Charting the Higgs self-coupling boundaries

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Based on 2209.00666, 2202.01228, 2110.06941 with Gauthier Durieux and Matthew McCullough

symmetry

Introduction: Higgs couplings

In the Standard Model, the Higgs self-coupling is predicted in terms of other input parameters. At tree level,

$$\mathcal{L}_{\mathrm{SM}} \supset -\, m_h^2 \sqrt{\frac{G_F}{2\sqrt{2}}}\; h^3$$

The same applies to the other, single-Higgs couplings, such as for instance hZZ :

$$\mathcal{L}_{\mathrm{SM}} \supset m_Z^2 \sqrt{\sqrt{2} G_F}\, h\, Z_\mu Z^\mu$$

Measuring these interactions and testing whether they agree with the SM or not, is central to LHC physics program

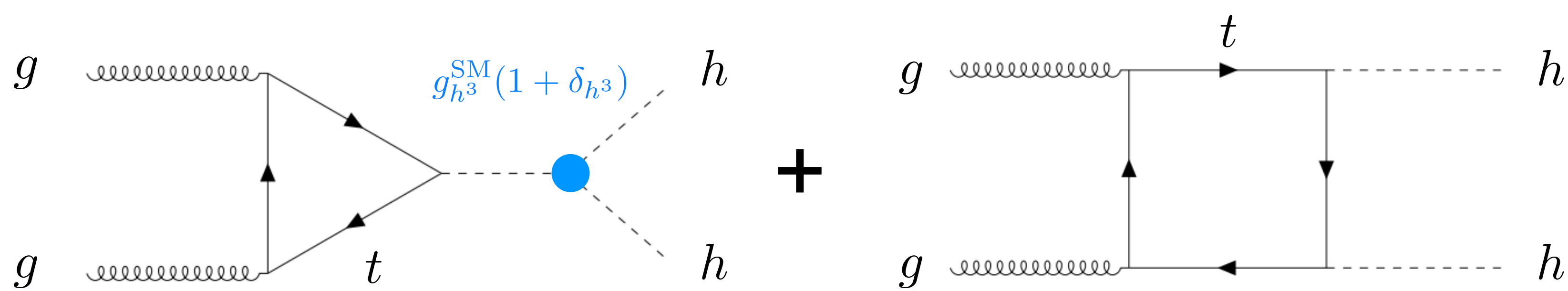
$$\delta_{h^3} \equiv \frac{g_{h^3} - g_{h^3}^{\mathrm{SM}}}{g_{h^3}^{\mathrm{SM}}} \qquad \delta_{VV} \equiv \frac{g_{hVV} - g_{hVV}^{\mathrm{SM}}}{g_{hVV}^{\mathrm{SM}}}$$

Are these different from zero?

The Higgs self-coupling

Measuring the Higgs self-coupling at the LHC is huge experimental challenge

Direct access in double Higgs production process:



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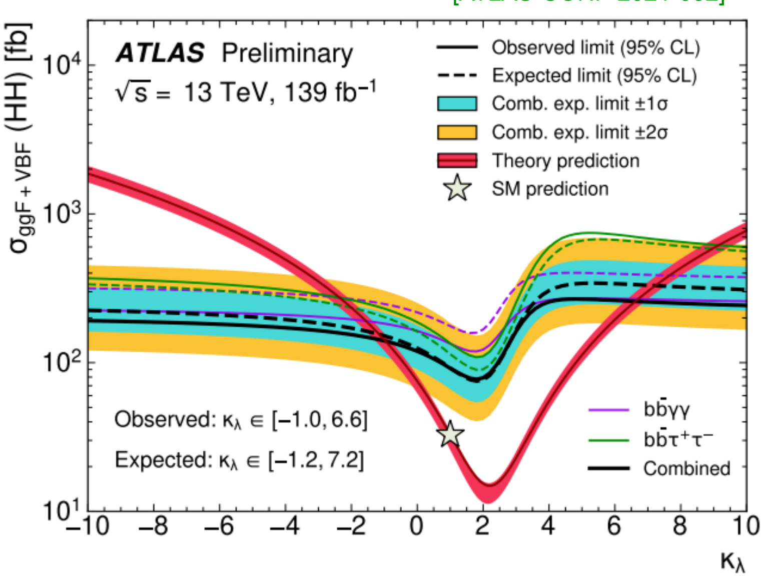

Run 2 measurements constrain (2σ)

$$-2.0 < \delta_{h^3} < 5.6$$

Very large deviations from SM are still allowed

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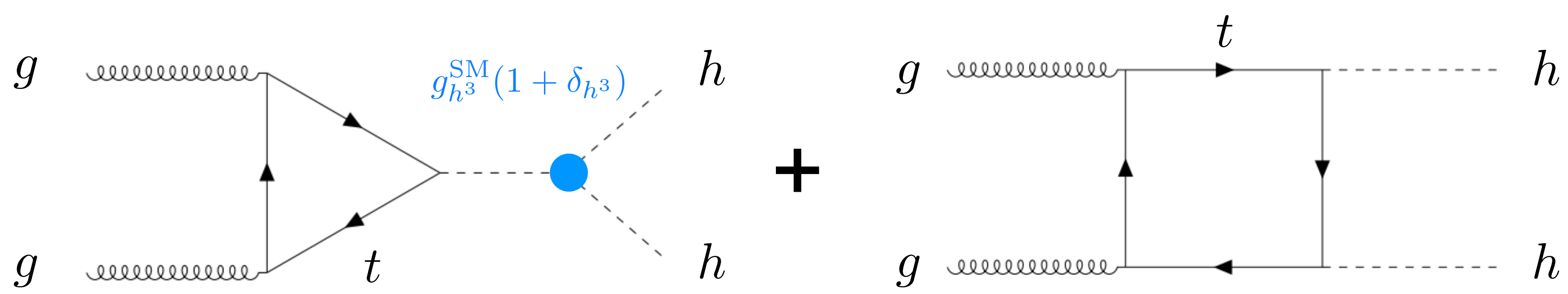

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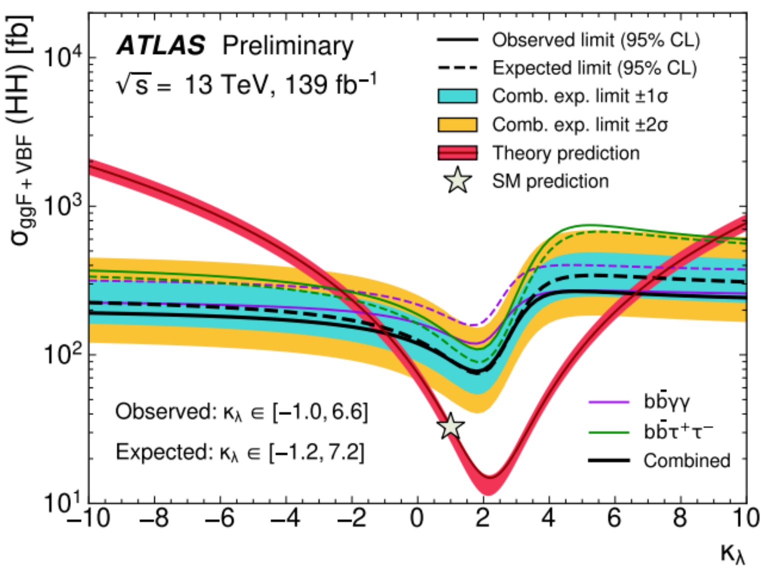


At High-Luminosity LHC, expect 100% precision

(rule out $\delta_{h^3} = 0$ at 2σ)

[de Blas et al. 1905.03764]

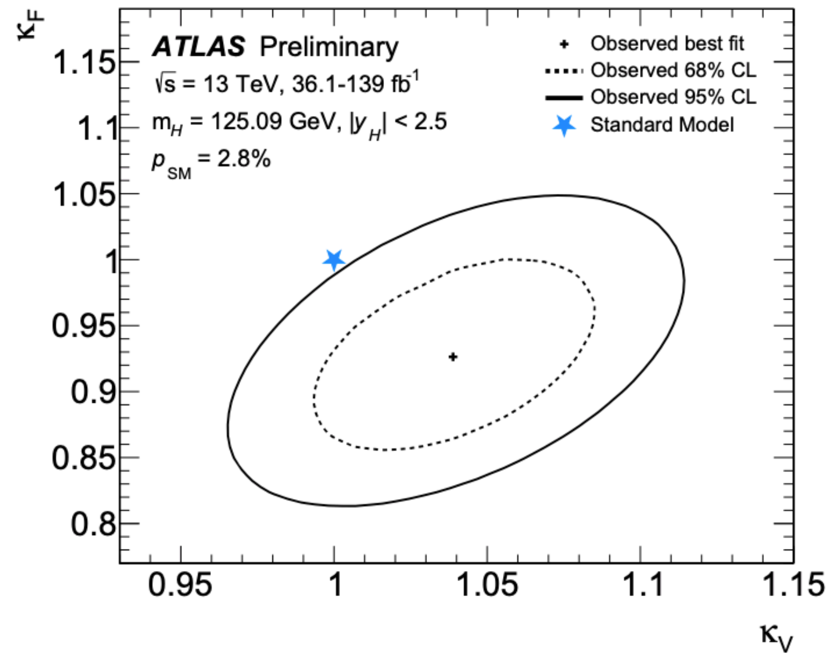
Single-Higgs couplings

Compare to measurements of single-Higgs couplings:

$$|\delta_{VV}| \lesssim 0.07$$

Already now at ~ 10% level

[ATLAS-CONF-2021-053]



