Seattle Snowmass Summer Meeting 2022
July 21, 2022

Higgs/EW Fit
From the HL-LHC to $\mu^+ \mu^-$ colliders

Jorge de Blas
University of Granada

Based on:
J.B., Y. Du, C. Grojean, J. Gu, V. Miralles, M. Peskin, J. Tian, M. Vos, E. Vryonidou
arXiv: 2206.08326 [hep-ph]

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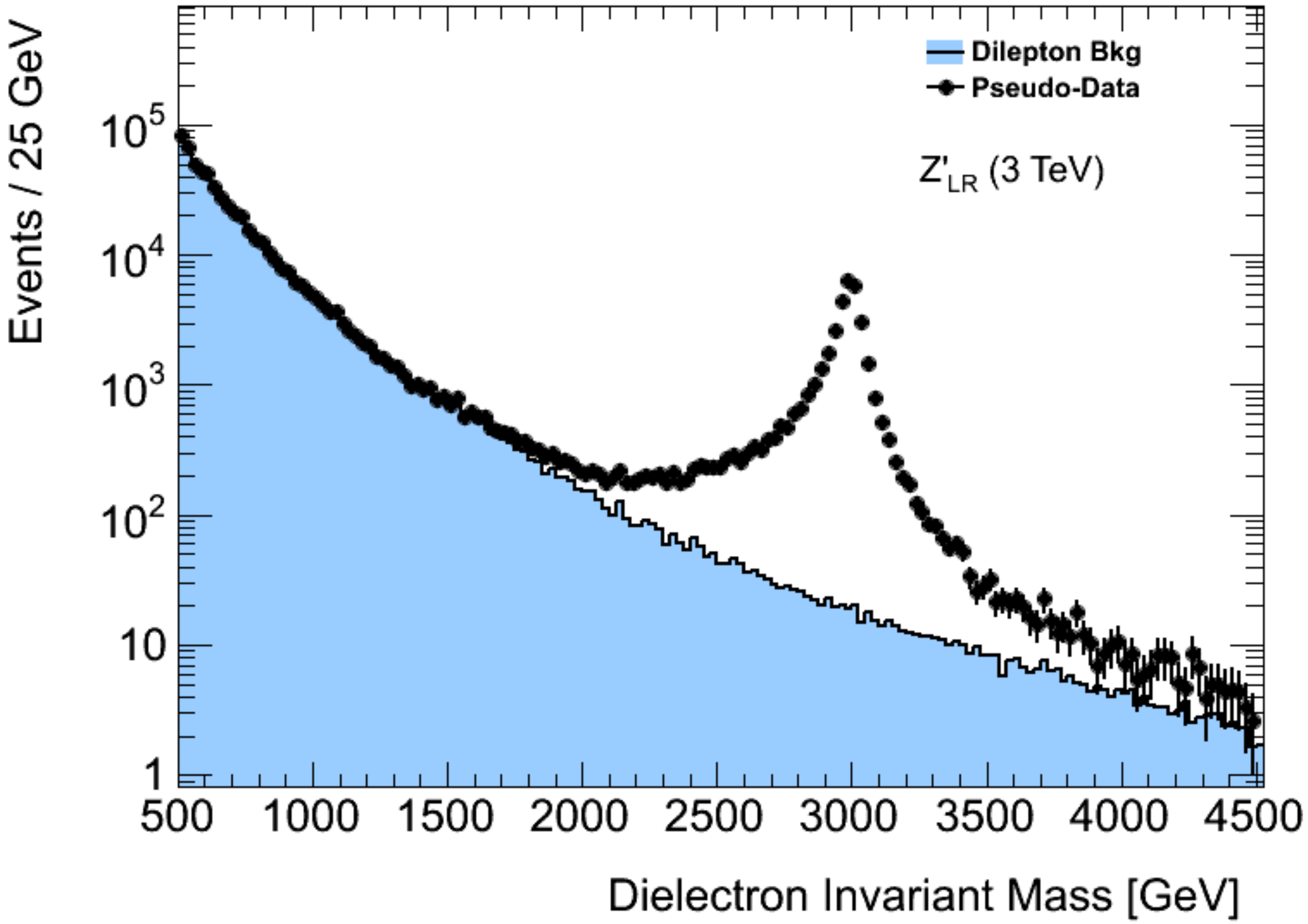
Effective Field Theories

- 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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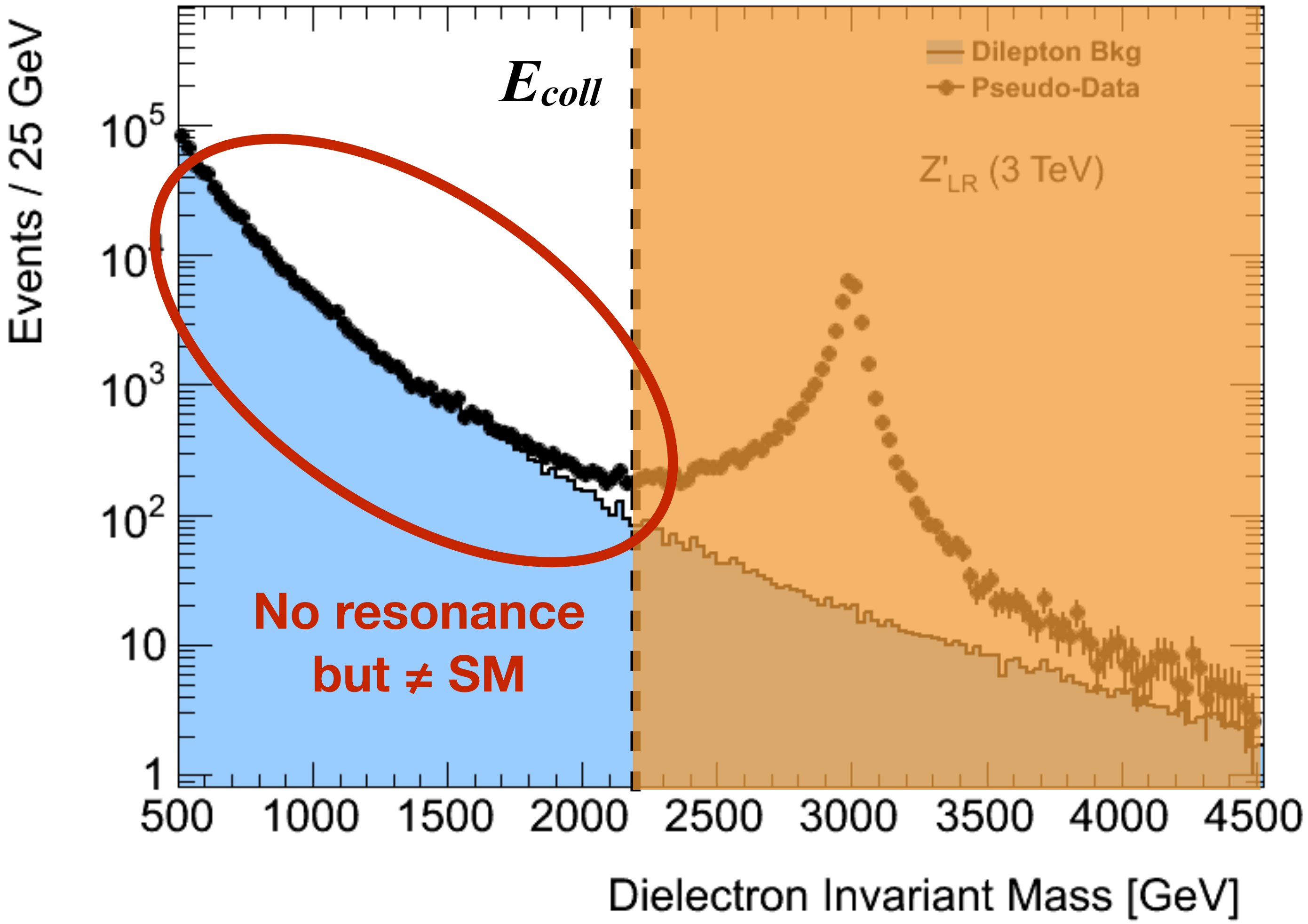
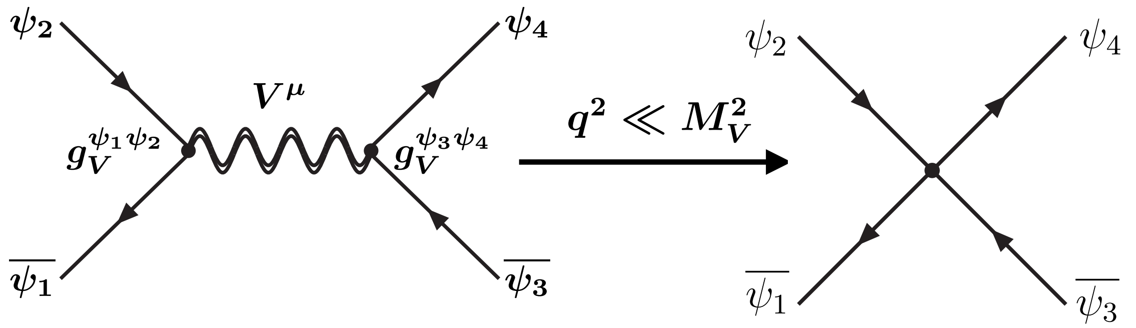


No resonance but ≠ SM

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

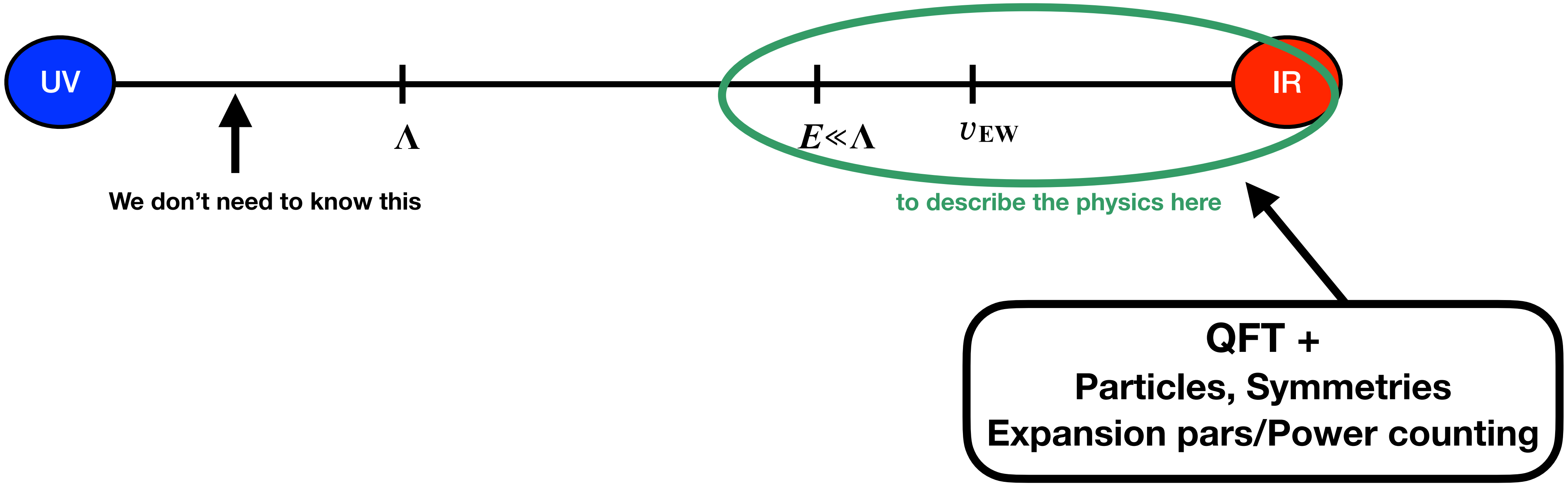


In general, the whole set of such possible deformations can be studied with minimal reference to the nature of the UV theory

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{Z'} + \mathcal{L}_{\mathrm{SM}-Z'} \quad \xrightarrow{q^2 \ll M_V^2} \quad \mathcal{L}_{\mathrm{Eff}}$$

Effective Field Theories

- The philosophy of Effective Field Theories:



QFT +
Particles, Symmetries
Expansion pars/Power counting

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

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

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

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

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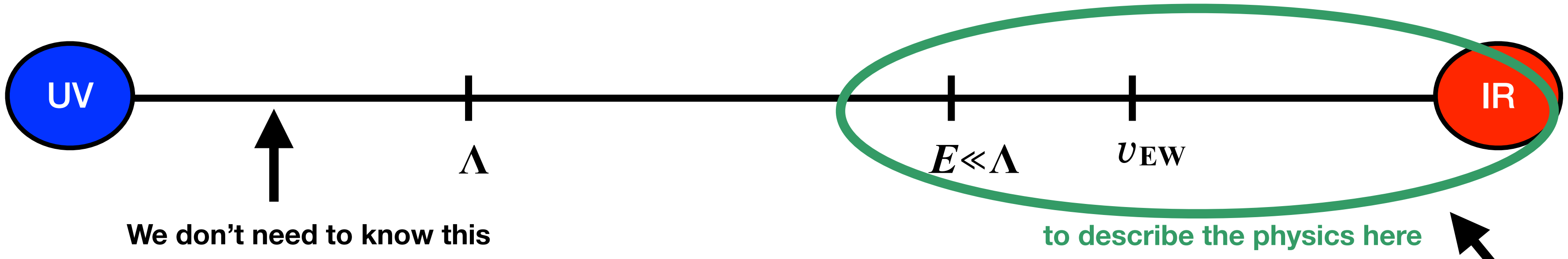

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$$q = v, E < \Lambda$$

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

Effective Field Theories: The SMEFT

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

Warsaw basis operators (Neglecting flavour)

Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)\,(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)\,(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)\,(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)\,(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\,i\sigma_2\,(\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\,i\sigma_2\,(\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
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$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde{\phi}\,B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde{\phi}\,W_{\mu\nu}^a$	$\mathcal{O}_{uW}$
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$\phi^\dagger\phi\;B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\;\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
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$\phi^\dagger\sigma_a\phi\;W_{\mu\nu}^aB^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\;\widetilde{W}_{\mu\nu}^aB^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
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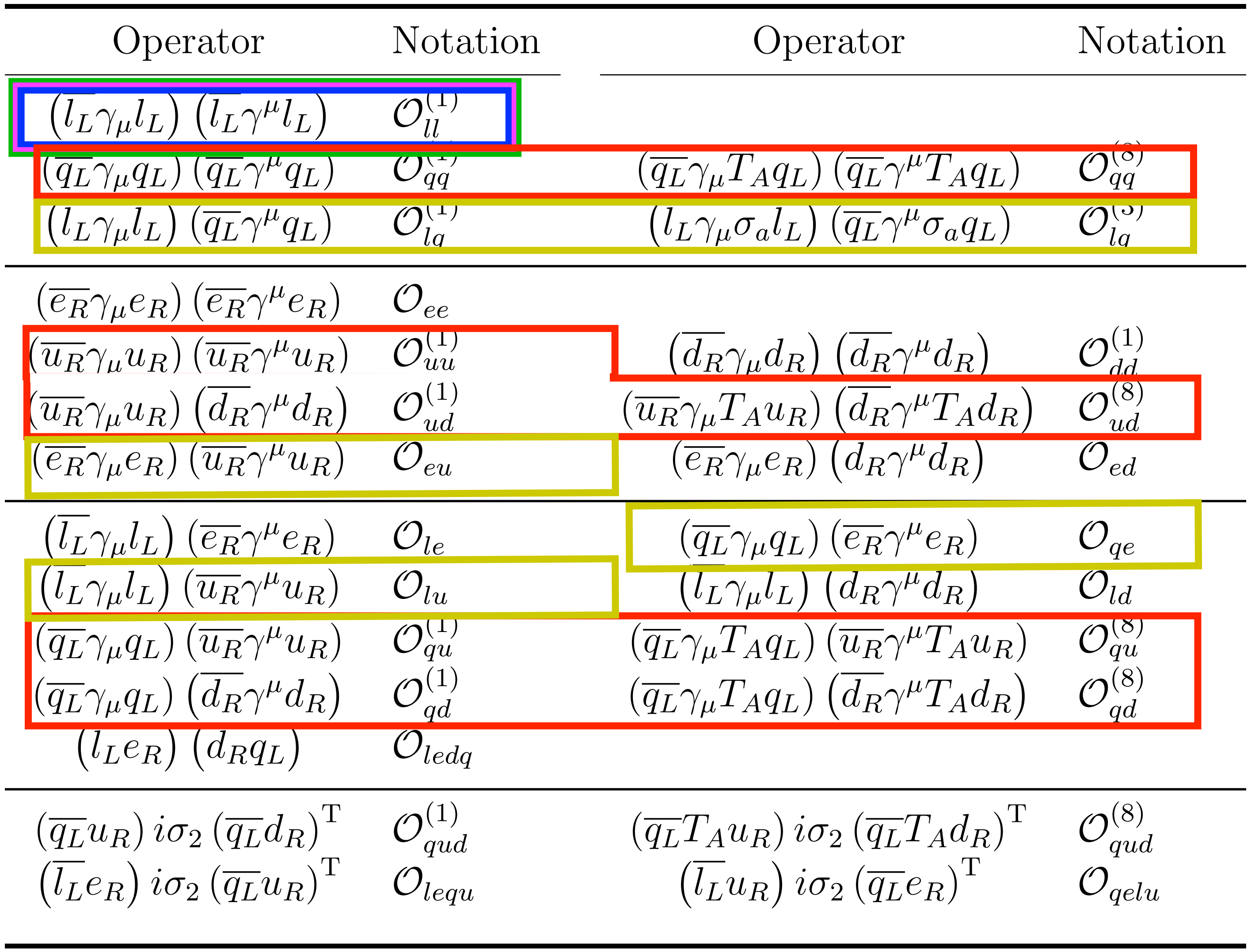

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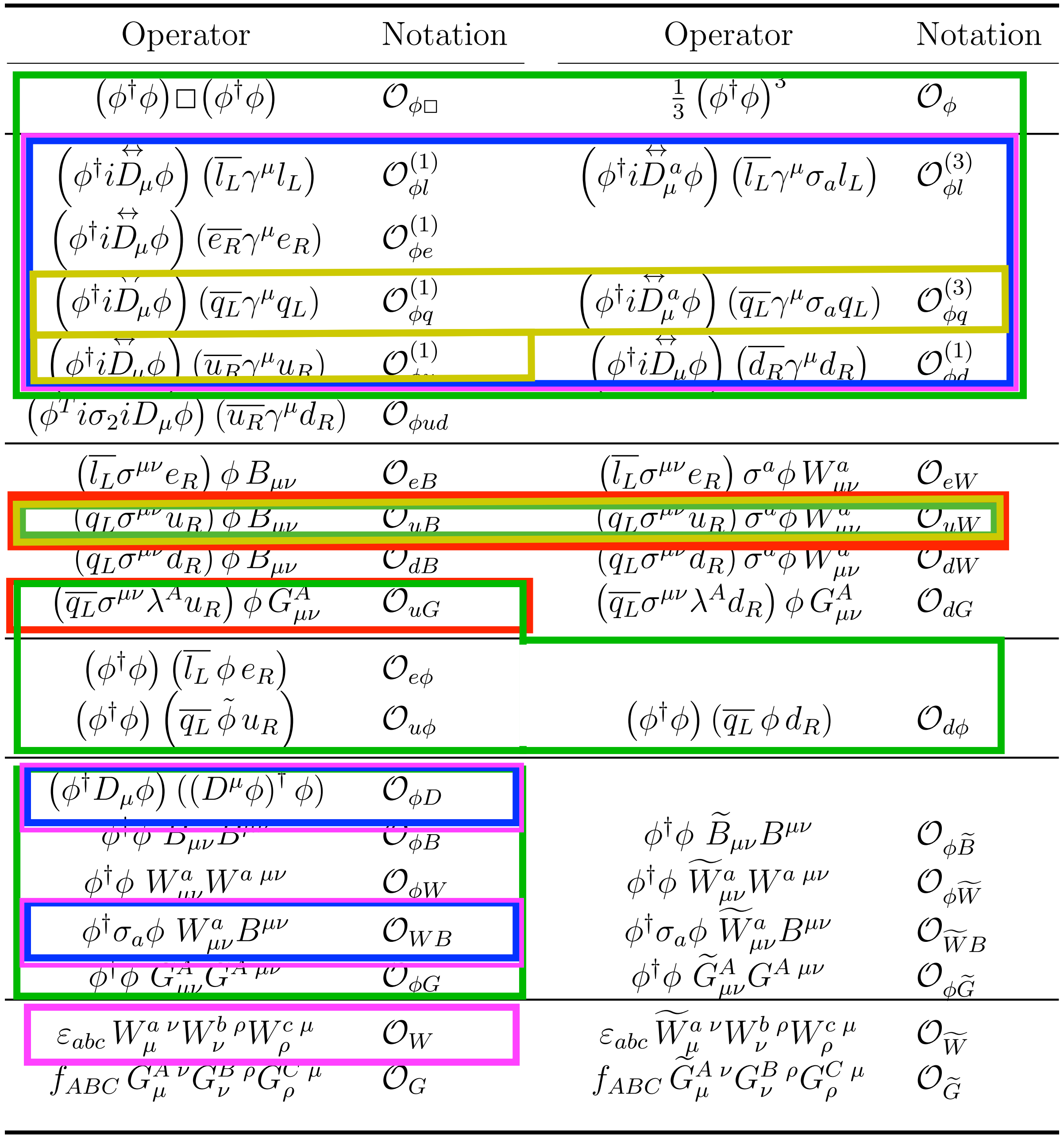

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CP-even dim 6 ops. interfering with SM

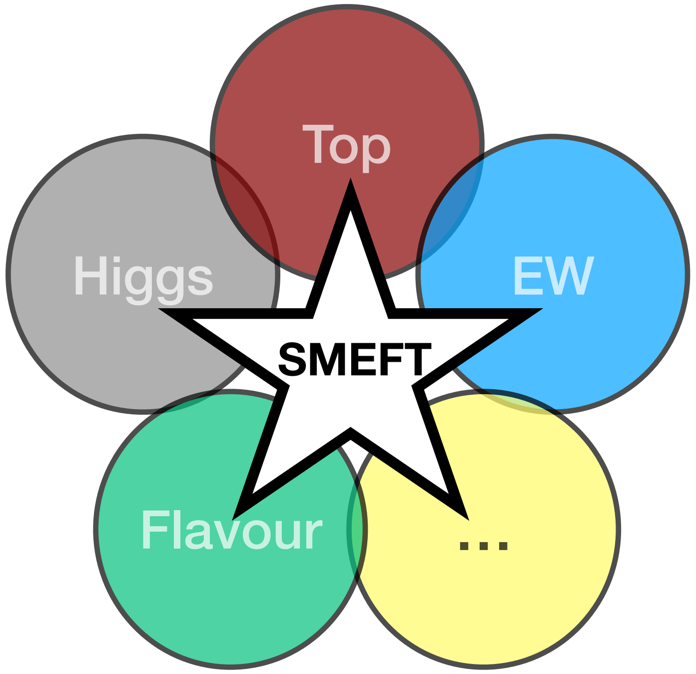
EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

Global SMEFT analyses

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

  "Model-independent" only when including ALL contributing operators

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



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

⇒ Use Global fit (i.e. EW/Higgs/Top/Flavor) to constraint all directions

- In this talk I will introduce (and discuss part of) the global SMEFT studies performed for the Snowmass.

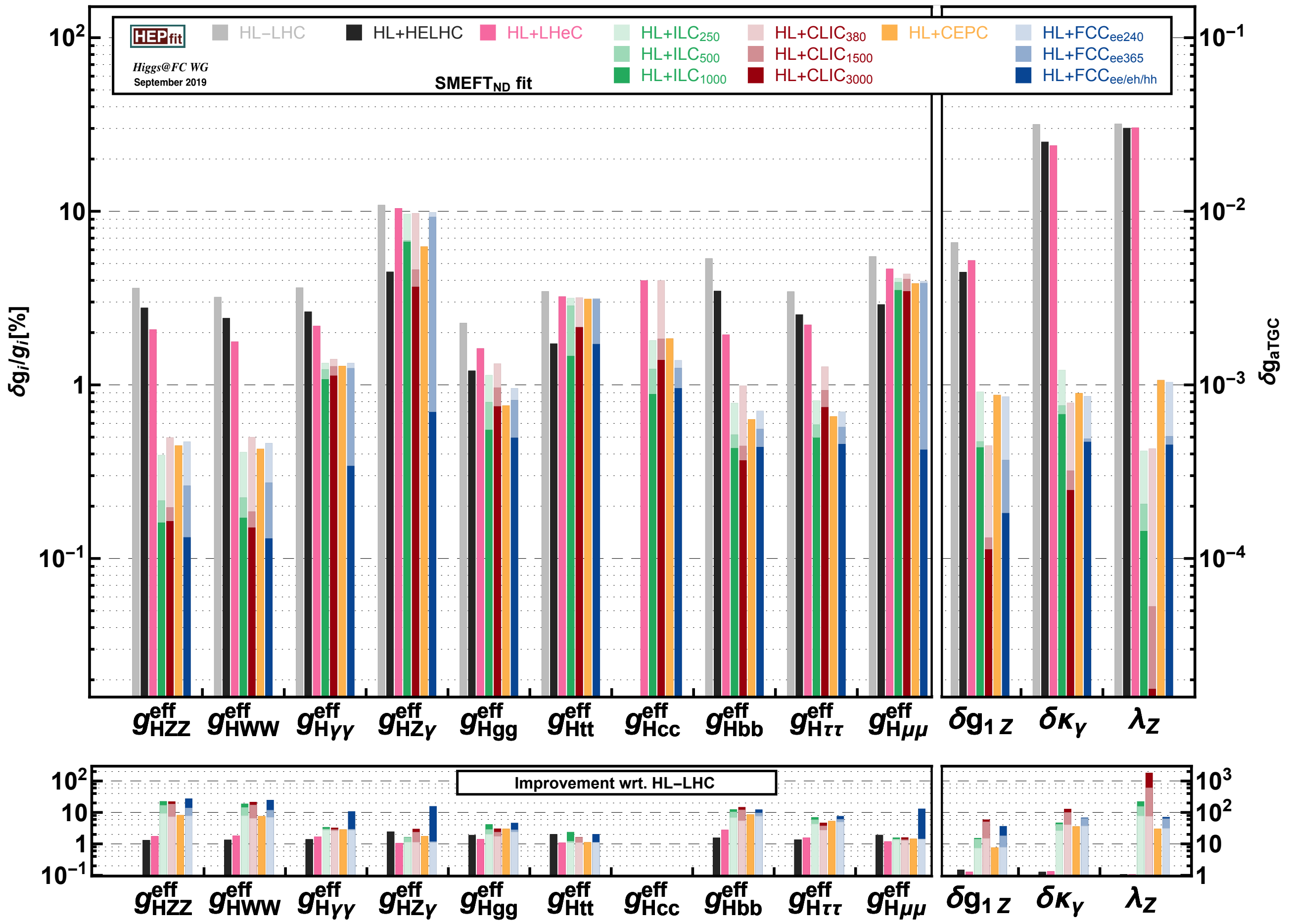
- More details in the following talks by M. Peskin, V. Miralles and Y. Du.

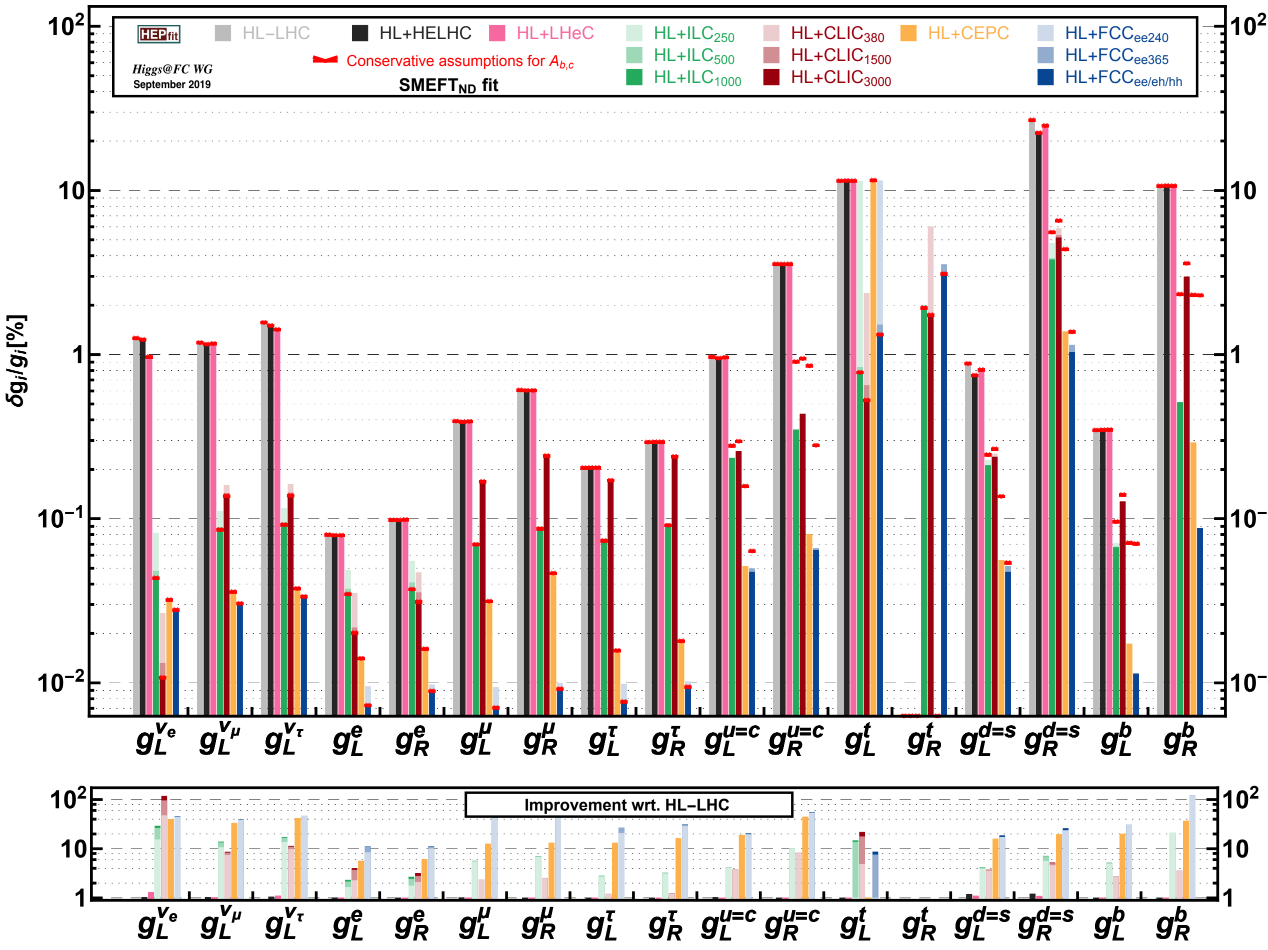
SMEFT studies at future colliders:

