HEP Seminar, Oklahoma State University
November 4, 2021

Testing the SM and Beyond:
EFTs at Present and Future Colliders

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Transformación Económica, Industria, Conocimiento y Universidades

UNIÓN EUROPEA
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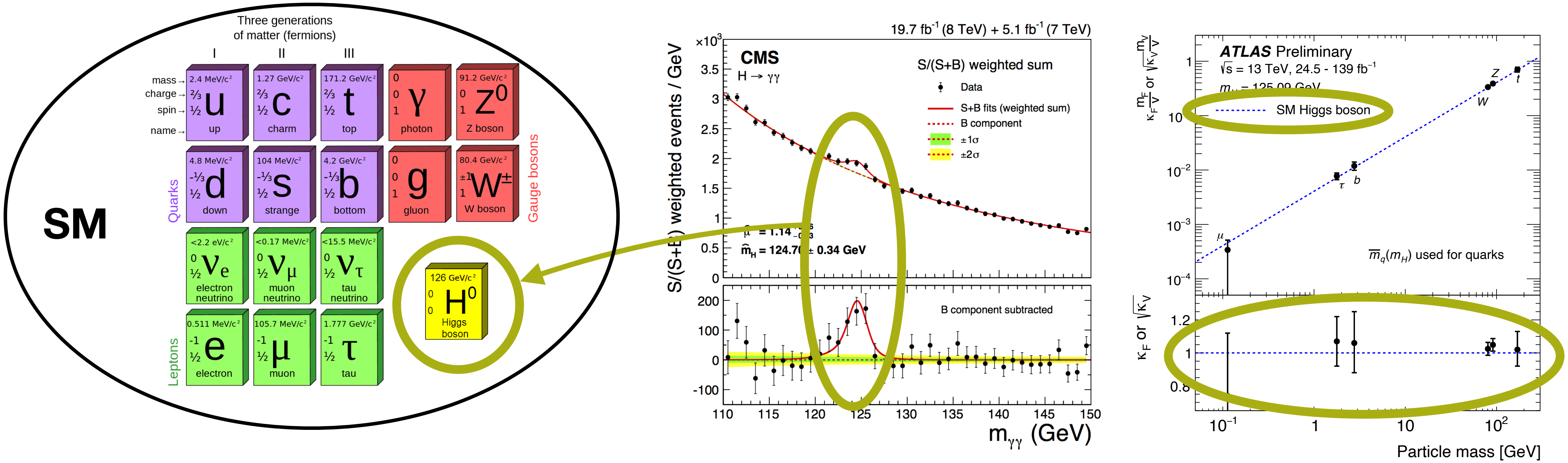
Project P18-FRJ-3735

Introduction

- **Particle Physics at the end of the HL-LHC?** The discovery of the 125 GeV Higgs boson may be the "only" discovery of the LHC
  - ✓ So we have all the ingredients required to confirm the validity of the SM at low energies…



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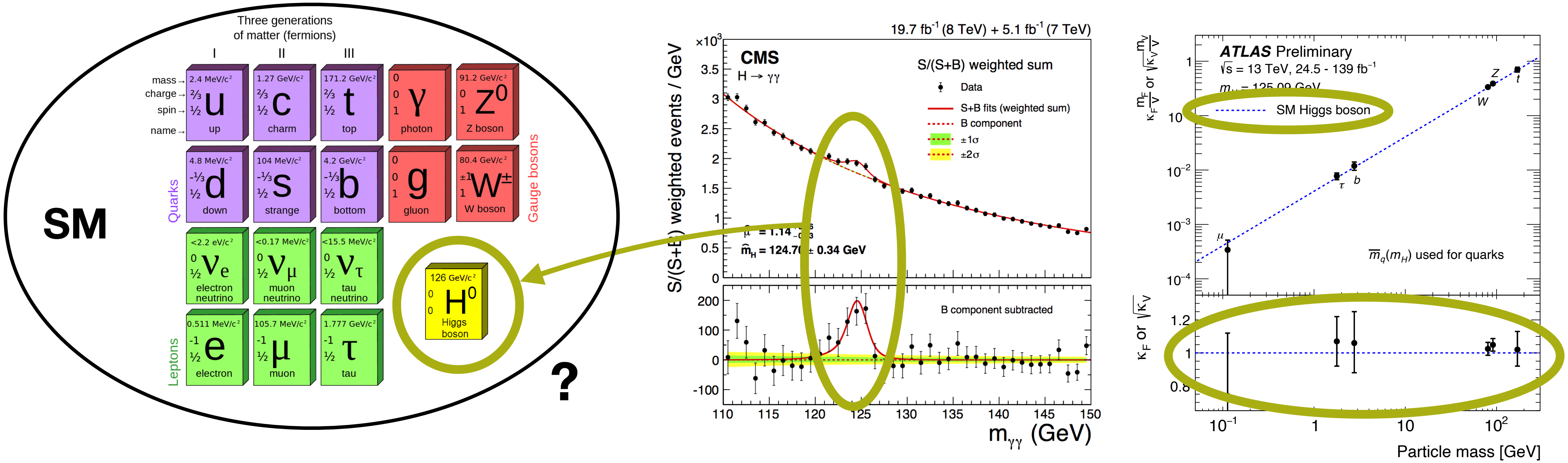
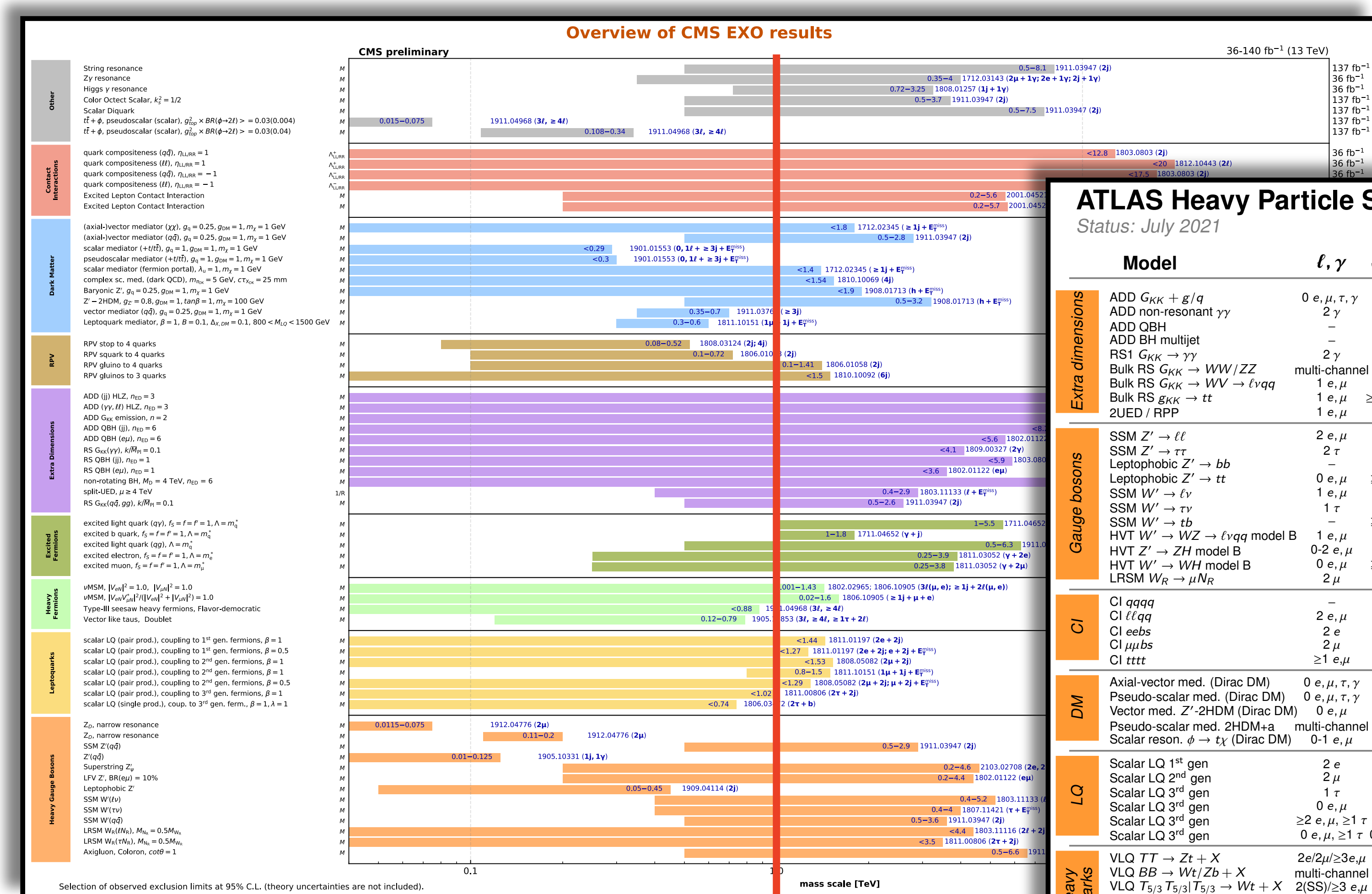


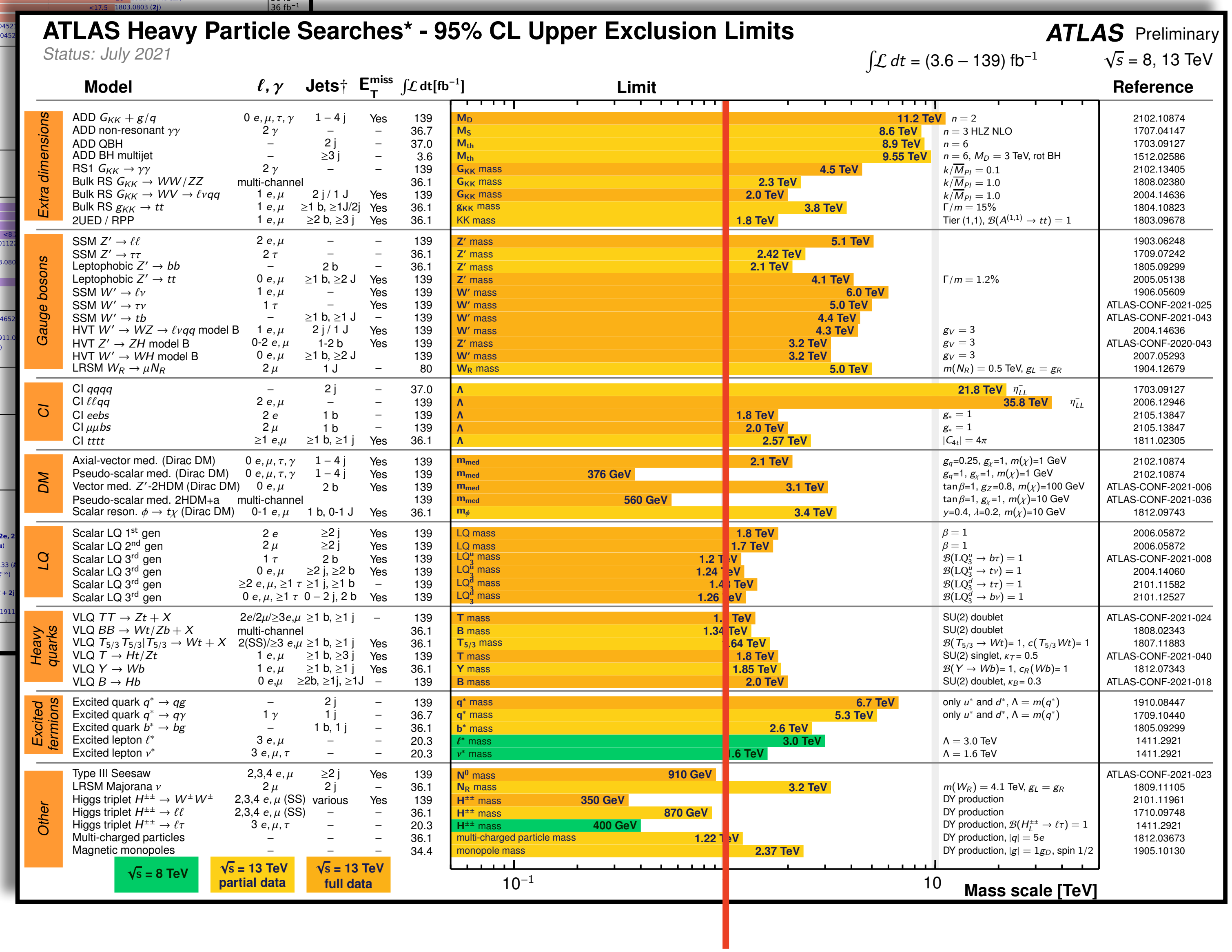
- **Is the SM enough?**

Introduction

- **Is the SM enough?** At least it seems a very good description of phenomena at the EW scale…



1 TeV

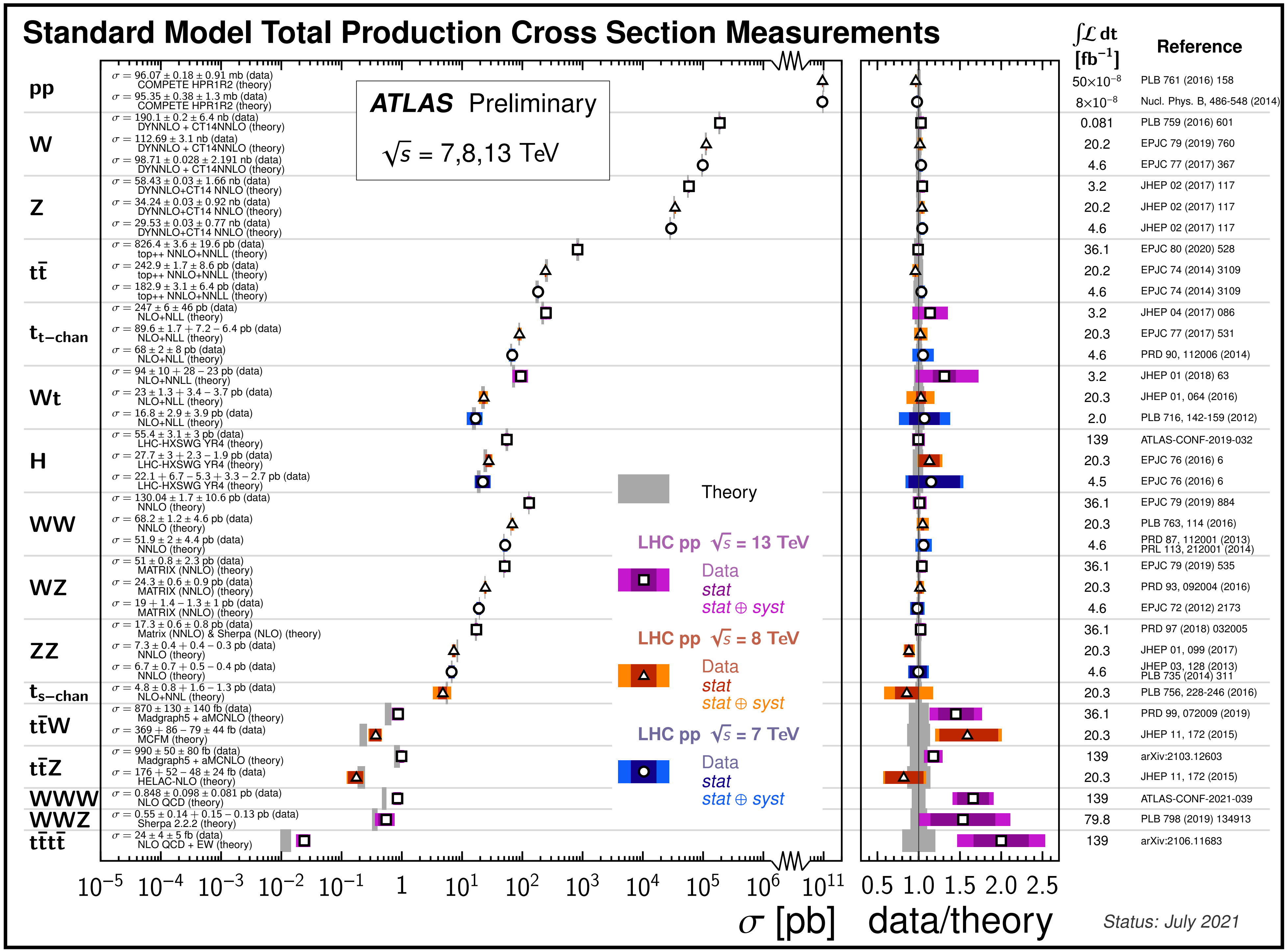


1 TeV

No direct sign of any kind of new particle we have thought of below the TeV scale…

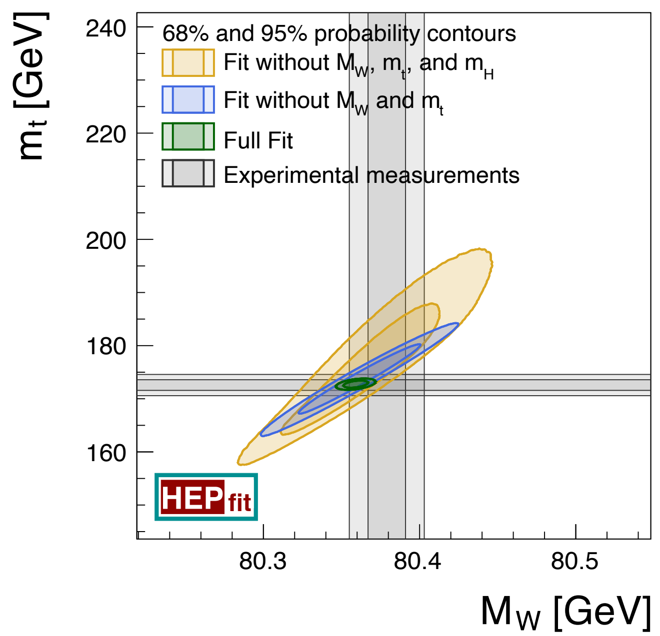
Introduction

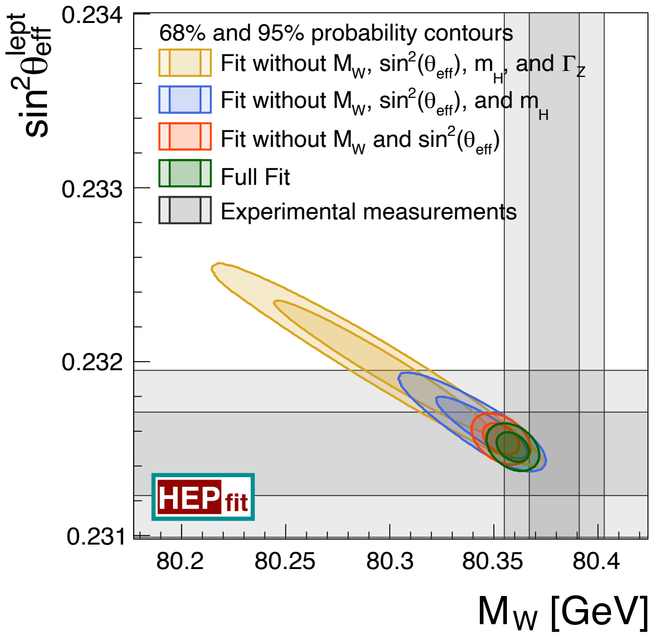
- **Is the SM enough?** Excellent agreement with measurements of "SM processes"…

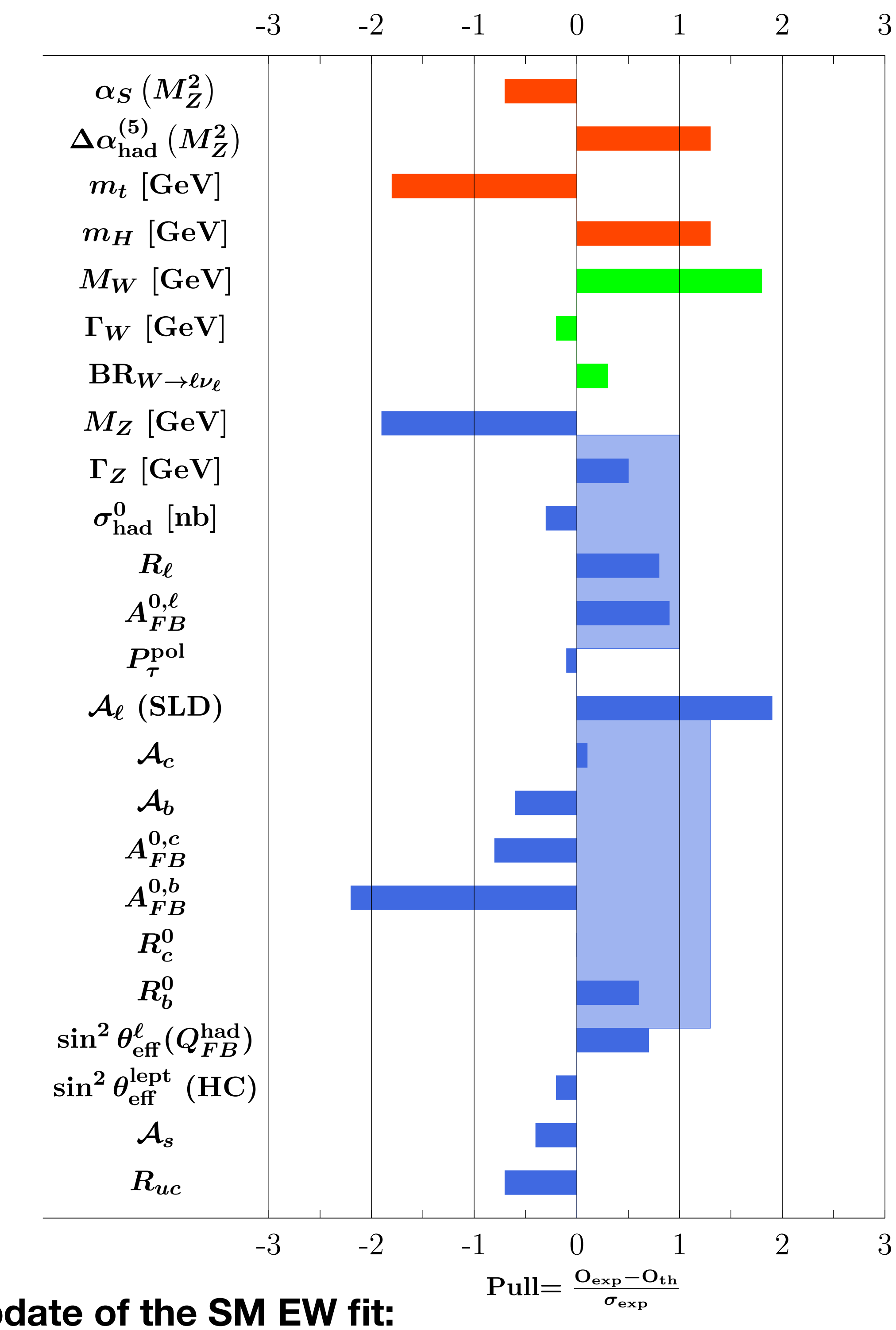


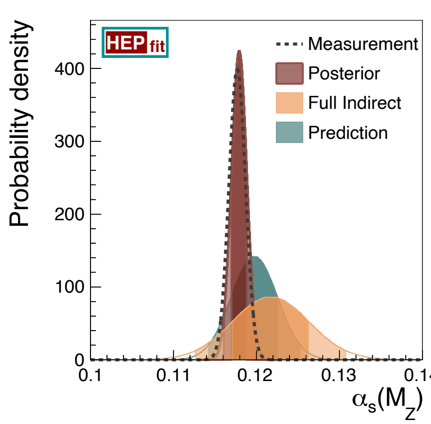
Introduction

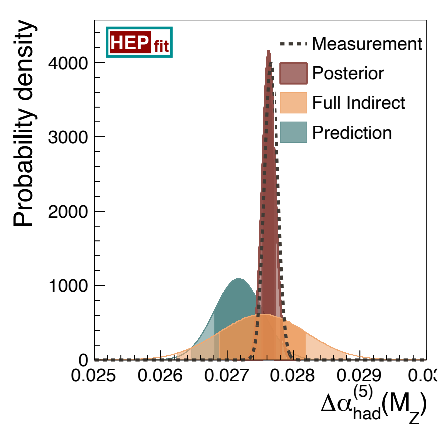
- **Is the SM enough?** Excellent agreement with EWPO (test up to 2-loops!)

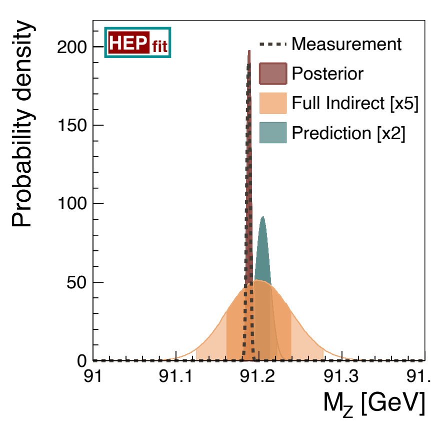


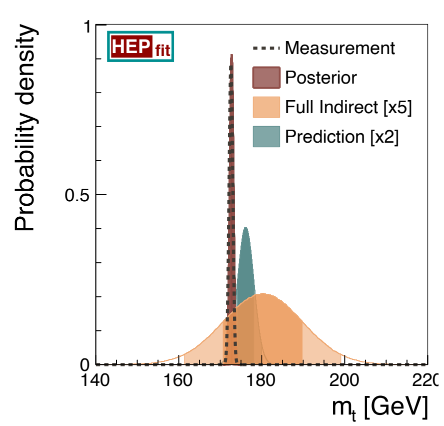


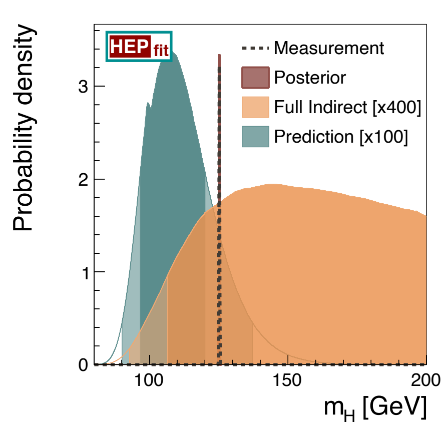










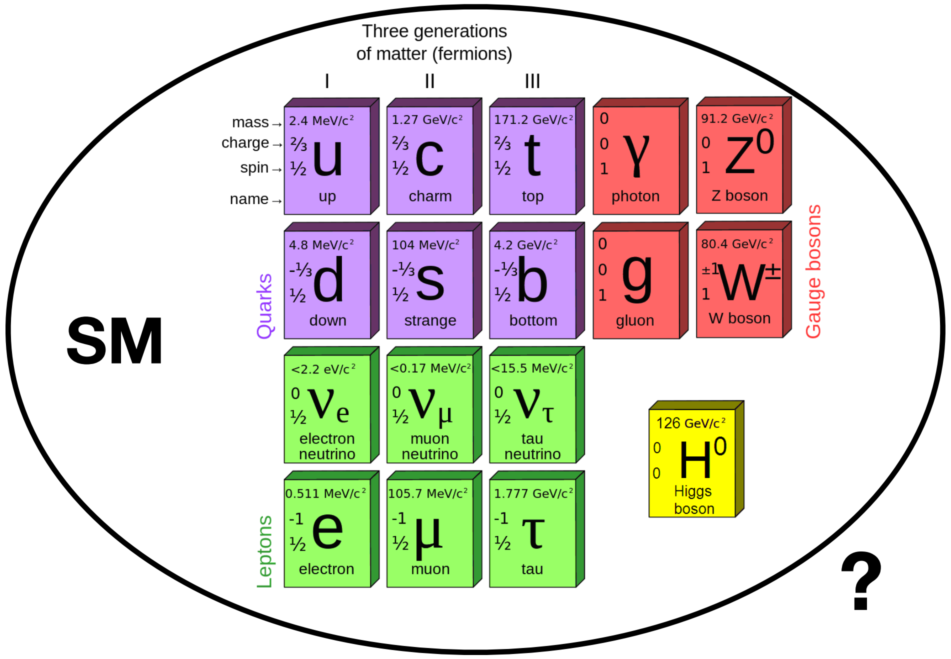


Update of the SM EW fit:

J. de Blas et a., arXiv: 2111.xxxxx hep-ph]

Introduction

- **Is the SM enough?** We know the SM cannot be the ultimate theory of fundamental physics…



Observational/Experimental issues

No Neutrino masses
No Dark Matter/Dark Energy
Matter/Anti-Matter asymmetry?
No explanation of gravity
…

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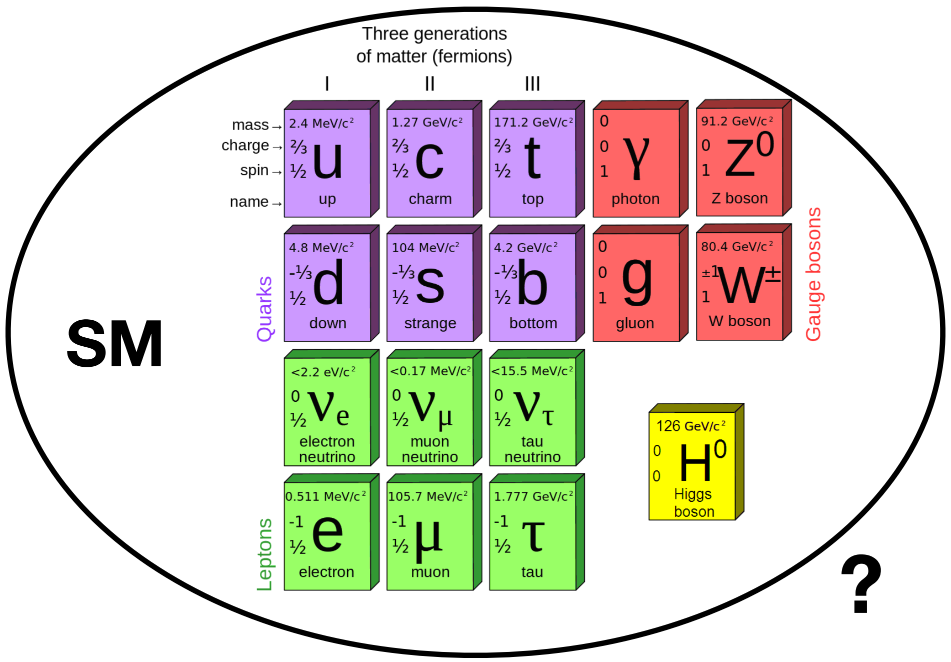

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- **Theoretical issues** e.g. the Higgs also reminds us of the limitations of the Standard Model…
  - How do we understand the mechanism of EWSB?
  - Hierarchy problem: Why $M_h \ll M_P$?

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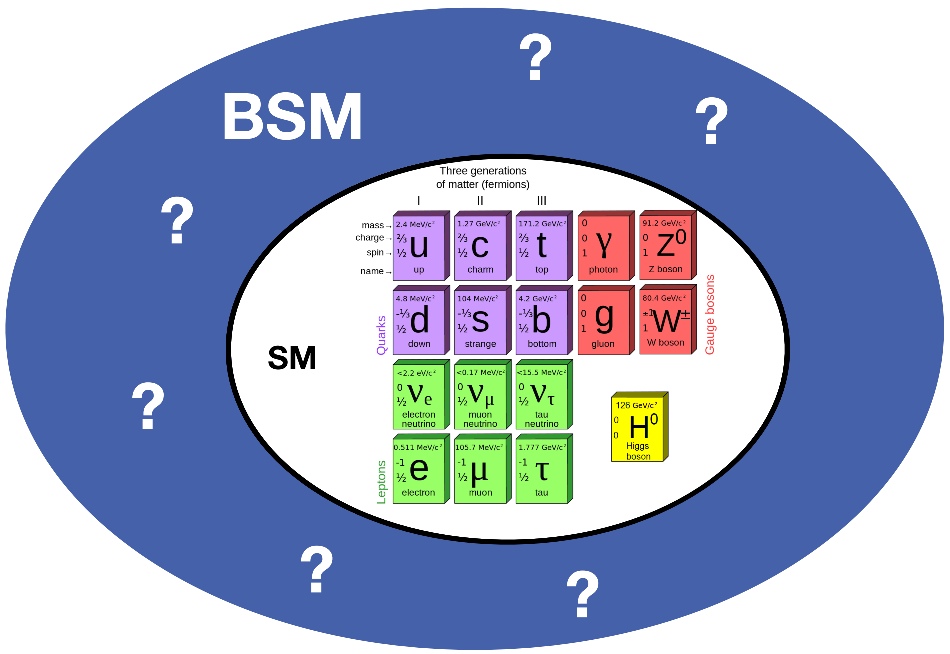

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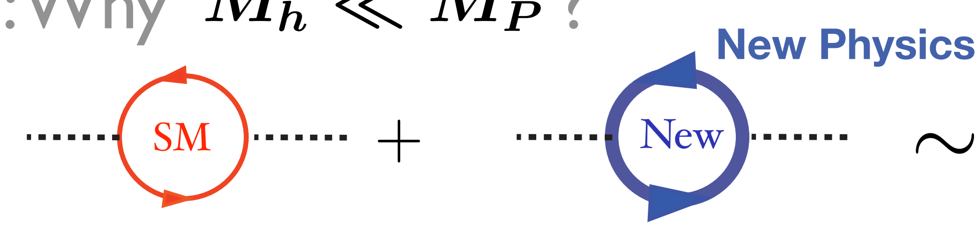
⇒ BSM: $\Delta M_h^2 =$



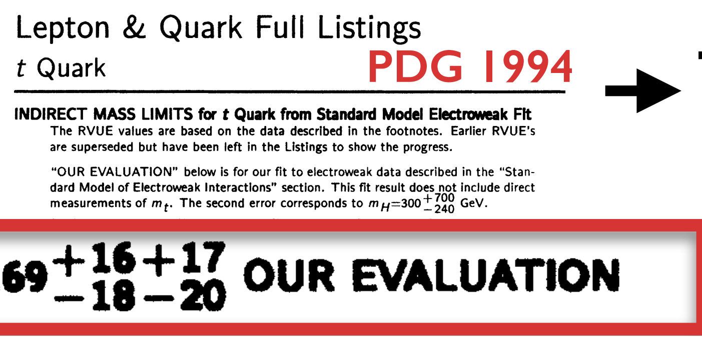
~ 0

- Other problems/questions: Strong CP problem, Flavor problem, Why 3 families?, Gauge Unification? Too many parameters?,…

Introduction

- **Going beyond:** Until now, we had the Standard Model (e.g. via EWPT) to guide our searches for the Top and Higgs …

… **W, Z bosons** →


Lepton & Quark Full Listings

t Quark PDG 1994

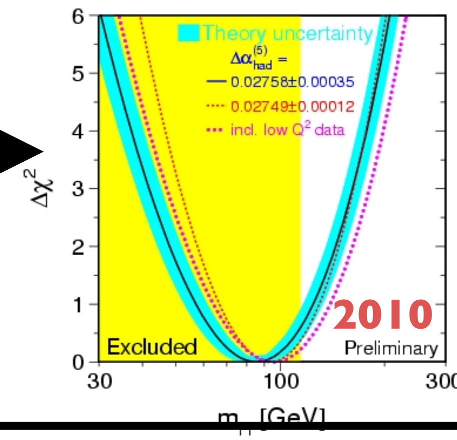
INDIRECT MASS LIMITS for t Quark from Standard Model Electroweak Fit

The RVUE values are based on the data described in the footnotes. Earlier RVUE's are superseded but have been left in the Listings to show the progress.

"OUR EVALUATION" below is for our fit to electroweak data described in the "Standard Model of Electroweak Interactions" section. This fit result does not include direct measurements of m_t. The second error corresponds to $m_H=300^{+700}_{-240}$ GeV.

$169^{+16}_{-18}{}^{+17}_{-20}$ OUR EVALUATION

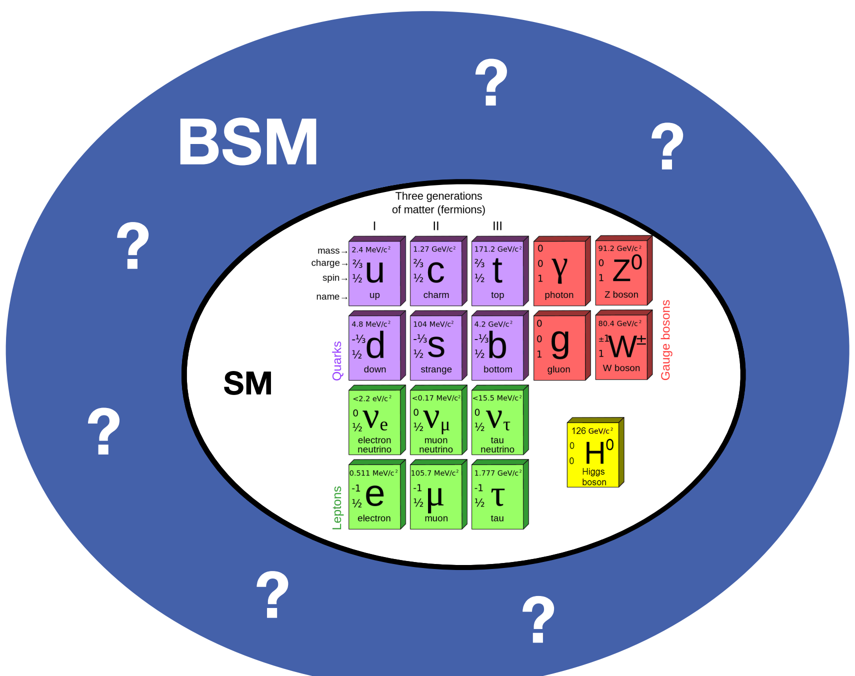
→ **Top quark** →



→ **Higgs boson** → **?**

SM ⋮ **BSM**

- … from here on, however, we are exploring the unknown with the only guidance of our (apparently unsuccessful) model-building experience



We know that this:

New Physics

$$\Delta M_h^2 = \cdots\cdots \text{SM} \cdots\cdots + \cdots\cdots \text{New} \cdots\cdots \sim 0$$

would naturally come with sizeable modifications of the Higgs couplings

R. Rattazzi's at ESU symposium, Granada

$$\frac{\delta g_h}{g_h} \sim \frac{m_h^2}{\Delta m_h^2} \equiv \epsilon_T \equiv \text{fine tuning} \qquad \left(\left.\frac{\delta g_h}{g_h}\right|_{\text{LHC}} \sim \mathcal{O}(10\text{ - }20)\%\right)$$

⇒ **Precision measurements is a key tool to learn from BSM <u>indirectly</u>**

⇒ **Indirect tests of New Physics**

Introduction

Why am I going to talk about EFT at LHC and Future Colliders?

- Direct reach is not going to improve significantly…
- …but more data (especially with the HL-LHC and future colliders) will enable the possibility of precision measurements

If there is new physics not far from the TeV scale we may be sensitive first to its indirect effects via precision measurements

- Finally, the data does not seem to hint towards any type of BSM model we have proposed…

Effective Field Theories

Theoretically robust framework to systematically study in a model-independent way indirect effects of new physics and combine all the information that will be accessible at the LHC (with previous and future experiments)

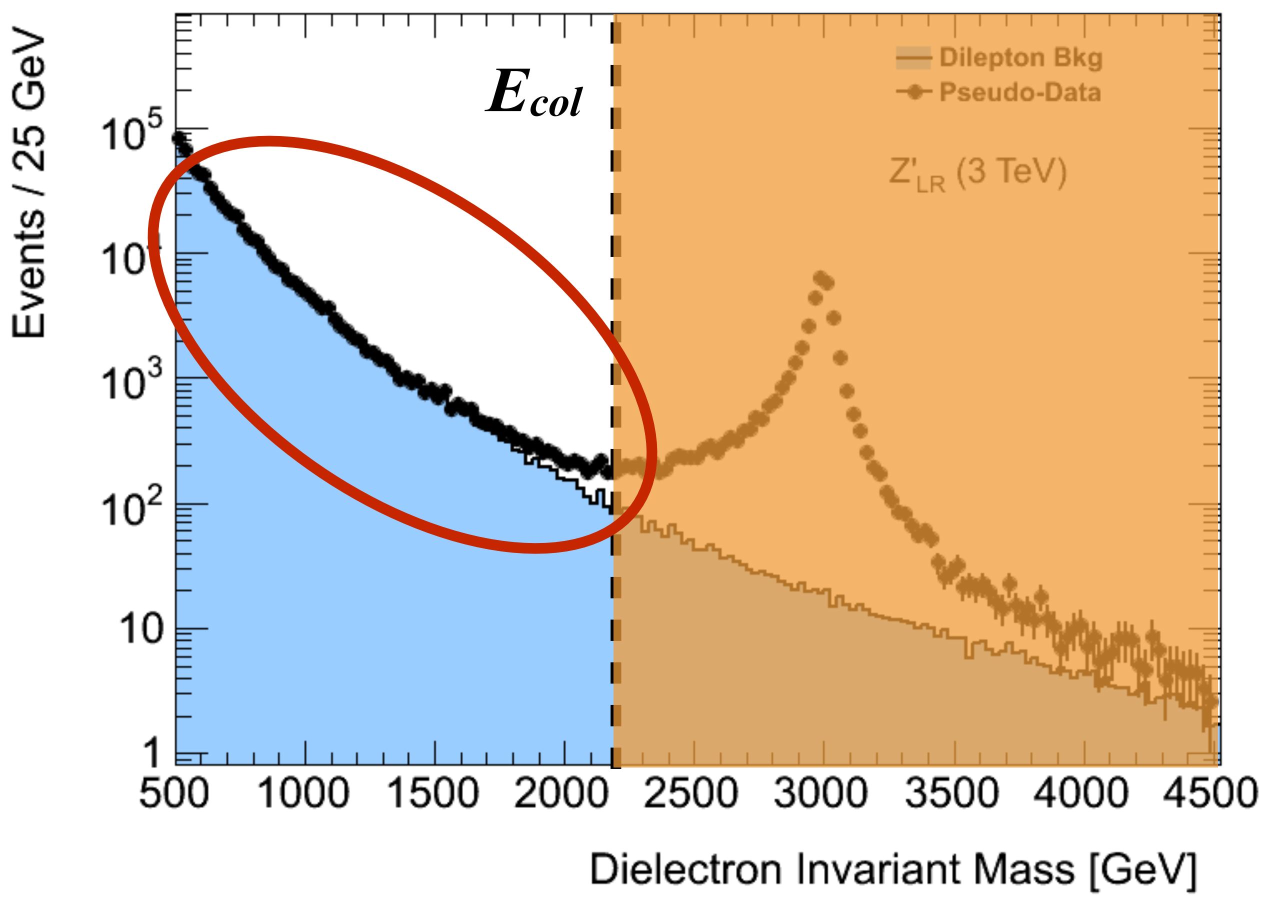
Outline

- ~~Introduction~~ Done
- The dimension-6 SMEFT
- The SMEFT at the LHC
- The SMEFT at Future EW/Higgs factories
- Conclusions

The dimension-6
Standard Model Effective Field Theory

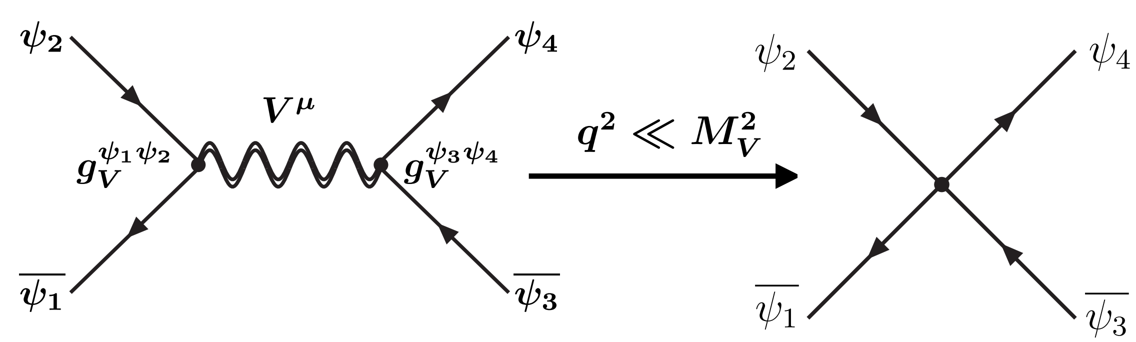
Effective Field Theories

- The philosophy of Effective Field Theories:
  - ✓ Think, e.g. of the Z' effects in di-lepton spectrum



If $E_{coll} < M_{Z'}$ test ***virtual effects*** of NP looking for "deformations" in SM measurements

$E_{coll} << M_{Z'}$: effects well described by effective interactions

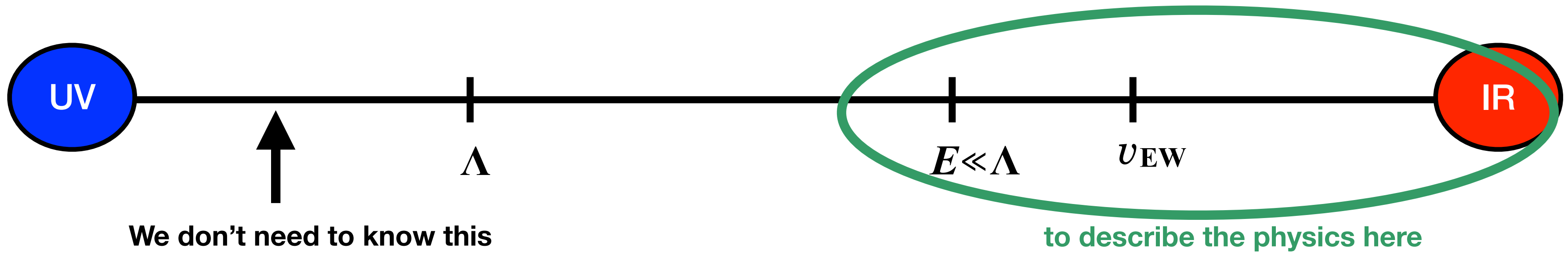


$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'} \quad \xrightarrow{q^2 \ll M_V^2} \quad \mathcal{L}_{\rm Eff}$$

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

Effective Field Theories

- 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 is actually enough to build an Effective Field Theory, which provides a robust theory framework to interpret experimental indirect tests of new physics

Effective Field Theories

- EFT provide a phenomenological tool to parameterise BSM deformations in a model-independent way (consistent with some general assumptions)
- Two EFTs consistent with the SM particles and symmetries at low energies, differing in the treatment of the scalar sector:
  - ✓ The non-linear/Higgs EFT (HEFT): EW symmetry non-linearly realised
  - ✓ The (dimension-6) SMEFT: EW symmetry linearly realised

SM ⊂ SMEFT ⊂ HEFT

- In short:
  - ✓ **HEFT:** when there are light BSM states (compared to EW scale) or BSM sources of symmetry breaking
  - ✓ **SMEFT:** when heavy new states (compared to EW scale)

See: R. Alonso, E. E. Jenkins, A. Manohar, JHEP 08 (2016) 10, arXiv: 1605.03602 [hep-ph]
T. Cohen, N. Craig, X. Lu, D. Sutherland, JHEP 03 (2021) 237, arXiv: 2008.08597 [hep-ph]
for a geometrical interpretation of the differences between HEFT and SMEFT

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I will focus on this for this talk

