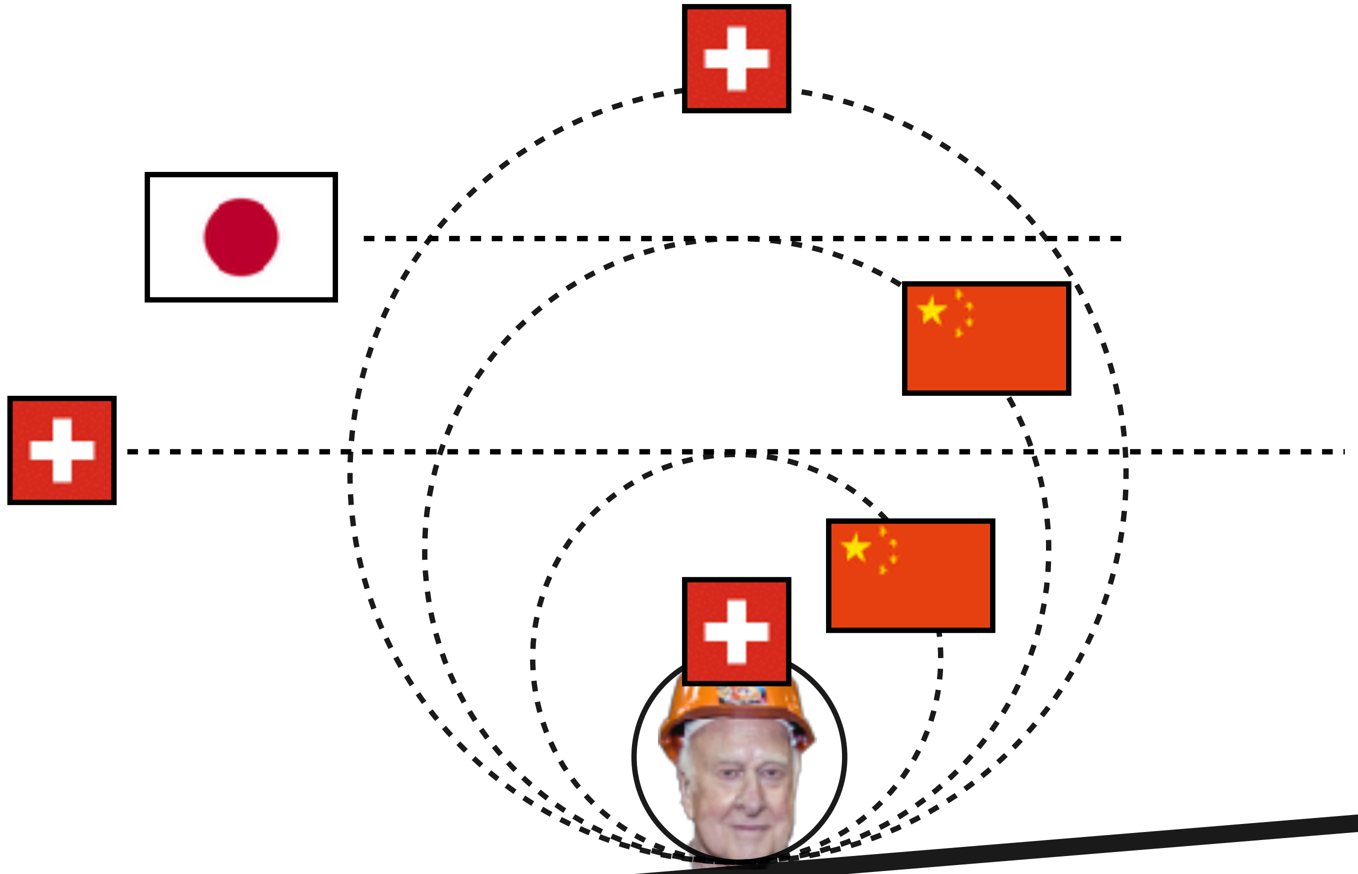
Future Colliders (2/3)

What the future colliders might how about the Higgs and BSM

Weihai High-Energy Physics School

August 26-28, 2019



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Guaranteed deliverables
Legacy measurements

The importance of precise measurements

FCC-ee physics potential

Material from A. Blondel, P. Janot et al.

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements
-- ~20-50 *(stat 400…)* fold improved precision on many EW quantities (eq. x 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\, m_W\, m_\tau)$, top quark couplings

~ Model-independent Higgs width and couplings measurements at percent-permil level.
~3σ, possibly 5 discovery of effect of Higgs self-coupling from Vertex corrections
possible investigation of Hee coupling at $\sqrt{s} = m_H$

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ $\tau\,\tau$
+ flavour physics (10^{12} bb events) (B→s $\tau\,\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DIRECT DISCOVERY of very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ and many opportunities in – e.g. QCD (H→ gg) etc….

FCC-ee physics potential

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+ and many opportunities in – e.g. QCD ($H \to gg$) etc….

Guaranteed deliverables

Exploration potential

FCC-ee EW measurement potential

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005 *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	20	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	<40	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s}$ = 365 GeV	~30%	~2%	<2%	QCD corr

To exploit this exquisite exp. precision some serious theory work has to be achieved

Proceeding of FCC-ee 2018 WS

arXiv.org > hep-ph > arXiv:1809.01830

Search or Ar
(Help | Advance

High Energy Physics – Phenomenology

Standard Model Theory for the FCC-ee: The Tera-Z

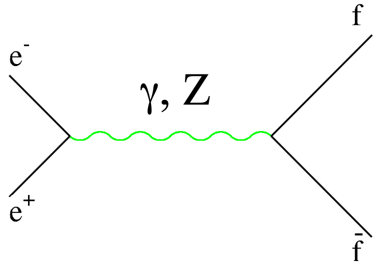
A. Blondel, J. Gluza, S. Jadach, P. Janot, T. Riemann, A. Akhundov, A. Arbuzov, R. Boels, S. Bondarenko, S. Borowka, C.M. Carloni Calame, I. Dubovyk, Y. Dydyshka, W. Flieger, A. Freitas, K. Grzanka, T. Hahn, T. Huber, L. Kalinovskaya, R. Lee, P. Marquard, G. Montagna, O. Nicrosini, C. G. Papadopoulos, F. Piccinini, R. Pittau, W. Placzek, M. Prausa, S. Riemann, G. Rodrigo, R. Sadykov, M. Skrzypek, D. Stockinger, J. Usovitsch, B.F.L. Ward, S. Weinzierl, G. Yang, S.A. Yost

(Submitted on 6 Sep 2018 (v1), last revised 22 Sep 2018 (this version, v2))

Stress test of SM

10^{12} Z

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$

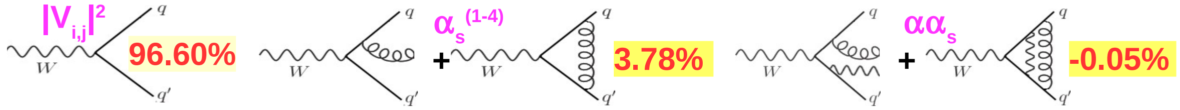
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}

The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$

10^8 W

$$\Gamma_{\mathrm{W,had}} = \frac{\sqrt{2}}{4\pi} G_F m_W^3 \sum_{\text{quarks i,j}} |V_{i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_s}{\pi}\right)^k + \delta_{\text{electroweak}}(\alpha) + \delta_{\text{mixed}}(\alpha\alpha_s)\right]$$

[EWK: -0.35%]



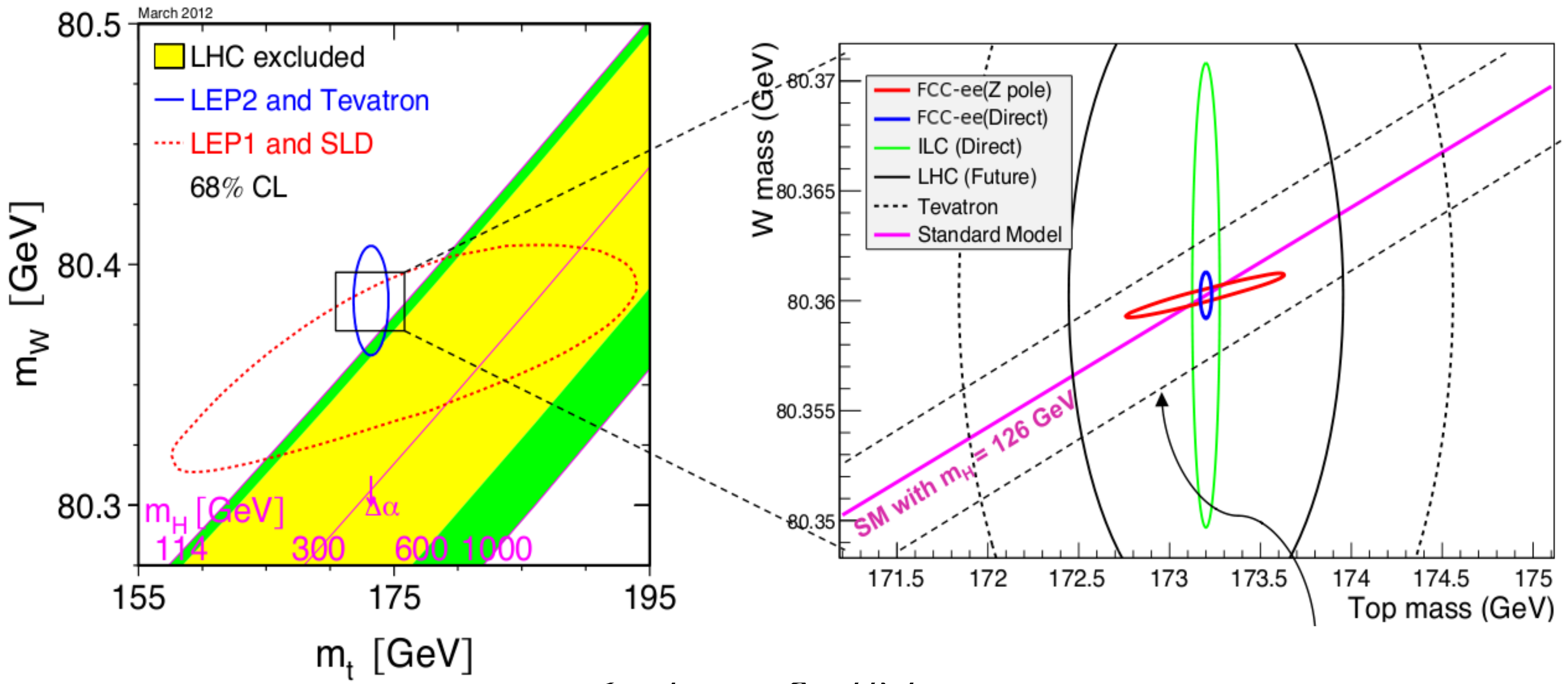
$\alpha_{QED}(m_Z)$ 10^{-5}

$\alpha_{QCD}(m_Z)$ 10^{-4}

Material from P. Janot

Material from D. d'Enterria

best test of QM beyond QED (and indirect probe of new physics up to ~40TeV)

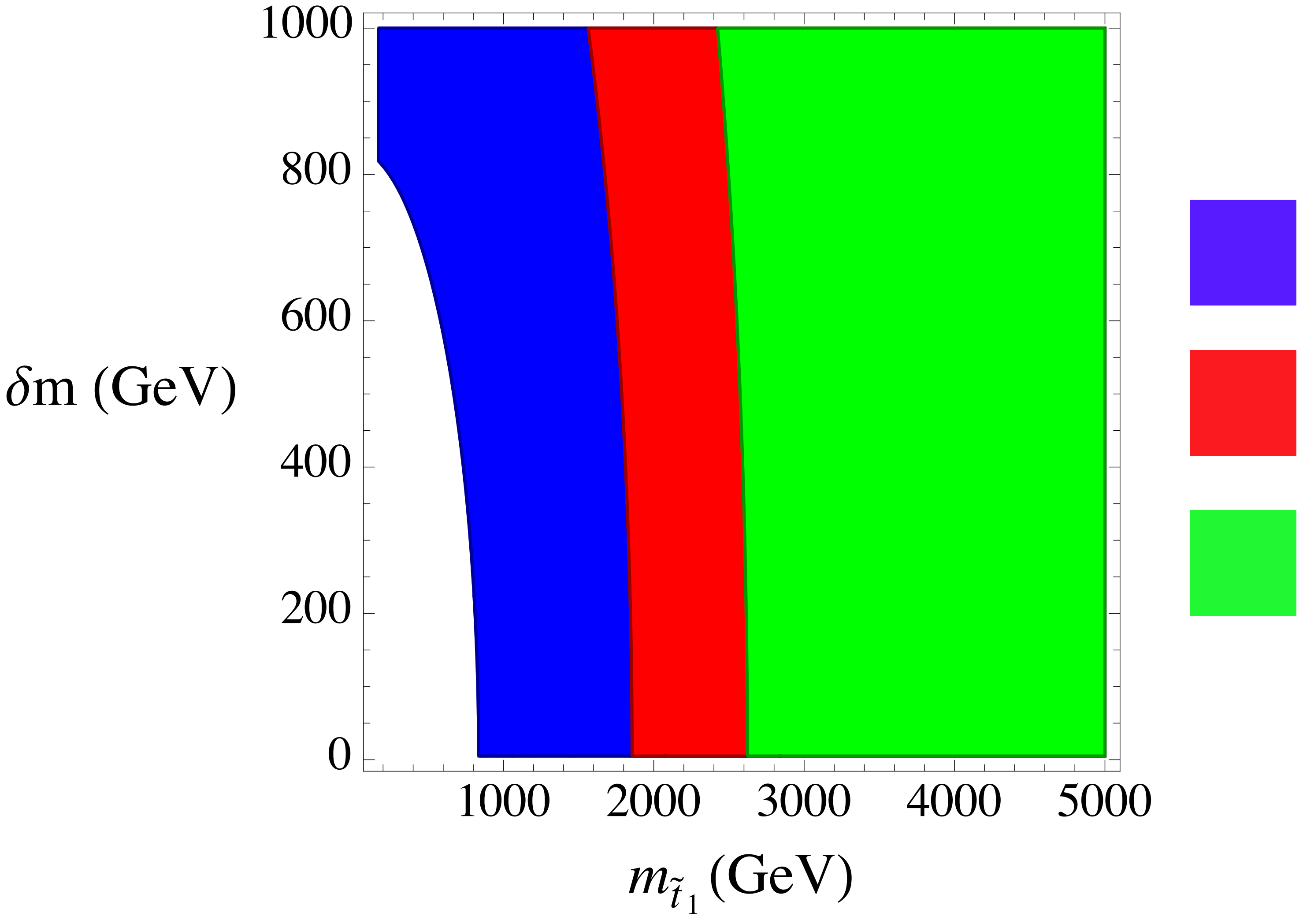


Implications for New Physics

In the SM, W mass is "predicted" in terms of Z mass, G_F, α_{em}...

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

Any deviation (if the TH uncertainty can be kept under control) tests NP



Probing MSSM stops

$\delta m_W < 5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 850\,\mathrm{GeV}$

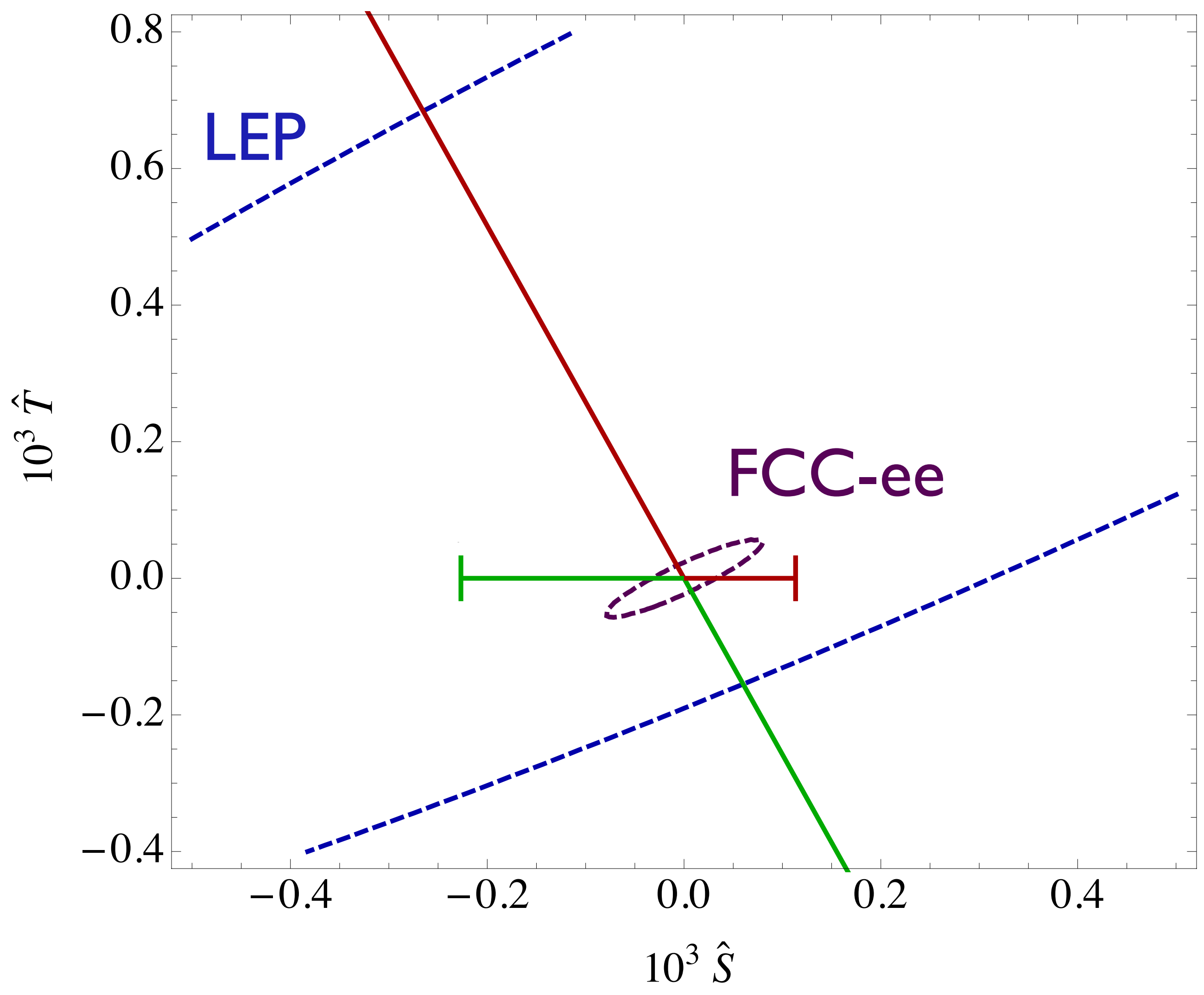
$\delta m_W < 1\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 1.9\,\mathrm{TeV}$

$\delta m_W < 0.5\,\mathrm{MeV} \Rightarrow m_{\tilde{t}_1} > 2.6\,\mathrm{TeV}$

TLEP (physics case) '13

Implications for New Physics

For Universal Models, EW measurements nicely captured by oblique parameters S,T…



$$\hat{S} = \frac{m_W^2}{m_{NP}^2} \quad \Rightarrow \quad \hat{S} < 10^{-6,5,4} \Leftrightarrow m_{NP} > 80, 25, 8\,\mathrm{TeV}$$

We'll see some concrete examples in specific UV models in tomorrow lecture

Guaranteed deliverables
Legacy measurements

The case of the Higgs boson

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 dictates (in part) 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

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, $\mu e/\tau\mu/\tau e$, …)
  - 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

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

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

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)% ⇔ $\Lambda_{\rm BSM}$ > 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

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!

