6th FCC Physics Workshop
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Higgs coupling fits

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Based on the Snowmass reports:
arXiv: 2206.08326 [hep-ph] (SMEFT fits)
arXiv: 2209.07510 [hep-ph] (Higgs physics)

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ugr Universidad de Granada

Transformación Económica, Industria, Conocimiento y Universidades

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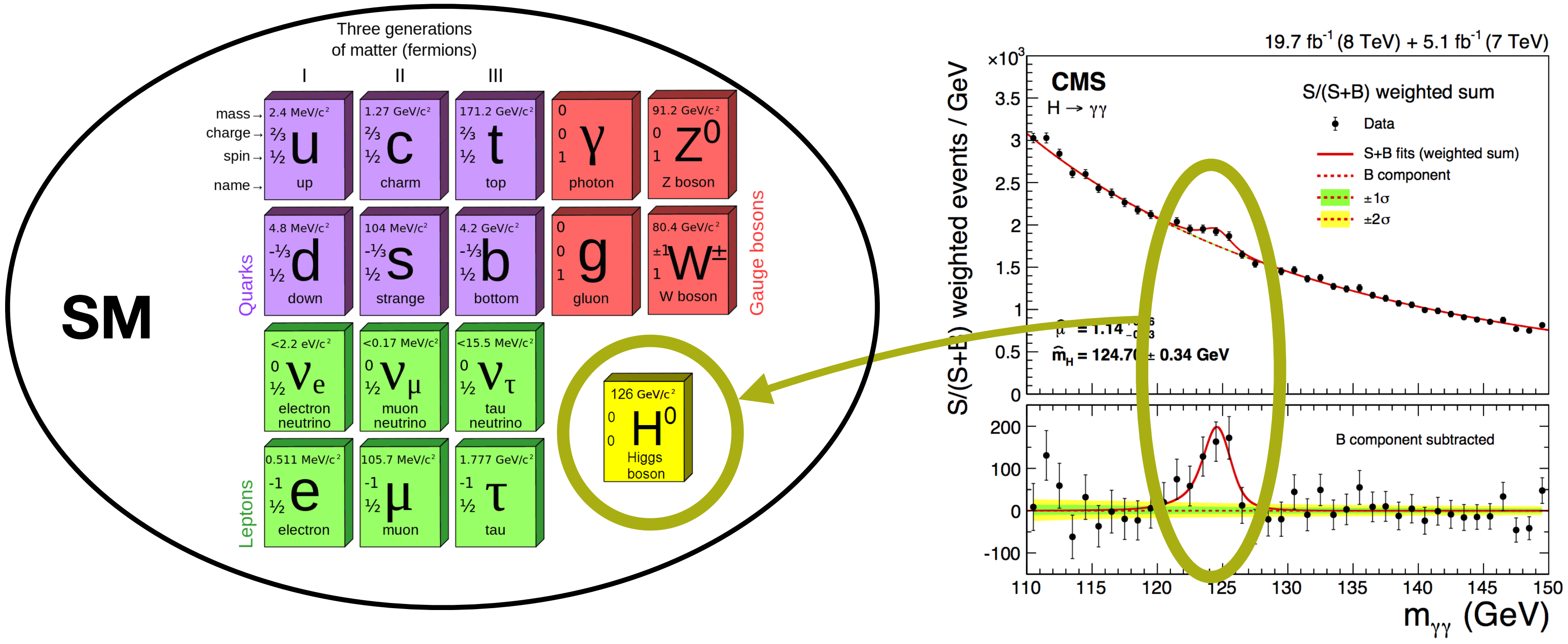
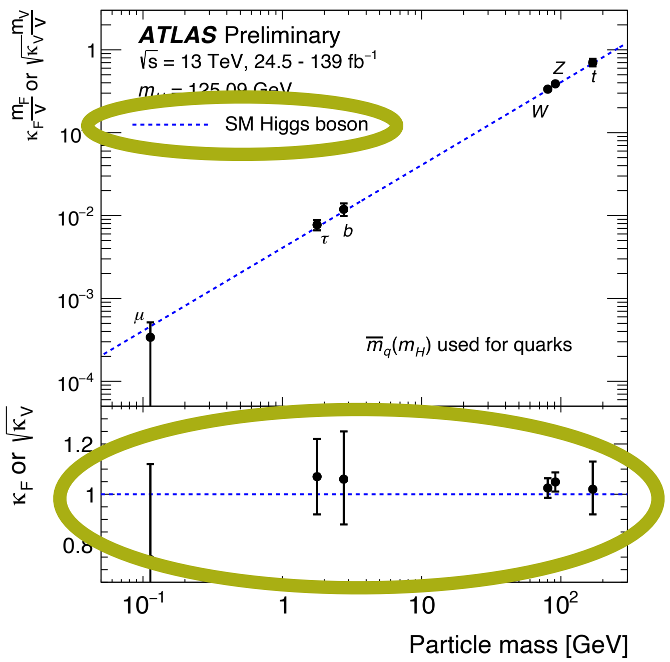
Introduction

- **The discovery of the 125 GeV Higgs boson is arguably the major achievement of the LHC (so far)**
  ✓ It finally provides evidence of the last ingredient required to confirm the validity of the SM at low energies…





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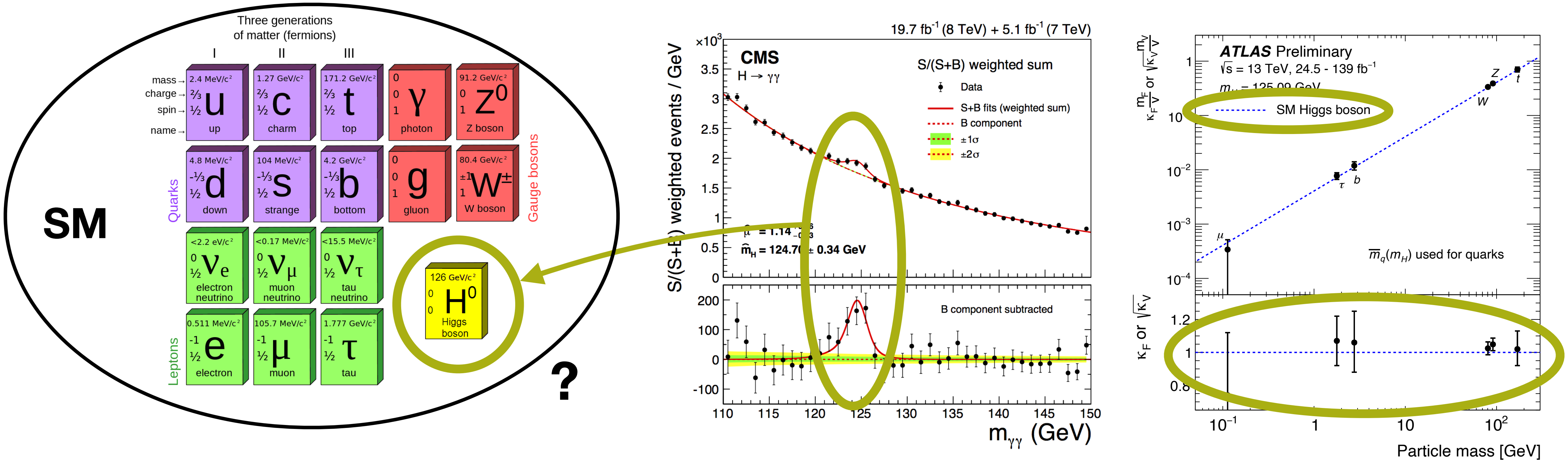

  - ✓ …but also reminds us of the limitations of the Standard Model…
    - How do we understand the mechanism of EWSB?
    - Hierarchy problem: Why $M_h \ll M_P$?

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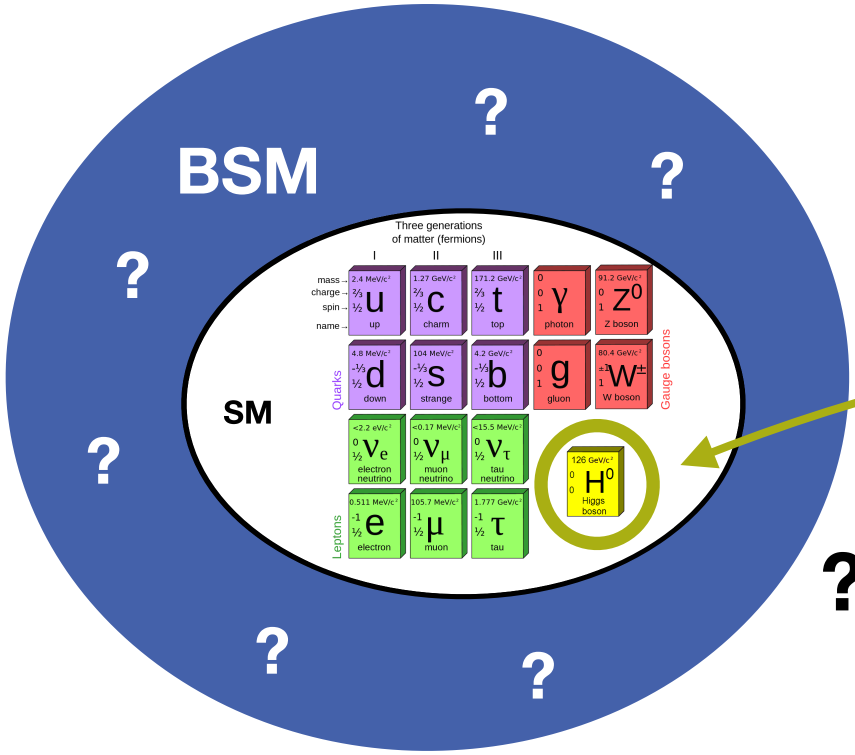

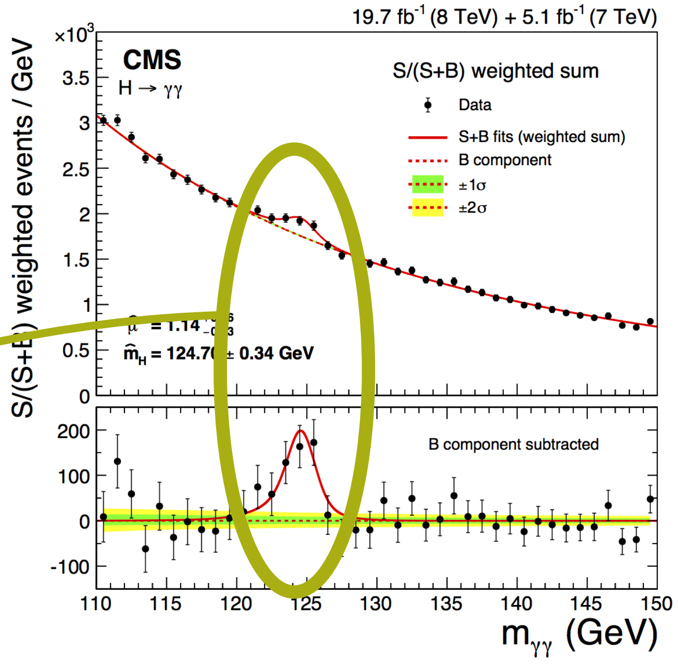

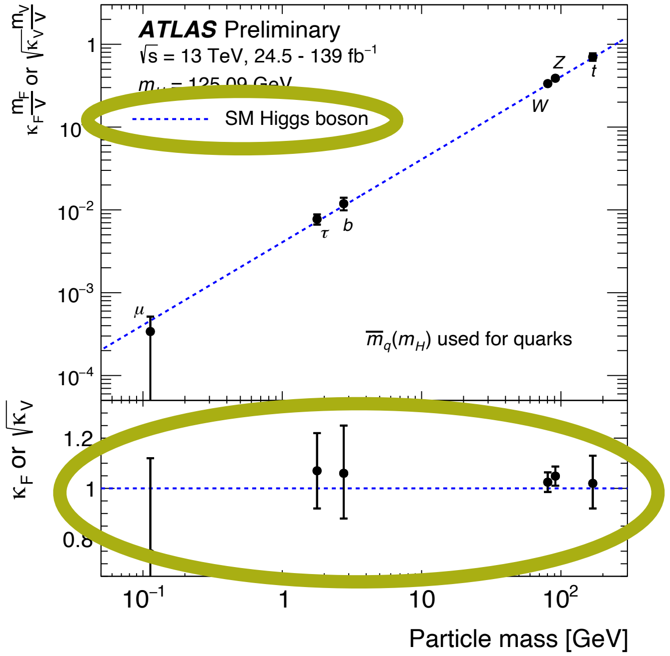

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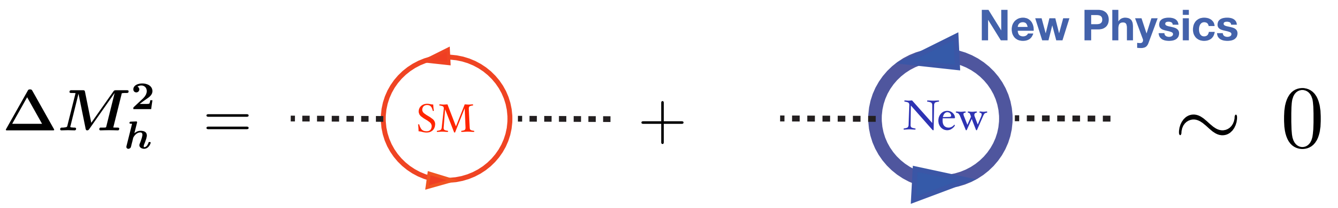
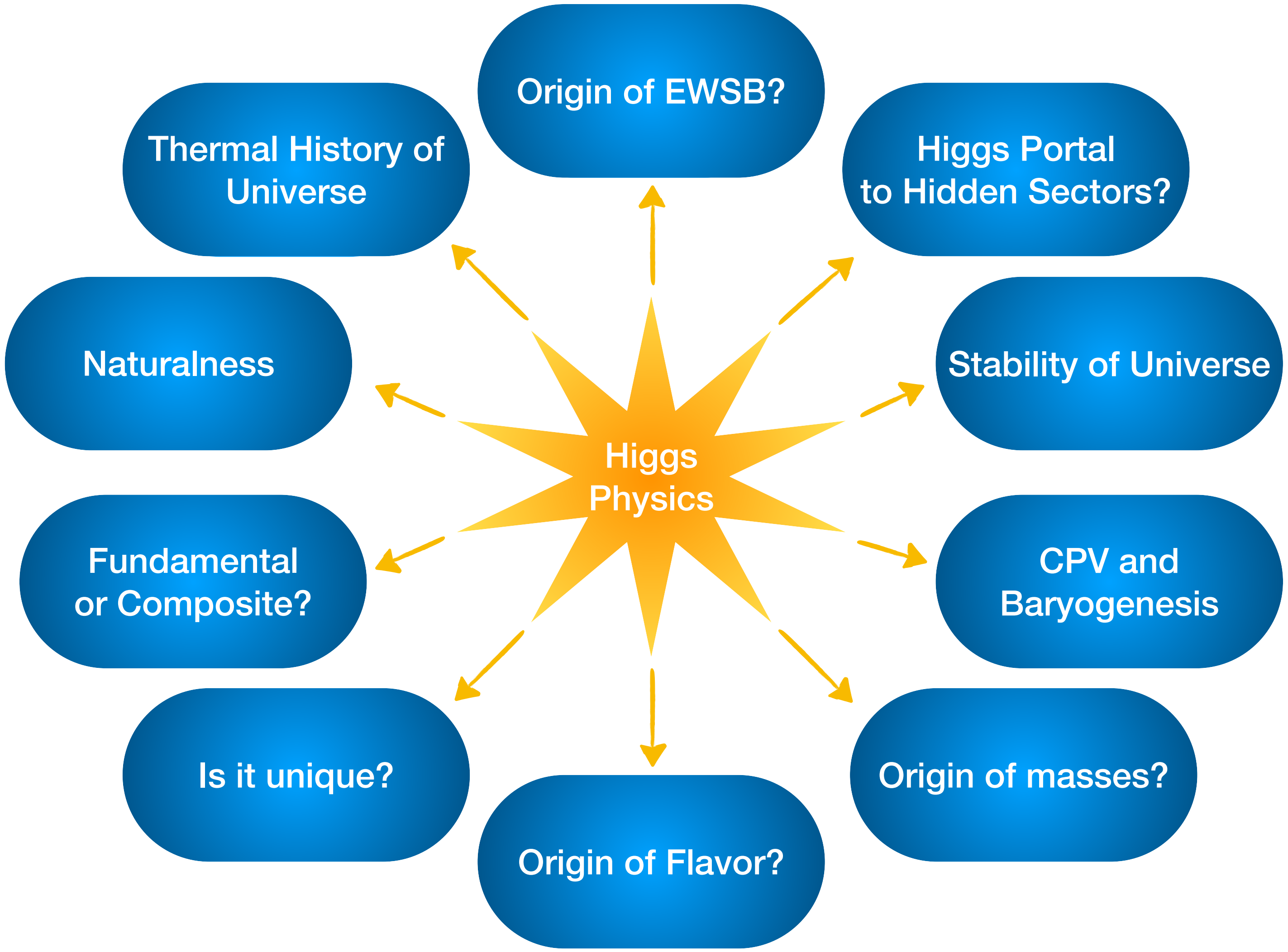
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?

⇒ BSM:



Introduction

- …and is connected to many interesting/relevant questions in HEP:



arXiv: 2209.07510 [hep-ph]

<u>BSM scenarios dealing with these questions tend to:</u>

1. **Introduce new particles in the scalar sector → Direct searches**
2. **Introduce modifications of the Higgs properties → Indirect tests of new physics**

The LHC is the only current experiment with direct access to both ways of testing the Higgs sector…

Introduction

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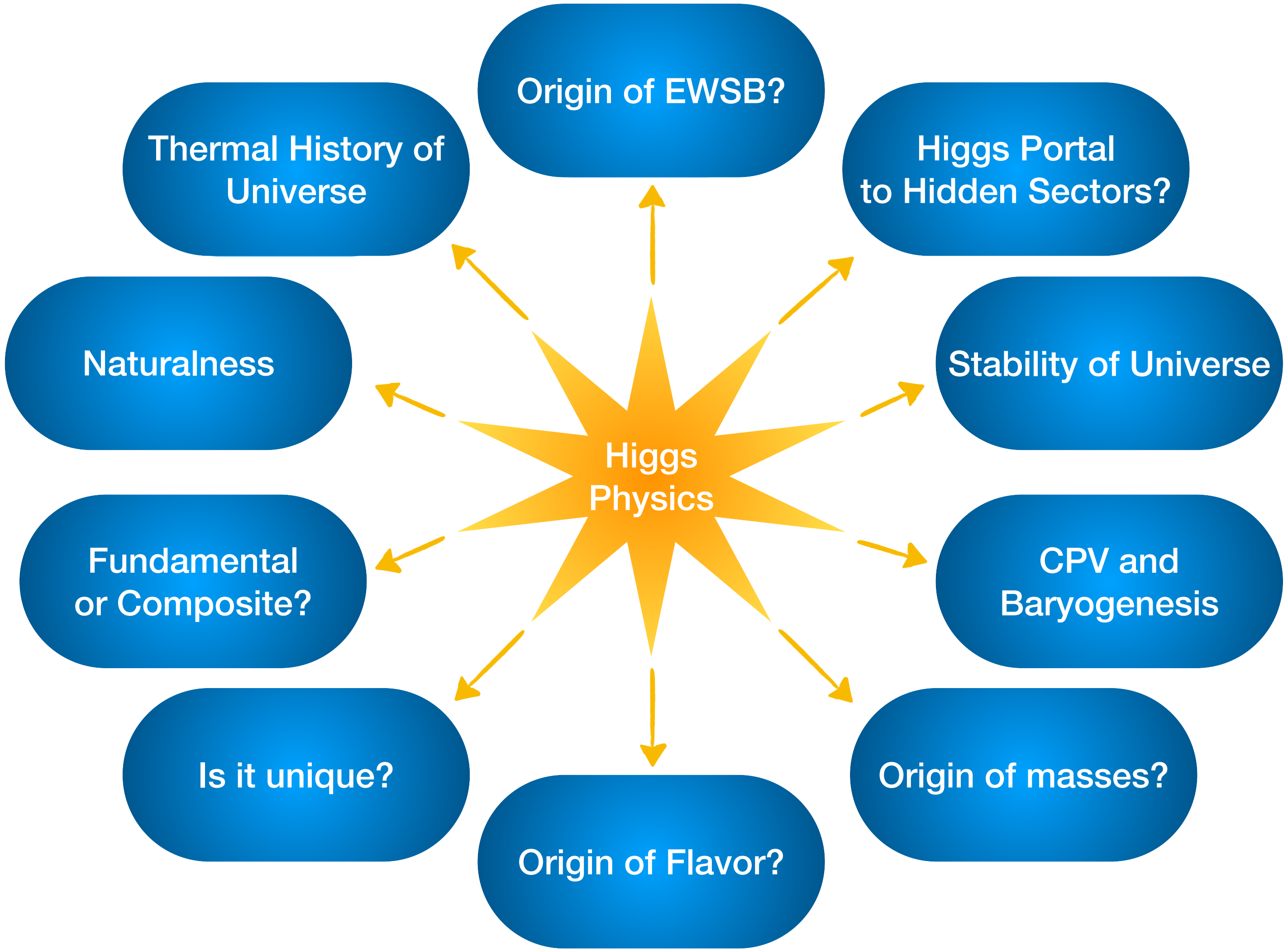

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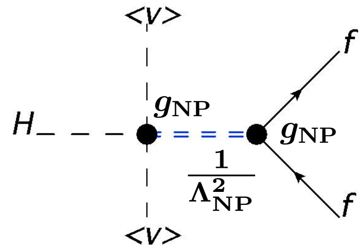
Introduction

- Higgs couplings modifications can tell us about BSM, but the O(10%) precision at the LHC gives limited information:

$$\left.\frac{\delta g_h}{g_h}\right|^{\text{Run II}}_{\text{LHC}} \sim O(10\text{ - }20)\%$$

Typical BSM deformation: $\frac{\delta g_h}{g_h} \sim \frac{g_{\rm NP}^2 v^2}{\Lambda_{\rm NP}^2} \Longrightarrow \Lambda_{\rm NP} \gtrsim 600 \frac{g_{\rm NP}}{g_{\rm SM}}$ GeV

E.g.

