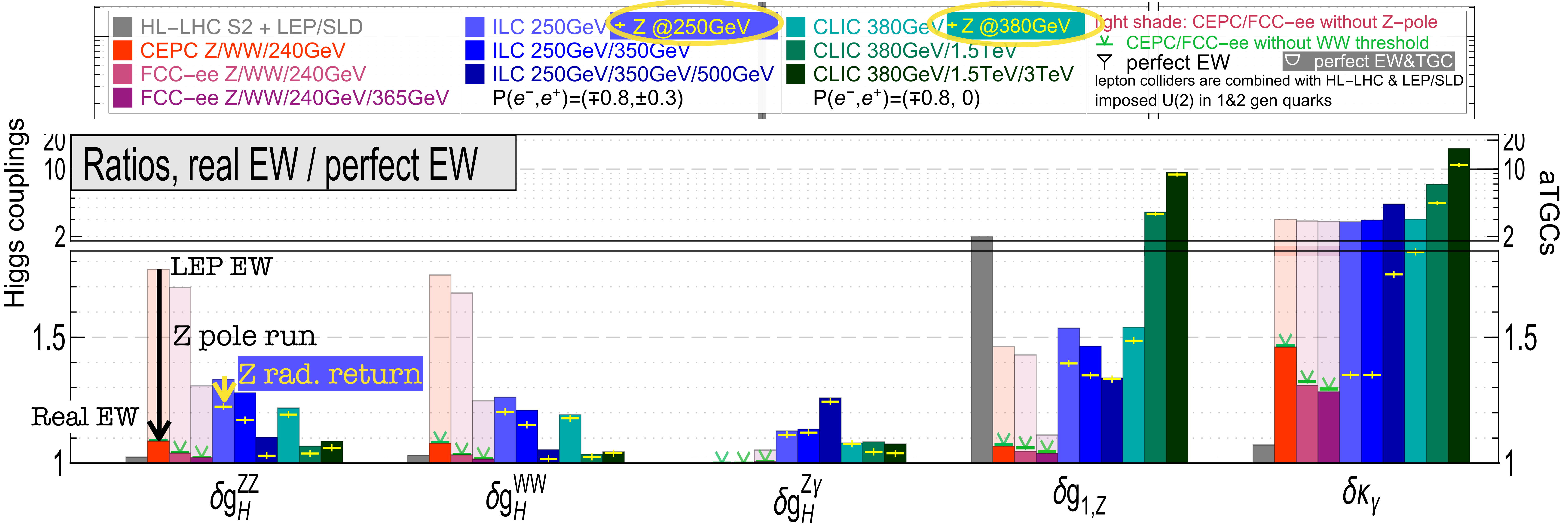

- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via Z-radiative return) help mitigating this issue

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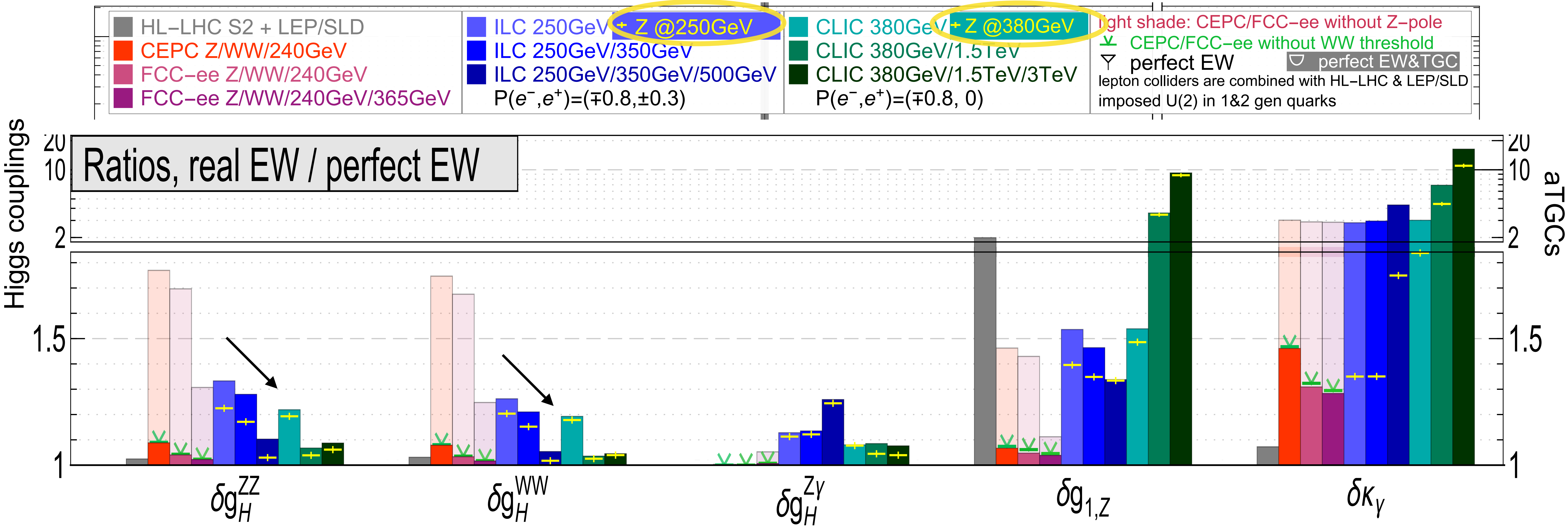

- Higher energy runs reduce the EW contamination in Higgs coupling extraction

Impact of Z-pole measurements

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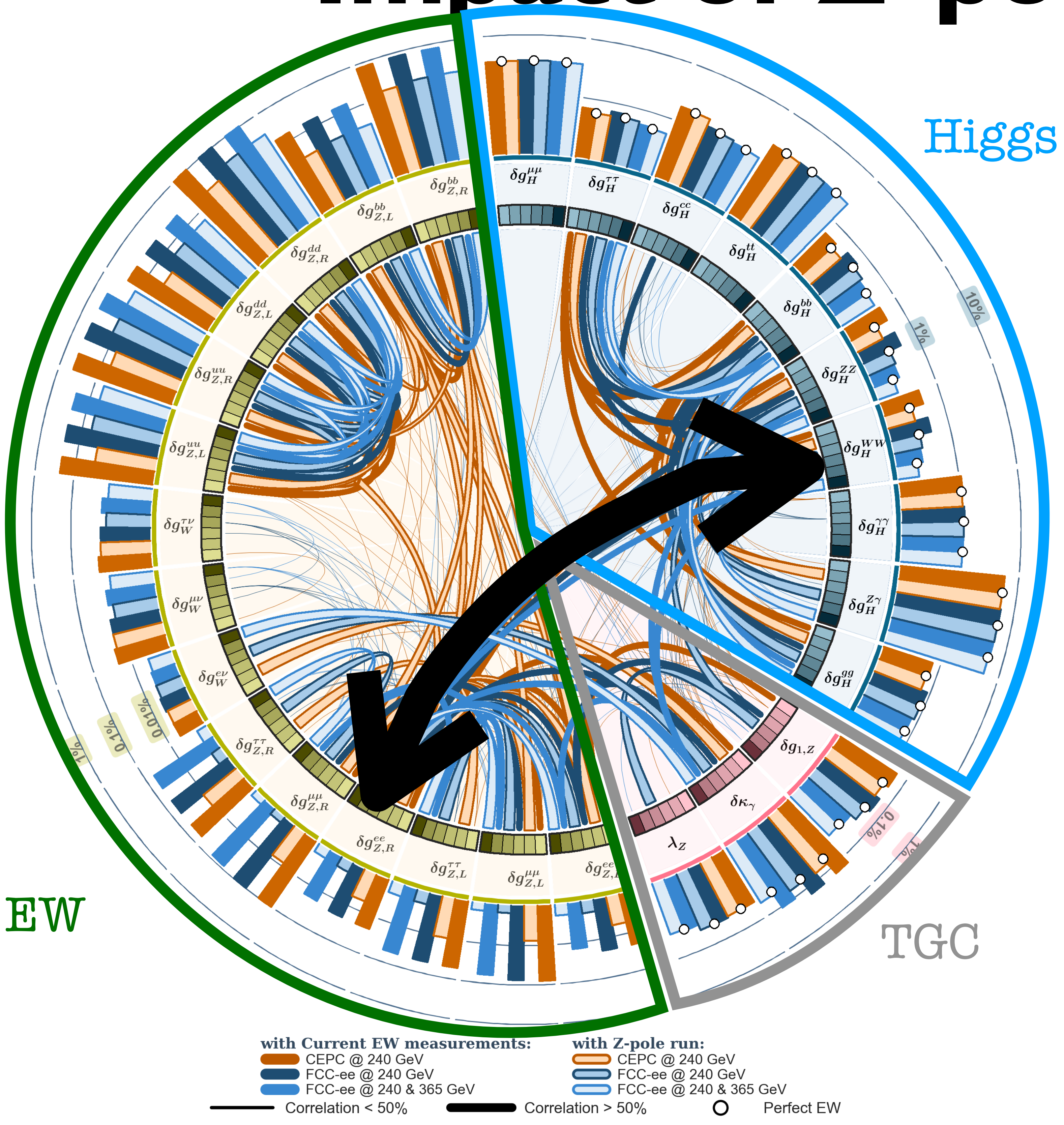