Higgs precision program is very much wanted to probe BSM physics

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

Which Higgs couplings?

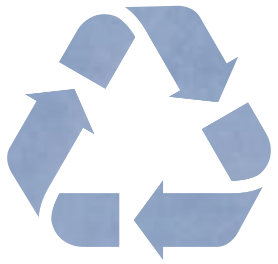
Within the SM, all the Higgs couplings are uniquely fixed by known quantities (G_F, m_W, m_Z, m_{quark}, m_{lepton})

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

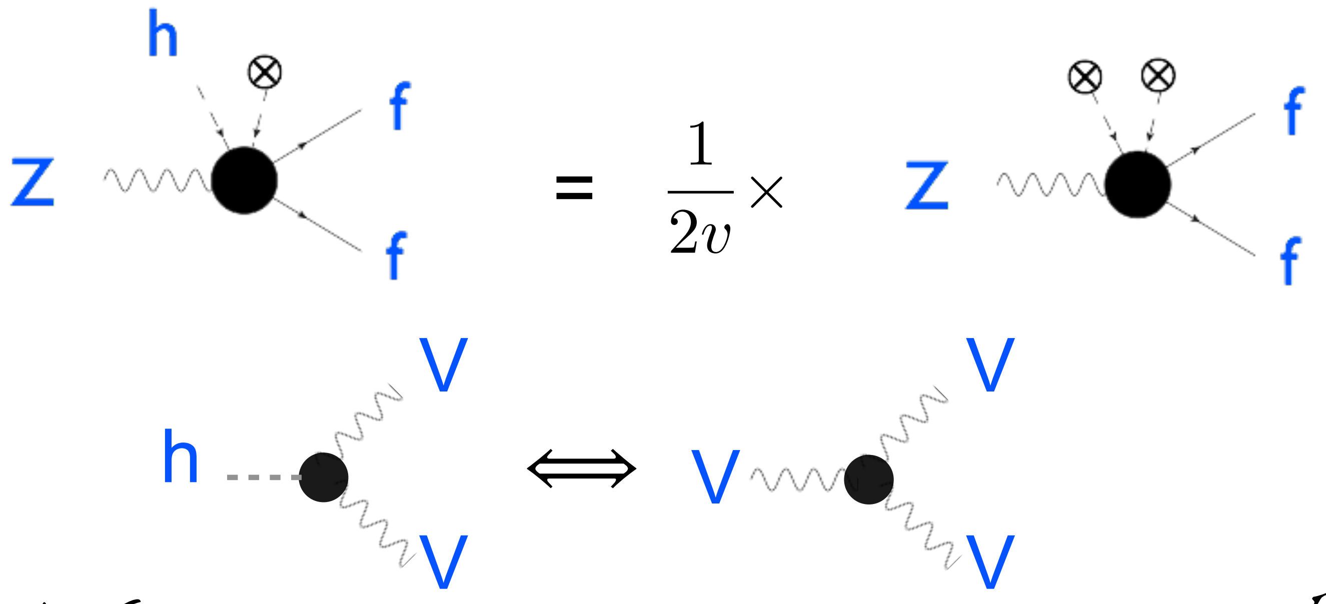
Study specific models



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

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"

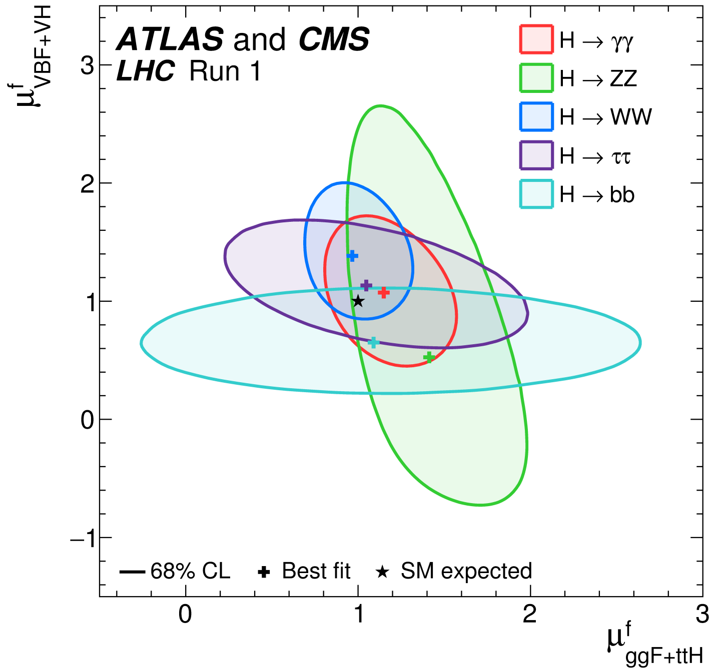
M. Zuckerberg, Harvard graduation ceremony speech, May 25, 2017

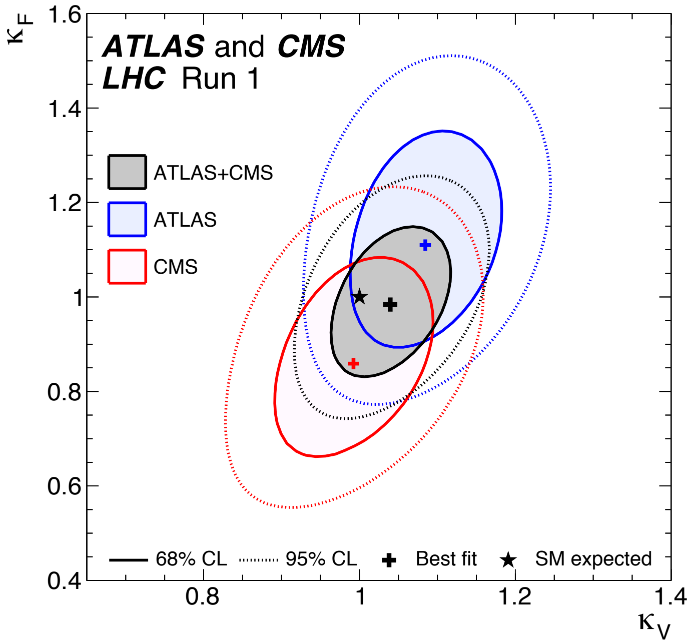
(before Cambridge analytica story)

How to report Higgs data: from κ to EFT

LHCHXSWG '12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$





$$(\sigma \cdot {\rm BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\rm SM}(gg \to H) \cdot {\rm BR}_{\rm SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

individual coupling rescaling factors

Well suited parametrization for inclusive measurements
but doesn't do justice to full possible deformations of SM & other rich diff. information

How to report Higgs data: from κ to EFT

LHCHXSWG '12

Main limitations of μ and κ

1) No manifestly gauge SU(2)xU(1) invariant formalism
(vertices with different number of Higgs bosons are not related to each others)

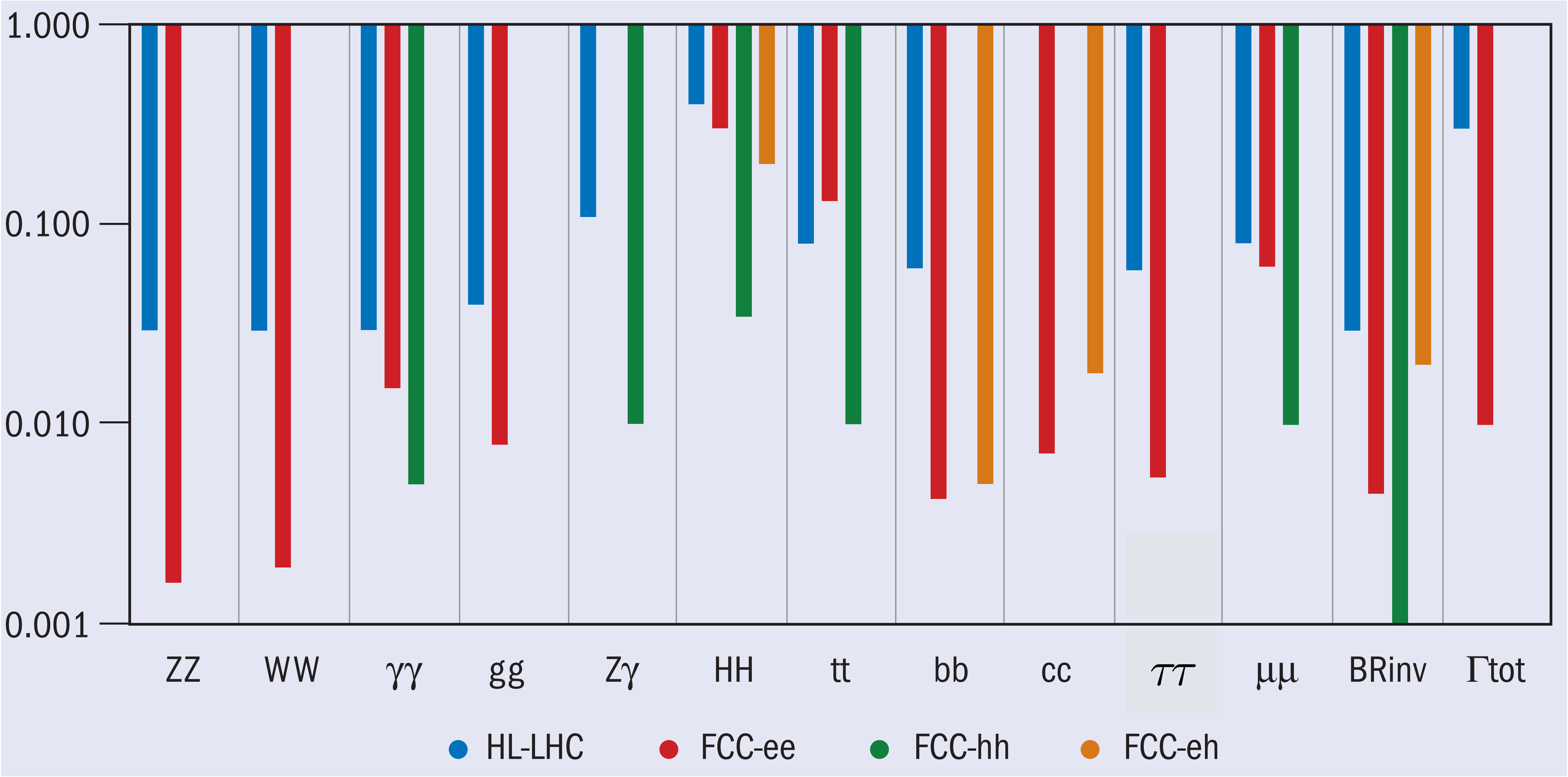
2) Missing some important symmetry properties of SM, already well constrained outside Higgs physics, e.g. in EW precision measurements

3) No general Lorentz structure (i.e. doesn't fully exploit diff. measurements)

3) very difficult to go beyond LO

Well suited parametrization for inclusive measurements
but doesn't do justice to full possible deformations of SM & other rich diff. information

How to report Higgs data: from κ to EFT



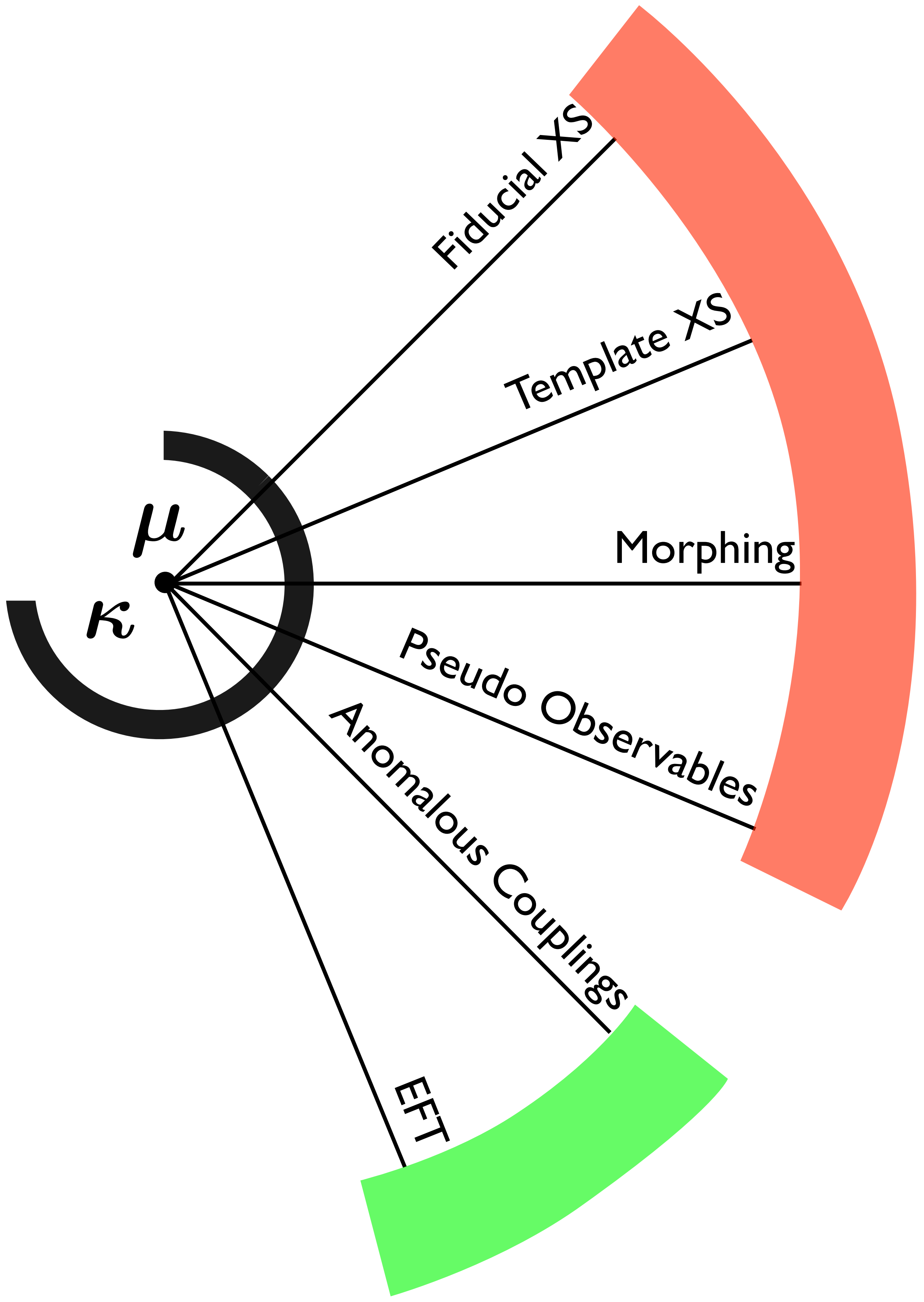
Oversimplified PR plot

1) not a unique coupling to each particle

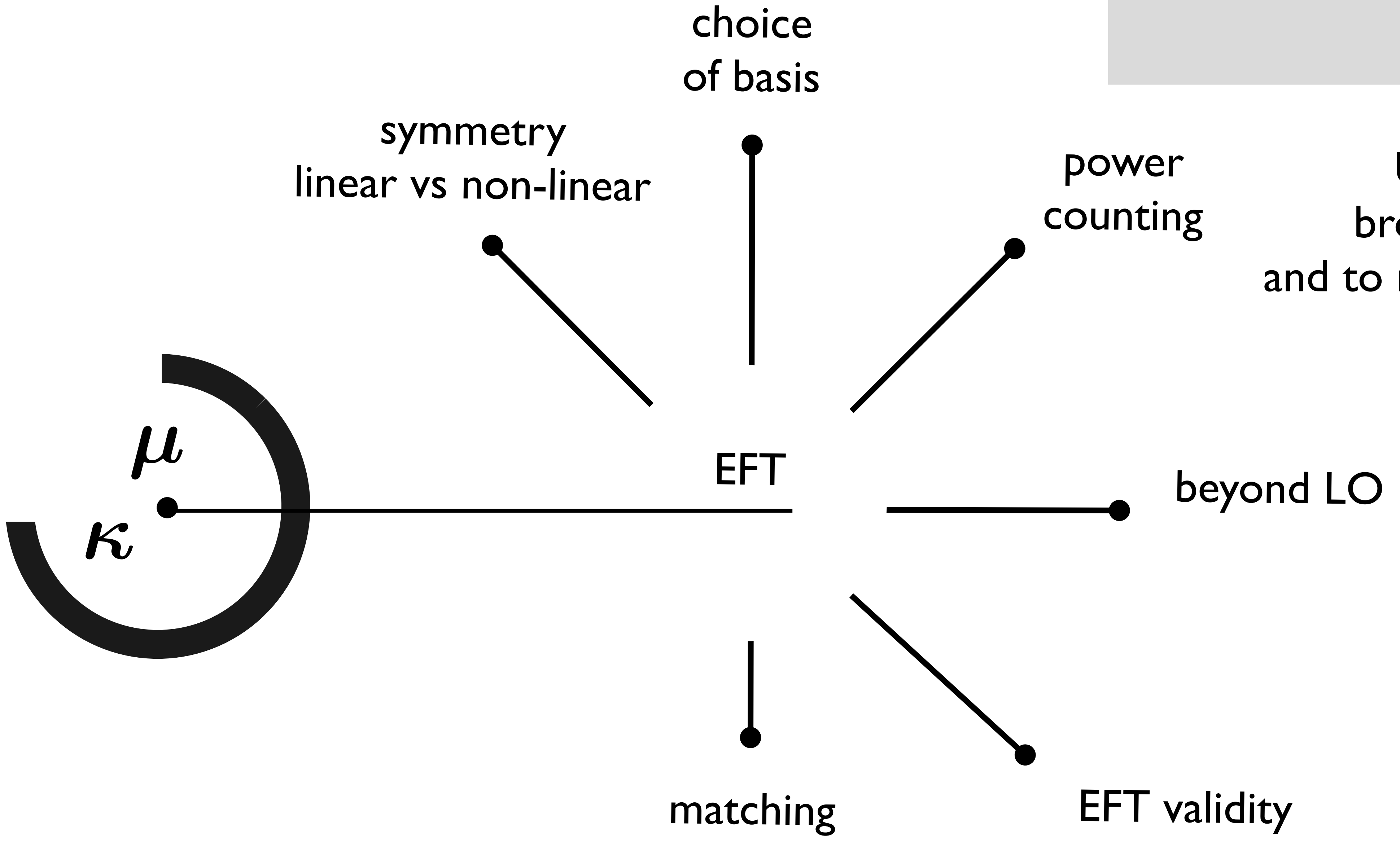
2) powerful complementarity/synergy with non-Higgs measurements not utilised (e.g. EW, diboson, top)

