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Global SMEFT Interpretation & Impact of Precision Measurements at Future Higgs Factories

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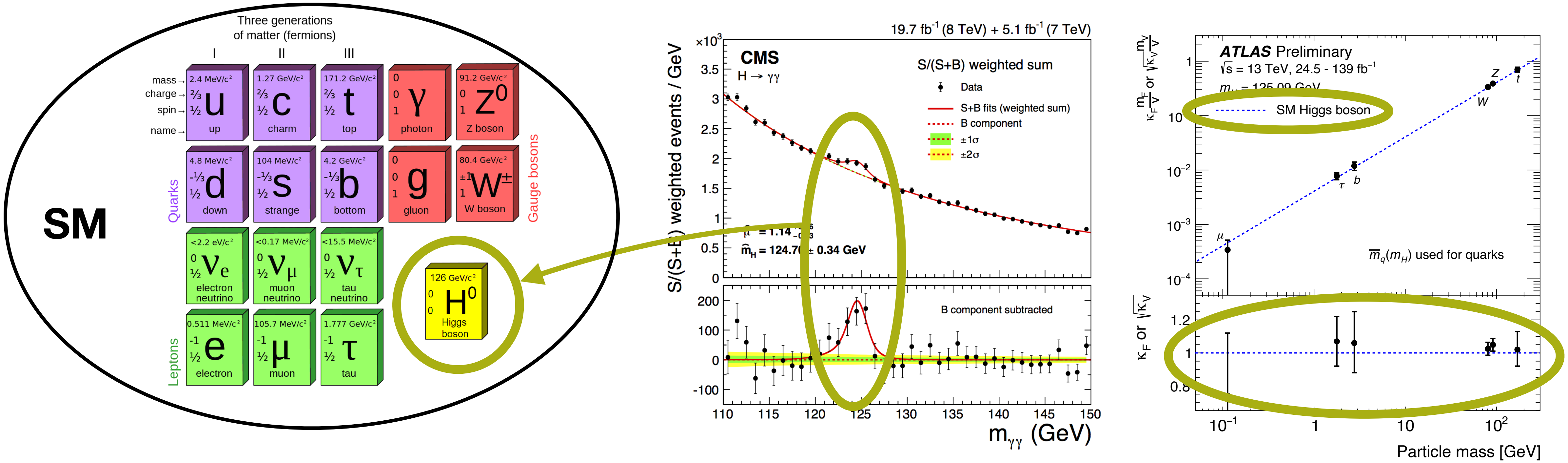
Introduction

- **10+ yrs after its discovery, the 125 GeV Higgs boson remains as the biggest achievement of the LHC**
  - ✓ It finally proves the existence of the last ingredient required to fully test the validity of the SM at low energies…



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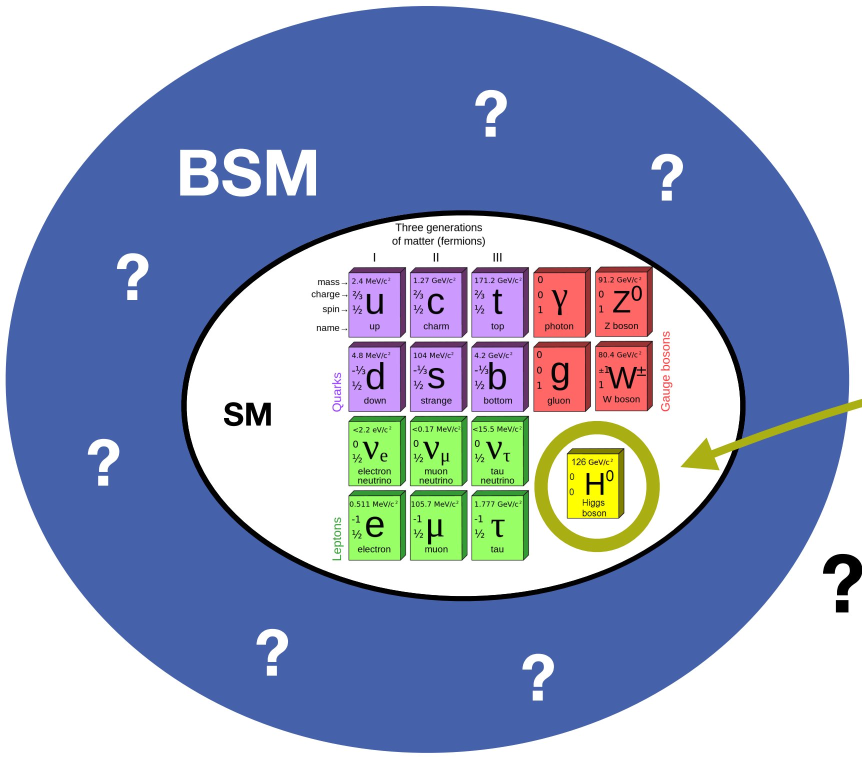
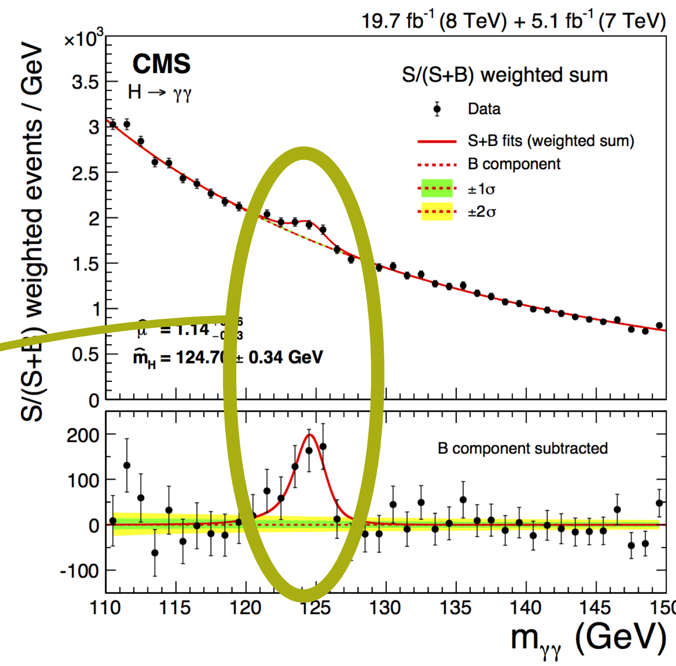
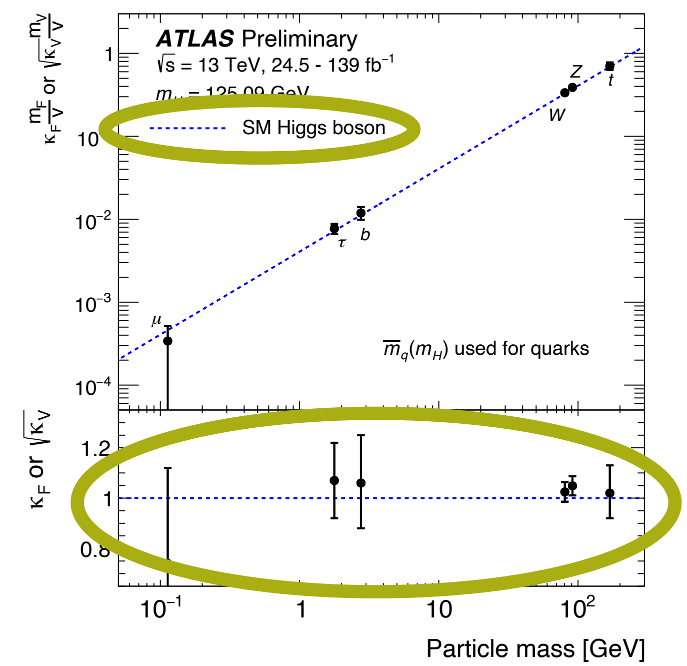
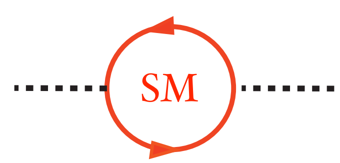
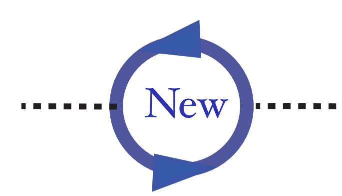




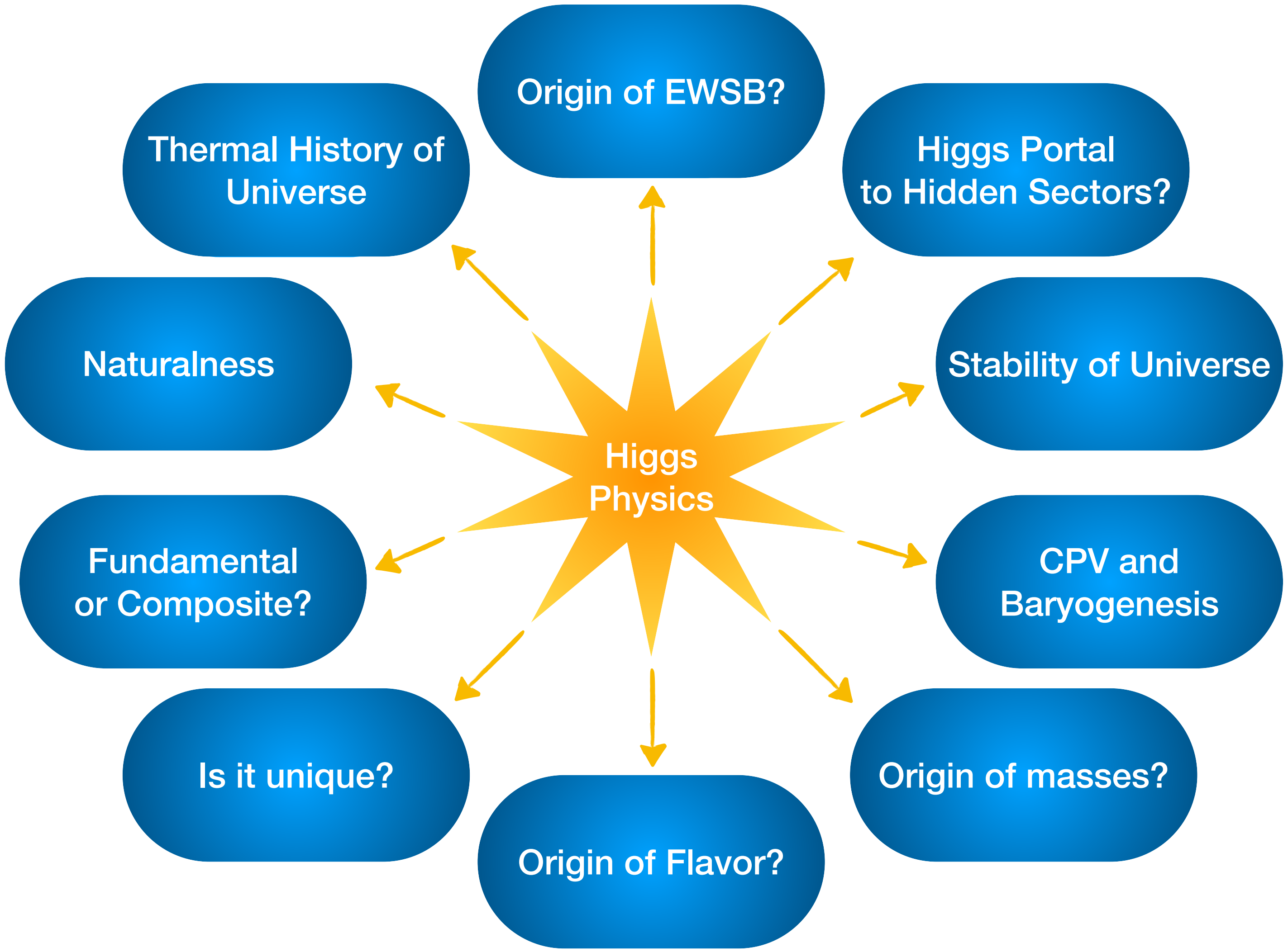


- ✓ …and at the same time reminds us of the limitations of the SM…
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?

⇒ **BSM:** $\Delta M_h^2 =$  $+$  ~ 0

Introduction

- In particular, the Higgs is connected to many interesting/relevant BSM questions:

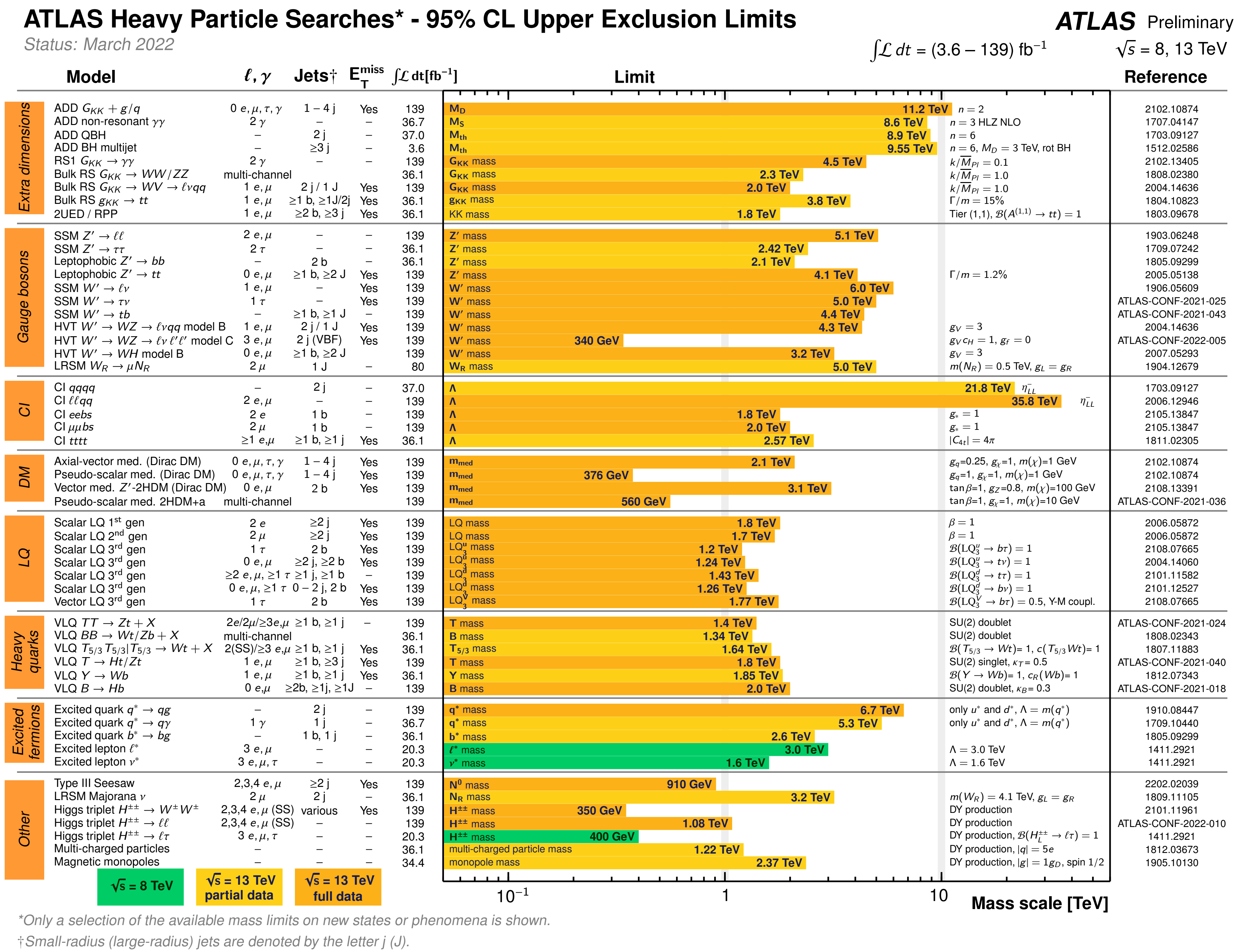


arXiv: 2209.07510 [hep-ph]

But where is the New Physics hiding?

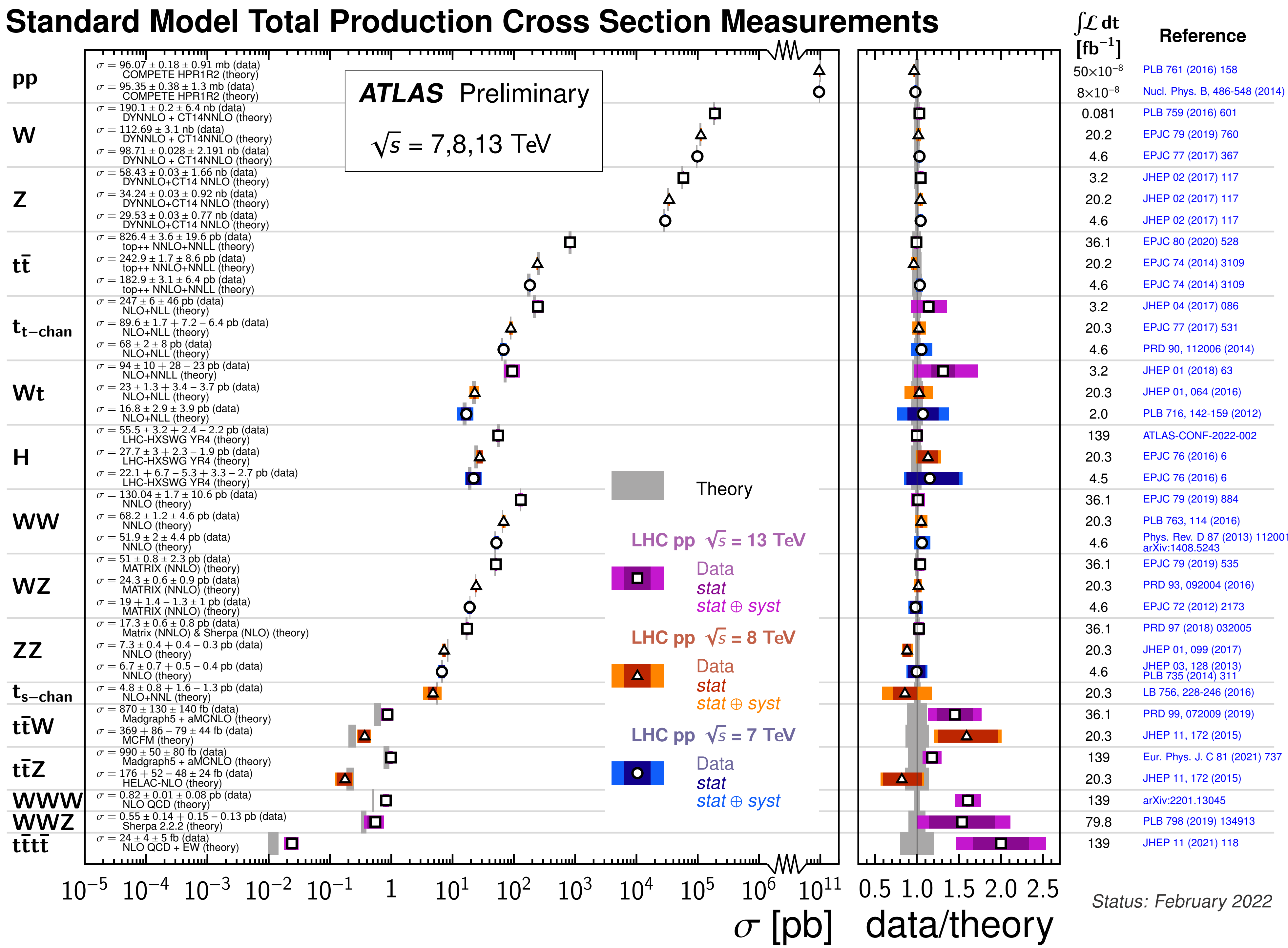
Introduction

- But the Higgs is the only "new" physics we have found so far…



Introduction

- …and (almost) everything we have measured agrees well with the SM…



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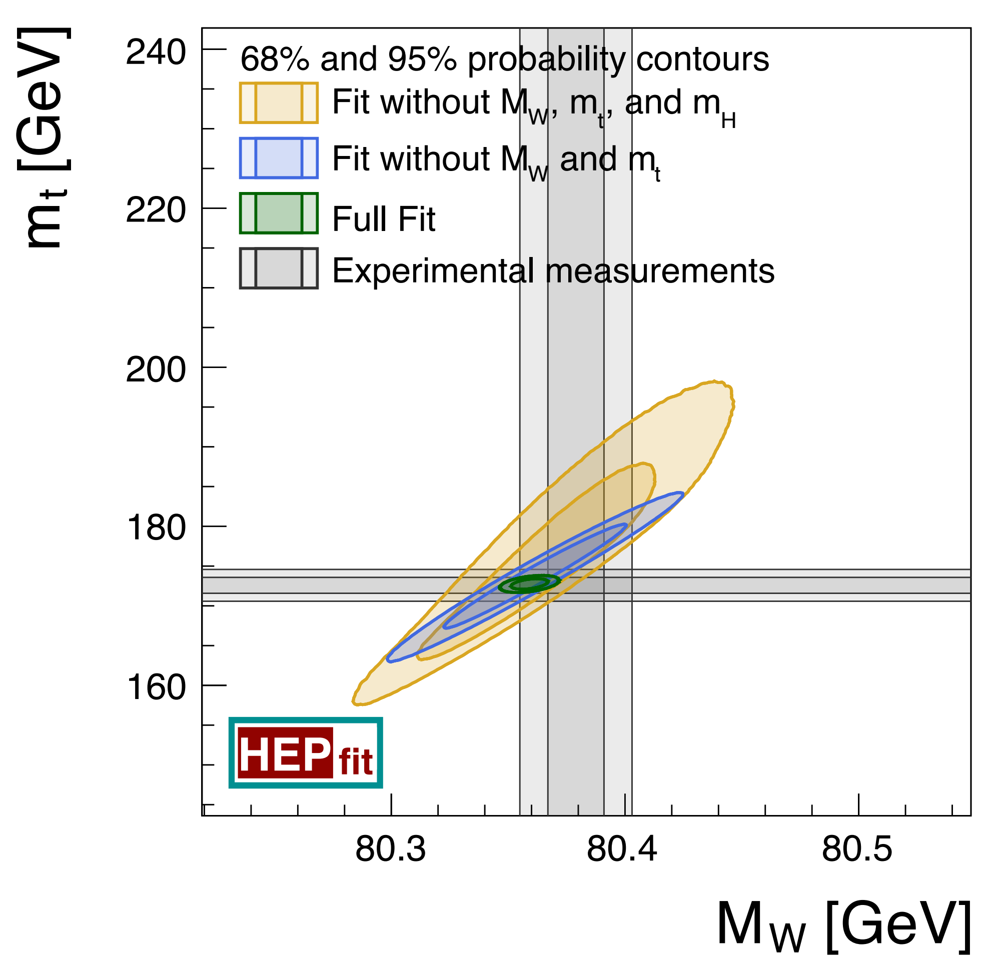
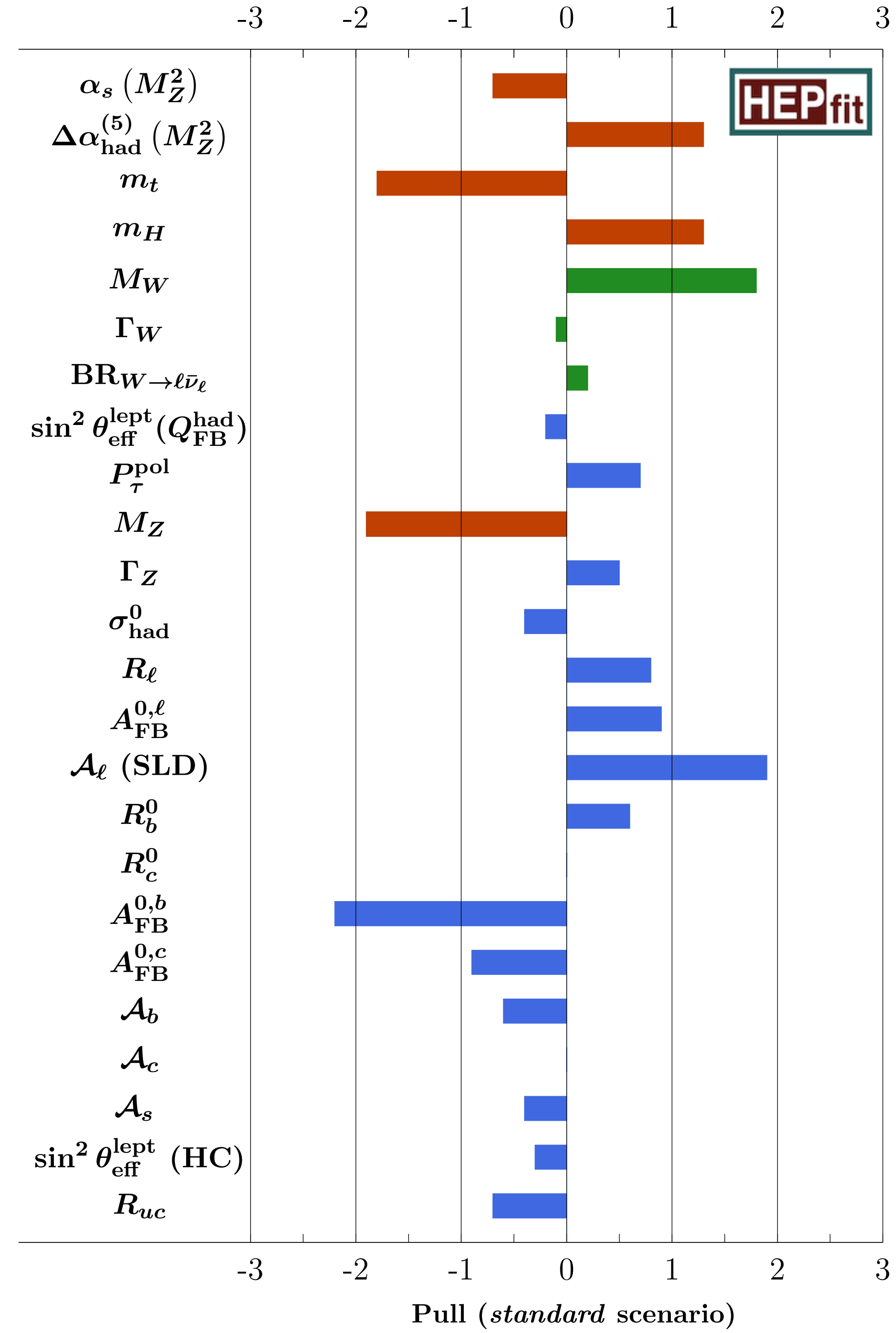
J.B. et al., Phys. Rev. D 106 (2022) 3, 033003



(Before April 2022)

Individual pulls

(Remove observable from fit → Predict)



Overall consistency of the SM fit at 1σ

p-value: 0.45

Introduction

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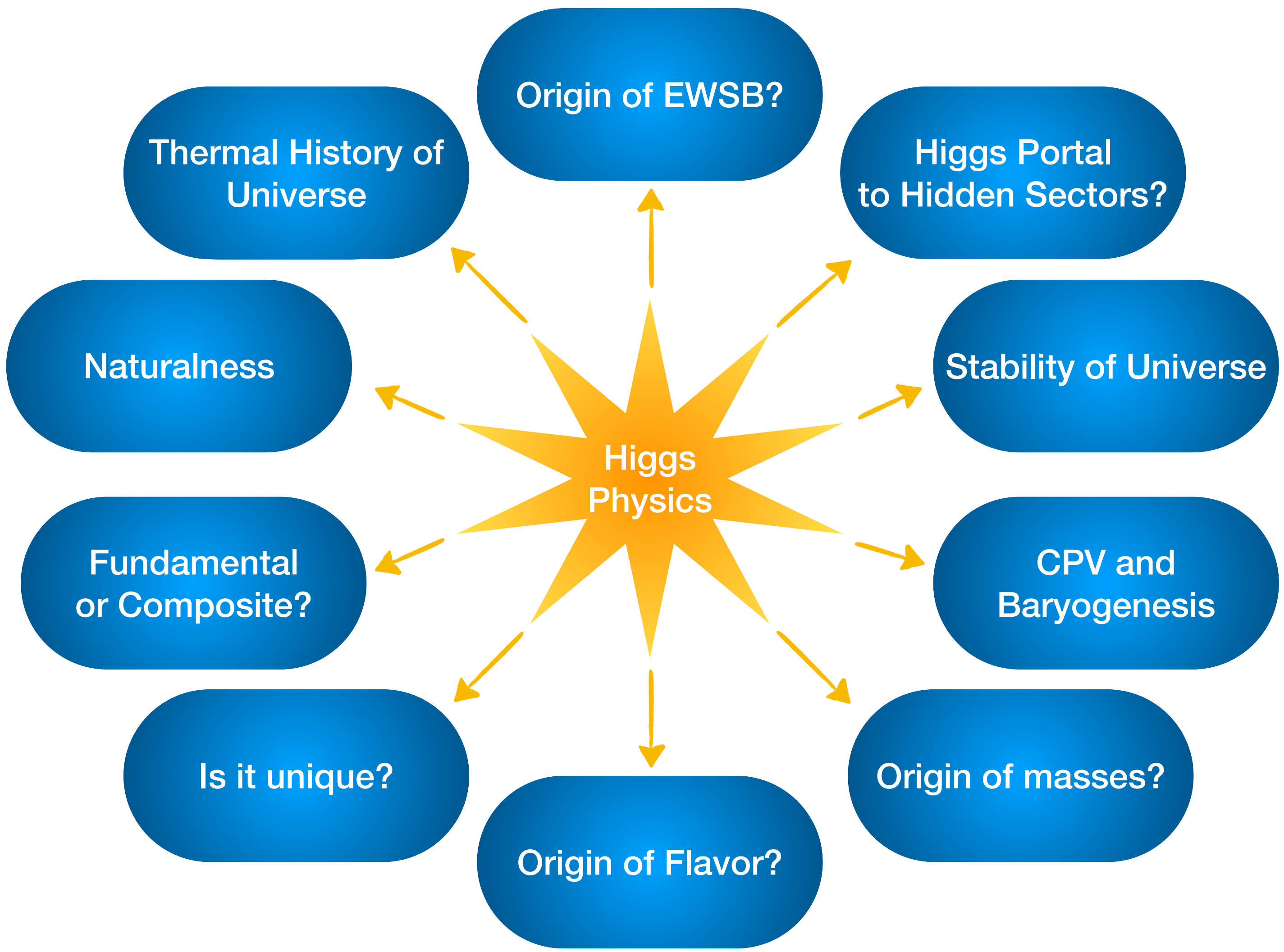

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BSM scenarios dealing with these questions typically introduce modifications of the Higgs properties → Indirect tests of new physics

- Higgs couplings modifications can tell us about BSM and the LHC is the only current experiment which can directly test the Higgs sector…

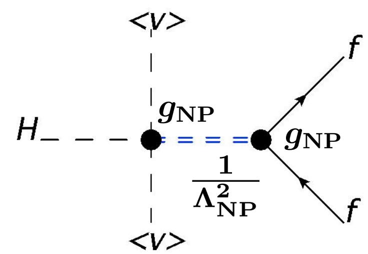
Introduction

- …but the O(10%) precision at the LHC gives limited information:

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

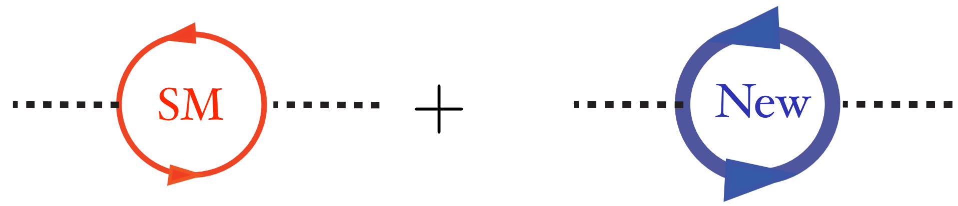
Typical BSM deformation: $$\frac{\delta g_h}{g_h} \sim \frac{g_{\mathrm{NP}}^2 v^2}{\Lambda_{\mathrm{NP}}^2} \Longrightarrow \Lambda_{\mathrm{NP}} \gtrsim 600 \frac{g_{\mathrm{NP}}}{g_{\mathrm{SM}}}\ \mathrm{GeV}$$

E.g.



