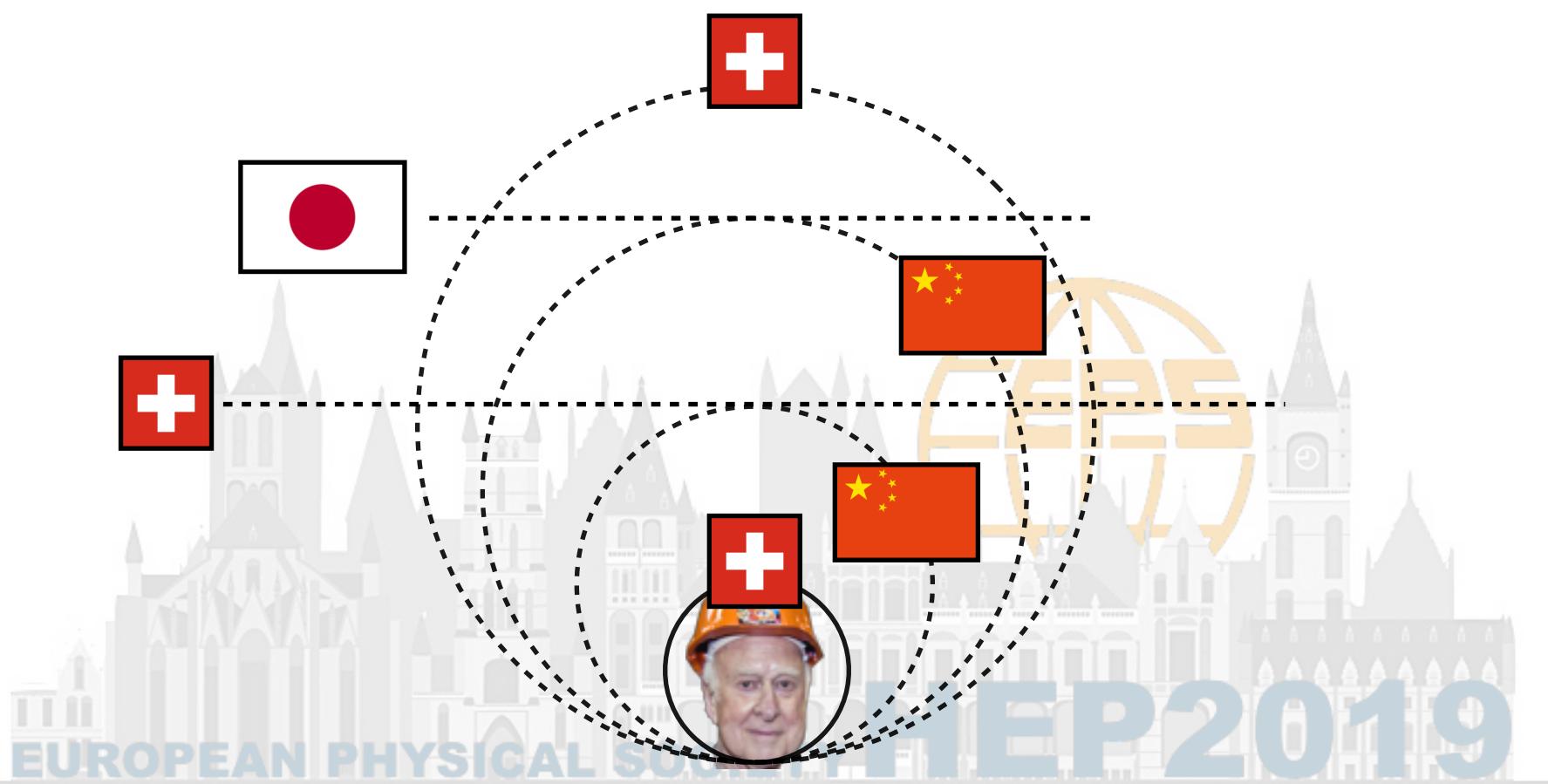


# Higgs at Future Colliders

## What will the Future Colliders know about the Higgs?

ECFA-EPS Special Session

Ghent, July 13, 2019



*Christophe Grojean*

DESY (Hamburg)  
Humboldt University (Berlin)

( christophe.grojean@desy.de )

# Mainly Based upon

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

## Higgs Boson studies at future particle colliders

- Preliminary Version -

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

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

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

---

Jorge de Blas,<sup>a,b</sup> Gauthier Durieux,<sup>c,d</sup> Christophe Grojean,<sup>c,e</sup> Jiayin Gu,<sup>f</sup> and  
Ayan Paul<sup>c,e</sup>

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

# 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  $m_{\text{proton}} < m_{\text{neutron}}$  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:  $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2 v^2}{\Lambda_{\text{BSM}}^2}$

**current (and future) LHC sensitivity**  
**O(10-20)%  $\Leftrightarrow \Lambda_{\text{BSM}} > 500(g^*/g_{\text{SM}})$  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  $h \rightarrow \mu \tau$ )

**Higgs precision program is very much wanted  
to probe BSM physics**

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

# 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/ $\gamma$ /g
  - Rare SM and BSM decays ( $H \rightarrow$ Meson+ $\gamma$ ,  $Z\gamma$ , 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

# High Energy Physics with a Higgs

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- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.

November 14th, 2018

Proposal on WG Higgs physics

13

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  $\Rightarrow$  exploration?
- ▶  $S/B \sim 10^{-10}$  (w/o trigger)
- $S/B \sim 0.1$  (w/ trigger)
- requires multiple detectors  
(w/ optimized design)
- ▶ only pdf access to  $\sqrt{s}$
- $\Rightarrow$  couplings to quarks and gluons

## Leptons

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

## Circular

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

## Linear

- easier to upgrade in energy
- easier to polarize beams
- “greener”: less power consumption\*
- ▶ large beamstrahlung
- ▶ 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)?

## Hadrons

- large mass reach  $\Rightarrow$  exploration?

► S/B

○ S/B

○ requ

► only

○  $\Rightarrow$  c

## Circu

○ high

○ several interaction points

○ precise E-beam measurement  
( $O(0.1\text{ MeV})$  via resonant depolarization)

►  $\sqrt{s}$  limited by synchrotron radiation

## Leptons

- $S/B \sim 1 \Rightarrow$  measurement?

(\$)

## Linear

- Higher luminosity
- Z-pole run

○ “greener”: less power consumption\*

► large beamstrahlung

► 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)?

## Hadrons

- large mass reach  $\Rightarrow$  exploration?

► S/B

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○ requ

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○  $\Rightarrow$  c

## Circu

○ high

○ sev

○ precise E-b

( $O(0.1\text{ MeV})$  via

►  $\sqrt{s}$  limited

## Leptons

- $S/B \sim L \Rightarrow$  measurement?

(\$)

## Linear

nsumption\*

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<sup>+</sup>e<sup>-</sup> Higgs**

factory  
Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- 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?

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

# 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 + ...

Higgs@FutureColliders

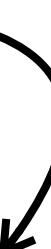
# Future of HEP



ECFA Higgs study group '19

## Subject to large uncertainty

- 1) need a scientific consensus
- 2) political approval



$T_0$

2032

2030

2035

2037

2030

2040

2045

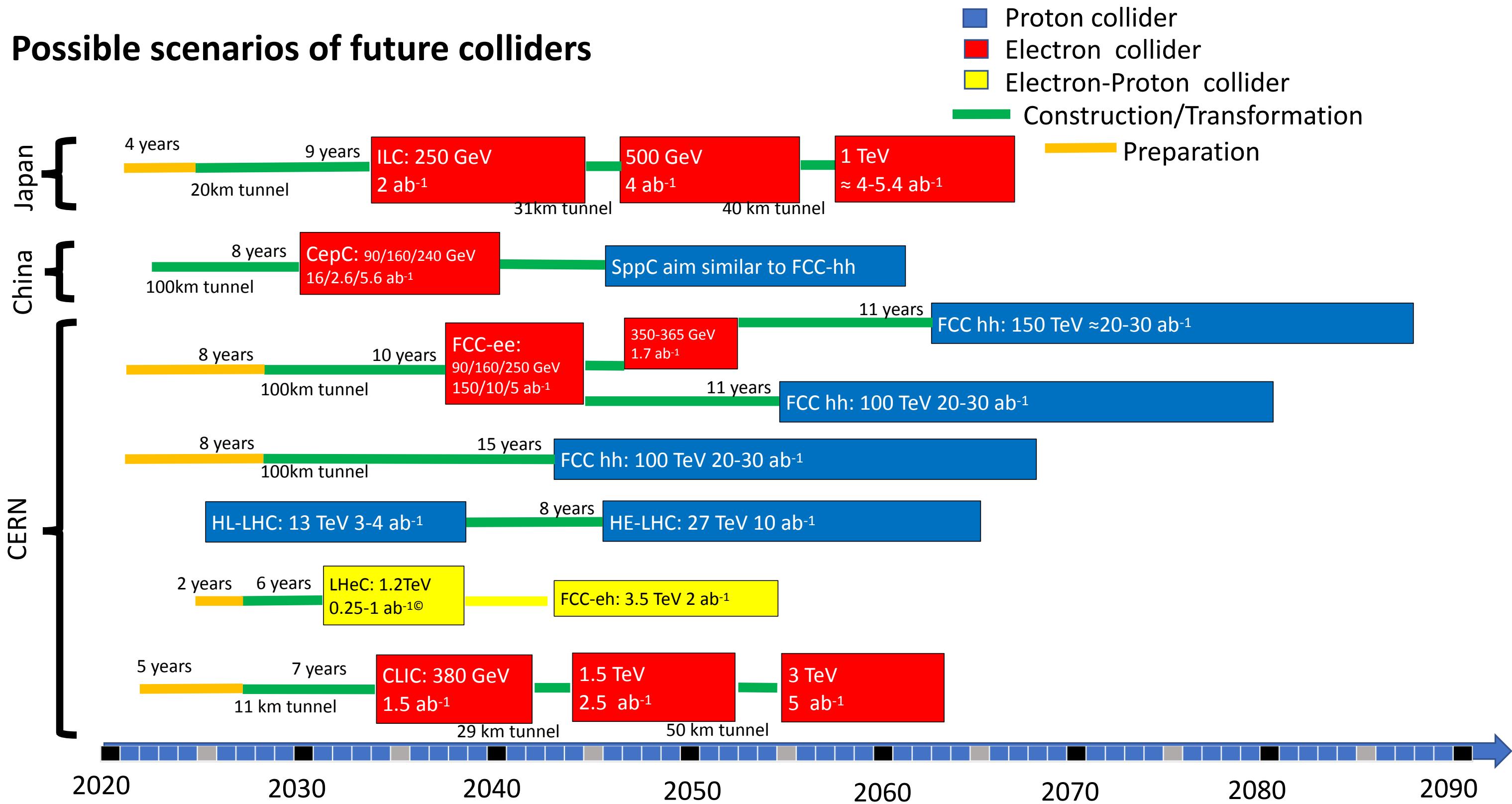
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+ muon-collider + gamma-gamma collider + ...

Higgs@FutureColliders

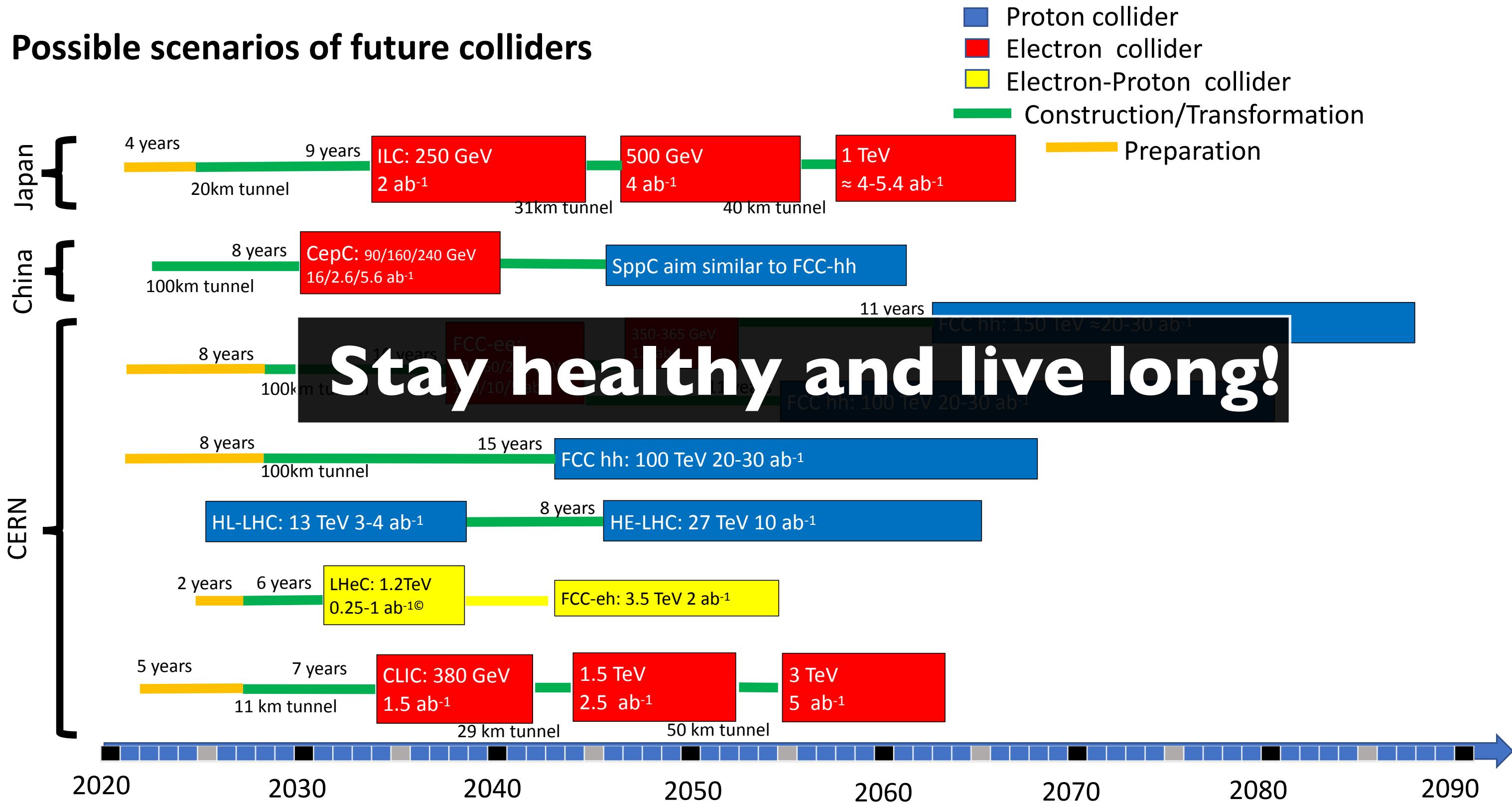
# Future of HEP

## Possible scenarios of future colliders



# Future of HEP

## Possible scenarios of future colliders



# Which Higgs couplings?

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

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

M. Mangano

# Which Higgs couplings?

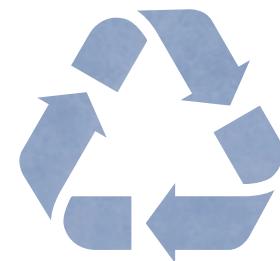
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## Two approaches to go BSM

Study  
specific models



Try to introduce  
continuous deformations of the SM

# Which Higgs couplings?

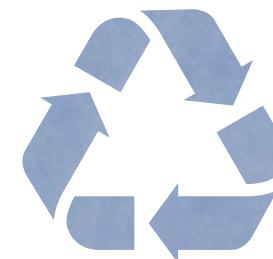
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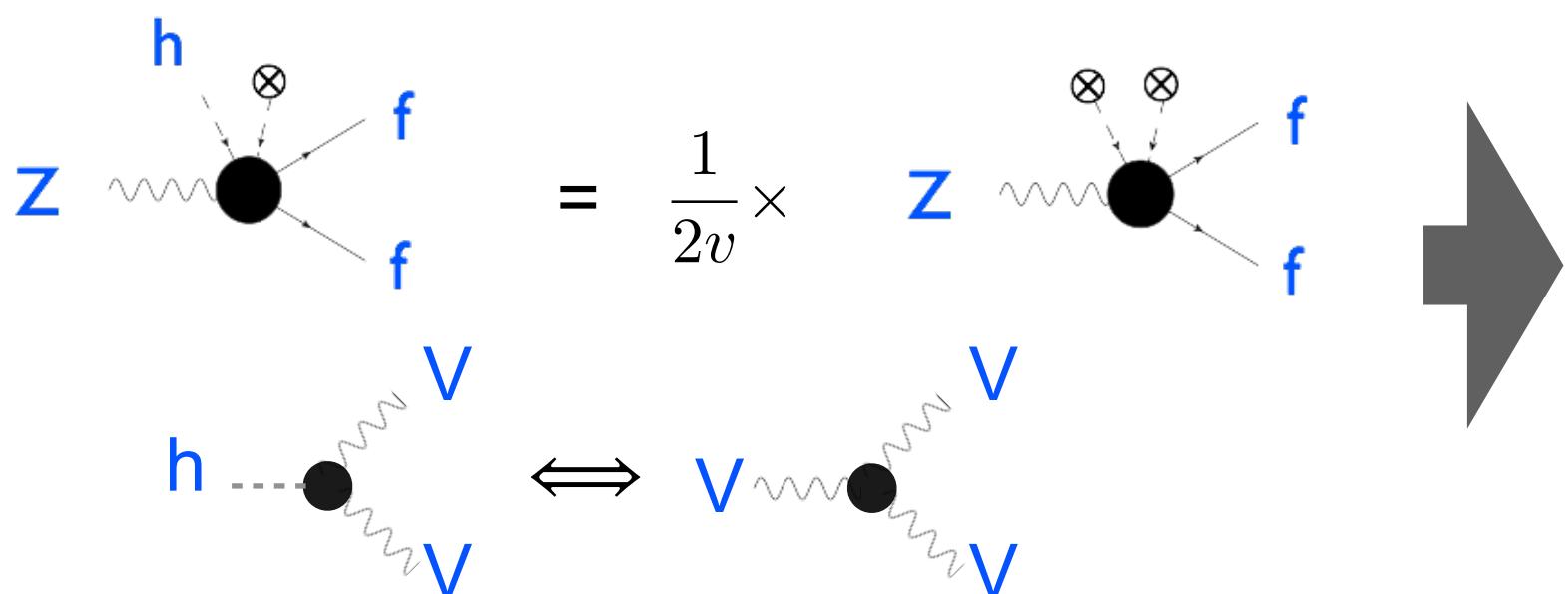
Study  
specific models