From the ESU2020 to Snowmass

SMEFT studies: ESU2020 → Snowmass

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





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

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

- Expressed in terms of "effective couplings":

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

SMEFT studies: ESU2020 → Snowmass

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

European Strategy Update

Inputs of SMEFT fits

Higgs

Rates (signal strength)

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

(Inclusive) cross section

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

Only possible at lepton colliders

aTGC

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

EWPO

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

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

Z physics via Z-pole:

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

or Rad. Return:

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

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

SMEFT studies: ESU2020 → Snowmass

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

NEW for Snowmass 2021

Inputs of SMEFT fits

Higgs

Rates (signal strength)

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

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

EWPO

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

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

Z physics via Z-pole:

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

or Rad. Return:

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

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

SMEFT studies: ESU2020 → Snowmass

NEW for Snowmass 2021

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

Inpu

HL-LHC *pp→WW, WZ*

EFT parametrisation from

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

Rates (signal strength)

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

(

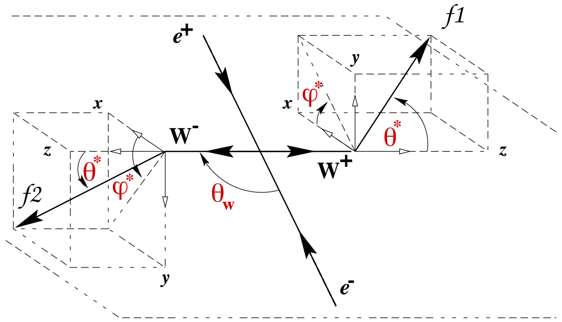
σ

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

Optimal Observable analysis of *e⁺e⁻→W⁻W⁺*

Max. Statistical info

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



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

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

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

See M. Peskin's talk for details

M_Z

$\sqrt{s}$

$\sqrt{s} >$

SMEFT studies: ESU2020 → Snowmass

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

NEW for Snowmass 2021

Inputs of SMEFT fits

Higgs

Rates (signal strength)

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

(Inclusive) cross section

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

Only possible at lepton colliders

aTGC

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

EWPO

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

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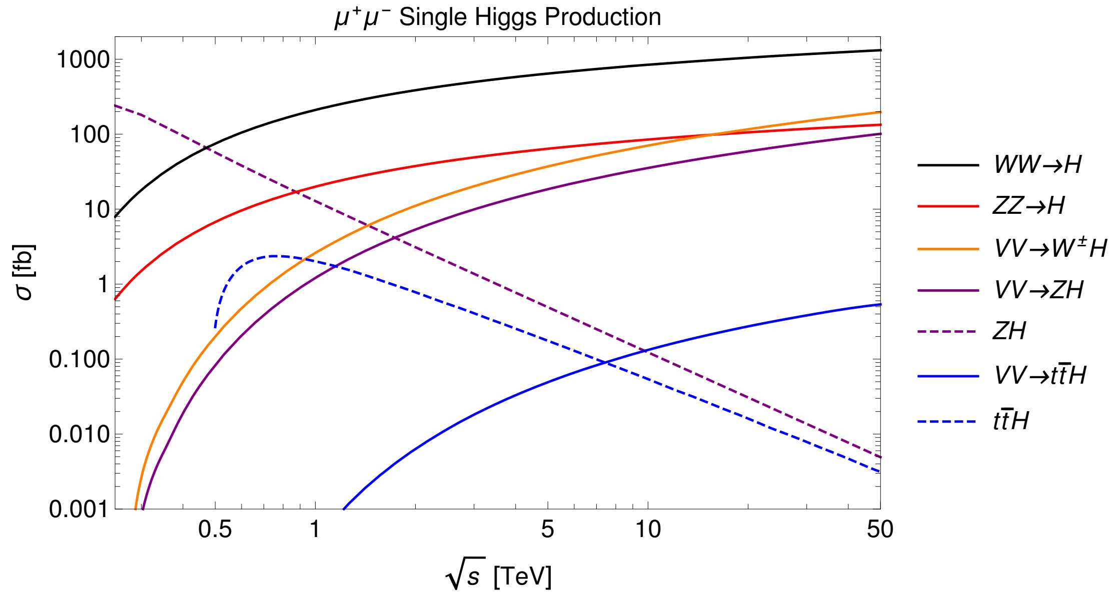
	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)	Top
HL-LHC	Yes (μ)			
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LH			
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LH			
CEPC	Update Yes (μ, σ_{ZH}) (Complete with HL-LH			
CLIC	Yes (μ, σ_{ZH})			
Muon Colliders	Yes (μ) 125 GeV/3 & 10 TeV	Full EFT param.	No. From LEP/SLD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

Muon Collider Higgs precision

High-E: via WBF or ZBF

M. Forslund, P. Meade, arXiv: 2203.09425 [hep-ph]



125 GeV: μμ→H

J.B., J. Gu, Z. Liu, arXiv: 2203.04324 [hep-ph]

SMEFT studies: ESU2020 → Snowmass

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

NEW for Snowmass 2021

Inputs of SMEFT fits

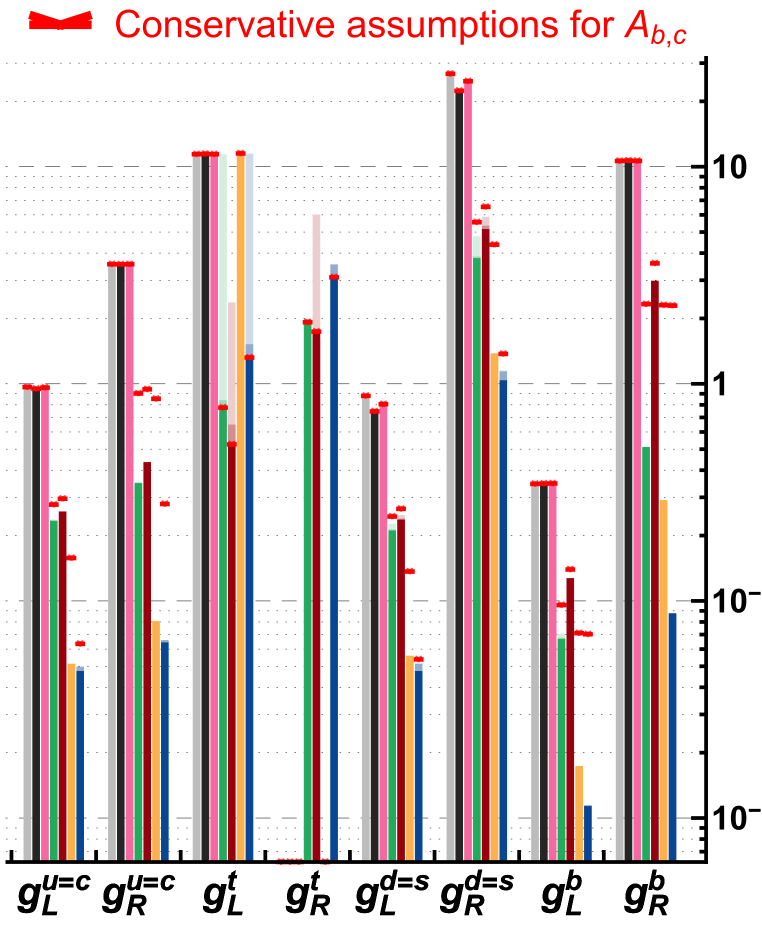
Higgs

Rates (signal strength)

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

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

EWPO updates



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

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

SMEFT studies: ESU2020 → Snowmass

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

Snowmass 2021

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

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

SMEFT studies: ESU2020 → Snowmass

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

SMEFT assumptions

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

Neutral Diagonal: SMEFT$_{\rm ND}$ 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

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

Vff/hVff

5 SM + 30 New Physics Parameters

SMEFT studies: ESU2020 → Snowmass

NEW for Snowmass 2021

- **Snowmass:** Updat

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

Also considered constraints on CP-odd boson operators

See Y. Du's talk in this session

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

4-fermion and dipole operators also included in Top observables

See V. Miralles' talk in this session

-Hff and Vff ($HVff$) diagonal in t

-Vff ($HVff$) flavour universality respected by first 2 quark families

EW

s

-Cumbersome from model-building point of view to avoid FCNC

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

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

Higgs/VVV

Vff/hVff

5 SM + 30 New Physics Parameters

SMEFT studies: ESU2020 → Snowmass

NEW for Snowmass 2021

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

SMEFT assumptions

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- No dipole operators (Relevant for general analysis of Top processes, but are neglected in our studies)
- Two types of flavor assumptions: flavour universal (18 NP pars) and flavour diagonal (30 NP pars)

Working on relaxing this assumption

More on this later…

N

-*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

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

Higgs/VVV

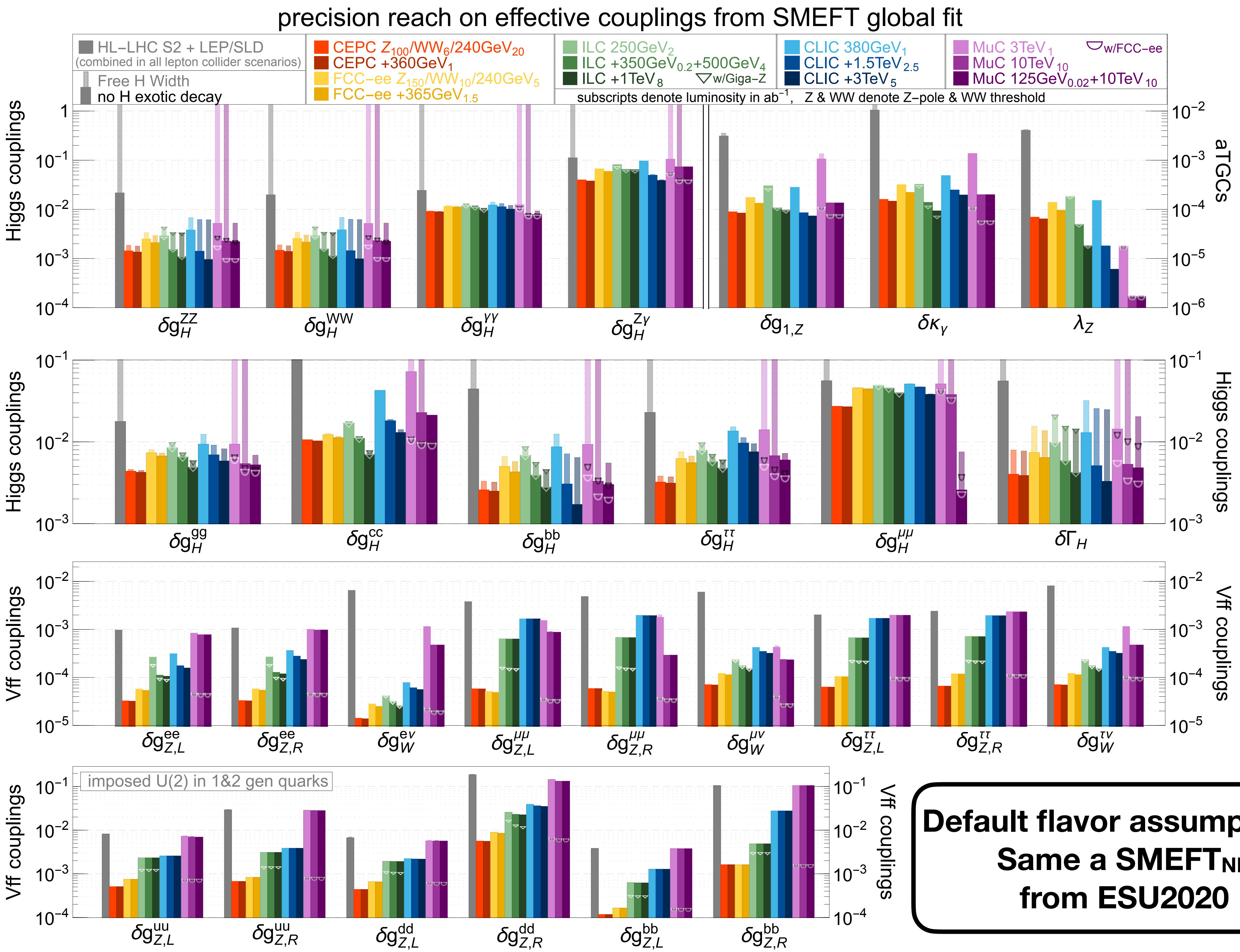
$$\mathrm{SMEFT_{ND}} \equiv \{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\}$$
$$+\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell,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