Not better than direct searches
(unless NP is strongly coupled)

- Higgs couplings also provide information about Naturalness

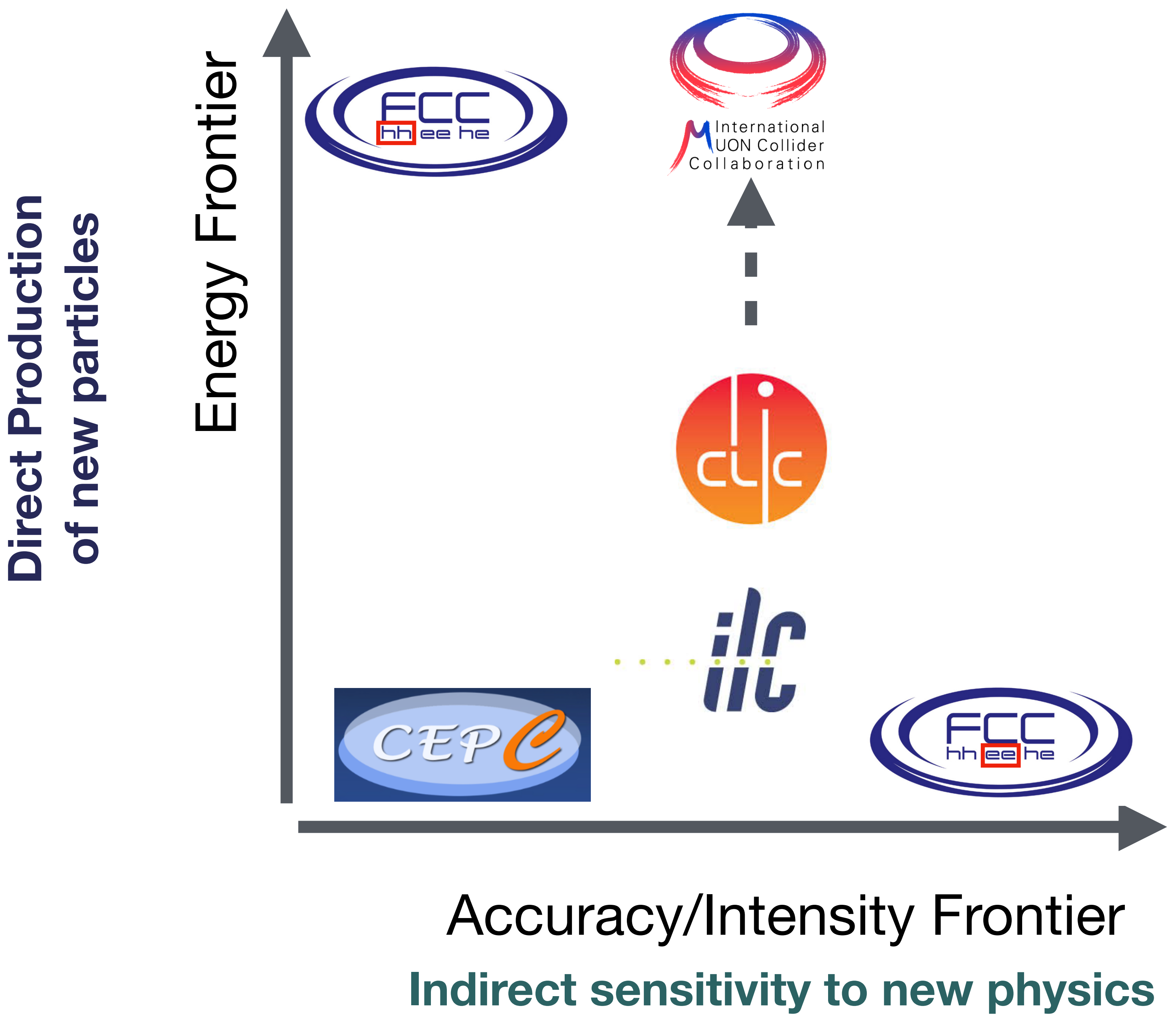
$\delta m_H^2 =$  ~ 0

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

⇒ Higgs precision physics is a key tool to learn from BSM
⇒ Need of an e^+e^- Higgs factory

Introduction

- Future collider projects: The Intensity/Energy frontier



Introduction

- The problem is, in the search of new physics, we no longer have guidance: The Higgs was "expected" within the SM, we knew what to look for…

But Future Collider physics will be an exploration of the unknown…

If there is new physics not far from the TeV *it may be of a form we have not though of* ⇒ *Model-independent approach*

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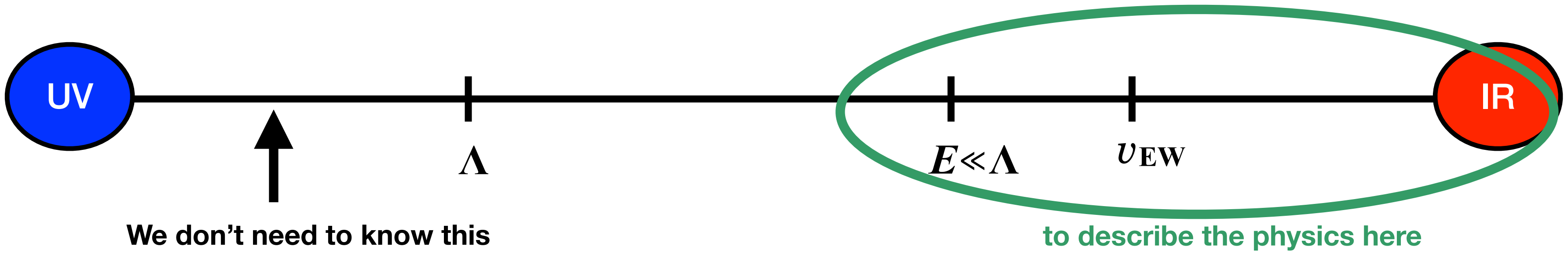
Effective Field Theories

Theoretically robust framework to systematically study indirect effects of new physics in model-independent way and combine all the information from different measurements



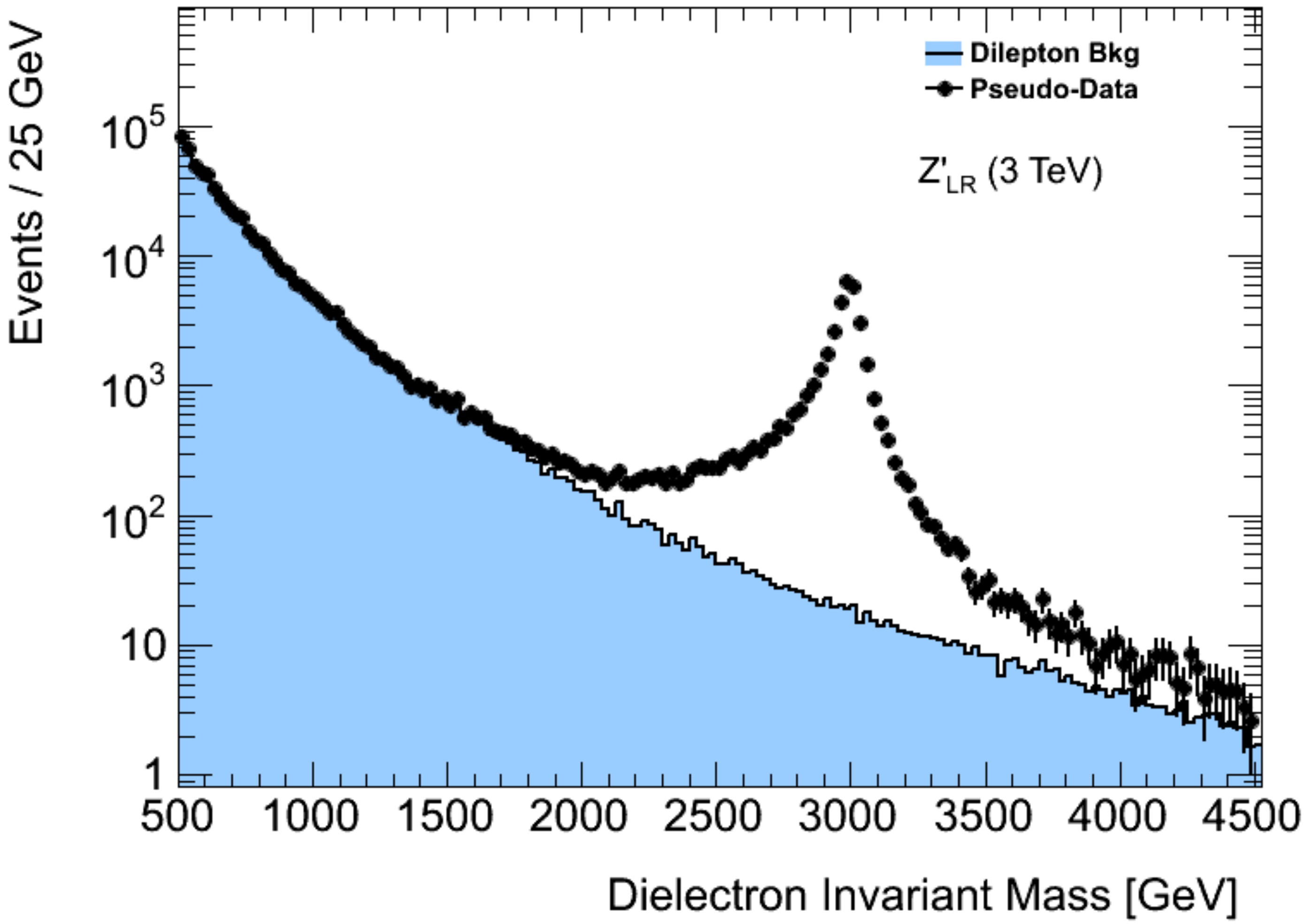
Theory framework
The Standard Model Effective Field Theory

Effective Field Theories for BSM physics

- Effective Field Theories for indirect tests of new physics

What direct searches look for

(e.g *Z'* search in dilepton spectrum)



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'}$$

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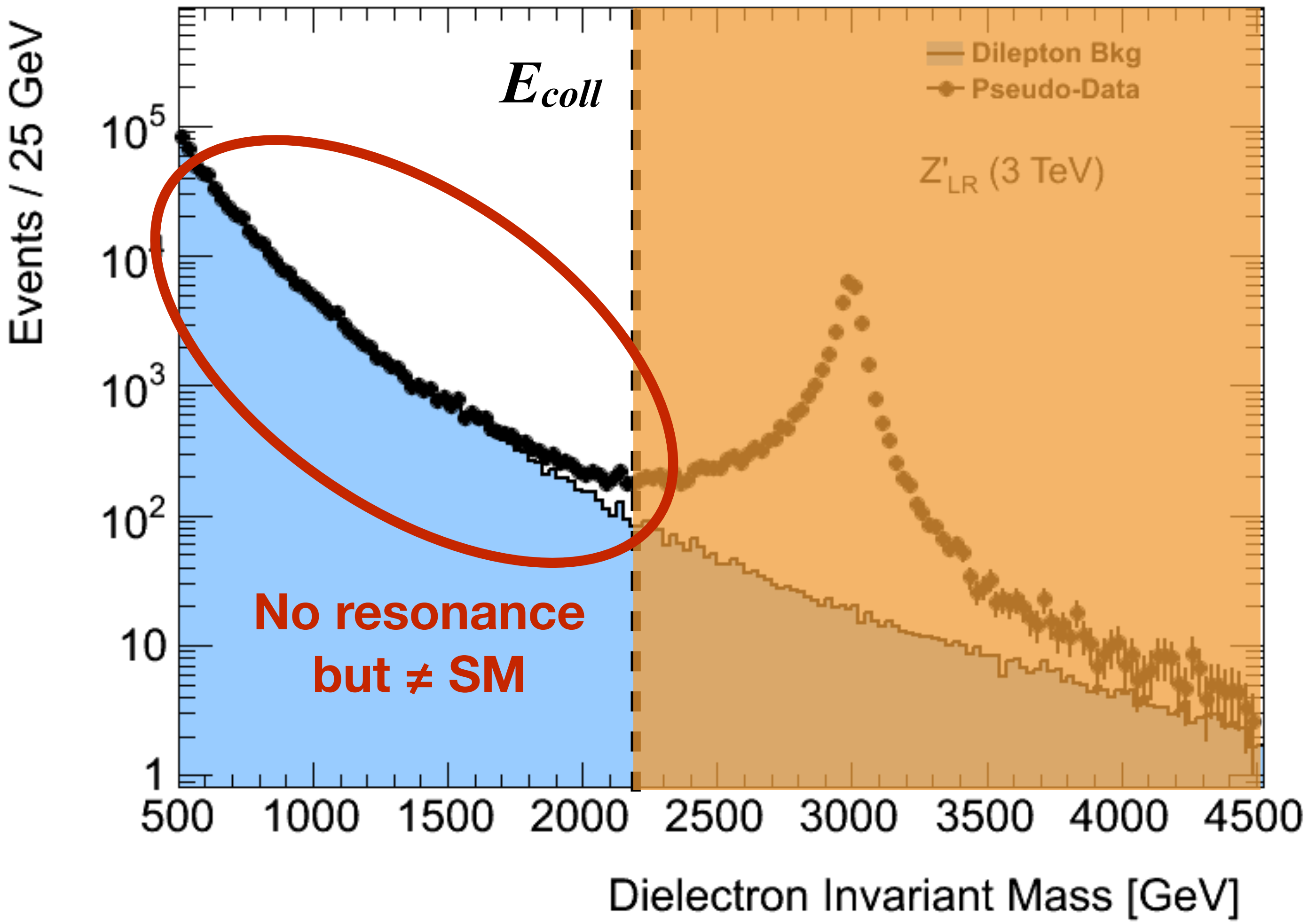
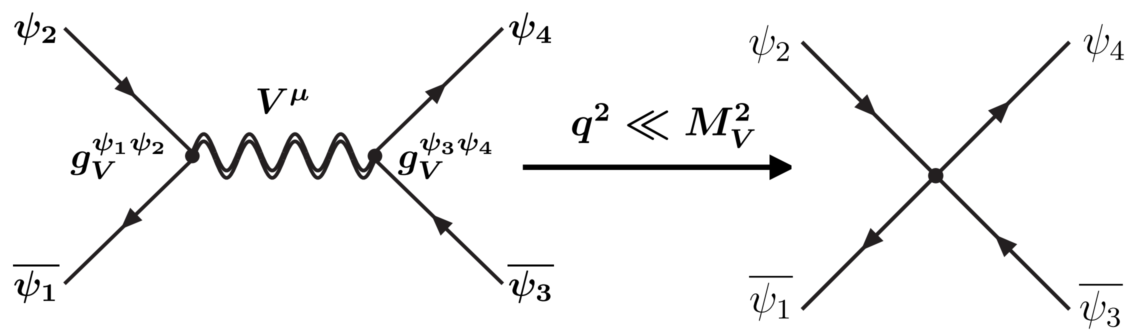


If $E_{coll} < M_{Z'}$ one can still test *virtual effects* of NP looking for “deformations” in SM measurements

For $E_{coll} << M_{Z'}$ these low-energy effects can be well described by effective interactions

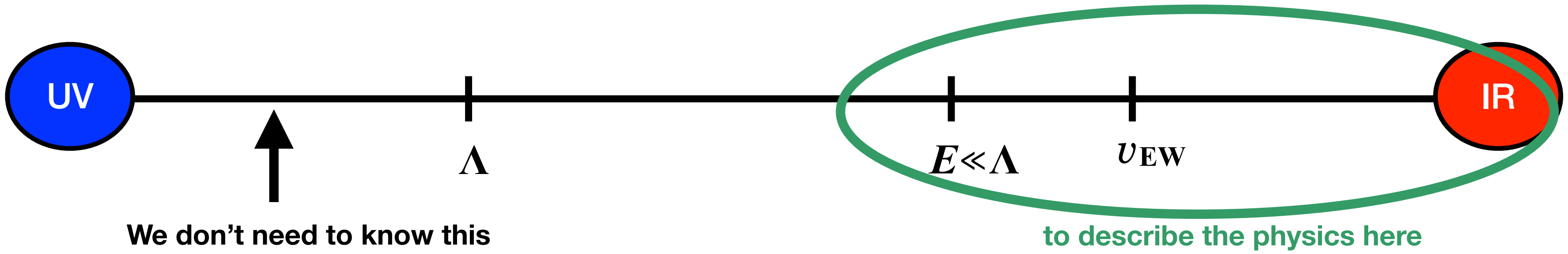


In general, the whole set of such possible deformations can be studied with minimal reference to the nature of the UV theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'} \xrightarrow{q^2 \ll M_V^2} \mathcal{L}_{\rm EFT}$$

Effective Field Theories for BSM physics

- The philosophy of Effective Field Theories:



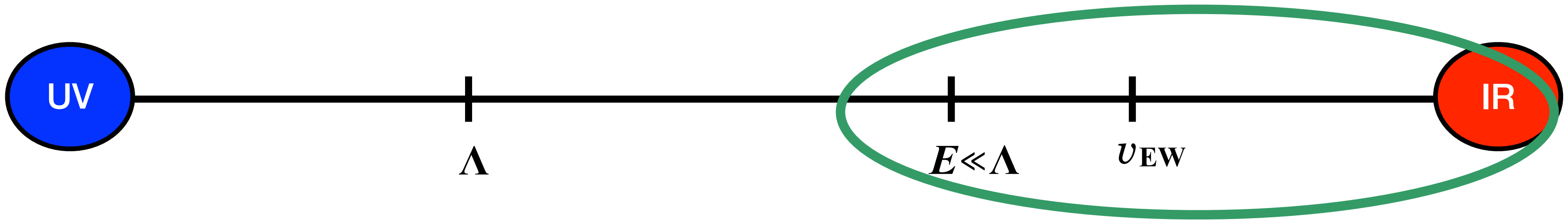
- We are interested in exploring BSM deformations without being "attached" to any particular model (no reason to do so)… What is reasonable to assume?
  - ✓ QFT
  - ✓ At low-energies the particle content seem to match the SM one
    - No new particles with masses ~ v_{EW} showing up in direct searches
      (Though this possibility cannot be completely excluded and much lighter particles also possible)
  - ✓ Similarly, SM gauge invariance seems to work well…
    (With respect to current precision…)
- This (+ a power counting rule) is actually enough to build an Effective Field Theory, which provides a robust theory framework to interpret experimental indirect tests of new physics

The Standard Model Effective Field Theory (SMEFT)

- **SMEFT:** general, theoretically consistent, QFT description of BSM effects for $E \ll \Lambda$ (EFT cutoff) with minimal assumptions:
  - Mass gap with new physics: $\Lambda \gg v$ (justified by absence of new particles in direct searches)

    ⇒ Low-energy particles & symmetries: SM (Higgs in $2 \sim SU(2)_L$)
  - Power counting: Decoupling NP. New effects → 0 as $\Lambda \to \infty$

    ⇒ Expansion of BSM effects in $1/\Lambda$



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

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

Leading Order (LO) Beyond the SM effects (assuming B & L)
⇒ Dim-6 SMEFT: 2499 operators

The dimension-6 SMEFT

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

Warsaw basis operators (Ignoring flavour)

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

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

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$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}$			
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}$			
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}$			
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			$\mathcal{O}_{\phi d}^{(1)}$
			$\mathcal{O}_{eW}$
			$\mathcal{O}_{uW}$
			$\mathcal{O}_{dW}$
			$\mathcal{O}_{dG}$
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$(\phi^\dagger\phi)(\overline{q_L}\tilde{\phi} u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\phi d_R)$	$\mathcal{O}_{d\phi}$
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$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\, \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
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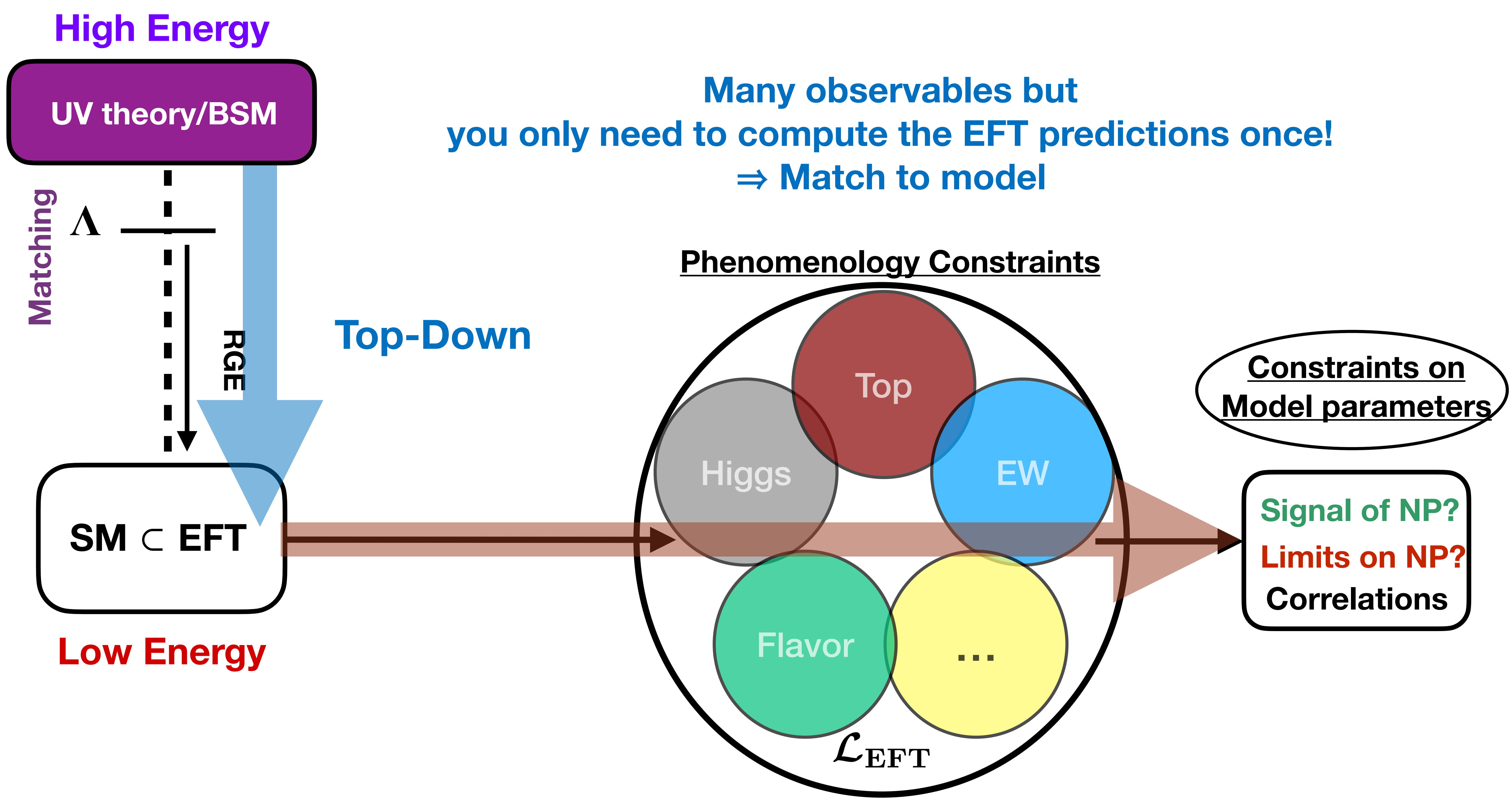
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\, \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_W$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

Fine… But what do we do with all this?…

How do we use EFTs as a tool for indirect searches?

