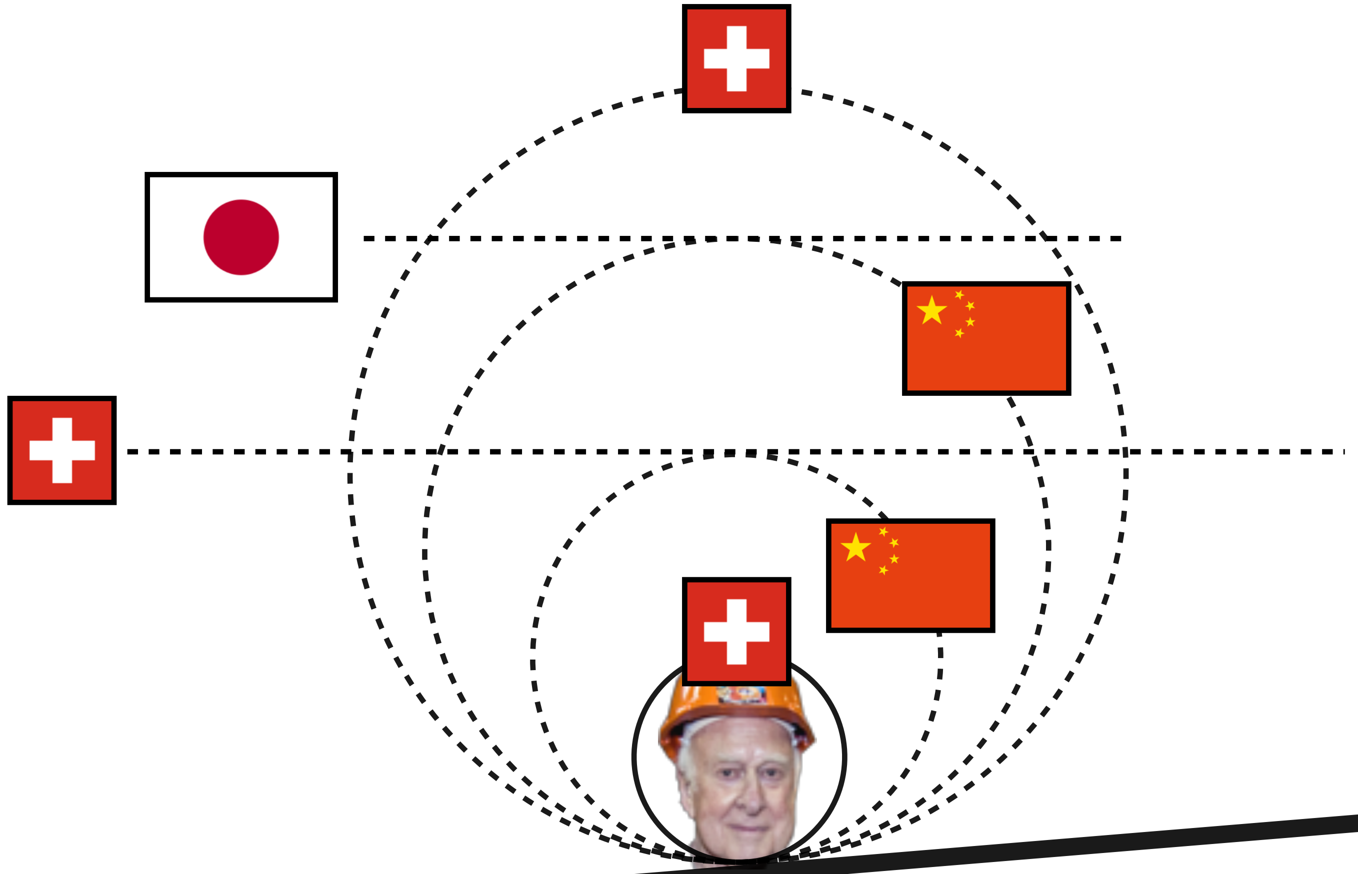
What will the Future Colliders know about the Higgs?

Planck 2019

Granada, June 6, 2019



Christophe Grojean

DESY (Hamburg)

Humboldt University (Berlin)

(christophe.grojean@desy.de)

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: $\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2 \, v^2}{\Lambda_{\rm BSM}^2}$

current (and future) LHC sensitivity
O(10-20)% ⇔ Λ_{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 a magic number to probe naturalness of EW sector

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

Measuring Higgs couplings to 1%
=
Probing Higgs structure to 1/10th of its Compton wave-length

i.e. learning if the Higgs is an elementary particle!

e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted to probe BSM physics

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

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 $Z/W/\gamma/g$
  - Rare SM and BSM decays ($H\to$Meson+γ, $Z\gamma$, 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

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→Meson+γ, Zγ, FCNC, μe/τμ/τe, …)
  - 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

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 ⇖

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 collider

Which Machine(s)?

Hadrons

- large mass reach ⇒ exploration?
- S/B
- S/B
- requ
- only
- ⇒ c

Leptons

- S/B ~ 1 ⇒ measurement?
- s)

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

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Circu

- high
- sev
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- √s limited by synchroton radiation

Linear

- “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 collider

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B
- S/B
- requ
- only
- ⇛ c

Leptons

- S/B ~ 1 ⇛ measurement?

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

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Circu

- high
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolariza
- √s limited by synchroton r

Linear

- ": less power consumption*
- amsthralung
- one IP only

Three questions addressed in this talk:
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 collider

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

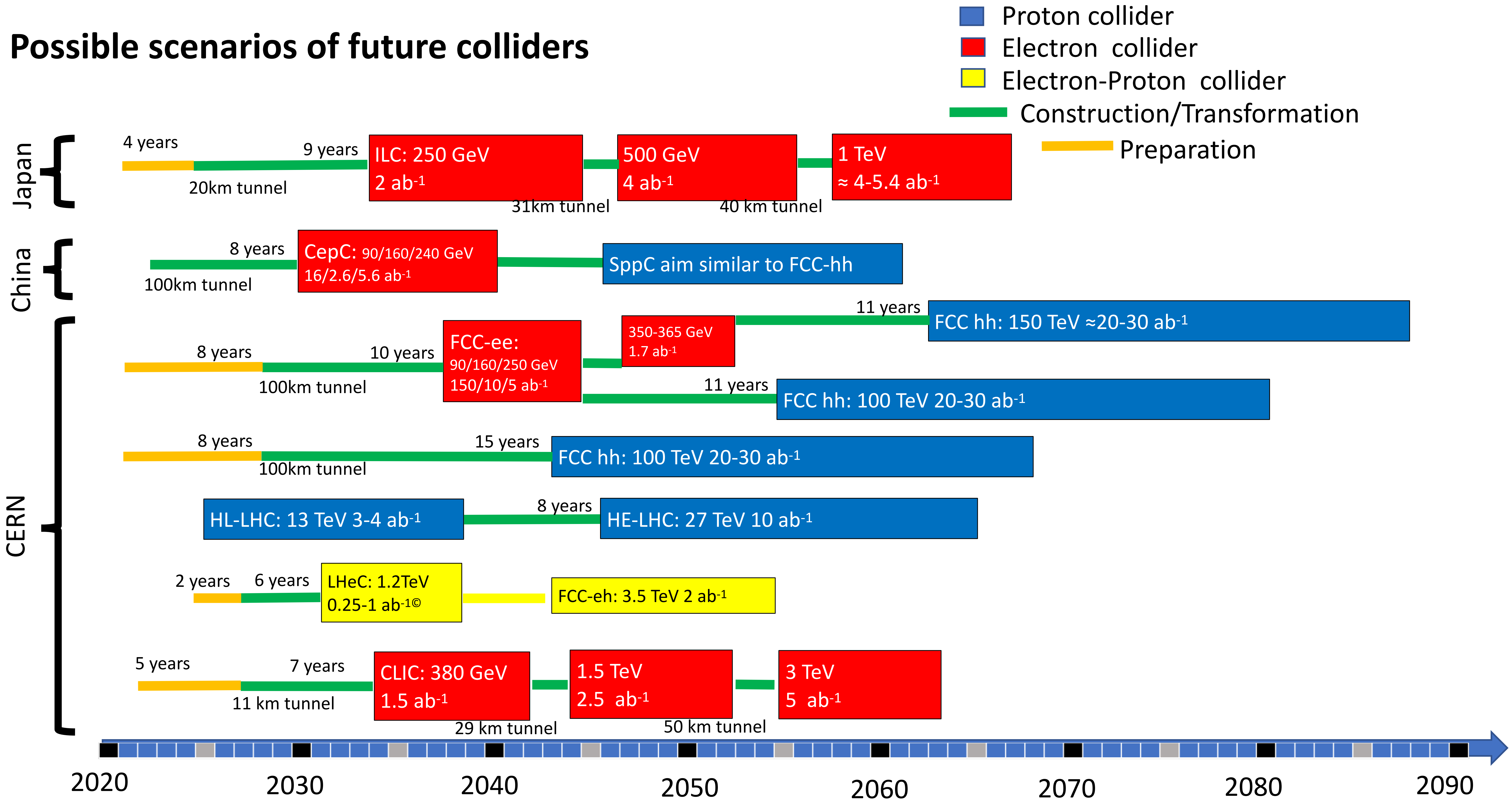
Subject to large uncertainty
1) need a scientific consensus
2) political approval

	T_0 … +5 … +10 … +15 … +20 … +26							T_0
ILC	0.5/ab 250 GeV		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

