Extended Scalar Sectors From All Angles

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Europe/Zurich timezone

"Accidental" Suppression of Wilson Coefficients in Higgs Coupling

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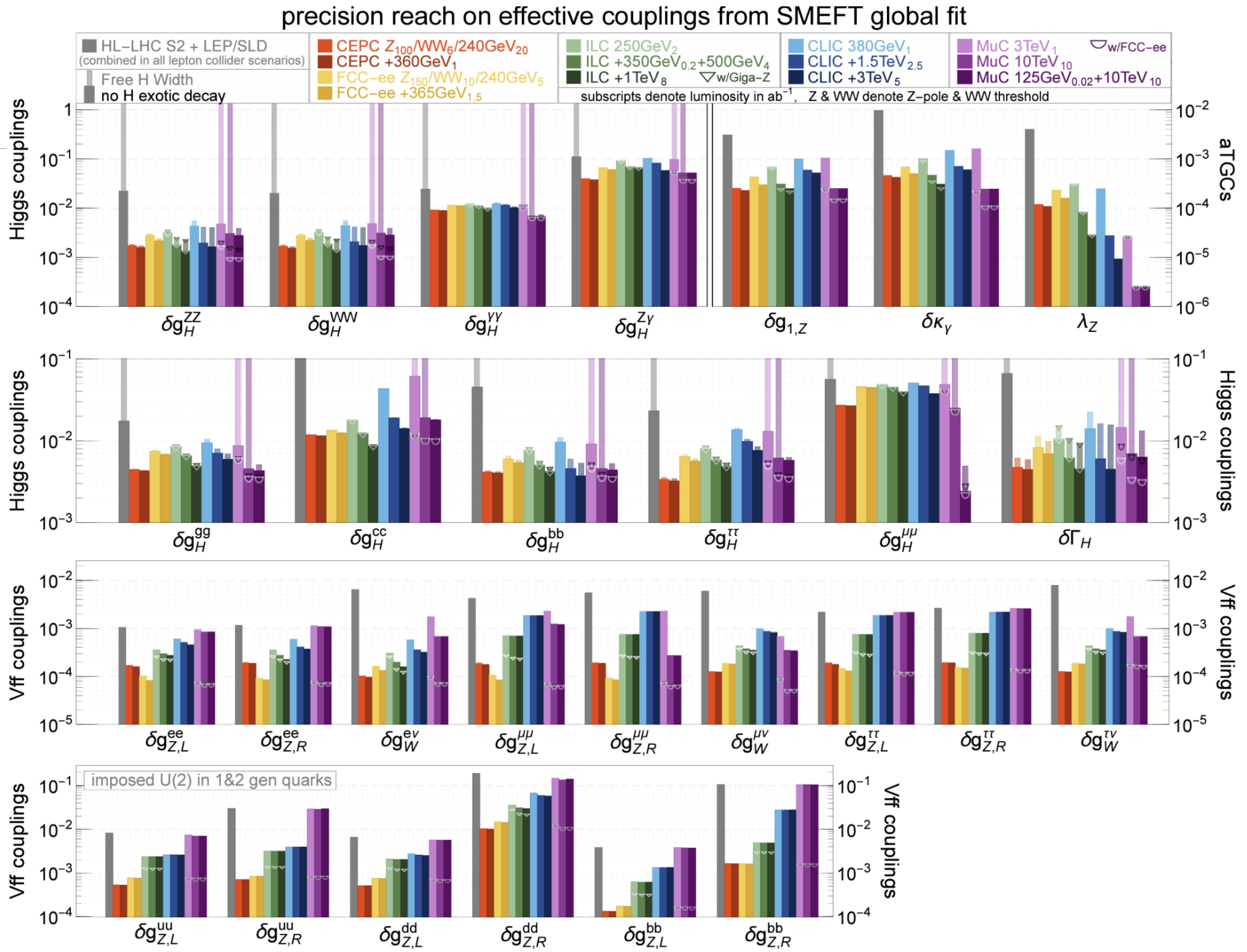
Mainly based on
Bao, Gu, ZL, Shu, Wang, 2408.08948

