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Testing Higgs naturalness at the FCC

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https://indico.cern.ch/event/1307378/

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Higgs naturalness problem solved by symmetry?

- Origin of electroweak symmetry breaking remains completely mysterious.
  Can we calculate the Higgs potential?

- Symmetry-based explanations remain the most plausible paradigm:
  - a spacetime symmetry (SUSY)

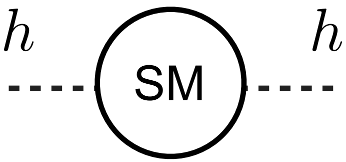
    or
  - a global symmetry (Higgs as a pseudo-Nambu-Goldstone boson, or pNGB)

- The LHC, the FCC, and any other future colliders must keep searching
  for the associated new physics, which renders the small Higgs mass "natural"

- I'll review some signatures of symmetry-based naturalness, using fine-tuning
  as (qualitative) guiding principle

Two reasons for tuning in the Higgs potential

Higgs mass ⟷ Direct searches for new particles (top partners of mass M)



$+\ \ldots \ \rightarrow\ \delta m_h^2 \sim \frac{N_c y_t^2}{4\pi^2} M^2 + \ldots \ \rightarrow\ \Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500\ \mathrm{GeV}}\right)^2$

Lower bounds on (QCD-charged) resonances imply fine tuning

Higgs vev ⟷ Deviations of Higgs couplings to SM particles X

$$\delta_{hXX} \equiv \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}} - 1 \ \rightarrow\ \Delta_{v^2} \sim \frac{\mathrm{constant}}{|\delta_{hXX}|}$$

SM-like measurements of Higgs couplings imply fine tuning

SUSY

[Gouskos, Sung, Incandela, CERN-ACC-2019-0036]

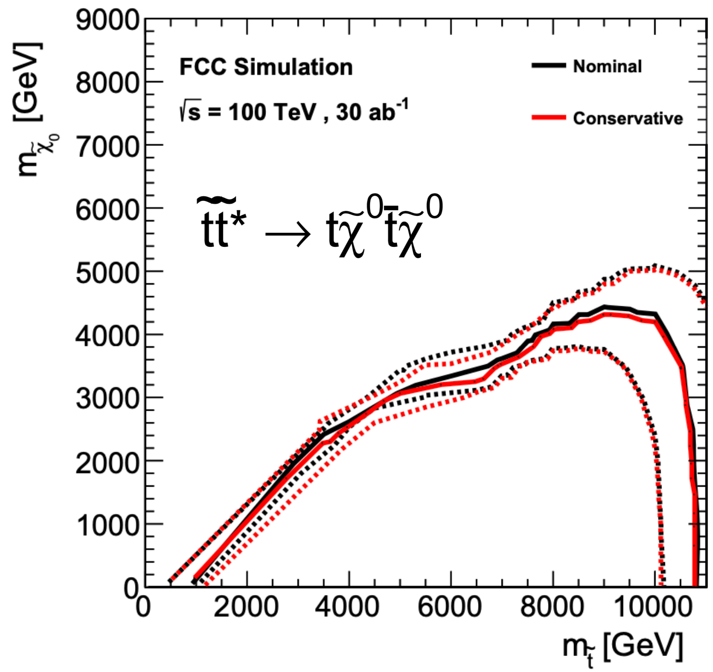
Mass tuning:

$$\Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500\ \mathrm{GeV}}\right)^2$$

The top partners are QCD-charged stops

FCC-hh: $M \gtrsim 10$ TeV → $\Delta_{m_h^2} \gtrsim 400$

Improve over LHC by ~ 2 orders of magnitude



[Bernal Casas, Moreno 2022.09103]

For vev tuning, 2HDM structure leads to:

$(\tan\beta \gg 1)$

$$\Delta_{v^2} \simeq \frac{4}{(\tan\beta)^2}\frac{m_A^2}{m_h^2}$$

$$\delta_{hbb} \simeq \frac{2m_Z^2}{m_A^2}$$

→

$$\Delta_{v^2} \simeq \frac{8}{(\tan\beta)^2}\frac{m_Z^2}{m_h^2}\frac{1}{\delta_{hbb}}$$

Connection between vev tuning and Higgs couplings is indeed precise, but:

$\tan\beta \gg 1$ can be a significant suppression

htt and hVV corrections even smaller

SUSY

[Gouskos, Sung, Incandela, CERN-ACC-2019-0036]

Mass tuning:

$$\Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500\ \text{GeV}}\right)^2$$

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FCC-hh: $M \gtrsim 10$ TeV ➔ $\Delta_{m_h^2} \gtrsim 400$

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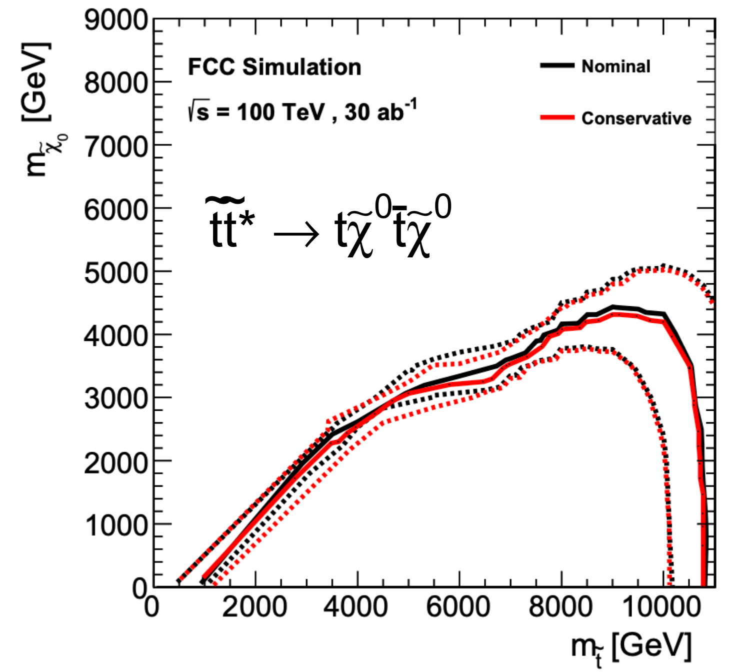


