Natural composite Higgs at FCC and Gegenbauer Goldstones

Gauthier Durieux
(CERN)

[2110.06941]
with Matthew McCullough and Ennio Salvioni

FCC Physics Meeting, 25 Oct 2021

The Higgs is a mystery.

Why does it look lighter than the SM cutoff?

Why does its couplings look SM-like?

Small mass

Global spontaneous symmetry breaking leads to massless scalars.
(Nambu-Goldstone bosons *aka* NGBs)

Small explicit symmetry breakings lead to small masses.
(NGBs become pNGBs)

e.g. pions:

SSB: $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$
ESB: quark masses/charges

pNGB Higgs

Another strong-sector confinement triggers a global SSB, and sets a new scale f by dimensional transmutation.

Small explicit breakings give NGB a potential, including a mass and a EWSB vev.

The Higgs is realized as a pNGB.

SM-like couplings

Higgs coupling modifications are controlled by v^2/f^2,
and naturally of order 1 in typical pNGB Higgs models.

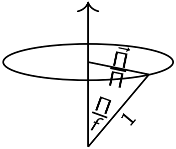
Fine-tuning $v^2/f^2 \ll 1$ is then required,
but is that *generic* or *specific* to typical models?

pNGB potentials

Let's consider spontaneous $\mathrm{SO}(N+1) \to \mathrm{SO}(N)$
and be agnostic about strong-sector specifics.

The low-energy EFT has N Nambu-Goldstone bosons $\vec{\Pi}$.

Field parameterisation: $\phi = (\frac{\vec{\Pi}}{\Pi} \sin\frac{\Pi}{f},\ \cos\frac{\Pi}{f})$
with $\Pi \equiv |\vec{\Pi}|$



Radiative stability

$V(\Pi)$ potential arises from explicit SO$(N+1)$ breaking preserving SO(N).

Take $V(\Pi) = \epsilon\, M^2 f^2\; G(\Pi/f)$
with a dimensionless function G
and ϵ small

Would strong-sector corrections upset any pattern?

One-loop potential

Quadratic divergence as diagnosis tool
from within the pNGB EFT

$$\delta V_{\text{1-loop}}^{\text{order }\epsilon} = \epsilon M^2 \frac{\Lambda^2}{32\pi^2}\Big(G'' + (N-1)\cot\tfrac{\Pi}{f}\, G'\Big)$$

One-loop potential

Quadratic divergence as diagnosis tool
from within the pNGB EFT

$$\delta V_{\text{1-loop}}^{\text{order }\epsilon} = \epsilon M^2 \frac{\Lambda^2}{32\pi^2}\left(\underline{G'' + (N-1)\cot\frac{\Pi}{f}\,G'}\right)$$

Radiative stability at 1-loop and linear ϵ order if $\propto G$

Gegenbauer polynomials $G(\frac{\Pi}{f}) = G_n^{(N-1)/2}(\cos\frac{\Pi}{f})$
satisfy exactly this differential eq!

All-loop argument

Explicit breaking of SO($N+1$) to SO(N) by an irrep spurion

$$K^{i_1 \dots i_n}\, \phi_{i_1} \cdots \phi_{i_n} \quad \text{(symmetric traceless).}$$

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

All-loop argument

Explicit breaking of SO($N+1$) to SO(N) by an irrep spurion

$$K^{i_1\dots i_n}\,\phi_{i_1}\cdots\phi_{i_n}\qquad \text{(symmetric traceless).}$$

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

$$\text{And}\qquad K^{i_1\dots i_n}\,\phi_{i_1}\cdots\phi_{i_n} \;=\; G_n^{(N-1)/2}(\cos\tfrac{\Pi}{f})\;!$$

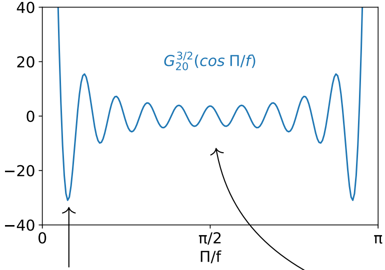
$\phi = (\frac{\vec{\Pi}}{\Pi}\sin\frac{\Pi}{f},\ \cos\frac{\Pi}{f})$

Gegenbauer polynomials

L. Gegenbauer
1849–1903

Eigenfunctions of linear renormalization
for $SO(N+1) \to SO(N)$ pNGB potentials.