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

$$g_{hXX} = \kappa_X g_{hXX}^{\text{SM}}$$

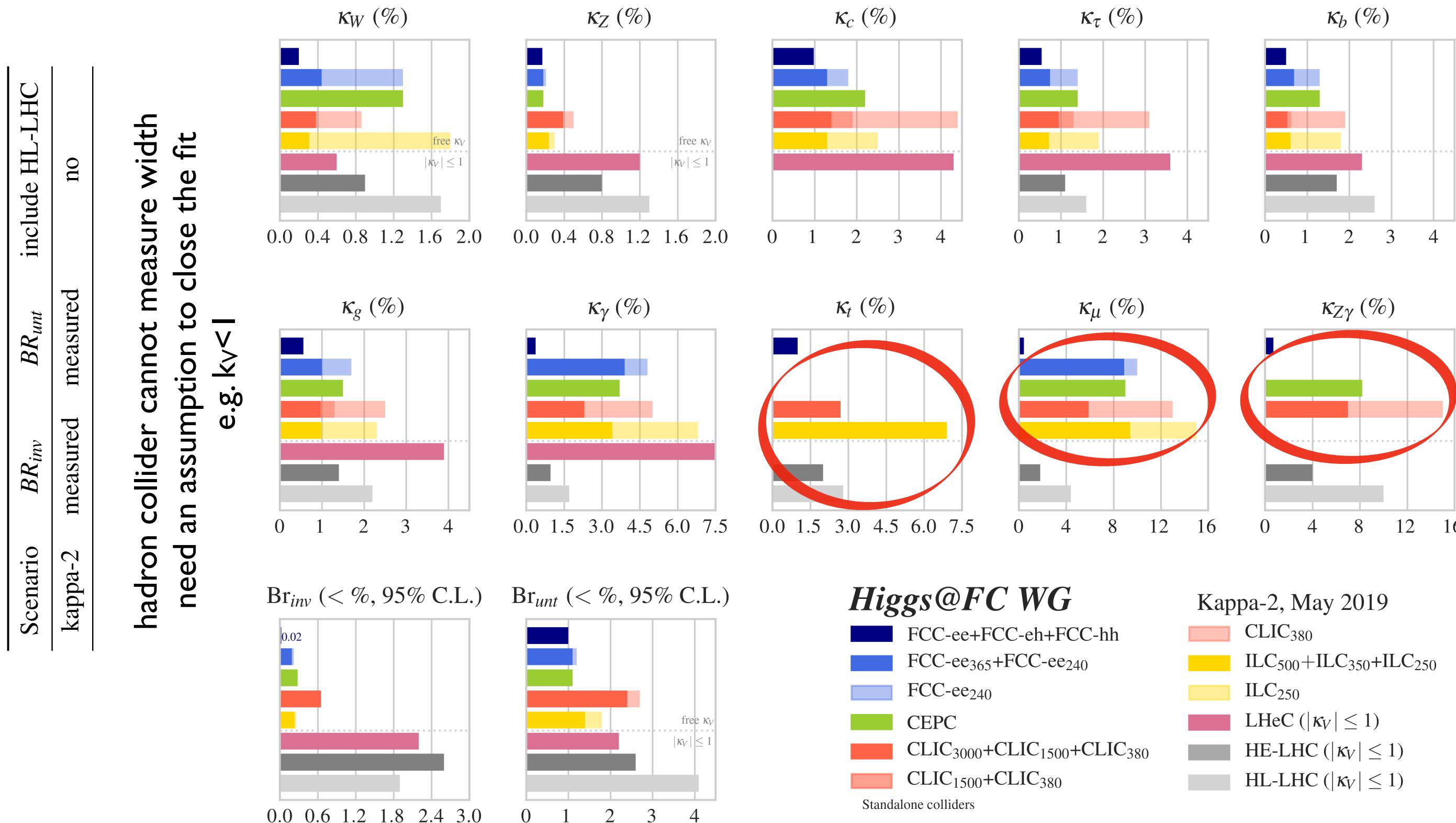
### EFT:

- 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

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

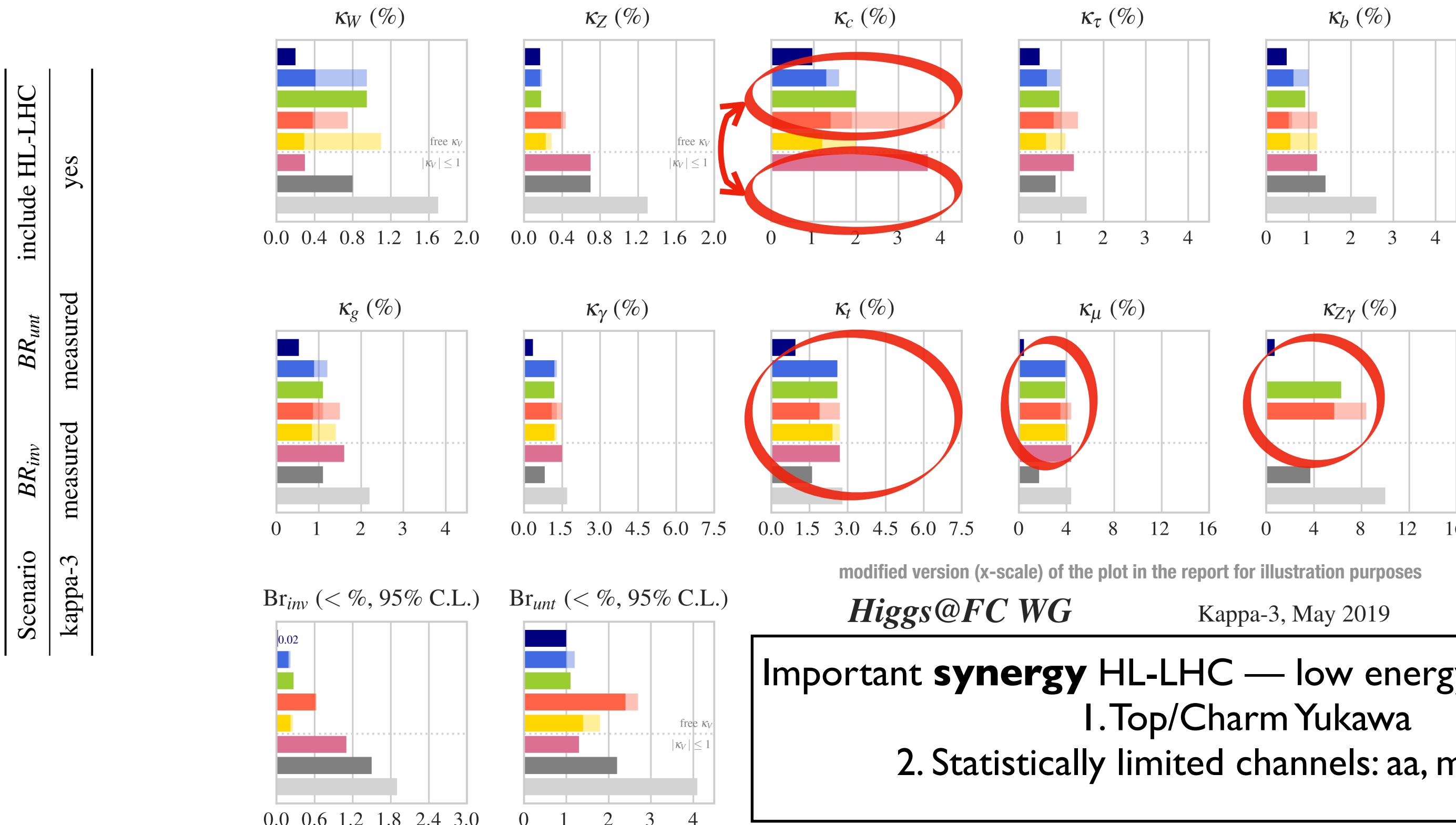
# Results of kappa-2 fit

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# Results of kappa-3 fit

ECFA Higgs study group '19



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**)

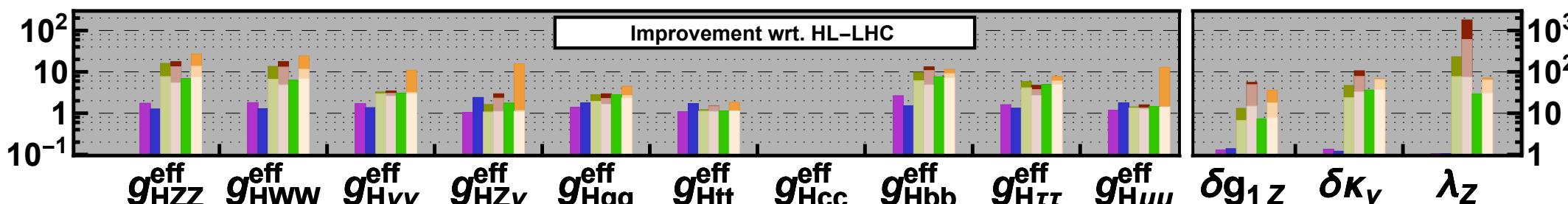
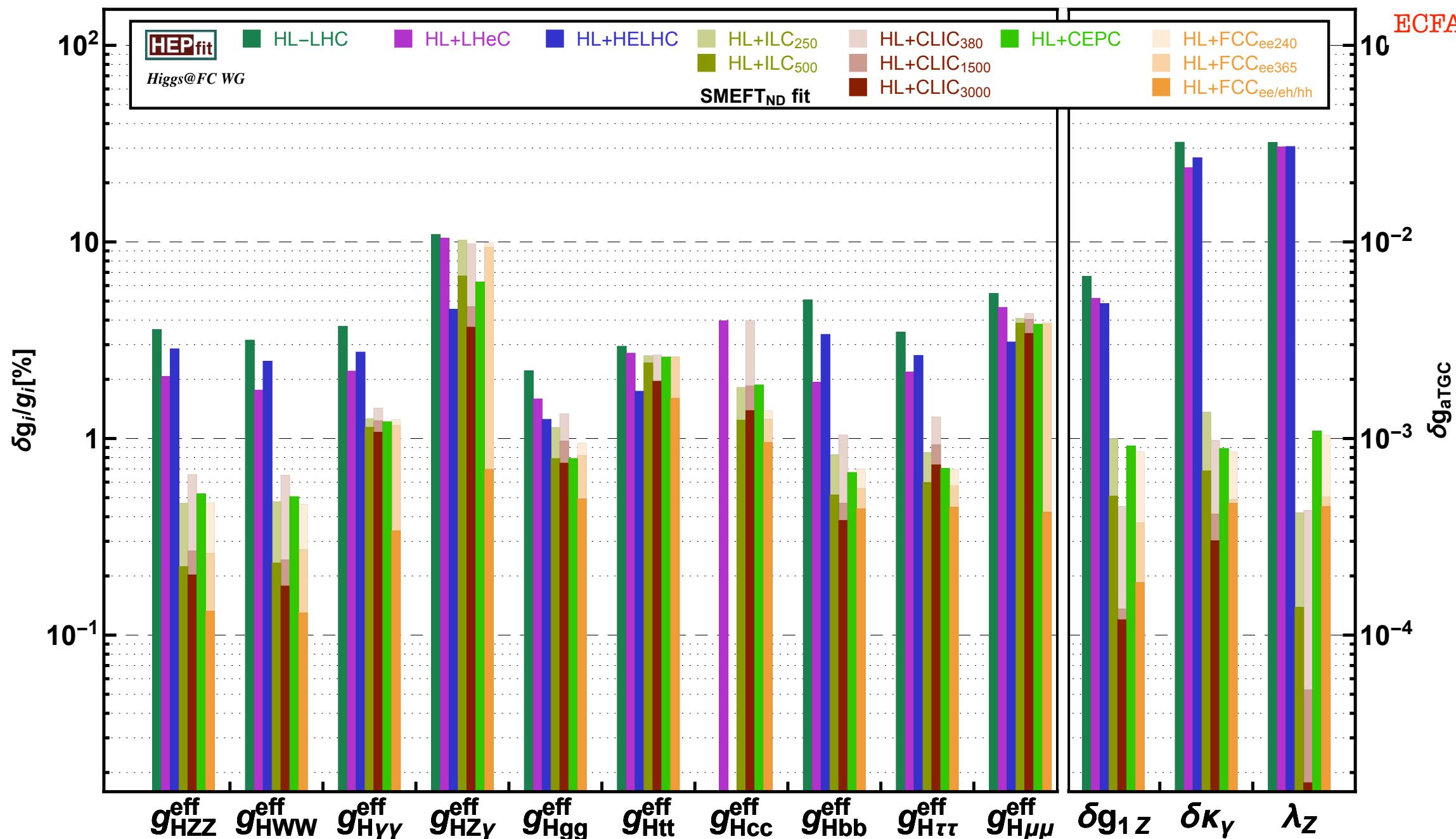
A linear ee Higgs factory operating above Z-pole can also preform EW measurements via **Z-radiative** return

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

Not included in the analyses yet

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes ( $\mu, \sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (aTGC dom.) <small>Warning</small>	Yes	Yes (365 GeV, Ztt)
ILC	Yes ( $\mu, \sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (HE limit) <small>Warning</small>	LEP/SLD (Z-pole) + HL-LHC + W (ILC)	Yes (500 GeV, Ztt)
CEPC	Yes ( $\mu, \sigma_{ZH}$ ) (Complete with HL-LHC)	Yes (aTGC dom) <small>Warning</small>	Yes	No
CLIC	Yes ( $\mu, \sigma_{ZH}$ )	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 ( $\mu, BR_i/BR_j$ ) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes ( $\mu$ )	N/A → LEP2	LEP/SLD + HL-LHC ( $M_W, \sin^2\theta_W$ )	-
FCC-eh	Yes ( $\mu$ ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

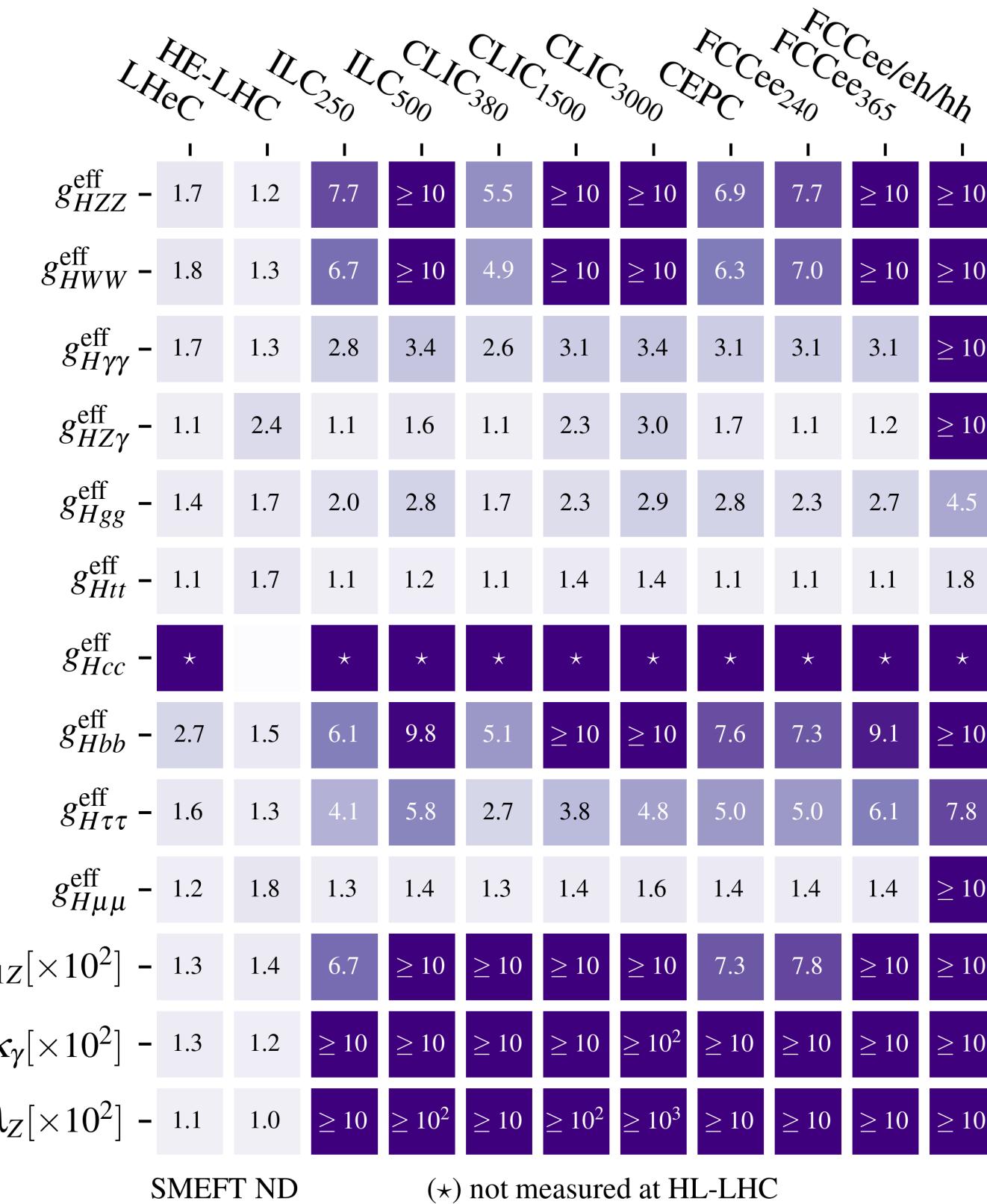
# Global EFT fit



There is life  
beyond HL-LHC

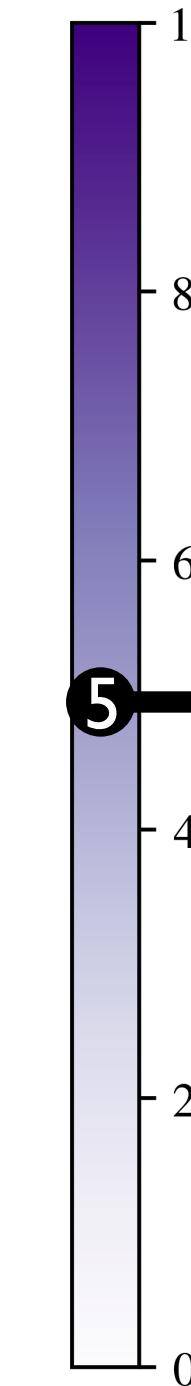
# Figures of Merit with Respects to HL-LHC

