9th Edition of the Large Hadron Collider Physics Conference

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Constraints on BSM
from the Higgs Sector

Jorge de Blas

University of Granada

Universidad de Granada

Transformación Económica, Industria, Conocimiento y Universidades

UNIÓN EUROPEA
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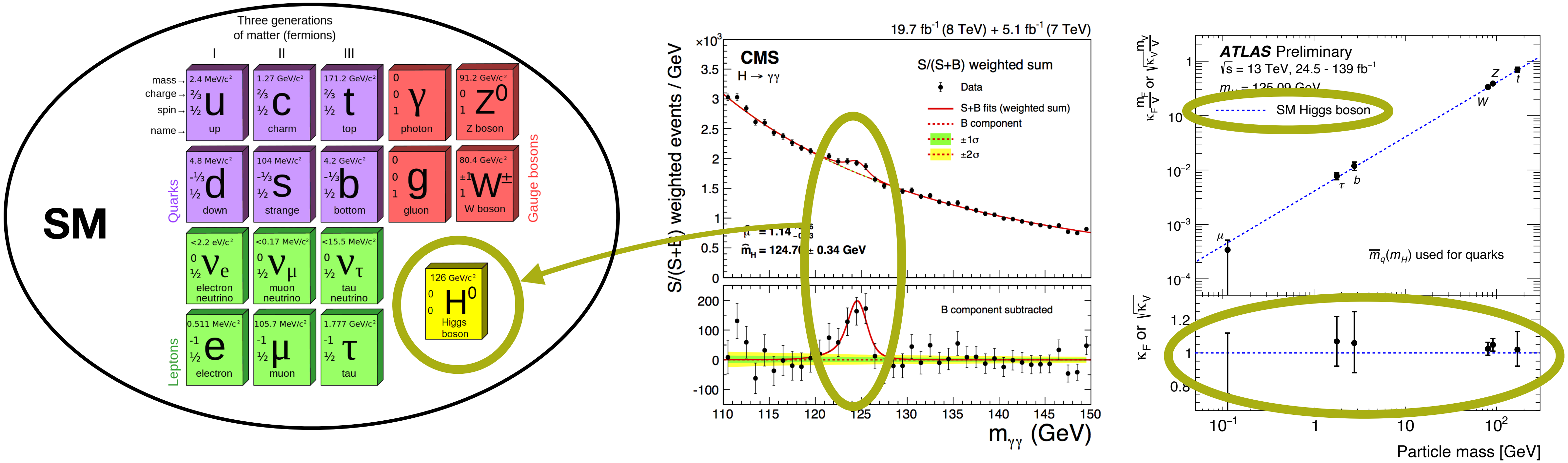
Introduction

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



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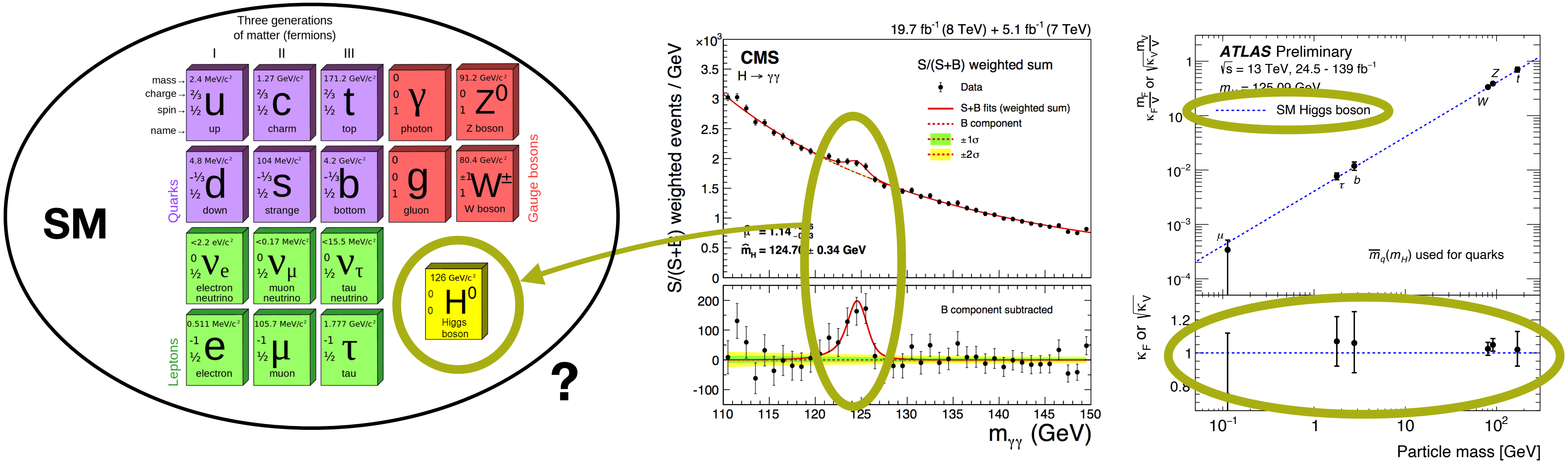

  - ✓ …but also reminds us of the limitations of the Standard Model…
    - How do we understand the mechanism of EWSB?
    - Hierarchy problem: Why $M_h \ll M_P$?

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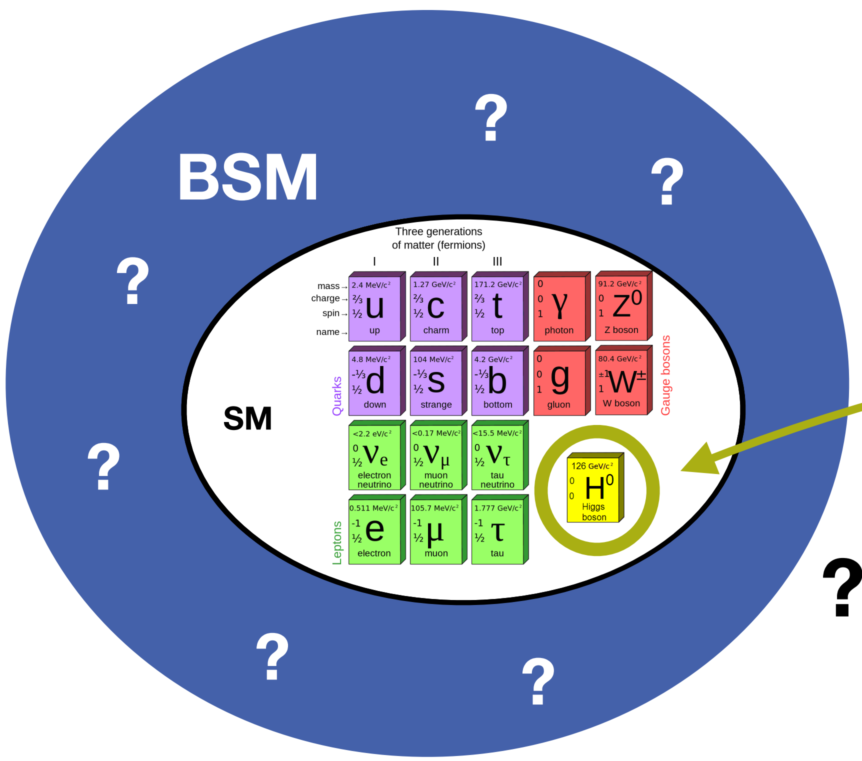

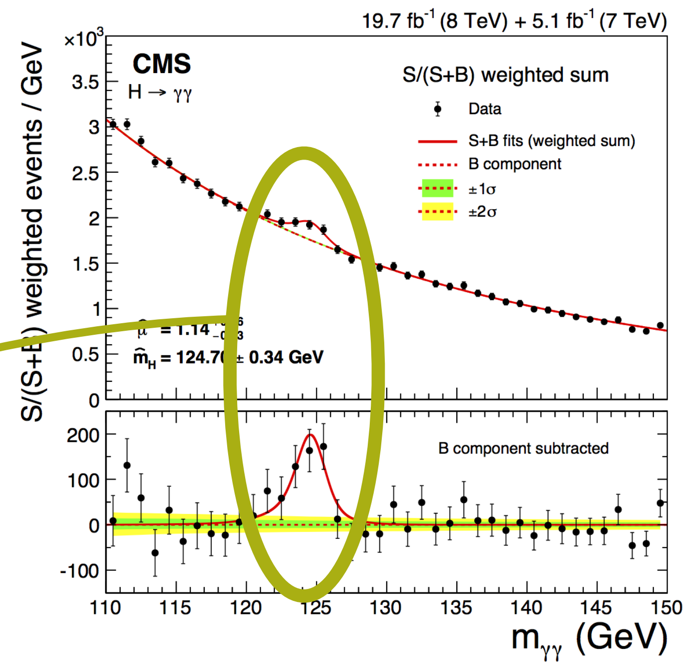

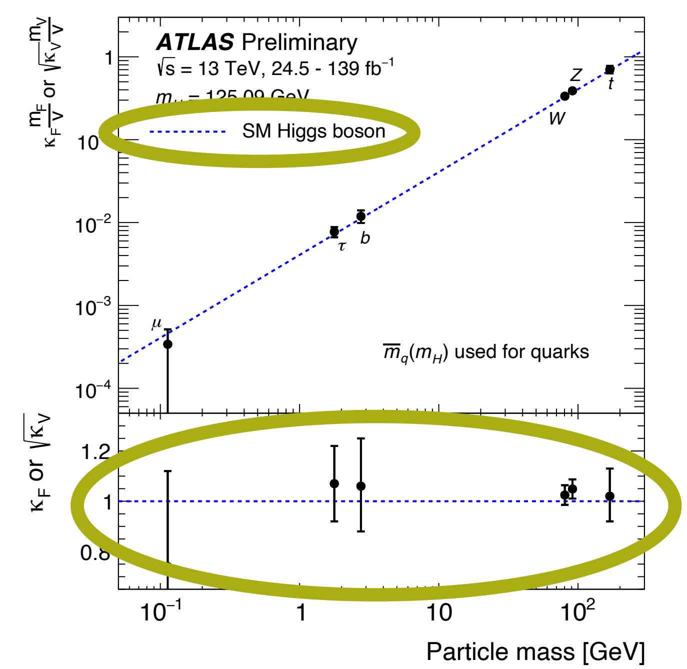

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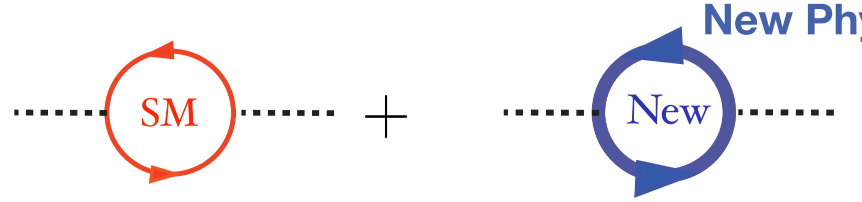
New Physics

⇒ BSM: $\Delta M_h^2 =$  ~ 0

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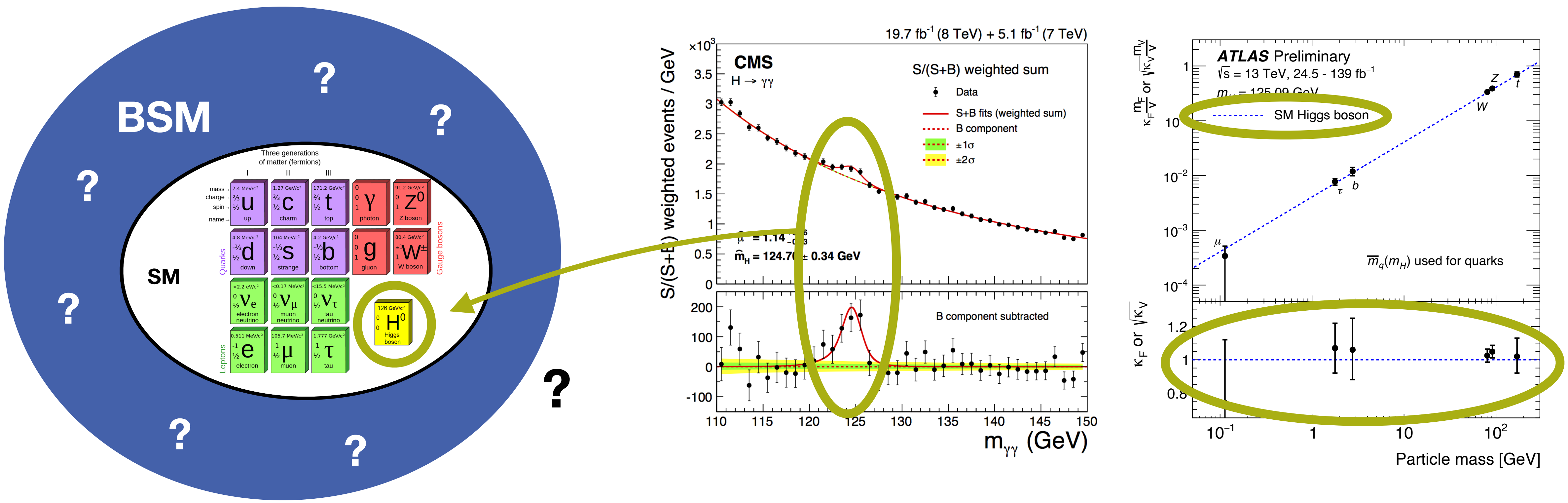
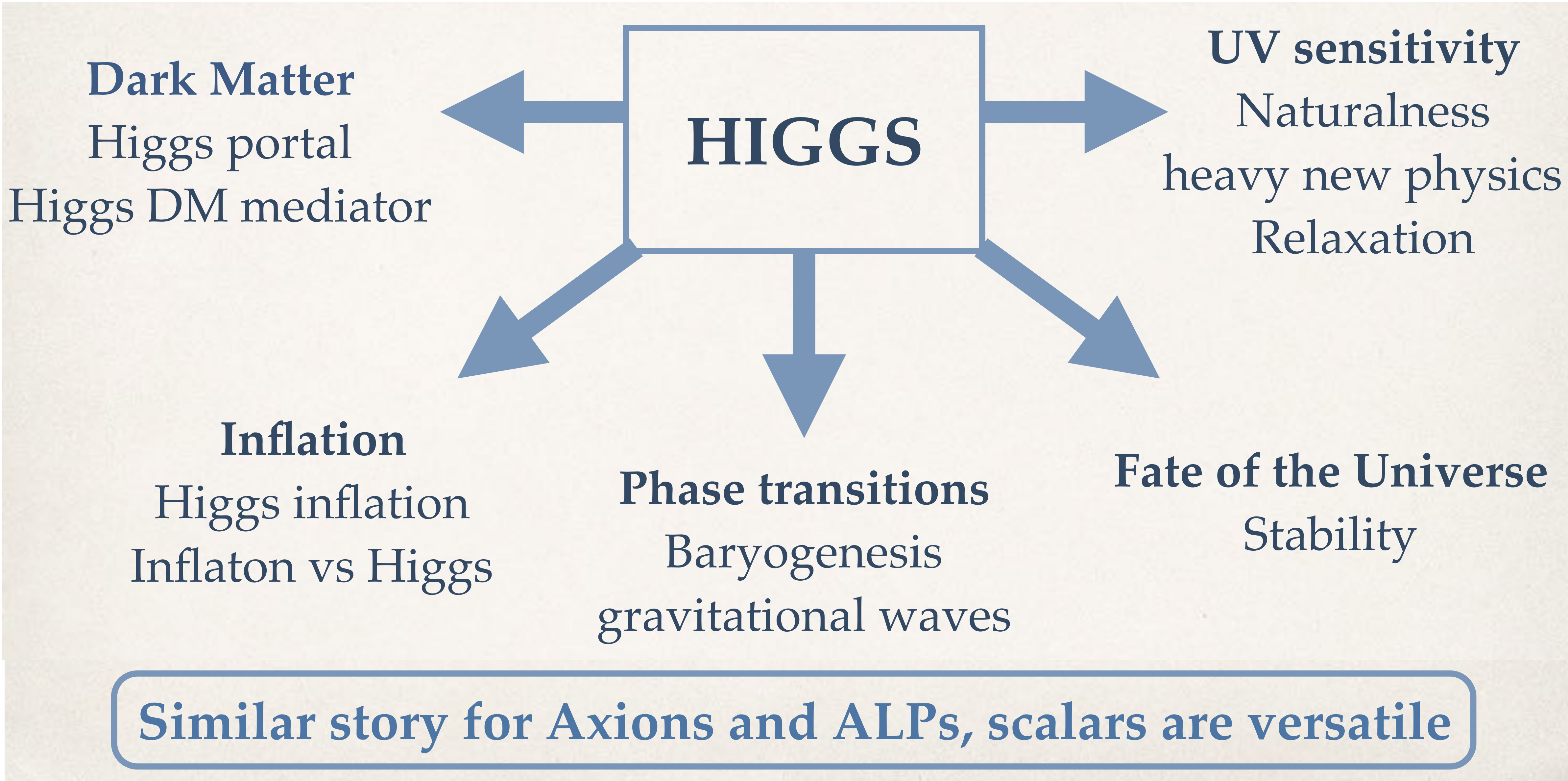


  - ✓ … and brings up further interesting (related) questions:
    - Is the Higgs an elementary particle or a composite state?
    - How does it interact with itself?
    - What is its role in answering other important questions?
    - Are there more scalars? Pseudo-scalars?