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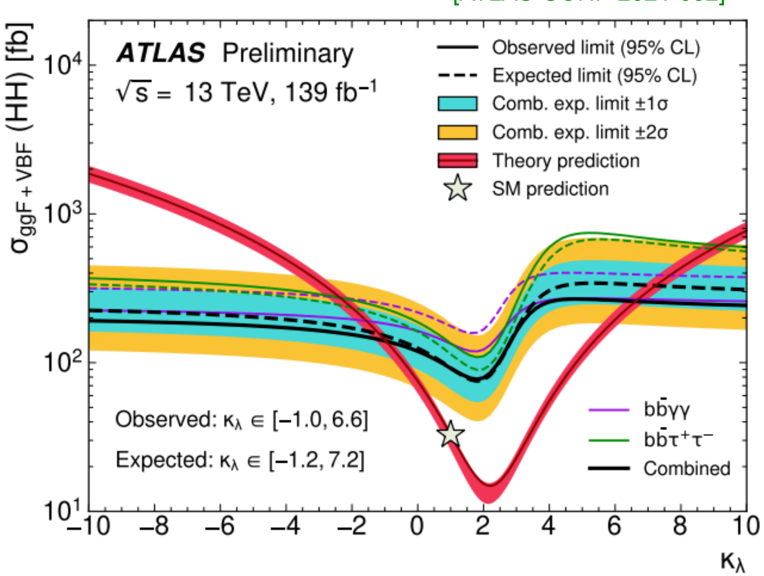

At High-Luminosity LHC, expect 100% precision

(rule out $\delta_{h^3} = 0$ at 2σ)

[de Blas et al. 1905.03764]

Theory question

Given that measuring the self-coupling is experimentally challenging,

and that we have not seen new physics so far:

How large can deviations in the Higgs self-coupling be,

if other (Higgs and electroweak) measurements are compatible with the SM?

To address this question, we ask how large

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right|$$

can be in generic ultraviolet completions of the SM [Durieux, McCullough, Salvioni 2209.00666]

generic = no fine tuning for the purpose of getting a specific value of h^3

generic $\neq$ canonical model

Part 1

An upper bound on δ_{h^3}/δ_{VV}

An upper bound on δ_{h^3}/δ_{VV}

Assume new physics is heavy enough to be described by SM effective field theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_6 + \mathcal{L}_8 + \dots$$

In terms of higher-dimension operators, a large δ_{h^3}/δ_{VV} corresponds to generating

$$\mathcal{O}_6 = -\frac{c_6}{M^2}|H|^6 \quad \gg \quad \mathcal{O}_H = \frac{c_H}{M^2}(\partial_\mu |H|^2)^2\,, \quad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2|D_\mu|^2\,, \quad \mathcal{O}_T = \frac{c_T}{M^2}|H^\dagger D_\mu H|^2$$

$|c_6| \gg |c_{H,R,T}|$

single-Higgs couplings

electroweak *T* parameter

Note peculiar property of c_6 : only SMEFT coefficient with dimension of $(\text{coupling})^4$

$\hbar$ counting $\quad \int DH e^{iS[H]/\hbar} \to S \sim \hbar \quad \longrightarrow$

field	$H \sim \hbar^{1/2}$
trilinear coupling	$g_* \sim \hbar^{-1/2}$
loop factor	$\sim \frac{\hbar}{(4\pi)^2}$

e.g. [Falkowski 2017]

An upper bound on δ_{h^3}/δ_{VV}

Imagine a UV completion with mass scale M and single coupling parameter

$$\kappa = g_*^4 \sim \hbar^{-2}$$

Then $\hbar$ counting enforces:

$$c_6 \sim \kappa \qquad c_{H,R,T} \sim \frac{\kappa}{(4\pi)^2} \qquad c_{H_8,R_8,T_8} \sim \kappa$$

Higgs self-coupling
at tree level dim-6

single-Higgs couplings and *T*
at 1 loop dim-6, or tree level dim-8

$$\mathcal{O}_{H_8,R_8,T_8} \equiv \frac{|H|^2}{M^2}\mathcal{O}_{H,R,T}$$

$$\mathcal{O}_6 = -\frac{c_6}{M^2}|H|^6 \quad \gg \quad \mathcal{O}_H = \frac{c_H}{M^2}(\partial_\mu |H|^2)^2\,, \quad \mathcal{O}_R = \frac{c_R}{M^2}|H|^2|D_\mu|^2\,, \quad \mathcal{O}_T = \frac{c_T}{M^2}|H^\dagger D_\mu H|^2$$

An upper bound on δ_{h^3}/δ_{VV}

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Higgs self-coupling
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single-Higgs couplings and *T*
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$$\delta_{h^3} \sim \frac{\kappa\, v^4}{M^2 m_h^2}$$

$$\delta_{VV},\ \widehat{T} \sim \frac{\kappa\, v^2}{M^2} \max\left[\frac{1}{16\pi^2}, \frac{v^2}{M^2}\right]$$

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \frac{M^2}{m_h^2}\right]$$

reaches ≈ 600
for $M > 4\pi v \approx 3\ \mathrm{TeV}$

Upper bound in generic UV completions

Implications for phenomenology

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \frac{M^2}{m_h^2}\right]$$

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Some examples

- Now: $|\delta_{VV}| \lesssim 0.07 \quad \rightarrow \quad |\delta_{h^3}| \lesssim 40$, compare to double Higgs exp $-2 < \delta_{h^3} < 5.6$

  HL-LHC: $|\delta_{VV}| \lesssim 2.6\,\% \quad \rightarrow \quad |\delta_{h^3}| \lesssim 15$, compare to exp $|\delta_{h^3}| \lesssim 100\,\%$

→ current and future LHC measurements of hh probe unexplored territory

- FCC-ee: $|\delta_{ZZ}| \lesssim 0.34\,\% \quad \rightarrow \quad |\delta_{h^3}| \lesssim 2$, compare to indirect FCC-ee $|\delta_{h^3}| < 48\,\%$

  and direct FCC-hh $|\delta_{h^3}| \lesssim 10\,\%$

→ even if FCC-ee observes SM, opportunities remain for FCC-hh

Implications for phenomenology

$$\left|\frac{\delta_{h^3}}{\widehat{T}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \frac{M^2}{m_h^2}\right]$$

reaches ≈ 600

for $M > 4\pi v \approx 3\ \mathrm{TeV}$

Important caveat: *T* parameter

If UV does not have custodial symmetry, electroweak precision bounds severely limit size of self-coupling deviations

Example: FCC-ee $|\,\widehat{T}\,| \lesssim 10^{-4} \quad \rightarrow \quad |\,\delta_{h^3}| \lesssim 6\,\%$

Loop factor is not enough, need custodially invariant theory

Concrete realization: custodial weak quadruplet

Find a simple extension of the SM, endowed with custodial symmetry,

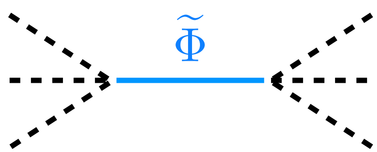
saturating δ_{h^3}/δ_{VV} upper bound:

- Weak $SU(2)_L$ quadruplet couples at renormalizable level to 3 Higgs fields: $\widetilde{\Phi} \sim \mathbf{4}_{3/2}$

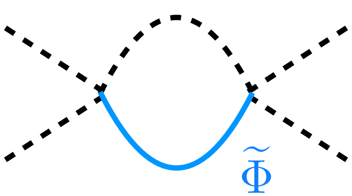
hypercharge

$$\mathcal{L} \supset -\lambda_{\widetilde{\Phi}} H_i^* H_j^* H_k^* \widetilde{\Phi}_{ijk} + \text{h.c.} + \ldots$$

