pNGb Higgs Naturalness at a Tipping Point

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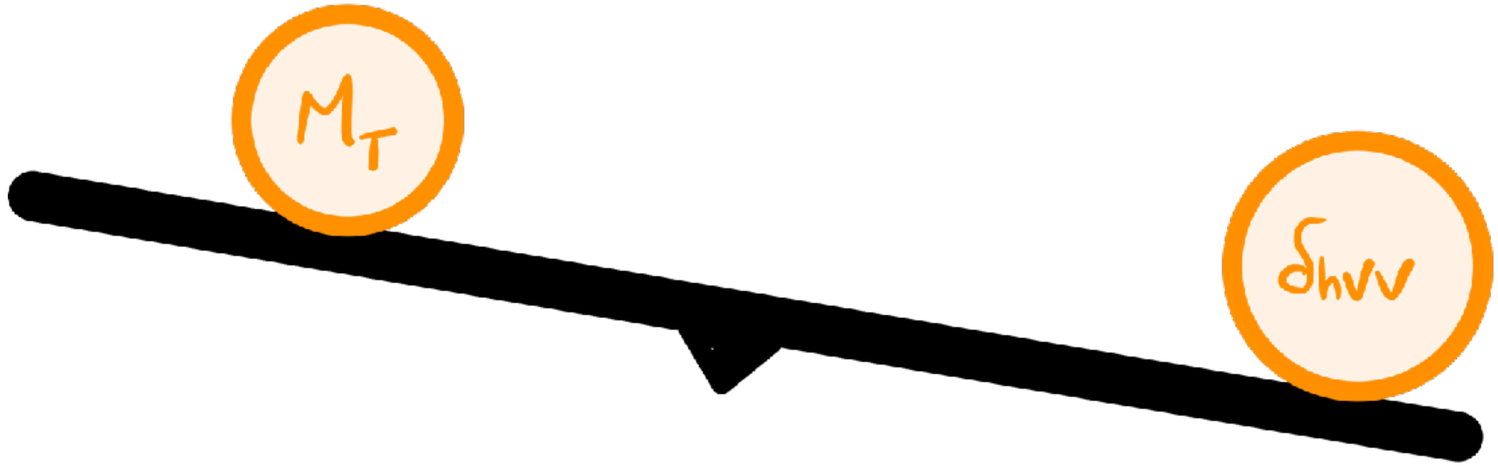
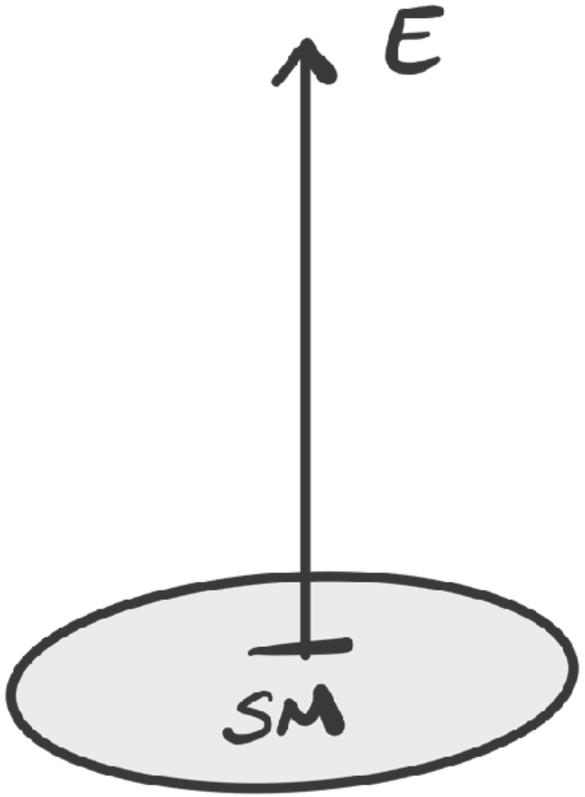
[hep-ph 2505.06052]