Effective Field Theories for BSM physics

- EFT as a phenomenological tool for BSM studies: **Two approaches**



Effective Field Theories for BSM physics

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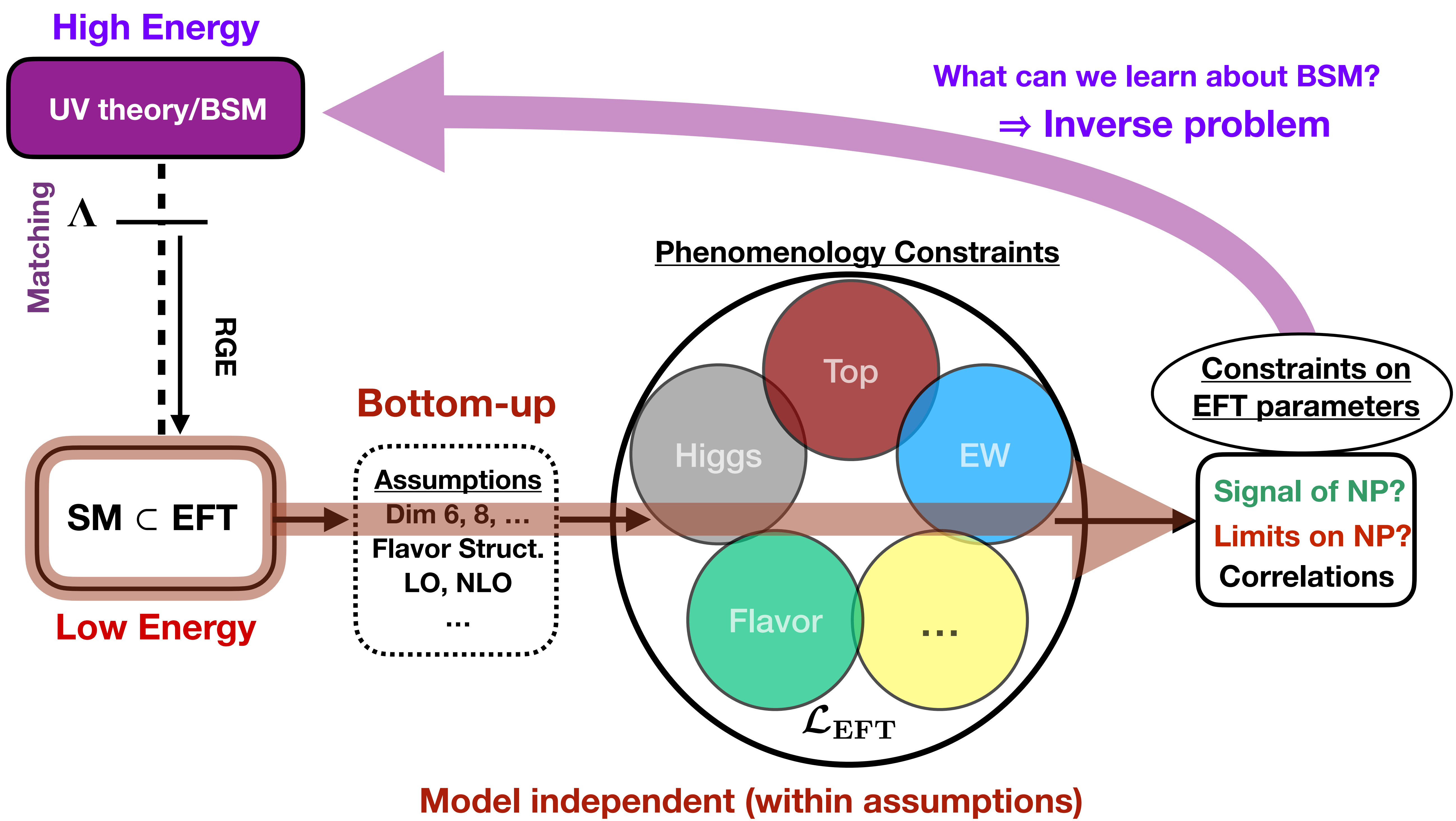

The dimension-6 SMEFT

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

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

CP-even dim 6 ops. interfering with SM

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

The dimension-6 SMEFT

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

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

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

CP-even dim 6 ops. interfering with SM

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We will focus on these sectors

The dimension-6 SMEFT

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$(\bar{l}_L\gamma_\mu l_L)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_L\gamma_\mu\sigma_a l_L)(\bar{q}_L\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\bar{u}_R\gamma_\mu u_R)(\bar{u}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{u}_R\gamma_\mu u_R)(\bar{d}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{l}_L\gamma_\mu l_L)(\bar{e}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{l}_L\gamma_\mu l_L)(\bar{u}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{q}_L\gamma_\mu q_L)(\bar{u}_R\gamma^\mu$ [illegible]	[illegible]	[illegible]	[illegible]
$(\bar{q}_L\gamma_\mu q_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_L\gamma_\mu T_A q_L)(\bar{d}_R\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\bar{l}_L e_R)(\bar{d}_R q_L)$	$\mathcal{O}_{ledq}$		
$(\bar{q}_L u_R)\, i\sigma_2\, (\bar{q}_L d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\bar{q}_L T_A u_R)\, i\sigma_2\, (\bar{q}_L T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\bar{l}_L e_R)\, i\sigma_2\, (\bar{q}_L u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\bar{l}_L u_R)\, i\sigma_2\, (\bar{q}_L e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{l}_L\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{l}_L\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}_L\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
[illegible]	[illegible]	[illegible] $(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
[illegible]	[illegible]	[illegible] $\sigma^a\phi W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
[illegible]	[illegible]	[illegible] $\sigma^a\phi W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
[illegible]	[illegible]	[illegible] $\sigma^a\phi W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
[illegible]	[illegible]	[illegible] $d_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\bar{q}_L\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\bar{q}_L\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$	$\phi^\dagger\phi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\,\widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\sigma_a\phi\,\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\sigma_a\phi\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\phi\,\widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$		
$\varepsilon_{abc}\, W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\,\widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{G}$	$f_{ABC}\,\widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

Only a relatively small subset is relevant for the description of EW and Higgs measurements

~*O*(20-30) operators depending on flavour assumptions

CP-even dim 6 ops. interfering with SM

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

We will focus on these sectors

The dimension-6 SMEFT

- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

Higgs parameterisation: LHCHXSWG-INT-2015-001

HVV

$$\Delta\mathscr{L}_6^{\rm hVV} = \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}$$
$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu}\Big]$$

$$\begin{aligned}
\delta c_w &= \delta c_z + 4\delta m,\\
c_{ww} &= c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},\\
c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\sin^2\theta_w c_{\gamma\gamma} - (g^2-g'^2)\sin^2\theta_w c_{z\gamma}\right]\\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)c_{zz} - e^2 c_{\gamma\gamma} - (g^2-g'^2)c_{z\gamma}\right],
\end{aligned}$$

aTGC

$$\Delta\mathscr{L}^{\rm aTGC} = ie\delta\kappa_\gamma A^{\mu\nu}W_\mu^+W_\nu^- + ig\cos\theta_w\left[\delta g_{1Z}(W_{\mu\nu}^+W^{-\mu} - W_{\mu\nu}^-W^{+\mu})Z^\nu + (\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma)Z^{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+\frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu}W_\nu^{-\rho}A_\rho^\mu + \cos\theta_w W_\mu^{+\nu}W_\nu^{-\rho}Z_\rho^\mu\right),$$

Hff

$$\Delta\mathscr{L}_6^{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\hat{\delta}y_f m_f \bar{f}f + \text{h.c.}$$

Vff & HVff

$$\Delta\mathscr{L}_6^{vff,hvff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left(\hat{\delta}g_L^{W\ell}\bar{\nu}\bar{\gamma}_\mu e + \hat{\delta}g_L^{Wq}\bar{u}\gamma_\mu d + \hat{\delta}g_R^{Wq}\bar{u}\gamma_\mu d + \text{h.c.}\right)$$
$$+ \sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\delta}g_L^{Zf}\bar{f}\gamma_\mu f + \sum_{f=u,d,e}\hat{\delta}g_R^{Zf}\bar{f}\gamma_\mu f\right]$$

The dimension-6 SMEFT

- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

Higgs parameterisation: LHCHXSWG-INT-2015-001

HVV

$$\Delta\mathcal{L}_6^{\rm hVV} = \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}$$
$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu}\Big]$$

Richer structure of hVV interactions than SM

$$\begin{aligned}
\delta c_w &= \delta c_z + 4\delta m,\\
c_{ww} &= c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},\\
c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\sin^2\theta_w c_{\gamma\gamma} - (g^2-g'^2)\sin^2\theta_w c_{z\gamma}\right]\\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)c_{zz} - e^2 c_{\gamma\gamma} - (g^2-g'^2)c_{z\gamma}\right],
\end{aligned}$$

aTGC

$$\Delta\mathcal{L}^{\rm aTGC} = ie\delta\kappa_\gamma A^{\mu\nu}W_\mu^+W_\nu^- + ig\cos\theta_w\left[\delta g_{1Z}\left(W_{\mu\nu}^+W^{-\mu} - W_{\mu\nu}^-W^{+\mu}\right)Z^\nu + \left(\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma\right)Z^{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+\frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu}W_\nu^{-\rho}A_\rho^\mu + \cos\theta_w W_\mu^{+\nu}W_\nu^{-\rho}Z_\rho^\mu\right),$$

Hff

$$\Delta\mathcal{L}_6^{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e}\hat{\delta}y_f m_f \bar{f}f + \text{h.c.}$$

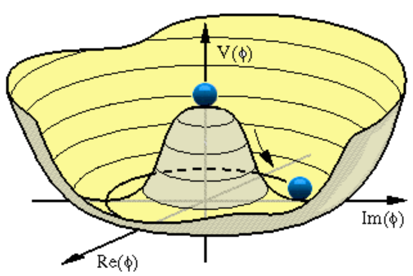
Vff & HVff

$$\Delta\mathcal{L}_6^{vff,hvff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left(\hat{\delta}g_L^{W\ell}\bar{\nu}\gamma_\mu e + \hat{\delta}g_L^{Wq}\bar{u}\gamma_\mu d + \hat{\delta}g_R^{Wq}\bar{u}\gamma_\mu d + \text{h.c.}\right)$$
$$+\sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\delta}g_L^{Zf}\bar{f}\gamma_\mu f + \sum_{f=u,d,e}\hat{\delta}g_R^{Zf}\bar{f}\gamma_\mu f\right]$$

$hVff$ contact interactions (not in SM)

The dimension-6 SMEFT

- **SMEFT:** Keeps tracks of correlations imposed by gauge invariance and linearly realised EW symmetry



"Linear" EW symm.

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

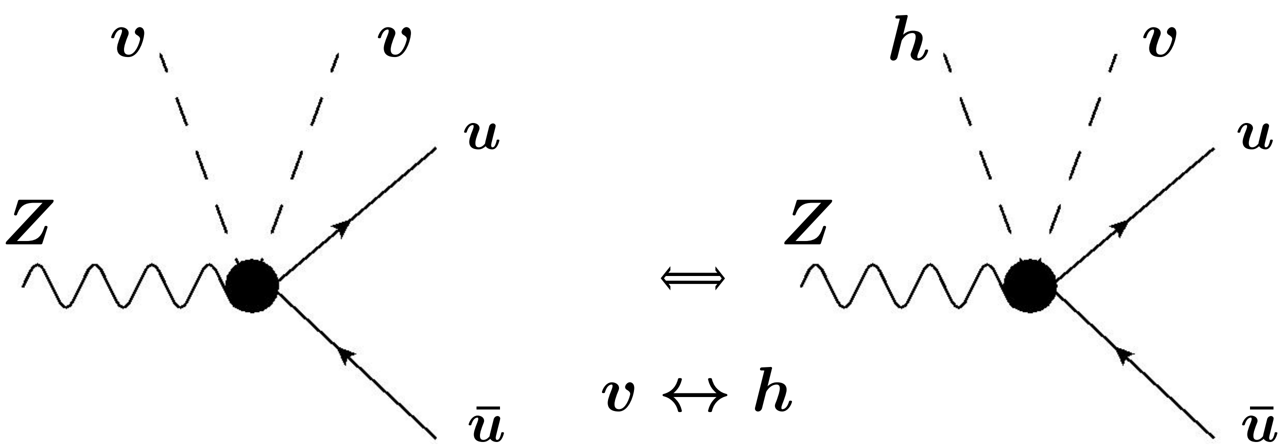
SM gauge invariance

$$D_\mu = \partial_\mu + i g A_\mu$$

$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{u}^i_R \gamma^\mu u^i_R)$

$Z\bar{u}u$

Vff



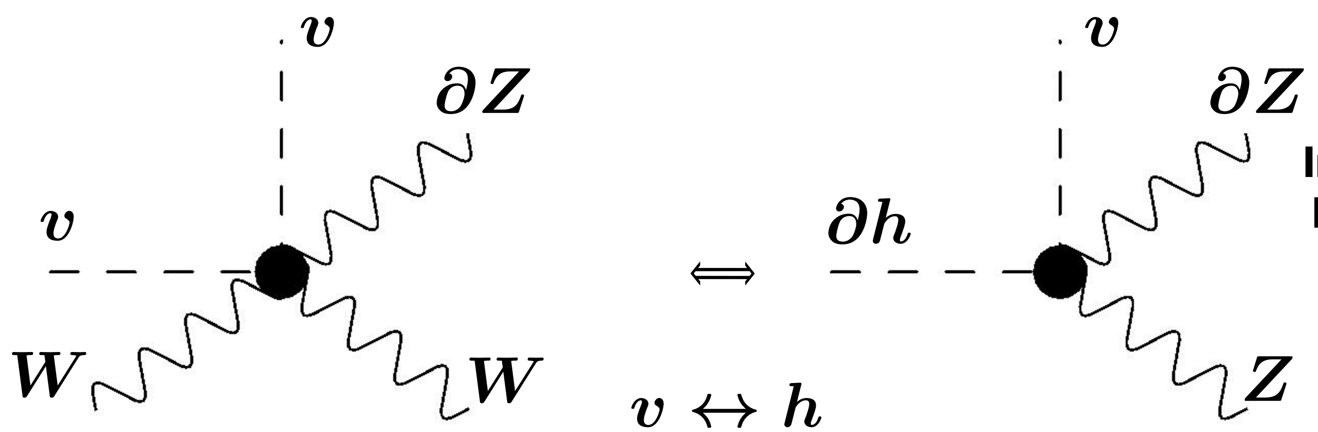
$hZ\bar{u}u$

hVff

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

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

aTGC



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

Integrate by parts →

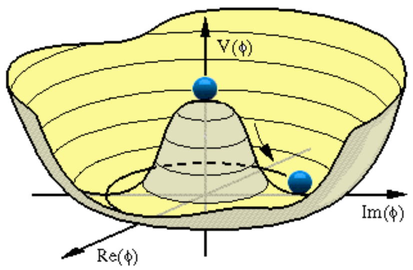
$hZ_\mu \partial_\nu Z^{\mu\nu}$

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

HVV

The dimension-6 SMEFT

- **SMEFT:** Keeps tracks of correlations imposed by gauge invariance and linearly realised EW symmetry



"Linear" EW symm.

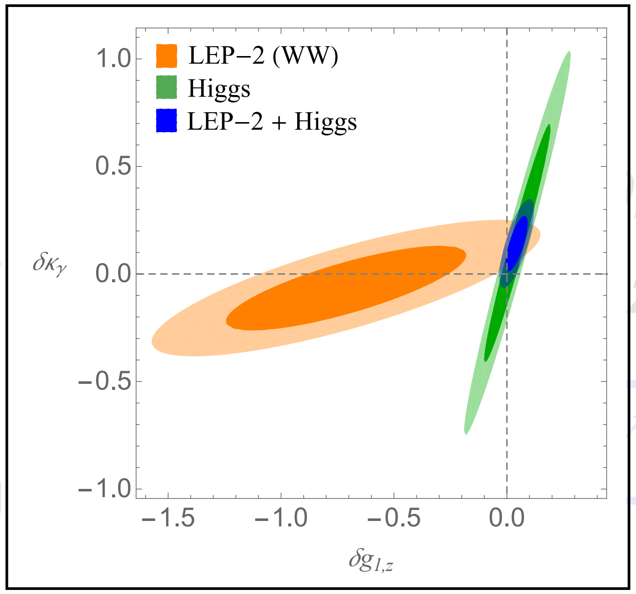
$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

SM gauge invariance

$$D_\mu = \partial_\mu + i g A_\mu$$

Use EWPO (Z-pole) to constrain $hZff$ interactions (Higgs)

Use di-Boson (aTGC) to constrain hVV interactions (Higgs) (or viceversa)



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

The dimension-6 SMEFT

- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

Higgs parameterisation: LHCHXSWG-INT-2015-001

HVV

$$\Delta\mathcal{L}_6^{\text{hVV}} = \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{w\Box} g^2 (W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}) + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}$$
$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu}\Big]$$

$$\delta c_w = \delta c_z + 4\delta m,$$
$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},$$
$$c_{w\Box} = \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2 \sin \ldots\right.$$
$$c_{\gamma\Box} = \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2) c_{zz} \ldots\right.$$

Richer structure than SM

13 independent d.o.f. (not counting flavor)

Connected to other par via SMEFT corr.

aTGC

$$\Delta\mathcal{L}^{\text{aTGC}} = ie\delta\kappa_\gamma A^{\mu\nu}W_\mu^+ W_\nu^- + ig\cos\theta_w\left[\delta g_{1Z}(W_{\mu\nu}^+ W^{-\mu} - W_{\mu\nu}^- W^{+\mu})Z^\nu + \left(\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma\right)Z^{\mu\nu}W_\mu^+ W_\nu^-\right]$$
$$+ \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu}W_\nu^{-\rho}A_\rho^\mu + \cos\theta_w W_\mu^{+\nu}W_\nu^{-\rho}Z_\rho^\mu\right),$$

Only λ_z is independent

δg_{1Z} and $\delta\kappa_\gamma$ related to ***HVV*** couplings

Hff

$$\Delta\mathcal{L}_6^{\text{hff}} = -\frac{h}{v}\sum_{f\in u,d,e}\hat{\delta}y_f\, m_f \bar{f} f + \text{h.c.}$$

Vff & HVff

$$\Delta\mathcal{L}_6^{vff,hvff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left(\hat{\delta}g_L^{W\ell}\bar{\nu}\gamma_\mu e + \hat{\delta}g_L^{Wq}\bar{u}\gamma_\mu d + \hat{\delta}g_R^{Wq}\bar{u}\gamma_\mu d + \text{h.c.}\right)$$
$$+ \sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\delta}g_L^{Zf}\bar{f}\gamma_\mu f + \sum_{f=u,d,e}\hat{\delta}g_R^{Zf}\bar{f}\gamma_\mu f\right]$$

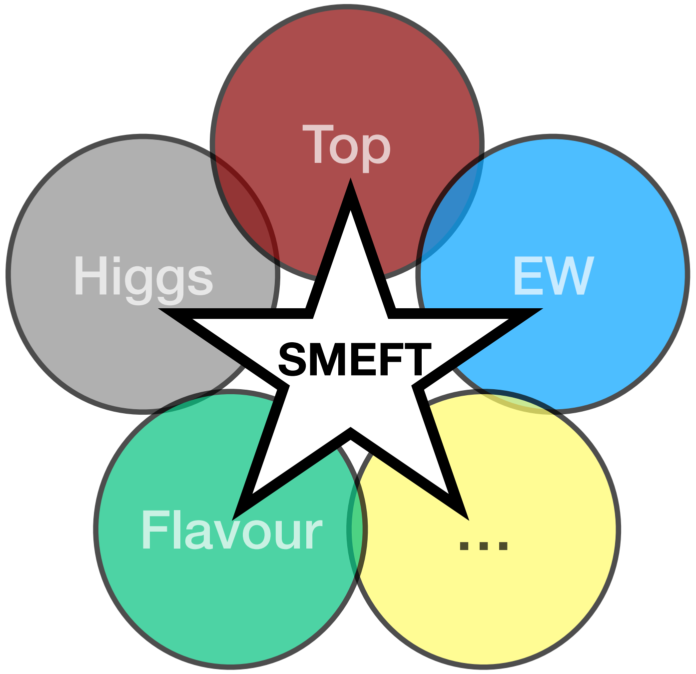
The dimension-6 SMEFT

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

$$O = O_{\mathrm{SM}} + \sum_i a_i \frac{C_i}{\Lambda^2}$$

"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

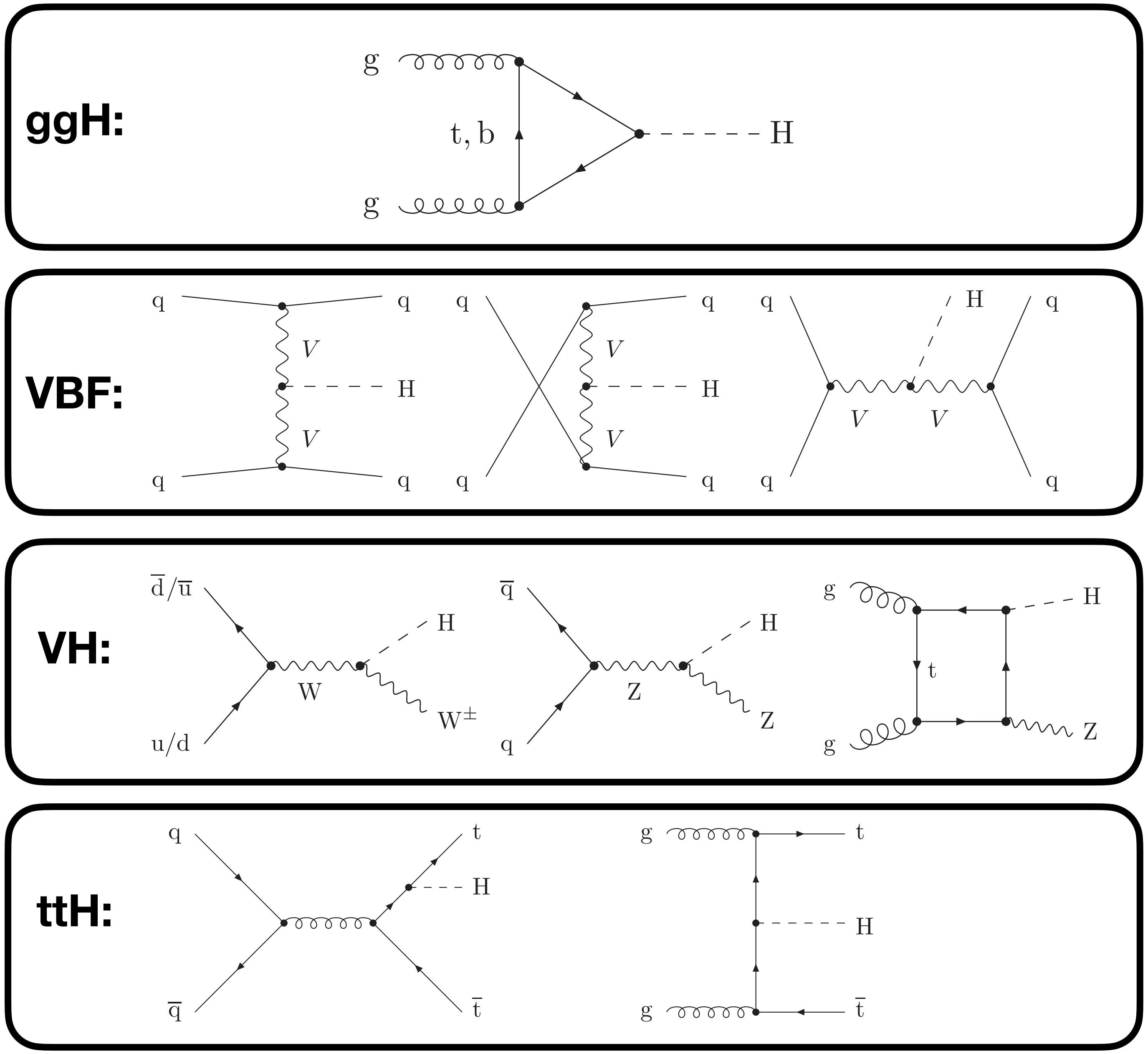
- In what follows I describe the inputs and the results of the global SMEFT studies performed for the 2020 European Strategy Update & Snowmass 2021

Precision Measurements at Future Colliders

Higgs physics

Higgs physics at the HL-LHC

- Higgs physics at the LHC

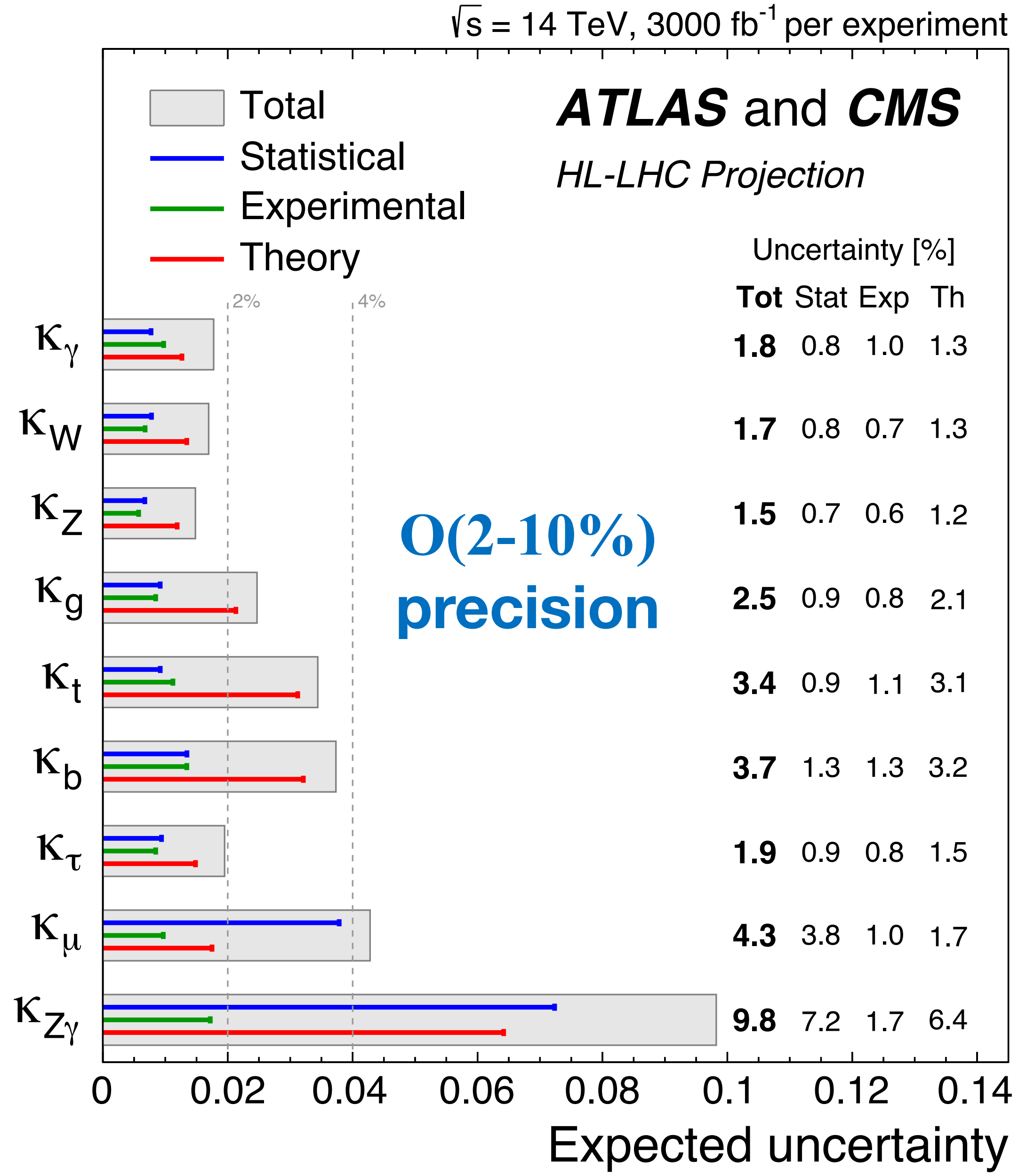


Run 2: ~8×10⁶ Higgses collected

HL-LHC: 15×10⁶ Higgses/year

Higgs couplings in "κ framework": From on-shell measurements

$$\mu_i^f \equiv \frac{\sigma . BR}{\sigma_{SM} . BR_{SM}} = \frac{\kappa_i^2 . \kappa_f^2}{\kappa_H^2} \qquad (\sigma . BR)(i \to H \to f) = \frac{\sigma_i . \Gamma_f}{\Gamma_H}$$

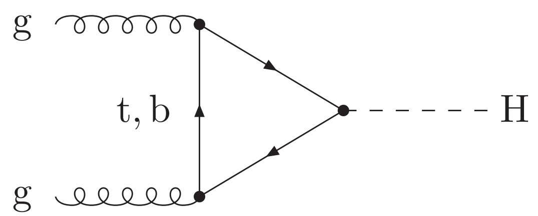


Higgs mass: expected ΔM_H~10-20 MeV

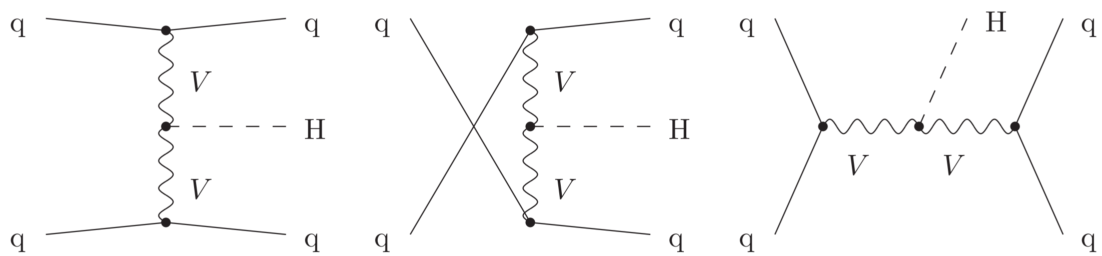
Higgs physics at the HL-LHC

- Higgs physics at the LHC

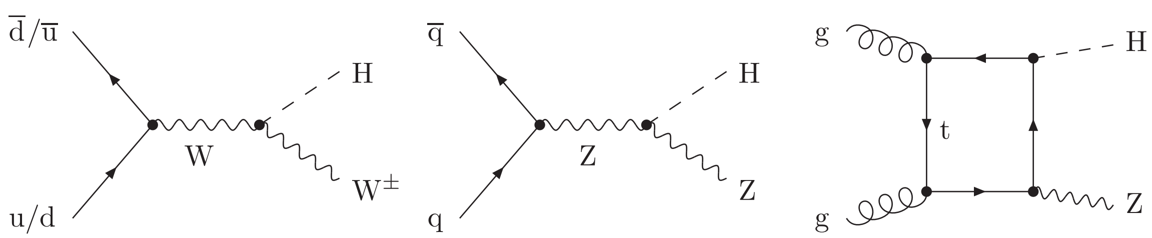
ggH:



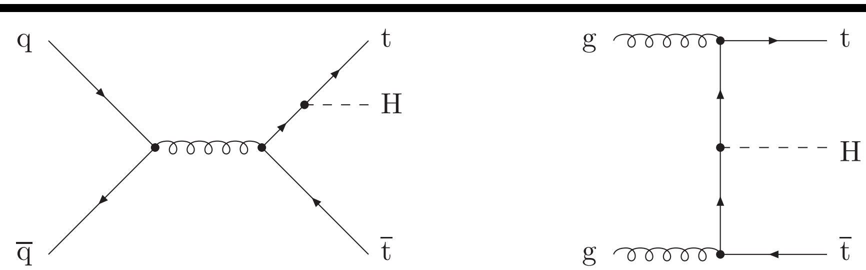
VBF:



VH:



ttH:



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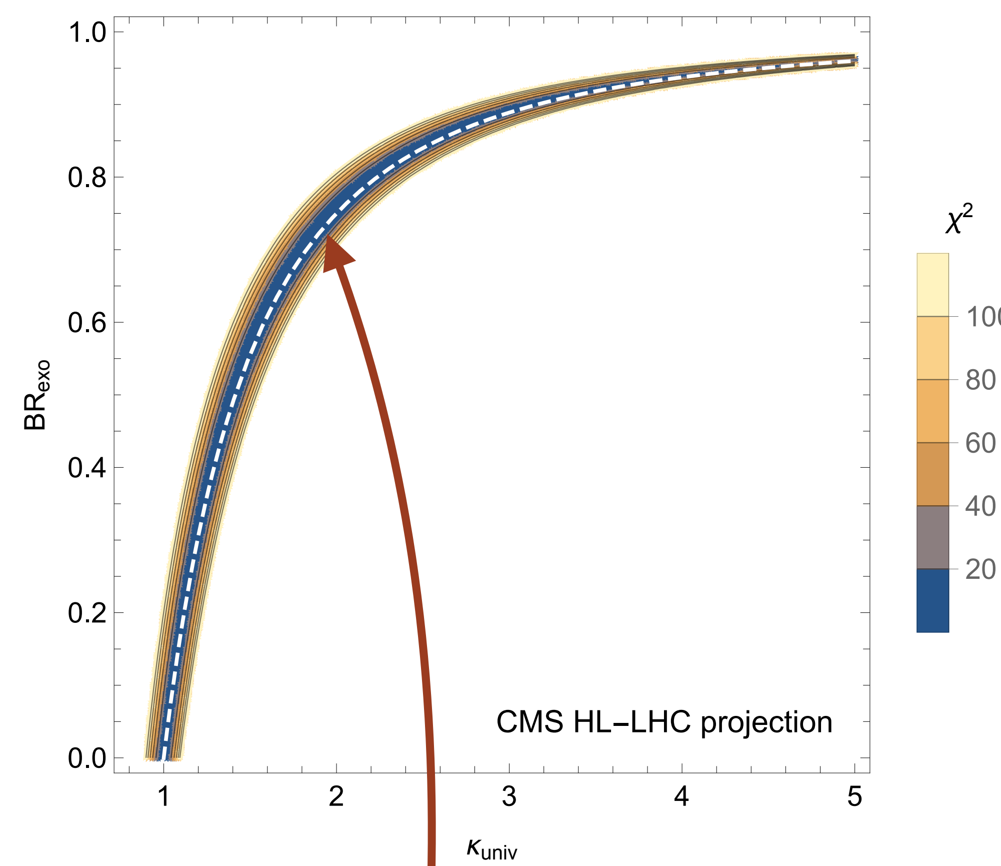
$$\mu_i^f \equiv \frac{\sigma . BR}{\sigma_{SM} . BR_{SM}} = \frac{\kappa_i^2 . \kappa_f^2}{\kappa_H^2} \qquad (\sigma . BR)(i \to H \to f) = \frac{\sigma_i . \Gamma_f}{\Gamma_H}$$