Factor of improvement  
in different channels  
viz. HL-LHC



SMEFT ND

(\*) not measured at HL-LHC



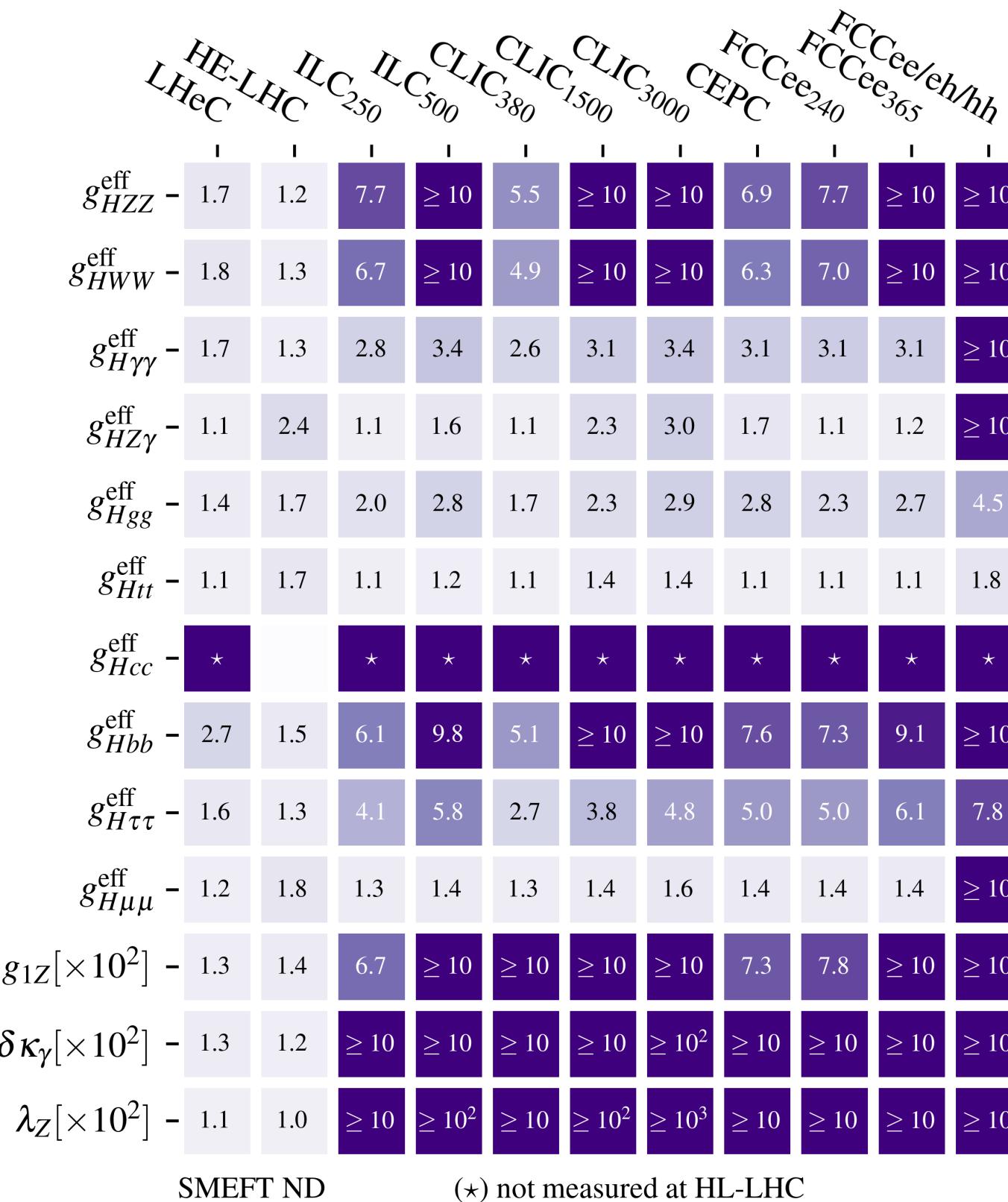
M. Cepeda for Higgs@FC WG

If no deviation seen at HL-LHC  
5 $\sigma$  discovery still possible  
at Future Collider

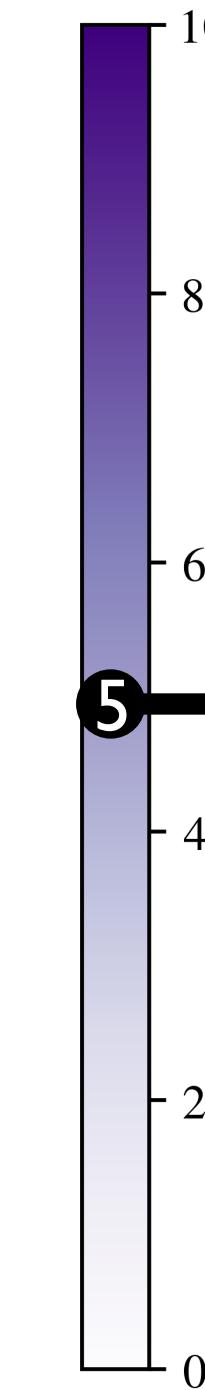
5

# Figures of Merit with Respects to HL-LHC

Factor of improvement  
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M. Cepeda for Higgs@FC WG



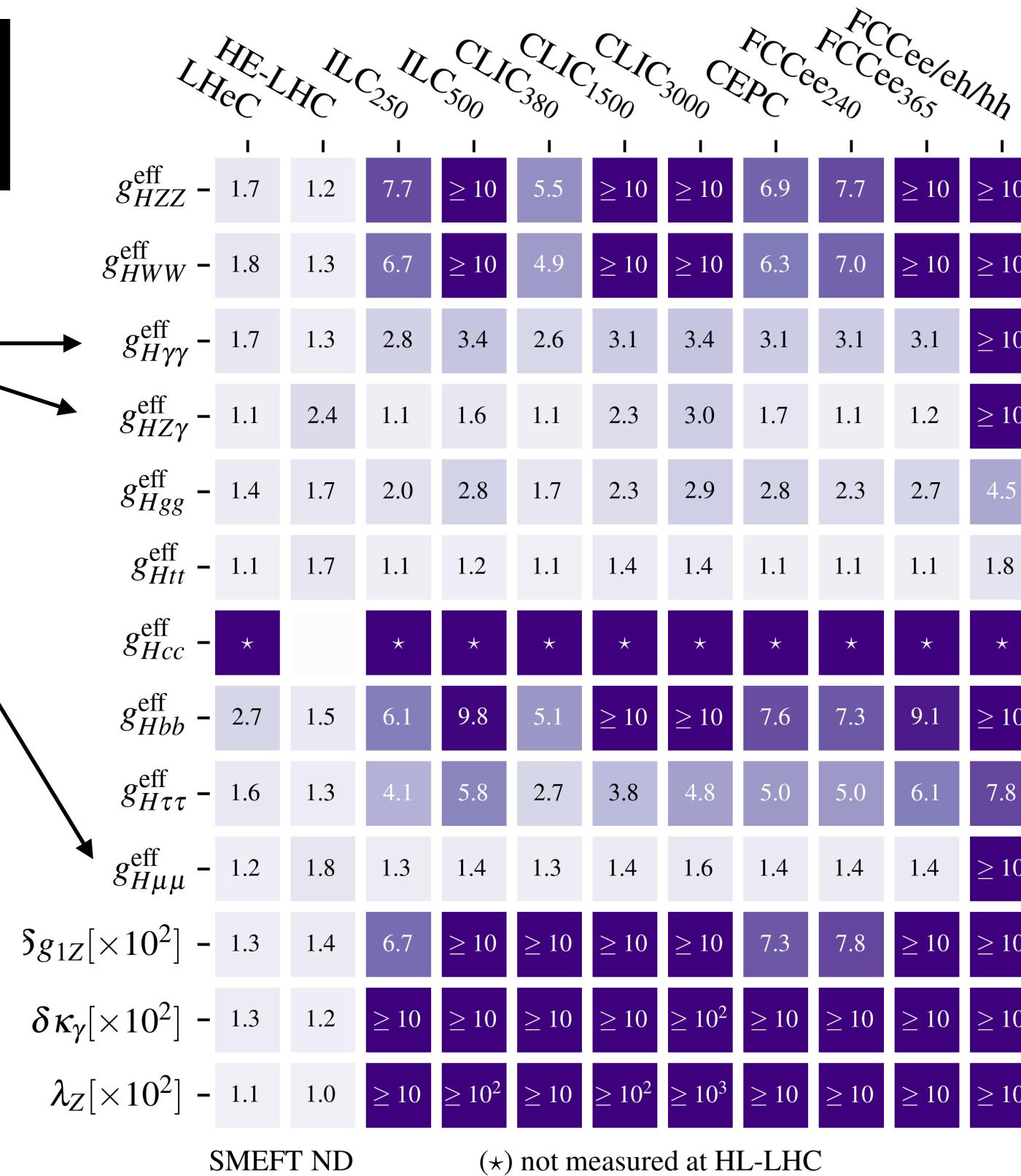
If no deviation seen at HL-LHC  
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Possible at all colliders  
(often in their initial stage)  
in most of the channels  
with a few exceptions

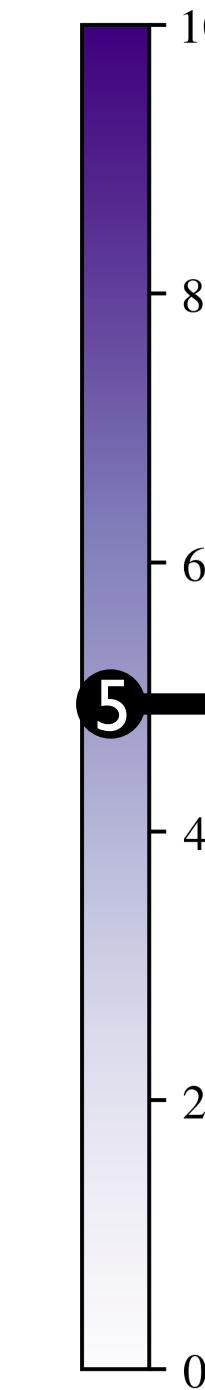
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Factor of improvement  
in different channels  
viz. HL-LHC

Stat. limited



M. Cepeda for Higgs@FC WG



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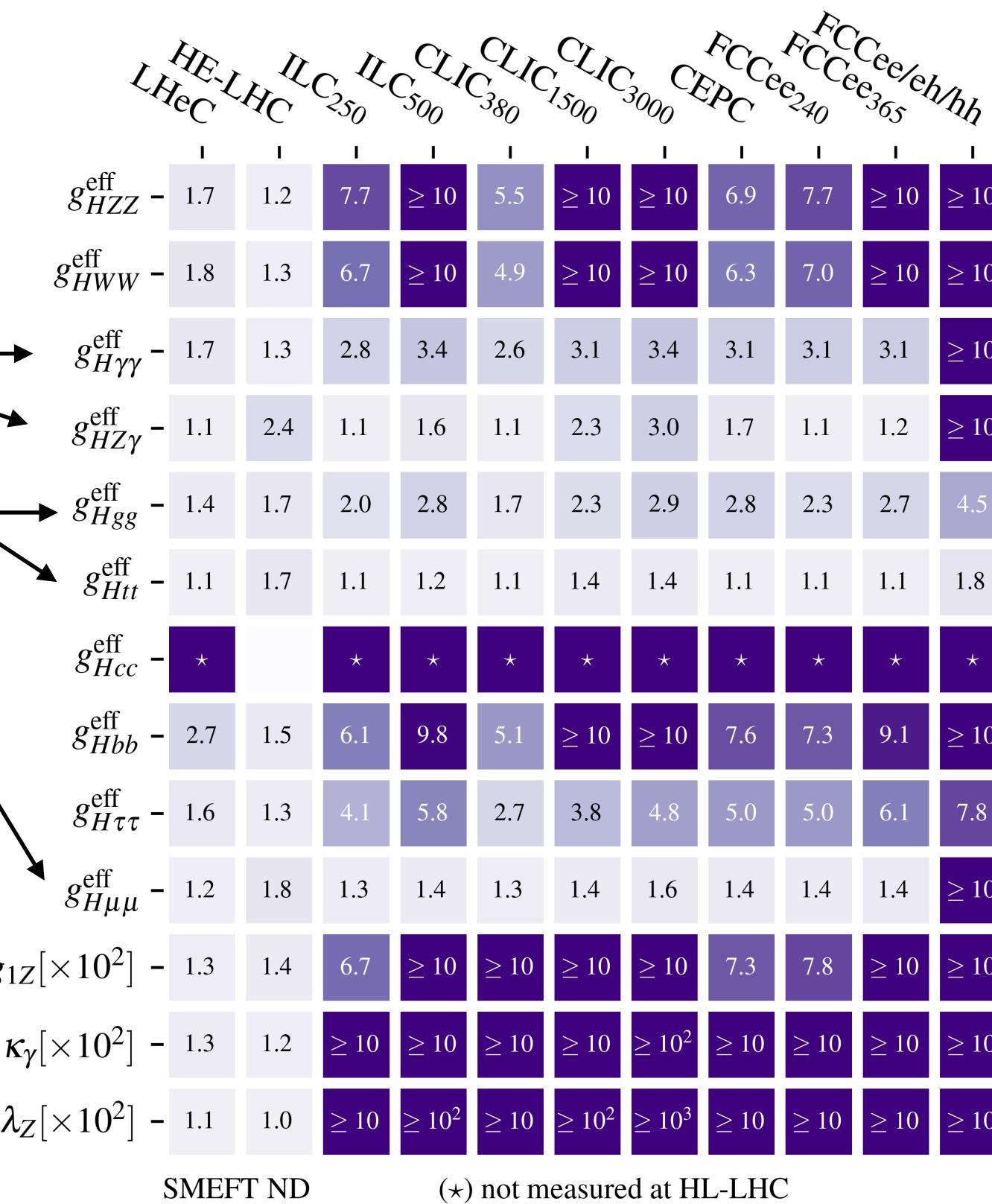
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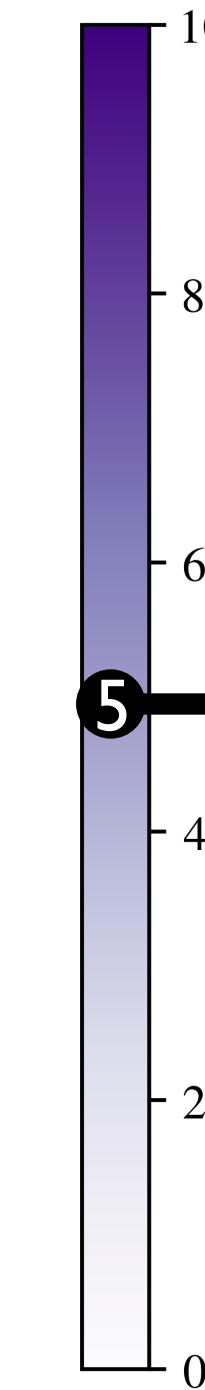
Factor of improvement  
in different channels  
viz. HL-LHC

Stat. limited

Top quark channels  
(LHC is a top factory and it is  
not so easy to outperform)