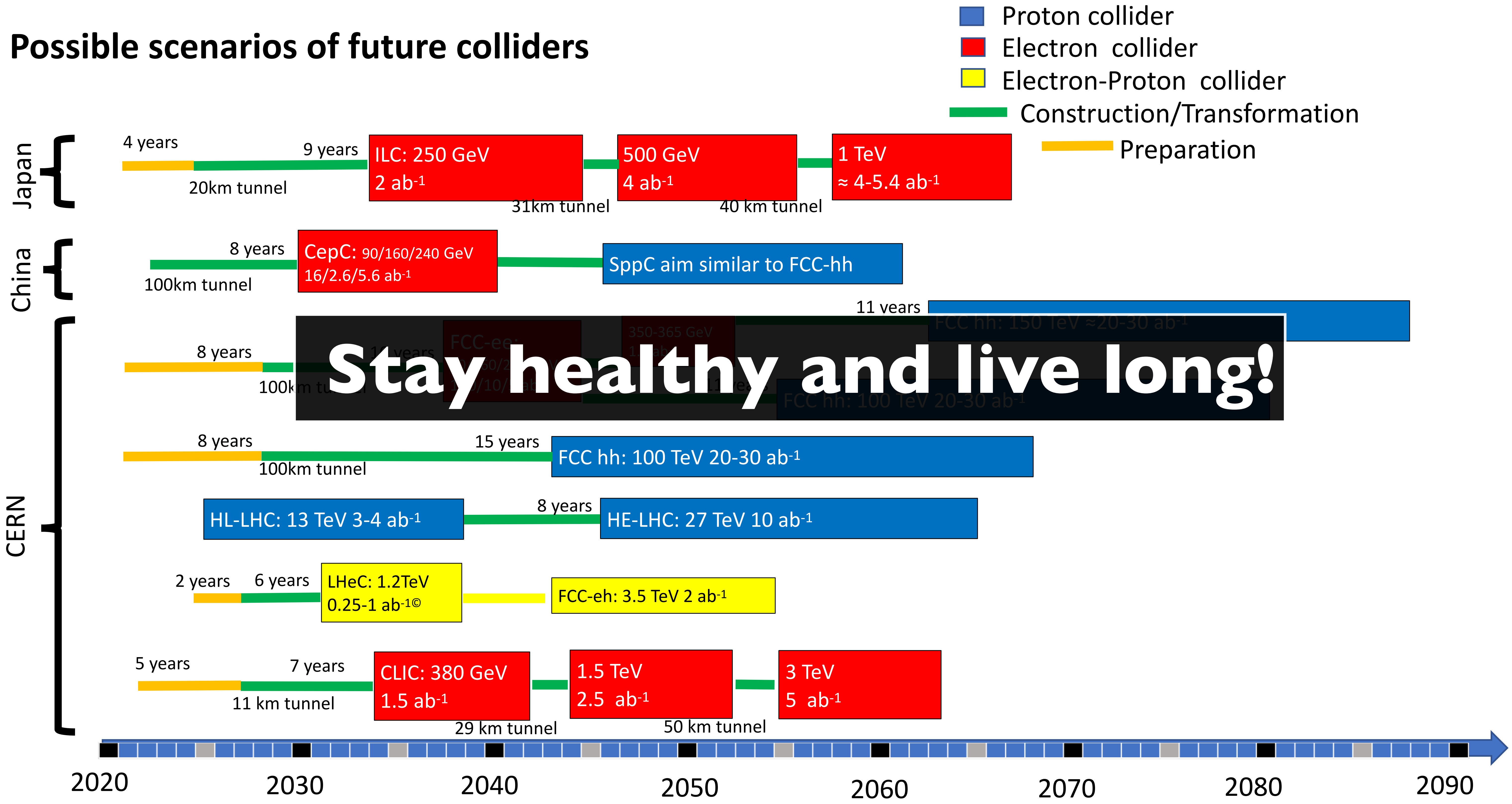
Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

Future of HEP

Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

Higgs: ee colliders vs LHC

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: m_H and Γ_H

↠ reduce parametric uncertainties in xs and BR

↠ control the fate of EW vacuum within the SM

↠ constrain new physics models (e.g. MSSM, twin Higgs)

(2) Precise and model-independent access to Higgs couplings

↠ 1% level

↠ identification of correlation patterns among deviations

↠ indirect test of extended Higgs sectors/composite nature

↠ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

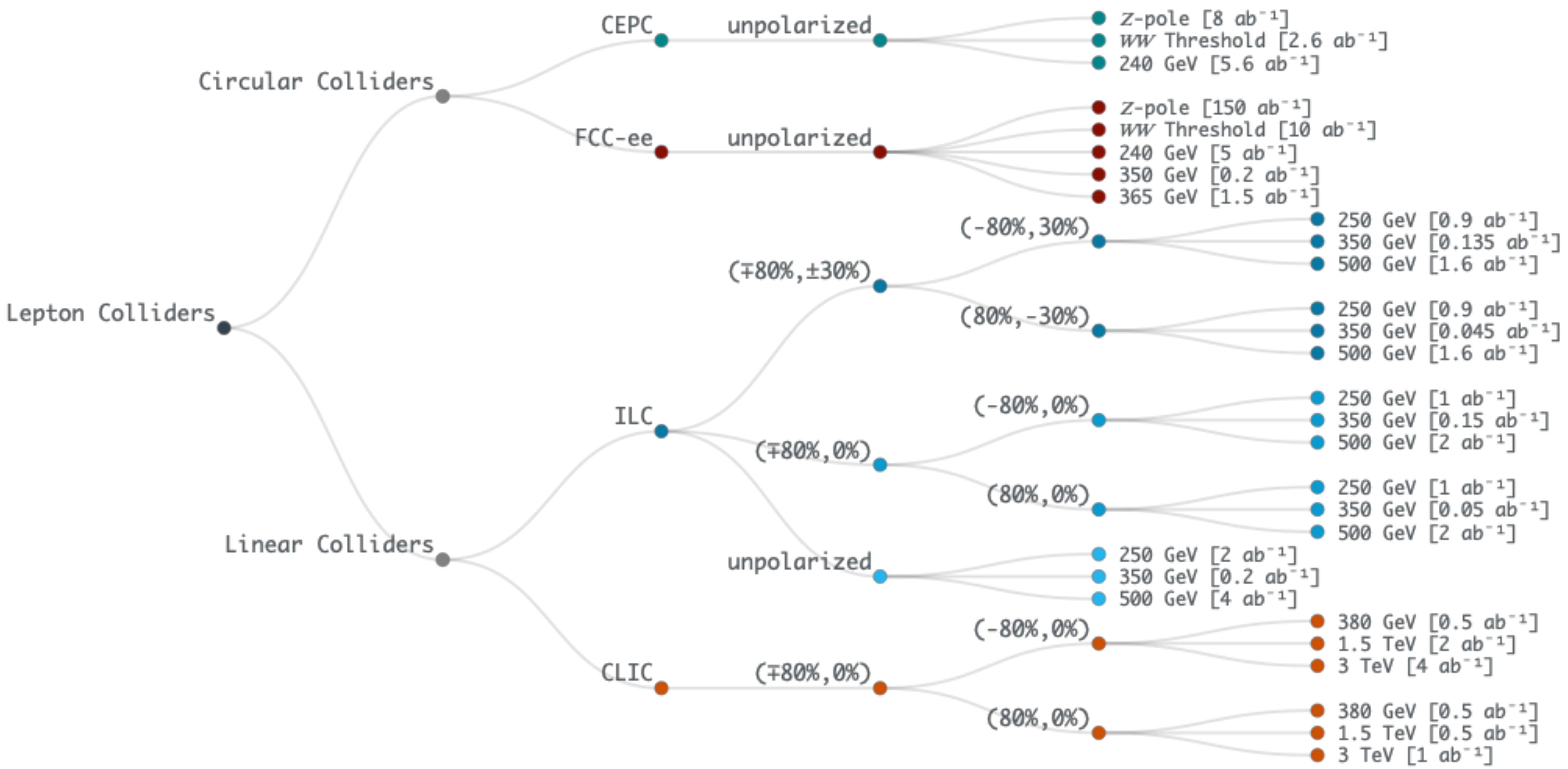
↠ bb/cc/gg

↠ exotic decay modes (⤷ portal models of Dark Matter)

(4) Constraints on Higgs flavour violating couplings

↠ shed light on the origin of fermion masses and flavours

The Leptonic Future



Higgs physics vs BSM

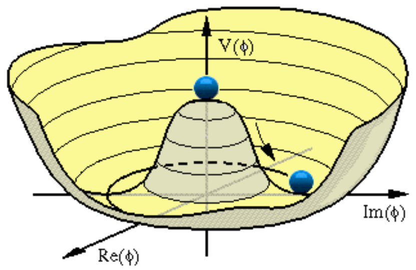
(assuming EW symmetry linearly realized and that new physics is heavy)

Several deformations
away from the SM
affecting Higgs properties
are already probed in the vacuum

(courtesy of A. Pomarol@Moriond2014)

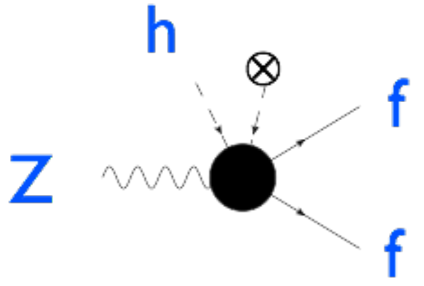
$\phi = v + h$

↳ vacuum

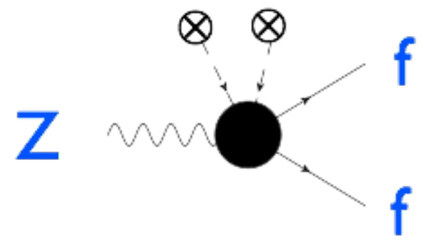


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

e.g.



$$= \frac{1}{2v} \times$$



$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

(assuming that the Higgs boson is part of a doublet)

Modifications in h→Zff related to Z→ff

consistency check
not discovery mode

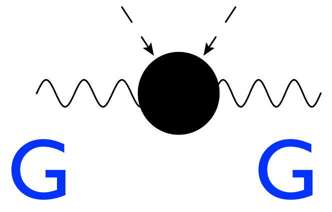
One can use h→ZZ→4l to probe this deformation
but hard time to compete with LEP bounds

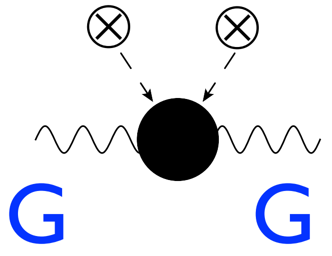
Higgs/BSM Primaries

There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

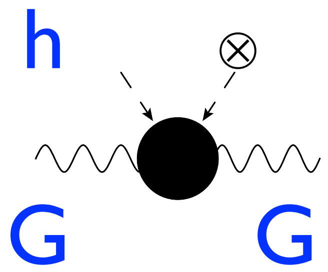
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





operator
not visible in the vacuum
(redefinition of input parameter)

But can affect h physics:



affects GG →h!

operator
visible in Higgs physics

Higgs/BSM Primaries

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

How many of these effects can we have?