LIO International Conference, 23^{rd} **May 2025**

Hierarchy Problem

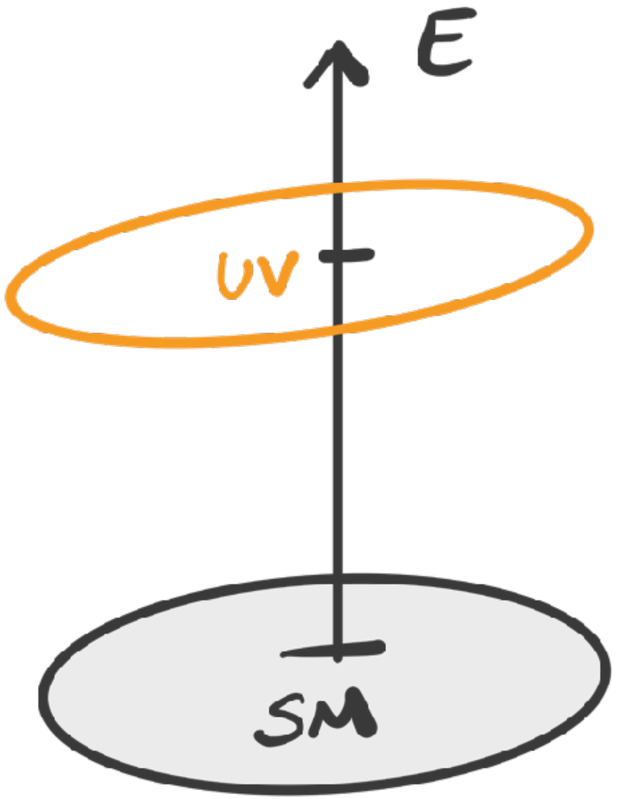
i) The SM is not complete



Hierarchy Problem

i) The SM is not complete

ii)UV completion implies new states

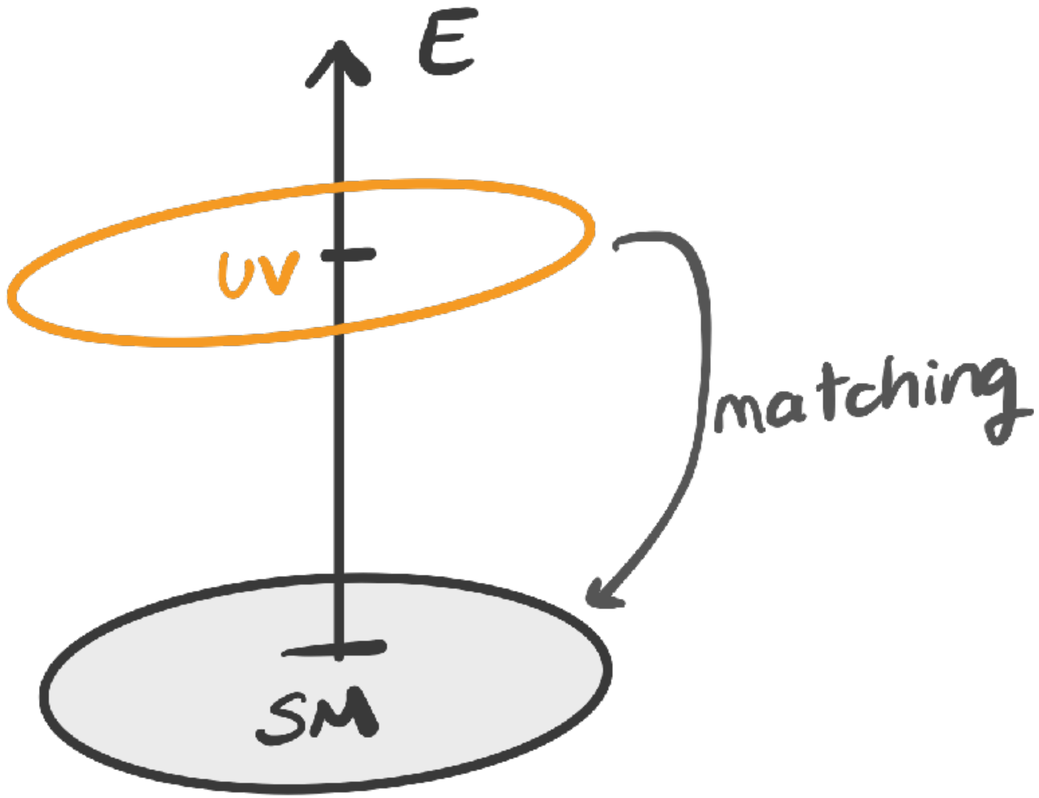


Hierarchy Problem

i) The SM is not complete

ii)UV completion implies new states

iii)New corrections to the Higgs mass at the UV scale



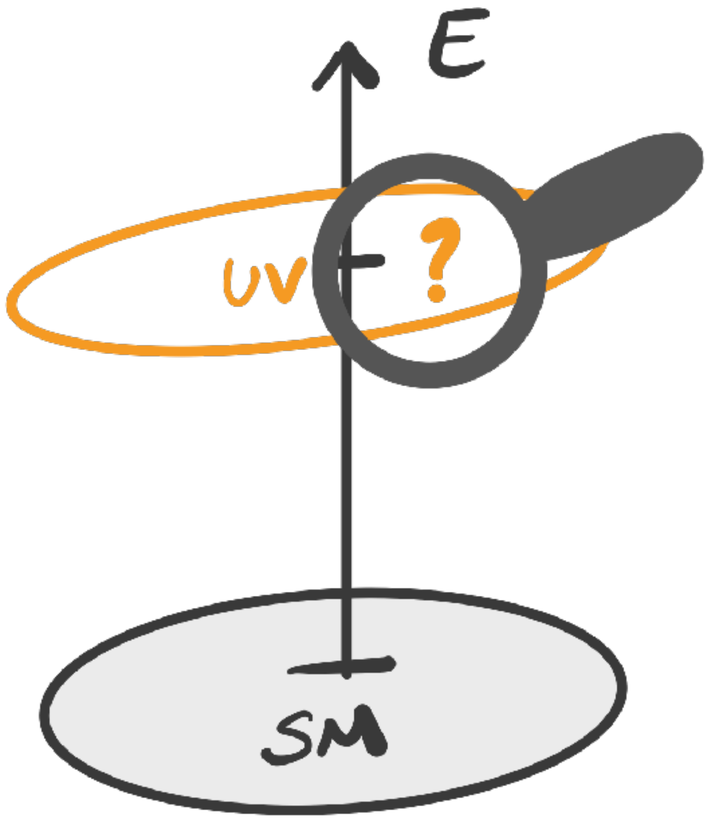
Hierarchy Problem

i) The SM is not complete

ii)UV completion implies new states

iii)New corrections to the Higgs mass at the UV scale

iv) No physics beyond the SM has been observed



The fine tuning question

$$\Delta \propto \delta_{hXX} \, , \frac{m_h^2}{M_R^2}$$

Higgs couplings

new resonances

The fine tuning question

$$\Delta \propto \delta_{hXX}\,, \frac{m_h^2}{M_R^2}$$

$\mathcal{L}_{now} = 140\ fb^{-1} \longrightarrow \mathcal{L}_{HL\text{-}LHC} = 3000\ fb^{-1}$

Indirect measurements will improve by a factor of $\sqrt{\frac{3000}{140}} \sim 4.6$

The fine tuning question

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Indirect measurements will improve by a factor of $\sqrt{\frac{3000}{140}} \sim 4.6$

Mass searches are expected to improve by a 1.5 -1.9 factor

The fine tuning question

$$\left.\frac{\Delta_{\text{indirect}}}{\Delta_{\text{direct}}}\right|_{\frac{3000}{140}} \approx \frac{1.7^2}{4.6} \sim 0.6$$