M. Cepeda for Higgs@FC WG

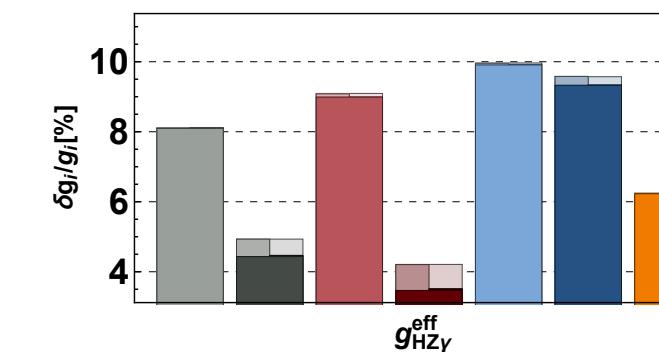
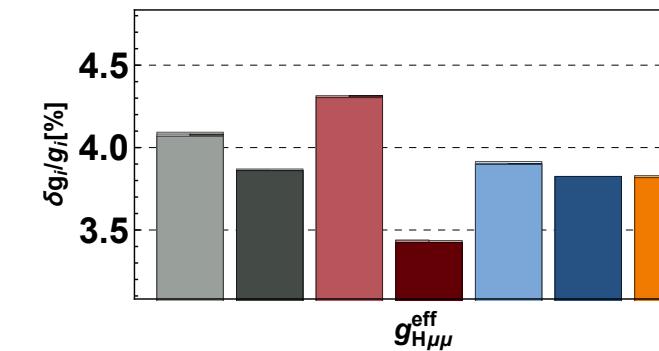
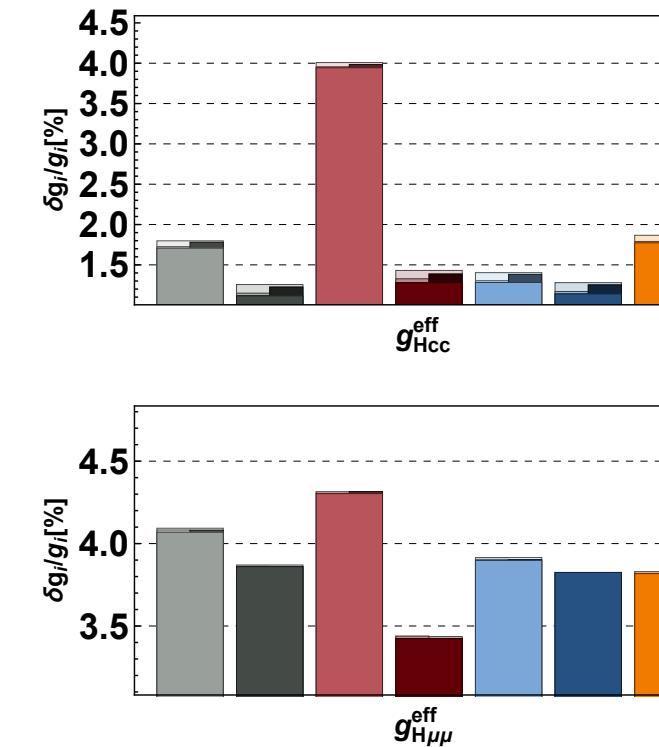
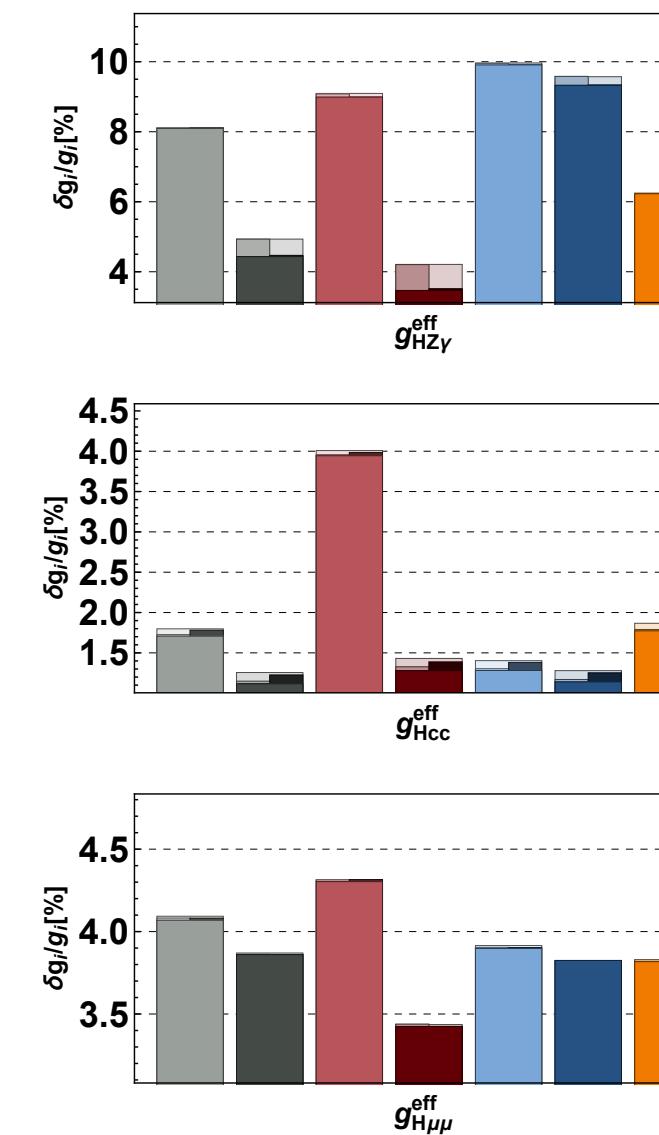
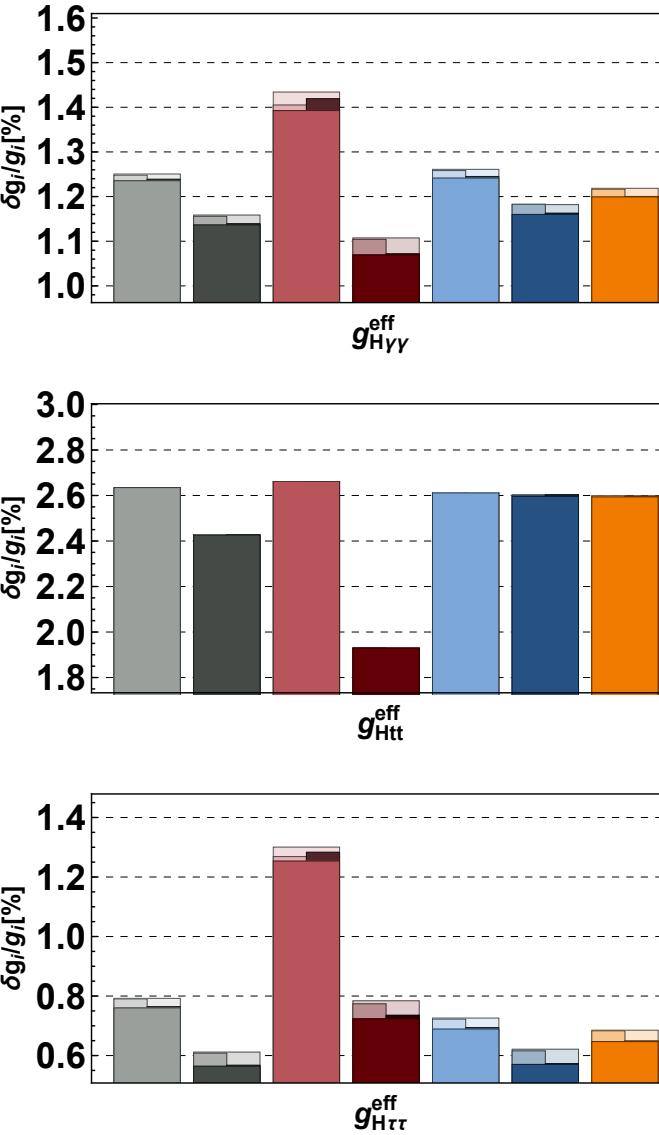
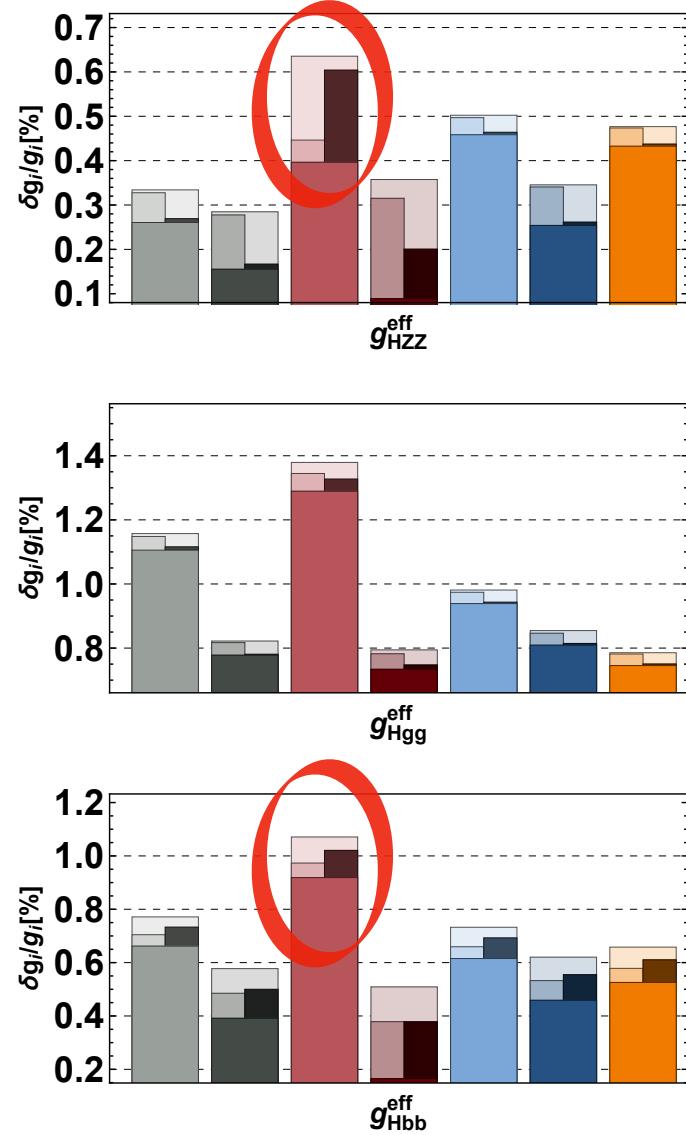


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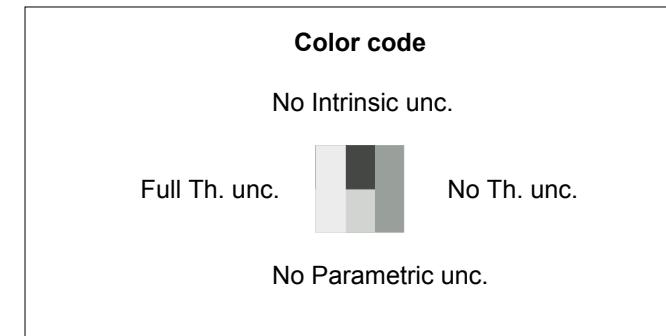
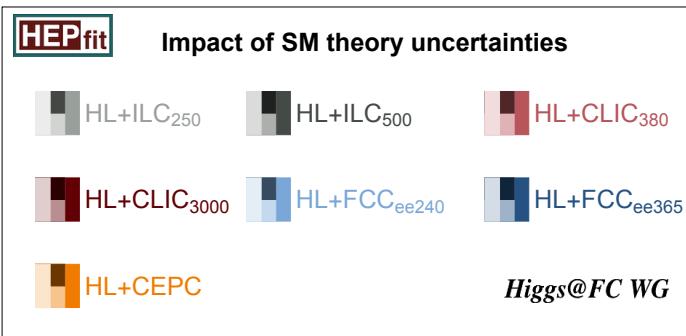
Possible at all colliders  
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in most of the channels  
with a few exceptions

# Theoretical Uncertainties

ECFA Higgs study group '19



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  $O_{\text{SM}}$ .
- Intrinsic theory uncertainties:** Estimate of the net size associated with the contributions to  $O_{\text{SM}}$  from missing higher-order corrections in perturbation theory.

# Theoretical Uncertainties

ECFA Higgs study group '19

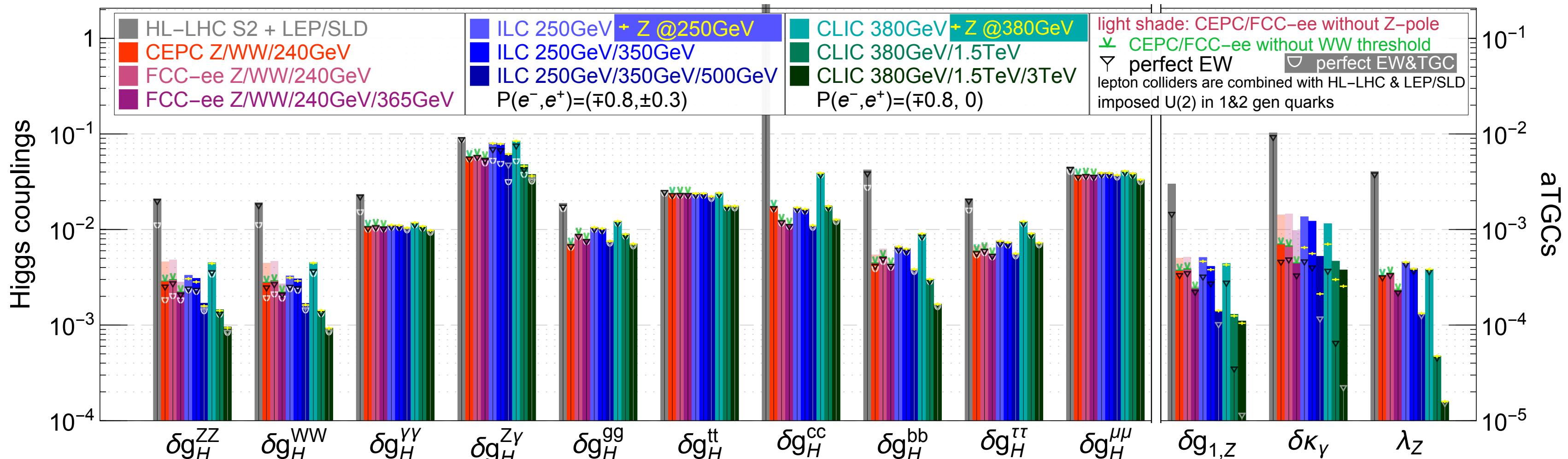
More theory work needed to match EXP uncertainties

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

# Impact of Z-pole measurements

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

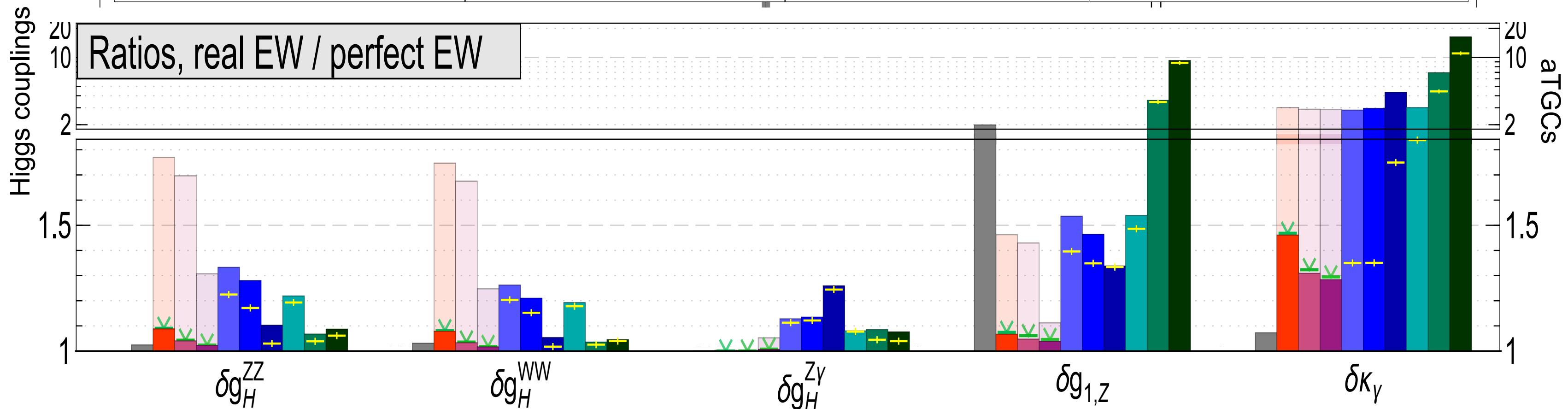
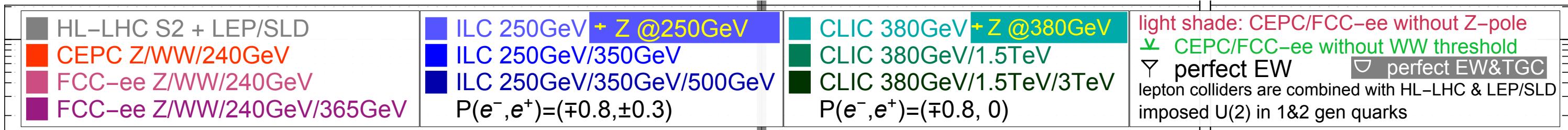
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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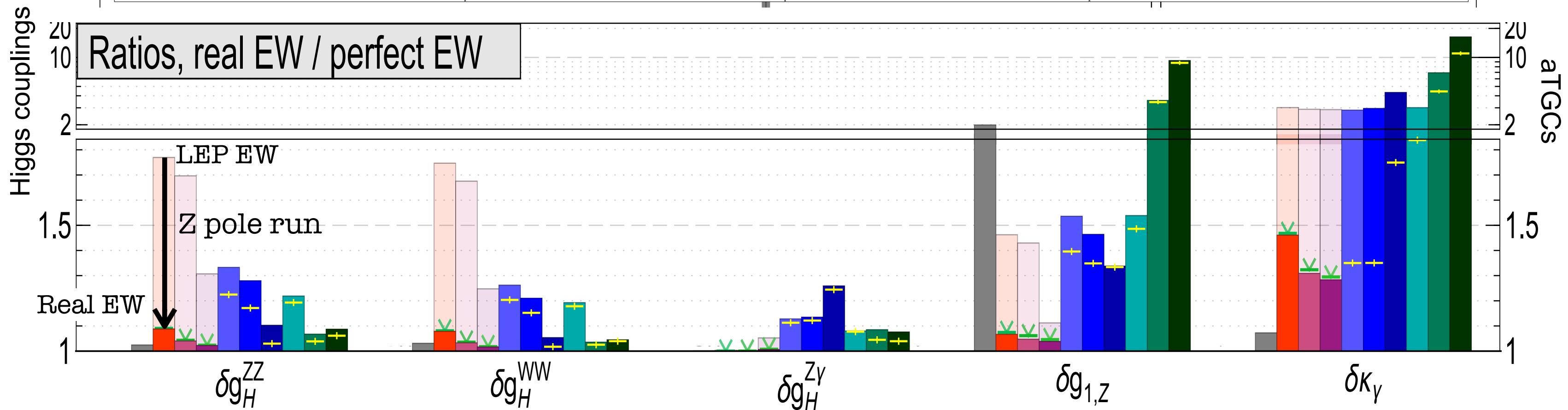
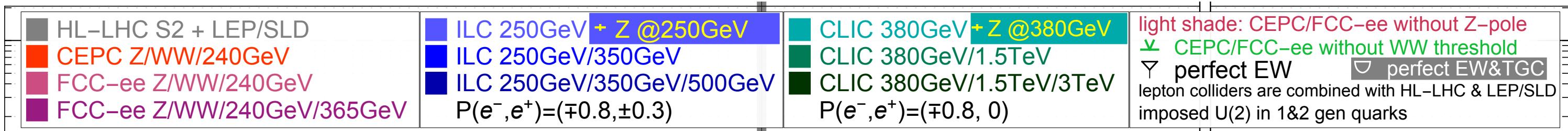
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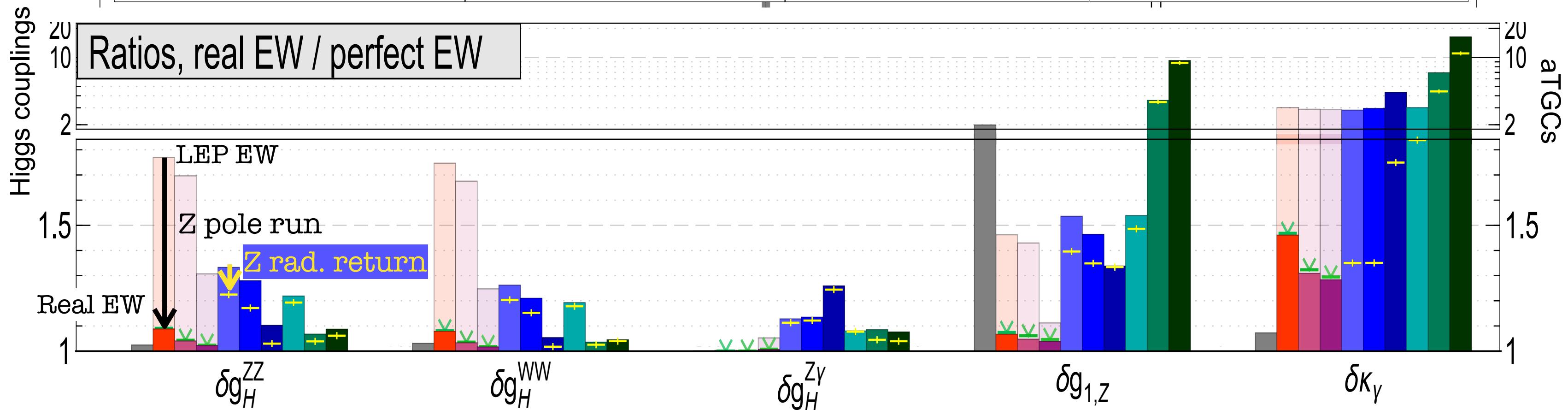
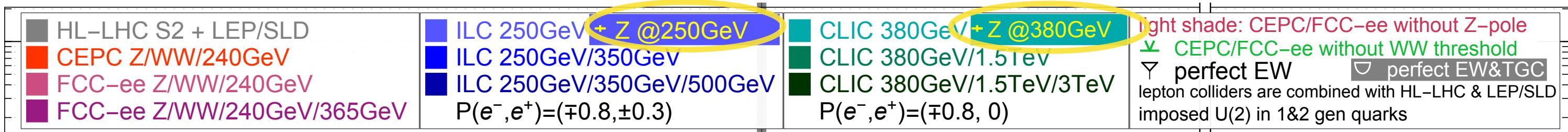


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
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# Impact of Z-pole measurements

