# Gegenbauer's Twin

natural composite Higgs at the LHC

with the self-coupling as harbinger

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(CERN)

*Gegenbauer Goldstones*, JHEP 01 (2022) 076, [2110.06941]
*Gegenbauer's Twin*, JHEP 05 (2022) 140, [2202.01228]
with Matthew McCullough and Ennio Salvioni

PASCOS – Heidelberg – 26 July 2022

# The Higgs at 10

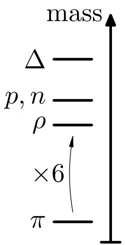
Ten years of LHC measurements
sharpened the naturalness puzzle.

Small mass?

SM-like couplings?

Symmetry explanations?

# Composite Higgs



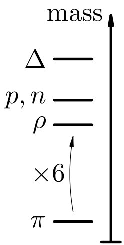

realise the Higgs as the
pseudo-Nambu-Goldstone boson (pNGB)
of a new strong sector

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

SM-like couplings require $v/f \ll 1$
which requires tuning in minimal models

# Composite Higgs

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small mass ... om the
expl ... O(5)
... SM

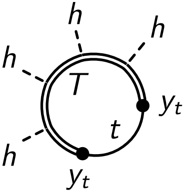
small mass!

SM-like ... $v/f \ll 1$
which require ... mal models

small vev?

# Minimal composite Higgs

$V(h) \sim$

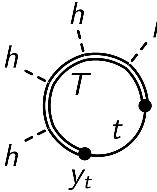



$$+ \cdots \sim \boldsymbol{\kappa}\, \frac{y_t^2 N_c}{16\pi^2} f^2 M_T^2 \left( -\sin^2 \frac{h}{f} + \boldsymbol{\delta}\, \sin^4 \frac{h}{f} \right)$$

$$\rightarrow \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f} = \frac{1}{2\delta} \qquad \text{vs.} \qquad \frac{c_{hVV}}{c_{hVV}^{\mathrm{SM}}} = \sqrt{1 - \frac{v^2}{f^2}} \gtrsim 0.94$$

$$\rightarrow m_h^2 = \kappa\, \frac{y_t^2 N_c}{4\pi^2} M_T^2 \left( 1 - \frac{1}{2\delta} \right) \qquad \text{vs.} \qquad M_T \gtrsim 1.3\,\mathrm{TeV}$$

# Minimal composite Higgs

$V(h) \sim$ 


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

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$1/\delta \lesssim 0.23$

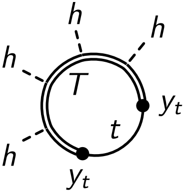
$\rightarrow m_h^2 = \kappa\, \frac{y_t^2 N_c}{4\pi^2} M_T^2 \left(1 - \frac{1}{2\delta}\right)$

$\kappa \lesssim 0.14$

$M_T \gtrsim 1.3\,\text{TeV}$

Few percent tuning wrt $1/\delta \gtrsim 1$, $\kappa \simeq 1$ expectation

# Minimal composite Higgs

$V(h) \sim$ 

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Gegenbauer fix

$$1/\delta \lesssim 0.23$$

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$$\kappa \lesssim 0.14$$

Twin fix

Few percent tuning wrt $1/\delta \gtrsim 1$, $\kappa \simeq 1$ expectation

# Small vev

Extra source of explicit SO(5) $\rightarrow$ SO(4) breaking,

leading to a radiatively stable potential.

Agnostic of the UV, considering the pNGBs EFT

with $\vec{\phi} = (\frac{\vec{h}}{h} \sin \frac{h}{f},\ \cos \frac{h}{f})$ where $h \equiv |\vec{h}|$ (CCWZ).

# Radiatively stable potentials

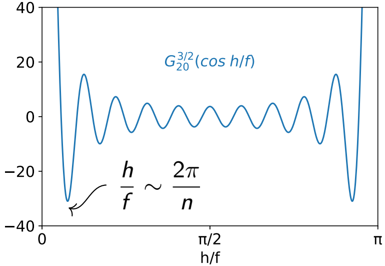
Explicit SO(5) $\to$ SO(4) breaking by an irrep spurion
(symmetric traceless)

$$K^{i_1 \ldots i_n}\, \phi_{i_1} \cdots \phi_{i_n}$$

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

Obtain Gegenbauer polynomials:

$$K^{i_1 \ldots i_n}\, \phi_{i_1} \cdots \phi_{i_n} \;=\; G_n^{3/2}(\cos \tfrac{h}{f})$$



# Radiatively stable potentials (II)

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

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

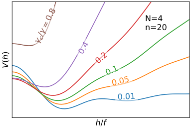
Radiative stability at one-loop and linear order order if $\propto V$