Mild hierarchy!

Tuning and direct searches

$$\delta^2_{m_h} \propto \frac{3y_t^2}{4\pi^2} M_T^2$$

mass of top partners

$$\Delta_{m_h^2} \lesssim 0.15 \left(\frac{1.2\text{TeV}}{M_T} \right)^2$$

The fine tuning in the mass may reach the **5% level**

Tuning and indirect searches

susy: $\Delta_{v^2} \propto \delta_{h\bar{t}t}$ $\qquad \delta_{h\bar{t}t} \sim \frac{2m_Z^2}{m_A^2} \cos^2\beta \cos 2\beta$

The $\tan\beta$ dependence makes statements less robust than for direct searches

Tuning and indirect searches

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The $\tan\beta$ dependence makes statements less robust than for direct searches

pNGb: $\Delta_{v^2} \propto 4\,|\,\delta_{hvv}\,|$

The tuning for a pNGb may evolve to the **5% level**, driven by $|\delta_{hVV}| < 1.3\,\%$

Tuning and indirect searches

Susy: $\Delta_{m^2} \propto \delta_{h\bar{t}t}$ $\quad \delta_{h\bar{t}t} \sim \dfrac{2m_Z^2}{\quad} \cos^2\beta \cos 2\beta$

The $\tan\beta$ depe … hes

This seems to suggest that for pNGb models, naturalness tensions will start to be driven by precision measurements.

pNGb: Δ

The tuning for a pNGb may evolve to the **5% level**, driven by $|\delta_{hVV}| < 1.3\,\%$

The kitchen sink

We construct a maximally (technical) natural model:

- pNGb à la Gegenbauer [See Matthew's talk yesterday]

- Twin Higgs

- SUSY

The kitchen sink

But… **why**????