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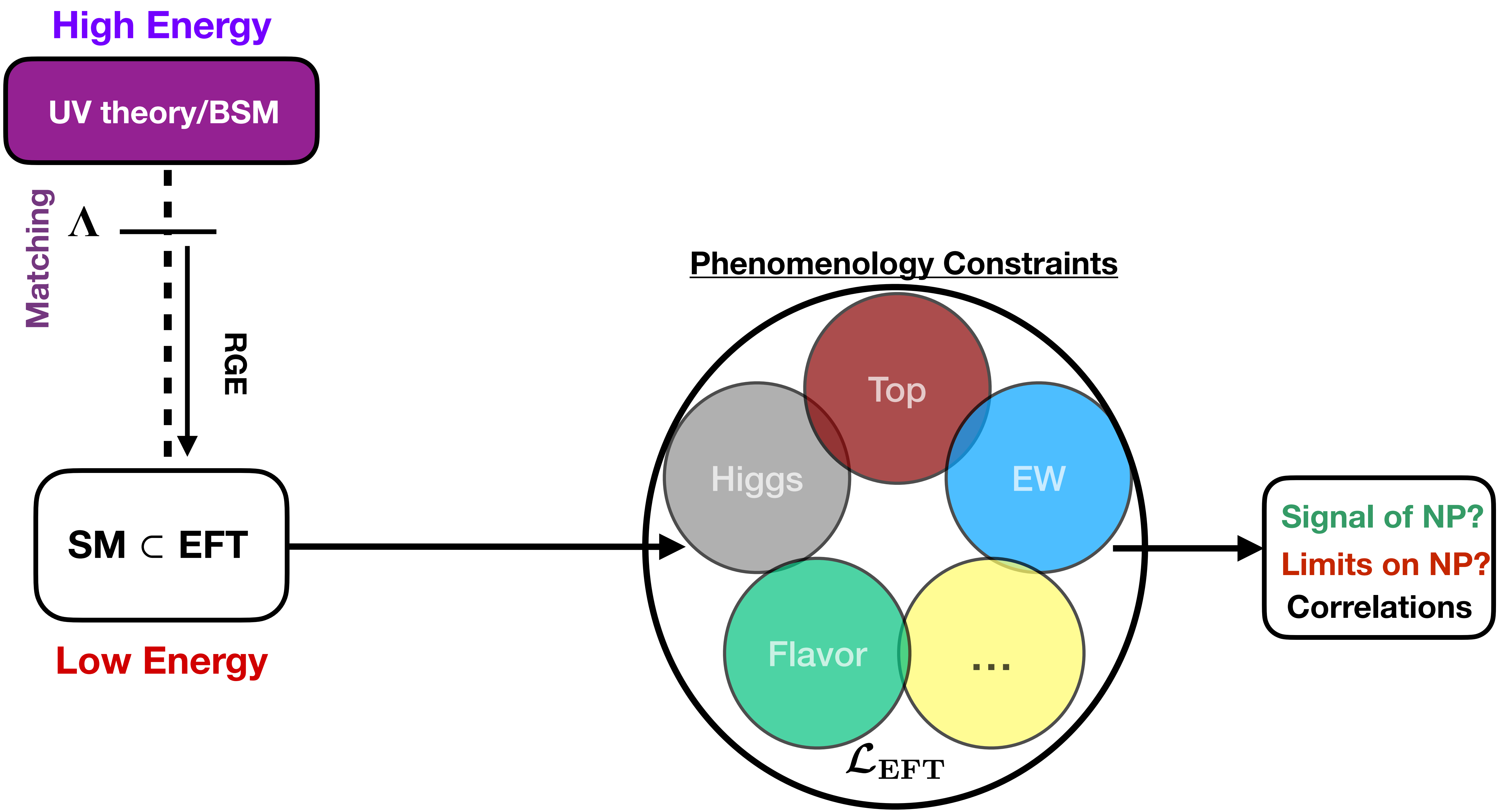
Effective Field Theories

- EFT as a phenomenological tool for indirect BSM searches



Effective Field Theories

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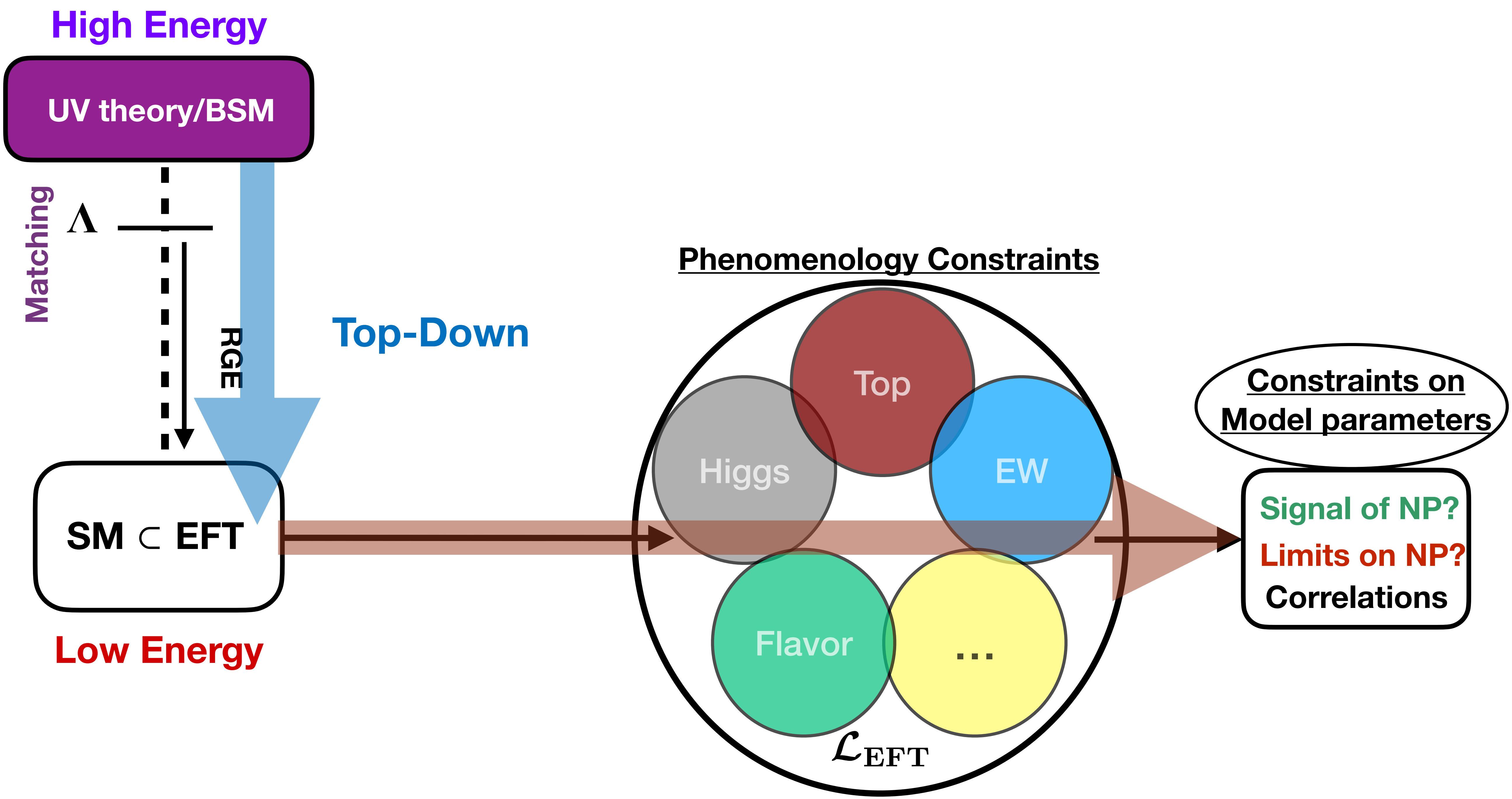

You only need to compute the EFT predictions once!
⇒ Match to model

Effective Field Theories

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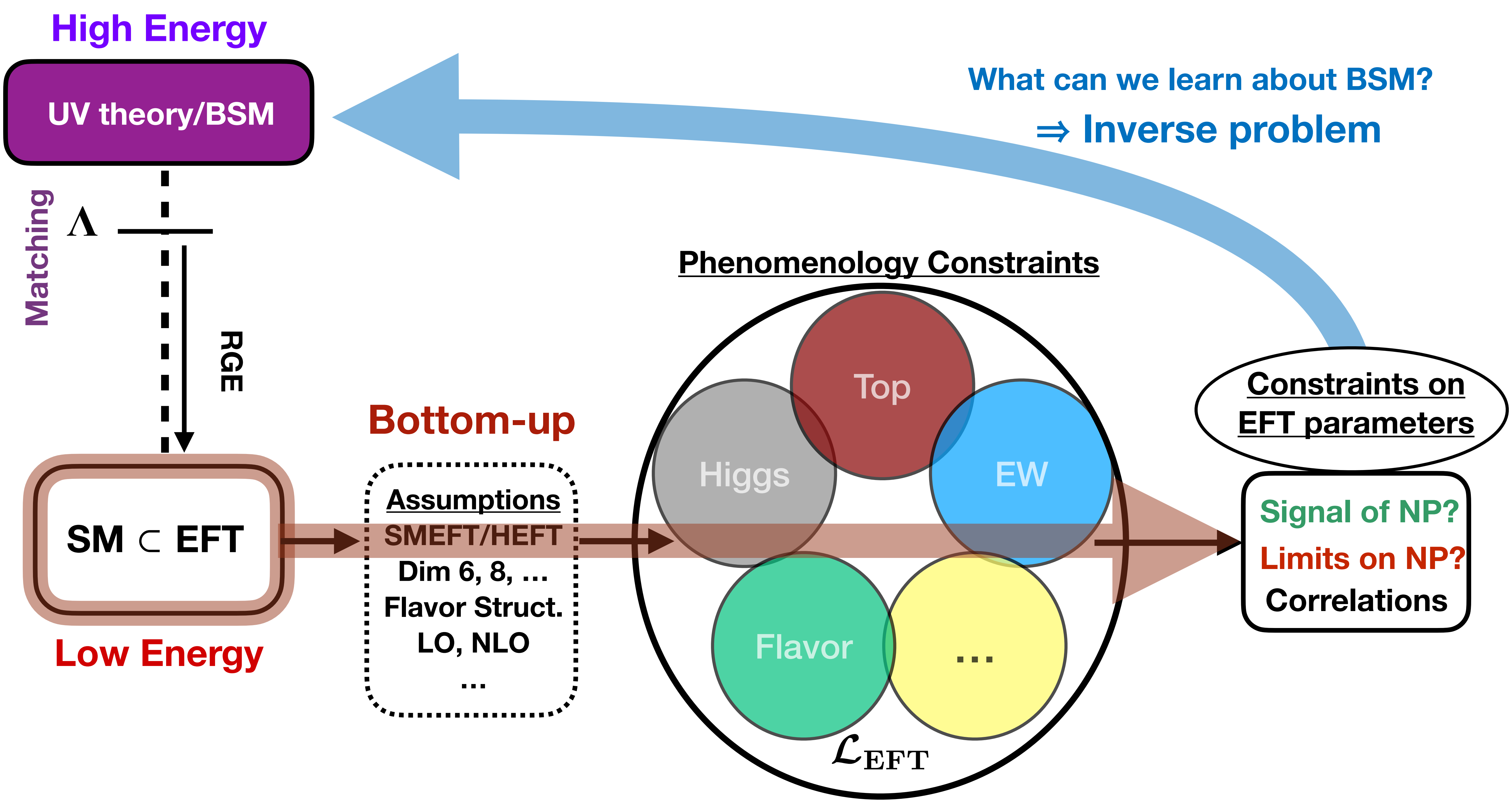

Effective Field Theories: SMEFT

- **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)

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

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

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

Warsaw basis operators (Neglecting flavour)

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

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

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

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]	$\mathcal{O}_{\phi d}^{(1)}$
[illegible]	[illegible]	[illegible]	$\mathcal{O}_{eW}$
[illegible]	[illegible]	[illegible]	$\mathcal{O}_{uW}$
[illegible]	[illegible]	[illegible]	$\mathcal{O}_{dW}$
[illegible]	[illegible]	[illegible]	$\mathcal{O}_{dG}$
[illegible]	[illegible]	[illegible]	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\, \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\, \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\, \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_W$	$\varepsilon_{abc}\widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}\widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

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

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

Effective Field Theories: 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

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

$$+\frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu}W_\nu^{-\rho}A_\rho^\mu + \cos\theta_w W_\mu^{+\nu}W_\nu^{-\rho}Z_\rho^\mu\right),$$

Hff

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

Vff & HVff

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

$$+ \sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}\hat{\delta}g_L^{Zf}\bar{f}\gamma_\mu f + \sum_{f=u,d,e}\hat{\delta}g_R^{Zf}\bar{f}\gamma_\mu f\right]$$

Effective Field Theories: SMEFT

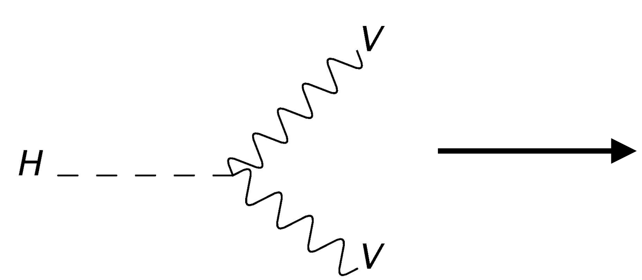
- **SMEFT** in the mass eigenstate basis (unitary gauge). LO EW/Higgs interactions:

HVV

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

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

Where to test these?



$H \to VV'$ $\quad$ $pp \to HV$

$gg \to H$ $\quad$ $e^+e^- \to HZ$

(Tree level)

Effective Field Theories: SMEFT

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

Higgs parameterisation G-INT-2015-001

HVV

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

$$\delta c_w = \delta c_z + 4\delta m,$$
$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},$$

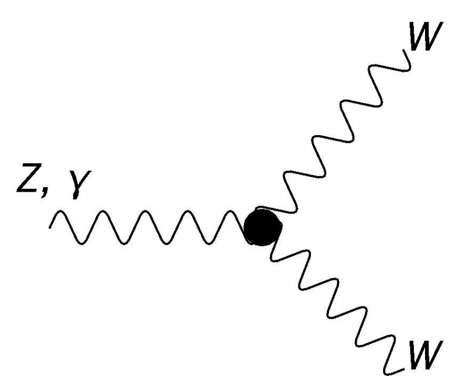
aTGC

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

Hff

Vff & HVff

Where to test these?



$\longrightarrow$

$e^+e^- \to W^+W^-$

$pp \to W^+W^-, WZ, W\gamma$

(Tree level)

Effective Field Theories: SMEFT

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

HVV

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

$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu}\Big]$$

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

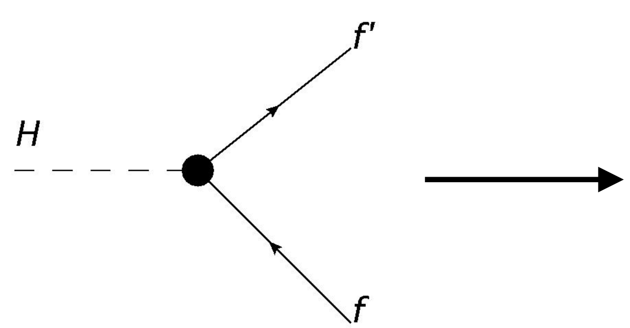
Hff

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

$$+\frac{\ldots}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu} W_\nu^{-\rho} A_\rho^\mu + \cos\theta_w W_\mu^{+\nu} W_\nu^{-\rho} Z_\rho^\mu\right),$$

Vff & HVff

Where to test these?



$$H \to f f'$$

$$pp \to t\bar{t}H$$

$$e^+e^- \to t\bar{t}H$$

(Tree level)

Effective Field Theories: SMEFT

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

HVV

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

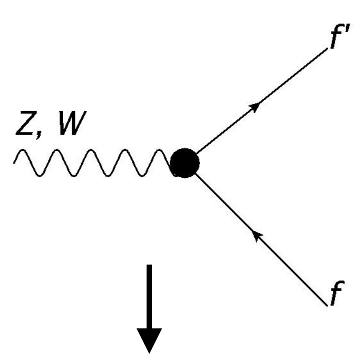
$$\delta c_w = \delta c_z + 4\delta m,$$
$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},$$
$$c_{w\Box} = \frac{1}{g^2 - g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2 \sin^2\theta_w c_{\gamma\gamma} - (g^2 - g'^2)\sin^2\theta_w c_{z\gamma}\right]$$

Vff & HVff

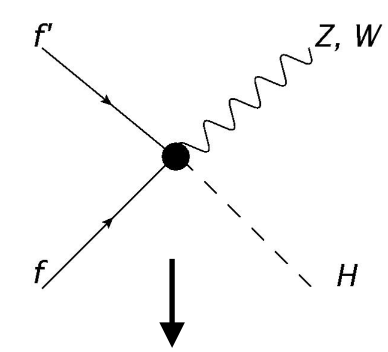
$$\Delta\mathcal{L}_6^{vff,hvff} = \frac{g}{\sqrt{2}}\left(1 + 2\frac{h}{v}\right) W_\mu^+ \left(\hat{\delta} g_L^{W\ell} \bar{\nu}\bar{\gamma}_\mu e + \hat{\delta} g_L^{Wq} \bar{u}\gamma_\mu d + \hat{\delta} g_R^{Wq} \bar{u}\gamma_\mu d + \text{h.c.}\right)$$
$$+ \sqrt{g^2+g'^2}\left(1 + 2\frac{h}{v}\right)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

Higgs parameterisa... ...G-INT-2015-001

Where to test these?



$e^+e^- \to Z \to f\bar{f}$



(Tree level)

$pp \to HV$ $\quad e^+e^- \to HZ$

Effective Field Theories: SMEFT

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

HVV

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

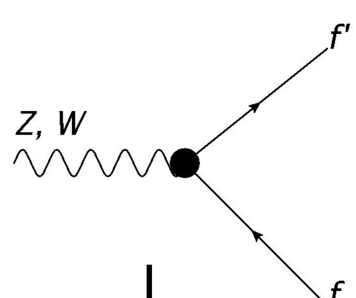
$$\delta c_w = \delta c_z + 4\delta m,$$
$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma},$$
$$c_{w\Box} = \frac{1}{g^2 - g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2 \sin^2\theta_w c_{\gamma\gamma} - (g^2 - g'^2)\sin^2\theta_w c_{z\gamma}\right]$$

Vff & HVff

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

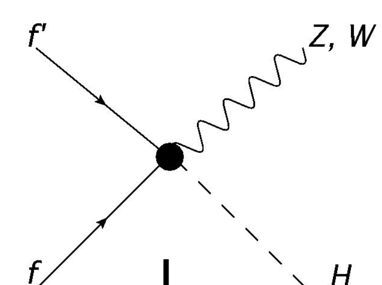
Higgs parameterisa... WG-INT-2015-001

Where to test these?



$e^+e^- \to Z \to f\bar{f}$

"Same" EFT interaction

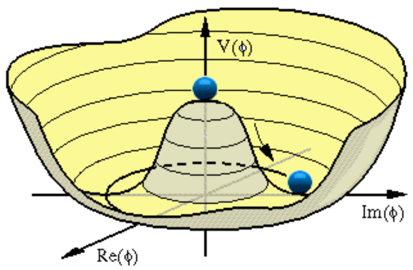


$pp \to HV$ $\quad e^+e^- \to HZ$

(Tree level)

Effective Field Theories: SMEFT

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



Linear EWSB

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

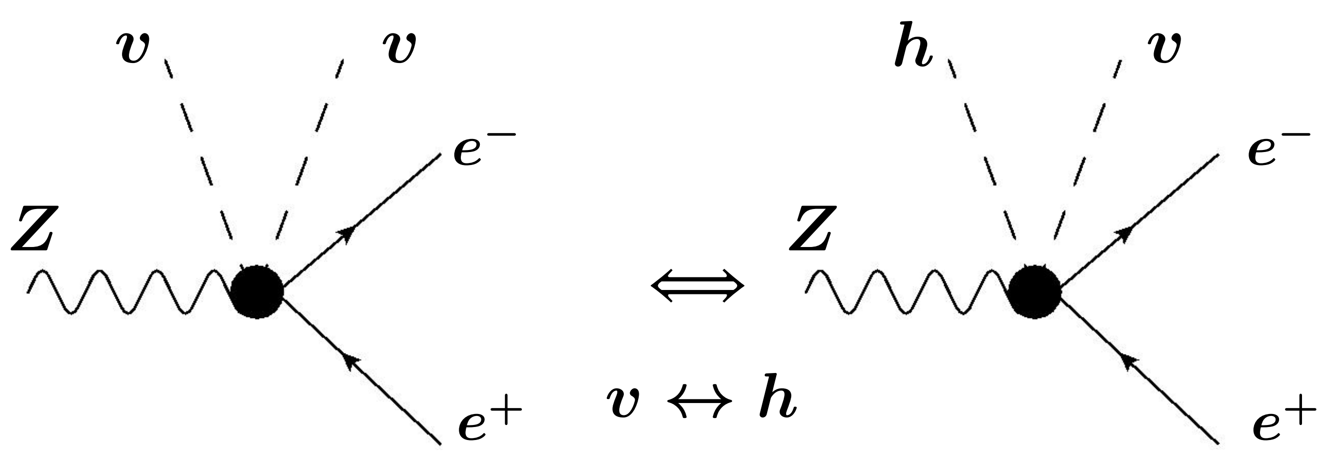
SM gauge invariance

$$D_\mu = \partial_\mu + igA_\mu$$

$(\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\bar{e}^i_R \gamma^\mu e^j_R)$

Ze^+e^-

Vff



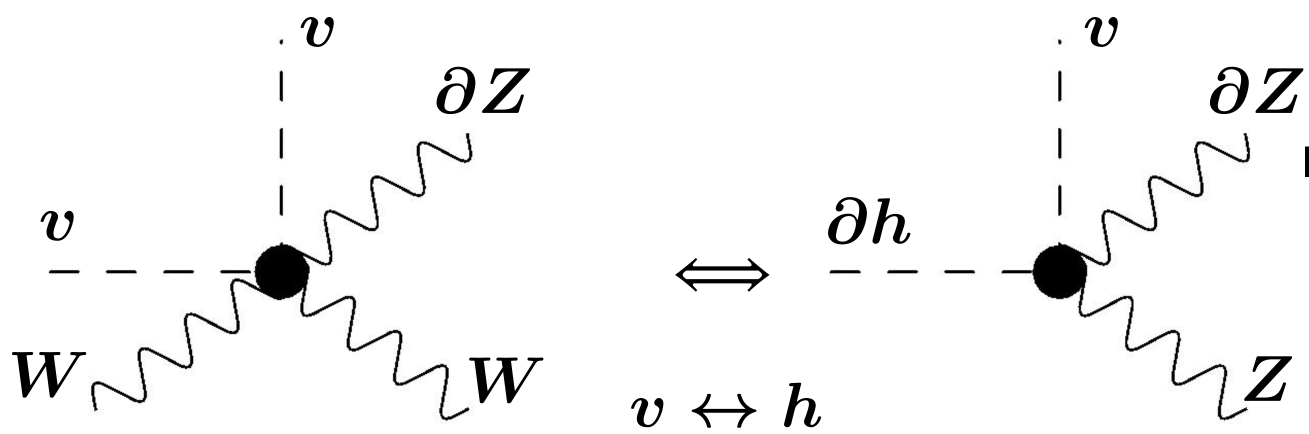
hZe^+e^-

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 →

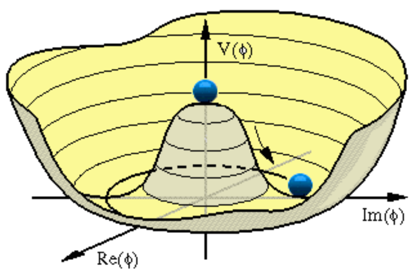
$hZ_\mu\partial_\nu Z^{\mu\nu}$

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

HVV

Effective Field Theories: SMEFT

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



Linear EWSB

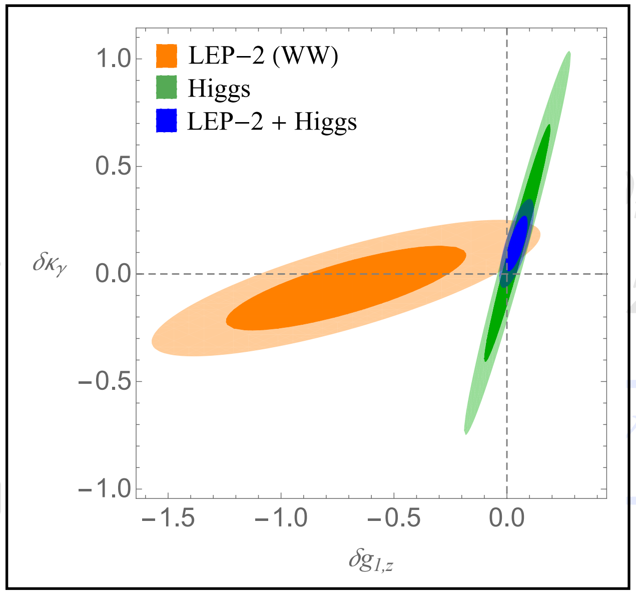
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

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

Effective Field Theories: SMEFT

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Higgs parameterisation: LHCHXSWG-INT-2015-001

HVV

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

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

Richer structure than SM

15 independent structures (not counting flavor)

Connected to other par via SMEFT corr.

aTGC

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

Only λ_z is independent

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

Hff

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

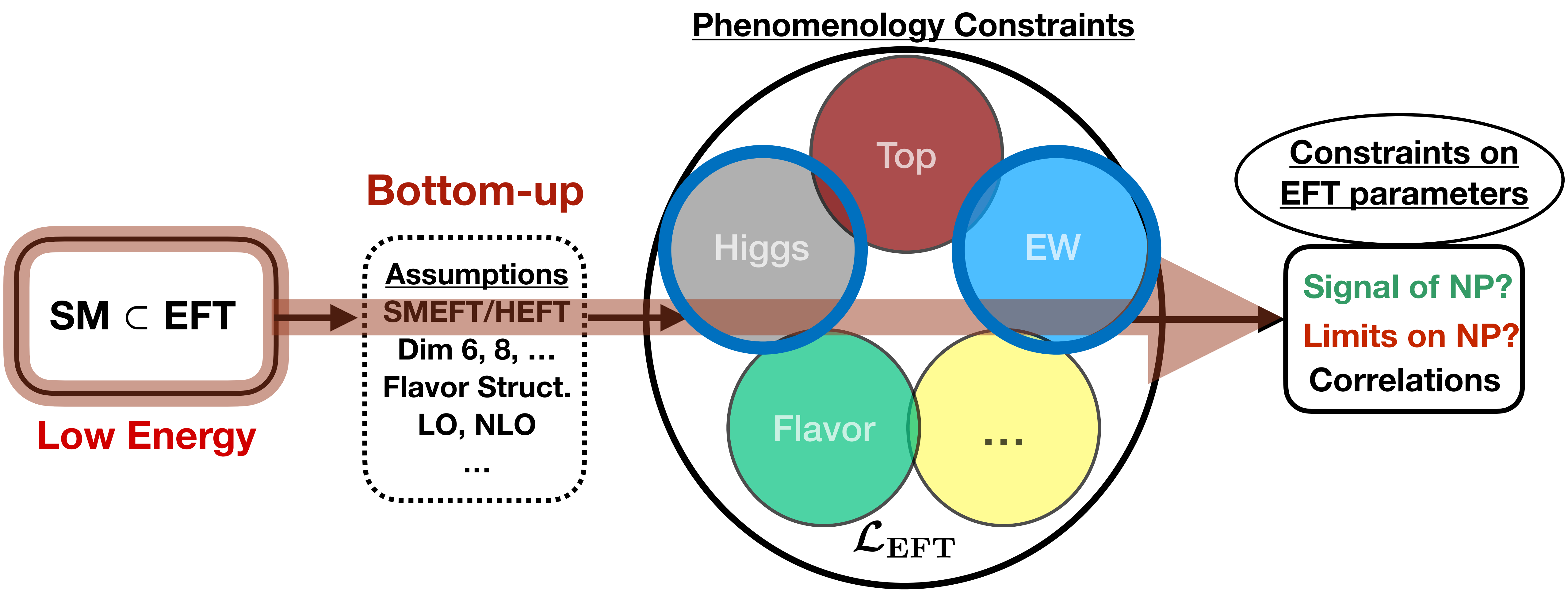
Vff & HVff

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

The SMEFT
at the LHC

The SMEFT at the LHC

- In the following slides, I will focus on the bottom-up approach, and obtain bounds on the dimension-6 SMEFT from a global fit to current EW and Higgs measurements at the LHC. Then we will have a look at what we expect such constraints to look like at future colliders



Fit to exp. observables, O, via log-likelihood (chi square)

$$\chi^2 = -2\log L = (\underbrace{O_{\rm obs}}_{\text{Observed}} - \underbrace{O_{\rm th}(C_i)}_{\text{Prediction}})^T V^{-1} (O_{\rm obs} - O_{\rm th}(C_i))$$

V^{-1}: (Inverse) Covariance: errors, correlations

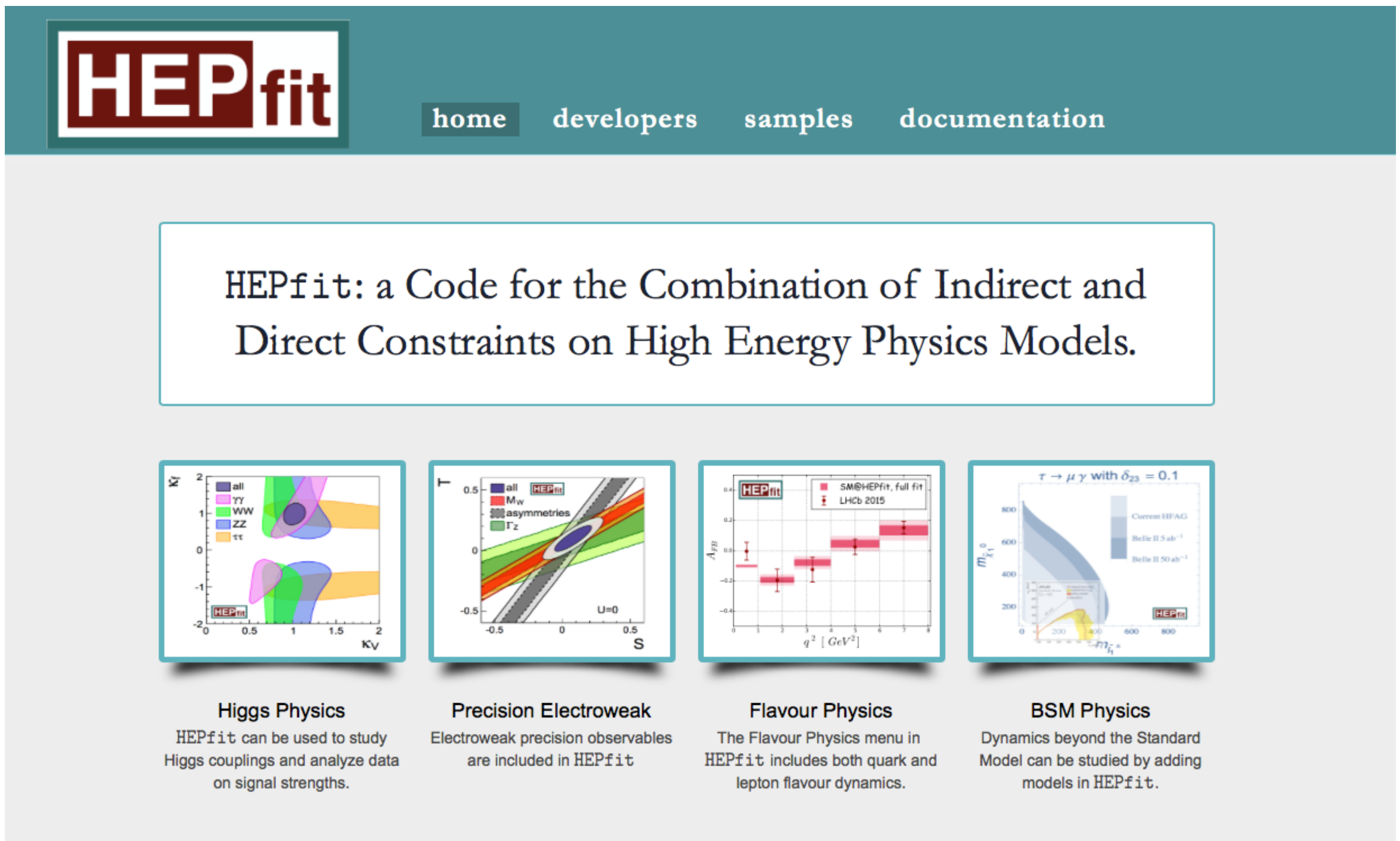
The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)

  https://github.com/silvest/HEPfit

  J.B. et al., Eur. Phys. J. C (2020) 80:456, arXiv: 1910.14012 [hep-ph]

- Webpage: **http://hepfit.roma1.infn.it**



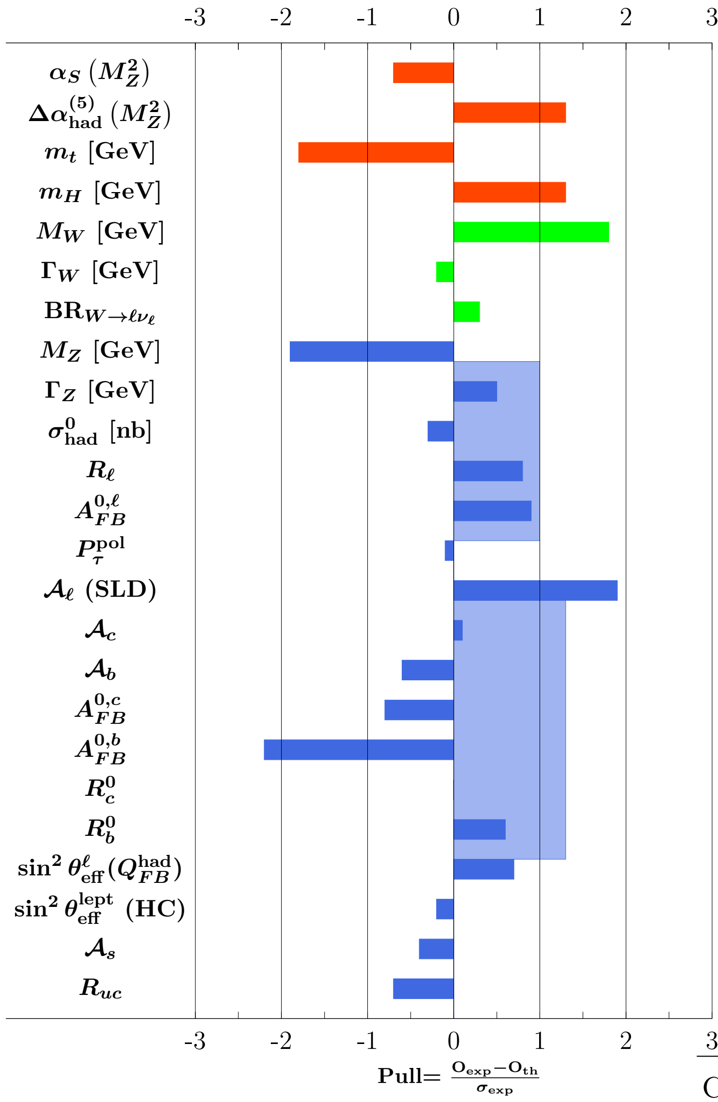
The HEPfit code

- EWPO computed analytically from scratch
- LHC Higgs observables (signal strengths and STXS) computed via in-house implementation of the dim-6 SMEFT in *FeynRules*:
  - ✓ Implementation in the Warsaw basis
  - ✓ Used in combination with *Madgraph5_aMC@NLO* to fit predictions to semi-analytical expressions of the form
  $$O = O_{\rm SM} + \sum_i a_i \frac{C_i}{\Lambda^2} + \sum_{i,j} b_{ij} \frac{C_i C_j^*}{\Lambda^4}$$
  - ✓ Cross-checks performed against the model set A of *The SMEFTsim package* from I. Brivio, Y. Jiang, M. Trott, JHEP 12 (2017) 070
- SMEFT parameterization of LEP2 $e^+e^- \longrightarrow W^+W^-$ from L. Berthier, M. Bjorn, M. Trott, JHEP 09 (2016) 157 currently available (testing our own implementation)
- SMEFT parameterisation of LHC diboson processes from J. Baglio et al., arXiv: 2003.07862 [hep-ph]

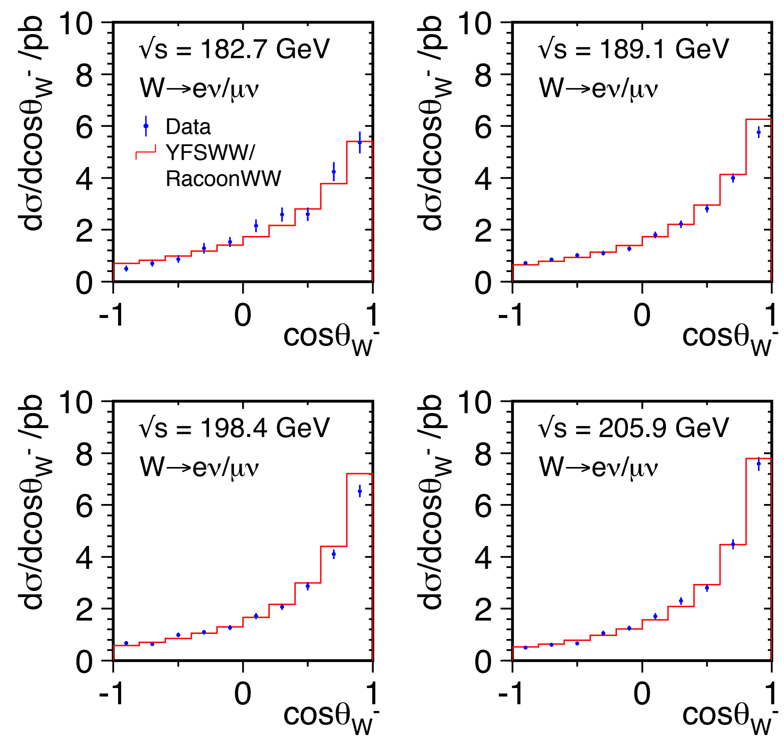
The SMEFT at the LHC

- What goes into the LHC SMEFT EW/Higgs fit…

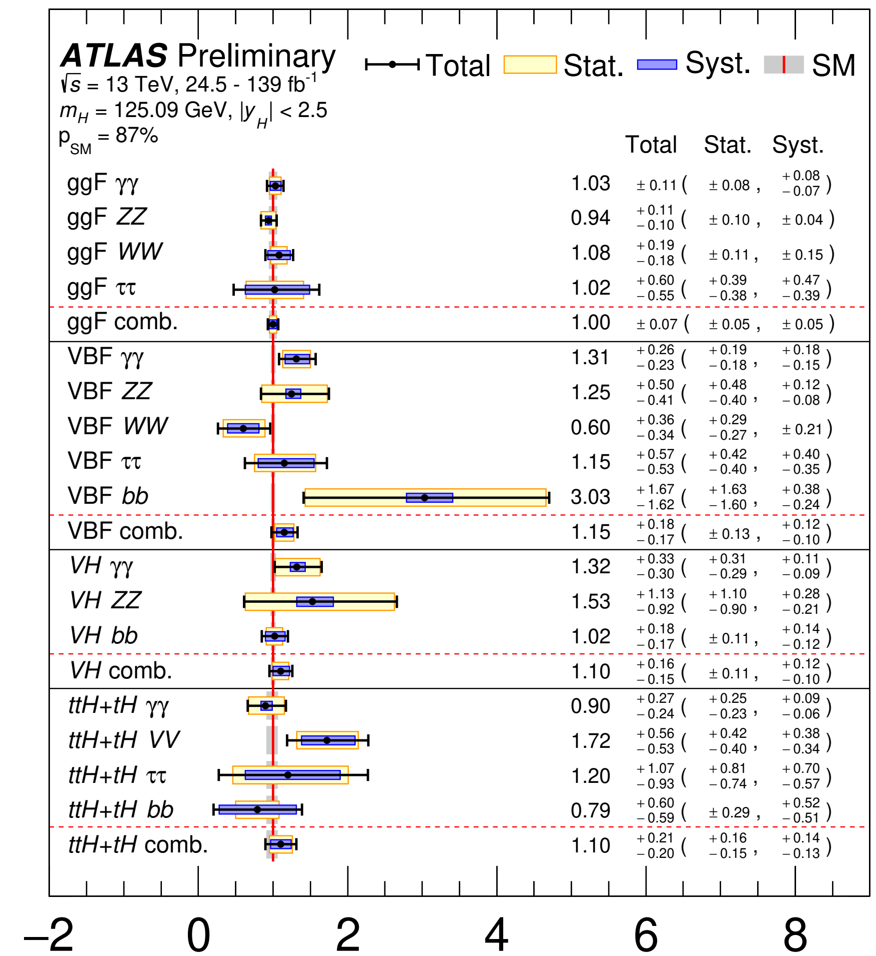
EWPO (LEP/SLC+Tevatron+LHC)



Diboson (LEP 2)



Higgs (Tevatron+ LHC Run 1+2)



σ × B normalized to SM

+ the corresponding CMS results

Diboson (LHC Run 1+2)

Channel	Distribution	# bins	Data set	Int. Lum.
$W^+W^- \to \ell^+\ell'^- + \not{E}_T$ (0j)	$p_T^{\text{leading,lepton}}$, Fig. 11	1	ATLAS 8 TeV	20.3 fb^{-1}
$W^+W^- \to e^\pm\mu^\mp + \not{E}_T$ (0j)	$p_T^{\text{leading,lepton}}$, Fig. 7	5	ATLAS 13 TeV	36.1 fb^{-1}
$W^\pm Z \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}, Fig. 5	2	ATLAS 8 TeV	20.3 fb^{-1}
$W^\pm Z \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$, Fig. 5	9	CMS 8 TeV	19.6 fb^{-1}
$W^\pm Z \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ} Fig. 4c	6	ATLAS 13 TeV	36.1 fb^{-1}
$W^\pm Z \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	m^{WZ}, Fig. 15a	3	CMS 13 TeV,	35.9 fb^{-1}

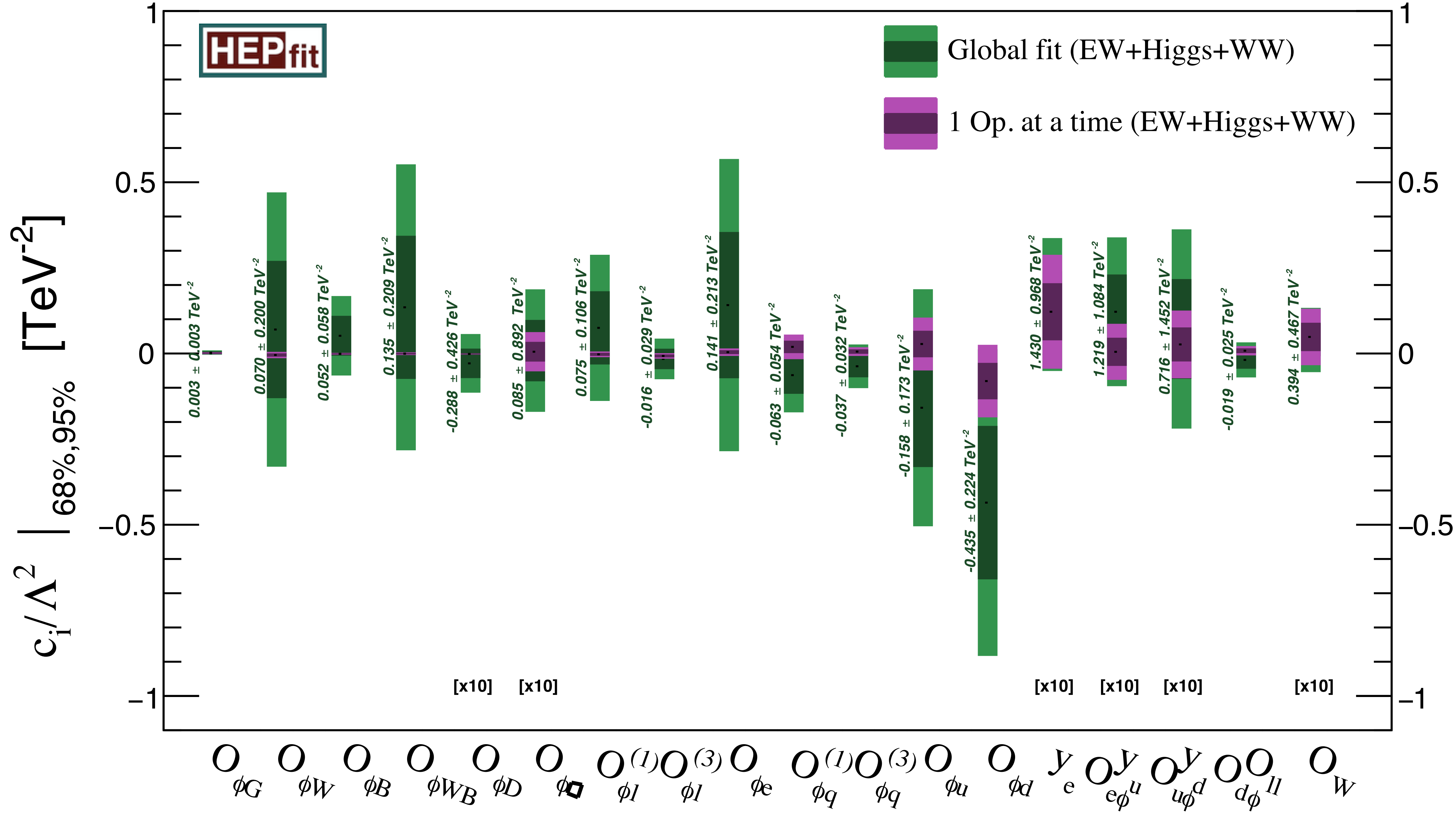
J. Baglio et al., arXiv: 2003.07862 [hep-ph]

J. B. et al., In preparation

The SMEFT at the LHC

- **Bayesian SMEFT fit to EW/Higgs/diBoson:**

LHC Run 1 + Run 2 (~36-140 fb^{-1})



New Physics assumptions: CP-even, U(3)^5

JB, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini, In preparation

The SMEFT at the LHC

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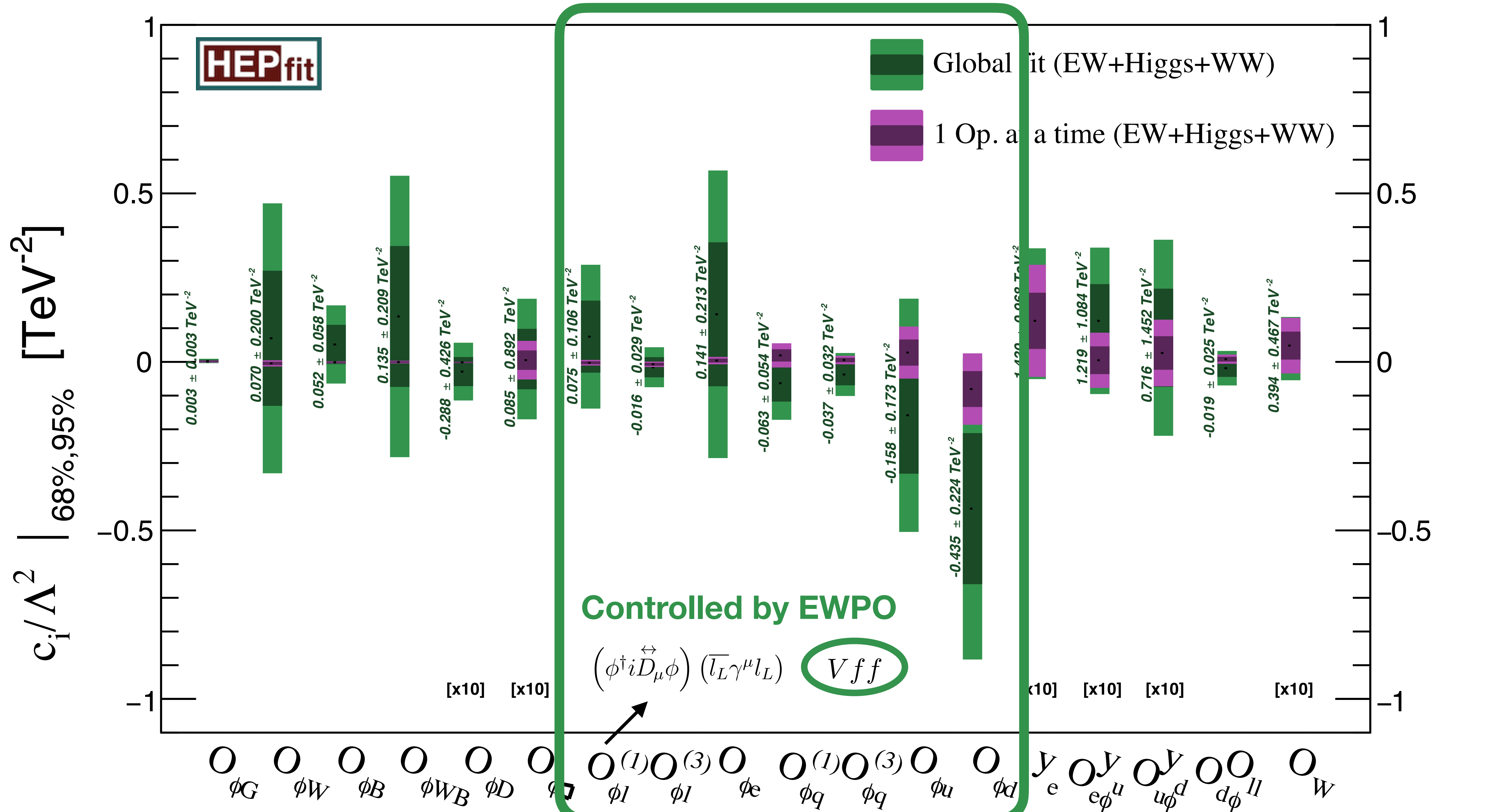

