Higgs couplings and naturalness

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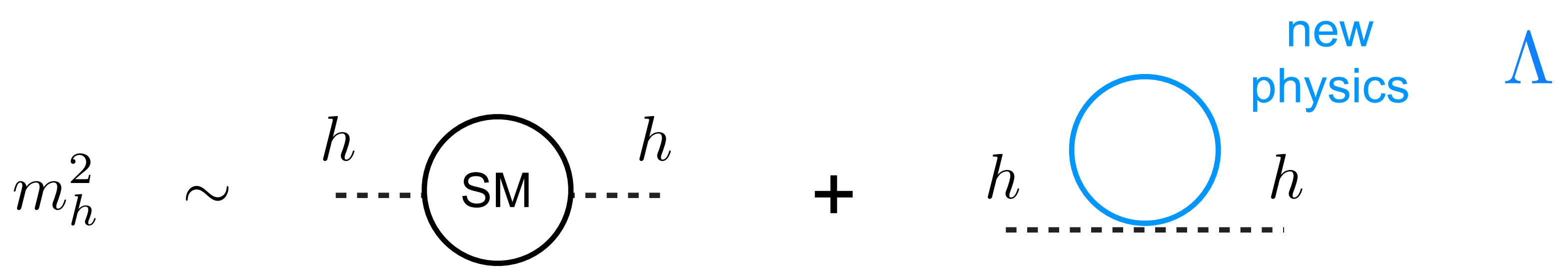
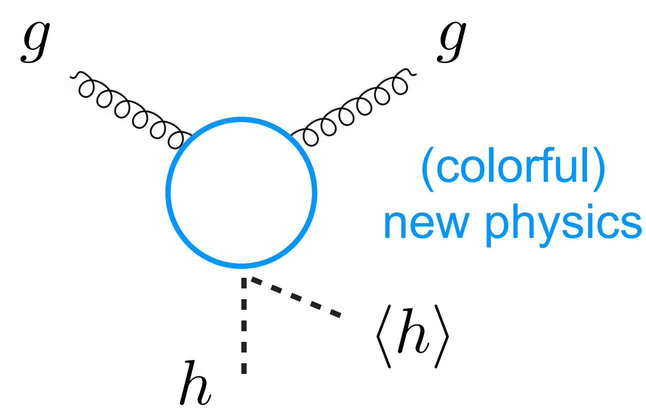
Higgs naturalness solved by symmetry?

- New states near the weak scale that contribute to Higgs **mass**…



… should modify Higgs **couplings** too: for instance



- Higgs coupling measurements as probe of naturalness

Higgs couplings as probe of naturalness

- Connection is robust, but with important quantitative variations

correction to
on-shell couplings

$$\frac{\delta g_h}{g_{h,\mathrm{SM}}} \sim \frac{g_*^2}{\Lambda^2} v^2$$

g_* new physics coupling

Λ new physics mass scale

For fixed BSM mass, effects are enhanced at strong coupling

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Weakly coupled solutions (supersymmetry)

$$g_* \sim g_{\mathrm{SM}}$$

$$c_{hff} = 1 \pm O\left(\frac{m_Z^2}{m_A^2}\right)$$

mass of second Higgs doublet

$$c_{hVV} = 1 - O\left(\frac{m_Z^4}{m_A^4}\right)$$

very small

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g_* new physics coupling

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Strongly coupled solutions (Higgs as composite pseudo-Goldstone boson)

$$g_* \gg g_{\mathrm{SM}}$$

$$\Lambda \sim g_* f$$

$$c_{hVV} = 1 - \frac{v^2}{2f^2}$$

Higgs "decay constant"
(think of f_π in chiral Lagrangian)