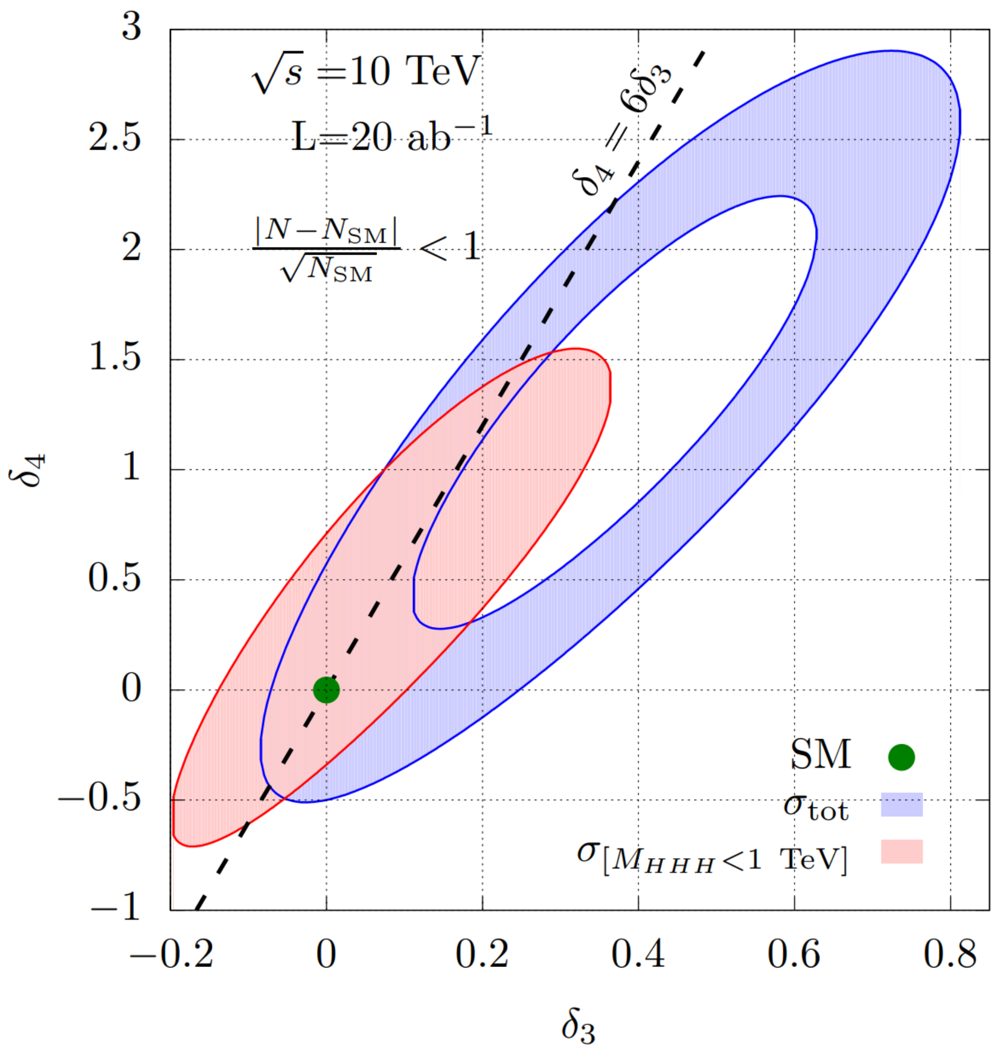
Higgs Precision

Higgs precision is one of the core physics programs for the current and any future colliders. Its precision often interpreted in bar plots with EFT picture behind.



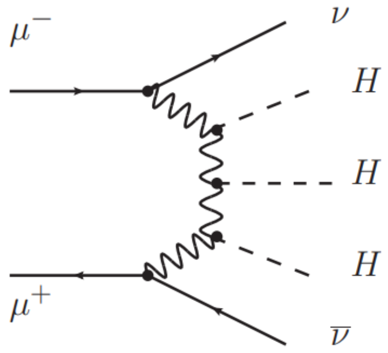
de Blas et al 2206.08326

Multi-Higgs & Higgs Self-couplings are particularly interesting

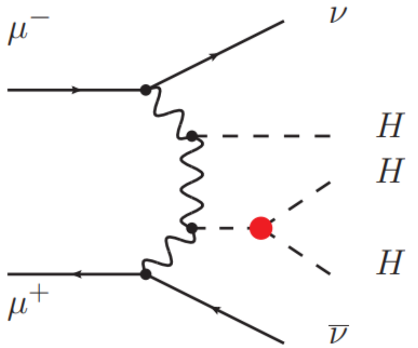


O(1) quartic determination possible.

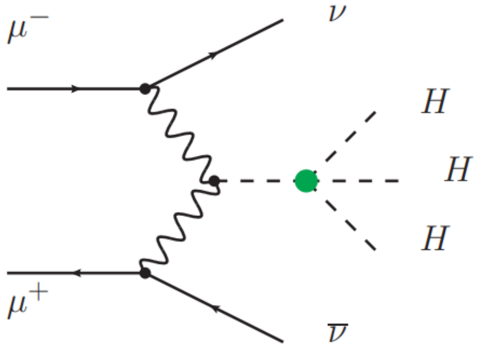
Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.13628



Correlated measurements of trilinear and quartic couplings reveals deep information about EFT and EWPT.