EFT

Not unique!
Useful tools to probe
broad classes of dynamics
and to report experimental results
in a meaningful way



EFT



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Pros:

- correlations between different channels/observables
- combination of measurements at different energies
  e.g. EW precision data and Higgs measurements
- test of self-consistency

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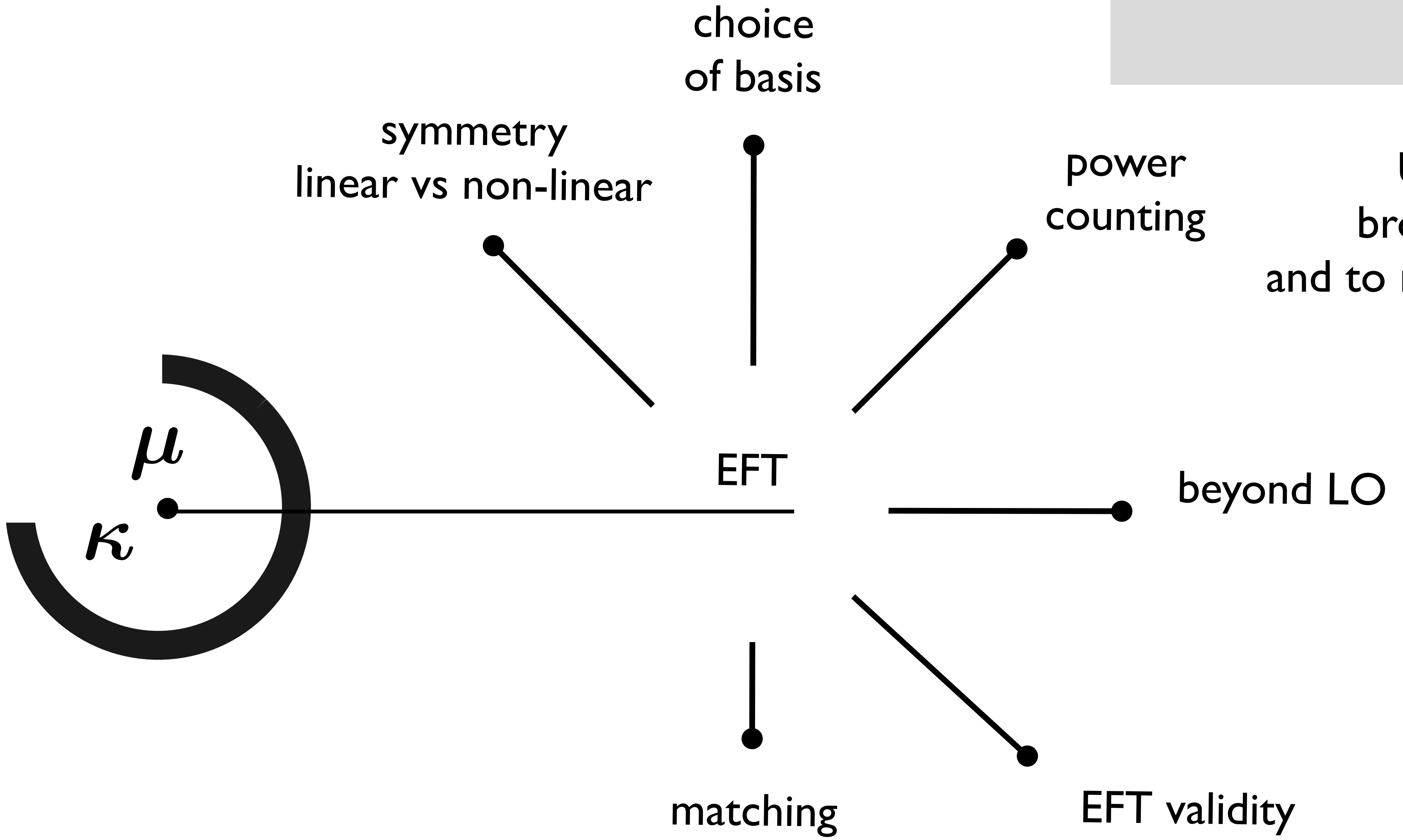

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- test of self-consistency

unique to EFT

allow to focus on channels yet unconstrained and more likely to offer new discovery opportunities

Better than kappa's?
Not necessarily
EFT assumes mass gap SM-BSM
Kappa's doesn't

EFT

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Useful tools to probe
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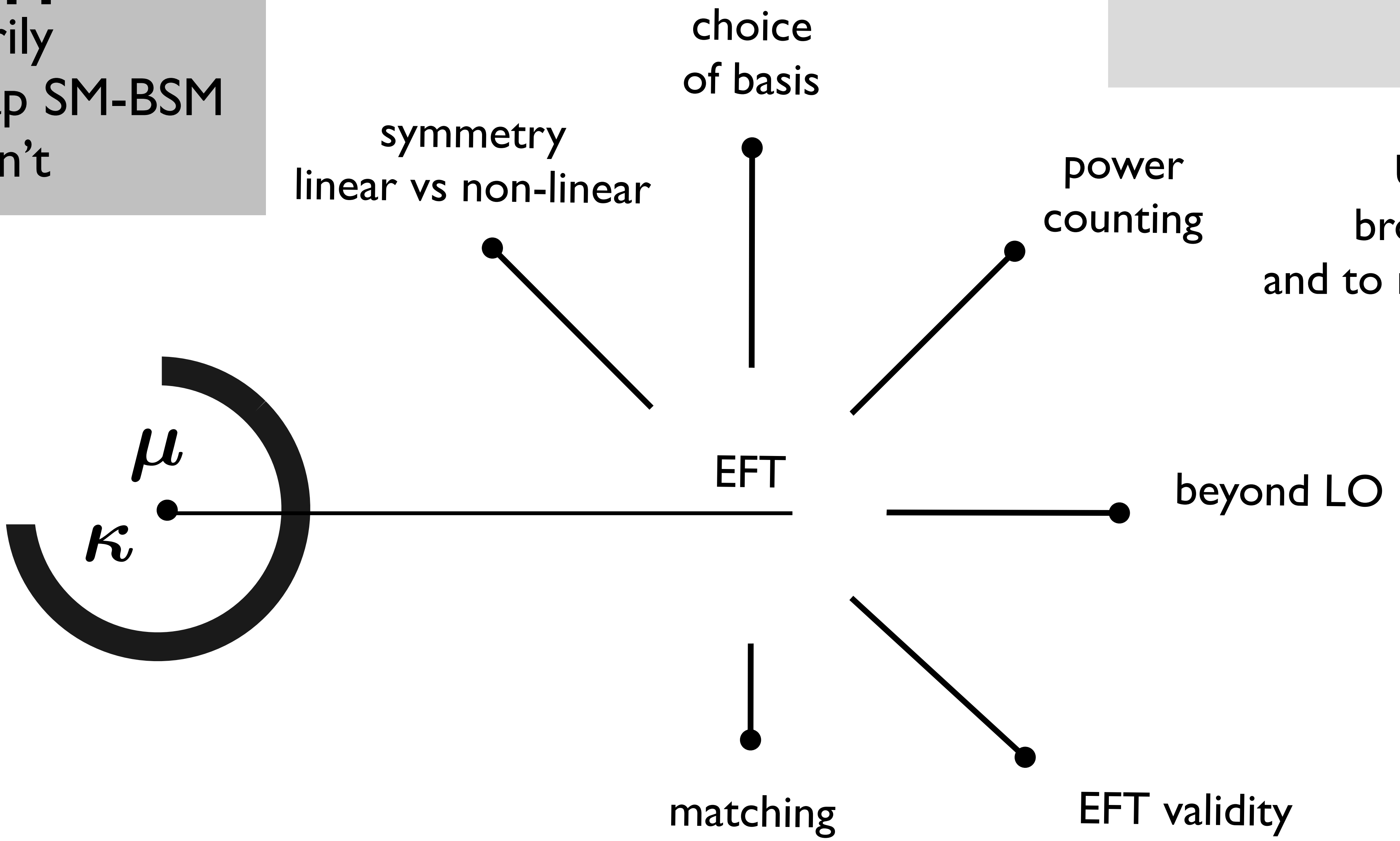

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Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, i.e. $\Lambda \gg v$
- Linearly realised SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

EFT Lagrangian beyond the SM expanded in operators of dimension D

Standard Model, operators up to D=4

Lepton number violating, hence too small to be probed at LHC

By assumption, subleading to D=6

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \cancel{\frac{1}{\Lambda}\mathcal{L}^{D=5}} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \cancel{\frac{1}{\Lambda^3}\mathcal{L}^{D=7}} + \cancel{\frac{1}{\Lambda^4}\mathcal{L}^{D=8}} + \ldots$$

Cutoff scale of EFT

Appear when starting from L-conserving BSM, and integrating out heavy particles with m≈Λ

Effective Theory Approach to BSM

Observable effects of D=6 operators

- Corrections to SM Z and W boson couplings to fermions (so-called vertex corrections)
- Corrections to SM Higgs couplings to matter and new tensor structures of these interactions
- Corrections to triple and quartic gauge couplings and new tensor structures of these interactions
- Contact 4-fermion interactions
- ... and much more

(courtesy of A. Falkowski)

Frontiers of knowledge

- Many EFT operators, especially those involving **leptons** or affecting **gauge boson** propagators are already strongly constrained by **LEP** and other low-energy experiments. LHC rarely can compete on this field.
- However, other operators, especially those involving **Higgs** bosons or **quarks**, are less strongly constrained, which opens opportunity for **LHC** to improve constraints (or discover new physics)
- There are observables where new physics effects grow with **energy**, which gives the LHC an advantage

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)

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

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

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

Higgs physics vs BSM

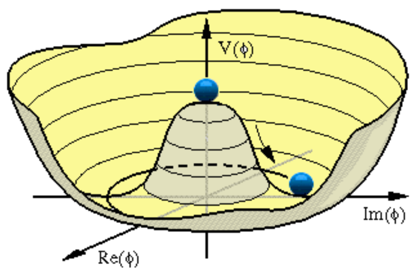
(assuming EW symmetry linearly realised and that new physics is heavy)

(courtesy of A. Pomarol@Moriond2014)

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

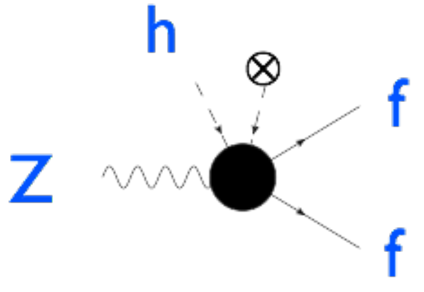
$\phi = v + h$

vacuum

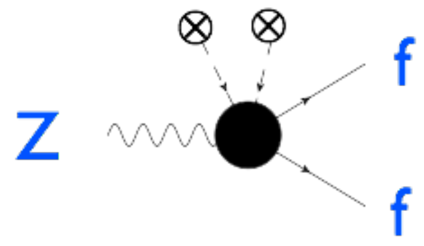


Potentially new BSM-effects in h physics
could have been already tested in the vacuum

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

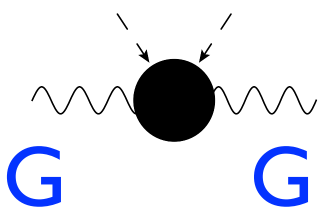
consistency check
not discovery mode

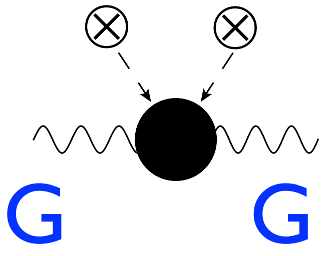
One can use h→ZZ→4l to probe this deformation
but hard time to compete with LEP bounds

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

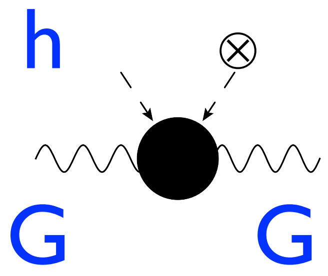
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$





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

But can affect h physics:



affects GG →h!

operator
visible in Higgs physics

(courtesy of A. Pomarol@HiggsHunting2014)

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

yet to be measured at the LHC

the 6 others have been measured (~15%)

Higgs/BSM Primaries

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

Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

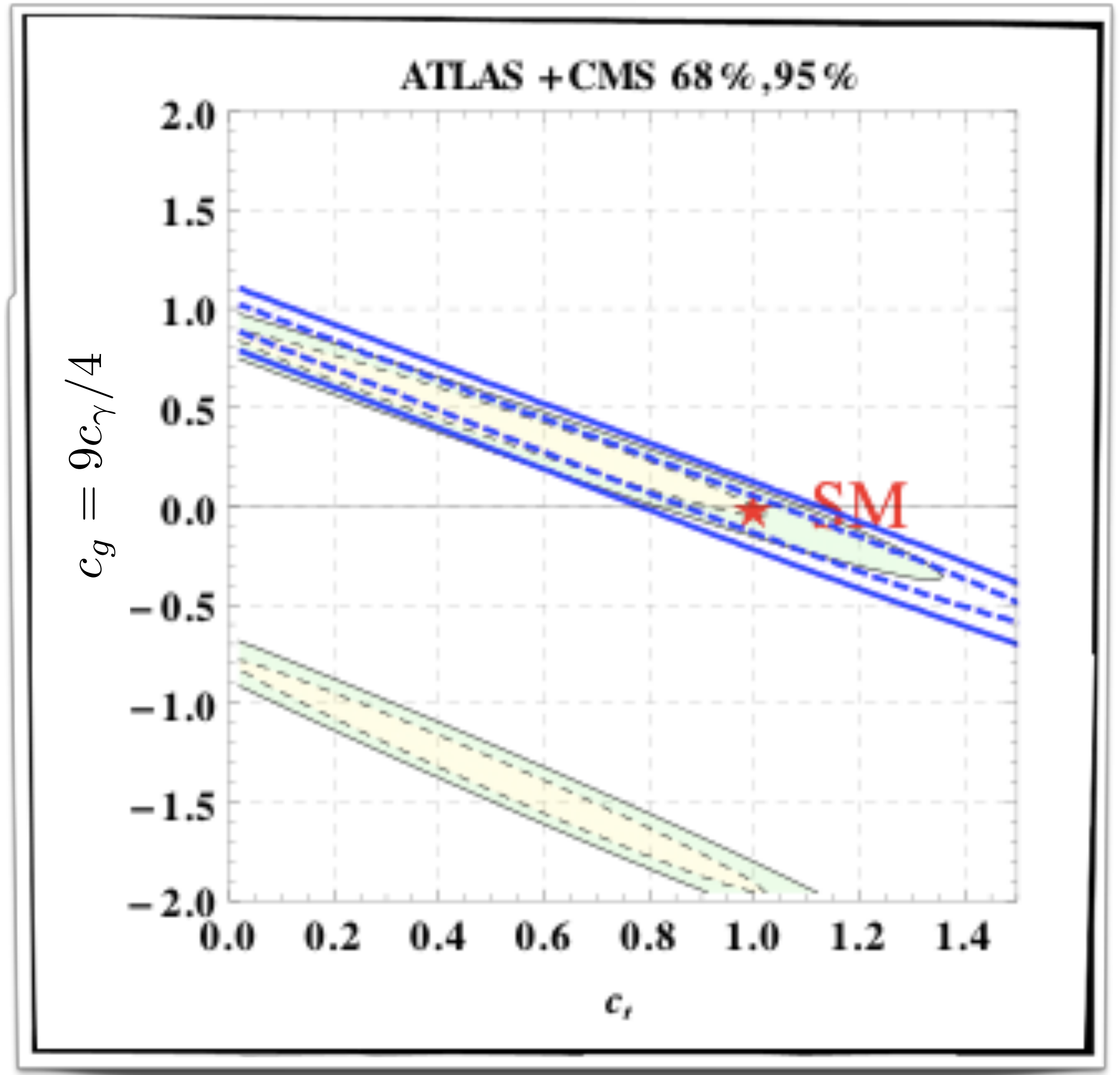
Atlas projection '2014

With some important differences:

1) width hypothesis built-in

2) κ_W/κ_Z is not a primary (constrained by Δρ and TGC)

3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions



Azatov '15

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

Higgs/BSM Primaries

At the Future Colliders, this separation of the three sectors
(EW precision measurements, diboson, Higgs)
doesn't hold and one needs to perform a global analysis
including all(?) EFT operators
that can affect the measurements in the three sectors

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)

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

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

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

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.