The Higgs connection to BSM

Stolen from V. Sanz's talk



BSM scenarios dealing with these issues tend to:

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

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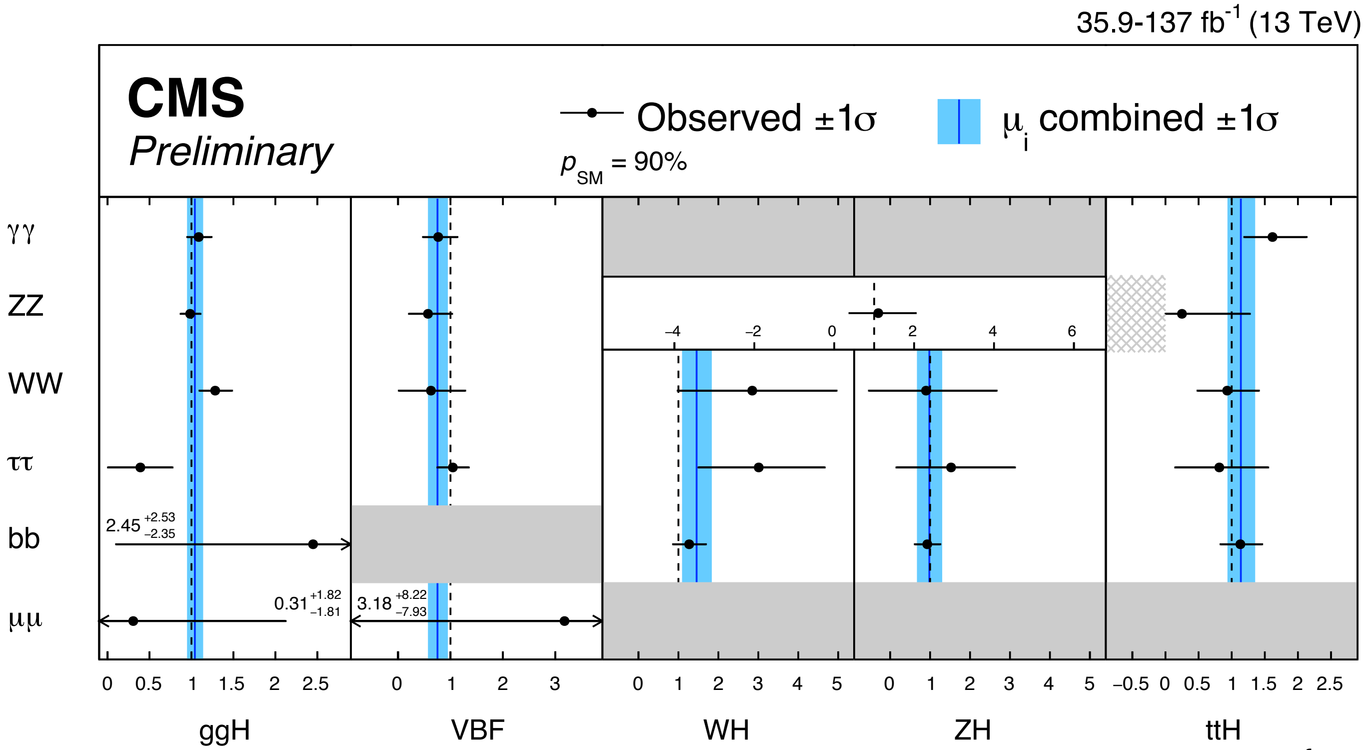
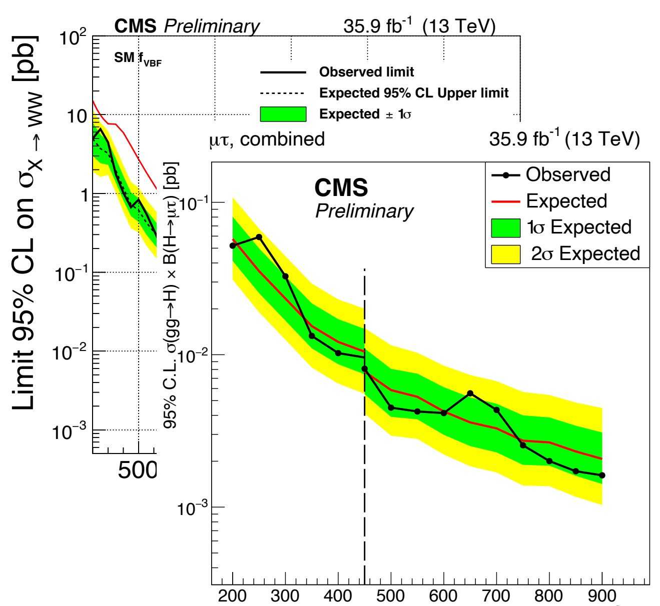
The Higgs at the LHC

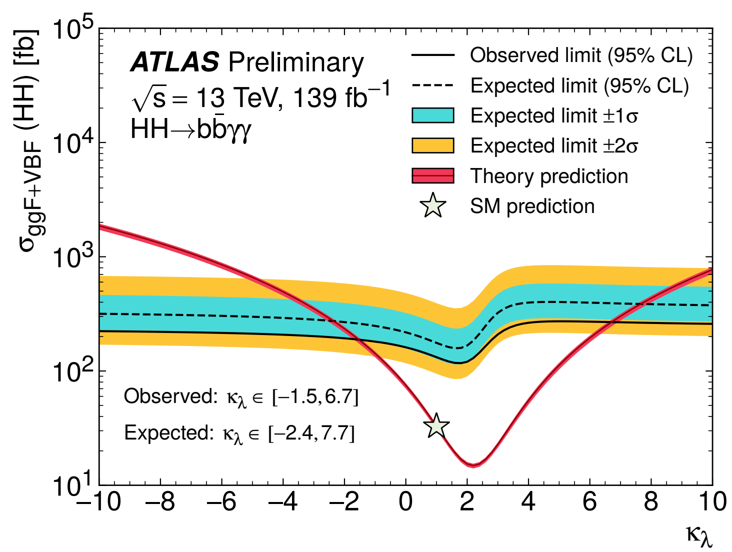
The LHC is the only current experiment with direct access to both ways of testing the Higgs sector (directly and indirectly)



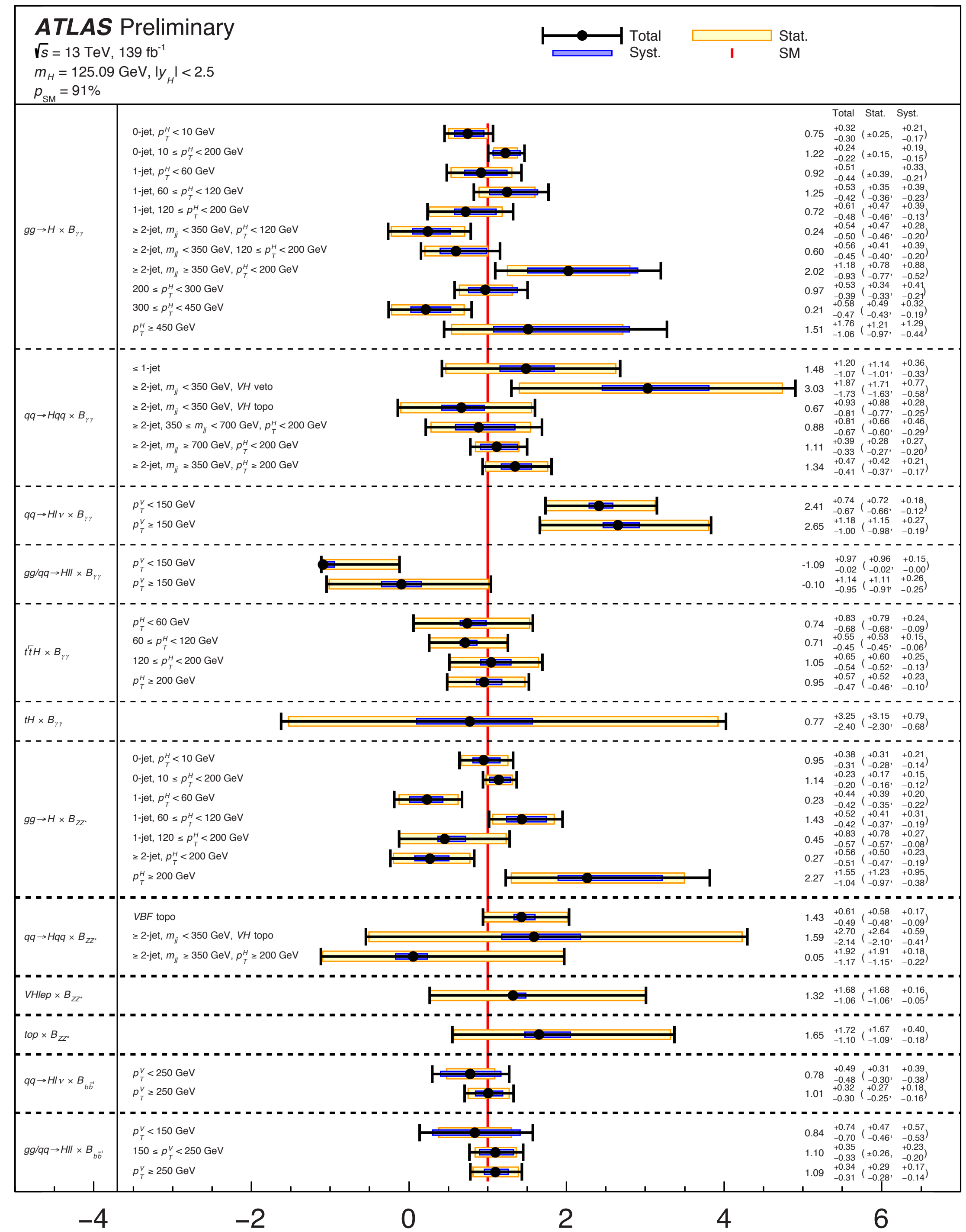
Signal strengths μ_i^f



Direct searches (Heavy scalars)



HH production



STXS

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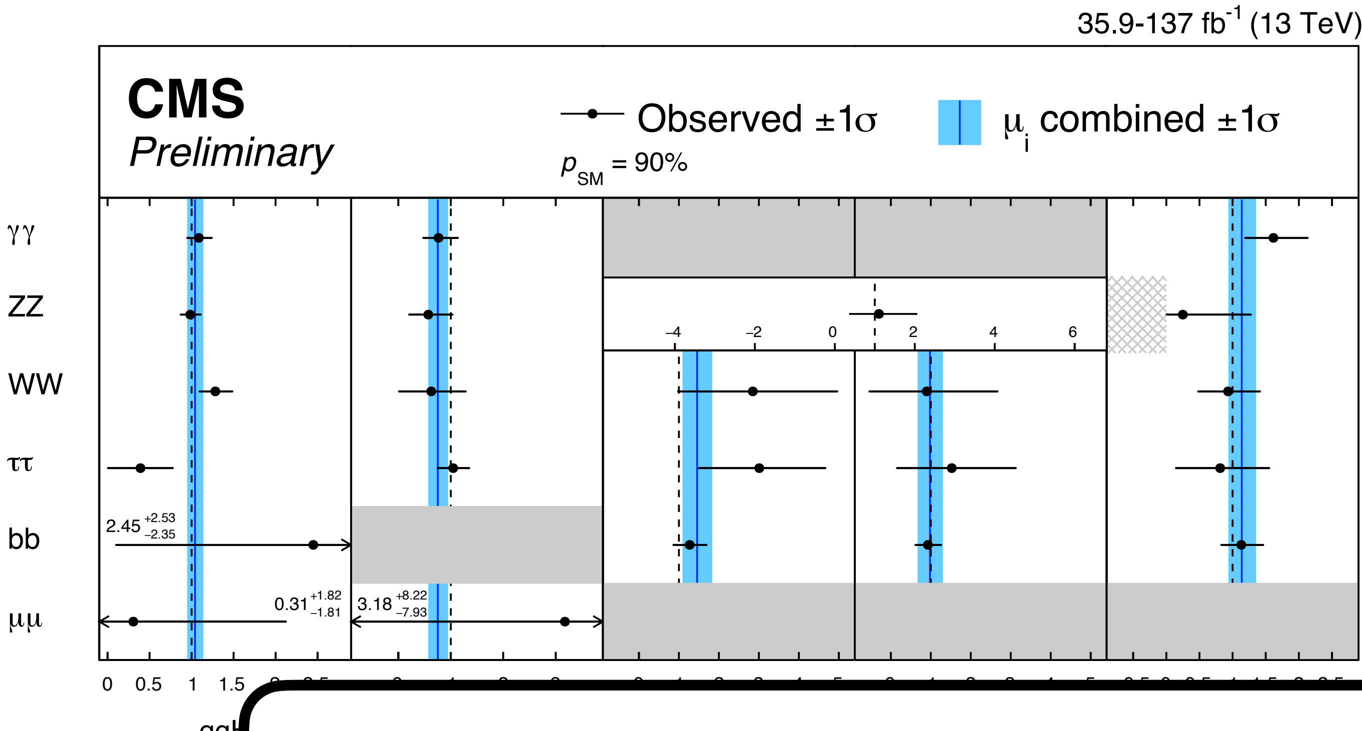
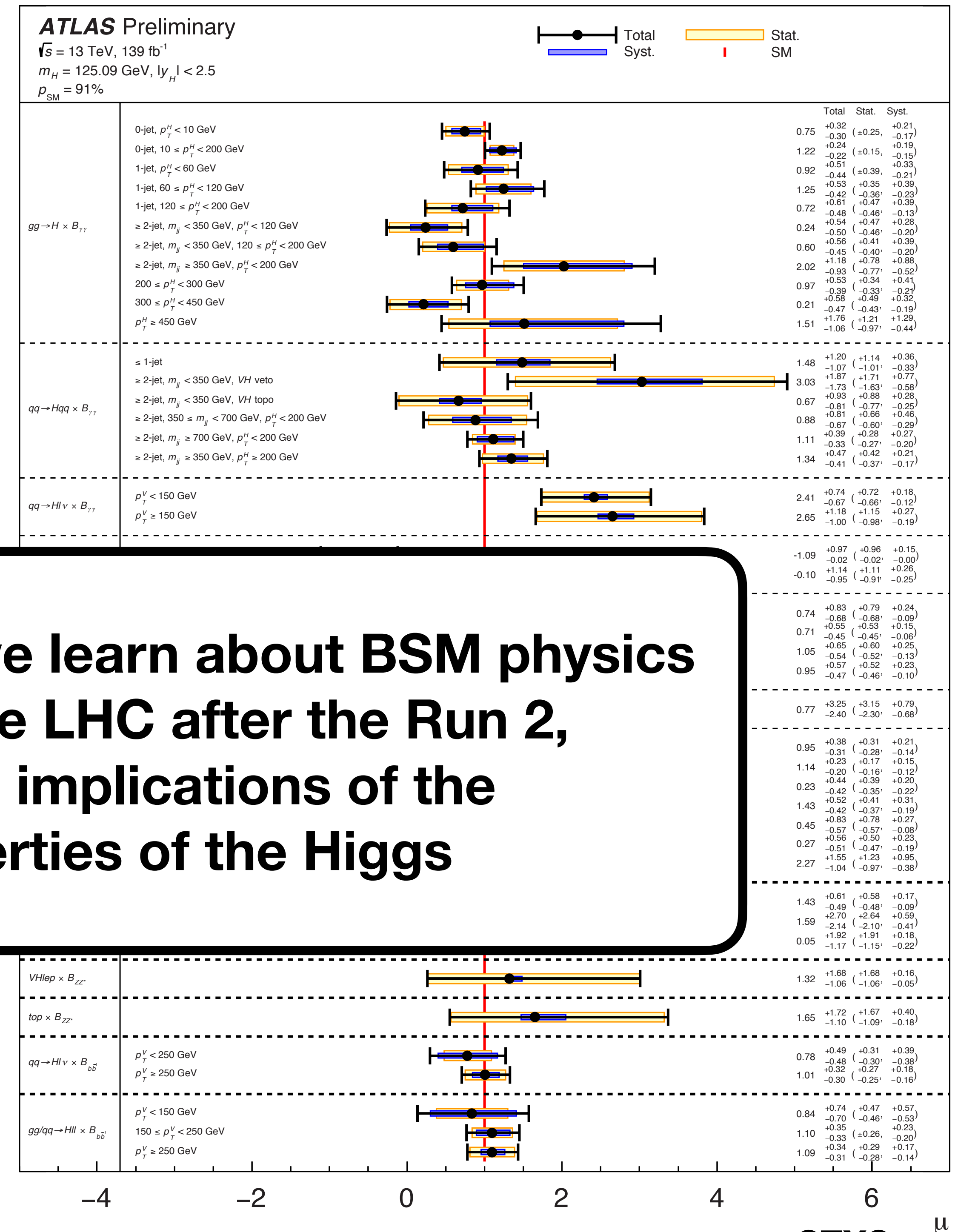
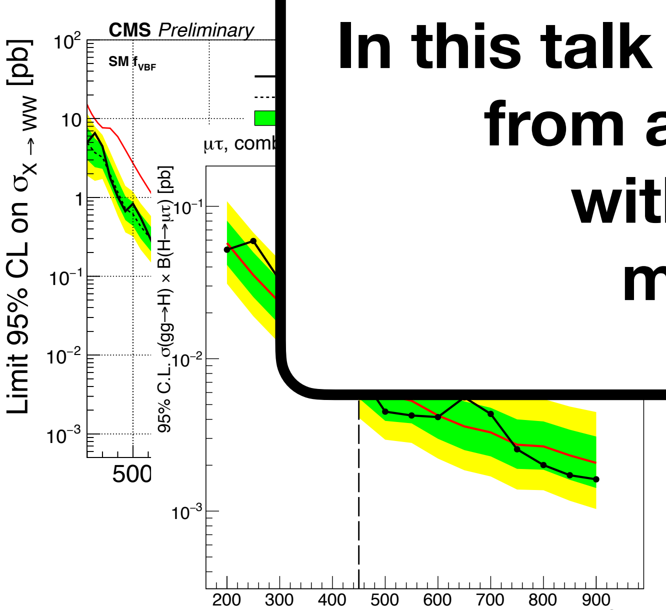




In this talk I will focus on what can we learn about BSM physics from all this information from the LHC after the Run 2, with special emphasis on the implications of the measurements of the properties of the Higgs



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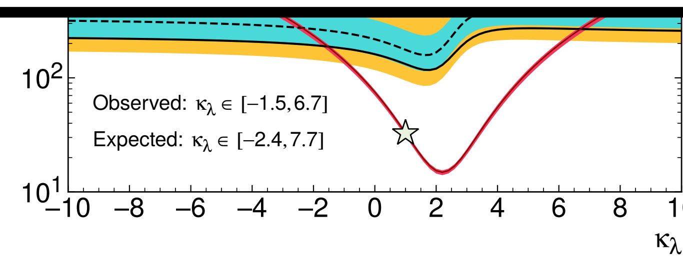

HH production

STXS

Constraints on BSM from Higgs Physics

Model-Independent

Modified Higgs couplings

- Several frameworks have been used to parameterise BSM deformations on Higgs interactions:

  ✓ The κ framework ← Used mainly during Run 1

  ✓ The EFT framework ← Being adopted in Run 2 results and for future interpretations

  ✓ 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 sym. 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

Effective Field Theories: HEFT

- **HEFT:** SM particles and symmetries at low energies, but *does not assume relation between the Higgs scalar and the Goldstone bosons of EWSB* (non-linear EWSB)

- **Leading order HEFT Lagrangian (L=0 in chiral (χ) dimensions):**

$$\begin{aligned}\mathcal{L}_{\rm LO} &= -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\\ &+ i\bar{q}_L \not{D} q_L + i\bar{\ell}_L \not{D}\ell_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{e}_R \not{D} e_R\\ &+ \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle (1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)\\ &- \frac{v}{\sqrt{2}}\left[\bar{q}_L Y_u(h) U P_+ q_R + \bar{q}_L Y_d(h) U P_- q_R + \bar{\ell}_L Y_e(h) U P_- \ell_R + \text{ h.c.}\right]\end{aligned}$$