Vff/hVff

5 SM + 30 New Physics Parameters

Snowmass SMEFT studies:
EW/Higgs fit results

Snowmass SMEFT studies: EW/Higgs fit

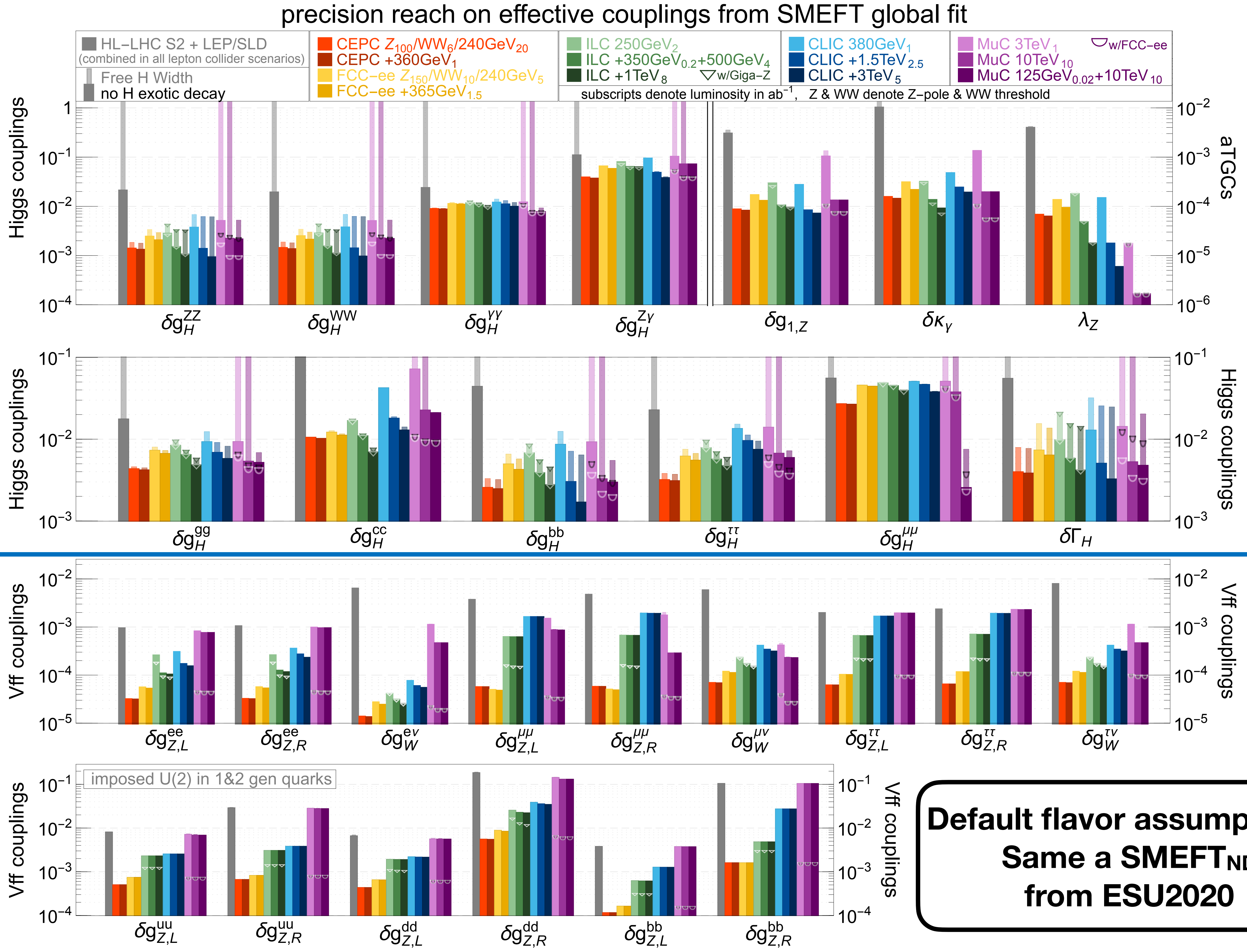

precision reach on effective couplings from SMEFT global fit

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

Snowmass SMEFT studies: EW/Higgs fit

Higgs interactions

aTGC

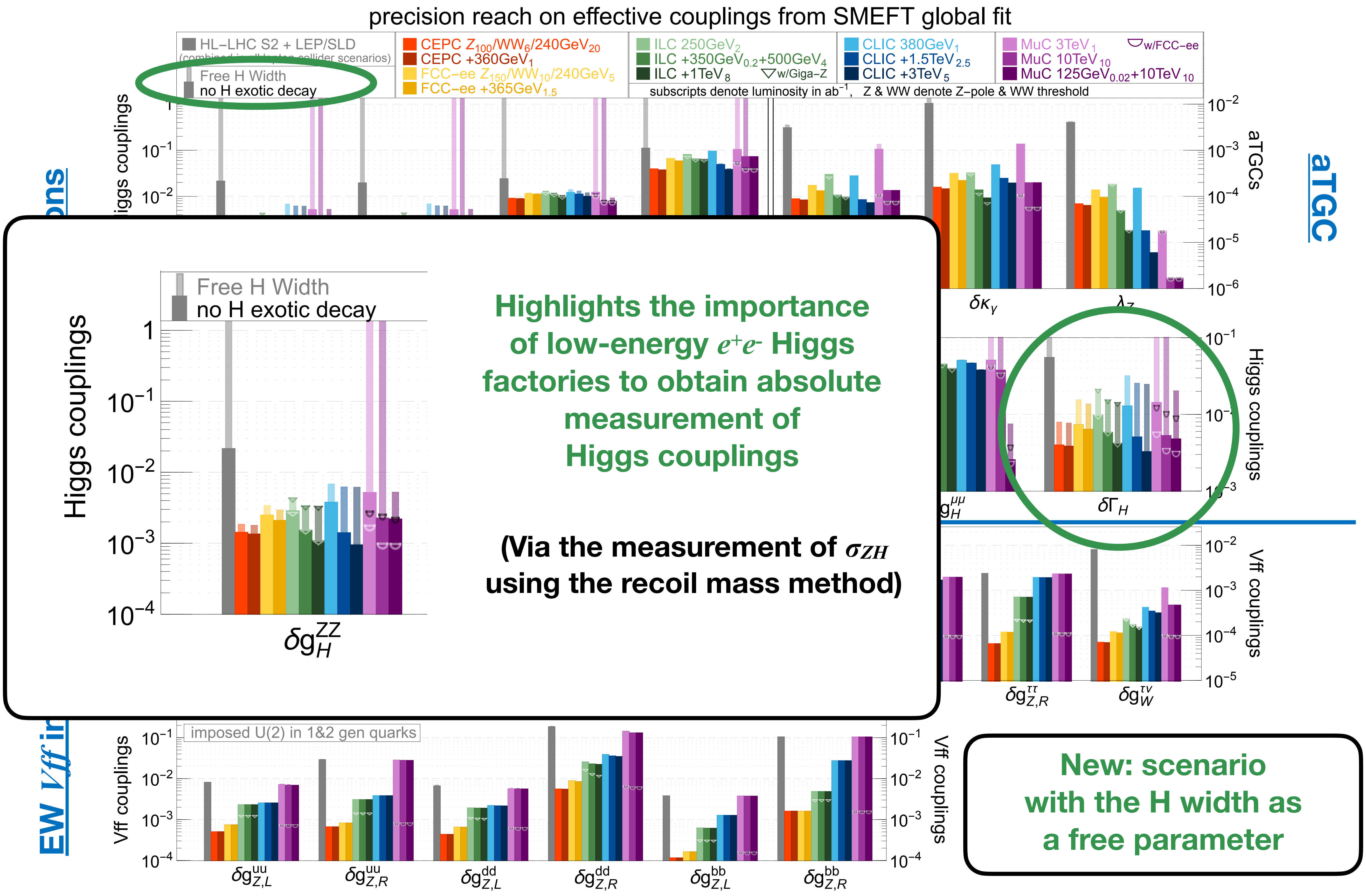


precision reach on effective couplings from SMEFT global fit

EW *Vff* interactions

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

Snowmass SMEFT studies: EW/Higgs fit



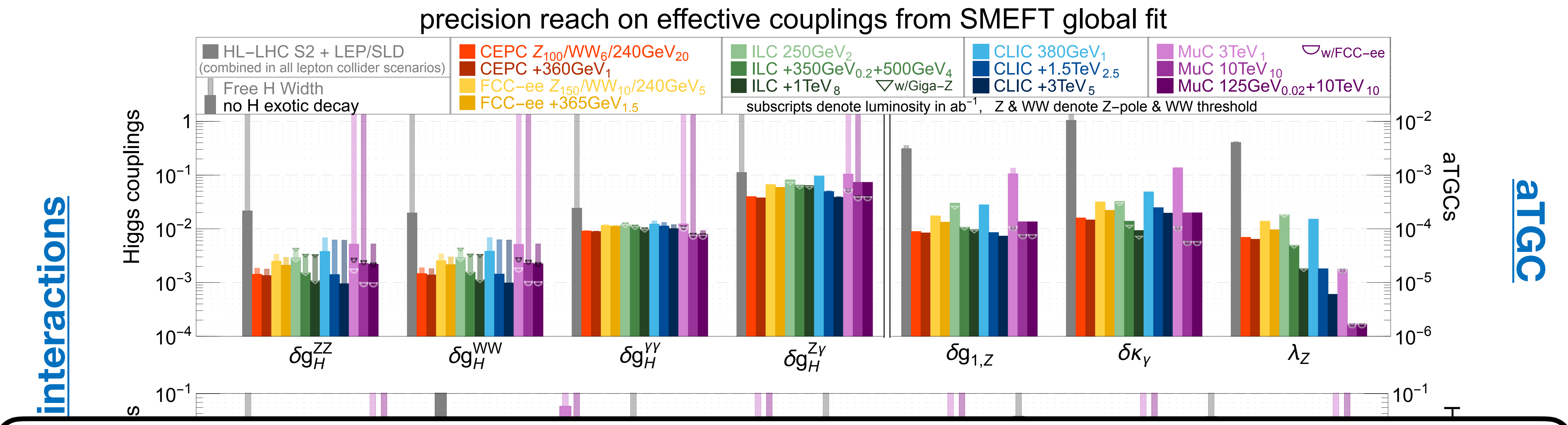
precision reach on effective couplings from SMEFT global fit

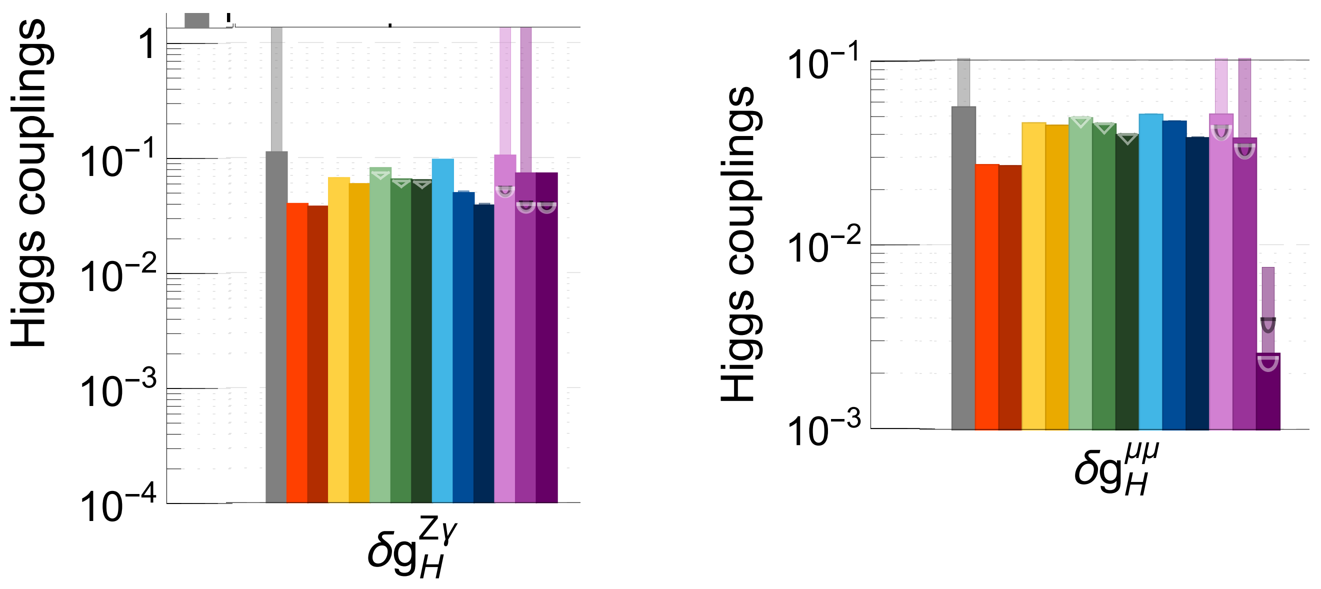
Highlights the importance of low-energy e^+e^- Higgs factories to obtain absolute measurement of Higgs couplings