Contamination EW/TGC/Higgs can be understood by looking at correlations

Without Z-pole runs, there are large correlations between EW and Higgs

Impact of Z-pole measurements

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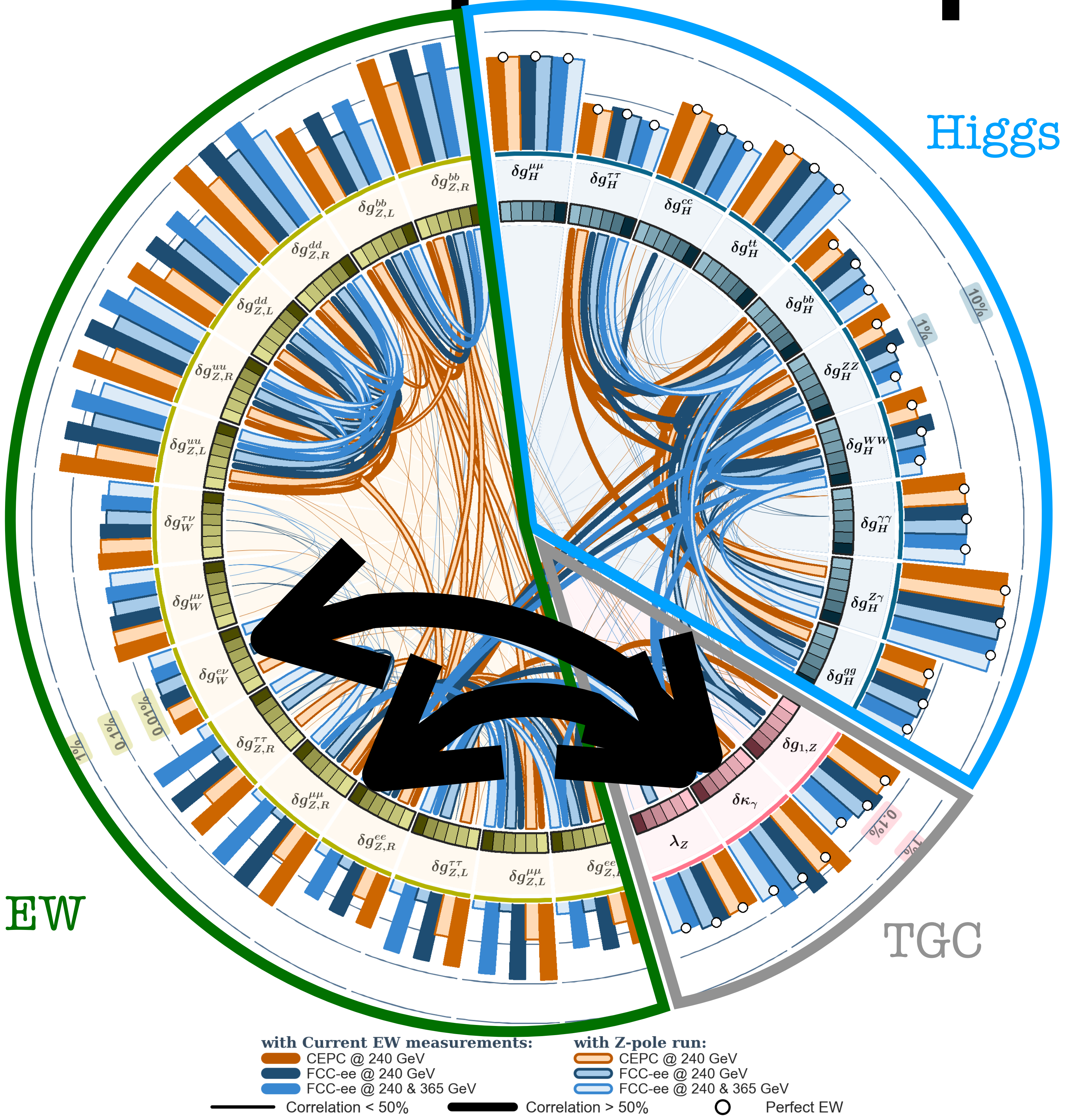

Contamination EW/TGC/Higgs can be understood by looking at correlations

With Z-pole runs, only correlations between EW and TGC remain

Impact of Z-pole measurements

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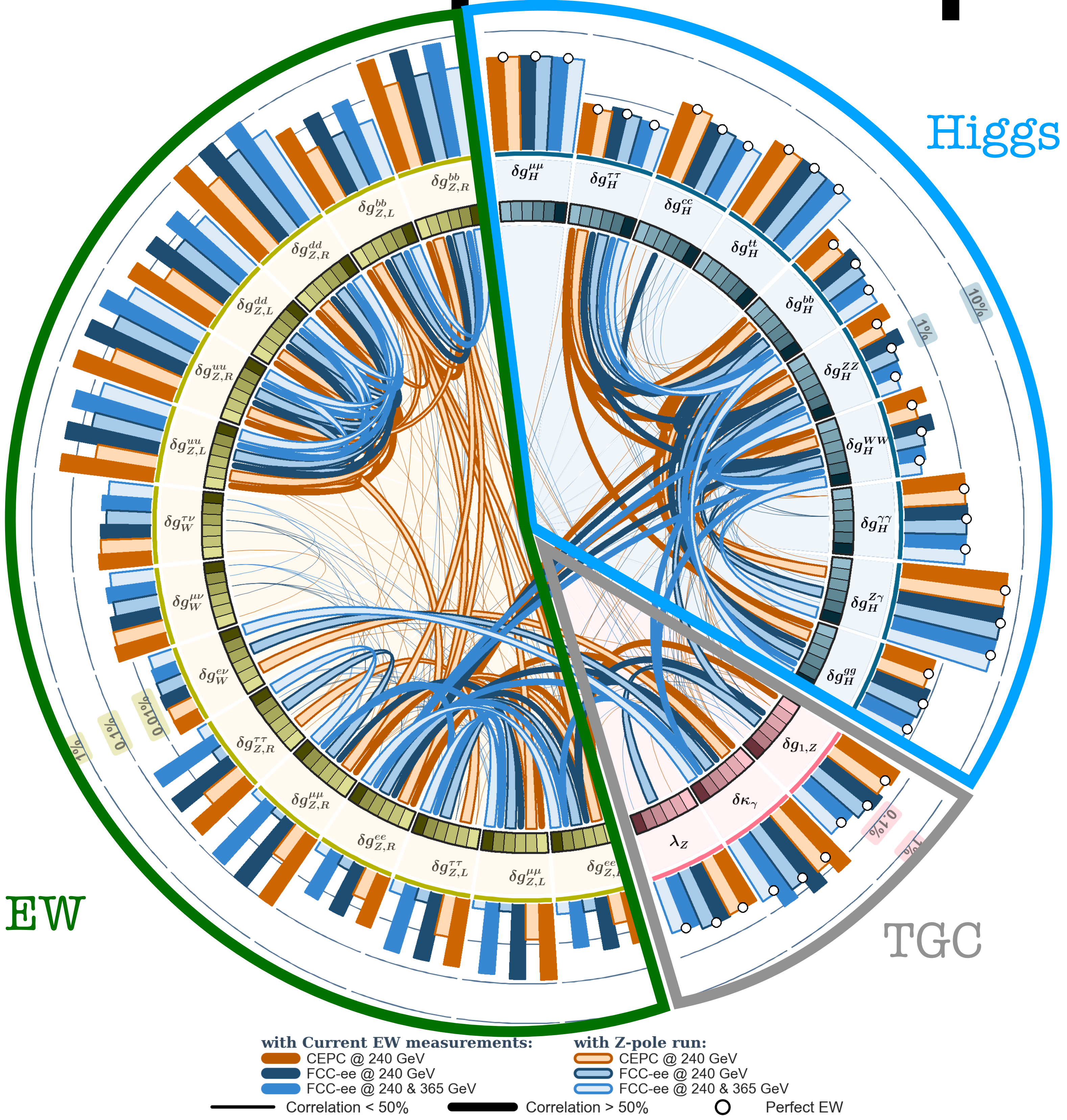
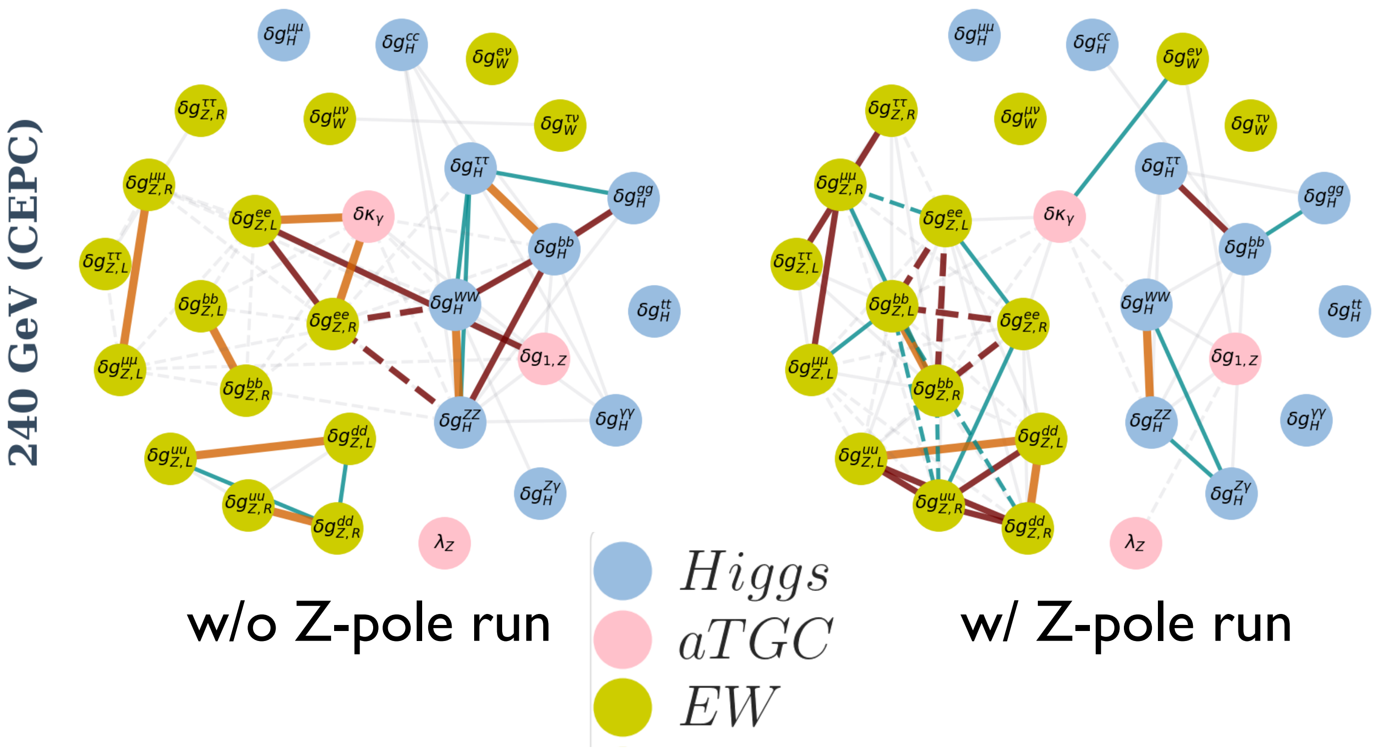