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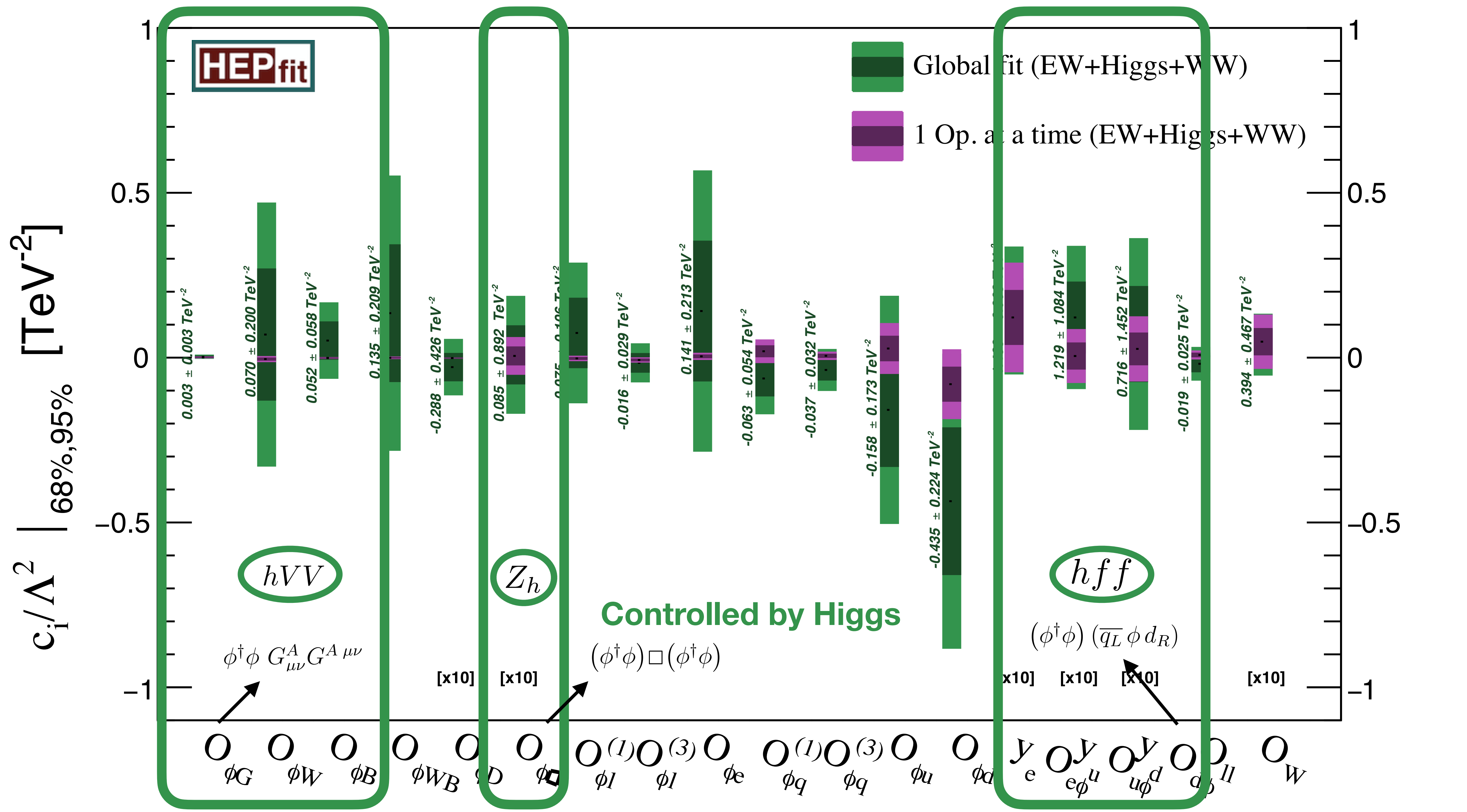
The SMEFT at the LHC

- **Bayesian SMEFT fit to EW/Higgs/diBoson:**

LHC Run 1 + Run 2 (~36-140 fb⁻¹)



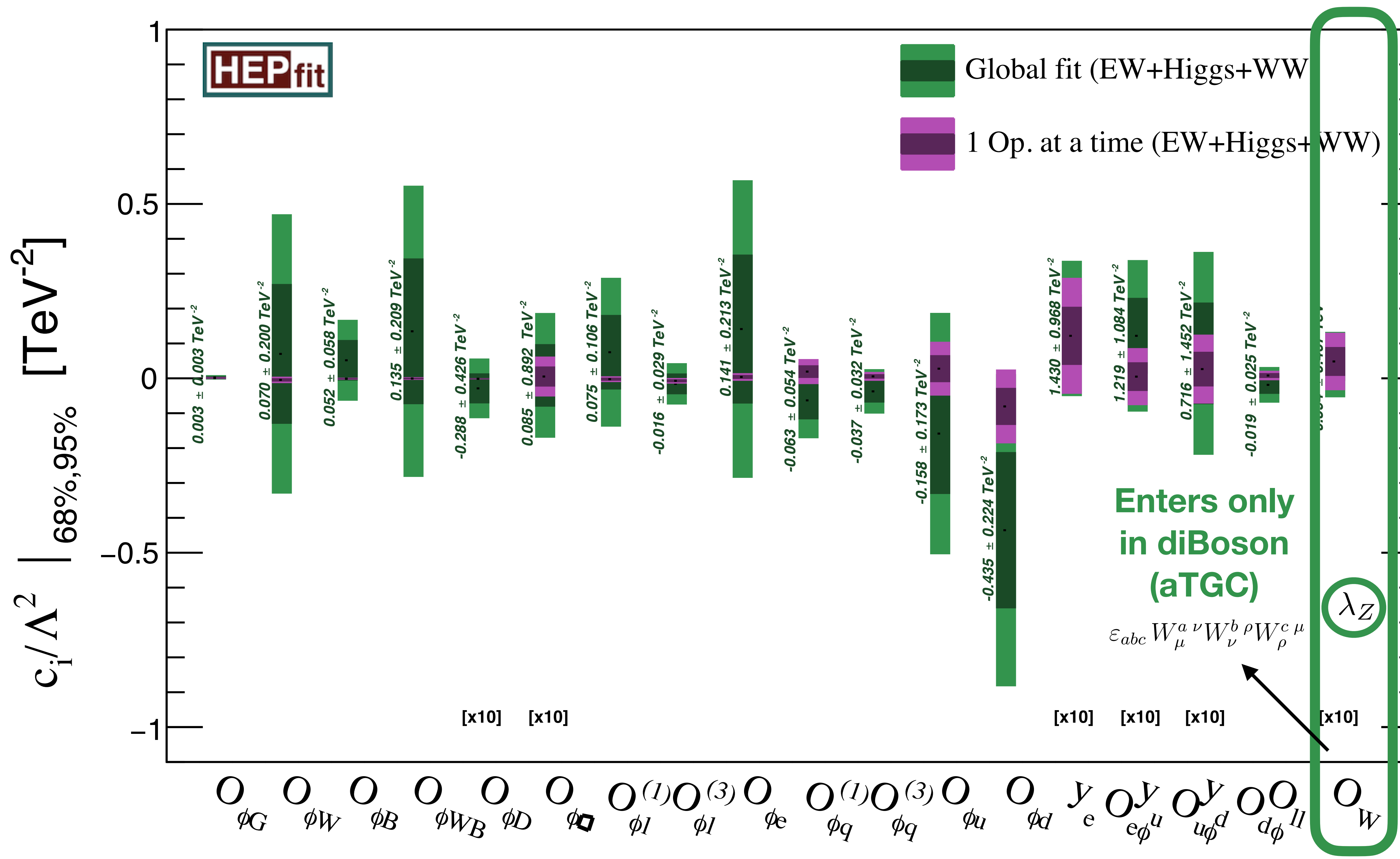
New Physics assumptions: CP-even, U(3)⁵

JB, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini, In preparation

The SMEFT at the LHC

- **Bayesian SMEFT fit to EW/Higgs/diBoson:**

LHC Run 1 + Run 2 (~36-140 fb^{-1})



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JB, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini, In preparation

The SMEFT at the LHC

- **Bayesian SMEFT fit to EW/Higgs/diBoson:** LHC Run 1 + Run 2 (~36-140 fb^{-1})

SMEFT EW/Higgs fit

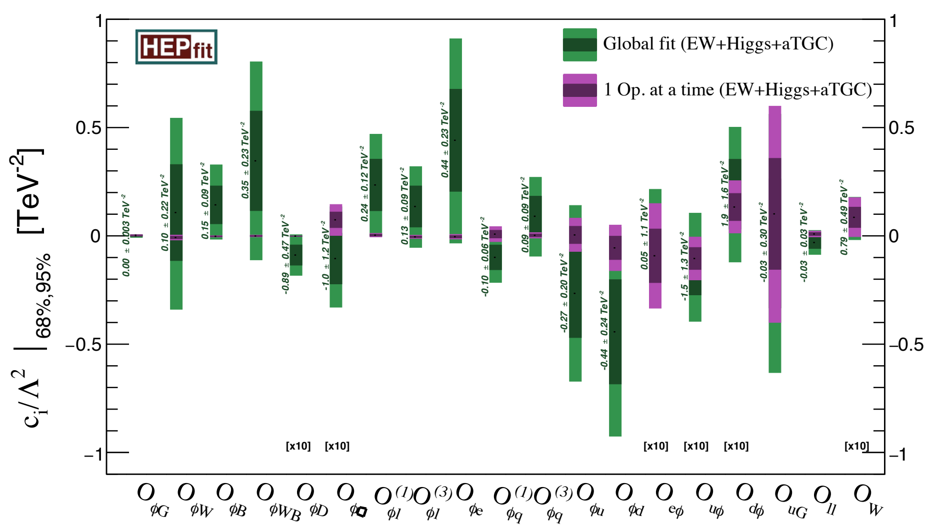
Correlations in the SMEFT fit

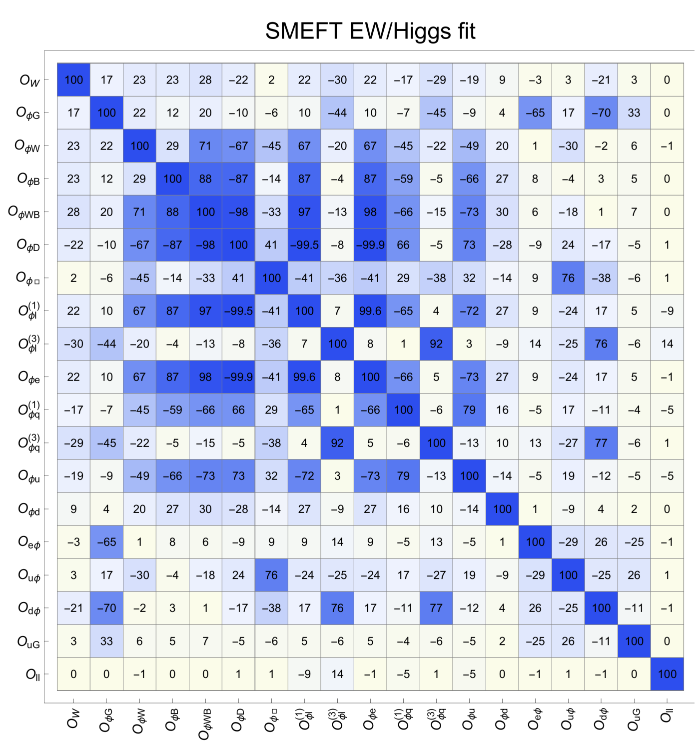
	O_W	$O_{\phi G}$	$O_{\phi W}$	$O_{\phi B}$	$O_{\phi WB}$	$O_{\phi D}$	$O_{\phi\Box}$	$O_{\phi l}^{(1)}$	$O_{\phi l}^{(3)}$	$O_{\phi e}$	$O_{\phi q}^{(1)}$	$O_{\phi q}^{(3)}$	$O_{\phi u}$	$O_{\phi d}$	$O_{e\phi}$	$O_{u\phi}$	$O_{d\phi}$	O_{uG}	O_{ll}
O_W	100	17	23	23	28	−22	2	22	−30	22	−17	−29	−19	9	−3	3	−21	3	0
$O_{\phi G}$	17	100	22	12	20	−10	−6	10	−44	10	−7	−45	−9	4	−65	17	−70	33	0
$O_{\phi W}$	23	22	100	29	71	−67	−45	67	−20	67	−45	−22	−49	20	1	−30	−2	6	−1
$O_{\phi B}$	23	12	29	100	88	−87	−14	87	−4	87	−59	−5	−66	27	8	−4	3	5	0
$O_{\phi WB}$	28	20	71	88	100	−98	−33	97	−13	98	−66	−15	−73	30	6	−18	1	7	0
$O_{\phi D}$	−22	−10	−67	−87	−98	100	41	−99.5	−8	−99.9	66	−5	73	−28	−9	24	−17	−5	1
$O_{\phi\Box}$	2	−6	−45	−14	−33	41	100	−41	−36	−41	29	−38	32	−14	9	76	−38	−6	1
$O_{\phi l}^{(1)}$	22	10	67	87	97	−99.5	−41	100	7	99.6	−65	4	−72	27	9	−24	17	5	−9
$O_{\phi l}^{(3)}$	−30	−44	−20	−4	−13	−8	−36	7	100	8	1	92	3	−9	14	−25	76	−6	14
$O_{\phi e}$	22	10	67	87	98	−99.9	−41	99.6	8	100	−66	5	−73	27	9	−24	17	5	−1
$O_{\phi q}^{(1)}$	−17	−7	−45	−59	−66	66	29	−65	1	−66	100	−6	79	16	−5	17	−11	−4	−5
$O_{\phi q}^{(3)}$	−29	−45	−22	−5	−15	−5	−38	4	92	5	−6	100	−13	10	13	−27	77	−6	1
$O_{\phi u}$	−19	−9	−49	−66	−73	73	32	−72	3	−73	79	−13	100	−14	−5	19	−12	−5	−5
$O_{\phi d}$	9	4	20	27	30	−28	−14	27	−9	27	16	10	−14	100	1	−9	4	2	0
$O_{e\phi}$	−3	−65	1	8	6	−9	9	9	14	9	−5	13	−5	1	100	−29	26	−25	−1
$O_{u\phi}$	3	17	−30	−4	−18	24	76	−24	−25	−24	17	−27	19	−9	−29	100	−25	26	1
$O_{d\phi}$	−21	−70	−2	3	1	−17	−38	17	76	17	−11	77	−12	4	26	−25	100	−11	−1
O_{uG}	3	33	6	5	7	−5	−6	5	−6	5	−4	−6	−5	2	−25	26	−11	100	0
O_{ll}	0	0	−1	0	0	1	1	−9	14	−1	−5	1	−5	0	−1	1	−1	0	100

The SMEFT at the LHC

- **Bayesian SMEFT fit to EW/Higgs/diBoson:**

Both errors and correlations needed to project EFT results to BSM



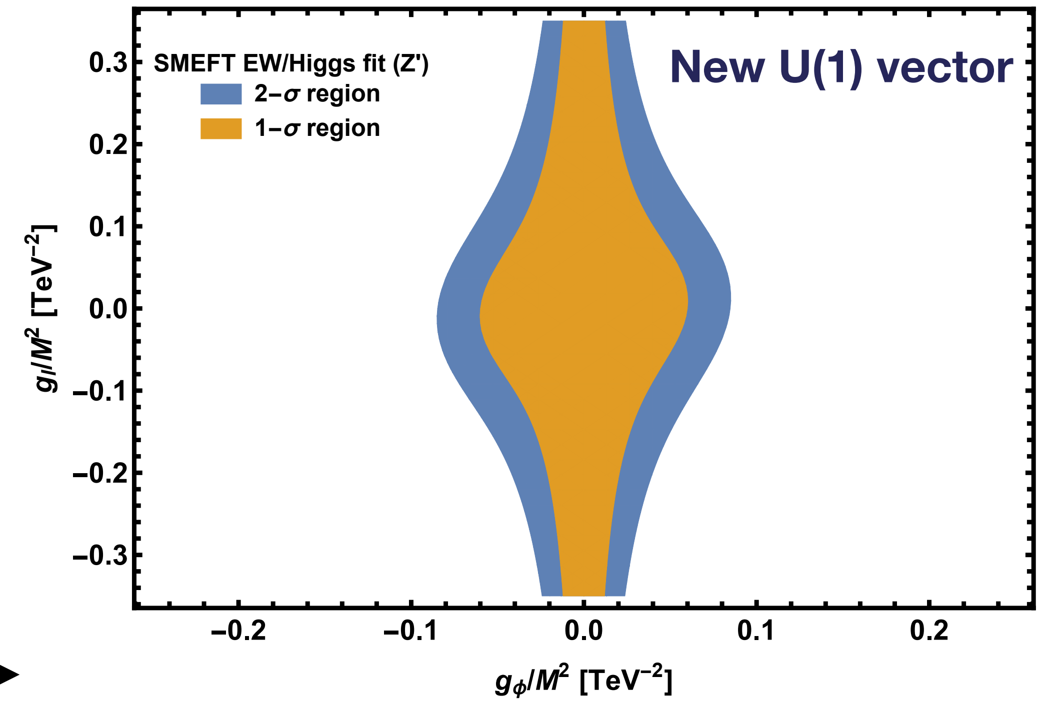


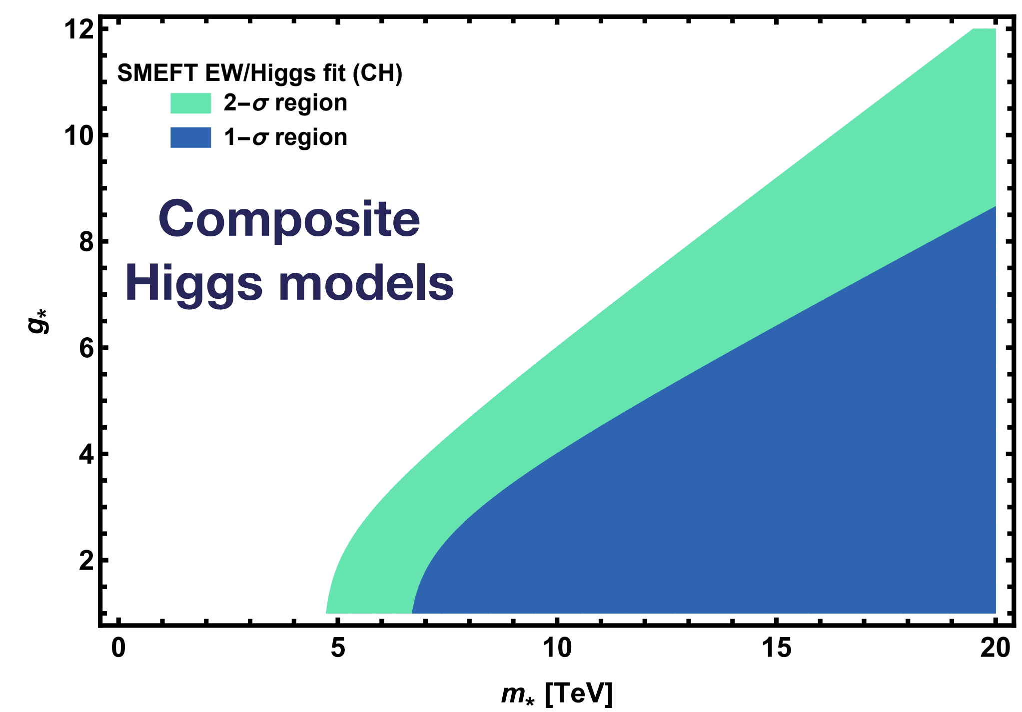
Project Likelihood via matching to favorite model

Matching dictionary available at tree level

J. B. et al, JHEP 1803 (2018) 109

(1-loop soon…)

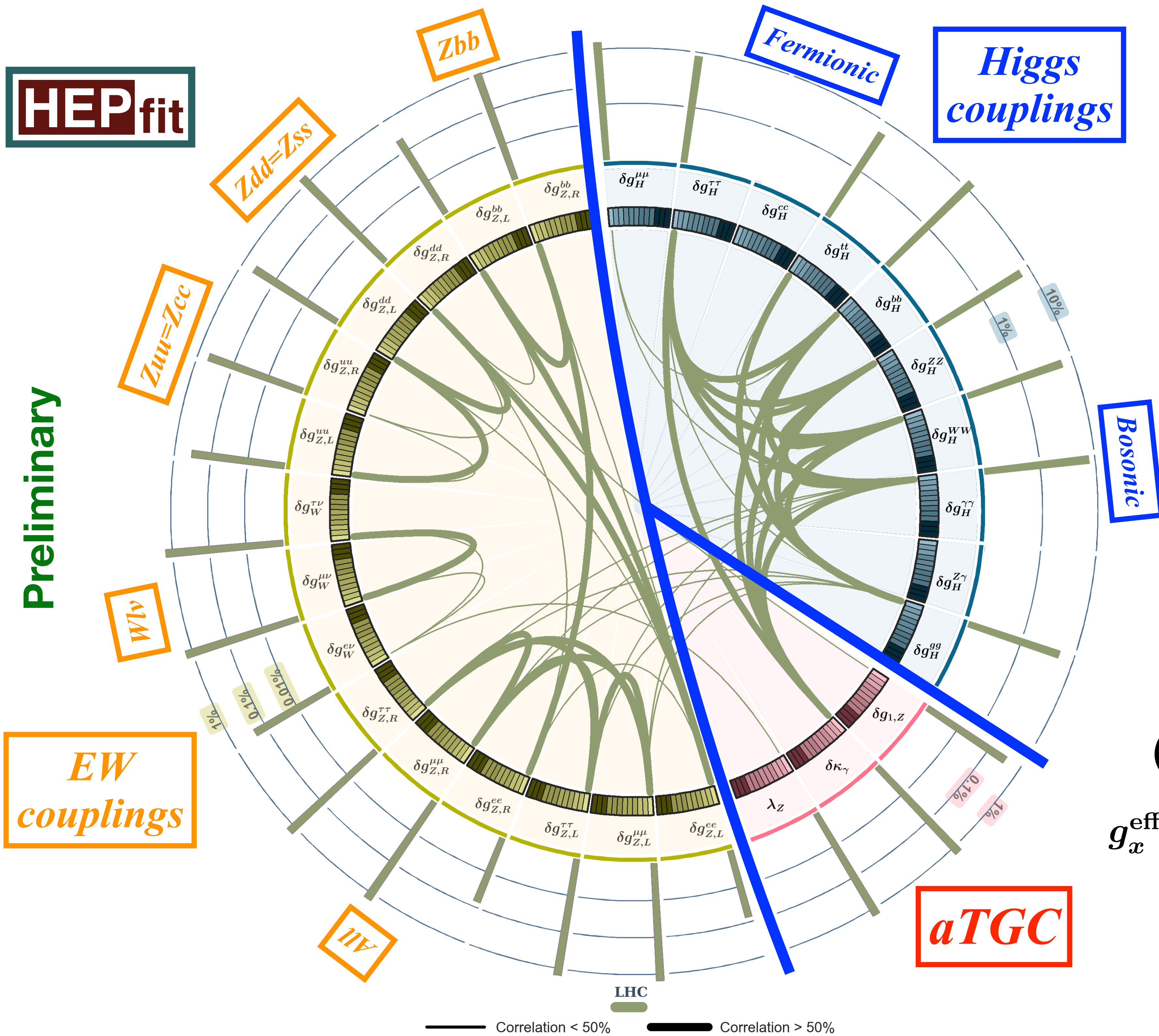




J. B. et al., In preparation

The SMEFT at the LHC

- **SMEFT fit to EW/Higgs/diBoson:** LHC Run 1 + Run 2 (~36-140 fb^{-1})



Sensitivity to BSM deformations of EW/Higgs interactions

New Physics assumptions: CP-even, NO U(3)^5

Fit in the Warsaw basis

$$\frac{C_i}{\Lambda^2}$$

⇩

Projected into deformations of effective couplings (defined from pseudo-observables)

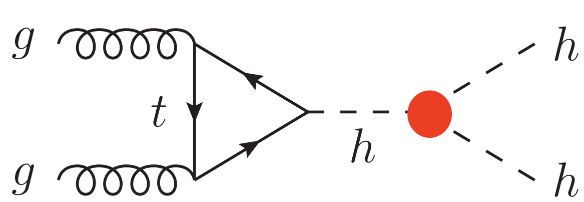
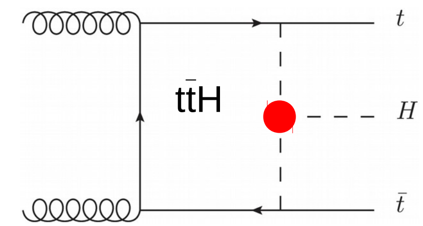
$$g_x^{\rm eff}\left(\frac{C_i}{\Lambda^2}\right) = g_x^{\rm eff}\big|_{\rm SM} + \sum \alpha_i^x \frac{C_i}{\Lambda^2} + O\left(\frac{C^2}{\Lambda^4}\right)$$

e.g. Higgs

$$g_H^{X\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\rm SM}_{H\to X}}$$

The SMEFT at the LHC

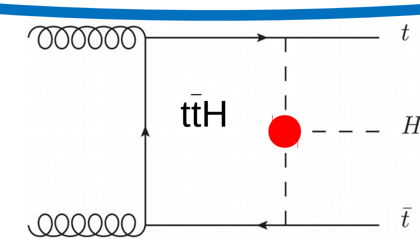
- A comment on the extraction of the **Higgs Trilinear at the LHC**
  (In the dim-6 SMEFT, κ_λ controlled independently by the operator $\mathcal{O}_\phi = (\phi^\dagger \phi)^3$)

	Higgs-pair production	**Via loop effect in single Higgs**
Hadron Colliders		
Lepton Colliders		

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

The SMEFT at the LHC

- A comment on the extraction of the **Higgs Trilinear at the LHC** (In the dim-6 SMEFT, κ_λ controlled independently by the operator $\mathcal{O}_\phi = (\phi^\dagger \phi)^3$)

	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		
Lepton Colliders		

Already being implemented in EXP analyses (see e.g. ATLAS-CONF-2019-049) but…

	di-Higgs	single-H
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The SMEFT at the LHC

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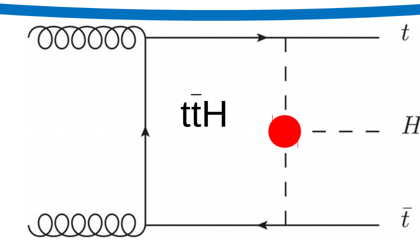
	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		
Lepton Colliders		

Already being implemented in EXP analyses (see e.g. ATLAS-CONF-2019-049) but…

…not enough for a model-independent determination

	di-Higgs	single-H
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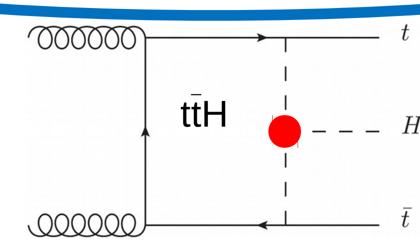
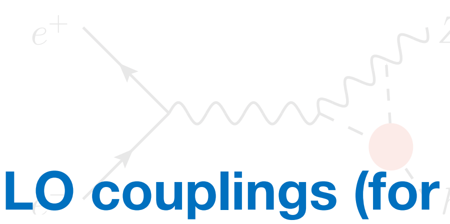
The SMEFT at the LHC

- A comment on the extraction of the **Higgs Trilinear at the LHC**
  (In the dim-6 SMEFT, κ_λ controlled independently by the operator $\mathcal{O}_\phi = (\phi^\dagger \phi)^3$)

	Higgs-pair production	Via loop effect in single Higgs
Hadron Colliders		
Lepton Colliders		

Not enough to add LO couplings (for the LHC)!… Why?

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
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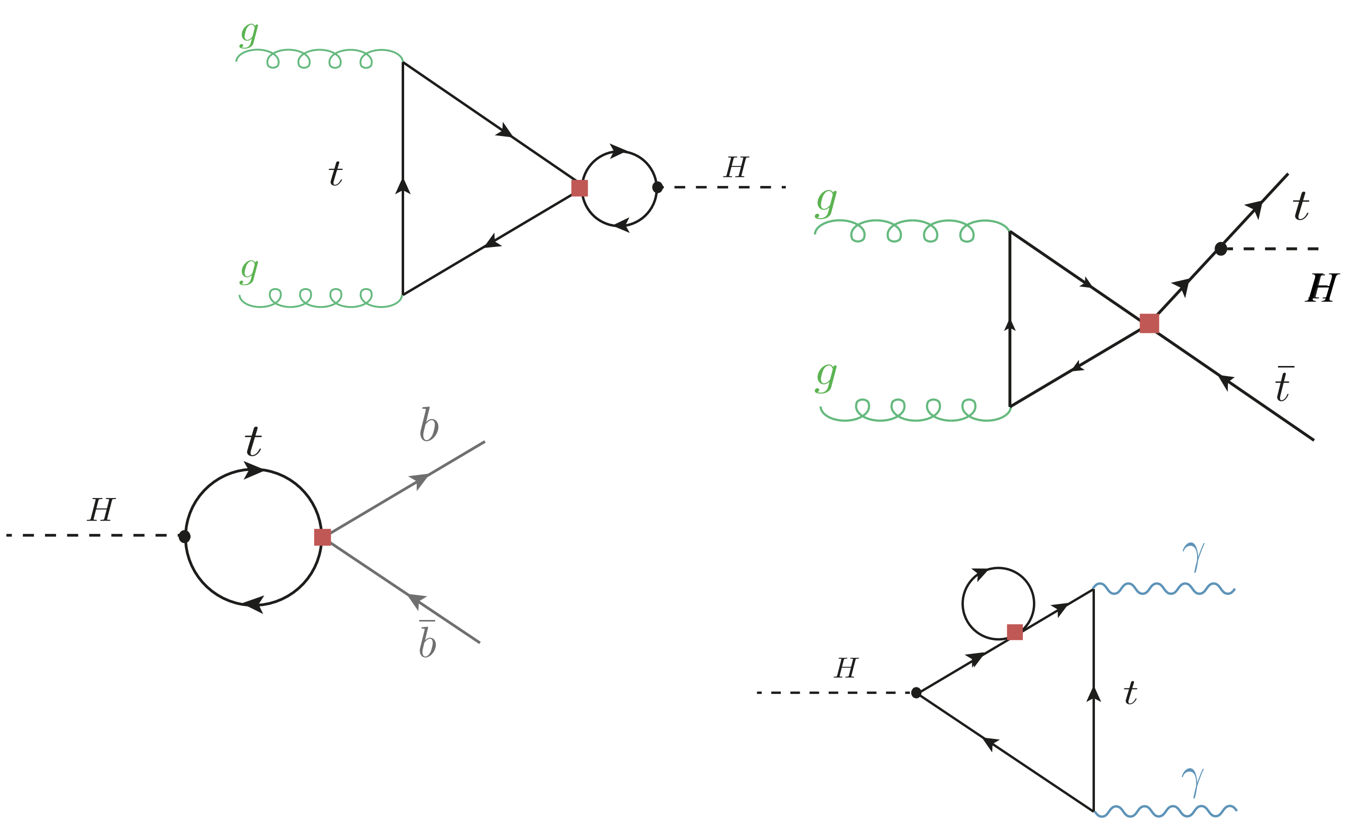
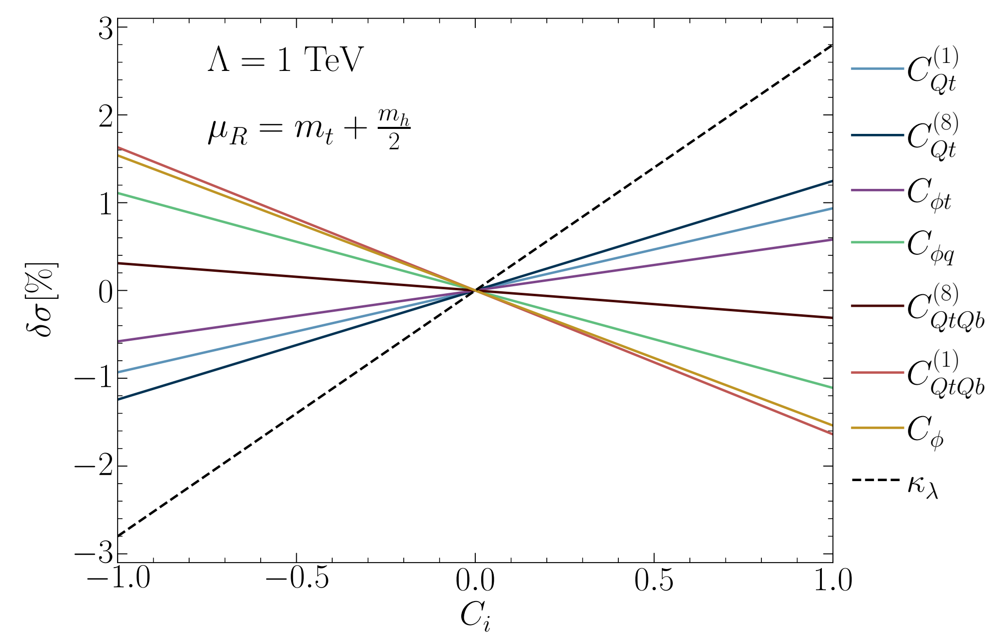
The SMEFT at the LHC

- The extraction of the **Higgs Trilinear at the LHC** can be "contaminated" by other poorly constrained SMEFT operators…

e.g. 4-Top operators enter in ggF, ttH, H→bb and H→γγ @ NLO
(same order in perturbation theory as Higgs trilinear)
and experimental bounds are weak





ttH: A simple estimation of the Leading Log contributions via the RGE shows the contribution of 4-heavy quark operators can be significant

L. Alasfar, J.B., R. Gröber, In preparation

The SMEFT at the LHC

- The extraction of the **Higgs Trilinear at the LHC** can be "contaminated" by other poorly constrained SMEFT operators… e.g. 4-Top operators

We computed the full NLO effects to LHC Higgs processes coming from 4-heavy-quark operators

Operator	Process	μ_R	$\delta R(C_i)^{fin}$	$\delta R(C_i)^{log}$
$\mathcal{O}_{Qt}^{(1)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$9.91 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-2.15 \cdot 10^{-3}$	$-0.60 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-4.29 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
$\mathcal{O}_{Qt}^{(8)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$1.32 \cdot 10^{-2}$	$3.68 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-2.87 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$6.53 \cdot 10^{-2}$	$4.41 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$7.30 \cdot 10^{-2}$	$4.41 \cdot 10^{-3}$
$\mathcal{O}_{QtQb}^{(1)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$4.22 \cdot 10^{-2}$	$1.37 \cdot 10^{-2}$
	$h \to \gamma\gamma$		$-8.07 \cdot 10^{-3}$	$-2.62 \cdot 10^{-3}$
	$h \to b\bar{b}$		$-7.58 \cdot 10^{-1}$	$-8.00 \cdot 10^{-2}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-3.04 \cdot 10^{-3}$	$0.88 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-2.2 \cdot 10^{-3}$	$0.88 \cdot 10^{-3}$
$\mathcal{O}_{QtQb}^{(8)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$8.03 \cdot 10^{-3}$	$2.60 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-1.53 \cdot 10^{-3}$	$-4.98 \cdot 10^{-3}$
	$h \to b\bar{b}$		$-1.50 \cdot 10^{-1}$	$-1.59 \cdot 10^{-2}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-1.61 \cdot 10^{-3}$	$0.67 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-1.10 \cdot 10^{-3}$	$0.67 \cdot 10^{-3}$
$\mathcal{O}_{QQ}^{(1)}$	$t\bar{t}h$ 13 TeV	–	$1.89 \cdot 10^{-3}$	–
	$t\bar{t}h$ 14 TeV		$2.31 \cdot 10^{-3}$	–
$\mathcal{O}_{QQ}^{(3)}$	$t\bar{t}h$ 13 TeV	–	$0.64 \cdot 10^{-3}$	–
	$t\bar{t}h$ 14 TeV		$0.43 \cdot 10^{-3}$	–
$\mathcal{O}_{tt}^{(1)}$	$t\bar{t}h$ 13 TeV	–	$7.50 \cdot 10^{-3}$	–
	$t\bar{t}h$ 14 TeV		$6.44 \cdot 10^{-3}$	–

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$C_1 \cdot 10^{-2}$	C_ϕ ($\Lambda = 1$TeV)
ggF/ $gg \to h$	-0.31
$t\bar{t}h$ 13 TeV	-1.64
$t\bar{t}h$ 14 TeV	-1.62
$h \to \gamma\gamma$	-0.23
$h \to b\bar{b}$	0.00
$h \to W^+W^-$	-0.34
$h \to ZZ$	-0.39
$pp \to Zh$ 13 TeV	-0.56
$pp \to Zh$ 14 TeV	-0.55
$pp \to W^\pm h$	-0.48
VBF	-0.30
$h \to 4\ell$	-0.38

Relative contribution from operators modifying H trilinear
Degrassi et al. '16

The SMEFT at the LHC

- The extraction of the **Higgs Trilinear at the LHC** can be "contaminated" by other poorly constrained SMEFT operators… e.g. 4-Top operators

We computed the full NLO effects to LHC Higgs processes coming from 4-heavy-quark operators

Operator	Process	μ_R	$\delta R(C_i)^{fin}$	$\delta R(C_i)^{log}$
$\mathcal{O}_{Qt}^{(1)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$9.91 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-2.15 \cdot 10^{-3}$	$-0.60 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-4.29 \cdot 10^{-1}$	$2.24 \cdot 10^{-3}$
$\mathcal{O}_{Qt}^{(8)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$1.32 \cdot 10^{-2}$	$3.68 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-2.87 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$6.53 \cdot 10^{-2}$	$4.41 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$7.30 \cdot 10^{-2}$	$4.41 \cdot 10^{-3}$
$\mathcal{O}_{QtQb}^{(1)}$	ggF/ $h \to gg$	$\frac{m_h}{2}$	$4.22 \cdot 10^{-2}$	$1.37 \cdot 10^{-2}$
	$h \to \gamma\gamma$		$-8.07 \cdot 10^{-3}$	$-2.62 \cdot 10^{-3}$
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L. Alasfar, J.B., R. Gröber, In preparation

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Sizable effects in ggF (dominant at LHC)…

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L. Alasfar, J.B., R. Gröber, In preparation

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Relative contribution from operators modifying H trilinear
Degrassi et al. '16

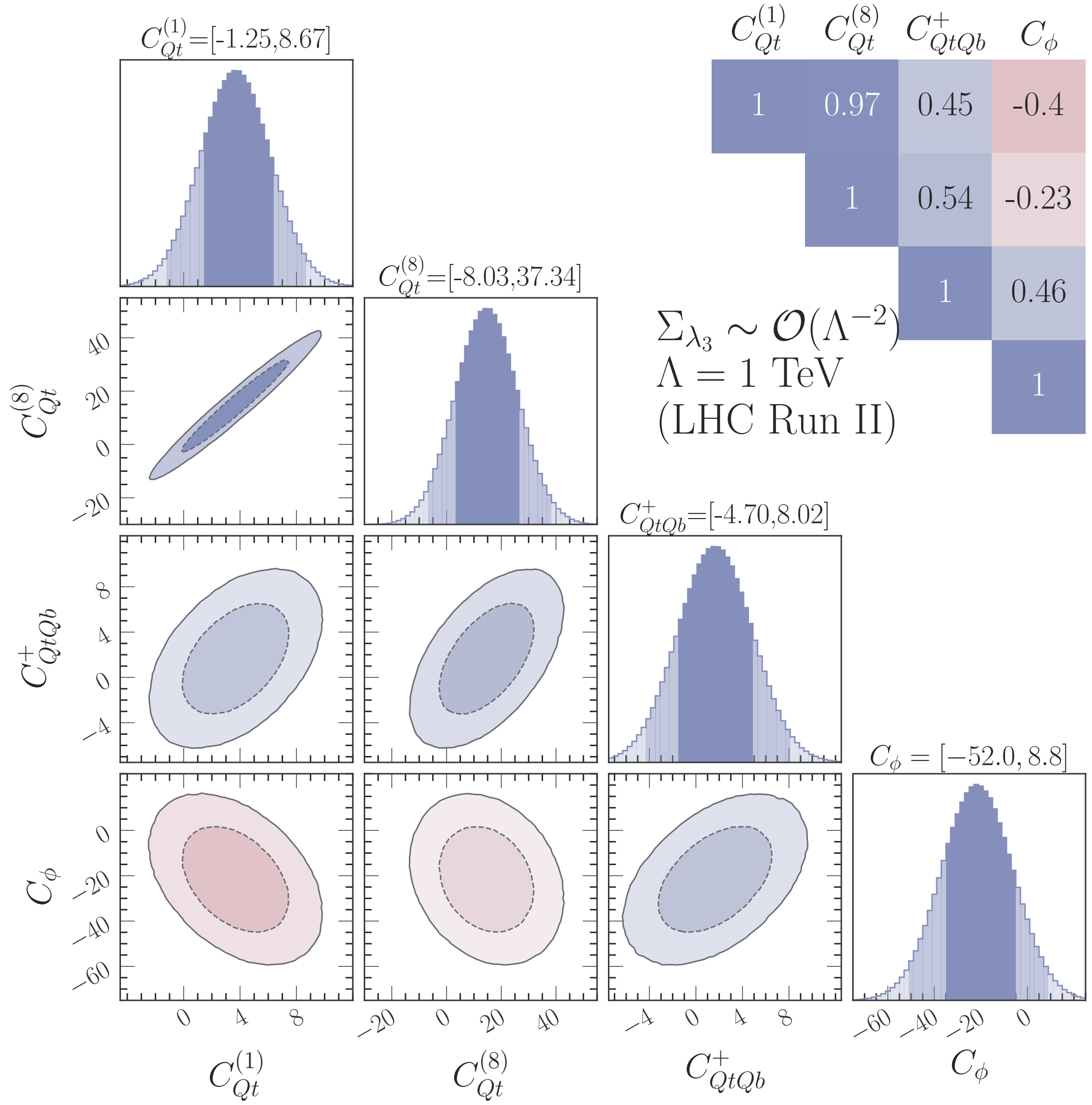
Sizable effects in ggF (dominant at LHC)…

… and ttH (strongest dependence on C_ϕ)…

The SMEFT at the LHC

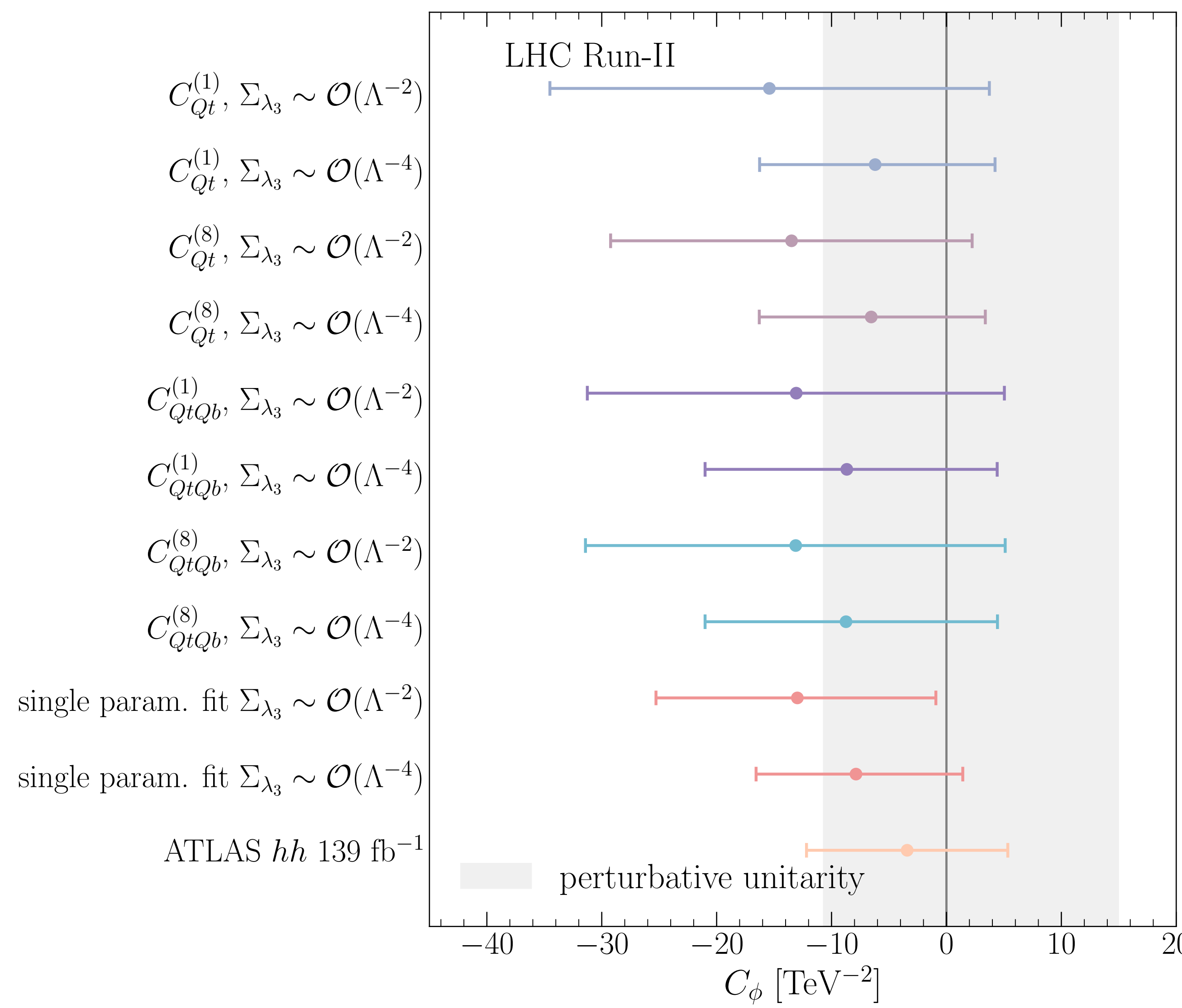
- The extraction of the **Higgs Trilinear at the LHC** can be “contaminated” by other poorly constrained SMEFT operators… e.g. 4-Top operators

Toy fit to LHC Higgs data: including modifications of Higgs trilinear (O_ϕ) and 4-Heavy quark operators



	$C_{Qt}^{(1)}$	$C_{Qt}^{(8)}$	C_{QtQb}^{+}	C_ϕ
$C_{Qt}^{(1)}$	1	0.97	0.45	-0.4
$C_{Qt}^{(8)}$		1	0.54	-0.23
C_{QtQb}^{+}			1	0.46
C_ϕ				1

