Higgs theory facing data

Gauthier Durieux
(CERN)

Gegenbauer Goldstones, JHEP 01 (2022) 076, [2110.06941]
Gegenbauer's Twin, JHEP 05 (2022) 140, [2202.01228]
Charting the Higgs self-coupling boundaries, JHEP 12 (2022) 148, [2209.00666]

with Matthew McCullough and Ennio Salvioni

LHCP – 24 May 2023

Where we stand

$$\mathcal{L}_{\mathsf{SM}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi + |D_\mu H|^2$$
$$+Y\bar{\psi}\psi' H + \mu^2|H|^2 - \lambda|H|^4$$

all particles seen
all parameters determined

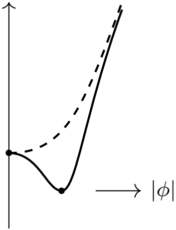
missing pieces
(neutrino oscillation, matter/antimatter asymmetry, dark matter, etc.)

untested correlations
(EW fit, CKM unitarity, $m_x/g_{hxx}/g_{hhxx}$)

structural weaknesses
(flavour hierarchies, strong CP, weak-scale and CC naturalness)

Electroweak symmetry breaking

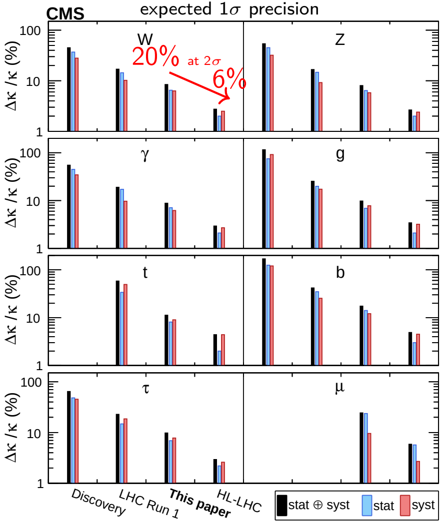
Phenomenological description of a more microscopic dynamics
like the Ginzburg-Landau theory of superconductivity?

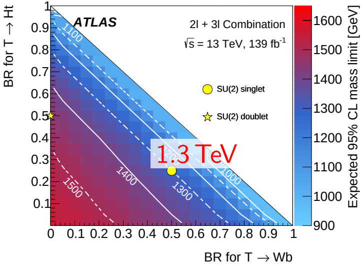


$$V(\phi) = \pm\mu^2|\phi|^2 + \lambda|\phi|^4$$

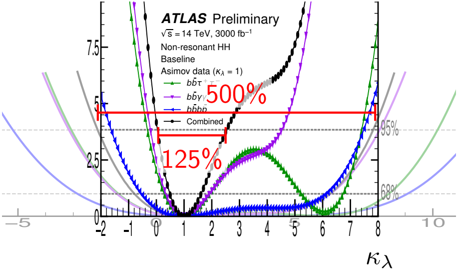
Data

[EXOT-2018-58]





[CMS-HIG-22-001]



[HDBS-2022-03]
[ATL-PHYS-PUB-2022-053]

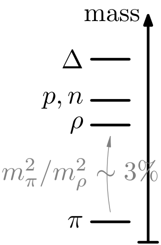
Any example of Higgs theory with

structural $\frac{m_h^2}{M_X^2} \sim \%$?

structural $\delta\kappa_V \sim \%$?

structural $\frac{\delta\kappa_V}{\delta\kappa_\lambda} \sim \%$? (bonus)

Composite Higgs



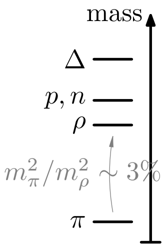
realise the Higgs as the
pseudo-Nambu-Goldstone boson (pNGB)
of a new strong sector

e.g. global SO(5) $\rightarrow$ SO(4) spontaneous breaking
at scale f

small mass obtained from the
explicit breaking of SO(5)
by e.g. the SM

small $\delta\kappa_V$ implies $v^2/f^2 \ll 1$
and requires fine-tuning in minimal models

Composite Higgs



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small ma … the
e …)
m

small(ish) m_h^2/M_X^2!