$[\text{bosons}]_\chi = 0$

$[\bar{\psi}\psi]_\chi = [\partial]_\chi = [g_{\rm weak}]_\chi = 1$

$[\Delta\mathcal{L}]_\chi = 2L+2$

$U = \exp(2i\frac{G_a}{v}T_a)$

$V(h),\ F_U(h),\ Y_\psi(h)$ polynomials in h

Terms relevant for single-Higgs processes

$$\mathcal{L}_{\rm fit} = 2c_V\left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\frac{h}{v} - \sum_\psi c_\psi m_\psi \bar{\psi}\psi\frac{h}{v}$$

Modifications of SM couplings (like κ framework)

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Modifications of SM couplings (like κ framework)

NLO local terms to properly parameterise corr. to SM rad. processes (Different than κ framework)

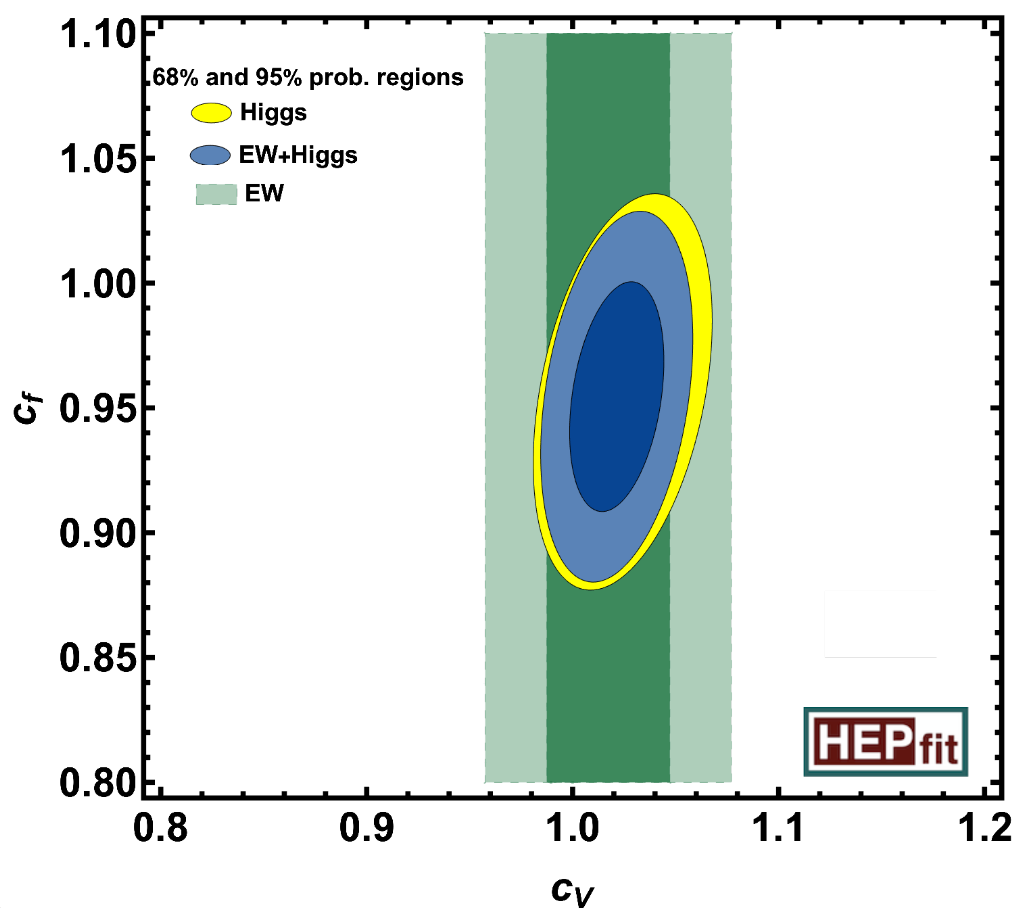
Effective Field Theories: HEFT

- **Fits to LHC Higgs observables:** Run 1 + Run 2 (~36-140 fb^{-1})

Custodial + Universal fermion interactions

	Fit result	95% Prob.	Correlations	
c_V	1.02±0.02	[0.99, 1.06]	1.00	
c_f	0.96±0.03	[0.89, 1.02]	0.36	1.00

⇒



Custodial

	Fit result	95% Prob.
c_V	1.02±0.04	[0.94, 1.09]
c_g	0.04±0.05	[−0.04, 0.13]
c_γ	0.02±0.14	[−0.26, 0.30]
$c_{Z\gamma}$	0.00 (Fixed)	–
c_t	0.94±0.06	[0.82, 1.05]
c_b	0.98±0.09	[0.81, 1.15]
c_μ	1.02±0.19	[0.64, 1.39]
c_τ	0.93±0.07	[0.78, 1.07]

⇑

EWPO:

$$c_V = 1.02 \pm 0.03$$

$$c_V \in [0.96, 1.08] \quad \textbf{95\% Prob.}$$

$$S = \frac{1}{12\pi}(1 - c_V^2)\log\frac{\Lambda^2}{m_h^2}$$

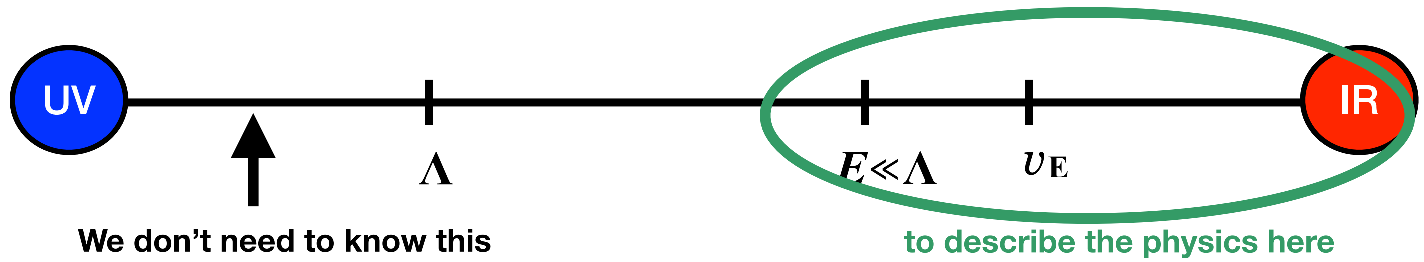
$$T = -\frac{3}{16\pi c_w^2}(1 - c_V^2)\log\frac{\Lambda^2}{m_h^2}$$

$$\Lambda = -\frac{4\pi v}{\sqrt{|1 - c_V^2|}}$$

Updated from JB, O. Eberhardt, C. Krause, JHEP 07 (2018) 048, arXiv 1803.00939 [hep-ph]

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)



See talks from
V. Sanz, A. Pomarol,
E. Vryonidou, I. Brivio,
S. Banerjee

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

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

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

Warsaw basis operators (Neglecting flavour)

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

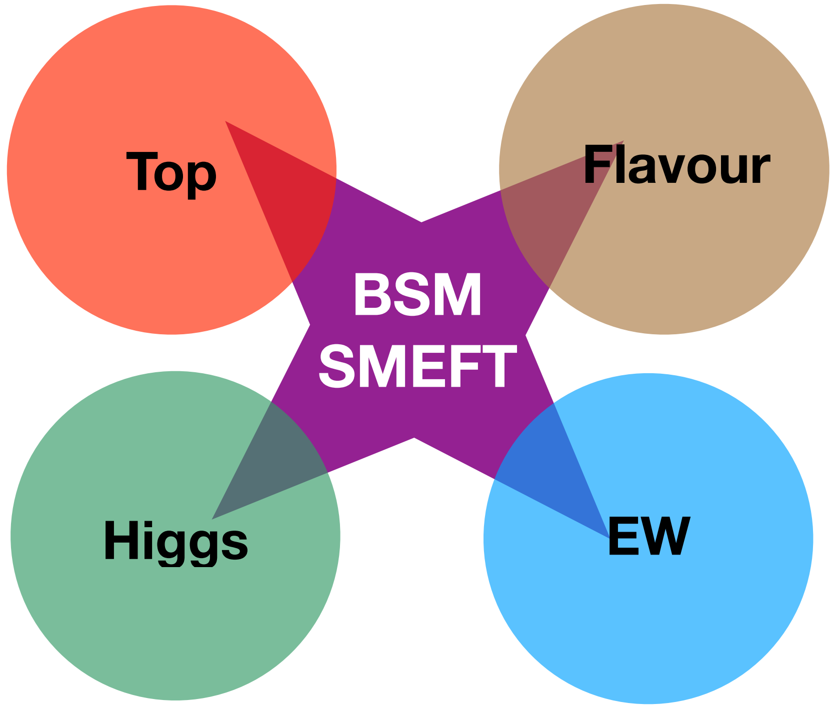
Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{l_L}\gamma^\mu\sigma_a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

Effective Field Theories: SMEFT

- Many EFT operators entering in Higgs processes at LO

  "Model-independent" only when including ALL contributing operators

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

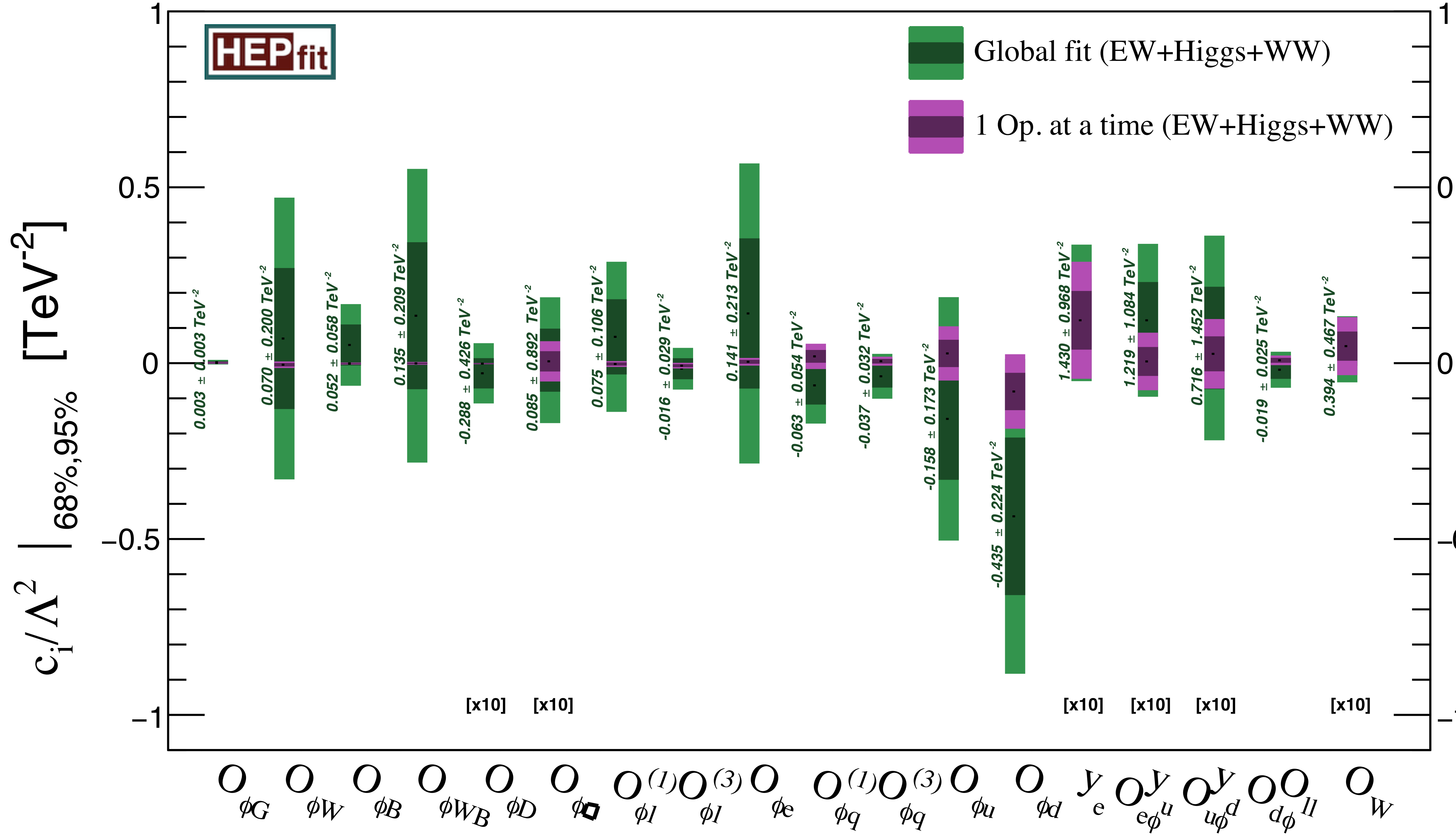


⇒ **Use Global fit to constraint all directions**

- Most EFT directions in Higgs processes in a LO EFT fit can be closed by combining Higgs with EWPO and Diboson (e.g. WW, WZ) observables

Effective Field Theories: SMEFT

- **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

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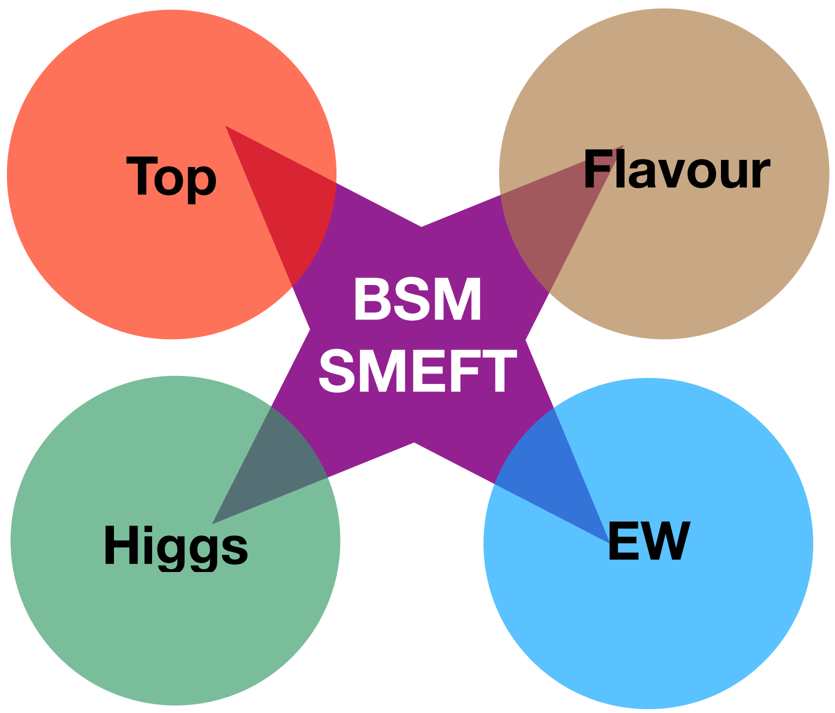

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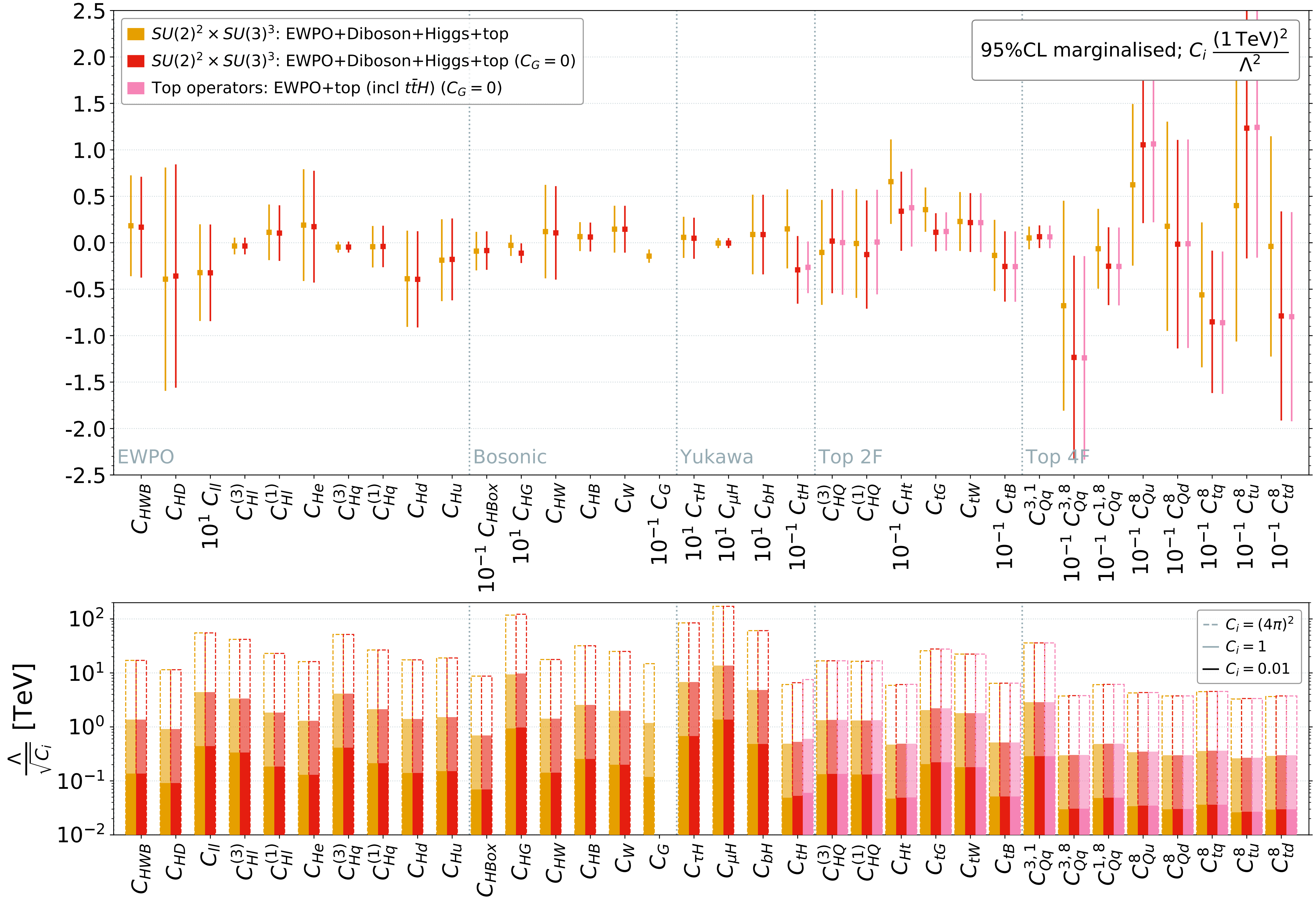
- Most EFT directions in Higgs processes in a LO EFT fit can be closed by combining Higgs with EWPO and Diboson (e.g. WW, WZ) observables
- A model independent description of ttH as well requires to add Top observables