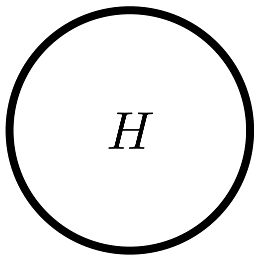
$$c_{hff} = 1 - O\left(\frac{v^2}{f^2}\right)$$

more model-dependent

Higgs as composite Goldstone boson

[Kaplan, Georgi 1984]
[Kaplan 1992]
[Agashe, Contino, Pomarol 2004]

strongly-interacting sector



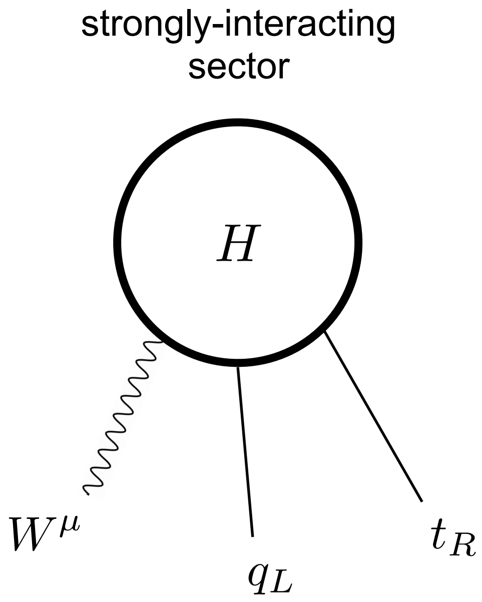
Tree level: Goldstone shift symmetry

$$H \to H + \epsilon \quad \longrightarrow \quad V(H) = 0$$

$m_h \ll \Lambda$ is natural

Higgs as composite Goldstone boson

[Kaplan, Georgi 1984]
[Kaplan 1992]
[Agashe, Contino, Pomarol 2004]



One loop: potential is generated by SM fields

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

↓

realistic vacuum needs some residual fine-tuning

$$\Delta = \frac{(\alpha/\beta)_{\text{required}}}{(\alpha/\beta)_{\text{expected}}} = \frac{2v^2/f^2}{1} \ll 1$$

(also called "minimal tuning"; some models need stronger cancellations)

[e.g. Panico, Wulzer 2015]

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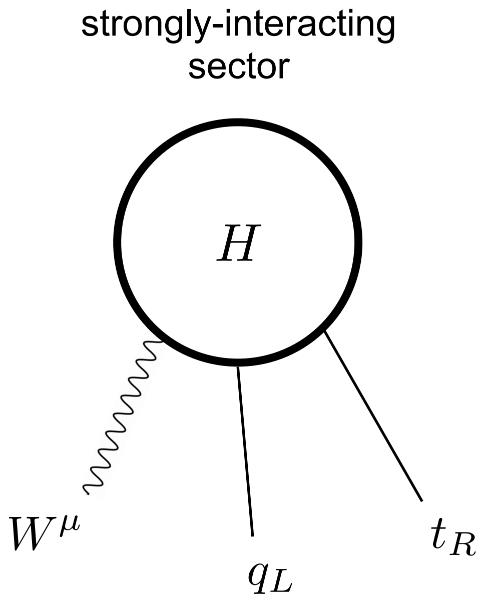

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- Therefore $\quad c_{hVV} = 1 - \frac{v^2}{2f^2} = 1 - \frac{\Delta}{4}$

"sharp" sense in which Higgs coupling measurements probe fine tuning

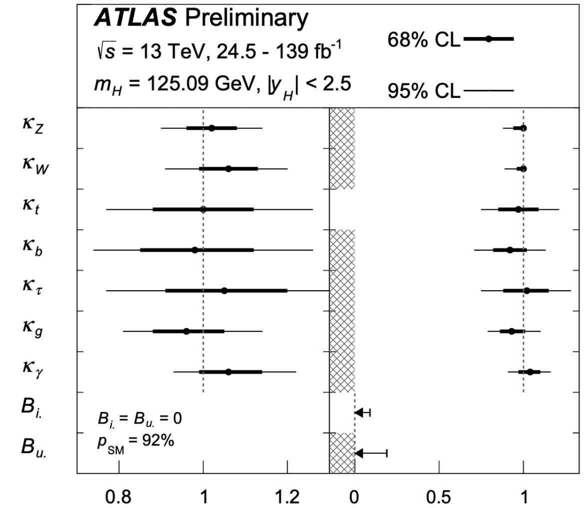
LHC: present and future

[ATLAS-CONF-2020-027]
[CMS-PAS-HIG-19-005]

- Run 2:

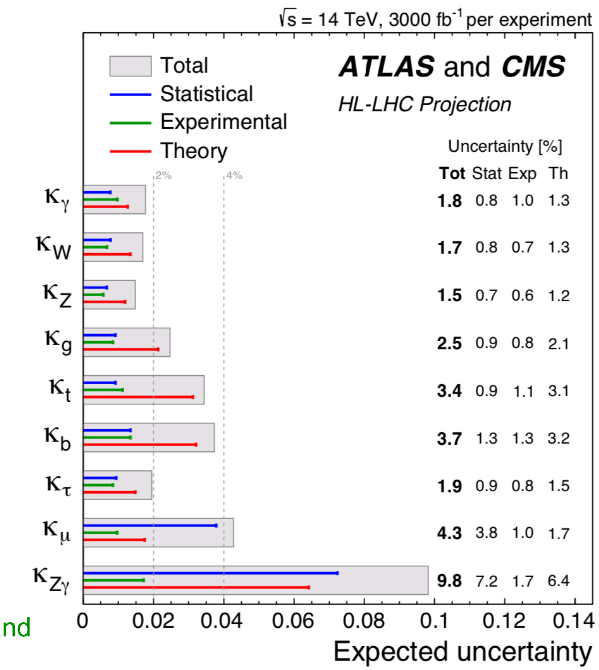
$$c_{hVV} \gtrsim 0.9 \quad \Rightarrow \quad \Delta \lesssim 30\%$$

(approx 95% CL)



- High Luminosity: uncertainties in 1.5 - 4% range

$$f > 1 \text{ TeV} \quad \Rightarrow \quad \Delta \lesssim 10\%$$



[Higgs physics @ HL- and HE-LHC,1902.00134]

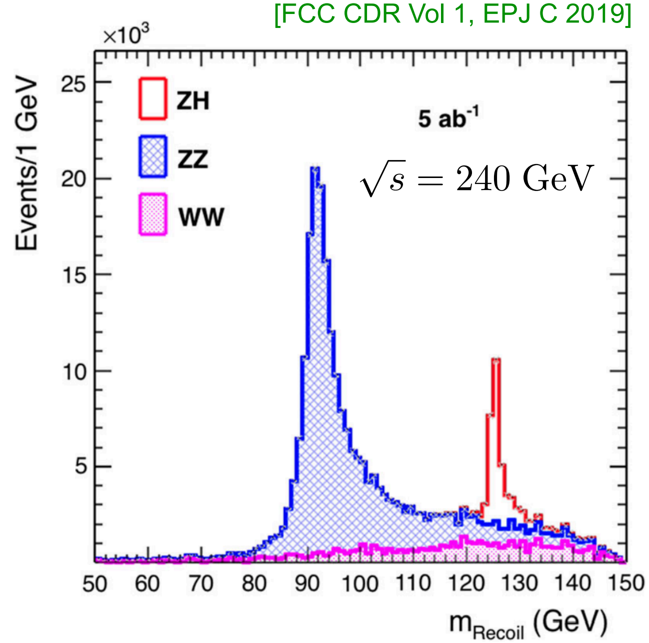
FCC-ee

- Explore one order of magnitude in fine tuning:

$$f > 3\ \mathrm{TeV} \quad \Rightarrow \quad \Delta \lesssim 1\,\%$$

(95% CL)

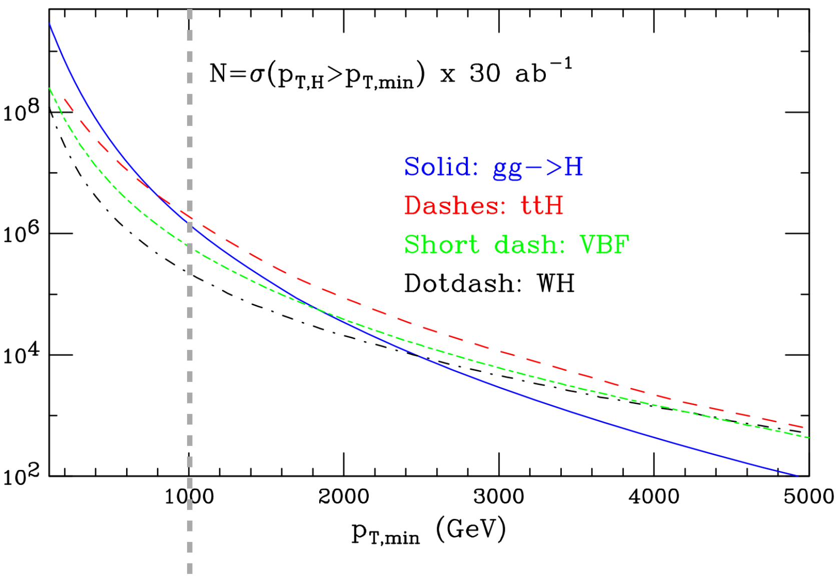
[FCC CDR Vol 1, EPJ C 2019]



Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	FCC-$ee_{240+365}$		(68% CL)
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16

FCC-hh

[FCC CDR Vol 1, EPJ C 2019]



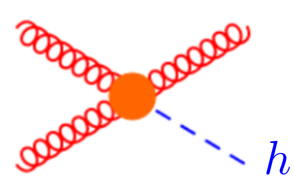
~ FCC-ee statistics,
but above 1 TeV!

- Program is fully complementary to FCC-ee
- Probes high - q^2 region with unprecedented sensitivity

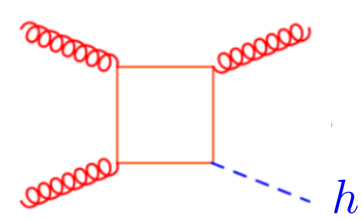
↓

$$H^\dagger H\, G^a_{\mu\nu} G^{\mu\nu\, a}$$

$$H^\dagger H\, \bar{q}_L \widetilde{H} t_R$$



tell apart from



$$\mathcal{M} \sim s$$

$$\mathcal{M} \sim \log^2 \frac{s}{m_t^2}$$

[Grojean, Salvioni, Schlaffer, Weiler 2013]
[Banfi, Martin, Sanz 2013]
[Azatov, Paul 2013]
…

More FCC-hh

- 1% measurement of g_{htt} coupling, exploiting ratio $\sigma(t\bar{t}h)/\sigma(t\bar{t}Z)$ to reduce systematics

[Mangano, Plehn, Reimitz, Schell, Shao 2015]

- Very important for composite Higgs framework, where most promising models (tuning, EW precision) single out with maximal size the operators

$$\frac{1}{f^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \qquad \frac{1}{f^2} y_t H^\dagger H \bar{q}_L \widetilde{H} t_R \qquad \frac{1}{f^2}(\bar{t}_R \gamma^\mu t_R)^2$$

$$c_{hVV} = 1 - \frac{v^2}{2f^2} \qquad c_{htt} = 1 - O\left(\frac{v^2}{f^2}\right)$$

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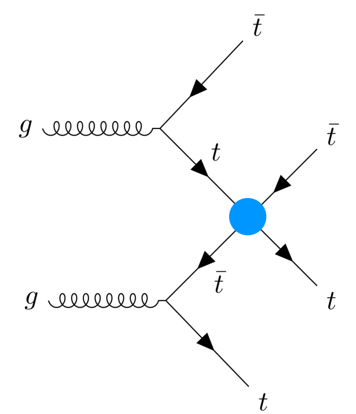

$$\mathcal{M} \sim \frac{s}{f^2}$$

grows with energy

Expected sensitivity from 4-top production @ FCC-hh:

$$f > 6.5 \text{ TeV}$$

[Banelli, Salvioni, Serra, Theil, Weiler 2020]

➡ key complementary observable

Where are the top partners?

- Top partners not too far above weak scale are essential for naturalness
- In “classic” scenarios, direct searches for color-charged particles are important tests (top squarks, vector-like quarks)

[Matsedonskyi, Panico, Wulzer 2012]
[Pomarol, Riva 2012]

- Concretely: in composite Higgs, observed Higgs mass requires $M_T \lesssim 1.5\, f$

$$M_T \approx 2\ \mathrm{TeV}$$

HL-LHC direct reach

$$f \gtrsim 1.2\ \mathrm{TeV}$$

“equivalent” reach,
comparable to Higgs couplings

Where are the top partners?