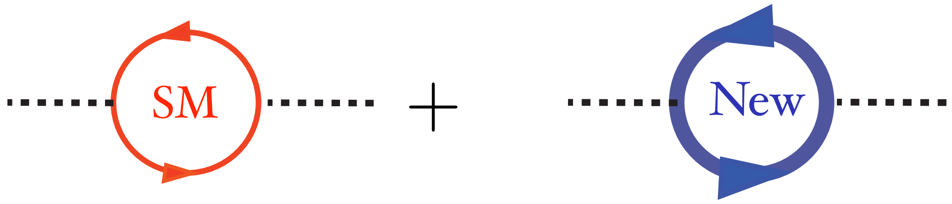


Not better than direct searches

(unless NP is strongly coupled)

- Higgs couplings also provide information about Naturalness

$$\delta m_H^2 =$$



$$\sim 0$$

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning}$$

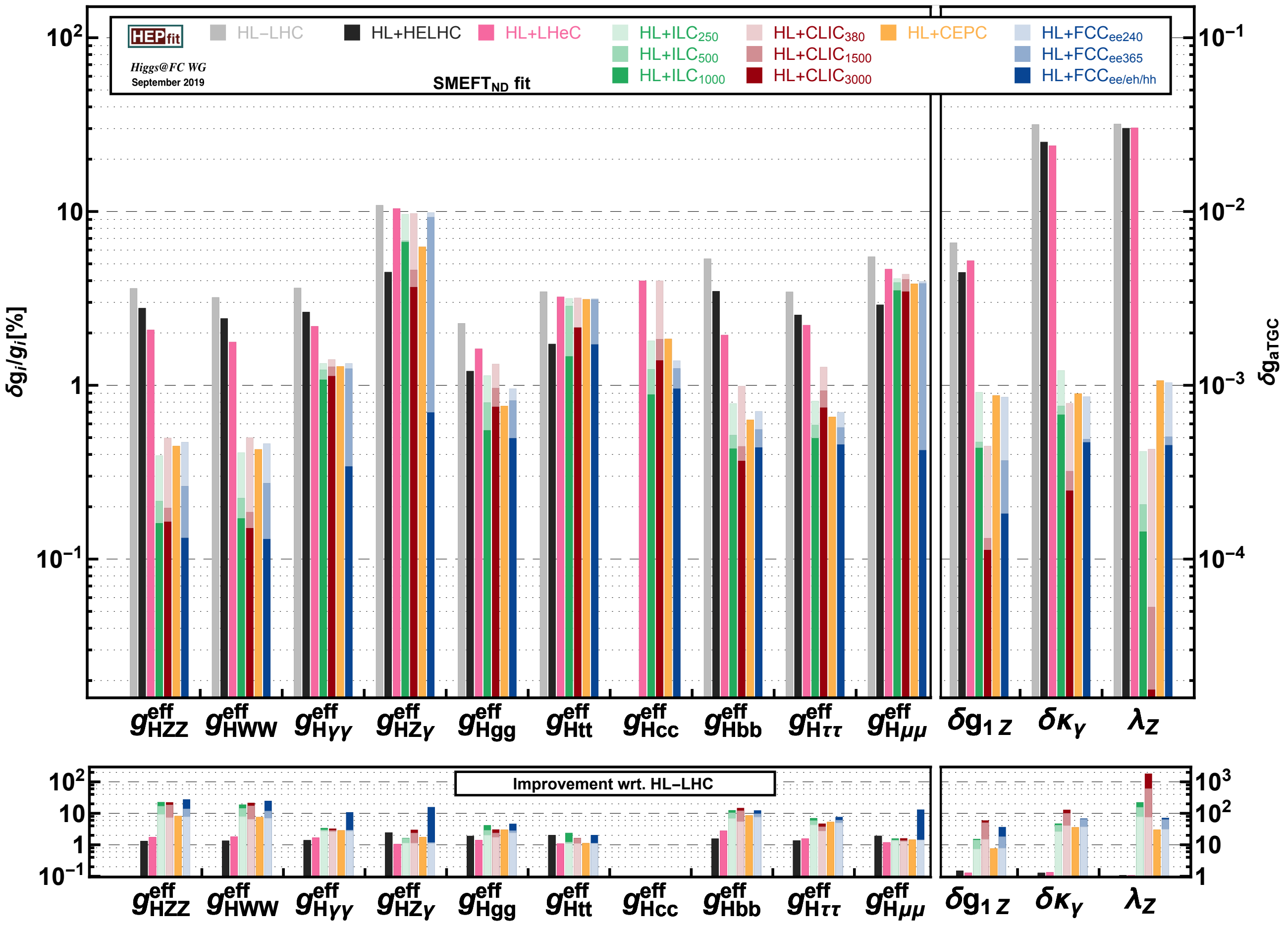
⇒ Higgs precision physics is a key tool to learn from BSM

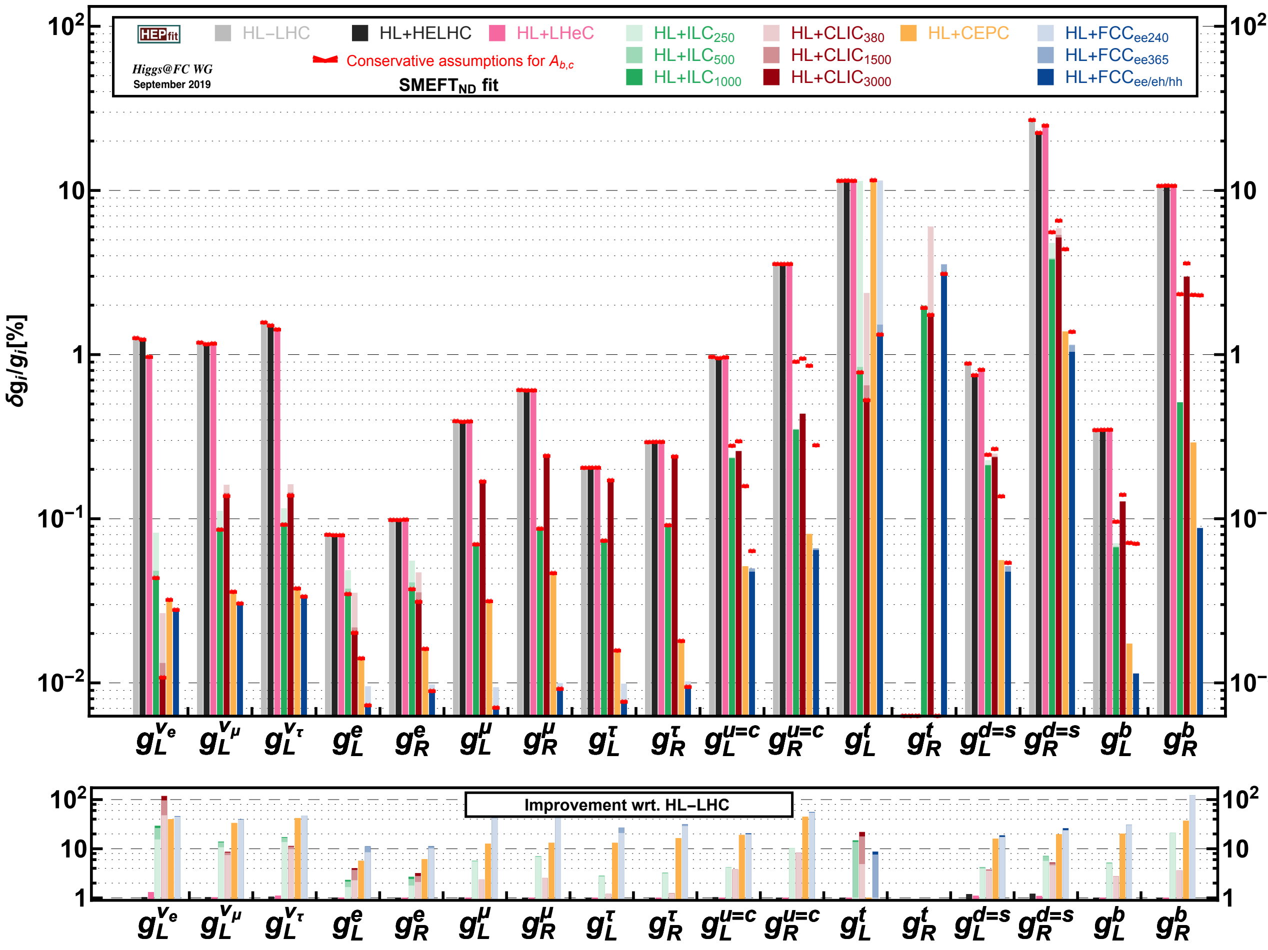
⇒ Need of an e^+e^- Higgs factory

Higgs coupling precision
at Future Colliders

Higgs couplings fits: ESU2020 → Snowmass

- **ESU2020:** The starting point for the Snowmass SMEFT studies





J. B. et al. , JHEP 01 (2020) 139

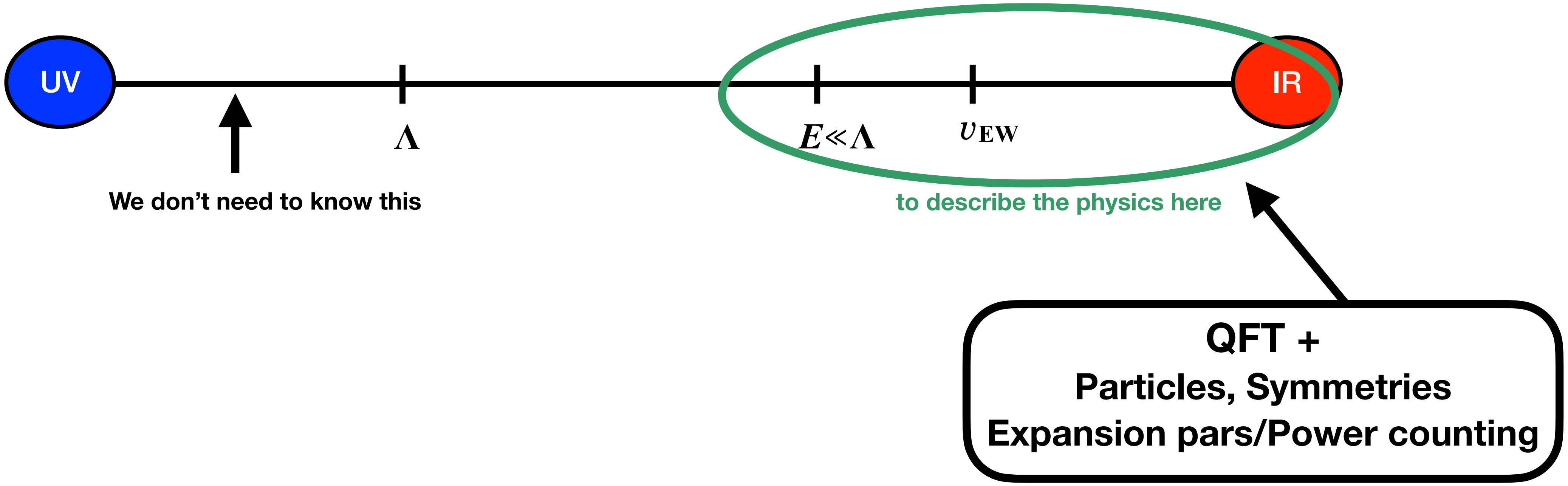
- Special emphasis on the Higgs sector and sensitivity to BSM deformations of Higgs couplings

- Expressed in terms of "effective couplings":

$$g_{HX}^{\text{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}. \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2\right), \qquad A_e = \frac{|g^{\text{eff}}_{Zee,L}|^2-|g^{\text{eff}}_{Zee,R}|^2}{|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2}.$$

The dimension-6 SMEFT

- The philosophy of Effective Field Theories:



We don't need to know this

to describe the physics here

QFT +
Particles, Symmetries
Expansion pars/Power counting

- **SMEFT:** SM particles and symmetries at low energies, with *the Higgs scalar in an SU(2)$_L$ doublet* + mass gap with new physics (entering at scale Λ, NP decoupled for $\Lambda \to \infty$)

$$\mathcal{L}_{\rm UV}(?) \xrightarrow[E \ll \Lambda]{} \quad \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

Observable Effects

$$q = v, E < \Lambda$$

The dimension-6 SMEFT

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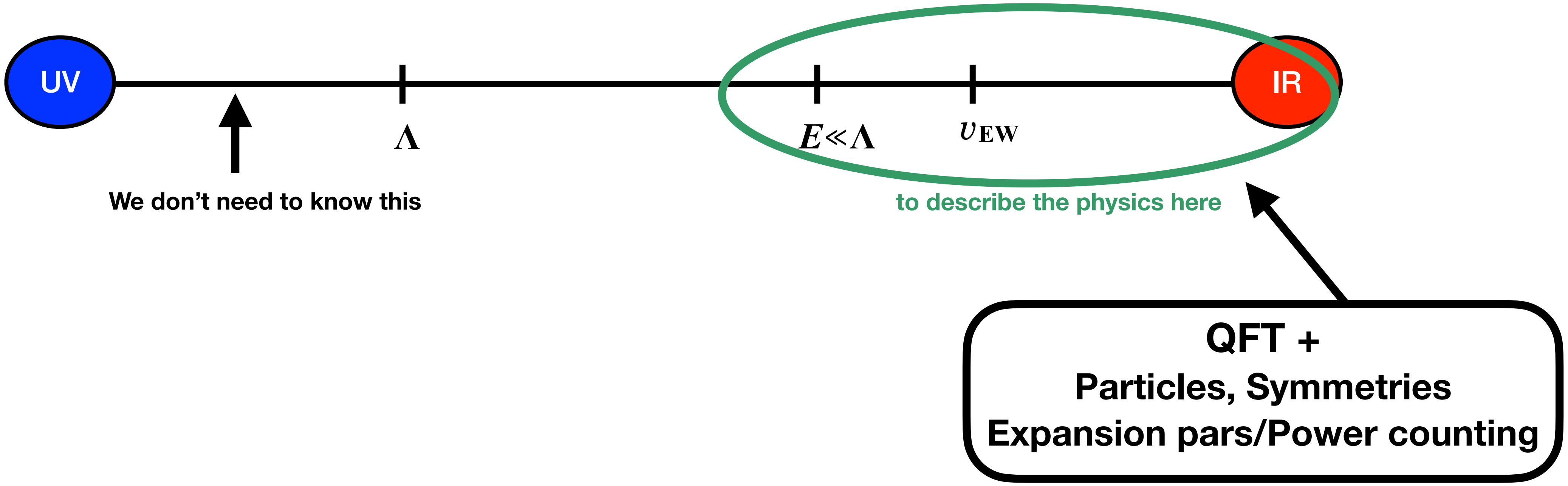

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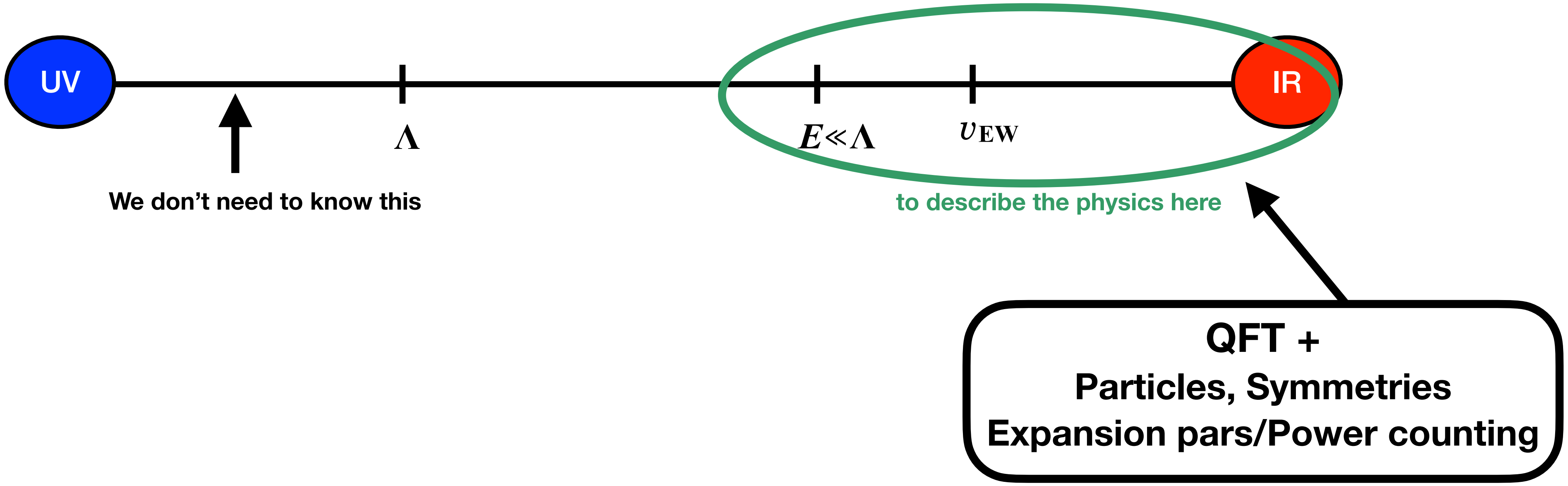
$$\mathcal{L}_d=\sum_i C_i^d\,\mathcal{O}_i \qquad [\mathcal{O}_i]=d \xrightarrow[\text{Observable Effects}]{} \left(\frac{q}{\Lambda}\right)^{d-4}$$

$$q=v,E<\Lambda$$

<u>Model-independent within assumptions</u>
General but does not necessarily capture
all possible interesting new physics scenarios

The dimension-6 SMEFT

- The philosophy of Effective Field Theories:



UV

IR

Λ

$E \ll \Lambda$

$v_{\rm EW}$

We don't need to know this

to describe the physics here

QFT +
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$$q = v, E < \Lambda$$

Leading Order (LO) Beyond the SM effects (assuming B & L)