4-par fit



2-par fits

L. Alasfar, J.B., R. Gröber, In preparation

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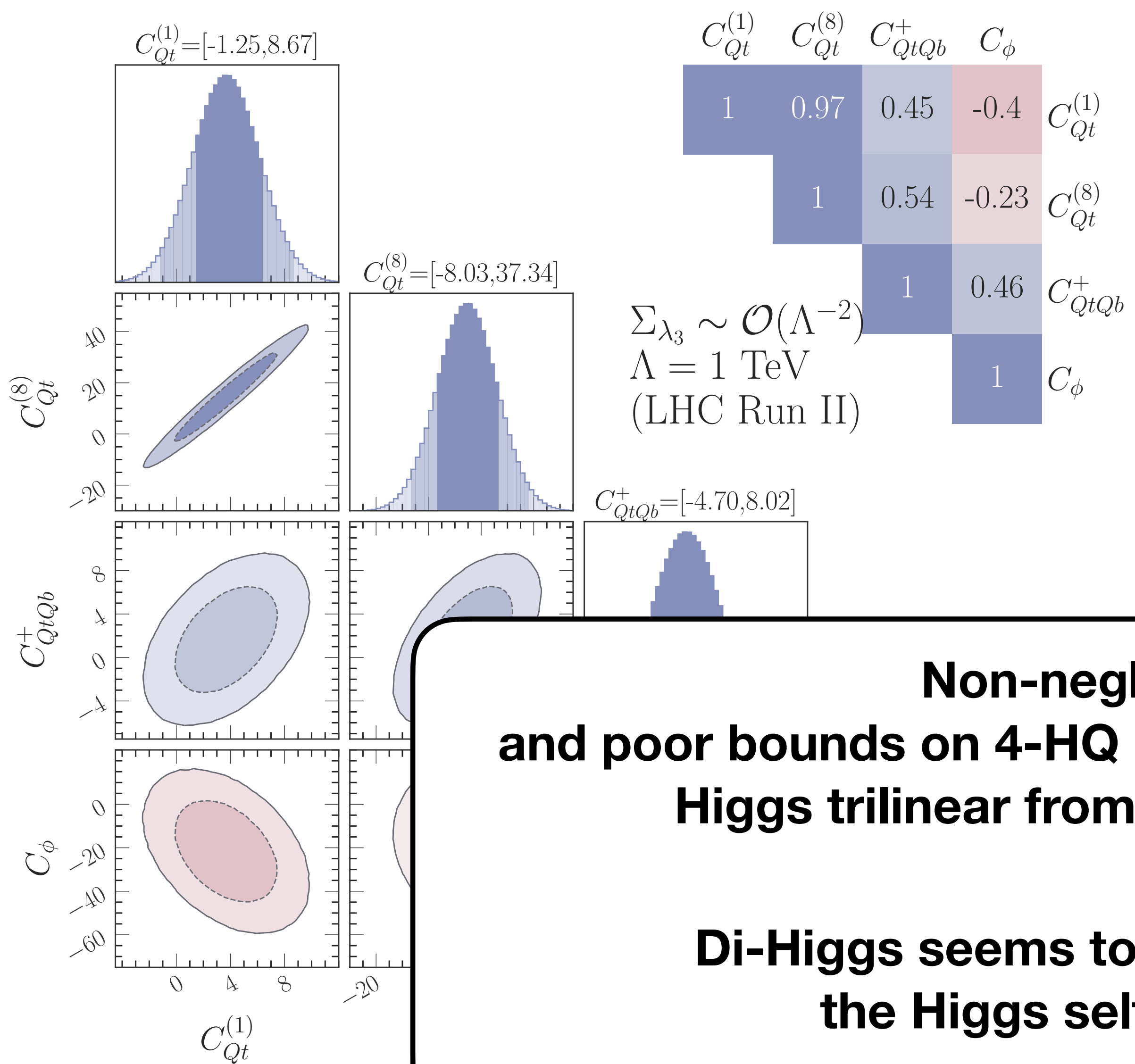
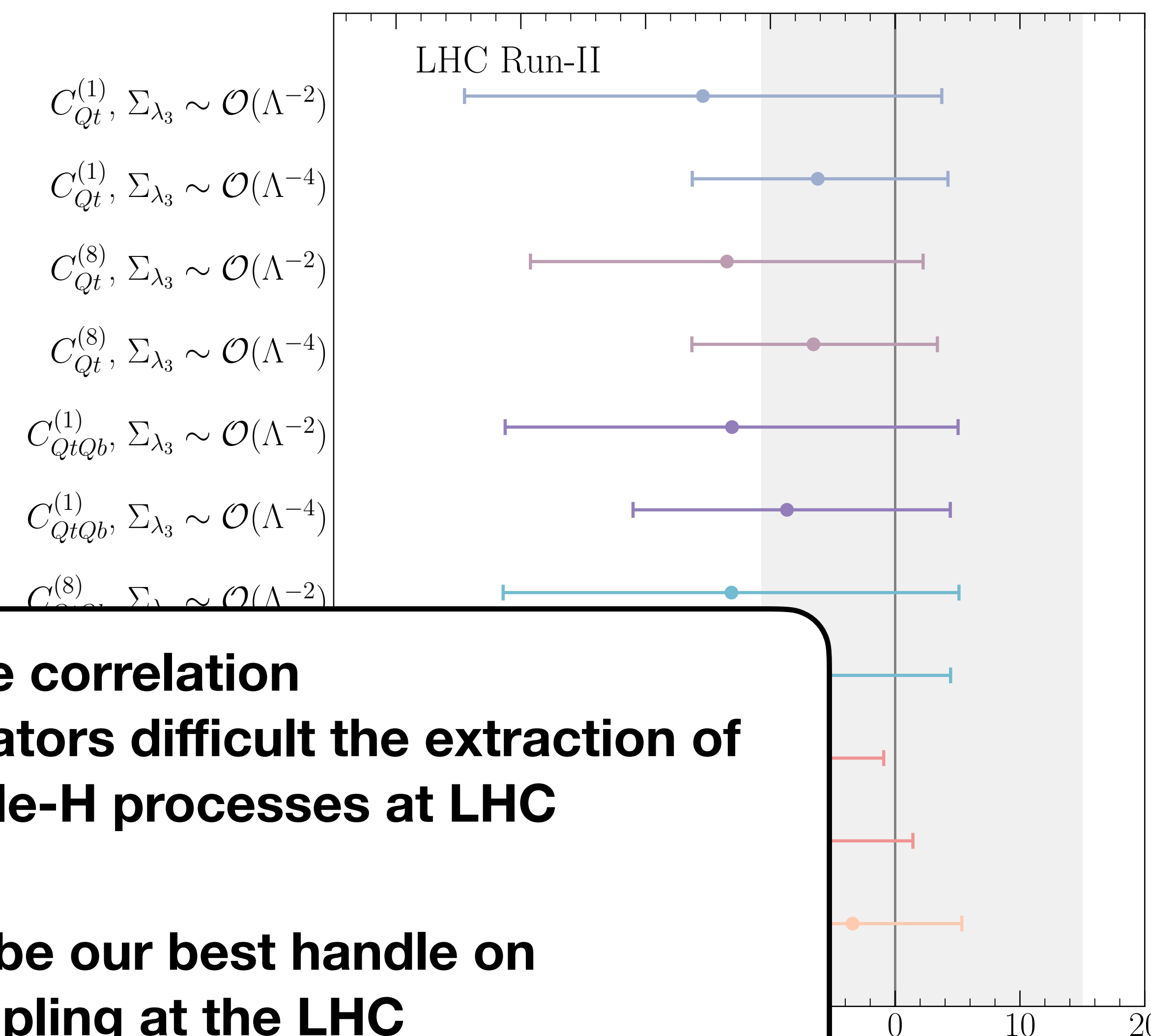


4-par fit



2-par fits

Non-negligible correlation and poor bounds on 4-HQ operators difficult the extraction of Higgs trilinear from single-H processes at LHC

Di-Higgs seems to still be our best handle on the Higgs self-coupling at the LHC

L. Alasfar, J.B., R. Gröber, In preparation

The SMEFT
at Future EW/Higgs Factories

Future Colliders

- Future e^+e^- Higgs factories:

Lepton Colliders

LEP/SLC $\xrightarrow{?}$ ILC, CLIC, CEPC, FCC-ee

Linear e+e- Colliders

	ILC	CLIC
$\sqrt{s}$ [GeV]	250 (350/500/1000?)	380/1500/3000
(P_{e^-}, P_{e^+})	±80%/∓30%	±80%/0%
$L[\mathrm{ab}^{-1}]$	2 (0.2/4/8?)	1/2.5/5

Circular e+e- Colliders

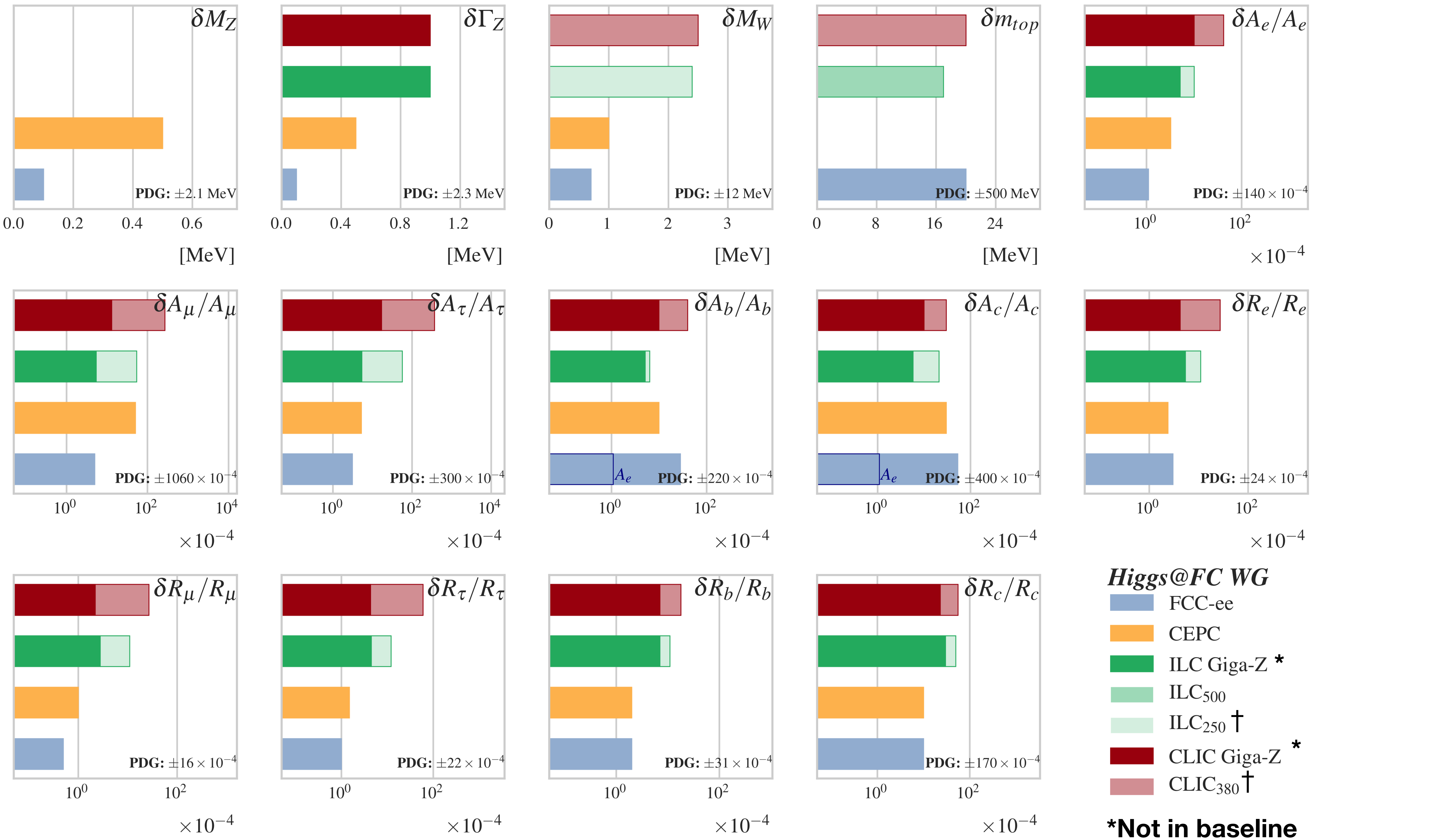
	CEPC	FCC-ee
$\sqrt{s}$ [GeV]	91/161/240	91/161/240/350/365
(P_{e^-}, P_{e^+})	-	-
$L[\mathrm{ab}^{-1}]$	16/2.6/5.6	150/10/5/1.5

(See backup slides for projected timeline)

- Different approaches for an EW/Higgs/Top factory, e.g.
  - ✓ LC: Polarization can help disentangling NP effects & control systematics
  - ✓ CC: High luminosity (plus several IP). Z-pole run → Tera Z
  - ✓ High-E runs → Access to tt (LC & CC), ttH and HH (LC) thresholds
- In this talk I will focus mostly on the EW/Higgs factory option

Future Colliders

- Expected improvements in EW physics (Z and W pole measurements):

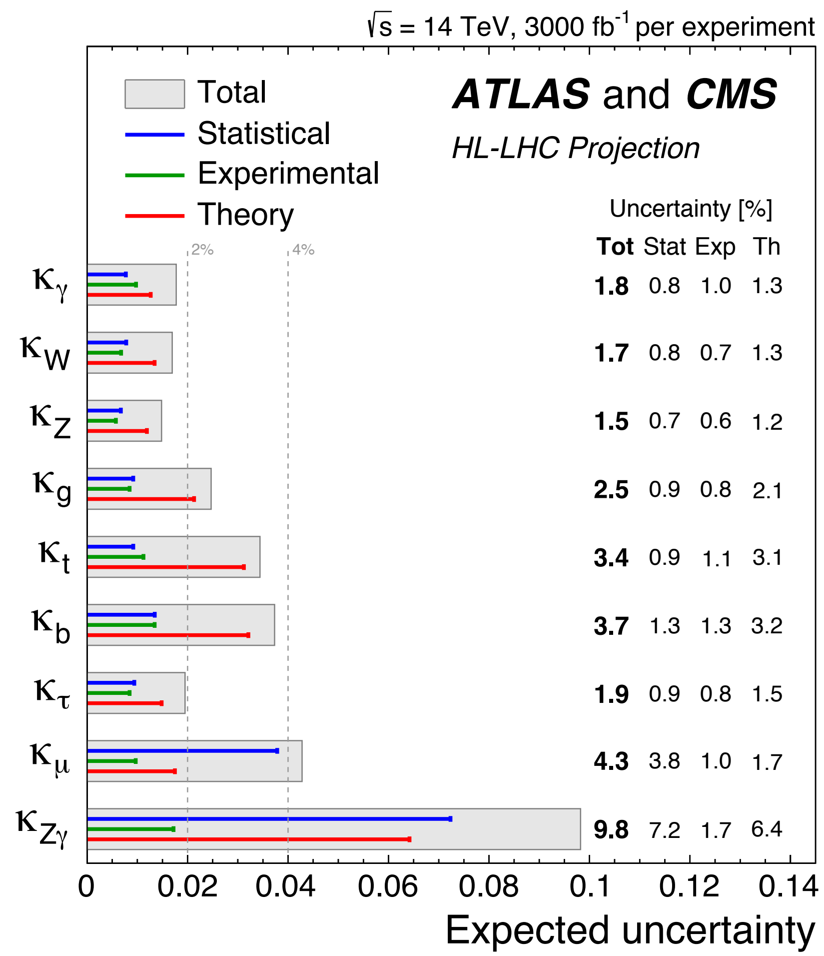


***Not in baseline**
† Via rad. Return to the Z

Future Colliders

- Precision Higgs physics at hadron vs lepton colliders

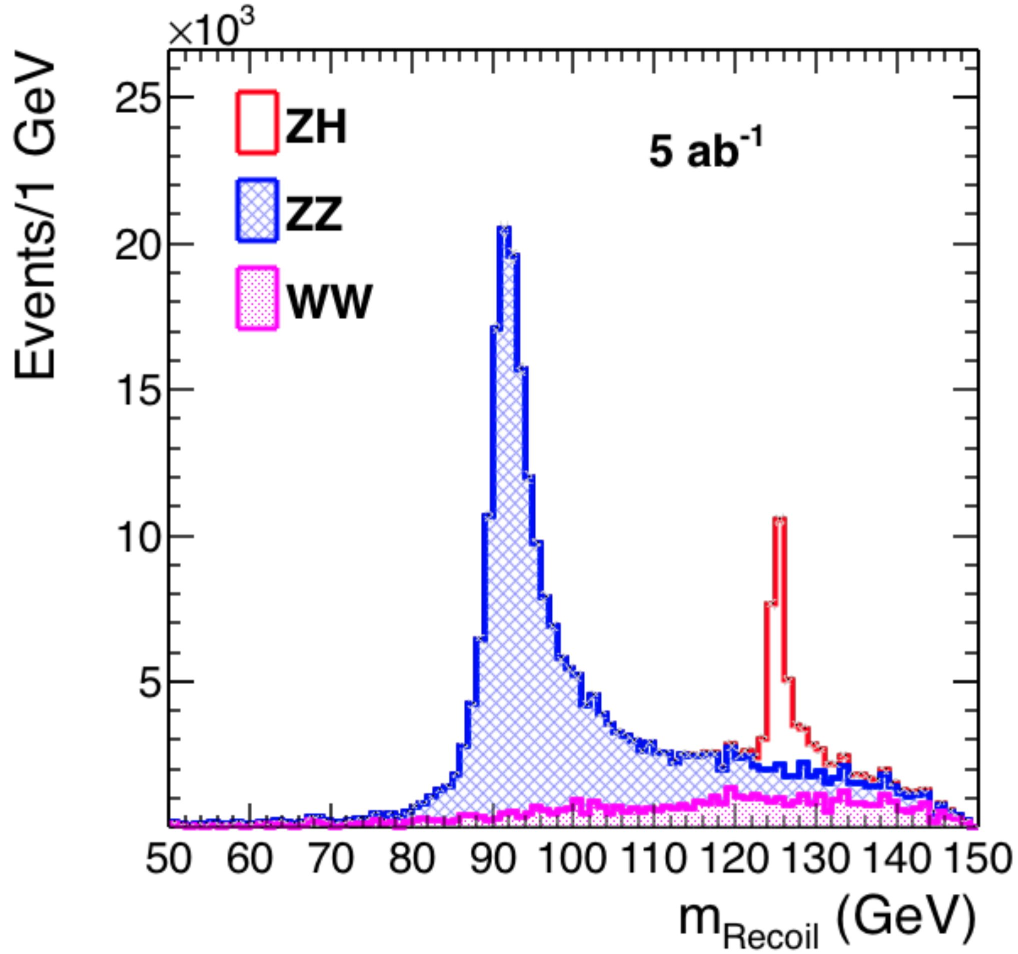
Hadron Collider Higgs
Main production: ggF, VBF, VH, ttH



O(1-10%) precision but model-dependent (BR_{NP}=0)

Ratios, no absolute couplings

Lepton Collider Higgs
Main production: *ZH*, *ννH* (WBF)



$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

Recoil mass method

(only possible at lepton colliders)
→inclusive measurement of σ_{ZH}

1) Normalizes all couplings (no ratios)
2) Allows model-independent measurement of Γ_H

Future Colliders

- Higgs physics at a future e^+e^- Higgs factory

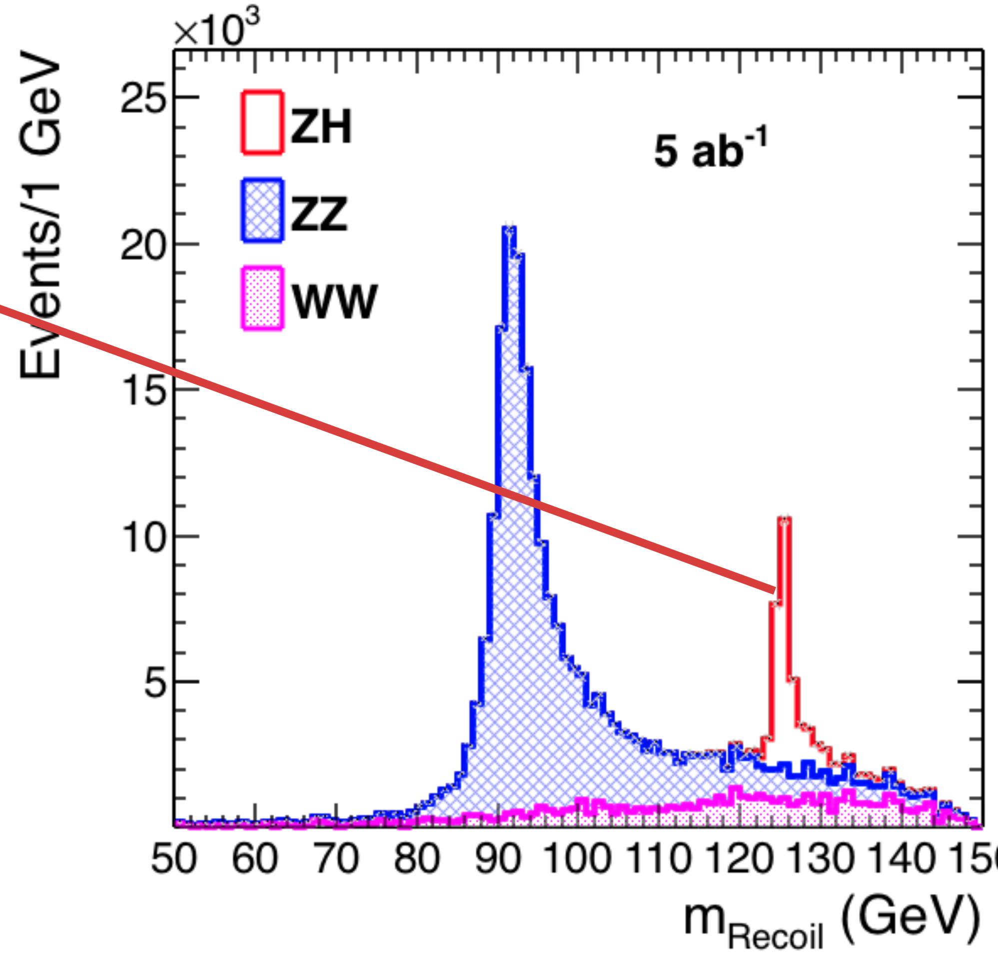
e.g. Circular Colliders (FCCee/CEPC)

(Similar results for Linear Colliders)

	FCC-ee$_{240}$	FCC-ee$_{365}$	CEPC
$\delta\sigma_{ZH}$	0.005	0.009	0.005
$\delta\mu_{ZH,bb}$	0.003	0.005	0.0031
$\delta\mu_{ZH,cc}$	0.022	0.065	0.033
$\delta\mu_{ZH,gg}$	0.019	0.035	0.013
$\delta\mu_{ZH,WW}$	0.012	0.026	0.0098
$\delta\mu_{ZH,ZZ}$	0.044	0.12	0.051
$\delta\mu_{ZH,\tau\tau}$	0.009	0.018	0.0082
$\delta\mu_{ZH,\gamma\gamma}$	0.09	0.18	0.068
$\delta\mu_{ZH,\mu\mu}$	0.19	0.40	0.17
$\delta\mu_{ZH,Z\gamma}$	–	–	0.16
$\delta\mu_{\nu\nu H,bb}$	0.031	0.009	0.030
$\delta\mu_{\nu\nu H,cc}$	–	0.10	–
$\delta\mu_{\nu\nu H,gg}$	–	0.045	–
$\delta\mu_{\nu\nu H,ZZ}$	–	0.10	–
$\delta\mu_{\nu\nu H,\tau\tau}$	–	0.08	–
$\delta\mu_{\nu\nu H,\gamma\gamma}$	–	0.22	–
BR_{inv}	<0.0015	<0.003	<0.0015

Lepton Collider Higgs

Main production: ZH, $\nu\nu H$ (WBF)



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Recoil mass method

(only possible at lepton colliders)

→inclusive measurement of σ_{ZH}

1) Normalizes all couplings (no ratios)
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Future Colliders

- A lot of work during the **European Strategy Update for Particle Physics 2020** was dedicated to establish the physics potential of these machines and lead to the following conclusions:

Guide through the statements

2 statements on **Major developments from the 2013 Strategy**
a) Focus on successful completion of HL-LHC upgrade remains a priority
b) Continued support for long-baseline experiments in Japan and US and the Neutrino Platform

3 statements on **General considerations for the 2020 update**
a) Preserve the leading role of CERN for success of European PP community
b) Strengthen the European PP ecosystem of research centres
c) Acknowledge the global nature of PP research

2 statements on **High-priority future initiatives**
a) Higgs factory as the highest-priority next collider and investigation of the technical and financial feasibility of a future hadron collider at CERN
b) Vigorous R&D on innovative accelerator technologies

Letters for itemizing the statements are introduced for identification, do not imply prioritization

4 statements on **Other essential scientific activities**
a) Support for high-impact, financially implementable, experimental initiatives world-wide
b) Acknowledge the essential role of theory
c) Support for instrumentation R&D
d) Support for computing and software infrastructure

2 statements on **Synergies with neighbouring fields**
a) Nuclear physics – cooperation with NuPECC

However, no consensus on the type of Higgs factory (Circular or Linear)

b) Relations with European Commission
c) Open science

4 statements on **Environmental and societal impact**
a) Mitigate environmental impact of particle physics
b) Investment in next generation of researchers
c) Knowledge and technology transfer
d) Cultural heritage: public engagement, education and communication

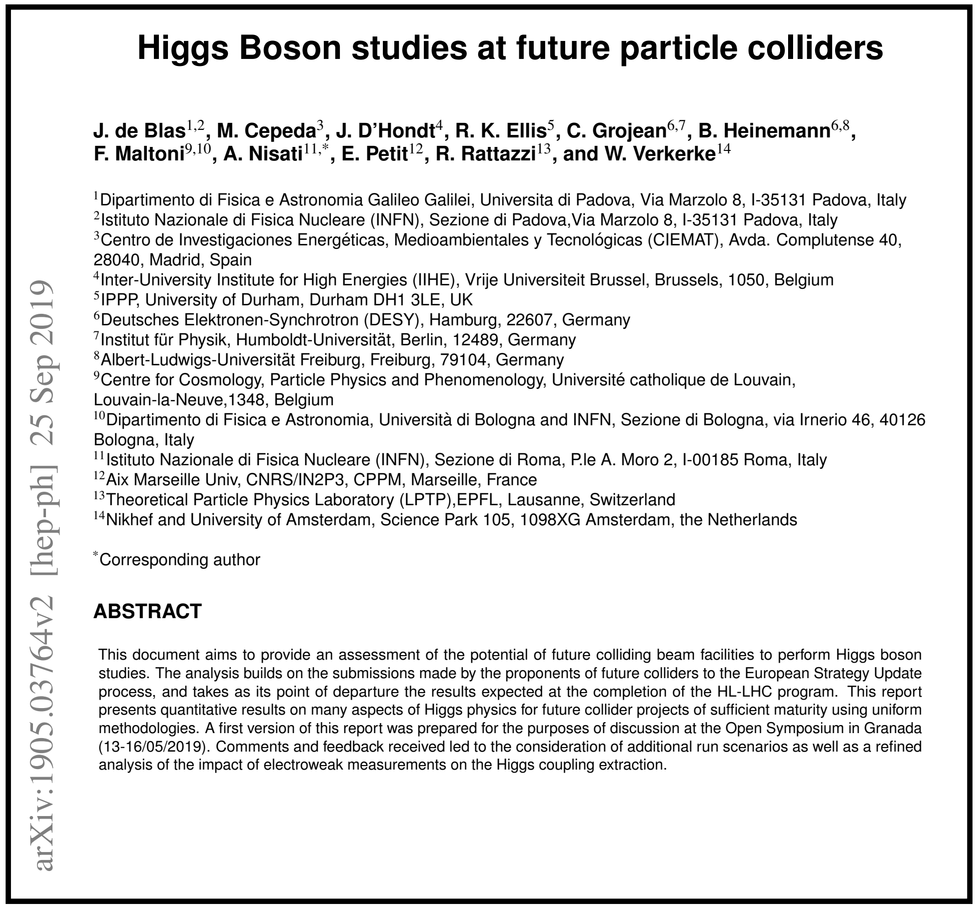
H. Abramowicz's talk at the CERN council meeting of June 19, 2020
See also F. Giannotti's talk on June 29, 2020 for further remarks

European Strategy Update

Future Colliders

- Decisions based on the results of the studies of the different Working Groups formed to assist the Physics Preparatory Group (PPG) in evaluating the physics potential of the different future experiments.

- The Higgs@Future Colliders WG was formed by RECFA for this purpose, to help in areas related to Higgs/EW physics. The main outcome of the WG studies is collected in the report in **JHEP 01 (2020) 139 (1905.03764 [hep-ph])** and summarized in the *Electroweak Physics* chapter of the **Physics Briefing Book**



Higgs Boson studies at future particle colliders

J. de Blas[1,2], M. Cepeda[3], J. D'Hondt[4], R. K. Ellis[5], C. Grojean[6,7], B. Heinemann[6,8], F. Maltoni[9,10], A. Nisati[11,*], E. Petit[12], R. Rattazzi[13], and W. Verkerke[14]

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[4]Inter-University Institute for High Energies (IIHE), Vrije Universiteit Brussel, Brussels, 1050, Belgium
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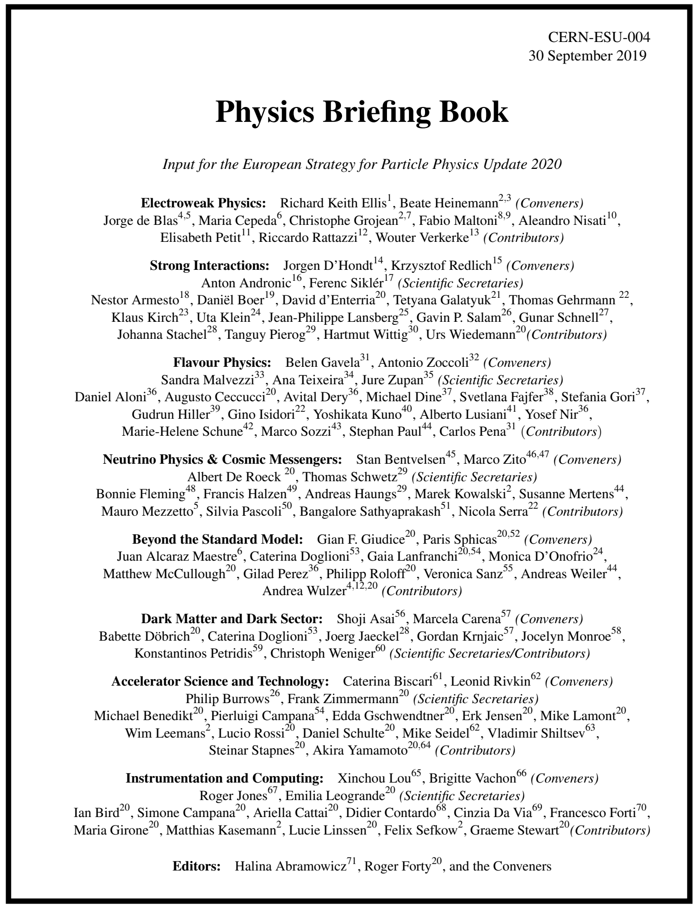
*Corresponding author

ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects of sufficient maturity using uniform methodologies. A first version of this report was prepared for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019). Comments and feedback received led to the consideration of additional run scenarios as well as a refined analysis of the impact of electroweak measurements on the Higgs coupling extraction.

arXiv:1905.03764v2 [hep-ph] 25 Sep 2019



CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

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Beyond the Standard Model: Gian F. Giudice[20], Paris Sphicas[20,52] *(Conveners)*
Juan Alcaraz Maestre[6], Caterina Doglioni[53], Gaia Lanfranchi[20,54], Monica D'Onofrio[24], Matthew McCullough[20], Gilad Perez[36], Philipp Roloff[20], Veronica Sanz[55], Andreas Weiler[44], Andrea Wulzer[4,12,20] *(Contributors)*

Dark Matter and Dark Sector: Shoji Asai[56], Marcela Carena[57] *(Conveners)*
Babette Döbrich[20], Caterina Doglioni[53], Joerg Jaeckel[28], Gordan Krnjaic[57], Jocelyn Monroe[58], Konstantinos Petridis[59], Christoph Weniger[60] *(Scientific Secretaries/Contributors)*

Accelerator Science and Technology: Caterina Biscari[61], Leonid Rivkin[62] *(Conveners)*
Philip Burrows[26], Frank Zimmermann[20] *(Scientific Secretaries)*
Michael Benedikt[20], Pierluigi Campana[54], Edda Gschwendtner[20], Erk Jensen[20], Mike Lamont[20], Wim Leemans[2], Lucio Rossi[20], Daniel Schulte[20], Mike Seidel[62], Vladimir Shiltsev[63], Steinar Stapnes[20], Akira Yamamoto[20,64] *(Contributors)*

Instrumentation and Computing: Xinchou Lou[65], Brigitte Vachon[66] *(Conveners)*
Roger Jones[67], Emilia Leogrande[20] *(Scientific Secretaries)*
Ian Bird[20], Simone Campana[20], Ariella Cattai[20], Didier Contardo[68], Cinzia Da Via[69], Francesco Forti[70], Maria Girone[20], Matthias Kasemann[2], Lucie Linssen[20], Felix Sefkow[2], Graeme Stewart[20]*(Contributors)*

Editors: Halina Abramowicz[71], Roger Forty[20], and the Conveners

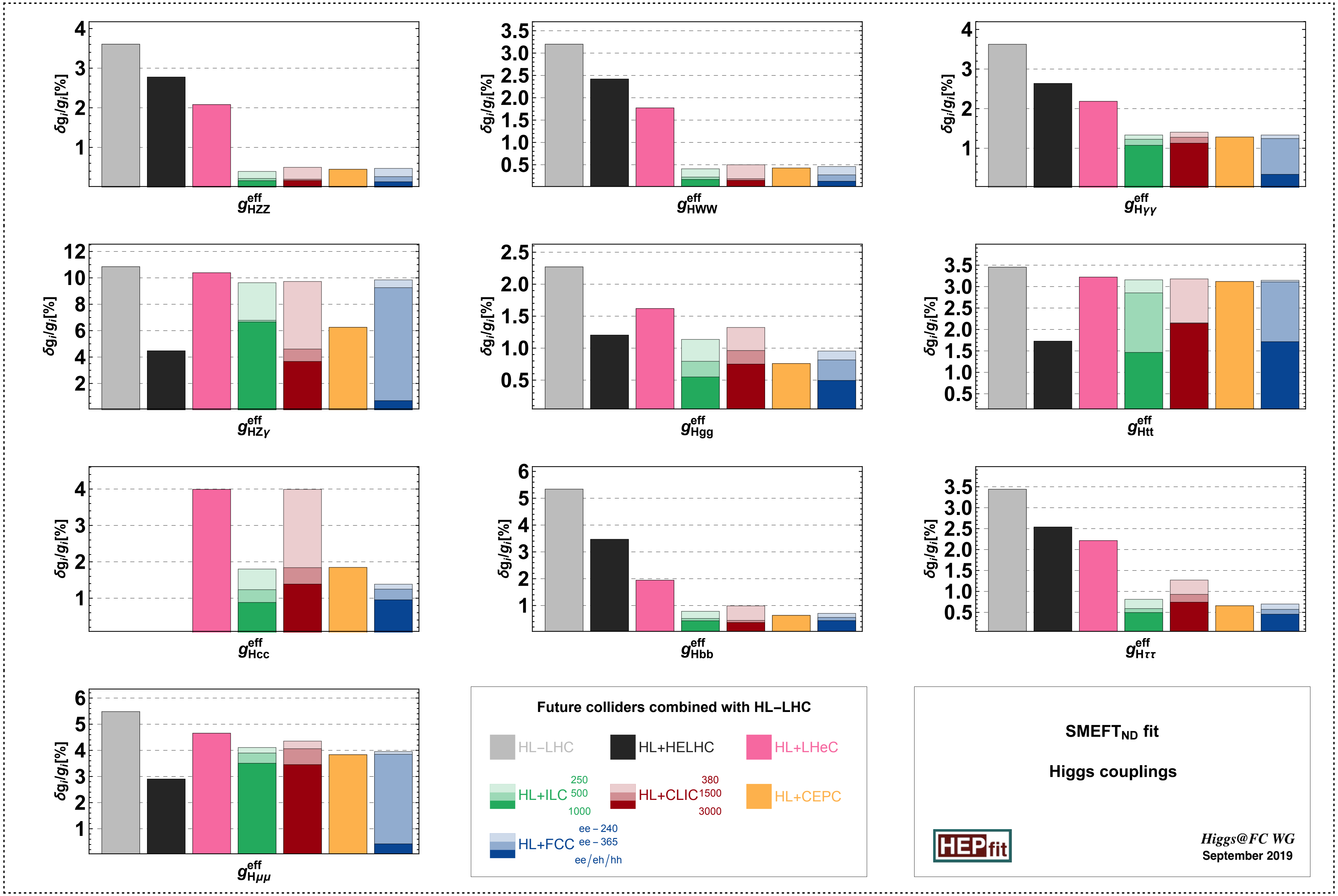
European Strategy Update

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

EFT results projected into effective Higgs couplings

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



Physics Briefing Book, arXiv: 1910.11775 [hep-ex]

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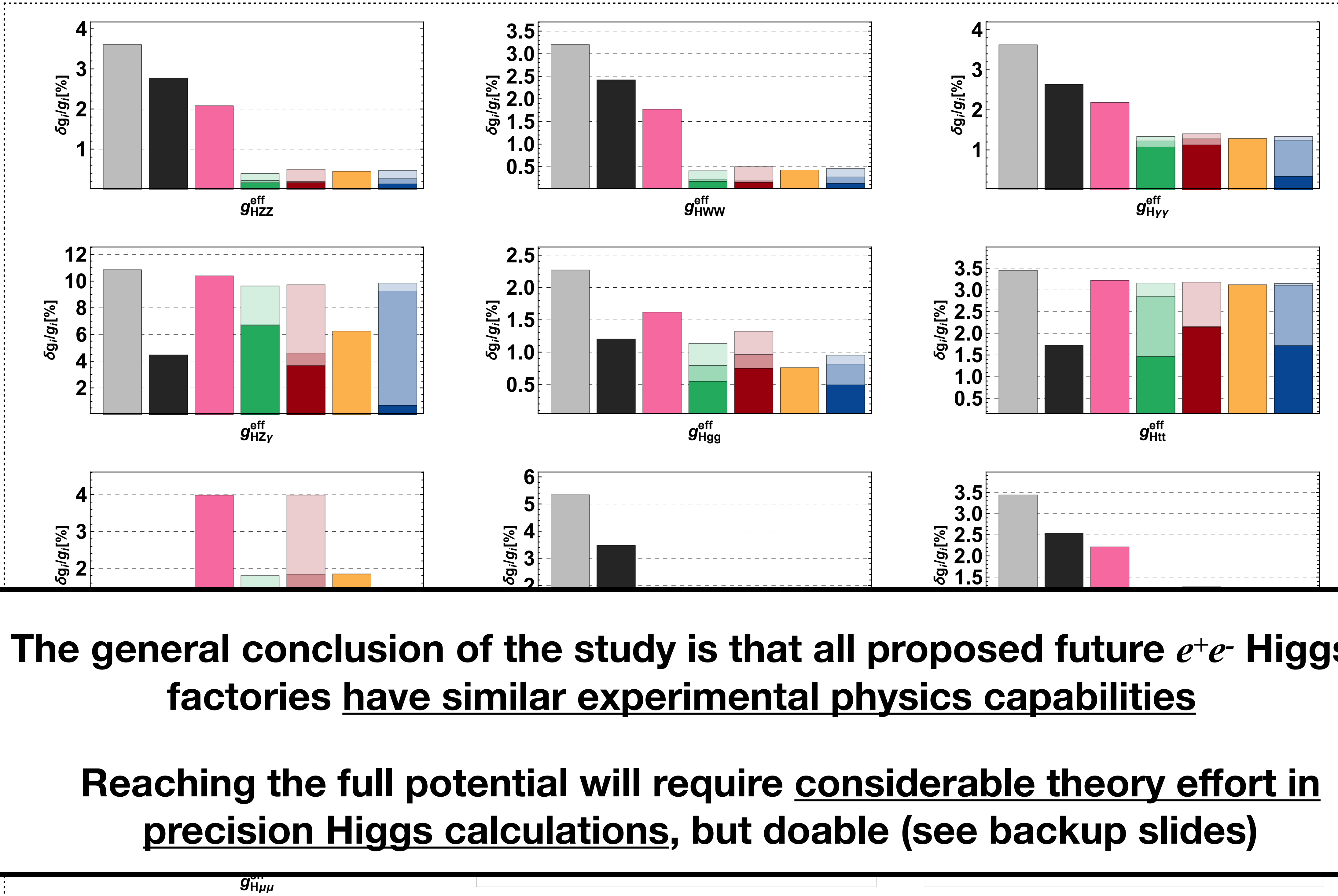

The general conclusion of the study is that all proposed future e^+e^- Higgs factories have similar experimental physics capabilities

Reaching the full potential will require considerable theory effort in precision Higgs calculations, but doable (see backup slides)

Physics Briefing Book, arXiv: 1910.11775 [hep-ex]

Higgs couplings at future Higgs factories

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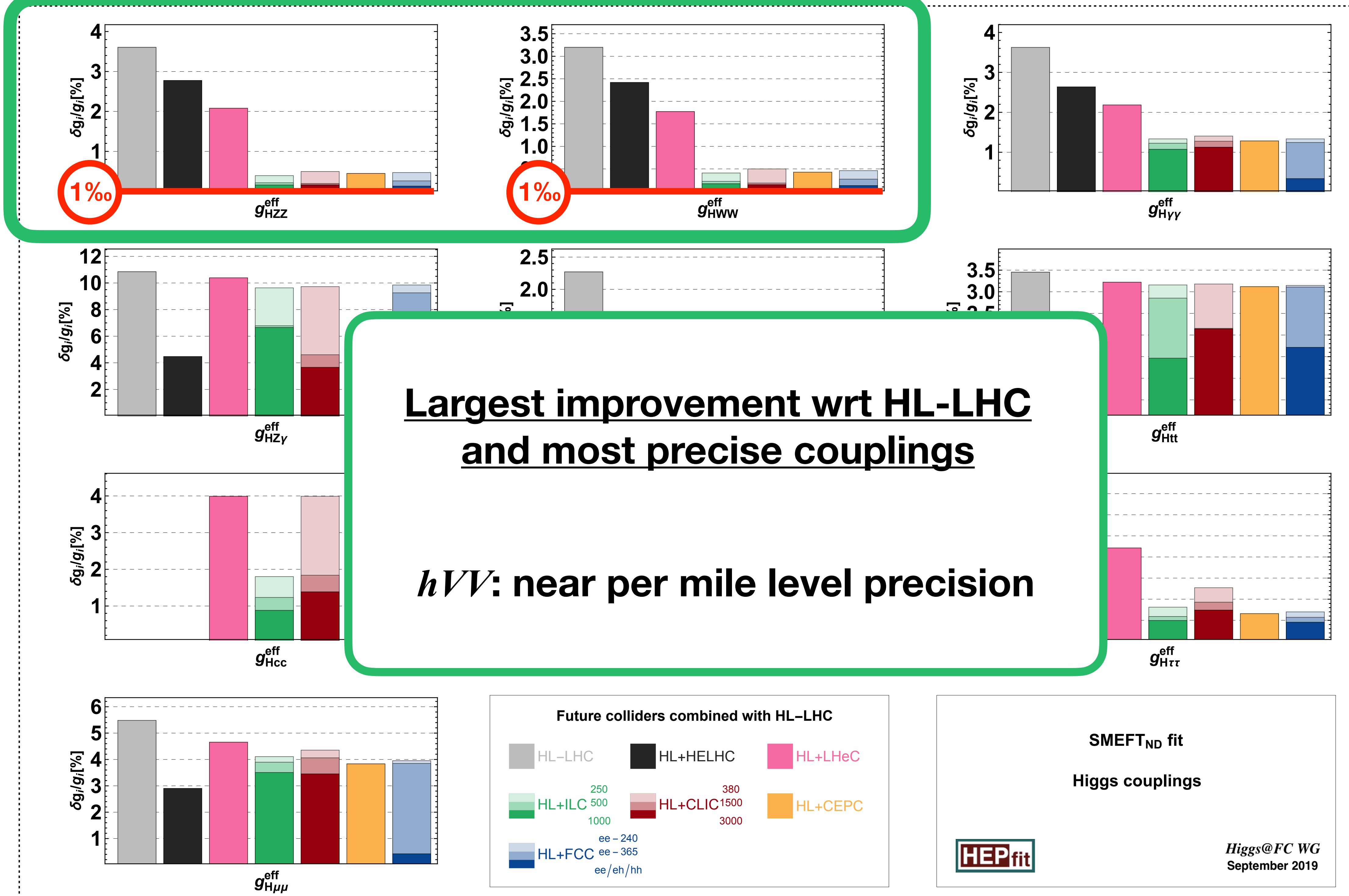

Largest improvement wrt HL-LHC and most precise couplings

hVV: near per mile level precision

Physics Briefing Book, arXiv: 1910.11775 [hep-ex]

Higgs couplings at future Higgs factories

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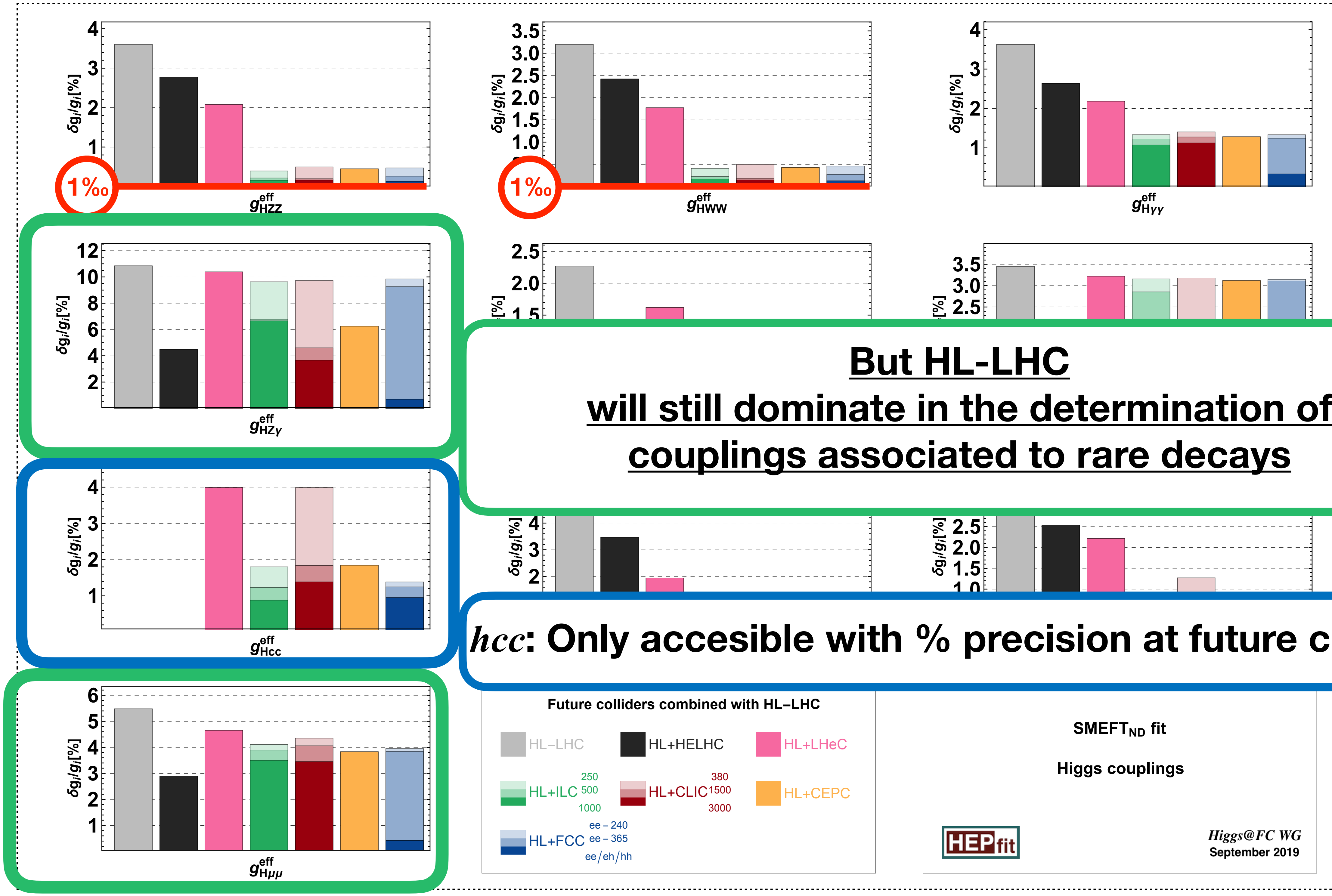

But HL-LHC will still dominate in the determination of couplings associated to rare decays

hcc: **Only accesible with % precision at future colliders**

Physics Briefing Book, arXiv: 1910.11775 [hep-ex]

Future Colliders

- A lot of work during the European Strategy Update for Particle Physics 2020 was dedicated to establish the physics potential of these machines for EW and, especially, Higgs physics…
- …but still many things to be done to have a full picture of the true physics potential of these future colliders

  ⇒ **The effort continues within the *Snowmass 2021 (2022)* process**

Specifically, the SMEFT fits are to be performed within the activities of the

Energy Frontier Topical Group

***EW Precision Physics and constraining new physics* (EF 04)**

Webpage: https://snowmass21.org/energy/ewk

Future Colliders

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The global SMEFT fit team for the Snowmass 2021 study

Current members:

J. B., Y. Du, C. Grojean, J. Gu, M. Peskin, J. Tian, M. Vos and E. Vryonidou

If you are interested in helping please contact J. Tiang (tian@icepp.s.u-tokyo.ac.jp)

- Some goals:

  ✓ Extend the ESU 2020 setup to a more global/model-independent scenario

  ✓ Understand the role and interplay of different measurements (Z pole, top threshold, beam polarisations, etc.)

  ✓ And, in as much as possible, compare the capabilities on equal footing (?)