Contamination EW/TGC/Higgs can be understood by looking at correlations

Z-pole runs at circular colliders isolate EW and Higgs sectors from each others



Impact of Beam Polarisation

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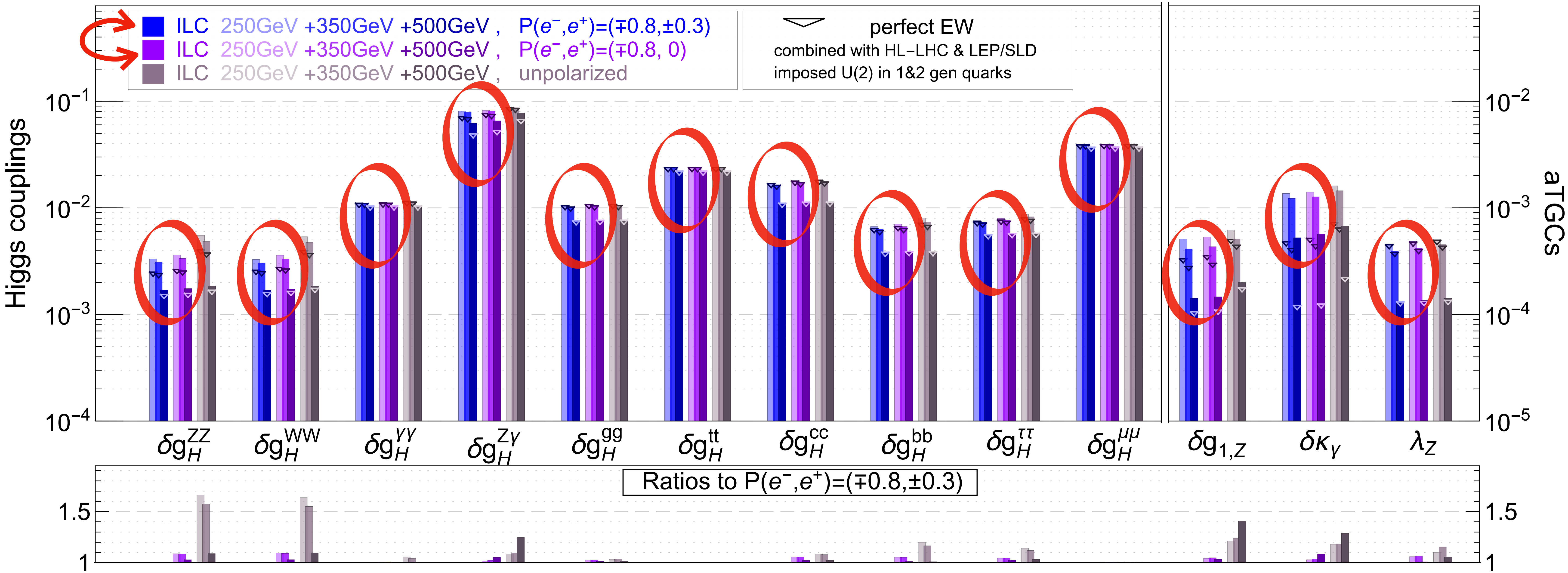

- Positron polarisation doesn't play a big role (for Higgs couplings determination)

Impact of Beam Polarisation

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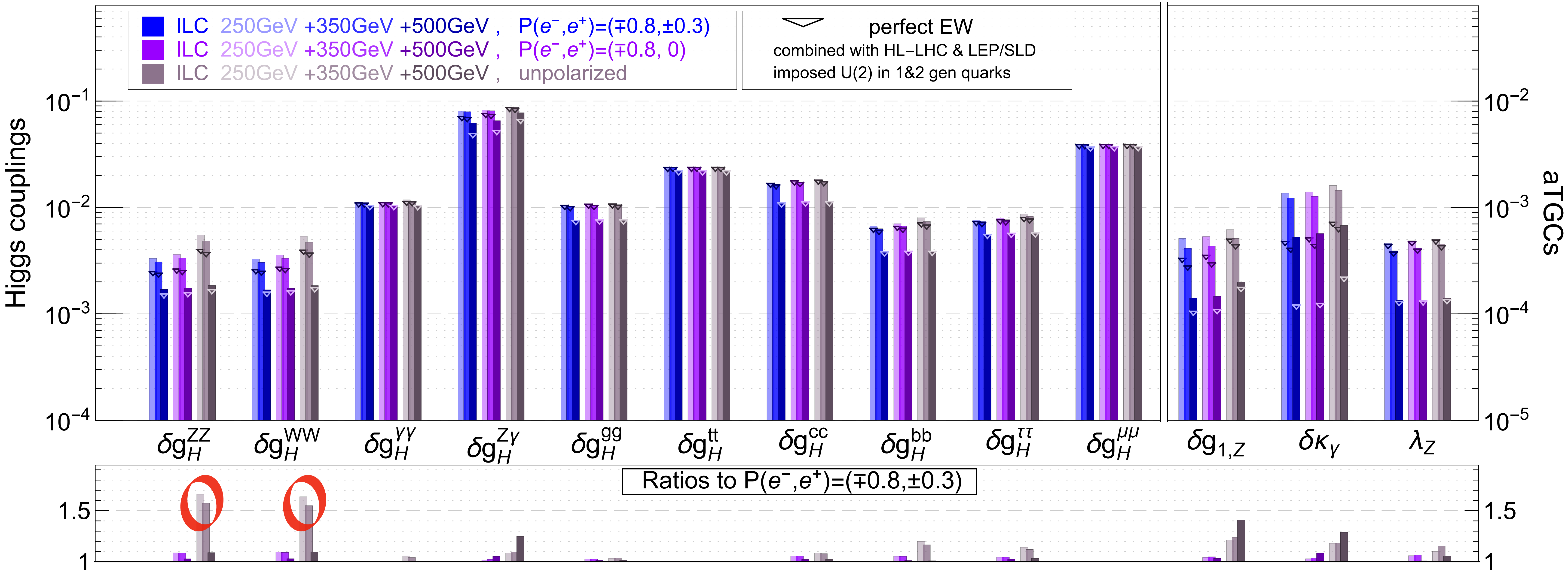
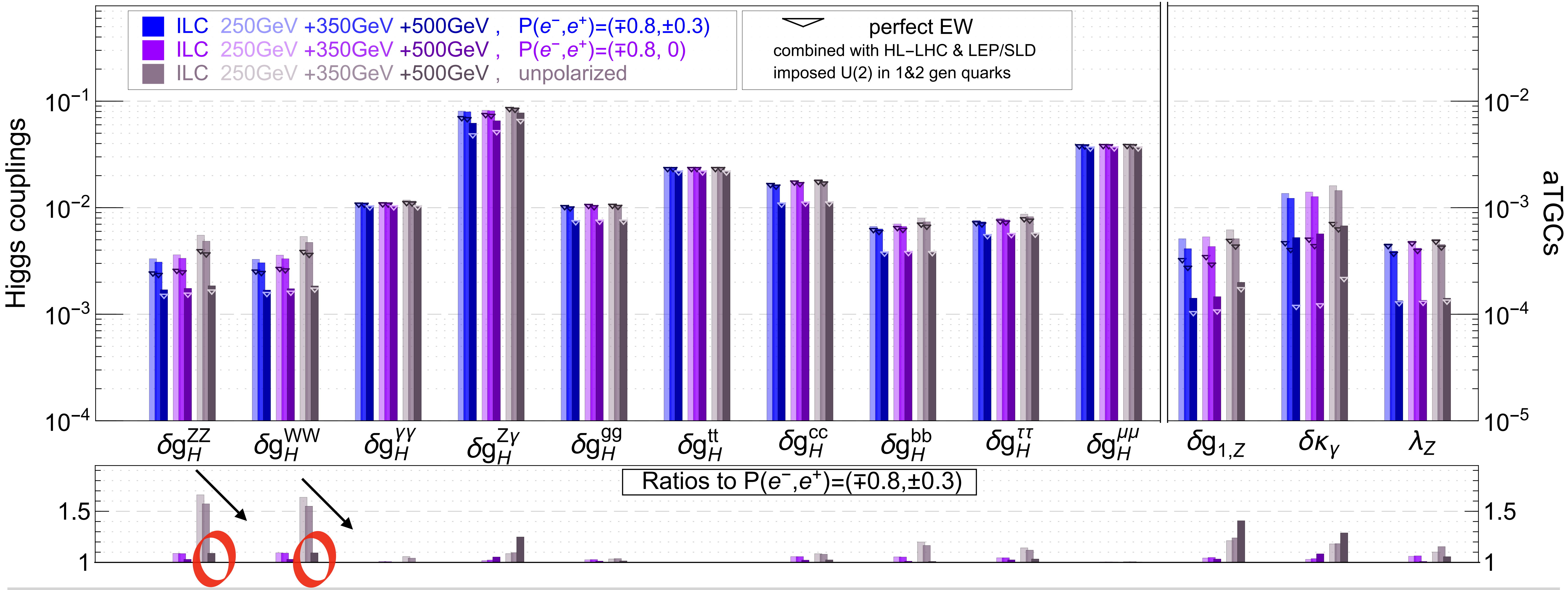


- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination

Impact of Beam Polarisation

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- Positron polarisation doesn't play a big role (for Higgs couplings determination)
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- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added

Impact of Beam Polarisation (@250GeV)

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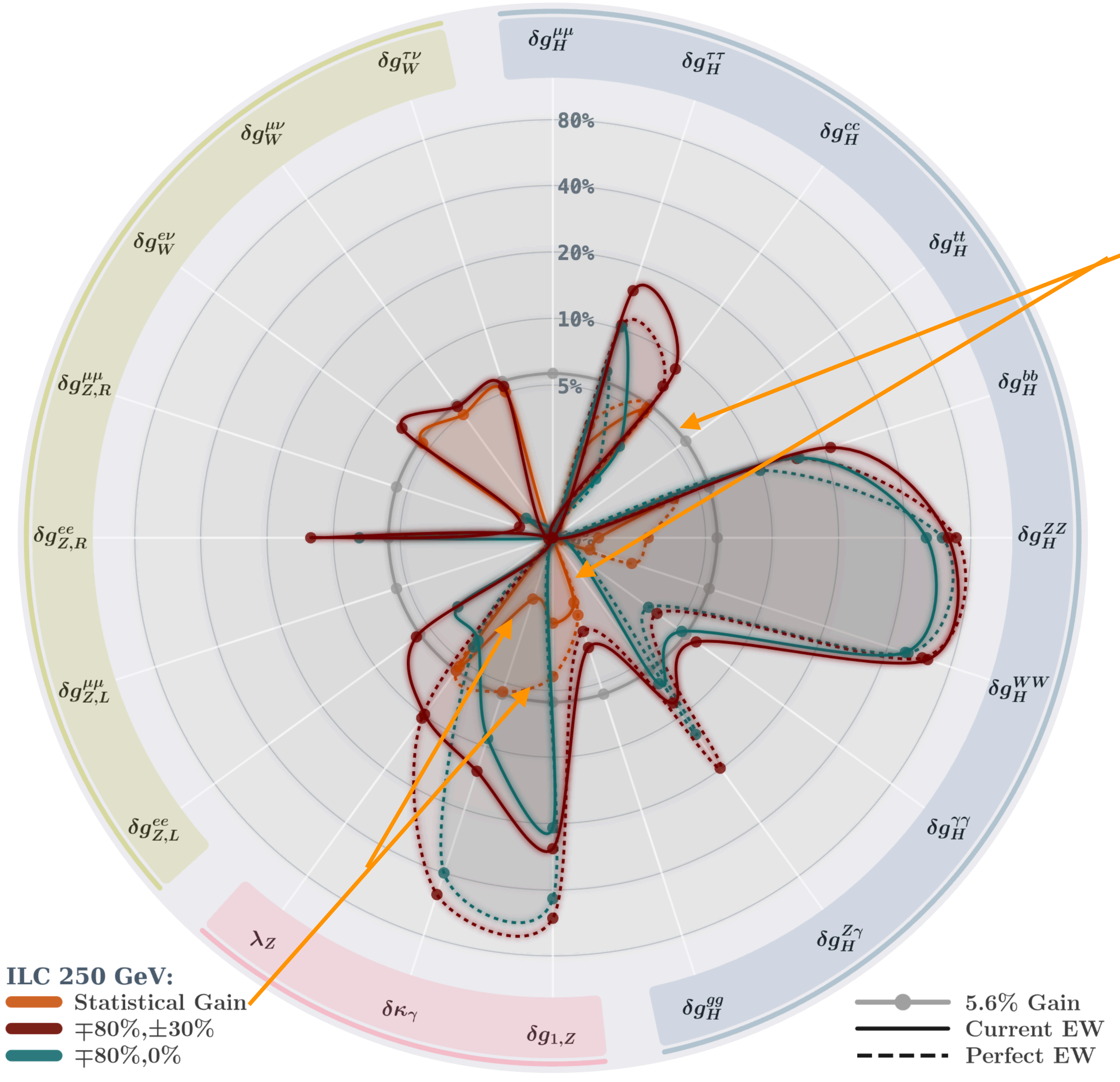

Statistical gain from increased rates

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

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

overall, one could expect
O(6%) increased coupling sensitivity

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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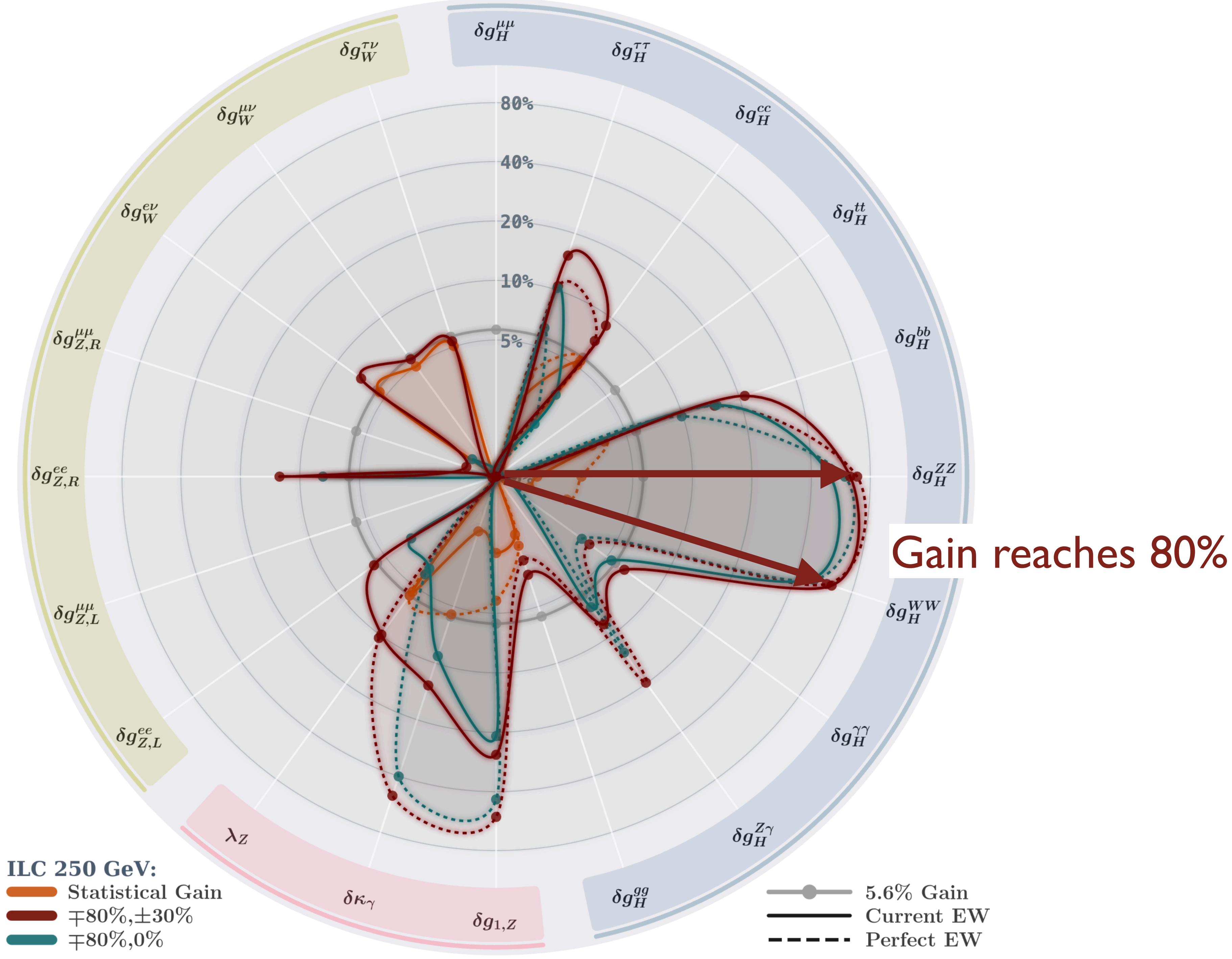