- Top partners not too far above weak scale are essential for naturalness
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- In neutral naturalness models, top partners are color-less

[Chacko, Goh, Harnik 2005]
and many more

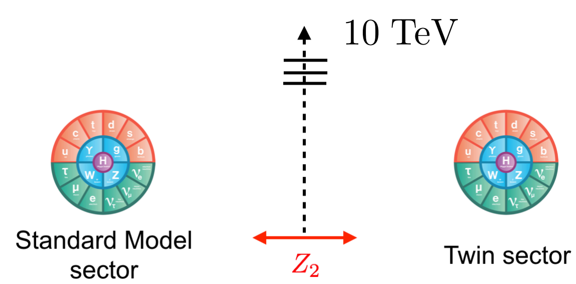
Twin Higgs:

➡ "Twin top" is light, but fully neutral under Standard Model

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

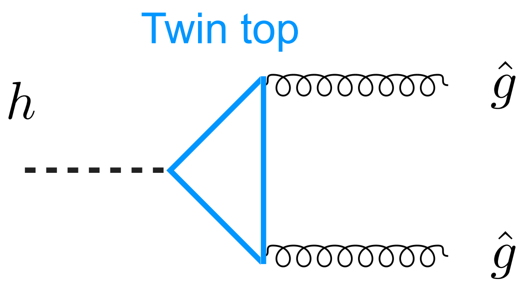
➡ new color-charged states can be close to $4\pi f \gtrsim 10 \text{ TeV}$

➡ direct discovery may need to wait for FCC-hh



Higgs → invisible decays

- In Twin Higgs there is an "irreducible" contribution from $h \to \text{Twin gluons}$



$$\mathrm{BR}(h \to \hat{g}\hat{g}) \approx \left(\frac{v}{f}\right)^4 \mathrm{BR}(h \to gg)$$

(invisible width can be larger, depending on twin fermion masses)

[Borgonovi et al. CERN-ACC-2018-0045]

$$\mathrm{BR}(h \to \mathrm{inv}) < 2.5 \times 10^{-4}$$

FCC-hh

⇒ $f \gtrsim 1.1\ \mathrm{TeV}$

- Many striking visible signals are possible (and model-dependent):

  Higgs exotic decays probe neutral naturalness [Craig, Katz, Strassler, Sundrum 2015]

see talks by Christophe Grojean this morning, Juliette Alimena on Thursday

Higgs cubic coupling

- HL-LHC has first sensitivity (50% on c_{hhh} , at 68% CL)
- FCC-ee will improve via loop effects (20%) [de Blas et al. 1905.03764]
- FCC-hh will truly pin it down (7%)

- Models of Higgs naturalness usually do not predict parametrically larger deviations in c_{hhh} than in single Higgs couplings

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- There are exceptions: “Gegenbauer’s Twin” [Durieux, McCullough, Salvioni 2202.01228]

- Twin Higgs model where explicit SO(8) breaking arises from higher-dimensional irreps

  ➡ (part of) Higgs potential is Gegenbauer polynomial, $v \ll f$ natural

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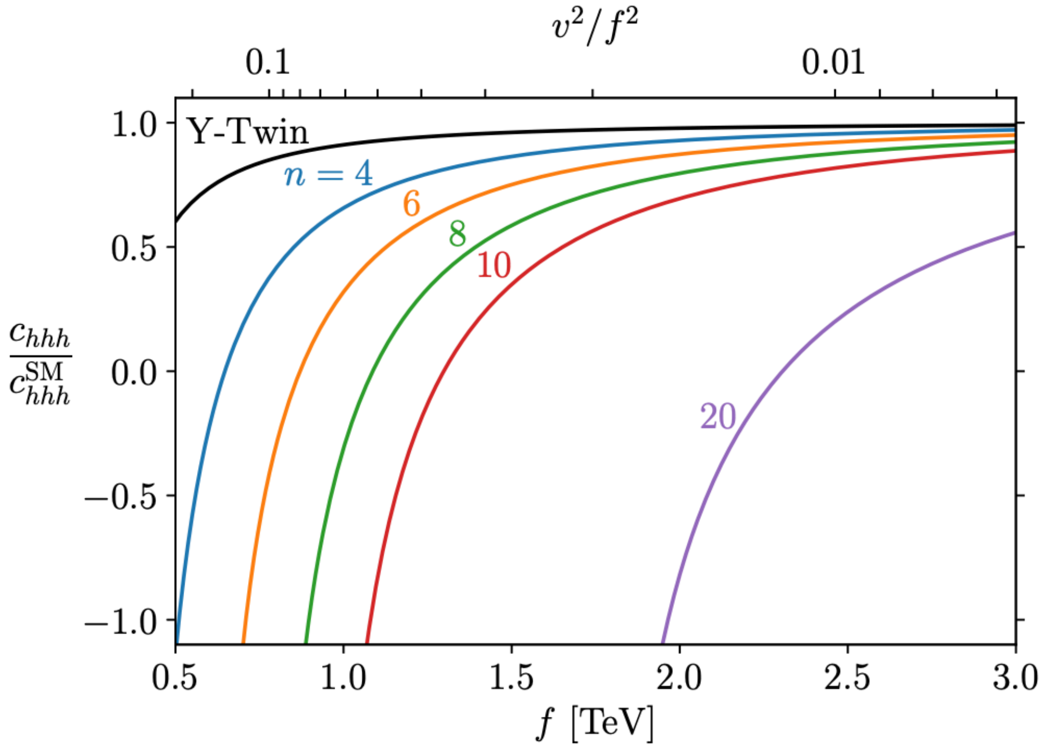
- Parametrically enhanced deviations in cubic self-coupling