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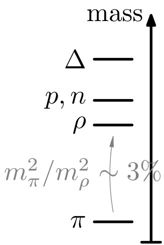
Composite Higgs



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small ma… the
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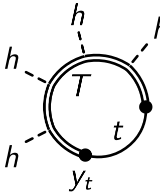
s… 1
and requ… models

no small $\delta\kappa_V$ or v/f!

Minimal composite Higgs

$V(h) \sim$



$$+ \cdots \sim \boldsymbol{\kappa}\, \frac{y_t^2 N_c}{16\pi^2} f^2 M_T^2 \left(-\sin^2\frac{h}{f} + \boldsymbol{\delta}\, \sin^4\frac{h}{f} \right)$$

$$\rightarrow \frac{v^2}{f^2} = \sin^2\frac{\langle h \rangle}{f} = \frac{1}{2\delta}$$

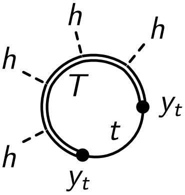
vs. $|\delta\kappa_V| \simeq \frac{v^2}{2f^2} \lesssim 6\%$

$$\rightarrow \frac{m_h^2}{M_T^2} = \kappa\, \underbrace{\frac{y_t^2 N_c}{4\pi^2}\left(1 - \frac{1}{2\delta}\right)}_{\sim 7\%}$$

vs. $M_T \gtrsim 2\,\text{TeV}$

Minimal composite Higgs

$V(h) \sim$



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$$\rightarrow \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f} = \frac{1}{2\delta}$$

$1/\delta \lesssim 0.24$

$|\delta\kappa_V| \simeq \frac{v^2}{2f^2} \lesssim 6\%$

$$\rightarrow \frac{m_h^2}{M_T^2} = \kappa \underbrace{\frac{y_t^2 N_c}{4\pi^2} \left(1 - \frac{1}{2\delta}\right)}_{\sim 7\%}$$

$\kappa \lesssim 0.06$

$M_T \gtrsim 2\,\text{TeV}$

Few percent fine-tuning wrt $\delta \lesssim 1$, $\kappa \simeq 1$ expectation

Structurally small vev

radiatively stable deepest minimum
close to the origin

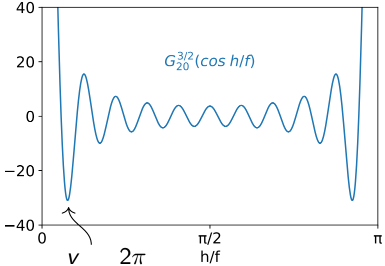
Radiatively stable potentials

Explicit SO(5) → SO(4) breaking by an irrep spurion K:
$$K^{i_1\ldots i_n}\,\phi_{i_1}\cdots\phi_{i_n} \qquad \text{(symmetric traceless)}$$

$\vec\phi \equiv (\frac{\vec h}{h}\sin\frac{h}{f},\ \cos\frac{h}{f}),\ \ h\equiv|\vec h|$

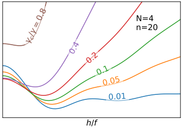
No other invariant, linear in K, can be constructed,
so all-loop linear renormalisation can only be multiplicative.

Actually, Gegenbauer polynomials:
$$K^{i_1\ldots i_n}\,\phi_{i_1}\cdots\phi_{i_n} \ \propto\ G_n^{3/2}(\cos\tfrac{h}{f})$$