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

New: scenario with the H width as a free parameter

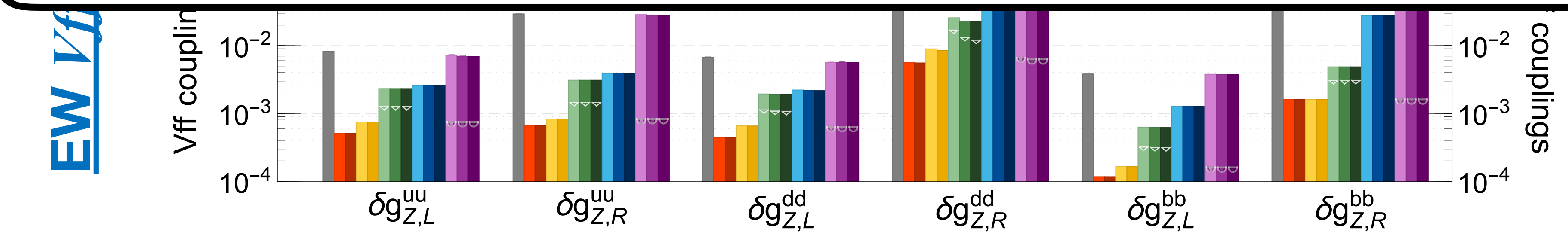
Snowmass SMEFT studies: EW/Higgs fit





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

Everywhere else e^+e^- improves precision typically by factor ~10

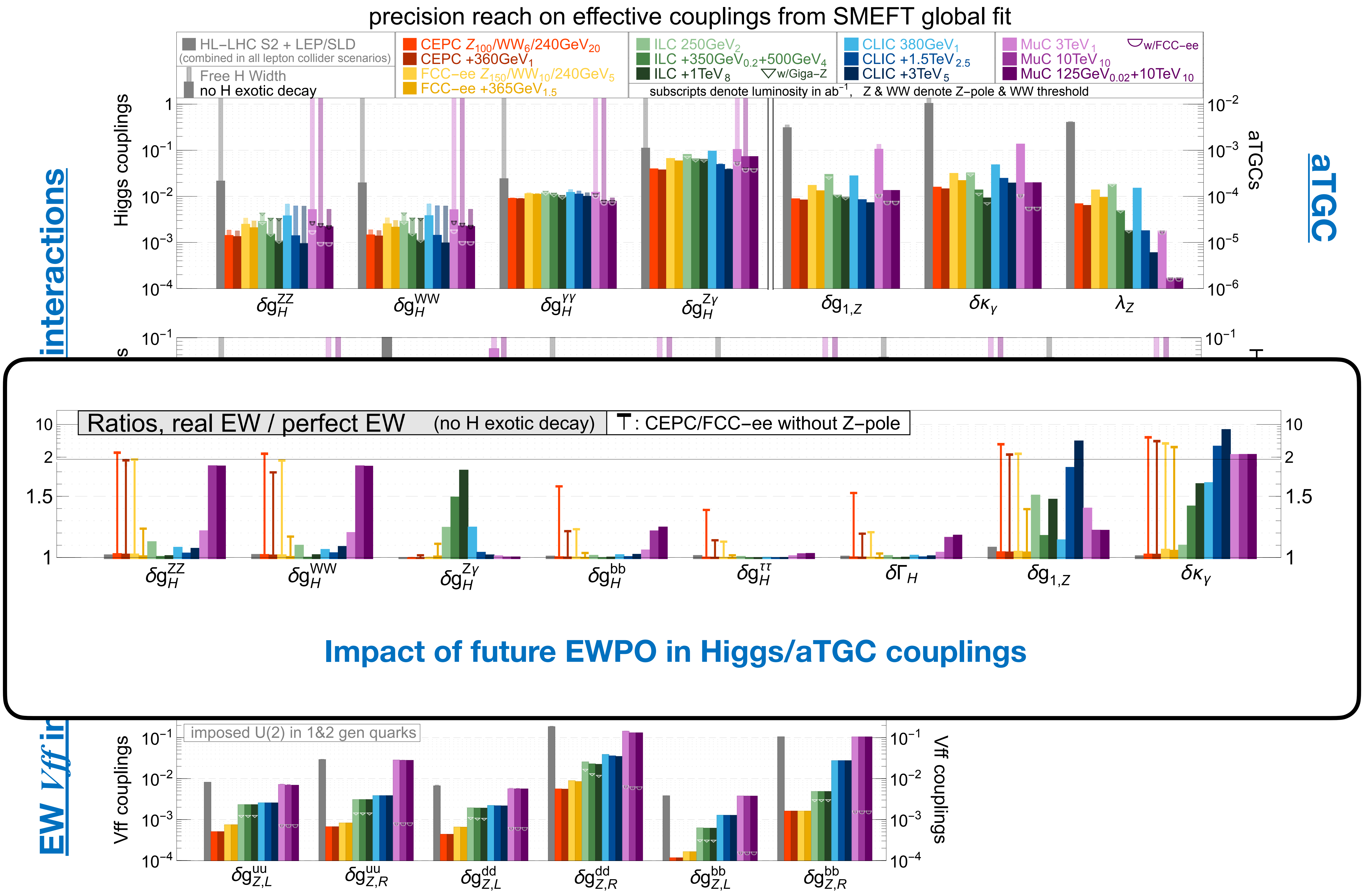


Snowmass SMEFT studies: EW/Higgs fit

interactions

EW *Vff* ir

aTGC

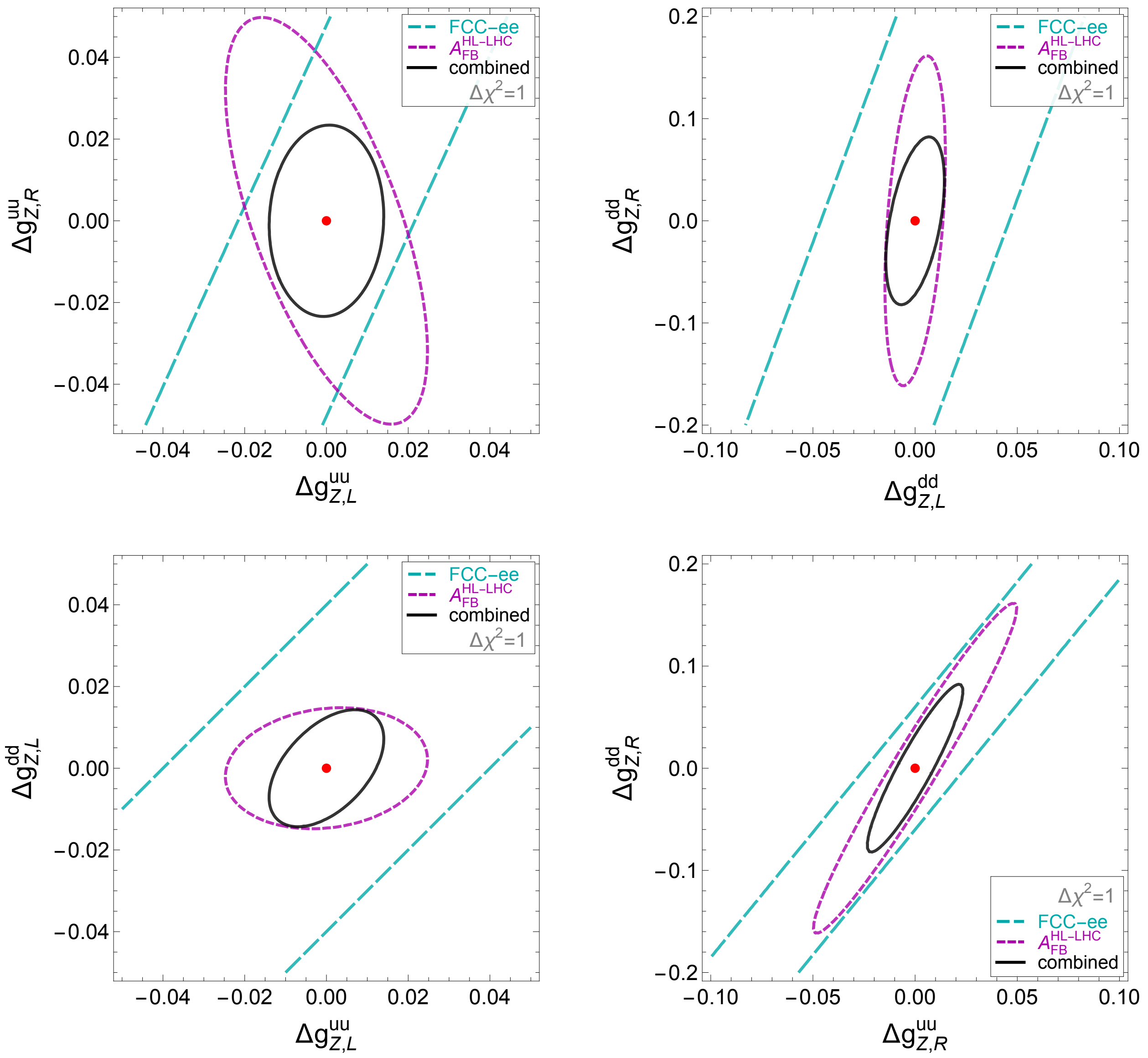


Impact of future EWPO in Higgs/aTGC couplings

Snowmass SMEFT studies: EW/Higgs fit

Preliminary

Relaxing the U(2) quark symmetry: Hadron collider probes of Zqq



1st two quark families cannot be cleanly separated with e^+e^- EWPO

Drell-Yan FB asymmetry at (HL-)LHC as a function of rapidity Y

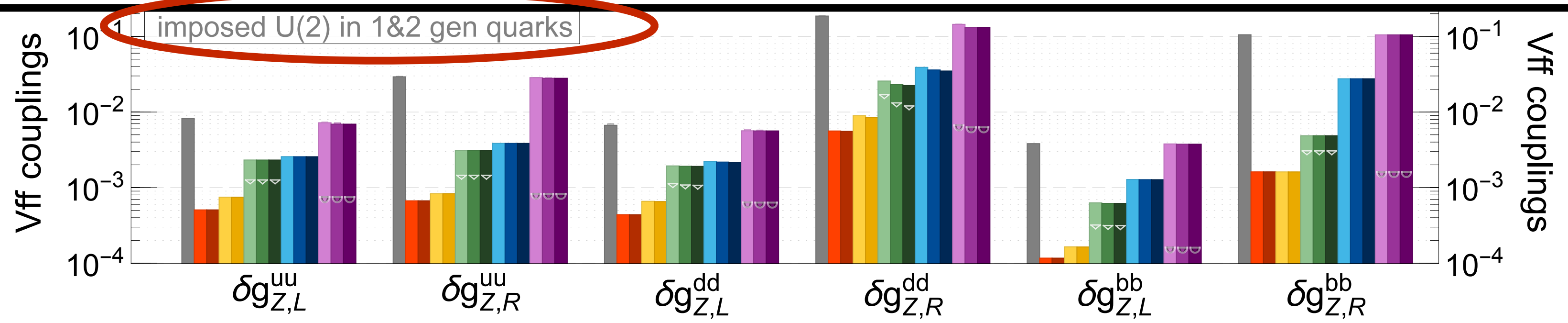
$$A_{FB}\left(Y,\hat{s}\right)=\frac{\sigma_F\left(Y,\hat{s}\right)-\sigma_B\left(Y,\hat{s}\right)}{\sigma_F\left(Y,\hat{s}\right)+\sigma_B\left(Y,\hat{s}\right)}$$

Clean observable: cancellations of QCD & PDF uncertainties

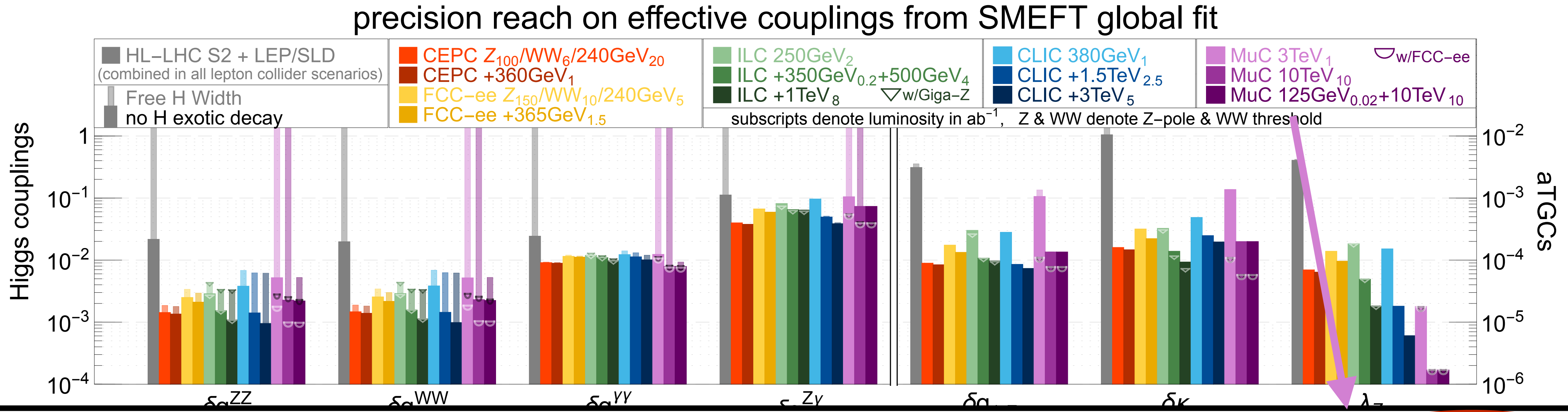
4 distinct rapidity bins enough to disentangle the corrections to L/R Zuu and Zdd couplings