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

Experimental Inputs

ECFA Higgs study group '19

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 (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	-

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)

(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 flavor violating couplings

↠ shed light on the origin of fermion masses and flavours

Higgs width (and coupling normalisation) from Z recoil

At **hadron** colliders, one needs to see the decay products of the Higgs to recognise that a Higgs has been produced ⇒ access to σxBR only and it is not possible to extract the coupling normalisation nor the total width

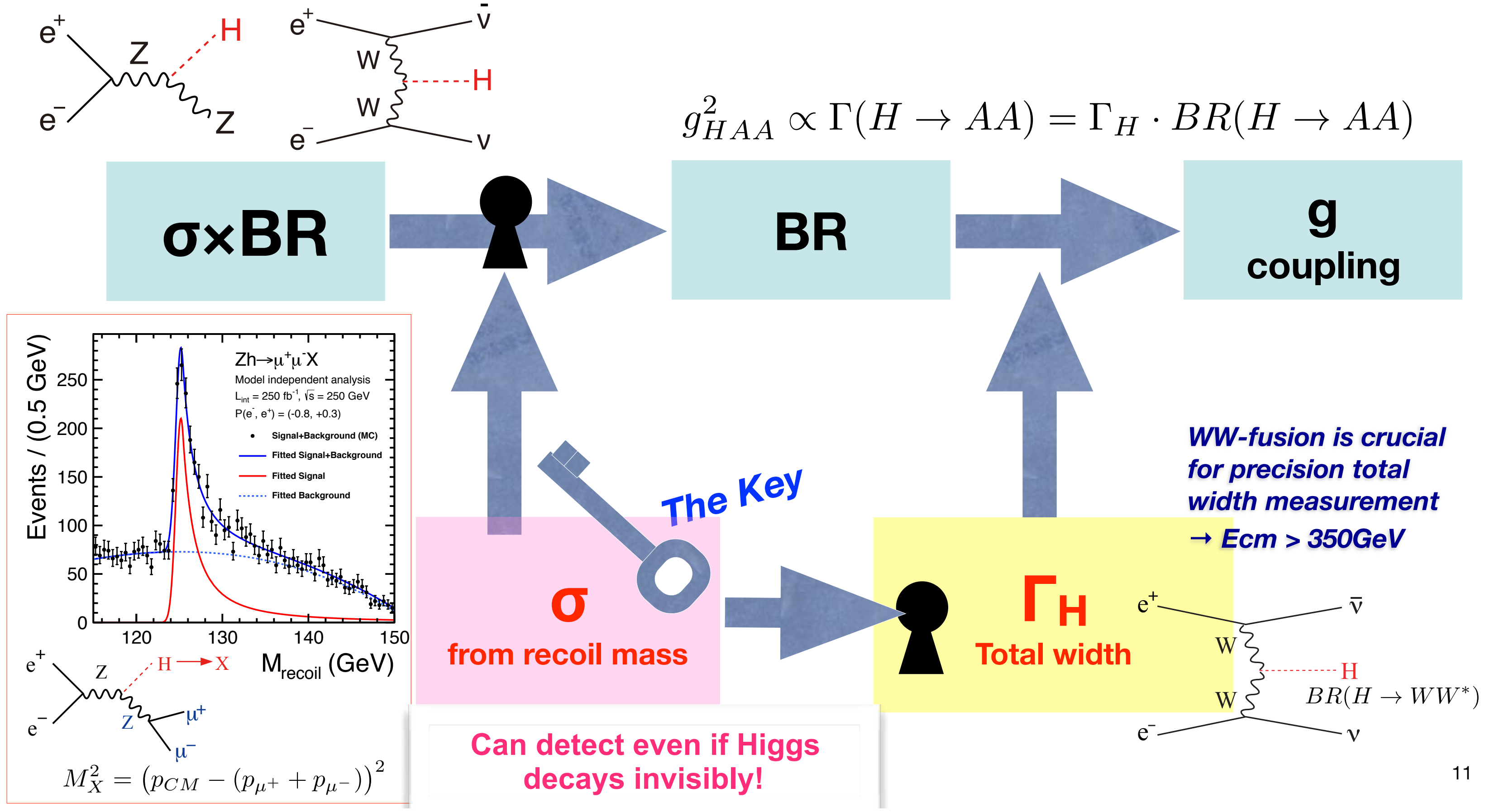
At **lepton** colliders instead, one can tag a Higgs without having to look at his decay simply by measuring the Z-recoil mass ⇒ access to σ directly

Conservation of Energy & Momentum for ee→ZH:

$$E_Z = \frac{s + m_Z^2 - m_h^2}{2\sqrt{s}}$$

At a 250GeV ee collider, the peak at E_Z~110GeV corresponds to events with a 125GeV Higgs produced

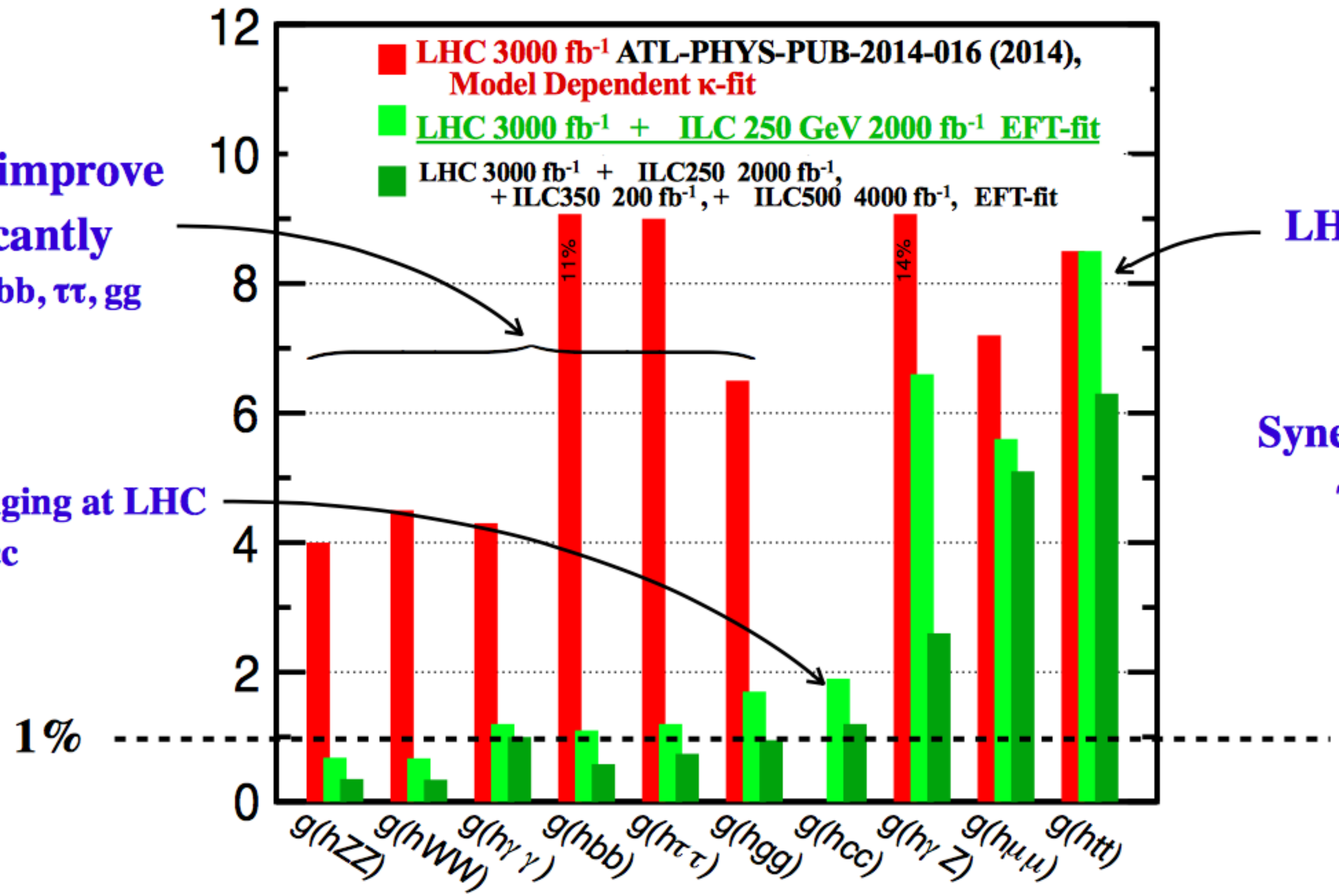
This way, one knows σ_{ZH} directly without having to rely on the Higgs decays