- In SUSY, difficult to draw general statements on tuning from Higgs couplings

  ➔ emphasis is on direct searches for QCD-charged stops

- Picture can change dramatically if the scalar top partners are QCD-neutral.

  E.g. if they are fully neutral under SM, “nightmare scenario” for naturalness*

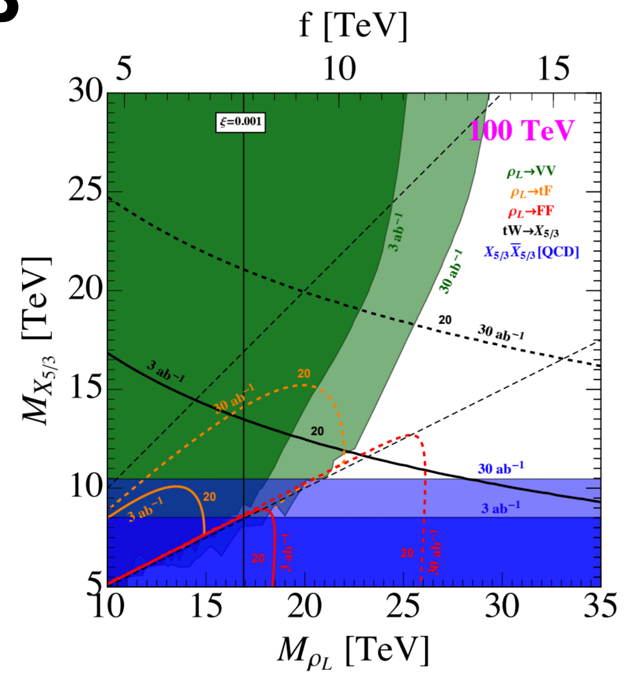
  However, models of SUSY neutral naturalness are somewhat contrived

(also [Craig, Cohen, Giudice, McCullough, 1803.03647], though Higgs is a pseudo-Goldstone boson)

[Burdman, Chacko, Goh, Harnik, hep-ph/0609152]
[Cohen, Craig, Lou, Pinner, 1508.05396]
* [Cheng, Li, Salvioni, Verhaaren, 1803.03651]

Higgs as a pNGB

[Liu, Wang, Xie, 1810.08954]



Mass tuning:

$$\Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500\ \text{GeV}}\right)^2$$

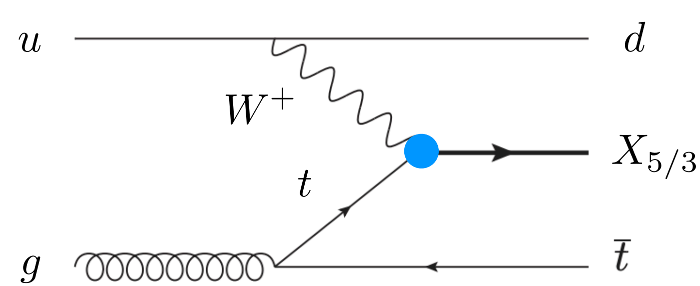
The top partners are QCD-charged fermions with

different EW quantum numbers: $T, X_{5/3}, \ldots$

FCC-hh: $M \gtrsim 10$ TeV $\Delta_{m_h^2} \gtrsim 400$

- Including single production can increase sensitivity on M by $O(1)$

Model-dependent couplings

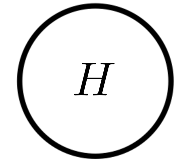


e.g. [De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663]

[in principle single production is possible also in SUSY, if R-parity violating]

Higgs as a pNGB

$\mathcal{G}/\mathcal{H}$



Vev tuning:

- The Higgs doublet is made of 4 Goldstone bosons: $H \to H + c$ under $\mathcal{G}/\mathcal{H}$

- Embedding the SM gauge interactions makes hVV couplings smaller than in SM,

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \cos\frac{\langle h \rangle}{f} \simeq 1 - \frac{v^2}{2f^2}$$

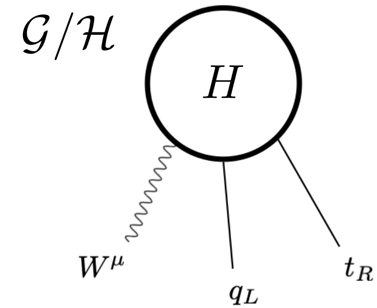
decay constant of the “pion-like” Higgs

The LHC already tells us we need $v \ll f$

How is the Higgs vev generated?