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

g_s	$\vert H\vert^2 G^A_{\mu\nu} G^{A\mu\nu}$	→ **GGh coupling**
g	$\vert H\vert^2 B_{\mu\nu} B^{\mu\nu}$	→ **hγγ coupling**
g'	$\vert H\vert^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	→ **hZγ coupling**
m_W	$\vert H\vert^2 \vert D_\mu H\vert^2$	→ **hVV*** (custodial invariant)
m_h	$\vert H\vert^6$	→ **h^3 coupling**
m_f (f=t,b,τ)	$\vert H\vert^2 \bar{f}_L H f_R + h.c.$	→ **htt, hbb, h$\tau\tau$**

Higgs/BSM Primaries

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

How many of these effects can we have?

As many as parameters in the SM: **8** for one family
(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	⟶	**GGh coupling**
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	⟶	**hγγ coupling**
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	⟶	**hZγ coupling**
m_W	$\|H\|^2 \|D_\mu H\|^2$	⟶	**hVV* (custodial invariant)**
m_h	$\|H\|^6$	⟶	**h^3 coupling**
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$		

yet to be measured at the LHC

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

Higgs/BSM Primaries

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

How many of these effects can we have?

As many as parameters in the SM: 8

for one family
(assuming CP-conservation)

g_s $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ ⟶ GGh coupling

g $|H|^2 B_{\mu\nu} B^{\mu\nu}$ ⟶ hγγ coupling

yet to be measured

This counting was relevant at LHC.
But it has to be revisited at future colliders
when Higgs measurements will improve and compete with EW/diboson sensitivity

m_W $|H|^2 |D_\mu H|^2$ ⟶ hVV* (custodial invariant)

m_h $|H|^6$ ⟶ h^3 coupling

m_f $|H|^2 \bar{f}_L H f_R + h.c.$
$(f=t,b,\tau)$

the 6 others have been measured (~15%)
up to a flat direction between between
the top/gluon/photon couplings

How to report Higgs data: from κ to EFT

one doesn't have to succeed on the first try

"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

M. Zuckerberg created FaceMash before Facebook

one doesn't have to succeed on the first try
"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

one doesn't have to succeed on the first try
"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

Beyonce wrote hundreds of songs before 'Halo'

one doesn't have to succeed on the first try
"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

M. Zuckerberg created FaceMash before Facebook

J.K. Rowling got rejected 12 times by editors before she published Harry Potter

Beyonce wrote hundreds of songs before 'Halo'

... Physicists used signal strengths to report Higgs data before ...

one doesn't have to succeed on the first try
"the success comes from the freedom to fail"

M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

LHCHXSWG '12

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 valid even with light new physics, i.e. exotic decays
- Captures leading effects of UV motivated scenarios (SUSY, composite)

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

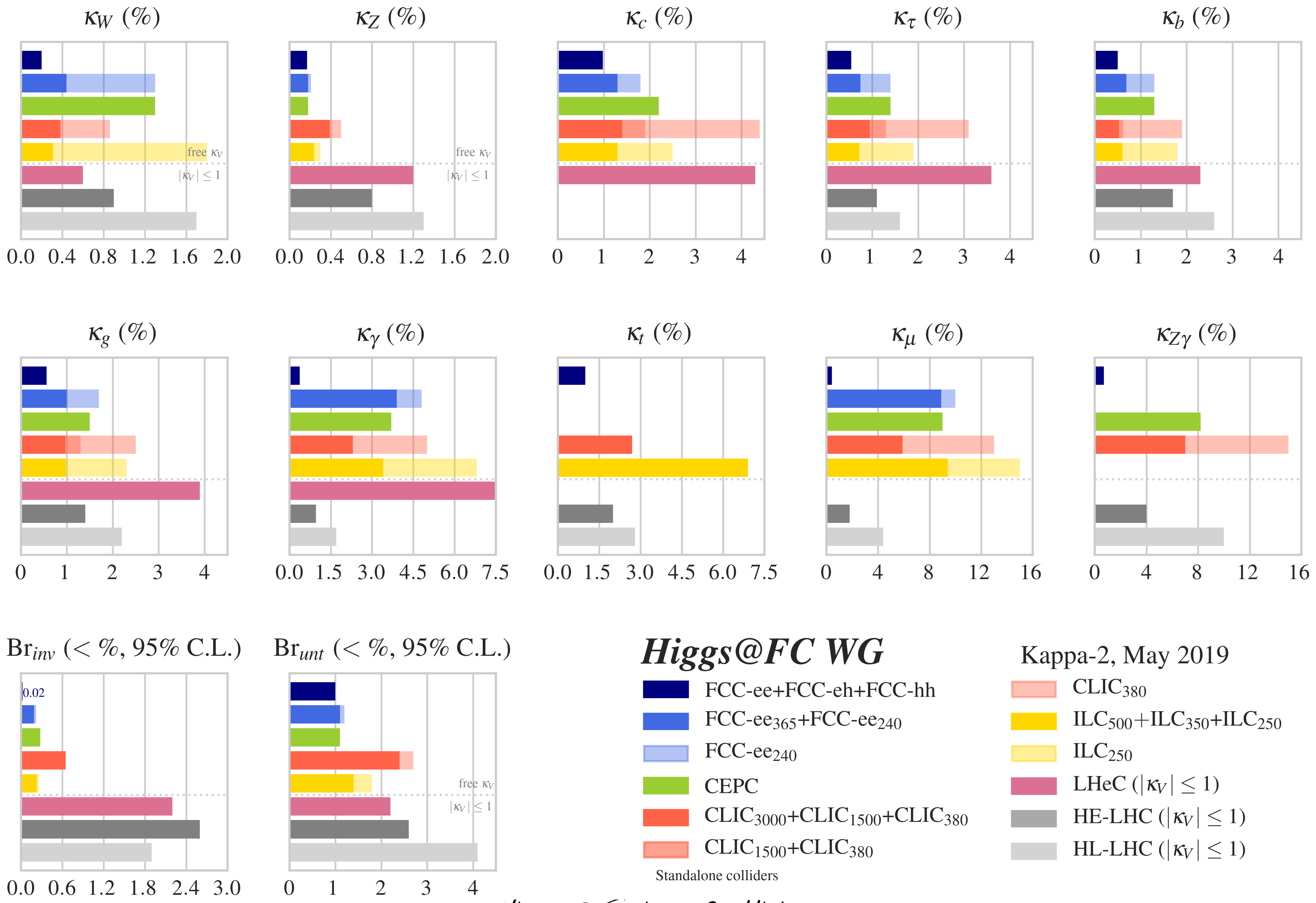
- Kappa fit method described in https://arxiv.org/abs/1209.0040 : *LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle.*
  - $k^2_X = \Gamma_{H\to X} / \Gamma^{SM}_{H\to X}$
  - for top coupling above the ttH threshold: $k^2_t = \sigma_{ttH} / \sigma^{SM}_{ttH}$
- 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