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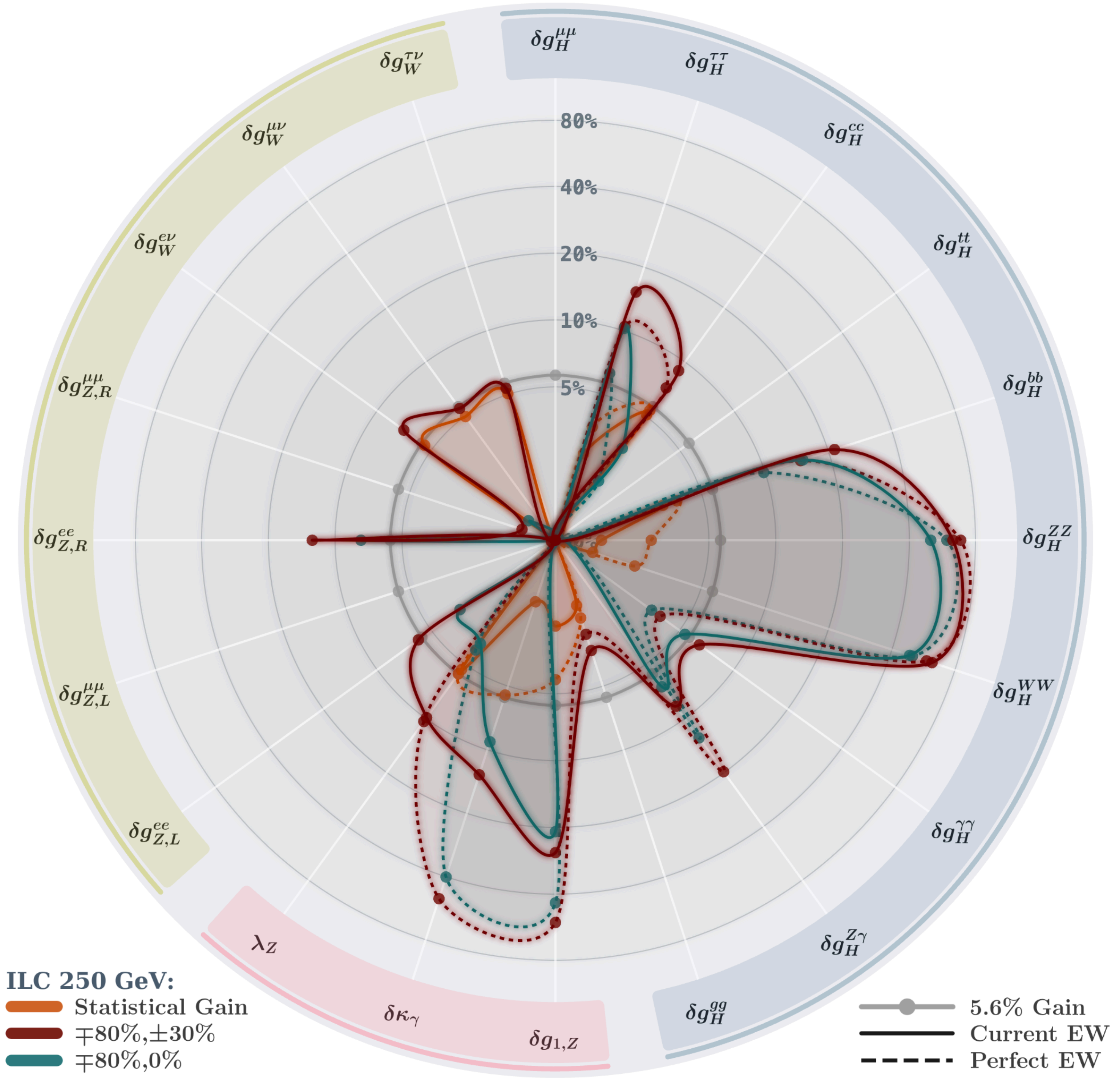

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overall, one could expect
O(6%) increased coupling sensitivity

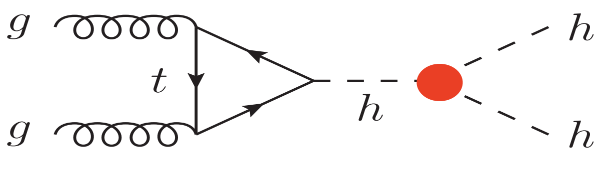
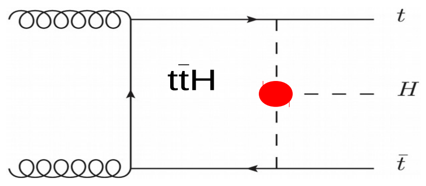
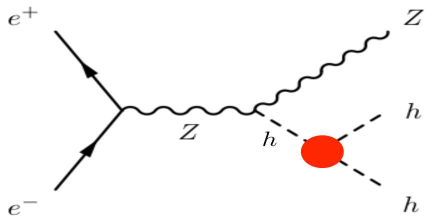
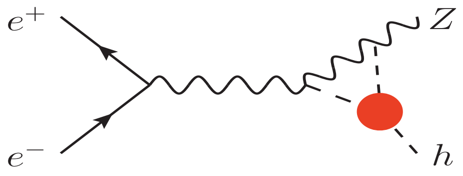
Gain is much higher in global EFT fit
since polarisation removes
degeneracies among operators

Polarisation benefit diminishes when other runs
at higher energies are added
Basically left only with statistical gain

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?
Do you need to reach HH production threshold to constrain h^3 coupling?

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

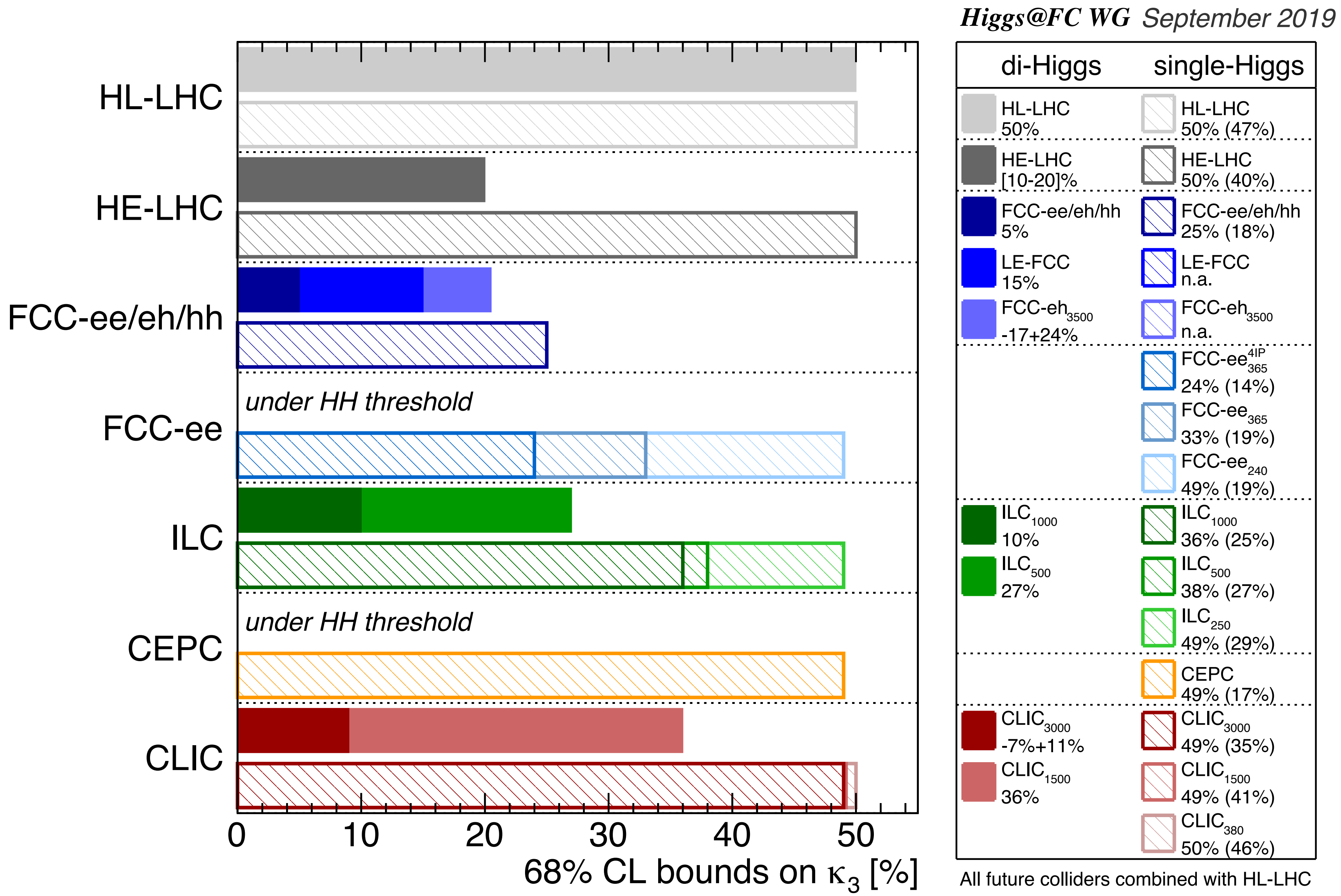
ECFA Higgs study group '19

	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

See also talks by G. Heinrich, S. Glaus, E. Vryonidou

Higgs Self-Coupling

ECFA Higgs study group '19



ee: Indirect ~34%

hh: Direct ~5-10%

Little indirect reach w/o 365 GeV run

Direct ~10%

Direct ~27%

Assuming upgrade to 500 GeV

50% sensitivity: establish that $h^3 \neq 0$ at 95%CL

20% sensitivity: 5σ discovery of the SM h^3 coupling

5% sensitivity: getting sensitive to quantum corrections to Higgs potential

h^3 and GW

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\ T = 100\ \text{GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}}\frac{T^2}{M_{Pl}} \sim 10^{-15}\ \text{GeV}$$

redshifted freq.