[e.g. Panico, Wulzer 1506.01961]

Higgs as a pNGB



Vev tuning:

- The Higgs is a Goldstone boson: at tree level, $V(h) = 0$
- At loop level, a potential is generated by SM gauge and (top) Yukawa interactions. Typical form is

$$V(h) \sim -\alpha f^2 \sin^2 \frac{h}{f} + \beta f^2 \sin^4 \frac{h}{f}$$

α, β are model-dependent constants

To obtain a viable $v \ll f$, need to tune parameters:

$$\Delta_{v^2} = \frac{(\alpha/\beta)_{\text{expected}}}{(\alpha/\beta)_{\text{required}}} \sim \frac{f^2}{v^2}$$

[e.g. Panico, Wulzer 1506.01961]

Higgs as a pNGB

Combine the previous two results:

$$\frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = \cos\frac{\langle h\rangle}{f} \simeq 1 - \frac{v^2}{2f^2}$$

$$\Delta_{v^2} = \frac{(\alpha/\beta)_{\mathrm{expected}}}{(\alpha/\beta)_{\mathrm{required}}} \sim \frac{f^2}{v^2}$$

$$\Delta_{v^2} \sim \frac{1}{2}\frac{1}{|\delta_{hVV}|}$$

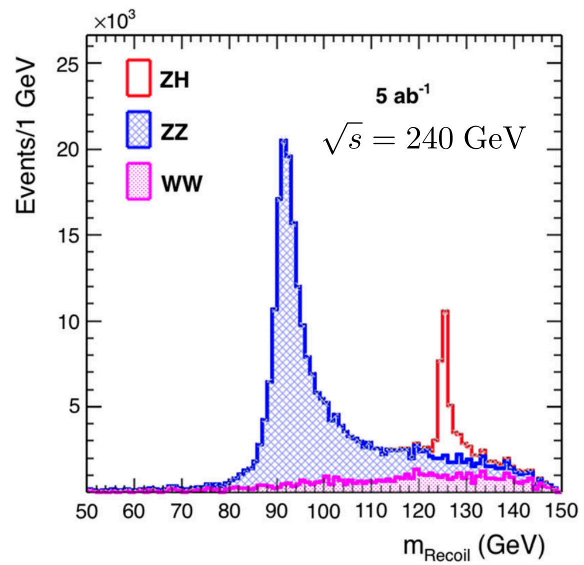
<u>Robust</u> connection between vev tuning and Higgs coupling sensitivity

[FCC CDR Vol 1, EPJ C 2019]

FCC-ee will reach $|\delta_{hZZ}| < 0.34\%$ $(f > 3\ \mathrm{TeV})$

by measuring recoil mass in $e^+e^- \to Zh$

$$\Delta_{v^2} \gtrsim 150$$



(95% CL)

Mass tuning vs vev tuning

In summary, for a pNGB Higgs we estimate:

$$\Delta_{m_h^2} \sim \frac{\delta m_h^2}{m_h^2} \sim \left(\frac{M}{500\ \mathrm{GeV}}\right)^2$$

FCC-hh: $M \gtrsim 10\ \mathrm{TeV}$ ➔ $\Delta_{m_h^2} \gtrsim 400$

$$\Delta_{v^2} \sim \frac{1}{2}\frac{1}{|\delta_{hVV}|}$$

FCC-ee: $|\delta_{hVV}| < 0.34\,\%$ ➔ $\Delta_{v^2} \gtrsim 150$

They are comparable (to be more quantitative, one needs to specify the model)

For pNGB Higgs, coupling measurements are crucial complement to direct searches

Moreover, clear path to remove mass tuning: the Twin Higgs framework.

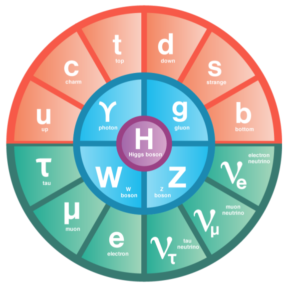
The top partners are SM-neutral fermions, direct searches have weak sensitivity

➔ Higgs couplings remain as only guaranteed signature

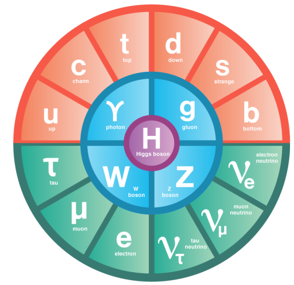
[Chacko, Goh, Harnik, 2005]

The Twin Higgs

SM



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



Twin SM

$\mathcal{G}/\mathcal{H}$

7 Goldstone bosons

$$\mathcal{G}/\mathcal{H} = SO(8)/SO(7)$$

3 Goldstones eaten by massive Twin gauge bosons; 4 make up the Higgs

top Yukawa: $\mathcal{L} = y_t Q H t + \hat{y}_t \hat{Q} \hat{H} \hat{t}$

The top partner *(Twin top)* is neutral under whole SM

Can still be sub-TeV

[Chacko, Goh, Harnik, 2005]

Twin Higgs at work

- The leading corrections to Higgs potential cancel, thanks to exchange symmetry:

$$V_t \supset \frac{N_c}{8\pi^2} y_t^2 f^2 M^2 \sin^2\frac{h}{f} + \frac{N_c}{8\pi^2}\hat{y}_t^2 f^2 \hat{M}^2 \cos^2\frac{h}{f}$$

scale of QCD-charged fermions ($\lesssim 4\pi f \gg 1$ TeV)

decay constant of Goldstone Higgs (~ 1 TeV)

$\mathcal{Z}_2$: $y_t = \hat{y}_t$, $M = \hat{M}$ $\rightarrow$ V_t = constant, no correction to Higgs mass

- What remains is much smaller potential, controlled by Twin top:

$$V_t \approx \frac{N_c}{32\pi^2} y_t^2 f^2 m_{\hat{t}}^2 \left[\sin^4\frac{h}{f}\log\frac{a}{\sin^2 h/f} + \cos^4\frac{h}{f}\log\frac{a}{\cos^2 h/f}\right]$$

$m_{\hat{t}} = y_t f/\sqrt{2}$
sub-TeV, but SM neutral

However, a tuning $\Delta_{v^2} \sim f^2/v^2$ is still needed, to achieve a small vev

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

A naturally small vev?