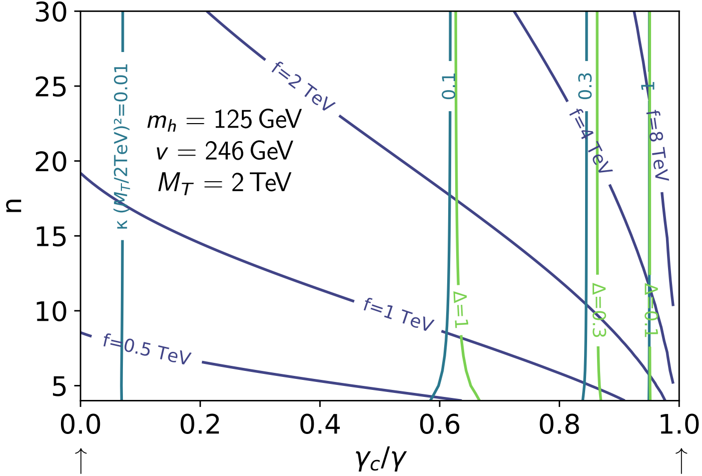


$$\frac{v}{f}\sim\frac{2\pi}{n}$$

The Gegenbauer Higgs



$$V(h) = \boldsymbol{\kappa} \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left[\sin^2 \frac{h}{f} + \gamma\, G_n^{3/2}\left(\cos \frac{h}{f}\right) \right]$$



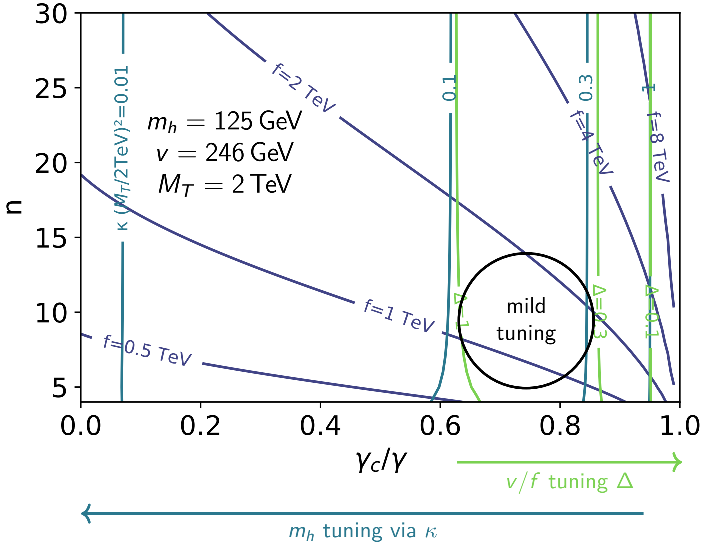
pure Gegenbauer
$v/f \approx 5.1/n$

$\gamma_c \sim 10^{-3}$

no EWSB
$v/f \to 0$

The Gegenbauer Higgs

$$V(h) = \kappa \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left[\sin^2\frac{h}{f} + \gamma\, G_n^{3/2}\left(\cos\frac{h}{f}\right)\right]$$



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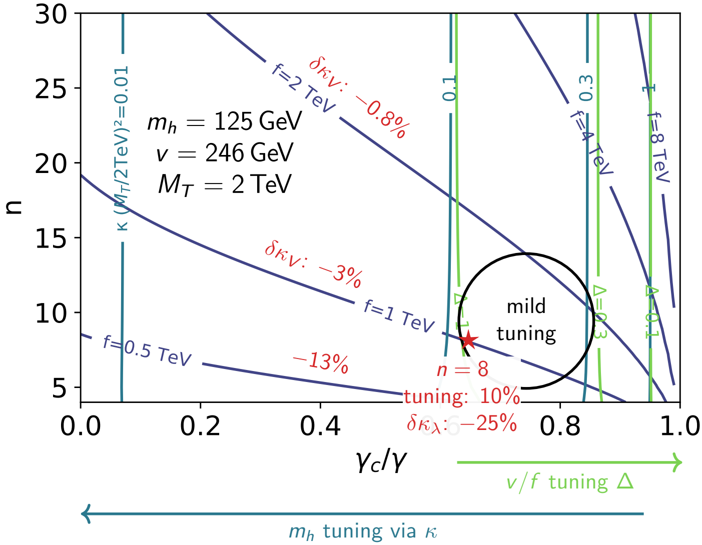