Effective Field Theories: SMEFT

- **SMEFT fit to EW/Higgs/diBoson/Top**



J.Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You, JHEP 04 (2021) 279, arXiv: 2012.02779 [hep-ph]

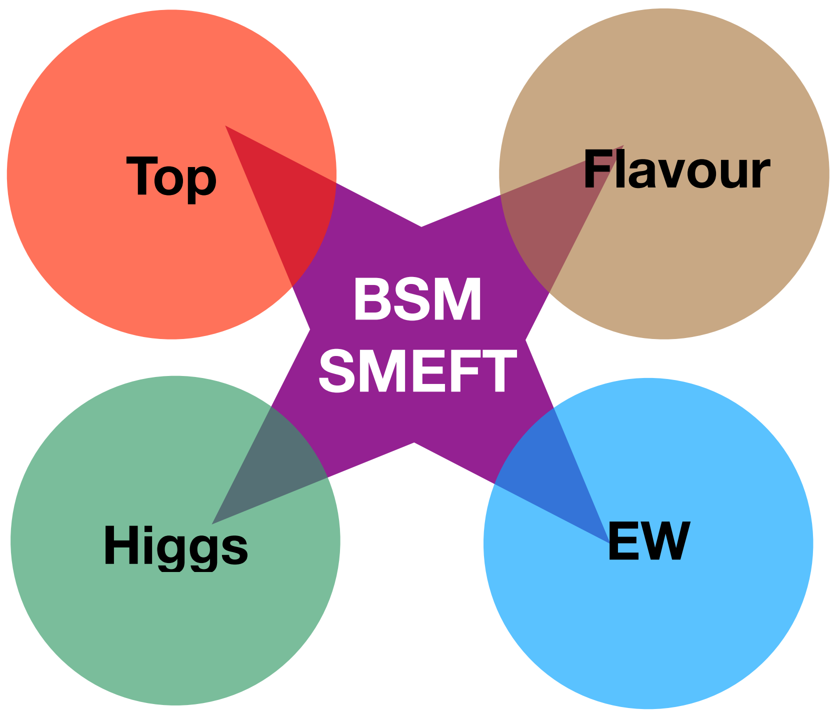
(See also J.J. Ethier, F. Maltoni, E. R. Nocera, J. Rojo, arXiv: 2105.00006 [hep-ph] for recent Higgs/diBoson/Top EFT interpretations)

Effective Field Theories: SMEFT

- Many EFT operators entering in Higgs processes at LO

  "Model-independent" only when including ALL contributing operators

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



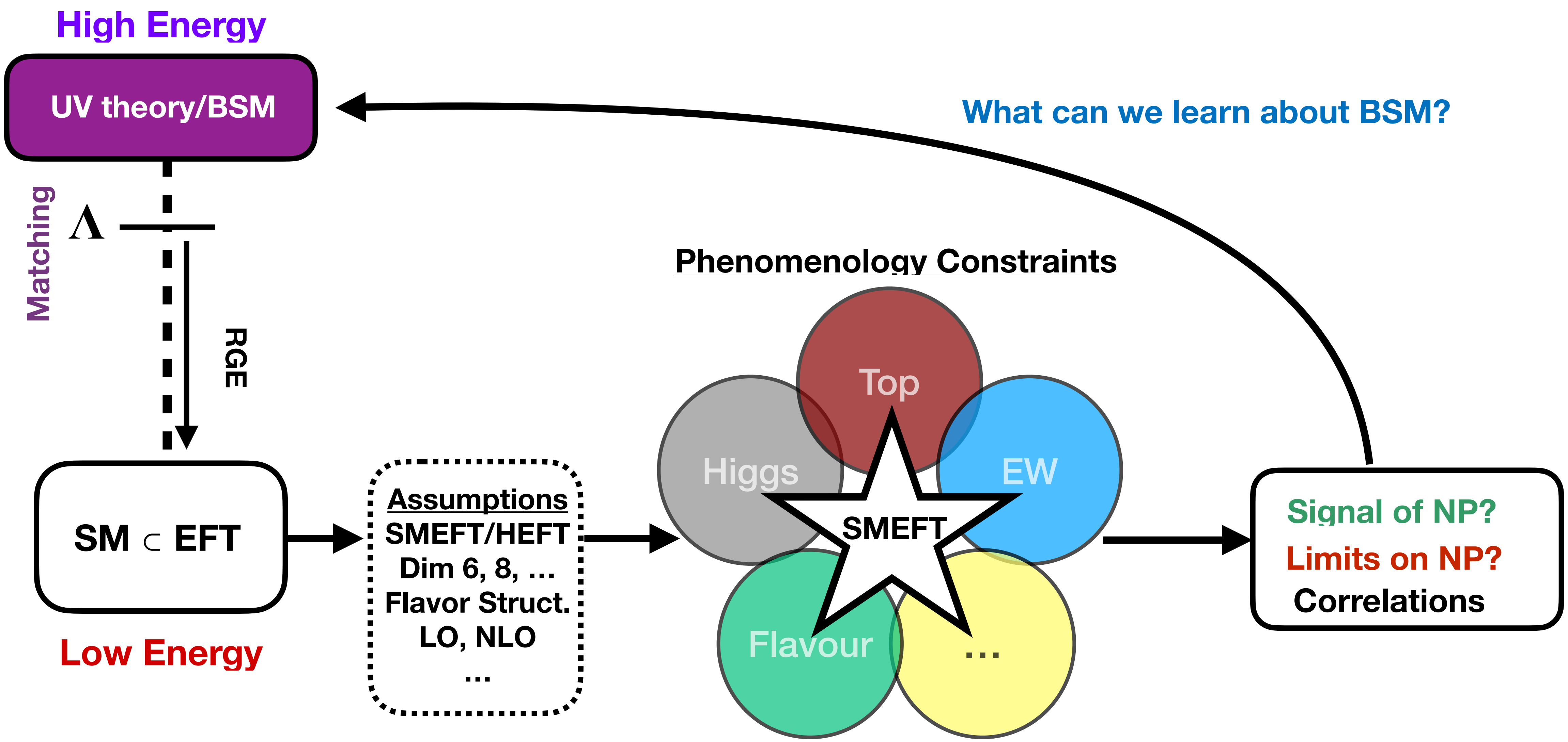
⇒ Use Global fit to constraint all directions

- Most EFT directions in Higgs processes in a LO EFT fit can be closed by combining Higgs with EWPO and Diboson (e.g. WW, WZ) observables
- A model independent description of ttH as well requires to add Top observables
- Consistent treatment of non-flavour-universal interactions requires combination with flavour observables ⇐ None yet

Constraints from Higgs Physics
Specific BSM scenarios

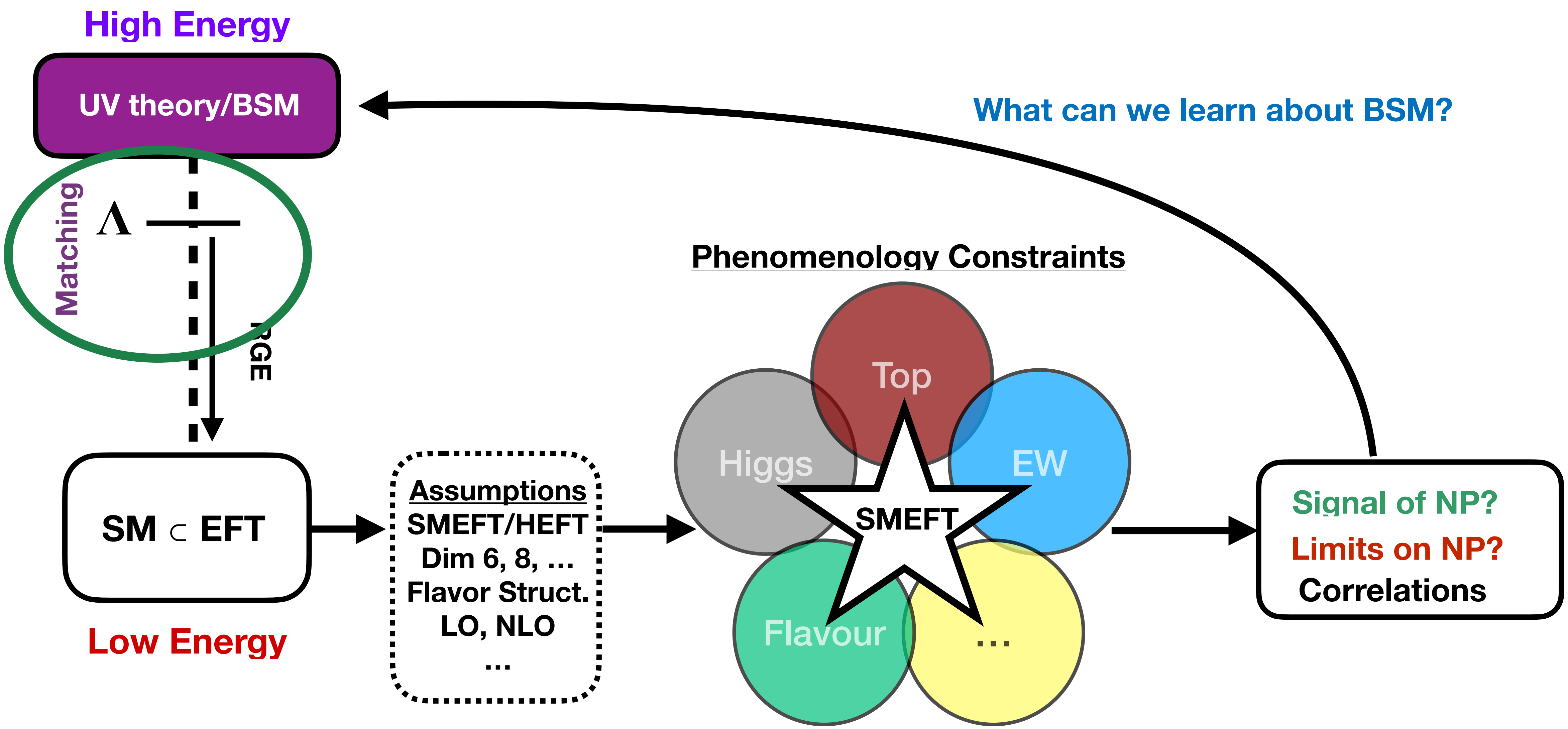
Effective Field Theories: Matching in the SMEFT

- EFT fits provide a useful phenomenological tool to learn from New Physics



Effective Field Theories: Matching in the SMEFT

- EFT fits provide a useful phenomenological tool to learn from New Physics



- Projecting (SM)EFT results to specific scenarios requires matching between the NP model and the EFT

Matching: Wilson coefficients as function of BSM model couplings and masses

Limits on EFT Wilson coefficients → Limits on BSM

Effective Field Theories: Matching in the SMEFT

- EFT fits provide a useful phenomenological tool to learn from New Physics
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Matching: Wilson coefficients as function of BSM model couplings and masses

Limits on EFT Wilson coefficients → Limits on BSM

- Matching fully classified at tree-level

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

Name	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

19 scalars bosons

Name	N	E	Δ_1	Δ_3	Σ	Σ_1
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

13 vector-like fermions

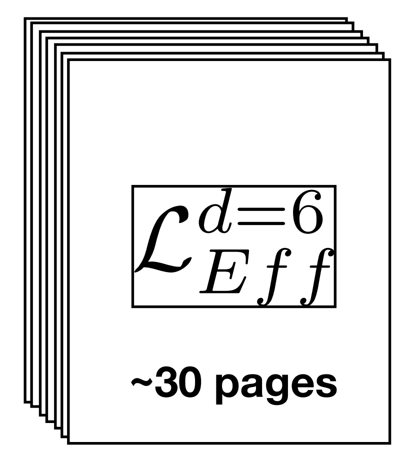
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$

Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

16 vector bosons

The full UV/IR tree-level dictionary:

48 multiplets contribute to dim 6

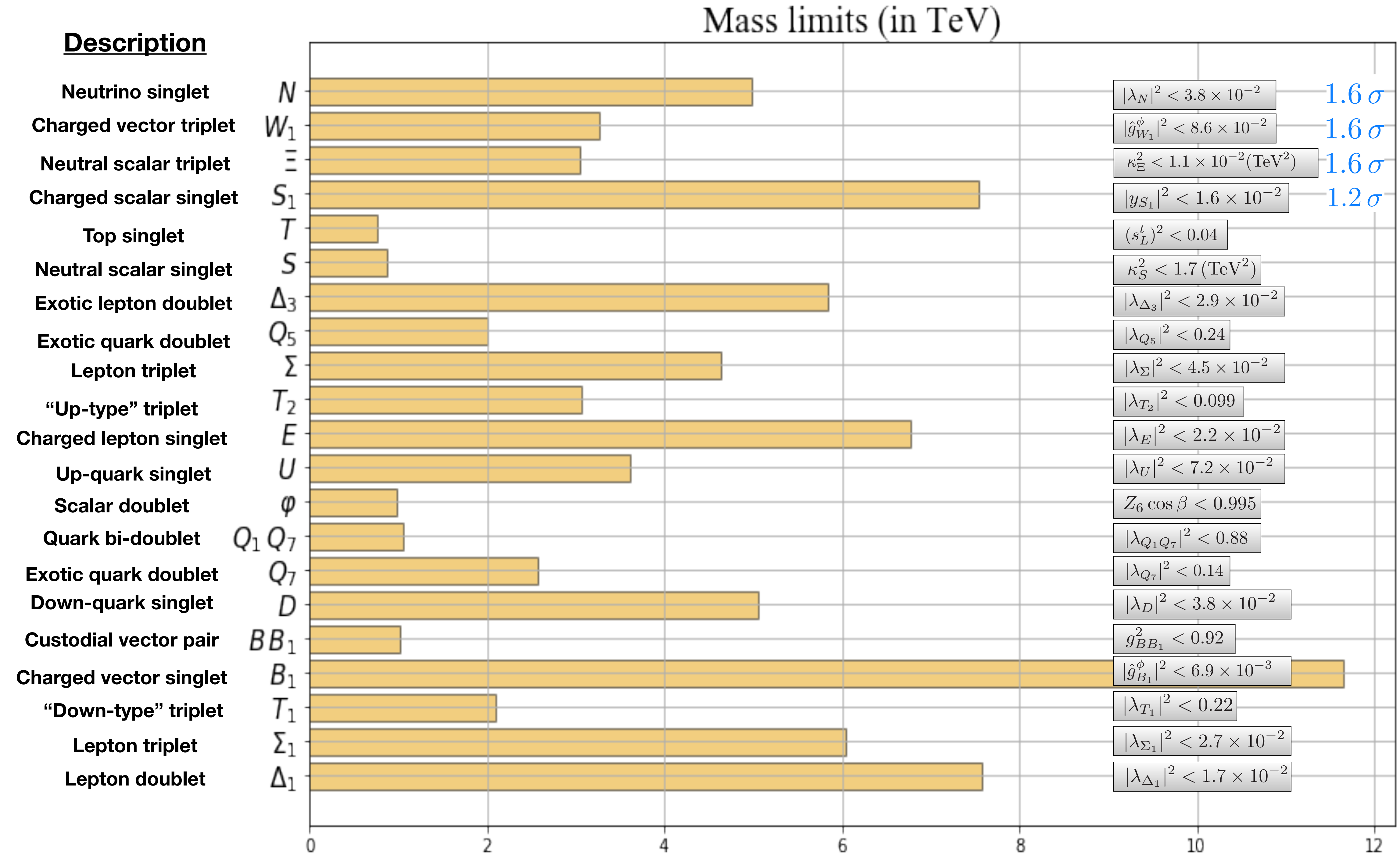


J. B., J.C. Criado, M. Pérez- Victoria, J. Santiago, JHEP 1803 (2018) 109

Effective Field Theories: Matching in the SMEFT

- EFT limits on simple BSM extensions contribution at tree-level to dimension 6:

Including limit on BSM benchmarks for EFT in Higgs and EW from LHC Higgs WG note LHC-HXSWG-2019-006 (arXiv: 2009.01249 [hep-ph])



J.Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You, JHEP 04 (2021) 279, arXiv: 2012.02779 [hep-ph]

Classical "Higgs" BSM scenarios

- Well-motivated BSM scenarios designed to address specific issues of the SM. In particular,
  - ✓ Naturalness models: to solve or ameliorate the hierarchy problem, e.g.
    - SUSY
    - Composite Higgs scenarios
    - Neutral Naturalness models
    - Relaxion, …
- These typically induce sizeable modifications of the Higgs couplings…
- … and involve extensions of the scalar sector, e.g.
  - ✓ SUSY → Two Higgs Doublet Models
  - ✓ Models with axion-like particles
- In what follows we go over a few of these scenarios and summarise some implications of current LHC Higgs measurements

Composite Higgs Models

- The Higgs is a resonance of some strong dynamics not far from the TeV
  - ✓ Dynamical explanation of strong dynamics scale m_* (as in QCD)
  - ✓ Motivated as solutions to the hierarchy problem

- Strongly Interacting Light Higgs (SILH) scenario: Strong dynamics, characterised by a single mass scale m_* and coupling g_*, generates a H doublet with same quantum numbers as the SM one (pNGB or accidentally light)
  - ✓ Leading effects in Higgs couplings

$$\Delta\mathcal{L}_{\mathrm{SILH}} = \frac{g_\star^2}{2m_\star^2} C_\phi \partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{g_\star^2}{m_\star^2} C_y \sum y_\psi \bar{\psi}_L \phi \psi_R (\phi^\dagger\phi)$$
$$+ \frac{g_\star^2 g_s^2}{16\pi^2 m_\star^2} C_g (\phi^\dagger\phi) G_{\mu\nu}^A G^{A\ \mu\nu} + \frac{g_\star^2 g'^2}{16\pi^2 m_\star^2} C_\gamma (\phi^\dagger\phi) B_{\mu\nu} B^{\mu\nu}$$

Modifications of Higgs couplings

$$c_V = 1 - \frac{C_\phi}{2}\xi, \quad c_f = 1 - (\frac{C_\phi}{2} + C_y)\xi, \quad c_g = 2C_g\xi, \quad c_\gamma = C_\gamma\xi$$

$$\xi \equiv \frac{g_\star^2 v^2}{m_\star^2} \equiv \frac{v^2}{f^2} \qquad C_{\phi,y,g,\gamma} \sim O(1)$$

Composite Higgs Models

- 95% probability bounds from Higgs physics on generic SILH scenarios:

	Scenario	C_ϕ	C_y	$\lvert C_g\rvert$	$\lvert C_\gamma\rvert$	$\xi_{95\%}$	$f_{95\%}$ [GeV]
CH models with pNGB H	SILH1a	1	0	0	0	0.049	1107
	SILH1b	1	1	0	0	0.054	1057
CH models with accidentally light H	SILH2a	1	0	1	1	0.029	1433
	SILH2b	1	1	1	1	0.039	1253