The kitchen sink

But… **why**????

1) To illustrate where the question of naturalness stands, from a phenomenological perspective, in the absence of new discoveries.

2) Adding SUSY allows us to interpolate between direct and indirect searches.

pNGb Higgs

Minimal composite Higgs model: $SO(5) \longrightarrow SO(4)$

$$V_t \approx \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left(a_2 \cos\frac{2h}{f} + a_4 \cos\frac{4h}{f} \right)$$

no separation of scales

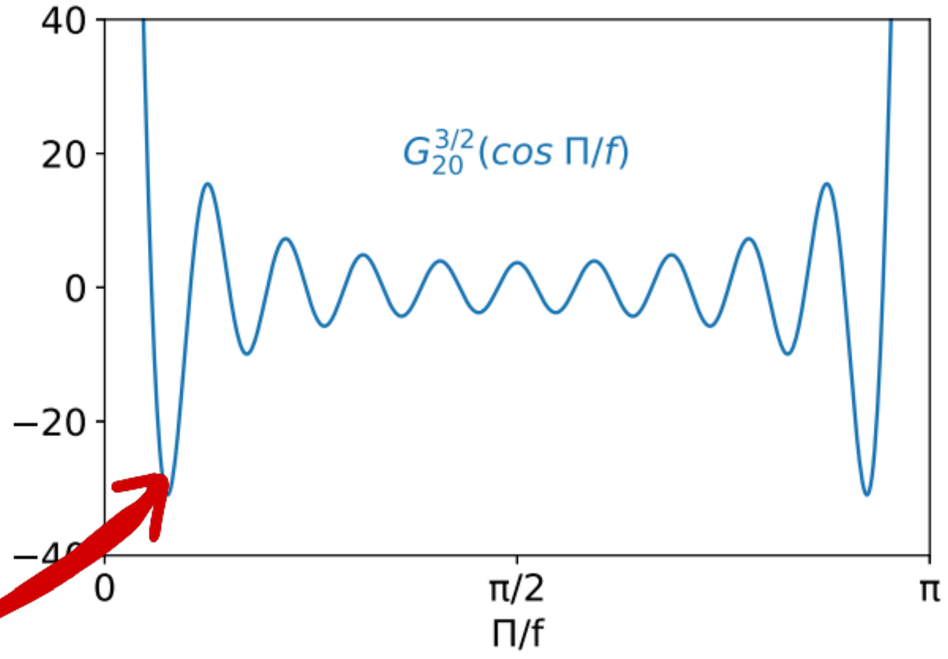
This is minimized at $\langle h \rangle = 0$ or $\langle h \rangle = f$

not viable!

Gegenbauer Higgs

Additional source of explicit breaking in a higher irrep

$$V_G^{(n)} = \epsilon f^2 M^2 G_n^{3/2}\left(\cos\frac{h}{f}\right)$$



Naturally small $\frac{v}{f}$

[Durieux, McCullough,Salvioni, ‘22]

Higgs mass

However,

$$V_t \approx \frac{N_c y_t^2}{16\pi^2} f^2 M_T^2 \left(a_2 \cos\frac{2h}{f} + a_4 \cos\frac{4h}{f} \right)$$

$$m_h^2 \approx N_c y_t^2 M_T^2/(4\pi^2)$$

$M_T \gtrsim 900\mathrm{GeV}$ requires additional tuning

Gegenbauer's Twin

$$V_t \approx \frac{N_c y_t^4}{64\pi^2} f^4 \left[\sin^4 \frac{h}{f} \log \frac{a}{\sin^2 \frac{h}{f}} + \cos^4 \frac{h}{f} \log \frac{a}{\cos^2 \frac{h}{f}} \right]$$

$$a \sim \frac{g_*^2}{y_t^2}$$

In a standard Twin-Higgs scenario: $g_* \sim 4\pi$ + v/f tuning

For the Gegenbauer's Twin: v/f natural but $a \lesssim 2$

Gegenbauer's Twin

$$a \sim \frac{g_*^2}{y_t^2}$$

$$V_t \approx \frac{N_c}{64}$$

The Gegenbauer Higgs may find its UV completion in a weakly coupled theory (SUSY)