Generalisation of $\cos(nx)$ for $N > 1$
of Legendre polynomials for $N > 2$
i.e. multipole expansion in *field* space



deepest minimum at $\frac{\Pi}{f} \sim \frac{2\pi}{n}$
for positive coefficient and n even

approx. periodic
$\sim \cos n\frac{\Pi}{f}$

Gegenbauer Higgs

Pure Gegenbauer potential

$N = 4$ for minimal composite Higgs
$\Pi = h, \quad m_h = 125\,\text{GeV}, \quad v = 246\,\text{GeV}$

$$\frac{v}{f} = \sin\frac{\langle h\rangle}{f} \approx \frac{5.1}{n} \text{ is naturally small for sizeable } n$$

→ small Higgs coupling modifications: $\frac{c_{hVV}}{c_{hVV}^{\text{SM}}} = \sqrt{1-\frac{v^2}{f^2}}$

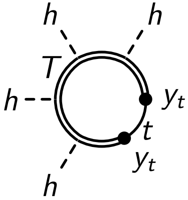
→ opposite trilinear self-coupling: $\frac{c_{hhh}}{c_{hhh}^{\text{SM}}} = -\sqrt{1-\frac{v^2}{f^2}}$

Top-sector contributions

The top Yukawa also provides sizeable explicit breaking.

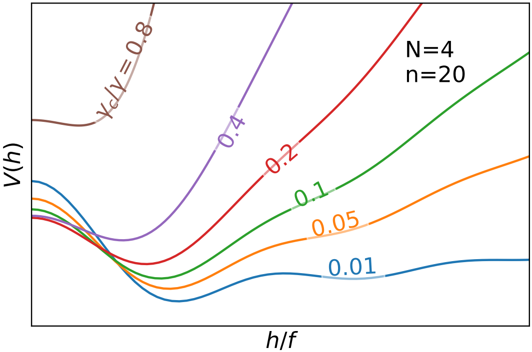
Leading contribution to potential of the form