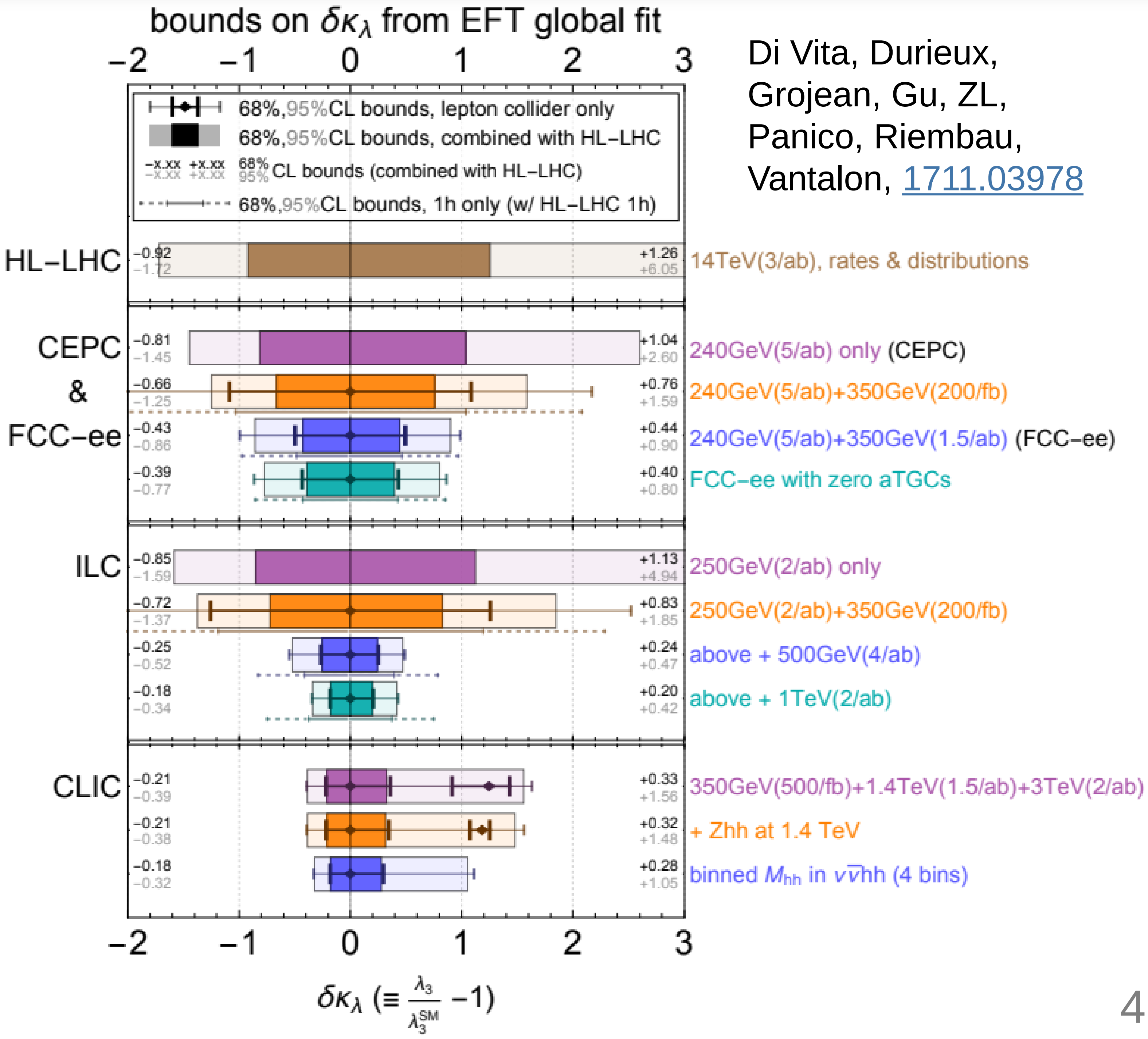


e.g, Huang, Joglekar, Wagner, 1512.00068, Falkowski, Gonzalez-Alonso, Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012; T. Han, D. Liu, I. Low, X. Wang, 2008.12204, 2312.07670.



HH@ Current and Future Colliders

- Other precision inputs and constraints are needed for trilinear extraction if one turns on a few couplings or with a given model;
- Single H allows consistent trilinear precision O(40%)
- Double H and differential crucial to reach O(10%)
- High Energy will do better (hopefully O(%) but studies are missing)



Di Vita, Durieux, Grojean, Gu, ZL, Panico, Riembau, Vantalon, 1711.03978

The BSM-driven EFT Pattern Matters

- Different BSM models give raise to different EFTs, with hierarchies between the Wilson coefficients, e.g., SILH
- The pattern gives raise different emphasis on observables, e.g., single Higgs coupling observables/precision, multi-Higgs productions.
- The EFT approach and direct BSM (resonance) searches complement each other.
- Do we have untuned/generic cases where Higgs self-coupling modifications are the most important observables?

Higgs Couplings with EWPT or Dark Sector

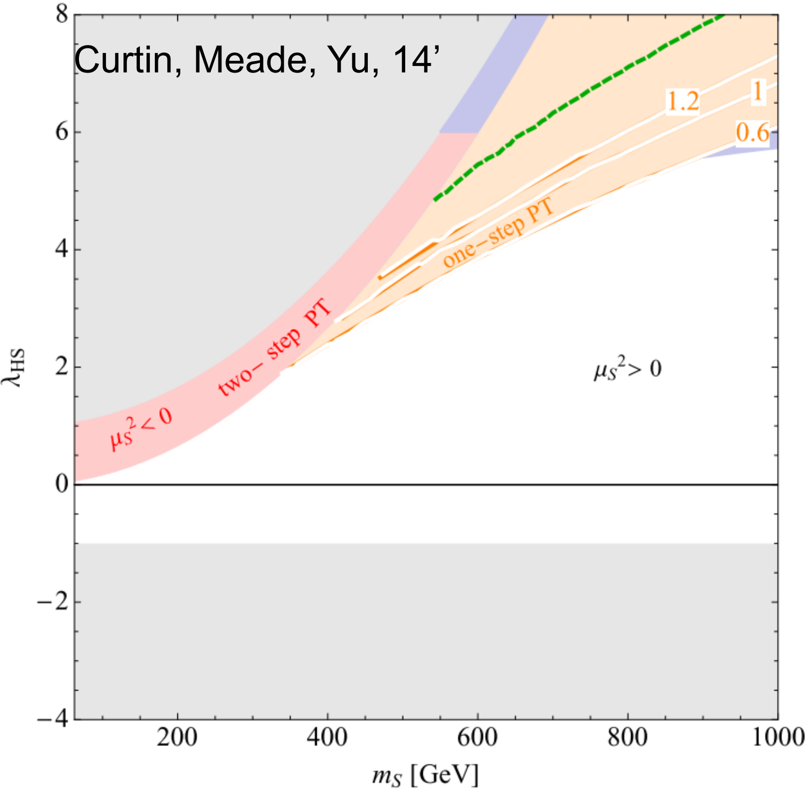
- Dark Sector if gauged, typically Higgsed. The dark Higgs will talk our SM Higgs through the portal;
- Enhancing the electroweak phase transition (EWPT) requires modifications to the Higgs potential, one of the easiest example is through other scalar fields, and one cannot forbid the Higgs portal coupling.