Integrate out:



$$\frac{H^6}{M_{\widetilde{\Phi}}^2}, \quad \frac{D^2 H^6}{M_{\widetilde{\Phi}}^4}$$



$$\frac{1}{(4\pi)^2} \frac{D^2 H^4}{M_{\widetilde{\Phi}}^2}$$

But this includes corrections to *T* parameter, @ 1 loop dim-6 or tree level dim-8

- Similarly for the other possible quadruplet, $\Phi \sim \mathbf{4}_{1/2}$

[de Blas et al. 2014]
[Henning et al. 2014]
…

Concrete realization: custodial weak quadruplet

Combine the two quadruplets into single rep. of custodial symmetry

$$SO(4) \simeq SU(2)_L \times SU(2)_R$$

H	$h_a \sim \mathbf{4}$	$(\mathbf{2}, \mathbf{2})$
$(\Phi, \widetilde{\Phi})$	$\hat{\Phi}^{abc} \sim \mathbf{16}$	$(\mathbf{4}, \mathbf{4})$

see also [Logan, Rentala 2015]
[Chala, Krause, Nardini 2018]

$$\mathcal{L} \supset -\lambda \hat{\Phi}^{abc} h_a h_b h_c \quad \rightarrow \quad -\lambda \left(H^* H^* (\epsilon H) \Phi + \frac{1}{\sqrt{3}} H^* H^* H^* \widetilde{\Phi} \right) + \text{h.c.}$$

Integrating out, get same operator classes but now $T = 0$:

$$\frac{2\lambda^2}{3M^2} |H|^6$$

$$\frac{2\lambda^2}{3M^4} \left(5|H|^4 |D_\mu H|^2 + |H|^2 \partial_\mu |H|^2 \partial^\mu |H|^2\right)$$

$$\frac{\lambda^2}{12\pi^2 M^2} \left(8|H|^2 |D_\mu H|^2 + \partial_\mu |H|^2 \partial^\mu |H|^2\right)$$

Higgs self-coupling at tree level dim-6

single-Higgs couplings at 1 loop dim-6, or tree level dim-8

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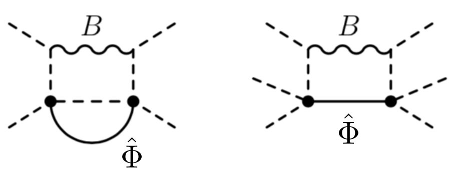
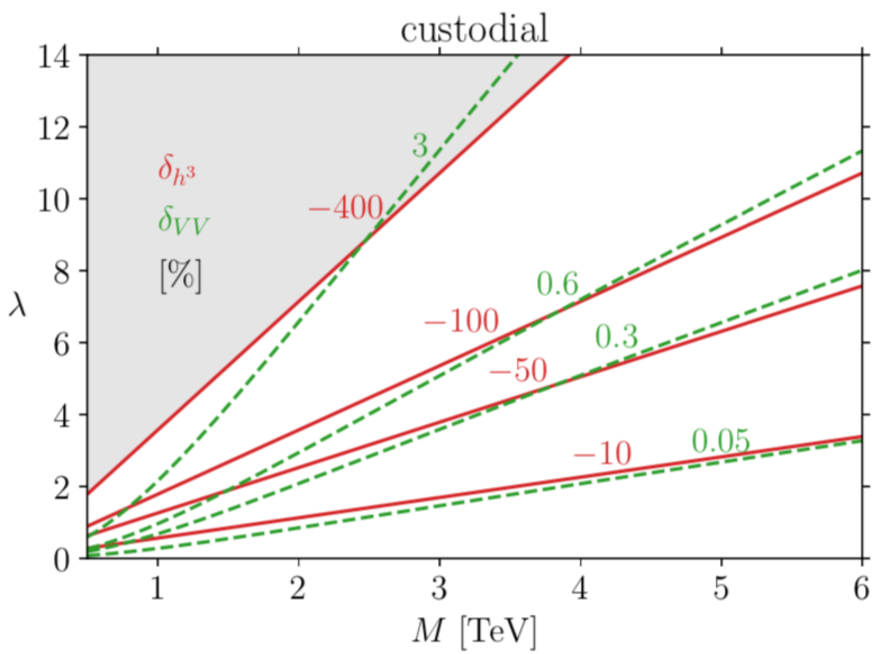
Integrating out, get same operator classes but now $T = 0$:

custodial violation happens @ 2 loops dim 6, or 1 loop dim 8, negligible



Custodial weak quadruplet: parameter space

[Durieux, McCullough, Salvioni 2209.00666]



$$\delta_{h^3} \equiv \frac{g_{h^3} - g_{h^3}^{\rm SM}}{g_{h^3}^{\rm SM}}$$

$$\delta_{VV} \equiv \frac{g_{hVV} - g_{hVV}^{\rm SM}}{g_{hVV}^{\rm SM}}$$

This model indeed saturates the upper bound I discussed:

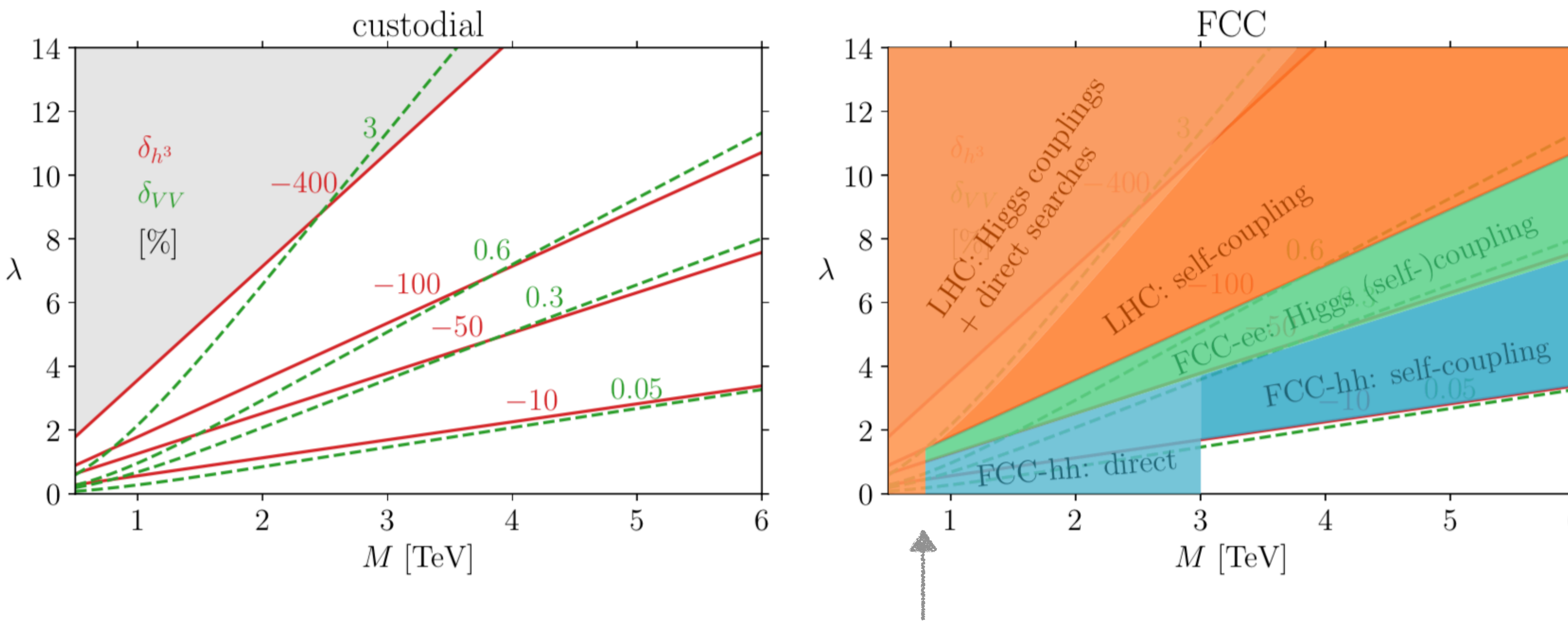
$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$

Recall: key was to have $\kappa \sim g_*^4$ coupling parameter

Here, $\lambda \sim g_*^2$ and the $\lambda\,\hat{\Phi}\,h^3$ interaction is invariant under $\lambda \to -\lambda$, $\hat{\Phi} \to -\hat{\Phi}$

→ in EFT where quadruplet is integrated out, only λ^2 can appear

Custodial weak quadruplet: prospects



direct HL-LHC reach (pair/single production)