Higgs: synergy ee + LHC

ILC can improve significantly
ZZ, WW, bb, ττ, gg

Very challenging at LHC
cc



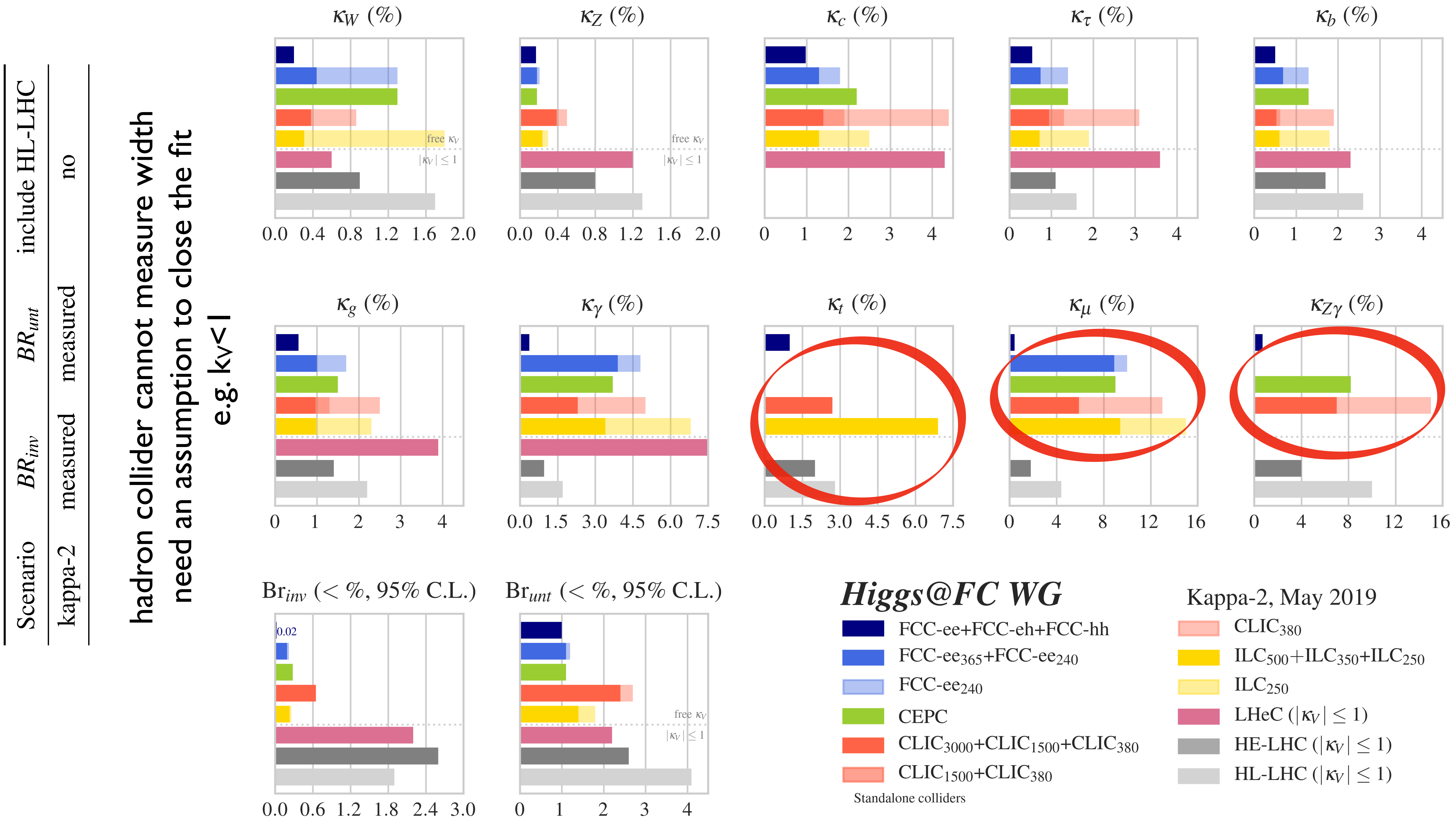
LHC is necessary
tt

Synergy with LHC
γγ, γZ, μμ

Results of kappa-2 fit

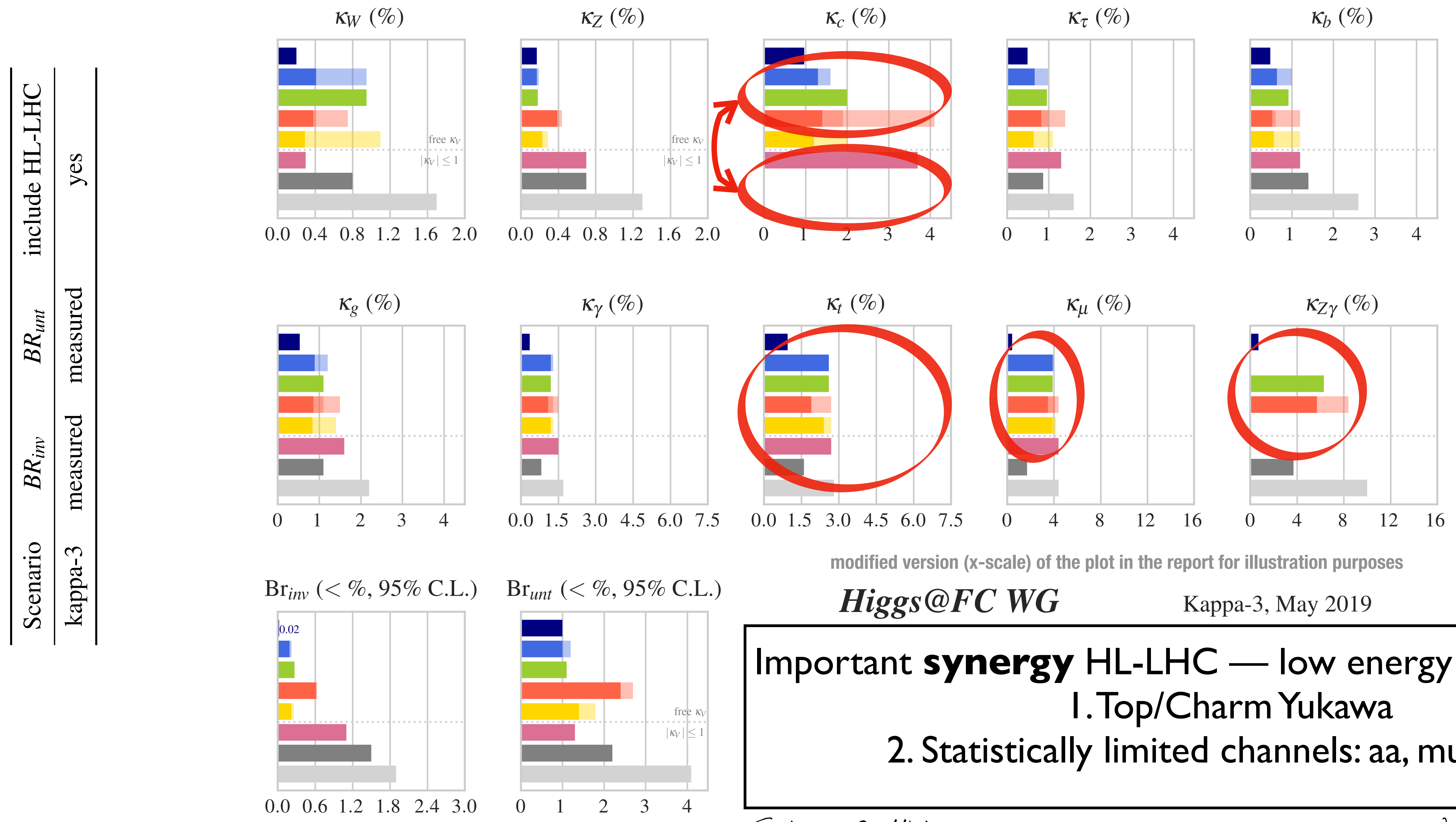
ECFA Higgs study group '19

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



Results of kappa-3 fit

ECFA Higgs study group '19

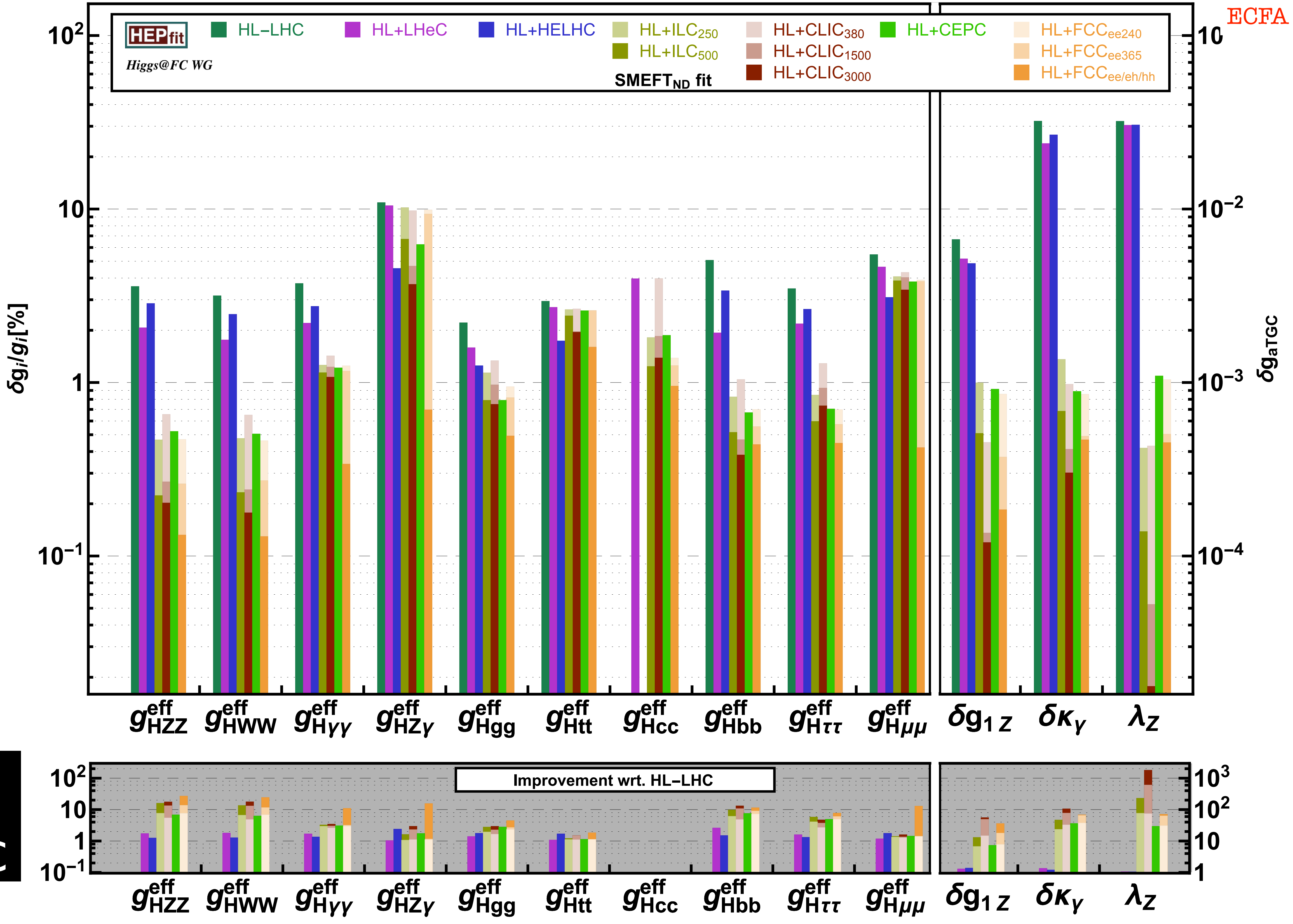


modified version (x-scale) of the plot in the report for illustration purposes

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

Global EFT fit



ECFA Higgs study group '19

There is life beyond HL-LHC

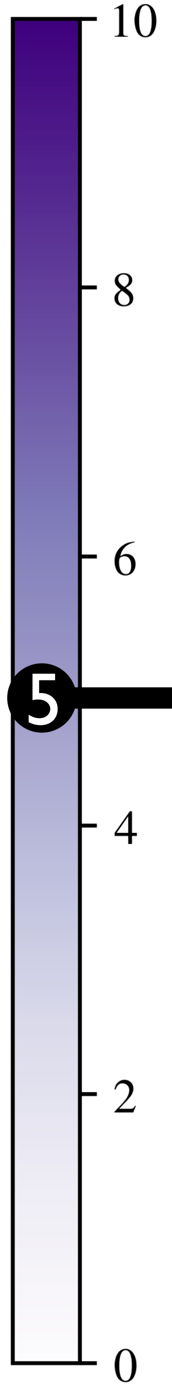
Figures of Merit with Respects to HL-LHC

ECFA Higgs study group '19

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
$g^{\rm eff}_{HZZ}$	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 (⋆) not measured at HL-LHC



Stat. limited

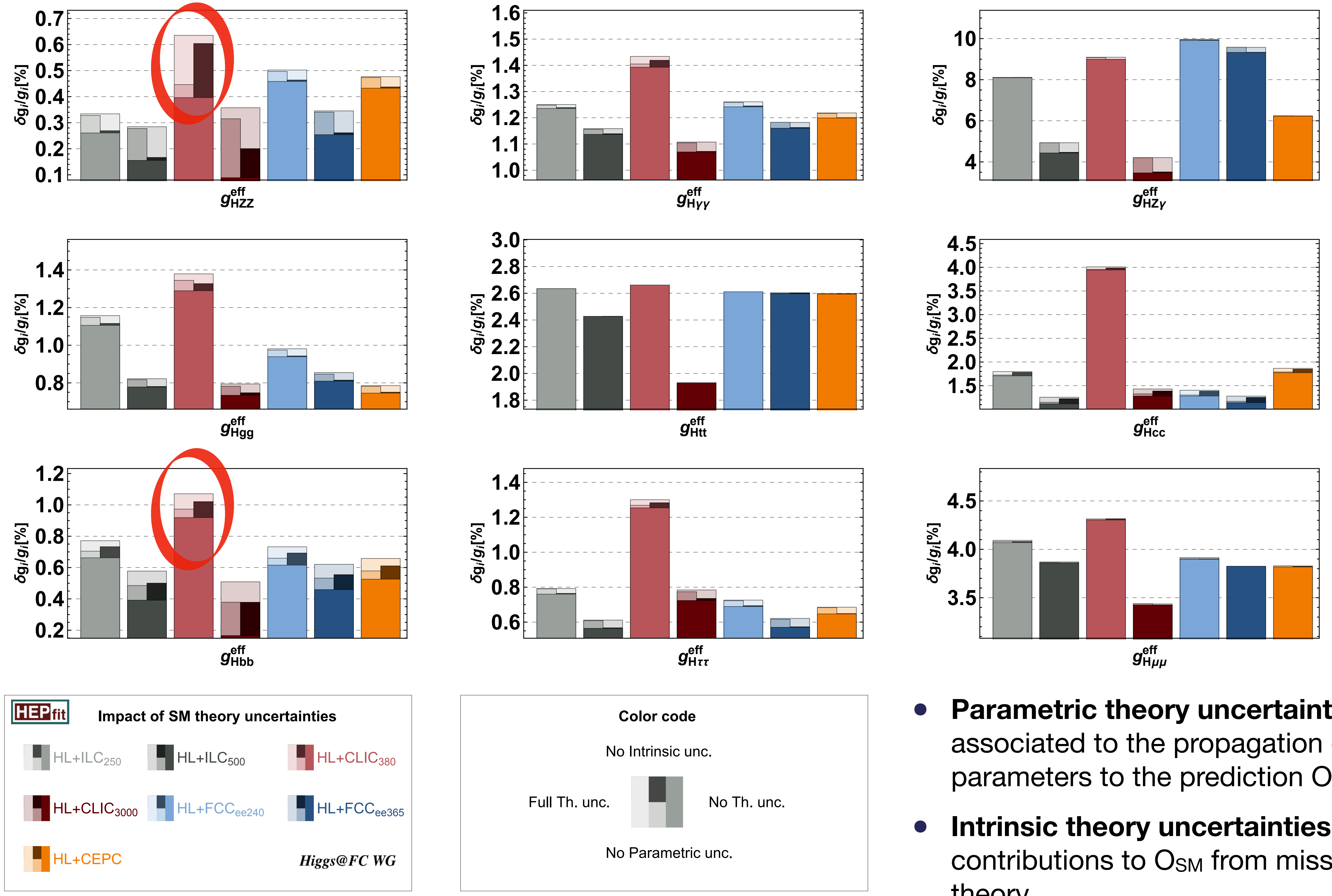
Top quark channels
(LHC is a top factory and it is not so easy to outperform)

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

Possible at all colliders
(often in their initial stage)
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_{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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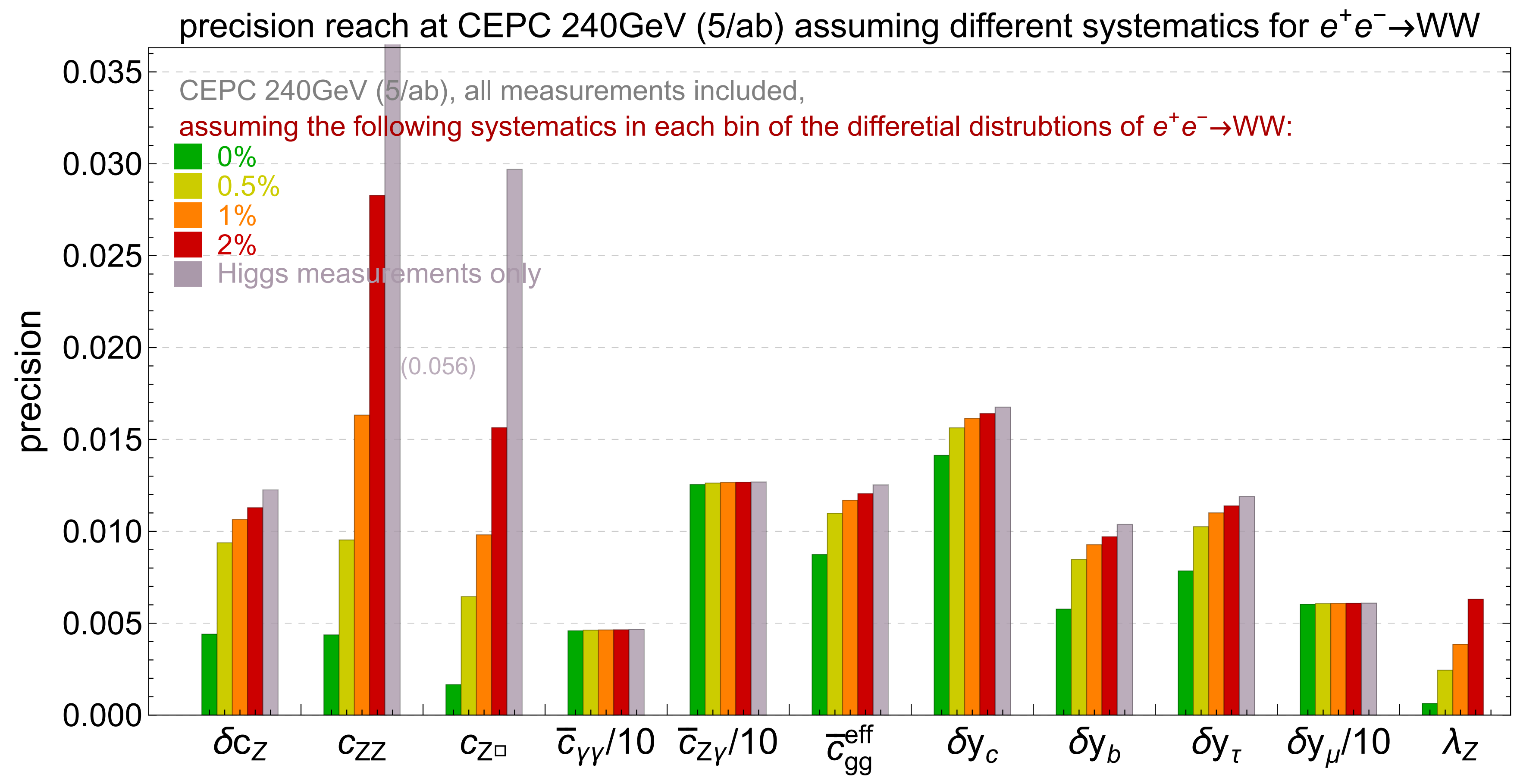
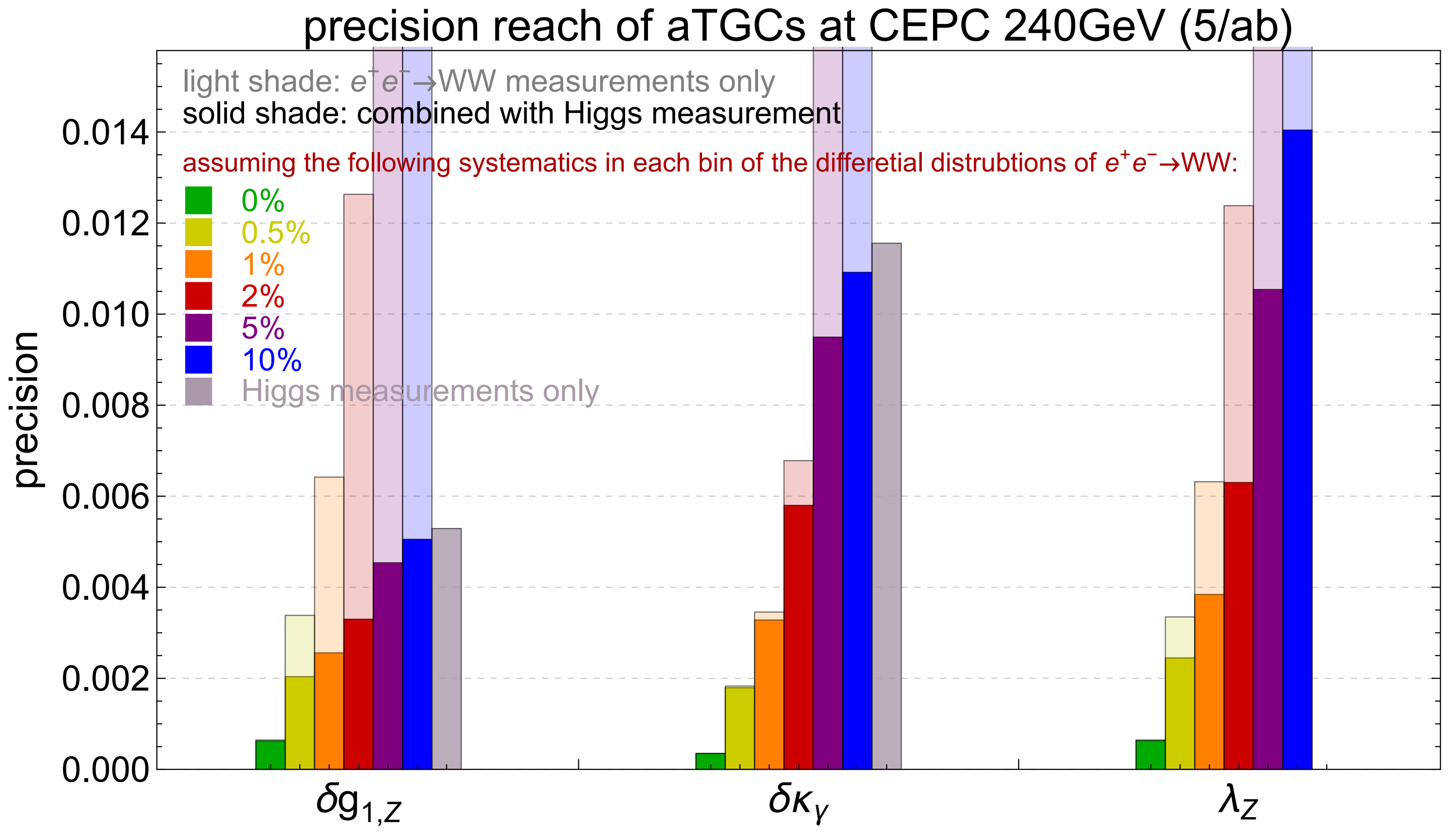
More theory work needed to match EXP uncertainties

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_Z[\text{MeV}]$	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
$\Delta \sin^2\theta^\ell_{\text{eff}}[10^{-5}]$	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

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)