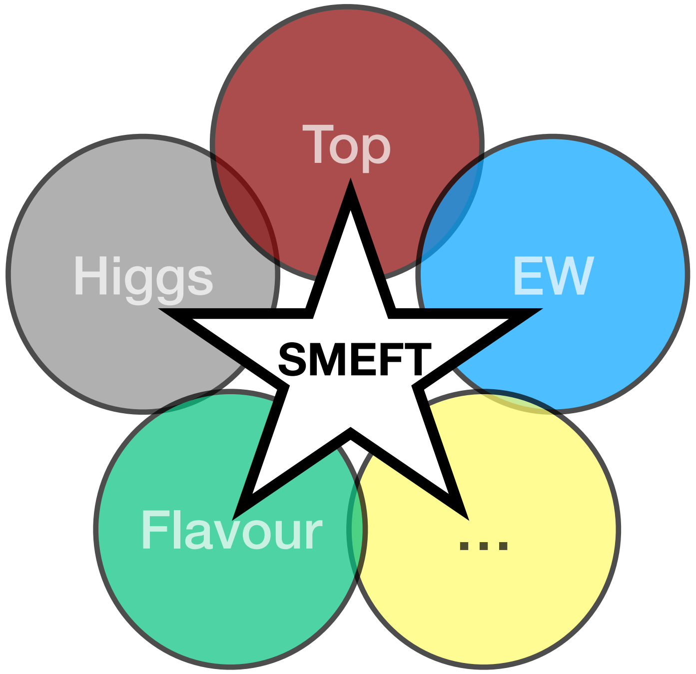
⇒ Dim-6 SMEFT: 2499 operators

The dimension-6 SMEFT

- Many EFT operators entering in Higgs processes at LO (tree level and $O(1/\Lambda^2)$)

  “Model-independent” only when including ALL contributing operators

- But SMEFT automatically incorporates correlations between Higgs and other processes imposed by gauge invariance + linearly realised EW symmetry



Study the different sectors globally (i.e. including all operators)

⇒ Use Global fit (i.e. EW/Higgs/Top/Flavor)

to constraint all directions

- In what follows I describe the results of the global SMEFT studies performed for the Snowmass, focusing on the Higgs couplings

Higgs couplings fits: ESU2020 → Snowmass

- **Snowmass:** Summary of collider scenarios considered in the SMEFT studies

Machine	Pol. (e^-, e^+)	Energy	Luminosity
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	$(\mp 80\%, \pm 30\%)$	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
	$(\mp 80\%, \pm 20\%)$	1 TeV	8 ab^{-1}
CLIC	$(\pm 80\%, 0\%)$	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

See Backup slides for details on the EW/Higgs inputs used from each collider project

Higgs couplings fits: ESU2020 → Snowmass

- **ESU2020:** The starting point for the Snowmass SMEFT studies

Inputs of SMEFT fits

Higgs

Rates (signal strength)

$$\mu \equiv \frac{\sigma\cdot \mathrm{BR}}{\sigma^{\mathrm{SM}}\cdot \mathrm{BR}^{\mathrm{SM}}}$$

(Inclusive) cross section

$$\sigma_{ZH} \equiv \sigma(e^+e^- \to ZH)$$

Only possible at lepton colliders

aTGC

$$\delta g_{1z},\ \delta\kappa_\gamma,\ \lambda_z$$

EWPO

$$M_Z,\ \Gamma_Z,\ \Gamma_{Z\to f},\ A^f_{FB,LR},\ \ldots$$

$$M_W,\ \Gamma_W,\ \Gamma_{W\to f}$$

Z physics via Z-pole:

$$\sqrt{s} = M_Z:\quad e^+e^- \to Z \to X$$

or Rad. Return:

$$\sqrt{s} > M_Z:\quad e^+e^- \to \gamma Z \to \gamma X$$

	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)	Top
HL-LHC	Yes (μ)	LEP2 (aTGC dom.)	LEP/SLD	No
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return, Giga-Z)	Yes

Higgs couplings fits: ESU2020 → Snowmass

- **Snowmass:** Updated for the SMEFT studies

NEW for Snowmass 2021

Inputs of SMEFT fits

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	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)	Top
HL-LHC	Yes (μ)	**HL-LHC Full EFT param.**	LEP/SLD	**Yes**
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	**Full EFT param.**	**Updated** Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	**Full EFT param.**	**Updated** Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	**Updated** Yes (μ, σ_{ZH}) (Complete with HL-LHC)	**Full EFT param.**	**Updated** Yes	No
CLIC	Yes (μ, σ_{ZH})	**Full EFT param.**	Yes (Rad. Return, Giga-Z)	Yes
Muon Colliders	**Yes (μ)** **125 GeV/3 & 10 TeV**	**Full EFT param.**	No. From LEP/SLD	No

Higgs couplings fits: ESU2020 → Snowmass

- **Snowmass:** Updated for the SMEFT studies

NEW for Snowmass 2021

HL-LHC *pp→WW, WZ*

EFT parametrisation from

C. Grojean, M. Montull, M. Riembau, JHEP 03 (2019) 020

Inpu

Rates (signal strength)

$\mu \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}}}$

(

σ

M_Z

$\sqrt{s}$

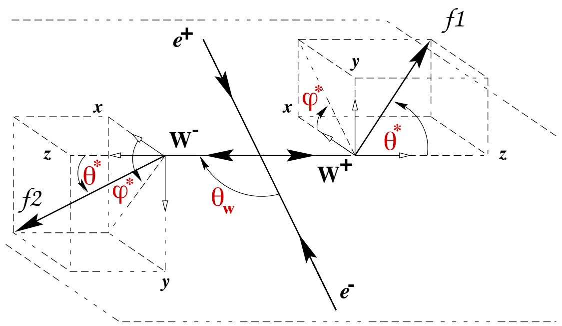
$\sqrt{s} > M_Z$: $e^+e^- \to \gamma Z \to \gamma X$

		diBoson (WW,WZ)	EWPO (Z pole, m$_W$, …)	Top
HL-LHC	Yes (μ)	HL-LHC Full EFT param.	LEP/SLD	Yes
	C)	Full EFT param.	Updated Yes	Yes (365 GeV, Ztt)
	ed C)	Full EFT param.	Updated Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
	C)	Full EFT param.	Updated Yes	No
		Full EFT param.	Yes (Rad. Return, Giga-Z)	Yes
Colliders	125 GeV/3 & 10 TeV	Full EFT param.	No. From LEP/SLD	No

Optimal Observable analysis of $e^+e^-\to W^-W^+$

Max. Statistical info

Explores all differential info in phase space distr. $S(\Phi)$:



$$S(\Phi) = S_0(\Phi) + \sum_i c_i S_i(\Phi)$$

$$\mathrm{cov}(c_i, c_j) = \left(\mathcal{L} \int d\Phi \frac{S_i(\Phi) S_j(\Phi)}{S_0(\Phi)}\right)^{-1} + \mathcal{O}(c_k)$$

J.B., G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117

Higgs couplings fits: ESU2020 → Snowmass

- **Snowmass:** Updated for the SMEFT studies

NEW for Snowmass 2021

Inputs of SMEFT fits

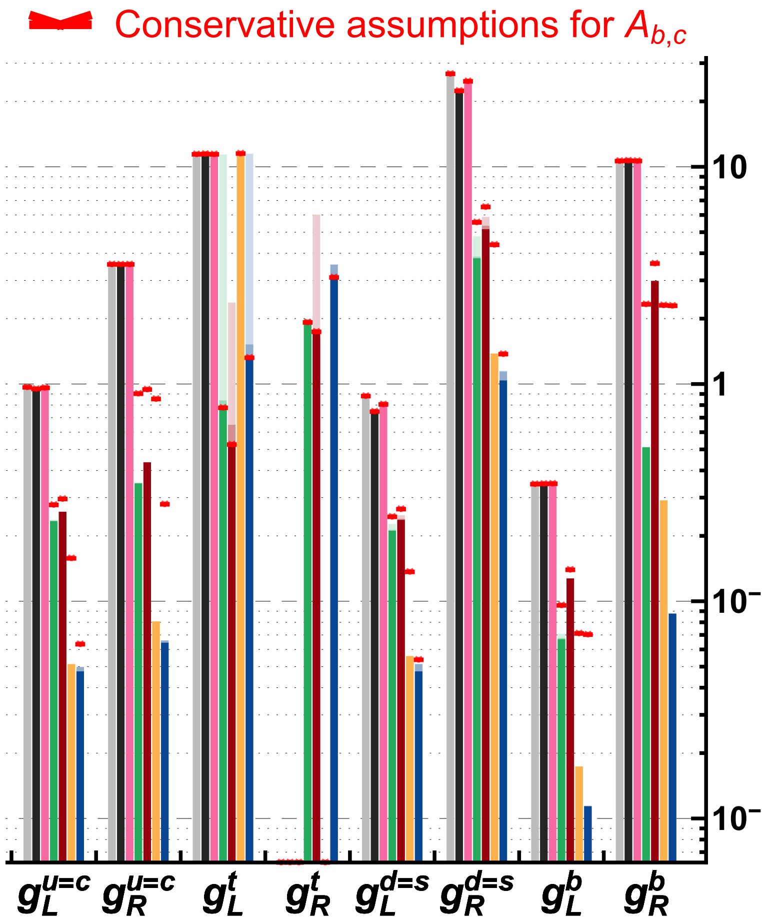
	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)	Top
HL-LHC	Yes (μ)	**HL-LHC Full EFT param.**	LEP/SLD	**Yes**
			Updated Yes	Yes (365 GeV, Ztt)
			Updated Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
			Updated Yes	No
			Yes (Rad. Return, Giga-Z)	Yes
			No. From LEP/SLD	No

Higgs

Rates (signal strength)

$$\mu \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}}}$$

EWPO updates



ESU2020:
Different e^+e^- colliders using different assumptions for common systematics (e.g. QCD in $A_{FB}^{b,c}$)

Snowmass:
Consistent assumptions on common systematics, applied uniformly to all e^+e^- collider proposals

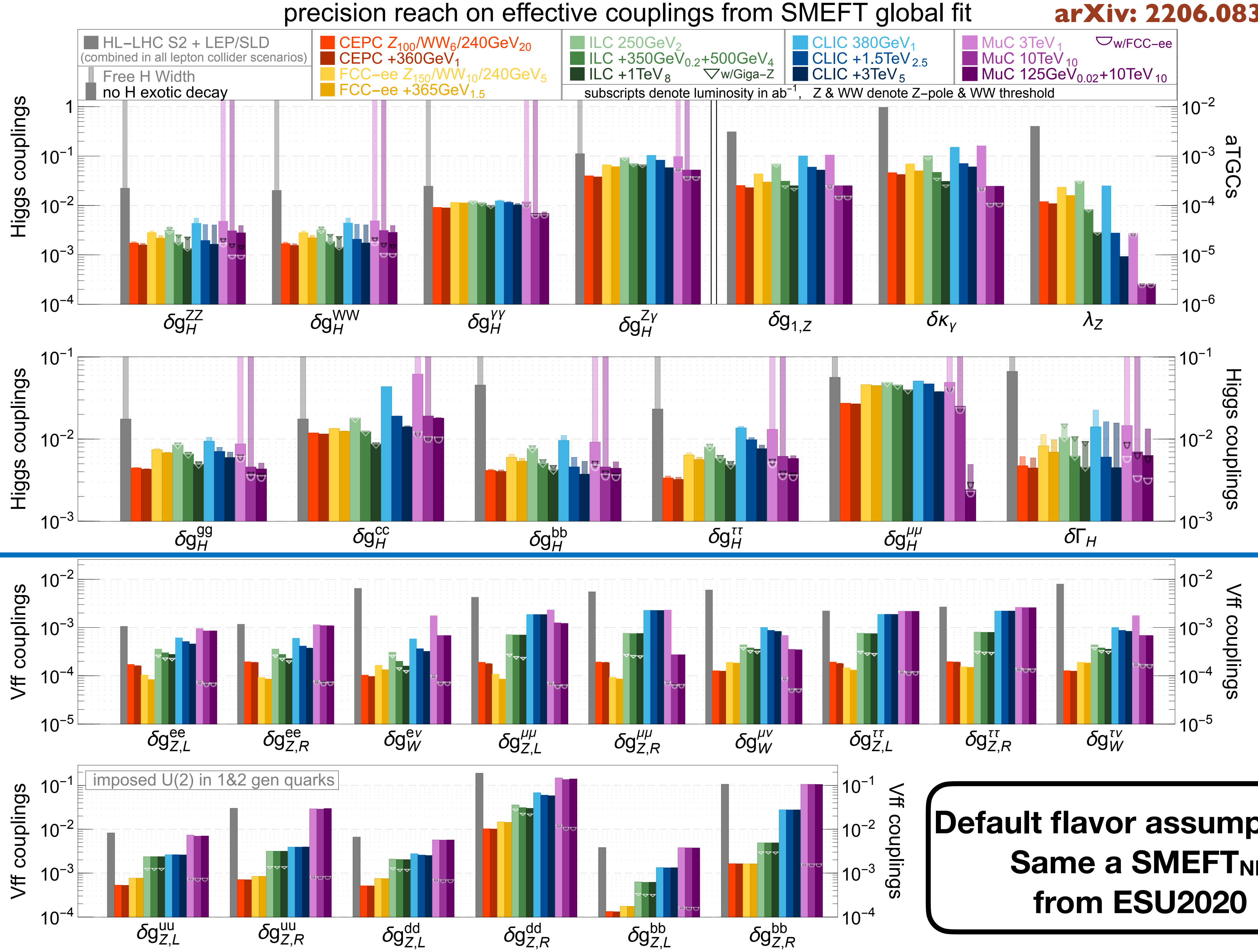
Higgs couplings in the dimension-6 SMEFT fit

arXiv: 2206.08326 [hep-ph]

Higgs interactions

aTGC

EW Vff interactions



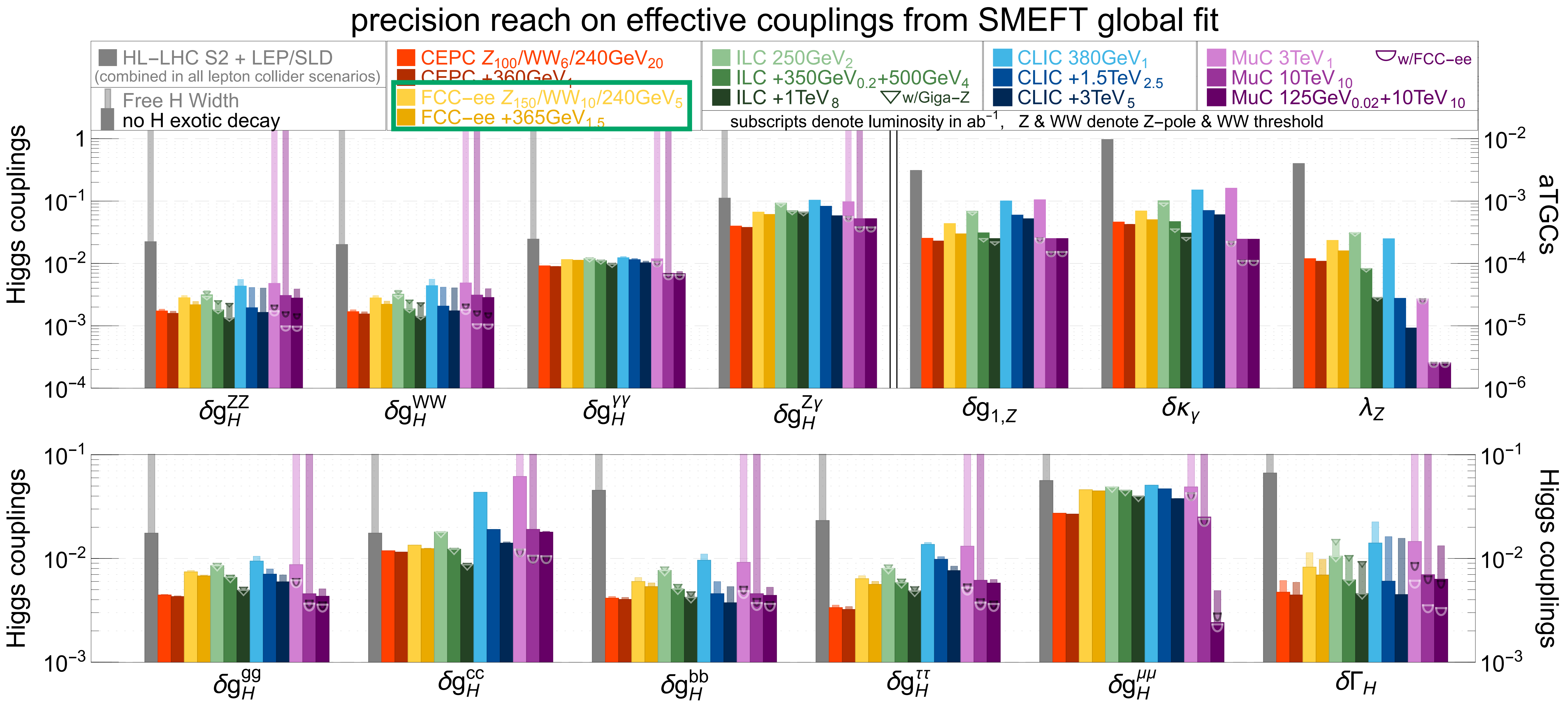
Default flavor assumptions:
Same a SMEFT$_{\text{ND}}$
from ESU2020

Effective couplings

$$g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}.\qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}\left(|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2\right),\qquad A_e = \frac{|g^{\text{eff}}_{Zee,L}|^2-|g^{\text{eff}}_{Zee,R}|^2}{|g^{\text{eff}}_{Zee,L}|^2+|g^{\text{eff}}_{Zee,R}|^2}.$$

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions



Effective Higgs couplings

$$g_{HX}^{\text{eff}\;2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}.$$

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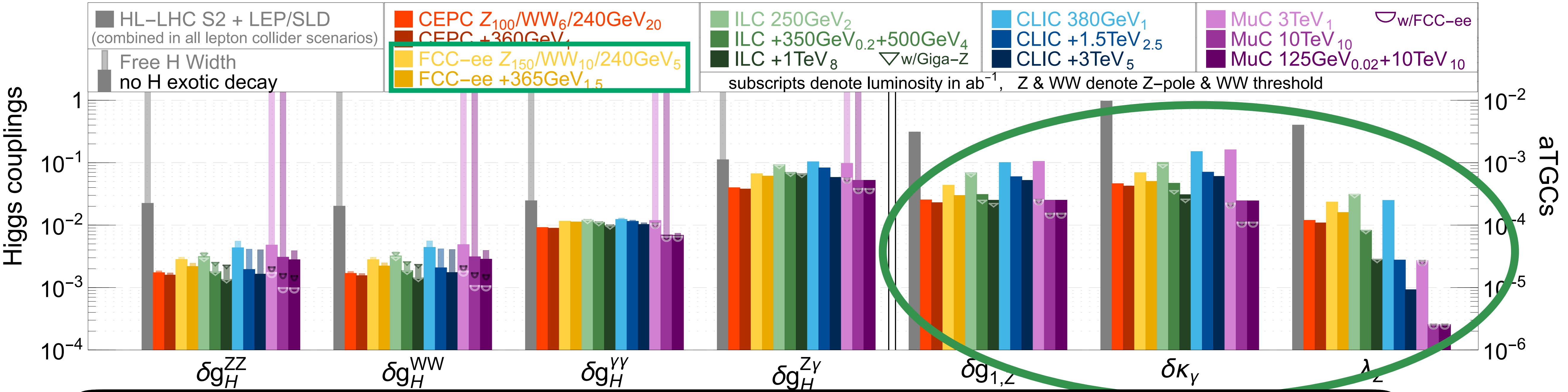
Higgs couplings in the dimension-6 SMEFT fit