In a standard Twin-Higgs scenario: $g_* \sim 4\pi$ + v/f tuning

For the Gegenbauer's Twin: v/f natural but $a \lesssim 2$

Kitchen sink

Explicit SUSY-breaking spurion: $\epsilon F^{i_1 \ldots i_{2n}} \phi_{i_1} \ldots \phi_{i_{2n}}$

Generates the IR potential

$$V_G^{(n)} = \epsilon H(\beta) \lambda^2 f^4 G_n^{3/2} \left(\cos \frac{2h}{f} \right)$$

Kitchen sink(sources of symmetry breaking)

Gegenbauer: $$V_G^{(n)} = \epsilon H(\beta)\lambda^2 f^4 G_n^{3/2}\left(\cos\frac{2h}{f}\right)$$

EW interactions: $$V_D = \frac{g_Z^2 f^4}{32}\cos^2 2\beta\,(s_h^4 + c_h^4)$$

Yukawa interactions:

$$V_{t+\tilde{t}}^{A,B} = \frac{N_c}{64\pi^2}\left[(2m_S^2 + y_t^2 s_\beta^2 f^2 s_h^2)^2\left(\log\frac{2m_S^2 + y_t^2 s_\beta^2 f^2 s_h^2}{2M^2} - \frac{1}{2}\right) - (y_t^2 s_\beta^2 f^2 s_h^2)^2\left(\log\frac{y_t^2 s_\beta^2 f^2 s_h^2}{2M^2} - \frac{1}{2}\right)\right]$$