Benchmarks from L. Vecchi contributions to HL-LHC WG2 report , arXiv: 1902.00134 [hep-ph]

- Reproduces well limits from minimal CH models based on SO(5)/SO(4):

$$c_V = \sqrt{1-\xi}, \quad c_f^{(4)} = \sqrt{1-\xi}, \quad c_f^{(5)} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

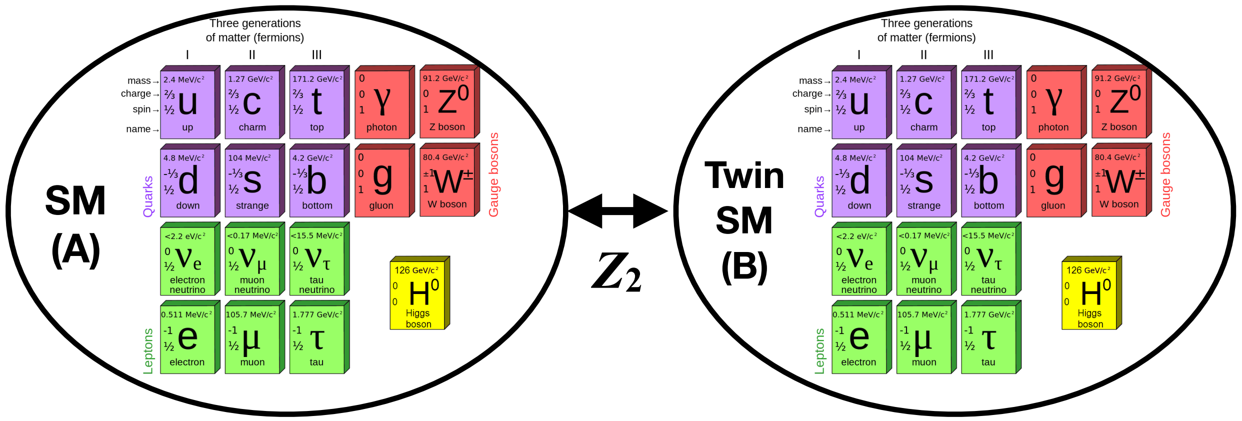
Fermion couplings depending on SO(5) irrep (here 4 or 5)

Scenario	$\xi_{95\%}$	$f_{95\%}$ [GeV]
Min CH-4	0.049	1117
Min CH-5	0.053	1067

Updated from JB, O. Eberhardt, C. Krause, JHEP 07 (2018) 048, arXiv 1803.00939 [hep-ph]

Neutral Naturalness

- SM comes with a Twin: Higgs sector invariant under a global U(4) symmetry



$$H = \begin{pmatrix} h_A \\ h_B \end{pmatrix} = \left(f + \frac{\sigma}{\sqrt{2}}\right) e^{i\frac{\sqrt{2}\Pi_a T_a}{f}} \Phi$$

$$V(H) = -m^2 |H|^2 + \lambda |H|^4 + \delta \left(|h_A|^4 + |h_B|^4\right)$$

U(4) symmetric

<H> breaks U(4)→U(3)

1 radial mode + 7 Goldstones

3 Long. W,Z / 3 Long. W_{Twin},Z_{Twin}

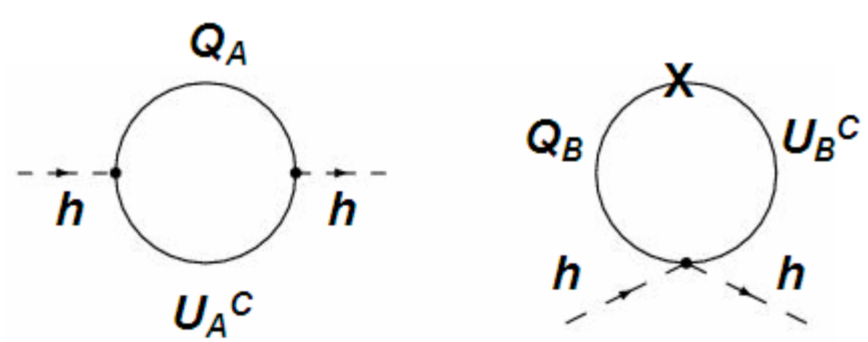
1 light scalar ←125 GeV Higgs (pNGB)

Explicit U(4)→U(3) breaking

(Gauge loops)

- Higgs mass protected by approximate global symmetries:
  - ✓ Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs
  - ✓ Symmetry also broken by Yukawas but Z_2 protects H mass

$$\Delta\mathcal{L}_{\rm Yuk} = y_t h_A \overline{Q}_A U_A + y_t h_B \overline{Q}_B U_B \to y_t h \overline{Q}_A U_A + y_t (f - \tfrac{|h|^2}{2f}) \overline{Q}_B U_B$$



Z. Chacko

Top divergences cancelled by non-coloured states ⇒ Neutral naturalness

Neutral Naturalness

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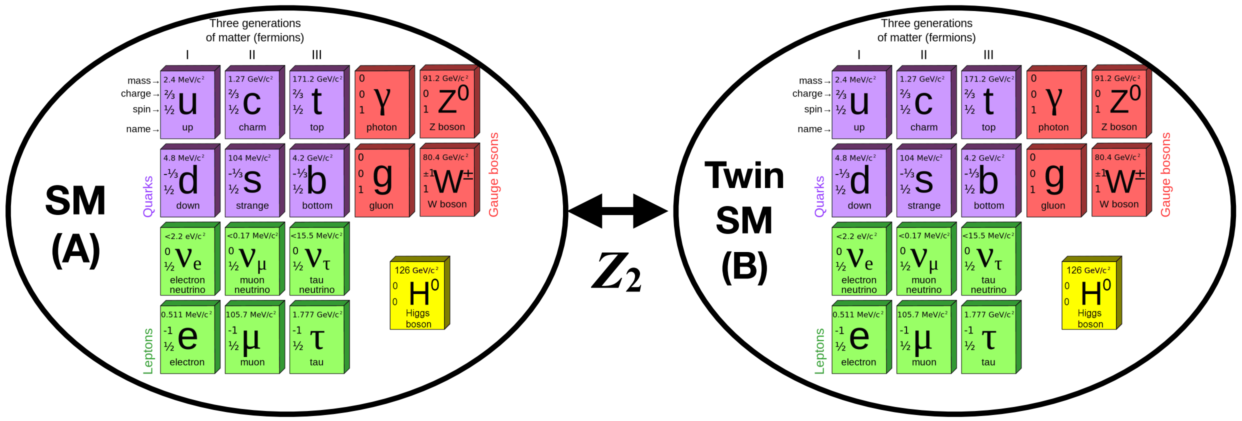

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Explicit U(4)→U(3) breaking (Gauge loops)

- Higgs mass protected by approximate global symmetries:
  - ✓ Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs
  - ✓

<u>Exotic decays</u> and deviations in Higgs couplings

Model dependent: depend on what is the lightest Twin particle

Generically, invisible decays and displaced leptons or jets

Current best constraint on invisible h decays: ATLAS Run 2 (ATLAS-CONF-2020-027)

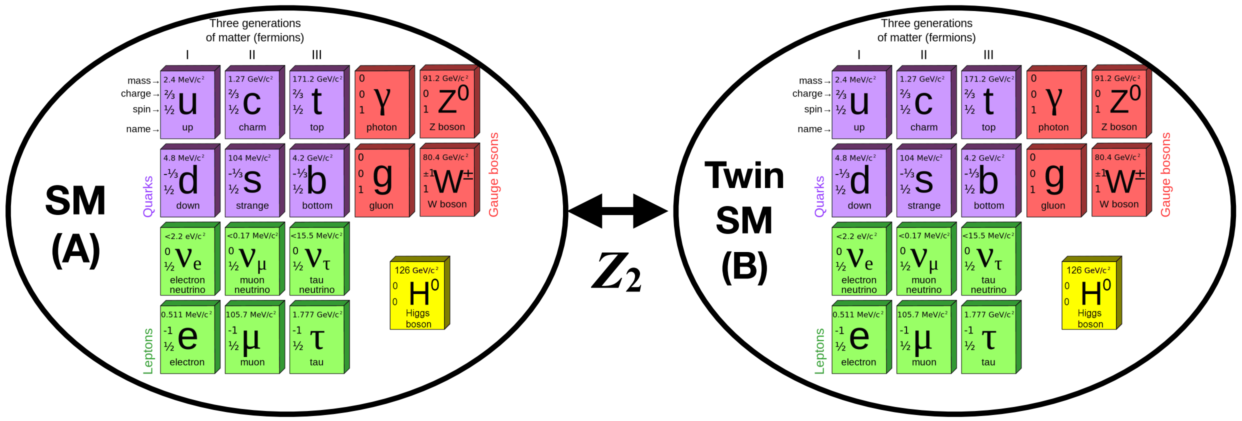
Br(h→inv.)<0.09 at 95% prob.

From Higgs coupling fits, assuming c_V<1

See also A. Albert's talk

Neutral Naturalness

- SM comes with a Twin: Higgs sector invariant under a global U(4) symmetry



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Explicit U(4)→U(3) breaking

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✓ Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs

Exotic decays and <u>deviations in Higgs couplings</u>

Generically, universal O(1) deviations in h couplings, unless tuned

$$\Delta\mathcal{L}_{\rm EFT} = \frac{1}{2f^2} C_\phi \partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \ldots \qquad C_\phi = \frac{1}{2} - 8\delta\frac{f^2}{m_\sigma^2}$$

Tuning~ $\xi^{-1} \equiv \frac{f^2}{v^2}$

From current LHC Higgs measurements (for $\delta \ll 1$)

$\xi \lesssim 0.108$ **at 95% probability**

Two-Higgs Doublet Models

- THDM (with softly broken Z_2 symmetry):

Scalar Sector

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i+\phi_i^0+iG_i}{\sqrt{2}} \end{pmatrix}$$

$$t_\beta \equiv \tan\beta \equiv \frac{v_2}{v_1}$$

$$\begin{aligned} \Phi_1^\pm &= c_\beta G^\pm - s_\beta H^\pm\,, \\ \Phi_2^\pm &= s_\beta G^\pm + c_\beta H^\pm\,, \\ \Phi_1^0 &= \tfrac{1}{\sqrt{2}}\left[v_1 + c_\alpha H - s_\alpha h + i c_\beta G - i s_\beta A\right] \\ \Phi_2^0 &= \tfrac{1}{\sqrt{2}}\left[v_2 + s_\alpha H + c_\alpha h + i s_\beta G + i c_\beta A\right] \end{aligned}$$

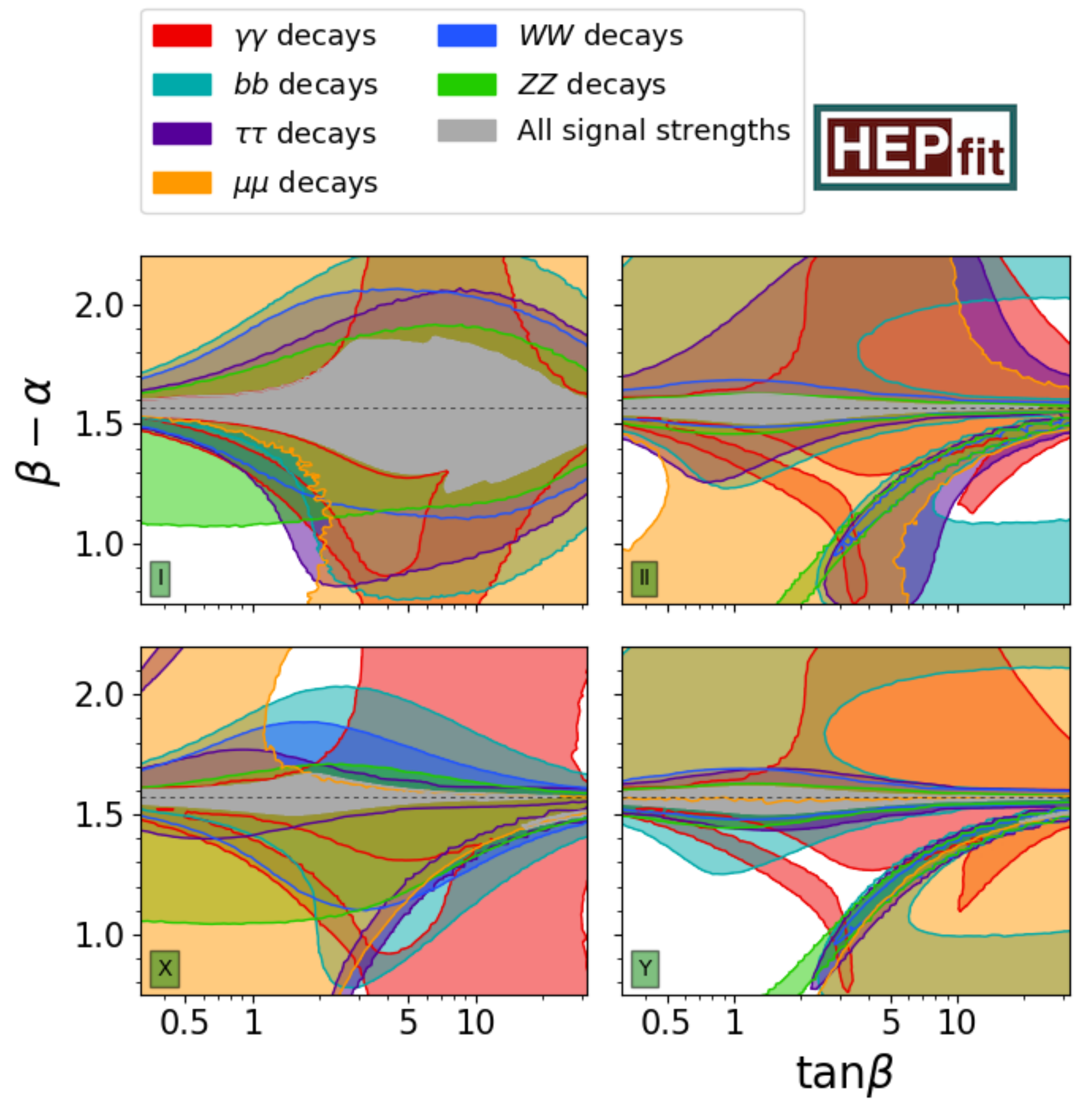
Physical: h, H, A, $H^\pm$
Goldstones: G, $G^\pm$

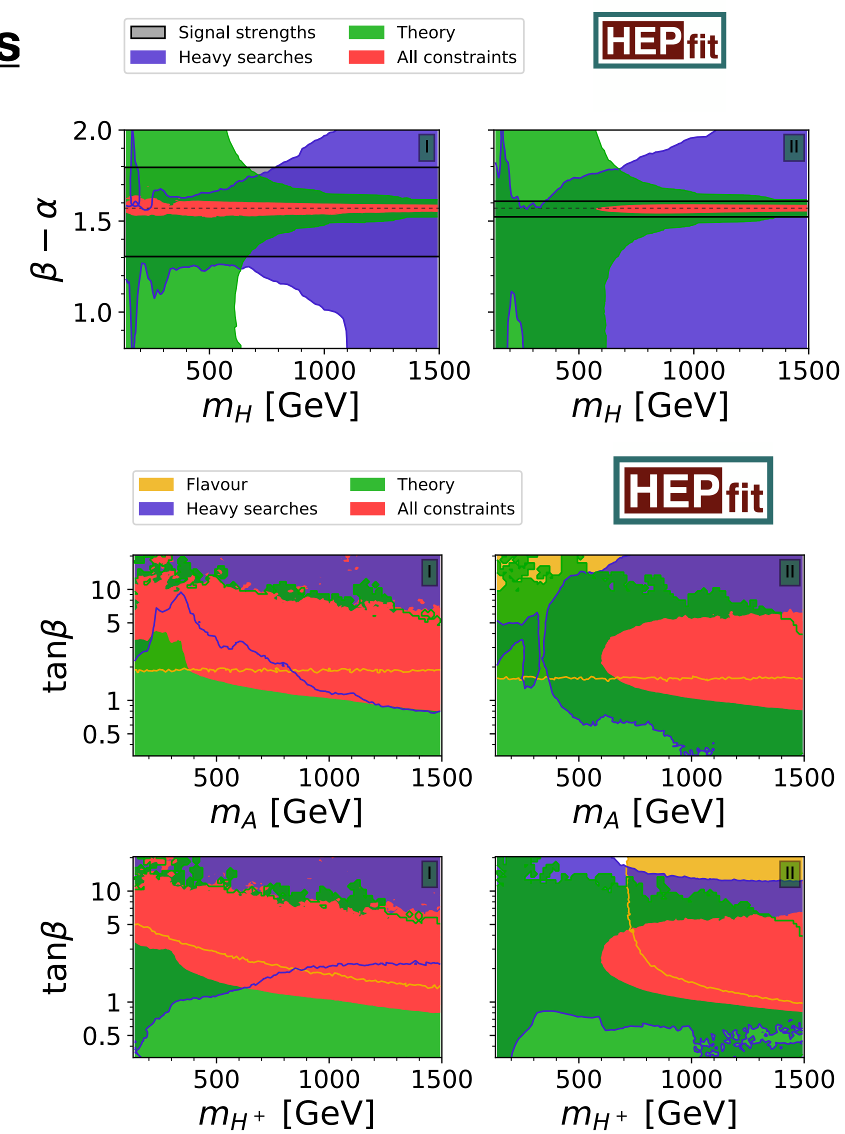
Yukawa interactions

$$\mathcal{L}_Y = -Y_t \bar{Q}_L i\sigma_2 \Phi_2^* t_R - Y_{b,1}\bar{Q}_L \Phi_1 b_R - Y_{b,2}\bar{Q}_L \Phi_2 b_R - Y_{\tau,1}\bar{L}_L \Phi_1 \tau_R - Y_{\tau,2}\bar{L}_L \Phi_2 \tau_R + \text{h.c.}$$

Type I	Type II	Type X ("lepton specific")	Type Y ("flipped")
$Y_{b,1}=Y_{\tau,1}=0$	$Y_{b,2}=Y_{\tau,2}=0$	$Y_{b,1}=Y_{\tau,2}=0$	$Y_{b,2}=Y_{\tau,1}=0$
$Y_{b,2}=Y_b^{\rm SM}/\sin\beta$	$Y_{b,1}=Y_b^{\rm SM}/\cos\beta$	$Y_{b,2}=Y_b^{\rm SM}/\sin\beta$	$Y_{b,1}=Y_b^{\rm SM}/\cos\beta$
$Y_{\tau,2}=Y_\tau^{\rm SM}/\sin\beta$	$Y_{\tau,1}=Y_\tau^{\rm SM}/\cos\beta$	$Y_{\tau,1}=Y_\tau^{\rm SM}/\cos\beta$	$Y_{\tau,2}=Y_\tau^{\rm SM}/\sin\beta$