$M \sim 600$ GeV

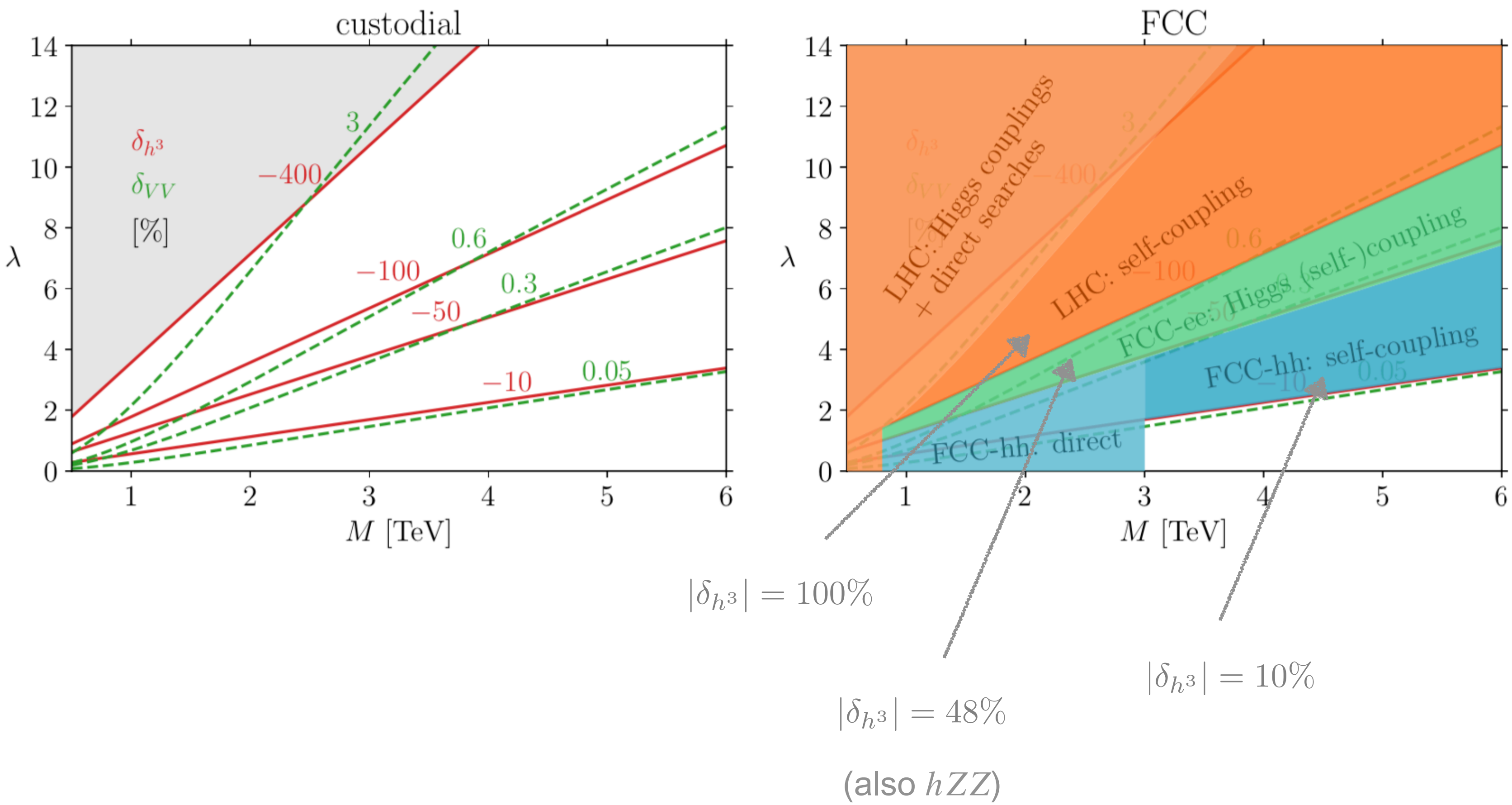
$\hat{\Phi} = \mathbf{4}_{3/2} + \mathbf{4}_{1/2}$

$SU(2)_L \times U(1)_Y$

By measuring the Higgs self-coupling,

HL-LHC, FCC-ee, FCC-hh will probe wide region of open parameter space

Custodial weak quadruplet: prospects



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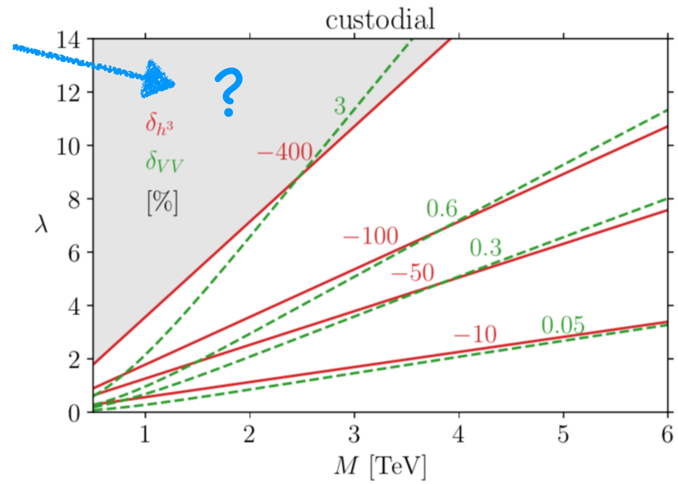
Vacuum stability

Discussion assumed only the coupling

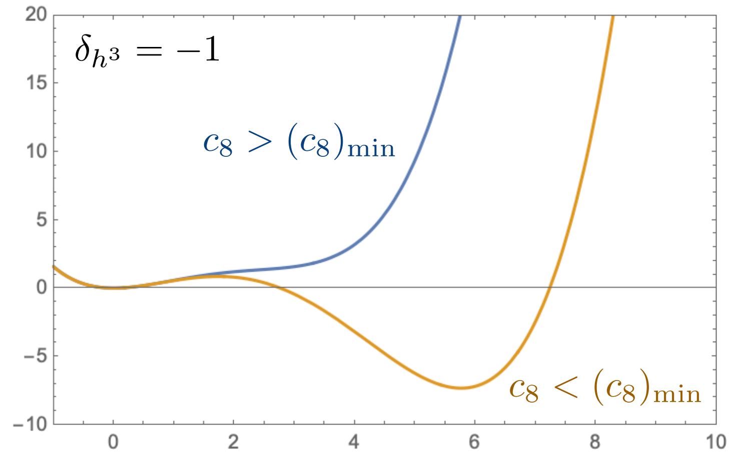


$$\mathcal{L}_{\rm UV} \sim \lambda\, \hat{\Phi}\, H^3 \quad \rightarrow \quad \mathcal{L}_{\rm EFT} \supset \frac{2\lambda^2}{3M^2}|H|^6$$

However, large $|H|^6$ needs to be accompanied by sizable $|H|^8$, to ensure vacuum stability:

$$-\mathcal{L}_{\rm BSM} = c_6\frac{|H|^6}{M^2} + c_8\frac{|H|^8}{M^4}$$

$$c_6 < 0$$



$$\widetilde{X} = \frac{2H^\dagger H - v^2}{v^2}$$

for ex. [Falkowski, Rattazzi 2019]

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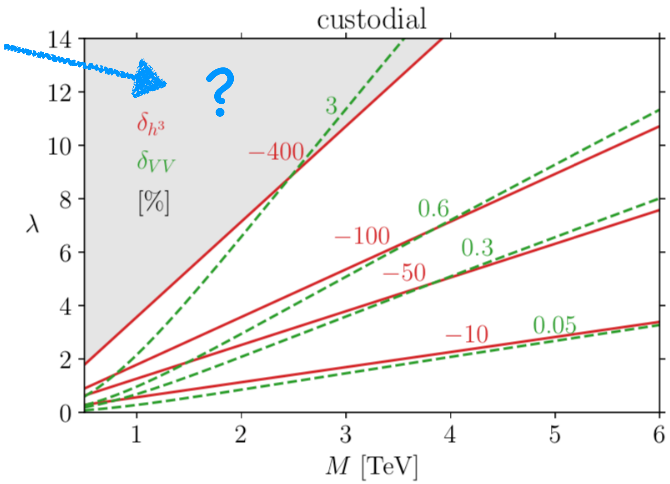


However, large $|H|^6$ needs to be accompanied by sizable $|H|^8$, to ensure vacuum stability:

in turn, Higgs self-coupling receives sizable contribution from $|H|^8$:

$$\delta_{h^3} = \delta^{(6)}_{h^3} + \delta^{(8)}_{h^3} \qquad \delta^{(8)}_{h^3} \geq -\delta^{(6)}_{h^3} + 1 - \sqrt{1 - 2\delta^{(6)}_{h^3}}$$