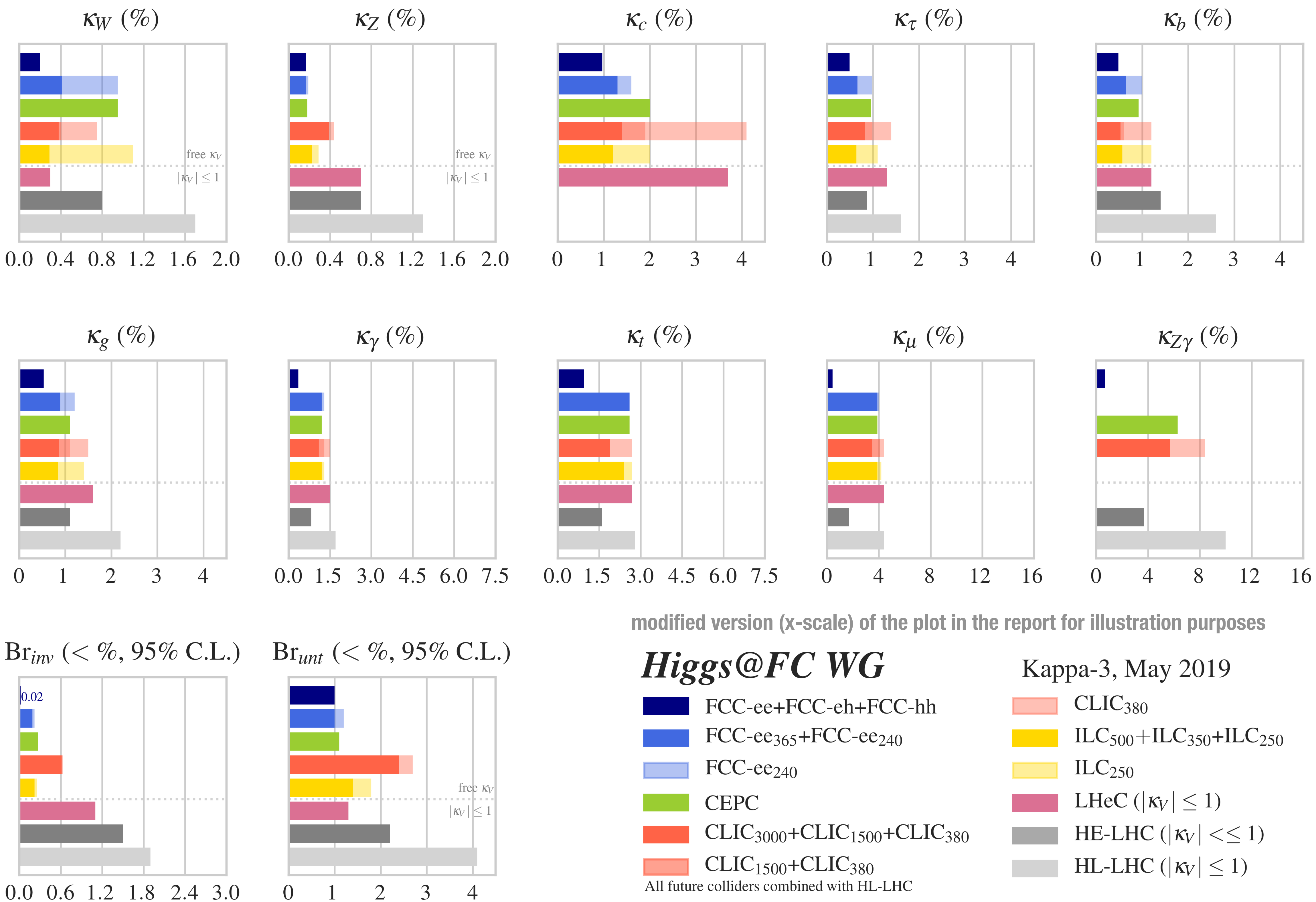
Results of kappa-2 fit

ECFA Higgs study group '19



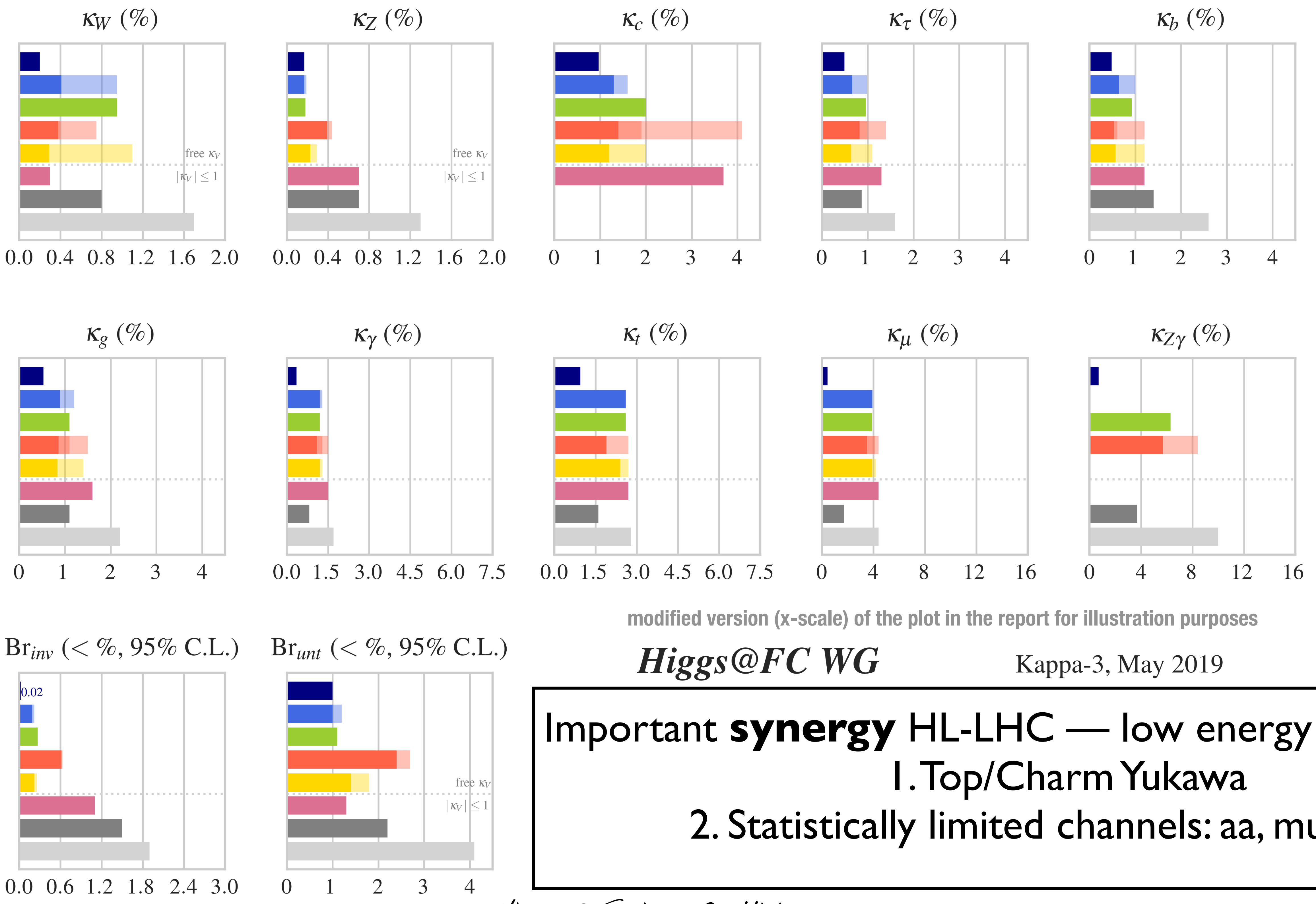
Results of kappa-3 fit

ECFA Higgs study group ‘19



Results of kappa-3 fit

ECFA Higgs study group ‘19



Important **synergy** HL-LHC — low energy lepton colliders

1. Top/Charm 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

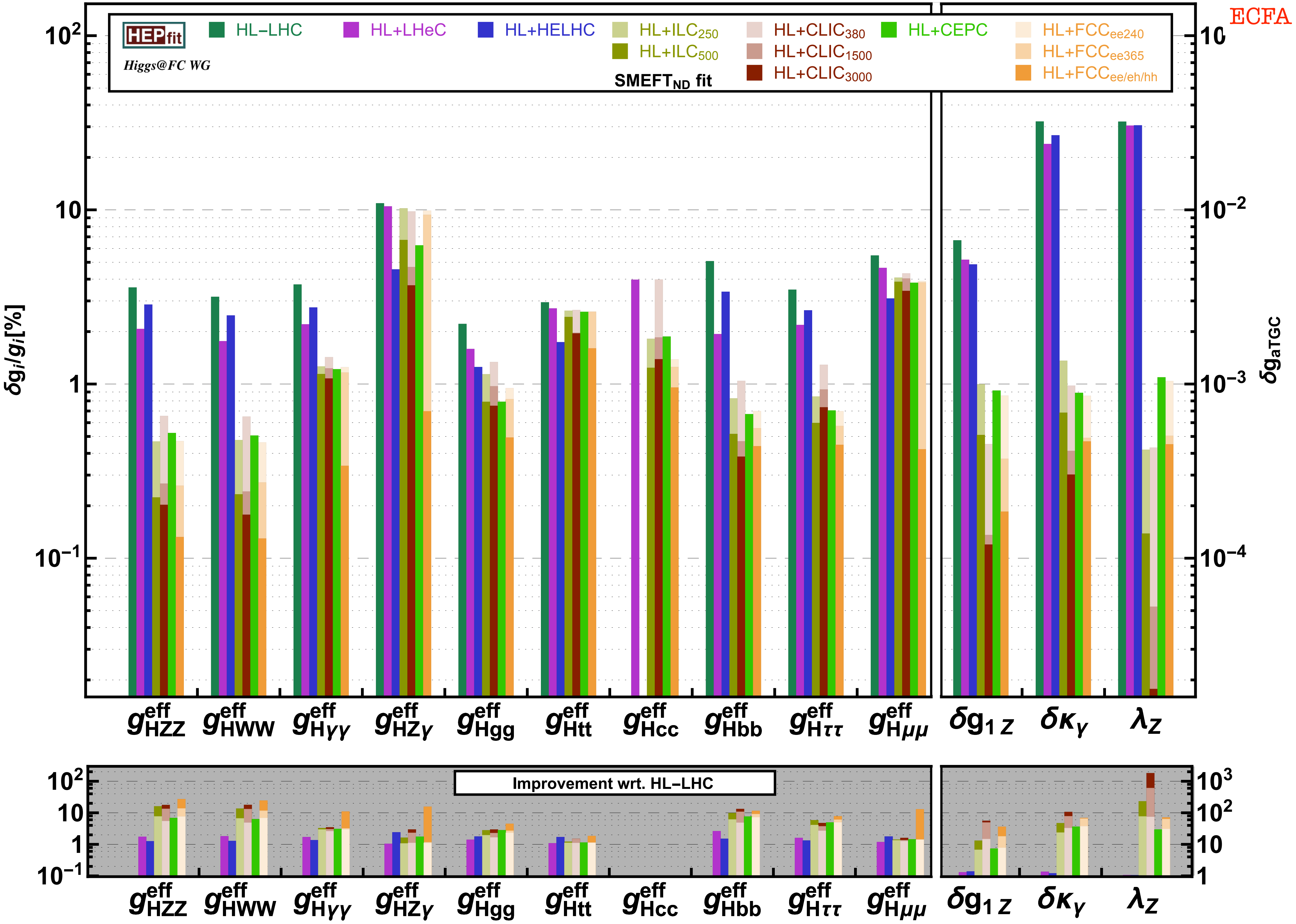
$$\mathrm{SMEFT_{ND}} \equiv \{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\} + \{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell,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