However, these only allow to measure "ratios of couplings"

Flat direction in κ fit if new d.o.f. contribute to Γ_H

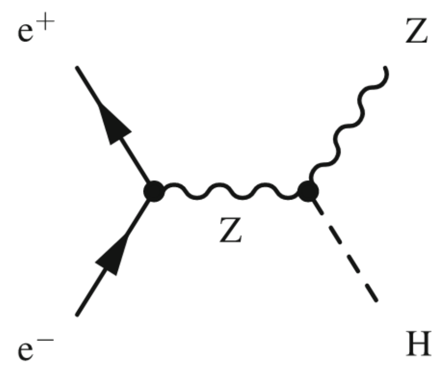


$$\mathrm{BR}_{\mathrm{exo}} = (\kappa_{\mathrm{univ}}^2 - 1)/\kappa_{\mathrm{univ}}^2$$

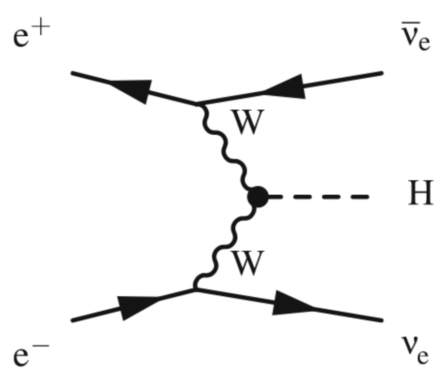
Higgs physics at e⁺e⁻ Higgs factories

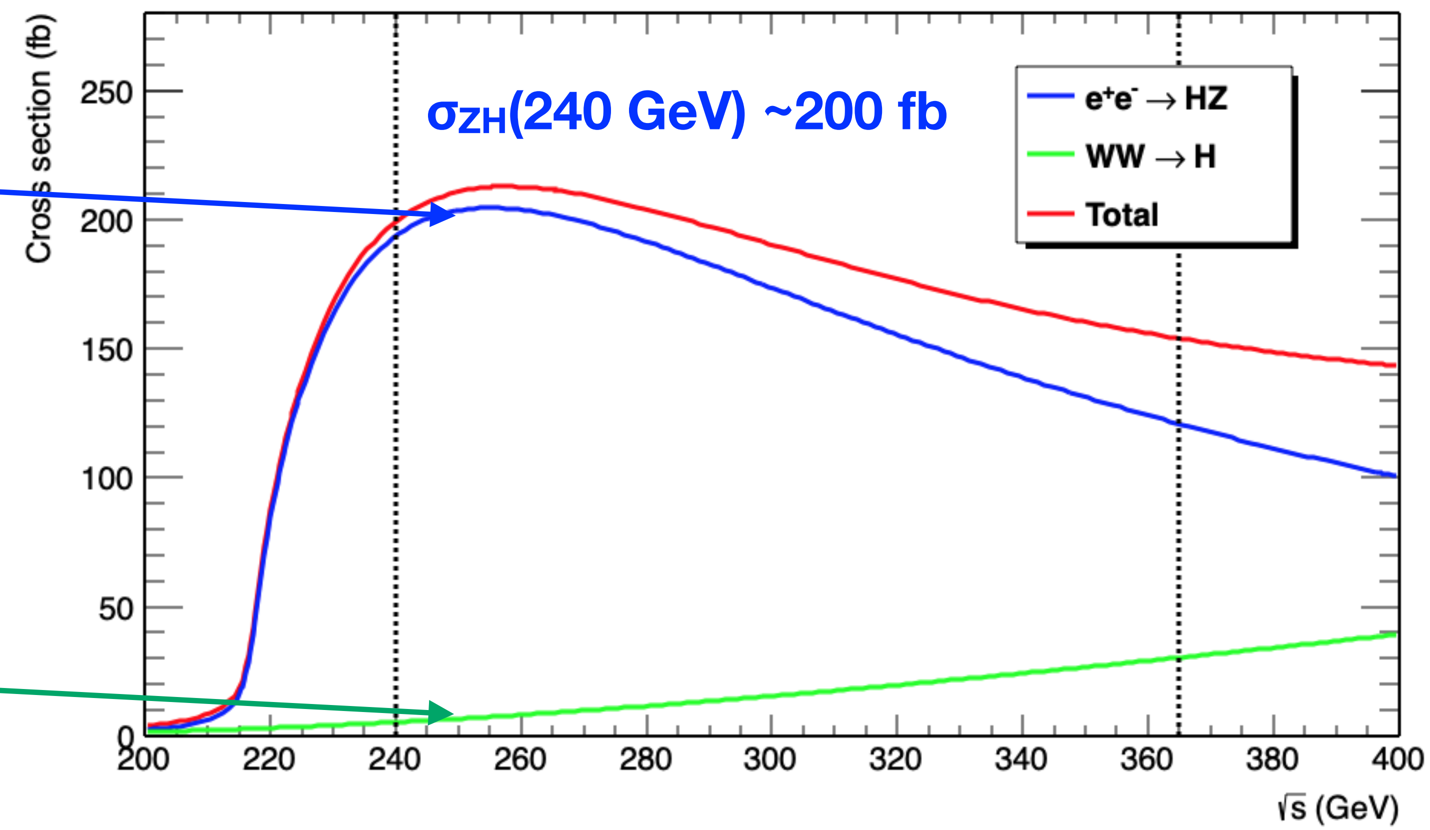
- Higgs physics at the e^+e^- colliders

ZH:



WWH:





Some example numbers (FCCee):

Statistics (2IPs):

10^6 (ZH) Higgses

~10^5 (WWH) Higgses

But in a clean environment:

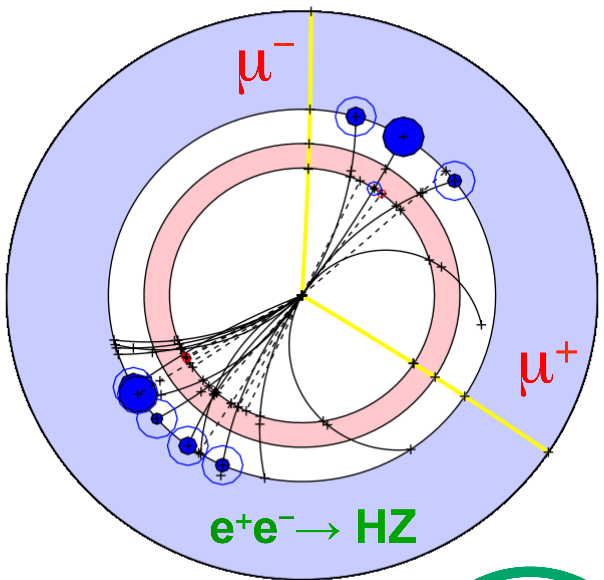
- **-No pileup**
- **-Beam background under control**
- **-E, p constraints**

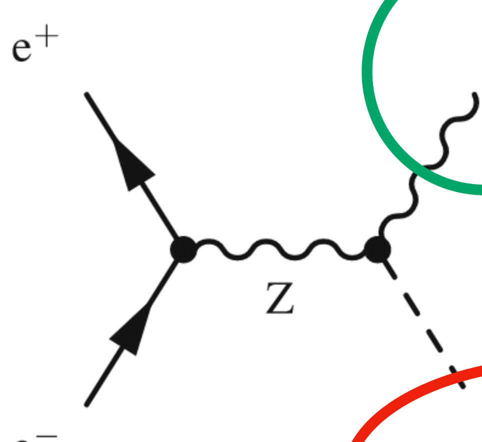
4 IPs: 1.7x Stats using same running time

Higgs physics at e⁺e⁻ Higgs factories

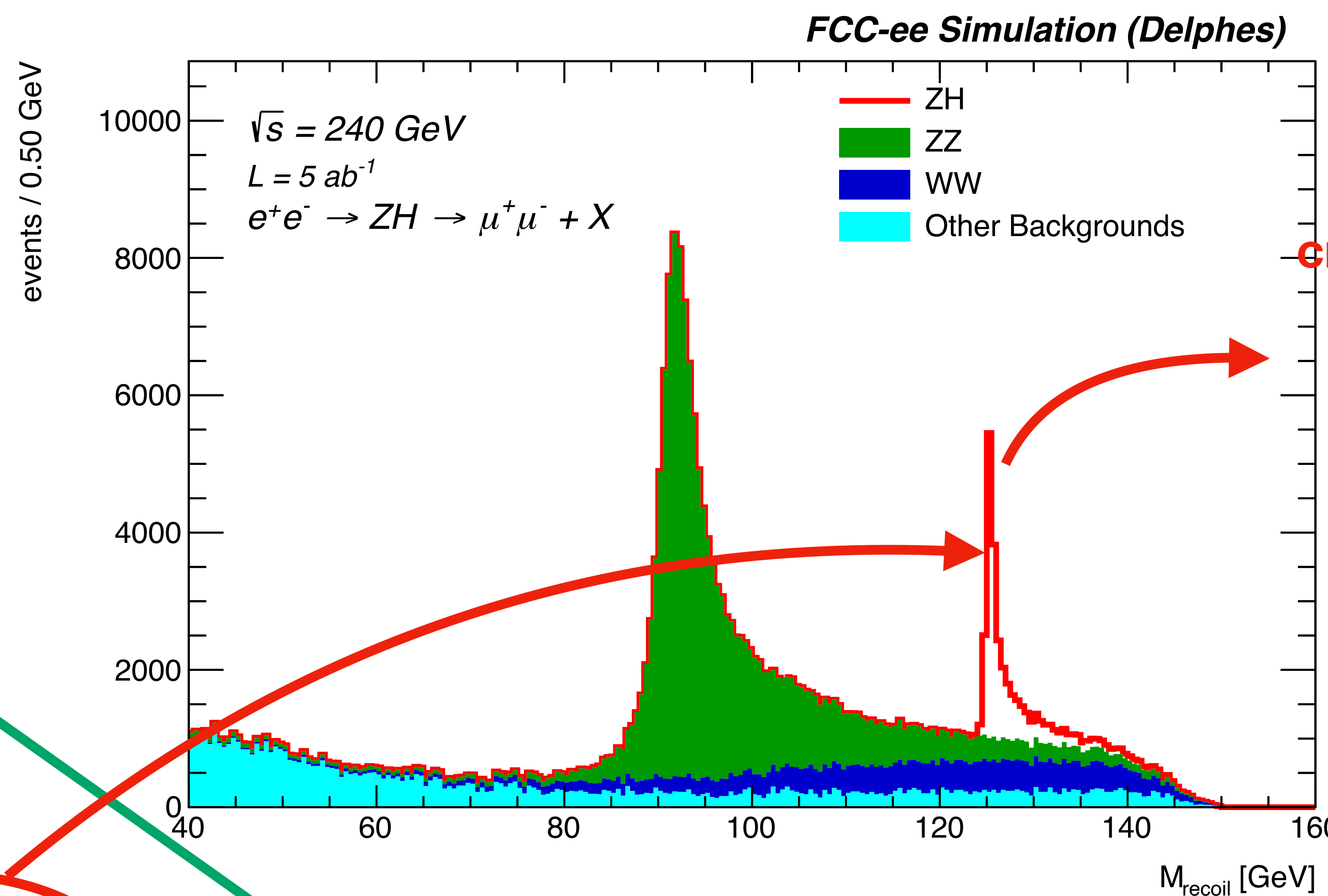
- Higgs physics at the e^+e^- colliders: Recoil mass measurement

Tag the Higgs from ZH looking at the Z in, e.g., $Z\to\mu^+\mu^-$





$$M^2_{\text{Recoil}} = M^2_H$$



Inclusive $e^+e^-\to ZH$ cross section

σ_{ZH}

$$M^2_{\text{Recoil}} = s + M^2_Z - 2E_Z\sqrt{2}$$

Measurement of σ_{ZH} ⇒ Absolute measurement of HZZ interactions (not ratios)

Precise Higgs mass determination: $\Delta M_H \sim O(\text{MeV})$

Higgs physics at e⁺e⁻ Higgs factories

- Higgs physics at the e⁺e⁻ colliders: Recoil mass measurement

Tag the Higgs from ZH looking at the Z in, e.g., $Z\to\mu^+\mu^-$

Measurement of σ_{ZH} + Rates ⇒ Determination of H couplings & width

From same 240 GeV run → $\sigma_{ZH}\mathrm{BR}_{ZZ} \propto \frac{g_{HZZ}^4}{\Gamma_H}$

From 365 GeV run → $\frac{\sigma_{WW\to H}\mathrm{BR}_{bb}}{\sigma_{ZH}\mathrm{BR}_{bb}\times\sigma_{ZH}\mathrm{BR}_{WW}} \propto \frac{g_{HZZ}^4}{\Gamma_H}$

→ Γ_H

$\sigma_{ZH} \propto g_{HZZ}^2$

→ g_{HXX}

$\sigma_{ZH}\mathrm{BR}_{XX} \propto g_{HZZ}^2 \frac{g_{HXX}^2}{\Gamma_H}$

sive
ZH
ection

Measurement of σ_{ZH} ⇒ Absolute measurement of HZZ interactions (not ratios)

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Higgs physics at e⁺e⁻ Higgs factories

- Higgs physics at the e^+e^- colliders: What do ~10^6 Higgses bring to the table?

E.g. FCCee Higgs precision (2IPs)

$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	$5\,\mathrm{ab}^{-1}$ (3 yrs)		$1.5\,\mathrm{ab}^{-1}$ (4 yrs)	
Channel	ZH	$\nu_e\bar{\nu}_e$ H	ZH	$\nu_e\bar{\nu}_e$ H
$H \to$ any	± 0.5		± 0.9	
$H \to b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \to c\bar{c}$	± 2.2		± 6.5	± 10
$H \to gg$	± 1.9		± 3.5	± 4.5
$H \to W^+W^-$	± 1.2		± 2.6	± 3.0
$H \to ZZ$	± 4.4		± 12	± 10
$H \to \tau^+\tau^-$	± 0.9		± 1.8	± 8
$H \to \gamma\gamma$	± 9.0		± 18	± 22
$H \to \mu^+\mu^-$	± 19		± 40	
$H \to$ invisible	< 0.3		< 0.6	

($H \to Z\gamma$ $\pm 17^*$ ← **Ongoing study. Extrapolated from CEPC precision**)

Statistical uncertainties:

Experimental systematics not expected to be a limiting factor for Higgs measurements

Higgs physics at e^+e^- Higgs factories

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($H \to Z\gamma$ $\pm 17^*$ ← **Ongoing study. Extrapolated from CEPC precision**)

0.5% precision in σ_{ZH}

SM: 1-loop EW corrections ~3%

Tests of quantum corrections in the Higgs sector

Statistical uncertainties:

Experimental systematics not expected to be a limiting factor for Higgs measurements

Precision Measurements at Future Colliders

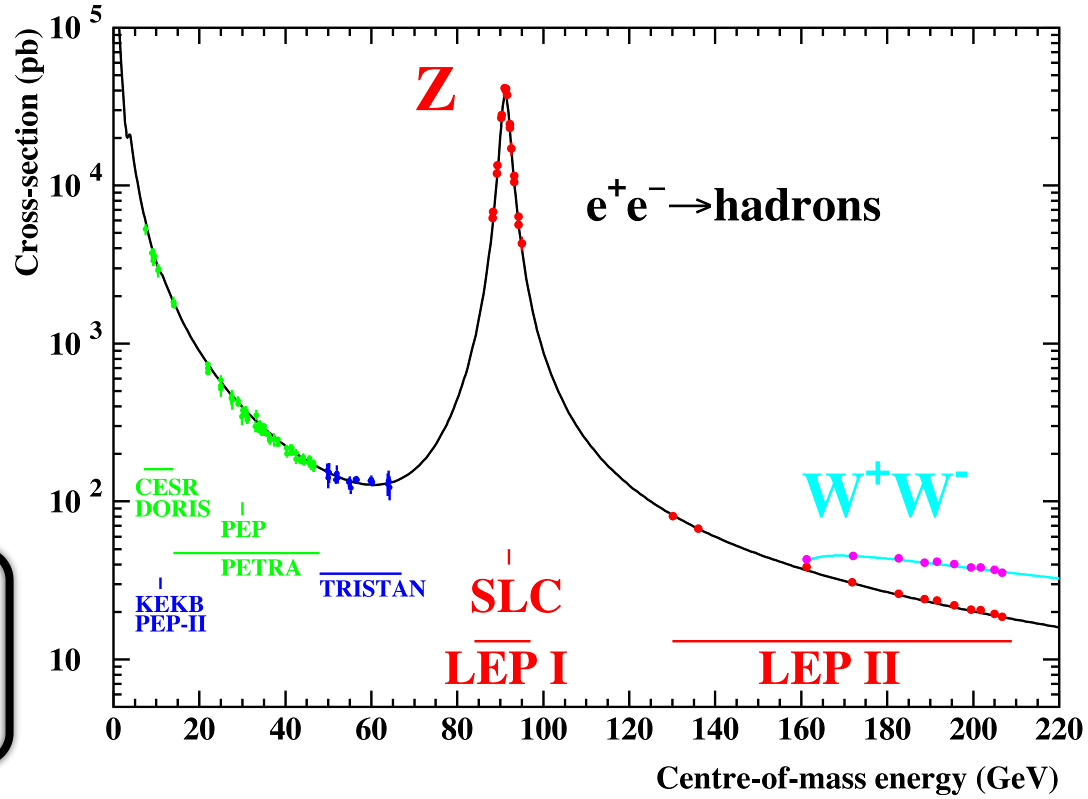
Electroweak physics

EW physics at e⁺e⁻ Higgs factories

- Future e+ e- factories will also help us improve our knowledge of the EW interactions:
  - Improved Z pole run:
    - LEP/SLC: ~10^7 Z → O(0.1-1%)
    - FCCee/CEPC: 10^{12} Z
    - ILC (GigaZ): 10^9 Z

Z-pole EWPO:

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$



- Significantly lower stats at linear colliders but can benefit from use of polarization ⇒ Extra observables wrt unpolarized case. E.g. asymmetries

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} \rightarrow$$

Polarized beams

Unpolarized beams

$$A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\frac{1}{\langle |P_e| \rangle} = A_e$$

$$A^f_{LR,FB} = \frac{3}{4} A_f$$

EW physics at e^+e^- Higgs factories

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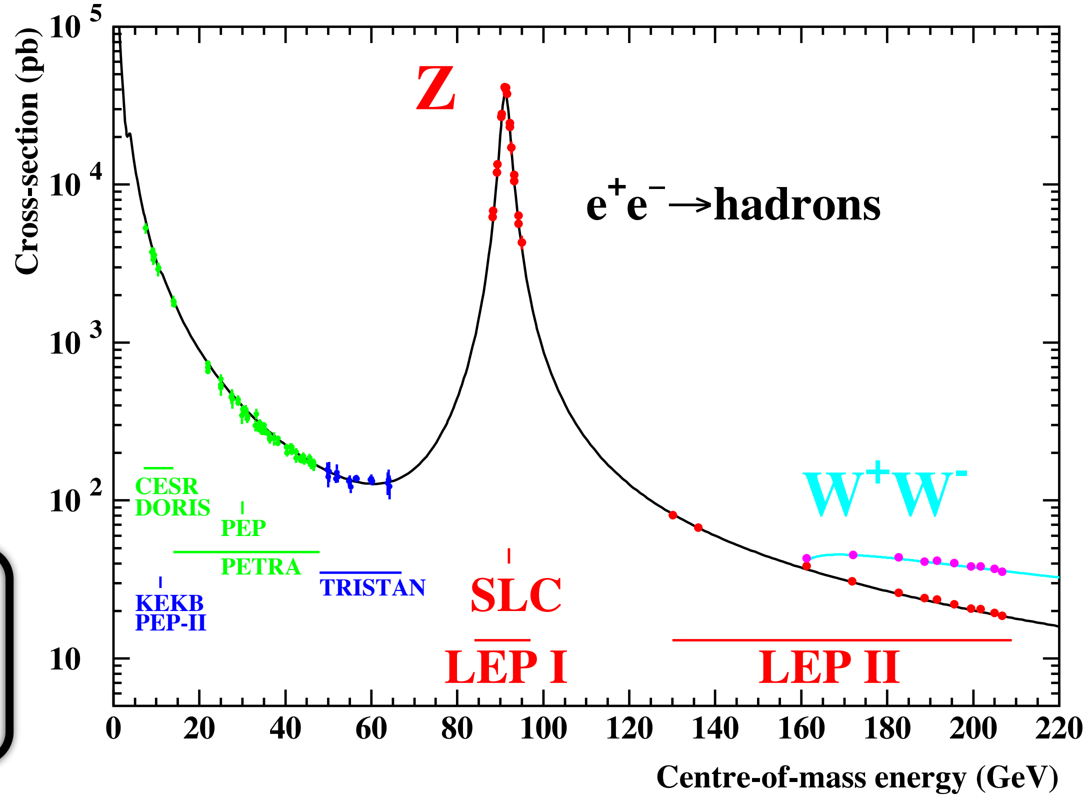
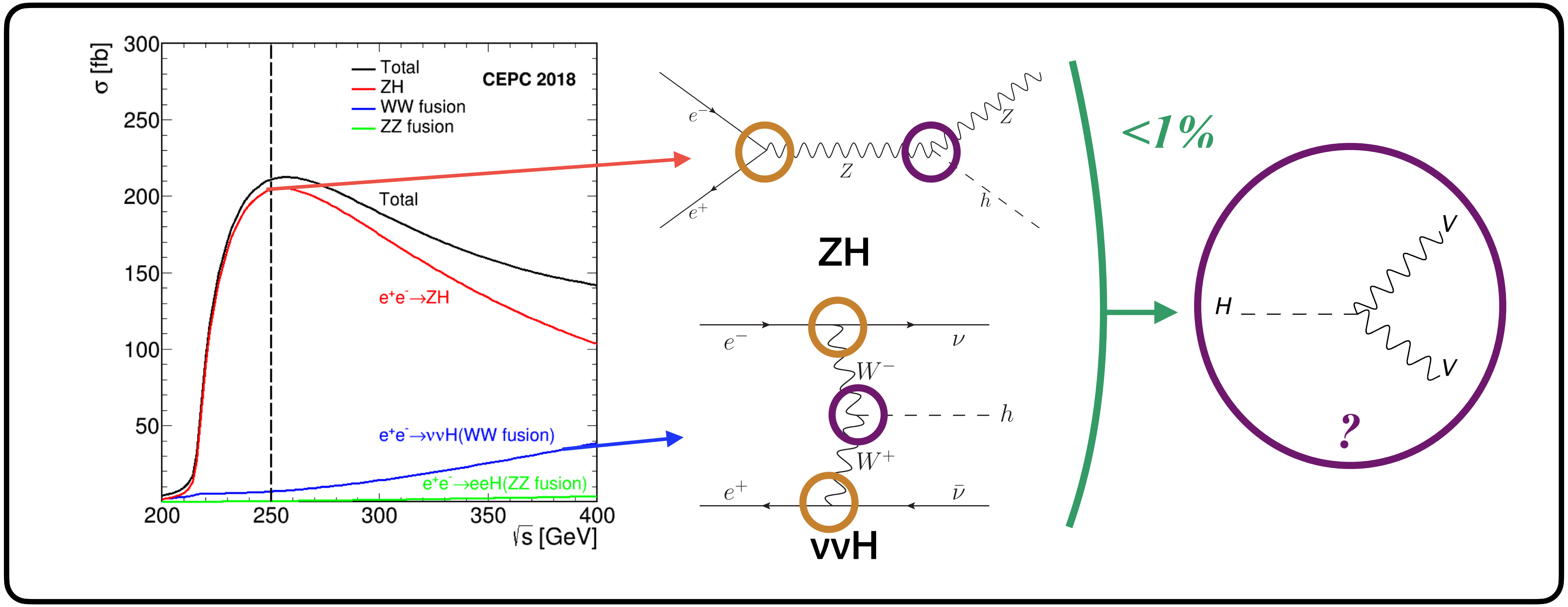


  - Significantly lower stats at linear colliders but can benefit from use of polarization ⇒ Extra observables wrt unpolarized case. E.g. asymmetries
  - Furthermore, all Higgs factories can perform "Z-pole" EW measurements using radiative return to the Z from 240/250 GeV
- Projected precision for EWPO: improvement in some cases of more than 1 order of magnitude

EW physics at e^+e^- Higgs factories

- EW measurements also important for Higgs interpretation at "low-energy" e^+e^- Higgs factories:



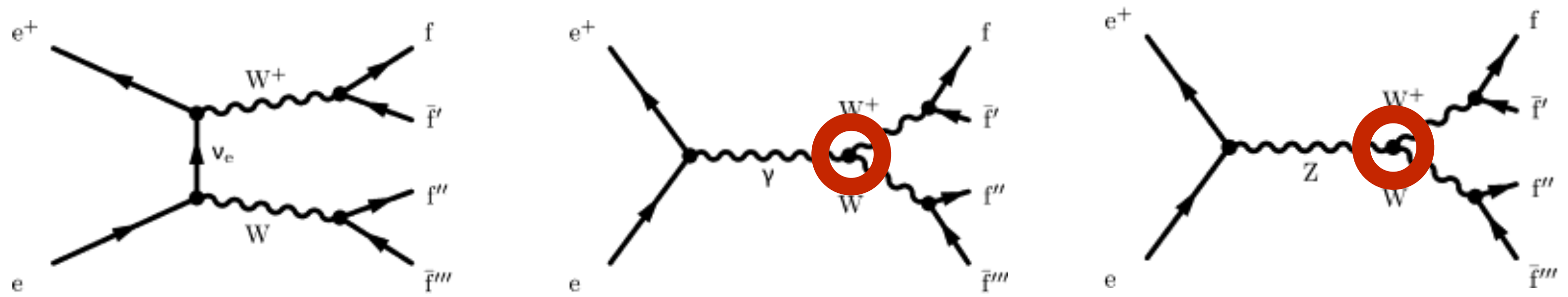
- With the precision of **Higgs measurements** expected to be close to per mille level in several cases, we need our knowledge of the **EW interactions** to be precise enough to neglect EW uncertainties in the extraction of **Higgs properties**. (Is LEP/SLD enough?)

EW physics at e⁺e⁻ Higgs factories

- Also important is to measure the properties of the W bosons:

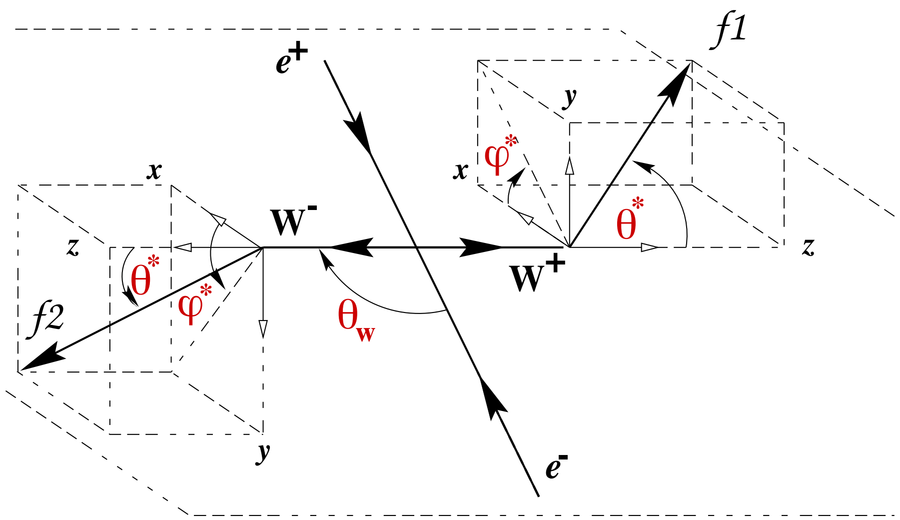
$$M_W,\ \Gamma_W,\ \mathrm{BR}_{W\to f}$$

- As well as pure gauge boson interactions, e.g. anomalous Triple Gauge Couplings (aTGC)
- Previously studied following LEP2 experience, using binned $cos\ \theta_W$ differential distributions in the aTGC-dominance approximation (relevant also for Higgs interpretation within the SMEFT)



aTGC dominance:
sizable NP effects only in aTGC

- Underutilizes all the differential info from the process (5 angles)!