Region shaded in gray is where $\left|\frac{\delta^{(8)}_{h^3}}{\delta^{(6)}_{h^3}}\right| \geq 1/2$

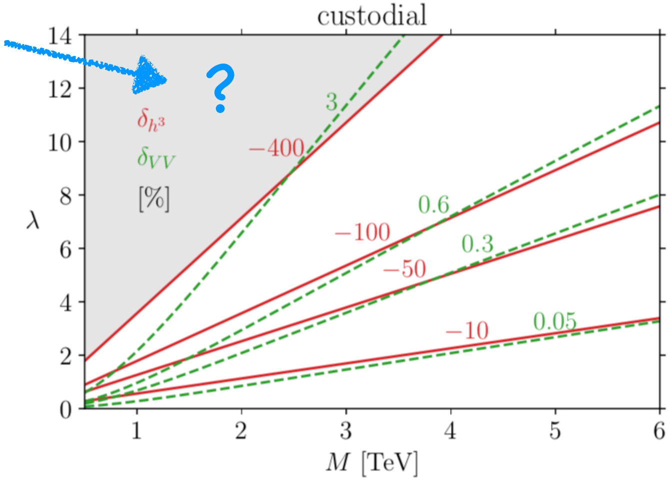
Here EFT based only on $|H|^6$ becomes unreliable, cannot ignore other UV couplings anymore

For example $|\hat{\Phi}|^2 |H|^2$, which leads to $|H|^8$ at tree level

Vacuum stability

Discussion assumed only the coupling

$$\mathcal{L}_{\rm UV} \sim \lambda\,\hat{\Phi}\,H^3 \quad \longrightarrow \quad \mathcal{L}_{\rm EFT} \supset \frac{2\lambda^2}{3M^2}|H|^6$$



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Region shaded in gray is where $\left|\frac{\delta_{h^3}^{(8)}}{\delta_{h^3}^{(6)}}\right| \geq 1/2$

Expect $O(1)$ changes in the Higgs couplings and their ratio, but qualitatively similar picture

Summary

How large can deviations in the Higgs self-coupling be,

if other (Higgs and electroweak) measurements are compatible with SM?

- Starting from simple $\hbar$ counting observation, derived upper bound in “generic” theories (no specific tuning for h^3)

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \; \frac{M^2}{m_h^2}\right]$$

Wrote down concrete model, custodial weak quadruplet, that saturates it

- Shows quantitatively that measuring Higgs self-coupling probes regions of parameters that remain otherwise inaccessible
- On the other hand, quadruplet model is unique example at tree level

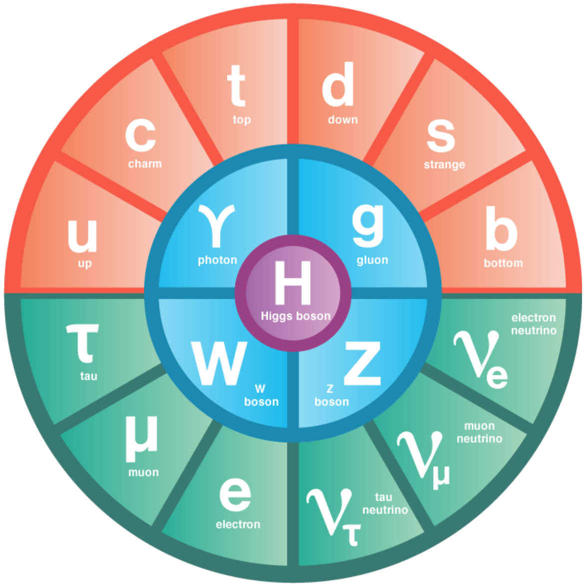
[Durieux, McCullough, Salvioni 2209.00666]

Part 2

Large δ_{h^3}/δ_{VV} for a pNGB Higgs

(Gegenbauer's Twin)

The Higgs mystery



$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

Can we calculate it within a more fundamental theory?

Motivation

Other scalar particles we know: pions

They are composite pseudo Nambu-Goldstone bosons (pNGBs)

$$\Pi \sim (\bar{q}q)$$

$$\Pi \to \Pi + \theta f$$

Goldstone shift symmetry
(leading-order transformation under broken generators)

$$f \sim 100\ \mathrm{MeV}$$

Old question: could the Higgs field be a (composite) pNGB too?

[Kaplan, Georgi 1984]
[Kaplan 1992]
[Agashe, Contino, Pomarol 2004]
and many, many others

$$H \to H + \theta f \quad \xrightarrow{\text{at leading order}} \quad V(H) = 0$$

$$f \sim \mathrm{TeV}$$

A light Higgs is natural

The need for $v \ll f$

Leading term of EFT for pNGBs:

$$\mathcal{L} = \frac{f^2}{2} D_\mu \phi^T D^\mu \phi$$

$SO(N+1)/SO(N)$

$$\phi = e^{i\Pi^a T^a / f} \begin{pmatrix} \vec{0}_N \\ 1 \end{pmatrix} = \begin{pmatrix} \sin \frac{\Pi}{f} \frac{\vec{\Pi}}{\Pi} \\ \cos \frac{\Pi}{f} \end{pmatrix} \qquad \Pi \equiv \sqrt{\vec{\Pi}^T \vec{\Pi}}$$

Introducing the SM weak interactions:

$$D_\mu \phi = \partial_\mu \phi - i g W_\mu^a T_L^a \phi - i g' B_\mu T_R^3 \phi$$

↓

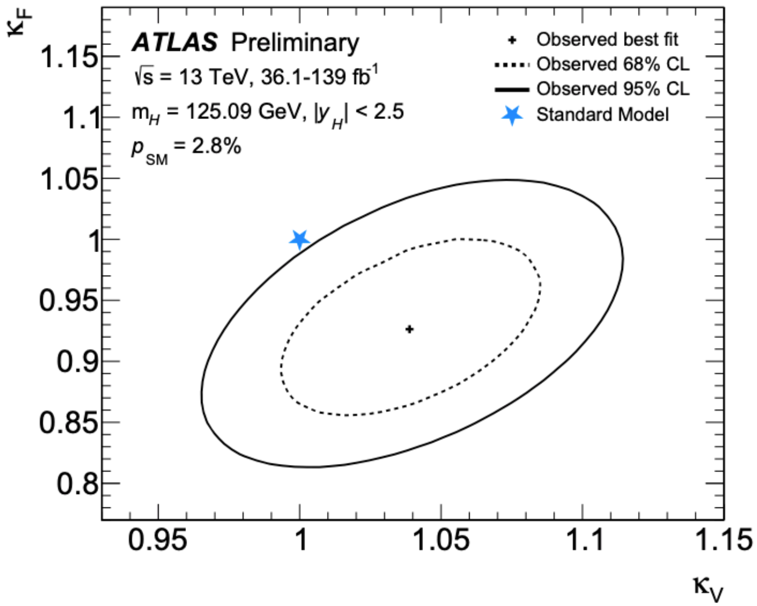
$$\frac{c_{hVV}}{c_{hVV}^{\mathrm{SM}}} = \cos \frac{\langle \Pi \rangle}{f} = \sqrt{1 - \frac{v^2}{f^2}}$$

suppression of Higgs couplings to other SM particles

$v \approx 246~\mathrm{GeV}$

The need for $v \ll f$

[ATLAS-CONF-2021-053]



LHC Run 2:

Higgs couplings agree with SM to ~ 10%

Need $v \ll f$ by a factor 3 ~ 4 at least

$$\frac{c_{hVV}}{c_{hVV}^{\rm SM}} = \cos\frac{\langle \Pi \rangle}{f} = \sqrt{1 - \frac{v^2}{f^2}}$$

suppression
of Higgs couplings
to other SM particles

$v \approx 246\ \mathrm{GeV}$

Realizing $v \ll f$

The vast majority of models require fine-tuning to achieve it

$$V_{1\text{ loop}} \sim \frac{y_t^2}{16\pi^2} M_T^2 f^2 \left(-\sin^2 \frac{\Pi}{f} + \sin^4 \frac{\Pi}{f} \right)$$

top partner mass

$$\Delta \sim \frac{v^2}{f^2} \lesssim 10\%$$

"minimal tuning" to get $v \ll f$

[Panico, Redi, Tesi, Wulzer 2012]