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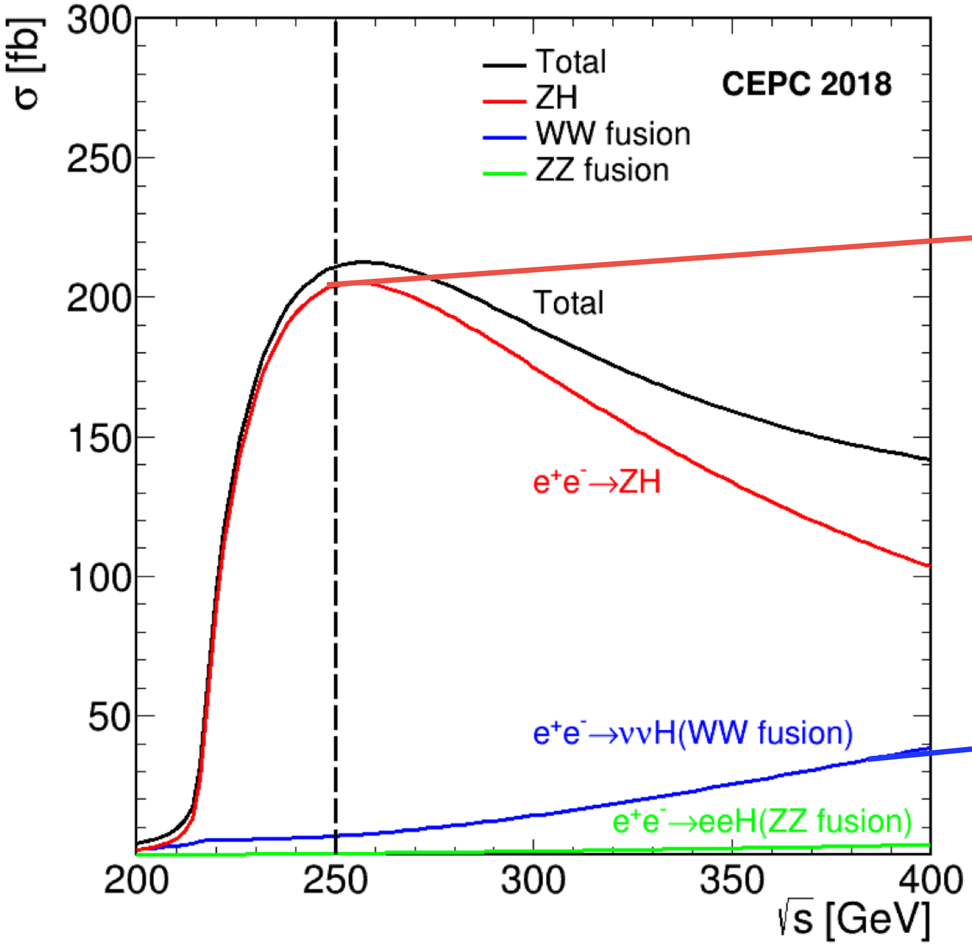
  Rest of this talk

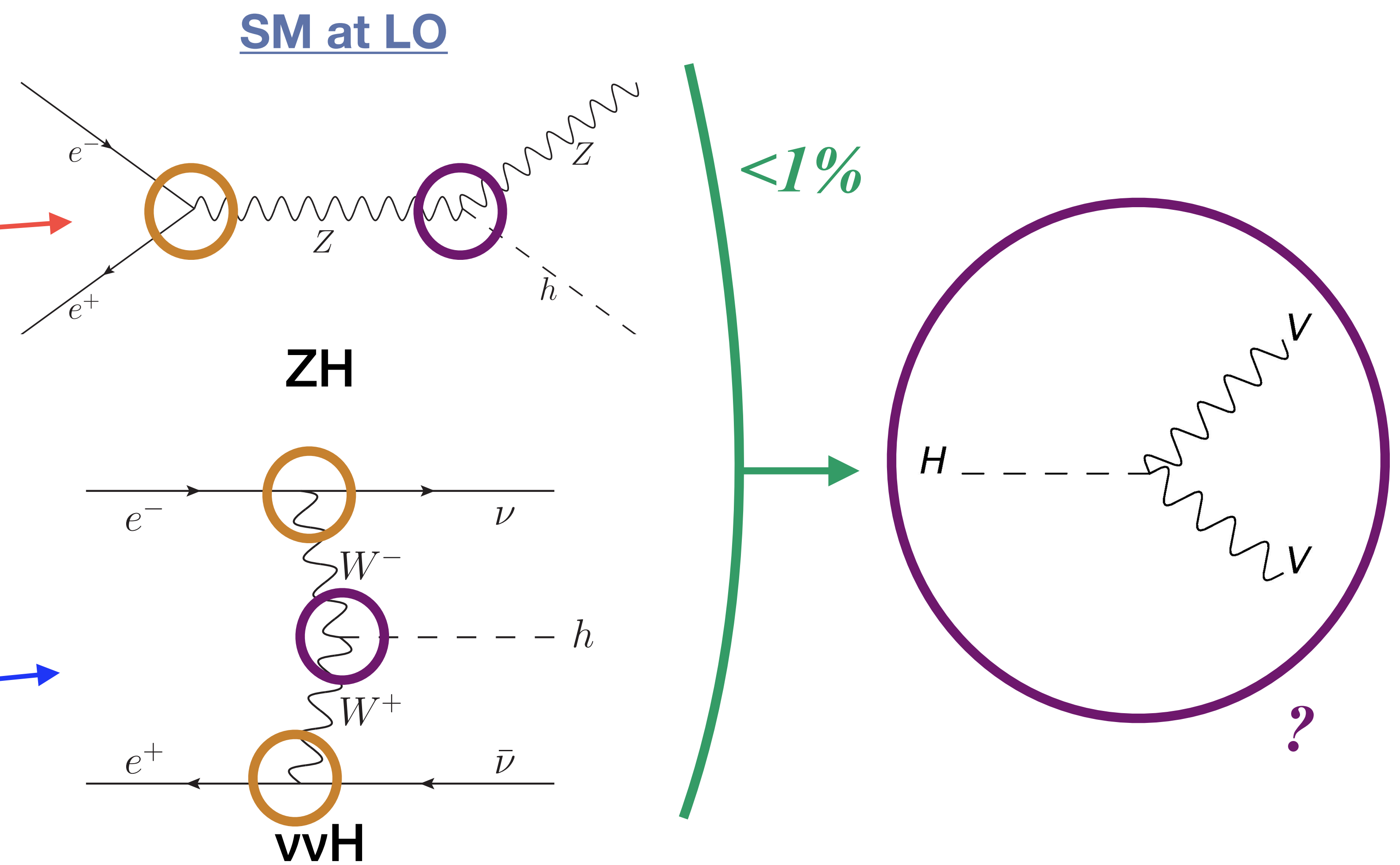
  ✓ Understand the role and interplay of different measurements (Z pole, top threshold, beam polarisations, etc.)

  ✓ And, in as much as possible, compare the capabilities on equal footing (?)

Interplay Higgs/EW factories

Higgs production at "low-energy" lepton colliders





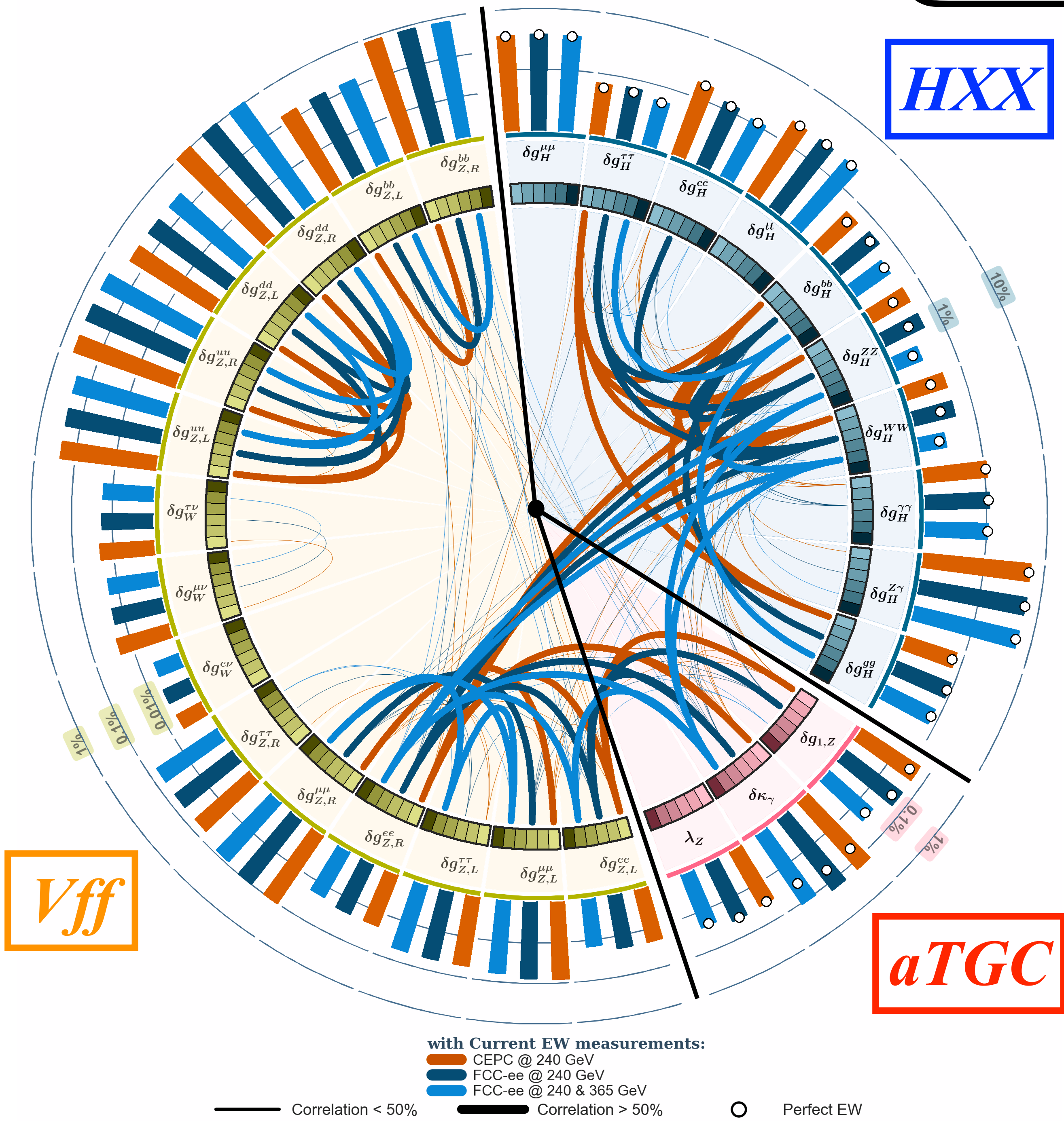
- Precision of **Higgs measurements** expected to be close to per mille level in several cases
- Is the knowledge of the **EW interactions** from LEP/SLD enough to neglect EW uncertainties in the extraction of **Higgs properties**?

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

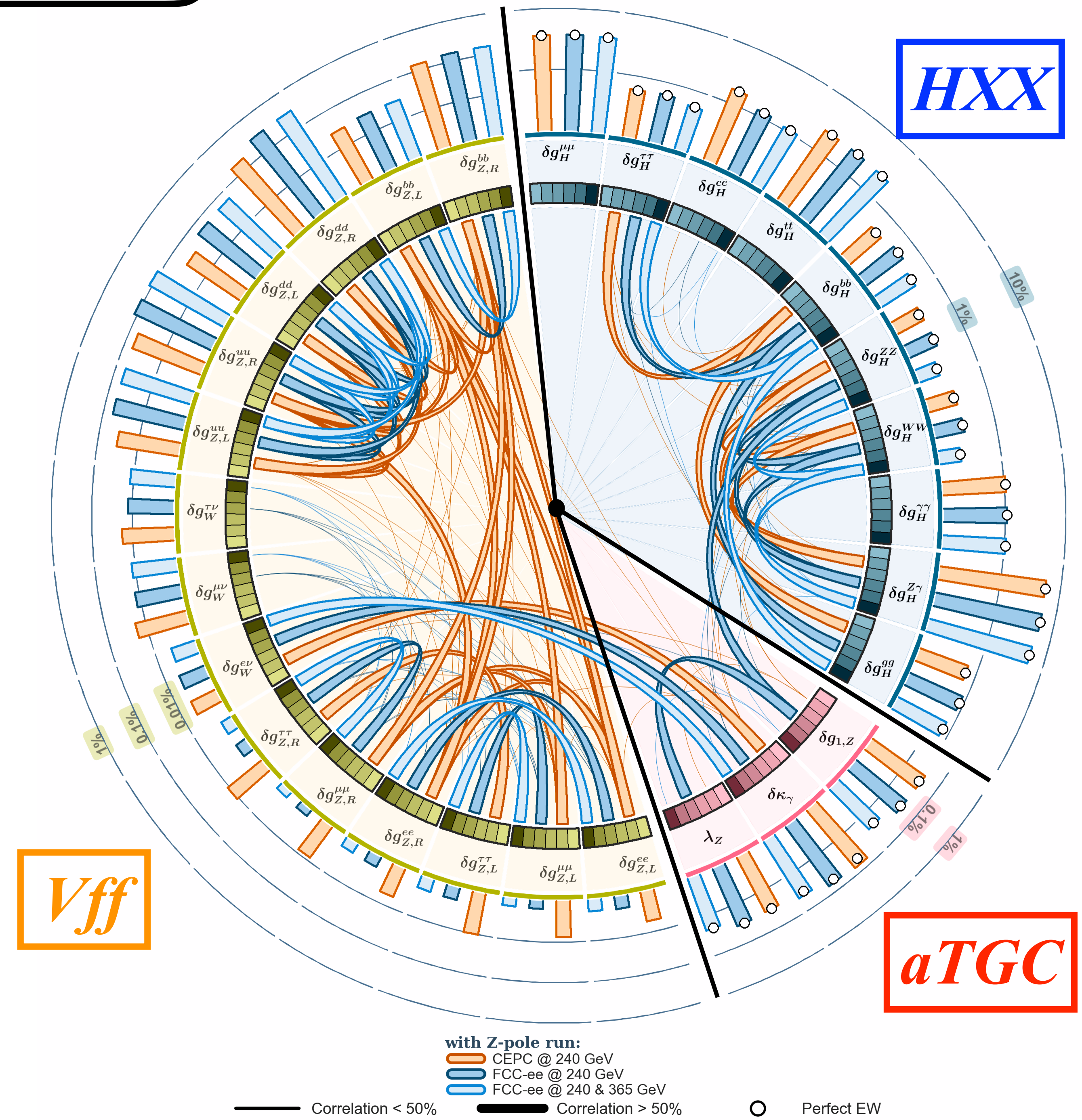
Interplay Higgs/EW factories

FCCee/CEPC

No future Z-pole run



With future Z-pole run



JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

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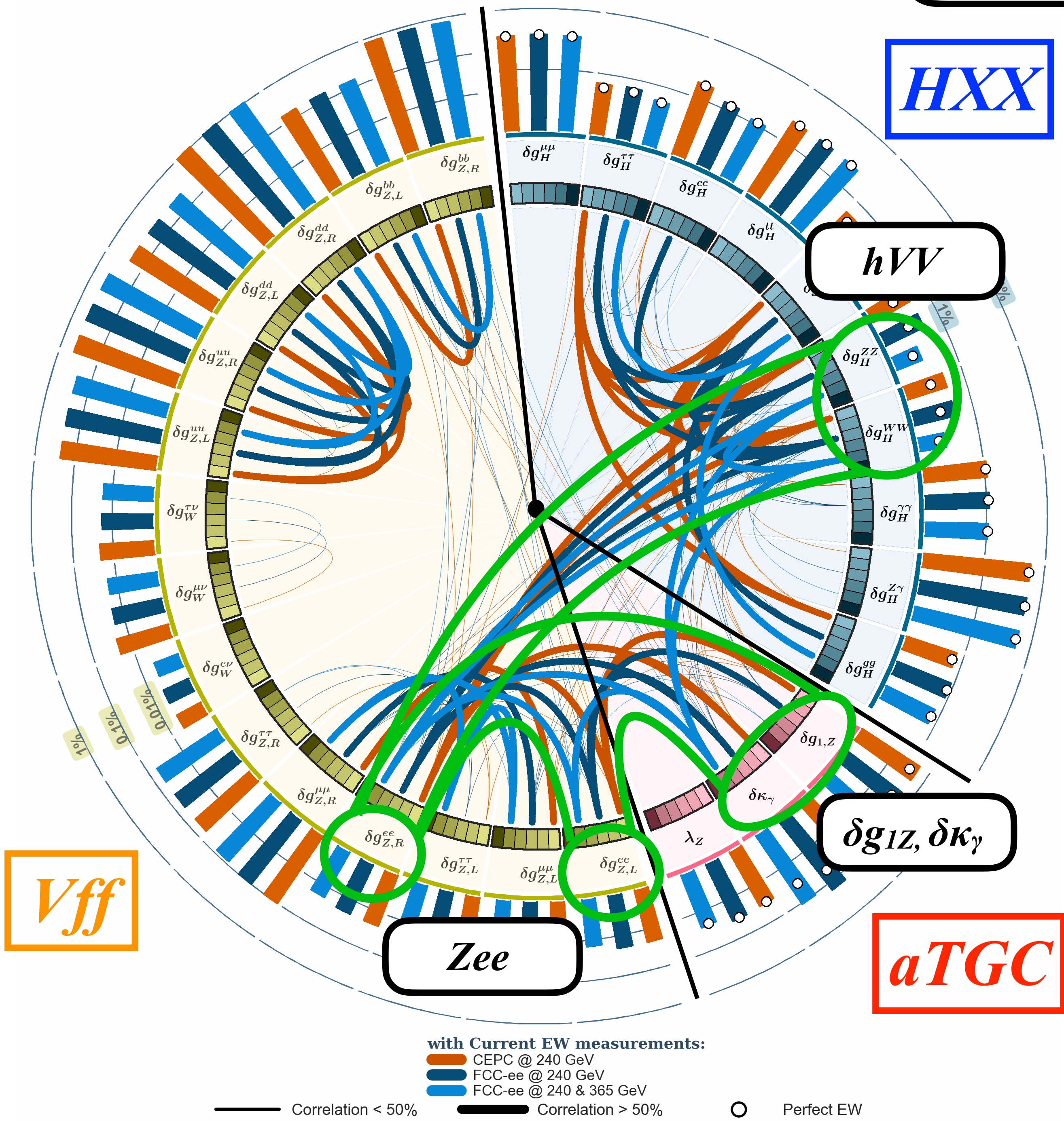
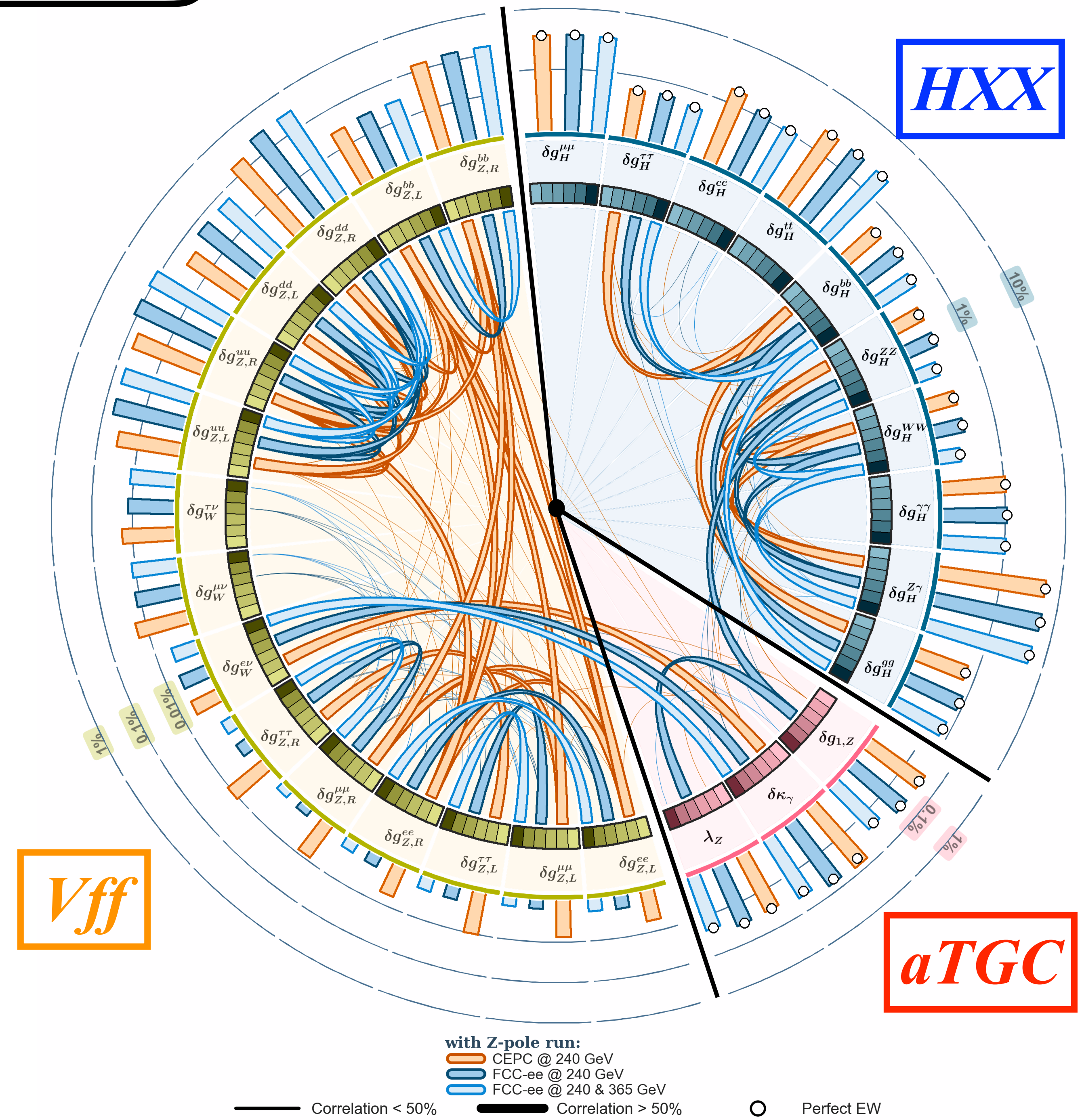


With future Z-pole run



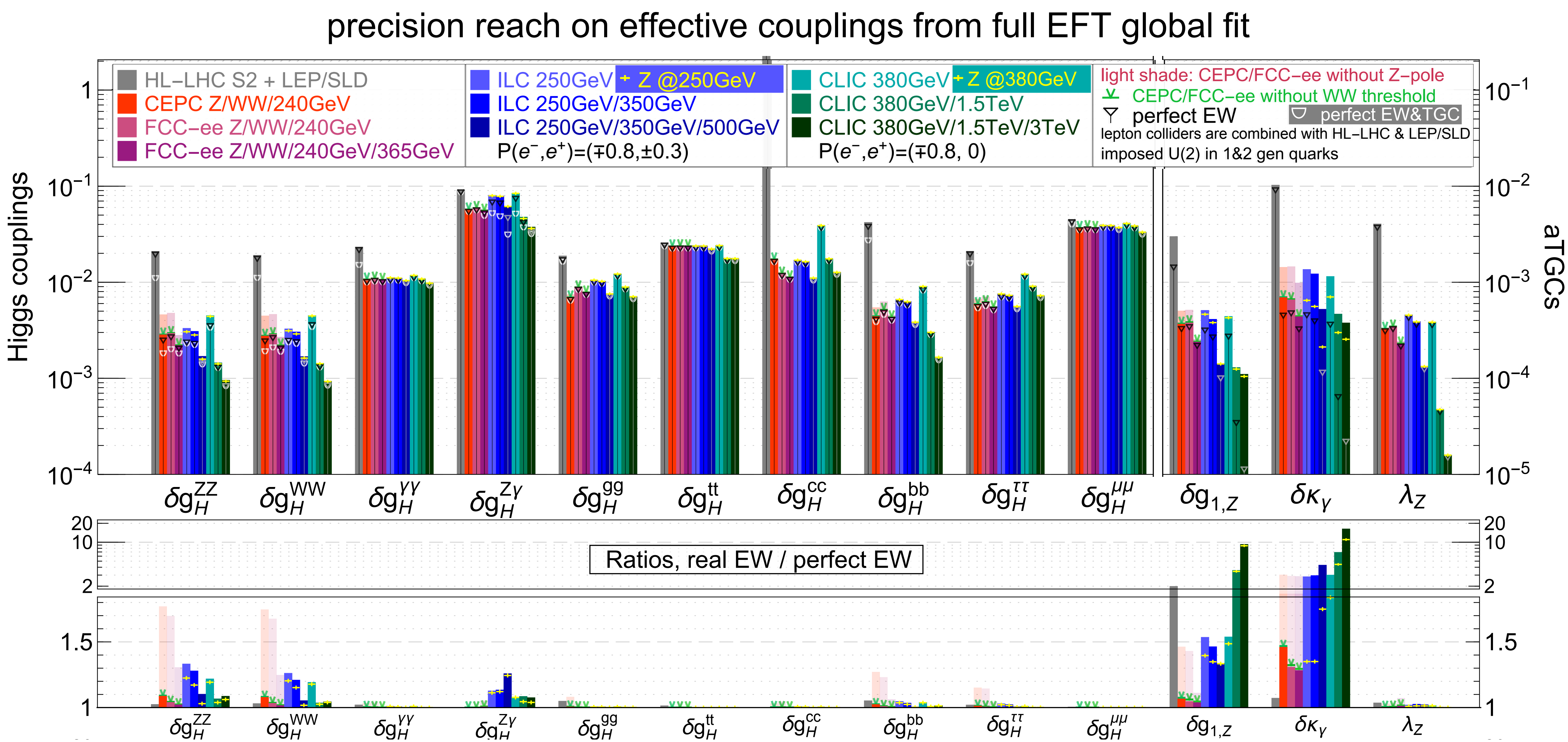
Future Z-pole run "decouples" EW and Higgs sectors

aTGC ($\delta\kappa_\gamma$) also decoupled from *Zee* but still correlated to $\delta g^{We\nu}$

-ph]

Interplay Higgs/EW factories

- What is the relevance of the EW factory for the Higgs runs:

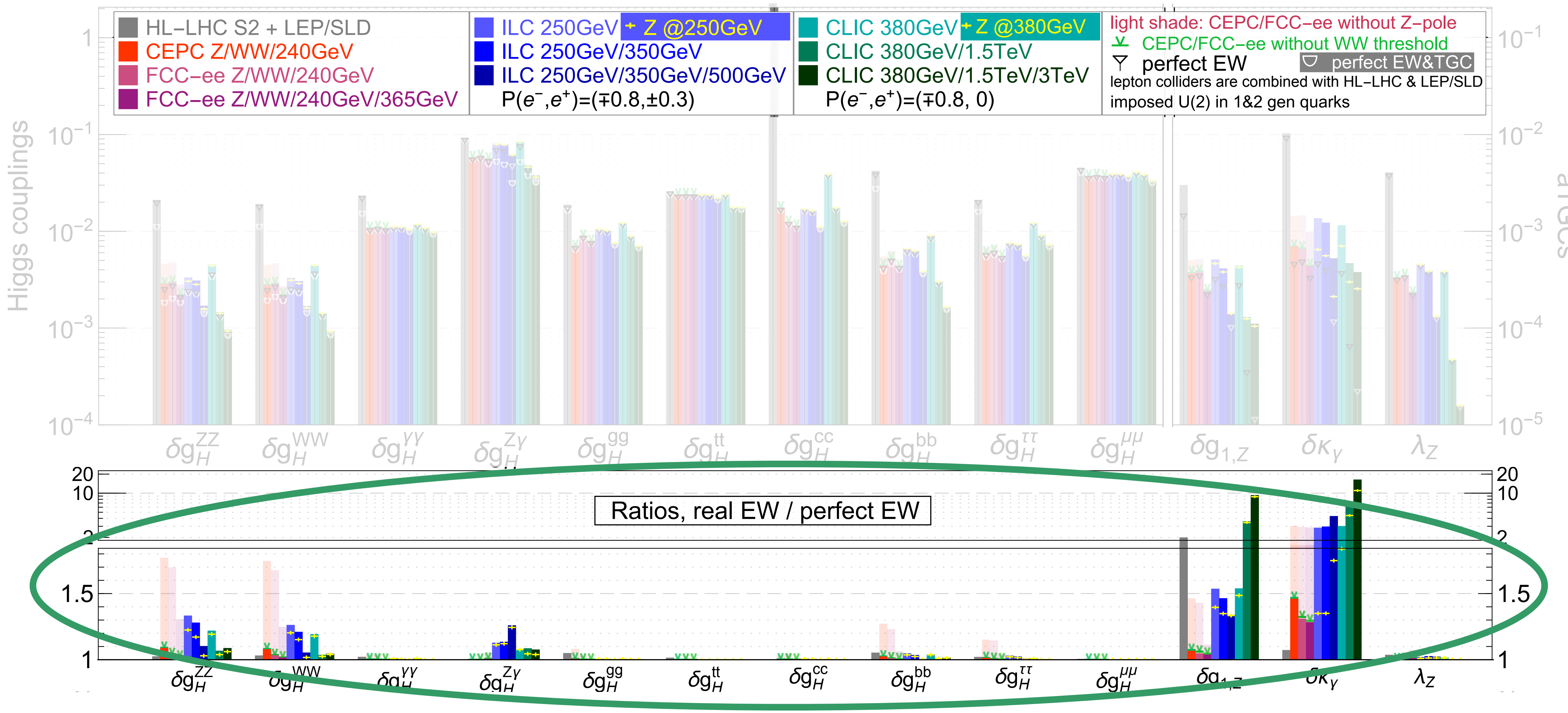


JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

Interplay Higgs/EW factories

- What is the relevance of the EW factory for the Higgs runs:

precision reach on effective couplings from full EFT global fit



Are LEP/SLD EW precision measurements enough?

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

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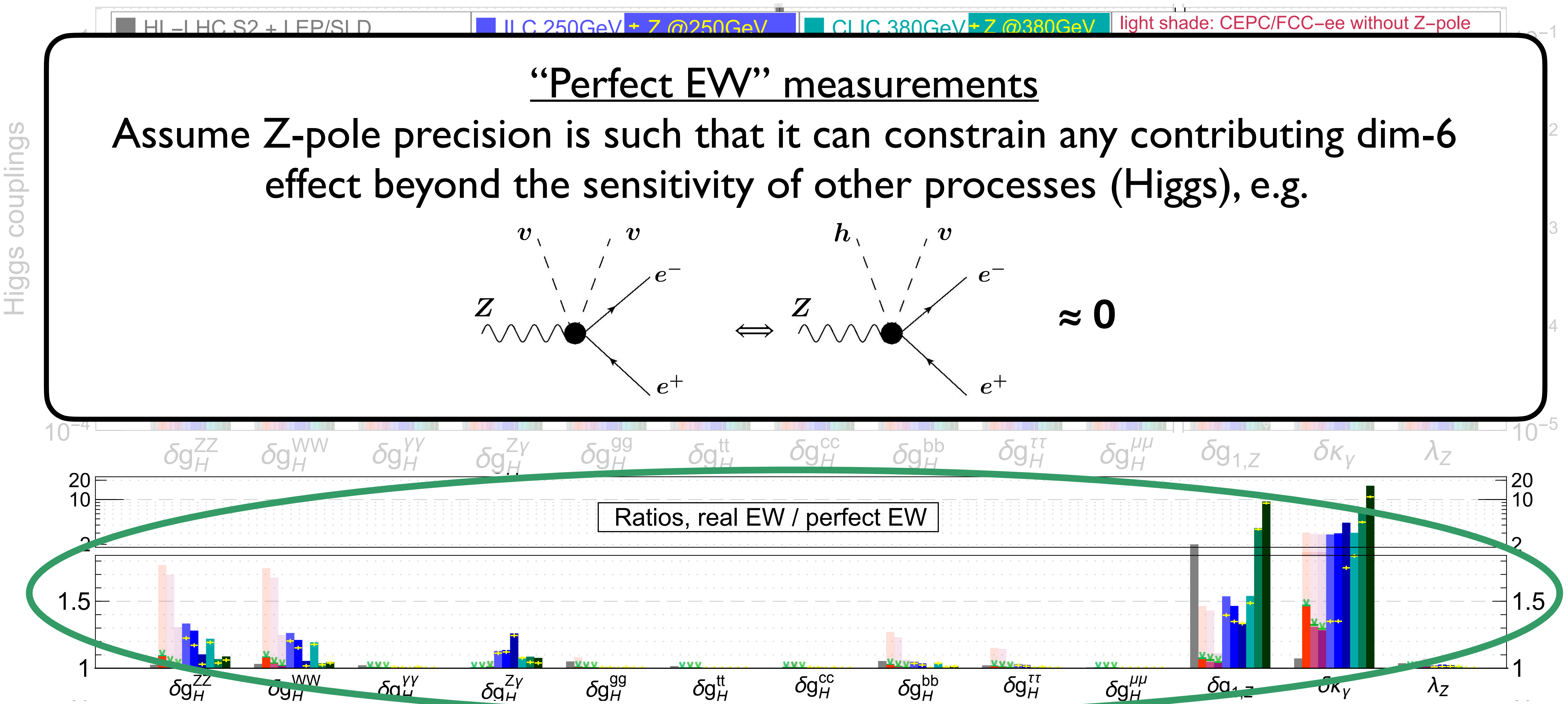

<u>"Perfect EW" measurements</u>

Assume Z-pole precision is such that it can constrain any contributing dim-6 effect beyond the sensitivity of other processes (Higgs), e.g.

$$v\,v\,Z\,e^-e^+ \Leftrightarrow h\,v\,Z\,e^-e^+ \approx 0$$

Are LEP/SLD EW precision measurements enough?

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

Interplay Higgs/EW factories

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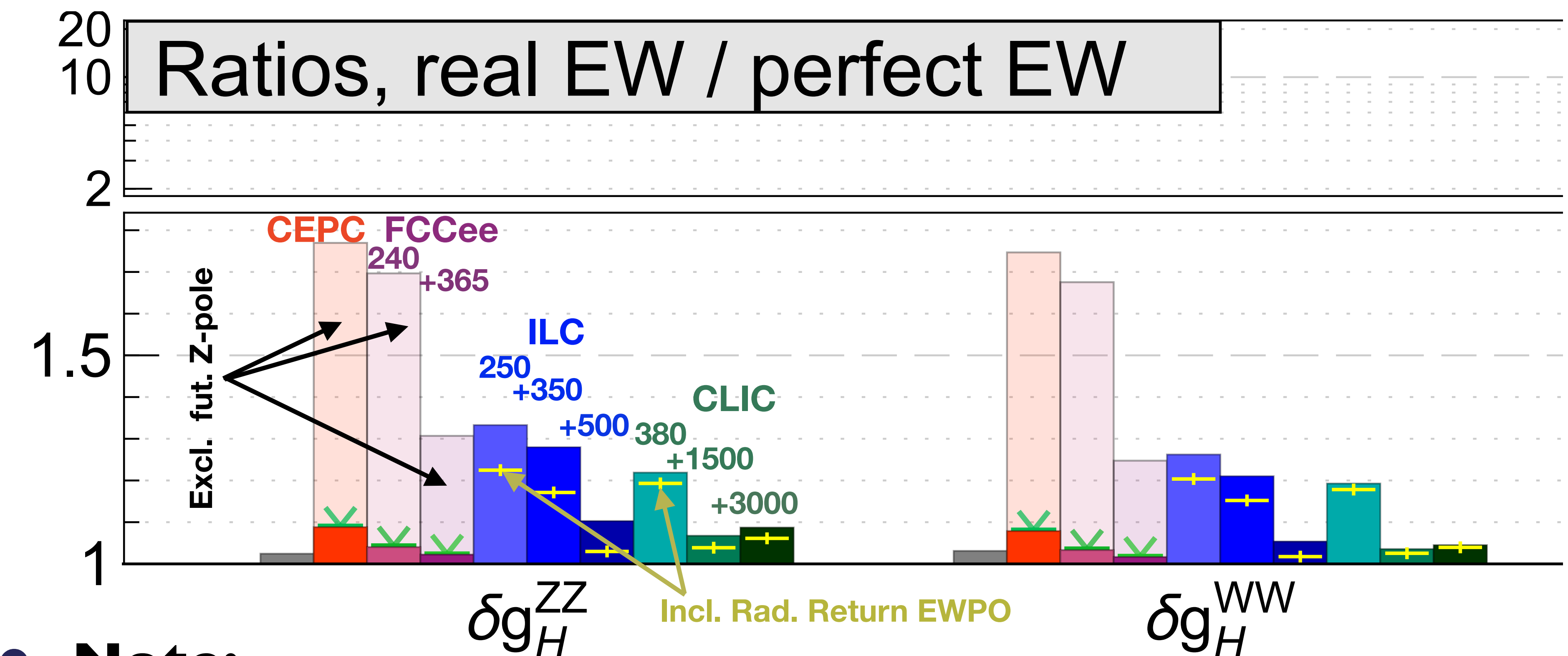


- **Note:**
  - ✓ Polarization partially compensates the absence of Z-pole at linear colliders…
  - ✓ …plus use rad. return to measure EWPO

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

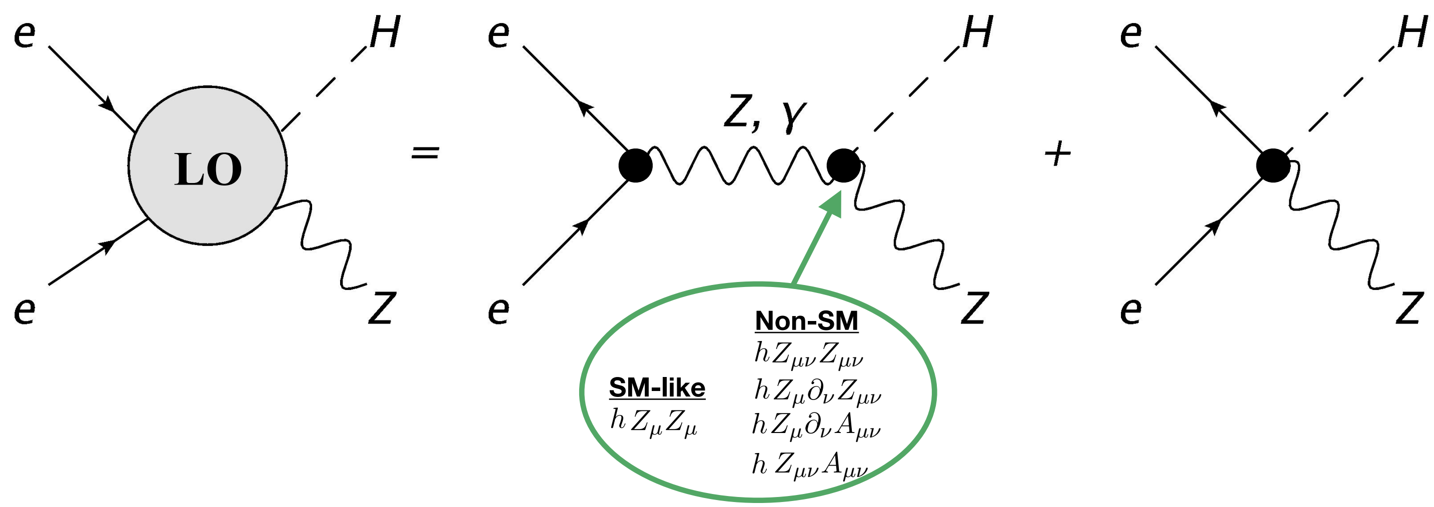
Interplay Higgs/EW factories

- What is the relevance of the EW factory for the Higgs runs:

But why?… Higgs production in the SMEFT framework

- New type of contributions: apart from new HVV' tensor structures, virtual exchange of BSM particles can generate contact interactions

Interference grows like E^2 wrt. SM



- Remember, these $HZff$ terms are connected to modifications of Zff couplings, e.g.

$$\phi^\dagger i \overleftrightarrow{D}_\mu \phi\, \overline{e_R}\gamma^\mu e_R \sim \frac{ev^2}{2sc} Z_\mu \overline{e_R}\gamma^\mu e_R + \frac{ev}{sc} H Z_\mu \overline{e_R}\gamma^\mu e_R + \dots$$

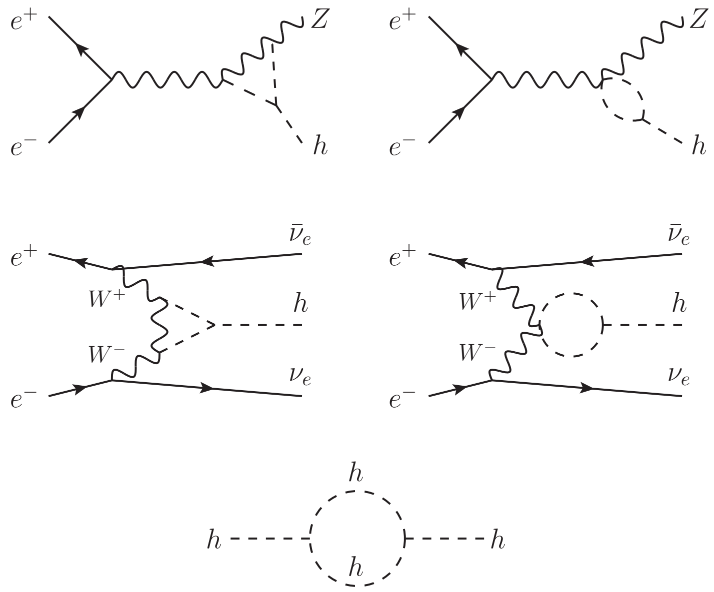
Uncertainty on *(H)Zee* introduces growing-with-*E* "contamination" in the extraction of *HZZ* interactions from *ZH* processes (0.1% in *Zee* →~1% in *HZee* at 250 GeV)

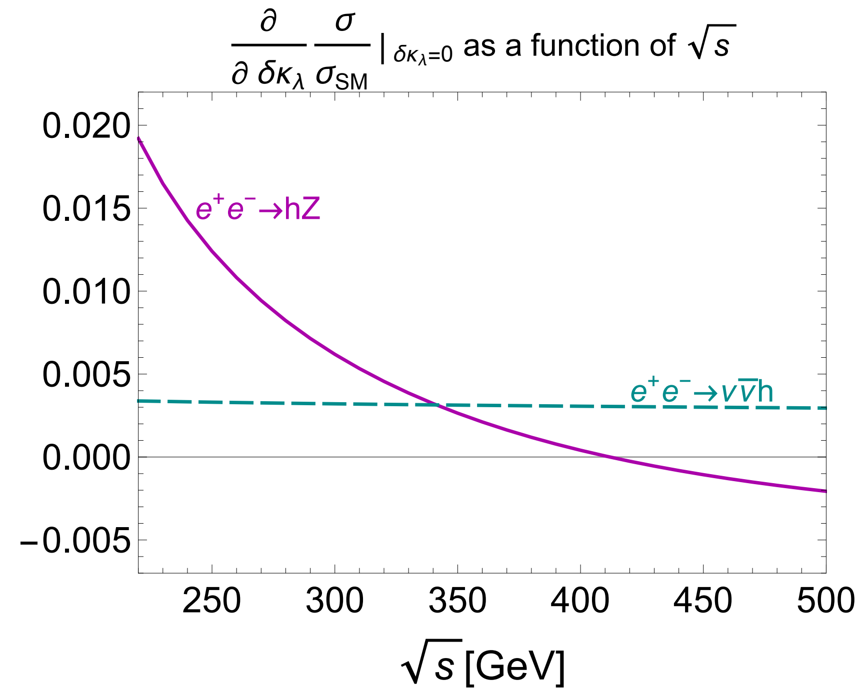
⇒ Need future EWPO (Z-pole data) to better constrain $Zee \to HZee$

pn]

Interplay Higgs/EW factories

- Impact in the determination of the Higgs trilinear at lepton colliders:





Need running at, at least, 2 different energies (240 GeV and 350/365 GeV) to get good constraints in a global fit!