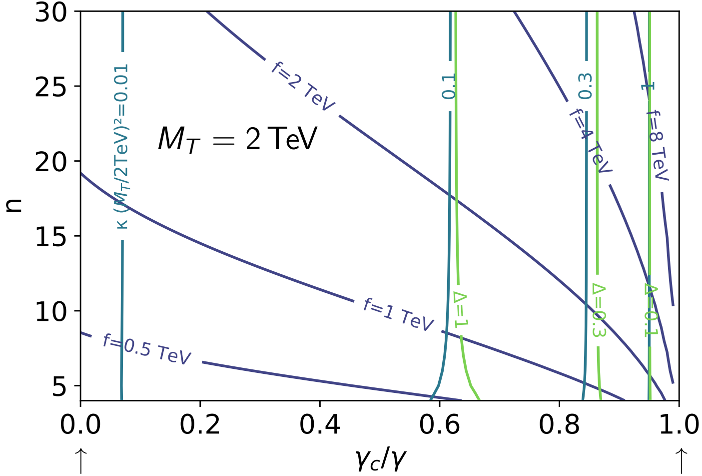
Differential equation of Gegenbauer polynomials

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

# Top+Gegenbauer potential

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




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

no EWSB
$v/f \to 0$

# Top+Gegenbauer potential

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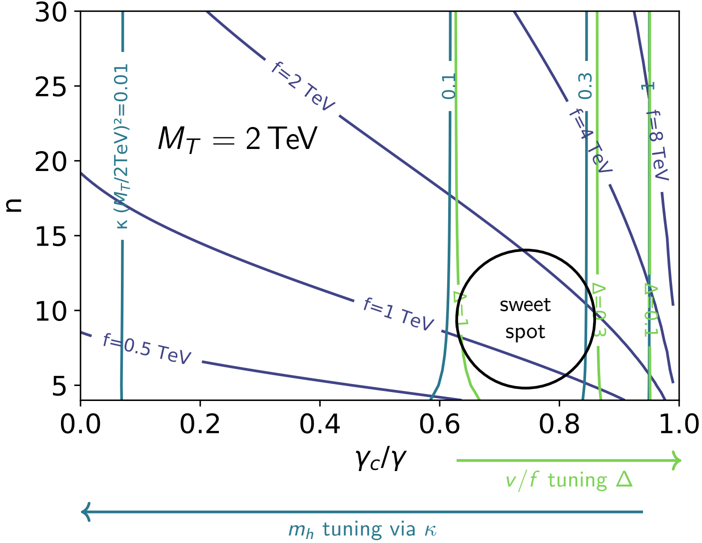

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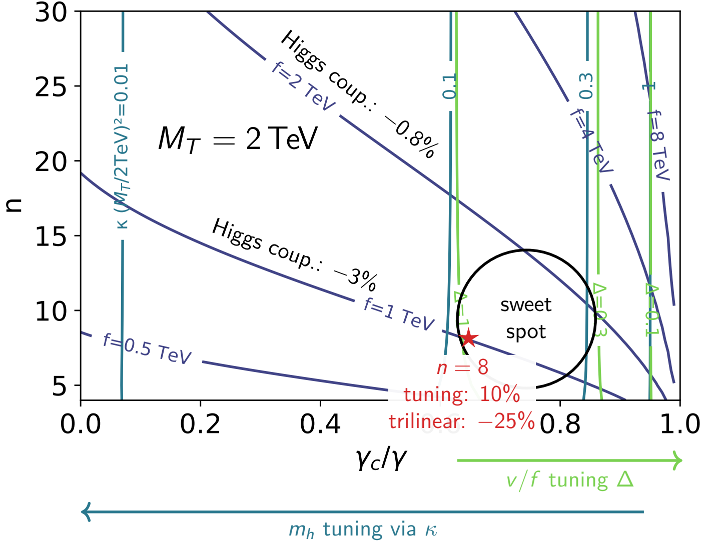

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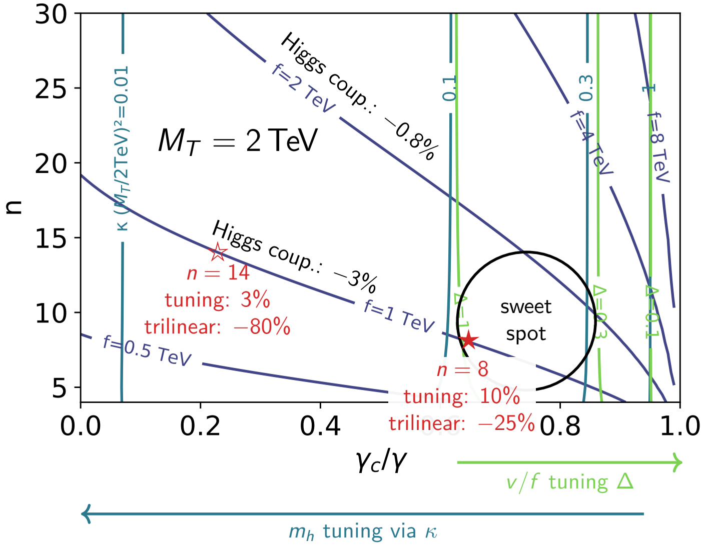
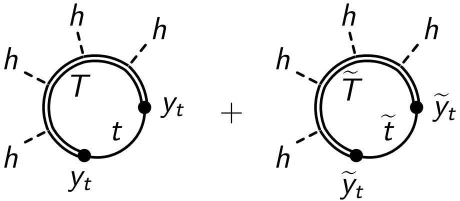