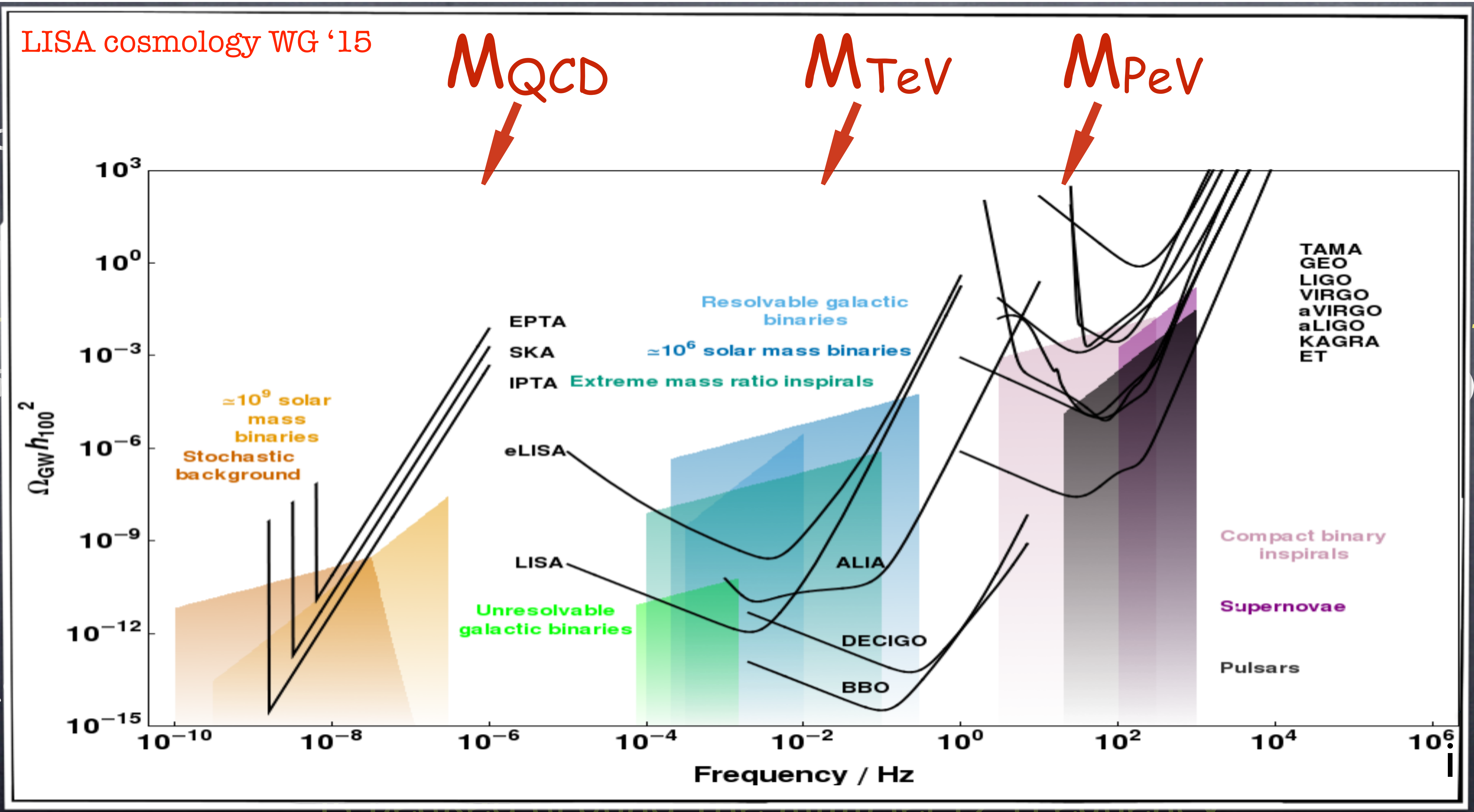
~ today ~

$$f \sim \# \frac{2 \cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\, 10^{-15}\ \text{GeV} \sim \# \, 10^{-5}\ \text{Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

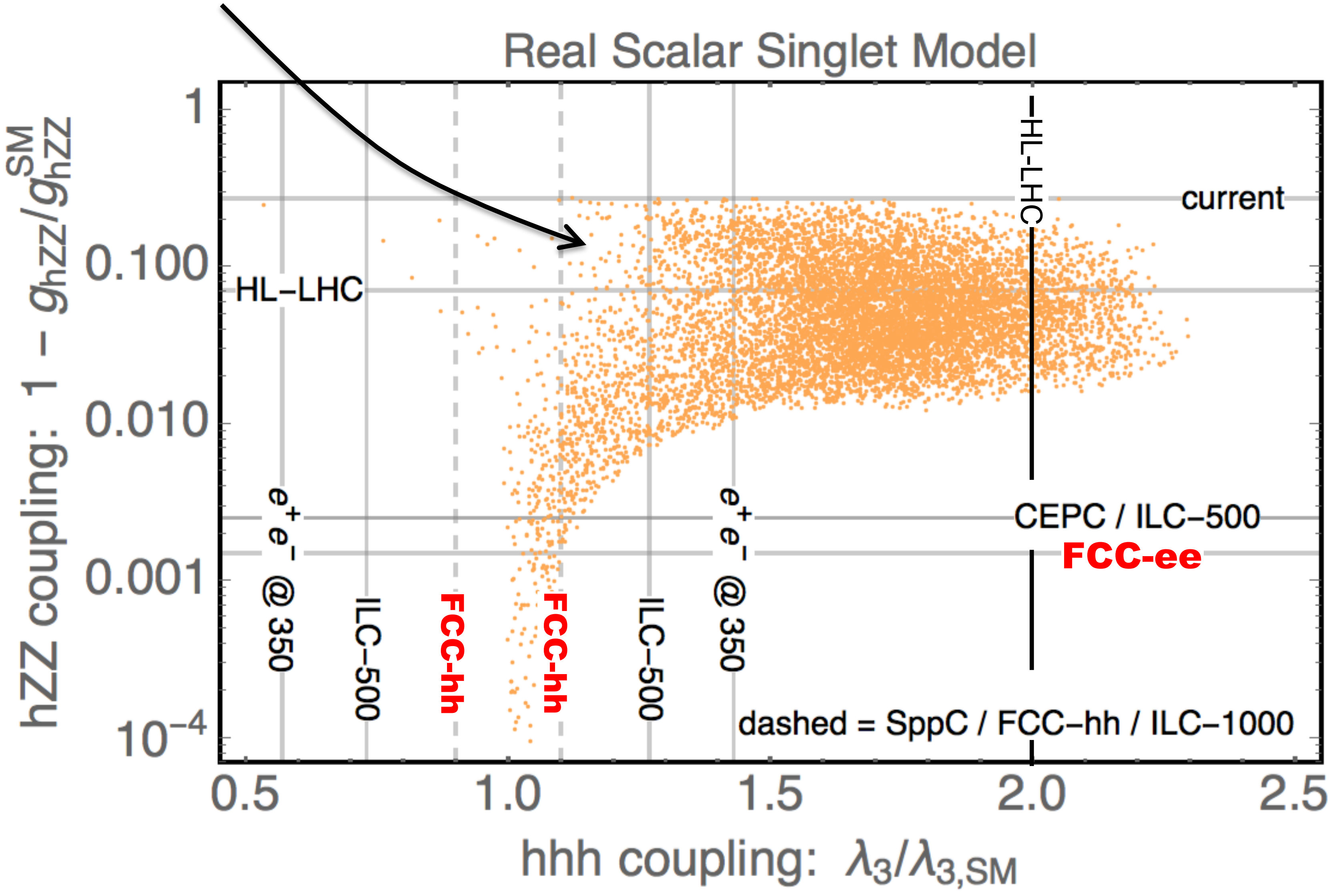
h³ and GW



Grojean, Servant '06

Window to early universe complementary GW - Colliders

EWPT is 1st order giving rise to GW stochastic background



See also talks by S. Kanemura

Huang, Long, Wang '16

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 (EW phase transition, naturalness…)

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

(different levels of detail, simulation and analysis maturity)

Don't Higgsxit!
Build a new collider!

Conclusions

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

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Higgscouplings whose sensitivity improves by 2/5/10 compared to HL-LHC

		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

B. Heinemann for Higgs@FC WG

Banker accounting:
Very important to get money

Specific BSM models will care maybe even more about correlations

Nobody knows what BSM is!
So impossible to compute the figure of merit.

Mainly Based upon

arXiv:1905.03764v1 [hep-ph] 9 May 2019

Higgs Boson studies at future particle colliders

- Preliminary Version -

J. de Blas[1,2], M. Cepeda[3], J. D'Hondt[4], R. K. Ellis[5], C. Grojean[6,7], B. Heinemann[6,8], F. Maltoni[9,10], A. Nisati[11,*], E. Petit[12], R. Rattazzi[13], and W. Verkerke[14]

arXiv:1907.04311v1 [hep-ph] 9 Jul 2019

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

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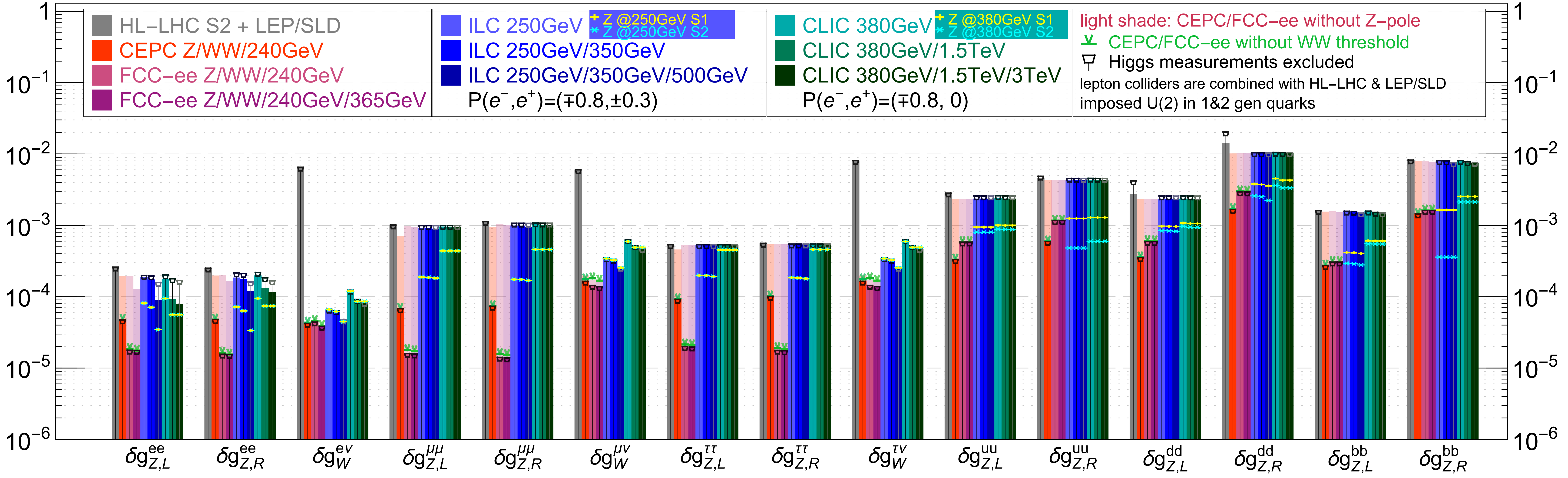
Jorge de Blas,[a,b] Gauthier Durieux,[c,d] Christophe Grojean,[c,e] Jiayin Gu,[f] and Ayan Paul[c,e]