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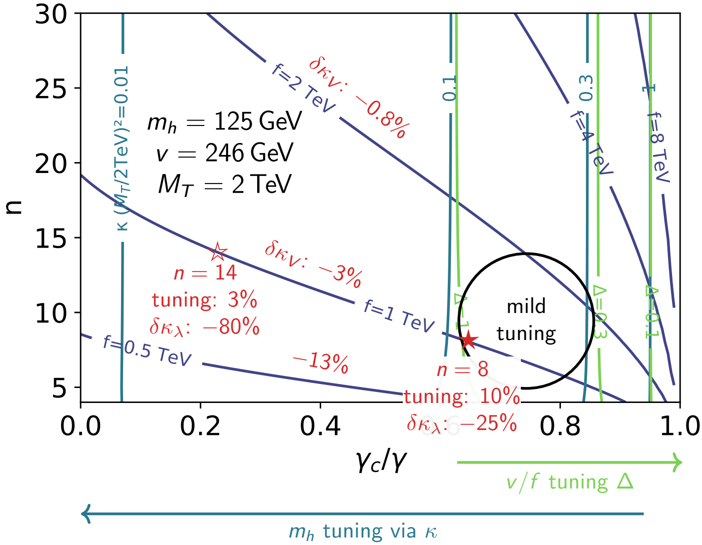
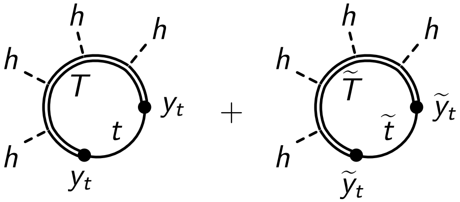


Structurally smaller mass

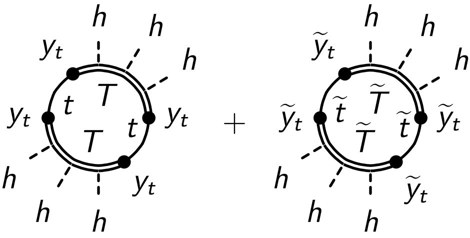


$$\frac{N_c y_t^2}{16\pi^2}\, f^2 M_T^2\, \sin^2\frac{h}{f} \quad + \quad \frac{N_{\widetilde{c}} \widetilde{y}_t^2}{16\pi^2}\, f^2 M_{\widetilde{T}}^2\, \cos^2\frac{h}{f}$$

if twin parity enforces $y_t = \widetilde{y}_t$ and $M_T = M_{\widetilde{T}}$
no M_T^2 sensitivity

Structurally smaller mass

[Chacko, Goh, Harnik '05]
[Barbieri, Greco, Rattazzi, Wulzer '15]



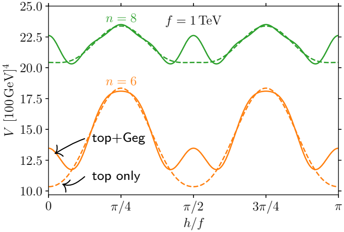
$$\frac{N_c y_t^4}{16\pi^2}\, f^4\, \sin^4\frac{h}{f}\, \log M_T \quad + \quad \frac{N_c \tilde{y}_t^4}{16\pi^2}\, f^4\, \cos^4\frac{h}{f}\, \log M_{\tilde{T}}$$