# Adding twins

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




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

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

# Adding twins

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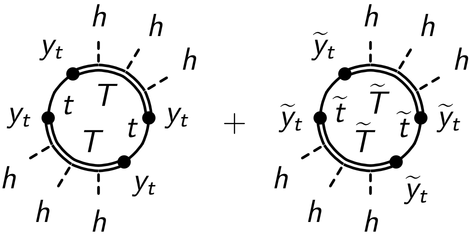



$$\frac{N_c y_t^4}{16\pi^2} f^4 \sin^4 \frac{h}{f} \log M_T \quad + \quad \frac{N_c \widetilde{y}_t^4}{16\pi^2} f^4 \cos^4 \frac{h}{f} \log M_{\widetilde{T}}$$

retaining $\log M_T$ sensitivity only

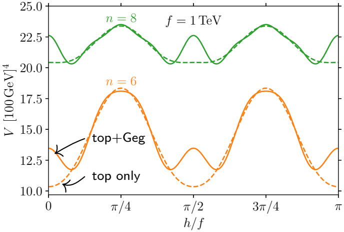
# Gegenbauer' Twin

- global $\mathrm{SO}(8) \supset \mathrm{SO}(4) \times \widetilde{\mathrm{SO}(4)}$

- spontaneous $\mathrm{SO}(8) \to \mathrm{SO}(7)$
  7 NGB
  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 $\mathrm{SO}(8) \to \mathrm{SO}(4) \times \widetilde{\mathrm{SO}(4)}$
  radiative stability from irrep spurion
  $G_n^{3/2}(\cos\frac{2h}{f})$ potential



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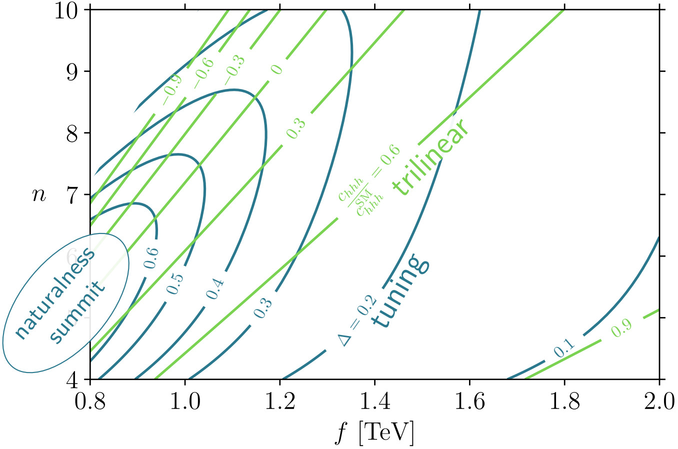
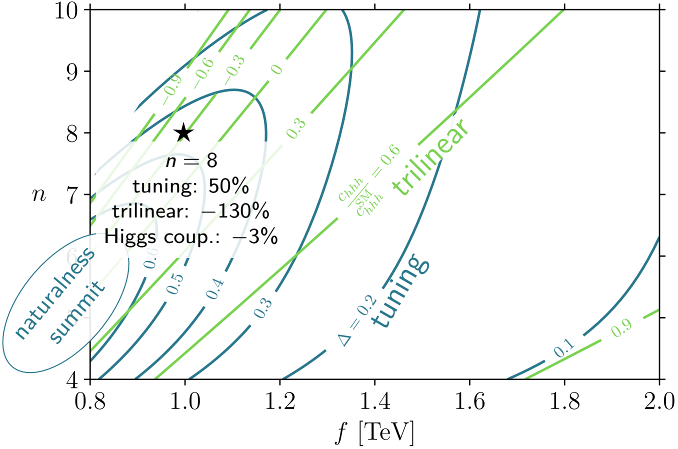



HL-LHC $2\sigma$ reach: trilinear: $\lesssim 100\%$
Higgs coup.: $\lesssim 2.6\%$

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

# Gegenbauer's Twin




HL-LHC $2\sigma$ reach: trilinear: $\lesssim 100\%$
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# Gegenbauer's Twin

Gegenbauer potentials are eigenfunctions of linear renorm.
for $\mathrm{SO}(N+1) \to \mathrm{SO}(N)$ pNGBs.