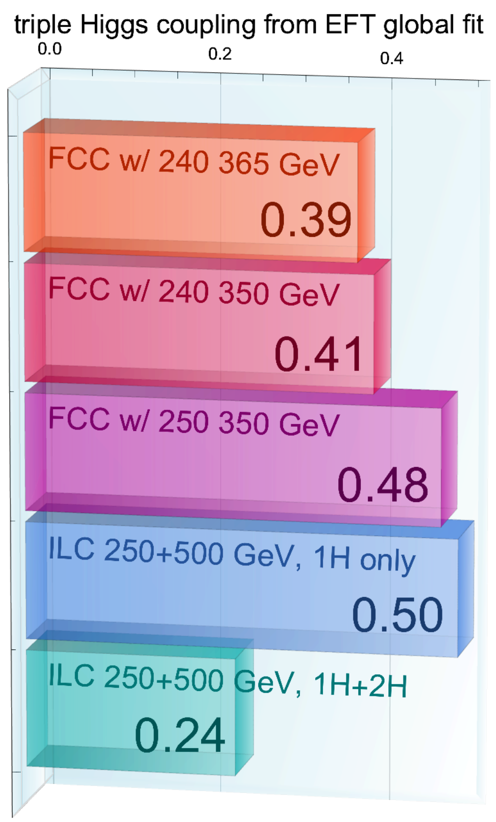
S. Di Vita et al., JHEP 02 (2018) 178, arXiv: 1711.03978 [hep-ph]

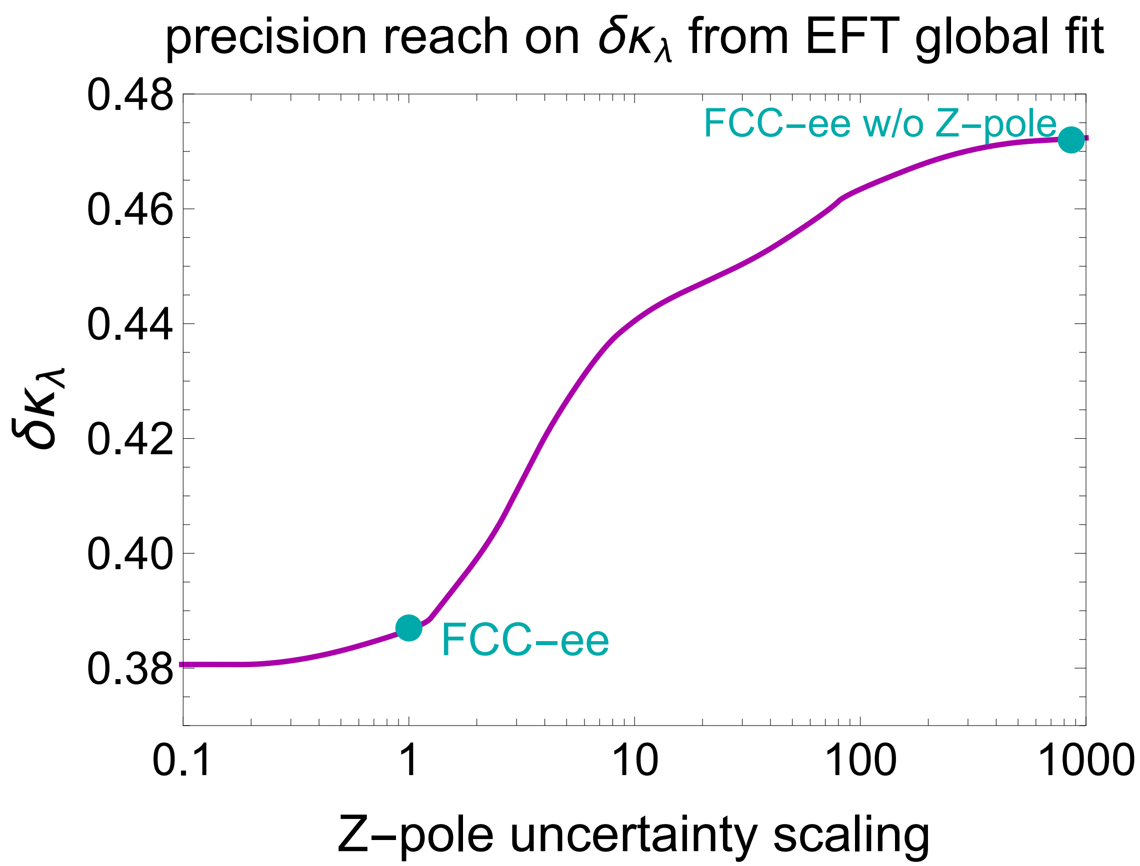
✓ Note that the extraction of the Higgs self coupling at lepton colliders is not affected by the presence of 4-HQ operators to the same extent as at the LHC, thanks to the absolute determination of the ZH cross section (insensitive to these effects at NLO)

✓ In a global analysis, however, it relies on the precision of the HVV interactions, which modify the production at LO…

Interplay Higgs/EW factories

- Snowmass updates on the triple Higgs determination at lepton colliders from global SMEFT fits (Work in progress):





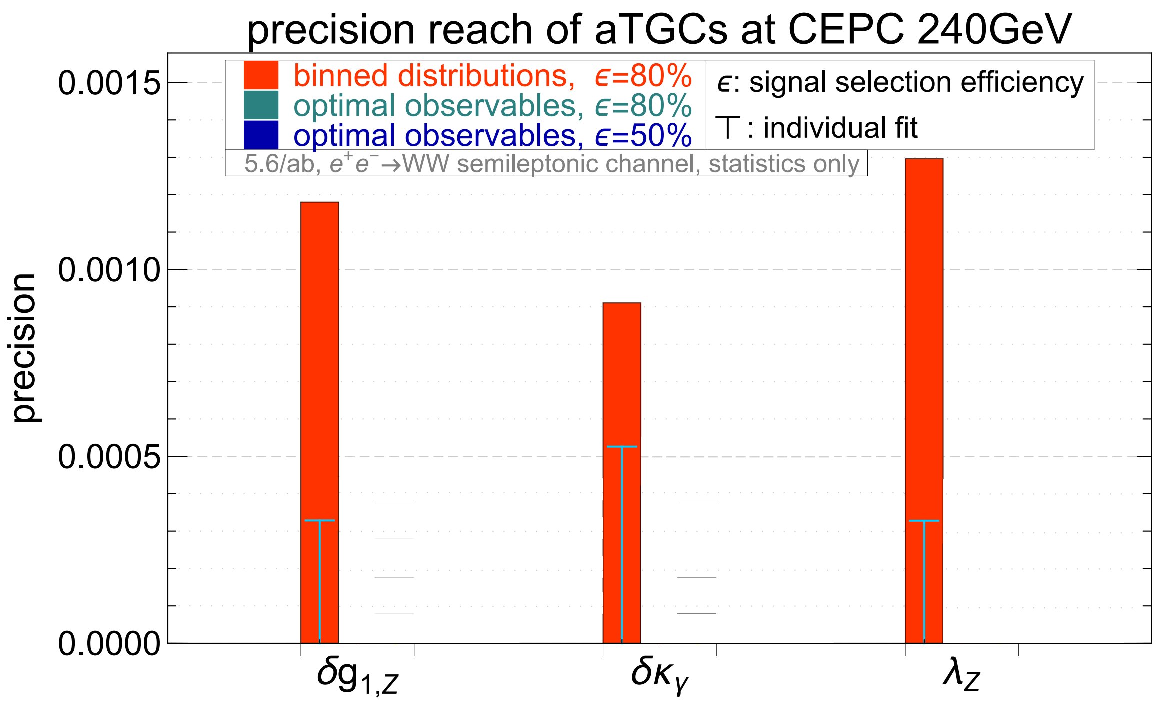
Thanks to J. Gu for preparing these figures

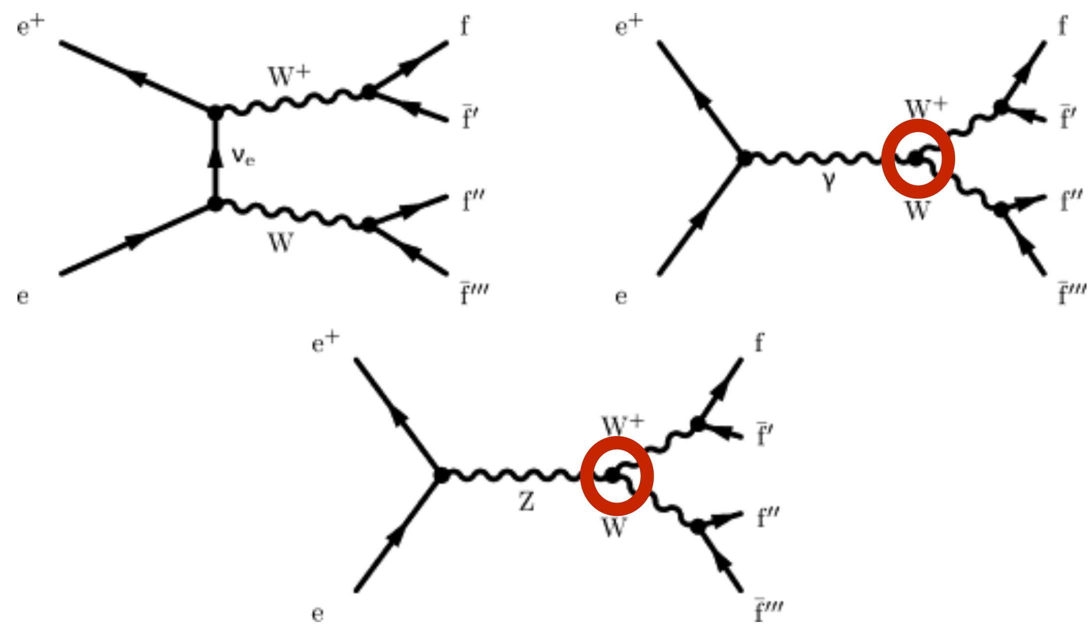
✓ Studying impact of using different energy points: 240+365GeV seem optimal

✓ Studying impact of Z-pole measurements found to be, again, non-negligible (due to its impact on the determination of HVV couplings)

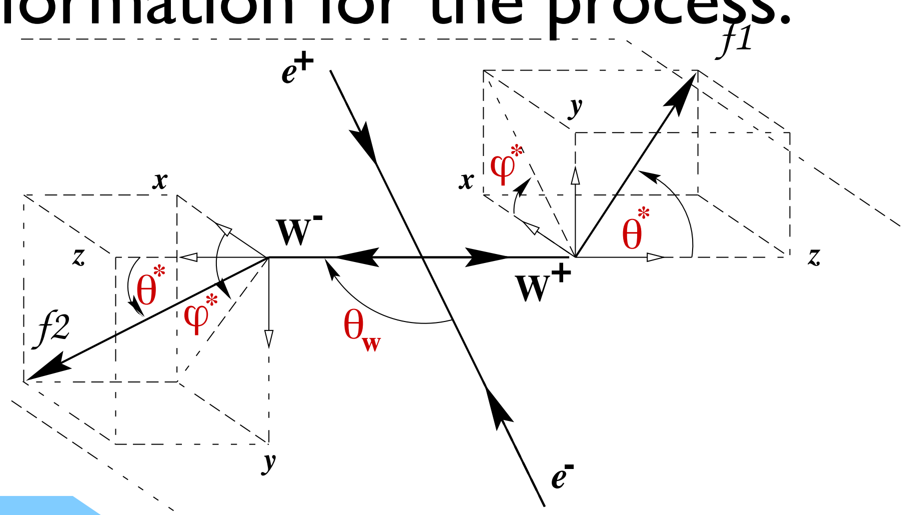
Interplay Higgs/EW factories

- Impact of di-Boson measurements in Higgs couplings
- Following the LEP2 experience, future collider studies of sensitivity to aTGC also use ONLY binned $cos\ \theta_W$ differential distributions (ignoring correlations)





- This is, however, not optimal, in the sense that it does not uses all the differential information for the process:



We prepared a global SMEFT study of WW using also the all differential info and the formalism of "Optimal statistical observables"

Optimal Observables

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

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

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

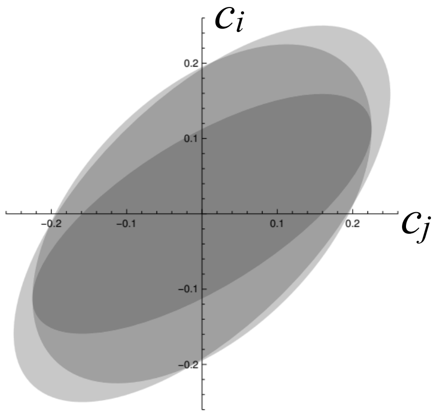
- In the limit of large statistics, the observables

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

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

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

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



OO minimize the volume of the 1-σ ellipsoid

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

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

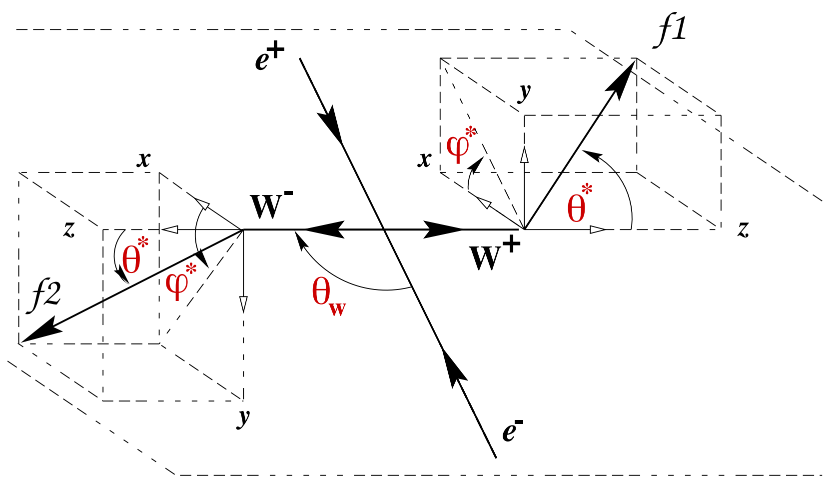
(For this study we take as default 50%. More on this later…)

Optimal Observables

- diBoson: We work with $e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu$

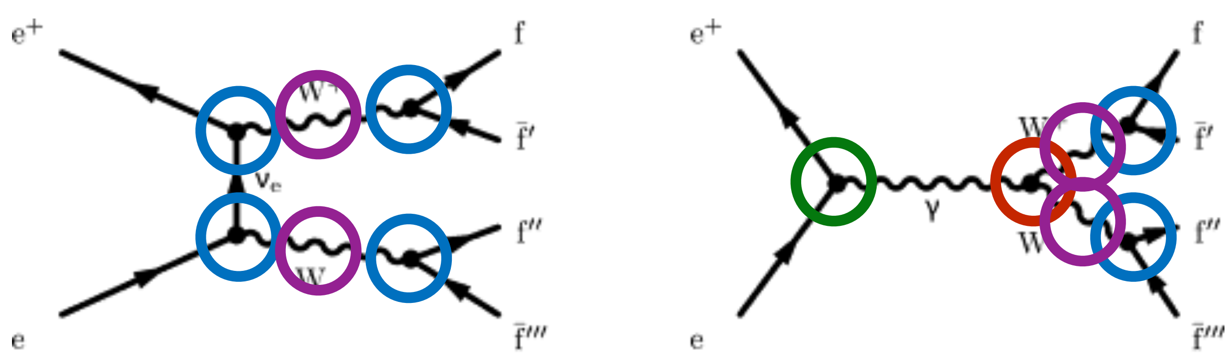
$$S(\Phi) = S_0(\Phi) + \textstyle\sum_i c_i S_i(\Phi)$$

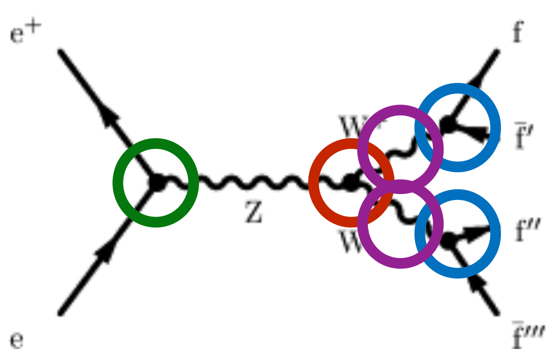
SMEFT: $S(\Phi) = \frac{d\sigma}{d\Phi}$ $\quad S_0(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\rm SM}$ $\quad c_i S_i(\Phi) = \frac{d\sigma}{d\Phi}\Big|_{\rm Interf.\ SM-NP}$



Optimal Observables function of 5 angles

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



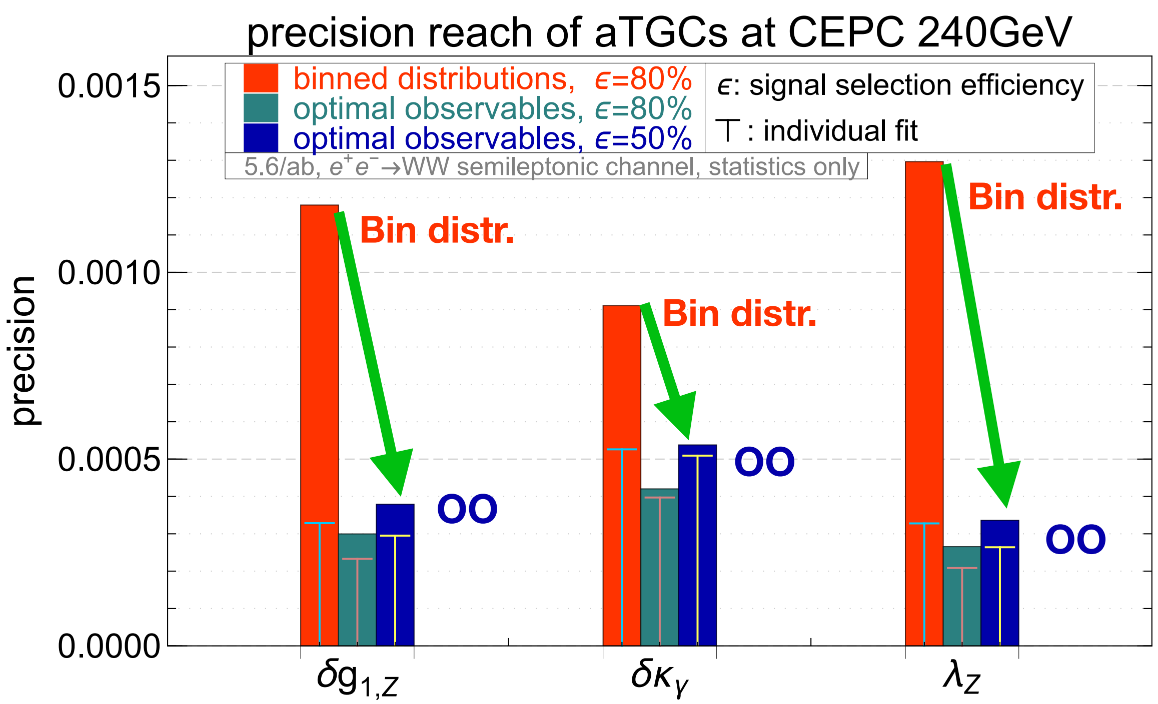


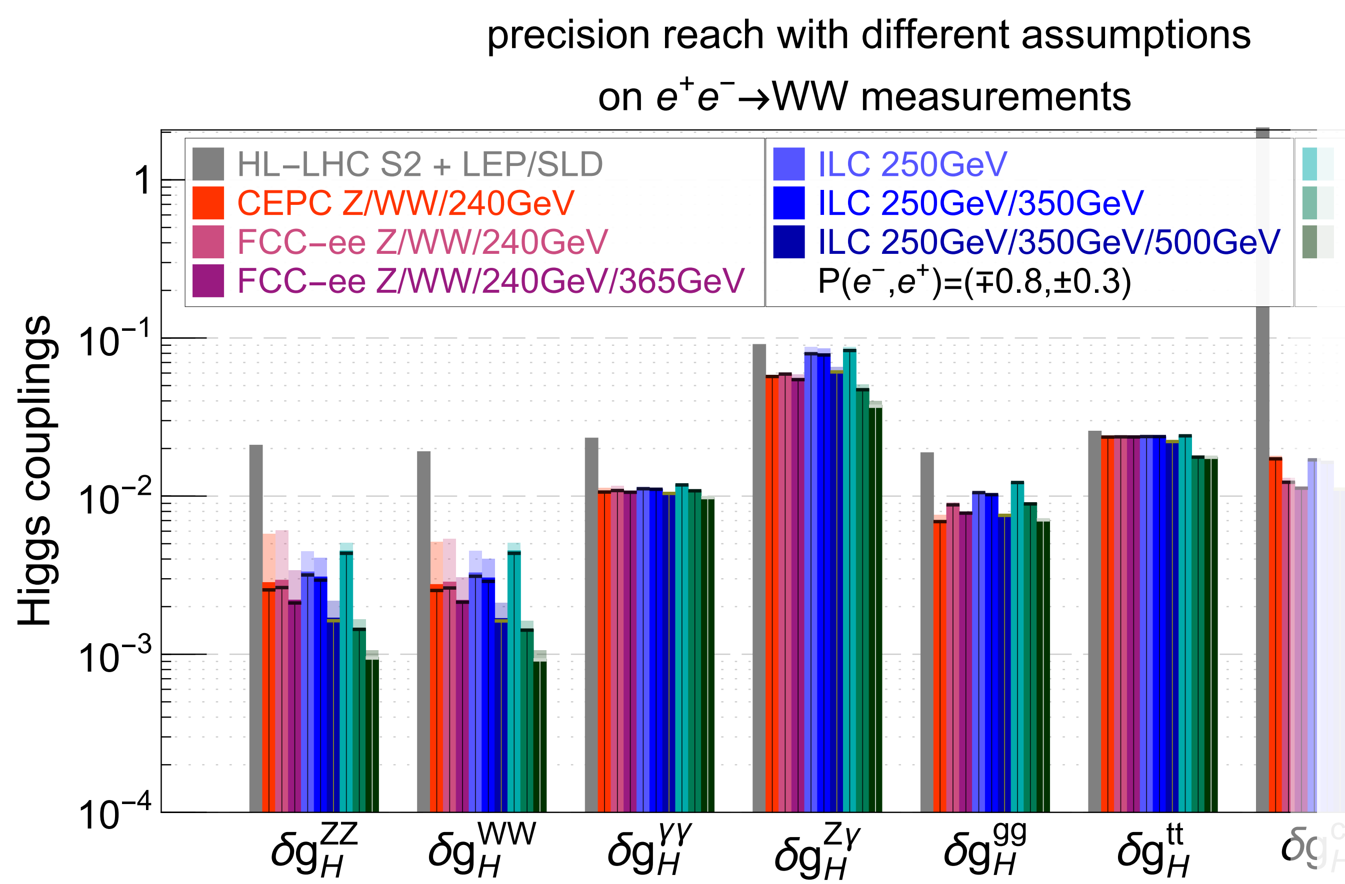
Full dim-6 SMEFT parameterization at LO: 10 independent BSM deformations

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

Interplay Higgs/EW factories

- Impact of di-Boson measurements in Higgs couplings
- Optimal Observable Analysis of EFT effects in $e^+e^- \to W^+W^- \to jj\ell\nu, \quad \ell = e, \mu$



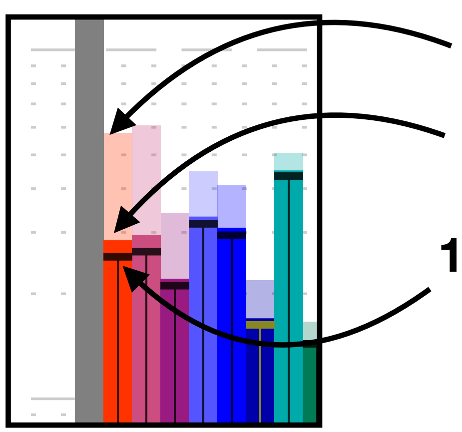


Full EFT parameterisation

Maximal differential information

Stat. Uncertainty only (idealised)

Compensate absence of sys. via efficiency



JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117, arXiv: 1907.04311 [hep-ph]

Interplay Higgs/EW factories

- Impact of di-Boson measurements in Higgs couplings
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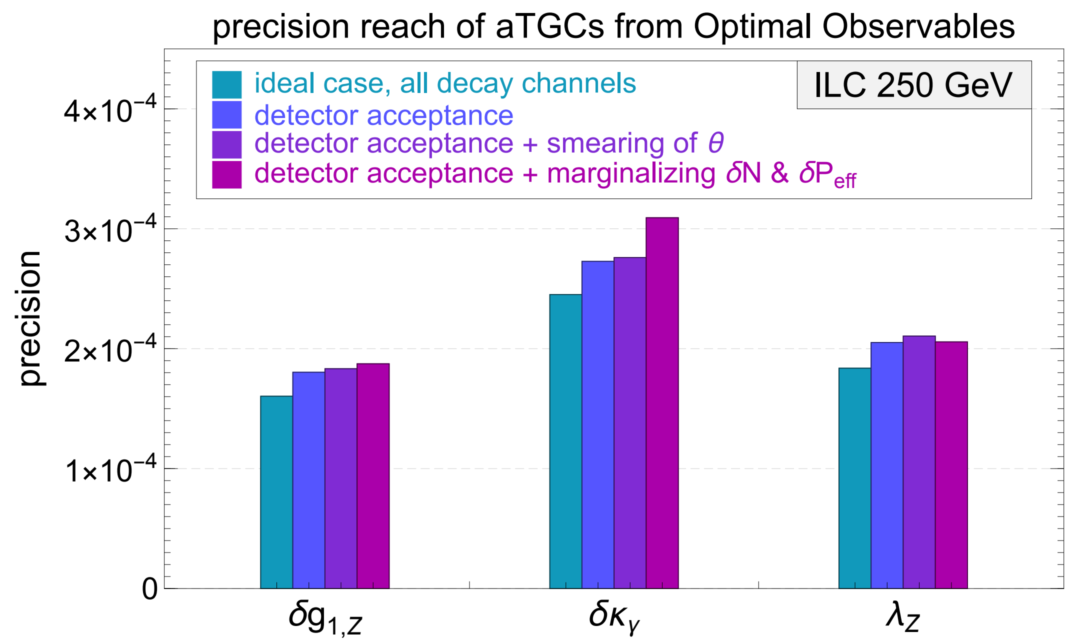
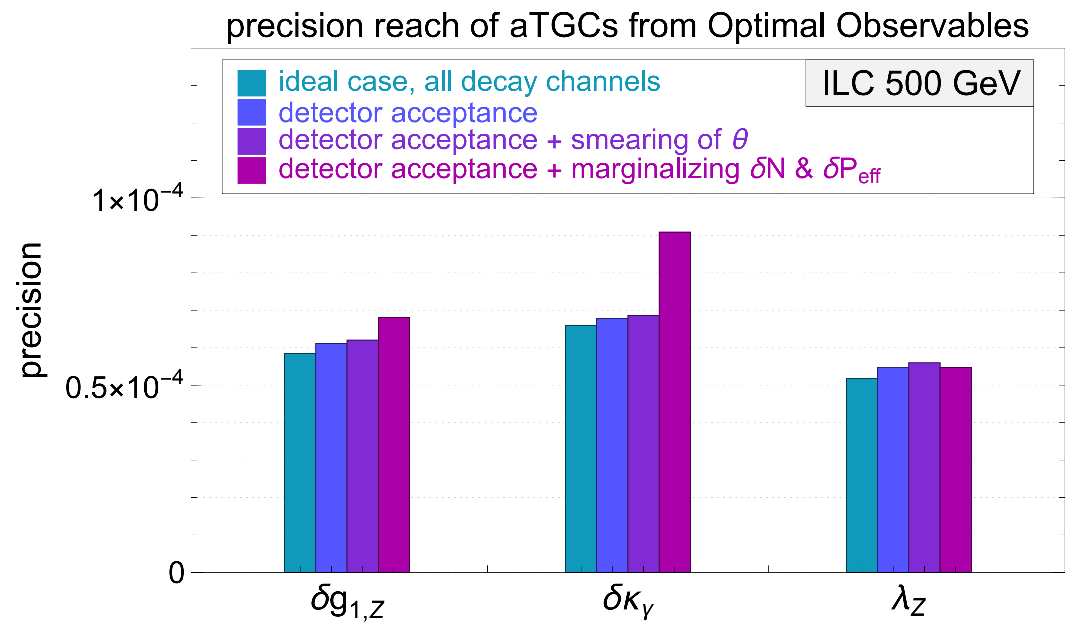
- Updates for Snowmass (Work in progress): extended analysis with
  - ✓ Detector acceptance effects ($|\cos\theta| < 0.9\ (0.95)$ for jets (leptons))
  - ✓ Smearing on the polar angle
  - ✓ Systematics in the determination of the total rate (δN) and effective beam polarisation (δP_{eff}), e.g. for ILC
  - ✓ Combination of all channels





Thanks to J. Gu for preparing these figures

Conclusions

Conclusions

- The future of BSM searches at the LHC and the next future collider will rely on precision measurements
  - ✓ They guided direct searches in the past and will be necessary before another high energy (100 TeV?) hadron collider is (hopefully) built
- A general model-independent interpretation of measurements can be done within the consistent theory framework of Effective Field Theories
- SMEFT interpretation benefits from the interplay of different types of measurements
  - ✓ At the LHC: e.g. LEP/SLD EWPO constrains many interactions entering in LHC processes
  - ✓ At future e^+e^- Higgs/EW/Top factories: a combination of all possible info in a truly global EW/Higgs/diBoson/Top fit (not available yet) still needed to precisely establish the indirect physics potential of these machines

⇒Work in Progress for the Snowmass 2021

- (And, remember, the SMEFT is not ALL!… HEFT? EFTs with extra light particles?…)

Backup Slides

The SMEFT at the LHC

- For anything related to the applications of EFT studies at the LHC, check the recently formed ***LHC Effective Field Theory WG***
- Six activity Areas:
  - ✓ EFT Formalism
  - ✓ Predictions and Tools
  - ✓ Experimental Measurements and Observables
  - ✓ Fits and Related Systematics
  - ✓ Benchmark Scenarios from UV Models
  - ✓ Flavor

Webpage: https://lpcc.web.cern.ch/lhc-eft-wg

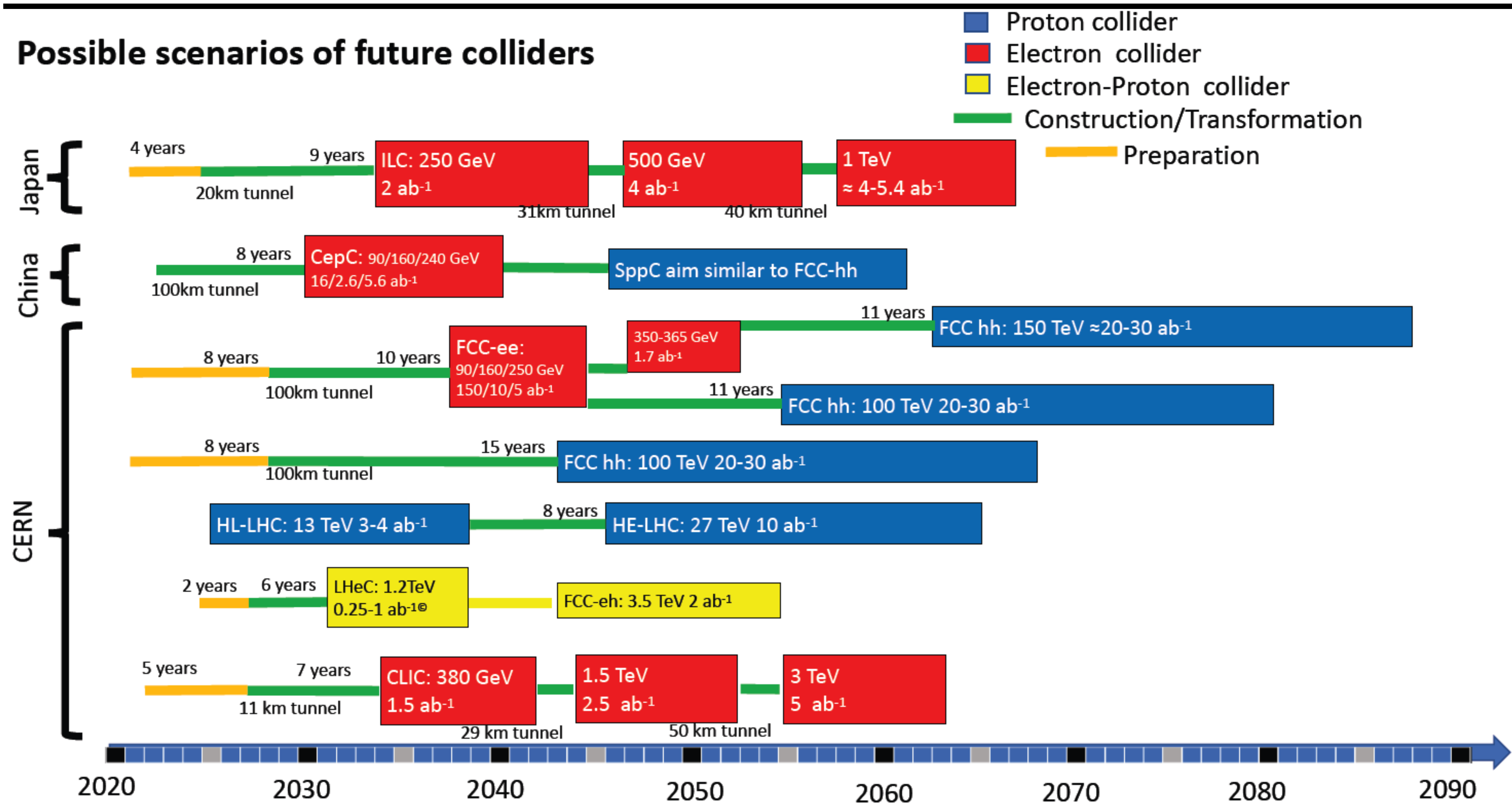
Twiki page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEFT

WG meetings: https://indico.cern.ch/category/12671/ → **3rd General Meeting on Nov. 22**

Reach us the conveners at: lhc-eftwg-admin@cern.ch

Subscribe to the Mailing list:
https://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-eftwg

Future Colliders



Ursula Bassler @ Granada

Future Colliders

General strategy for calculation of future sensitivities to BSM effects

- Fit to new physics effects parameterized by the dimension 6 SMEFT:

  √ Bayesian fit using HEPfit

  √ **Future 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.

  √ **New physics effects:** Working at the linear-level in the EFT effects (interference with SM amplitudes)

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

  √ **SM theory uncertainties:** SM intrinsic and parametric uncertainties reduced according to future projections. Included in the analysis when available.

Main results presented with SM parametric uncertainties

(Impact of different TH uncertainties discussed later)

Higgs couplings at future Higgs factories

Lots of work at the different Fut. Collider Projects: Condensed in ESU study

What goes into this figure?

Warsaw basis

SM +

$\mathcal{O}_{\phi f}^{(n)}$ $\mathcal{O}_{f\phi}$ $\mathcal{O}_{\phi V}$

$\mathcal{O}_{\phi\Box}$ $\mathcal{O}_{\phi D}$ $\mathcal{O}_{ll}$

...

5 SM pars
+
30 NP pars

↓

Dim 6 mass eigenstate Lag.

Assumptions/Simplifications

- CP-even. *Hff* and *Vff* (*HVff*) diagonal in the physical basis
- No 4-fermion, dipole ops.
- *Vff* (*HVff*) flavour universality respected by first 2 quark families

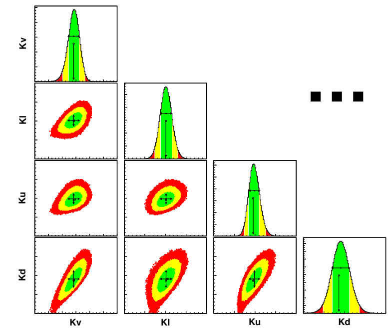
- Dim-6 + truncation at linear level. TH unc.: SM only.

→

Fit to
Higgs
EWPO
WW (aTGC)
Top

→

Posterior C_i

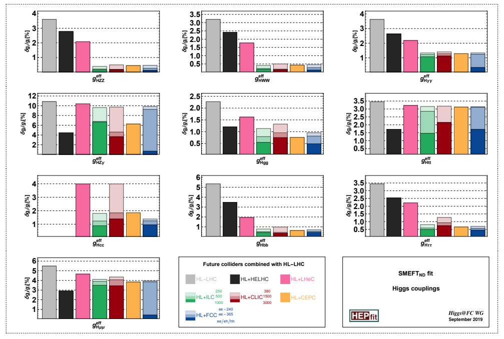


...

→

Posterior predictions for PO

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



Higgs couplings at future Higgs factories

SM Theory uncertainties in Higgs calculations

- Impact of SM precision calculations and uncertainties

Decay	Partial width [keV]	Projected future unc. $\Delta\Gamma/\Gamma$ [%] Th_{Intr}	$\text{Th}_{\text{Par}}(m_q)$	$\text{Th}_{\text{Par}}(\alpha_s)$	$\text{Th}_{\text{Par}}(m_H)$
$H\to b\bar{b}$	2379	0.2	$0.6^\flat$	$<0.1^\sharp$	–
$H\to\tau^+\tau^-$	256	<0.1	–	–	–
$H\to c\bar{c}$	118	0.2	$1.0^\flat$	$<0.1^\sharp$	–
$H\to\mu^+\mu^-$	0.89	<0.1	–	–	–
$H\to WW^*$	883	$\lesssim 0.4$	–	–	$0.1^\ddagger$
$H\to gg$	335	1.0	–	$0.5^\sharp$	–
$H\to ZZ^*$	108	$\lesssim 0.3^\dagger$	–	–	$0.1^\ddagger$
$H\to\gamma\gamma$	–	<1.0	–	–	–
$H\to Z\gamma$	2.1	1.0	–	–	$0.1^\ddagger$

†From $e^+e^-\to ZH$.
‡For $\delta M_H = 10$ MeV. Adjusted for Higgs mass precision at CLIC.
$^\flat$For $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV. (Lattice projection).
$^\sharp$For $\delta\alpha_s = 0.0002$. (Lattice projection).

Intrinsic TH unc in production

e.g. $e^+e^-\to Z\,H$

LO to NLO: 5-10%

Missing 2-loop: O(1%)

Full 2-loop should reduce uncertainty to O(0.1%)

Z width effects relevant at this level of precision?

Assessment of TH uncertainty may require full 2->3 NNLO

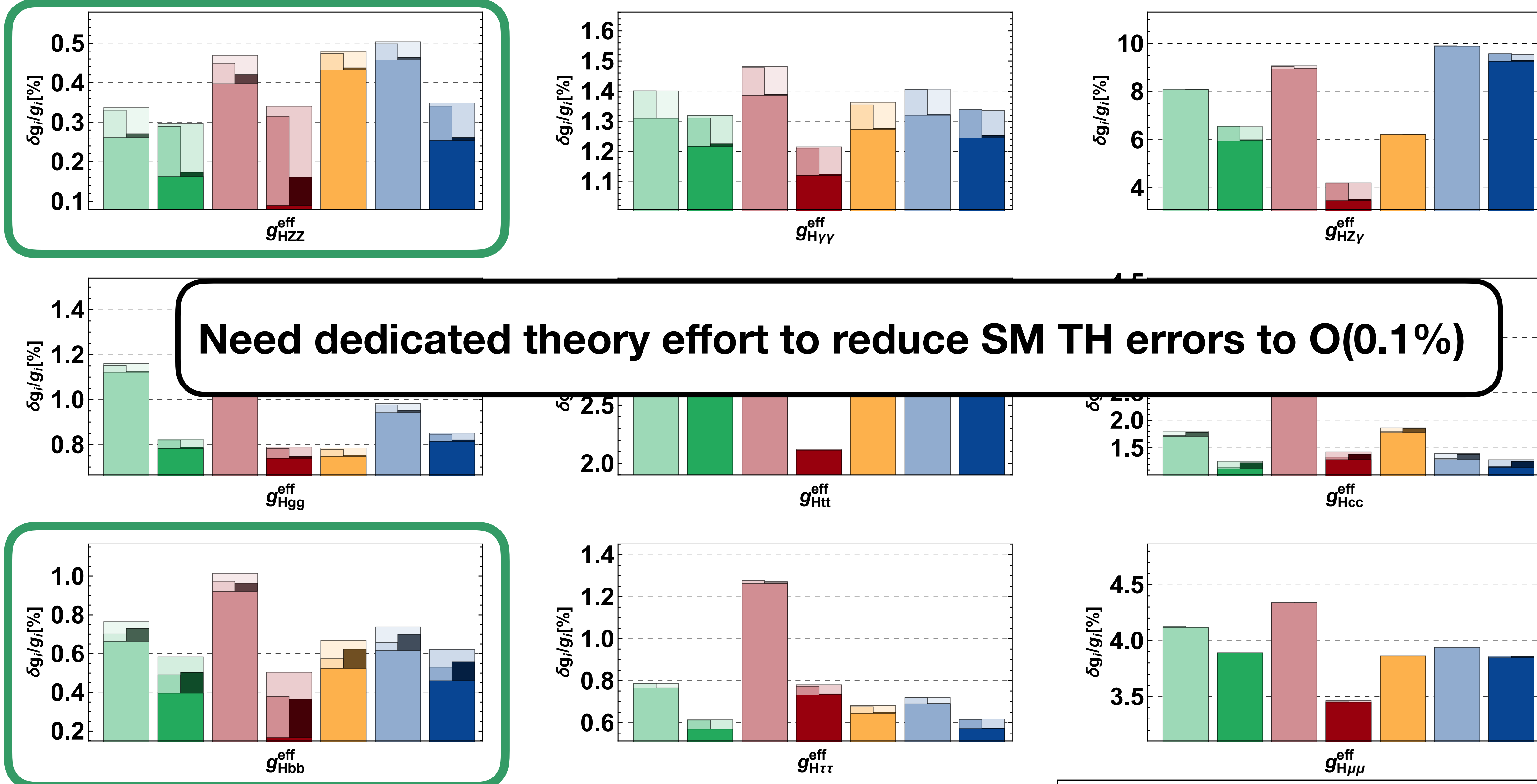
In any case, reducible with necessary effort from theory side

A. Freitas et al., arXiv: 1906.05379 [hep-ph]

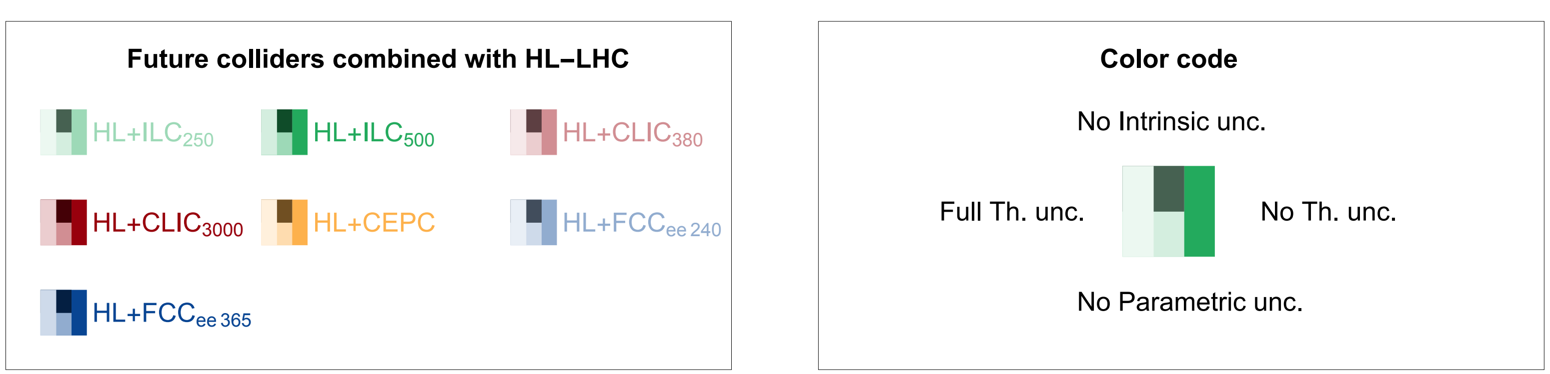
Higgs couplings at future Higgs factories

SM Theory uncertainties in Higgs calculations

- Impact of SM precision calculations and uncertainties



Need dedicated theory effort to reduce SM TH errors to O(0.1%)



Largest effect on HVV couplings

Differences in other couplings mainly due to unc. in production

Exception: Hbb

Electroweak precision observables in the SM

- Impact of SM theory uncertainties of SM calculations of EWPO:

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z [MeV]	2.1	–	0.1			
$\Delta\Gamma_Z$ [MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{eff} [10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b [10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell [10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

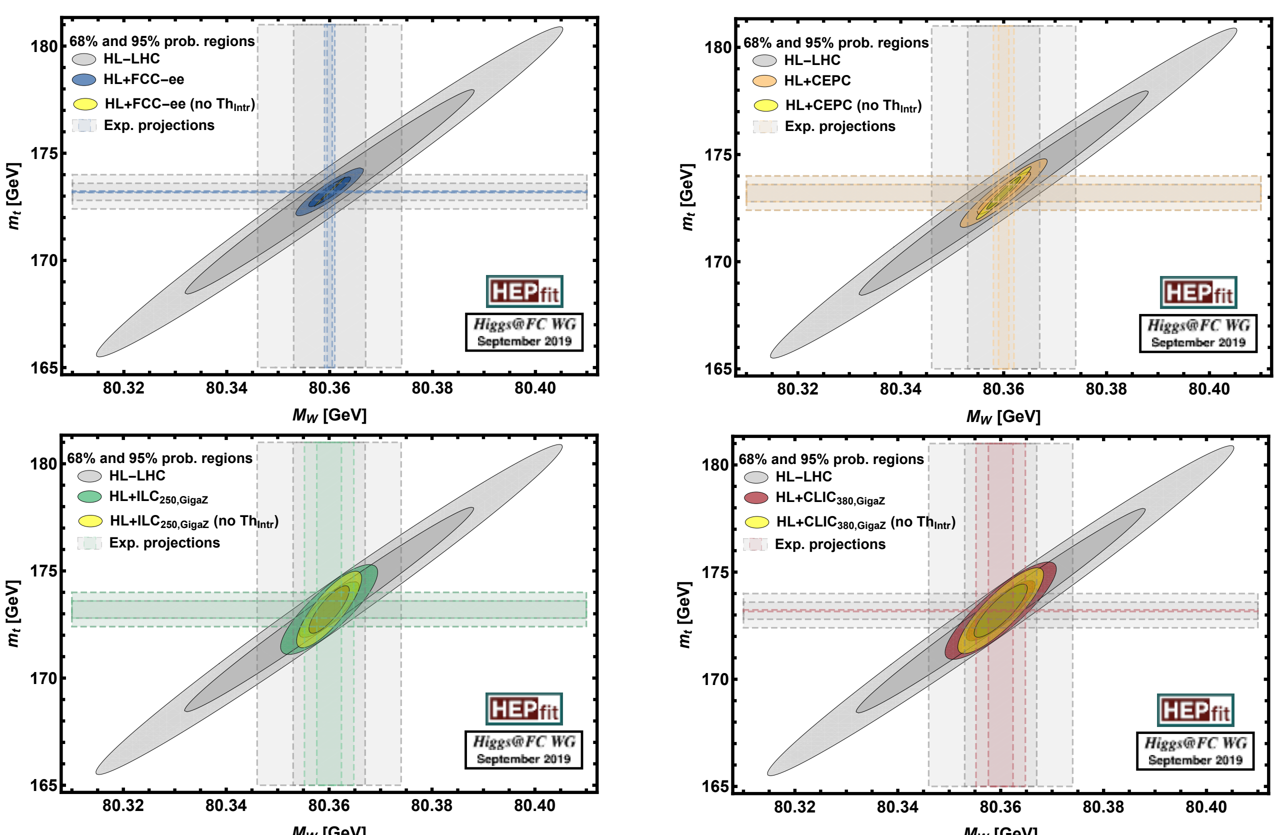
A. Freitas et al., arXiv: 1906.05379 [hep-ph]

Current: Full 2-loop corrections
(Not enough for future Exp. precision)
⇩
Prospects: Extrapolation assuming EW & QCD 3-loop corrections are known

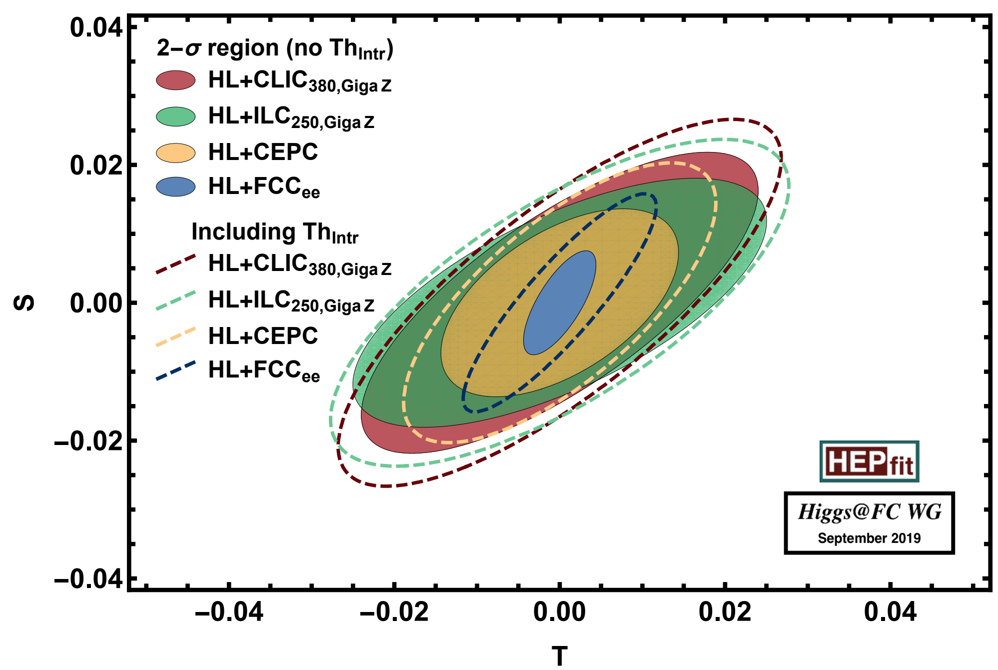
Technically challenging but feasible

Only briefly explored in ESU studies: Future projections still a limiting factor

SM: M_W vs. m_t



BSM: Oblique parameters



Need to study the impact on all directions in the SMEFT fits

Electroweak precision observables in the SM

- Impact of SM theory uncertainties of SM calculations of EWPO:

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
$\Delta M_Z[\mathrm{MeV}]$	2.1	–	0.1			
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Current: Full 2-loop corrections
(Not enough for future Exp. precision)
⇩
Prospects: Extrapolation assuming EW & QCD 3-loop corrections are known

...sible

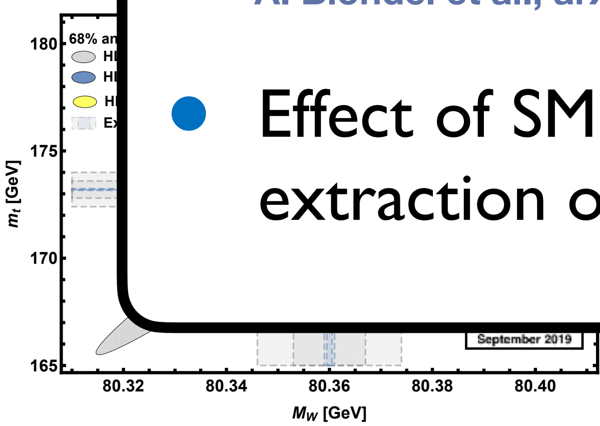
<u>SM uncertainties on *WW* production?</u>

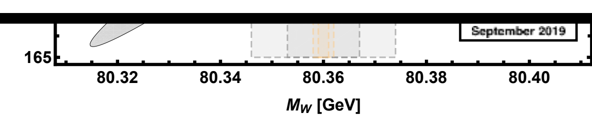
- Studied at threshold (relevant for W mass measurement):

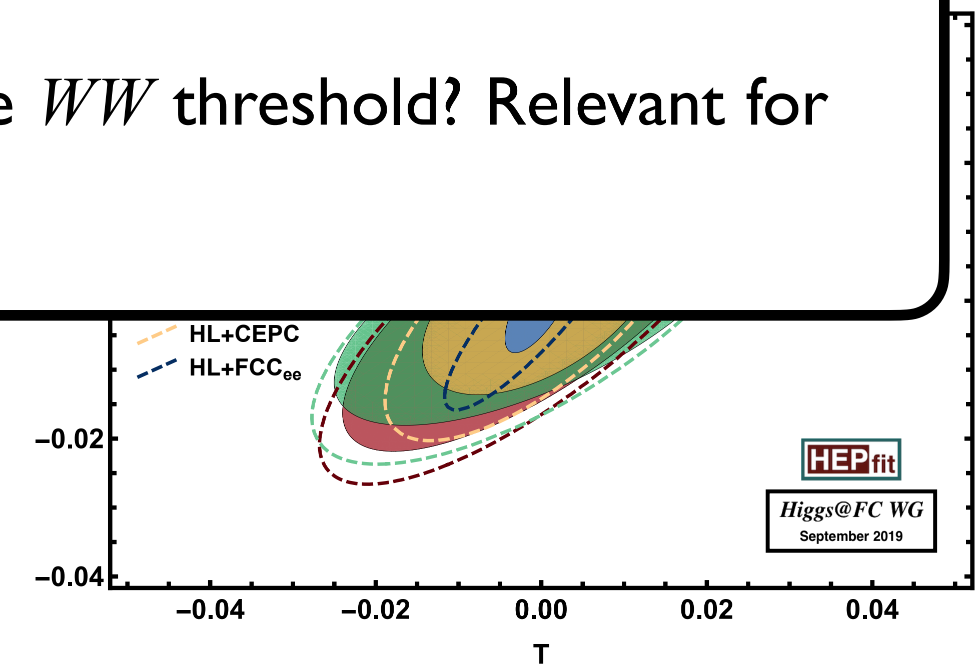
$$\Delta\sigma_{\mathrm{NNLO}} \approx 0.1\% \times \sigma_{\mathrm{Born}} \qquad \Delta\sigma_{\mathrm{N^3LO}} \approx \mathrm{few} \times 0.01\% \times \sigma_{\mathrm{Born}} \quad \rightarrow \quad \Delta M_W = (0.15 - 0.45)\ \mathrm{MeV}$$

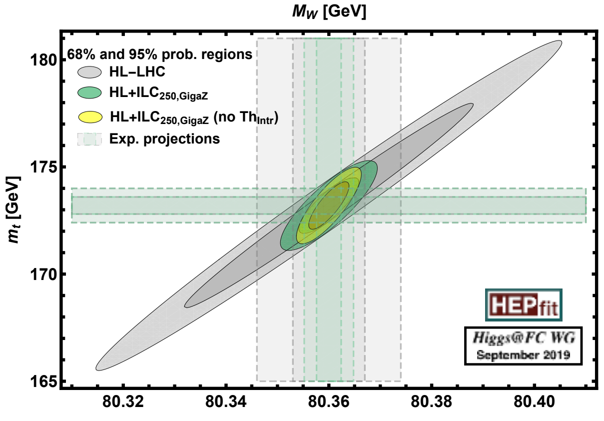
A. Blondel et al., arXiv: 1905.05078 [hep-ph]