In JHEP12 (2019) 117
we prepared a global SMEFT study of WW using all differential info and the formalism of "Optimal statistical observables"
(Later updated for the Snowmass 2021 studies)

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

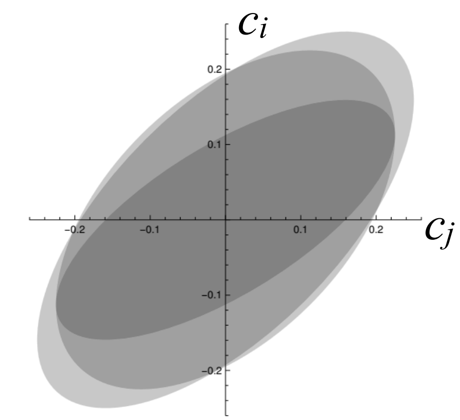
- In the limit of large statistics, the observables

(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

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

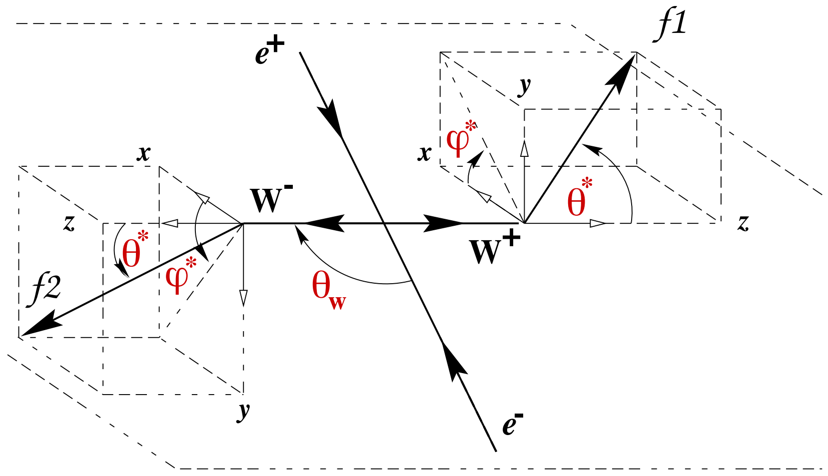
(For this study we take as default 45%. Chosen to agree with results of ILC 500 GeV studies)

Optimal Observables

- diBoson process: E.g. $e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu$

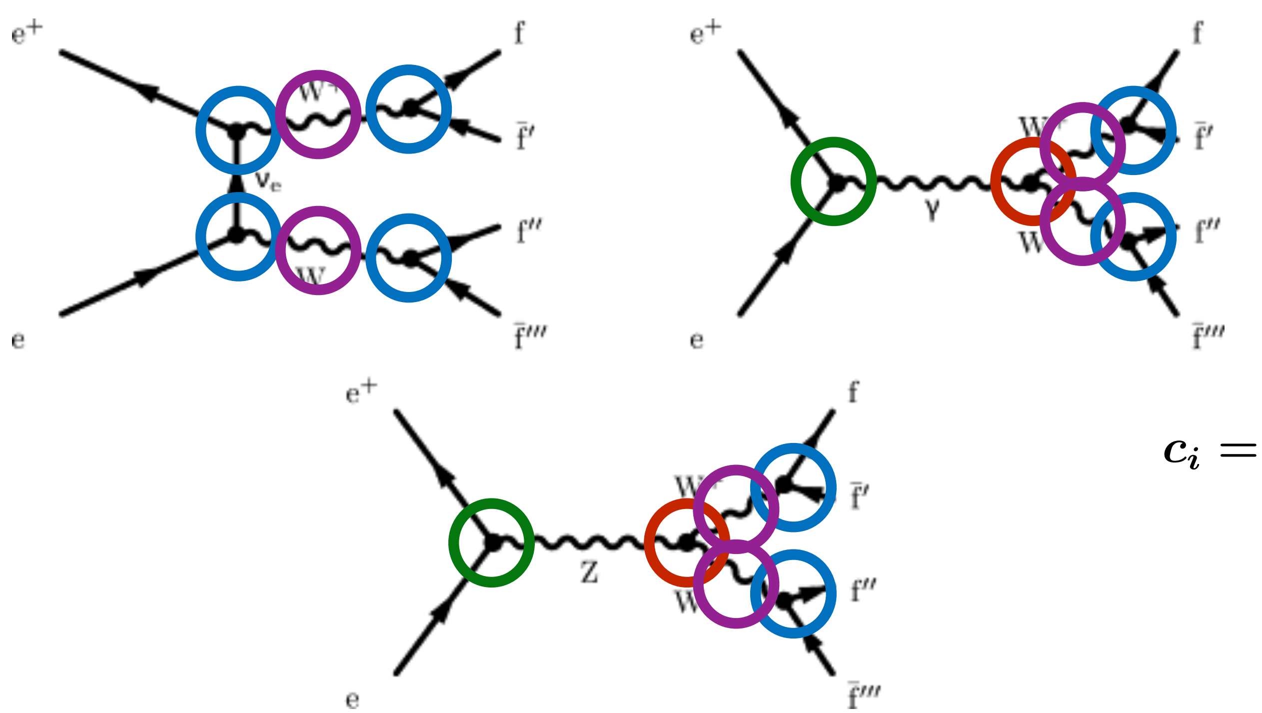
$$S(\Phi) = S_0(\Phi) + \sum_i c_i S_i(\Phi)$$

SMEFT: $S(\Phi) = \frac{d\sigma}{d\Phi}$ $\quad S_0(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\rm SM}$ $\quad c_i S_i(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\rm Interf.\ SM-NP}$



Optimal Observables function of 5 angles

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

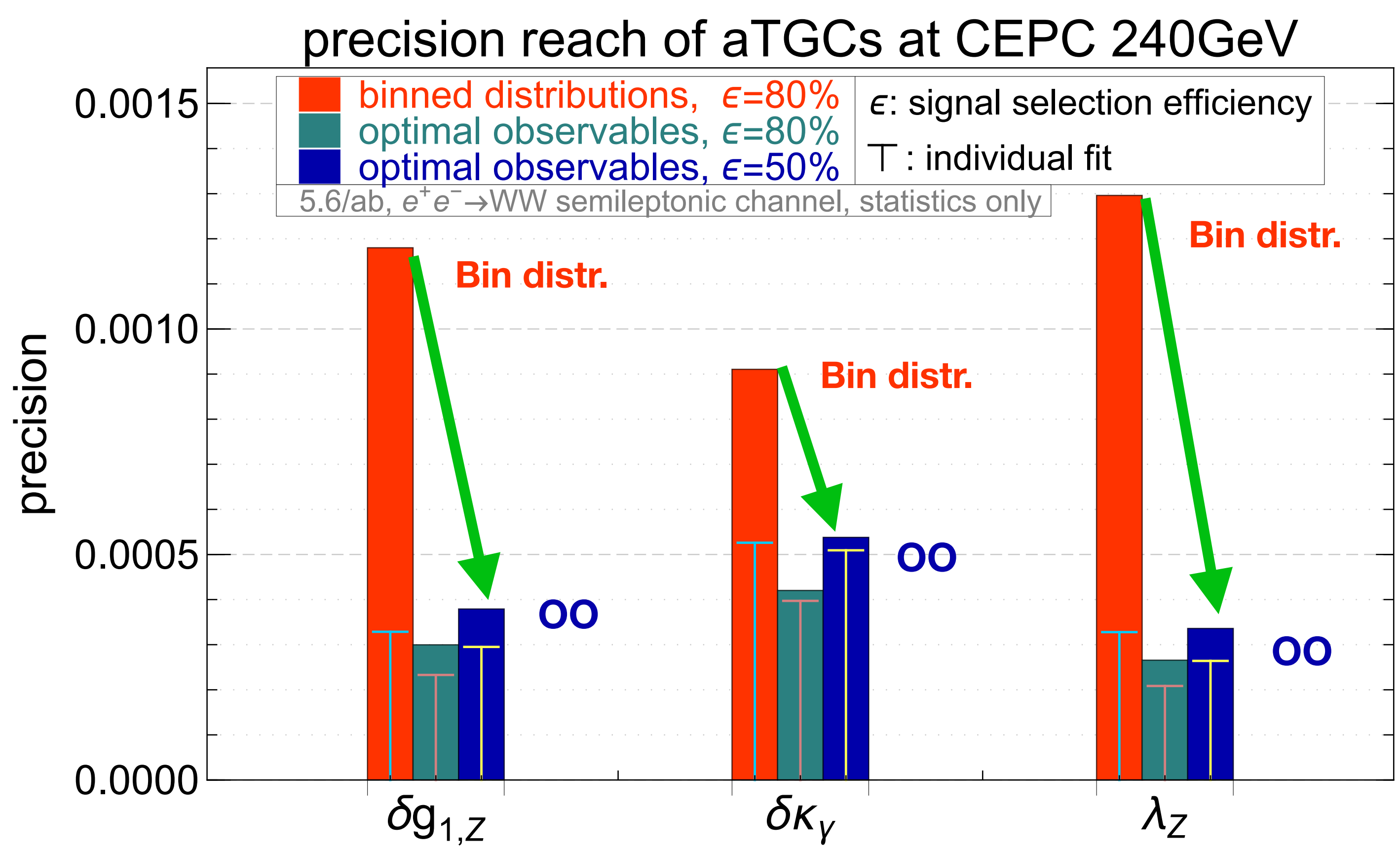


Full dim-6 SMEFT parameterization at LO:
10 independent BSM deformations

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

Optimal Observables

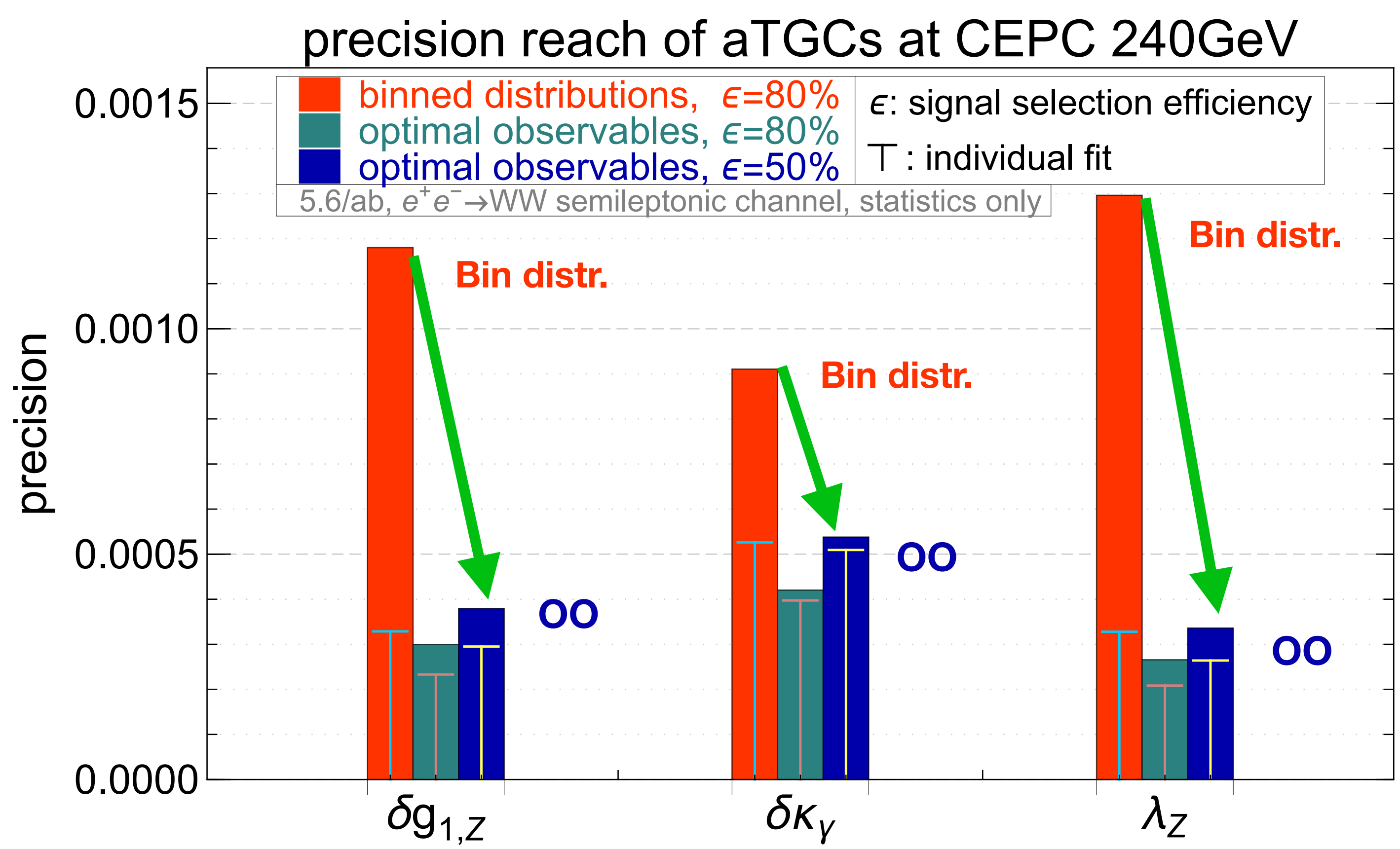
- diBoson process: E.g. $e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu$



OO vs. $cos\ \theta_W$ distr: Improvement in aTGC ~2-4x

Optimal Observables

- diBoson process: E.g. $e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu$



OO vs. $\cos\theta_W$ distr: Improvement in aTGC ~2-4x

But cannot resolve all EFT pars with WW only,
e.g. 2 flat directions in (δg_{1Z}, δg_{Le}, δg_{Re}) at amplitude level

⇒ Combine with EWPO/Higgs in global study

SMEFT fits
at future colliders

SMEFT fits at future colliders

- Collider scenarios considered in the Snowmass 2021 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}

HiLumi HL-LHC PROJECT

ilc

clic

FCC hh ee he

CEPC

International UON Collider Collaboration

SMEFT fits at future colliders

- Summary of inputs used for Snowmass 2021 SMEFT studies

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:

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

See Backup slides for details

	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)
HL-LHC	Yes (μ)	pp→WW, WZ Differential Info	LEP/SLD
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	$e^+e^-\to W^+W\to$All Optimal Obs.	Yes (Tera Z)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	$e^+e^-\to W^+W\to$All Optimal Obs.	Yes (Rad. Return, Giga-Z)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	$e^+e^-\to W^+W\to$All Optimal Obs.	Yes (Tera Z)
CLIC	Yes (μ, σ_{ZH})	$e^+e^-\to W^+W\to$All Optimal Obs.	Yes (Rad. Return, Giga-Z)
Muon Colliders	Yes (μ) 125 GeV/3 & 10 TeV	Optimal Obs.	No. From LEP/SLD

SMEFT fits at future colliders

- Fit assumptions (limited by the amount of available projections)

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)
- Flavor assumptions: non-universal but flavour diagonal (30 NP pars)

Neutral Diagonal: SMEFT$_{ND}$ 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

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

Vff/hVff

5 SM + 30 New Physics Parameters

Fitting framework

General strategy for calculation of future sensitivities

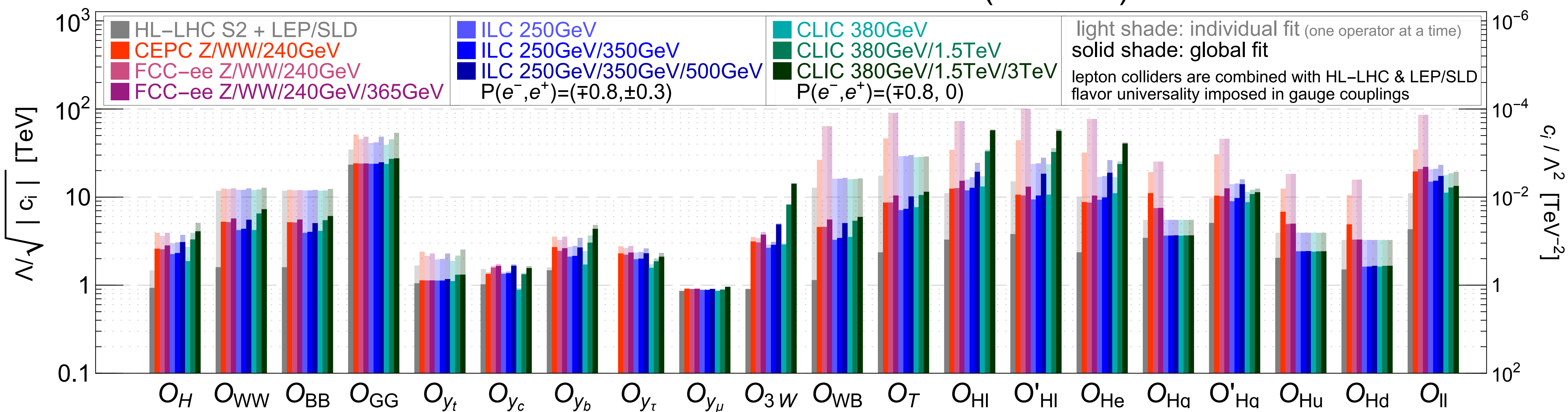
- Fit to new physics effects parameterized by the dimension 6 SMEFT:
  - ✓ Bayesian fit using HEPfit
  - ✓ Sensitivity from posterior info (NP-parameters/Observables errors/limits)
- Assumptions:
  - ✓ Likelihood: SM predictions as central values for future "experimental" measurements. Errors given by projected experimental uncertainties.
  - ✓ Baseline: Results for each future collider given in combination with LEP/SLD and HL-LHC
  - ✓ SM theory uncertainties: SM intrinsic and parametric uncertainties reduced according to future projections. Parametric included in default analysis. Intrinsic studied separately
  - ✓ New physics effects: Working at the linear-level in the EFT effects (interference with SM amplitudes)

$$O = O_{\rm SM} + \delta O_{\rm NP} \frac{1}{\Lambda^2}$$

SMEFT fits at future colliders

- Results typically presented as bounds on the Wilson Coefficients/Interaction scale of the new operators:

95% CL reach from the full EFT fit (Warsaw)



J.B., G. Durieux, C. Grojean, J. Gu and A. Paul, JHEP12 (2019) 117

- Pros: easier BSM interpretation   Cons: Depend on the basis, correlations

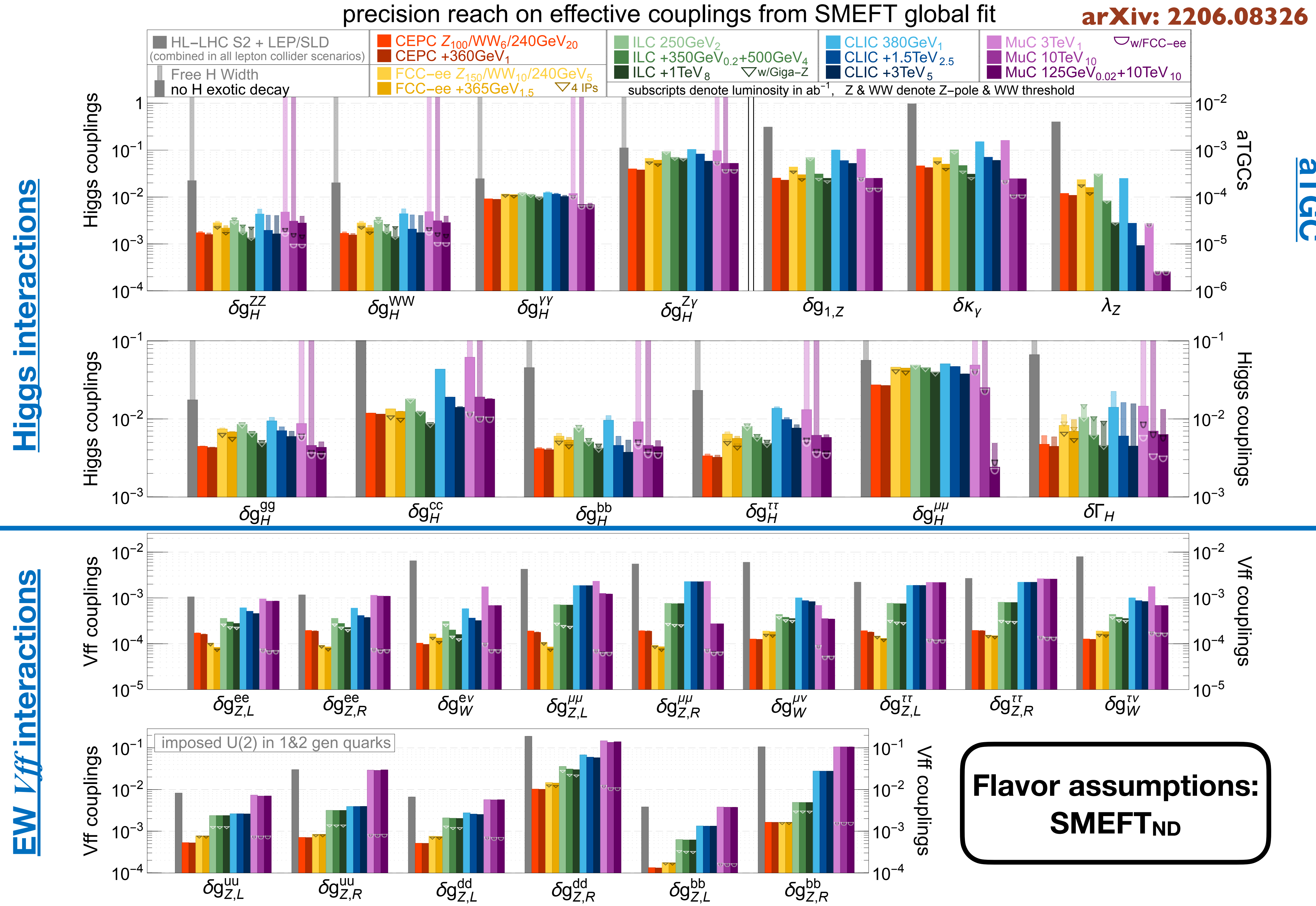
- We will compare sensitivities projecting the SMEFT fit results into (pseudo) observable quantities → Effective couplings, e.g.

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

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

SMEFT fits at future colliders

arXiv: 2206.08326 [hep-ph]



Flavor assumptions: SMEFT$_{ND}$

Effective couplings

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

SMEFT fits at future colliders

precision reach on effective couplings from SMEFT global fit

arXiv: 2206.08326 [hep-ph]

Future Collider Legend

Circular e^+e^- Colliders	Linear e^+e^- Colliders		Circular $\mu^+\mu^-$ Colliders
CEPC $Z_{100}/WW_6/240GeV_{20}$	ILC $250GeV_2$	CLIC $380GeV_1$	MuC $3TeV_1$ (w/FCC–ee)
CEPC $+360GeV_1$	ILC $+350GeV_{0.2}+500GeV_4$	CLIC $+1.5TeV_{2.5}$	MuC $10TeV_{10}$
FCC–ee $Z_{150}/WW_{10}/240GeV_5$	ILC $+1TeV_8$ (w/Giga–Z)	CLIC $+3TeV_5$	MuC $125GeV_{0.02}+10TeV_{10}$
FCC–ee $+365GeV_{1.5}$			

subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold

Flavor assumptions: SMEFT_{ND}

Effective couplings

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

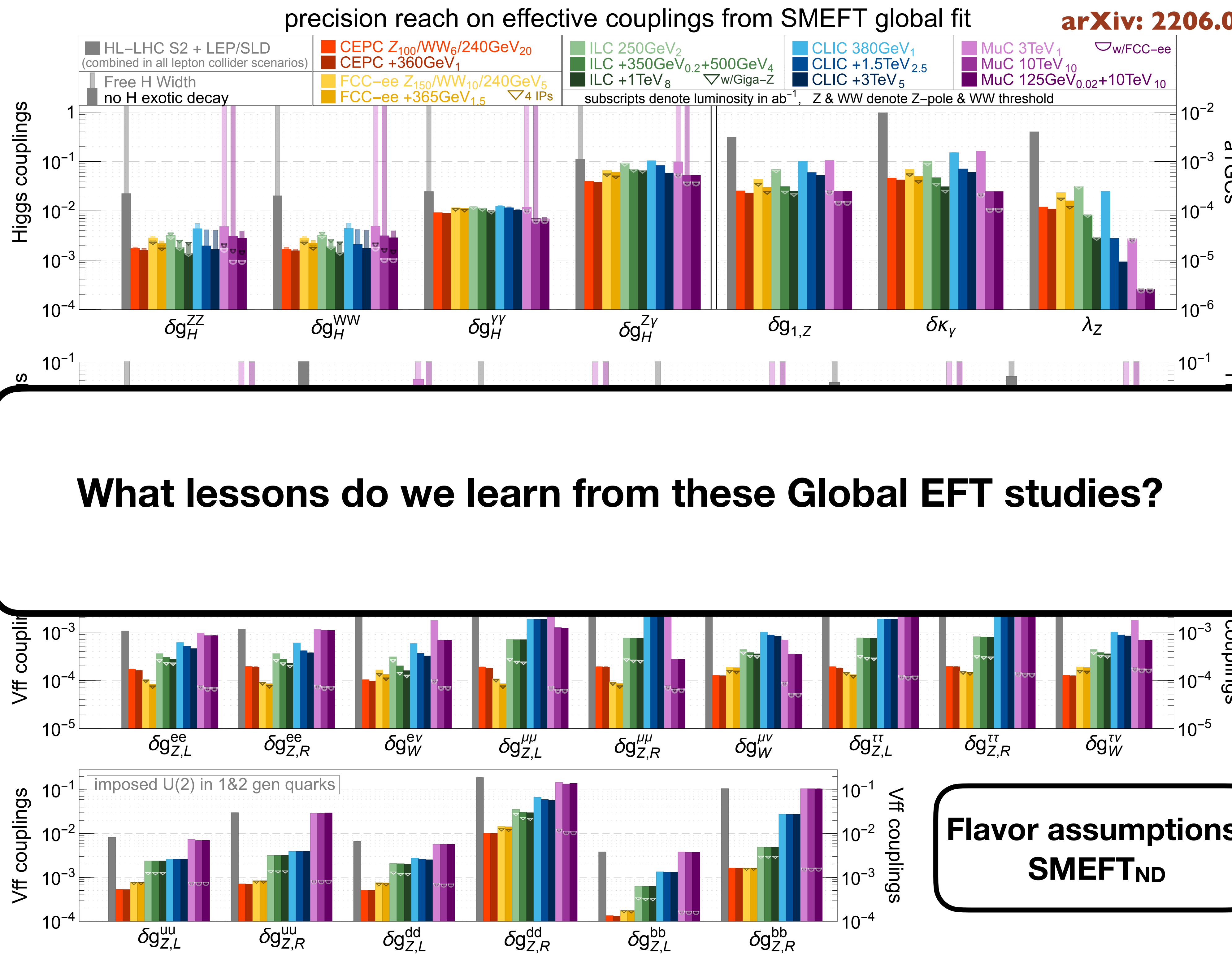
SMEFT fits at future colliders

arXiv: 2206.08326 [hep-ph]

Higgs interactions

aTGC

EW Vff interactions



What lessons do we learn from these Global EFT studies?