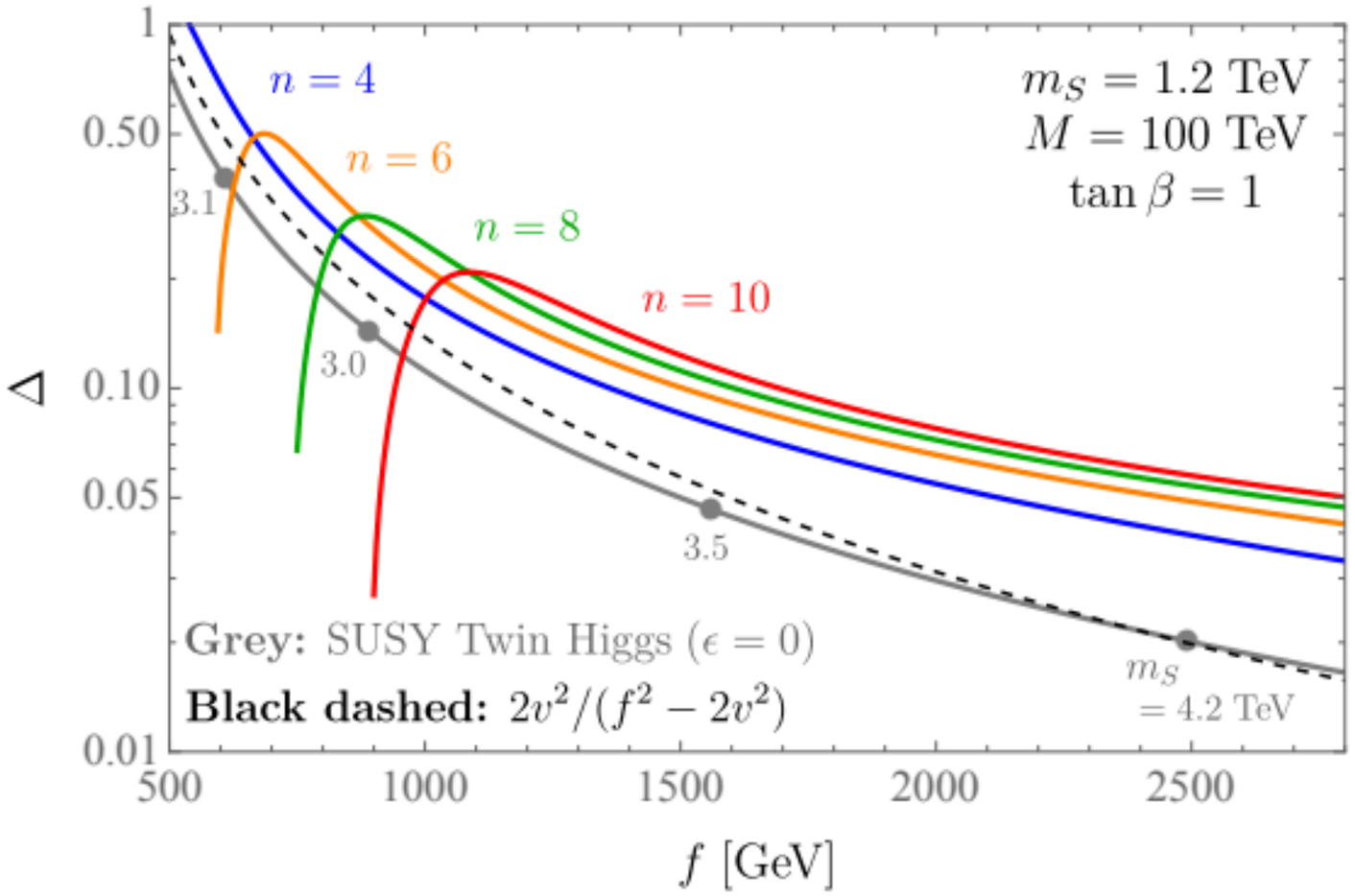
Kitchen sink

$$V^{A+B}_{t+\tilde{t}}(\mathscr{Z}_2 \text{ sym}) + V_D \simeq \frac{N_c (y_t s_\beta)^4 f^4}{64\pi^2}\left[s_h^4 \log\frac{a}{s_h^2} + c_h^4 \log\frac{a}{c_h^2} + b_6(s_h^6 + c_h^6)\right]$$

$$\log a = \frac{3}{2} + \log\frac{2m_S^2}{y_t^2 s_\beta^2 f^2} + g_Z^2 \cos^2 2\beta \frac{2\pi^2}{N_c y_t^4 s_\beta^4}\,, \qquad b_6 = \frac{y_t^2 s_\beta^2 f^2}{6m_S^2}\,.$$

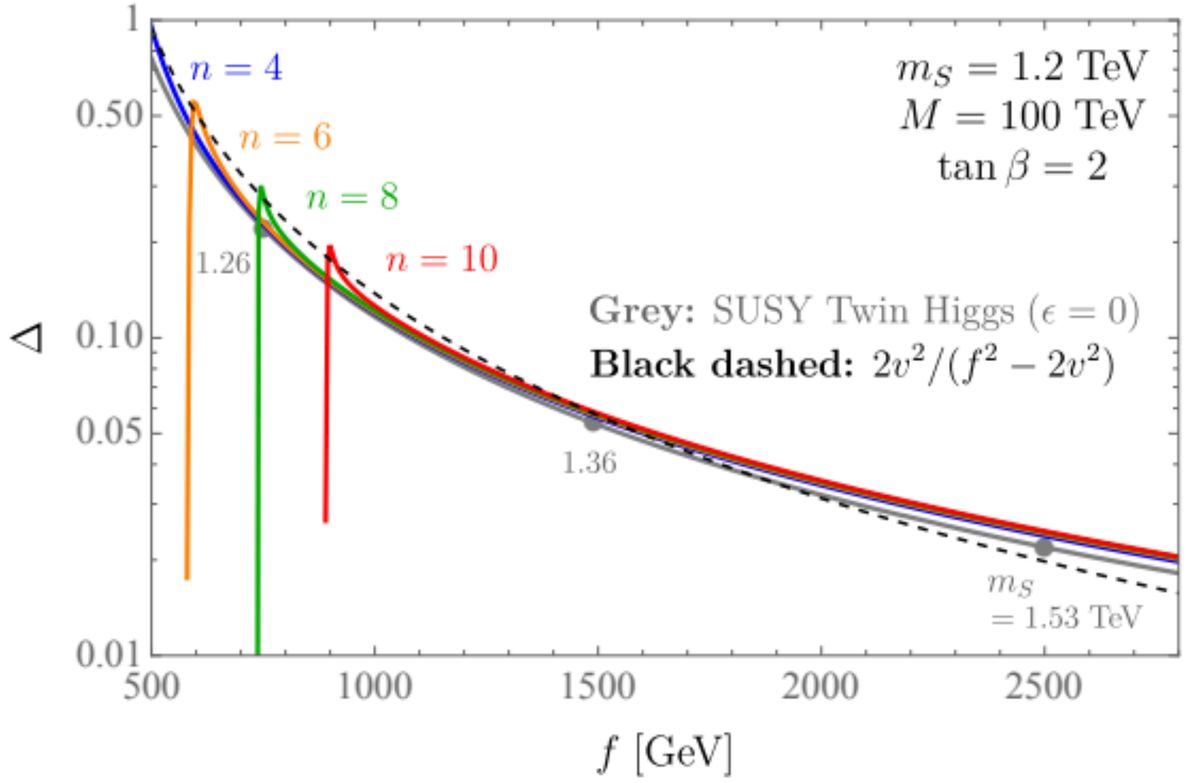
The addition of the Gegenbauer **prevents a natural EWSB** if $m_{S,A} = m_{S,B}$