Experimental constraints





D. Chowdhury, O. Eberhardt, JHEP 05 (2018) 161, arXiv: 1711.02095 [hep-ph]

Two-H

- THD

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i + \phi_i^0 + iG_i}{\sqrt{2}} \end{pmatrix}$$

$$t_\beta \equiv \tan\beta \equiv \frac{v_2}{v_1}$$

LHC Run 2 searches of neutral and charged scalars (36 fb-1)

Channel	Experiment		Mass range [GeV]	$\mathcal{L}$ [fb^{-1}]
$pp \to H/A \to bb$	CMS	[75]	[0.55;1.2]	2.69
$gg \to H/A \to \tau\tau$	ATLAS	[76]	[0.2;2.25]	36.1
	CMS	[77]	[0.09;3.2]	12.9
$bb \to H/A \to \tau\tau$	ATLAS	[76]	[0.2;2.25]	36.1
	CMS	[77]	[0.09;3.2]	12.9
$pp \to H/A \to \gamma\gamma$	ATLAS	[78]	[0.2;2.7]	36.7
$gg \to H/A \to \gamma\gamma$	CMS	[79]	[0.5;4]	35.9
$gg \to H/A \to Z\gamma[\to (\ell\ell)\gamma]$	ATLAS	[45]	[0.25;2.4]	36.1
$gg \to H/A \to Z\gamma$	CMS	[80]	[0.35;4]	35.9
$gg \to H \to ZZ[\to (\ell\ell)(\ell\ell, \nu\nu)]$	ATLAS	[81]	[0.2;1.2]	36.1
$VV \to H \to ZZ[\to (\ell\ell)(\ell\ell, \nu\nu)]$	ATLAS	[81]	[0.2;1.2]	36.1
$pp \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$	CMS	[82]	[0.6;2.5]	35.9
$gg \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$	CMS	[83]	[0.2;0.6]	2.3
$VV \to H \to ZZ[\to (\ell\ell)(\nu\nu)]$	CMS	[83]	[0.2;0.6]	2.3
$(VV + VH) \to H \to ZZ \to (\ell\ell)(\ell\ell)$	CMS	[84]	[0.13;2.53]	12.9
$pp \to H \to ZZ[\to (\ell\ell)(qq)]$	CMS	[85]	[0.5;2]	12.9
$gg \to H \to ZZ[\to (\ell\ell, \nu\nu)(qq)]$	ATLAS	[86]	[0.3;3]	36.1
$VV \to H \to ZZ[\to (\ell\ell, \nu\nu)(qq)]$	ATLAS	[86]	[0.3;3]	36.1
$gg \to H \to WW[\to (e\nu)(\mu\nu)]$	ATLAS	[87]	[0.25;4]	36.1
$VV \to H \to WW[\to (e\nu)(\mu\nu)]$	ATLAS	[87]	[0.25;3]	36.1
$(gg{+}VV) \to H \to WW \to (\ell\nu)(\ell\nu)$	CMS	[88]	[0.2;1]	2.3
$gg \to H \to WW[\to (\ell\nu)(qq)]$	ATLAS	[89]	[0.3;3]	36.1
$VV \to H \to WW[\to (\ell\nu)(qq)]$	ATLAS	[89]	[0.3;3]	36.1
$pp \to H \to VV[\to (qq)(qq)]$	ATLAS	[90]	[1.2;3]	36.7
$pp \to H \to hh \to (bb)(bb)$	ATLAS	[91]	[0.3;3]	13.3
	CMS	[92]	[0.26;1.2]	35.9
$gg \to H \to hh \to (bb)(bb)$	CMS	[93]	[1.2;3]	35.9
$pp \to H \to hh[\to (\gamma\gamma)(bb)]$	ATLAS	[94]	[0.275;0.4]	3.2
$pp \to H \to hh \to (\gamma\gamma)(bb)$	CMS	[95]	[0.25;0.9]	35.9
$pp \to H \to hh \to (bb)(\tau\tau)$	CMS	[96]	[0.25;0.9]	35.9
$pp \to H \to hh \to (bb)(VV \to \ell\nu\ell\nu)$	CMS	[97]	[0.26;0.9]	36
$gg \to H \to hh[\to (\gamma\gamma)(WW)]$	ATLAS	[98]	[0.25;0.5]	13.3
$gg \to A \to hZ \to (bb)Z$	ATLAS	[99]	[0.2;2]	36.1
$b\bar{b} \to A \to hZ \to (bb)Z$	ATLAS	[99]	[0.2;2]	36.1

Channel	Experiment		Mass range [TeV]	$\mathcal{L}$ [fb^{-1}]
$pp \to H^\pm \to \tau^\pm\nu$	ATLAS	[100]	[0.2;2]	14.7
	CMS	[101]	[0.18;3]	12.9
$pp \to H^+ \to t\bar{b}$	ATLAS	[102]	[0.3;1]	13.2
	ATLAS	[103]	[0.2;0.3]∪[1;2]	13.2

Yukawa interactions

$$- Y_{b,1}\bar{Q}_L\Phi_1 b_R - Y_{b,2}\bar{Q}_L\Phi_2 b_R - Y_{\tau,1}\bar{L}_L\Phi_1\tau_R - Y_{\tau,2}\bar{L}_L\Phi_2\tau_R + \text{h.c.}$$

Type II	Type X (“lepton specific”)	Type Y (“flipped”)
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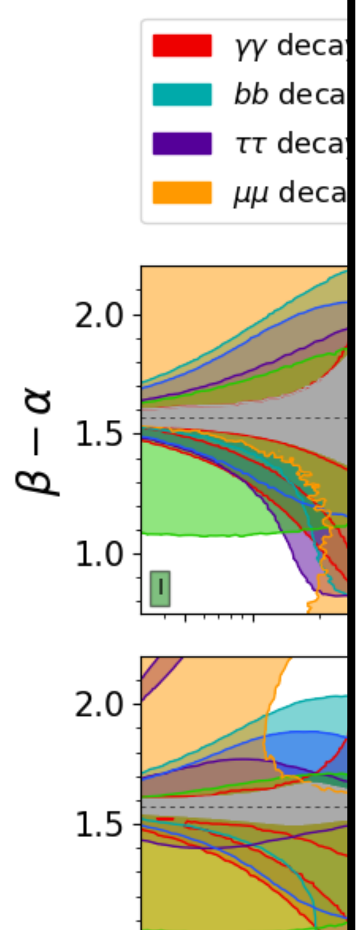
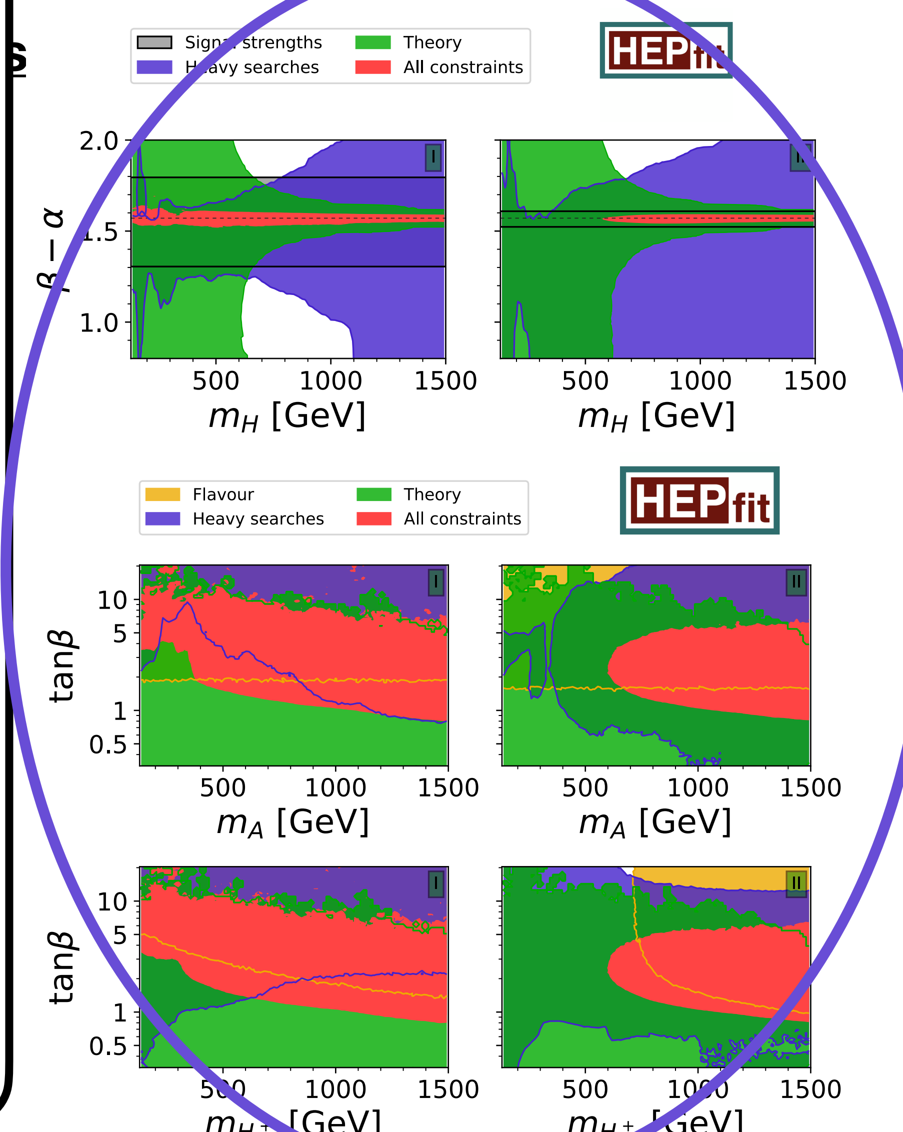
$Y_{b,1} = Y_b^{\text{SM}}/\cos\beta$	$Y_{b,2} = Y_b^{\text{SM}}/\sin\beta$	$Y_{b,1} = Y_b^{\text{SM}}/\cos\beta$
$Y_{\tau,1} = Y_\tau^{\text{SM}}/\cos\beta$	$Y_{\tau,1} = Y_\tau^{\text{SM}}/\cos\beta$	$Y_{\tau,2} = Y_\tau^{\text{SM}}/\sin\beta$





See J. Tao’s talk for the updates on new Higgs Boson searches

D. Chowdhury, O. Eberhardt, JHEP 05 (2018) 161, arXiv: 1711.02095 [hep-ph]

Two-Higgs Doublet Models

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Physical: $h, H, A, H^\pm$

Goldstones: $G, G^\pm$

Yukawa interactions

$$\mathcal{L}_Y = -Y_t \bar{Q}_L i\sigma_2 \Phi_2^* t_R - Y_{b,1}\bar{Q}_L \Phi_1 b_R - Y_{b,2}\bar{Q}_L \Phi_2 b_R - Y_{\tau,1}\bar{L}_L \Phi_1 \tau_R - Y_{\tau,2}\bar{L}_L \Phi_2 \tau_R + \text{h.c.}$$

Type I	Type II	Type X ("lepton specific")	Type Y ("flipped")
$Y_{b,1} = Y_{\tau,1} = 0$	$Y_{b,2} = Y_{\tau,2} = 0$	$Y_{b,1} = Y_{\tau,2} = 0$	$Y_{b,2} = Y_{\tau,1} = 0$
$Y_{b,2} = Y_b^{SM}/\sin\beta$	$Y_{b,1} = Y_b^{SM}/\cos\beta$	$Y_{b,2} = Y_b^{SM}/\sin\beta$	$Y_{b,1} = Y_b^{SM}/\cos\beta$
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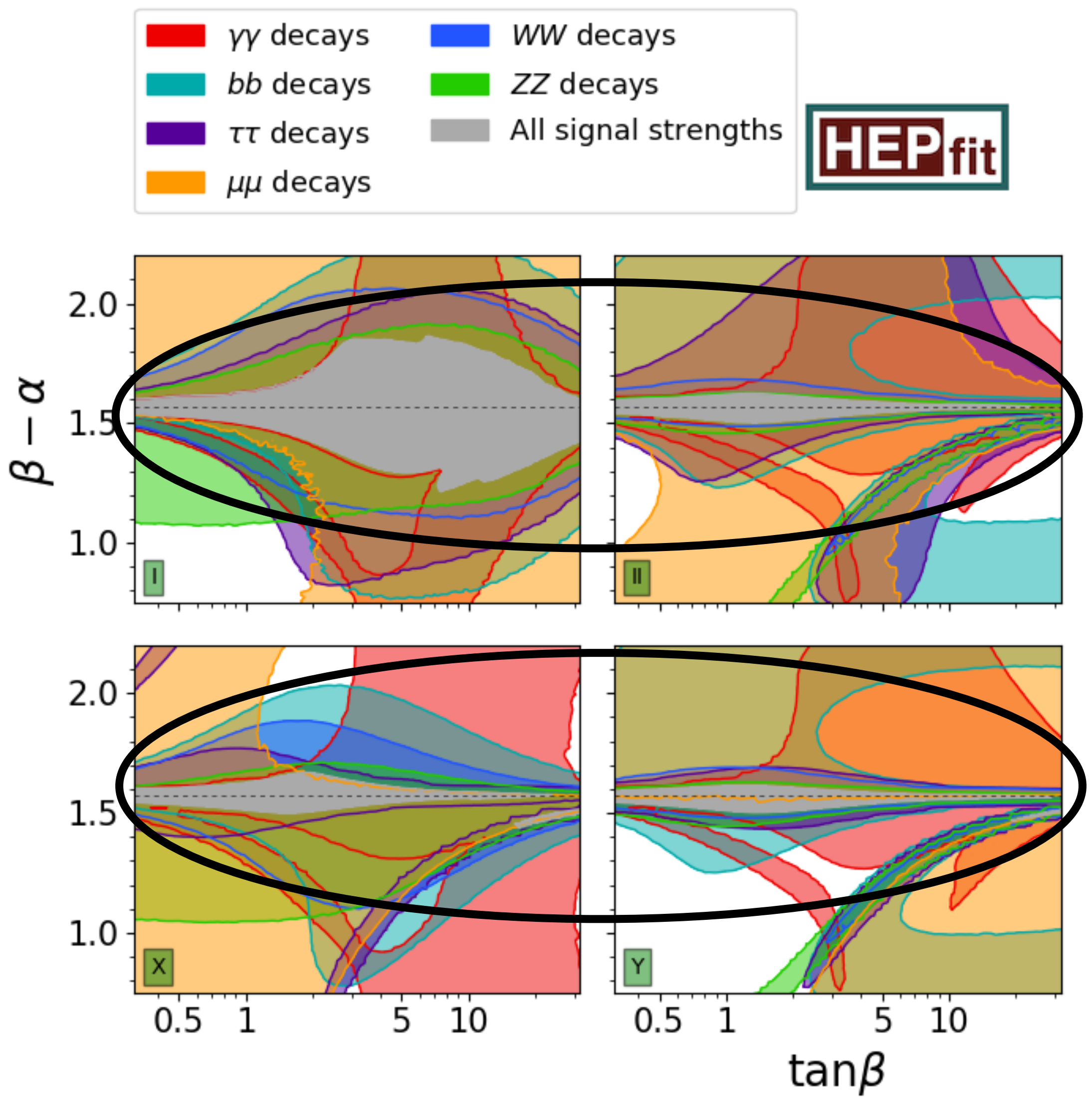
Experimental constraints

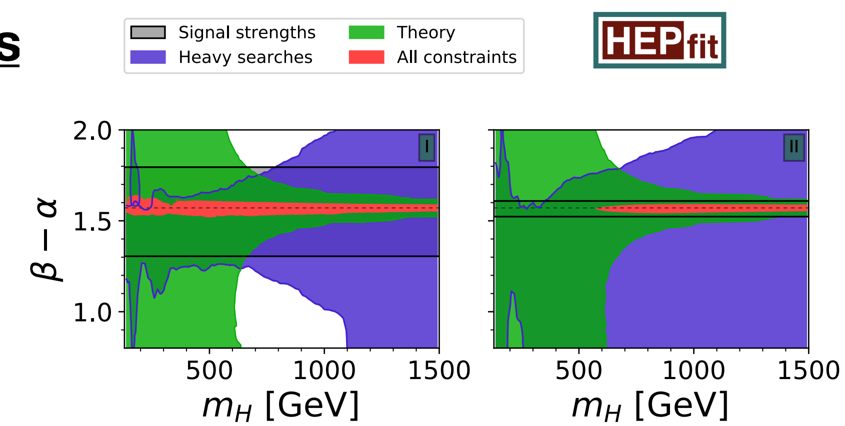


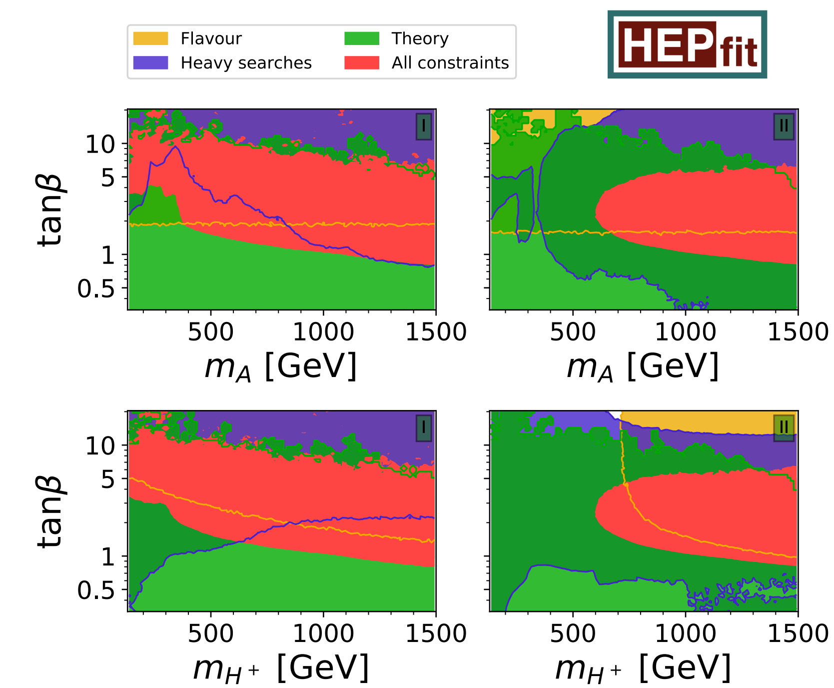
Higgs signal strengths (LHC Run 1 + Run 2 [36 fb^{-1}]) push THDM towards alignment limit

$$|\cos(\beta-\alpha)| \ll 1$$

e.g. for type II (type I)

$$|\cos(\beta-\alpha)| < 0.05\ (0.26)$$





D. Chowdhury, O. Eberhardt, JHEP 05 (2018) 161, arXiv: 1711.02095 [hep-ph]

Two-Higgs Doublet Models

- THDM (with softly broken Z_2 symmetry):