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



ECFA Higgs study group '19

There is life beyond HL-LHC

Figures of Merit with Respects to HL-LHC

M. Cepeda for Higgs@FC WG

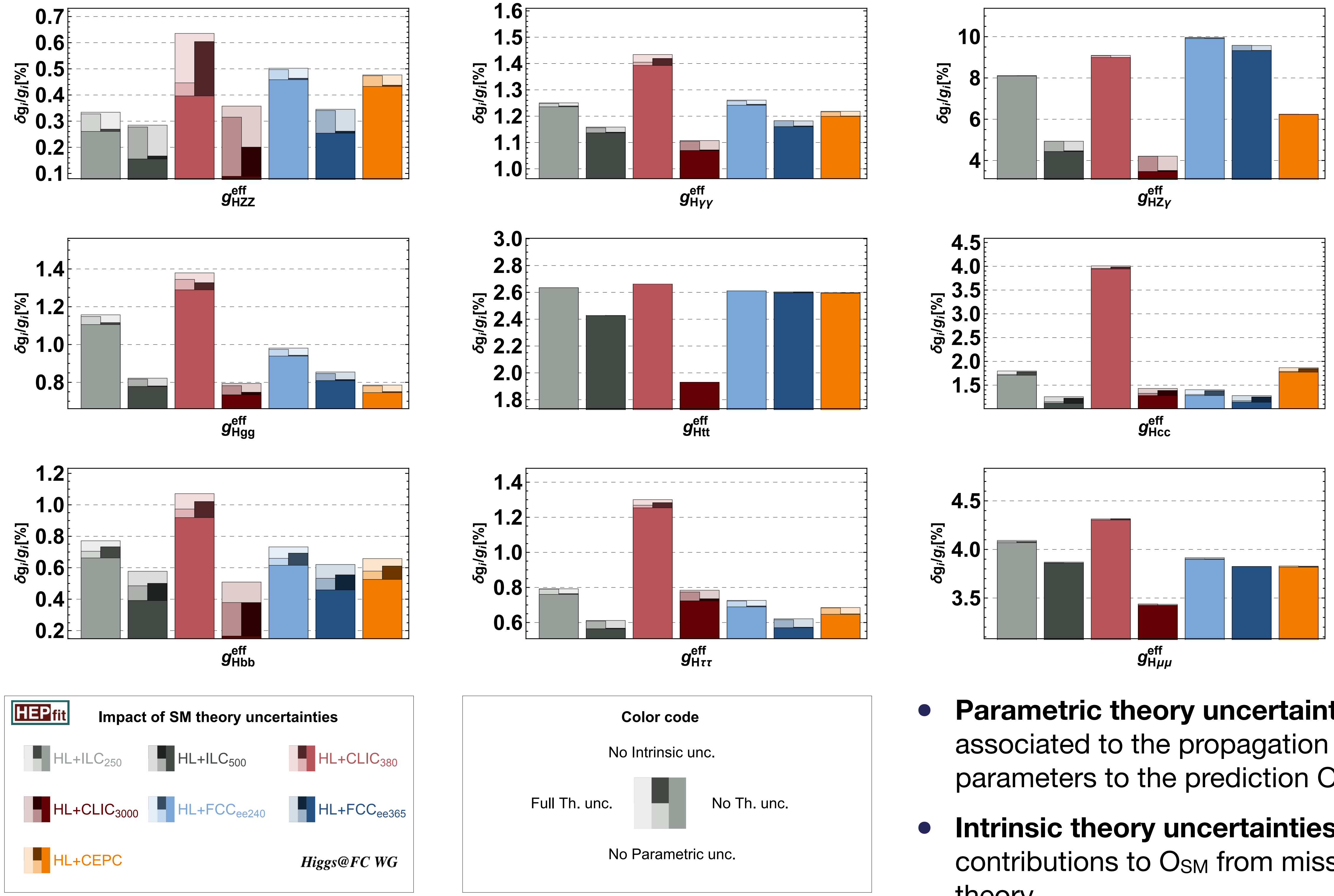
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
$g^{\rm eff}_{HZZ}$	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
$g^{\rm eff}_{HWW}$	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{\rm eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4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

There is life beyond HL-LHC

Theoretical Uncertainties

ECFA Higgs study group ‘19



Theorists

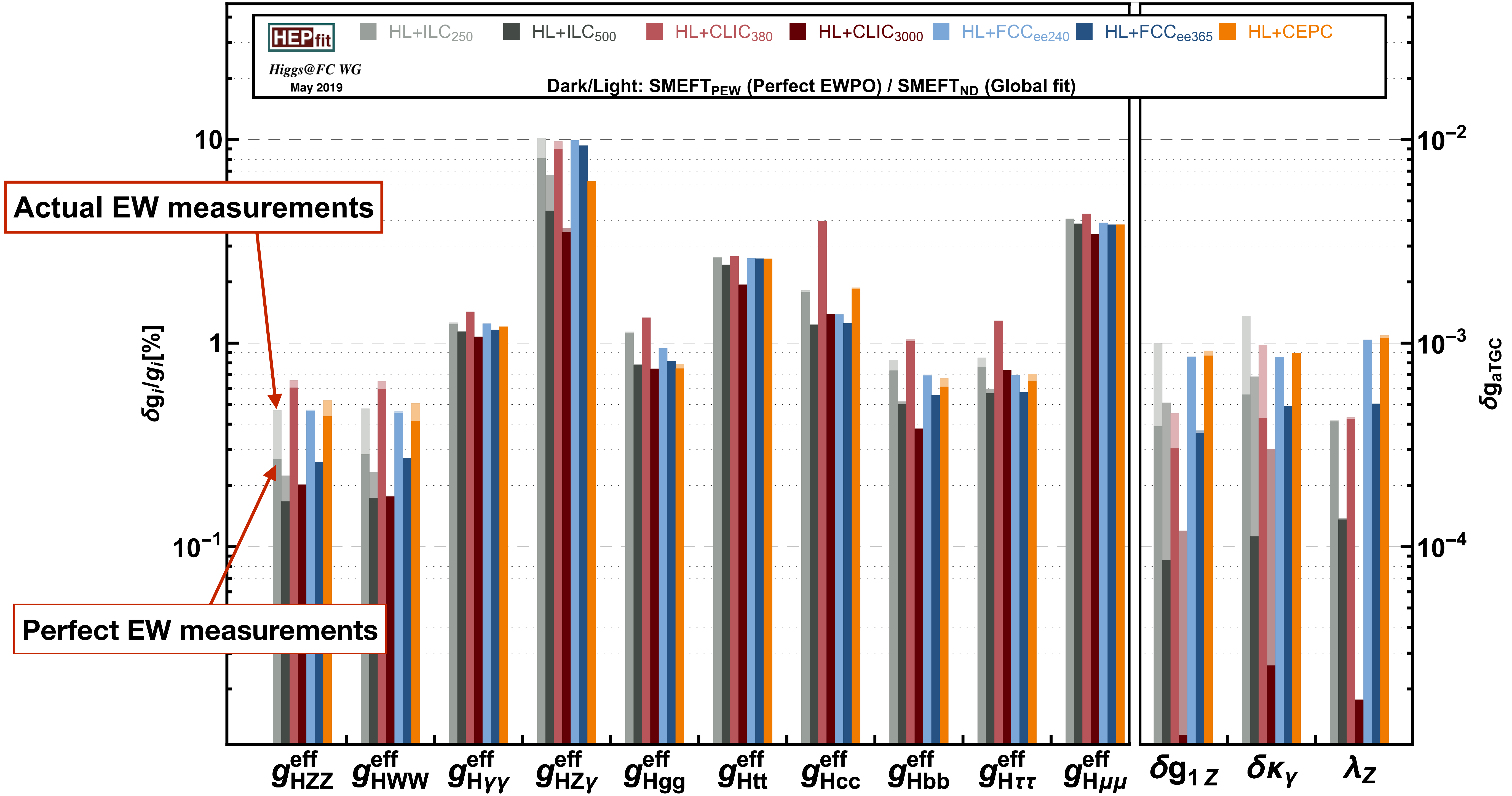
can do better

in few channels

- **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



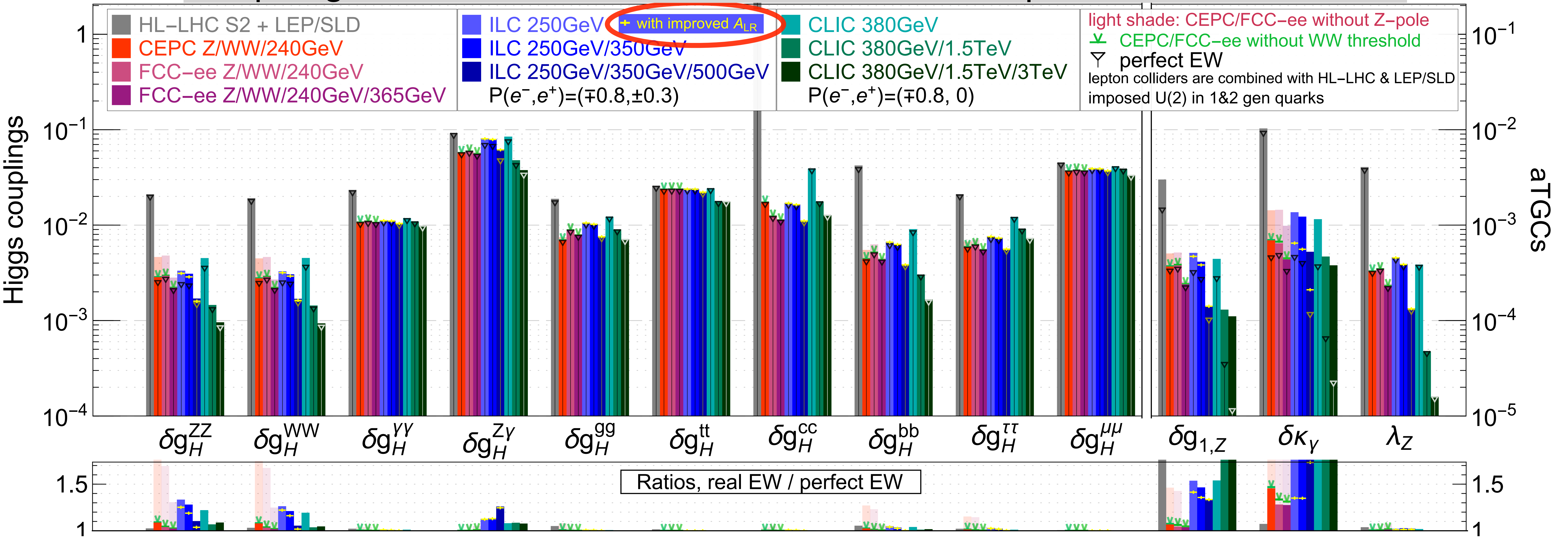
Difference due to absence of precise enough EWPO at LC (no Z pole run)