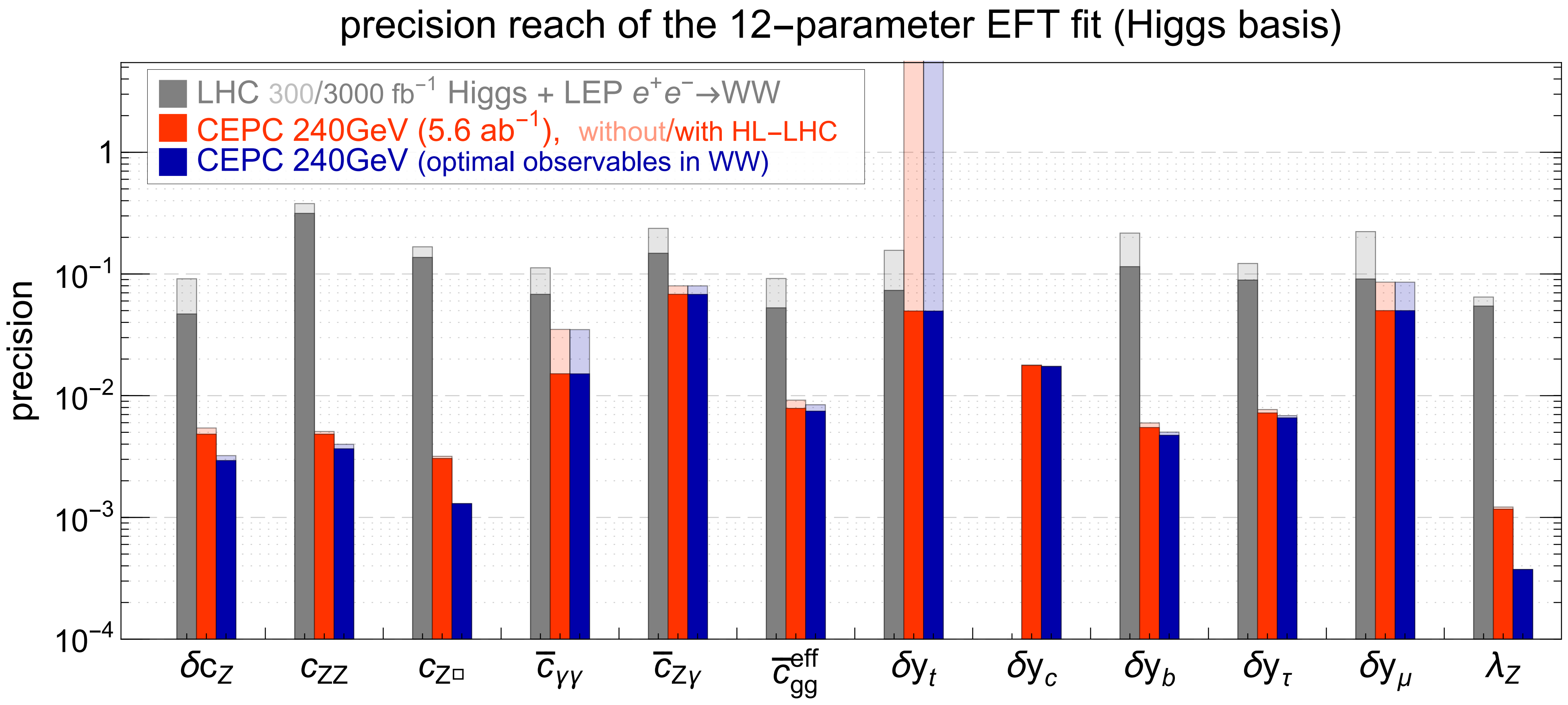


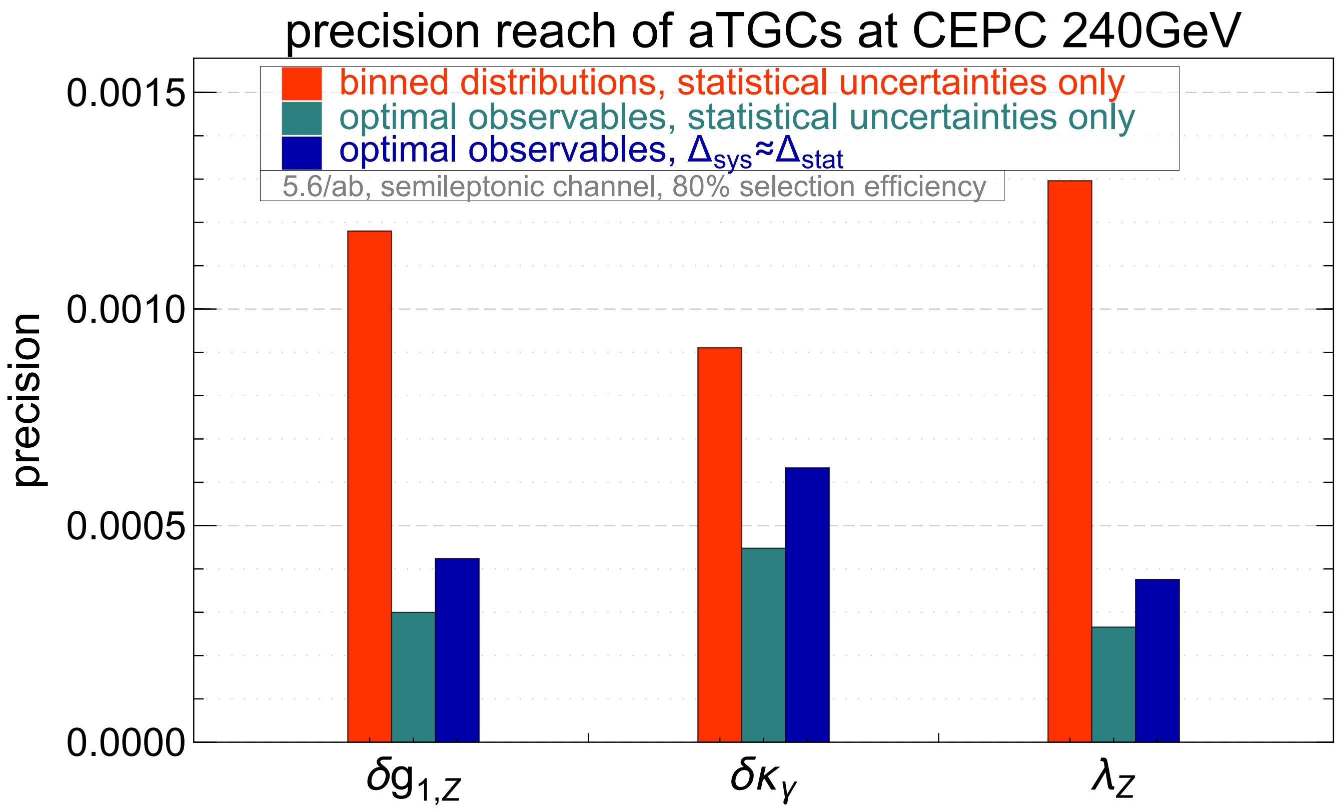
Durieux, Grojean, Gu, Wang '17

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)

Diboson analysis can still be improved, e.g., using optimised observables





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

Impact of Z-pole measurements

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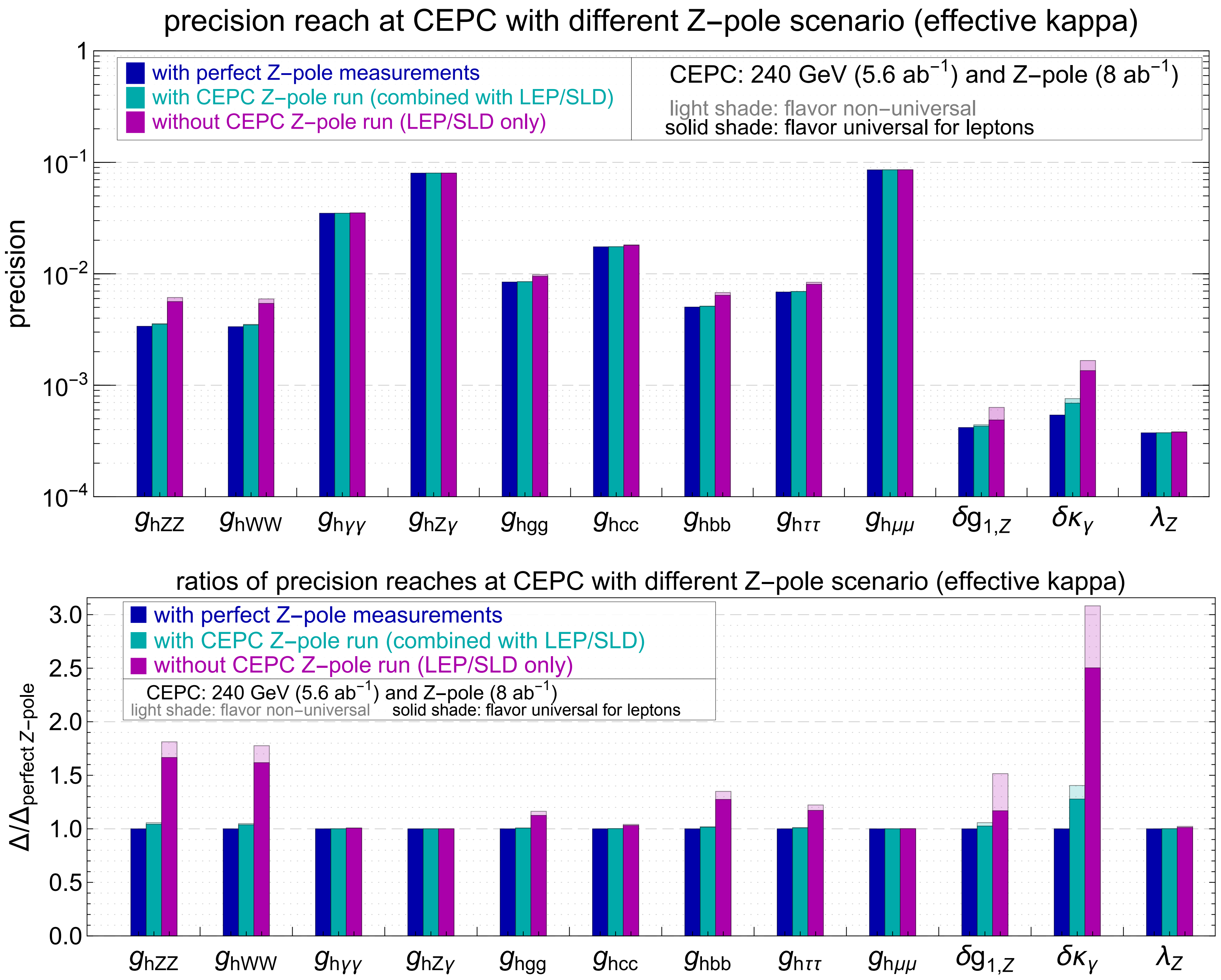

Z-pole run needed
LEP/SLD is not enough
Issue for ILC?

Linear: L ↗ w/ E

Circular: L ↘ w/E

EFT fit translated into postdicted Higgs couplings

(*e.g.* $g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}}$)

✗ CEPC alone

(combination with HL-LHC projections on its way)

Impact of Z-pole measurements

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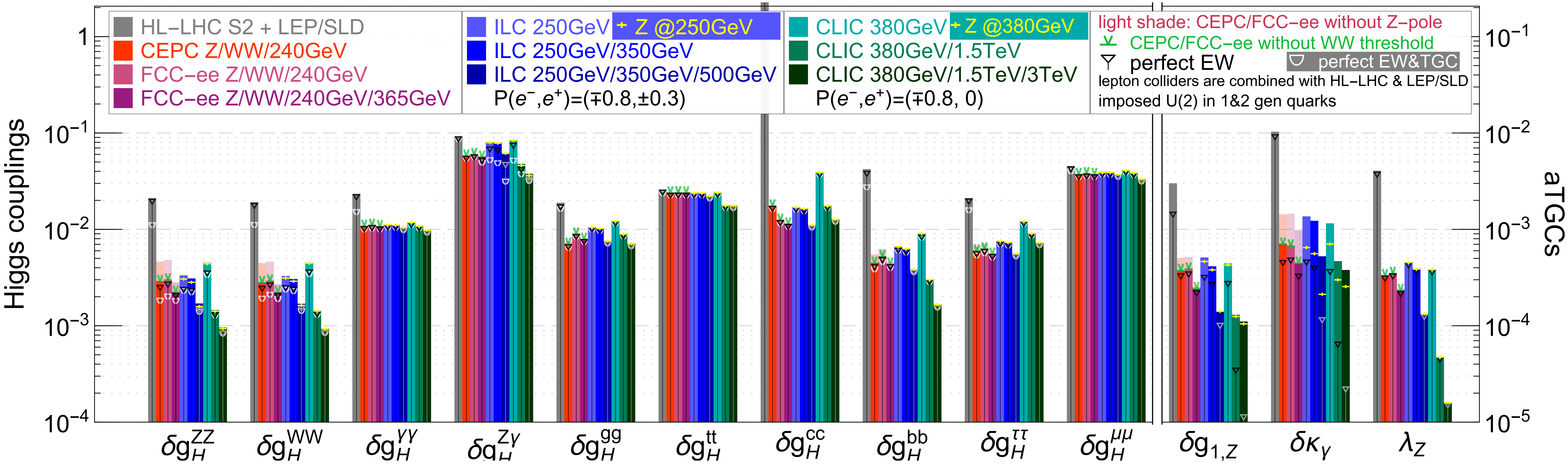
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



Impact of Z-pole measurements

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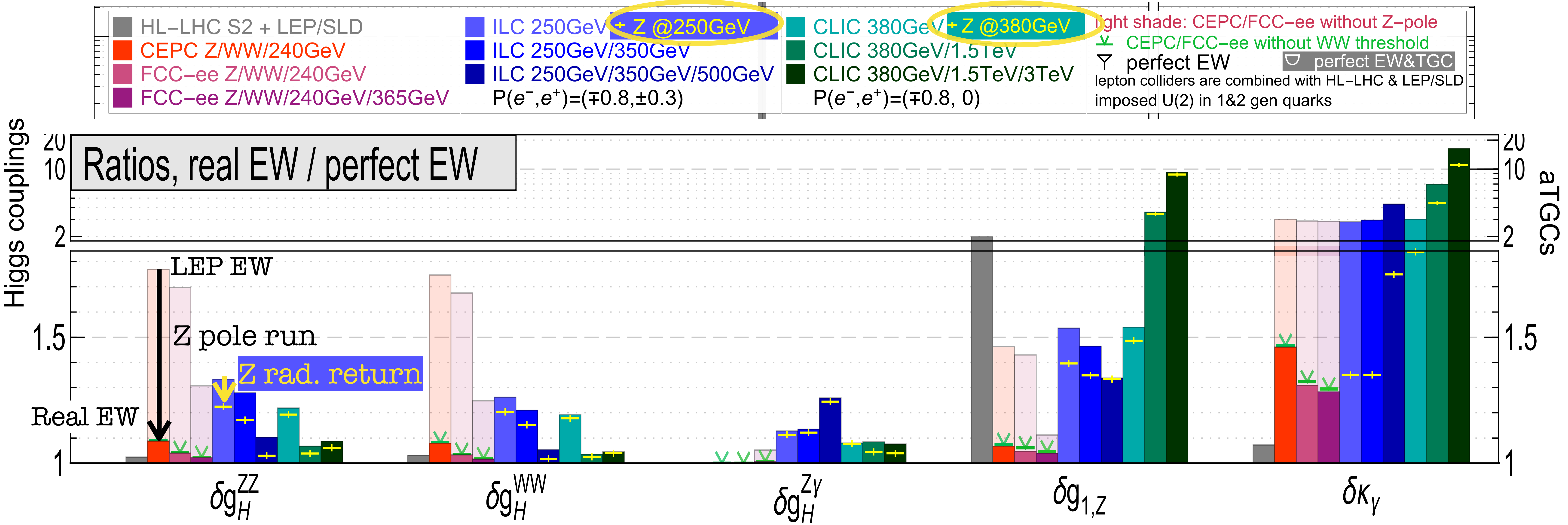

- FCC-ee and CEPC benefit a lot (>50% on HVV) from Z-pole run
- FCC-ee and CEPC EW measurements are almost perfect for what concerns Higgs physics (<10%).
- LEP EW measurements are a limiting factor (~30%) to Higgs precision at ILC, especially for the first runs
  But EW measurements at high energy (via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

Impact of Z-pole measurements

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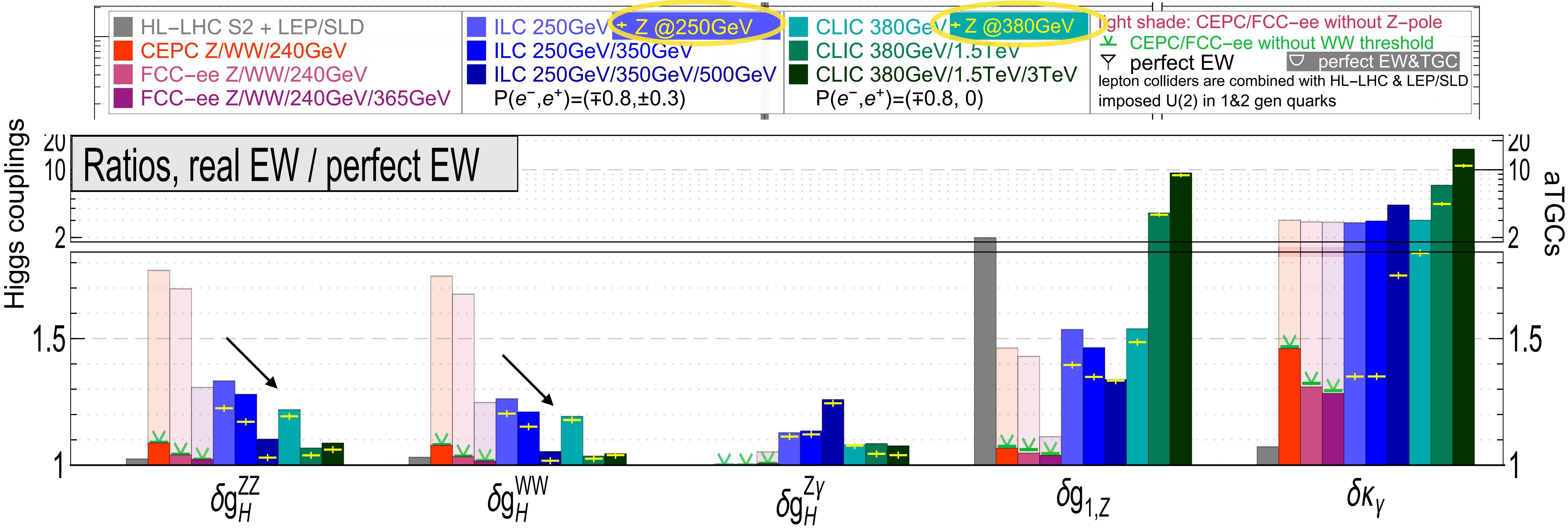
Comparing 3 EW scenarios: LEP/SLD, actual EW measurements, perfect EW measurements



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

Impact of Z-pole measurements

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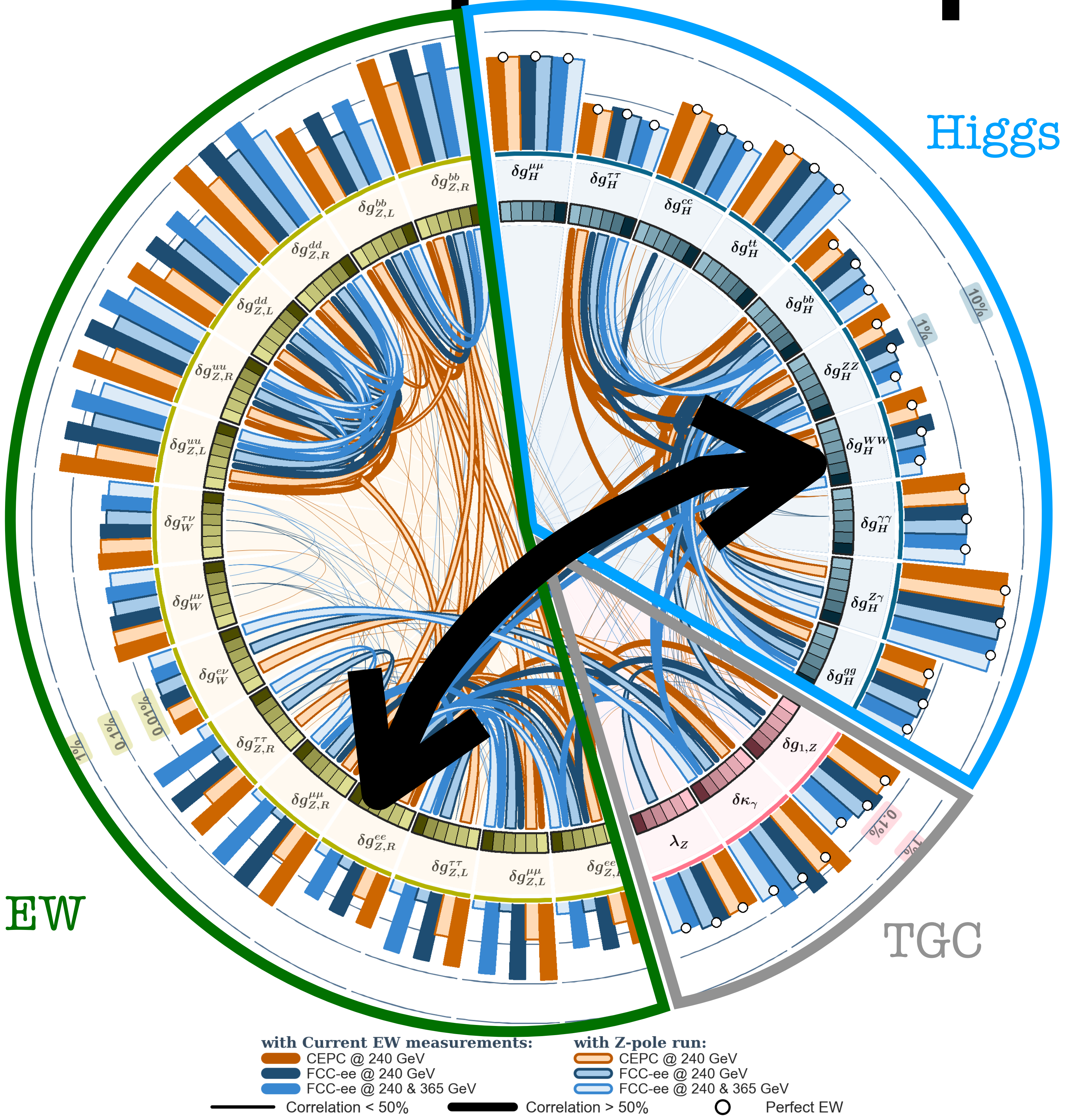