Scalar Sector

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i + \phi_i^0 + iG_i}{\sqrt{2}} \end{pmatrix}$$

$$t_\beta \equiv \tan\beta \equiv \frac{v_2}{v_1}$$

$$\begin{aligned} \Phi_1^\pm &= c_\beta G^\pm - s_\beta H^\pm\,, \\ \Phi_2^\pm &= s_\beta G^\pm + c_\beta H^\pm\,, \\ \Phi_1^0 &= \tfrac{1}{\sqrt{2}}\left[v_1 + c_\alpha H - s_\alpha h + i c_\beta G - i s_\beta A\right] \\ \Phi_2^0 &= \tfrac{1}{\sqrt{2}}\left[v_2 + s_\alpha H + c_\alpha h + i s_\beta G + i c_\beta A\right] \end{aligned}$$

Physical: $h, H, A, H^\pm$
Goldstones: $G, G^\pm$

Yukawa interactions

$$\mathcal{L}_Y = -Y_t \overline{Q}_L i\sigma_2 \Phi_2^* t_R - Y_{b,1}\overline{Q}_L \Phi_1 b_R - Y_{b,2}\overline{Q}_L \Phi_2 b_R - Y_{\tau,1}\overline{L}_L \Phi_1 \tau_R - Y_{\tau,2}\overline{L}_L \Phi_2 \tau_R + \text{h.c.}$$

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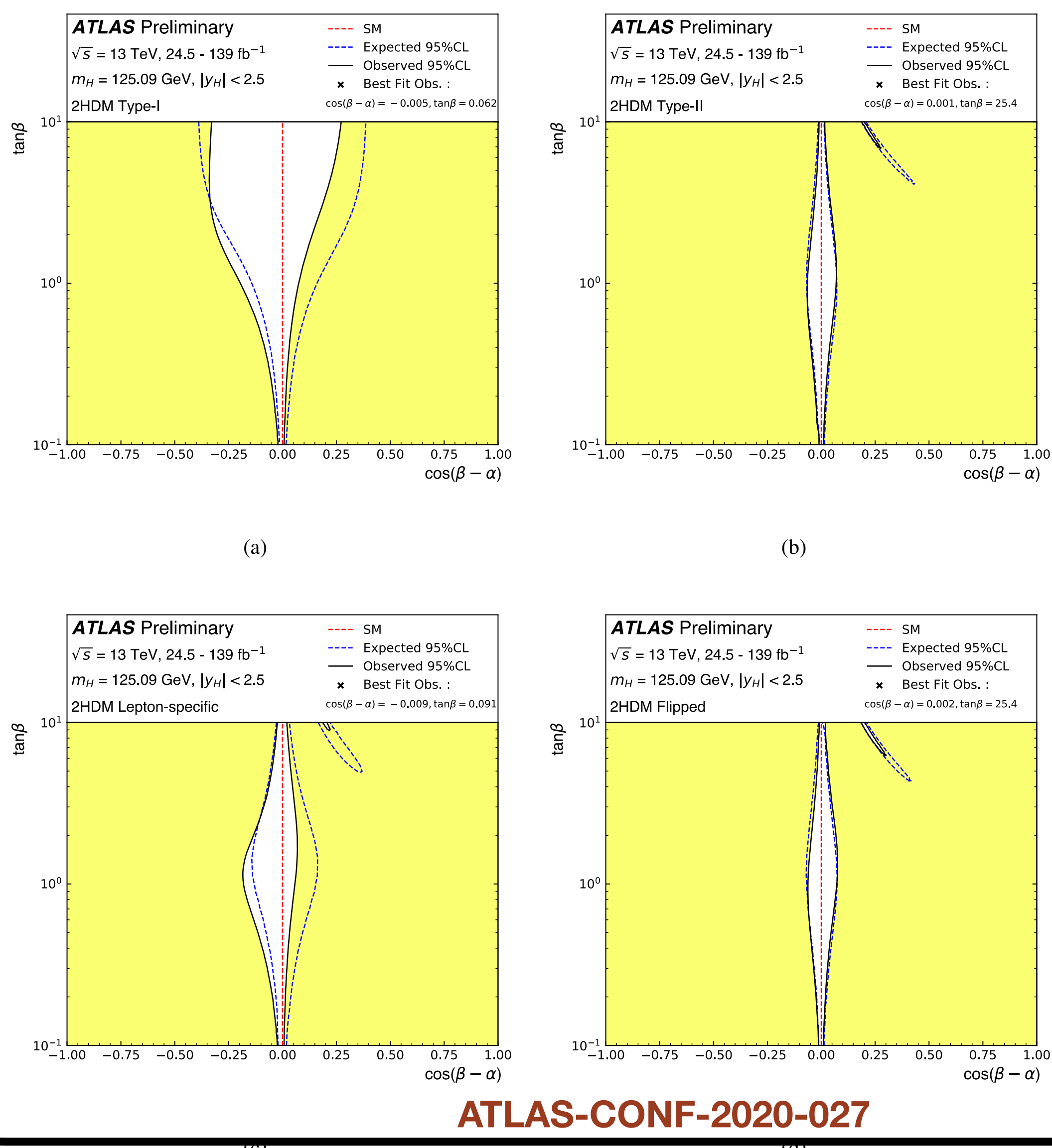

ATLAS-CONF-2020-027

Experimental constraints

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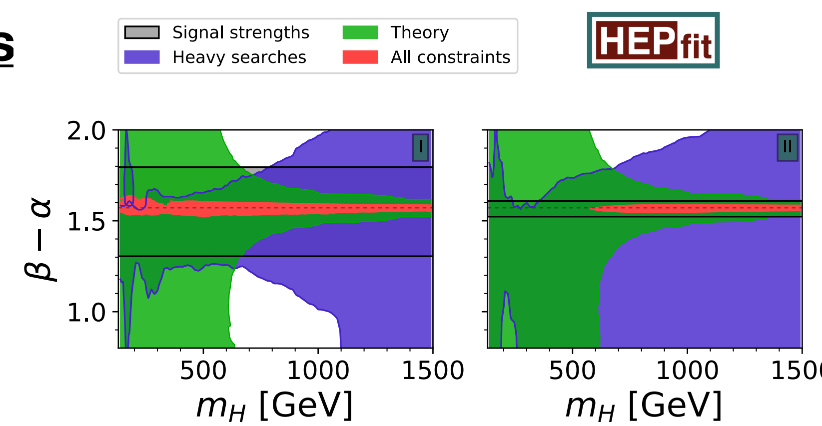
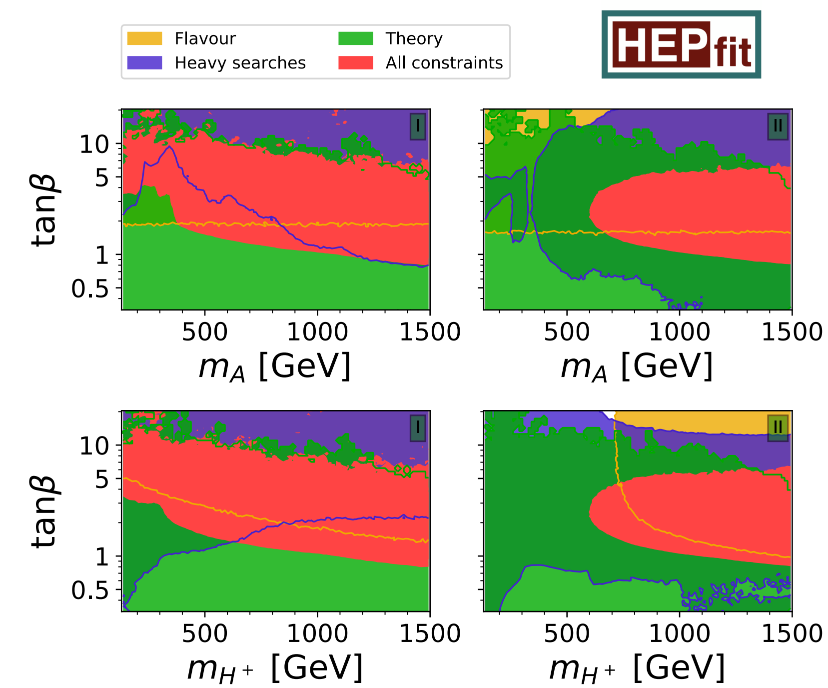
$$|\cos(\beta - \alpha)| \ll 1$$

e.g. for type II (type I)

$$|\cos(\beta - \alpha)| < 0.05\ (0.26)$$

Similar results using ATLAS full Run 2 data ALONE





Axion-Like Particles (ALPs)

- Light, gauge-singlet pseudo-scalar particles arising as:
  - ✓ PQ solutions to strong CP problem (the original QCD axion)
  - ✓ pNBG of spontaneously broken global symmetries in extensions of the SM, e.g. in composite Higgs models
  - ✓ Dark Matter candidates or mediators

- Leading dim ≤ 6 axion interactions with SM particles

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f + g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A}$$
$$+\,e^2\,C_{\gamma\gamma}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\,C_{\gamma Z}\,\frac{a}{\Lambda}\,F_{\mu\nu}\,\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\,C_{ZZ}\,\frac{a}{\Lambda}\,Z_{\mu\nu}\,\tilde{Z}^{\mu\nu}\,,$$

$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}}{\Lambda^3}\,(\partial^\mu a)\left(\phi^\dagger\,iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

See also P. Foldenauer's talk

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Axion decays, e.g.

$$a \to \gamma\gamma$$

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Axion production in Higgs decays

$$h \to aa,\ Za$$

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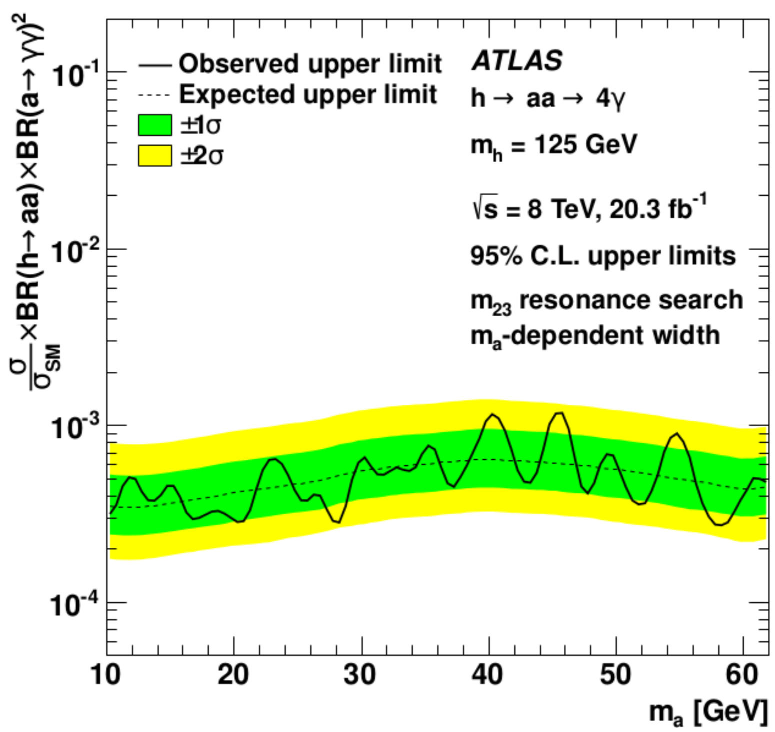
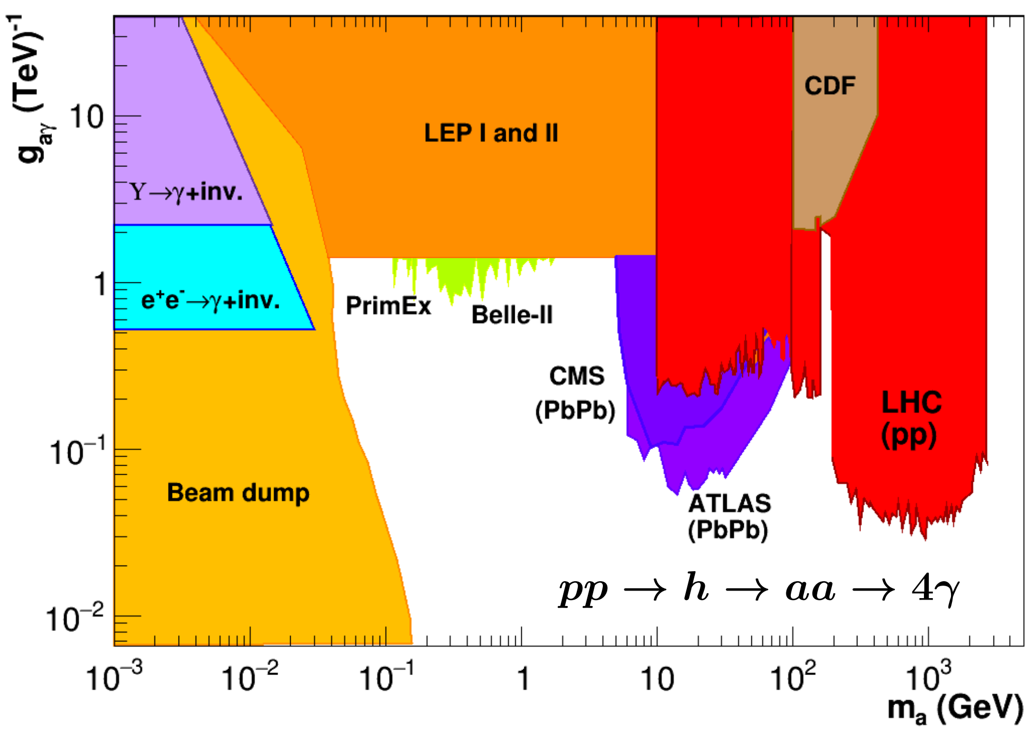
Testable at LHC in exotic Higgs decays





D. d'Enterria, arXiv: 2102.08971 [hep-ex]

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- Leading dim ≤ 6 axion interactions with SM particles

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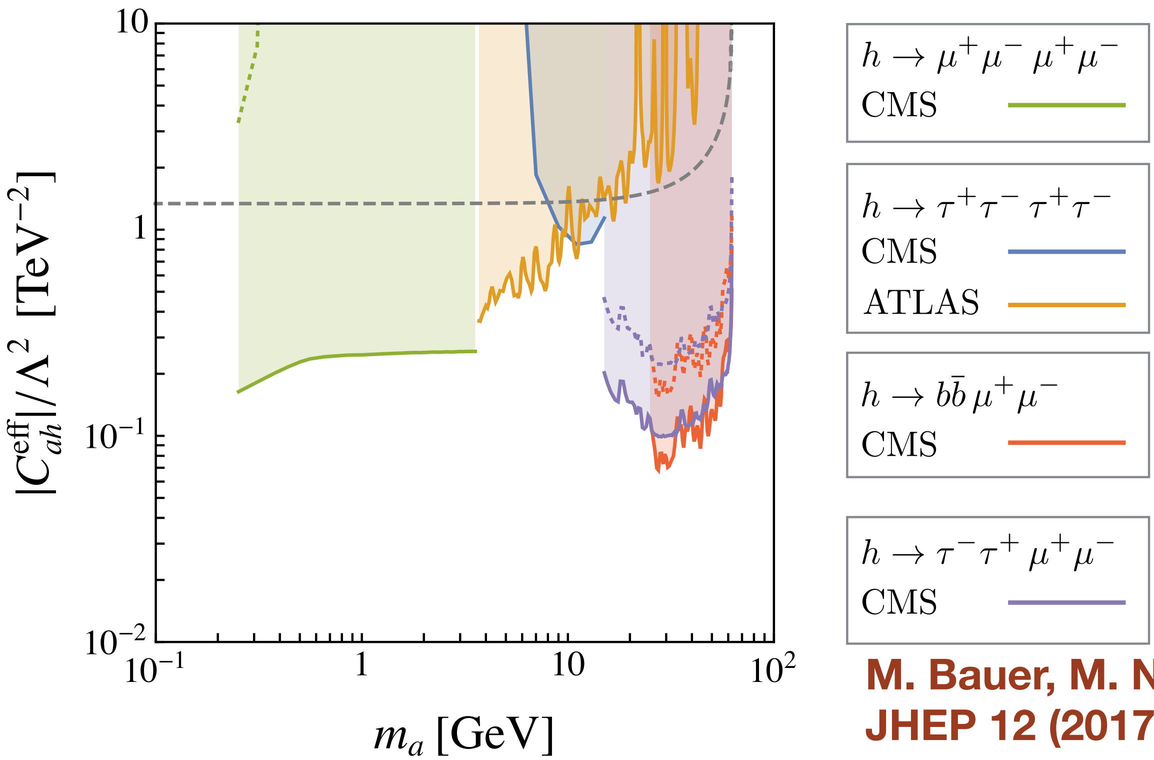
Axion production in Higgs decays

$h \to aa,\; Za$

Testable at LHC in exotic Higgs decays

Dedicated $h \to aa$ searches



See also
K. Schmieden's an I.Riu's talks

M. Bauer, M. Neubert, A. Thamm,
JHEP 12 (2017) 044, arXiv: 1708.00443 [hep-ph]

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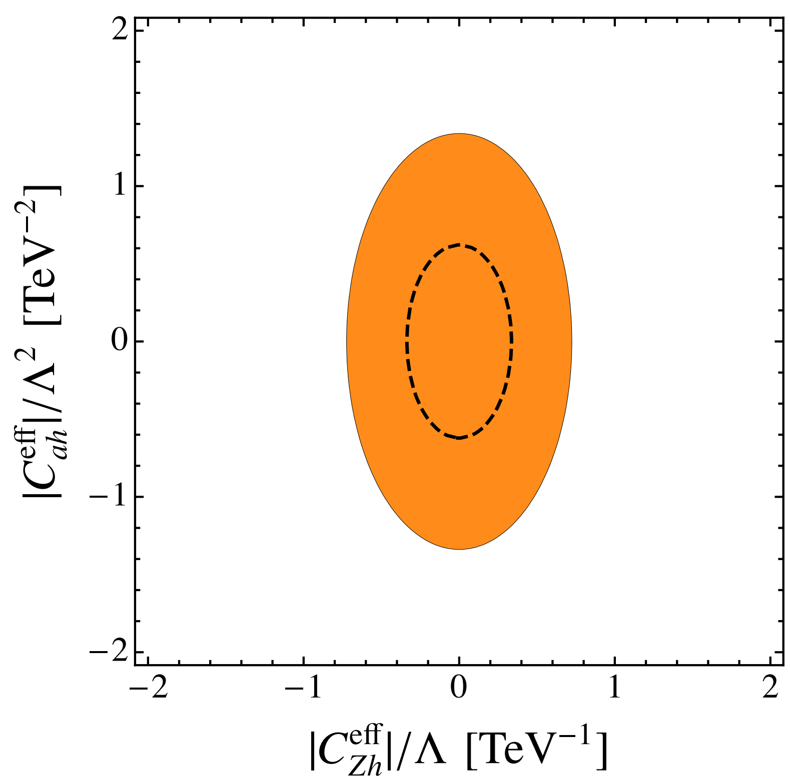