Flavor assumptions: SMEFT$_{ND}$

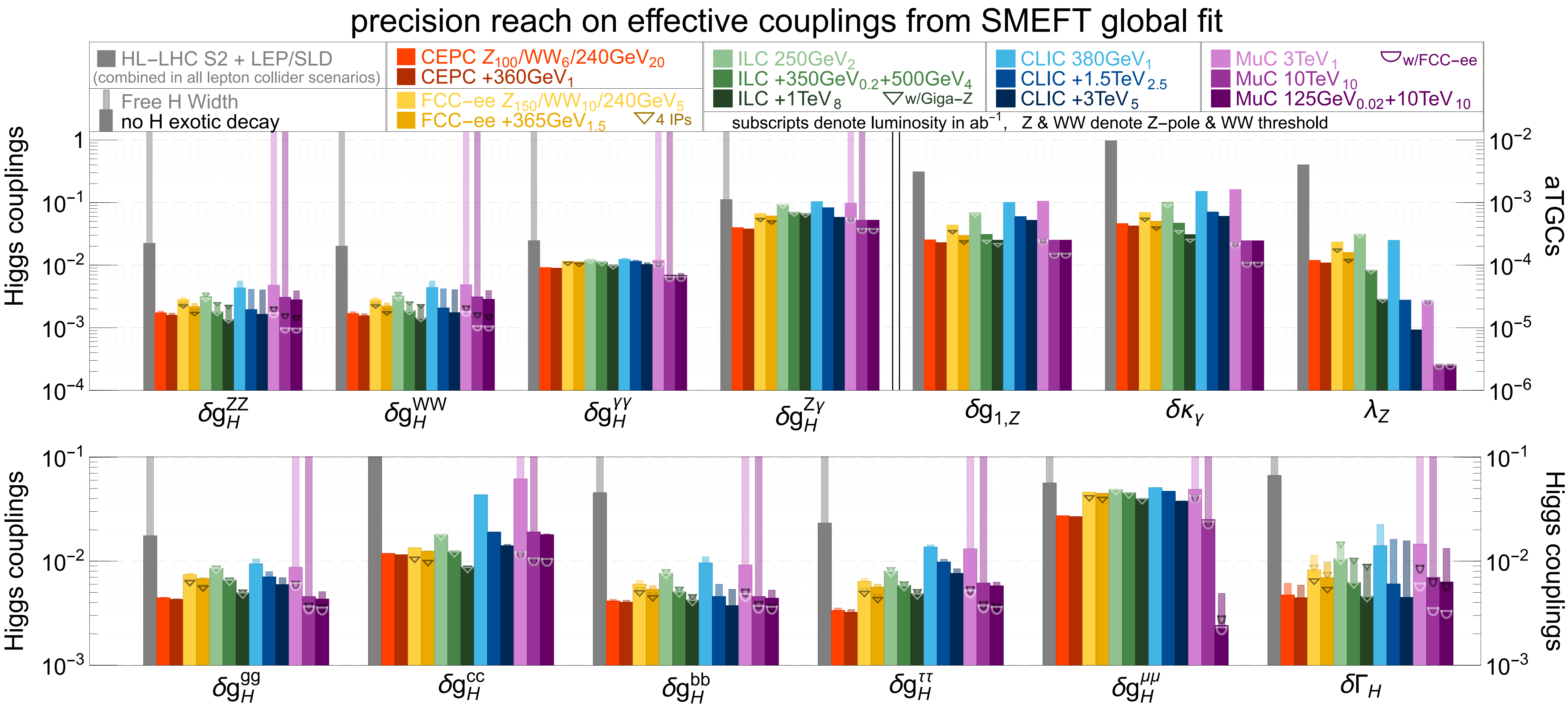
Effective couplings

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

Higgs couplings
at future colliders

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions



Effective Higgs couplings

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

arXiv: 2206.08326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

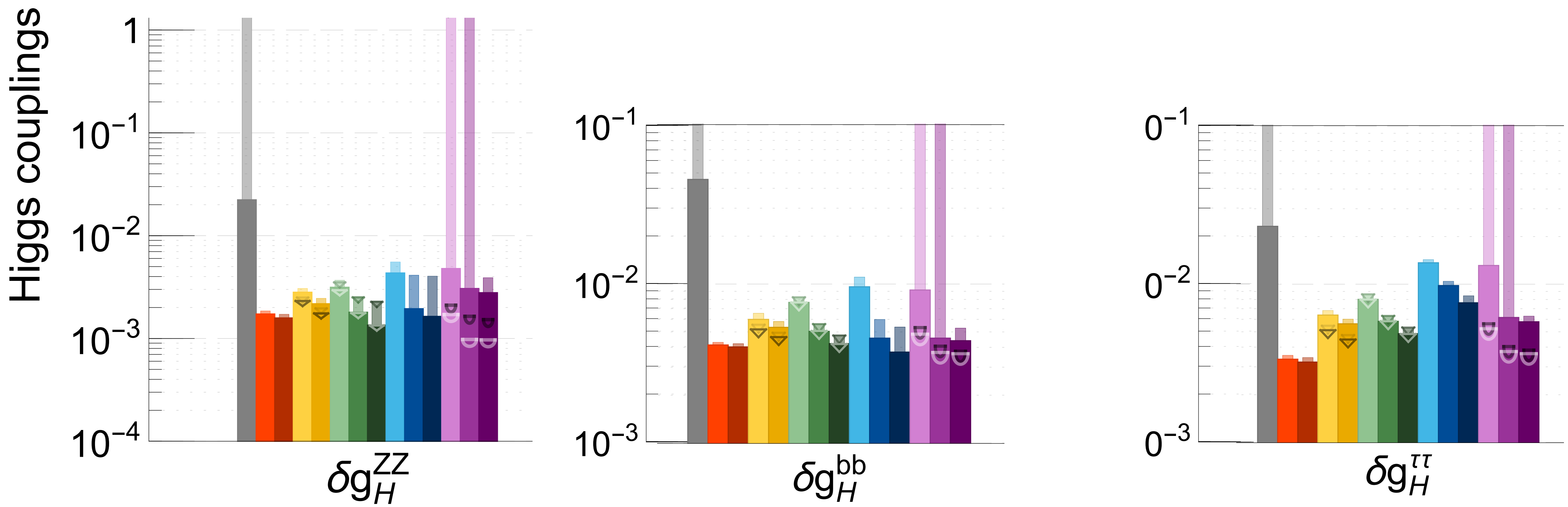
Higgs interactions

precision reach on effective couplings from SMEFT global fit

HL–LHC S2 + LEP/SLD (combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z_{100}/WW_6/240GeV$_{20}$
CEPC +360GeV$_1$
FCC-ee Z_{150}/WW_{10}/240GeV$_5$
FCC-ee +365GeV$_{1.5}$ ▽4 IPs
ILC 250GeV$_2$
ILC +350GeV$_{0.2}$+500GeV$_4$
ILC +1TeV$_8$ ▽w/Giga-Z
CLIC 380GeV$_1$
CLIC +1.5TeV$_{2.5}$
CLIC +3TeV$_5$
MuC 3TeV$_1$ ▽w/FCC-ee
MuC 10TeV$_{10}$
MuC 125GeV$_{0.02}$+10TeV$_{10}$
subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold

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

Reaching in some cases few per mile accuracy



$$\Lambda_{NP} \gtrsim 4500 \frac{g_{NP}}{g_{SM}}\ \text{GeV}$$

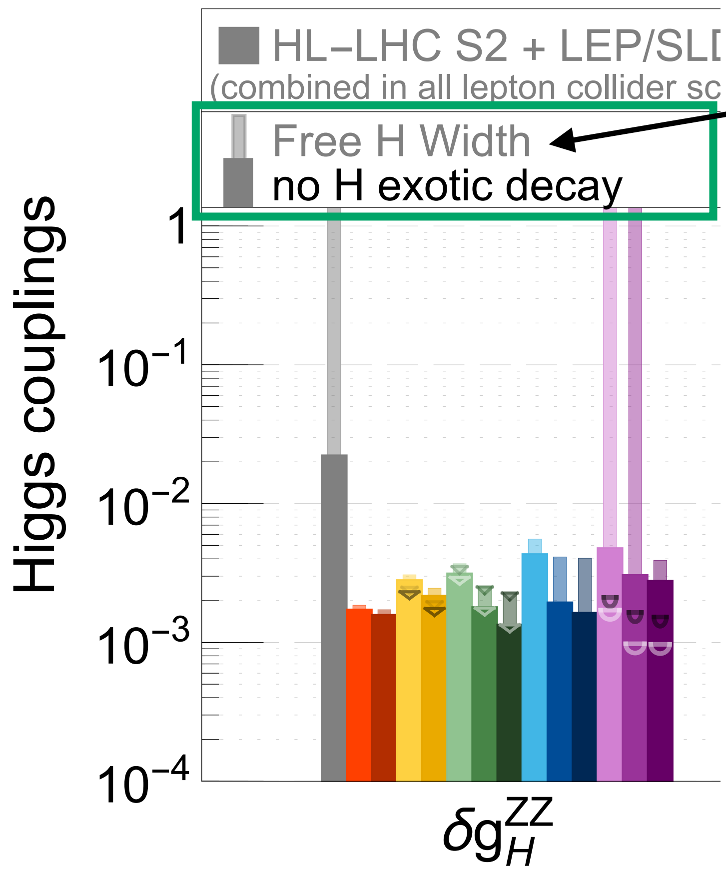
Effective Higgs couplings $g_{HX}^{\text{eff}\,2} = \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{SM}}$.

arXiv: 2206.08326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

Higgs interactions

precision reach on effective couplings from SMEFT global fit



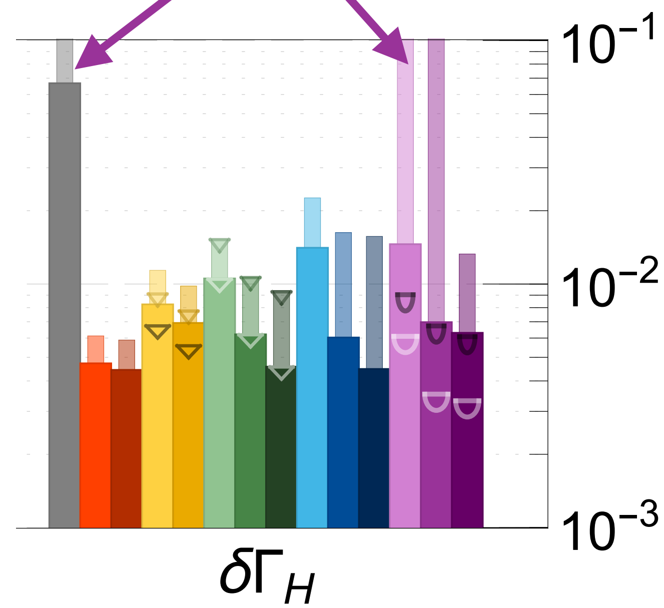
Fit with free Γ_H

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)

$\delta\Gamma_H$ ~1% precision

Flat directions @ non e^+e^- colliders



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

arXiv: 2206.08326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

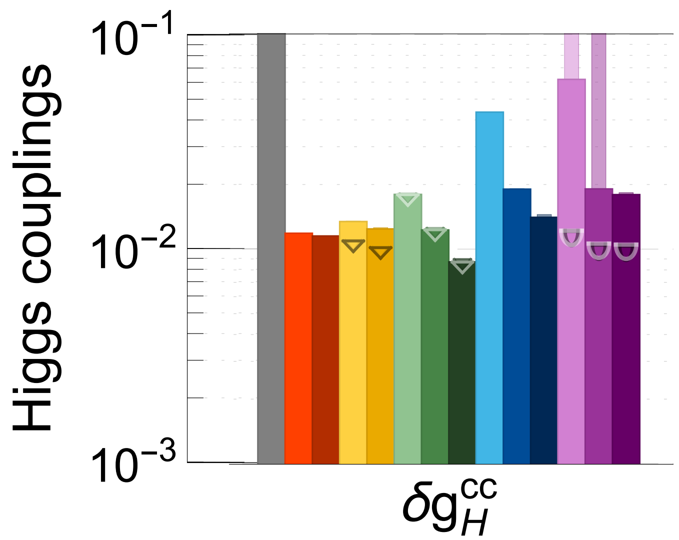
Higgs interactions

precision reach on effective couplings from SMEFT global fit

HL–LHC S2 + LEP/SLD (combined in all lepton collider scenarios) | Free H Width | no H exotic decay | CEPC $Z_{100}/WW_{6}/240GeV_{20}$ | CEPC $+360GeV_{1}$ | FCC–ee $Z_{150}/WW_{10}/240GeV_{5}$ | FCC–ee $+365GeV_{1.5}$ | 4 IPs | ILC $250GeV_{2}$ | ILC $+350GeV_{0.2}+500GeV_{4}$ | ILC $+1TeV_{8}$ | w/Giga–Z | CLIC $380GeV_{1}$ | CLIC $+1.5TeV_{2.5}$ | CLIC $+3TeV_{5}$ | MuC $3TeV_{1}$ | MuC $10TeV_{10}$ | MuC $125GeV_{0.02}+10TeV_{10}$ | w/FCC–ee

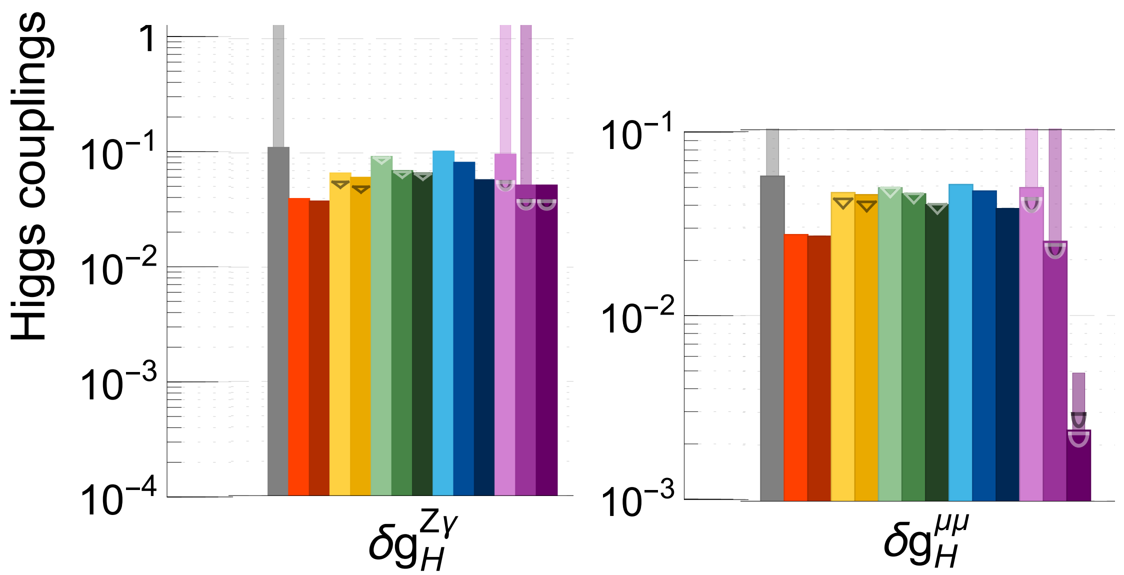
subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold

e^+e^- gives access to the second family of quarks. Very difficult at the HL-LHC…



O(1%) precision for charm coupling

…but HL-LHC still provides the leading constraints on couplings modifying rare decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)



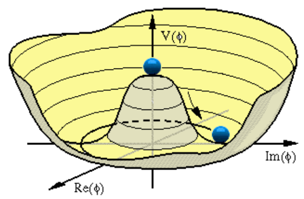
O(5-10%) precision

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

arXiv: 2206.08326 [hep-ph]

Higgs couplings in the dimension-6 SMEFT fit

- The **Higgs self coupling** κ_λ:



$$V(\phi) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 \longrightarrow V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}}$$

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

- It characterizes the structure of the Higgs potential. Relevant for BSM questions, e.g. baryogengesis

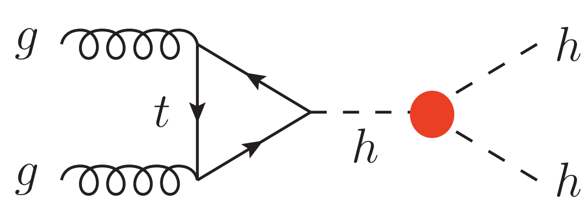
- A few operators contribute to κ_λ in the SMEFT but *only one does it exclusively:*

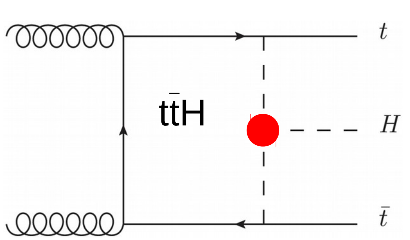
$$\Delta\mathcal{L}_{\rm SMEFT}^{d=6} = \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3, \qquad \rightarrow \qquad \delta\kappa_\lambda = -2\frac{C_\phi v^4}{m_h^2\Lambda^2}$$

- Two approaches

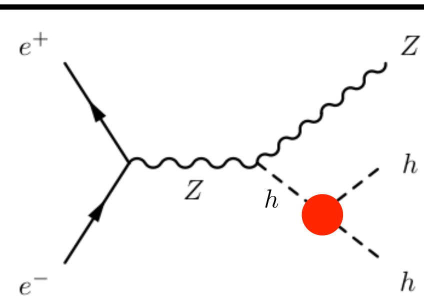
Higgs-pair production | **Via loop effect in single Higgs**

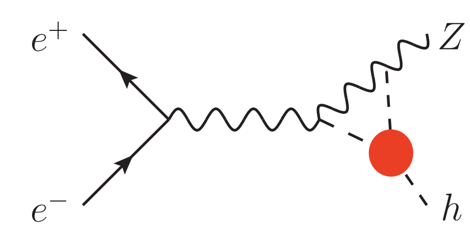
Hadron Colliders





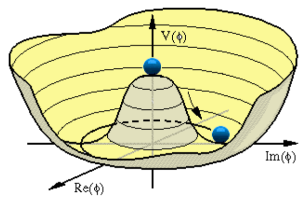
Lepton Colliders





Higgs couplings in the dimension-6 SMEFT fit

- The **Higgs self coupling** κ_λ**:**



$$V(\phi) = -\mu_\phi^2 \, |\phi|^2 + \lambda_\phi \, |\phi|^4 \longrightarrow V($$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \lambda_\phi =$$

- It characterizes the structure of the Hig
questions, e.g. baryogengesis

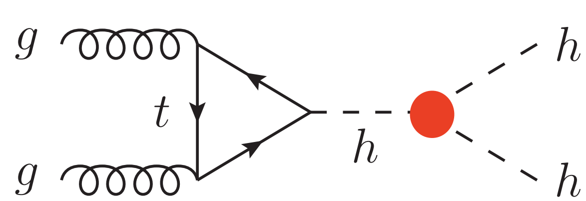
- A few operators contribute to κ_λ in th

$$\Delta\mathcal{L}_{\rm SMEFT}^{d=6} = \frac{C_\phi}{\Lambda^2}(\phi^\dagger \phi)^3, \qquad \rightarrow$$

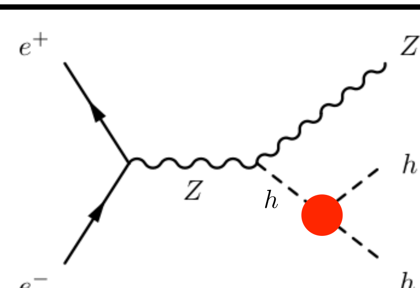
- Two approaches

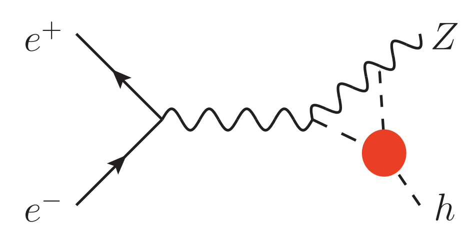
Higgs-pair production

Hadron Colliders

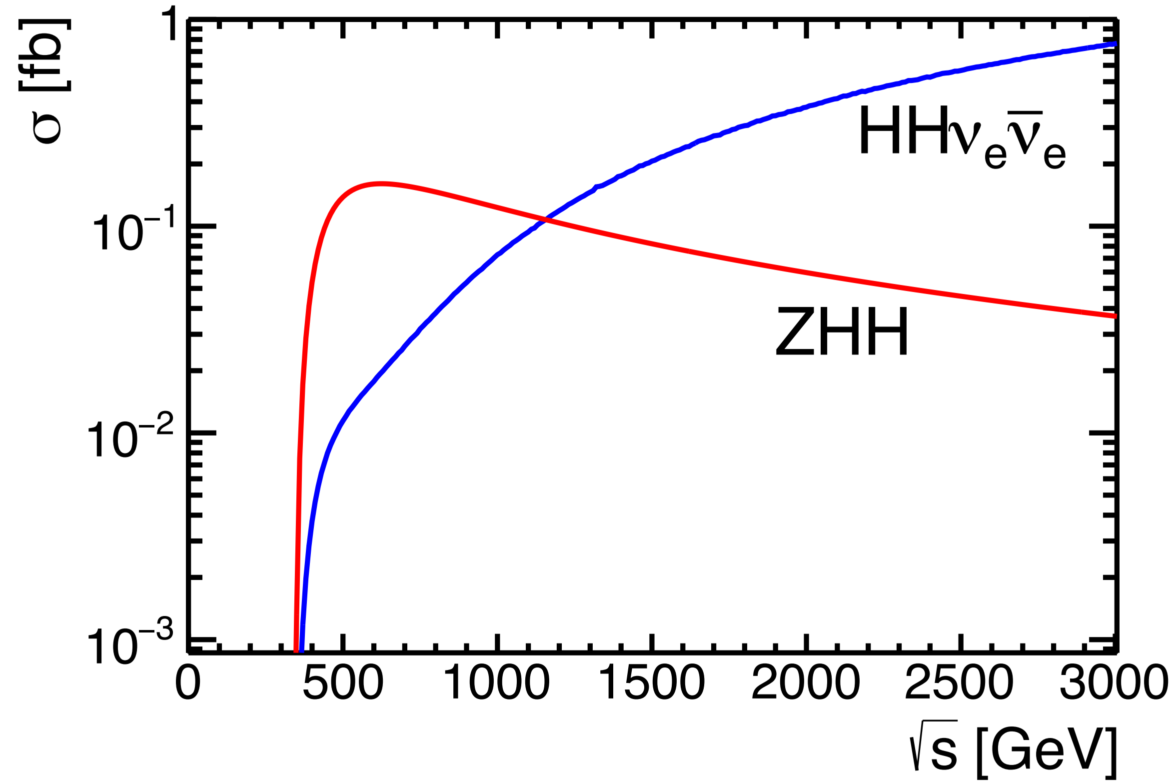


Lepton Colliders





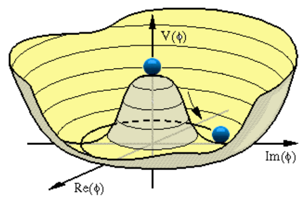
e+e-: Requires √s significantly higher than nominal threshold



Accessible at high-energy linear colliders √s≳500 GeV

Higgs couplings in the dimension-6 SMEFT fit

- The **Higgs self coupling** κ_λ**:**



$$V(\phi) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 \longrightarrow V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}}$$

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

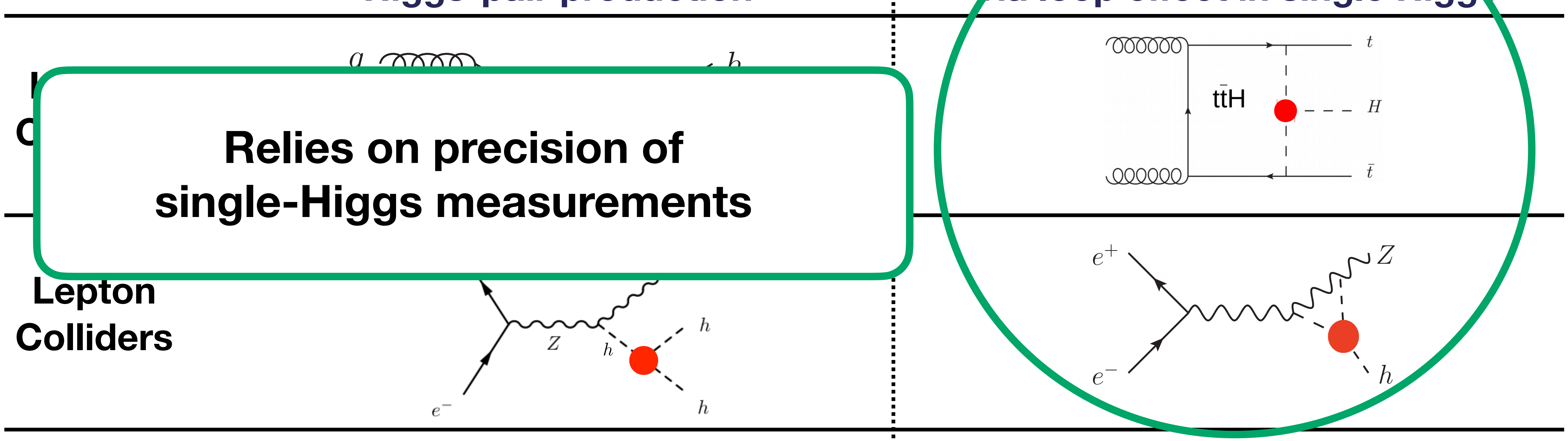
- It characterizes the structure of the Higgs potential. Relevant for BSM questions, e.g. baryogengesis

- A few operators contribute to κ_λ in the SMEFT but *only one does it exclusively:*

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

- Two approaches

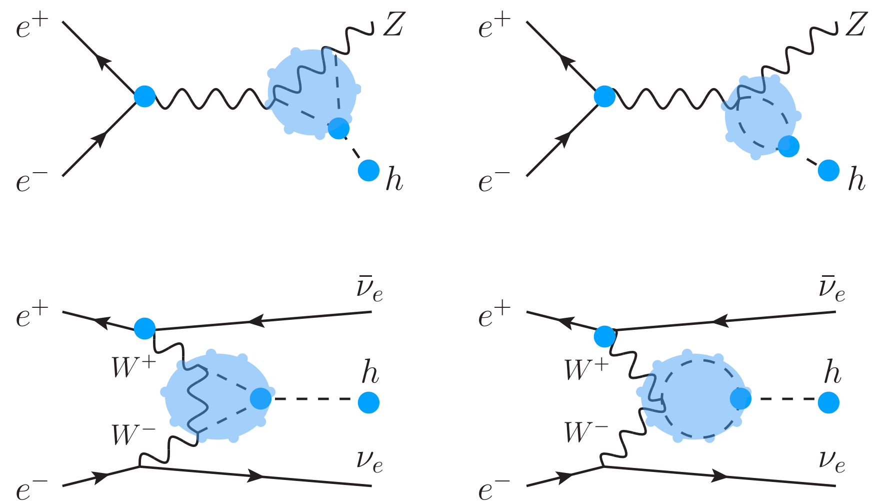
Higgs-pair production | **Via loop effect in single Higgs**

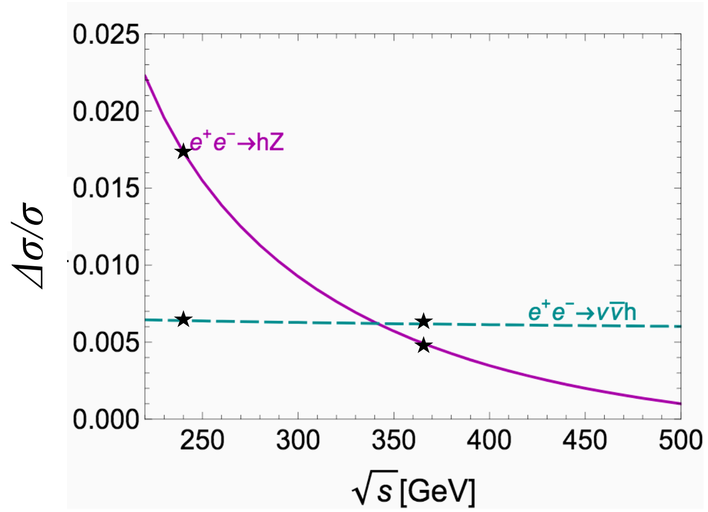


Higgs couplings in the dimension-6 SMEFT fit

- The **Higgs selfcoupling**: Higgs precision at future e+e- colliders can test the structure of radiative corrections

$\Rightarrow$ Use single-Higgs precision to test NLO corrections from κ_λ





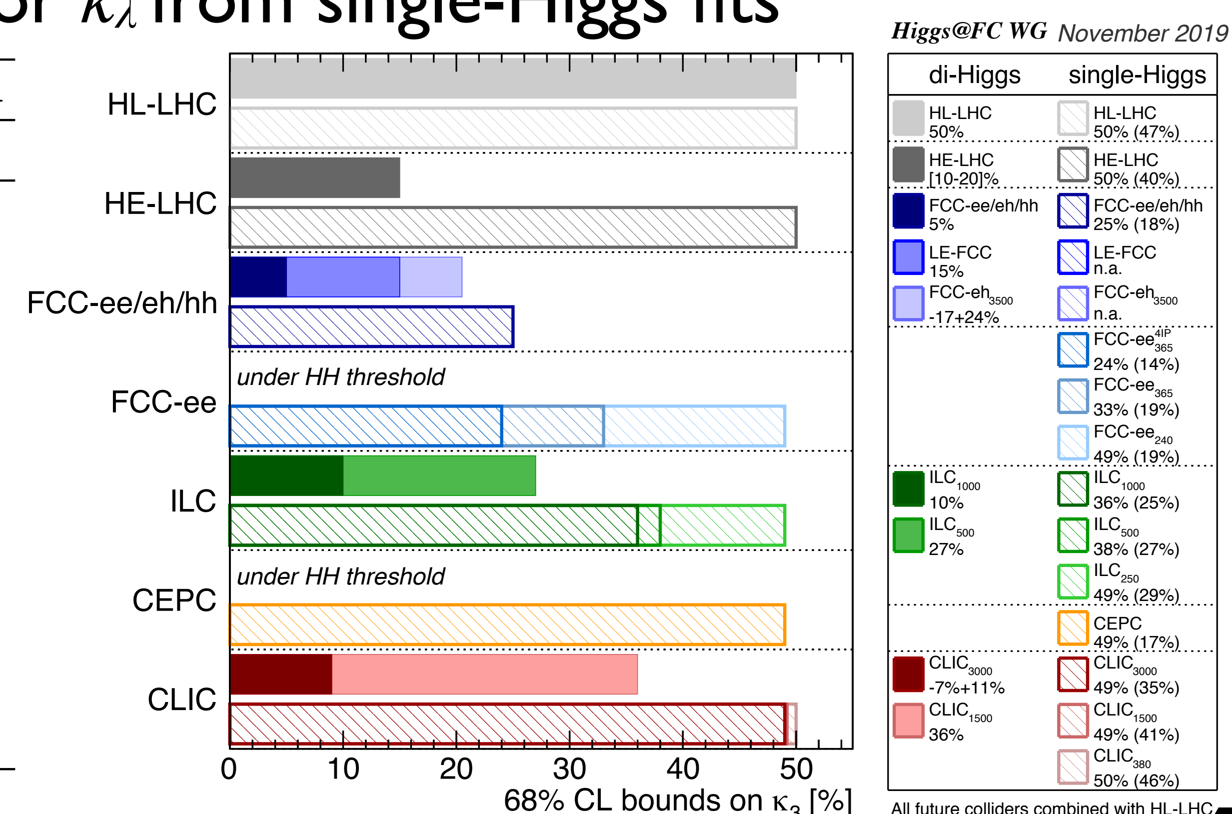
M. McCullough, PRD90 (2014) no.1, 015001
S. Di Vita et al., JHEP 1802 (2018) 178

Combination of 240+365 GeV provide a sensible global bound on h³ coupling (no flat directions)

- *Indirect determination* of the precision for κ_λ from single-Higgs fits

collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	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%

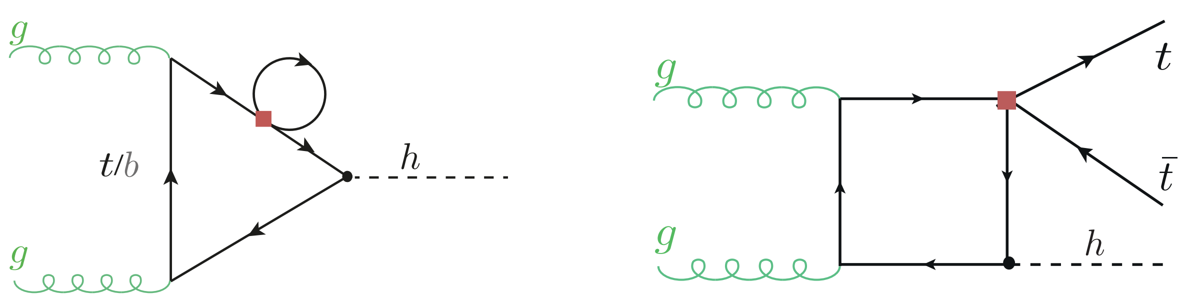
Combined with HLLHC 50%



Higgs couplings in the dimension-6 SMEFT fit

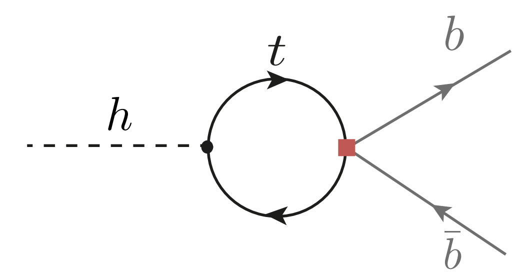
- The **Higgs selfcoupling**: Higgs precision at future e^+e^- colliders can test the structure of radiative corrections

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. E.g. 4-Top quark operators