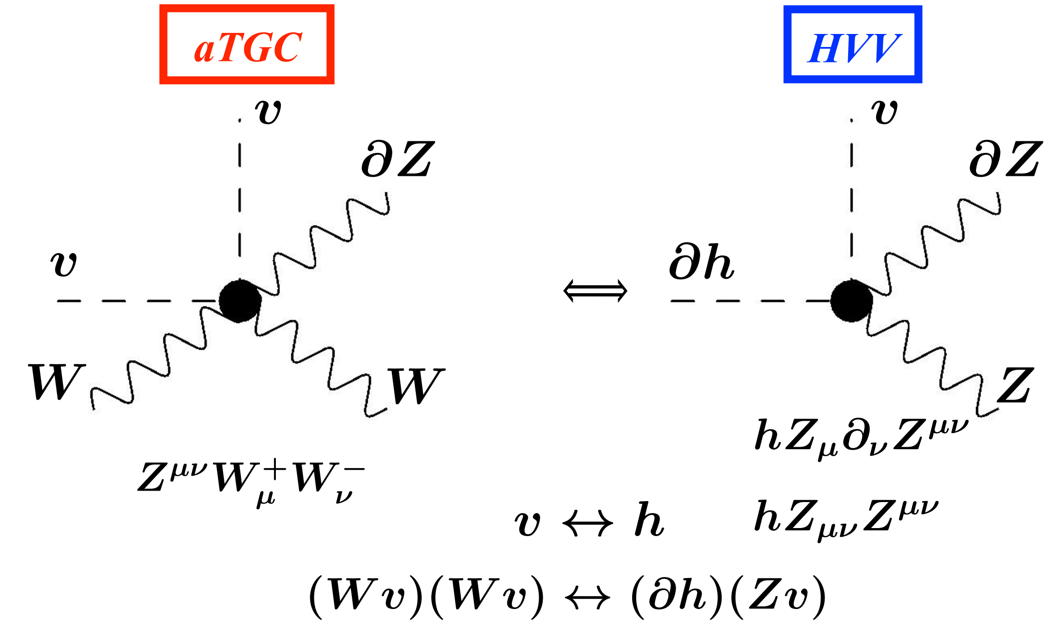
Higgs interactions

precision reach on effective couplings from SMEFT global fit



aTGC-Higgs SMEFT correlations

$iD_\mu\phi^\dagger D_\nu\phi B_{\mu\nu}$

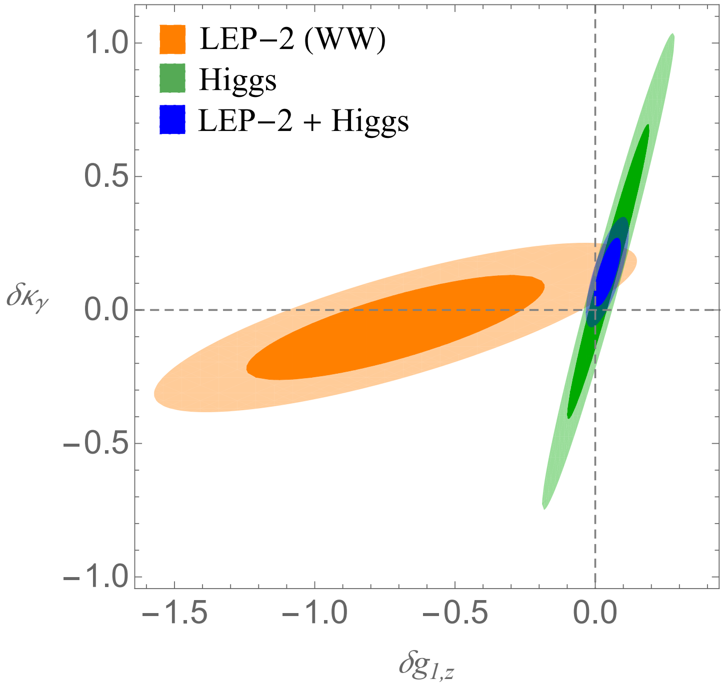


$Z^{\mu\nu}W^+_\mu W^-_\nu$

$hZ_\mu\partial_\nu Z^{\mu\nu}$

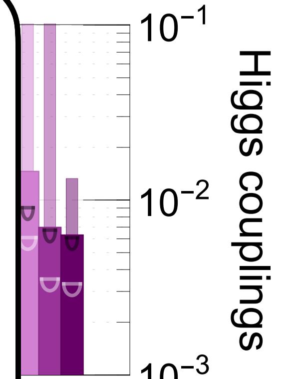
$v \leftrightarrow h$ $\quad hZ_{\mu\nu}Z^{\mu\nu}$

$(Wv)(Wv) \leftrightarrow (\partial h)(Zv)$



A. Falkowski et al., PRL 116 (2016) 011801

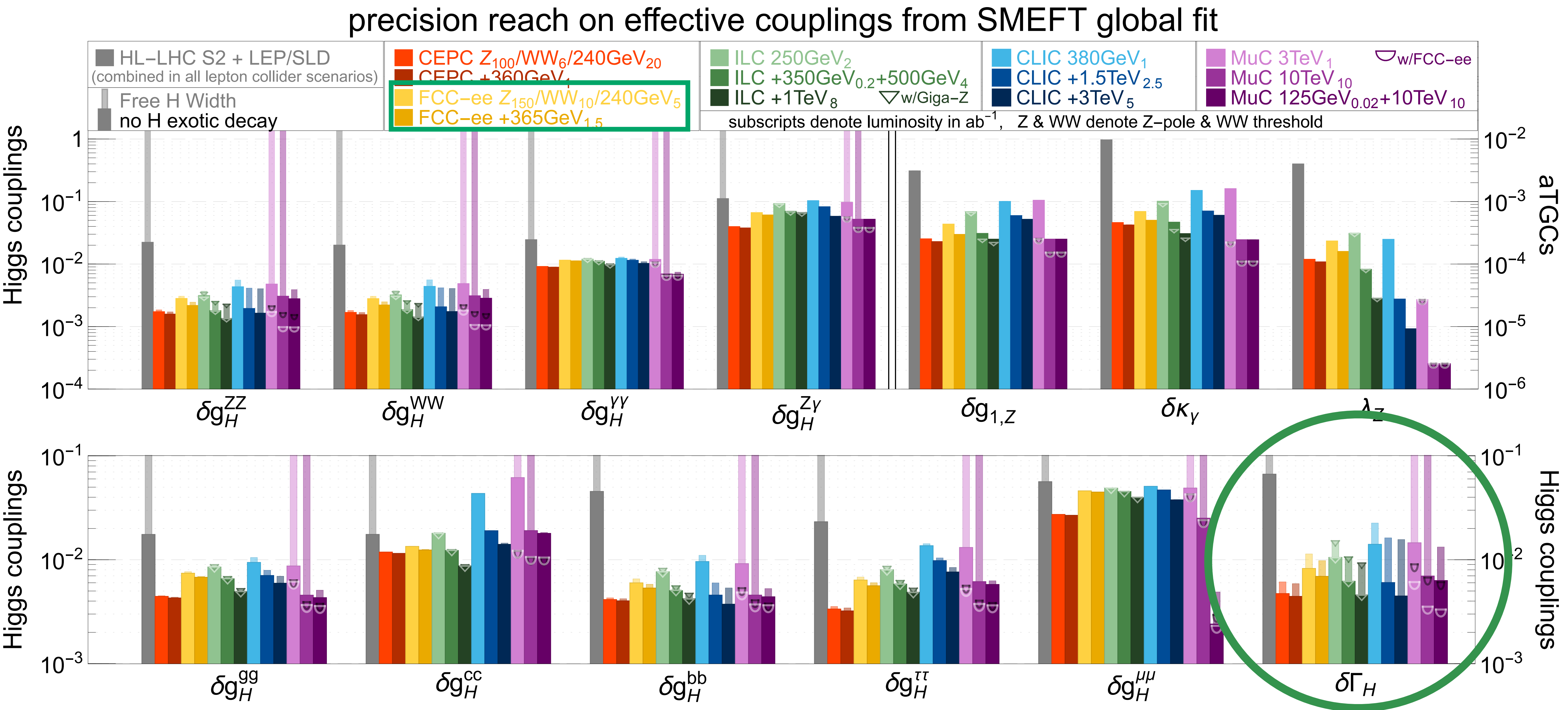
aTGC updated with Optimal Observable analysis of $e^+e^-\to W^-W^+$



326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions



New: scenario with the H width as a free parameter

arXiv: 2206.08326 [hep-ph]

Effective Higgs couplings

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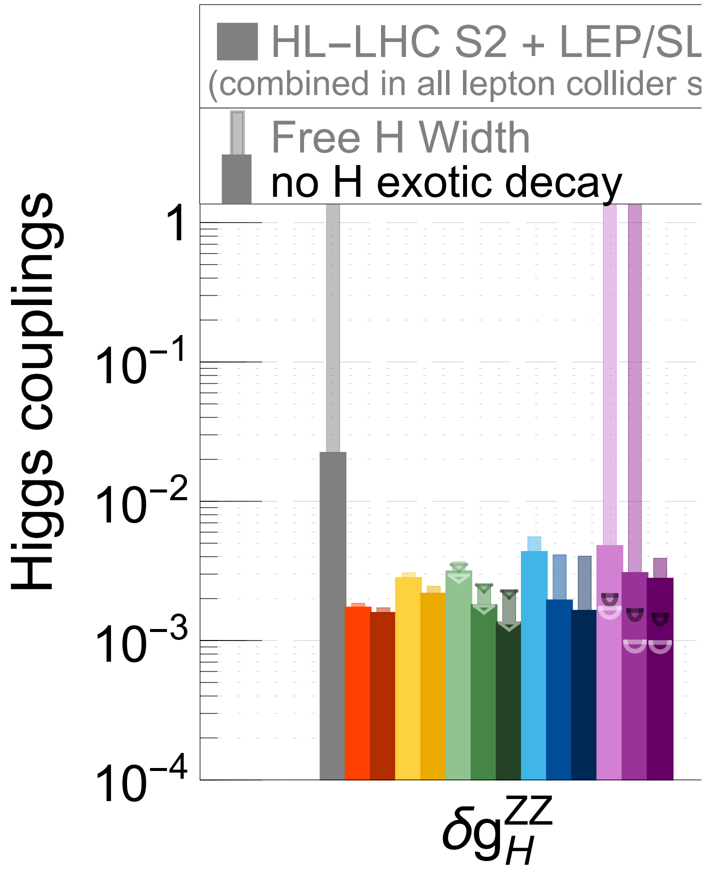
Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions

precision reach on effective couplings from SMEFT global fit



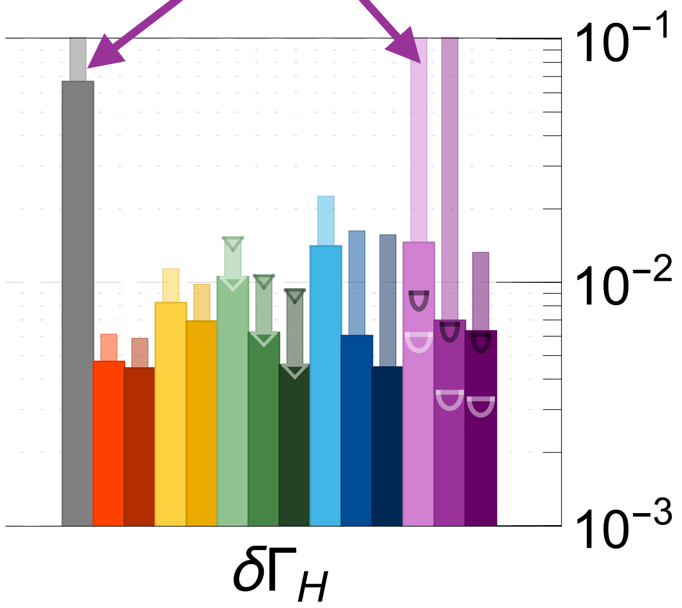
Fit with free Γ_H

Highlights the importance of low-energy e^+e^- Higgs factories to obtain absolute measurement of Higgs couplings

(Via the measurement of σ_{ZH} using the recoil mass method)

FCC-ee: Γ_H ~1% precision

Flat directions @ non e^+e^- colliders



New: scenario with the H width as a free parameter

Effective Higgs couplings

$$g^{\text{eff}\ 2}_{HX} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}}.$$

arXiv: 2206.08326 [hep-ph]

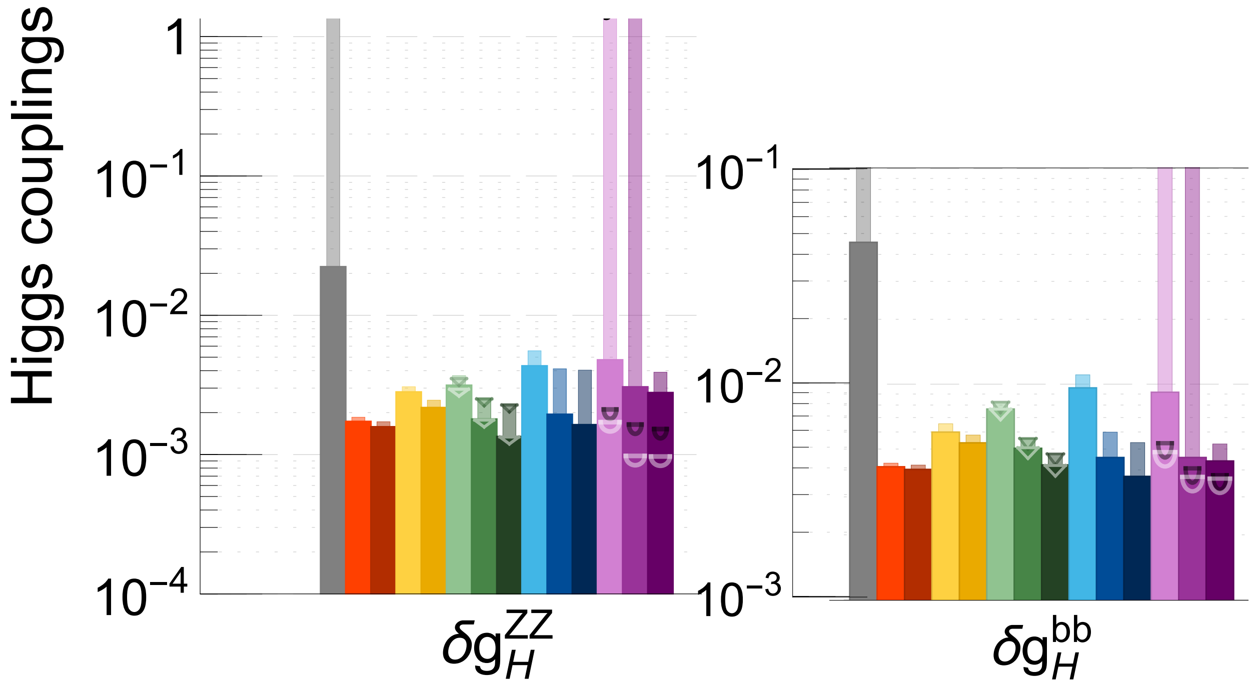
Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions

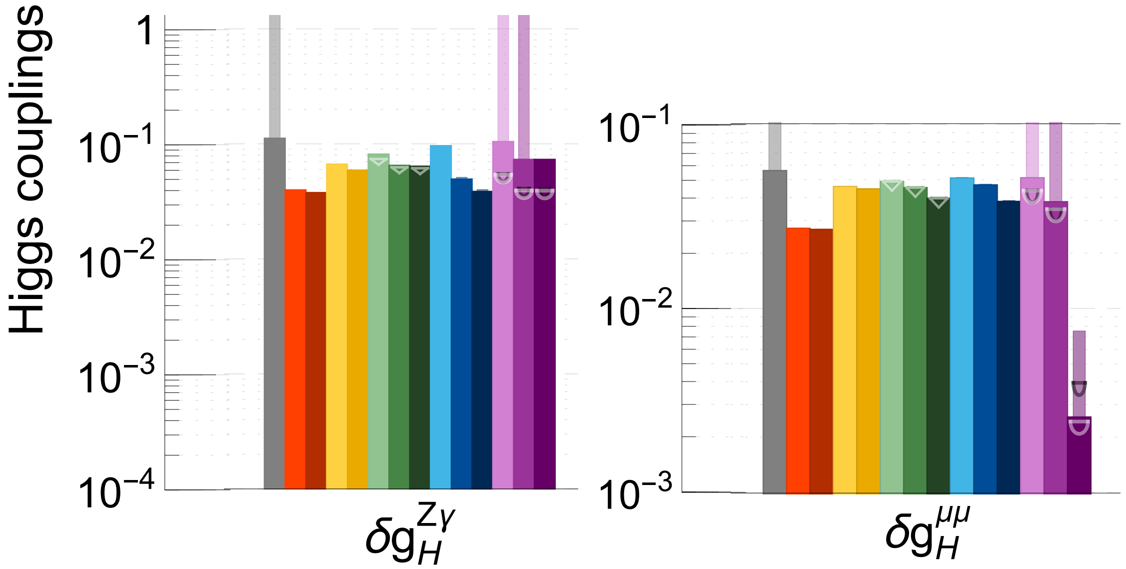
precision reach on effective couplings from SMEFT global fit

e^+e^- improves precision typically by a factor ~10

(Small improvement wrt ESU analysis)



HL-LHC will provide the leading constraints on couplings modifying rare decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)



FCCee: $\Lambda_{\rm NP} \gtrsim 4500 \frac{g_{\rm NP}}{g_{\rm SM}}$ GeV

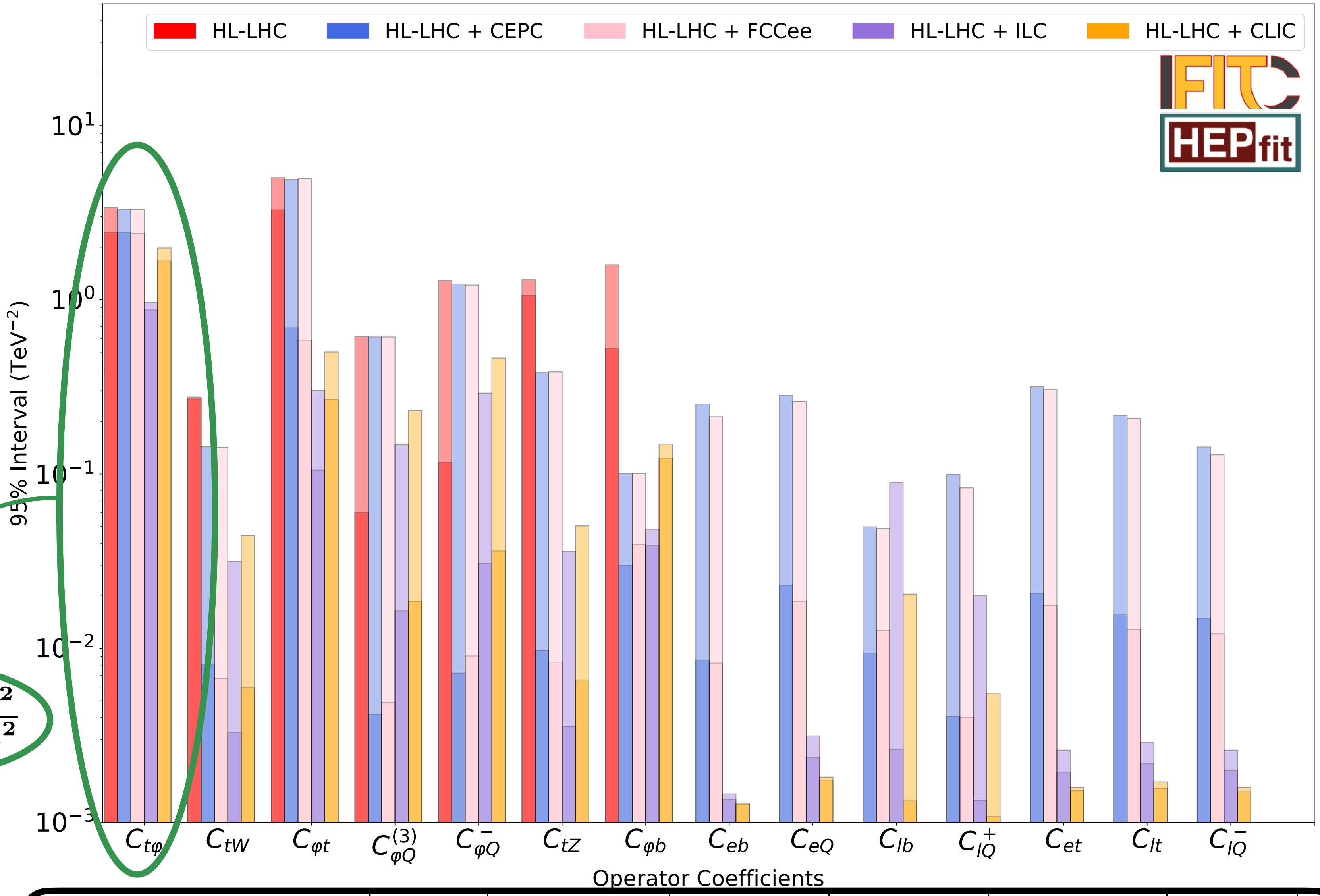
Effective Higgs couplings $g_{HX}^{\text{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\rm SM}}.$

arXiv: 2206.08326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions

Top Yukawa coupling not "accessible" at low-E e^+e^-: Set by HL-LHC



arXiv: 2206.08326 [hep-ph]