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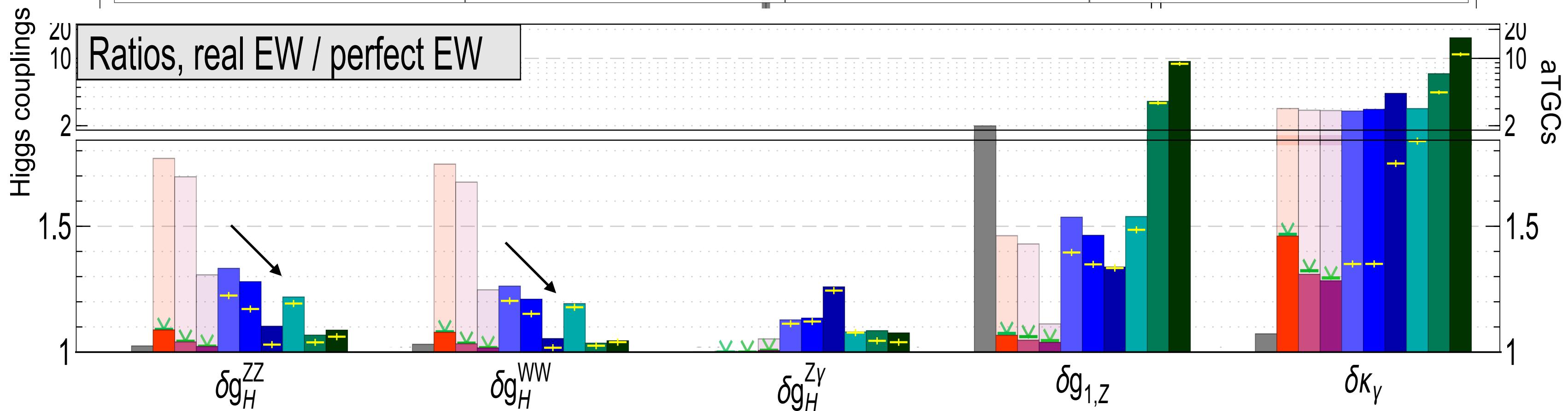
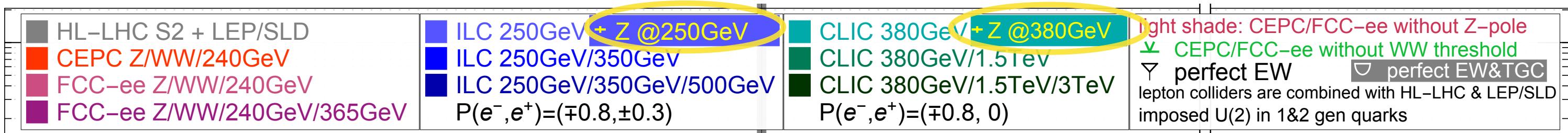


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs  
But EW measurements at high energy (via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

# Impact of Z-pole measurements

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

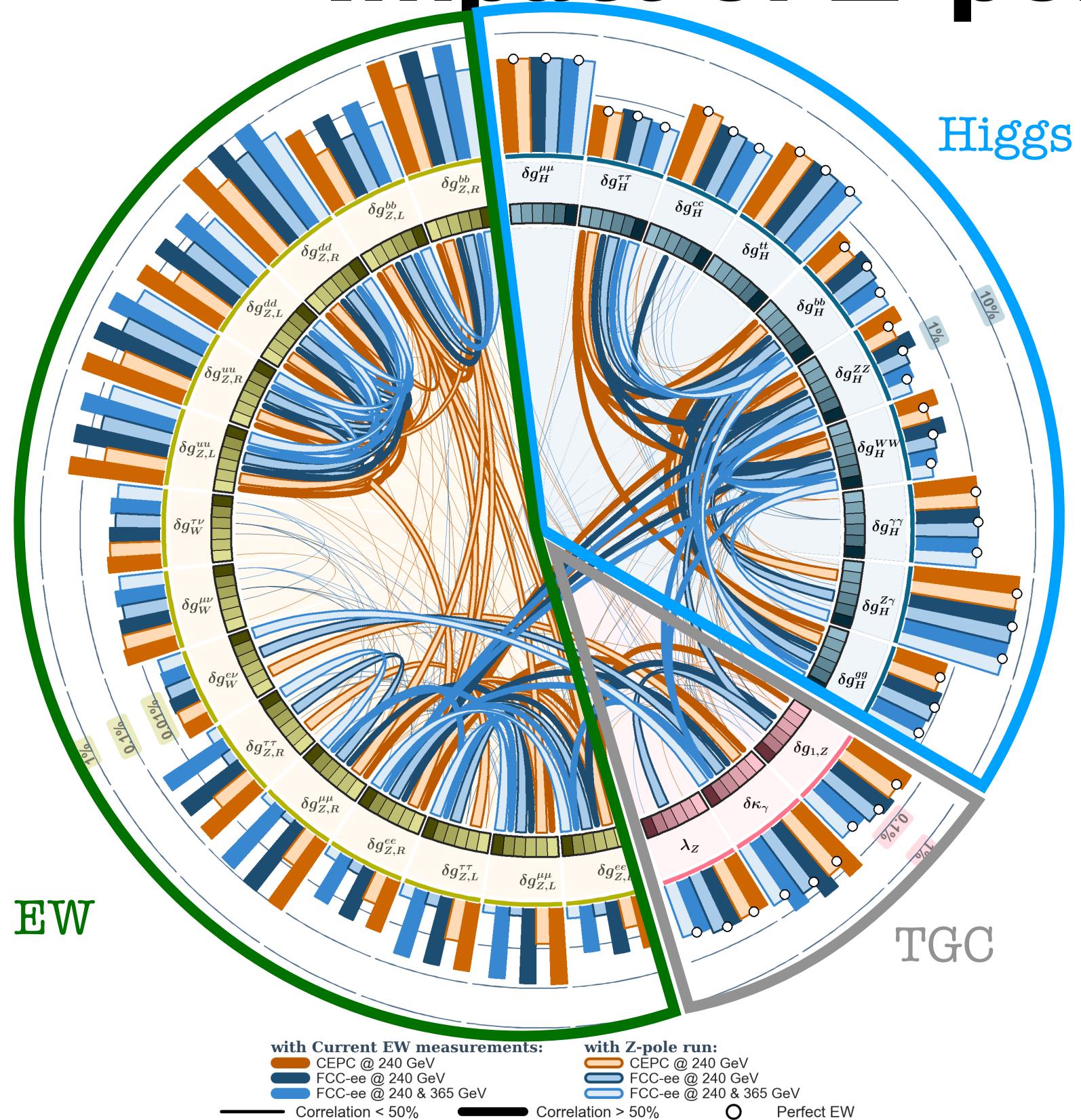
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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

# Impact of Z-pole measurements

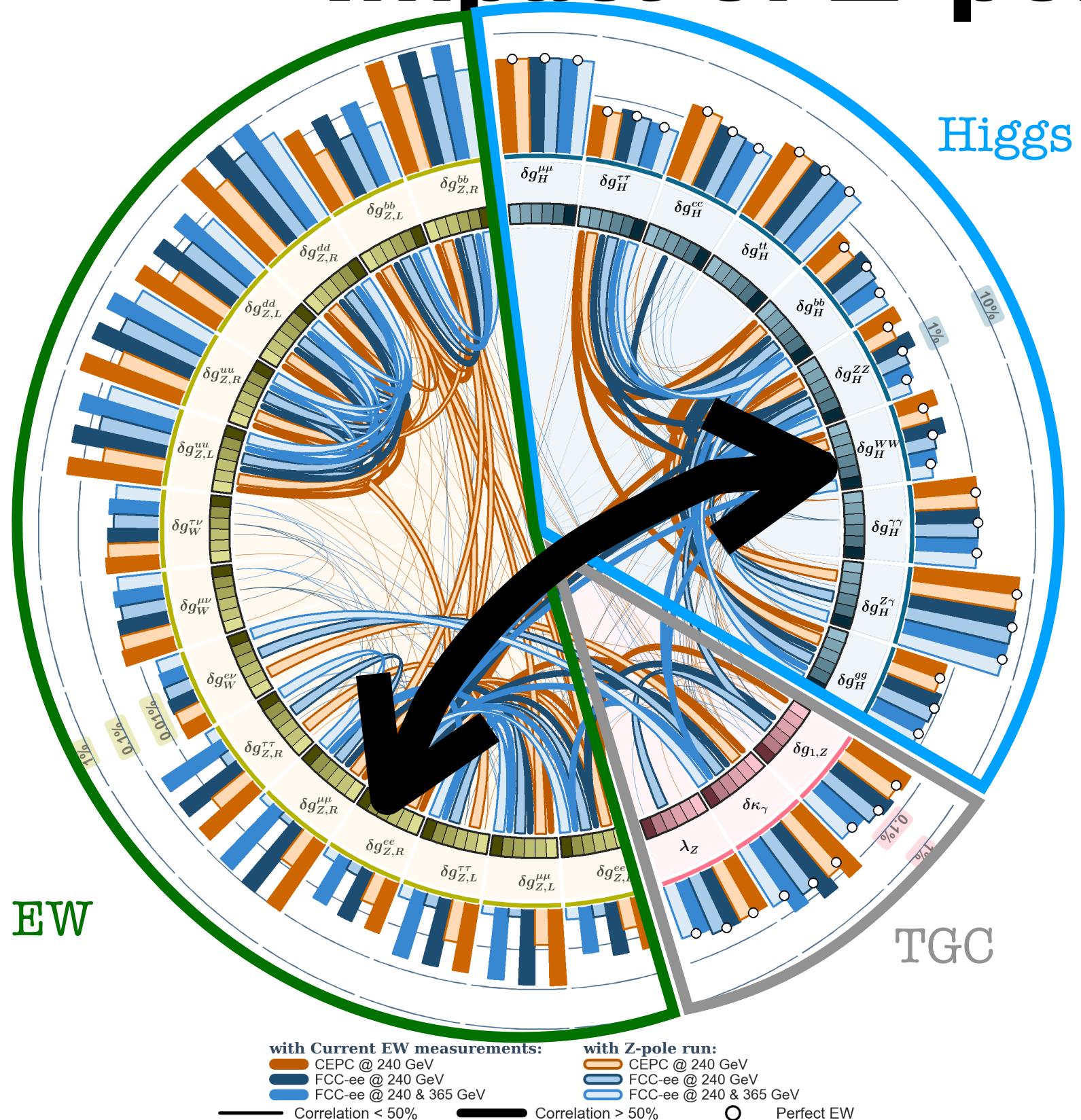
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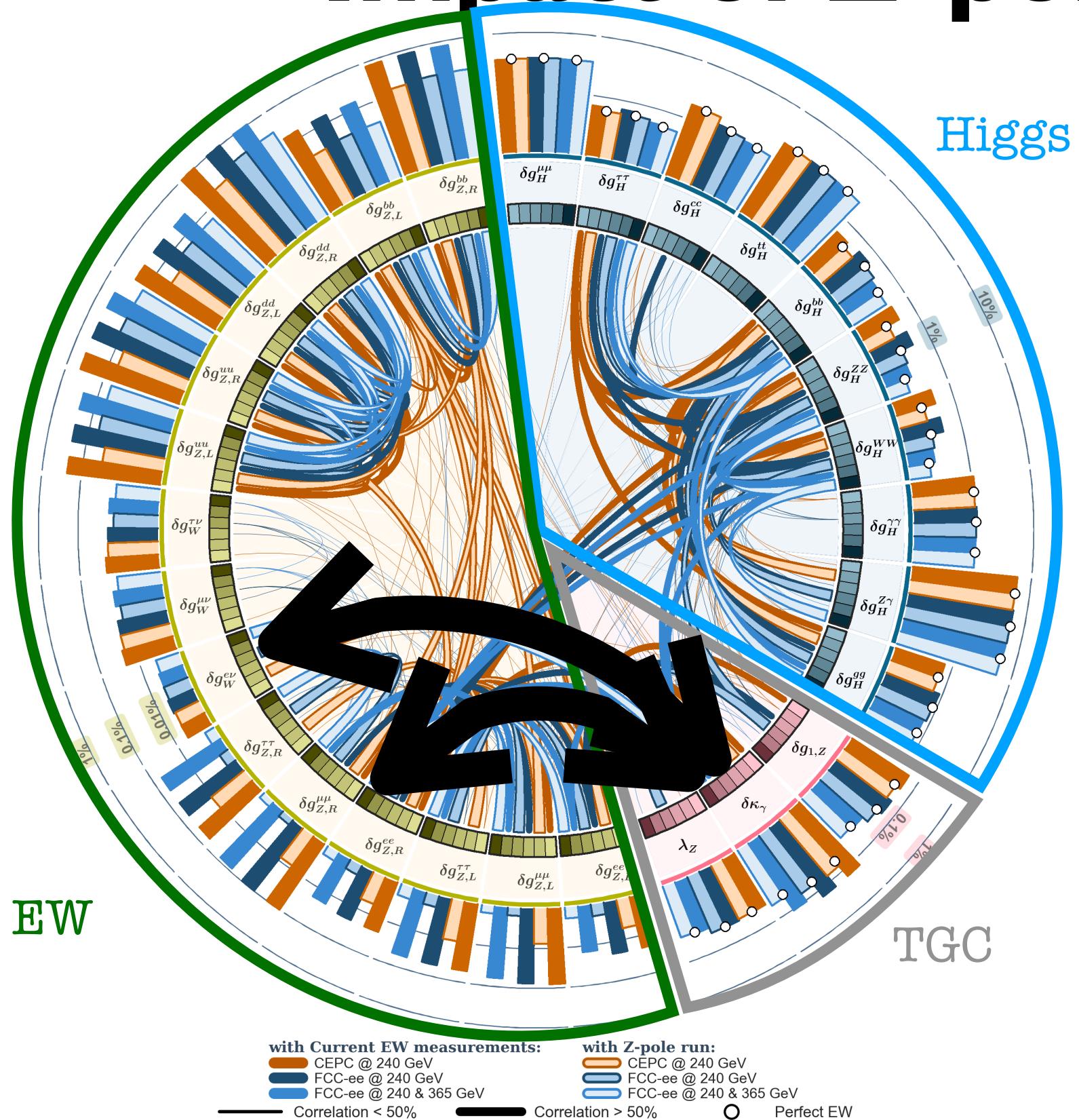


Contamination EW/TGC/Higgs can be understood by looking at correlations

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

# Impact of Z-pole measurements

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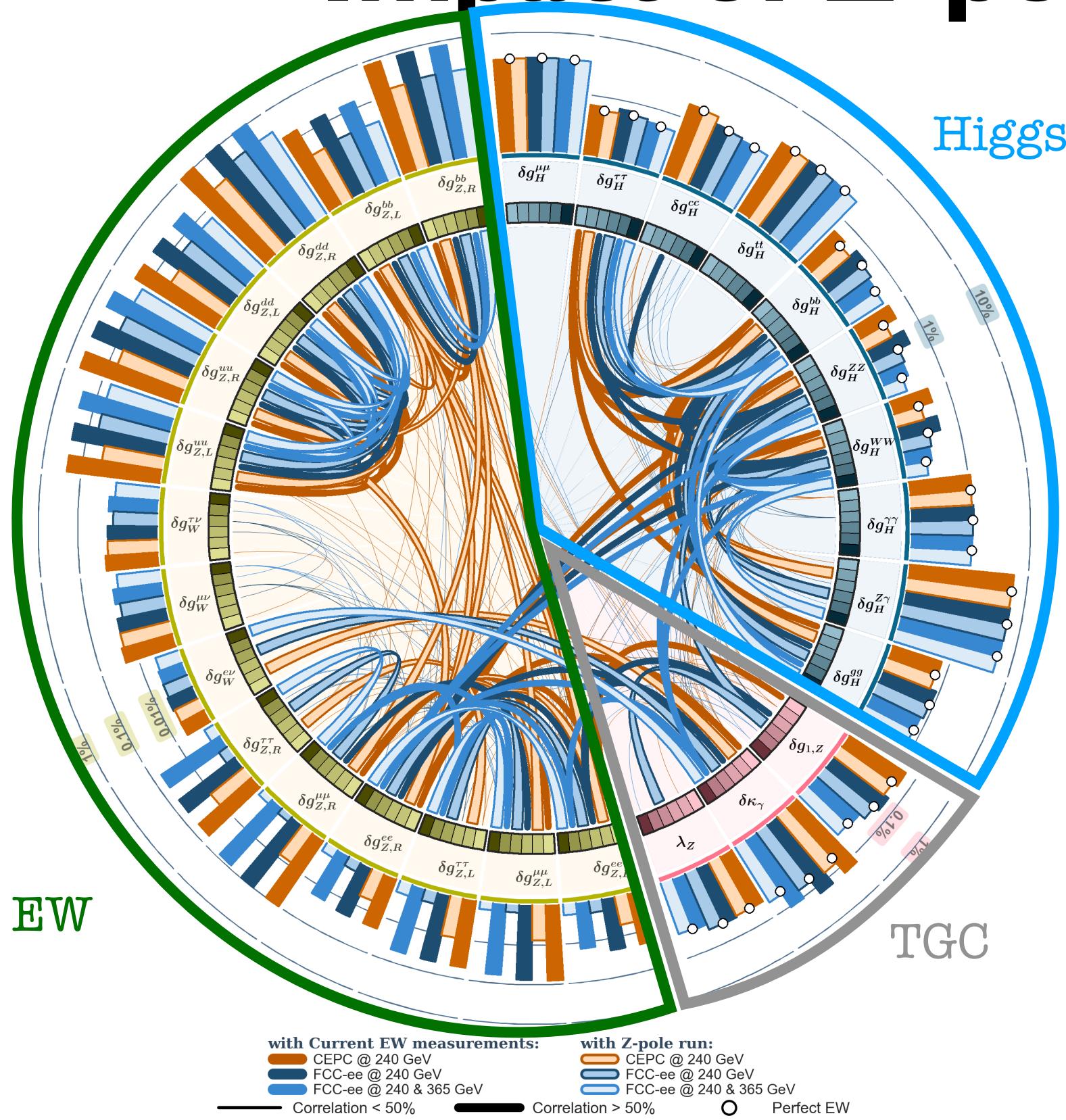