V. Bresó-Pla, A. Falkowski, M. González-Alonso, JHEP 08 (2020) 021

EW *Vff* i



Snowmass SMEFT studies: EW/Higgs fit

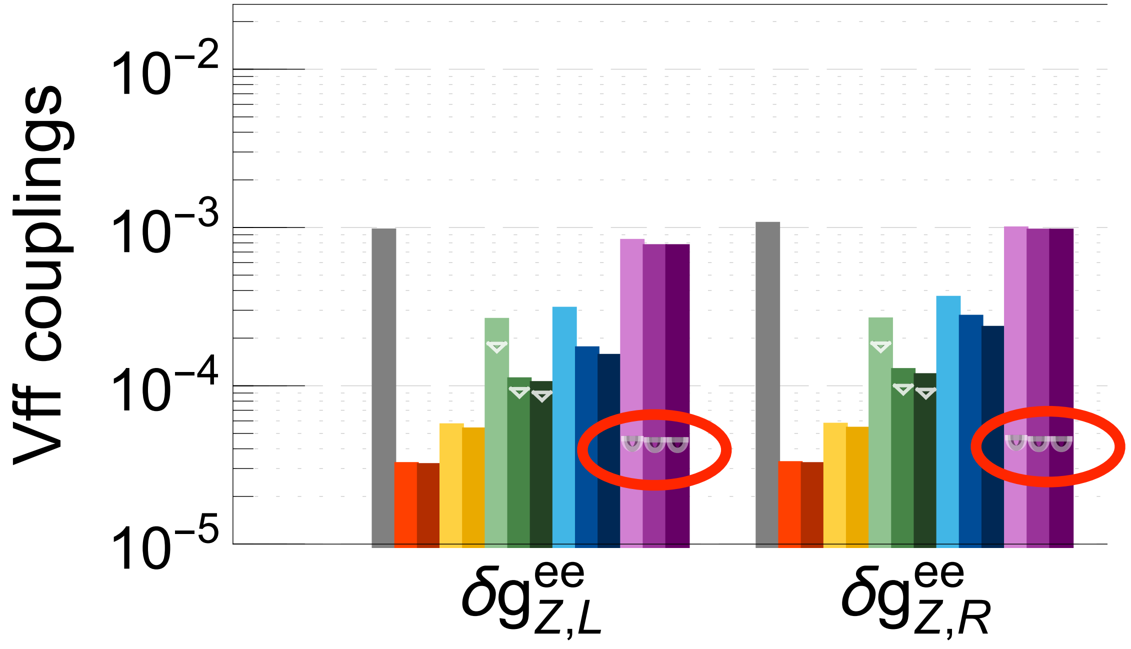

precision reach on effective couplings from SMEFT global fit

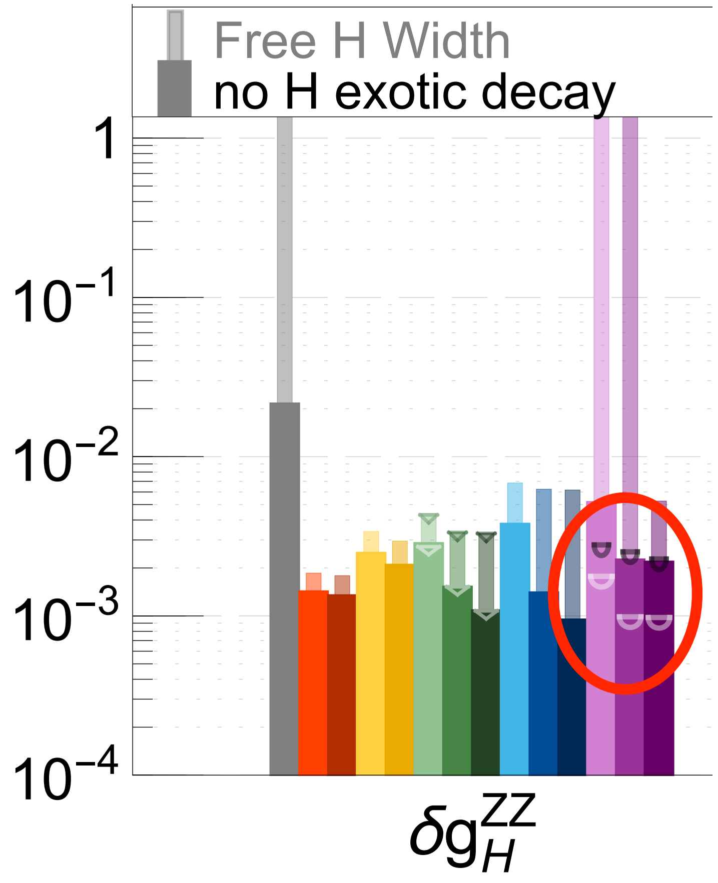
eractions

aTGC

Complementarity $e^+e^-/\mu^+\mu^-$ colliders

From EWPO inputs

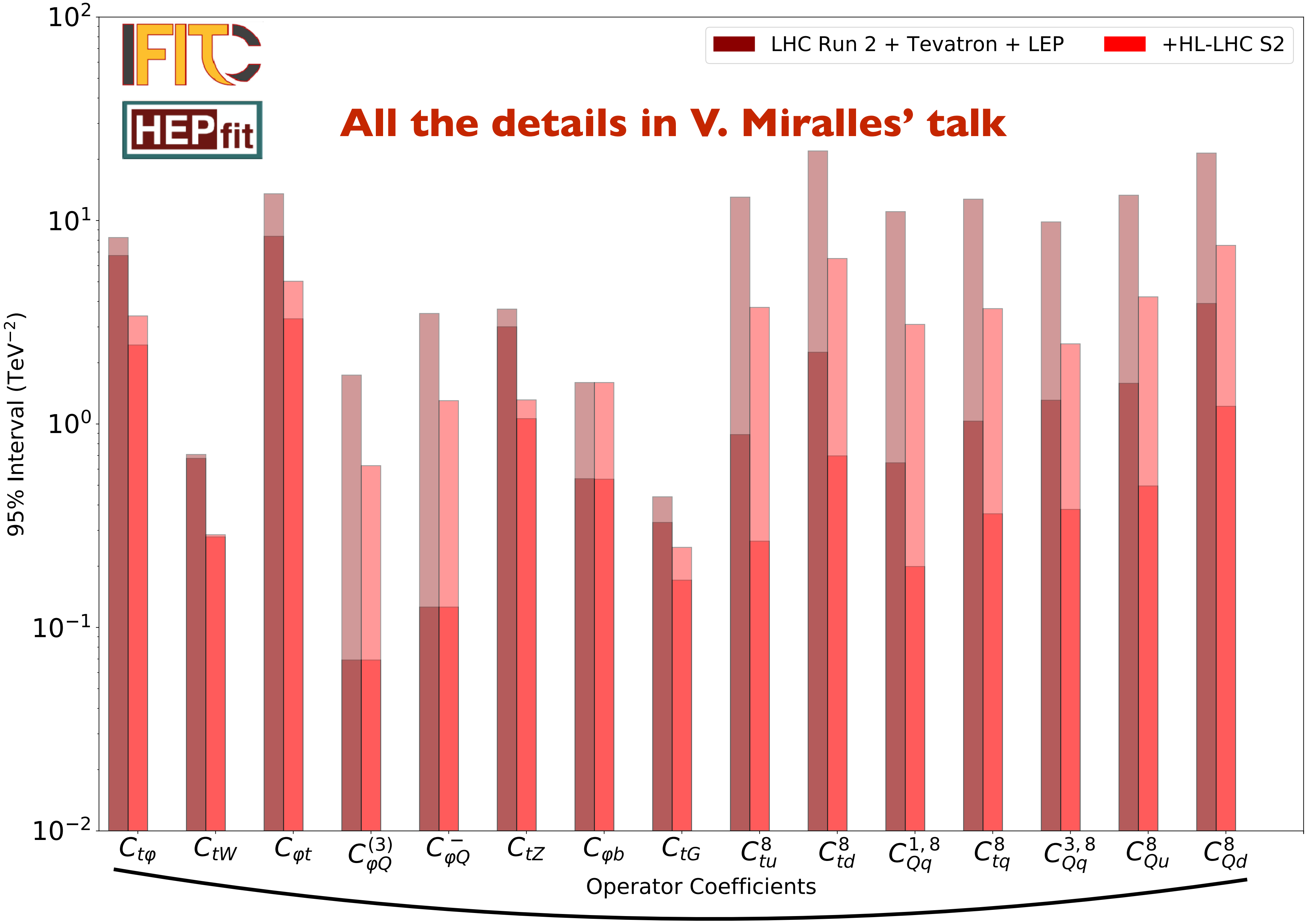




From σ_{ZH}

Snowmass SMEFT studies: EW/Higgs fit

The Top Yukawa coupling

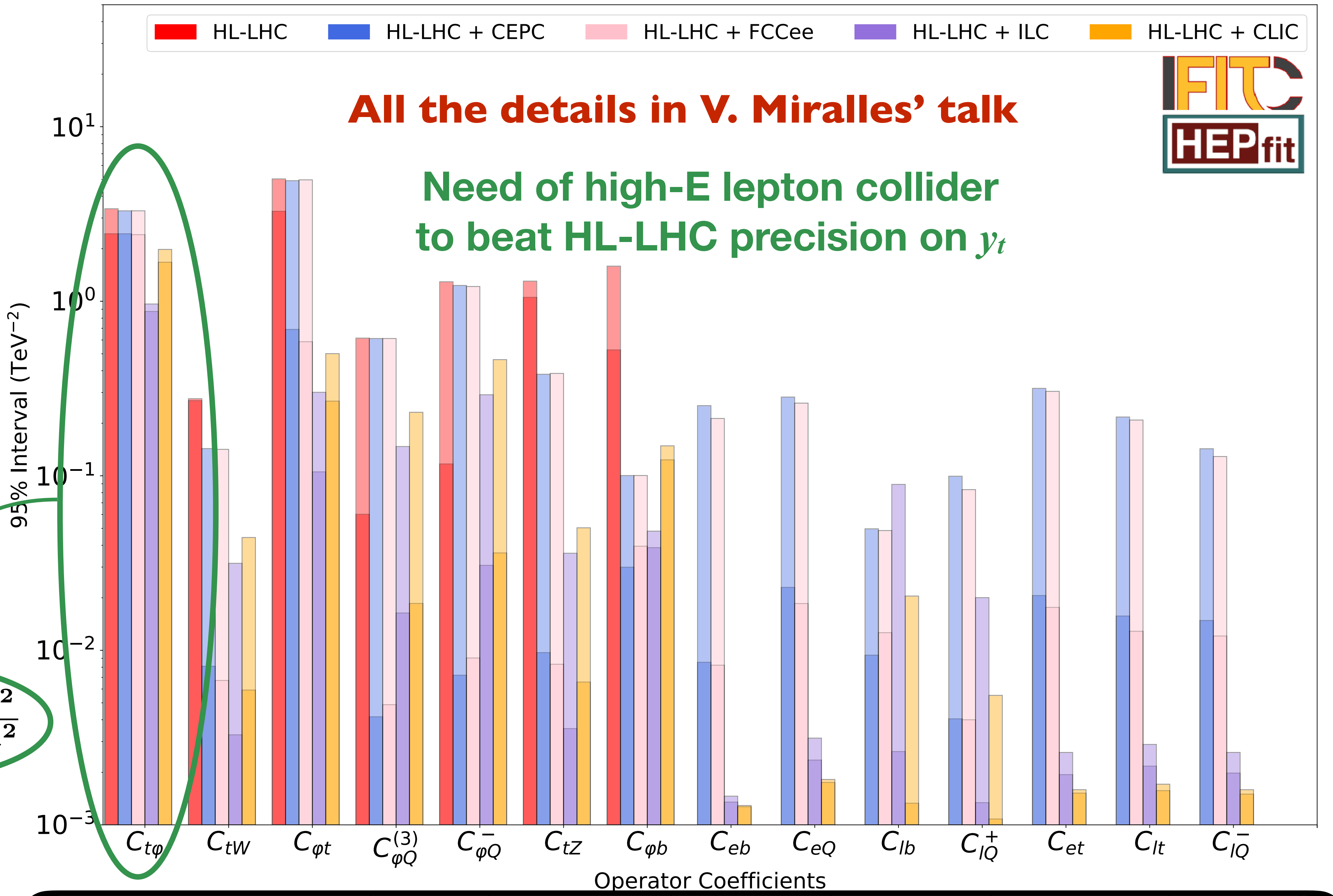


All the details in V. Miralles' talk

Global fit: including 4-fermion, dipoles, etc

Snowmass SMEFT studies: EW/Higgs fit

The Top Yukawa coupling



All the details in V. Miralles' talk

Need of high-E lepton collider to beat HL-LHC precision on y_t

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

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

SMEFT studies at future colliders:
Muon Colliders and the High E frontier

Snowmass SMEFT studies: High-E $\mu^+\mu^-$ colliders

- **Muon colliders:** direct reach benefits from absence of Parton Luminosity suppression

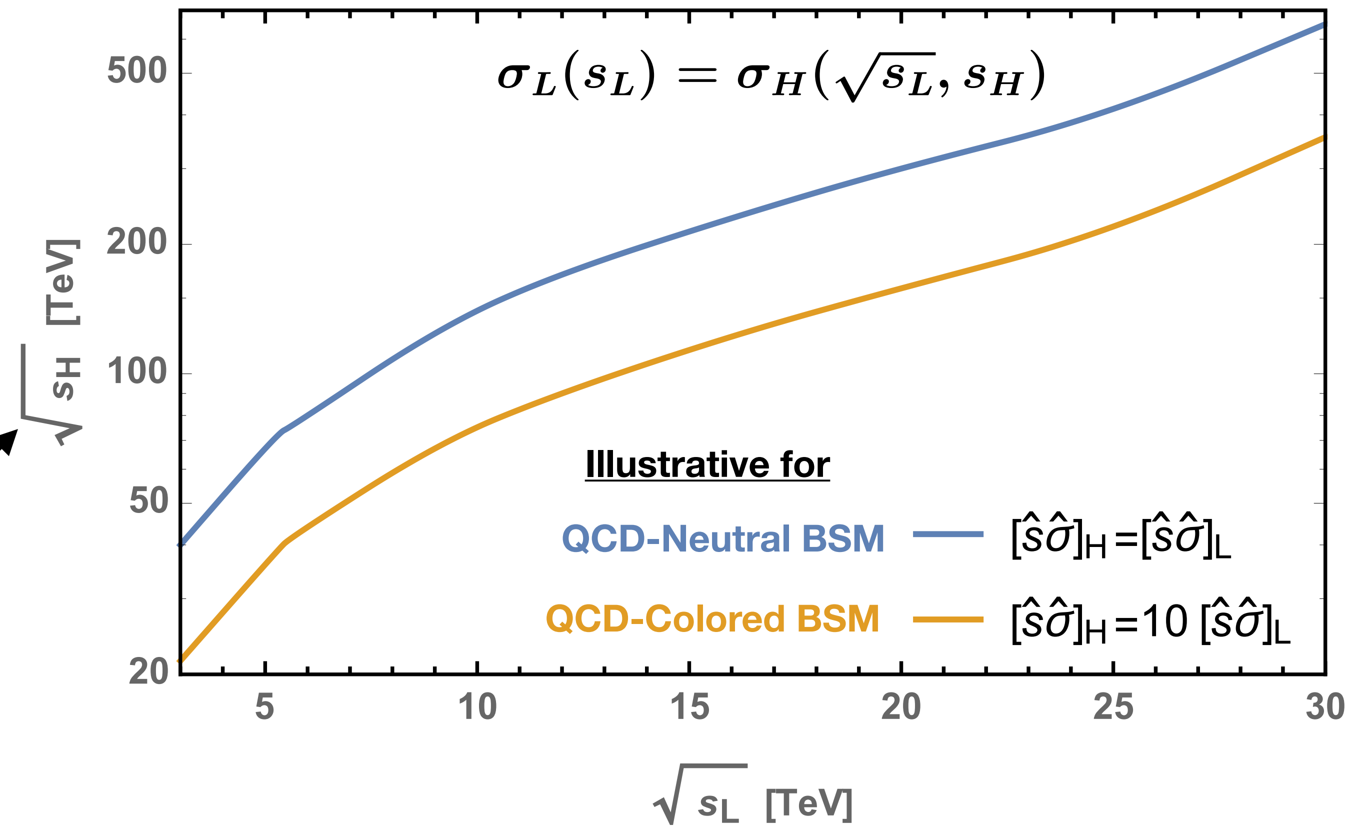
Muon Coll. $\sqrt{s_L}$

$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L$$

Hadron Coll. $\sqrt{s_H}$

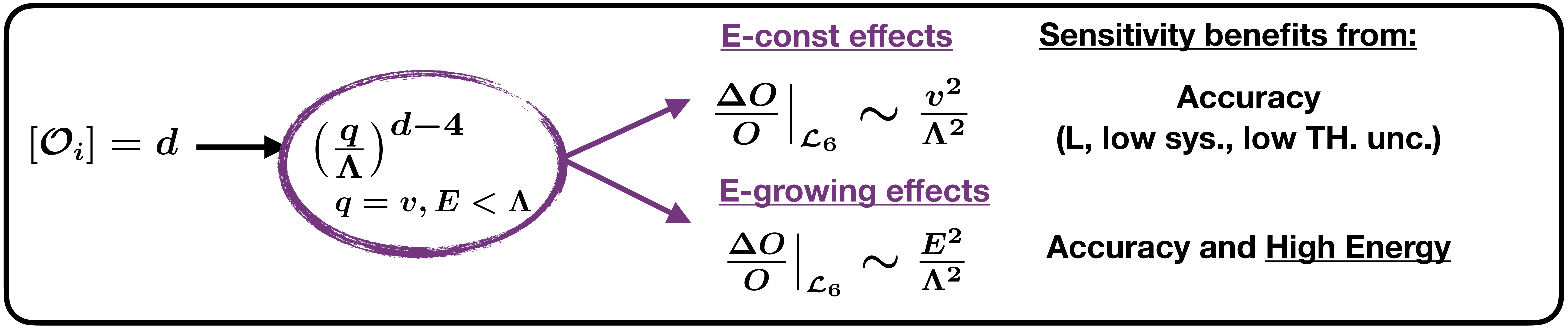
$$\sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1} \frac{d\tau}{\tau}\frac{dL}{d\tau}[\hat{s}\hat{\sigma}]_H$$

From A. Wulzer



Hadron Coll. operating energy $\sqrt{s_H}$ to give same BSM cross section at E= $\sqrt{s_L}$ as Muon collider

- The access to high-E also benefits SMEFT studies, increasing sensitivity to operators in processes where their contribution grows with energy:



$$[\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4} \quad q = v, E < \Lambda$$

E-const effects

$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{v^2}{\Lambda^2}$$

E-growing effects

$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{E^2}{\Lambda^2}$$

Sensitivity benefits from:

Accuracy (L, low sys., low TH. unc.)