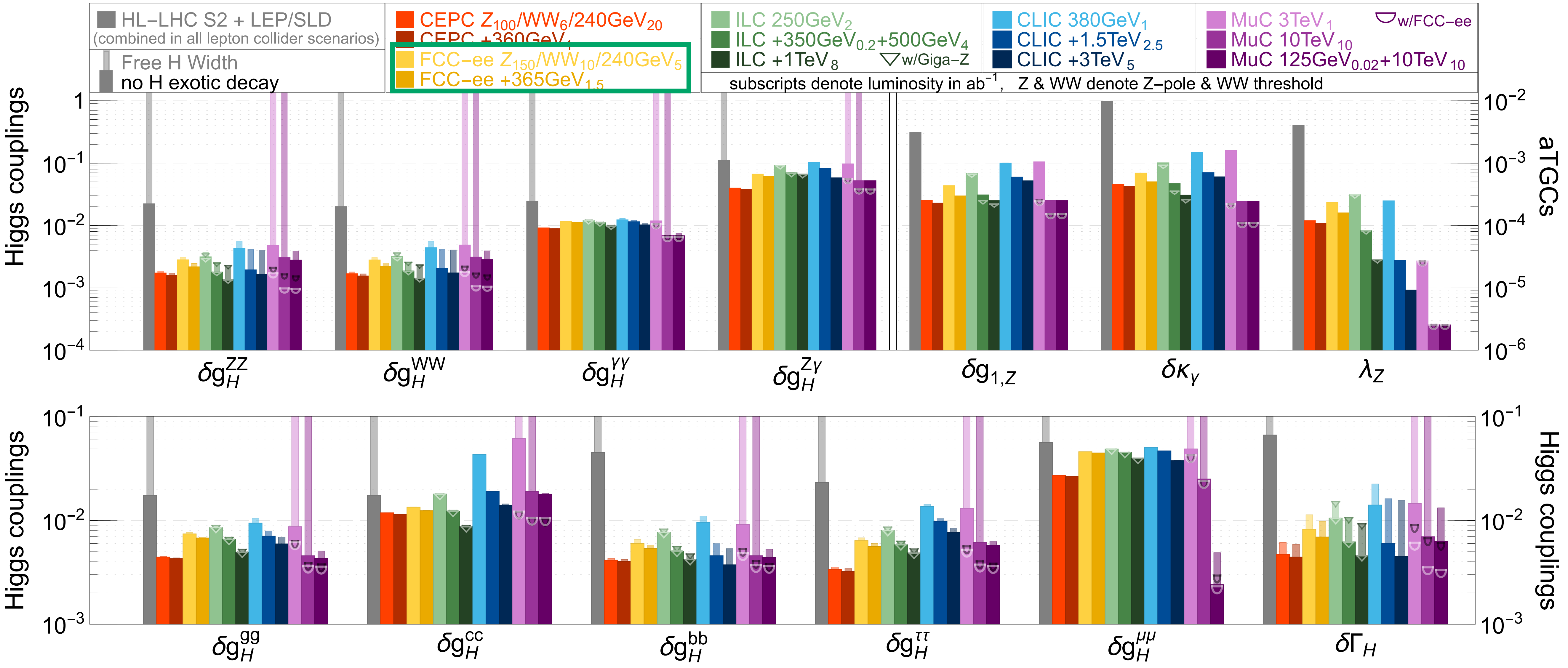
Values from global fit to Top data including all LO SMEFT operators

$$\delta y_t \sim -\frac{C_{t\phi}}{2}\frac{v^2}{\Lambda^2}$$

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	6.12	2.53	1.57	1.30	0.739	1.48
	Indiv. fit	5.08	1.85	1.41	1.17	0.705	1.26

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions


precision reach on effective couplings from SMEFT global fit

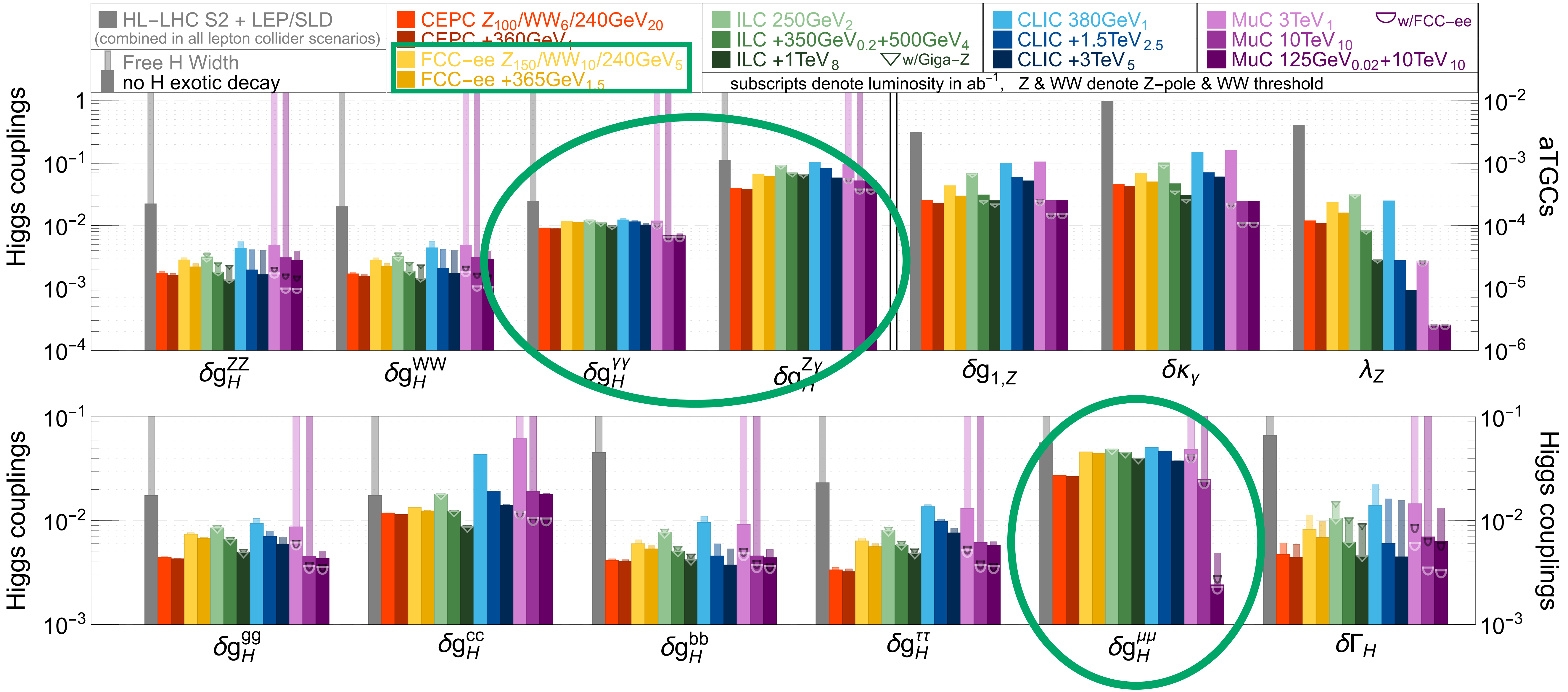
Effective Higgs couplings

$$g_{HX}^{\mathrm{eff}\ 2} = \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}.$$

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions: adding FCC-eh, FCC-hh

precision reach on effective couplings from SMEFT global fit



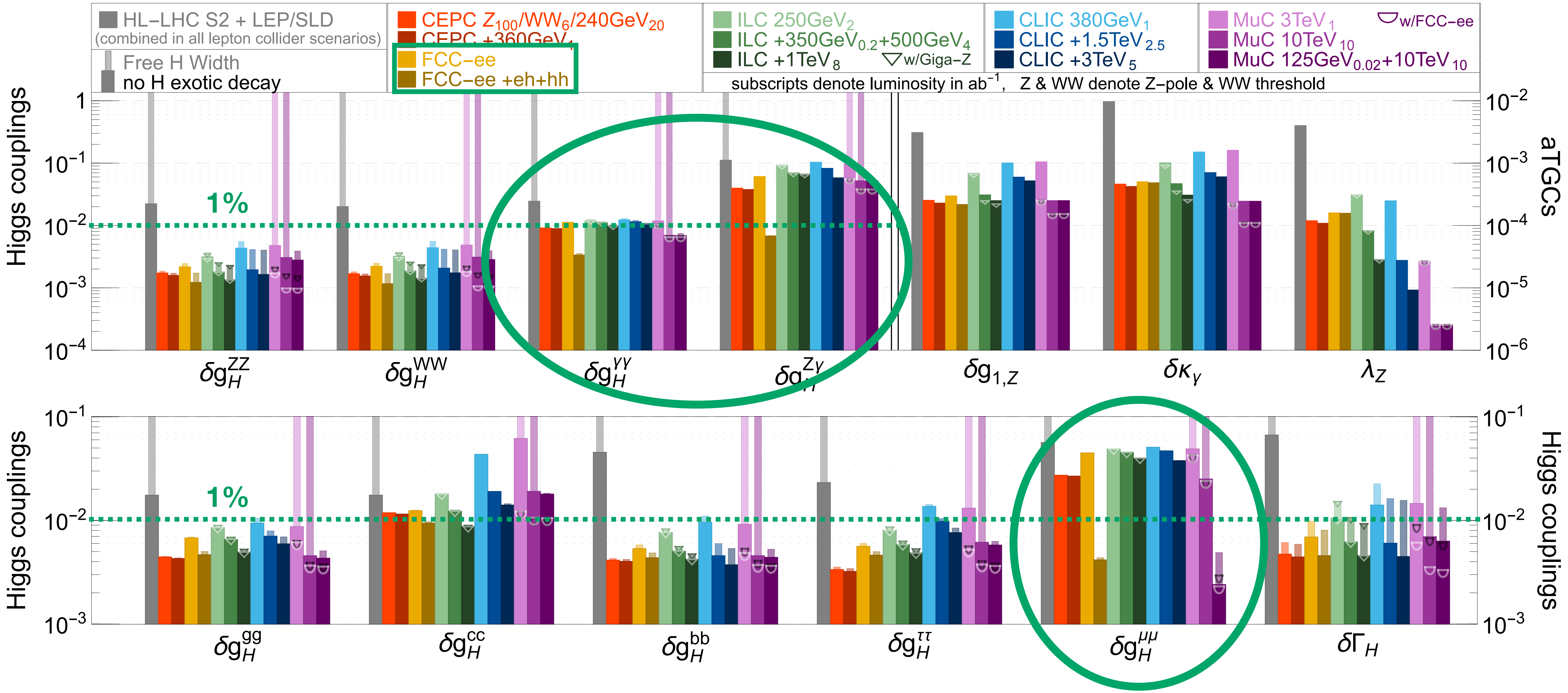
HL-LHC+FCC-ee: Precision controlled by HL-LHC

Effective Higgs couplings

$$g_{HX}^{\mathrm{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\mathrm{SM}}_{H\to X}}.$$

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions: adding FCC-eh, FCC-hh


precision reach on effective couplings from SMEFT global fit

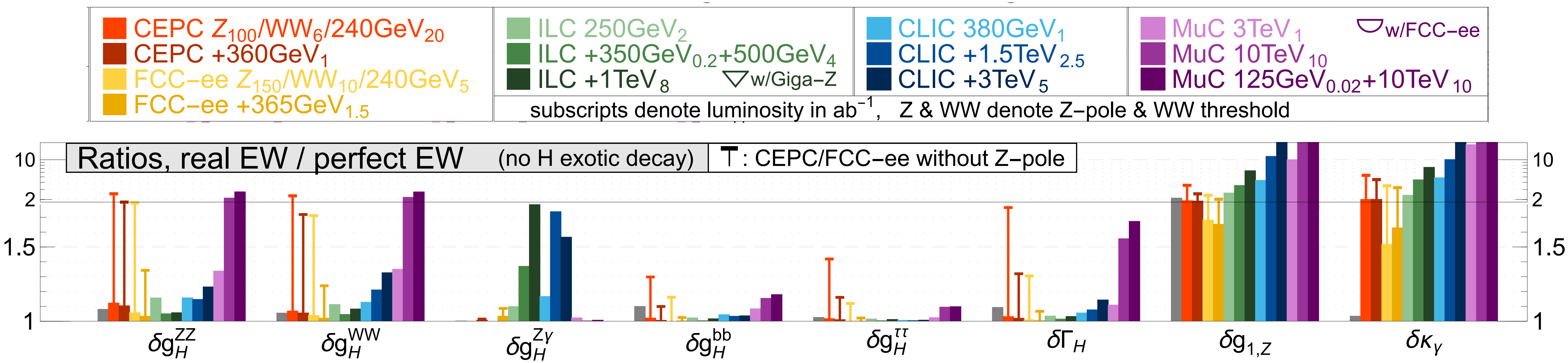
FCC-hh brings remaining Higgs interactions below 1% ($\delta g_H^{tt,FCC}$ ~ 0.9%)

Effective Higgs couplings

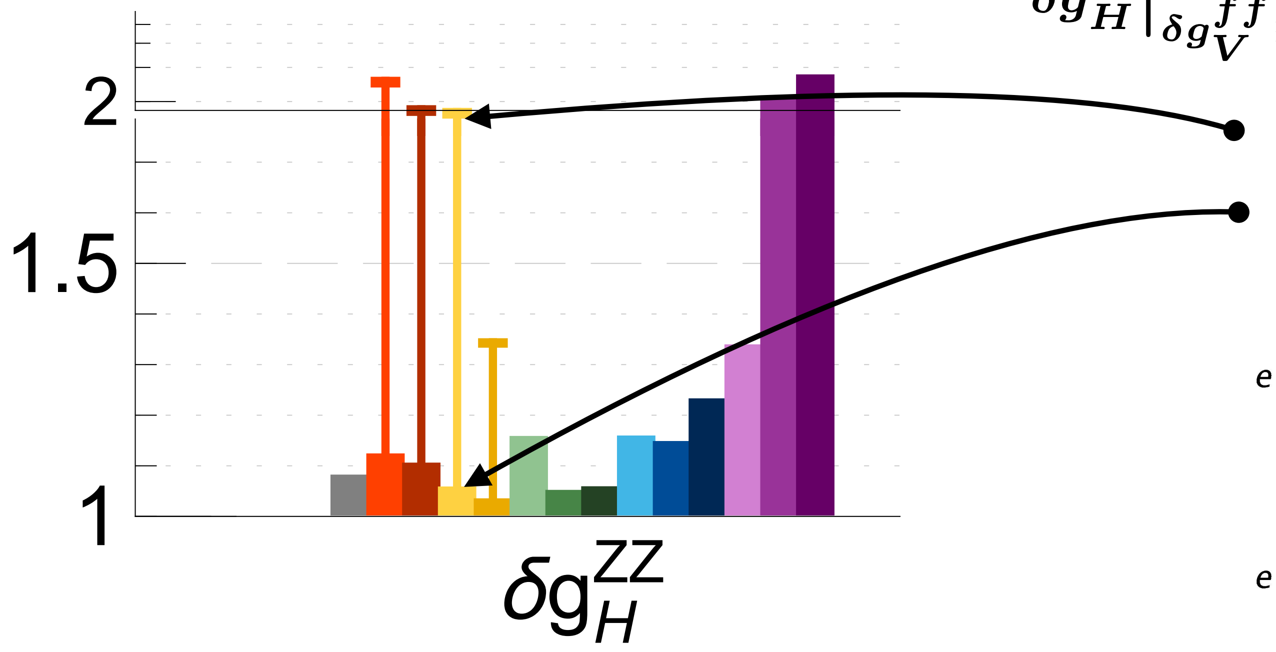
$$g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}.$$

Interplay EW/Higgs at future colliders

Impact of future EWPO in Higgs/aTGC couplings

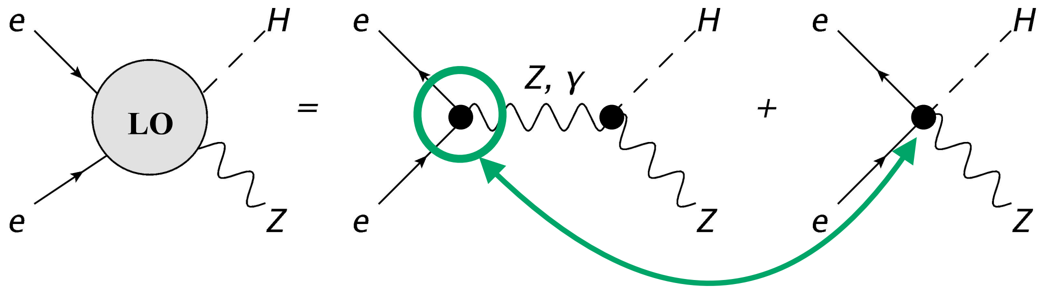


$$\frac{\delta g_H^x\Big|_{\delta g_V^{ff}\ \text{fit}}}{\delta g_H^x\Big|_{\delta g_V^{ff}\equiv 0}}$$



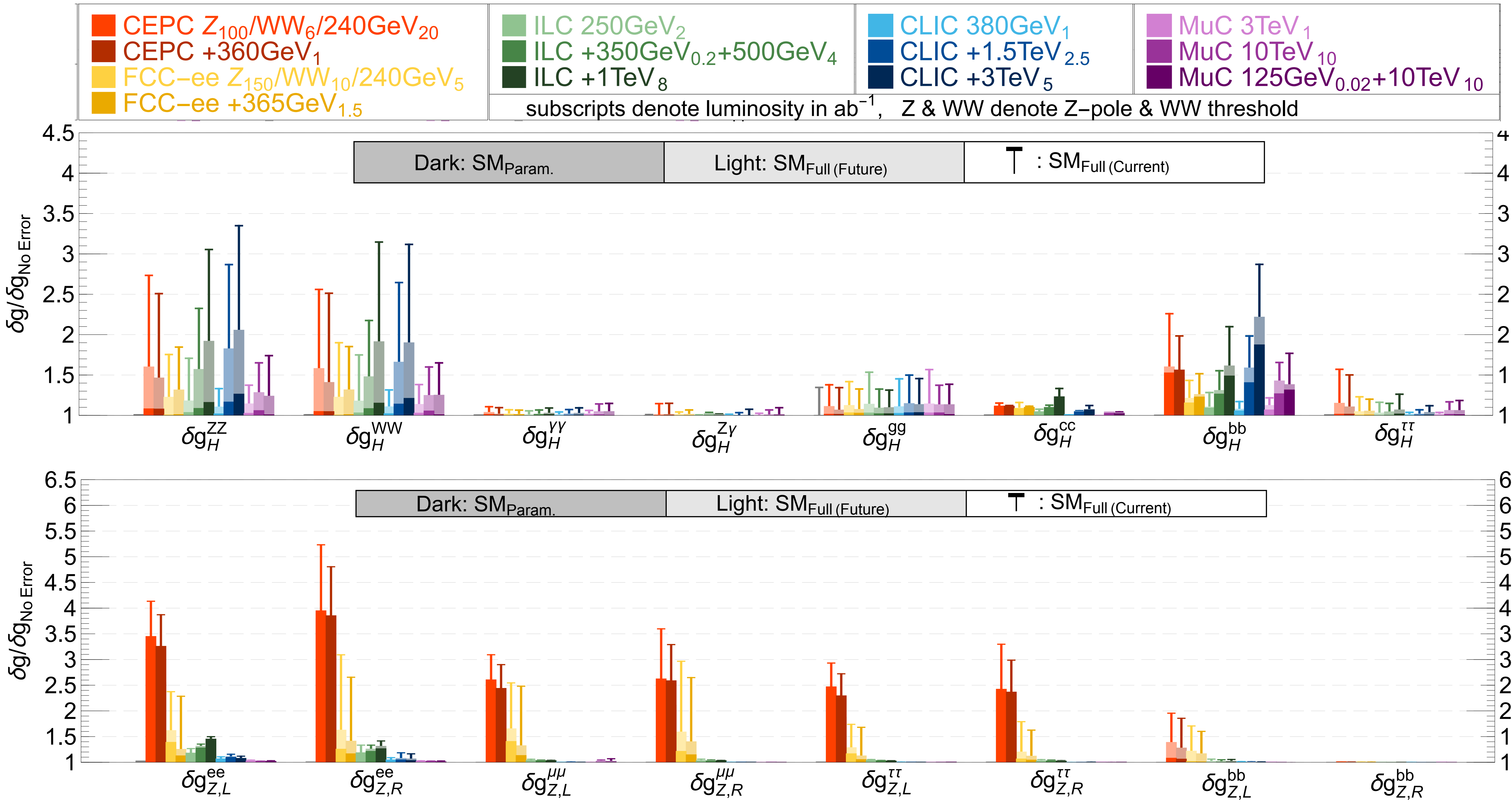
- fit assuming **LEP/SLD Z-pole measurements**
- fit including **Future Z-pole measurements**