retaining $\log M_T$ sensitivity only

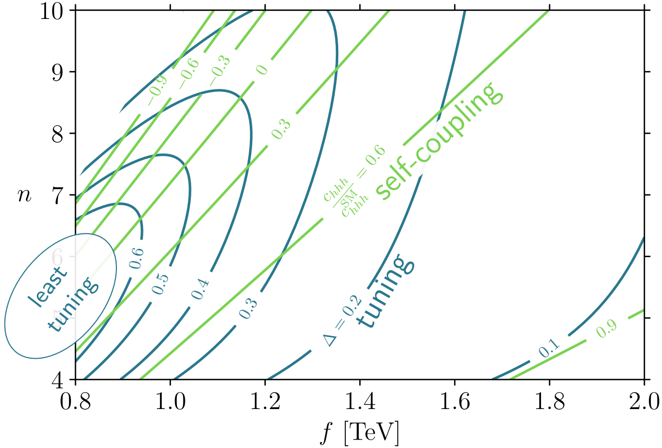
Gegenbauer's Twin


Leopold B. Gegenbauer
1849–1903

- global $SO(8) \supset SO(4) \times \widetilde{SO(4)}$
- spontaneous $SO(8) \to SO(7)$
  7 NGBs
  6 eaten by $W^\pm, Z$ and $\widetilde{W}^\pm, \widetilde{Z}$
  1 Higgs: $\vec{\phi} = (\vec{0}_3,\ \sin\frac{h}{f};\ \ \vec{0}_3,\ \cos\frac{h}{f})^T$ in unitary gauge
- minimal explicit breaking is insufficient
- explicit $SO(8) \to SO(4) \times \widetilde{SO(4)}$
  radiative stability from irrep spurion
  $G_n^{3/2}(\cos\frac{2h}{f})$ potential

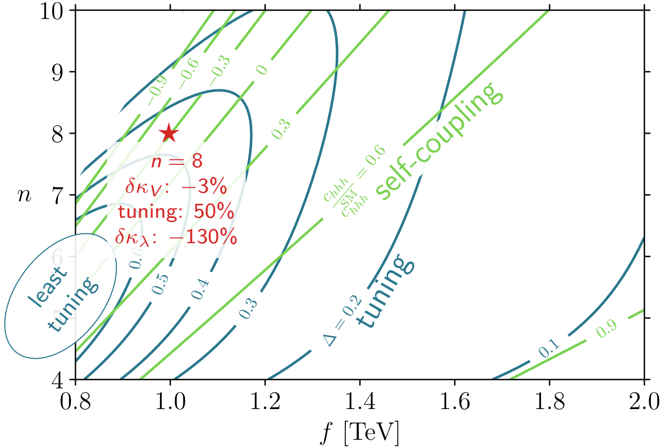


Gegenbauer's Twin



(and possibly large M_T, with unitarity violating H scattering towards 6 TeV)

Gegenbauer's Twin

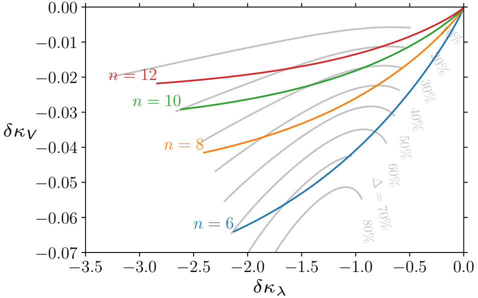


(and possibly large M_T, with unitarity violating H scattering towards 6 TeV)

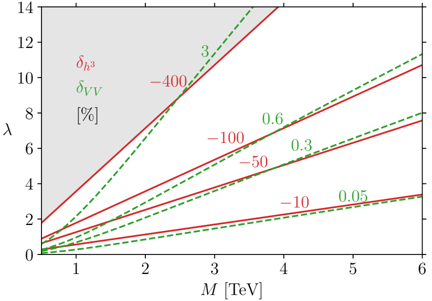
Structurally large $\delta\kappa_\lambda/\delta\kappa_V$

see also: [Di Luzio, Gröber, Spannowsky '17]
[Gupta, Rzehak, Wells '13] [Falkowski, Rattazzi '19]
[Logan, Rentala '15] [Chala, Krause, Nardini '18] [etc.]