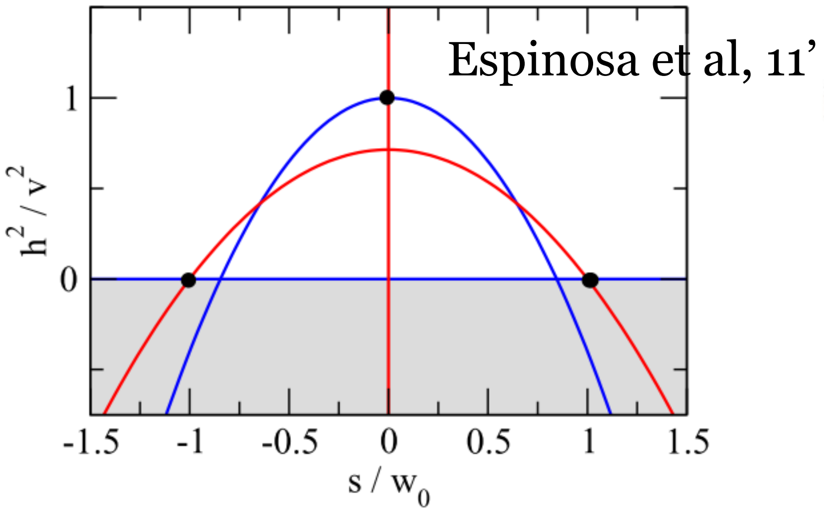
Enhancing EWPT

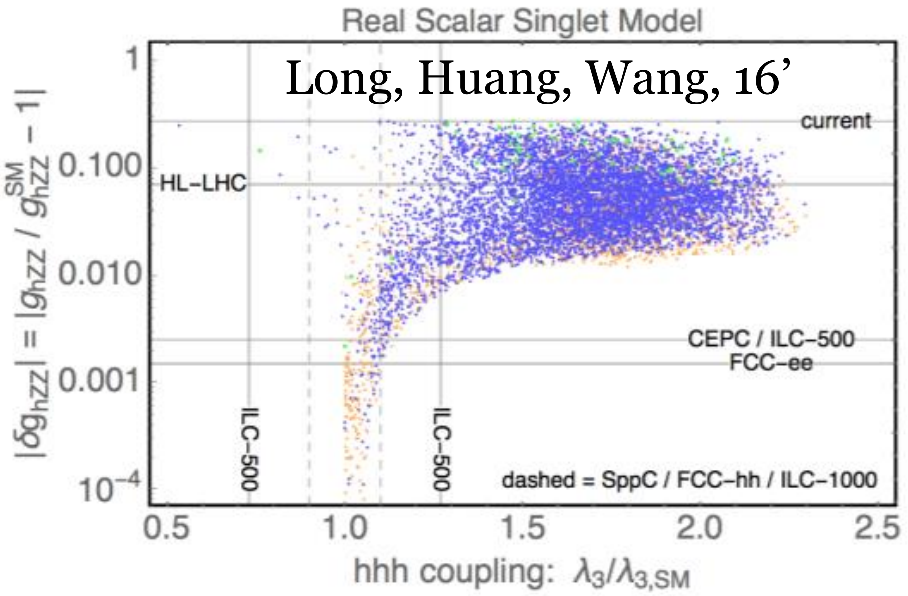
One of the most generic extensions to Enhance EWPT;
An important benchmark to understand;

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

$$+(\text{explicit Z2} - \text{breaking terms})$$







also Ramsey-Musolf et al, 09'

Spontaneous Z2 breaking Singlet Extension: a special case

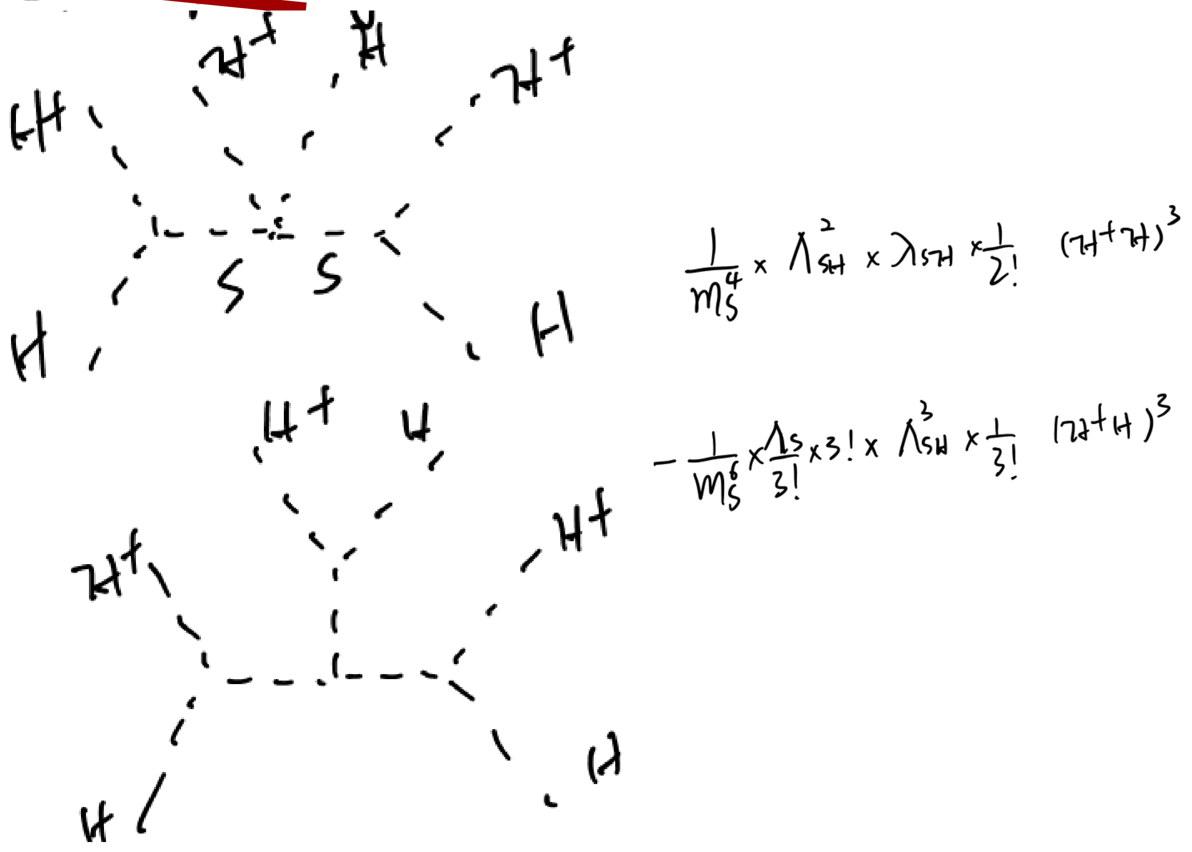
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

Z2: S→-S

$$+(\text{explicit Z2} - \text{breaking terms})$$

One can also get a feeling of the challenge by performing the usual EFT analysis:

- **tree-level** integrate out of the singlet at the broken phase generates $(H^+H)^3$;
- Operator generated only at loop-level, insufficient modify the Higgs potential enough to enhance the EWPT



We also explored the above EFT in our S->hh on-shell interference study, Carena, ZL, Riembau 1801.00794.This renders Spontaneous broken case hard to enhance EWPT through the usual way, we found other ways Carena, ZL, Wang, 1911.10206 and yields Higgs exotic decays, +others 2203.08206.