EW-Higgs SMEFT correlations



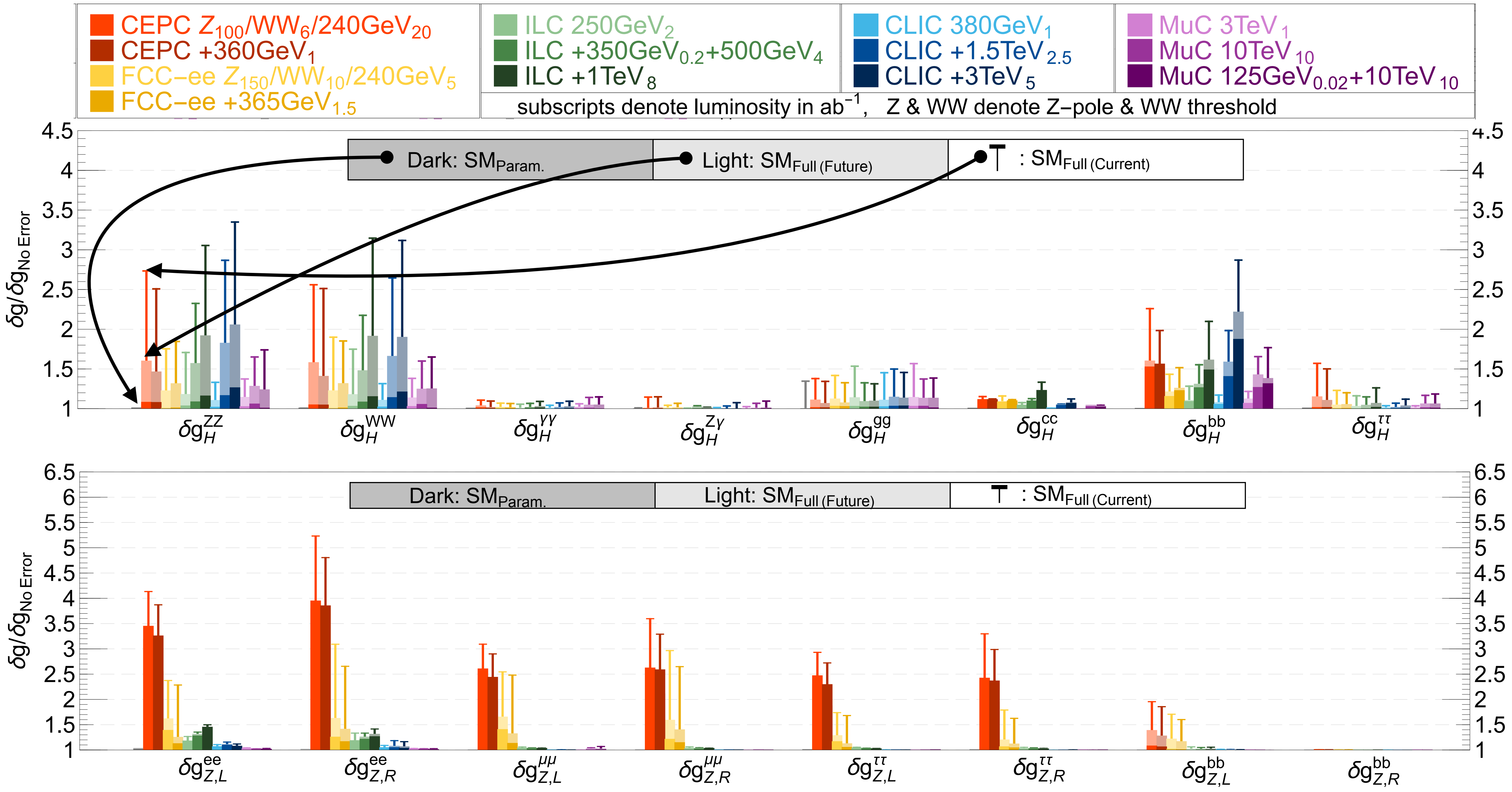
Higgs couplings: Theory uncertainties

Impact of future theory uncertainties



Higgs couplings: Theory uncertainties

Impact of future theory uncertainties



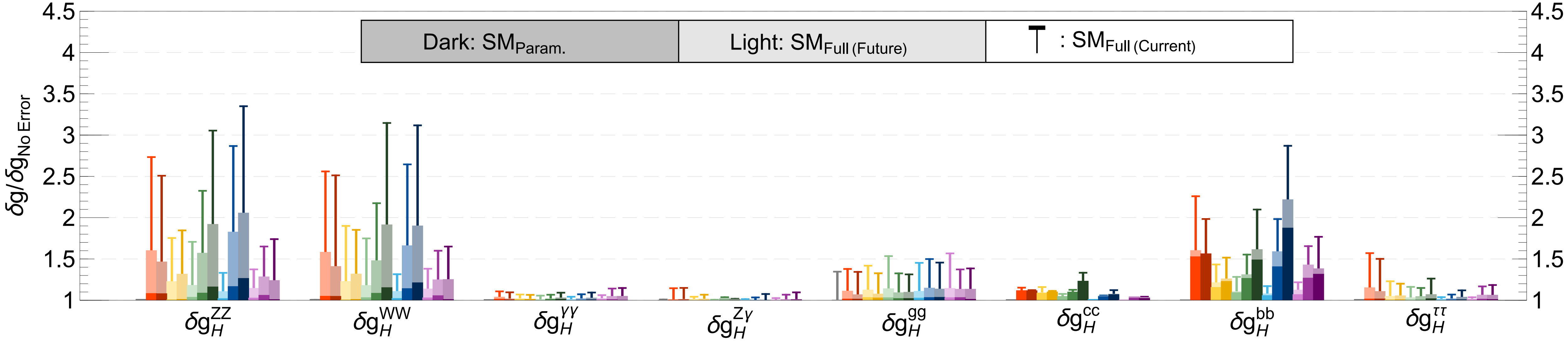
SM$_{\text{Param.}}$: Consider only SM parametric uncertainties (Default)

SM$_{\text{Full(Future)}}$: Consider SM parametric uncertainties + projected future TH calculations

SM$_{\text{Full(Current)}}$: Consider SM parametric uncertainties + current TH calculations

Higgs couplings: Theory uncertainties

Impact of future theory uncertainties



Production

	Current	**Future**	
$e^+e^- \to ZH$	O(1%)	<0.3%	**Full 2 loop***
$e^+e^- \to \bar{\nu}\nu H$		<1%	**Partial 2 loop**

***See A. Freitas, Q. Song, arXiv: 2209.07612, X. Chen et al., arXiv: 2209.14953 for recent results**

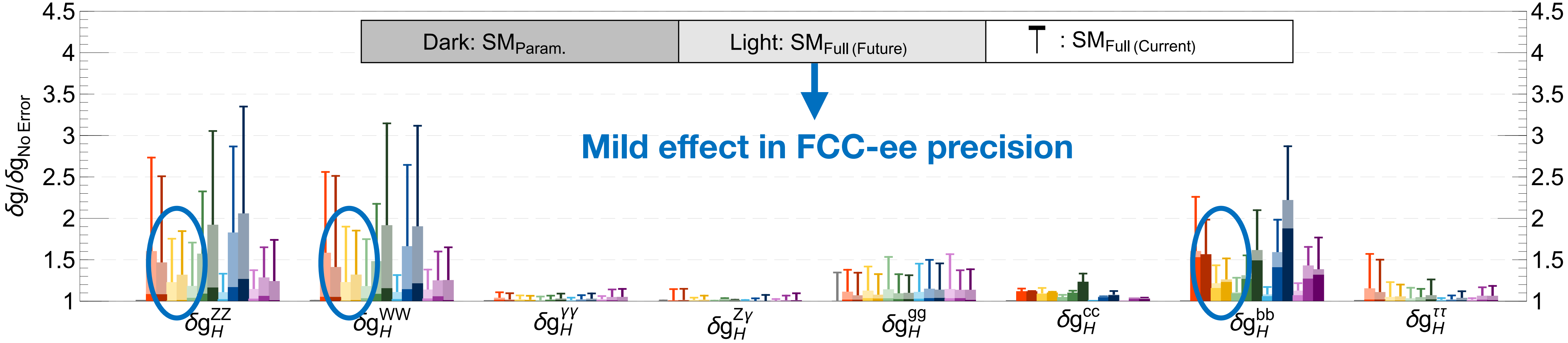
Decay

Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	$\mathrm{Th_{Intr}}$	$\mathrm{Th_{Par}^{m_q}}$	$\mathrm{Th_{Par}^{\alpha_s}}$	$\mathrm{Th_{Par}^{m_H}}$	$\mathrm{Th_{Intr}}$	$\mathrm{Th_{Par}^{m_q}}$	$\mathrm{Th_{Par}^{\alpha_s}}$	$\mathrm{Th_{Par}^{m_H}}$
$H \to b\bar{b}$	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	0.5	–	–	2.6	0.3	–	–	0.1
$H \to gg$	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	5.0	–	–	2.1	1.0	–	–	0.1

$\Delta m_b = 13$ MeV, $\Delta m_c = 7$ MeV, $\Delta m_t = 50$ MeV, $\Delta\alpha_s = 0.0002$ $\Delta m_H = 10$ MeV

Higgs couplings: Theory uncertainties

Impact of future theory uncertainties



Mild effect in FCC-ee precision

Production

	Current	**Future**	
$e^+e^- \to ZH$	$O(1\%)$	$<0.3\%$	**Full 2 loop***
$e^+e^- \to \bar{\nu}\nu H$		$<1\%$	**Partial 2 loop**

***See A. Freitas, Q. Song, arXiv: 2209.07612, X. Chen et al., arXiv: 2209.14953 for recent results**

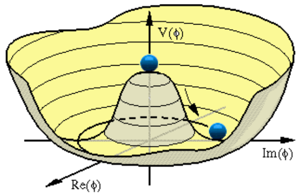
Decay

Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	Th_{Intr}	$\text{Th}_{\text{Par}}^{m_q}$	$\text{Th}_{\text{Par}}^{\alpha_s}$	$\text{Th}_{\text{Par}}^{m_H}$	Th_{Intr}	$\text{Th}_{\text{Par}}^{m_q}$	$\text{Th}_{\text{Par}}^{\alpha_s}$	$\text{Th}_{\text{Par}}^{m_H}$
$H \to b\bar{b}$	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	0.5	–	–	2.6	0.3	–	–	0.1
$H \to gg$	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	5.0	–	–	2.1	1.0	–	–	0.1

$\Delta m_b = 13$ MeV, $\Delta m_c = 7$ MeV, $\Delta m_t = 50$ MeV, $\Delta\alpha_s = 0.0002$ $\Delta m_H = 10$ MeV

Higgs couplings in the dimension-6 SMEFT fit

- The **Higgs self coupling** κ_λ



$$V(\phi) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 \longrightarrow V(h) = \tfrac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \tfrac{1}{4}\lambda_4 h^4$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \lambda_\phi = \frac{G_\mu m_h^2}{\sqrt{2}} \approx 0.129$$

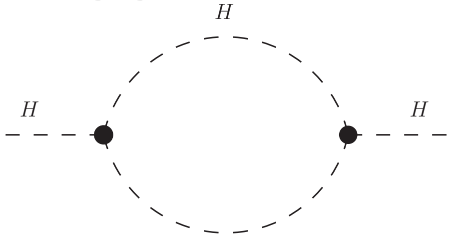
- Why are Higgs self-interactions important?
  - ✓ It characterises the structure of the Higgs potential

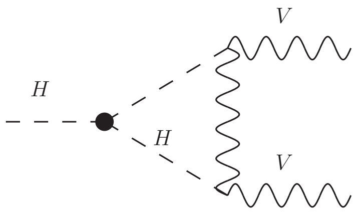
    ⇒ Does EWSB follow from a Ginzburg- Landau ϕ^4 potential?
  - ✓ Test the validity of the SM. Not SM-like? ⇒ Information about BSM physics
    - Sizable deviations expected, e.g., in models of composite Higgs or models with Higgs portal interactions
  - ✓ Control the properties of the electroweak phase transition (EWPT)
    - (Electroweak) Baryogenesis?
    - Models predicting strong 1st order transition → O(1) deviations
- A few operators contribute to κ_λ in the SMEFT but *only one does it exclusively:*

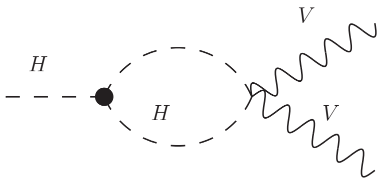
$$\Delta\mathcal{L}_{\rm SMEFT}^{d=6} = \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3, \qquad \rightarrow \qquad \delta\kappa_\lambda = -2\frac{C_\phi v^4}{m_h^2\Lambda^2}$$

Higgs self coupling precision

- Extending the SMEFT fit with the operator O_ϕ and including the NLO effects from the **Higgs self coupling** in **single-Higgs** processes





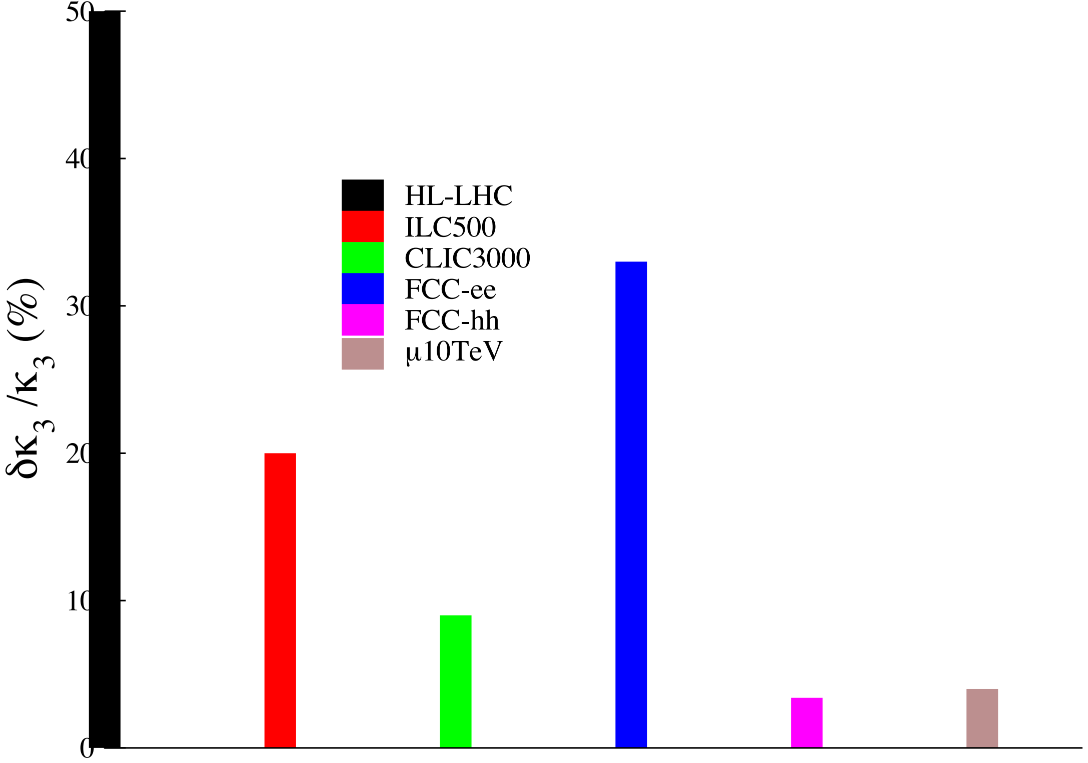


...

- we obtain an *indirect determination* of the precision for κ_λ from single-Higgs fits

arXiv: 2209.07510 [hep-ph]

collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
$\text{ILC}_{250}/\text{C}^3\text{-}250$	49%	–	49%
$\text{ILC}_{500}/\text{C}^3\text{-}550$	38%	20%	20%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	3.4-7.8%	3.4-7.8%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

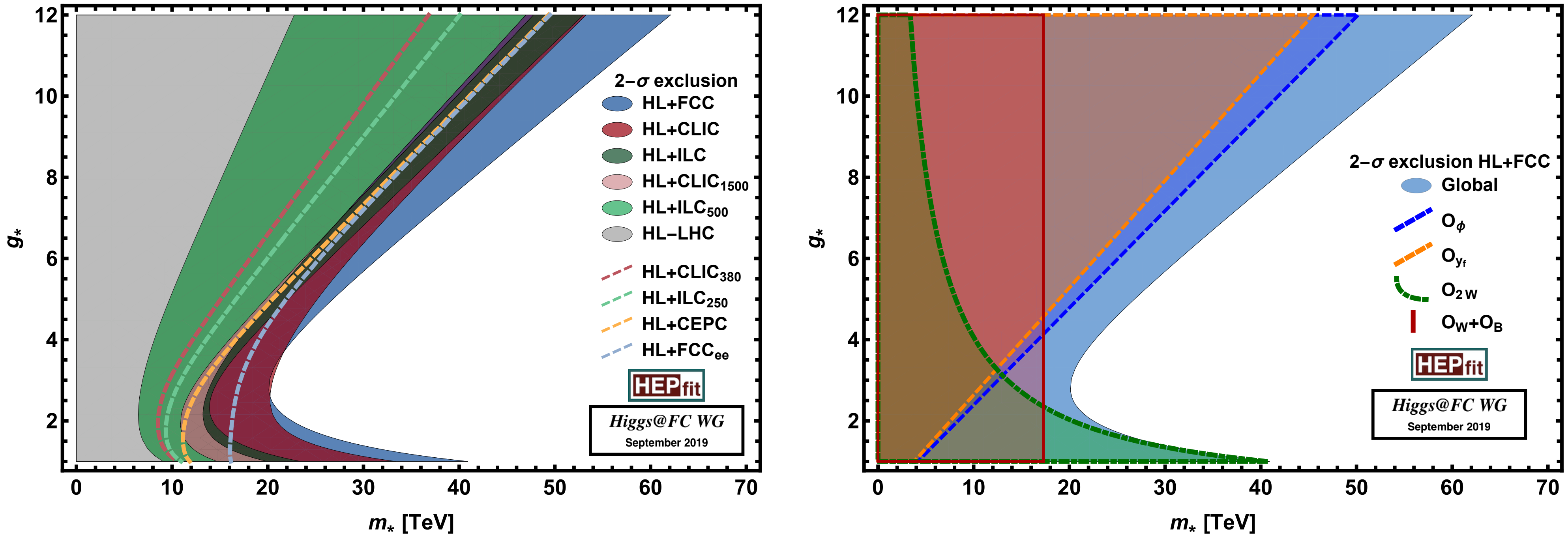


- **CAREFUL:** This indirect determination may not be "robust" if other poorly constrained operators correct the process at NLO. All operators entering at NLO must be included.