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

Impact of Z-pole measurements

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

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

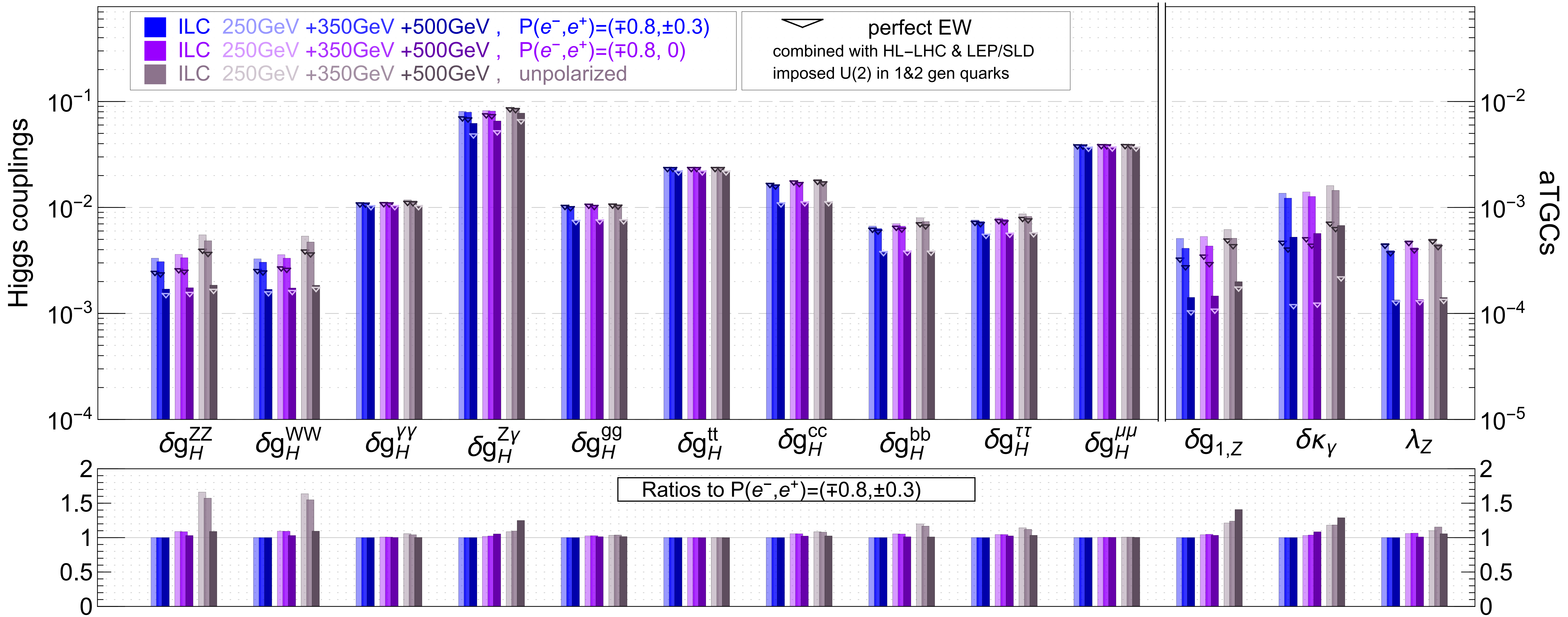


- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics
- LEP EW measurements are a limiting factor to Higgs precision at ILC, especially for the first runs

Impact of Beam Polarisation

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

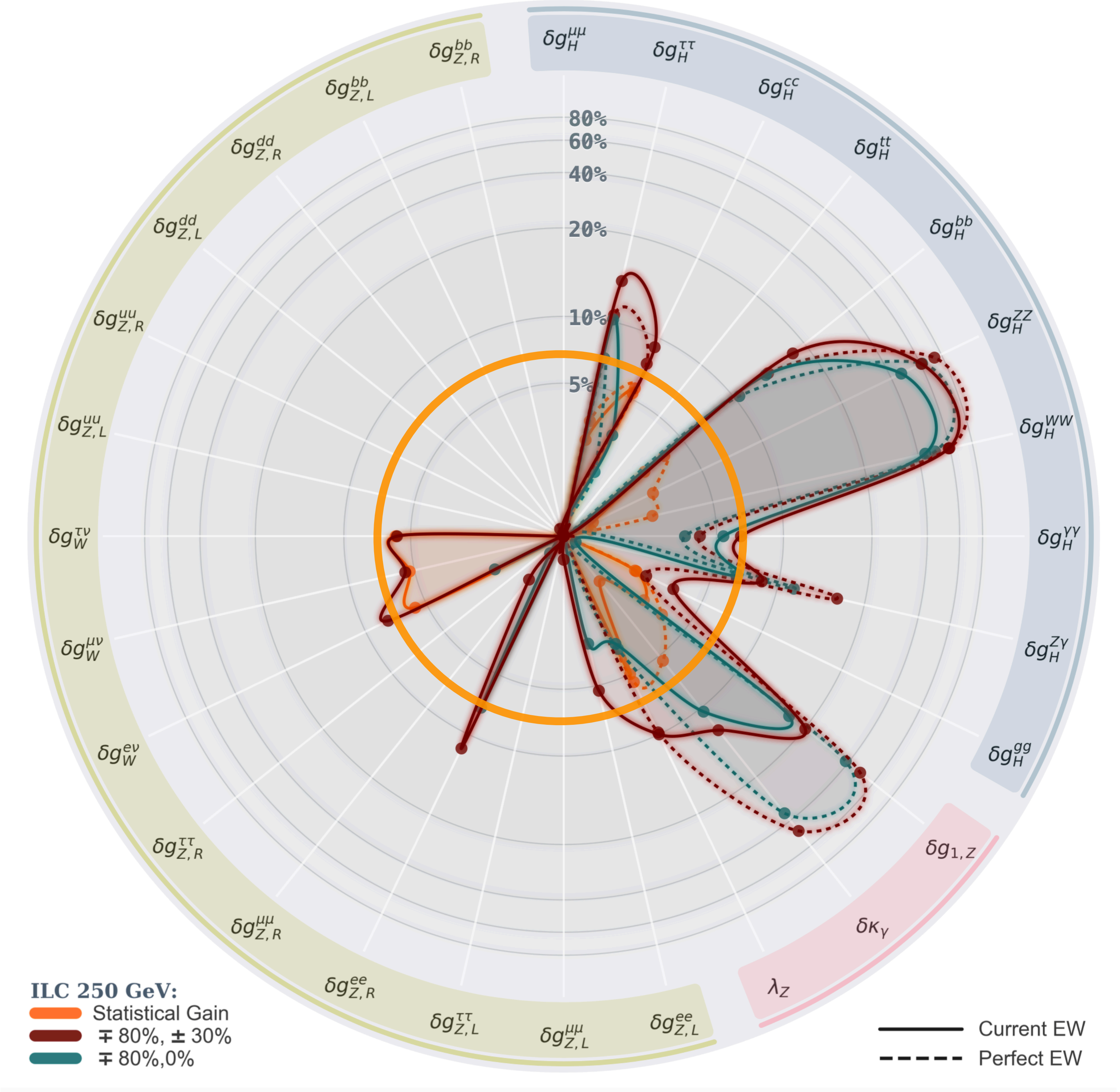
precision reach on effective couplings from full EFT global fit



- Positron polarisation doesn’t play a big role
- Polarisation benefit diminishes when other runs at higher energies are added

Impact of Beam Polarisation

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



increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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(10%) 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

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?

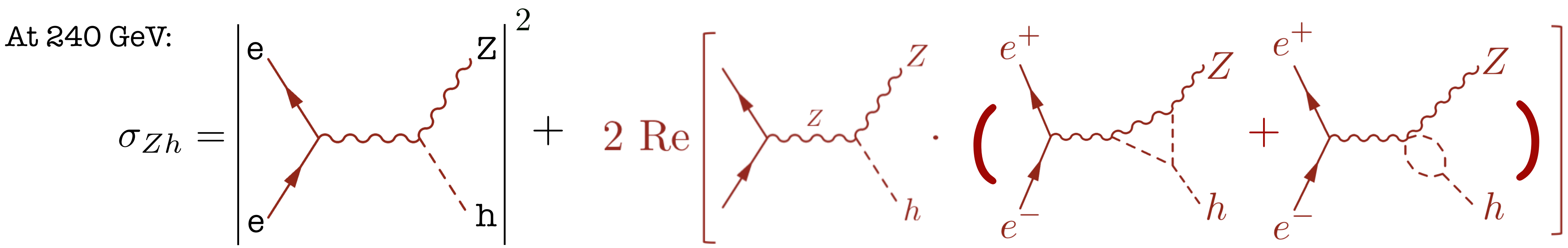
Do you need to reach HH production threshold to constrain h^3 coupling?

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?

M. McCullough '14



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Is a deviation in ZH sourced by modified hZZ coupling or by h^3?
Need a global fit analysis

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?

	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!