And many discussions with colleagues from CEPC, CLIC, FCC, ILC…

EXTRA RESULTS

Sensitivity on EW couplings

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



Sensitivity on EW couplings

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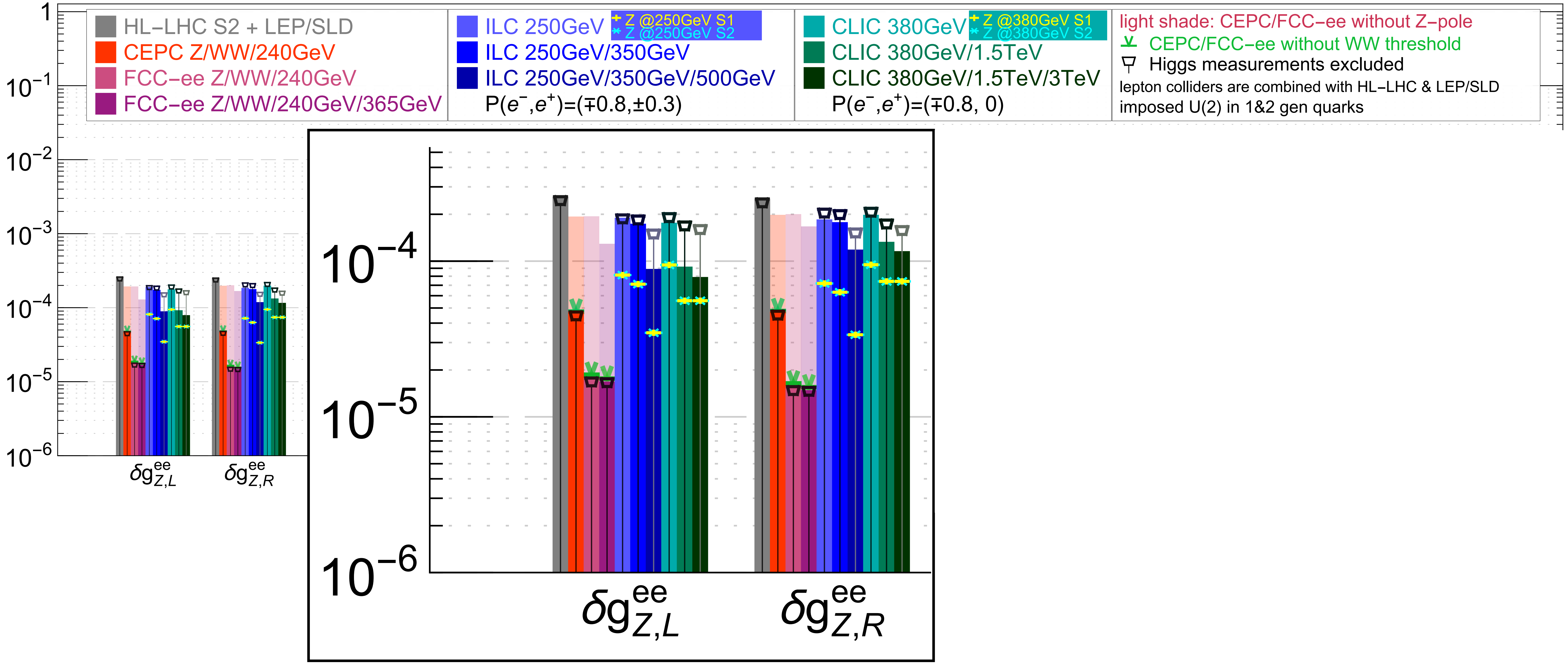

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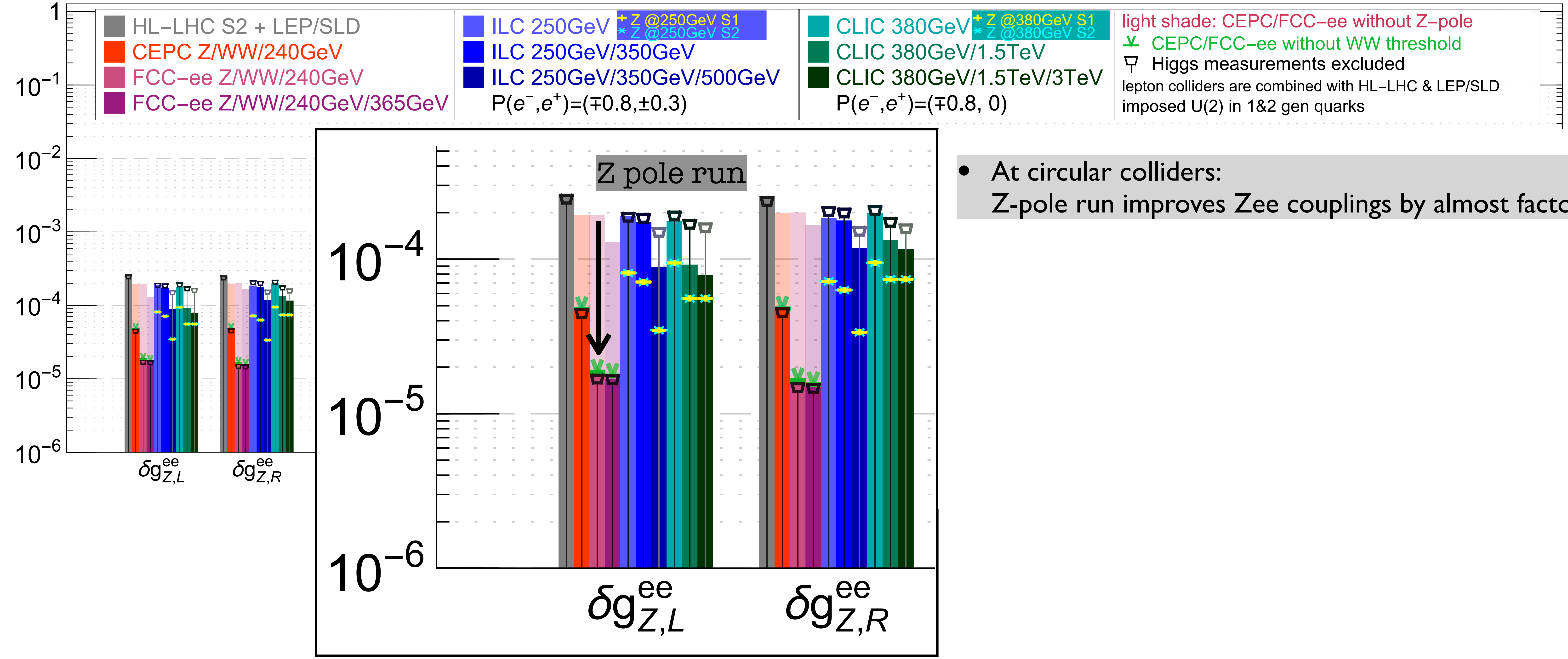

- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10

Sensitivity on EW couplings

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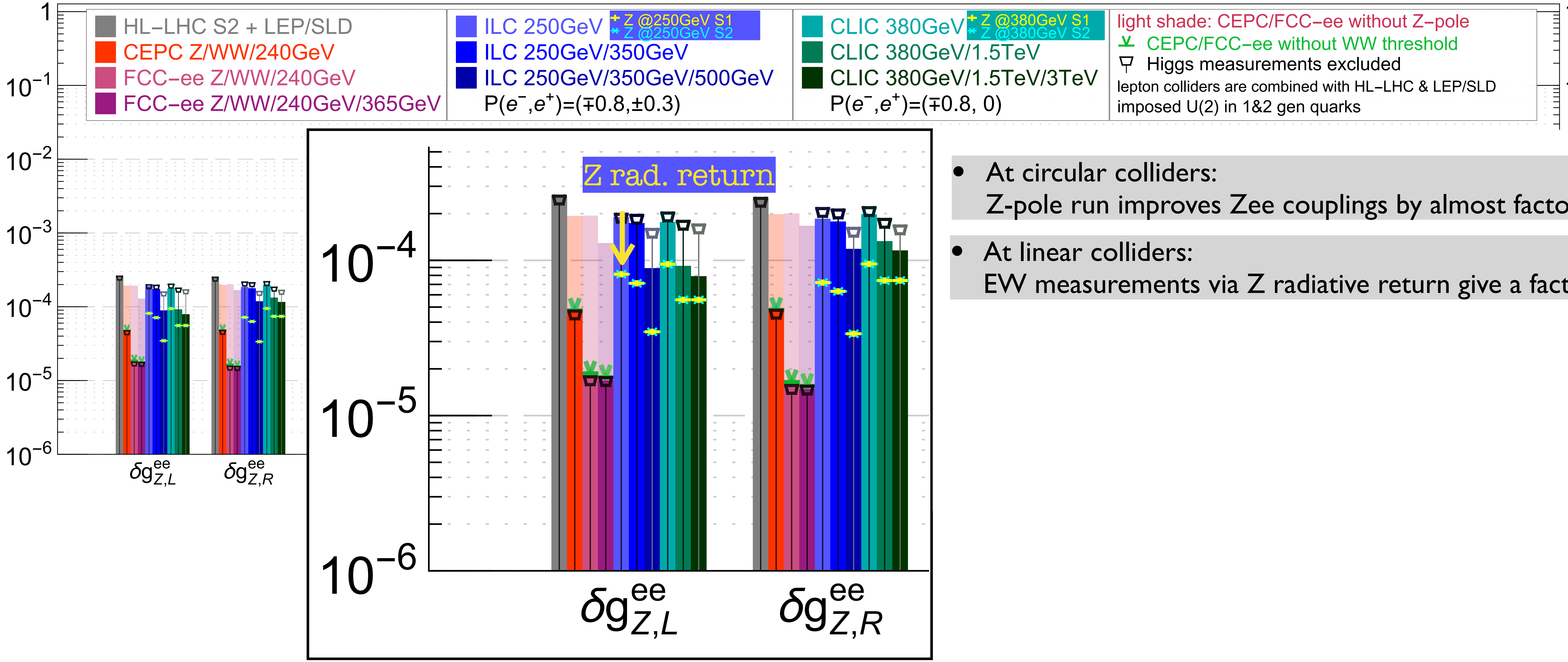