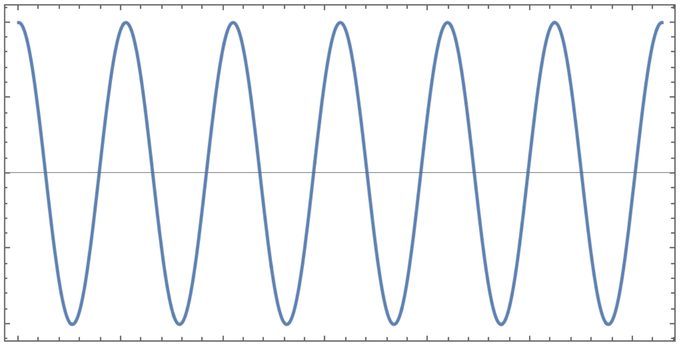
Here I present a new class of potentials giving this naturally: "Gegenbauer Goldstones"

The shape of the Higgs potential is strongly modified compared to SM

→ large Higgs self-coupling deviations

Inspiration: Abelian Goldstone

example: $n = 6$



For a single $U(1)$ Goldstone,

we know a simple way to get $v/f \ll 1$

$$\frac{\langle \Pi \rangle}{f} = \frac{\pi}{n} \ll 1$$

$$\mathcal{L} = \partial_\mu \Phi^* \partial^\mu \Phi - \lambda \left(\Phi^* \Phi - f^2 \right)^2$$

Make it a pNGB: explicit breaking from operator of charge n

$$\delta V = \frac{\epsilon \lambda}{f^{n-4}} \Phi^n + \text{h.c.}$$

$$\Phi = f e^{i\Pi/f}$$

$$\delta V \sim \epsilon \lambda f^4 \cos\left(\frac{n\Pi}{f} \right)$$

$$\mathcal{Z}_n : \quad \Pi \rightarrow \Pi + \frac{2\pi}{n} f$$

Non-Abelian Goldstones

Consider N Goldstone bosons, from spontaneous breaking of global symmetry

$SO(N+1)/SO(N)$ (best studied pattern for pNGB Higgs)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi^T \partial^\mu \Phi - \lambda \left(\Phi^T \Phi - f^2\right)^2$$

How to get $v \ll f$ naturally?

Non-Abelian Goldstones

Consider N Goldstone bosons, from spontaneous breaking of global symmetry

$SO(N+1)/SO(N)$ (best studied pattern for pNGB Higgs)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi^T \partial^\mu \Phi - \lambda \left(\Phi^T \Phi - f^2\right)^2$$

Explicit breaking to $SO(N)$ by spurion in n-index symmetric tensor irrep of $SO(N+1)$

$$\delta V = \frac{\epsilon\,\lambda}{f^{n-4}} K_n^{i_1 \ldots i_n} \Phi_{i_1} \ldots \Phi_{i_n}$$

irrep $\rightarrow$ traceless

Radiatively stable at $O(\epsilon)$ and all loop orders, because only operator allowed.

Corrections at $O(\epsilon^2)$ and higher

[in d = 2: Brézin, Zinn-Justin, Le Guillou 1976]

Enter Gegenbauer

Parametrize

$$\Phi = f\phi \qquad \phi = e^{i\Pi^a T^a/f}\begin{pmatrix}\vec{0}_N \\ 1\end{pmatrix} = \begin{pmatrix}\sin\frac{\Pi}{f}\frac{\vec{\Pi}}{\Pi} \\ \cos\frac{\Pi}{f}\end{pmatrix} \qquad \Pi \equiv \sqrt{\vec{\Pi}^T\vec{\Pi}}$$

$$\delta V = \epsilon\lambda f^4 G_n^{(N-1)/2}(\cos\Pi/f)$$

potential is a Gegenbauer polynomial

↗

$$\delta V = \frac{\epsilon\,\lambda}{f^{n-4}} K_n^{i_1\ldots i_n}\,\Phi_{i_1}\ldots\Phi_{i_n}$$

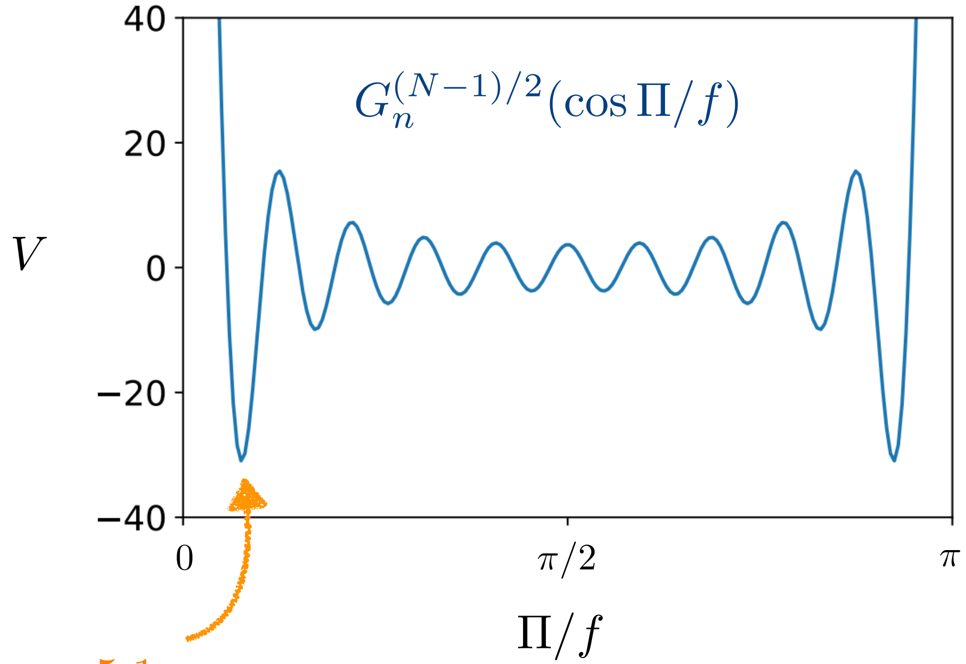
irrep → traceless

Radiatively stable at $O(\epsilon)$ and all loop orders, because only operator allowed.

Corrections at $O(\epsilon^2)$ and higher

[in *d* = 2: Brézin, Zinn-Justin, Le Guillou 1976]

The shape of Gegenbauers



$N = 4$

$SO(5)/SO(4)$

Even n

$n = 20$

$$\frac{\langle \Pi \rangle}{f} \approx \frac{j_{N/2,1}}{n + \frac{N-1}{2}} \approx \frac{5.1}{n} \ll 1$$

for large n

Differently from Abelian case,

not periodic (only approximately)

A radiatively stable way to obtain $\langle \Pi \rangle \ll f$ for non-Abelian Goldstones

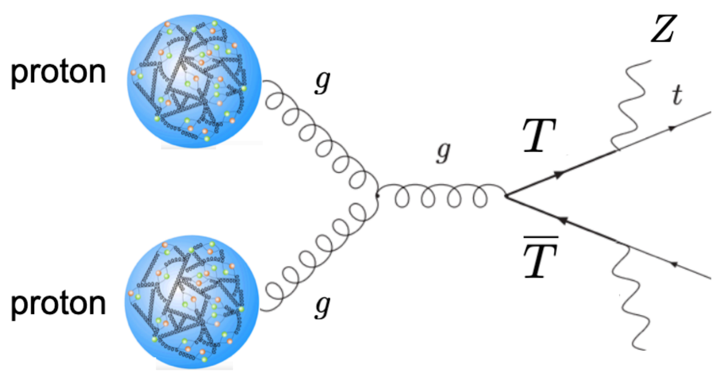
Gegenbauer Higgs

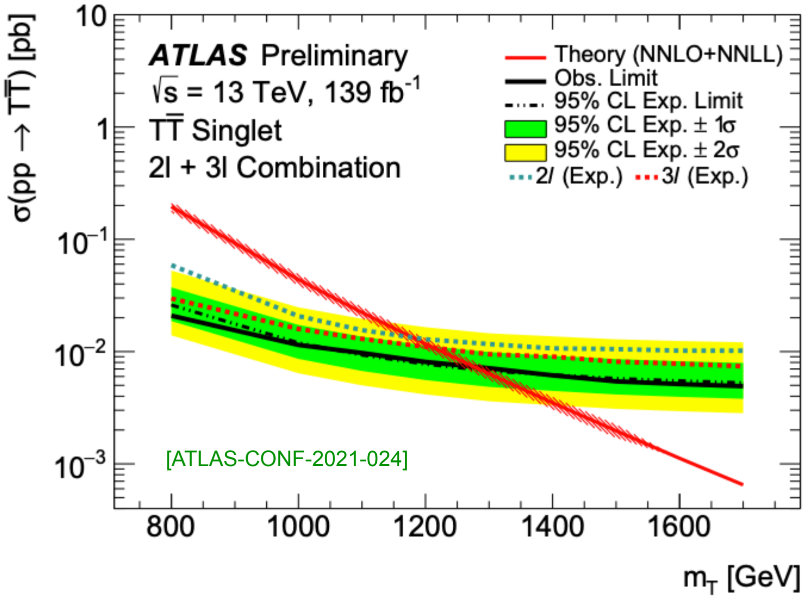
Gegenbauer potential can realize $v \ll f$ naturally