Gegenbauer's Twin



custodial weak-quadruplet scalar



$$\lambda\, H^* H^* (\epsilon H)\Phi + \lambda \frac{1}{\sqrt{3}} H^* H^* H^* \widetilde{\Phi}$$

- a loop factor allowed dimensionally (or v^2/M_X^2 if dim-6/dim-8)
- dim$\gg$6 operators may be very relevant
- vacuum stability as limiting constraint

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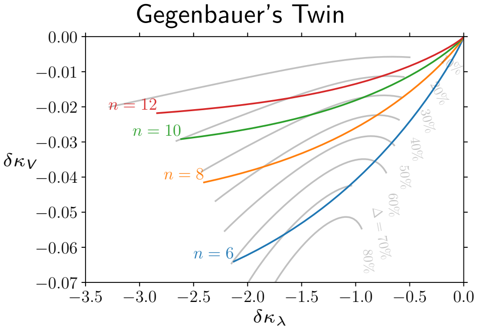

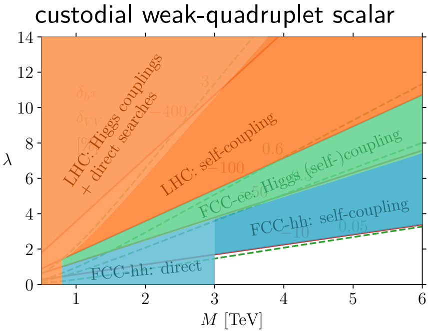

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- a loop factor allowed dimensionally (or v^2/M_X^2 if dim-6/dim-8)
- dim$\gg$6 operators may be very relevant
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Higgs theory facing data

An example Higgs theory exists with structural $\frac{m_h^2}{M_X^2} \sim \%$

structural $\delta\kappa_V \sim \%$

structural $\frac{\delta\kappa_V}{\delta\kappa_\lambda} \sim \%$ (bonus)

Namely, a composite Higgs scenario
with non-minimal global symmetry breaking source.

In passing, we determined the pNGB potentials that are eigenfunctions of linear renormalisation.

A custodial quadruplet scalar also achieves $\frac{\delta\kappa_V}{\delta\kappa_\lambda} \sim \%$.

Extras

Radiatively stable SO(5) $\rightarrow$ SO(4) potentials (II)

Linear one-loop correction to $V(\frac{h}{f})$:

$$\frac{\Lambda^2}{32\pi^2 f^2}\left(\underbrace{V'' + 3\cot\frac{h}{f}\ V'}\right)$$

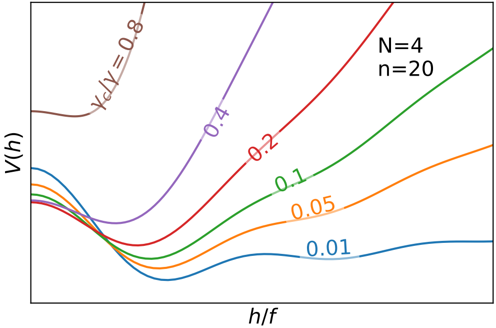
Radiative stability at one-loop and linear order order if $\propto V$

Differential equation of Gegenbauer polynomials

$$V(\tfrac{h}{f}) \propto G_n^{3/2}(\cos\tfrac{h}{f})$$

Gegenbauer Higgs potential

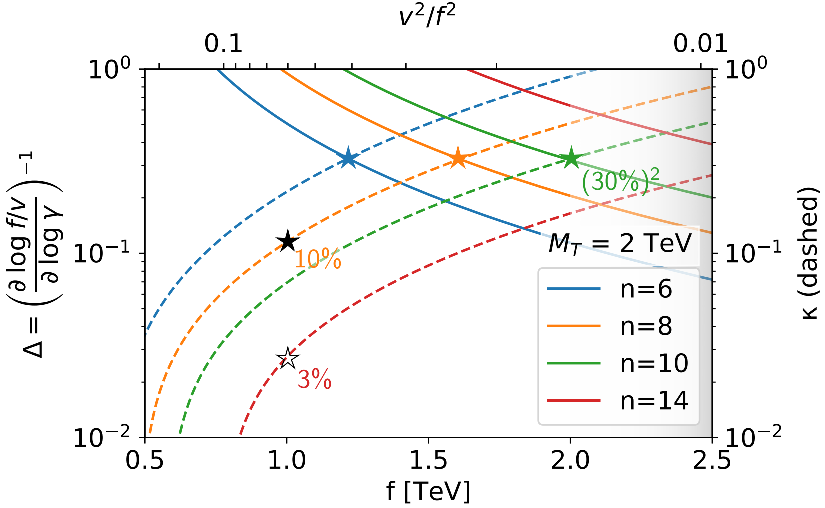
$$V(h) = \kappa \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left[\sin^2 \frac{h}{f} + \gamma\, G_n^{3/2}\left(\cos \frac{h}{f}\right)\right]$$