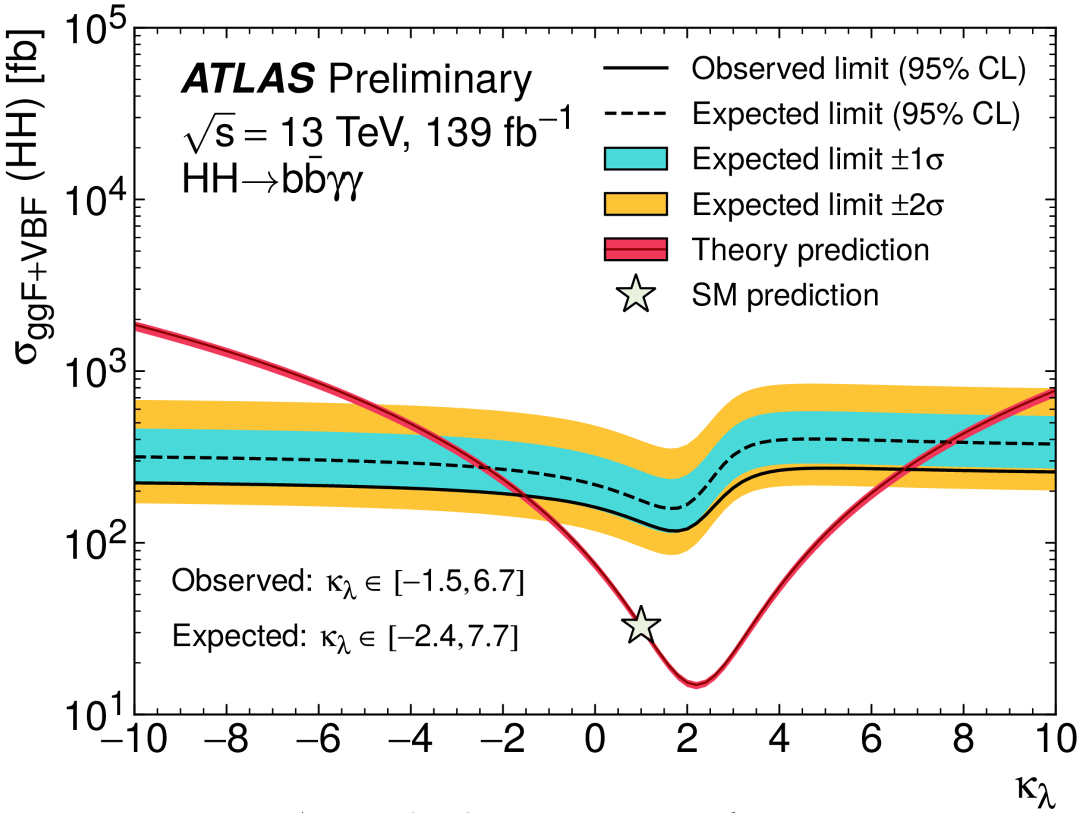
From ATLAS+CM Run 1 combination:
Br(h→BSM)<0.32 at 95% prob. (Outdated)

e.g. ATLAS Run 2 (ATLAS-CONF-2020-027):
Br(h→BSM)<0.19 at 95% prob.

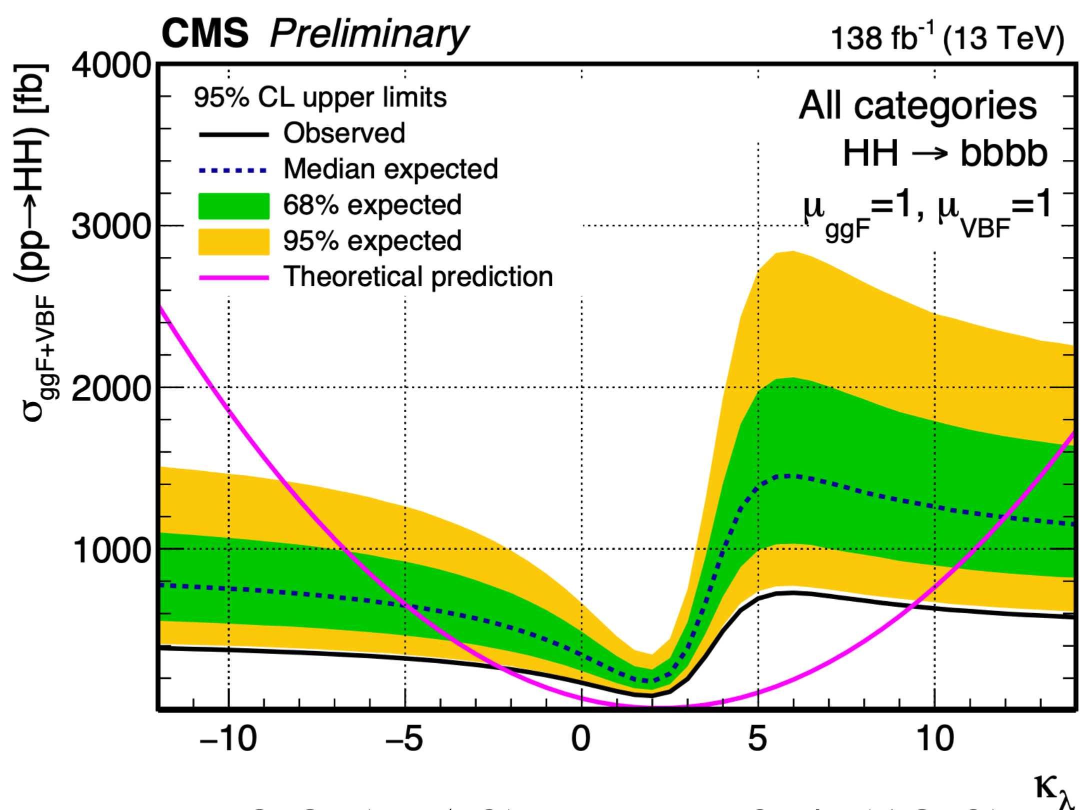
M. Bauer, M. Neubert, A. Thamm,
JHEP 12 (2017) 044, arXiv: 1708.00443 [hep-ph]

Two slides on Higgs pair production and BSM

- The measurement of the Higgs self-interaction is directly connected to our understanding of EWSB and can have important implications from the point of view of, e.g. EW baryogenesis
- Higgs pair production is a difficult process to measure at the LHC



$$-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$$



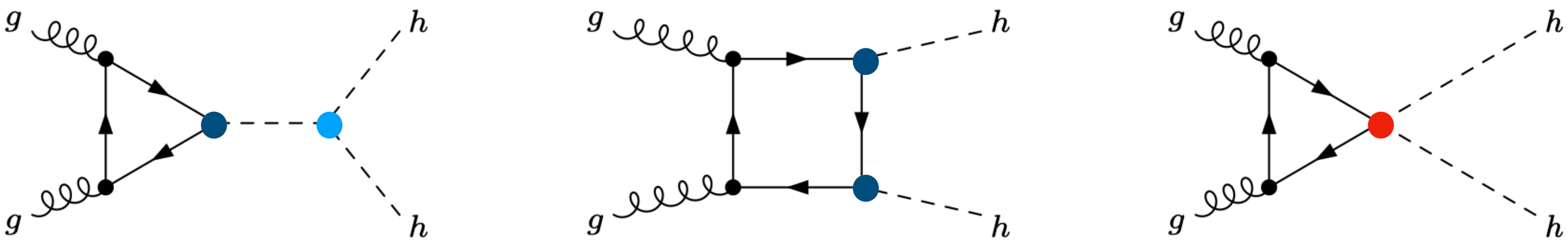
$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$

See L. Pereira's and P. Bortignon's talks

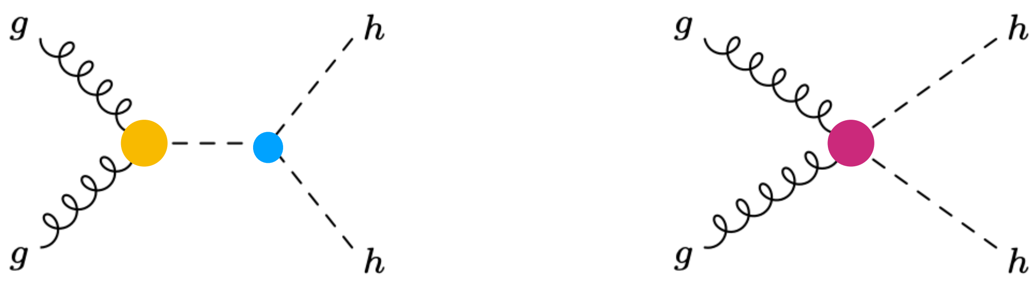
HL-LHC projection (3 ab⁻¹): $0.52 \le \kappa_\lambda \le 1.5$ **68% prob.**

Two slides on Higgs pair production and BSM

- New physics effects can enter the process in many different places, affecting the hh distributions, e.g. in the SMEFT:



Most of these interactions can be better measured in other processes, using SMEFT correlations, with the exception of the h³ coupling



From R. Groeber's talk

- But from the point of view of models of naturalness, the bounds from single Higgs couplings dominate over any limit from hh that will be set at the (HL-)LHC

- Similarly, for models of the EWPT, large (tree-level) contrib. to $O_6 = (H^\dagger H)^3$ always come with other operators at the same order
  - ✓ Exceptions: Custodial scalar quadruplets or fermio-phobic scalar doublets

M. Chala et al. , JHEP 07 (2018) 062

hh at (HL-)LHC could still provide some limited sensitivity to this type of scenarios

Summary

Summary

- Despite the LHC success in finding the Higgs boson, new physics beyond the Standard Model (BSM) still proves to be elusive to existing searches
- Such searches, however, provide valuable information to constraint many of the ideas that theorist have proposed to address the problems of the SM
- In particular, LHC Higgs physics provides crucial information to constrain solutions to the hierarchy problem:
  - ✓ The consistency of the Higgs couplings with the SM predictions imposes some of the strongest bounds on these scenarios
  - ✓ Direct searches for exotic decays and non-SM extra scalars keep also pushing the scale of new physics
- In this talk I have presented some of the implications of current LHC measurements of the Higgs properties on different BSM scenarios
- With the Run 3, and the future HL-LHC we are entering the LHC precision era for measurements of the Higgs properties
  - ✓ Indirect constraints will become more relevant…
  - ✓ …and hence also the precision with which we know the SM
  - ✓ The (SM) theory role: to keep learning from BSM it is crucial to keep improving our SM calculations!

See B. Mistlberger's talk

Backup Slides

Modified Higgs couplings: The κ framework

- Compact parameterisation of new physics in single Higgs processes:

$$(\sigma \cdot \mathrm{BR})(i \to H \to f) = \kappa_i^2 \sigma^{\mathrm{SM}}(i \to H) \frac{\kappa_f^2 \Gamma^{\mathrm{SM}}(H \to f)}{\Gamma_H}$$

$$\Gamma_H = \Gamma_H^{\mathrm{SM}} \frac{\sum_i \kappa_i^2 \mathrm{BR}_i^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{inv}} - \mathrm{BR}_{\mathrm{unt}}}$$

- **κ_i interpreted as modified Higgs couplings** + describes non-SM decays

  ✓ No BSM calculation needed per se

  ✓ Applicable to a good approximation to interesting NP scenarios (e.g. Composite Higgs, MSSM)

  ✓ Limited to single Higgs processes and total rates (no kinematics)

  ✓ No consistent Lagrangian/EFT interpretation in the general case (i.e. with general $\kappa_{g,\gamma,Z\gamma}$)

Modified Higgs couplings: The κ framework

- **Fits to LHC Higgs observables:** Run 1 + Run 2 (~36-140 fb^{-1})

Custodial + Universal fermion interactions

	Fit result	95% Prob.	Correlations	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	0.96 ± 0.03	[0.89, 1.02]	0.36	1.00

Non custodial + non universal fermion interactions

	Fit result	95% Prob.
κ_W	1.03 ± 0.04	[0.95, 1.10]
κ_Z	0.99 ± 0.04	[0.90, 1.07]
κ_t	0.98 ± 0.04	[0.89, 1.06]
κ_b	0.96 ± 0.08	[0.80, 1.12]
κ_μ	1.02 ± 0.18	[0.65, 1.38]
κ_τ	0.90 ± 0.07	[0.77, 1.04]

Non custodial + non universal fermion interactions
+ independent κ for rad. processes

	Fit result	95% Prob.
κ_W	1.05 ± 0.04	[0.96, 1.13]
κ_Z	0.99 ± 0.04	[0.89, 1.07]
κ_g	1.01 ± 0.05	[0.91, 1.11]
κ_γ	1.04 ± 0.05	[0.94, 1.13]
$\kappa_{Z\gamma}$	1.29 ± 0.40	[0.39, 2.04]
κ_t	0.94 ± 0.06	[0.82, 1.05]
κ_b	0.99 ± 0.09	[0.82, 1.17]
κ_μ	1.02 ± 0.19	[0.64, 1.38]
κ_τ	0.93 ± 0.07	[0.79, 1.08]

Two-Higgs Doublet Models

- "Flavour-Aligned" THDM:

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + S_1 + i\,G^0) \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + i\,S_3) \end{bmatrix},$$

Physical CP-even neutral scalars

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\tilde\alpha & \sin\tilde\alpha \\ -\sin\tilde\alpha & \cos\tilde\alpha \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}$$

General scalar Potential

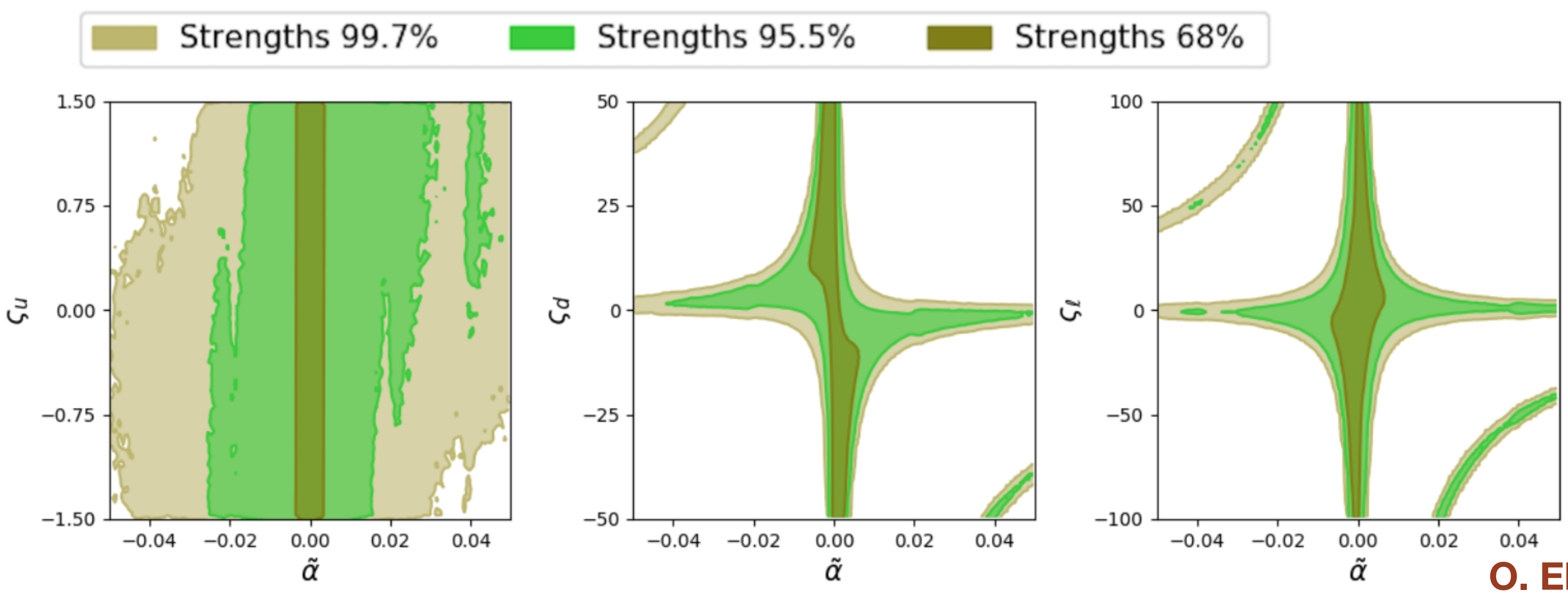
$$\begin{aligned} V &= \mu_1\,\Phi_1^\dagger\Phi_1 + \mu_2\,\Phi_2^\dagger\Phi_2 + \left[\mu_3\,\Phi_1^\dagger\Phi_2 + \mu_3^*\,\Phi_2^\dagger\Phi_1\right] \\ &+ \tfrac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \tfrac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ &+ \left[\left(\tfrac{1}{2}\lambda_5\,\Phi_1^\dagger\Phi_2 + \lambda_6\,\Phi_1^\dagger\Phi_1 + \lambda_7\,\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right], \end{aligned}$$

Assume Yukawa interactions "aligned" in flavour space

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= -\frac{\sqrt{2}}{v} H^+ \left\{\bar u \left[\varsigma_d V_{\rm CKM} M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V_{\rm CKM}\mathcal{P}_L\right] d + \varsigma_\ell\,\bar\nu M_\ell \mathcal{P}_R \ell\right\} \\ &- \frac{1}{v}\sum_{i,f} y_f^{\varphi_i^0}\,\varphi_i^0\,\left[\bar f M_f \mathcal{P}_R f\right] + \text{h.c.}\,, \qquad \varphi_i^0 = h, H, A \end{aligned}$$

SM-like Higgs couplings: Fit to LHC signal strengths

$$g_{hVV} = \cos\tilde\alpha\; g_{hVV}^{\rm SM} \qquad y_{d,\ell}^h = \cos\tilde\alpha + \sin\tilde\alpha\;\varsigma_{d,\ell}\,, \qquad y_u^h = \cos\tilde\alpha + \sin\tilde\alpha\;\varsigma_u^*\,,$$



Most LHC Higgs observables not sensitive to sign of Yukawas → 2 types of solutions $y_f^h \approx \pm 1$

For the "right-sign" solution

$$|\tilde\alpha| \le 0.003 \quad (68\%\ \text{probability}),$$
$$|\tilde\alpha| \le 0.023 \quad (95.5\%\ \text{probability}).$$

O. Eberhardt et al. arXiv: 2012.09200 [hep-ph]