Accuracy and High Energy

Snowmass SMEFT studies: High-E $\mu^+\mu^-$ colliders

- **Muon colliders:** SMEFT effects in high-E processes

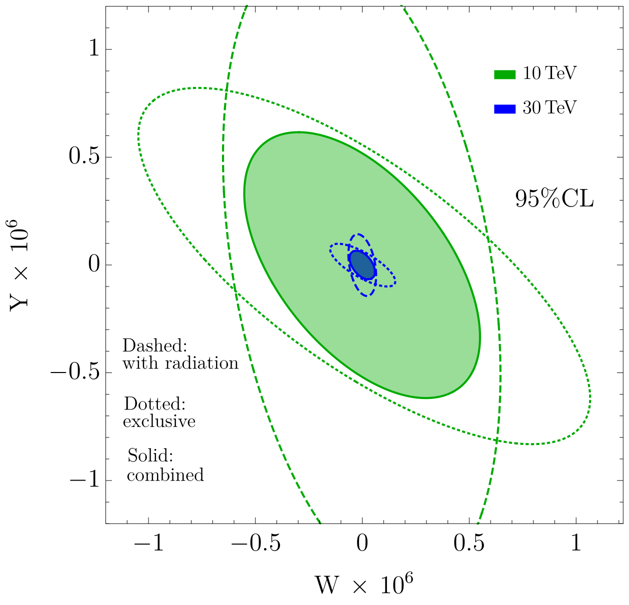
S. Chen et al. , JHEP 05 (2022) 180

W & Y parameters in 2→2 fermion processes

$$\begin{array}{lcll} O_{2W} = (D_\mu W^{\mu\nu,a})^2 & & J_L^{a,\mu} J^a_{L,\mu} & J_L^{a,\mu} = \frac{1}{2}\sum_f \bar{f}\gamma^\mu\sigma^a f + \ldots \\ & \longrightarrow & & \\ O_{2B} = (\partial_\mu B^{\mu\nu})^2 & & J_Y^{\mu} J_{Y,\mu} & J_Y^{\mu} = \sum_f Y_f \bar{f}\gamma^\mu f + \ldots \end{array}$$

Induce 4-fermion operators:

Contribution to cross section for $\sim \frac{E^2}{\Lambda^2}$

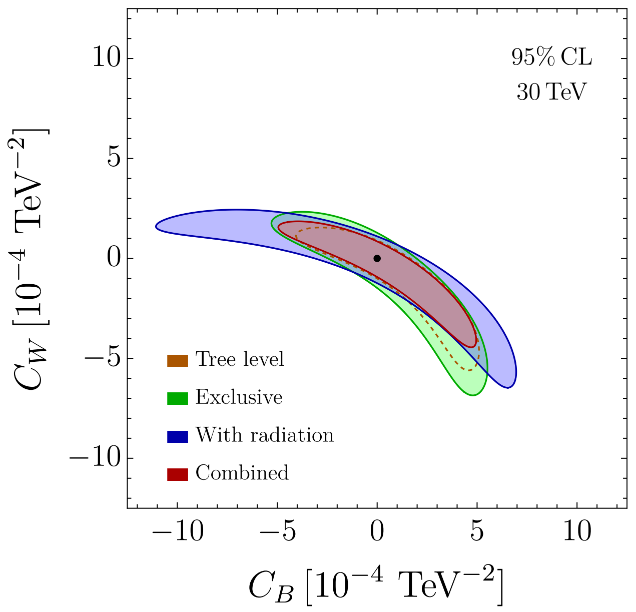


Vector bosons and Higgs production (*Zh, WW, Wh, WZ*)

$$\begin{array}{lcl} O_W = \frac{ig}{2}(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu} & & \frac{g^2}{4}(H^\dagger i\overleftrightarrow{D}_\mu \sigma^a H)(\bar{L}_L\gamma^\mu\sigma^a L_L) + \ldots \\ & \longrightarrow & \\ O_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu} & & -\frac{g'^2}{4}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L) - \frac{g'^2}{2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_R\gamma^\mu l_R) + \ldots \end{array}$$

Induce *VHff* operators:

Contribution to cross section $\sim \frac{E^2}{\Lambda^2}$



For the Snowmass the 3 & 10 TeV options were considered and these results were combined with the inputs from Higgs physics

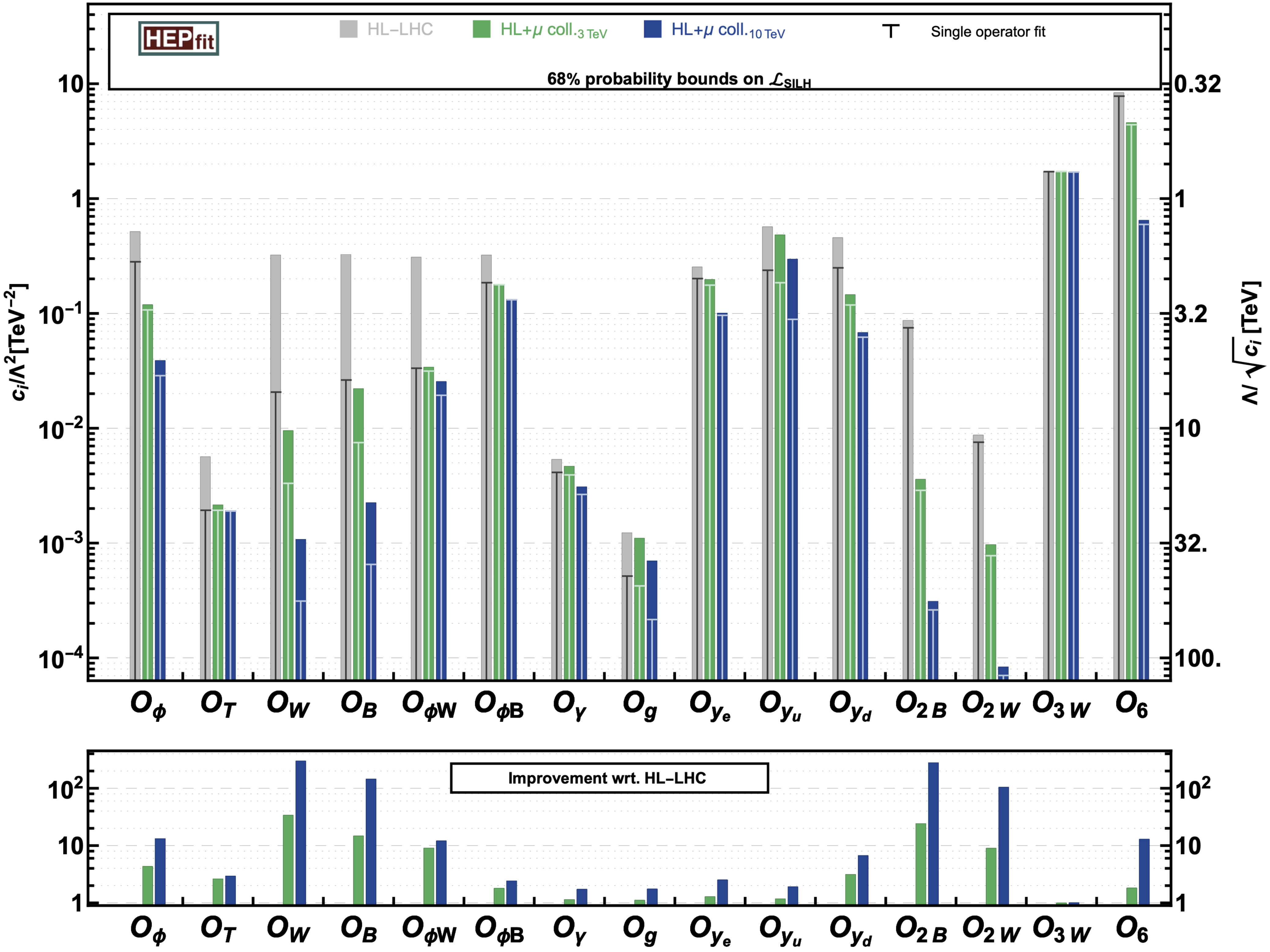
Jorge de Blas
University of Granada

Snowmass SMEFT studies

Snowmass 2021

- **Muon colliders:** SMEFT effects in high-E processes **J. B. et al. , arXiv: 2203.07261 [hep-ph]**

EFT results for the SILH effective Lagrangian

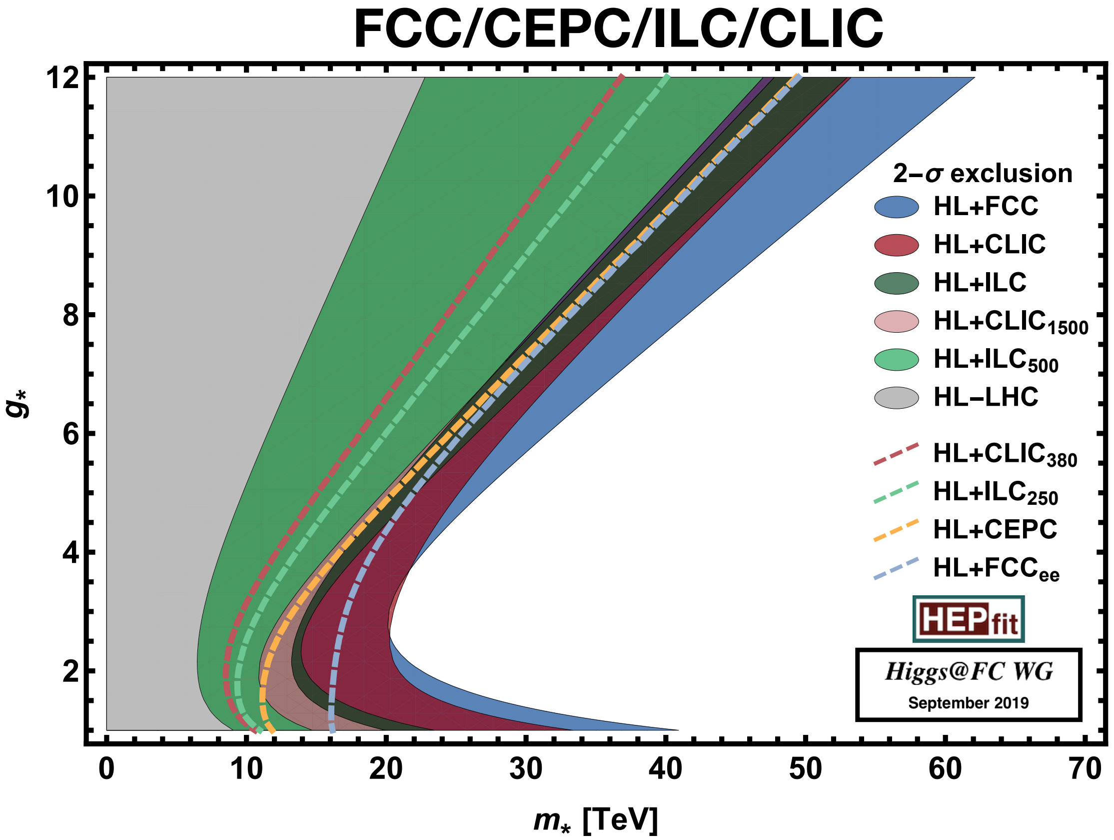


Snowmass SMEFT studies

- **Muon colliders:** SMEFT effects in high-E processes **J. B. et al. , arXiv: 2203.07261 [hep-ph]**

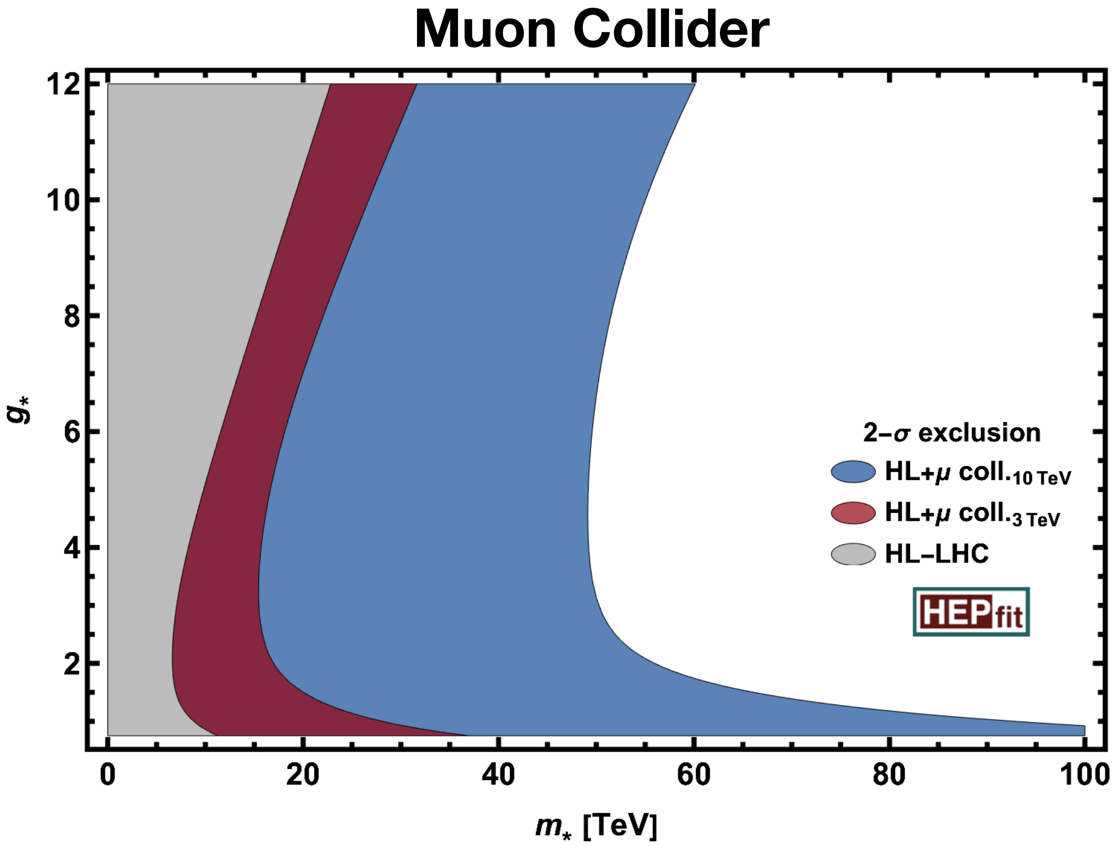
Universal Composite Higgs Models

FCC/CEPC/ILC/CLIC



Warning: not updated since ESU2020

Muon Collider



$g_\star(m_\star)$: **typical coupling strength (mass scale) of the strong sector**

$$\frac{c_{\phi,6,y_f}}{\Lambda^2}=\frac{g_\star^2}{m_\star^2},\qquad \frac{c_{W,B}}{\Lambda^2}=\frac{1}{m_\star^2},\qquad \frac{c_{2W,2B,2G}}{\Lambda^2}=\frac{1}{g_\star^2}\frac{1}{m_\star^2},$$

$$\frac{c_T}{\Lambda^2}=\frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{\gamma,g}}{\Lambda^2}=\frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{\phi W,\phi B}}{\Lambda^2}=\frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{3W,3G}}{\Lambda^2}=\frac{1}{16\pi^2}\frac{1}{m_\star^2}.$$

SILH mapping ($O(1)$ factors set to 1)

Summary and Conclusions

Summary and Conclusions

- Starting from the ESU studies, we updated and extended the projections for sensitivity to BSM deformations at future colliders in the SMEFT formalism

- Focusing on the EW/Higgs sector and in the legacy of HL-LHC measurements:
  - ✓ Sensitivity to modifications of coupling entering in rare Higgs decays will be controlled by HL-LHC limits
  - ✓ Studied the determination of the Top Yukawa in a global manner, including all relevant operators for ttH in a global Top fit (See V. Miralle's talk):
    - Many operators (4-fermion, dipoles) but the fit closes
    - Need e^+e^- above ttH threshold to surpass the HL-LHC sensitivity to Top Yukawa
  - ✓ The use of HL-LHC electroweak observables helps to separate BSM contributions to EW couplings of the 1st two quark families
  - ✓ Not discussed (but also relevant): HL-LHC also the natural place to test interactions such 4-light-quark operators

- For e^+e^- machines ⇒ See M. Peskin's talk

Summary and Conclusions

- On high-Energy muon colliders:
  - ✓ High-Energy allows precise measurements of Higgs couplings as well as to significantly increase the sensitivity to several operators whose effects grow with energy in 2→2 processes
  - ✓ Important complementarity with e^+e^- factories:
    - Electroweak precision measurements
    - Higgs width

- Still some work to be done before the final report:
  - ✓ Studying impact of SM theory uncertainties
  - ✓ Refining optimal observable analysis in $e^+e^-\to W^+W^-$ (detect effects, sys, …)
  - ✓ Sensitivity to Higgs self-coupling (via loop effects)