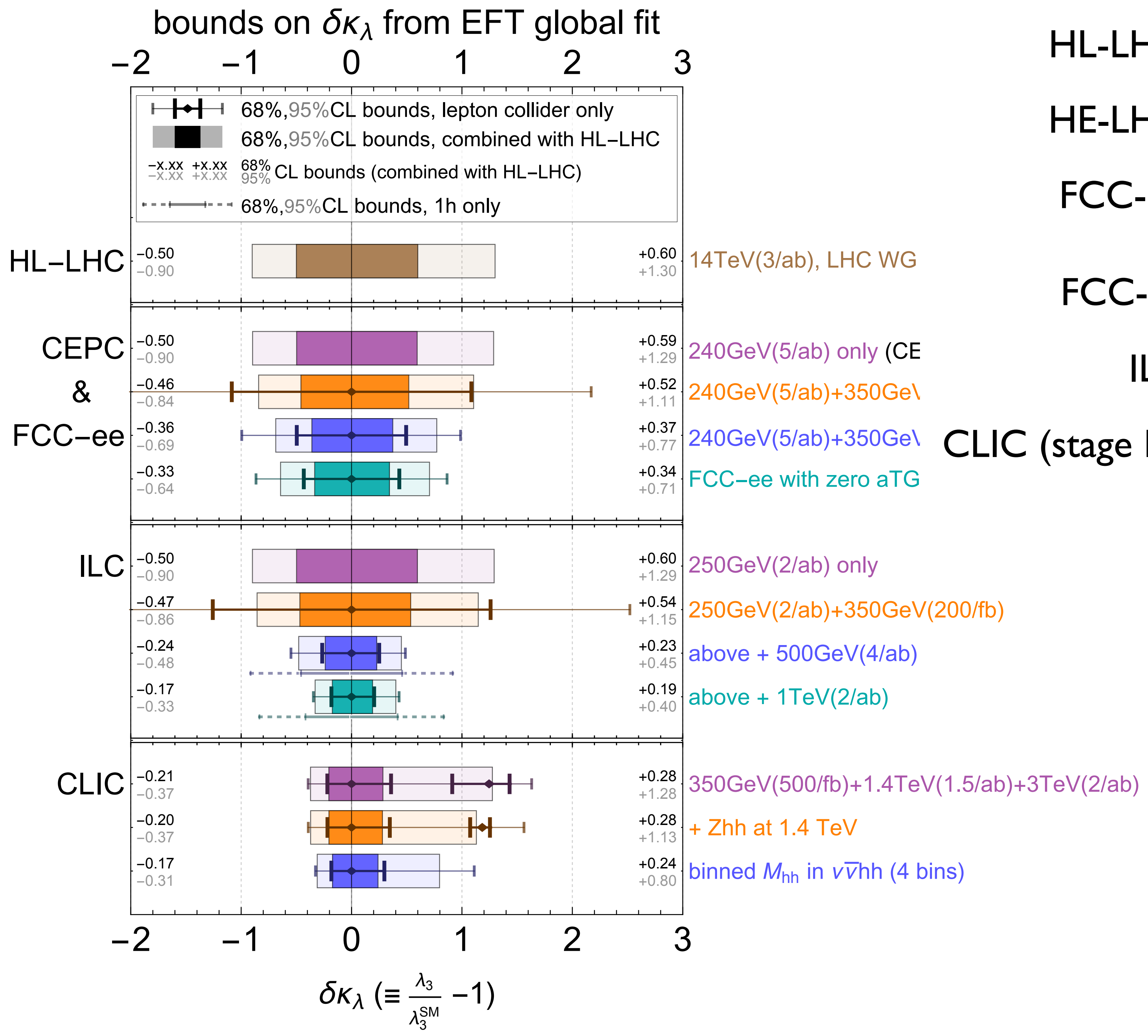
Higgs self-coupling

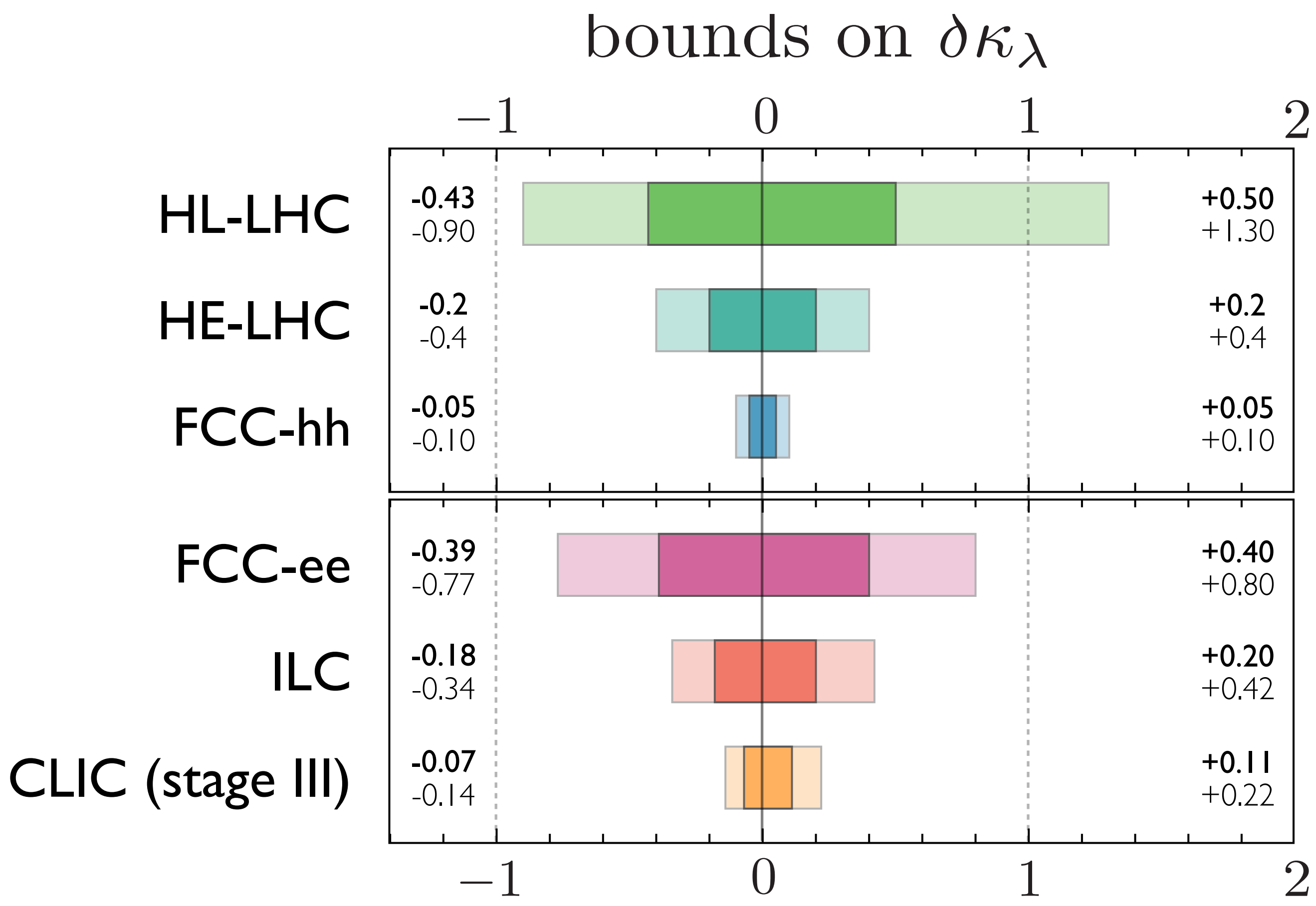
ECFA Higgs study group '19

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%

Higgs self-coupling

DiVita et al, arXiv: 1711.03978
(updated with latest HL-LHC) projections





Dark: 68%CL, Light: 95%CL

ee colliders
will establish at 95%CL that
the Higgs self-coupling exists
ILC will establish it at 5σ
FCC-hh
will probe
the quantum corrections
of the Higgs potential

Conclusions

Conclusions

Don’t Higgsxit!
Build a new collider!

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…)

Don't Higgsxit!
Build a new collider!

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

Don't Higgsxit!

Build a new collider!

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

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
2^{nd}/3rd Run ee	FCC-ee365	10	8	6	15
	CLIC1500	10	7	7	17
hh	HE-LHC	1	0	0	20
	ILC500	10	8	6	22
	CLIC3000	11	7	7	28
ee,eh & hh	FCC-ee/eh/hh	12	11	10	>50

B. Heinemann for Higgs@FC WG

Banker accounting:
Very important to get money

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

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

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

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

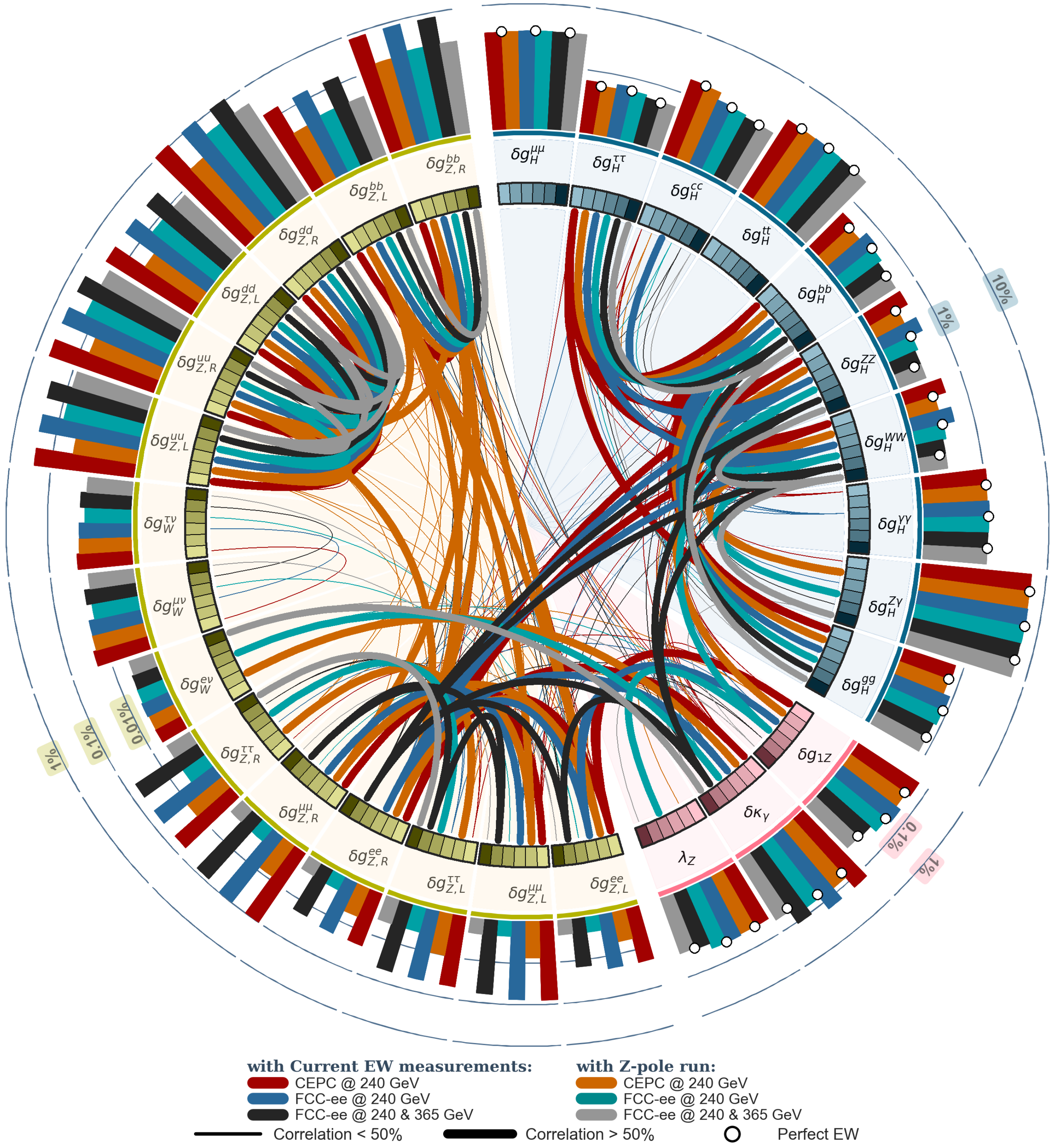
Specific BSM models will care maybe even more about correlations