Generic SM Singlet EFT expectations

$$e^{i\mathcal{S}_{\mathrm{EFT}}(H)} \propto \int \mathcal{D}S \;\exp(i\mathcal{S}_{\mathrm{UV}}(H,S))$$

$$\mathcal{S}_{\mathrm{EFT}} \supset -\int \mathrm{d}^4x\, V(H, S_c(H)) \quad \text{with} \quad 0 = \left.\frac{\partial V(H,S)}{\partial S}\right|_{S=S_c(H)}$$

$$\mathcal{L}_{\mathrm{UV}} = \frac{1}{2} S\left(-\Box - m_S^2\right) S + SJ(H)$$

$$\to \mathcal{L}_{\mathrm{EFT}} = J(H)\frac{1}{-\Box - m_S^2} J(H) = -\frac{1}{2}\left(\frac{J^2}{m_S^2} + \frac{J\Box J}{m_S^4} + \ldots\right)$$

- We see direct multi-Higgs modification operators (making multi-Higgs unique)

$$O_{2n} \equiv \frac{1}{\Lambda^{2n-4}} (H^+H)^n$$

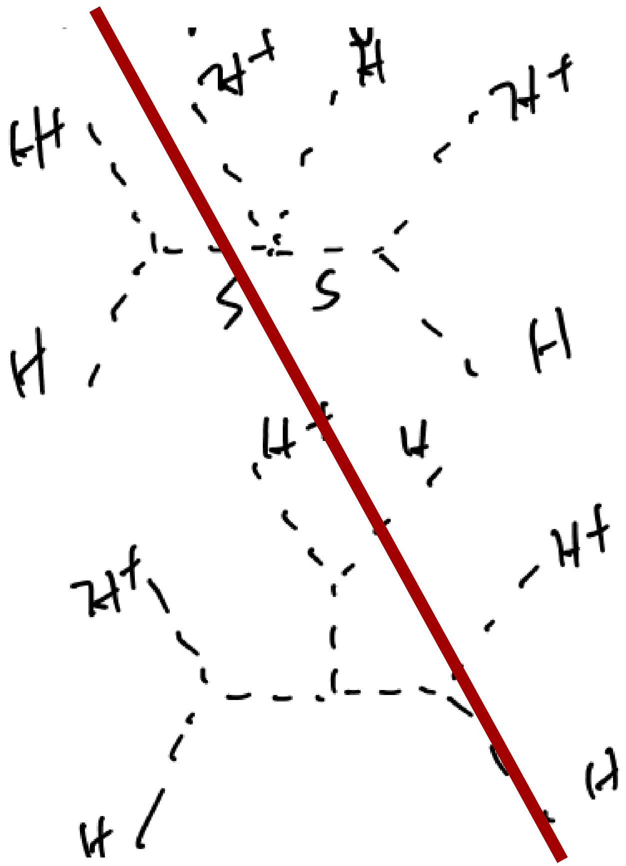
- And Higgs wave-function normalization operators (making single Higgs precision important)

$$O_{H2n} \equiv \frac{1}{\Lambda^{2n-4}} (H^+H)^{n-3} \left(\partial |H|^2\right)^2$$

One can show that all operators of the form

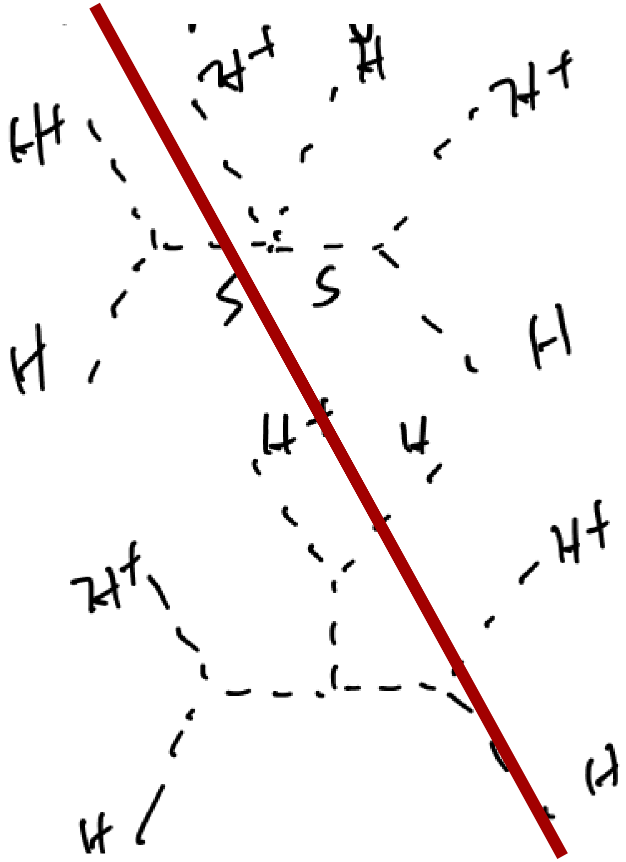
$$c_{2n} \text{ for } O_{2n} \equiv \frac{1}{\Lambda^{2n-4}} (H^{+}H)^{n}$$

vanish at tree-level. **Why?**



A first Naïve guess that the SSB “remembers” the Z2 symmetry

	c_H		c_6	
Exact $\mathbb{Z}_2$	1-loop	[eq. (3.4)]	1-loop	[eq. (3.4)]
SSB $\mathbb{Z}_2$			1-loop	[eq. (3.8)]
$\not{\mathbb{Z}}_2$	tree	[eq. (3.12)]	tree	[eq. (3.12)]



One can show that all operators of the form

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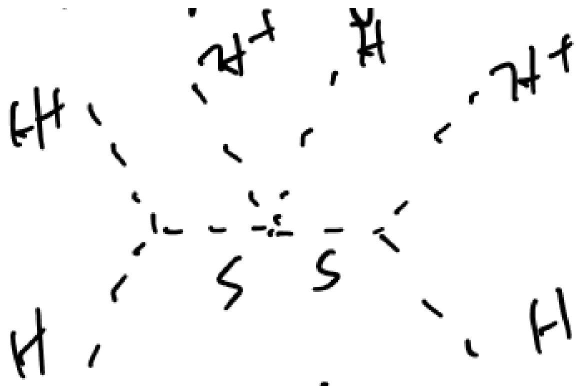
vanish at tree-level. **Why?**