- At circular colliders:
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- At linear colliders:
  EW measurements via Z radiative return give a factor 3

Sensitivity on EW couplings

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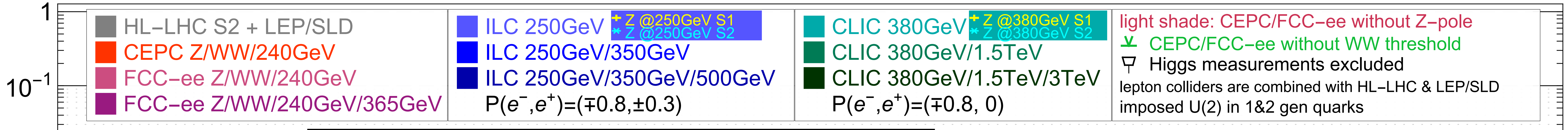

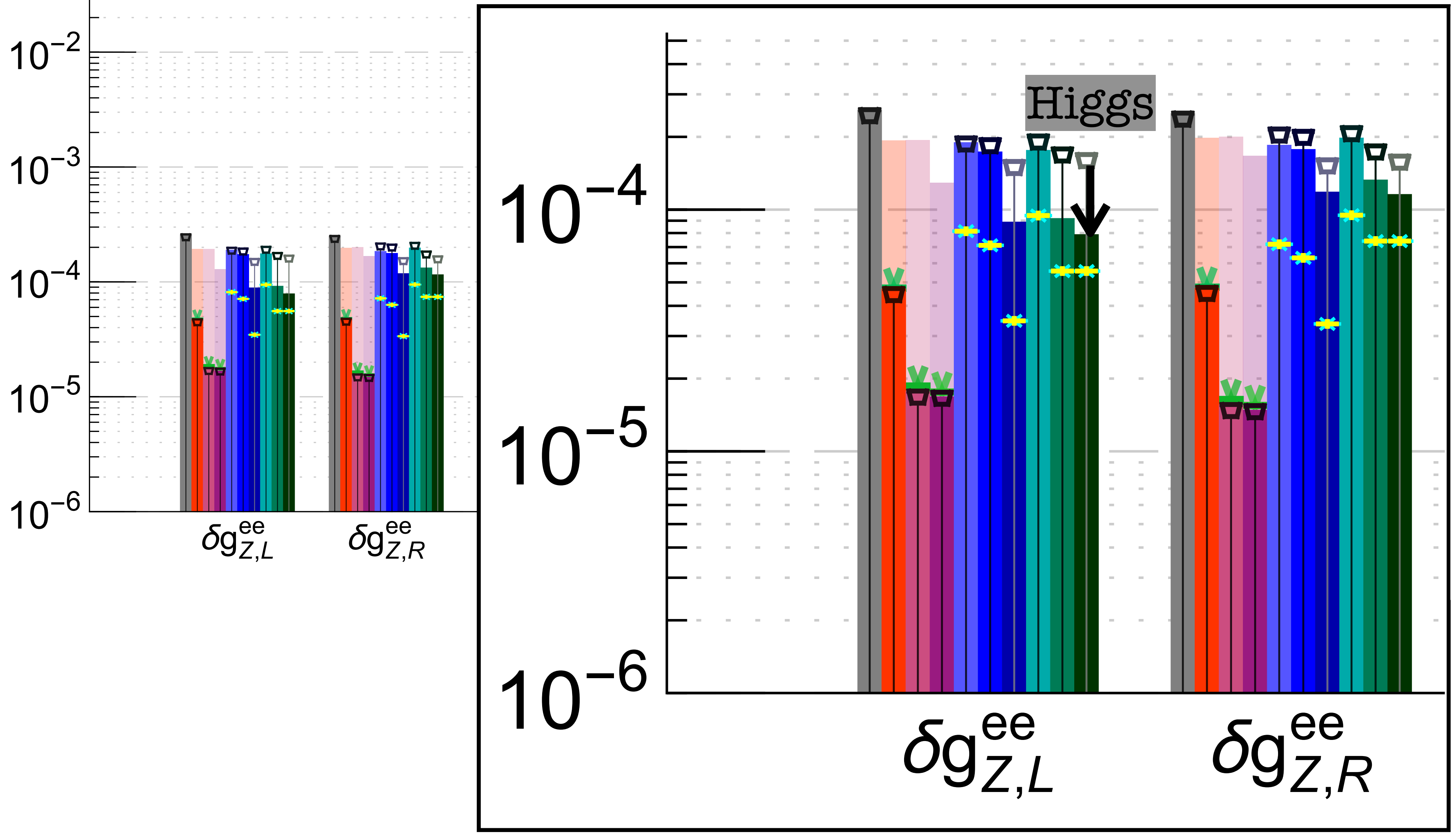

- At circular colliders:
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- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

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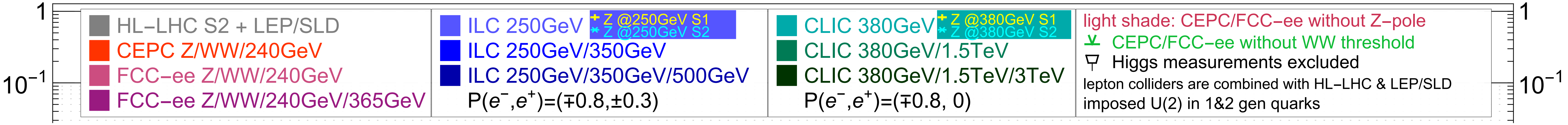
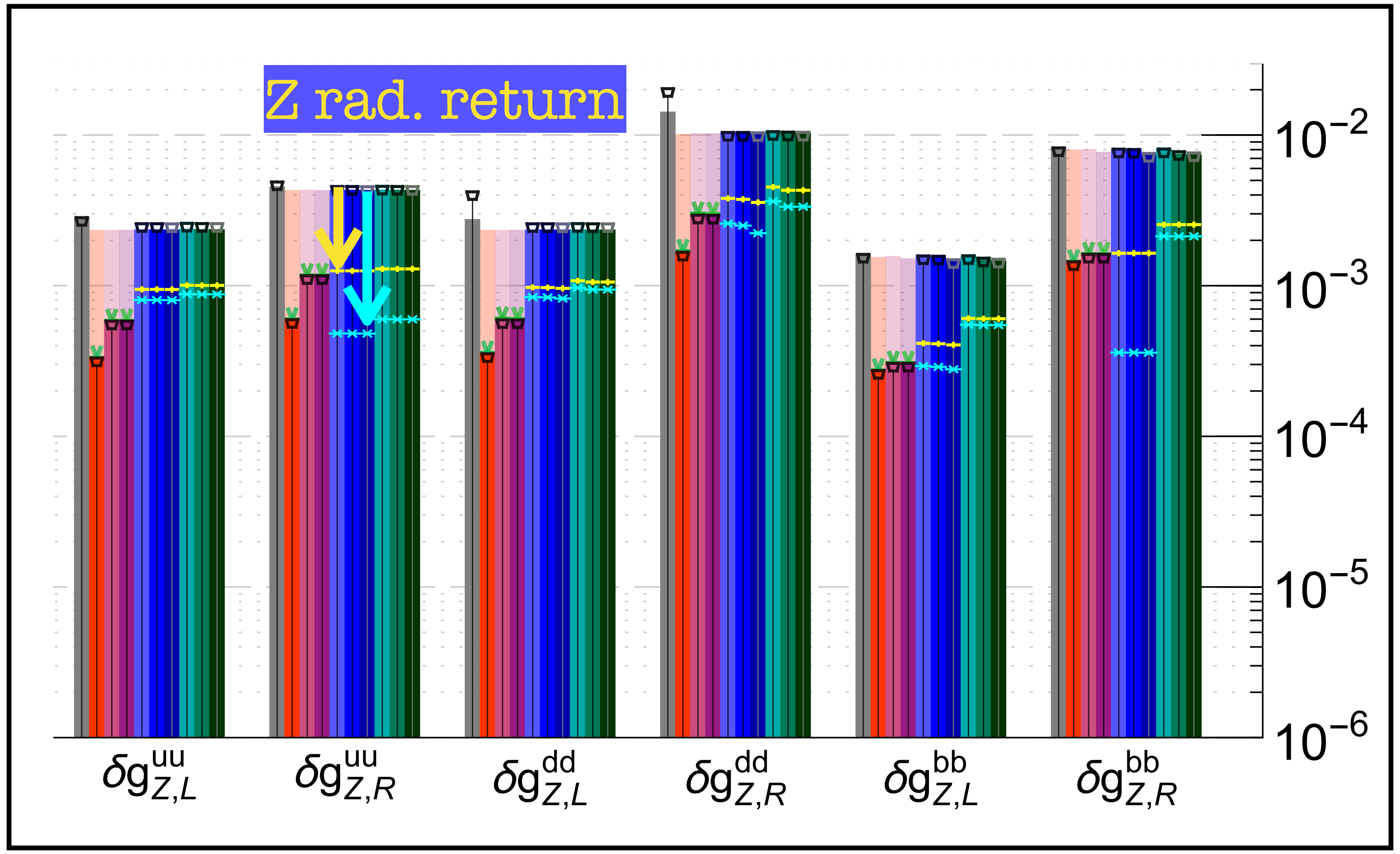


- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  Yellow: LEP/SLD systematics / 2
  Blue: small EXP and TH systematics



Impact of Diboson Systematics

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311