$$v/f \searrow 0 \quad \text{as} \quad \gamma \searrow \gamma_c$$

$$\frac{m_h^2}{\kappa \frac{N_c y_t^2}{16\pi^2} M_T^2} \searrow \quad \text{as} \quad \gamma \searrow \gamma_c \quad \text{relaxing} \quad \kappa \nearrow 1$$

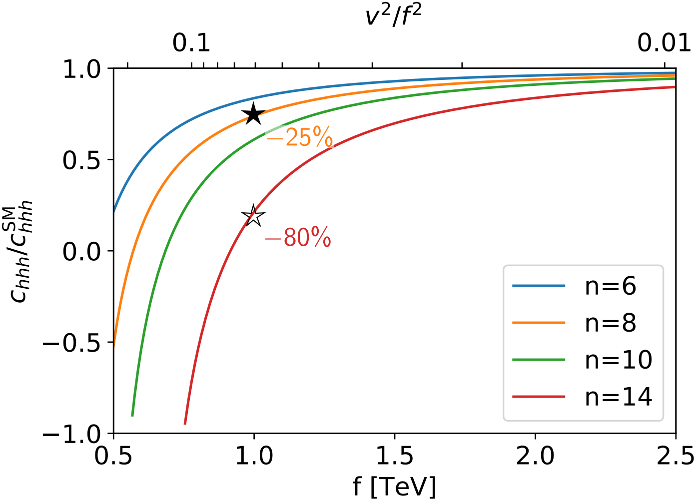
Gegenbauer Higgs tunings



$(M_T \gtrsim y_t f/\sqrt{2}$ since $m_t \sim M_T v/f$ for $y_t f \gg M_T)$

$$\Delta \approx 30\% \left(\frac{f}{4v}\,\frac{5.1}{n}\right)^{-2.1} \qquad \kappa \approx 30\% \left(\frac{f}{4v}\,\frac{5.1}{n}\,\frac{2\,\mathrm{TeV}}{M_T}\right)^{2}$$

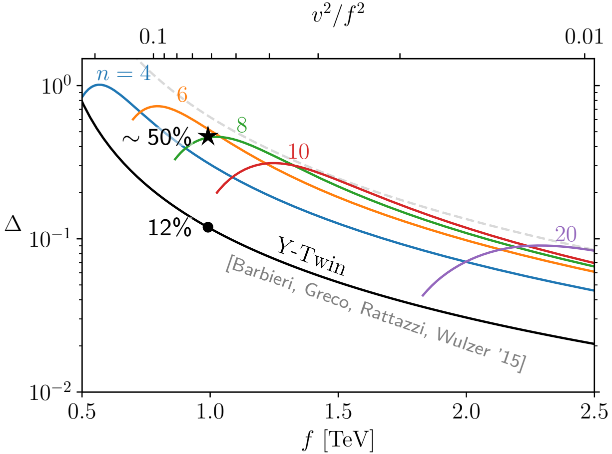
Gegenbauer Higgs self-coupling



$$\frac{c_{hhh}}{c_{hhh}^{SM}} \approx 1 - 1.2\left(\frac{f}{v}\frac{5.1}{n+\lambda}\right)^{-2} \qquad \text{when close to 1}$$

Gegenbauer's Twin tunings

- conservative definition RMS(eig. log-derivative matrix)
- dominated by top-sector dependence of v/f
- about 4 times better than usual $\Delta \approx 2v^2/f^2$ minimum



Gegenbauer's Twin self-coupling