- As we just saw, a tuning $\Delta_{v^2} \sim f^2/v^2$ to achieve a small Higgs vev is common issue in (Twin) models of Higgs as pNGB

- Can we remove this tuning with extra model building?

  If yes, would obtain a *fully natural* Higgs potential, consistently with LHC results:

Twin structure → ~~mass tuning~~ "Extra model building" → ~~vev tuning~~

- This is especially interesting because models that achieve this*

  predict large corrections to h^3 coupling (shape of potential differs at $\mathcal{O}(1)$ from SM)

  → h^3 measurement will add genuine new information beyond single-Higgs couplings

*at least, those I know of

Gegenbauer Goldstones

- Idea is to include, beyond the top sector potential V_t , a new "wiggly" component that will naturally set the minimum close to the origin

[Durieux, McCullough, Salvioni 2202.01228 + 2209.00666]

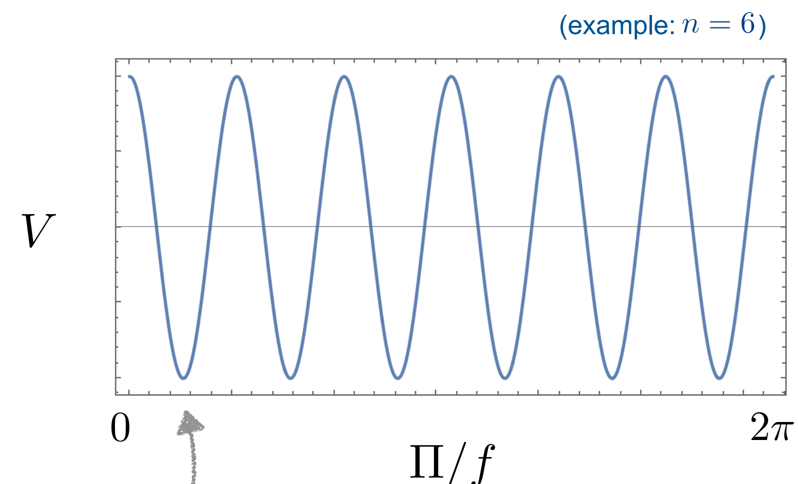
- For an Abelian $U(1)$ Goldstone, we know that wiggly potentials are obtained from explicit breaking that preserves a $\mathcal{Z}_n$ discrete symmetry:

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

Explicit breaking from operator of charge n

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

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



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

Moderately large n sets vev parametrically close to origin

Gegenbauer Goldstones

- Generalizing to non-Abelian case, which is relevant for Higgs as pNGB, one finds Gegenbauer polynomials:

[Durieux, McCullough, Salvioni 2202.01228 + 2209.00666]

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

↓

Explicit breaking to $SO(N)$ by 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 → traceless

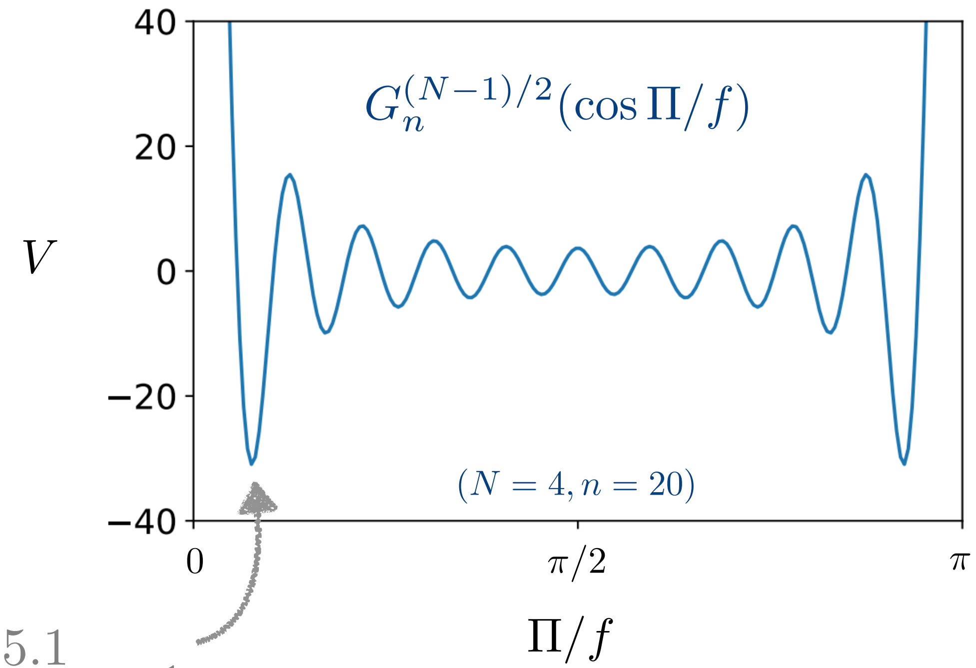
↓

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

potential is a Gegenbauer polynomial

Leopold Gegenbauer

Gegenbauer Goldstones



$$\frac{\langle \Pi \rangle}{f} \approx \frac{5.1}{n} \ll 1$$

First minimum is parametrically close to origin

Differently from Abelian case, not periodic (only approximately)