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

Conclusions

Conclusions

Correlations among different observables at various Future Colliders

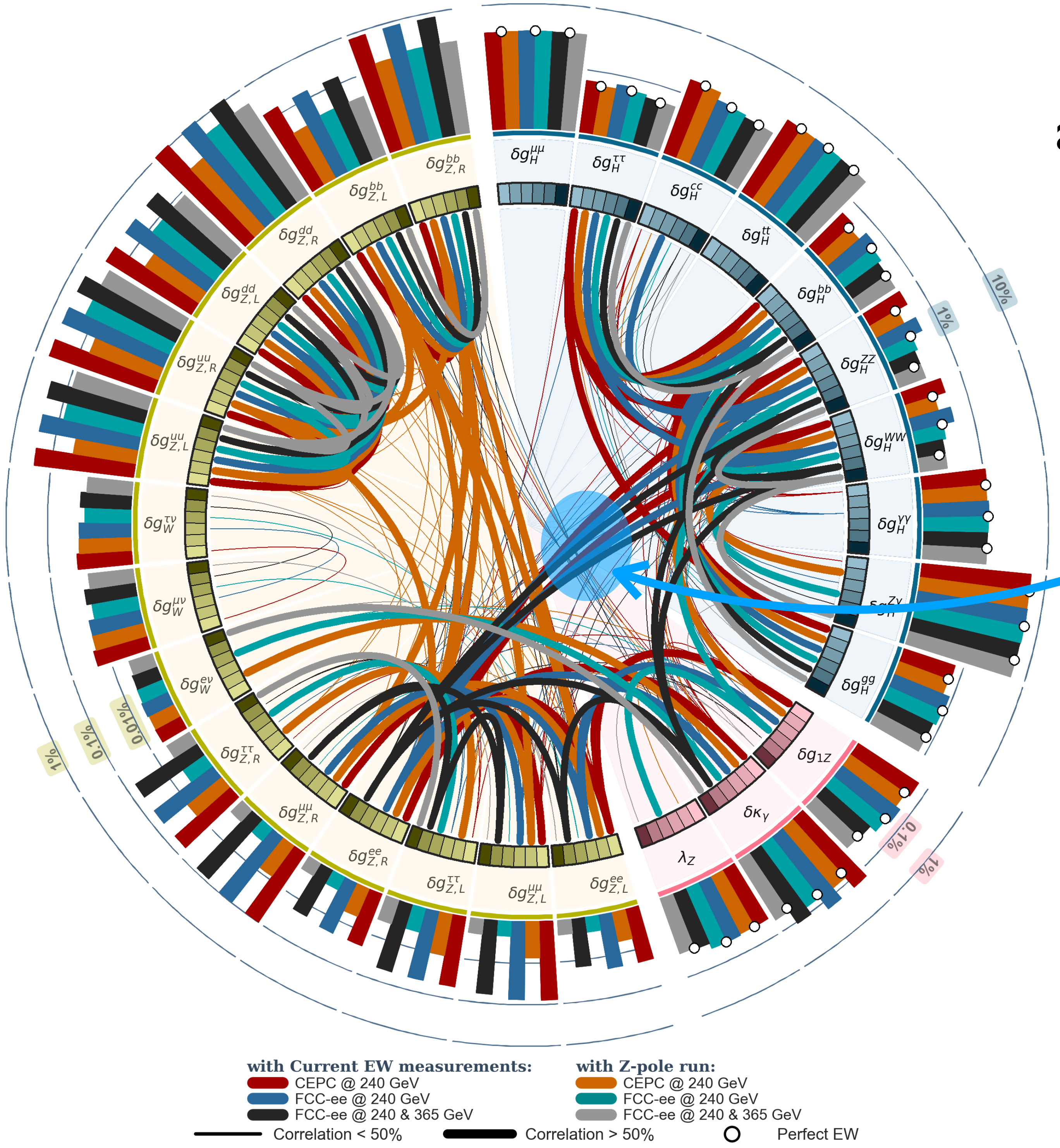


De Blas, Durieux, Grojean, Gu, Paul 'in progress

Conclusions

Correlations among different observables at various Future Colliders

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

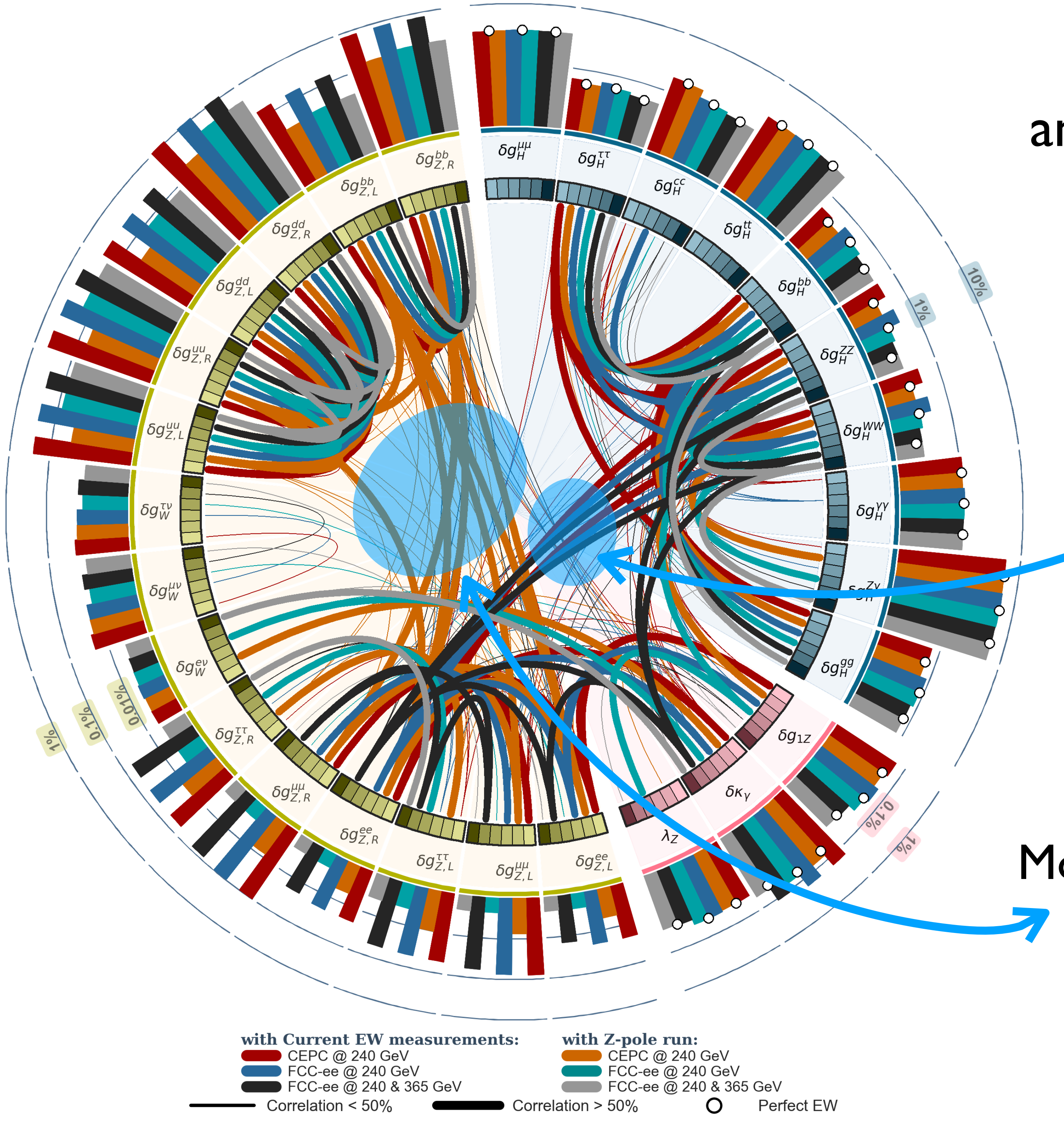


Look carefully at the plot and you'll see that, with a dedicated Z-pole, the correlations between Higgs and EW observables go away

Conclusions

Correlations among different observables at various Future Colliders

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?