Summary and Conclusions

Summary and Conclusions

- Higgs coupling precision is key to learn from BSM physics, e.g. CH models



- Starting from the ESU2020 studies, for the Snowmass process we updated & extended the projections for sensitivity to BSM deformations at future colliders in the SMEFT formalism

- Focusing on the Higgs sector @ FCC:
  - ✓ FCC-ee: Permille precision is achievable for BSM deviations in the main H couplings (mild dependence on precision of TH calculations and SM inputs)
  - ✓ FCC-ee+eh+hh → subpercent precision across all single H couplings
  - ✓ Higgs selfcoupling: FCC-ee~30% → FCC-hh ~5%

Summary and Conclusions

- At the moment, these Higgs coupling fits mostly focus on the main Higgs interactions and do not fully reflect the potential for other types of measurements possible at FCC-ee and that were not discussed here:
  - ✓ Electron Yukawa: Running @ 125 GeV: ~3 times SM
  - ✓ Flavor violating couplings?
  - ✓ CP-violation

- Finally, Higgs physics is only part of the physics program of the FCC…
  - ✓ …and Higgs interpretations depends on the precision of other EW measurements (at the Z pole or above) → important role in optimizing the precision of measurements of the Higgs sector
  - ✓ In particular, precision on aTGC from WW measurements is relevant for SMEFT Higgs analysis, but detailed EXP future collider study including systematics, etc… still needs to be done

Backup slides

The dimension-6 SMEFT

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Neglecting flavour)

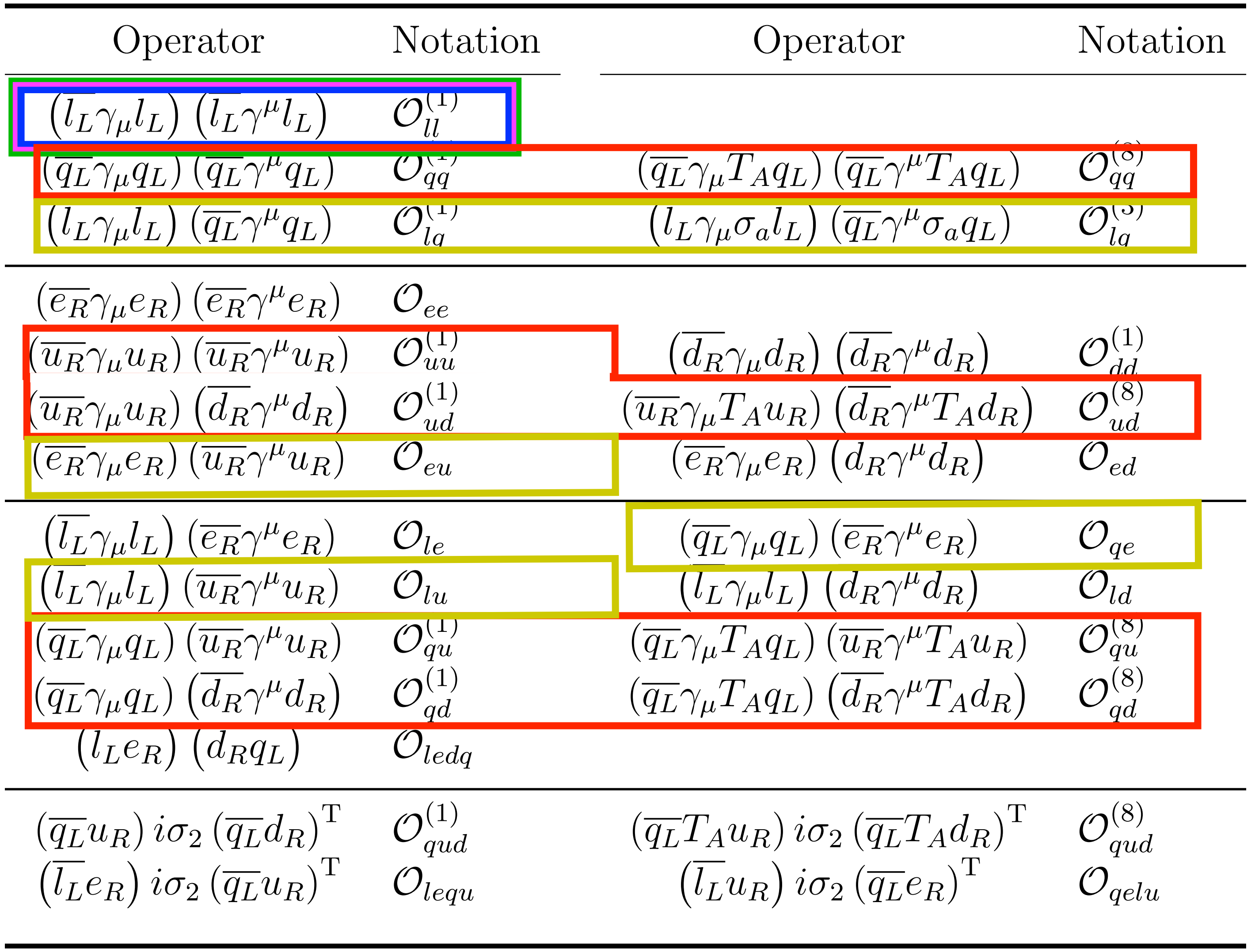
Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)\,(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\,i\sigma_2\,(\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\,i\sigma_2\,(\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\,i\sigma_2\,(\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\,i\sigma_2\,(\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}\left(\phi^\dagger\phi\right)^3$	$\mathcal{O}_{\phi}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)\,(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)\,(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)\,(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)\,(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde\phi\,B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\,B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\,W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\tilde\phi\,G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\,G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)\,(\overline{l_L}\,\phi\,e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)\,\left(\overline{q_L}\,\tilde\phi\,u_R\right)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)\,(\overline{q_L}\,\phi\,d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)\,((D^\mu\phi)^\dagger\,\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\;B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\;\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\;W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\;\widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\;W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\;\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\;G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\;\widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\,W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\,\widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\,G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{G}$	$f_{ABC}\,\widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

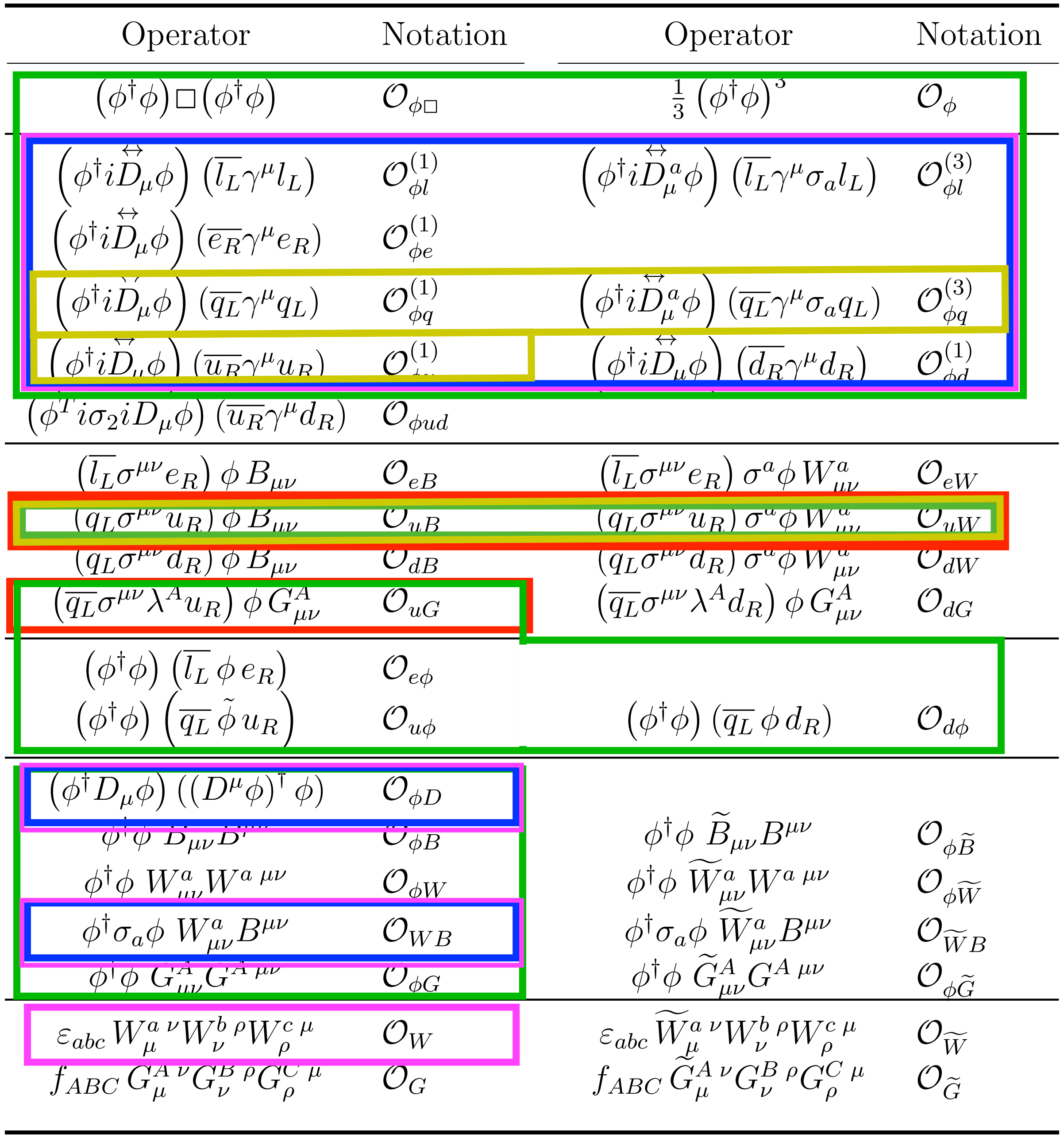
The dimension-6 SMEFT

- **LO SMEFT Lagrangian** (assuming B & L) ⇒ Dim-6 SMEFT: 2499 operators

Warsaw basis operators (Neglecting flavour)



Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$



Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\overline{l_L}\,\phi\, e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)(\overline{q_L}\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\; B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\; \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\; W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\; \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\; W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\; \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\; G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\; \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_W$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

CP-even dim 6 ops. interfering with SM

EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

SMEFT studies: ESU2020 → Snowmass

- **ESU2020:** The starting point for the Snowmass SMEFT studies

European Strategy Update

SMEFT assumptions

- SMEFT truncated at the dim 6 in the EFT expansion (Calculations performed in a modified version of the Warsaw basis)
- CP-even operators
- Neglect effects from 4-fermion operators other than the 4-lepton operator contributing to μ decay (and hence to G_F).
  - 4-fermion operators assumed to be constrained better in non-Higgs processes (e.g. $pp \to ff$ or $e^+e^- \to ff$ at high E)
- No dipole operators (Relevant for general analysis of Top processes, but are neglected in our studies)
- Two types of flavor assumptions: flavour universal (18 NP pars) and flavour diagonal (30 NP pars)

Neutral Diagonal: SMEFT$_{\mathrm{ND}}$ fit

-Hff and Vff ($HVff$) diagonal in the physical basis
-Vff ($HVff$) flavour universality respected by first 2 quark families

-Better for exploration of H & EW capabilities at future colliders
-Cumbersome from model-building point of view to avoid FCNC

Parameter counting in the parameterization of LHCHXSWG-INT-2015-001

Higgs/VVV

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

Vff/hVff

5 SM + 30 New Physics Parameters

SMEFT studies: ESU2020 → Snowmass

NEW for Snowmass 2021

- **Snowmass:** Updated for the SMEFT studies

4-fermion operators included in Snowmass studies, combining low-energy and and $e^+e^-\to ff$ at high-E

Also considered constraints on CP-odd boson operators

- SMEFT truncated at the di rsion of the Warsaw basis)
- CP-even operators
- Neglect effects from 4-fermion operators other than the 4-lepton operator contributing to μ decay (and hence to G_F).
  - 4-fermion operators assumed to be constrained better in non-Higgs processes (e.g. $pp \to ff$ or $e^+e^- \to ff$ at high E)
- No dipole operators (Relevant for general analysis of Top processes, but are neglected in our studies)
- Two types of flavor assump pars)

4-fermion and dipole operators also included in Top observables

-Hff and Vff ($HVff$) diagonal in the physical basis
-Vff ($HVff$) flavour universality respected by first 2 quark families

-Better for exploration of H & EW capabilities at future colliders
-Cumbersome from model-building point of view to avoid FCNC

Parameter counting in the parameterization of LHCHXSWG-INT-2015-001

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

Higgs/VVV

Vff/hVff

5 SM + 30 New Physics Parameters

Snowmass SMEFT fit inputs

- Gauge invariant operators included in the EW/Higgs fit:

		Operator	Notation	Operator	Notation
Class 1	X^3	$\varepsilon_{abc}W_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$	$\mathcal{O}_W$		
	ϕ^6	$(\phi^\dagger\phi)^3$	$\mathcal{O}_\phi$	**(←Included in the discussion of the H self coupling)**	
	ϕ^4D^2	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$
	$X^2\phi^2$	$\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi W^a_{\mu\nu}W^{a\mu\nu}$	$\mathcal{O}_{\phi W}$
		$\phi^\dagger\sigma_a\phi W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$\phi^\dagger\phi G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{\phi G}$
Class 2	$\psi^2\phi^2$	$(\phi^\dagger\phi)(\bar{l}^i_L\phi e^j_R)$	$(\mathcal{O}_{e\phi})_{ij}$		
		$(\phi^\dagger\phi)(\bar{q}^i_L\phi d^j_R)$	$(\mathcal{O}_{d\phi})_{ij}$	$(\phi^\dagger\phi)(\bar{q}^i_L\tilde{\phi}u^j_R)$	$(\mathcal{O}_{u\phi})_{ij}$
Class 3	$\psi^2\phi^2D$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}^i_L\gamma^\mu l^j_L)$	$\left(\mathcal{O}^{(1)}_{\phi l}\right)_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}^i_L\gamma^\mu\sigma_a l^j_L)$	$(\mathcal{O}^{(3)}_{\phi l})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}^i_R\gamma^\mu e^j_R)$	$(\mathcal{O}_{\phi e})_{ij}$		
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}^i_L\gamma^\mu q^j_L)$	$(\mathcal{O}^{(1)}_{\phi q})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}^i_L\gamma^\mu\sigma_a q^j_L)$	$(\mathcal{O}^{(3)}_{\phi q})_{ij}$
		$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}^i_R\gamma^\mu u^j_R)$	$(\mathcal{O}_{\phi u})_{ij}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}^i_R\gamma^\mu d^j_R)$	$(\mathcal{O}_{\phi d})_{ij}$

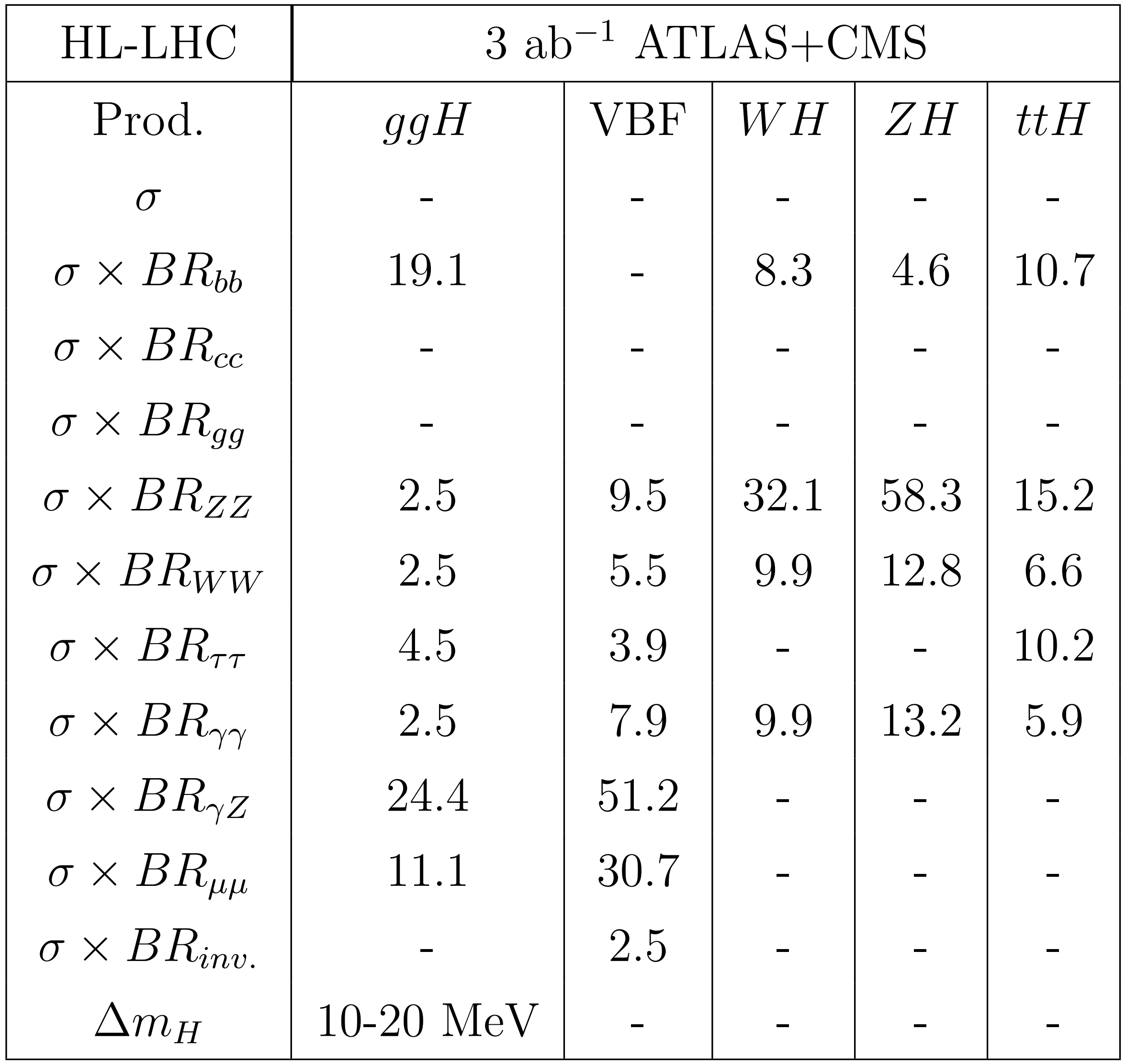
Snowmass SMEFT fit inputs

- **Electroweak precision observables**

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8^*	17.8^*		3.8 (1.2)	17.8^*	
Δm_W (MeV)	12^*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1^*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1^*
Δm_H (MeV)	170^*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42^*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3^*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3^*
ΔA_e ($\times 10^5$)	190^*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64
ΔA_μ ($\times 10^5$)	1500^*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400^*	86 (4.5)	3 (8)	0.5 (**20**)	1.2 (**6.9**)	570
ΔA_b ($\times 10^5$)	2000^*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700^*	140 (25)	20 (37)	20 (15)	6 (**30**)	200
$\Delta\sigma^0_{\text{had}}$ (pb)	37^*			0.035 (4)	0.05 (2)	37^*
δR_e ($\times 10^3$)	2.4^*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	1.6^*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	2.2^*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	3.0^*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
δR_c($\times 10^3$)	17^*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

Snowmass SMEFT fit inputs

- **Higgs observables: HL-LHC**



HL-LHC	3 ab^{-1} ATLAS+CMS				
Prod.	ggH	VBF	WH	ZH	ttH
σ	-	-	-	-	-
$\sigma \times BR_{bb}$	19.1	-	8.3	4.6	10.7
$\sigma \times BR_{cc}$	-	-	-	-	-
$\sigma \times BR_{gg}$	-	-	-	-	-
$\sigma \times BR_{ZZ}$	2.5	9.5	32.1	58.3	15.2
$\sigma \times BR_{WW}$	2.5	5.5	9.9	12.8	6.6
$\sigma \times BR_{\tau\tau}$	4.5	3.9	-	-	10.2
$\sigma \times BR_{\gamma\gamma}$	2.5	7.9	9.9	13.2	5.9
$\sigma \times BR_{\gamma Z}$	24.4	51.2	-	-	-
$\sigma \times BR_{\mu\mu}$	11.1	30.7	-	-	-
$\sigma \times BR_{inv.}$	-	2.5	-	-	-
Δm_H	10-20 MeV	-	-	-	-

Snowmass SMEFT fit inputs

- **Higgs observables: Circular e^+e^- Colliders (FCCee/CEPC)**

	FCCee240 5ab^{-1}		CEPC240 20ab^{-1}	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.5(0.537)	-	0.26	-
$\sigma \times BR_{bb}$	0.3(0.380)	3.1(2.78)	0.14	1.59
$\sigma \times BR_{cc}$	2.2(2.08)	-	2.02	-
$\sigma \times BR_{gg}$	1.9(1.75)	-	0.81	-
$\sigma \times BR_{ZZ}$	4.4(4.49)	-	4.17	-
$\sigma \times BR_{WW}$	1.2(1.16)	-	0.53	-
$\sigma \times BR_{\tau\tau}$	0.9(0.822)	-	0.42	-
$\sigma \times BR_{\gamma\gamma}$	9(8.47)	-	3.02	-
$\sigma \times BR_{\gamma Z}$	(17*)	-	8.5	-
$\sigma \times BR_{\mu\mu}$	19(17.9)	-	6.36	-
$\sigma \times BR_{inv.}$	0.3(0.226)	-	0.07	-