But all cH(2n) operators remain

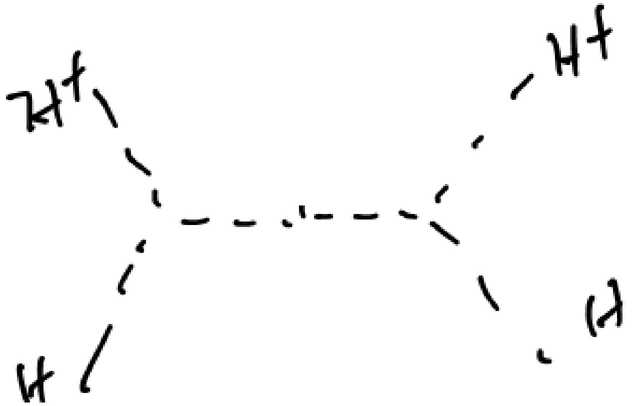
$$O_{H(2n)} \equiv \frac{1}{\Lambda^{2n-4}} (H^{+}H)^{n-3} \left(\partial |H|^2\right)^2$$

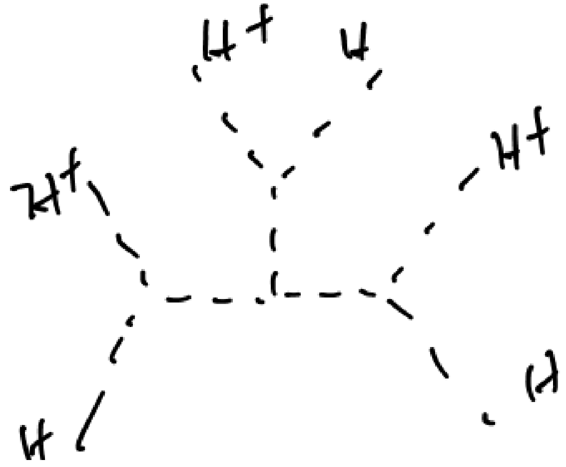
	c_H		c_6	
Exact $\mathbb{Z}_2$	1-loop	[eq. (3.4)]	1-loop	[eq. (3.4)]
SSB $\mathbb{Z}_2$	tree	[eq. (3.9)]	1-loop	[eq. (3.8)]
$\not{\mathbb{Z}}_2$	tree	[eq. (3.12)]	tree	[eq. (3.12)]



Z2 symmetry forbids these diagrams, but SSB generates modifications to Higgs wave-function normalization and quartic Higgs term (that absorbed to fix SM relations, vev and mh).

As an EFT, it is truncated series in H^4 but all orders exists for cH(2n)





Is it a simple symmetry protection?

- Both O_H (all O_{H2n}) and O_6 (all O_{2n}) are tree-level forbidden for exact Z2 models
- But only O_6 (all $O_{2n}, n \geq 3$) is forbidden with SSB
- Let me show toy examples with SSB Z2 or Zn that generates all orders in O_{H2n}, but finite O_{2n}

To see why it is not Z2

- A toy Z2 model with terms up to dim6

$$-\mathcal{L} = \mu_h^2|H|^2 + \frac{1}{2}\mu_s^2 S^2 + \frac{\lambda_h}{4}|H|^4 + \frac{\lambda_m}{2}|H|^2 S^2 + \frac{\lambda_s}{4}S^4 + \frac{\lambda_{s6}}{6}S^6 + \frac{\lambda_{h6}}{36}|H|^6 + \frac{\lambda_{s2h4}}{2}S^2|H|^4 + \frac{\lambda_{s4h2}}{4}S^4|H|^2$$

- The saddle point solution to integrate out S is

$$S_c^{(0)\,2} = -\frac{\lambda_s + \lambda_{s4h2}|H|^2}{2\lambda_{s6}} \pm \frac{\sqrt{\Delta}}{2\lambda_{s6}}$$

- So long as Δ is not a complete square, we have all the $(H^+H)^n$ operators generated.
- But if Δ is, we will have again a truncated $(H^+H)^n$ stops at n=3.

$$(\lambda_s\lambda_{s4h2} - 2\lambda_{s6}\lambda_m)^2 - (\lambda_s^2 - 4\lambda_{s6}\mu_s^2)(\lambda_{s4h2}^2 - 4\lambda_{s6}\lambda_{s2h4}) = 0$$

Or from another generic toy model

- A toy Z_n model

$$\mathcal{L}_{\rm UV} = -\frac{1}{2} S \Box S + \frac{f(H)}{n} S^n - \frac{\lambda_{2n}}{2n} S^{2n}$$