[Durieux, McCullough, Salvioni 2110.06941]

But for standard composite pNGB Higgs, some tuning remains:

QCD-charged top partner masses are constrained by LHC data





Gegenbauer's Twin

Gegenbauer potential can realize $v \ll f$ naturally

But for standard composite pNGB Higgs, some tuning remains:

QCD-charged top partner masses are constrained by LHC data

Twin Higgs models can reduce size of top potential: top partners are QCD-neutral

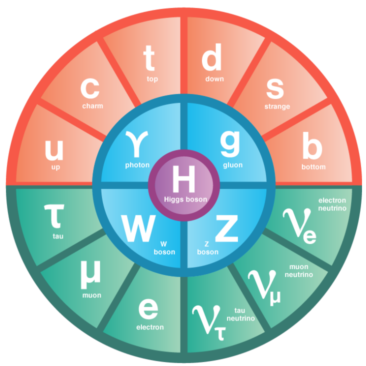
[Chacko, Goh, Harnik 2005]

Merge the two: Gegenbauer's Twin

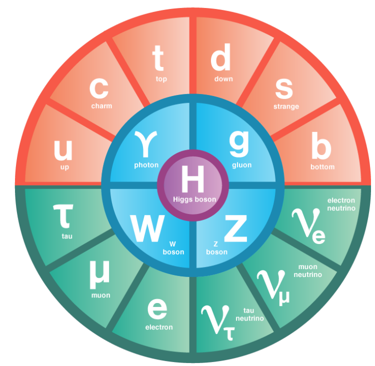
Twin Higgs

Standard Model

Twin Standard Model



$\overset{\mathcal{Z}_2}{\longleftrightarrow}$



$$\mathcal{L} = y_t Q_A H_A t_A + \hat{y}_t Q_B H_B t_B$$

The top partners are neutral under whole SM (& charged under Twin QCD)
They can still be really light

The $\mathcal{Z}_2$ protects Higgs mass from quadratic corrections

Twin Higgs potential

Quartic terms do not cancel exactly, but resulting potential is not realistic:

$v = 0$ or $v = f$

$$V_t \approx \frac{3y_t^4 f^4}{64\pi^2}\left[\sin^4\frac{h}{f}\log\frac{a}{\sin^2 h/f} + \cos^4\frac{h}{f}\log\frac{a}{\cos^2 h/f}\right]$$

[Craig, Katz, Strassler, Sundrum 2015]
[Barbieri, Greco, Rattazzi, Wulzer 2015]

Gegenbauer's Twin

<u>Quartic</u> terms do not cancel exactly, but resulting potential is not realistic:

$$v = 0 \qquad \text{or} \qquad v = f$$

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We introduce a Gegenbauer contribution:

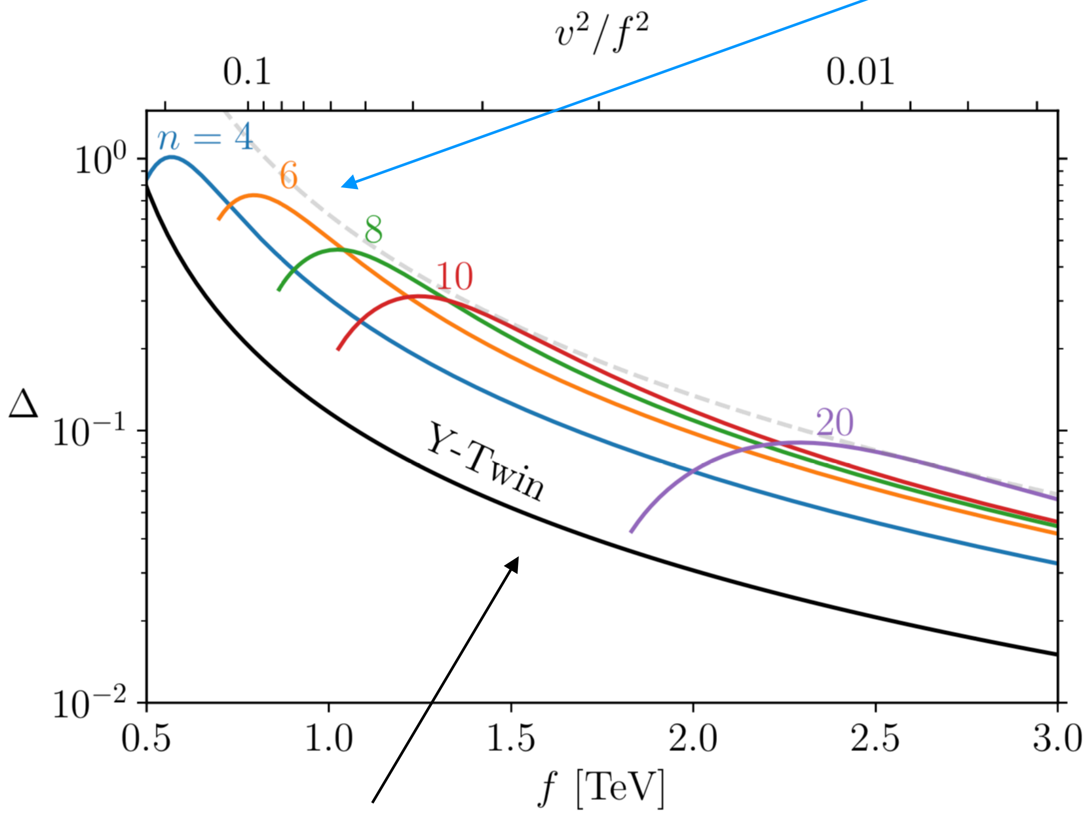
generalize construction to $SO(8) \to SO(4) \times SO(4)$ explicit breaking

$$V_G^{(n)} = \epsilon f^4 G_n^{3/2}(\cos 2h/f)$$

Gegenbauer's Twin

Fine tuning:

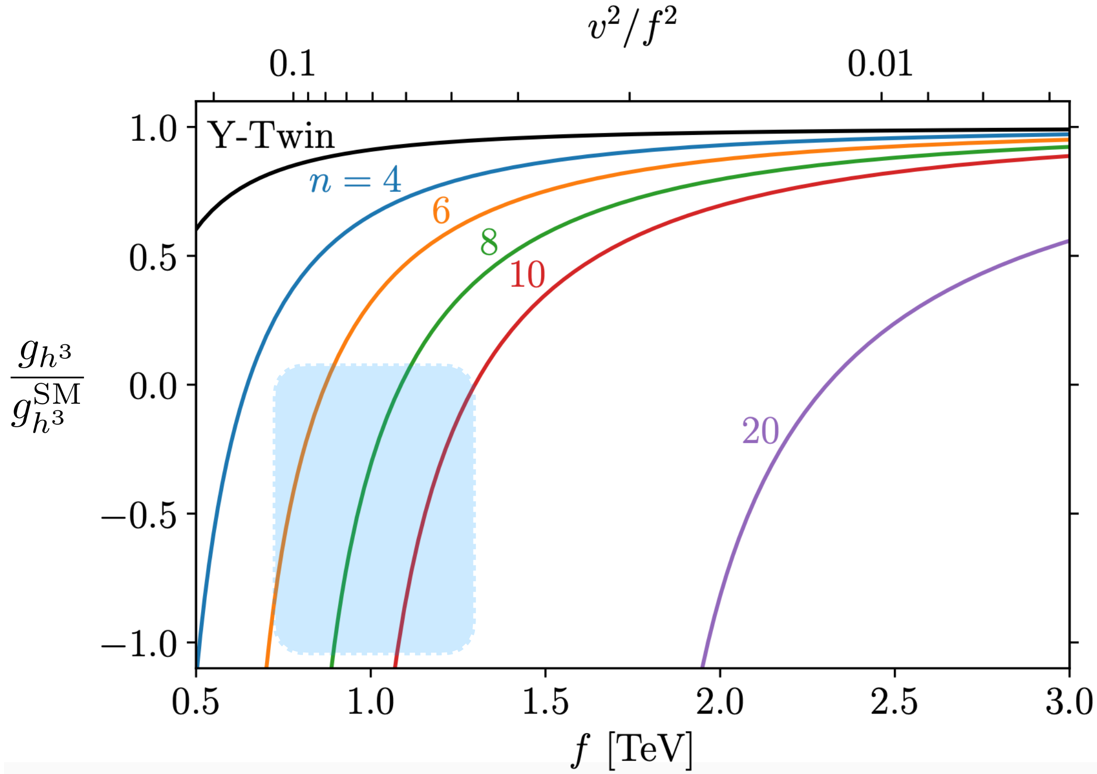
Gegenbauer's Twin with
$n = 6$ or $n = 8$ and $f \sim 1$ TeV
has essentially no tuning



standard Twin model (Twin hypercharge not gauged)