Summary and Conclusions

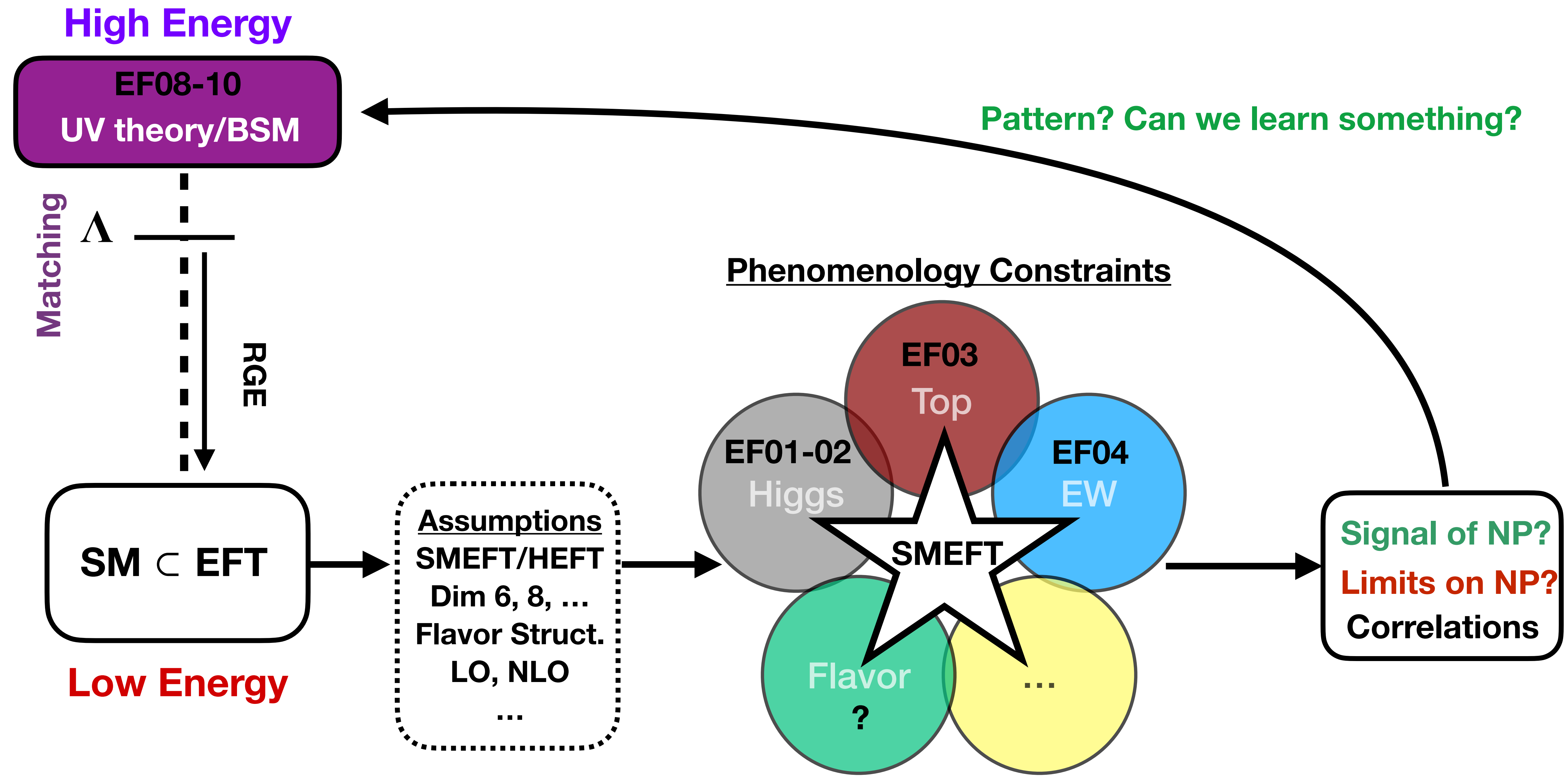
- Thanks to all the members of this SMEFT fit task force who, since November 2020 have been preparing this study and, for now more than one year, have coordinated across the globe to meet weekly and complete this work

Not easy to find a time that works well for all for our regular meetings…

Backup Slides

Global SMEFT analyses

- **The Goal:** combine inputs from the different EF to obtain a global SMEFT fit which can be used to learn from BSM scenarios



Snowmass SMEFT fit inputs

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

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

Snowmass SMEFT fit inputs

- **Electroweak precision observables**

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

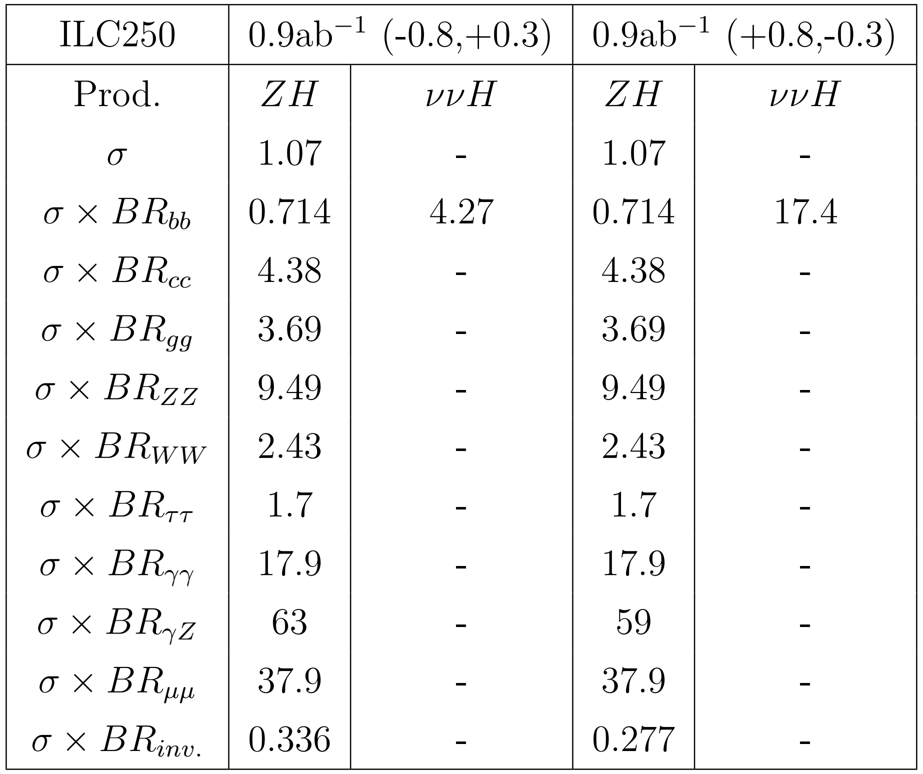
- **Higgs observables: Circular e^+e^- Colliders (FCCee/CEPC)**

	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	-

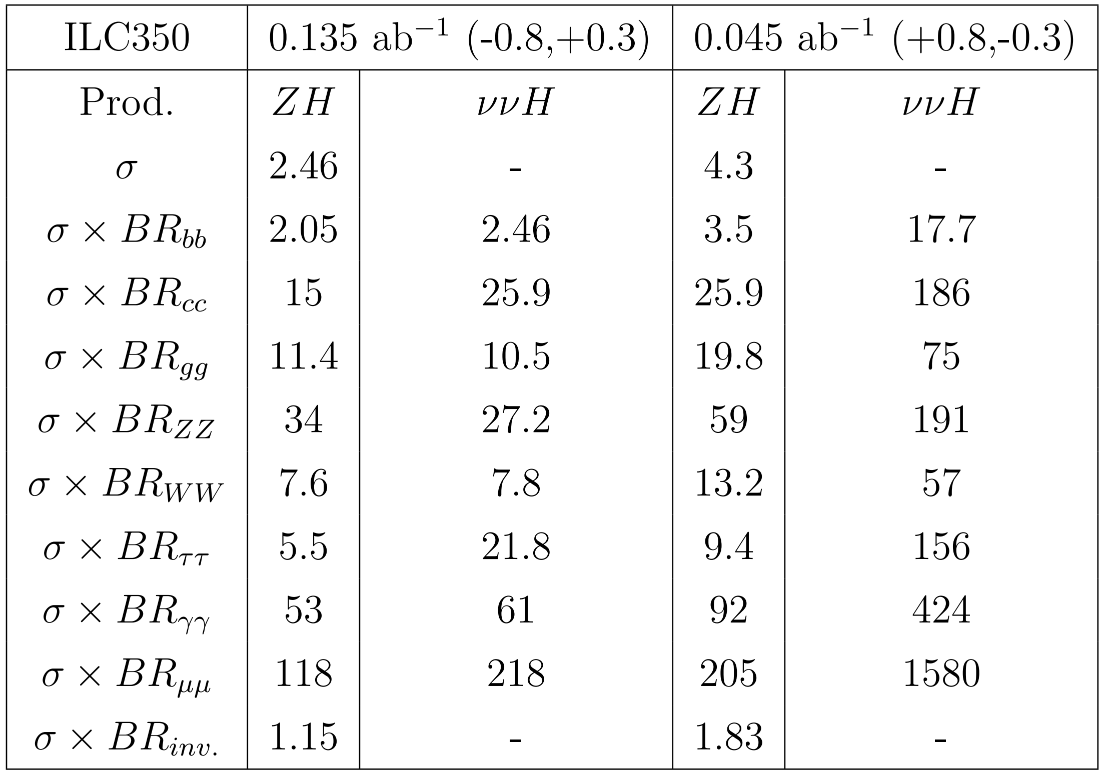
	1.5 ab^{-1} FCC-ee365		1.0 ab^{-1} CEPC360	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.9(0.84)	-	1.4(1.02)	-
$\sigma \times BR_{bb}$	0.5(0.71)	0.9(1.14)	0.90(0.86)	1.1(1.39)
$\sigma \times BR_{cc}$	6.5(5.0)	10(11.9)	8.8(6.1)	16(14.5)
$\sigma \times BR_{gg}$	3.5(3.8)	4.5(4.8)	3.4(4.7)	4.5(5.9)
$\sigma \times BR_{ZZ}$	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

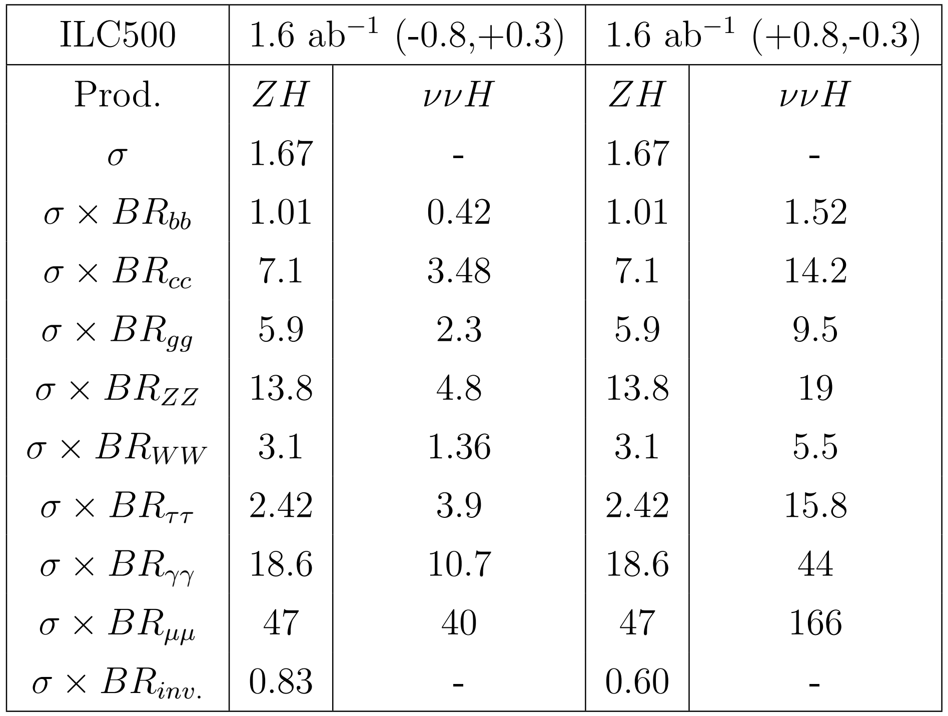
- **Higgs observables: Linear e^+e^- Colliders (ILC)**



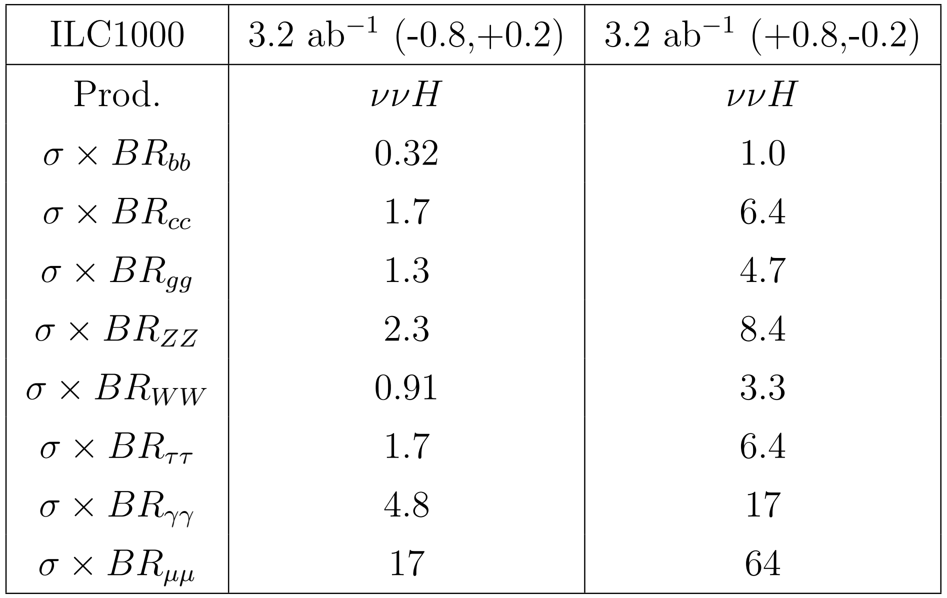
ILC250	0.9ab^{-1} (-0.8,+0.3)		0.9ab^{-1} (+0.8,-0.3)	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	1.07	-	1.07	-
$\sigma \times BR_{bb}$	0.714	4.27	0.714	17.4
$\sigma \times BR_{cc}$	4.38	-	4.38	-
$\sigma \times BR_{gg}$	3.69	-	3.69	-
$\sigma \times BR_{ZZ}$	9.49	-	9.49	-
$\sigma \times BR_{WW}$	2.43	-	2.43	-
$\sigma \times BR_{\tau\tau}$	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	$0.135\ \text{ab}^{-1}$ (-0.8,+0.3)		$0.045\ \text{ab}^{-1}$ (+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	$1.6\ \text{ab}^{-1}$ (-0.8,+0.3)		$1.6\ \text{ab}^{-1}$ (+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	$3.2\ \text{ab}^{-1}$ (-0.8,+0.2)	$3.2\ \text{ab}^{-1}$ (+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	-