Contamination EW/TGC/Higgs can be understood by looking at correlations

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

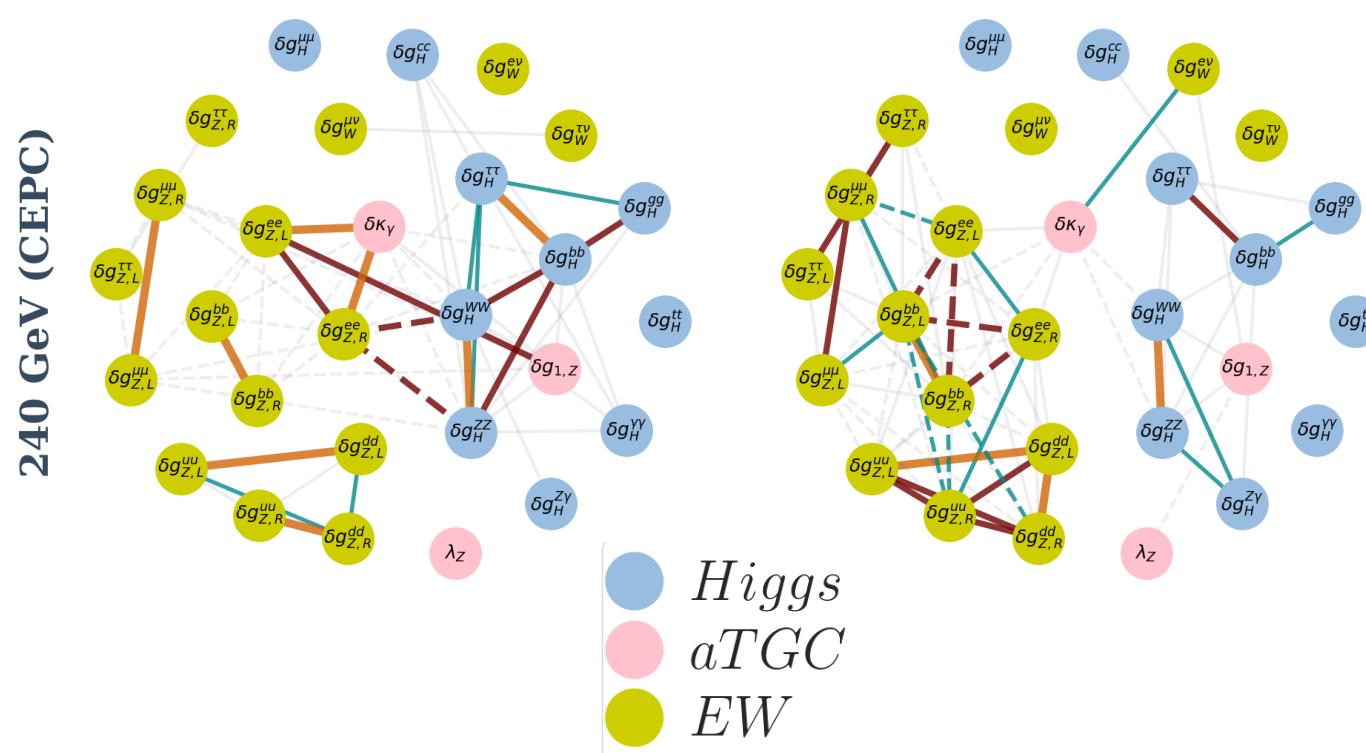
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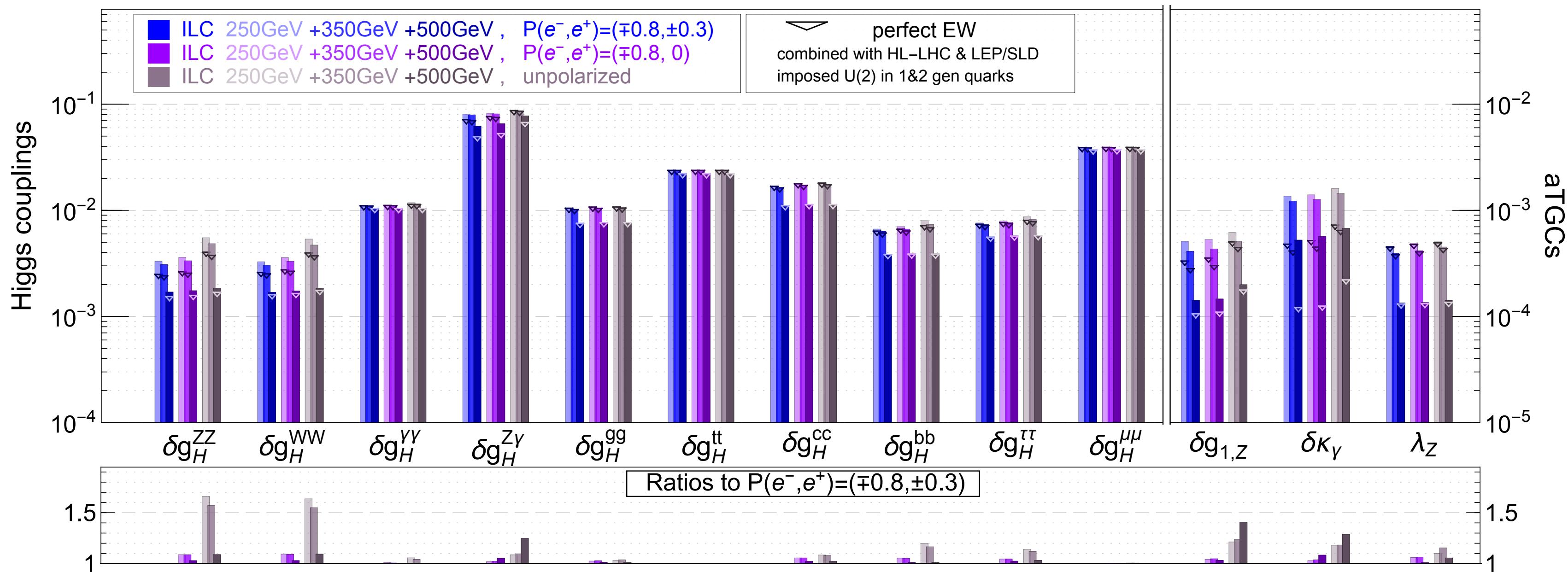
Contamination EW/TGC/Higgs can be understood by looking at correlations

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



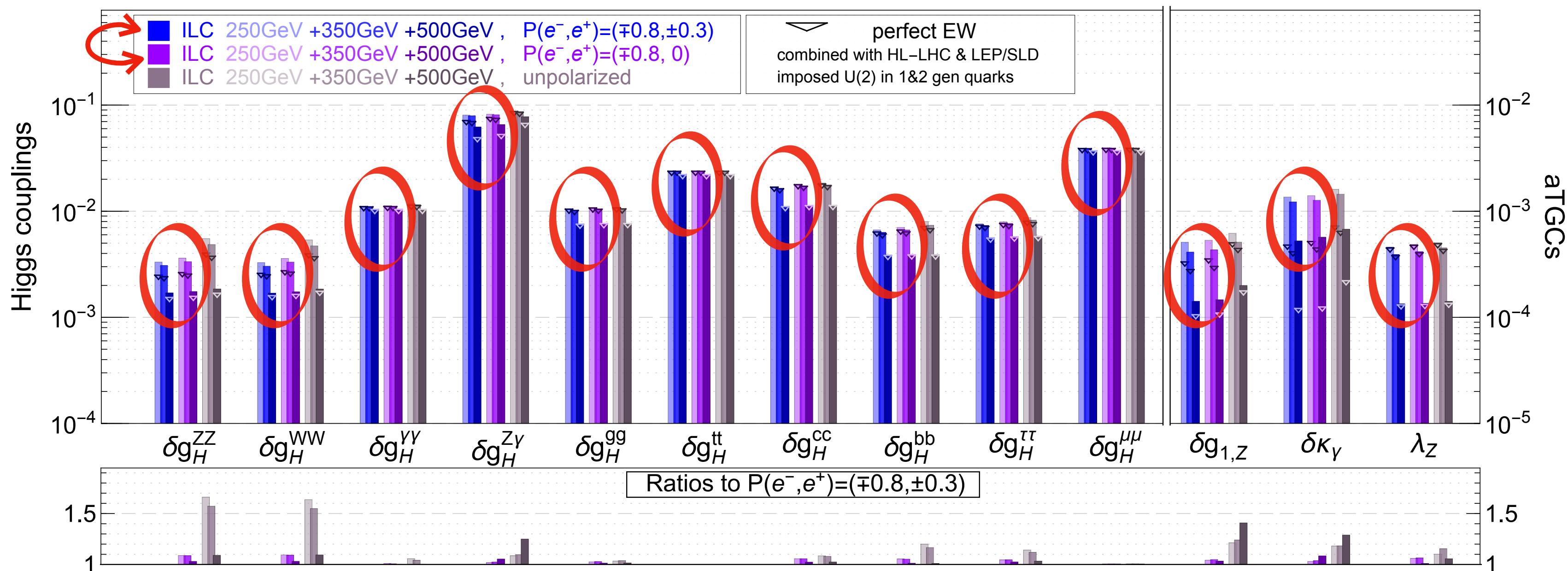
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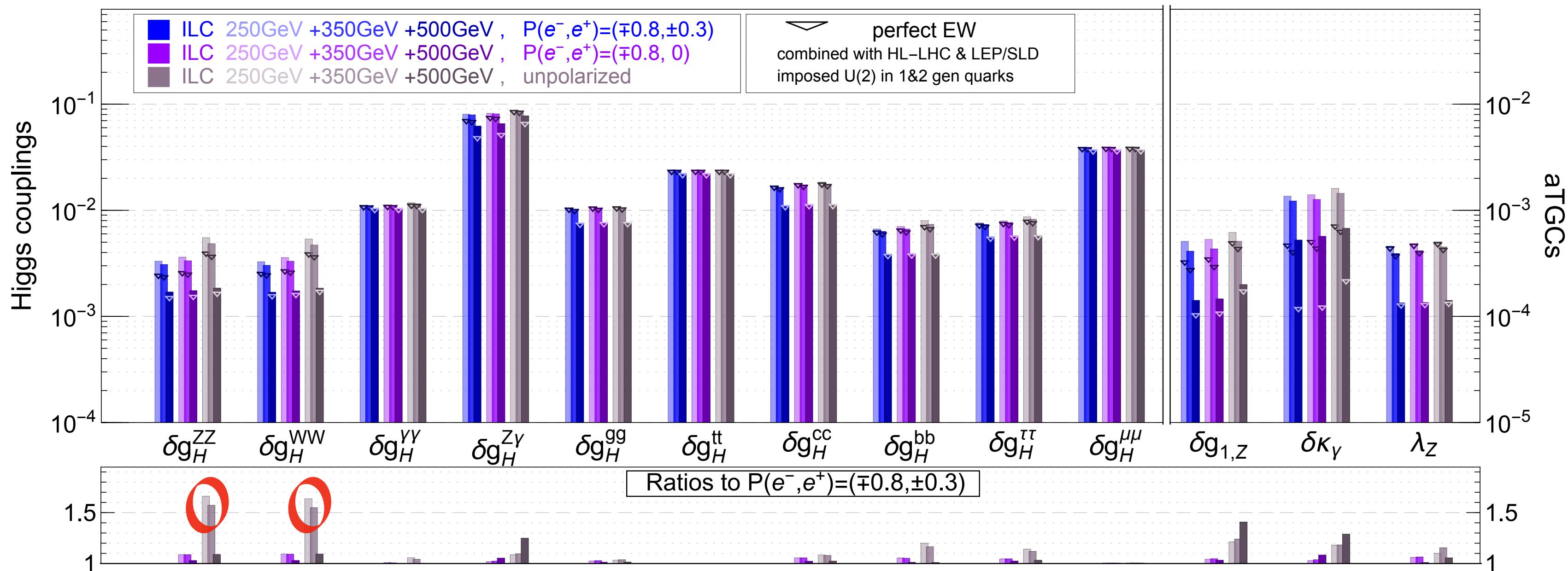
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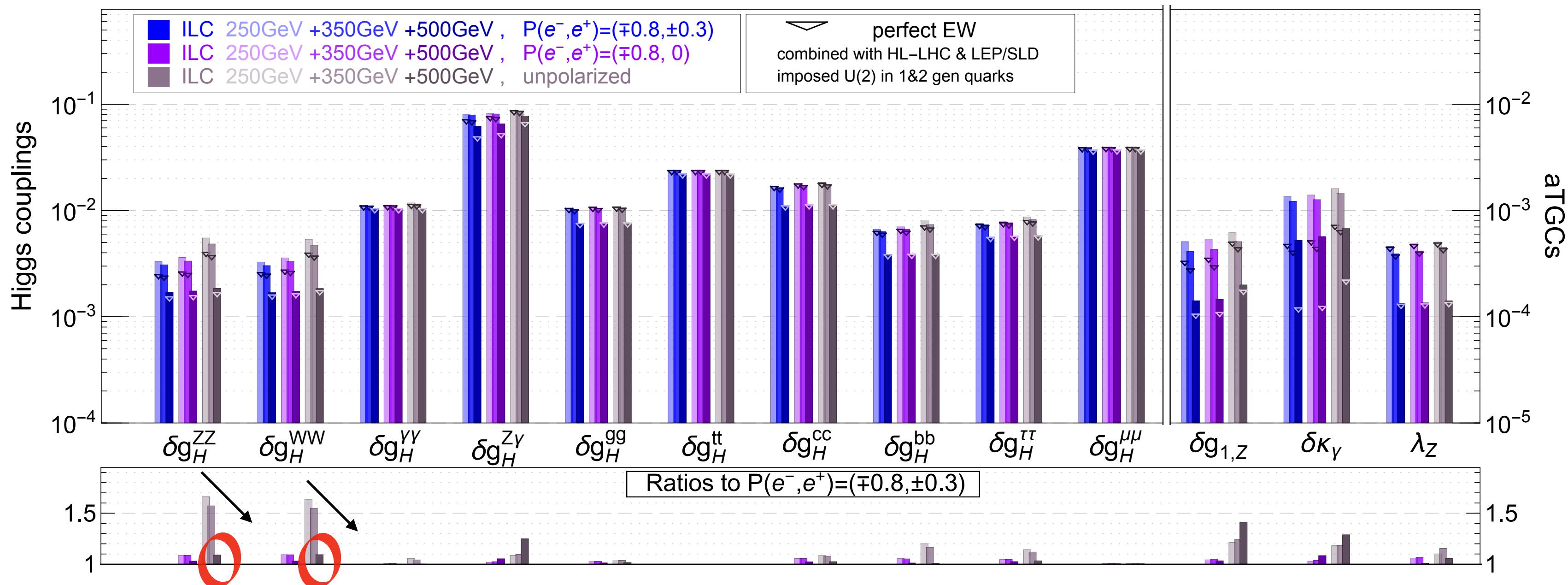
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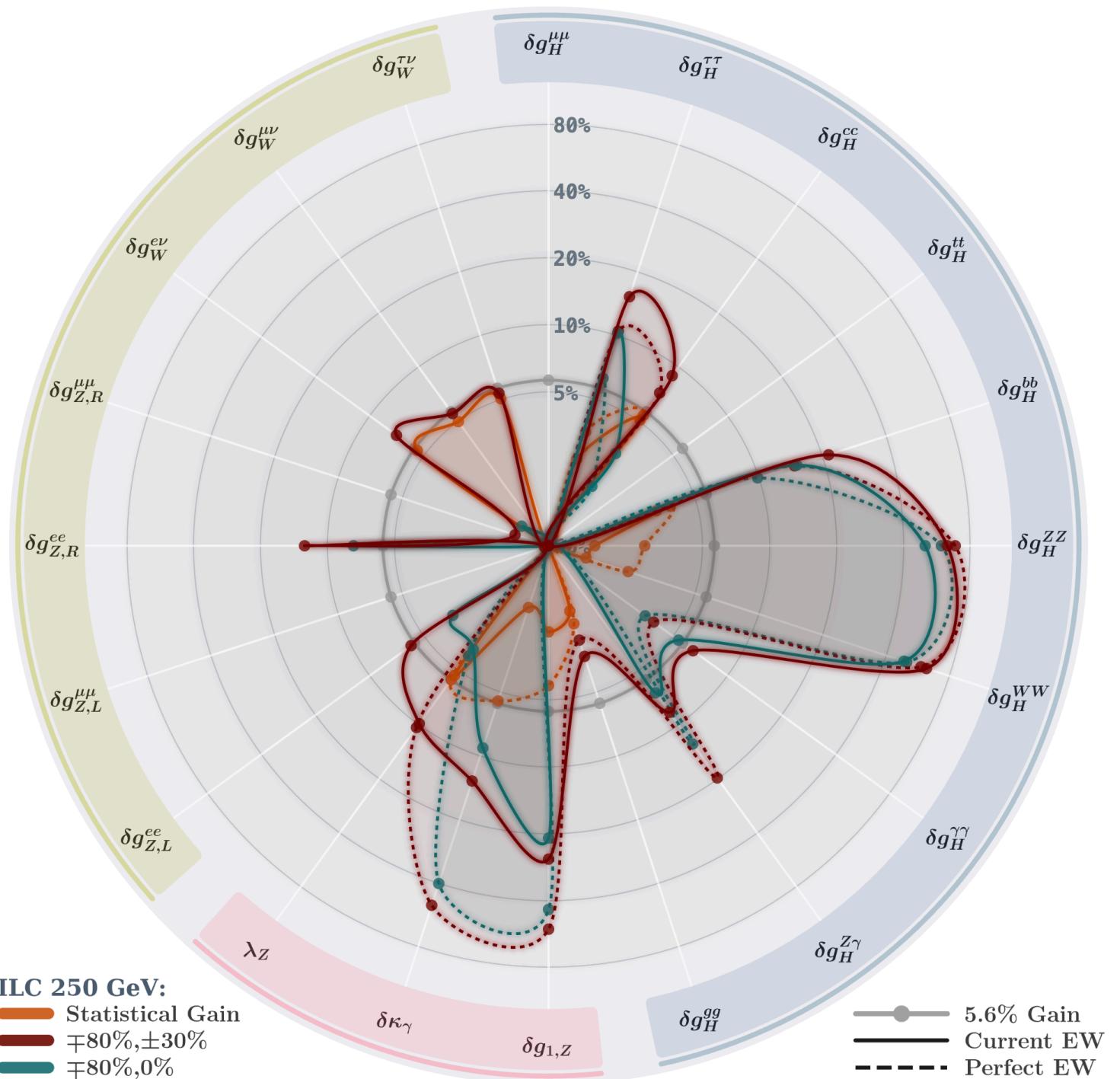
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# Impact of Beam Polarisation (@250GeV)

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



Statistical gain from increased rates

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

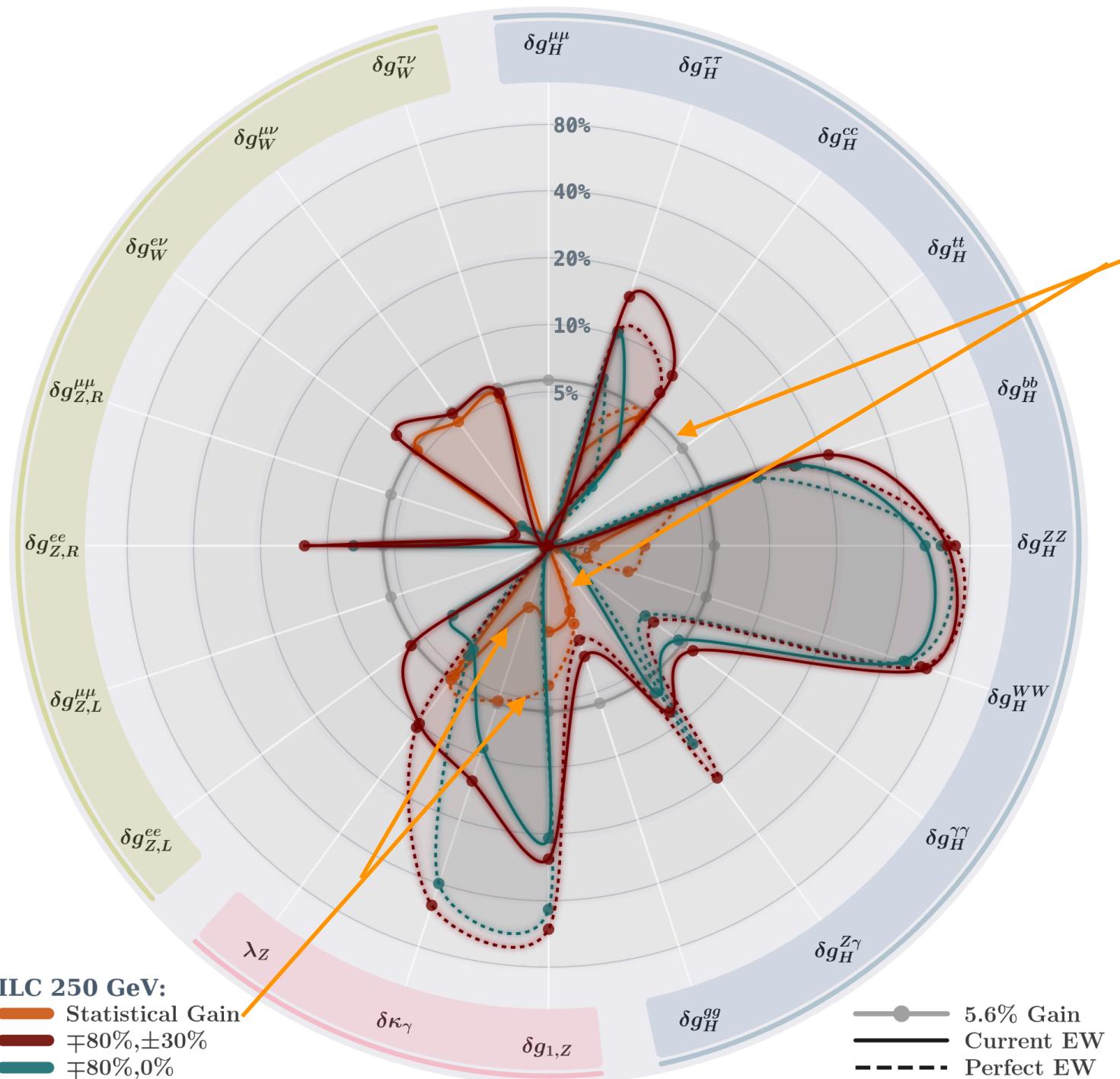
From  $ee \rightarrow Zh$ ,  $A_{LR} \sim 0.15$  so  $\sigma_{-80,+30} \sim 1.4 \sigma_0$