Finally: the Higgs self-coupling

For Gegenbauer's Twin, corrections are parametrically enhanced

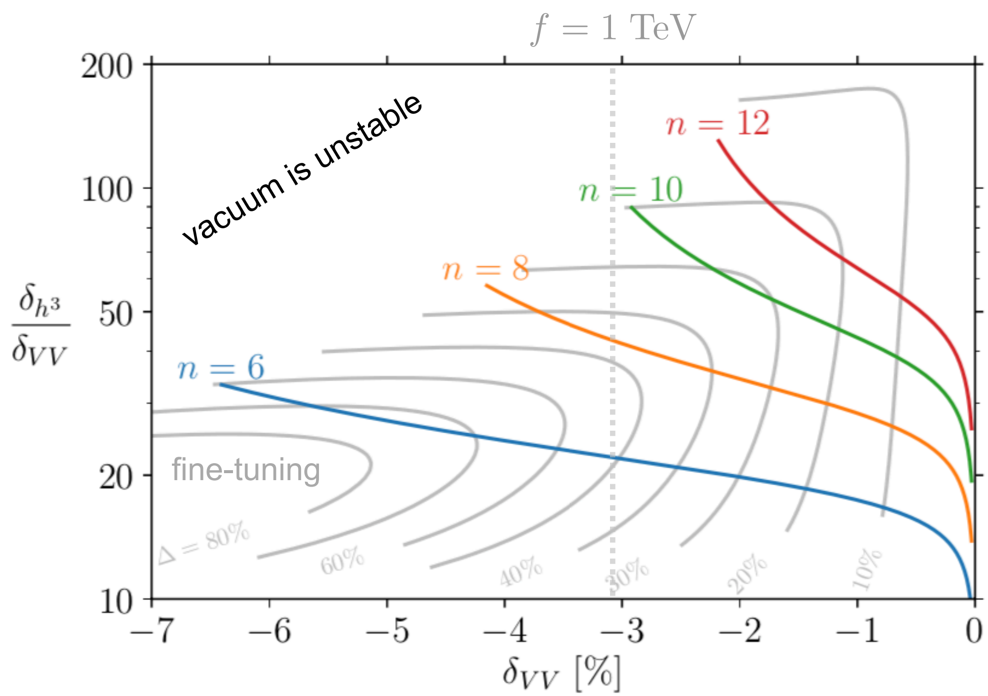


"Smoking gun" signal: could even be first deviation observed at LHC

[Durieux, McCullough, Salvioni 2202.01228 + 2209.00666]

Back to the δ_{h^3}/δ_{VV} ratio

$$\delta_{VV} = \sqrt{1 - \frac{v^2}{f^2}} - 1 \simeq -\frac{v^2}{2f^2}$$



A ratio between 10 and 100 is generic in parameter space of Gegenbauer's Twin

Another class of models where Higgs self-coupling measurements probe new ground

Conclusions

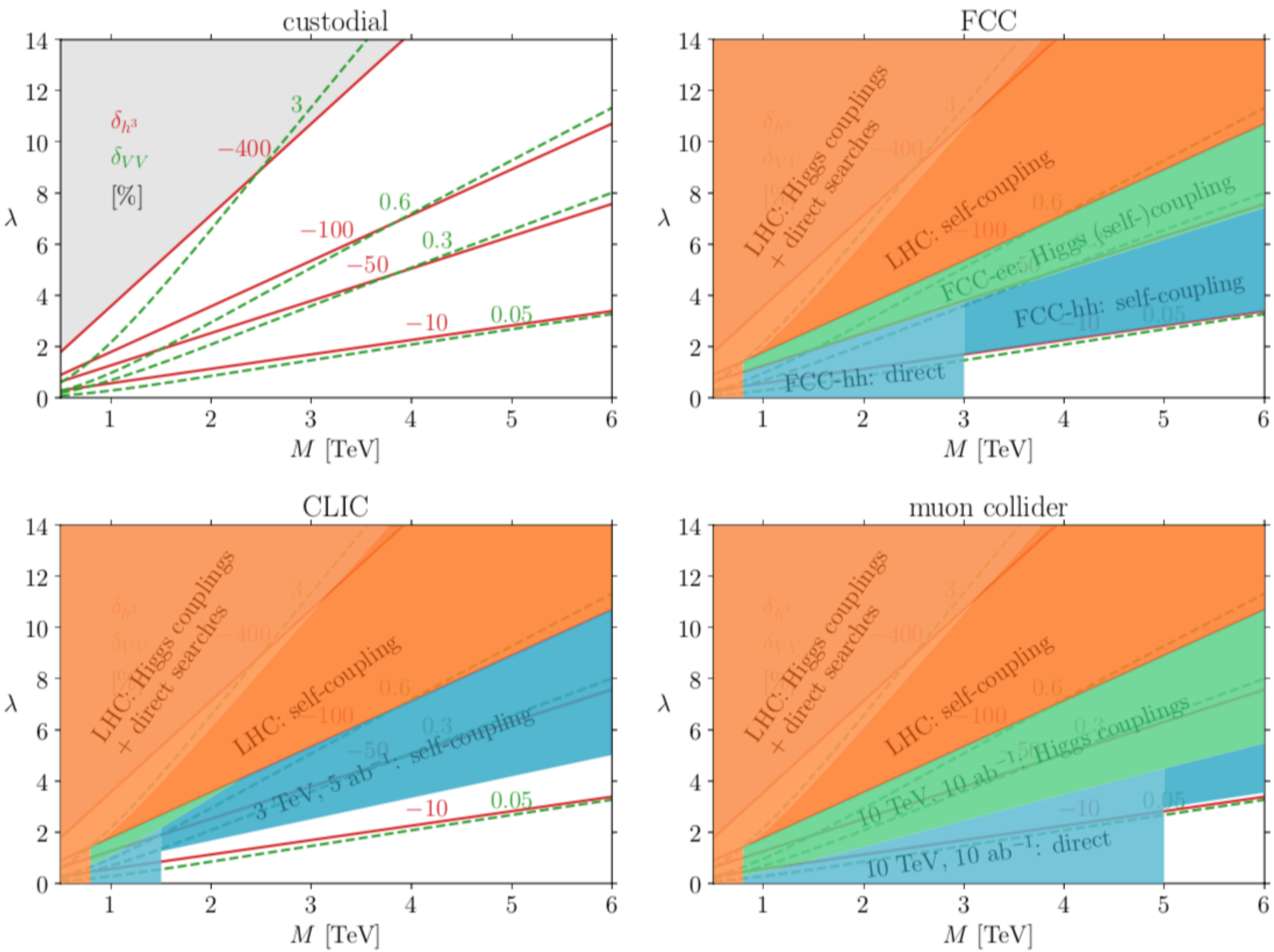
Gegenbauer's Twin shows that fully natural electroweak breaking
is still compatible with LHC results

Large modifications of Higgs self-coupling are generic.
Ratio δ_{h^3}/δ_{VV} is between 10 and 100, promising for future measurements

Requires to drop often assumed "minimality criteria" about origin
of (explicit) symmetry breaking

Backup slides

Custodial quadruplet: HELCs



[Durieux, McCullough, Salvioni 2209.00666]

Gegenbauer?

Gegenbauer polynomials can be seen as generalization of Legendre polynomials to $D \neq 3$ spatial dimensions

$$D = 3 \qquad SO(3) \to SO(2)$$

multipole expansion of axi-symmetric function of spacetime coordinates

$$f(\vec{r}) = \sum_{\ell=0}^{\infty} c_\ell P_\ell(\cos\theta)$$

$$(m = 0)$$

They appear in many areas of physics, for example in the expansion of conformal blocks in CFT_d

[Hogervorst, Rychkov 2013]

Here, they arise from explicit breaking of internal symmetry $SO(N+1) \to SO(N)$, variables are pNGB fields