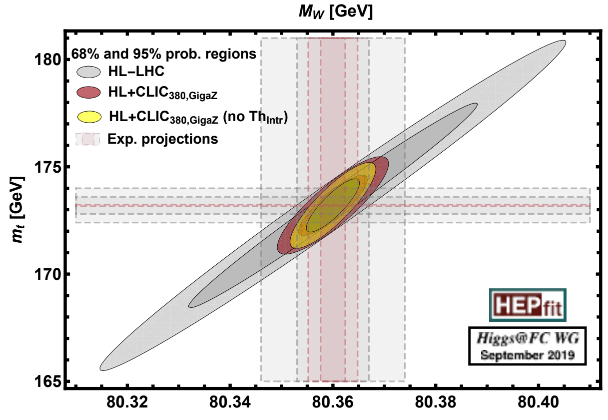
- Effect of SM uncertainty in $e^+e^- \rightarrow 4f$ above WW threshold? Relevant for extraction of, e.g., aTGC







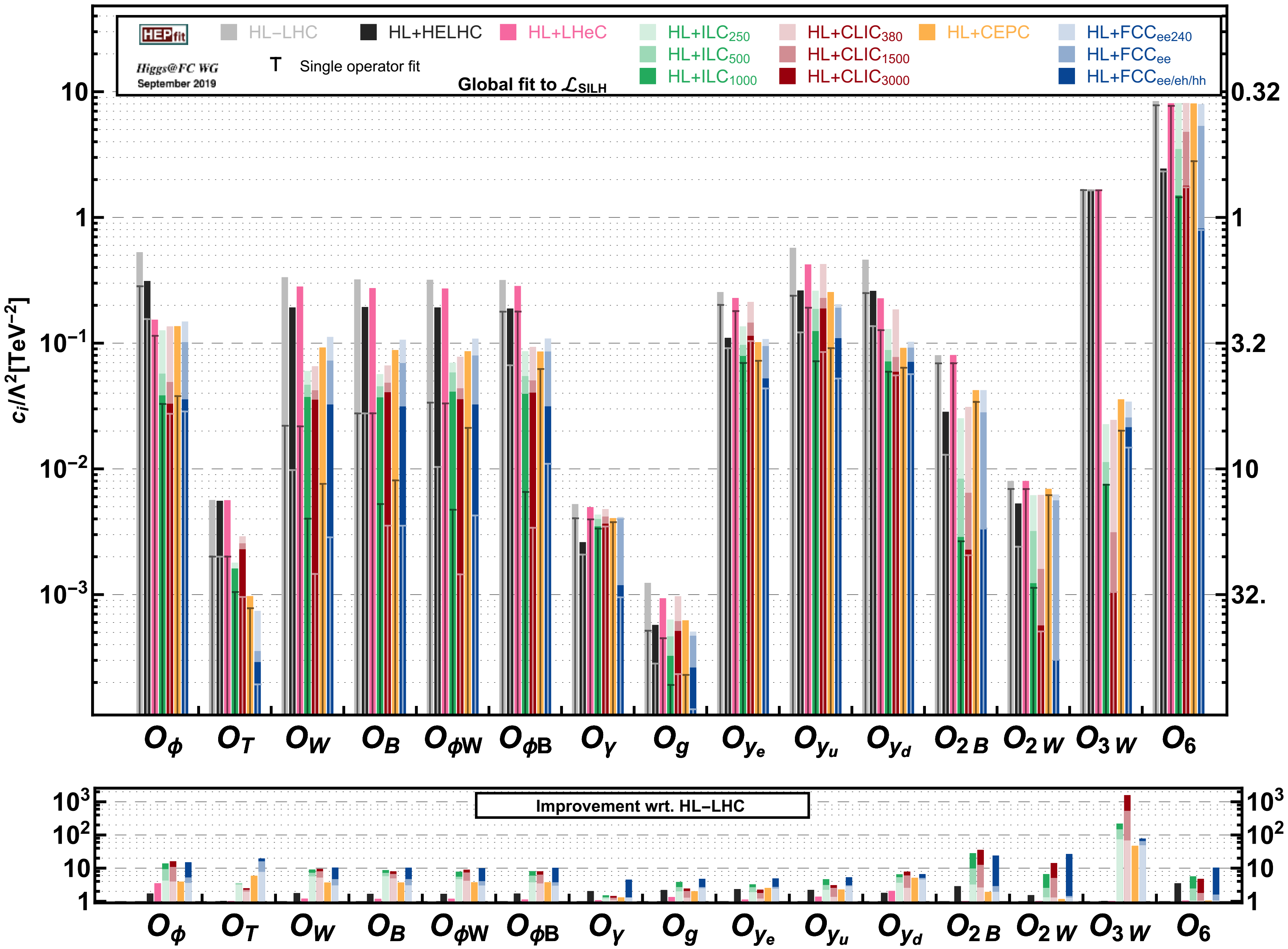




Need to study the impact on all directions in the SMEFT fits

European Strategy Update Results

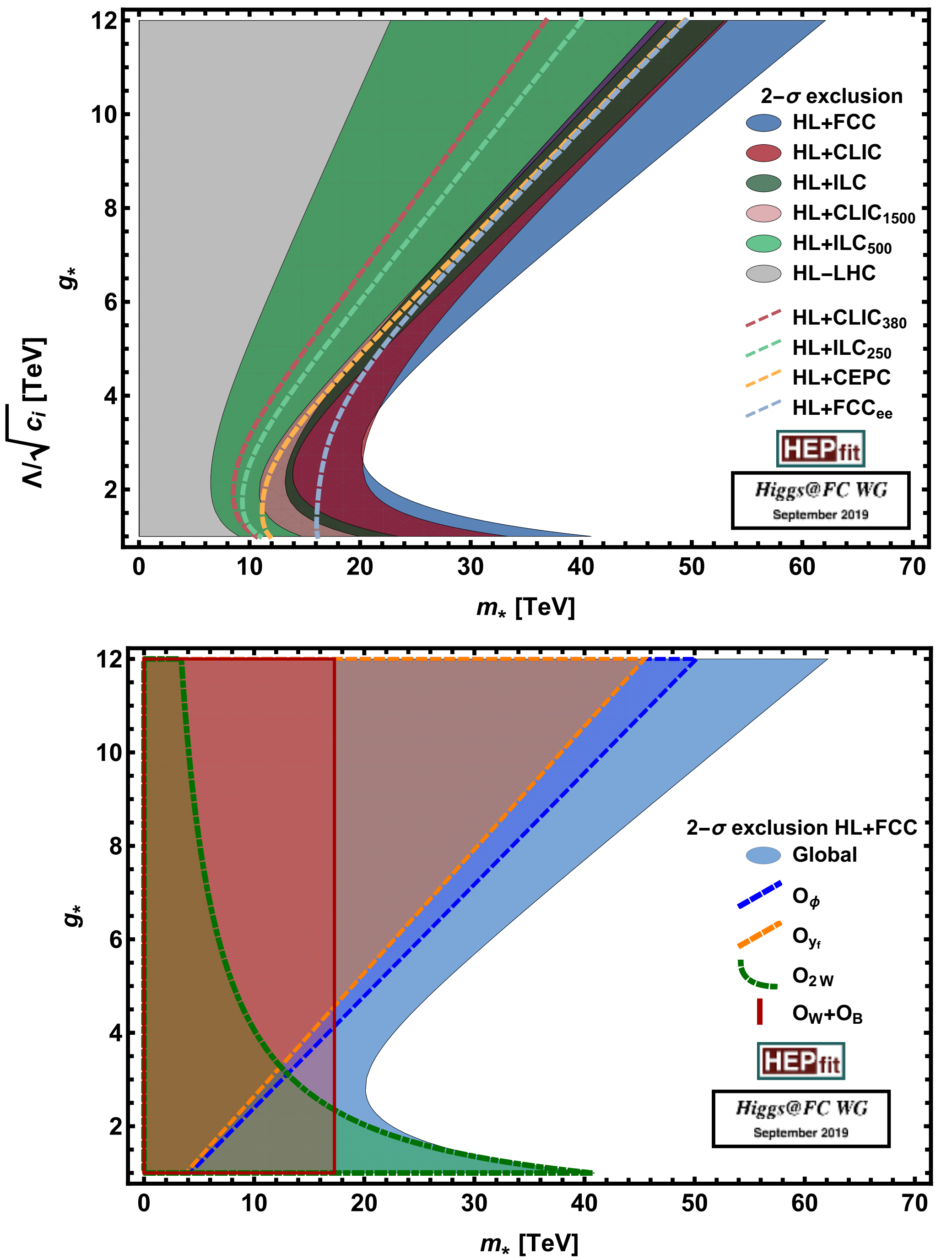
- With its limitations, the ESU study was enough to constraint a reasonably large set of EFT interactions relevant for "Higgs" BSM scenarios



SILH operators

(Only a subset of the interactions that can be constrained in a global fit)

Composite Higgs

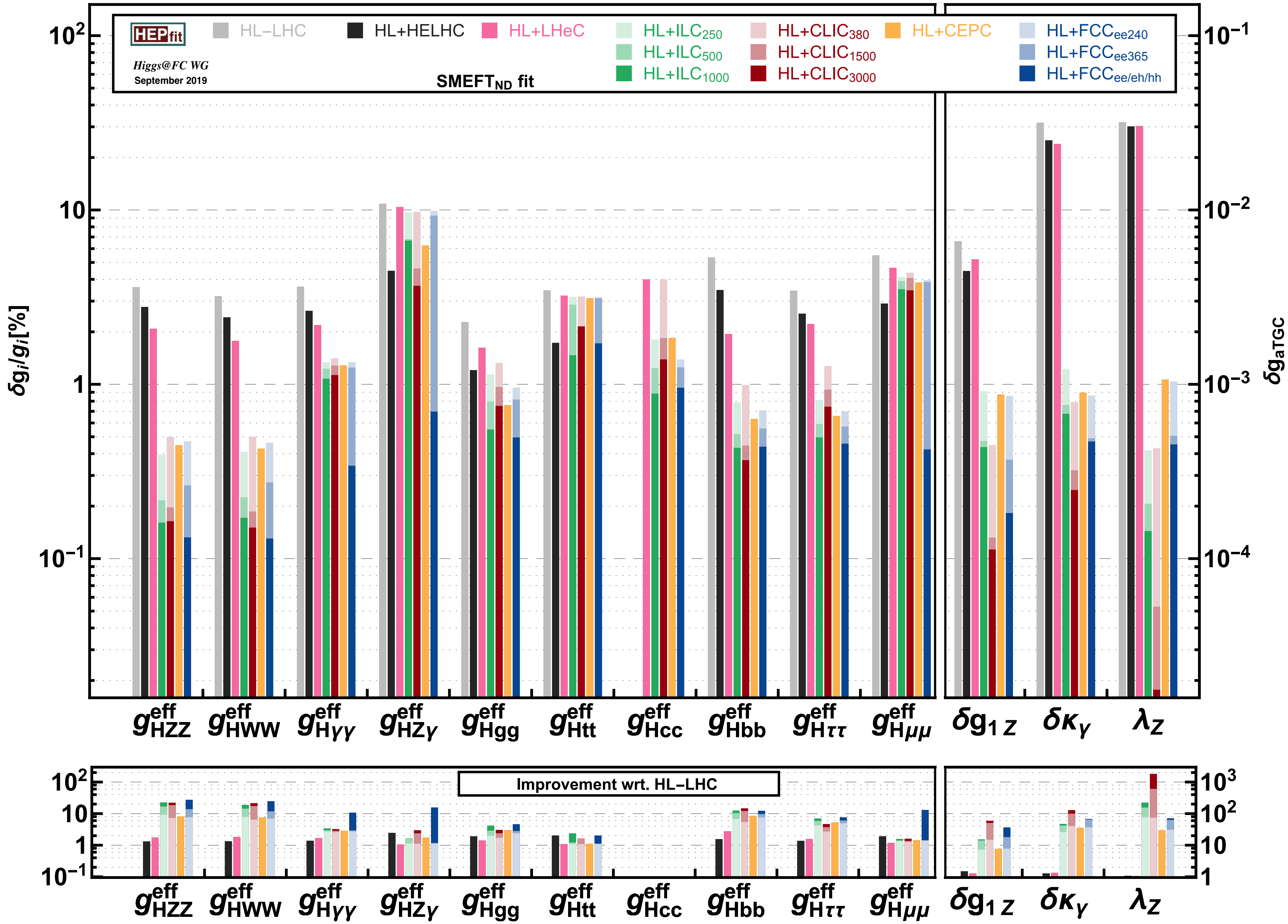


European Strategy Update Results

SMEFT fit results: Non-Flavor Universal

EFT results projected into effective Higgs couplings and aTGC

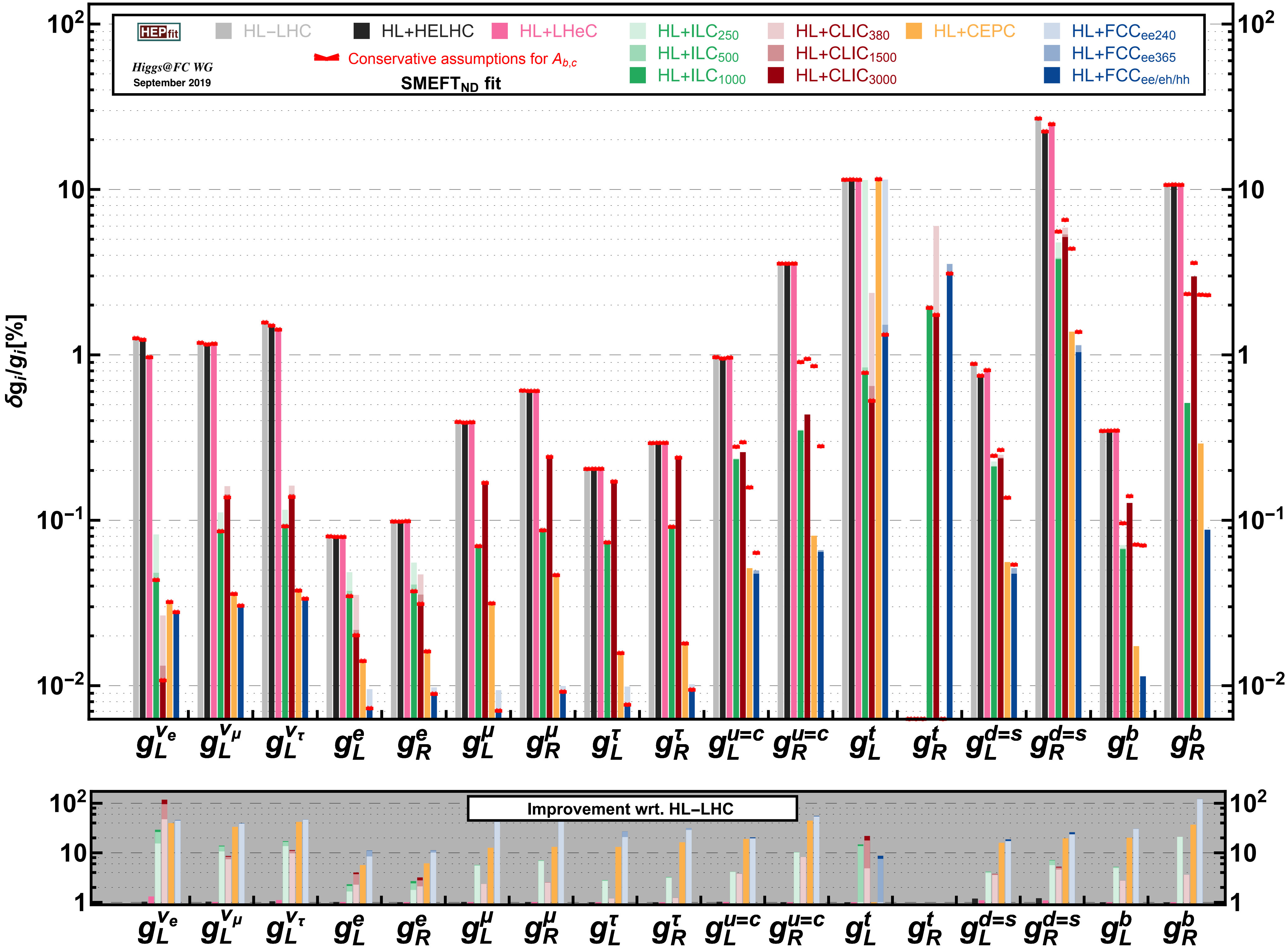
$$g_{HX}^{\text{eff }2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}$$



European Strategy Update Results

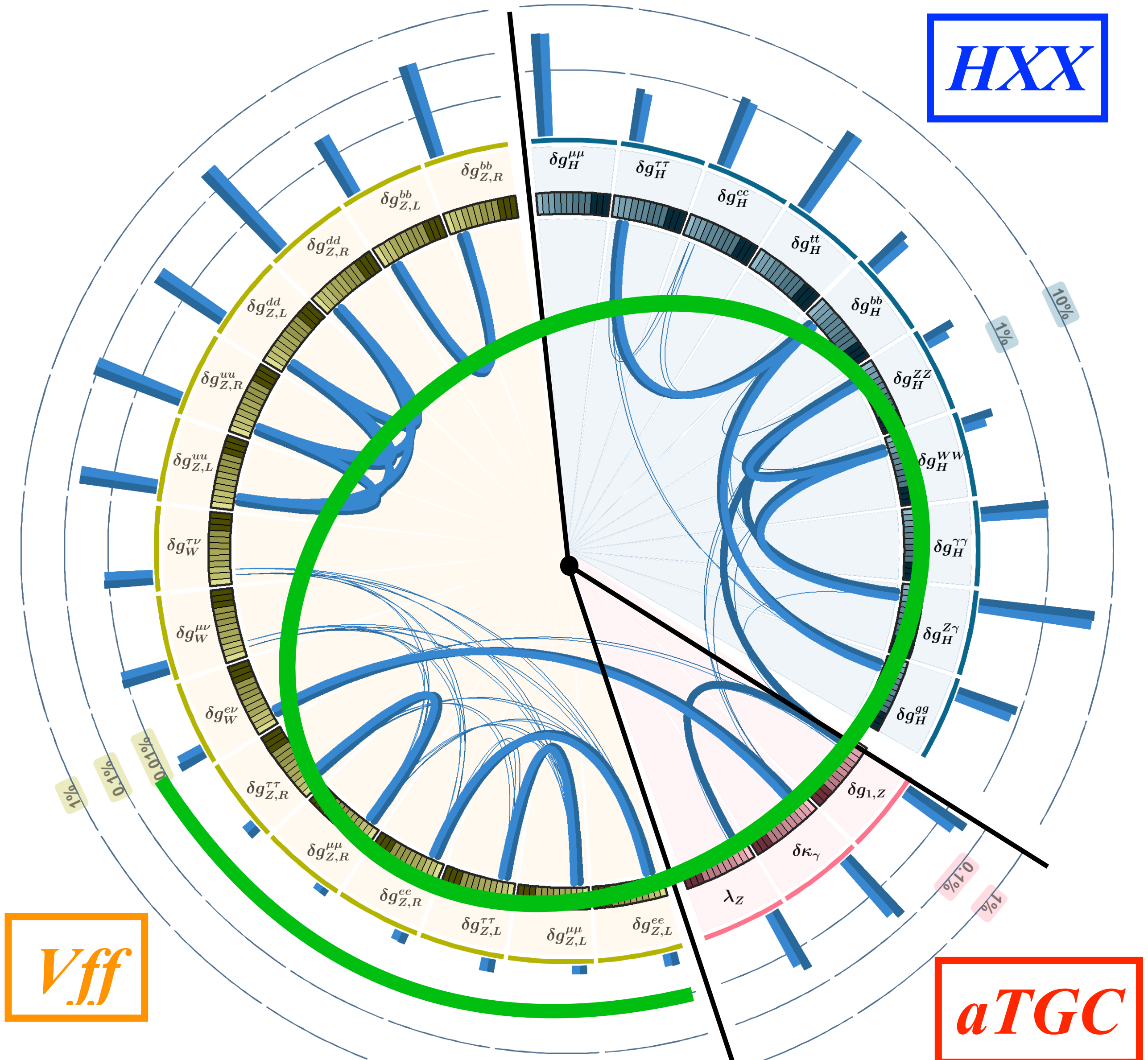
SMEFT fit results: Non-Flavor Universal

EFT results projected into effective Zff couplings

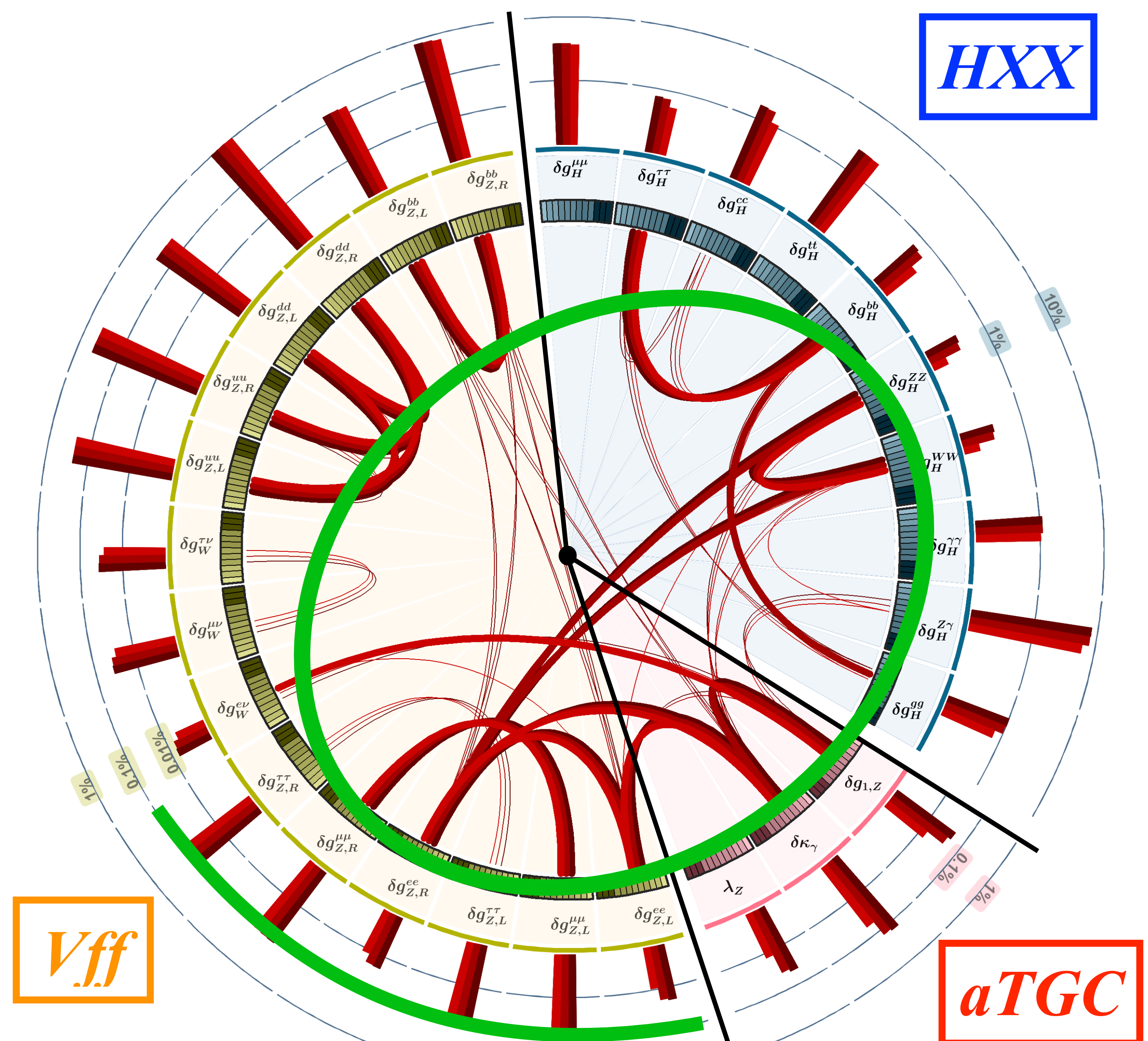


Interplay Higgs/EW factories

FCCee



ILC



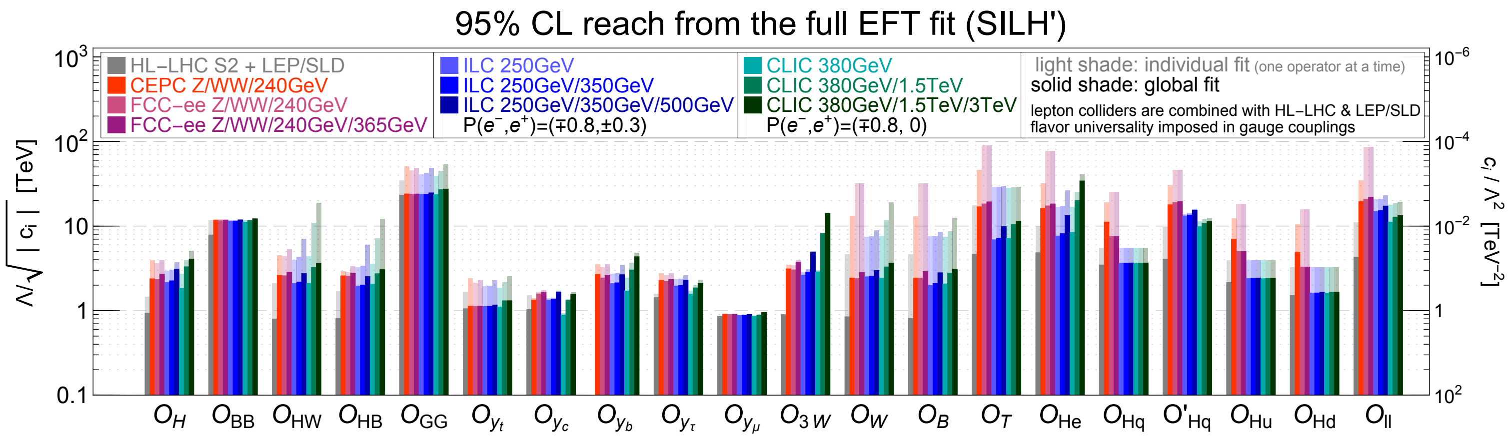
CEPC: 240 GeV
FCC-ee: 240 GeV; 240 & 365 GeV
Correlation < 50%

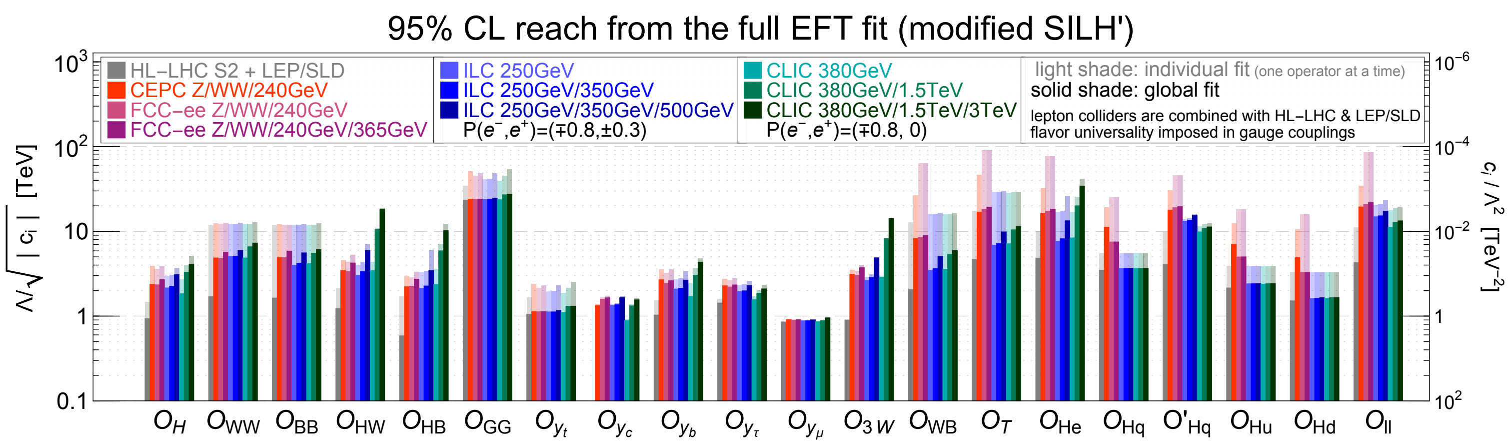
Polarization partially compensates the impact on H measurements of no Z-pole run but cannot replace the net value of EWPO:

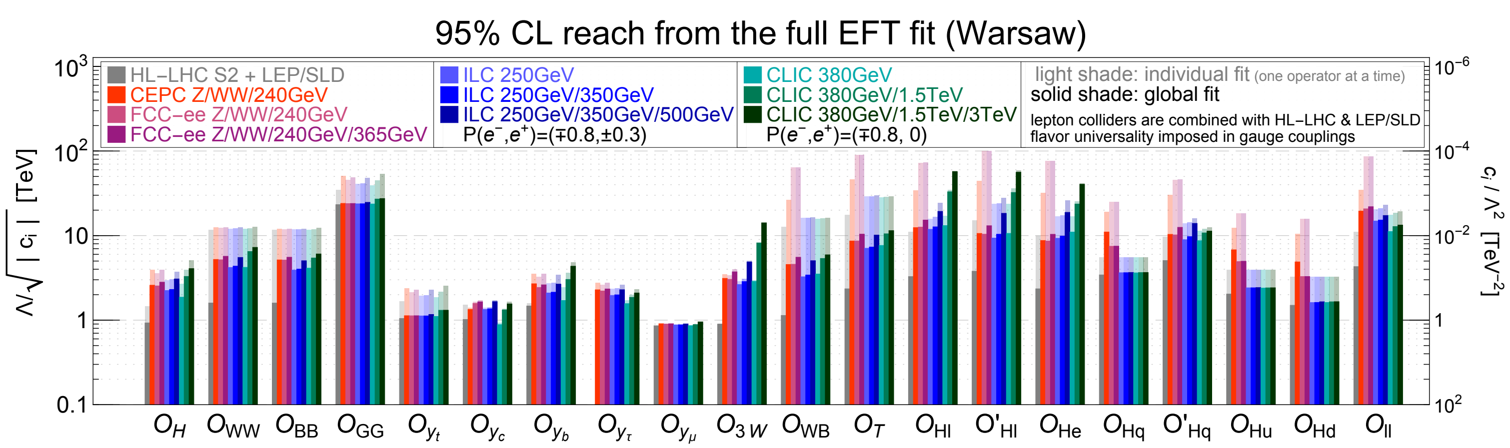
Z-pole EWPO largely improves precision on Vff couplings
+ removes correlations not only with the H sector, but also with the aTGC

Summary and Conclusions

- Results in manifestly gauge-invariant dim-6 bases







Notation

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

Fits assuming flavour universality in O_{Hf} and O'_{Hf}

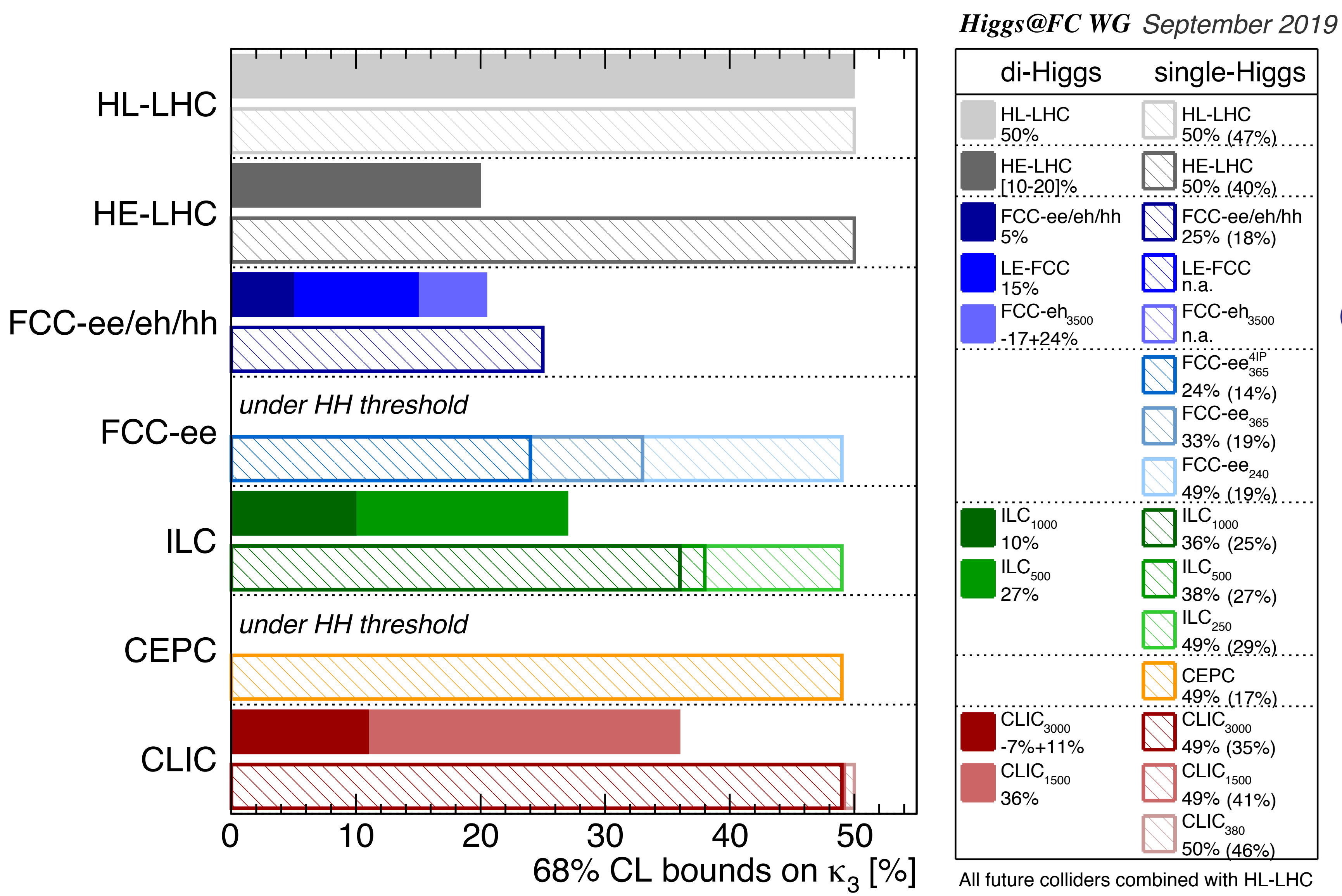
Summary and Conclusions

Several issues not covered in the ESU studies

- EW precision observables:
  - ✓ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  - ✓ Clarify systematics for heavy flavor observables (A_q, R_q).
  - ✓ Exploit EW obs. outside the Z-pole (low and high energy) ⇒ add 4-fermion ops.
  - ✓ Flavor (and CP violation): not explored in the ESU SMEFT fits.
- Higgs and Multi-boson processes:
  - ✓ Boosted Higgs, Higgs off-shell measurements, …
  - ✓ Full EFT studies of $e^+e^- \to W^+W^-$. Use of "optimal" observables.
  - ✓ High-E probes of EFT effects that grow with the energy.
  - ✓ Vector boson scattering: not included in ESU studies.
- Interplay EW/Higgs/Top: Top sector only explored superficially:
  - ✓ Consider effects from 4-fermion operators or top dipole operators.
  - ✓ Exploit NLO effects of Top couplings in H/EW.
- SMEFT assumptions:
  - ✓ Impact of SMEFT uncertainties: NLO, $(\text{dim-6})^2$ vs. dim 8, …
  - ✓ Non-universality: combine with flavor data to explore more flavor BSM scenarios
  - ✓ HEFT?

The Higgs self-coupling

- Comparison of capabilities to measure the h³ coupling



HL-LHC di-Higgs ~50%

HE-LHC di-Higgs ~15%

FCC ee: single-Higgs ~34%
hh: di-Higgs ~5-10%

CEPC Little sensitivity via single-Higgs w/o 365 GeV run

CLIC di-Higgs ~10%

ILC di-Higgs ~27% (10%)
Assuming upgrade to 500 GeV (1000 GeV)

JB, M. Cepeda, J.D'Hondt, R.K. Ellis, C. Grojean, B. Heinemann, F. Maltoni, A. Nisati, E. Petit, R. Rattazzi, W. Verkerke,
JHEP 01 (2020) 139, arXiv: 1905.03764 [hep-ph]

The Higgs width

- **Hadron colliders:**

  ✓ Diphoton interference studies ~8-22 x SM
  ✓ κ-fit requires extra constraints (e.g. $|\kappa_V|<1$)
  ✓ HZZ on-shell vs off-shell: ~20% precision but model-dependent

- **Lepton colliders:** absolute measurement of σ_{ZH} (→couplings) increases model independence

Example: κ-framework

From recoil mass method →
From H rates →

$$\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)}=\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H}\simeq\left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}}\times\Gamma_H$$

Enough data to extract Higgs width in EFT formalism too (see, e.g. ILC studies)

Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	2.3	EFT fit [3, 4]	2.2
ILC_{500}	1.6	EFT fit [3, 4, 14]	1.1
ILC_{1000}	1.4	EFT fit [4]	1.0
CLIC_{380}	4.7	κ-framework [98]	2.5
CLIC_{1500}	2.6	κ-framework [98]	1.7
CLIC_{3000}	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103, 104]	1.7
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.8
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.1

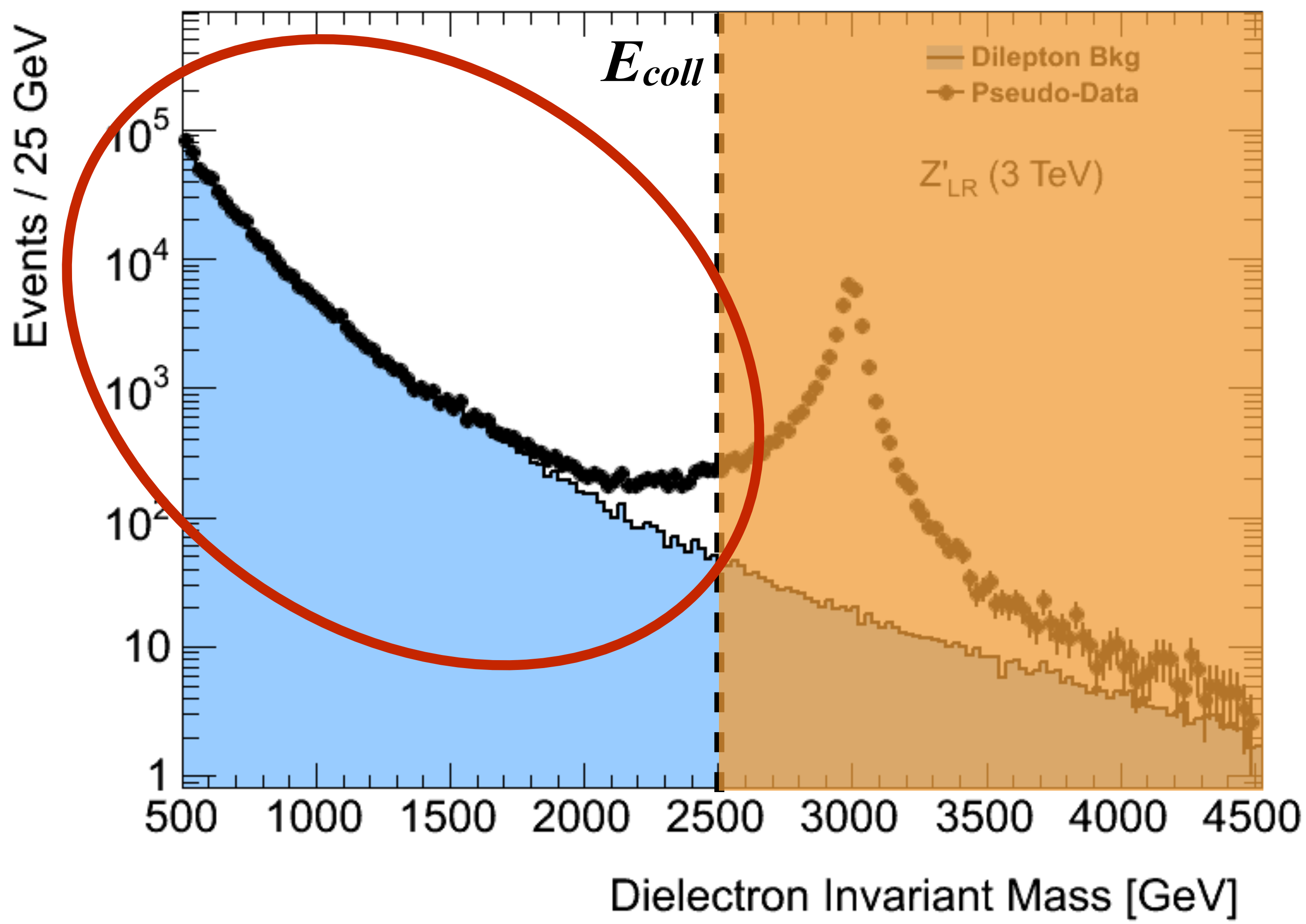
Indirect determination of H width with O(1-2%) precision

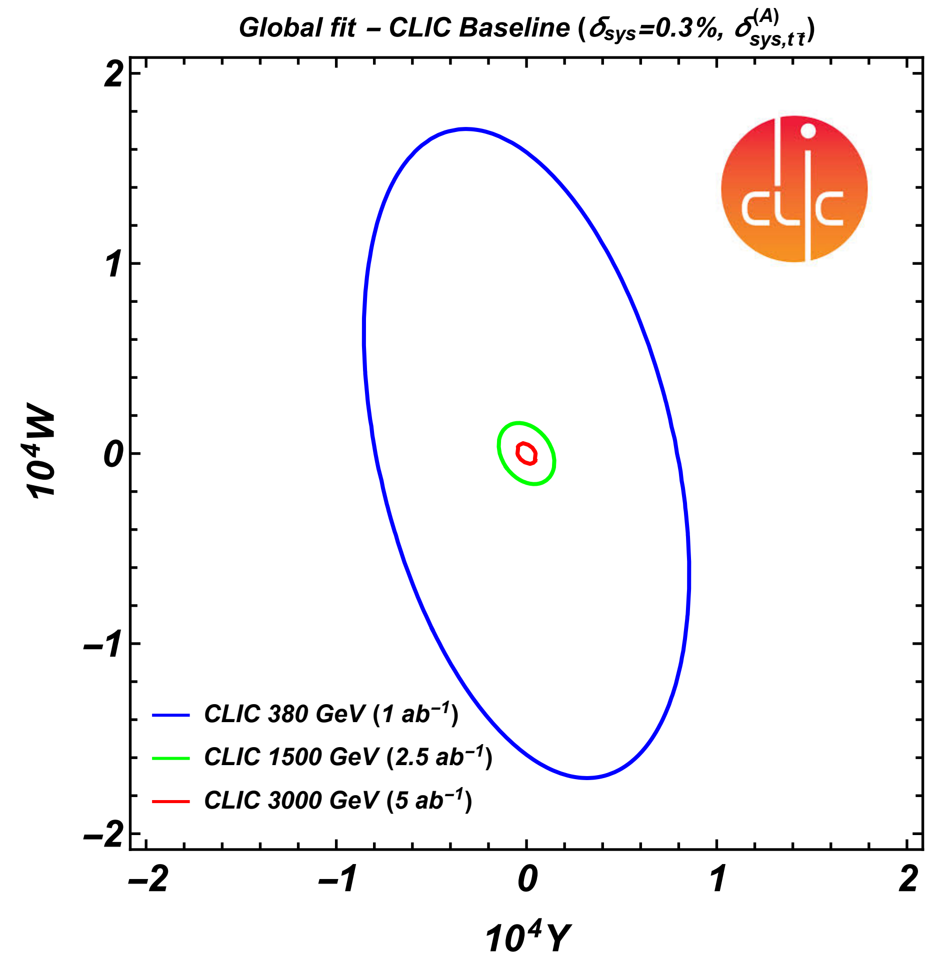
EW/Higgs physics in High-E tails

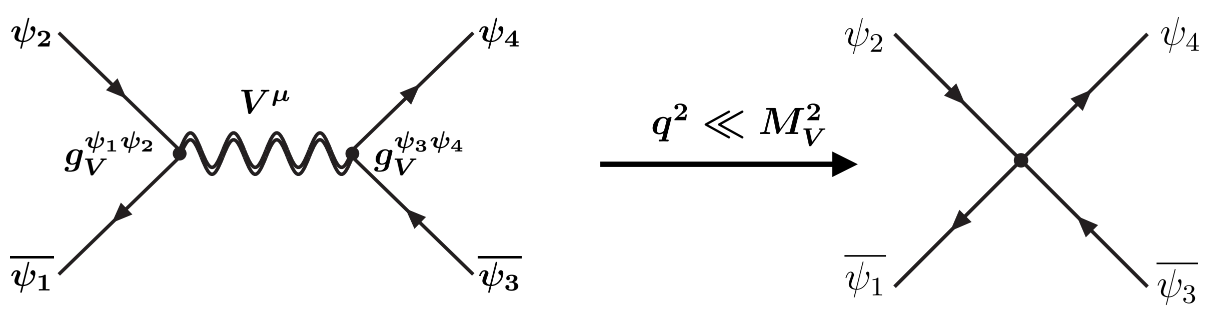
- Electroweak interactions beyond the Z-pole: precision via high E

High Energy probes of new physics:

e.g. growing with energy-effects in 2 → 2 fermion processes







$$\frac{\Delta O}{O_{SM}} \sim \frac{E^2}{\Lambda^2}$$

Universal NP

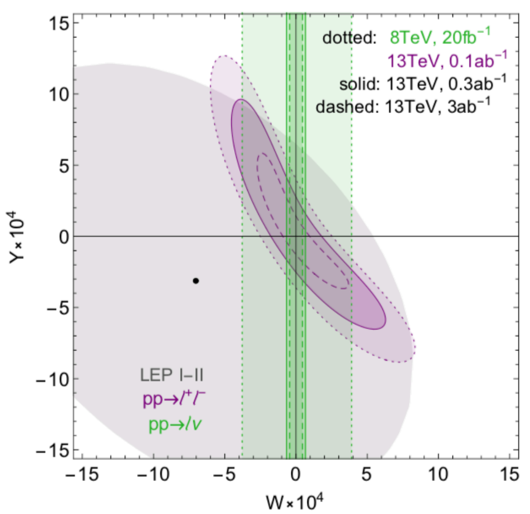
***W* & *Y* parameters**

CLIC~25x better than HL-LHC
Similar to 100 TeV FCC-hh

EW/Higgs physics in High-E tails

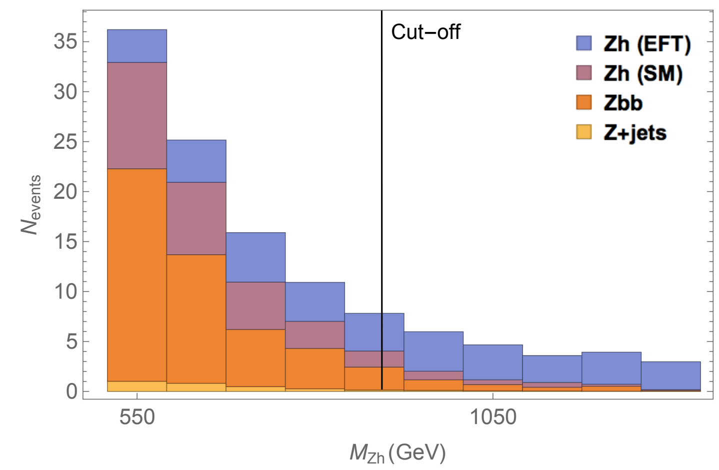
- High-E processes included in the study (when available in the literature)

W & Y in $pp, e^+e^-\to ff$



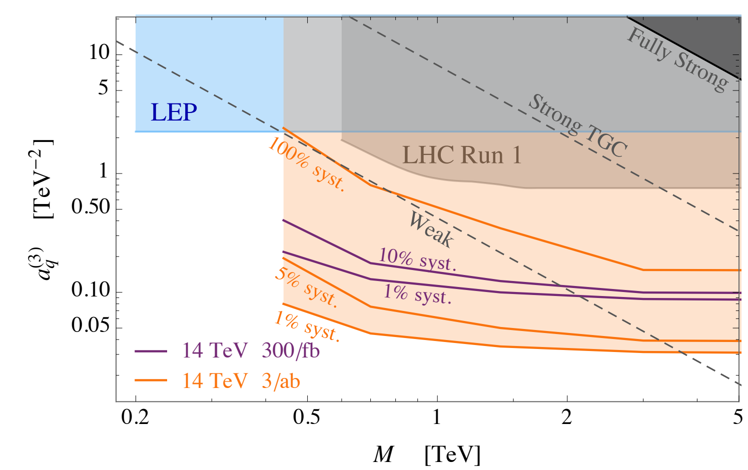
arXiv: 1902.00134 [hep-ph], CERN YRM Vol. 3 (2018), arXiv: 1908.11299 [hep-ex]