	1.5 ab^{-1} FCC-ee365		1.0 ab^{-1} CEPC360	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.9(0.84)	-	1.4(1.02)	-
$\sigma \times BR_{bb}$	0.5(0.71)	0.9(1.14)	0.90(0.86)	1.1(1.39)
$\sigma \times BR_{cc}$	6.5(5.0)	10(11.9)	8.8(6.1)	16(14.5)
$\sigma \times BR_{gg}$	3.5(3.8)	4.5(4.8)	3.4(4.7)	4.5(5.9)
$\sigma \times BR_{ZZ}$	12(11.4)	10(12.5)	20(13.9)	21(15.3)
$\sigma \times BR_{WW}$	2.6(2.55)	(3.6)	2.8(3.12)	4.4(4.4)
$\sigma \times BR_{\tau\tau}$	1.8(1.83)	8(10)	2.1(2.24)	4.2(12.2)
$\sigma \times BR_{\gamma\gamma}$	18(17.7)	22(28.1)	11(21.7)	16(34.4)
$\sigma \times BR_{\mu\mu}$	40(40)	(100)	41(48)	57(123)
$\sigma \times BR_{inv.}$	0.60(0.42)	-	(0.49)	-

Snowmass SMEFT fit inputs

- **Higgs observables: Linear e^+e^- Colliders (ILC)**

ILC250	0.9ab^{-1} (-0.8,+0.3)		0.9ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.07	-	1.07	-
$\sigma \times BR_{bb}$	0.714	4.27	0.714	17.4
$\sigma \times BR_{cc}$	4.38	-	4.38	-
$\sigma \times BR_{gg}$	3.69	-	3.69	-
$\sigma \times BR_{ZZ}$	9.49	-	9.49	-
$\sigma \times BR_{WW}$	2.43	-	2.43	-
$\sigma \times BR_{\tau\tau}$	1.7	-	1.7	-
$\sigma \times BR_{\gamma\gamma}$	17.9	-	17.9	-
$\sigma \times BR_{\gamma Z}$	63	-	59	-
$\sigma \times BR_{\mu\mu}$	37.9	-	37.9	-
$\sigma \times BR_{inv.}$	0.336	-	0.277	-

ILC350	0.135 ab^{-1} (-0.8,+0.3)		0.045 ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	2.46	-	4.3	-
$\sigma \times BR_{bb}$	2.05	2.46	3.5	17.7
$\sigma \times BR_{cc}$	15	25.9	25.9	186
$\sigma \times BR_{gg}$	11.4	10.5	19.8	75
$\sigma \times BR_{ZZ}$	34	27.2	59	191
$\sigma \times BR_{WW}$	7.6	7.8	13.2	57
$\sigma \times BR_{\tau\tau}$	5.5	21.8	9.4	156
$\sigma \times BR_{\gamma\gamma}$	53	61	92	424
$\sigma \times BR_{\mu\mu}$	118	218	205	1580
$\sigma \times BR_{inv.}$	1.15	-	1.83	-

ILC500	1.6 ab^{-1} (-0.8,+0.3)		1.6 ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.67	-	1.67	-
$\sigma \times BR_{bb}$	1.01	0.42	1.01	1.52
$\sigma \times BR_{cc}$	7.1	3.48	7.1	14.2
$\sigma \times BR_{gg}$	5.9	2.3	5.9	9.5
$\sigma \times BR_{ZZ}$	13.8	4.8	13.8	19
$\sigma \times BR_{WW}$	3.1	1.36	3.1	5.5
$\sigma \times BR_{\tau\tau}$	2.42	3.9	2.42	15.8
$\sigma \times BR_{\gamma\gamma}$	18.6	10.7	18.6	44
$\sigma \times BR_{\mu\mu}$	47	40	47	166
$\sigma \times BR_{inv.}$	0.83	-	0.60	-

ILC1000	3.2 ab^{-1} (-0.8,+0.2)	3.2 ab^{-1} (+0.8,-0.2)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.32	1.0
$\sigma \times BR_{cc}$	1.7	6.4
$\sigma \times BR_{gg}$	1.3	4.7
$\sigma \times BR_{ZZ}$	2.3	8.4
$\sigma \times BR_{WW}$	0.91	3.3
$\sigma \times BR_{\tau\tau}$	1.7	6.4
$\sigma \times BR_{\gamma\gamma}$	4.8	17
$\sigma \times BR_{\mu\mu}$	17	64

Snowmass SMEFT fit inputs

- **Higgs observables: Linear e^+e^- Colliders (CLIC)**

CLIC380	0.5 ab^{-1} (-0.8,0)		0.5 ab^{-1} (+0.8,0)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.5(1.43)	-	1.8(1.43)	-
$\sigma \times BR_{bb}$	0.81(1.2)	1.4(1.47)	0.92(1.2)	4.1(4.4)
$\sigma \times BR_{cc}$	13(8.7)	19(15.3)	15(8.7)	24(46)
$\sigma \times BR_{gg}$	5.7(6.6)	3.3(6.2)	6.5(6.6)	20(18.8)
$\sigma \times BR_{ZZ}$	(19.7)	(16.1)	(19.7)	(46)
$\sigma \times BR_{WW}$	5.1(4.4)	(4.6)	(4.4)	(14)
$\sigma \times BR_{\tau\tau}$	5.9(3.2)	(12.9)	6.6(3.2)	(39)
$\sigma \times BR_{\gamma\gamma}$	(31)	(36)	(31)	(108)
$\sigma \times BR_{\mu\mu}$	(69)	(129)	(69)	(129)
$\sigma \times BR_{inv.}$	0.57(0.68)	-	0.64(0.64)	-

CLIC1500	2 ab^{-1} (-0.8,0)	0.5 ab^{-1} (+0.8,0)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.25	1.5
$\sigma \times BR_{cc}$	3.9	24
$\sigma \times BR_{gg}$	3.3	20
$\sigma \times BR_{ZZ}$	3.6	22
$\sigma \times BR_{WW}$	0.67	4.0
$\sigma \times BR_{\tau\tau}$	2.8	17
$\sigma \times BR_{\gamma\gamma}$	10	60
$\sigma \times BR_{\gamma Z}$	28	170
$\sigma \times BR_{\mu\mu}$	24	150

CLIC3000	4 ab^{-1} (-0.8,0)	1 ab^{-1} (+0.8,0)
Prod.	$\nu\nu H$	$\nu\nu H$
$\sigma \times BR_{bb}$	0.17	1.0
$\sigma \times BR_{cc}$	3.7	22
$\sigma \times BR_{gg}$	2.3	14
$\sigma \times BR_{ZZ}$	2.1	13
$\sigma \times BR_{WW}$	0.33	2.0
$\sigma \times BR_{\tau\tau}$	2.3	14
$\sigma \times BR_{\gamma\gamma}$	5.0	30
$\sigma \times BR_{\gamma Z}$	16	95
$\sigma \times BR_{\mu\mu}$	13	80

Snowmass SMEFT fit inputs

- **Higgs observables: Muon Colliders**

MuC3000	$3\ \text{ab}^{-1}$	
Prod.	$\nu\nu H$	$\mu\mu H$
$\sigma \times BR_{bb}$	0.8	2.6
$\sigma \times BR_{cc}$	12	72
$\sigma \times BR_{gg}$	2.8	14
$\sigma \times BR_{ZZ}$	11	34
$\sigma \times BR_{WW}$	1.5	7.5
$\sigma \times BR_{\tau\tau}$	3.8	21
$\sigma \times BR_{\gamma\gamma}$	6.4	23
$\sigma \times BR_{\gamma Z}$	45	-
$\sigma \times BR_{\mu\mu}$	28	-

MuC10000	$10\ \text{ab}^{-1}$	
Prod.	$\nu\nu H$	$\mu\mu H$
$\sigma \times BR_{bb}$	0.22	0.77
$\sigma \times BR_{cc}$	3.6	17
$\sigma \times BR_{gg}$	0.79	3.3
$\sigma \times BR_{ZZ}$	3.2	11
$\sigma \times BR_{WW}$	0.40	1.8
$\sigma \times BR_{\tau\tau}$	1.1	4.8
$\sigma \times BR_{\gamma\gamma}$	1.7	4.8
$\sigma \times BR_{\gamma Z}$	12	-
$\sigma \times BR_{\mu\mu}$	5.7	-

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions

in %	HL-LHC	CEPC		FCC-ee		ILC						CLIC			muon-collider		
		240 +Z/WW	+360	240 +Z/WW	+365	250	Giga-Z	+500	Giga-Z	+1TeV	Giga-Z	380	+1.5TeV	+3TeV	3TeV	10TeV	10TeV +125
δg_H^{ZZ}	2.2 –	0.17 0.19	0.16 0.17	0.28 0.31	0.22 0.25	0.31 0.37	0.29 0.35	0.18 0.26	0.18 0.25	0.13 0.23	0.13 0.23	0.43 0.56	0.19 0.41	0.16 0.4	0.48 –	0.31 –	0.28 0.39
δg_H^{WW}	2. –	0.17 0.18	0.15 0.17	0.28 0.31	0.22 0.25	0.32 0.37	0.31 0.36	0.19 0.26	0.18 0.26	0.14 0.24	0.14 0.23	0.44 0.56	0.21 0.42	0.17 0.41	0.49 –	0.31 –	0.28 0.39
$\delta g_H^{\gamma\gamma}$	2.5 –	0.91 0.91	0.89 0.9	1.2 1.2	1.1 1.1	1.2 1.2	1.2 1.2	1.1 1.1	1.1 1.1	0.98 1.	0.97 1.	1.2 1.3	1.1 1.2	1. 1.1	1.2 –	0.7 –	0.69 0.74
$\delta g_H^{Z\gamma}$	11. –	4. 4.	3.8 3.8	6.7 6.7	6.1 6.1	9.3 9.3	9.1 9.1	7. 7.	6.8 6.8	6.7 6.7	6.6 6.6	10. 10.	8.3 8.3	5.8 5.8	9.7 –	5.2 –	5.2 5.2
$\delta g_{1,Z}$	0.31 0.31	0.025 0.025	0.023 0.023	0.044 0.043	0.03 0.03	0.069 0.069	0.067 0.067	0.031 0.031	0.025 0.025	0.025 0.025	0.022 0.022	0.1 0.1	0.06 0.06	0.052 0.052	0.1 0.1	0.025 0.025	0.025 0.025
$\delta\kappa_\gamma$	0.97 0.97	0.046 0.046	0.042 0.043	0.069 0.069	0.05 0.05	0.1 0.1	0.092 0.092	0.047 0.047	0.036 0.036	0.031 0.031	0.026 0.026	0.15 0.15	0.071 0.071	0.06 0.061	0.16 0.16	0.025 0.025	0.024 0.025
λ_Z	0.4 0.4	0.012 0.012	0.011 0.011	0.023 0.023	0.016 0.016	0.031 0.031	0.031 0.031	0.0082 0.0083	0.0082 0.0082	0.0028 0.0028	0.0028 0.0028	0.025 0.025	0.0028 0.0028	0.00092 0.00092	0.0027 0.0027	0.00026 0.00026	0.00025 0.00026
δg_H^{gg}	1.8 –	0.44 0.45	0.43 0.44	0.74 0.77	0.68 0.69	0.85 0.9	0.85 0.89	0.66 0.69	0.66 0.69	0.49 0.53	0.49 0.53	0.94 1.1	0.71 0.79	0.59 0.69	0.87 –	0.46 –	0.43 0.51
δg_H^{cc}	1.8 –	1.2 1.2	1.1 1.1	1.3 1.4	1.2 1.3	1.8 1.8	1.8 1.8	1.2 1.2	1.2 1.2	0.87 0.9	0.87 0.9	4.3 4.3	1.9 1.9	1.4 1.5	6.2 –	1.9 –	1.8 1.8
δg_H^{bb}	4.5 –	0.41 0.43	0.4 0.42	0.6 0.66	0.53 0.58	0.77 0.83	0.77 0.83	0.5 0.56	0.51 0.56	0.42 0.48	0.42 0.47	0.96 1.1	0.46 0.6	0.37 0.54	0.92 –	0.46 –	0.44 0.53
$\delta g_H^{\tau\tau}$	2.3 –	0.34 0.36	0.32 0.34	0.64 0.68	0.56 0.6	0.8 0.87	0.8 0.86	0.58 0.63	0.58 0.63	0.49 0.53	0.48 0.53	1.4 1.4	0.98 1.	0.76 0.84	1.3 –	0.62 –	0.58 0.63
$\delta g_H^{\mu\mu}$	5.6 –	2.7 2.7	2.7 2.7	4.6 4.6	4.5 4.5	4.9 4.9	4.9 4.9	4.5 4.5	4.5 4.5	4. 4.	4. 4.	5.1 5.1	4.7 4.7	3.8 3.8	4.9 –	2.5 –	0.24 0.49
$\delta\Gamma_H$	6.7 –	0.47 0.61	0.44 0.59	0.82 1.1	0.69 0.98	1.1 1.5	1. 1.5	0.62 1.1	0.62 1.1	0.46 0.94	0.46 0.93	1.4 2.3	0.6 1.6	0.45 1.6	1.5 –	0.7 –	0.63 1.3

Optimal Observables

- Consider a Phase-space distribution linear in some coefficients c_i:

$$S(\Phi) = S_0(\Phi) + \sum_i c_i S_i(\Phi)$$

SMEFT: $S(\Phi) = \frac{d\sigma}{d\Phi}$ $S_0(\Phi) = \left.\frac{d\sigma}{d\Phi}\right|_{\mathrm{SM}}$ $c_i S_i(\Phi) = \left.\frac{d\sigma}{d\Phi}\right|_{\mathtt{Interf.\ SM-NP}}$

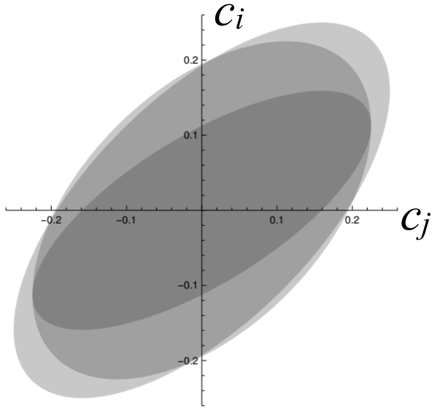
- In the limit of large statistics, the observables

(See e.g., Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

$$O_i(\Phi) = \frac{S_i(\Phi)}{S_0(\Phi)}$$

provide the most precise statistical information about the coefficients c_i around the point $c_i=0$, $\forall i$

$$\mathrm{cov}(c_i, c_j) = \left(\mathcal{L} \int d\Phi \frac{S_i(\Phi) S_j(\Phi)}{S_0(\Phi)}\right)^{-1} + \mathcal{O}(c_k)$$



OO minimize the volume of the 1-σ ellipsoid

- Idealized (no systematics) ⇒ We compensate omission of systematics via conservative selection efficiency ε

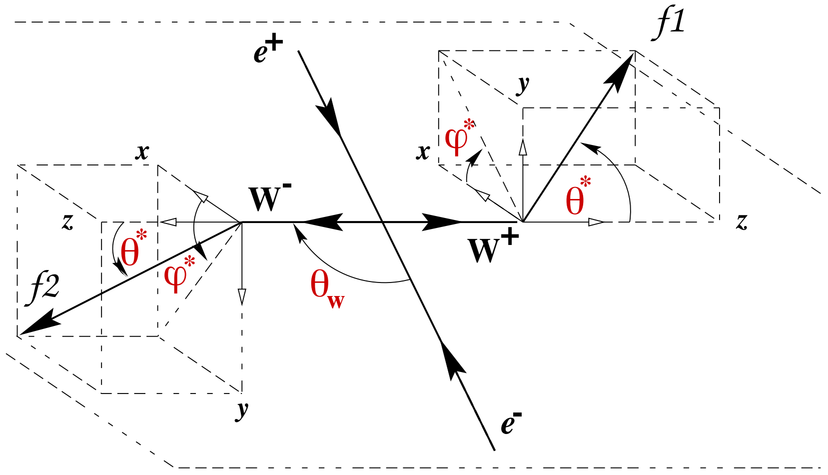
$$\mathcal{L} \longrightarrow \varepsilon \mathcal{L}$$

Optimal Observables

- diBoson: We work with $e^+e^- \to W^+W^-$ **(All final state decays)**

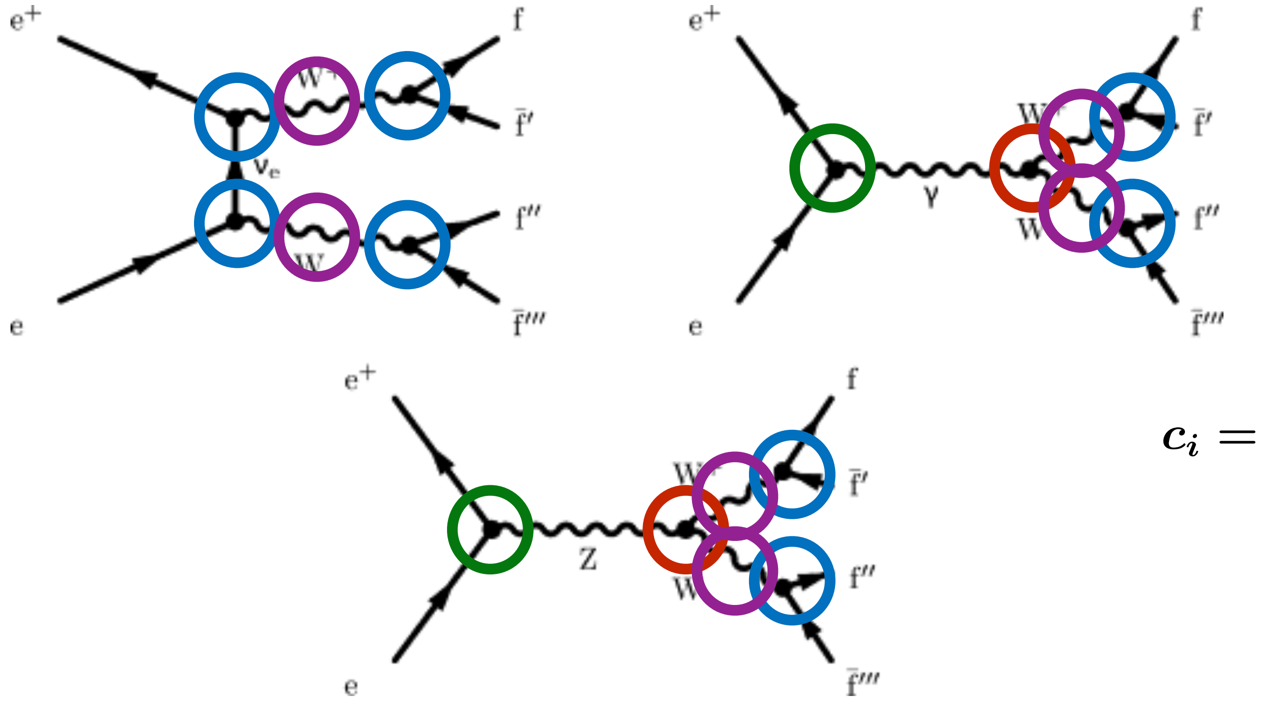
$$S(\Phi) = S_0(\Phi) + \sum_i c_i S_i(\Phi)$$

SMEFT: $S(\Phi) = \frac{d\sigma}{d\Phi}$ $S_0(\Phi) = \left.\frac{d\sigma}{d\Phi}\right|_{\mathrm{SM}}$ $c_i S_i(\Phi) = \left.\frac{d\sigma}{d\Phi}\right|_{\mathtt{Interf.\ SM-NP}}$



Optimal Observables function of 5 angles

$$S(\Phi) = \frac{d\sigma}{d\cos\theta_W\, d\varphi_1\, d\cos_{\theta_1}\, d\varphi_2\, d\cos_{\theta_2}}$$



Full dim-6 SMEFT parameterization at LO:
10 independent BSM deformations

$$c_i = \left\{\underline{\delta g_{1Z},\ \delta\kappa_\gamma,\ \lambda_Z},\ \underline{(\delta g^{Ze}_{L,R})_e},\ \underline{(\delta g^{W\ell\nu}_L)_\ell,\ ,\ (\delta g^{Wud}_L)_{q_i}},\ \underline{\delta m}\right\}$$