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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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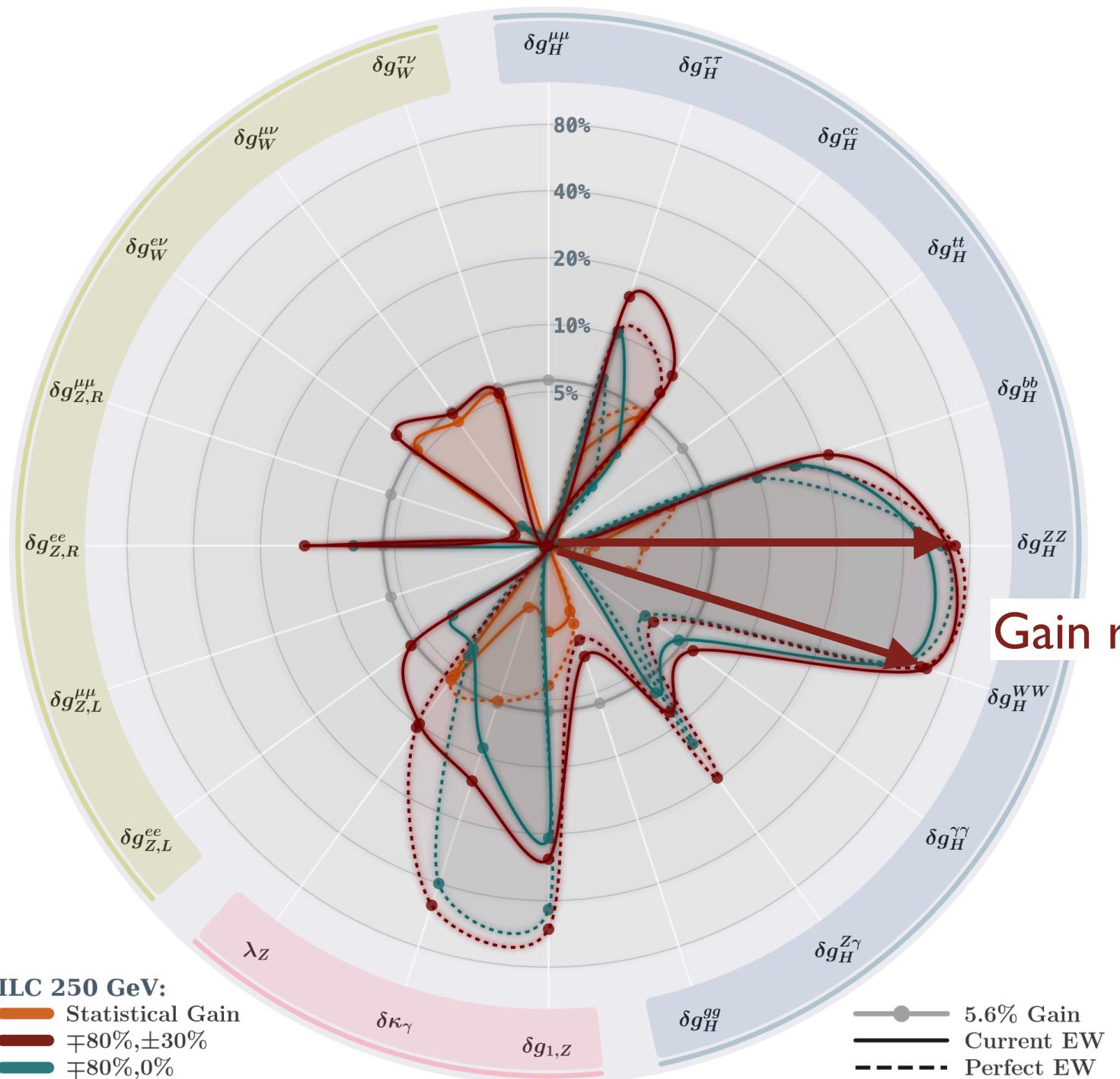
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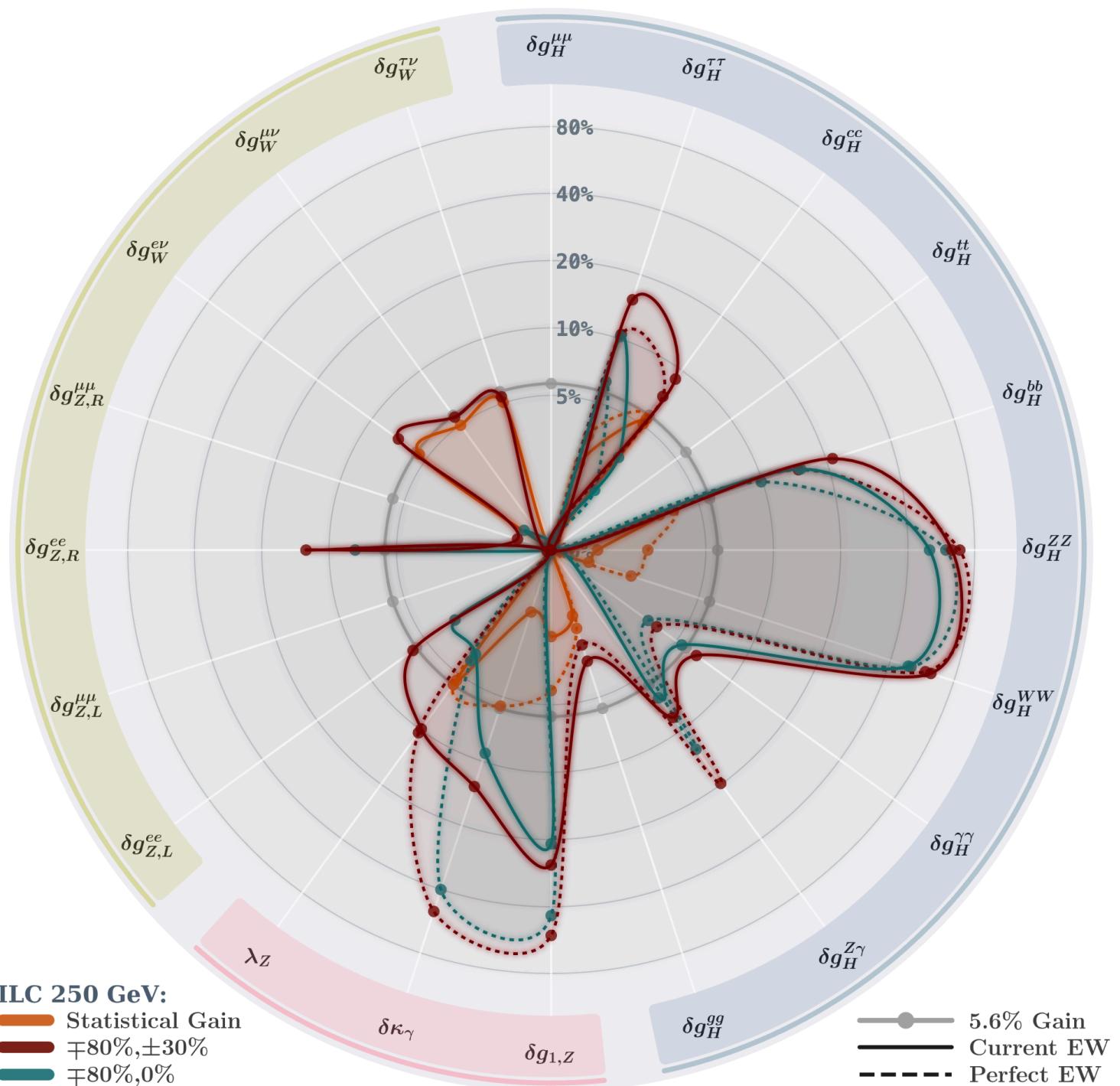
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Polarisation benefit diminishes when other runs  
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Basically left only with statistical gain

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# Higgs Self-Coupling

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

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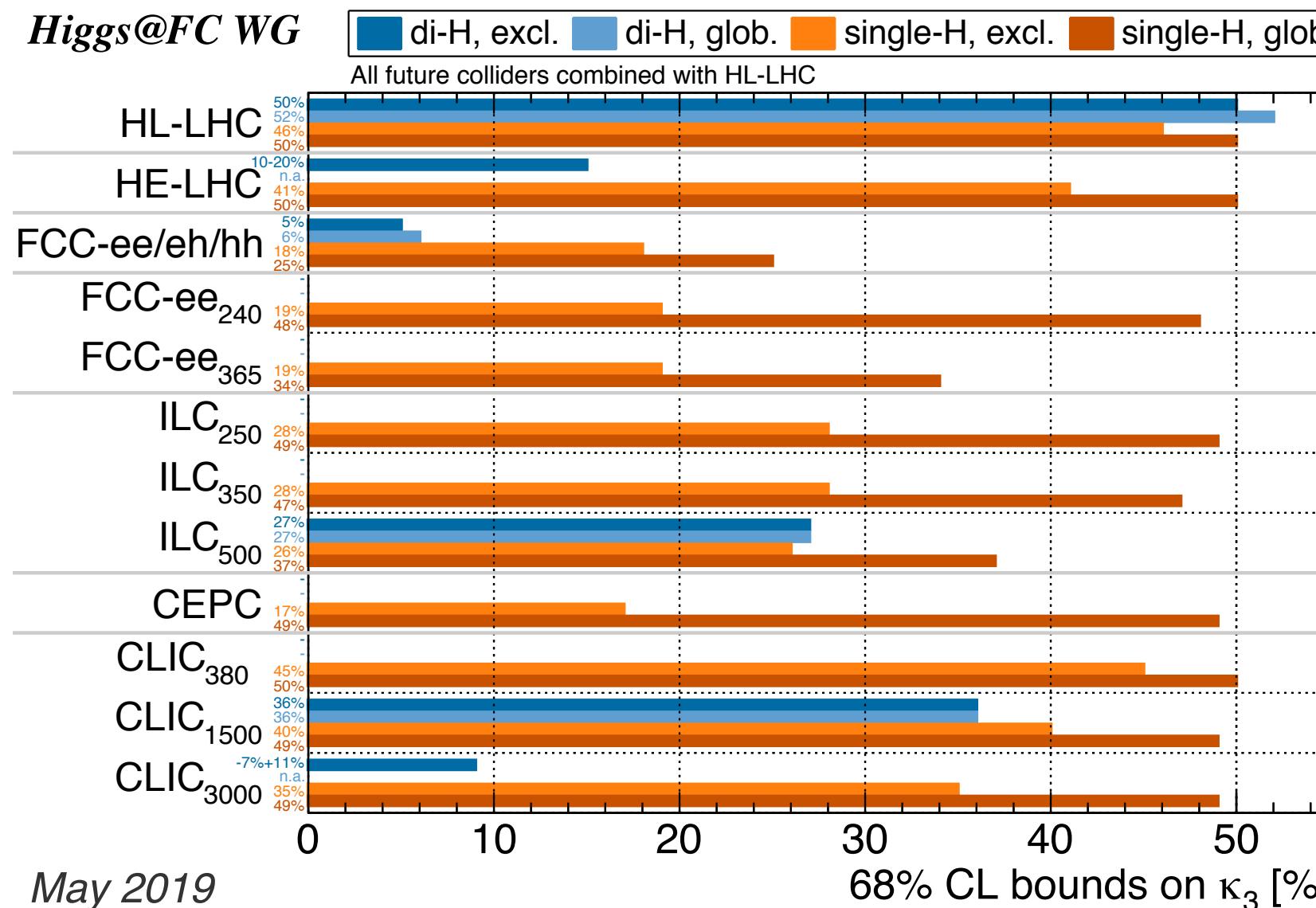
ECFA Higgs study group ,19

		Directly: Higgs-pair prod	Indirectly: via single Higgs
		Hadron Colliders	
Lepton Colliders	exclusive		
	global	<p><b>di-Higgs</b></p> <p><b>1. di-H, excl.</b></p> <ul style="list-style-type: none"> <li>• Use of <math>\sigma(HH)</math></li> <li>• only deformation of <math>\kappa\lambda</math></li> </ul> <p><b>2. di-H, glob.</b></p> <ul style="list-style-type: none"> <li>• Use of <math>\sigma(HH)</math></li> <li>• deformation of <math>\kappa\lambda</math> + of the single-H couplings</li> <li>(a) do not consider the effects at higher order of <math>\kappa\lambda</math> to single H production and decays</li> <li>(b) these higher order effects are included</li> </ul>	<p><b>single-H</b></p> <p><b>3. single-H, excl.</b></p> <ul style="list-style-type: none"> <li>• single Higgs processes at higher order</li> <li>• only deformation of <math>\kappa\lambda</math></li> </ul> <p><b>4. single-H, glob.</b></p> <ul style="list-style-type: none"> <li>• single Higgs processes at higher order</li> <li>• deformation of <math>\kappa\lambda</math> + of the single Higgs couplings</li> </ul>

# Higgs Self-Coupling

ECFA Higgs study group '19

*Higgs@FC WG*



**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:** 5 $\sigma$  discovery of the SM  $h^3$  coupling  
**5% sensitivity:** getting sensitive to quantum corrections to Higgs potential

# Conclusions

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Don't Higgsxit!  
Build a new collider!

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

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# Higgs couplings whose sensitivity improves by 2/5/10 compared to HL-LHC

	Factor $\geq 2$	Factor $\geq 5$	Factor $\geq 10$	Years from $T_0$
Initial run	CLIC380	9	6	4
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	HE-LHC	1	0	0
hh	ILC500	10	8	6
	CLIC3000	11	7	7
ee,eh & hh	FCC-ee/eh/hh	12	11	>50

Banker accounting:

Very important to get money

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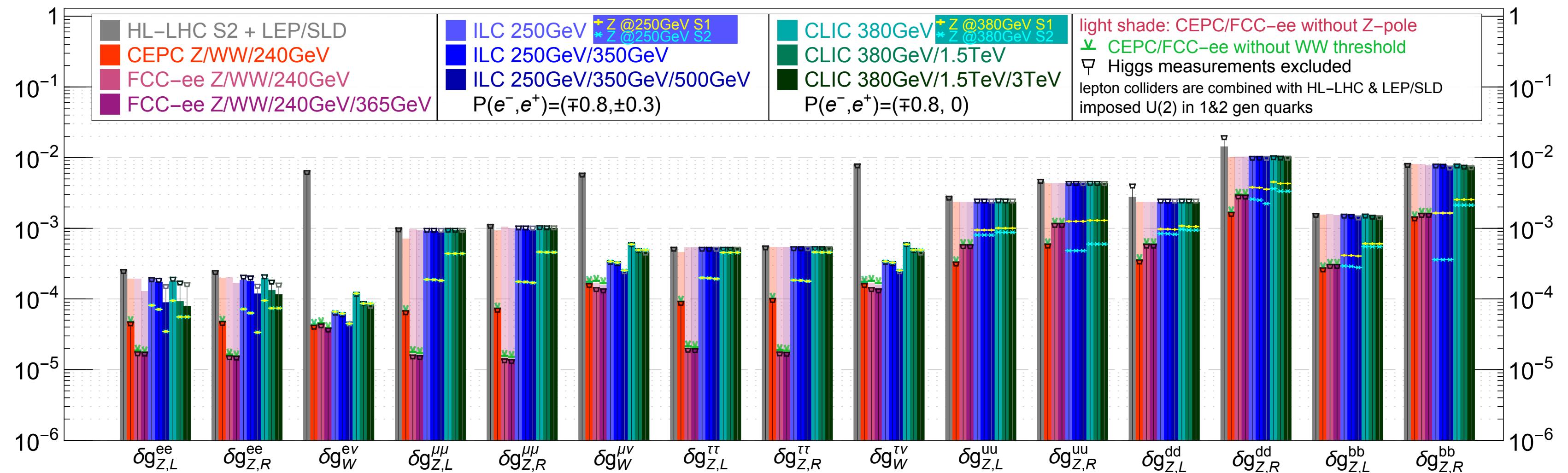
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B. Heinemann for Higgs@FCC WG  
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 will care maybe even more  
 about correlations  
 Nobody knows  
 what BSM is!  
 So impossible to compute  
 the figure of merit.