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

potential is a Gegenbauer polynomial

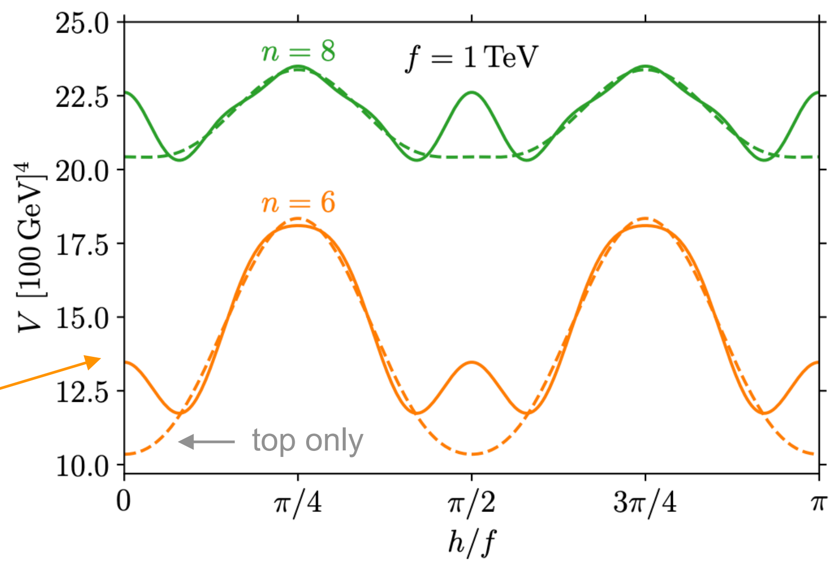
Leopold Gegenbauer

Gegenbauer's *Twin*

- Twin Higgs mechanism generates small potential: $m_h \approx 125\ \mathrm{GeV}$ is natural
- Gegenbauer potential generates small vev: $v \ll f$ is natural

Marry the two: *Gegenbauer's Twin*

Fully natural electroweak breaking, yet hiding from LHC so far



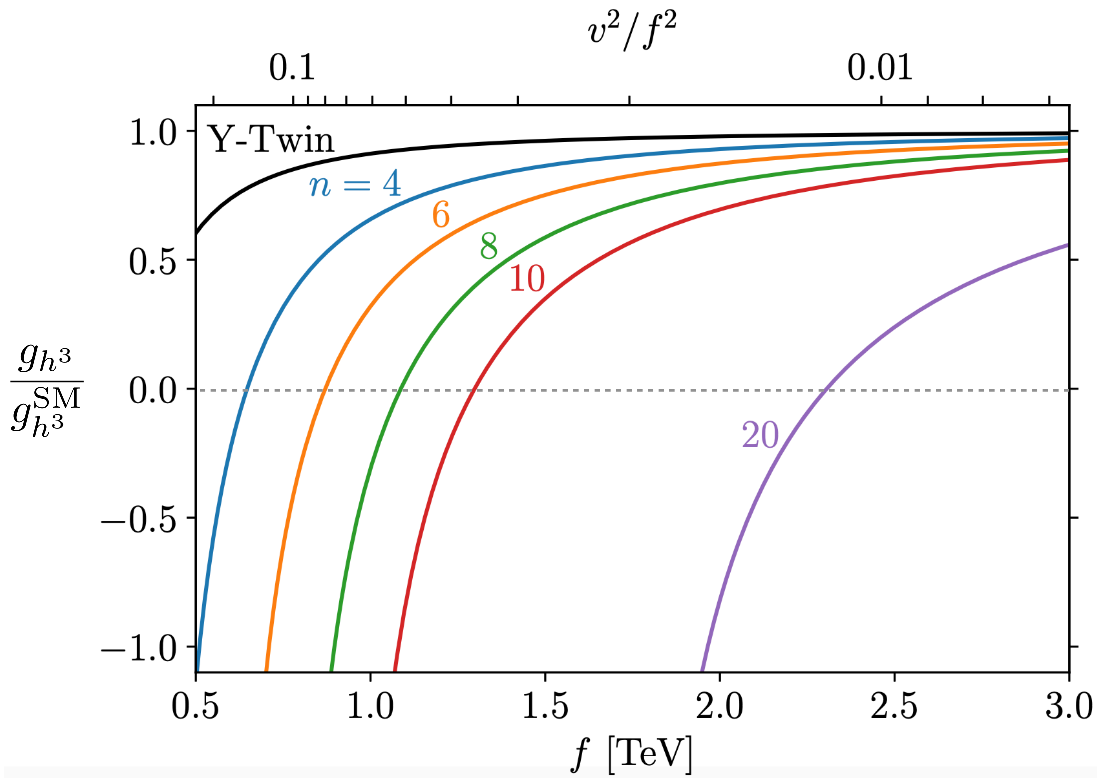
top + Gegenbauer

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

(generalized Gegenbauer story to $SO(8) \to SO(4) \times SO(4)$ explicit breaking)