M_{ZH} in $pp\to ZH\to Zbb$



arXiv: 1807.01796 [hep-ph]

p_{TV} in $pp\to WZ$



JHEP 1802 (2018) 111

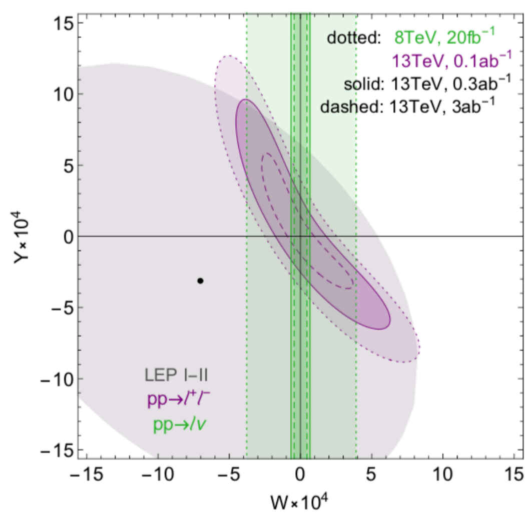
- Studied using a SILH-like effective Lagrangian (applied to CH models):

$$
\begin{aligned}
\mathscr{L}_{\rm SILH} =& \frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{c_T}{\Lambda^2}\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\phi^\dagger \overleftrightarrow{D}^\mu \phi) - \frac{c_6}{\Lambda^2}\lambda(\phi^\dagger\phi)^3 + \left(\frac{c_{y_f}}{\Lambda^2} y^f_{ij}\phi^\dagger\phi\bar{\psi}_{Li}\phi\psi_{Rj} + \text{h.c.}\right) \\
&+ \frac{c_W}{\Lambda^2}\frac{ig}{2}\left(\phi^\dagger \overleftrightarrow{D}^a_\mu \phi\right) D_\nu W^{a\,\mu\nu} + \frac{c_B}{\Lambda^2}\frac{ig'}{2}\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\partial_\nu B^{\mu\nu} + \frac{c_{\phi W}}{\Lambda^2} igD_\mu\phi^\dagger\sigma_a D_\nu\phi W^{a\,\mu\nu} + \frac{c_{\phi B}}{\Lambda^2} ig' D_\mu\phi^\dagger\sigma_a D_\nu\phi B^{\mu\nu} \\
&+ \frac{c_\gamma}{\Lambda^2} g'^2\phi^\dagger\phi B^{\mu\nu}B_{\mu\nu} + \frac{c_g}{\Lambda^2} g_s^2\phi^\dagger\phi G^{A\,\mu\nu}G^A_{\mu\nu} \\
&- \frac{c_{2W}}{\Lambda^2}\frac{g^2}{2}(D^\mu W^a_{\mu\nu})(D_\rho W^{a\,\rho\nu}) - \frac{c_{2B}}{\Lambda^2}\frac{g'^2}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{c_{2G}}{\Lambda^2}\frac{g_S^2}{2}(D^\mu G^A_{\mu\nu})(D_\rho G^{A\,\rho\nu}) \\
&+ \frac{c_{3W}}{\Lambda^2} g^3\varepsilon_{abc}W^{a\ \nu}_\mu W^{b\ \rho}_\nu W^{c\ \mu}_\rho + \frac{c_{3G}}{\Lambda^2} g_S^3 f_{ABC}G^{A\ \nu}_\mu G^{B\ \rho}_\nu G^{C\ \mu}_\rho,
\end{aligned}
$$

EW/Higgs physics in High-E tails

- High-E processes included in the study (when available in the literature)

W & Y in $pp,\ e^+e^-\to ff$



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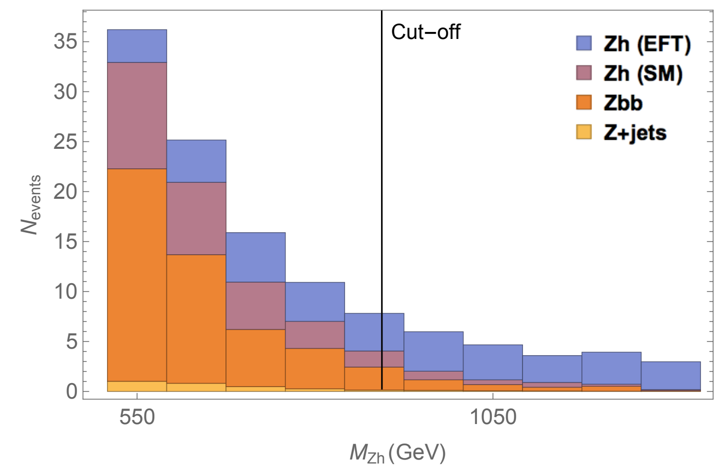
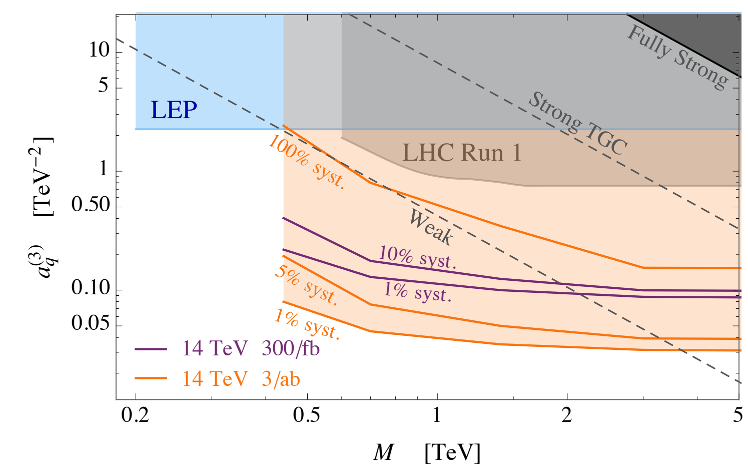
M_{ZH} in $pp\to ZH\to Zbb$



arXiv: 1807.01796 [hep-ph]

p_{TV} in $pp\to WZ$

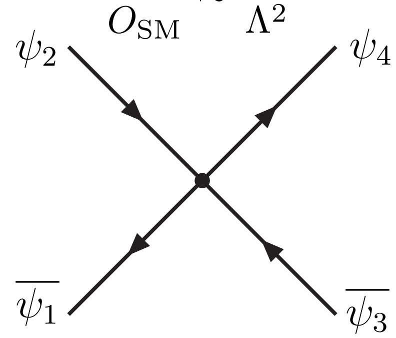


JHEP 1802 (2018) 111

- Studied using a SILH-like effective Lagrangian (applied to CH models):

$$\begin{aligned}\mathscr{L}_{\rm SILH} =\ & \frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{c_T}{\Lambda^2}\frac{1}{2}(\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\phi^\dagger\overleftrightarrow{D}^\mu\phi) - \frac{c_6}{\Lambda^2}\lambda(\phi^\dagger\phi)^3 + \Big(\frac{c_{y_f}}{\ldots}\ldots + \text{h.c.}\Big)\\ & + \frac{c_W}{\Lambda^2}\frac{ig}{2}\left(\phi^\dagger\overleftrightarrow{D}^a_\mu\phi\right)D_\nu W^{a\,\mu\nu} + \frac{c_B}{\Lambda^2}\frac{ig'}{2}\left(\phi^\dagger\overleftrightarrow{D}_\mu\phi\right)\partial_\nu B^{\mu\nu} + \frac{c_{\phi W}}{\Lambda^2}ig \ldots D_\nu\phi B^{\mu\nu}\\ & + \frac{c_\gamma}{\Lambda^2}g'^2\phi^\dagger\phi B^{\mu\nu}B_{\mu\nu} + \frac{c_g}{\Lambda^2}g_s^2\phi^\dagger\phi G^{A\,\mu\nu}G^A_{\mu\nu}\\ & - \frac{c_{2W}}{\Lambda^2}\frac{g^2}{2}(D^\mu W^a_{\mu\nu})(D_\rho W^{a\,\rho\nu}) - \frac{c_{2B}}{\Lambda^2}\frac{g'^2}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{c_{2G}}{\Lambda^2}\ldots\\ & + \frac{c_{3W}}{\Lambda^2}g^3\varepsilon_{abc}W^{a\ \nu}_{\mu}W^{b\ \rho}_{\nu}W^{c\ \mu}_{\rho} + \frac{c_{3G}}{\Lambda^2}g_S^3 f_{ABC}G^{A\ \nu}_{\mu}G^{B\ \rho}_{\nu}G^{C\ \mu}_{\rho},\end{aligned}$$

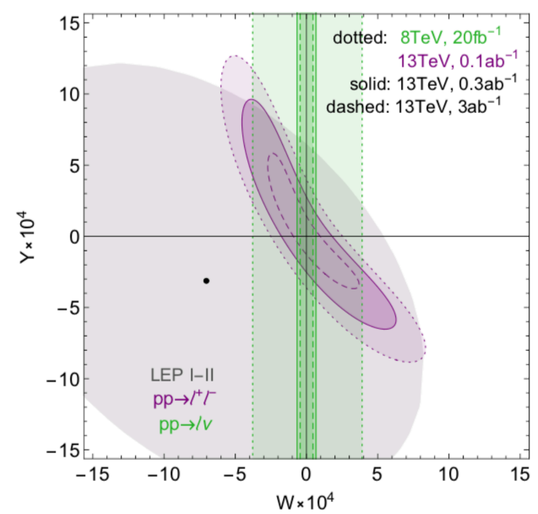
$$\frac{\Delta O}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$



EW/Higgs physics in High-E tails

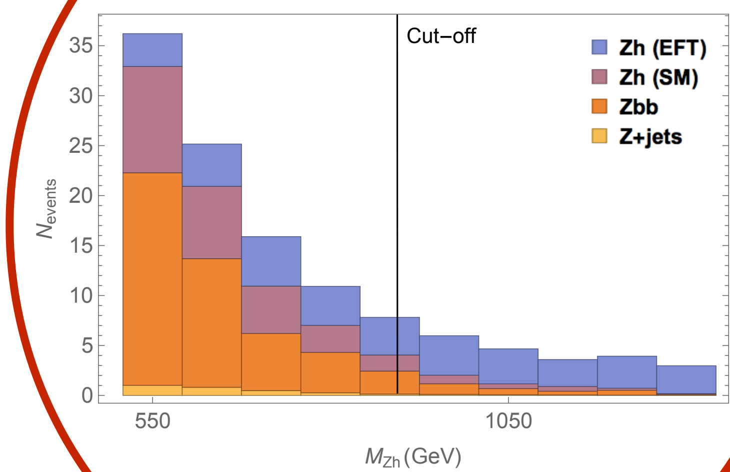
- High-E processes included in the study (when available in the literature)

W & Y in *pp, e⁺e⁻→ff*



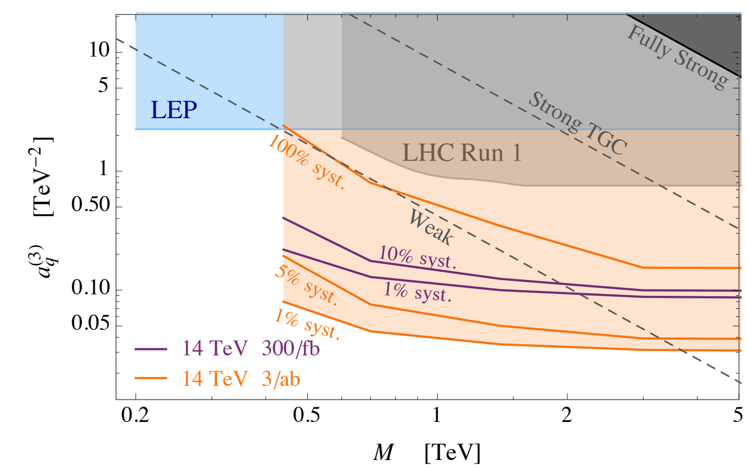
arXiv: 1902.00134 [hep-ph], CERN YRM Vol. 3 (2018), arXiv: 1908.11299 [hep-ex]

M_{ZH} in *pp→ZH→Zbb*



arXiv: 1807.01796 [hep-ph]

p_{TV} in *pp→WZ*



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$$+ \frac{c_W}{\Lambda^2}\frac{ig}{2}\left(\phi^\dagger\overleftrightarrow{D}^a_\mu\phi\right)D_\nu W^{a\,\mu\nu} + \frac{c_B}{\Lambda^2}\frac{ig'}{2}\left(\phi^\dagger\overleftrightarrow{D}_\mu\phi\right)\partial_\nu B^{\mu\nu} + \frac{c_{\phi W}}{\Lambda^2}igD_\mu\phi^\dagger\sigma_a D_\nu\phi W^{a\,\mu\nu} + \frac{c_{\phi B}}{\Lambda^2}ig'D_\mu\phi^\dagger\sigma_a D_\nu\phi B^{\mu\nu}$$
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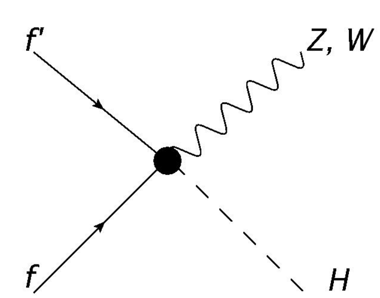

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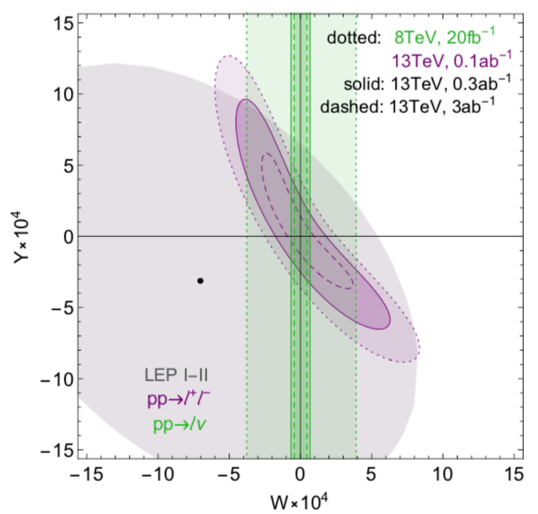
W & Y in pp, $e^+e^- \to ff$



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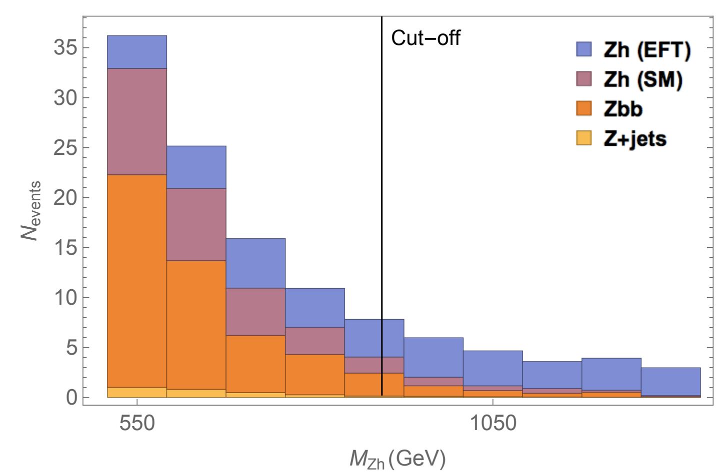
M_{ZH} in $pp \to ZH \to Zbb$



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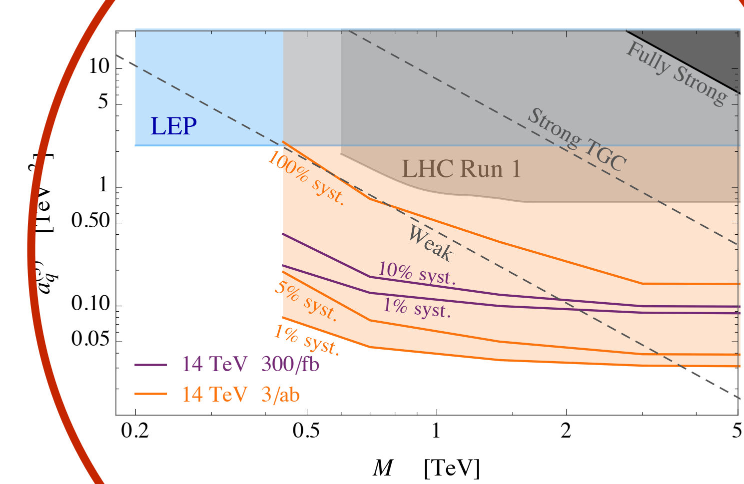
p_{TV} in $pp \to WZ$



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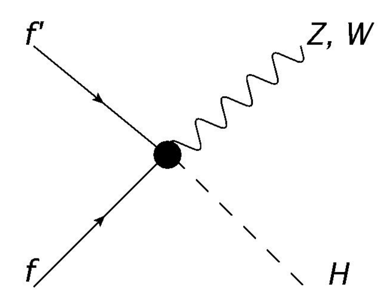
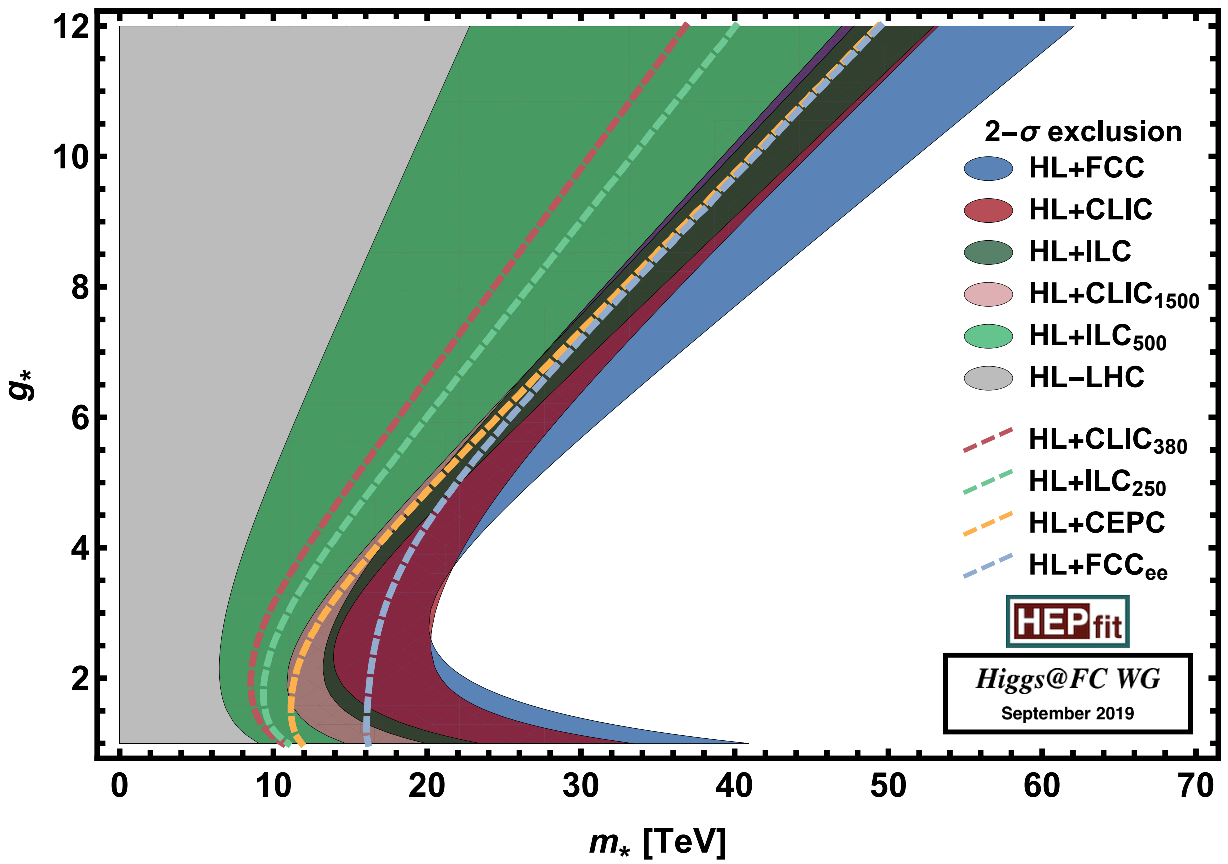
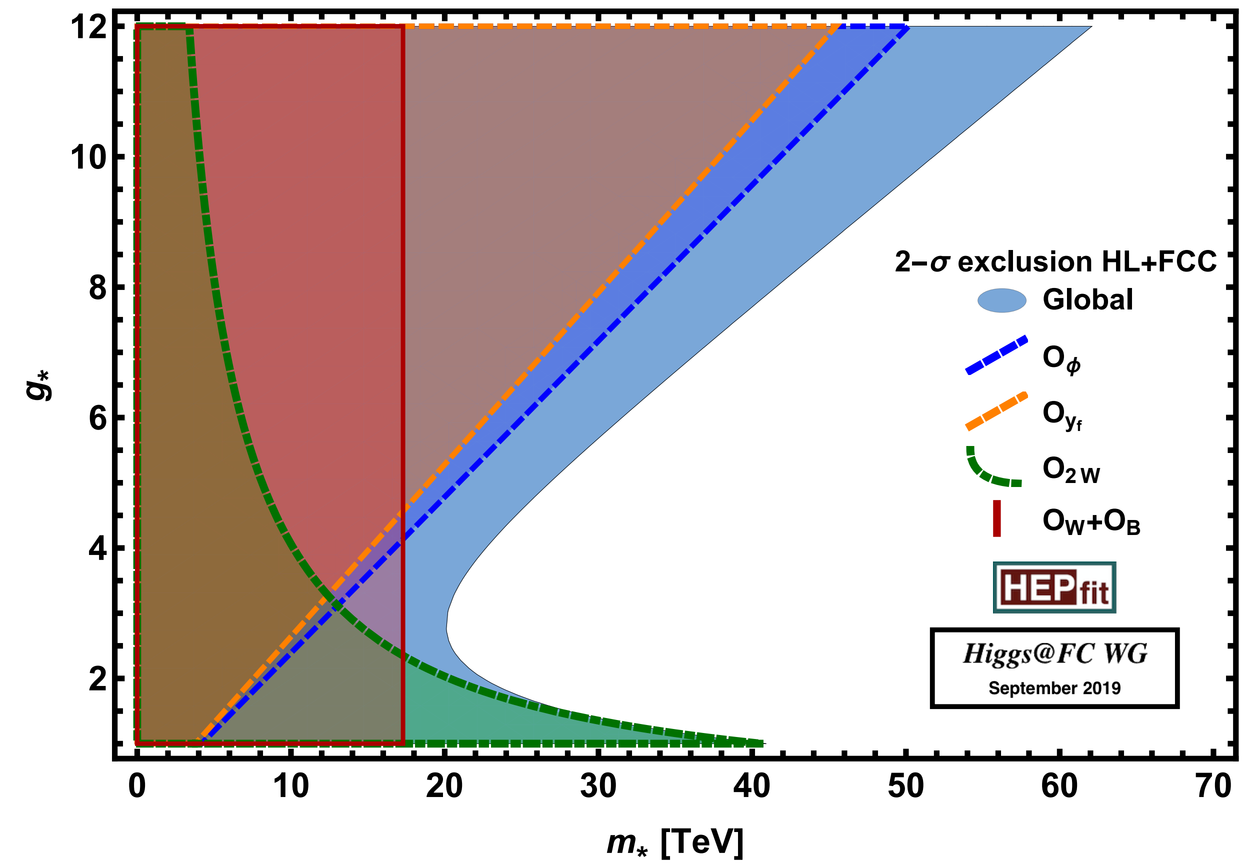


EW/Higgs physics in High-E tails

- Example:

Indirect constraints in Composite Higgs models





Simplified CH benchmark: 1 coupling (g_*) - 1 scale (m_*)

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

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

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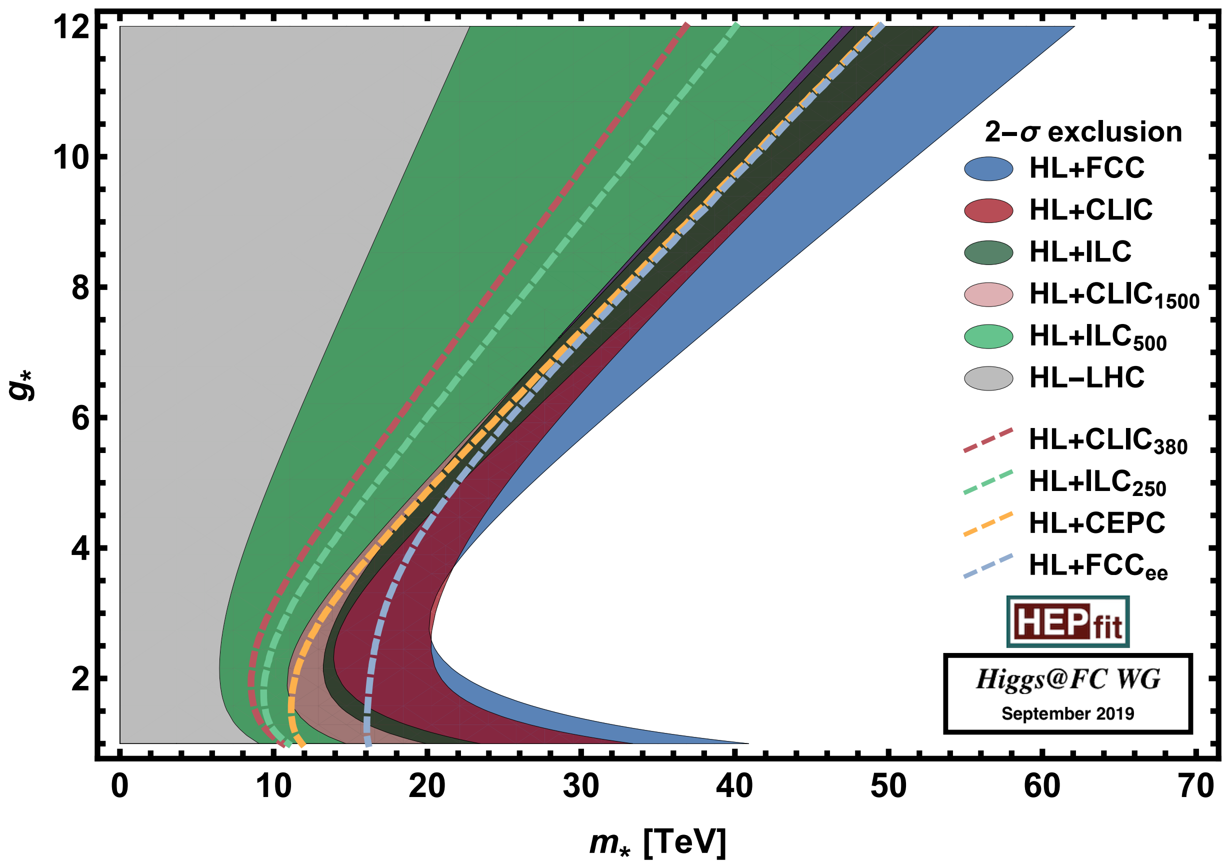

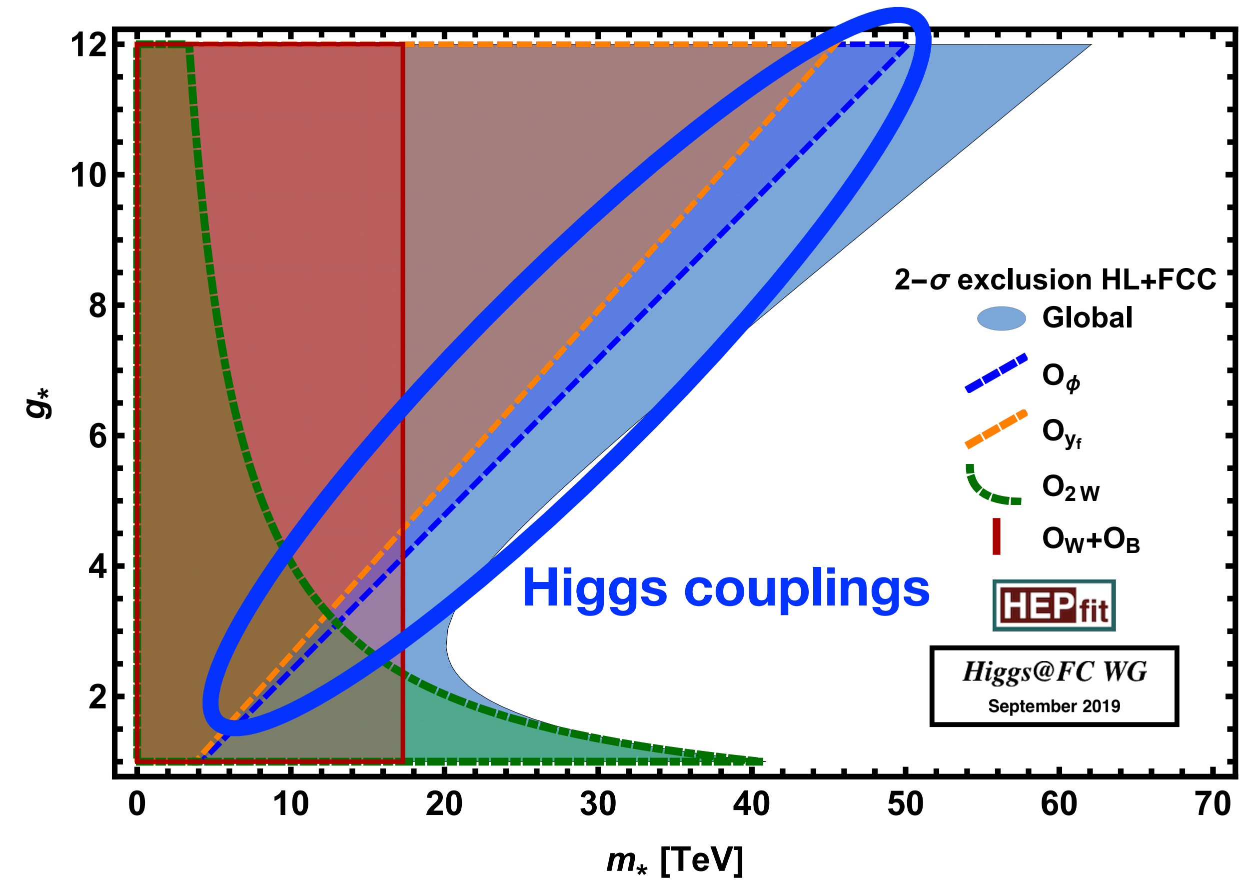

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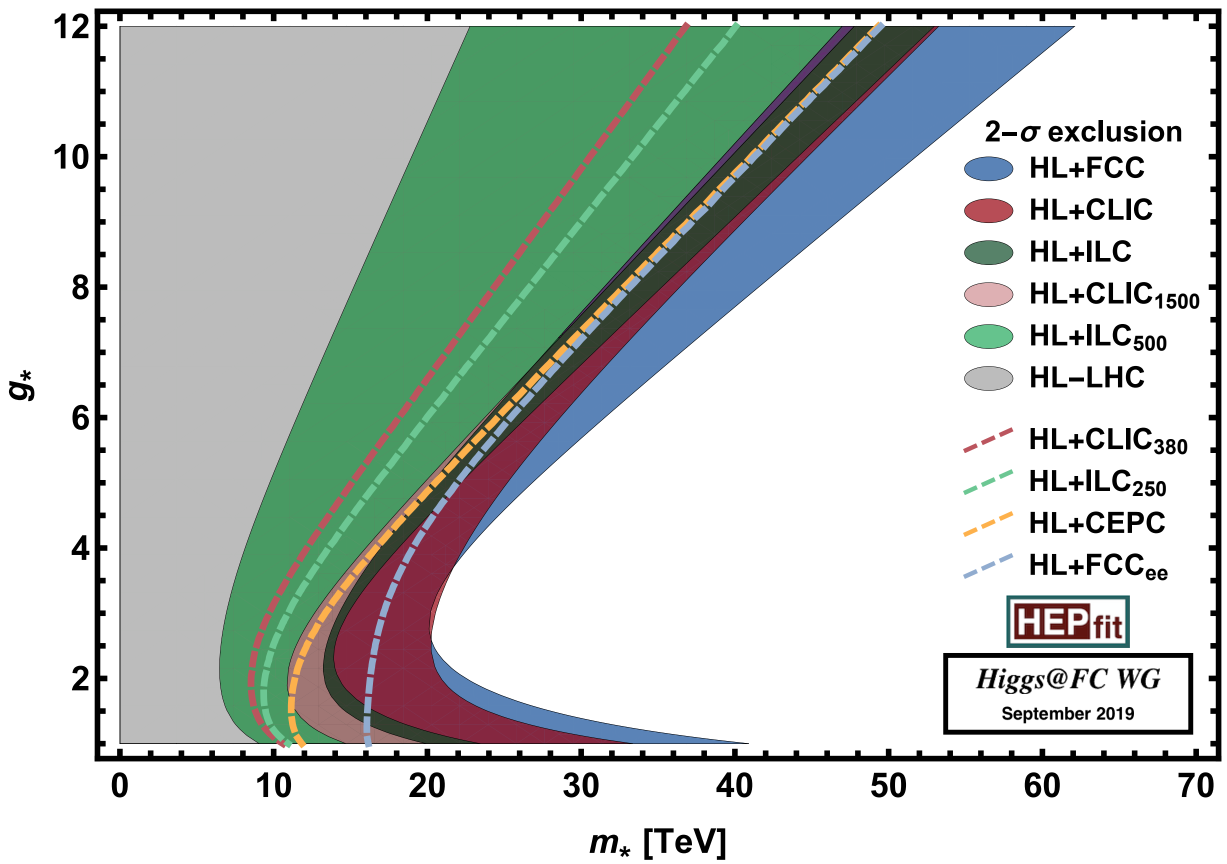

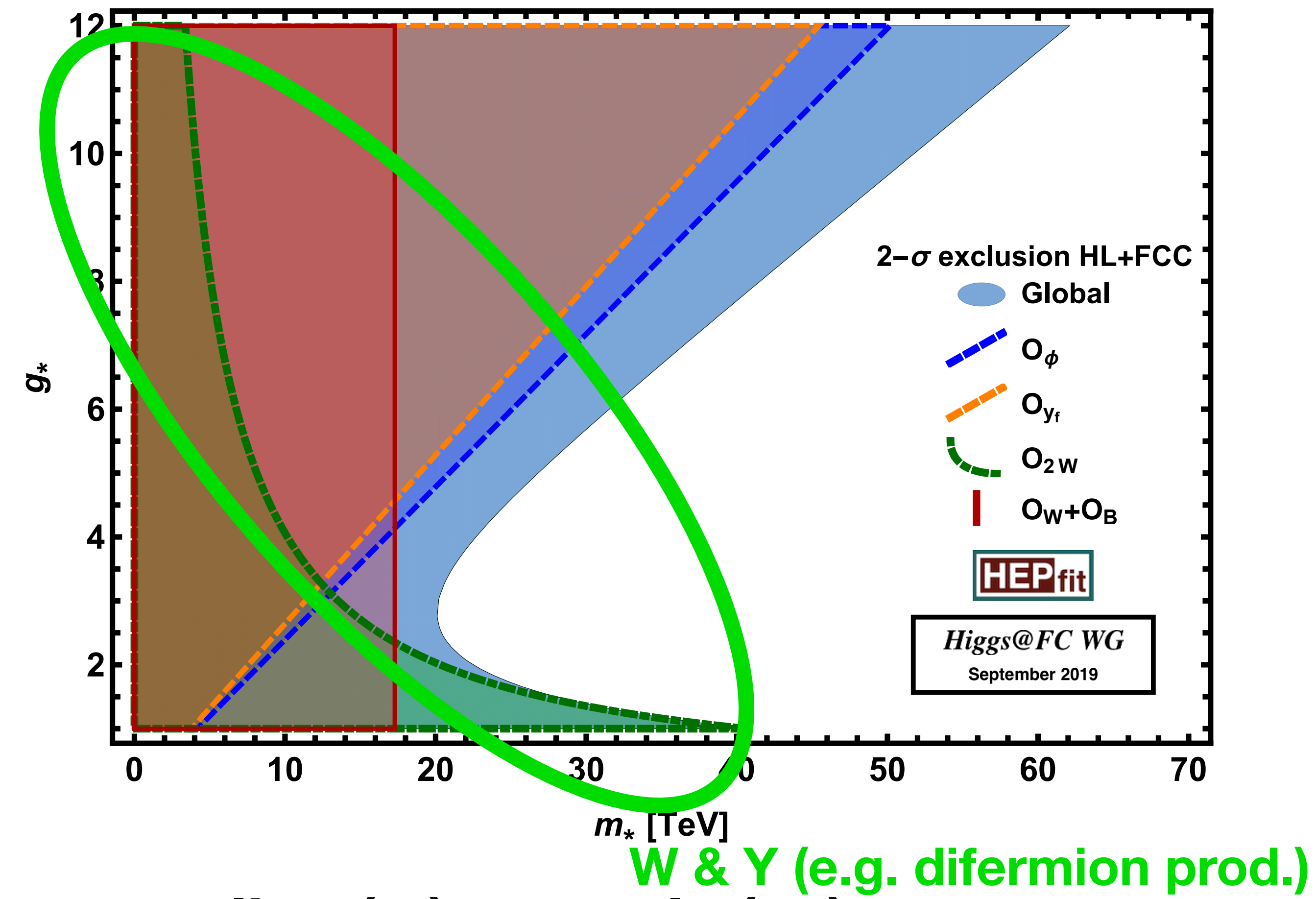

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$$\frac{c_T}{\Lambda^2} = \frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2}, \quad \frac{c_{\gamma,g}}{\Lambda^2} = \frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2}, \quad \frac{c_{\phi W,\phi B}}{\Lambda^2} = \frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2}, \quad \frac{c_{3W,3G}}{\Lambda^2}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

EW/Higgs physics in High-E tails

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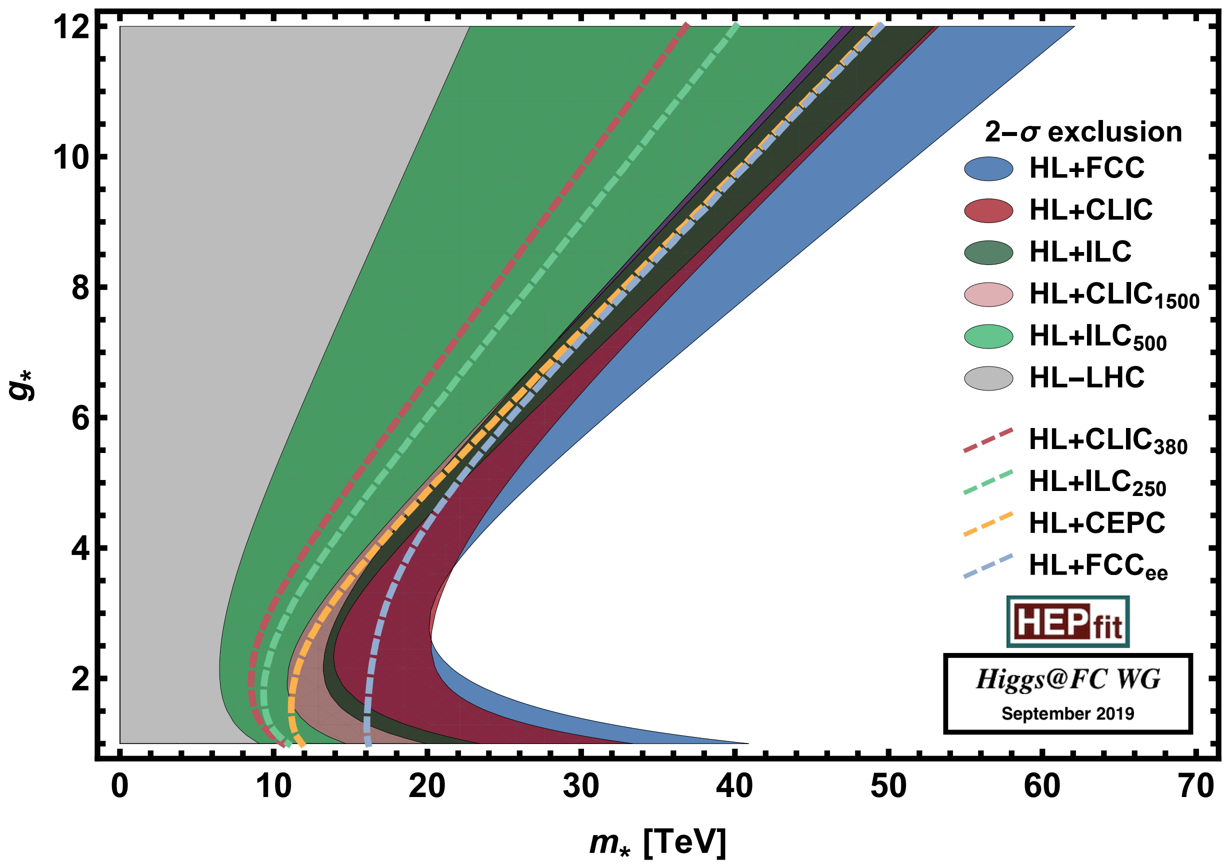
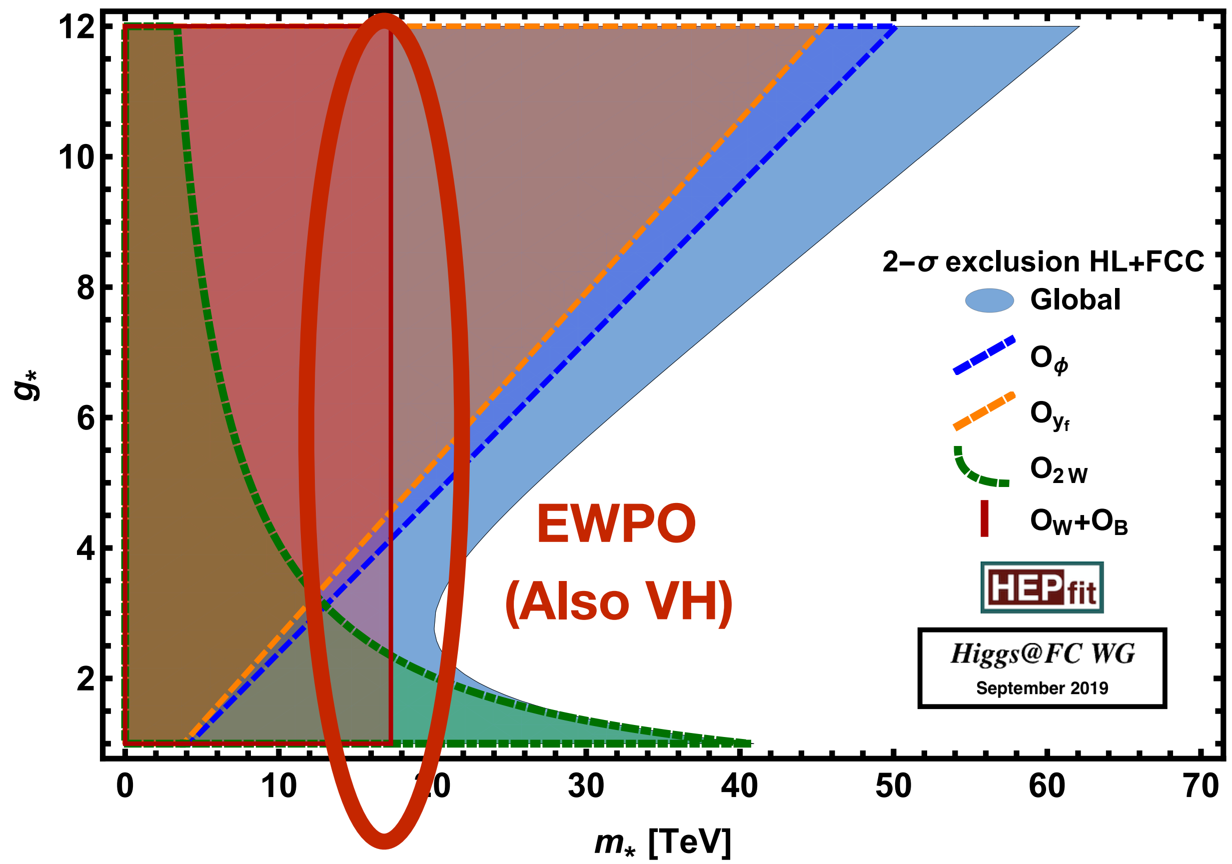
Indirect constraints in Composite Higgs models





Simplified CH benchmark: 1 coupling (g_*) - 1 scale (m_*)

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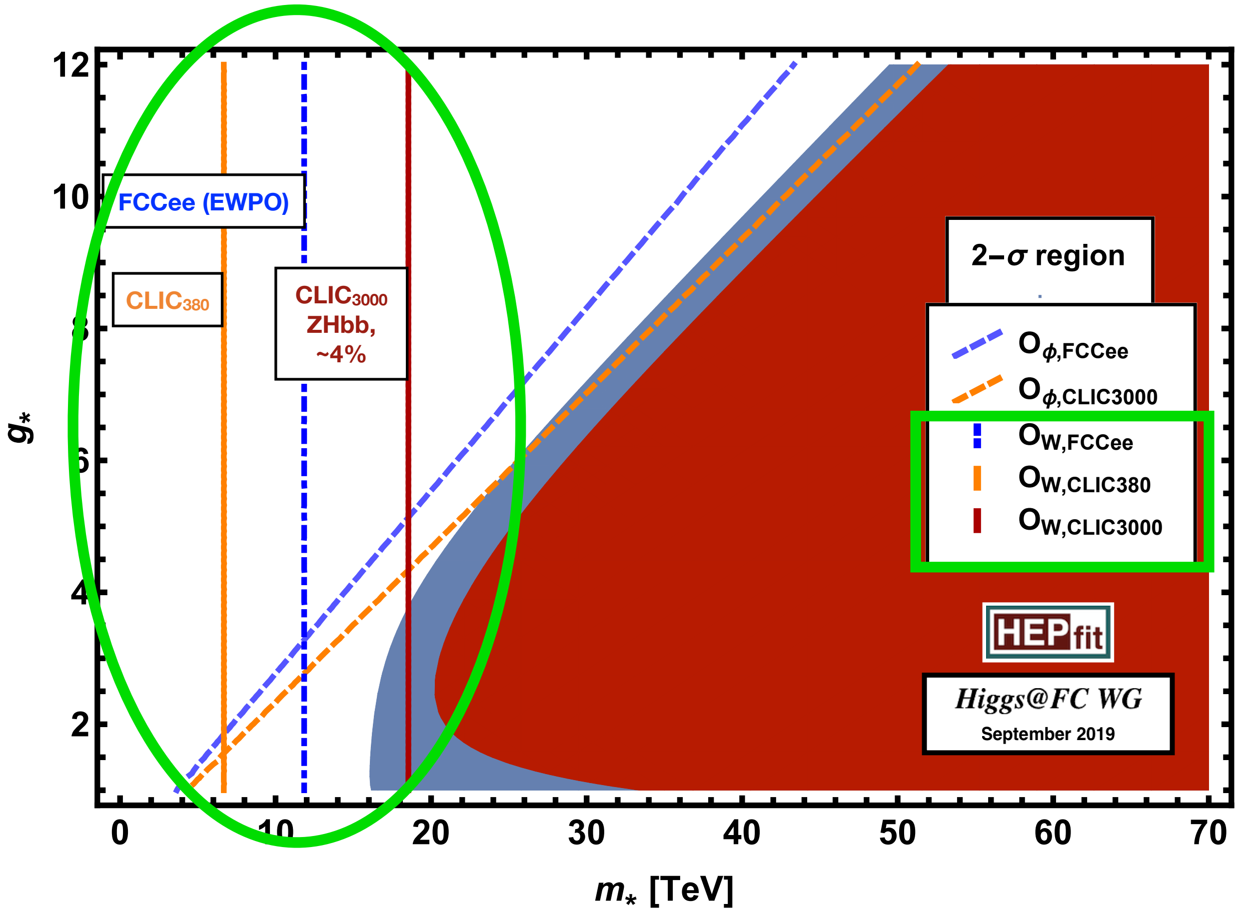
$$\frac{c_T}{\Lambda^2}=\frac{y_t^4}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{\gamma,g}}{\Lambda^2}=\frac{y_t^2}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{\phi W,\phi B}}{\Lambda^2}=\frac{g_\star^2}{16\pi^2}\frac{1}{m_\star^2},\qquad \frac{c_{3W,3G}}{\Lambda^2}=\frac{1}{16\pi^2}\frac{1}{m_\star^2}$$

EW/Higgs physics in High-E tails

- Example:

Indirect constraints in Composite Higgs models: Precision vs Energy



Similar sensitivity to same operators via:
(1) Low-E high precision (EWPO)
(2) High-E moderate precision (ZH)

Simplified CH benchmark: 1 coupling (g_*) - 1 scale (m_*)

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

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

Different ways of testing the compositeness scale (via $O_{W,B}$):
Low-Energy precision (FCCee) vs High-Energy (CLIC)