Contamination EW/TGC/Higgs can be understood by looking at correlations

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

Impact of Z-pole measurements

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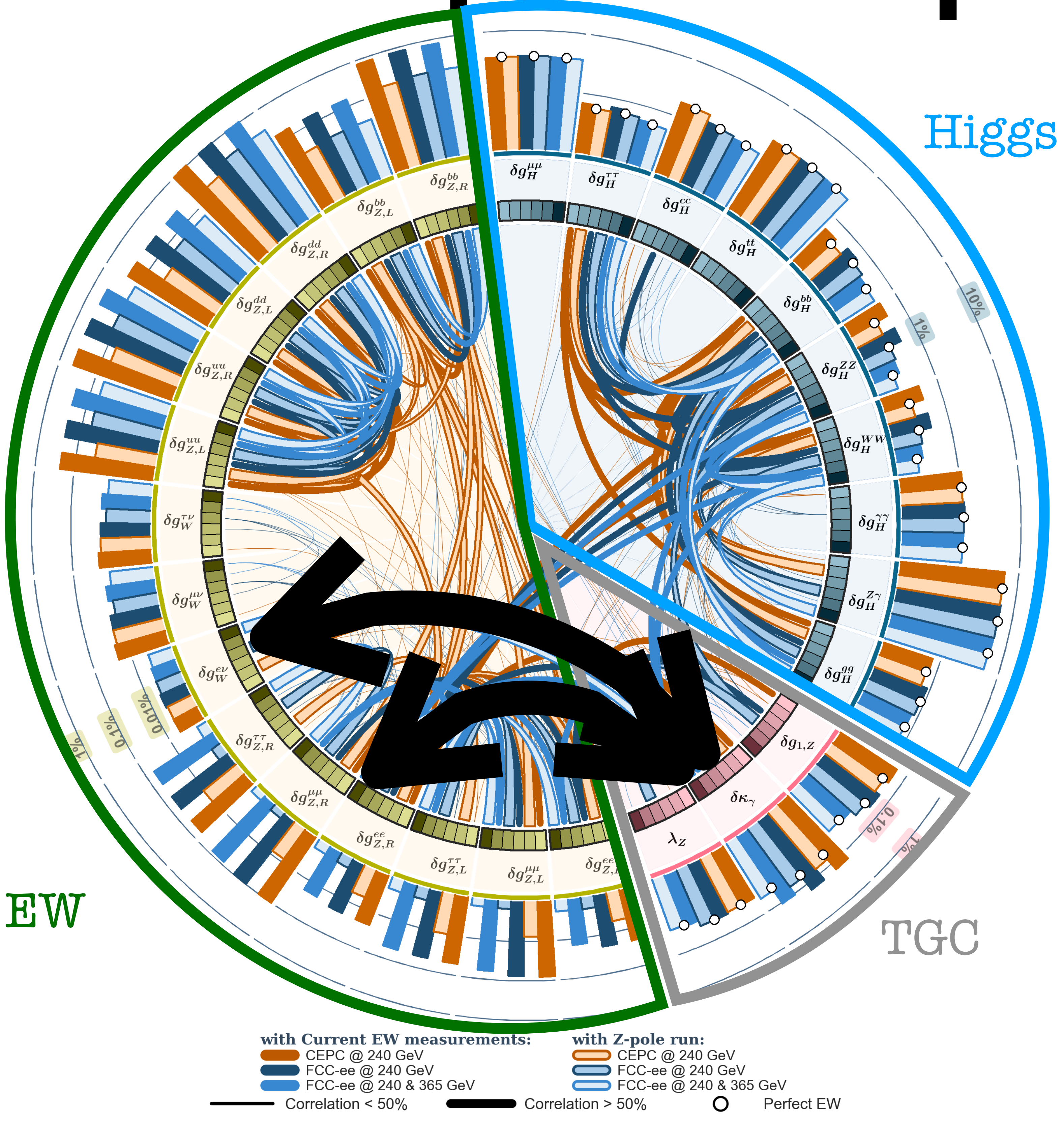

Contamination EW/TGC/Higgs can be understood by looking at correlations

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

Impact of Z-pole measurements

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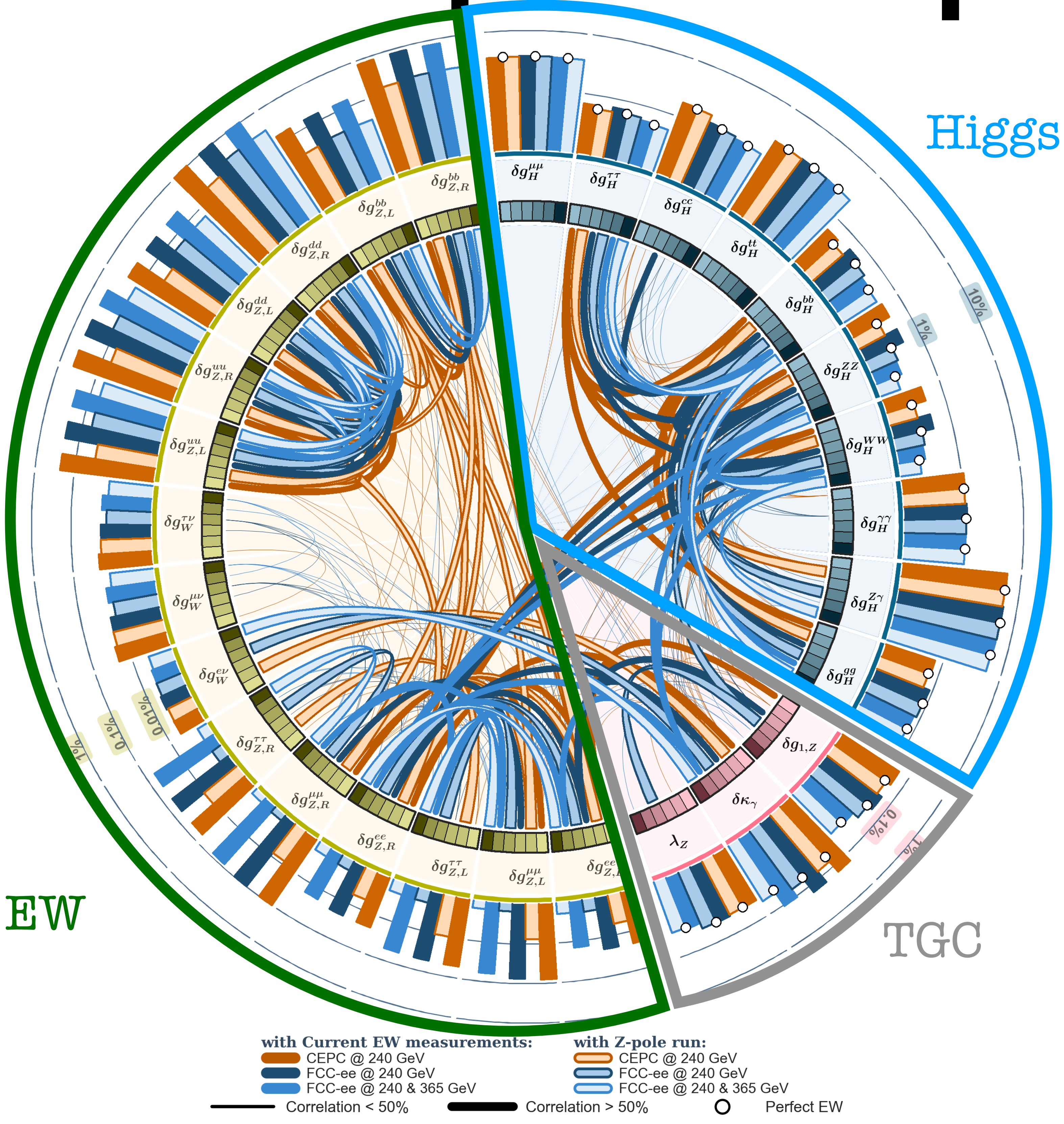
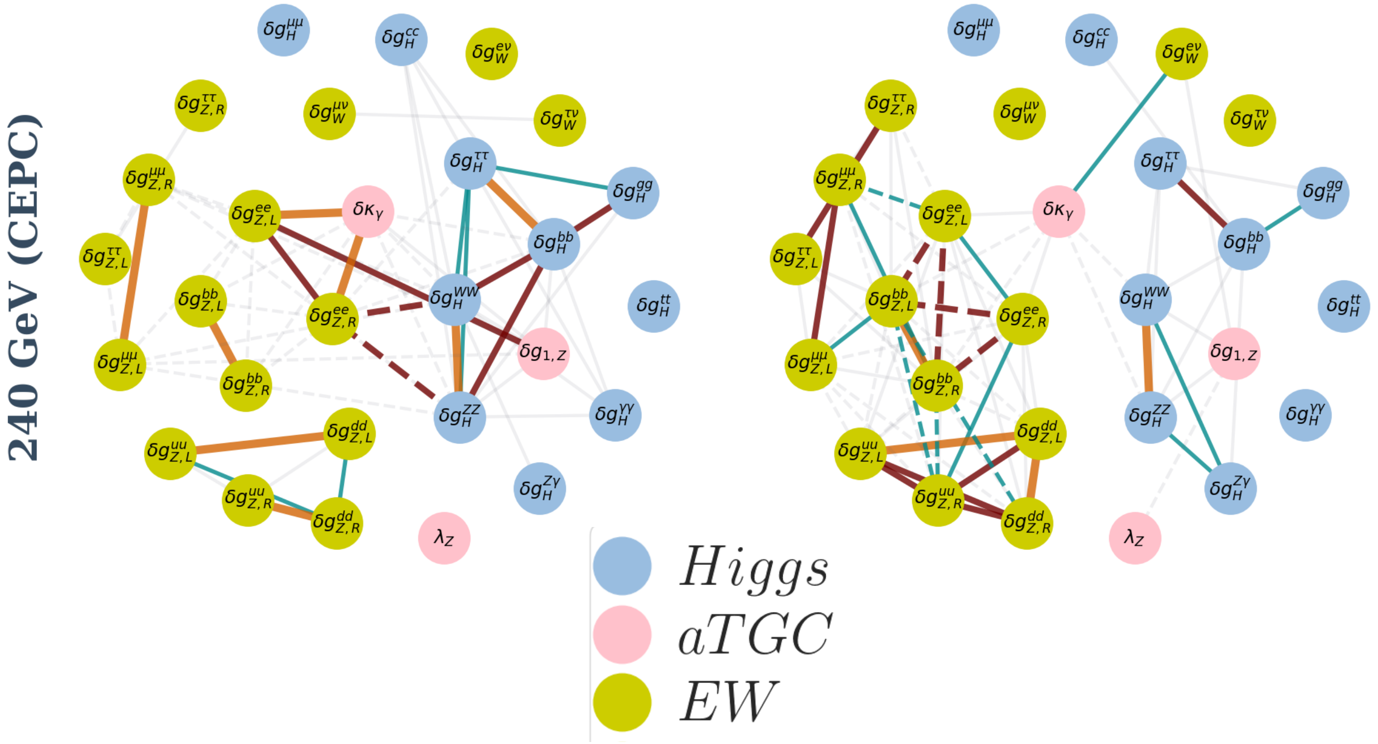


Contamination EW/TGC/Higgs can be understood by looking at correlations

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



Impact of Beam Polarisation

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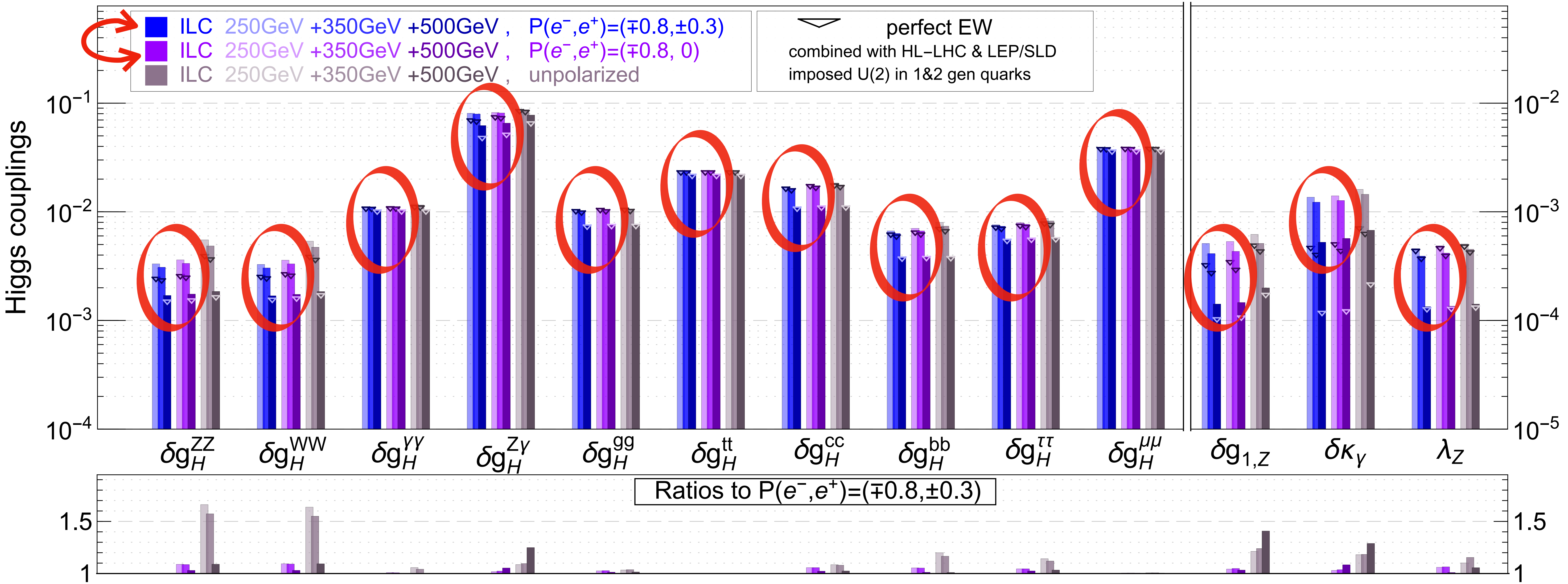

- Positron polarisation doesn't play a big role (for Higgs couplings determination)

Impact of Beam Polarisation

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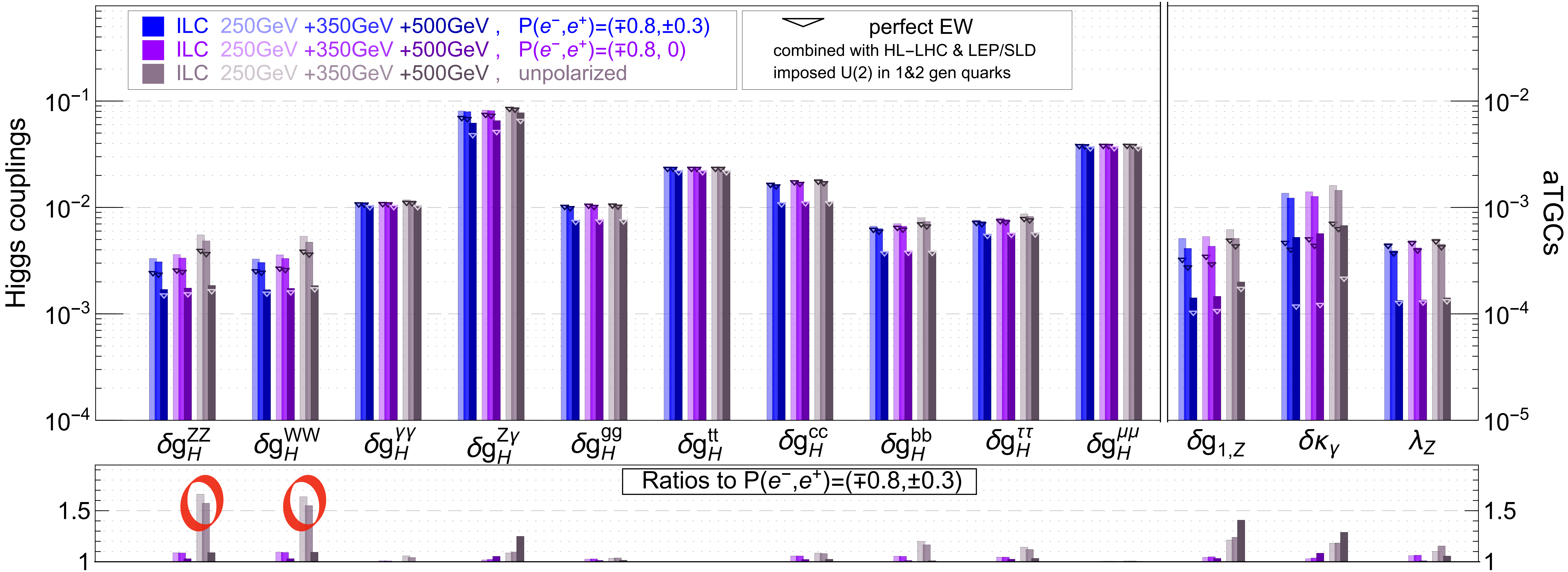

- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination

Impact of Beam Polarisation

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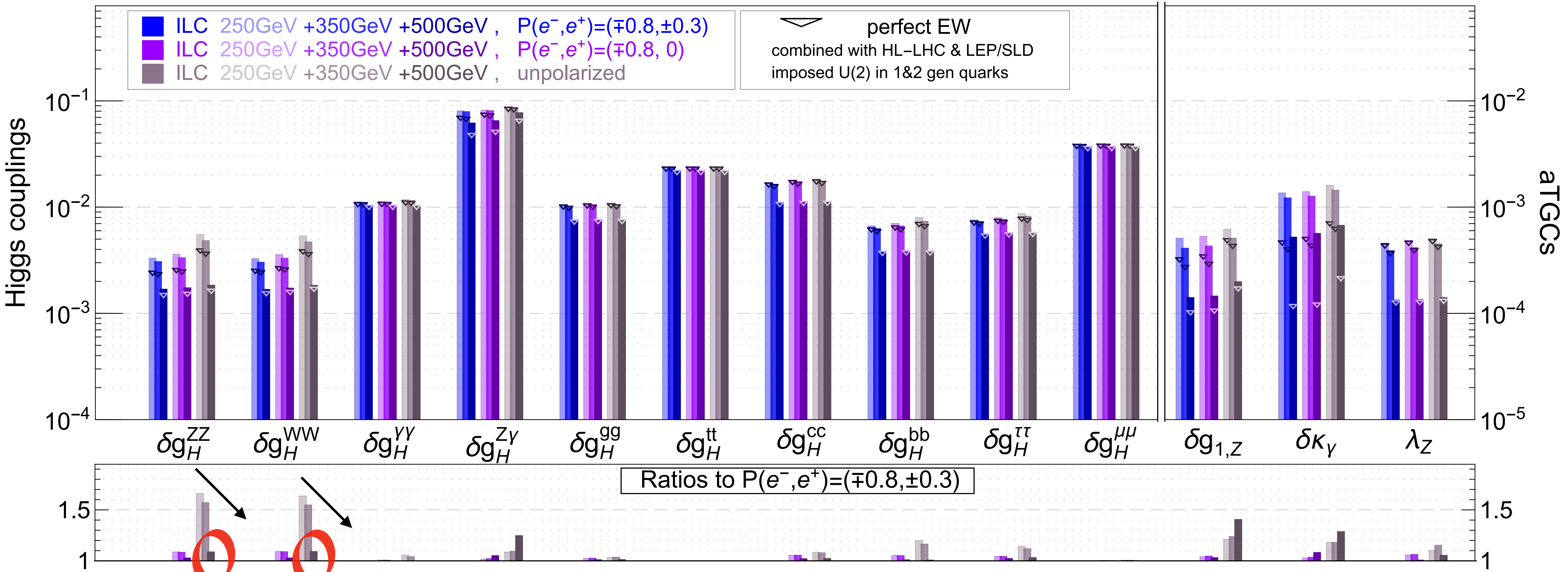
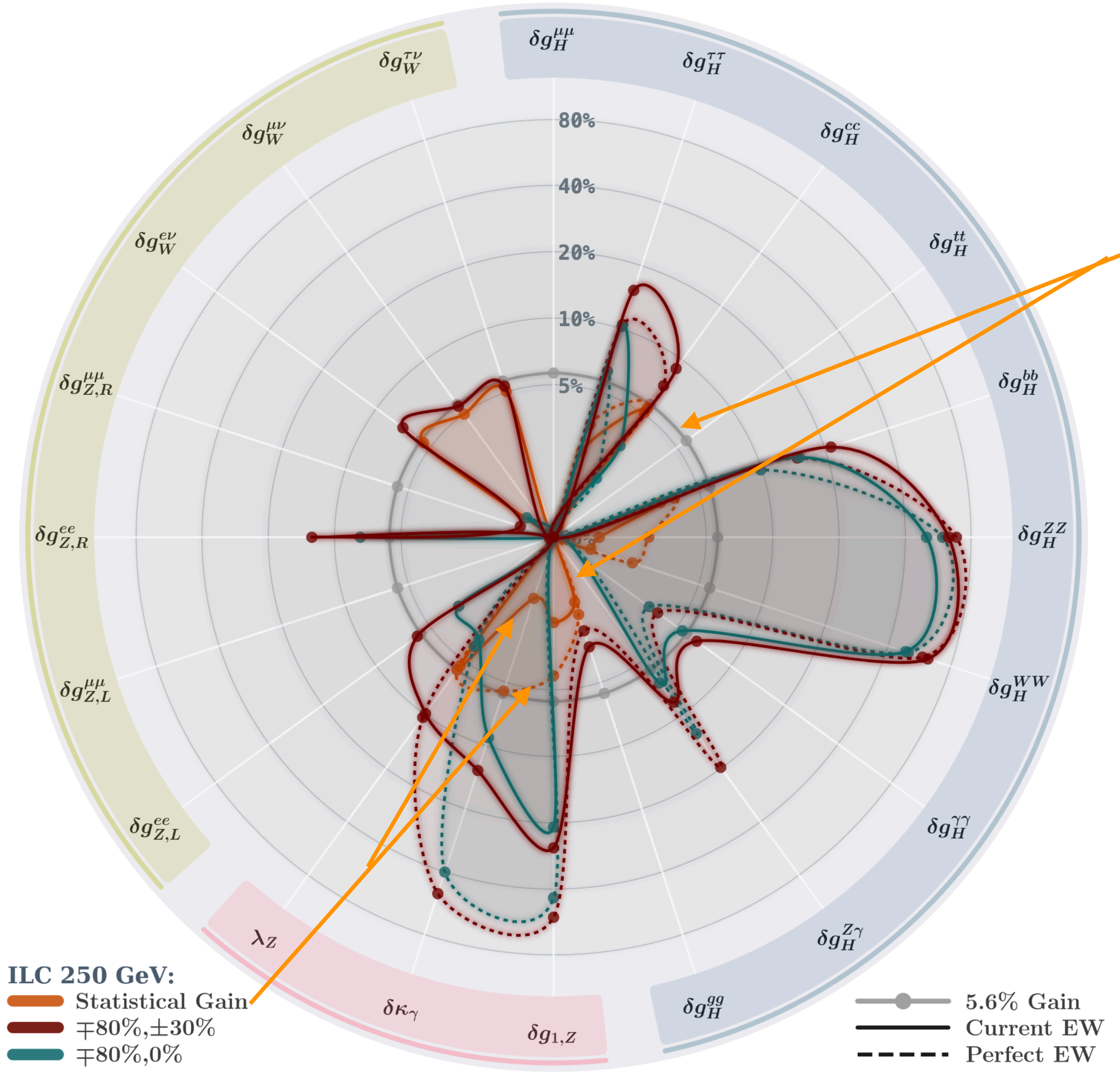


- Positron polarisation doesn't play a big role (for Higgs couplings determination)
- If 250GeV run only: electron polarisation improves significantly (>50%) hVV determination
- Polarisation-benefit diminishes (in relative and absolute terms) when other runs at higher energies are added

Impact of Beam Polarisation (@250GeV)

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



Statistical gain from increased rates

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

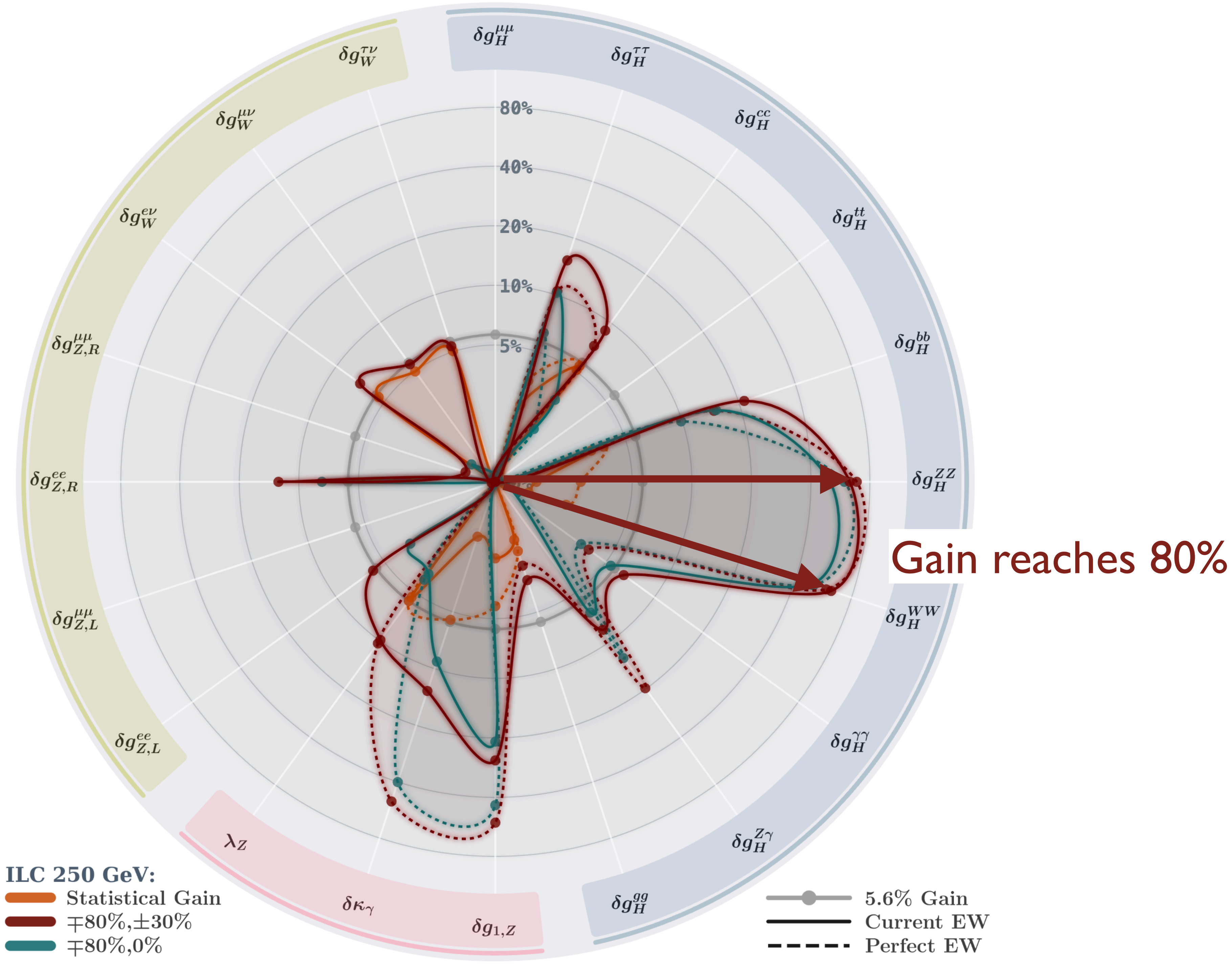
From ee→Zh, A_{LR}~0.15 so $\sigma_{-80,+30} \sim 1.4\,\sigma_0$

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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

Impact of Beam Polarisation (@250GeV)

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



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

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

Impact of Beam Polarisation (@250GeV)

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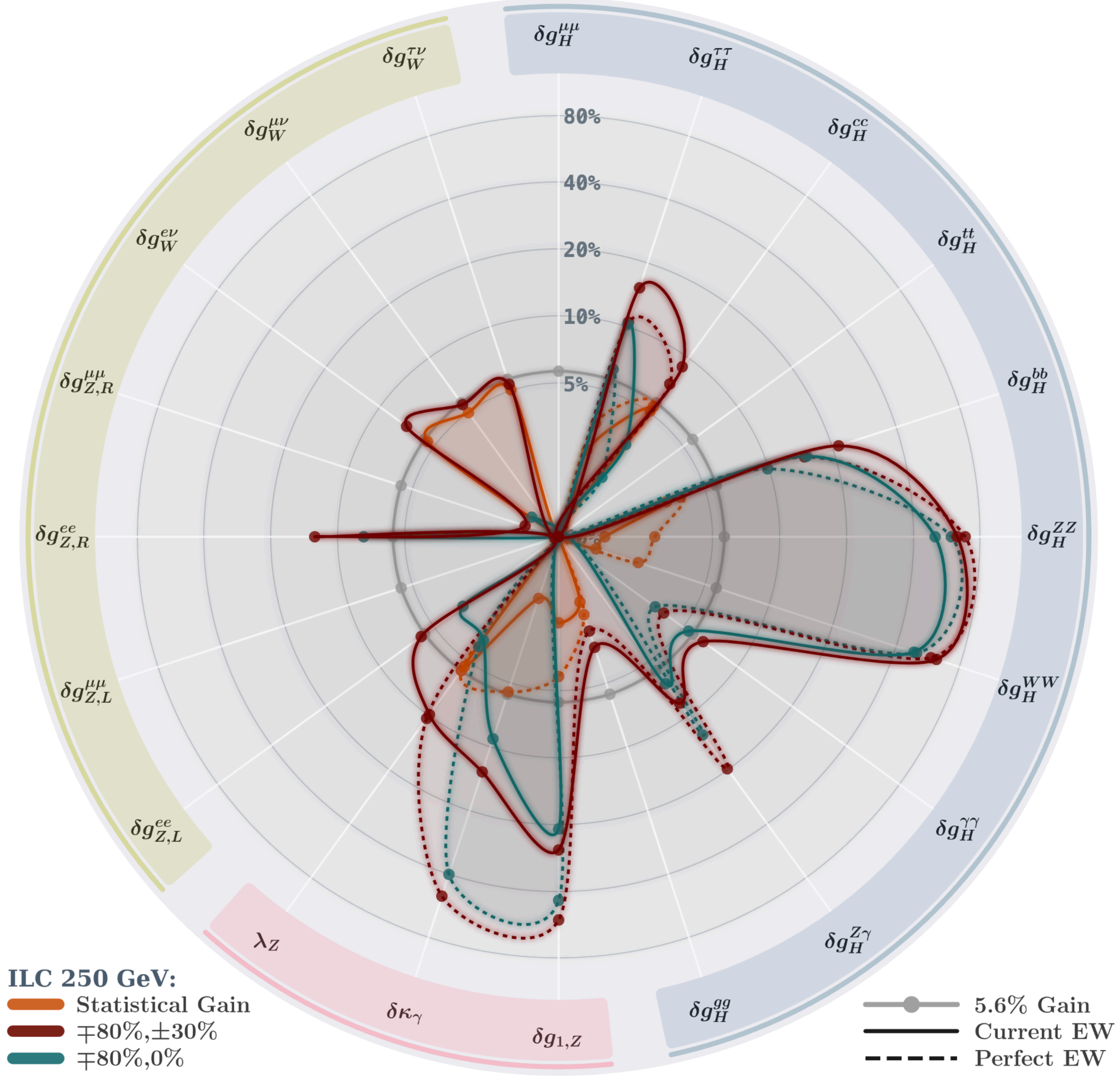

increased sensitivities Polarised vs. Unpolarised scenarios @ 250GeV

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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 portals and Higgs exotic decays

|H|² and HL are SM-singlet of low dimension

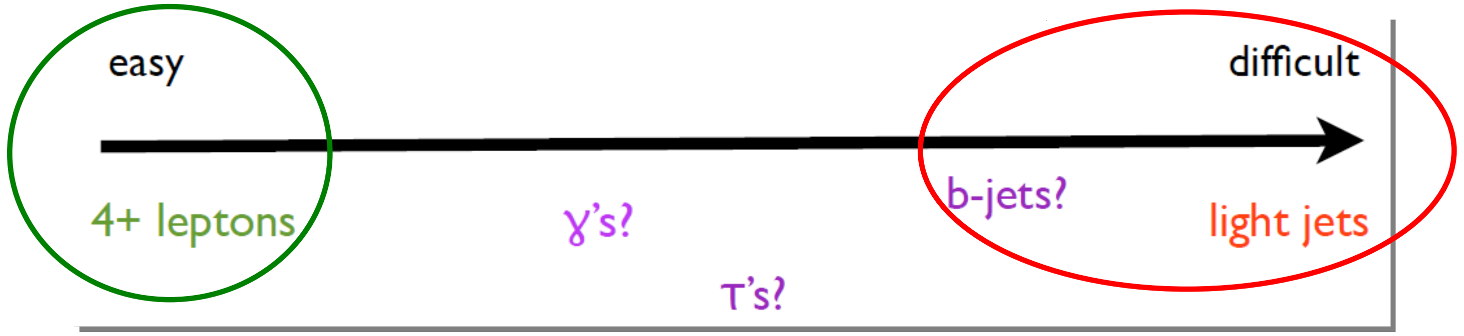
they can have large (renormalizable) couplings to hidden/dark sector that could
(i) make up the DM relic abundance
or (ii) be key agents in models of neutral naturalness

new exotic/invisible decay modes: ee sensitivity $BR_{exo}<1\%$

(if $m_{NP} > m_H/2$: possible production via off-shell Higgs but limited reach Craig et al '14)

$Z_{\mu\nu}Z_D^{\mu\nu}$	$\lvert H\rvert^2\lvert S\rvert^2$	HLN
$H\to ZZ_D$	$H\to ss$	$H\to LN$
new force	new Higgses	new matter

Gori @ LCWS'15



Example:
h ⟶ ZZ_D ⟶ 4l
These can be seen by the LHC pretty easily:
BRs ~ 10^{-6} – 10^{-7} can be probed by the HL-LHC
Curtin, Essig, SG, Shelton 1412.0018

See Liu, Potter, 1309.0021 for a ILC h ⟶ 4τ analysis

Example: (as in the NMSSM)
h ⟶ ss ⟶ 4b
Background limited at the LHC.
Theory studies show that BRs ~ 0.1 might be reached Cao et al, 1309.4939

~ Complementarity with LHC searches

~ Importance to measure Higgs width

Higgs portals and Higgs exotic decays

$|H|^2$ and HL are SM-singlet of low dimension

they can have large (renormalizable) couplings to hidden/dark sector that could

(i) make up the DM relic abundance

or (ii) be key agents in models of neutral naturalness

arXiv:1612.09284