Sizable effect in production at hadron colliders

L. Alasfar, JB, R. Gröber, JHEP 05 (2022) 111

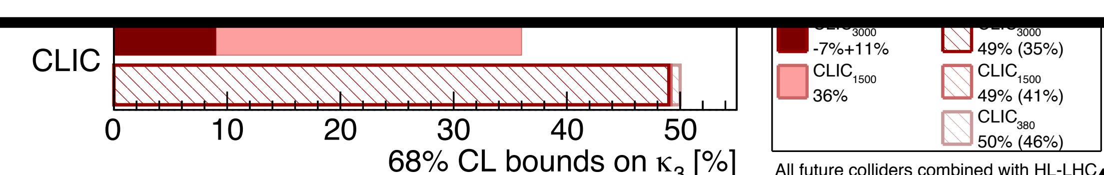


Also affects e^+e^- measurements

Much milder effect from 4 top operators expected at e^+e^- (EW production+ inclusive ZH) but global analysis including all operators at NLO needed to assess robustness of K_λ determination

μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

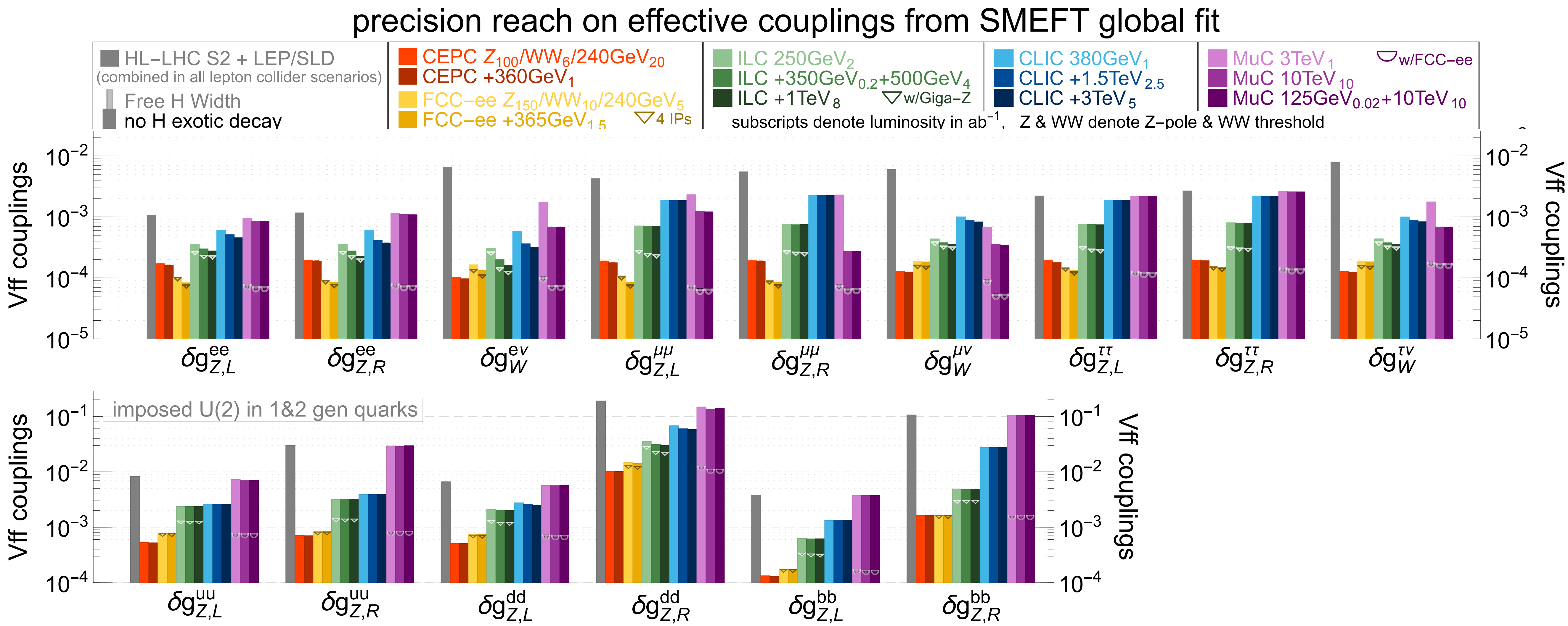
Combined with HLLHC 50%



Electroweak couplings
at future colliders: Interplay with Higgs

EW couplings in the dimension-6 SMEFT fit

Electroweak interactions



Effective EW couplings

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g^{\rm eff}_{Zee,L}|^2 + |g^{\rm eff}_{Zee,R}|^2\right), \qquad A_e = \frac{|g^{\rm eff}_{Zee,L}|^2 - |g^{\rm eff}_{Zee,R}|^2}{|g^{\rm eff}_{Zee,L}|^2 + |g^{\rm eff}_{Zee,R}|^2}.$$

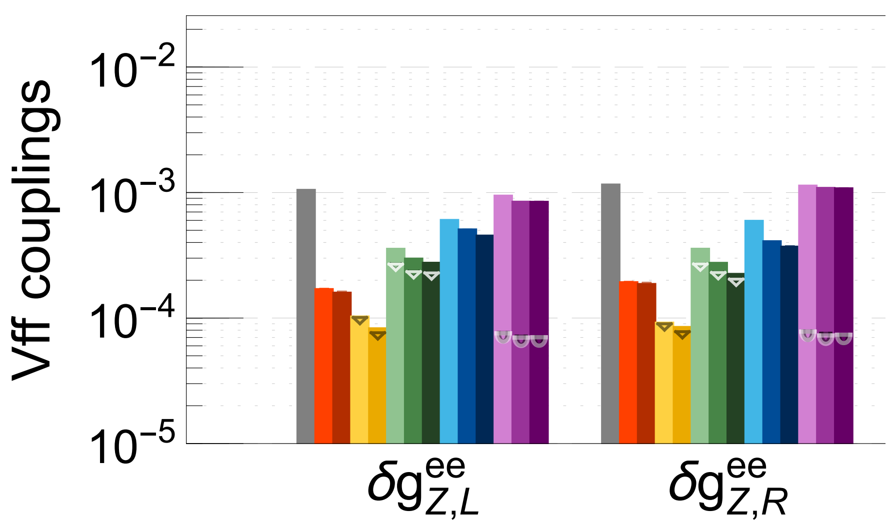
EW couplings in the dimension-6 SMEFT fit

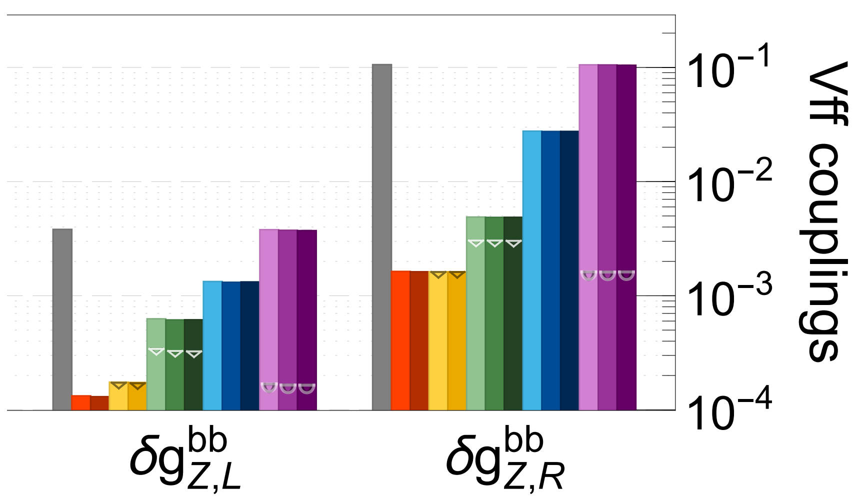
Electroweak interactions

precision reach on effective couplings from SMEFT global fit

HL–LHC S2 + LEP/SLD (combined in all lepton collider scenarios)
Free H Width
no H exotic decay
CEPC Z_{100}/WW_6/240GeV_{20}
CEPC +360GeV_1
FCC-ee Z_{150}/WW_{10}/240GeV_5
FCC-ee +365Ge$V_{1.5}$ 4 IPs
ILC 250GeV_2
ILC +350Ge$V_{0.2}$+500GeV_4
ILC +1TeV_8 w/Giga–Z
CLIC 380GeV_1
CLIC +1.5Te$V_{2.5}$
CLIC +3TeV_5
MuC 3TeV_1 w/FCC-ee
MuC 10TeV_{10}
MuC 125Ge$V_{0.02}$+10TeV_{10}
subscripts denote luminosity in ab^{-1}, Z & WW denote Z–pole & WW threshold

e^+e^- improves current precision by more than 1 order of magnitude





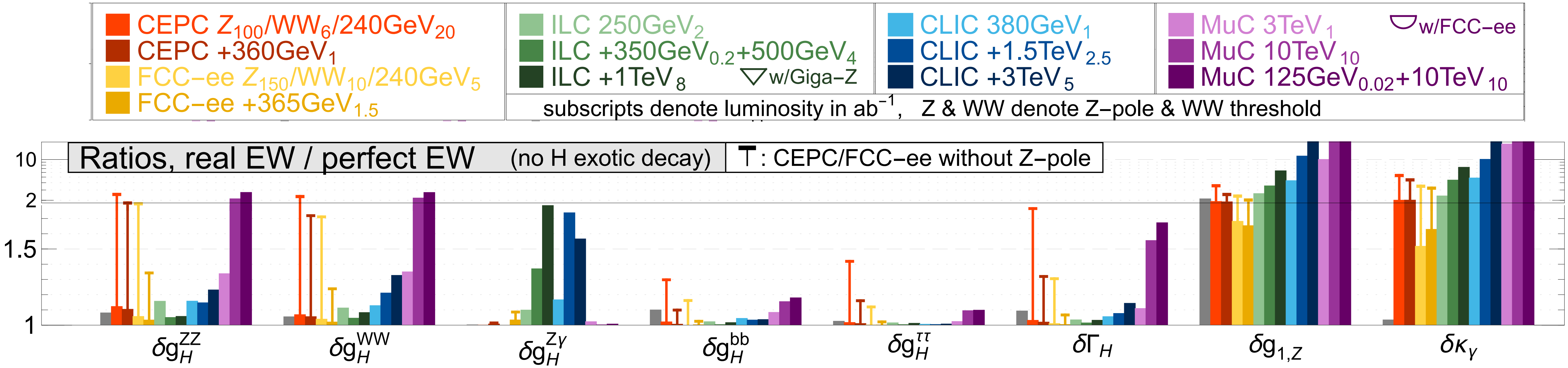
Radiative return measurements still bring a significant improvement in our knowledge of EW interactions

Still, a clear advantage for the Tera Z option (and Giga Z for most couplings) in terms of precision reach

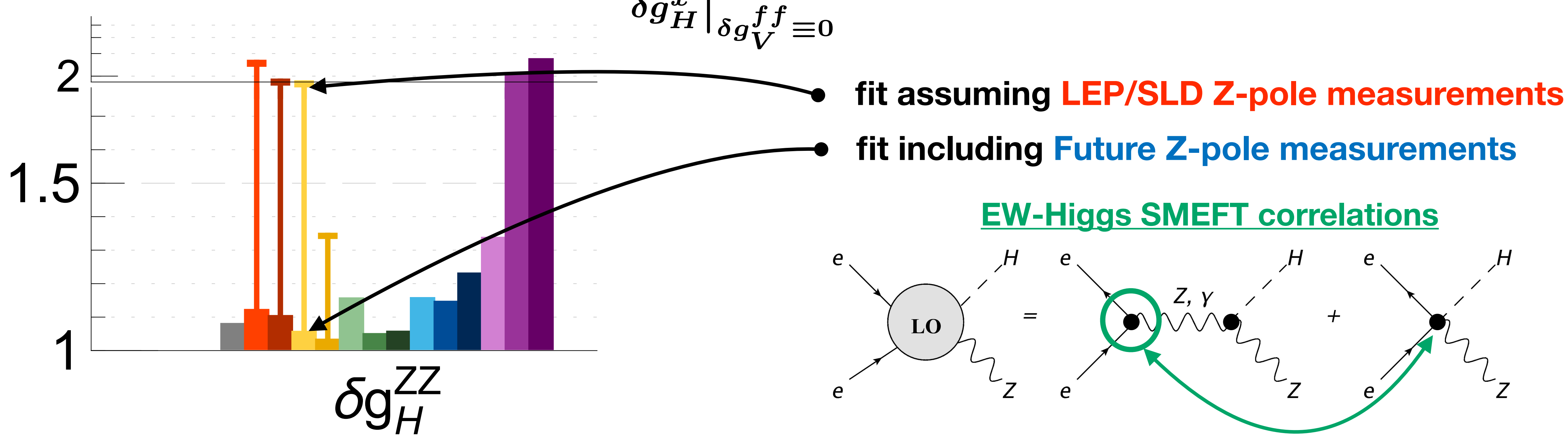
EW couplings

Interplay EW/Higgs in the dimension-6 SMEFT fit

Impact of future EWPO in Higgs/aTGC couplings



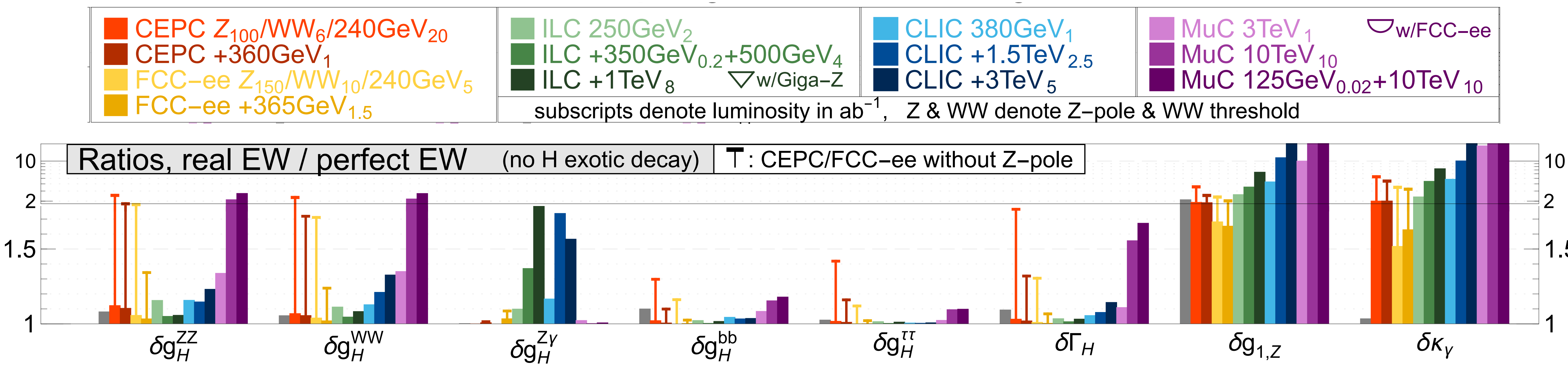
Impact of Z-pole run

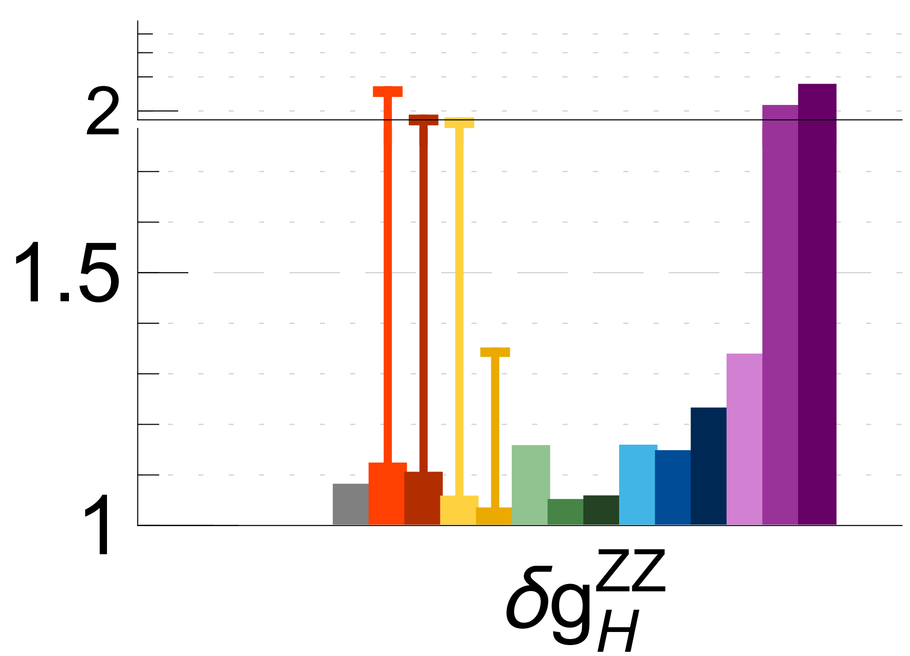


$$\frac{\delta g_H^x\Big|_{\delta g_V^{ff}\ \text{fit}}}{\delta g_H^x\Big|_{\delta g_V^{ff}\equiv 0}}$$

Interplay EW/Higgs in the dimension-6 SMEFT fit

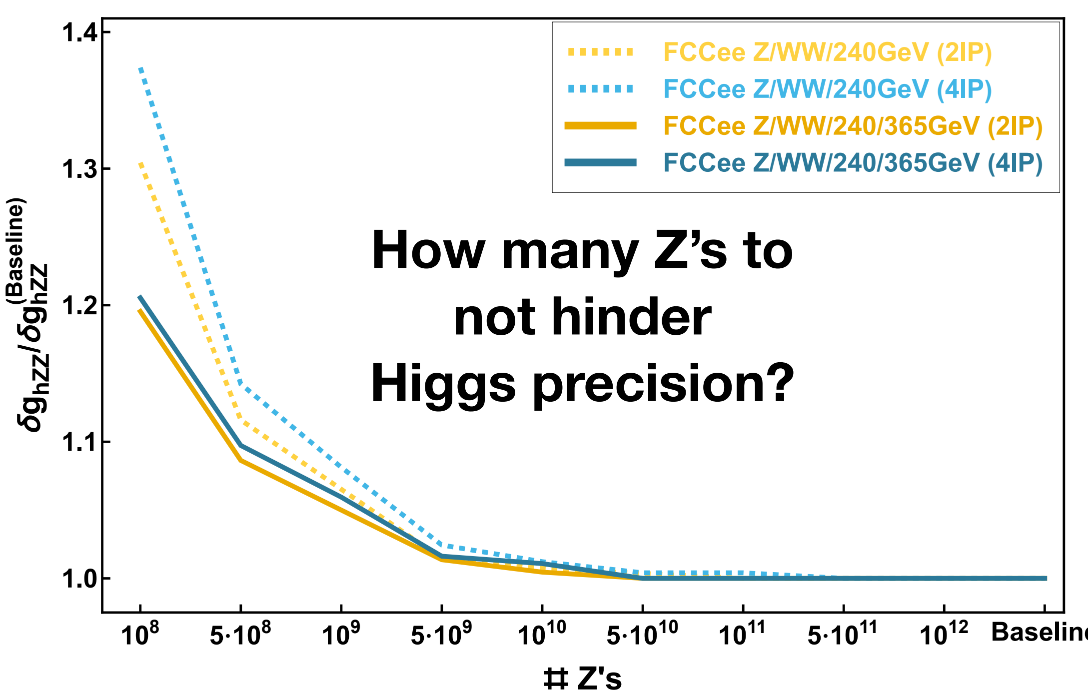
Impact of future EWPO in Higgs/aTGC couplings





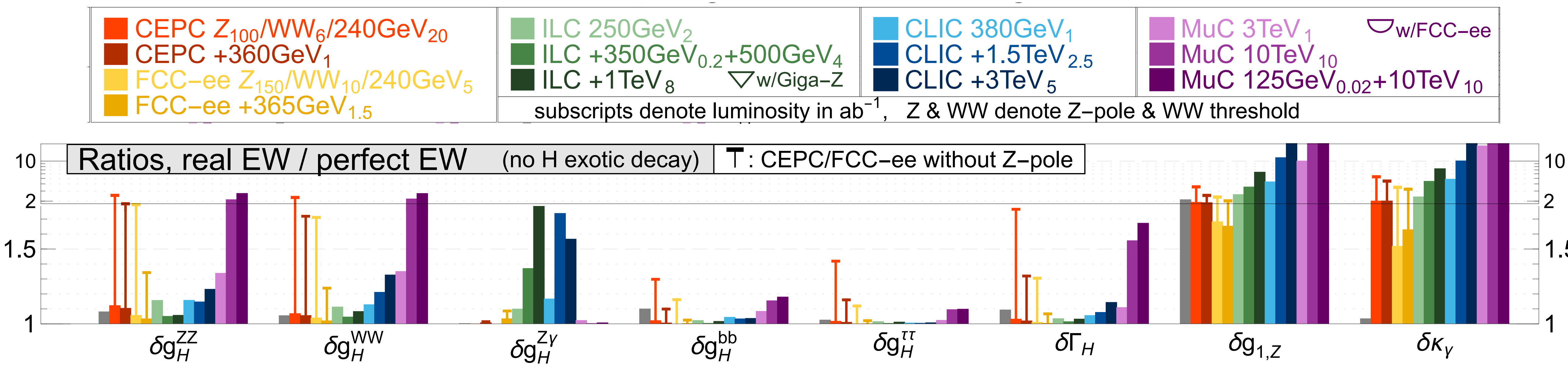
$$\frac{\delta g_H^x\big|_{\delta g_V^{ff}\ \text{fit}}}{\delta g_H^x\big|_{\delta g_V^{ff}\equiv 0}}$$

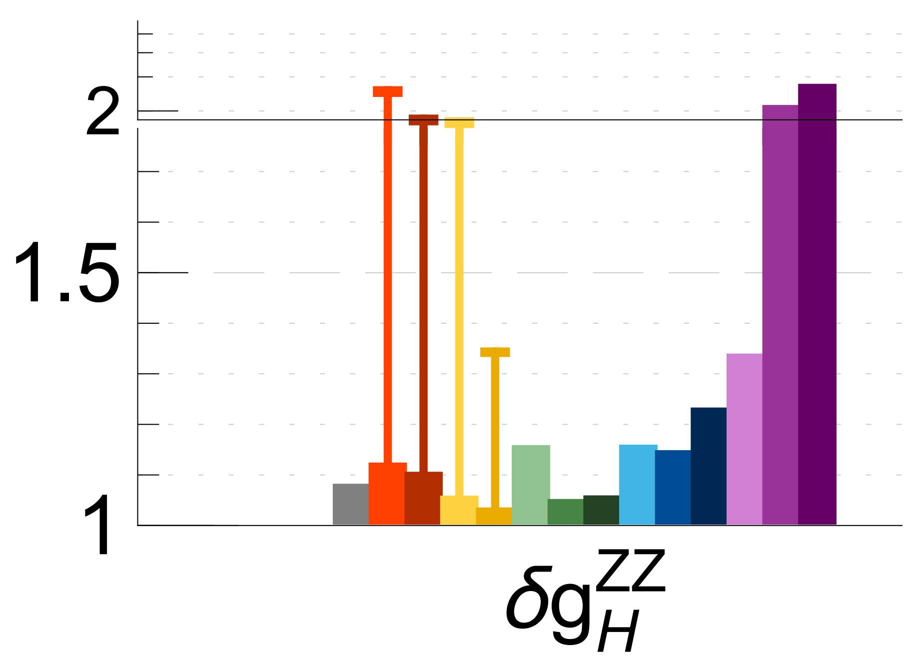
Impact of Z-pole run



Interplay EW/Higgs in the dimension-6 SMEFT fit

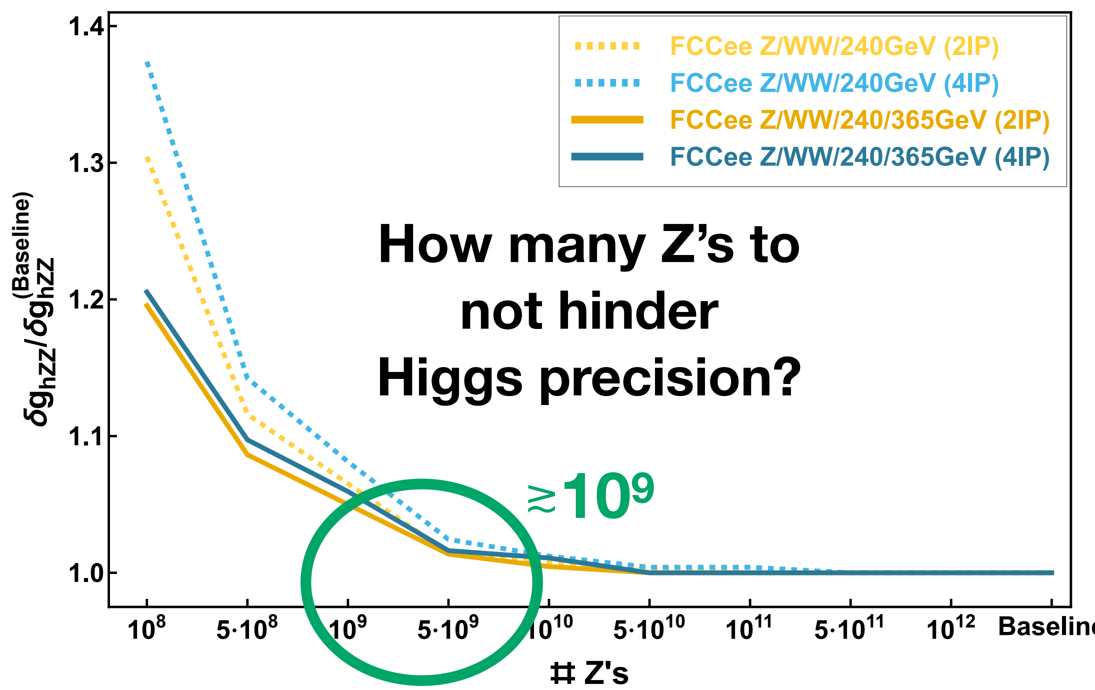
Impact of future EWPO in Higgs/aTGC couplings





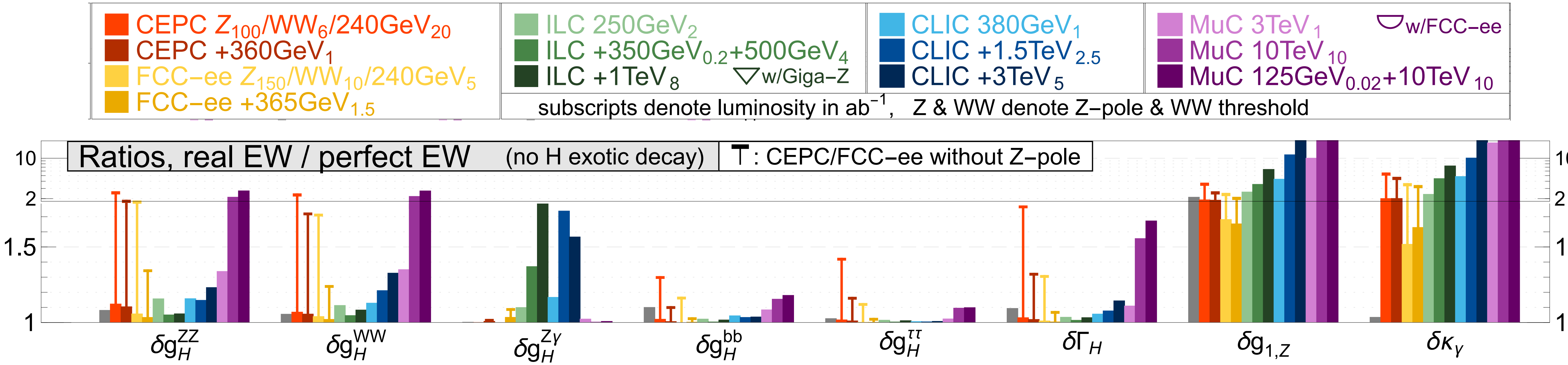
$$\frac{\delta g_H^x\big|_{\delta g_V^{ff}\ \text{fit}}}{\delta g_H^x\big|_{\delta g_V^{ff}\equiv 0}}$$

Impact of Z-pole run



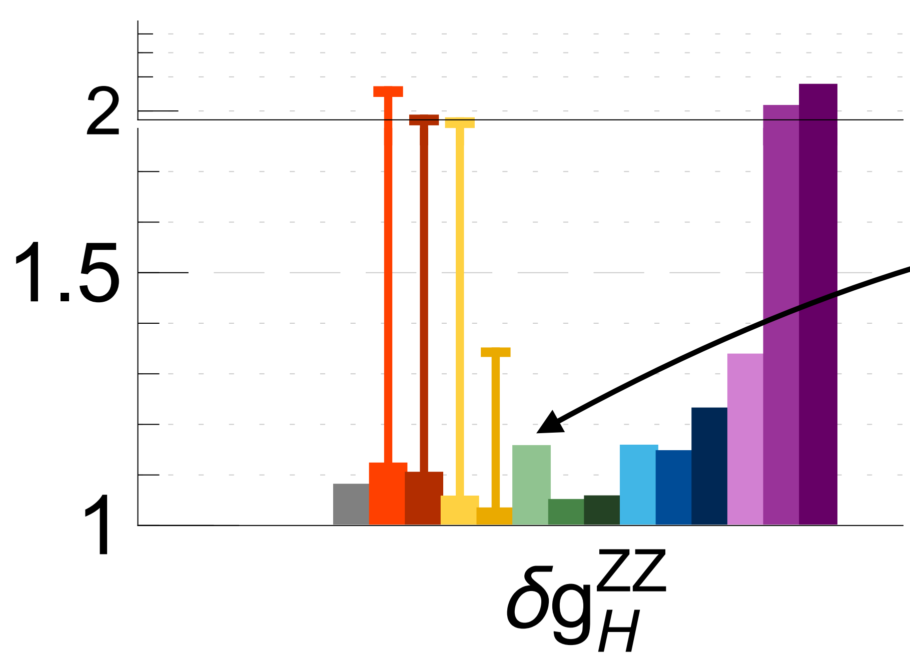
Interplay EW/Higgs in the dimension-6 SMEFT fit