$$\kappa \, \frac{N_c y_t^2}{16\pi^2} \, f^2 M_T^2 \, \sin^2 \frac{h}{f}$$



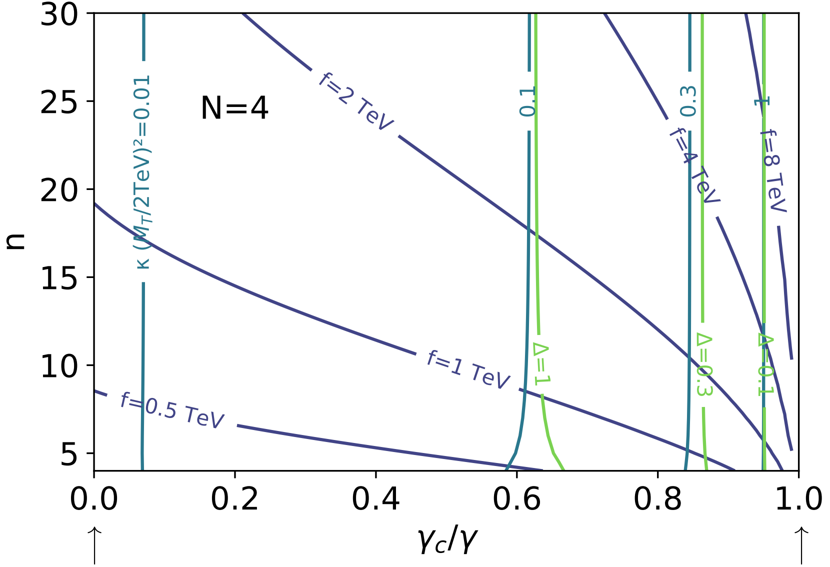
Top+Gegenbauer potential

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



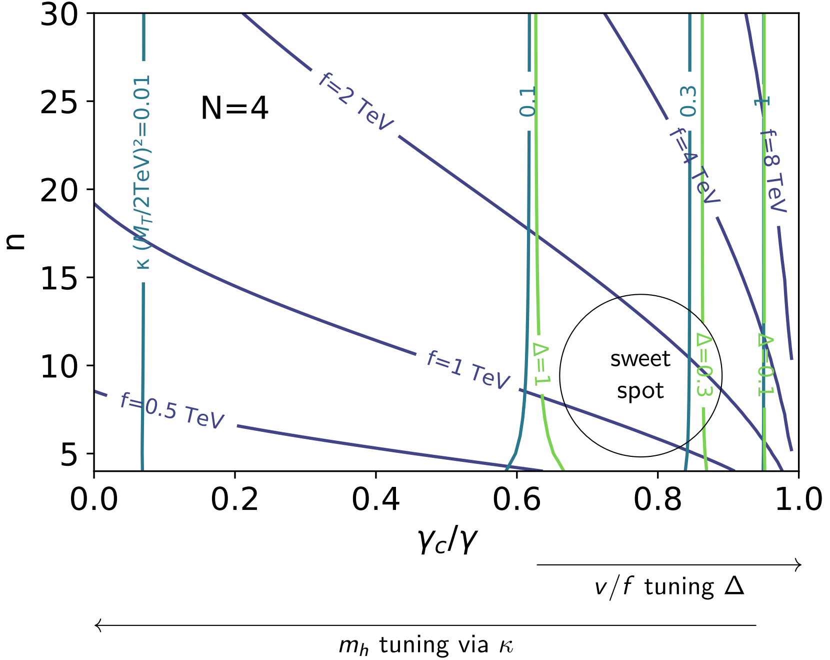
$$v/f \searrow 0 \quad \text{as} \quad \gamma \searrow \gamma_c$$

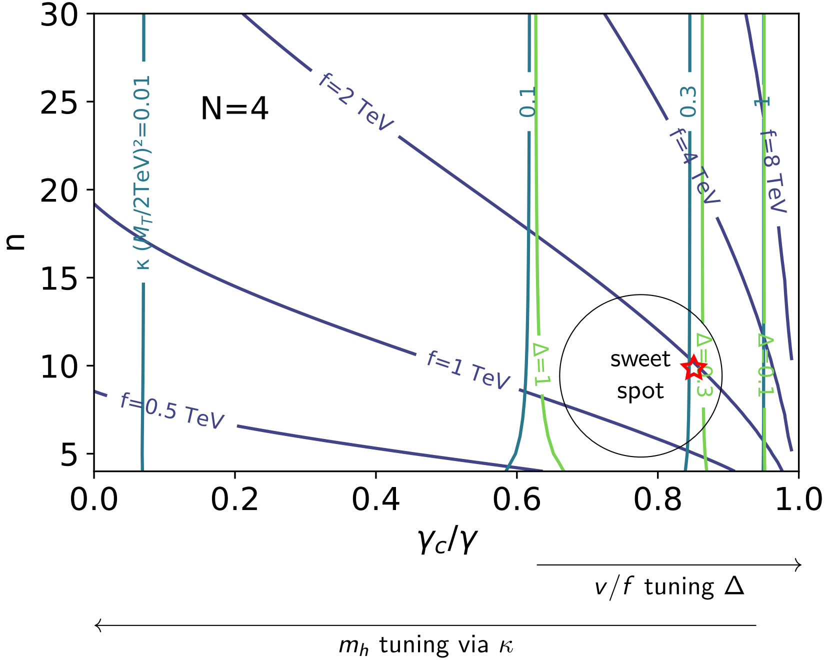
$$\frac{m_h^2}{\kappa \frac{N_c y_t^2}{16\pi^2} M_T^2} \nearrow \quad \text{as} \quad \gamma \nearrow \quad \text{compensated by} \quad \kappa \searrow$$



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

$v/f \to 0$


N=4
n
γc/γ
κ (MT/2TeV)²=0.01
0.1
0.3
1
f=0.5 TeV
f=1 TeV
f=2 TeV
f=4 TeV
f=8 TeV
Δ=1
Δ=0.3
Δ=0.1
sweet spot
v/f tuning Δ
mh tuning via κ



N=4
κ (M_T/2TeV)²=0.01
0.1
0.3
1
f=0.5 TeV
f=1 TeV
f=2 TeV
f=4 TeV
f=8 TeV
Δ=1
Δ=0.3
Δ=0.1
sweet spot
n
γ_c/γ
v/f tuning Δ
m_h tuning via κ