The Higgs self-coupling

For Gegenbauer's Twin, corrections to h^3 are parametrically enhanced



$$\frac{g_{hXX}}{g_{hXX}^{\text{SM}}} \simeq 1 - \frac{v^2}{2f^2}$$

[Durieux, McCullough, Salvioni
2202.01228 + 2209.00666]

Smoking gun signal: could even be the first deviation from SM observed at colliders

Another route: tadpole-induced EWSB

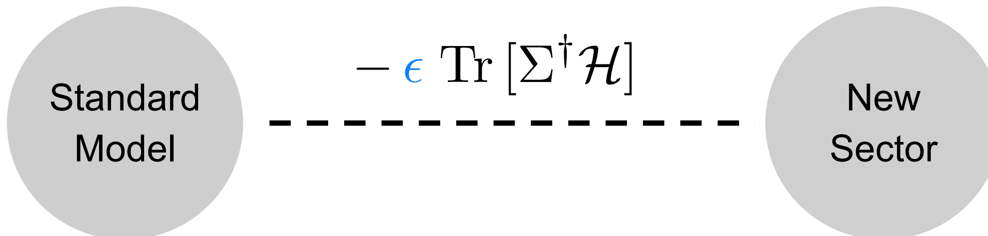
Another viable approach to remove v/f tuning in Twin Higgs

is tadpole-induced EWSB

[Harnik, Howe, Kearney, 1603.03772]

Basic idea:

$$-\,\epsilon\;\mathrm{Tr}\,[\Sigma^\dagger \mathcal{H}]$$



$$+\,m_H^2 |H|^2 \qquad\qquad \langle\Sigma\rangle = f_\Sigma$$

$$\longrightarrow \quad V(h) \sim +\,m_H^2 h^2 - \epsilon\, f_\Sigma\, h$$

Large deviations in h^3 are expected here, too

(self-interactions are structurally suppressed)

Updated analysis of constraints is missing

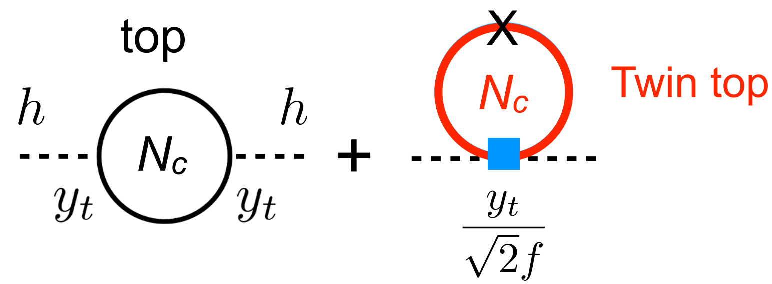
[Azatov, Galloway, Luty, 2011]
[Galloway, Luty, Tsai, Zhao, 2013]
[Chang, Galloway, Luty, Salvioni, Tsai, 2014]
[Galloway, Kagan, Martin, 2016]
[Contino, Greco, Mahbubani, Rattazzi, Torre, 2017]

Probing the Twin top directly

Twin top is SM-neutral, but must couple to the Higgs as:

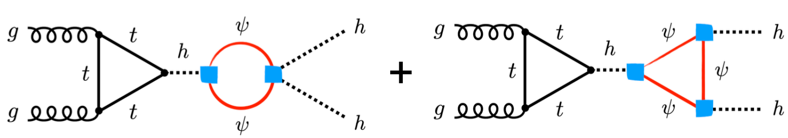
$$\mathcal{L} = -m_{\hat{t}}\,\bar{\hat{t}}\hat{t} + \frac{y_t}{\sqrt{2}}\frac{|H|^2}{f}\,\bar{\hat{t}}\hat{t} \qquad \delta m_h^2 \sim$$

$m_{\hat{t}} = y_t f/\sqrt{2}$



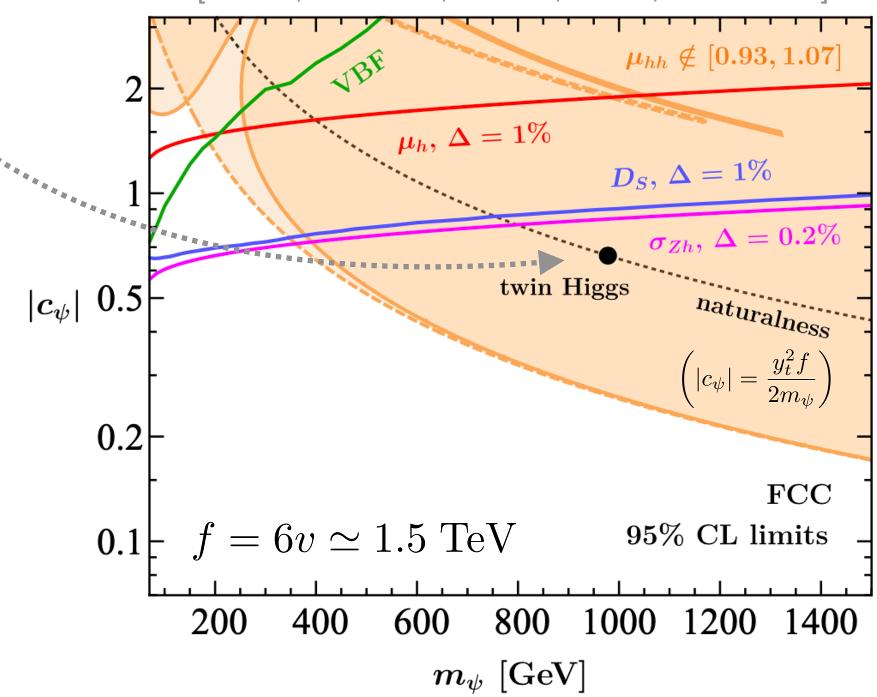
Probes at LHC, HE-LHC, FCC have been studied very recently

Interestingly, double Higgs production appears to be sensitive at loop level



(see paper for assumptions on dim-6 ops.)