- The classical solution (if SSB) would be

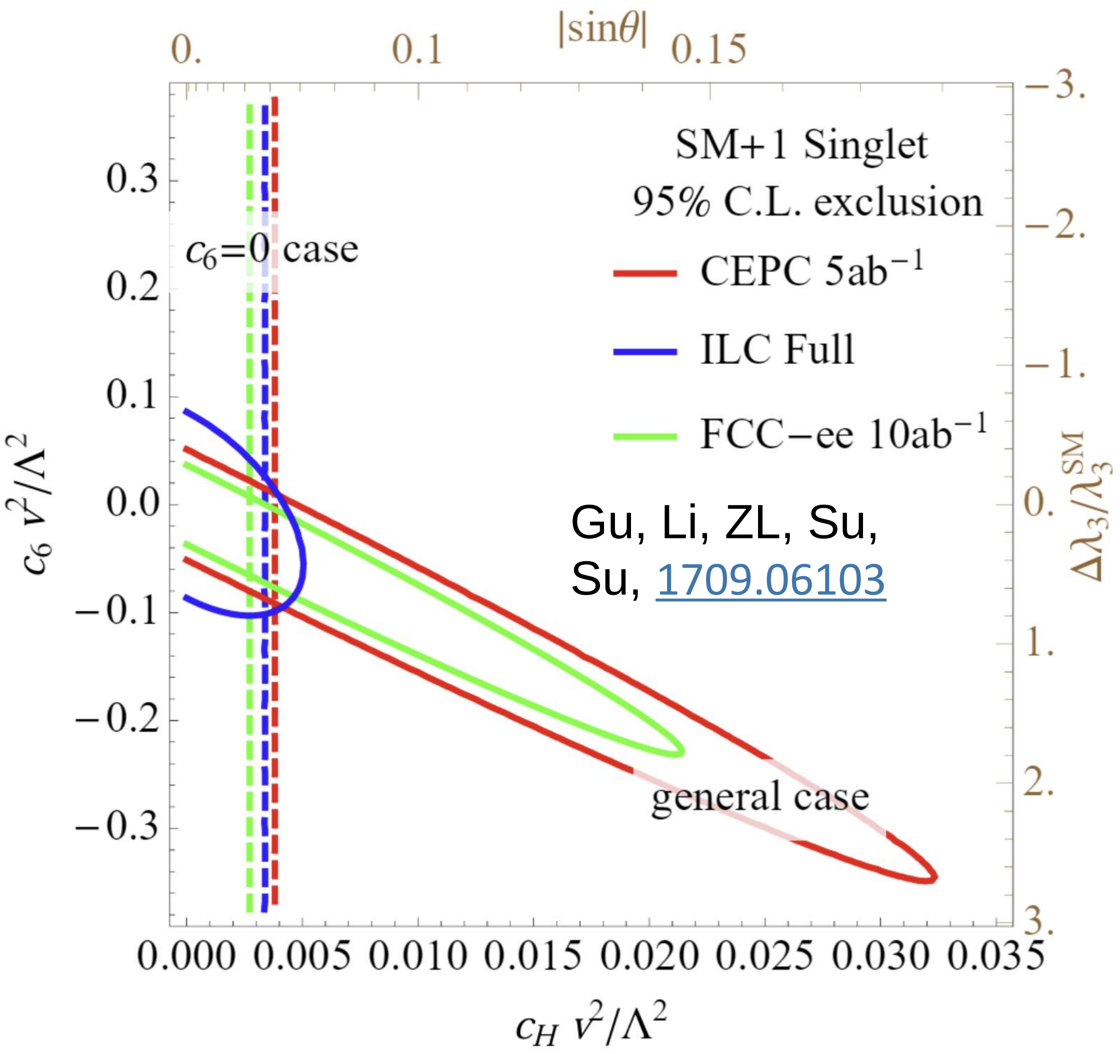
$$0 = \frac{\delta \mathcal{S}_{\rm UV}}{\delta S} = S^{n-1} \left[f(H) - \lambda_{2n} S^n \right] \implies S_c^{(0)} = \left[\frac{f(H)}{\lambda_{2n}} \right]^{1/n}$$

- And the result tree-level EFT is again automatically truncated (so long as $f(H)$ is a finite polynomial) in O_{2n} but all powers of O_{H2n} exist

$$\mathcal{L}_{\rm EFT} \supset \frac{[f(H)]^2}{2n\lambda_{2n}} - \frac{1}{2} \left(\frac{f(H)}{\lambda_{2n}} \right)^{1/n} \Box \left(\frac{f(H)}{\lambda_{2n}} \right)^{1/n}$$

- Here we can understand the n=2 case easily, for renormalizable theory, the only SSB solution is a finite polynomial containing H^2 order!