[Durieux, McCullough, Salvioni 2202.01228]

Conclusion

- HL-LHC + FCC program will be extraordinary probe of Higgs naturalness.
  Push minimal fine tuning from few $10^{-1} \rightarrow$ few 10^{-3}, if no discovery

- If top partners are color-less, as in neutral naturalness models, resonance detection could be possible only at FCC-hh.
  Until then (and after), measuring Higgs properties is key to progress

- Could not do justice to many more interesting theory ideas and their tests, nor characterization in presence of deviations from Standard Model

Supplementary material

Higgs $\rightarrow$ invisible, above threshold

- Neutral naturalness models where Higgs is pseudo-Goldstone boson predict coupling corrections $\sim v^2/(2f^2)$ $\Rightarrow$ allows for robust test

- In models where this is absent, may need to probe naturalness cancellation directly:

$$\mathcal{L} = -y_t^2 |\tilde{u}_1|^2 |H|^2 - y_t^2 |\tilde{u}_2|^2 |H|^2$$

Standard Model-singlet
scalar top partners

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

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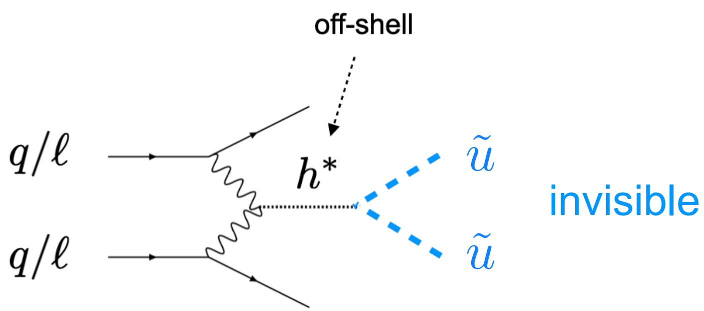
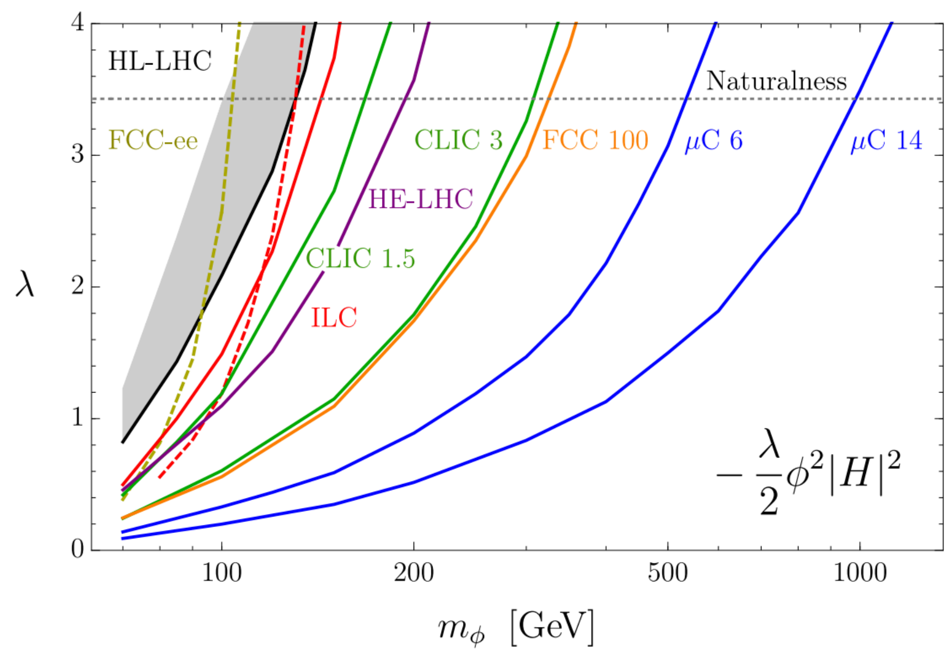
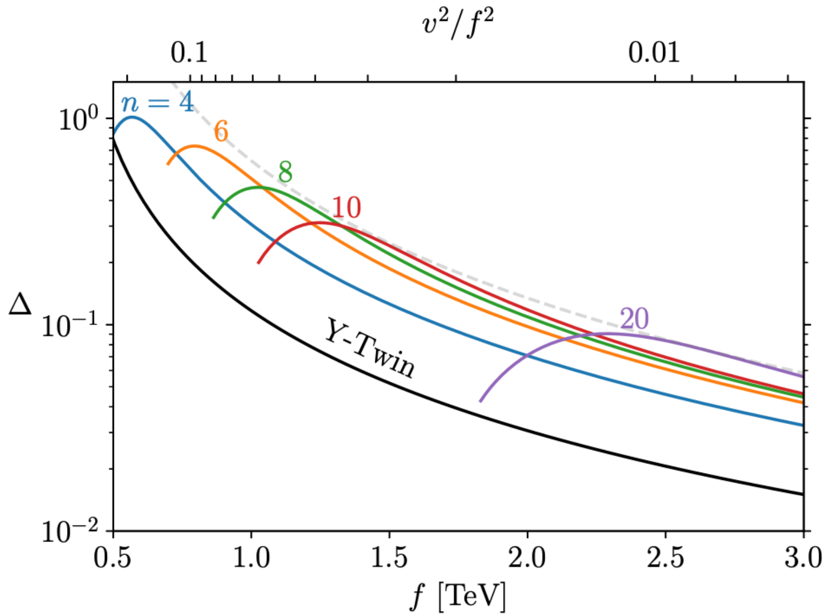


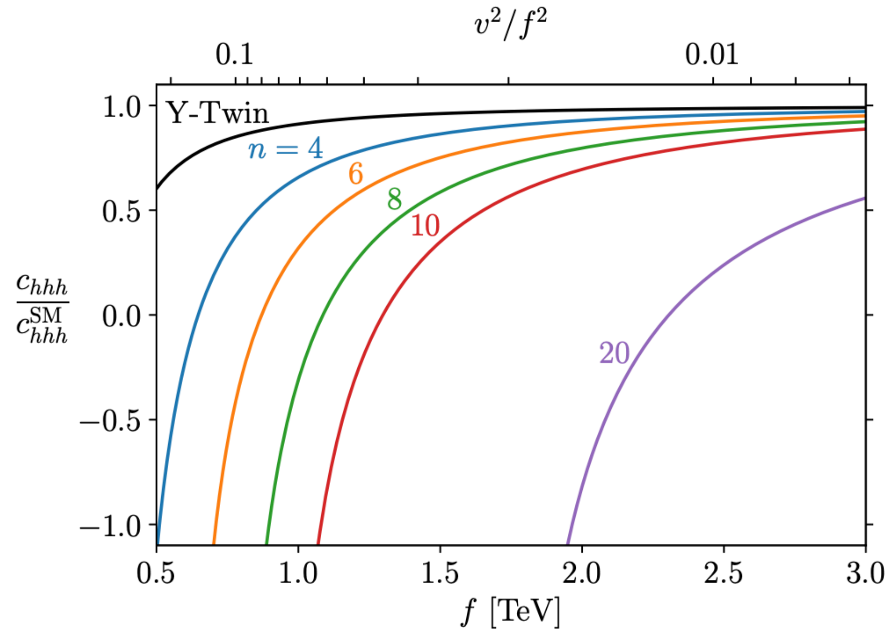
FCC-hh: $m_{\tilde{u}} > 330\ \text{GeV}$



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

Gegenbauer's Twin





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