# EXTRA RESULTS

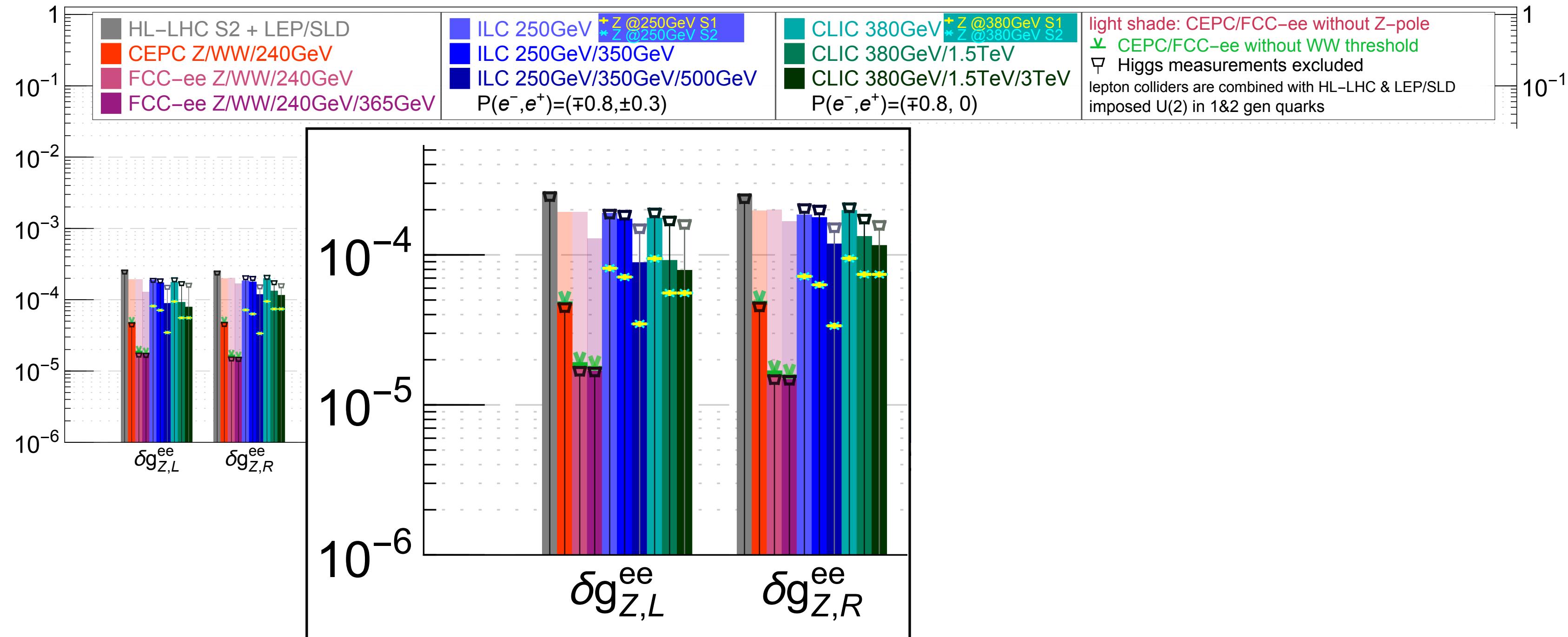
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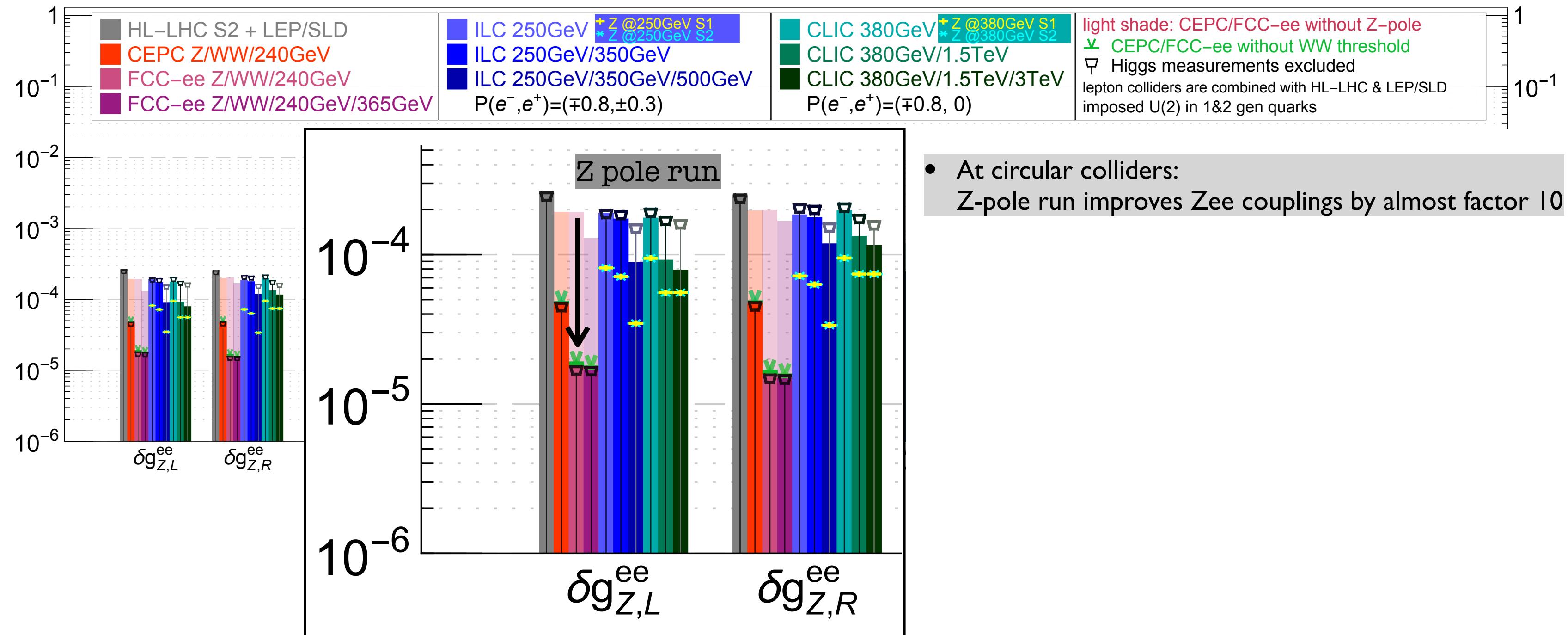
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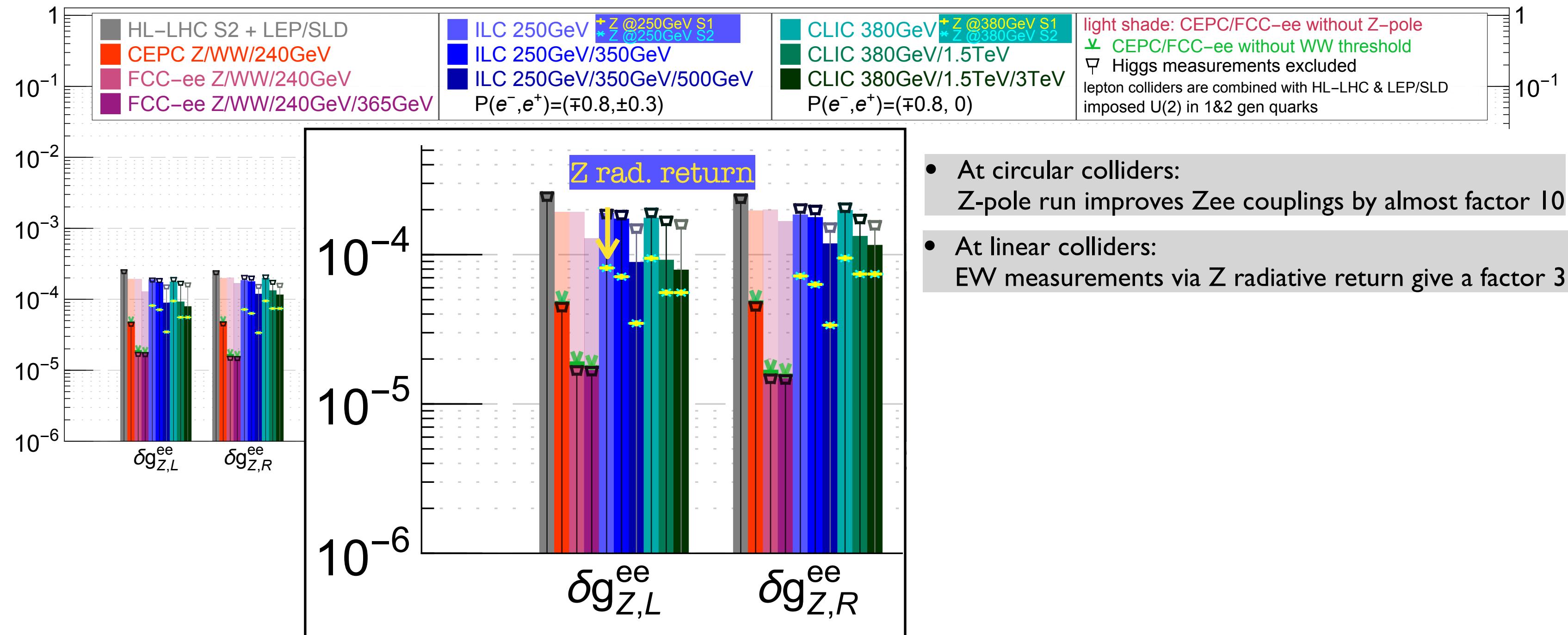
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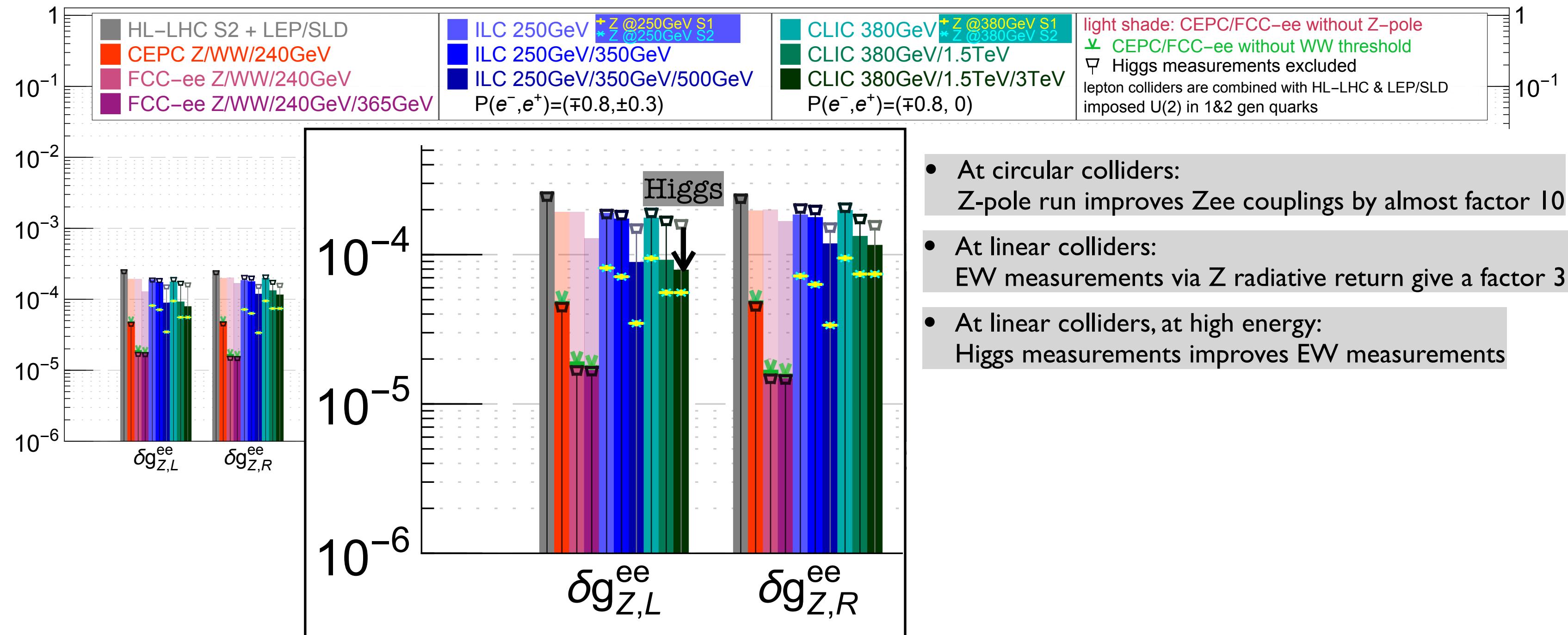
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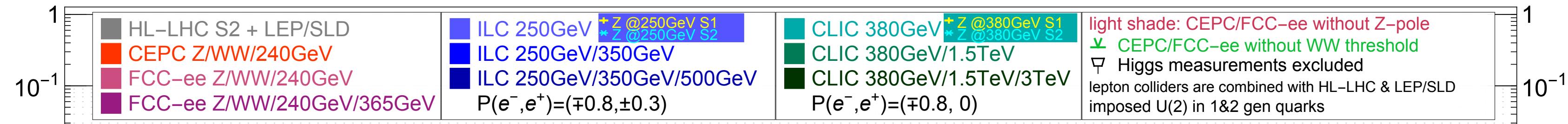
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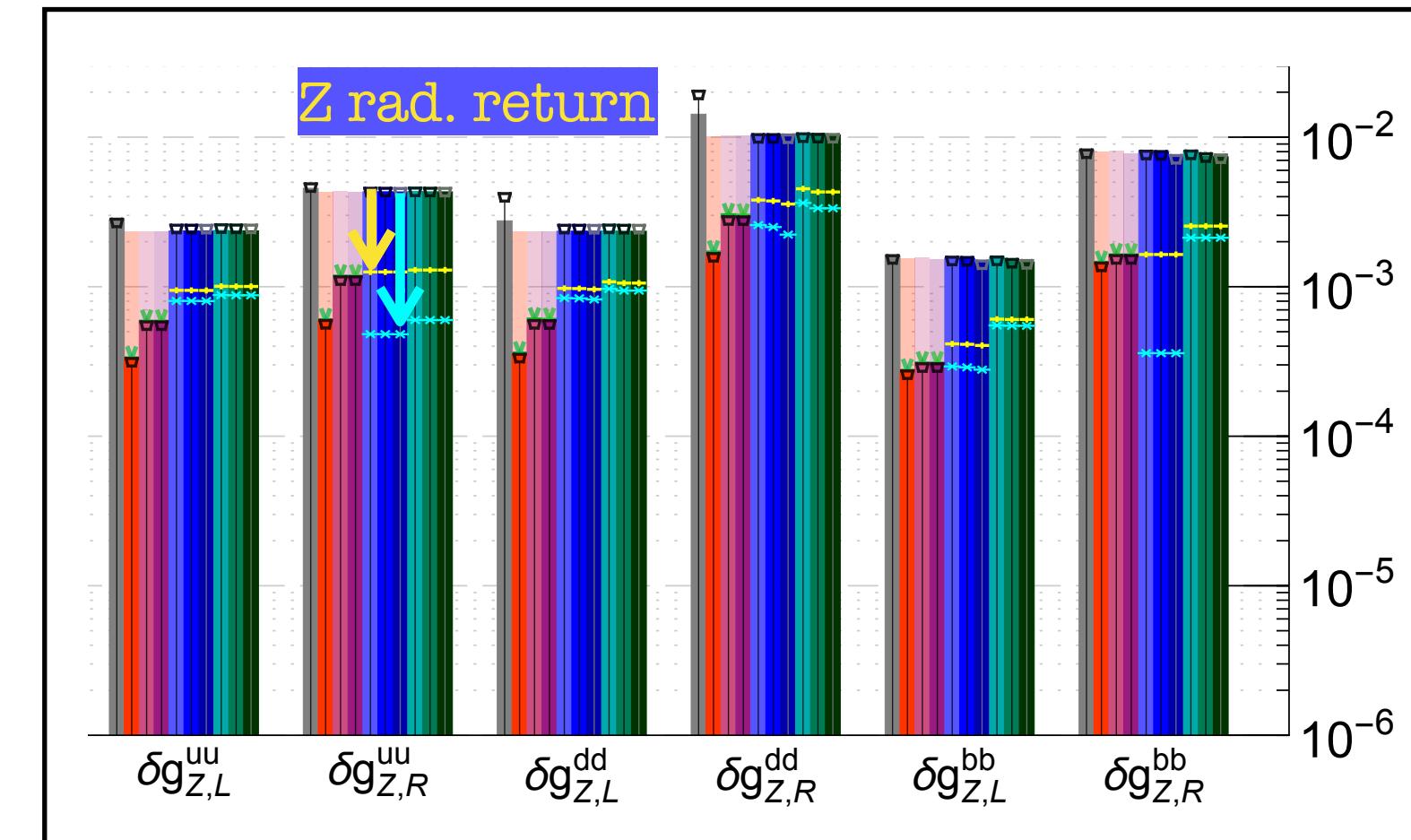


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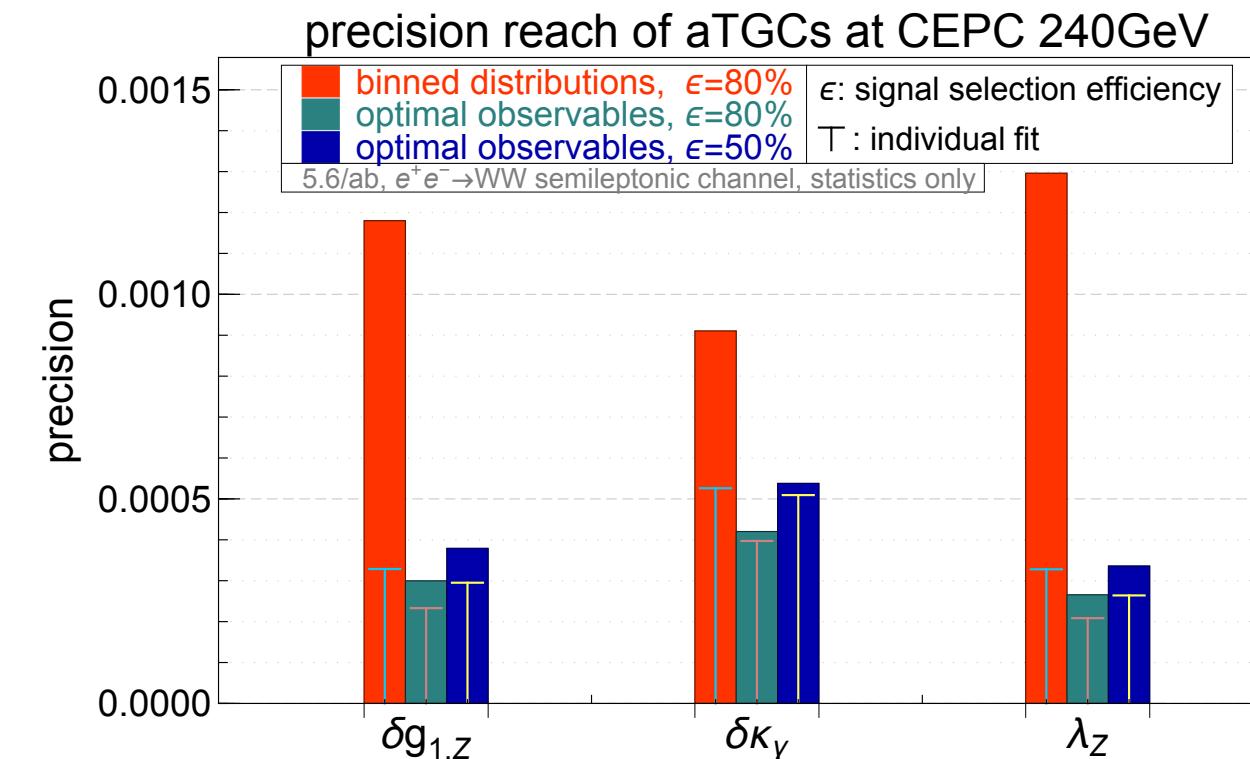


- At linear colliders, at high energy:  
EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties
  - Yellow: LEP/SLD systematics / 2
  - Blue: small EXP and TH systematics



# Impact of Diboson Systematics

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