They lead to a small Higgs vev,
naturally accommodating % deviations in Higgs couplings.

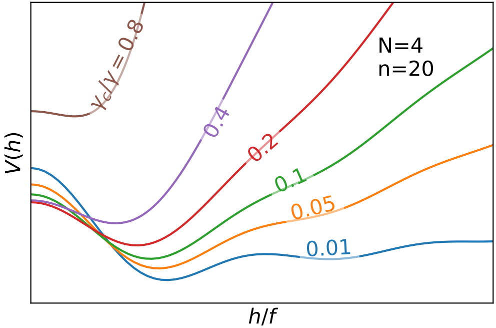
Symmetry-based naturalness is still being probed at the LHC!

The Higgs self-coupling could be the first signal!

# Extras

# Top+Gegenbauer potential

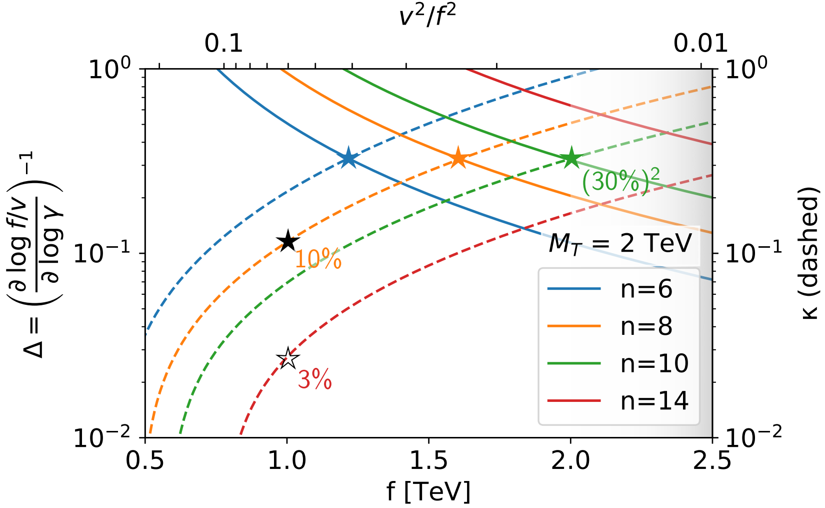
$$V(h) = \kappa \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left[ \sin^2 \frac{h}{f} + \gamma\, G_n^{3/2}\left(\cos \frac{h}{f}\right)\right]$$




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

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

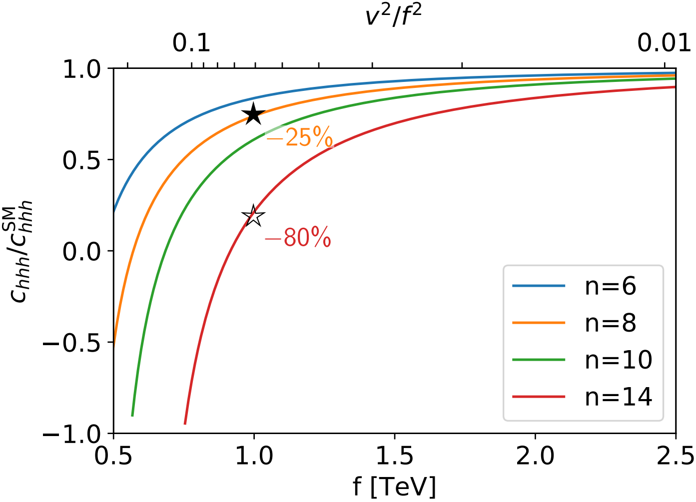
# Top+Gegenbauer: $v/f$ and $m_h$ tunings




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

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

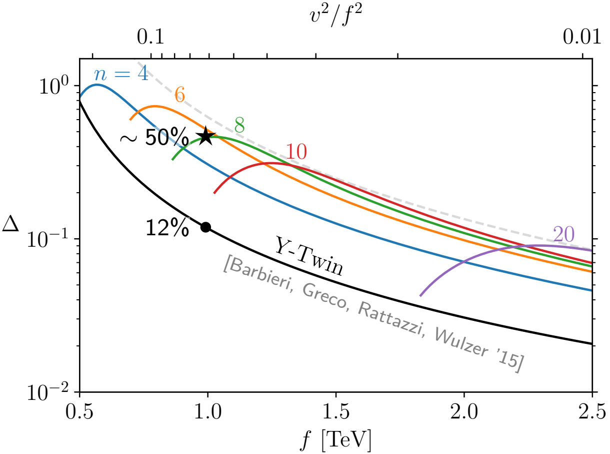
# Top+Gegenbauer: Trilinear Higgs self-coupling




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

# Gegenbauer's Twin: $v/f$ and $m_h$ 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: Trilinear Higgs self-coupling