Impact of future EWPO in Higgs/aTGC couplings



Impact of Z-pole run

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



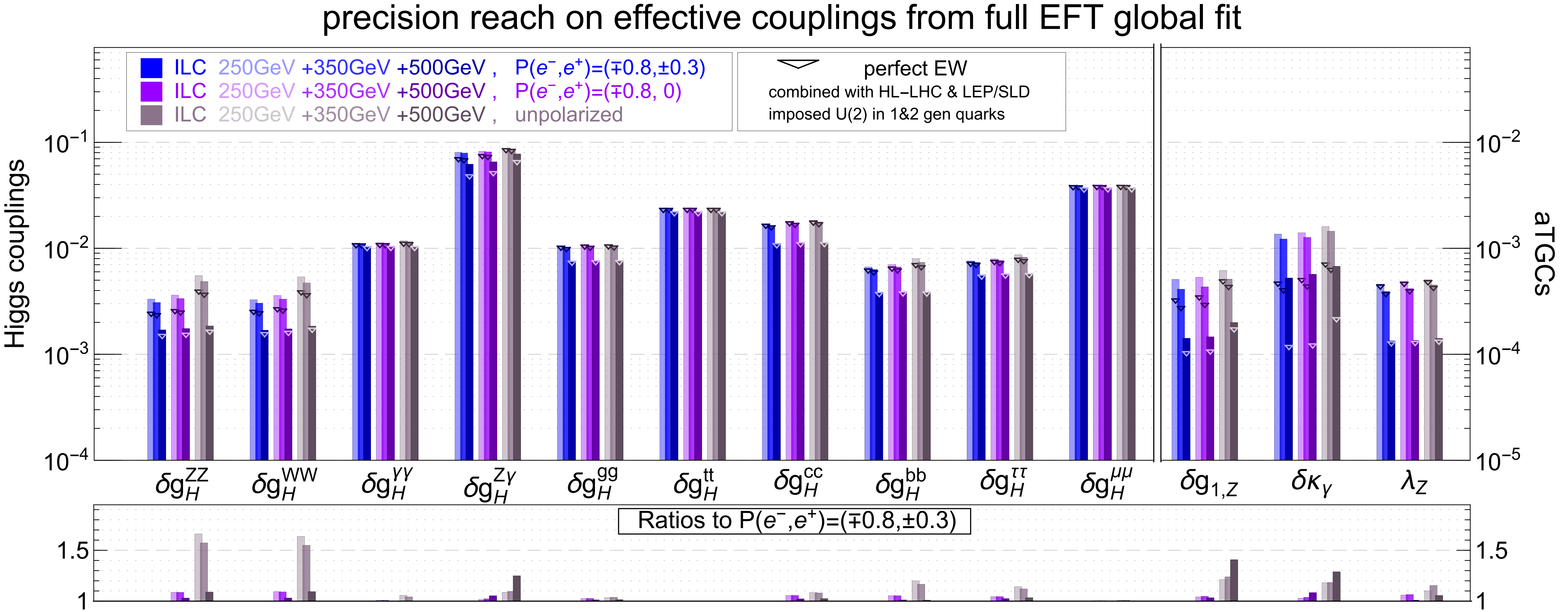
Milder effect at Linear Colliders

fit assuming LEP/SLD Z-pole measurements AND future 250 GeV EW measurements

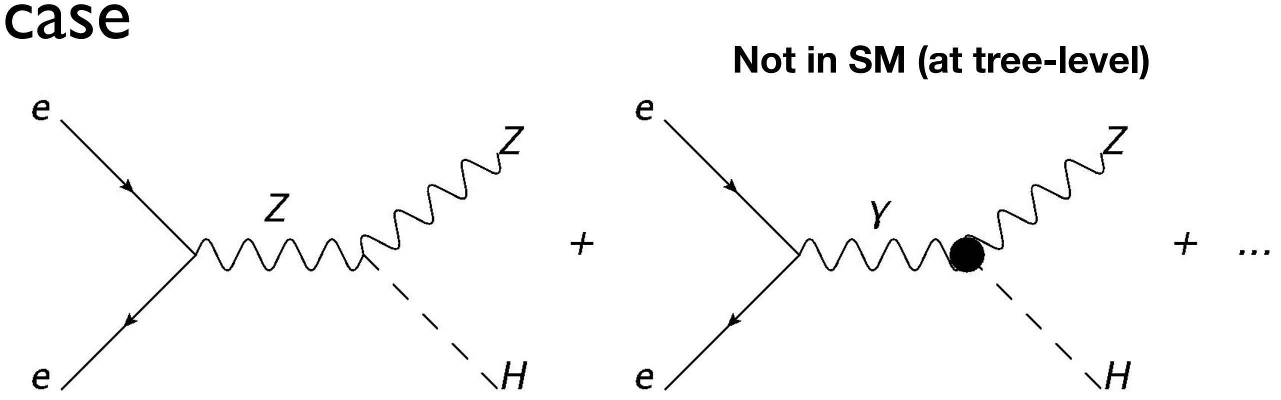
Most of the palliative effect comes from polarization: it separates contributions from γ-exchange diagrams

Interplay EW/Higgs in the dimension-6 SMEFT fit

Impact of polarization



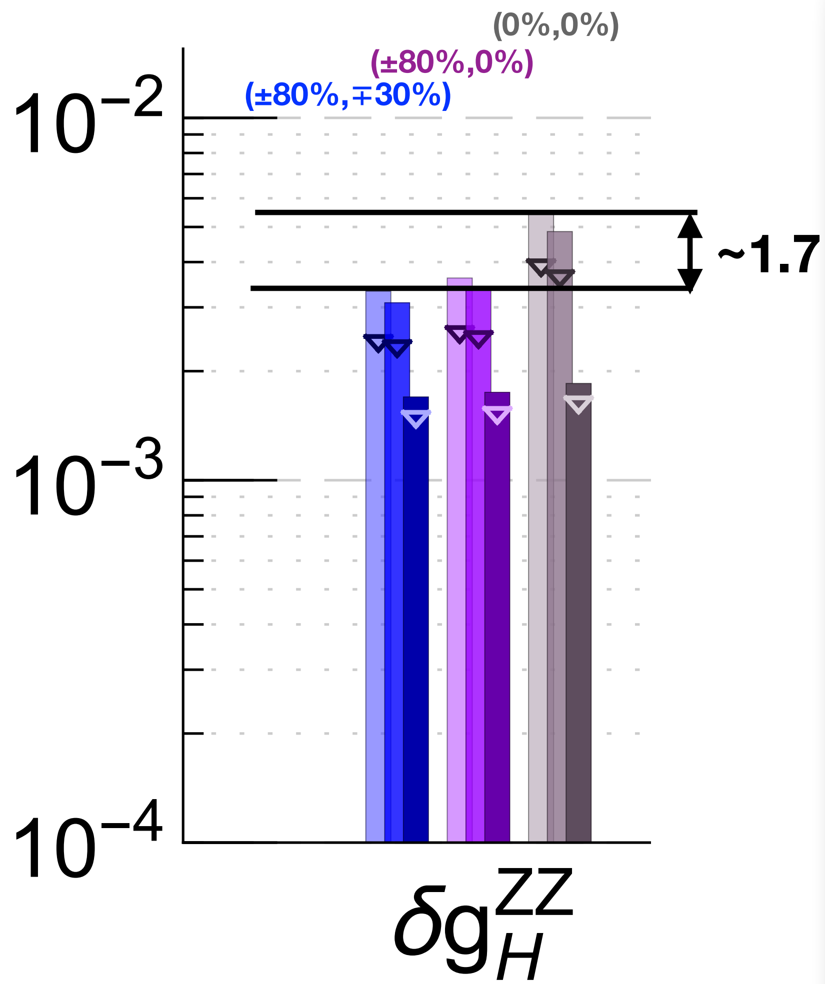
- Polarization solves degeneracies appearing in the ZH rate in the unpolarized case



$g_{Z,L}^{ee} \approx -g_{Z,R}^{ee}$ ⇒ **interference with Zγ diagrams cancel (approximately) for unpolarized beams**

Interplay EW/Higgs in the dimension-6 SMEFT fit

Impact of polarization



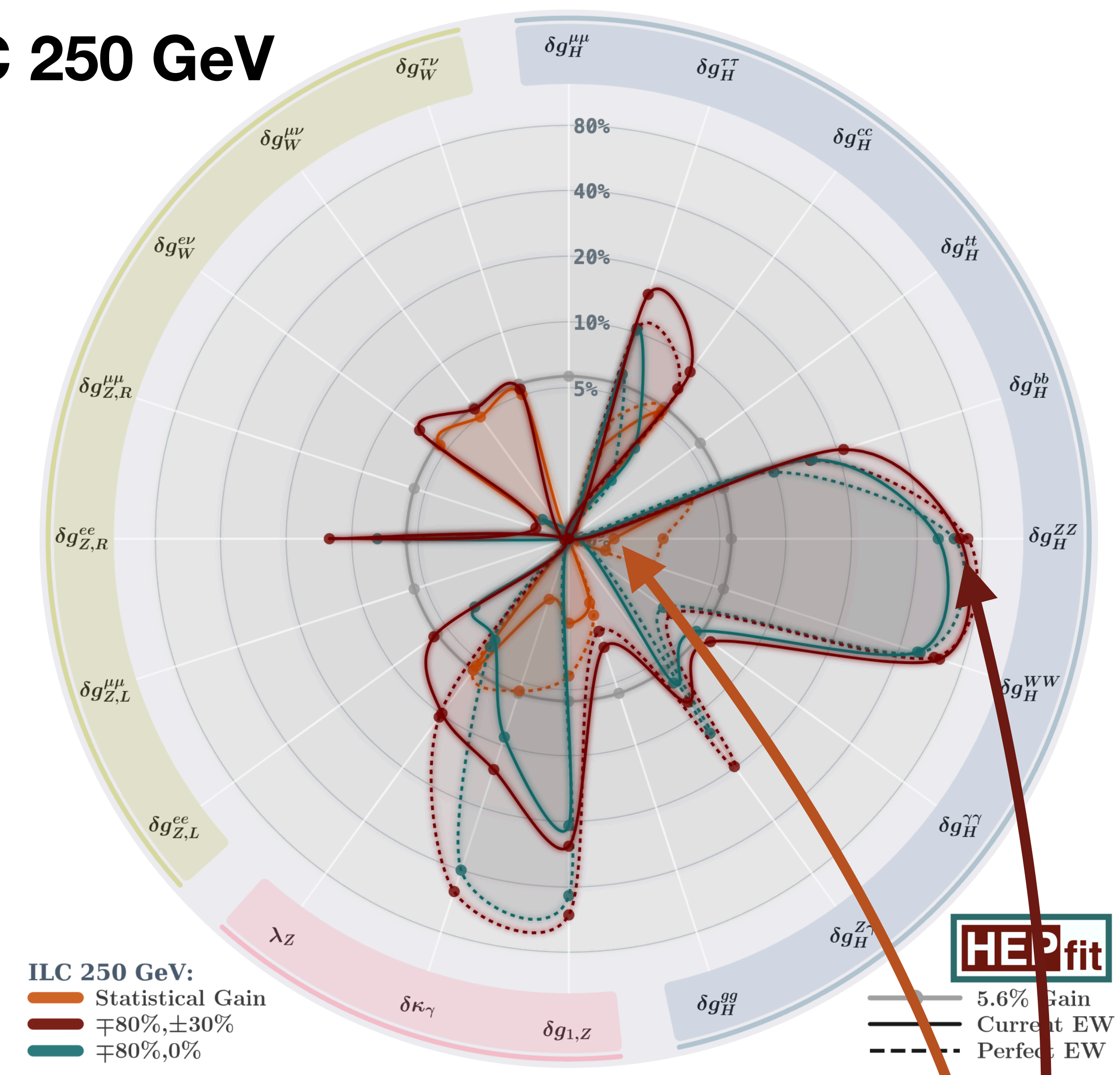
ILC 250+350+500 GeV

Similar effect achieved by using multiple energies

→Negligible effect at 500 GeV

More than an effect of increased statistics

ILC 250 GeV



$\delta g_{unpol.}/\delta g_{unpol.(L\times1.12)}$ -1 : Increased stats.

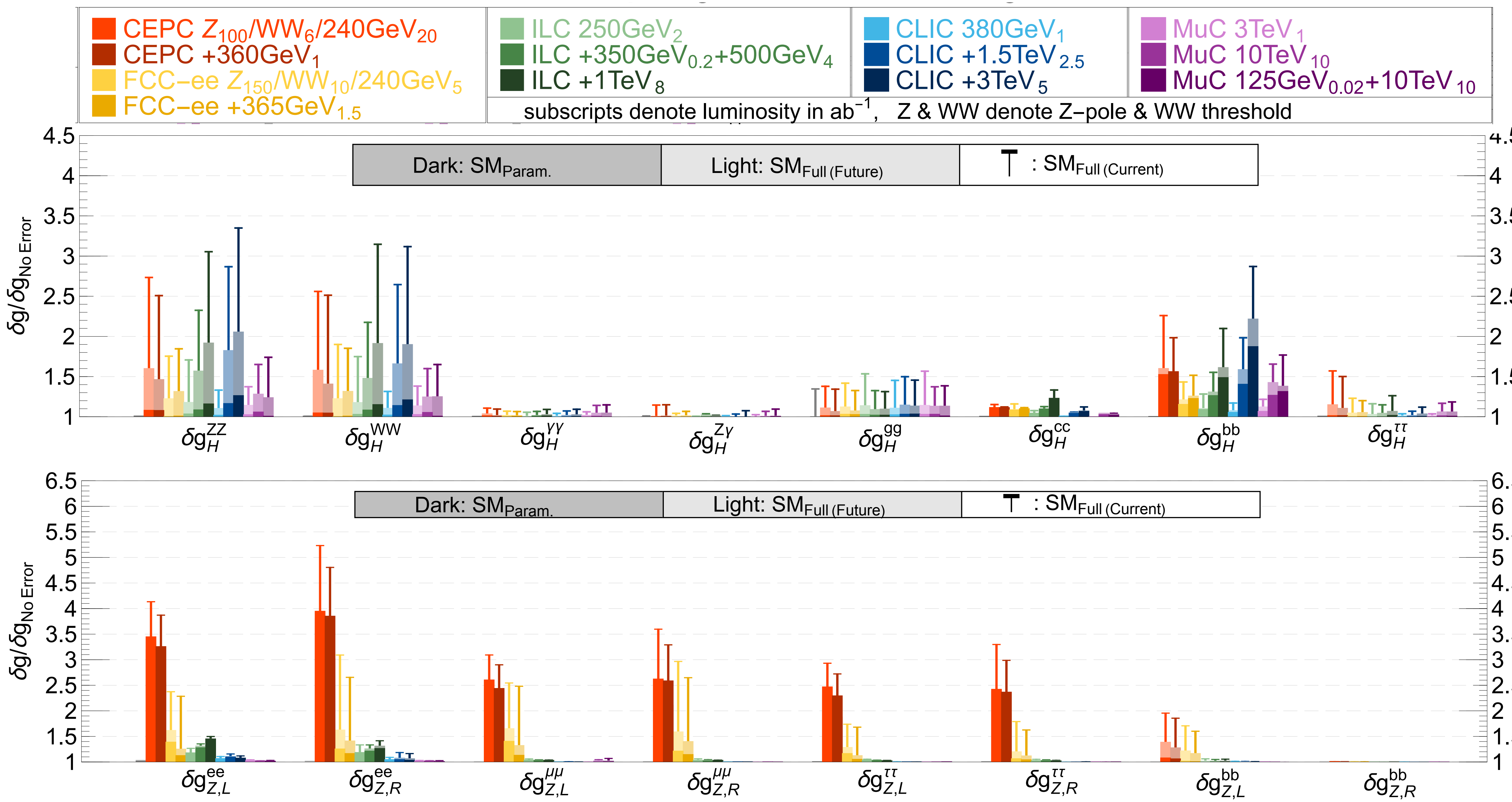
$\delta g_{unpol.}/\delta g_{(\pm80\%,\mp30\%)}$ -1 : Increased stats. + resolving degeneracies

Theory challenges

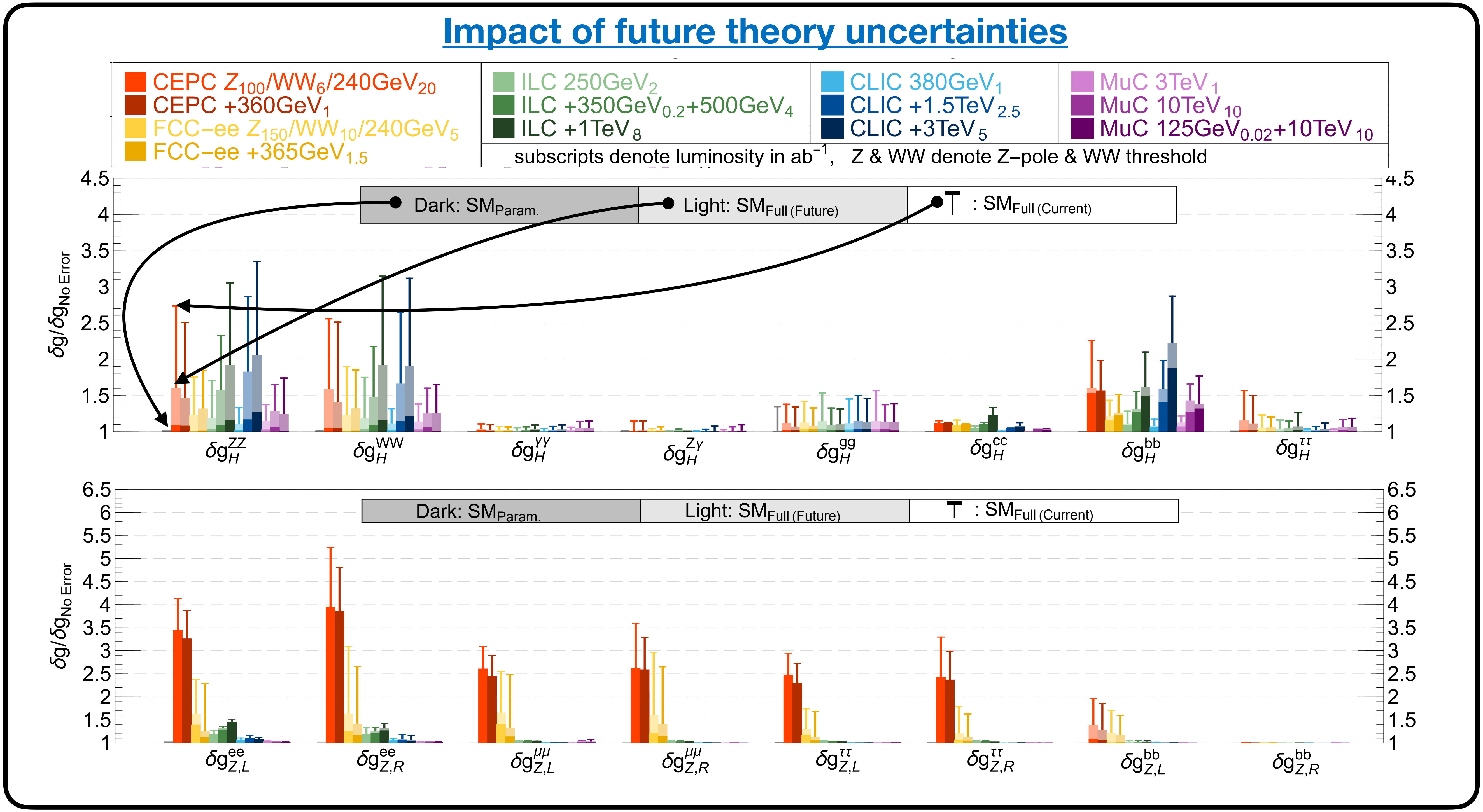
Impact of SM theory calculations

EW/Higgs couplings in the dimension-6 SMEFT fit

Impact of future theory uncertainties



EW/Higgs couplings in the dimension-6 SMEFT fit



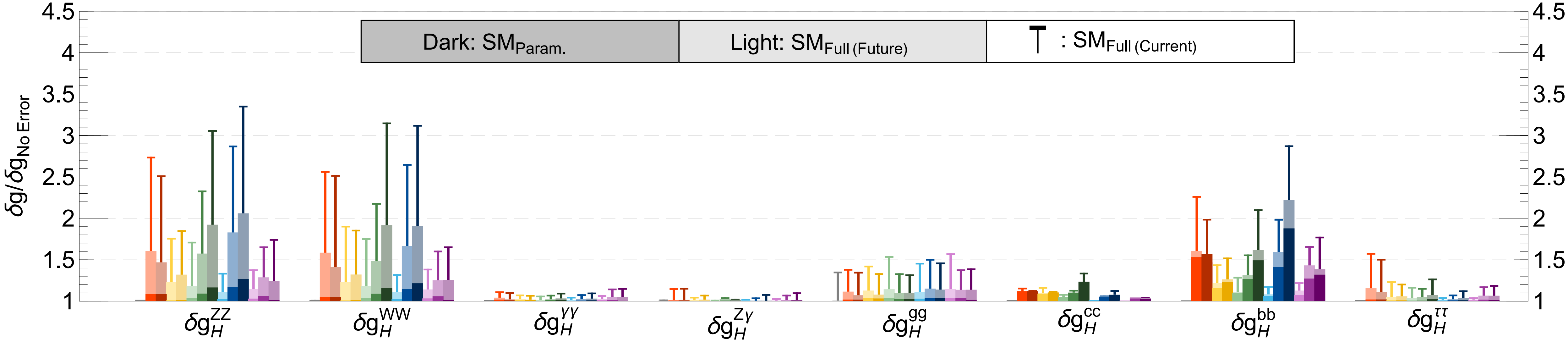
$SM_{Param.}$: Consider only SM parametric uncertainties (Default)

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

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

EW/Higgs couplings in the dimension-6 SMEFT fit

Impact of future theory uncertainties: Higgs



Production

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

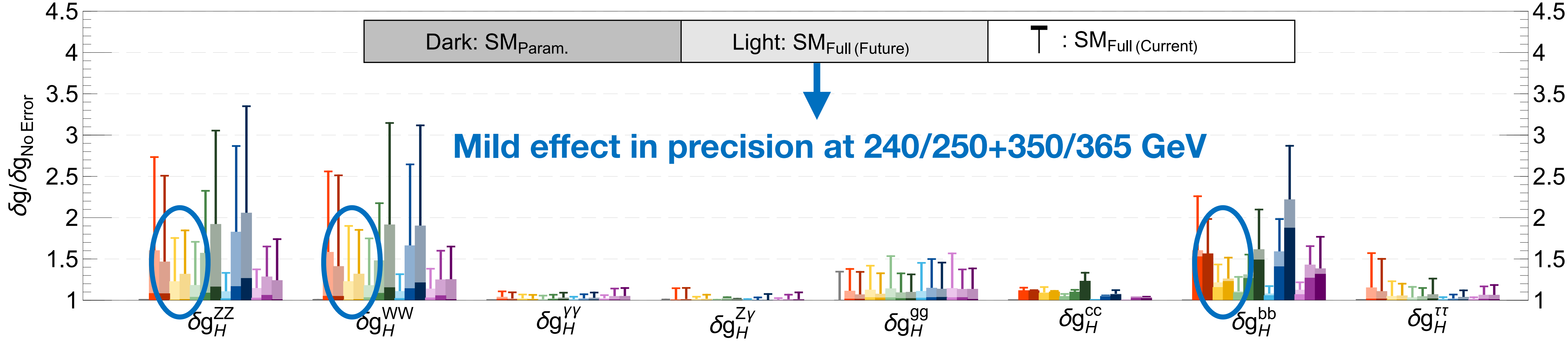
*See A. Freitas, Q. Song, arXiv: 2209.07612, X. Chen et al., arXiv: 2209.14953 for recent results

Decay

Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}^{m_q}$	$\mathrm{Th}_{\mathrm{Par}}^{\alpha_s}$	$\mathrm{Th}_{\mathrm{Par}}^{m_H}$	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}^{m_q}$	$\mathrm{Th}_{\mathrm{Par}}^{\alpha_s}$	$\mathrm{Th}_{\mathrm{Par}}^{m_H}$
$H \to b\bar{b}$	< 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

EW/Higgs couplings in the dimension-6 SMEFT fit



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$e^+e^- \to ZH$	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

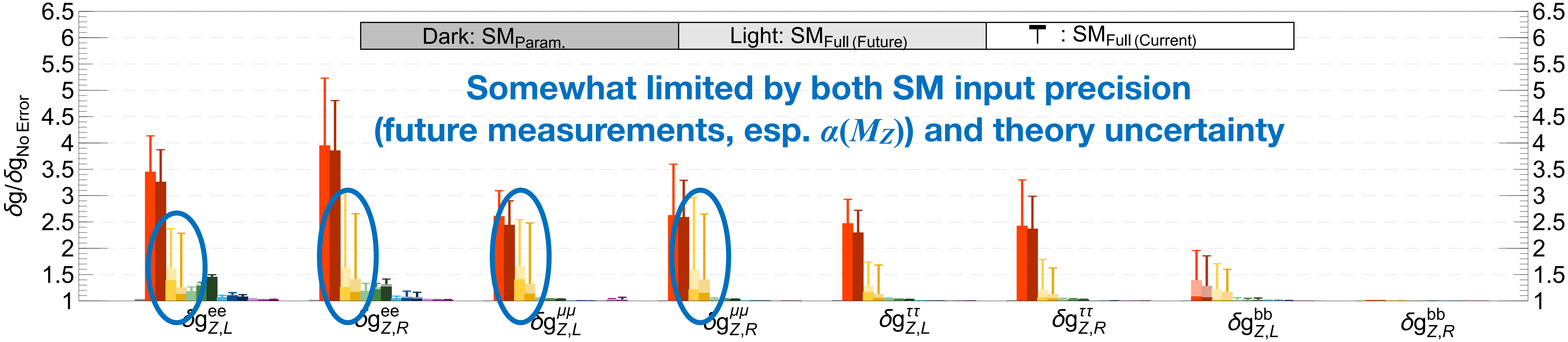
Decay

Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	$\mathrm{Th_{Intr}}$	$\mathrm{Th^{m_q}_{Par}}$	$\mathrm{Th^{\alpha_s}_{Par}}$	$\mathrm{Th^{m_H}_{Par}}$	$\mathrm{Th_{Intr}}$	$\mathrm{Th^{m_q}_{Par}}$	$\mathrm{Th^{\alpha_s}_{Par}}$	$\mathrm{Th^{m_H}_{Par}}$
$H \to b\bar{b}$	< 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

EW/Higgs couplings in the dimension-6 SMEFT fit

Impact of future theory uncertainties: EW



EWPO calculations

Current: 2-loop calculations + leading 3-loop

L. Chen, A. Freitas, SciPost Phys.Proc. 7 (2022) 019

Future projections assume full 3-loop + leading 4-loop (Y_t enhanced)

EWPO	current unc. ΔO		future unc. ΔO	
	Th$_{\text{Intr}}$	Th$_{\text{Par}}$	Th$_{\text{Intr}}$	Th$_{\text{Par}}$
M_W [MeV]	4	4.2	1	2.4/0.6
$\sin^2\theta_W$	$5\cdot10^{-5}$	$4\cdot10^{-3}$	$1.5\cdot10^{-5}$	$4.5\cdot10^{-5}/10^{-5}$
Γ_Z [MeV]	0.4	0.6	0.15	0.16/0.1
σ^0_{had} [pb]	6	5.3	n/a	1/1
R^0_ℓ	$6\cdot10^{-3}$	$6.3\cdot10^{-3}$	$1.5\cdot10^{-3}$	$1.5\cdot10^{-3}/1.2\cdot10^{-3}$
R^0_c	$5\cdot10^{-5}$	$2\cdot10^{-5}$	n/a	$4.7\cdot10^{-6}/3.9\cdot10^{-6}$
R^0_b	$11\cdot10^{-5}$	$2\cdot10^{-5}$	$5\cdot10^{-5}$	$2.8\cdot10^{-6}/2.3\cdot10^{-6}$

Summary

Summary

- EW/Higgs physics at future e^+e^- colliders will bring a giant step forward with respect to HL-LHC:
  - ✓ Increase precision x10→per-mile level in Higgs couplings (not ratios)
  - ✓ Access to interactions not easy or impossible to access at HL-LHC:
    - ▸ Charm Yukawa
    - ▸ Improved determination of self-coupling
  - ✓ Higgs width with 1% precision
- Optimizing Higgs precision also relies in other measurements of the EW sector: Z-pole observables, diBoson production, adding to the own value of those measurements
- Current studies the EW/Higgs precision physics program at e^+e^- allows to test around O(30) from EW/Higgs measurements…
- … But still a lot of work to do:
  - ✓ Strange Yukawa, light quark EW interactions, CP-violation, Flavor violating couplings,…
  - ✓ Projections: systematics in WW?

Summary

- Ongoing efforts as part of the ECFA e^+e^- Higgs/EW/Top factory studies:

ECFA
European Committee for Future Accelerators

ECFA workshops on e+e- Higgs/EW/Top factory

May 31, 2021 to September 30, 2025
Europe/Zurich timezone

Enter your search term

- Overview and Activities
- WG1 group activities
- WG2 group activities
- WG3 group activities
- Focus Topics
- Committees
- E-groups

Overview and Activities

Based on the recommendations of the European Strategy for Particle Physics Update, the European Committee for Future Accelerators (ECFA) has launched a series of workshops on physics studies, experiment design, and detector technologies towards a future electron-positron Higgs/EW/Top factory. The aim is to bring together the efforts of various e^+e^- projects, to share challenges and expertise, to explore synergies, and to respond coherently to this high-priority strategy item.

To set up the relevant structures and to define a path towards such workshops, an International Advisory Committee (IAC) was formed, which established three Working Groups led by conveners from both experiment and theory.

For information on the ECFA study activities, please see the wiki pages:

https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories

Backup slides

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 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 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	-