[Haisch, Ruhdorfer, Schmid, Weiler, 2311.03995]



Conclusions

- Both direct searches for top partners and Higgs coupling measurements test naturalness, but implications differ for SUSY and Higgs as pNGB

- In SUSY, Higgs coupling deviations are model-dependent (and can be quite suppressed). Emphasis on direct searches for QCD-charged stops

- For pNGB Higgs, direct searches and Higgs couplings are both important probes. In Twin Higgs scenarios, Higgs couplings remain as the only guaranteed signature

- Twin Higgs still suffers from fine tuning to achieve a small Higgs vev, $v \ll f$

  Models that remove this (Gegenbauer, tadpole, …?) predict large deviations in h^3, stressing importance of its measurement to make progress on naturalness

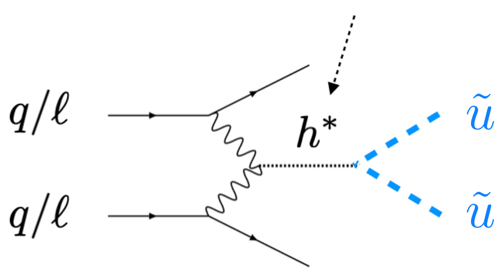
Backup slides

Probing *scalar* top partners directly

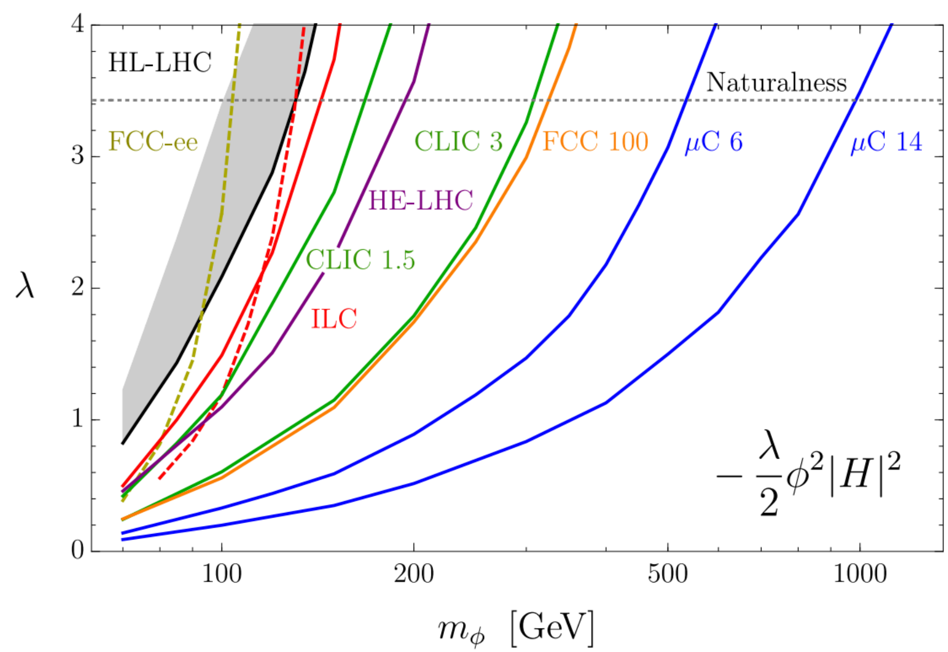
- If the Higgs is not a pseudo-Goldstone boson, $\sim v^2/(2f^2)$ corrections to Higgs couplings are not expected
- Need to probe naturalness cancellation directly: $\mathcal{L} = -y_t^2|\tilde{u}_1|^2|H|^2 - y_t^2|\tilde{u}_2|^2|H|^2$

[Cheng, Li, Salvioni, Verhaaren 2018]
see also [Cohen, Craig, Giudice, McCullough 2018]

e.g. Standard Model-singlet scalar top partners



FCC-hh: $m_{\tilde{u}} > 330\ \text{GeV}$



[Ruhdorfer, Salvioni, Weiler 2019]
[Craig, Lou, McCullough, Thalapillil 2014]