Benchmark phenomenology

$n = 10$ and $f \sim M_T \sim 2\,\text{TeV}$

$\rightarrow$ both v/f and m_h tunings $\sim 30\%$, so $\sim 10\%$ total

$\rightarrow$ Higgs coupling modifications $\frac{v^2}{f^2} \sim 1\%$

$\rightarrow$ Higgs self-coupling modification $\lesssim 10\%$

$\rightarrow$ top partners just escape HL-LHC searches

Benchmark phenomenology

$n = 10$ and $f \sim M_T \sim 2\,\text{TeV}$

$\rightarrow$ both v/f and m_h tunings $\sim 30\%$, so $\sim 10\%$ total

$\rightarrow$ Higgs coupling modifications $\frac{v^2}{f^2} \sim 1\%$ $\Leftarrow$ FCC-ee

$\rightarrow$ Higgs self-coupling modification $\lesssim 10\%$

$\rightarrow$ top partners just escape HL-LHC searches $\Leftarrow$ FCC-hh

Summary

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

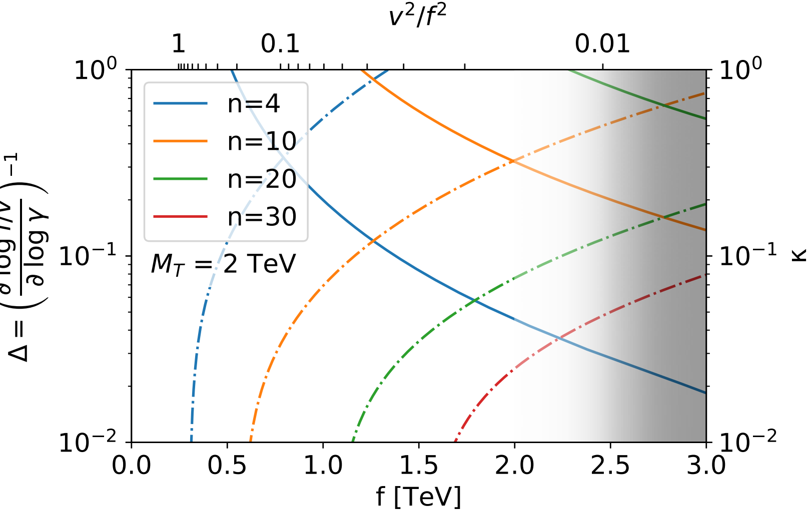
They naturally suppress v/f,
resulting in a SM-like composite Higgs.

The trilinear Higgs self-coupling is opposite to the SM,
in the absence of top-sector contributions.

Higgs coupling measurements at FCC-ee and
top-partner searches at FCC-hh
would still probe natural pNGB Higgs parameter space.

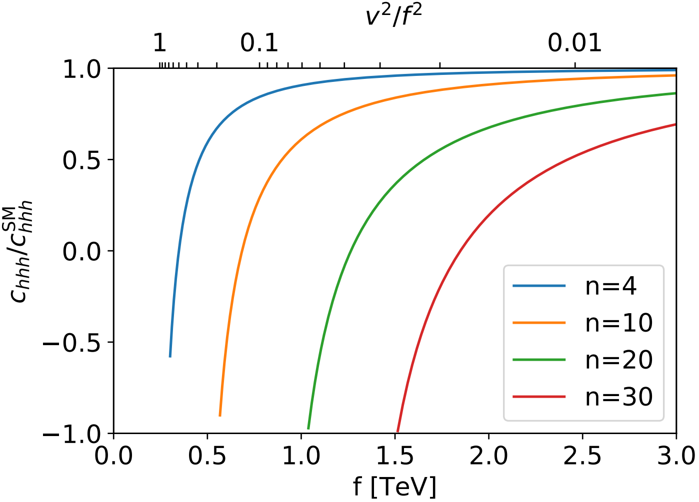
Backup

Gegenbauer Higgs tuning



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

Trilinear Higgs self-coupling



$$\frac{c_{hhh}}{c_{hhh}^{\rm SM}} \approx 1 - 1.2\left(\frac{f}{v}\frac{5.1}{n+\lambda}\right)^{-2}$$ (in the vicinity of 1)