Collider Imprints



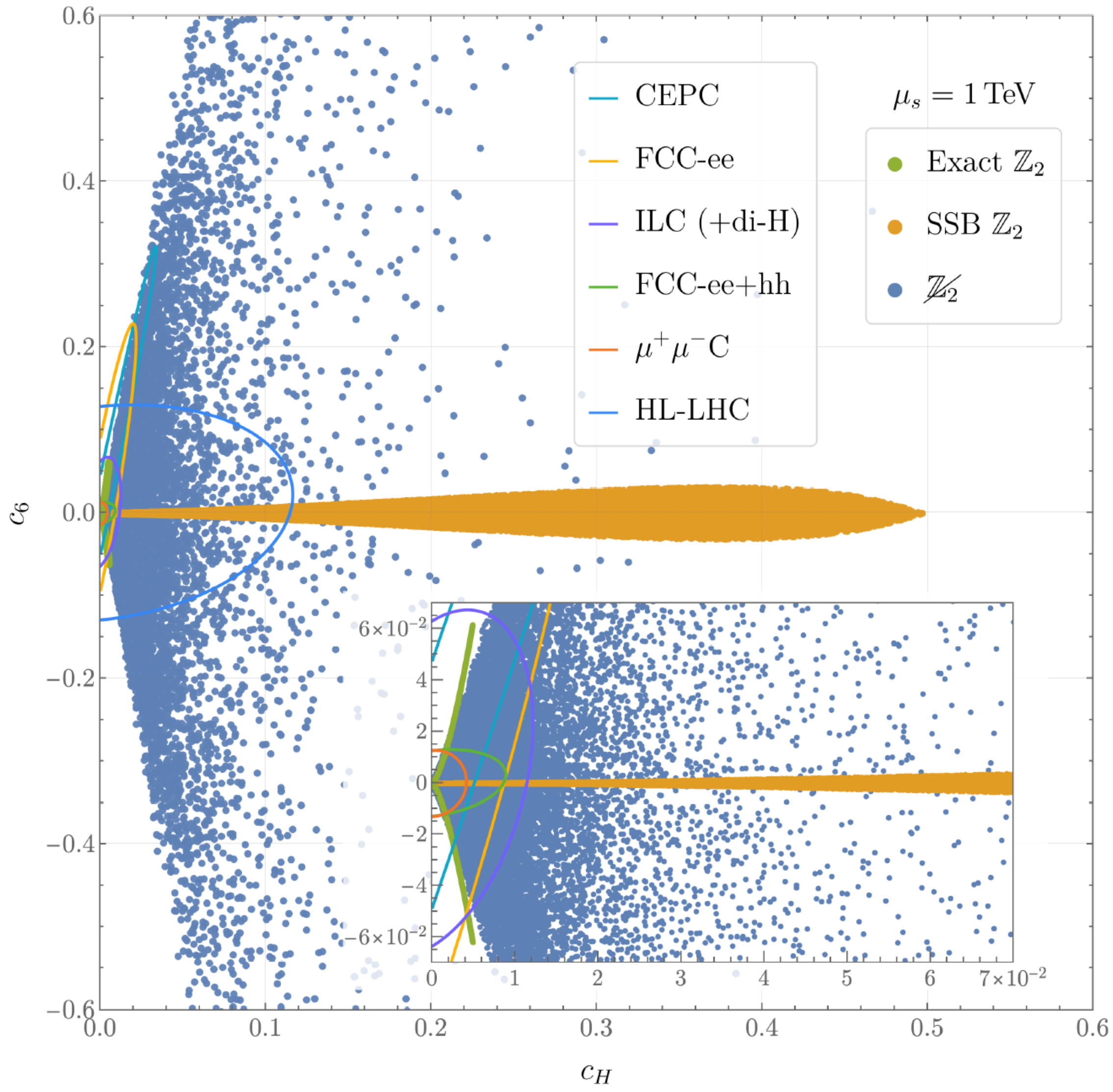
Gu, Li, ZL, Su,
Su, 1709.06103

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{SM}}, \quad \delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2} c_H$$

*I flipped my sign convention between this study (2017) and the next plot (2024), sorry!

The Pattern Matters

- A general parameter scan for three cases:
  - Exact
  - SSB
  - Explicitly broken
- Current and future colliders probes
  - horizontal direction mainly from single Higgs measurements
  - Vertical direction mainly from multiHiggs measurements
- The EFT pattern is clear!



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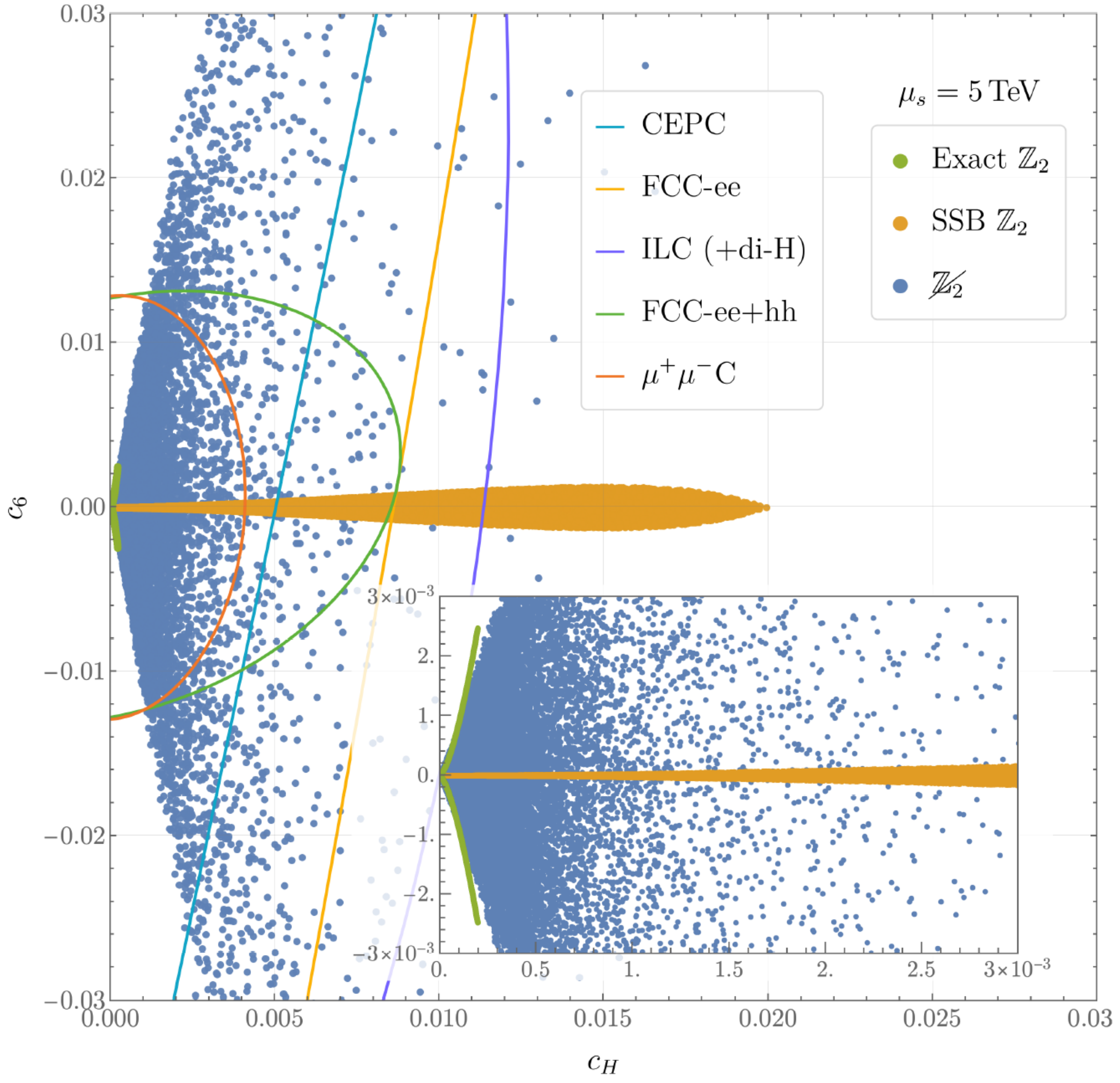

Summary

- A class of generic Higgs portal SSB model motivated EFTs exhibits truncations in non-derivative operators but not those with derivatives
  - Motivated by Dark Higgs
  - Motivated by enhanced EWPT
  - Motivated by Higgs Self-coupling measurements
- These truncations are not from simple symmetry arguments, as the resulting EFT are different from both explicit breaking and symmetry preserving cases.
- These suppressions are general in SSB and understood as renormalizable theories' classical solution are all finite polynomials. (one can also understand the same result in fermion portals resulted EFT, which is a simpler case of the above discussion.)
- These truncations has strong impact for Higgs program single Higgs and multi-Higgs observables.
- It would be fun to understand more their meanings and implications.