Probing *scalar* top partners directly

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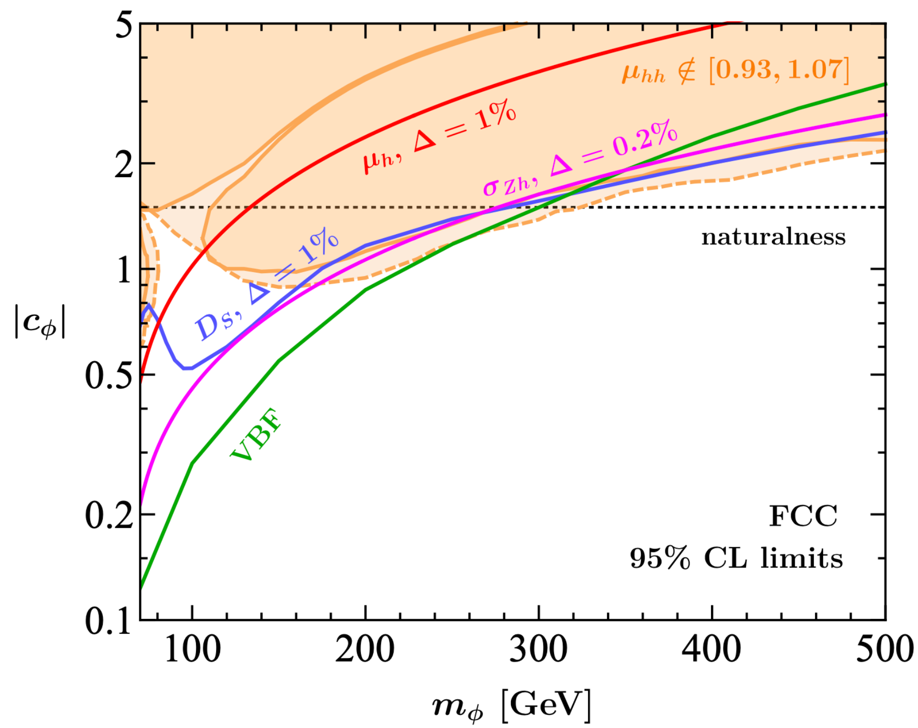
[Cheng, Li, Salvioni, Verhaaren 2018]
see also [Cohen, Craig, Giudice, McCullough 2018]

e.g. Standard Model-singlet scalar top partners

Loop-level probes (off-shell Higgs, double Higgs) studied in

[Haisch, Koole, 2022]



Naturalness and $\delta_{h^3}/\delta_{hVV}$

Single-Higgs coupling measurements will reach precision stage far before tests of h^3

This makes $\left|\frac{\delta_{h^3}}{\delta_{hVV}}\right|$ an important quantity for a new physics model:

if it is large, self-coupling measurements probe genuinely new ground

However, in canonical models addressing hierarchy problem (composite Higgs, SUSY)

Example: Minimal Composite Higgs 5+5,
Composite Twin Higgs 8+1

$$\left|\frac{\delta_{h^3}}{\delta_{\text{single } h}}\right| \sim O(1)$$

$$\delta_{h^3} \simeq -\frac{3}{2}\frac{v^2}{f^2} \qquad \delta_{hVV} \simeq -\frac{1}{2}\frac{v^2}{f^2}$$

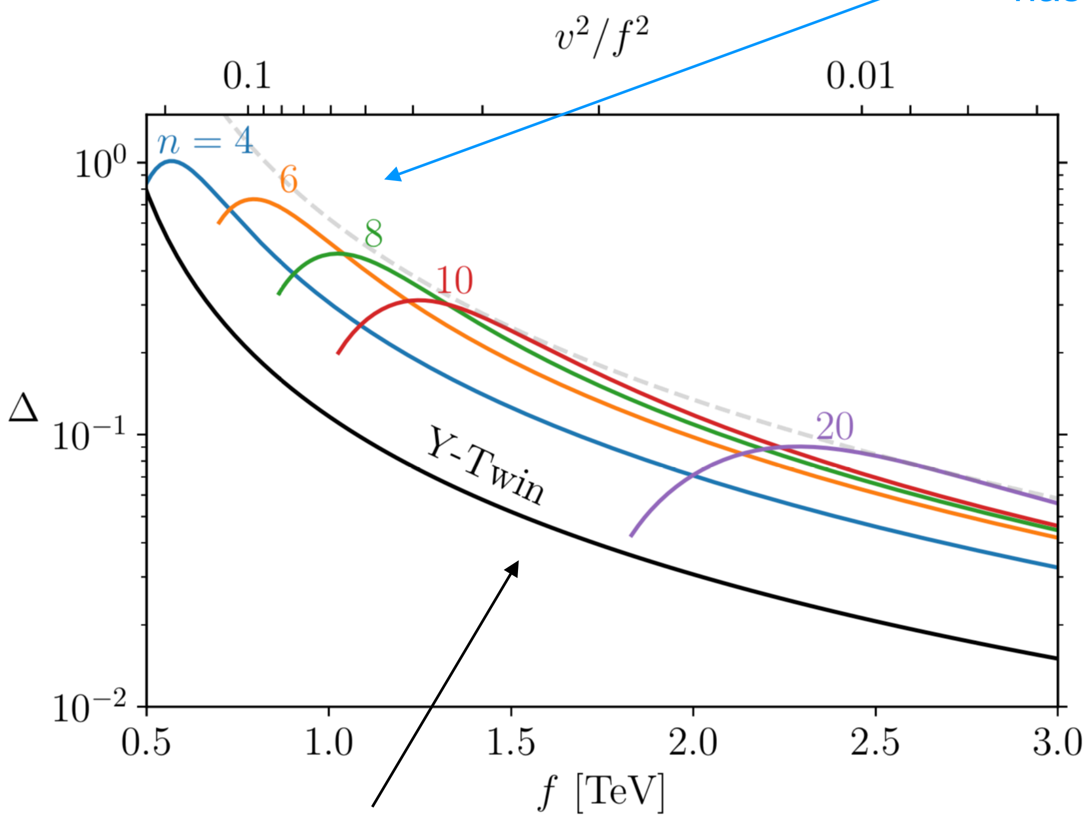
$$\left|\frac{\delta_{h^3}}{\delta_{hVV}}\right| \simeq 3$$

and prospects to observe deviations in h^3 are limited

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)