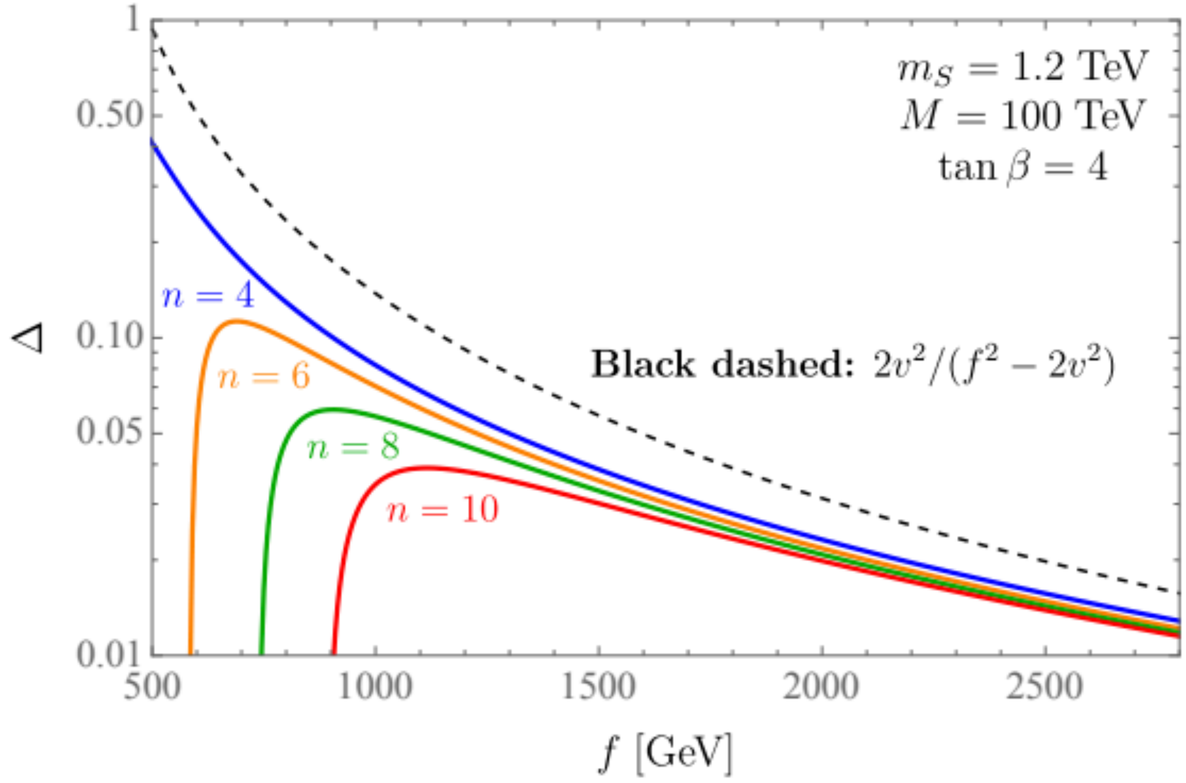
Tuning in the kitchen sink



Tuning computed w.r.t. $\{\epsilon, m_S^2, \delta m^2\}$

$\tan\beta$


$n = 4$
$n = 6$
$n = 8$
$n = 10$
1.26
1.36
m_S = 1.53 TeV
$m_S = 1.2$ TeV
$M = 100$ TeV
$\tan\beta = 2$
Grey: SUSY Twin Higgs ($\epsilon = 0$)
Black dashed: $2v^2/(f^2 - 2v^2)$
1
0.50
0.10
0.05
0.01
500
1000
1500
2000
2500
Δ
f [GeV]


$n = 4$
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$m_S = 1.2$ TeV
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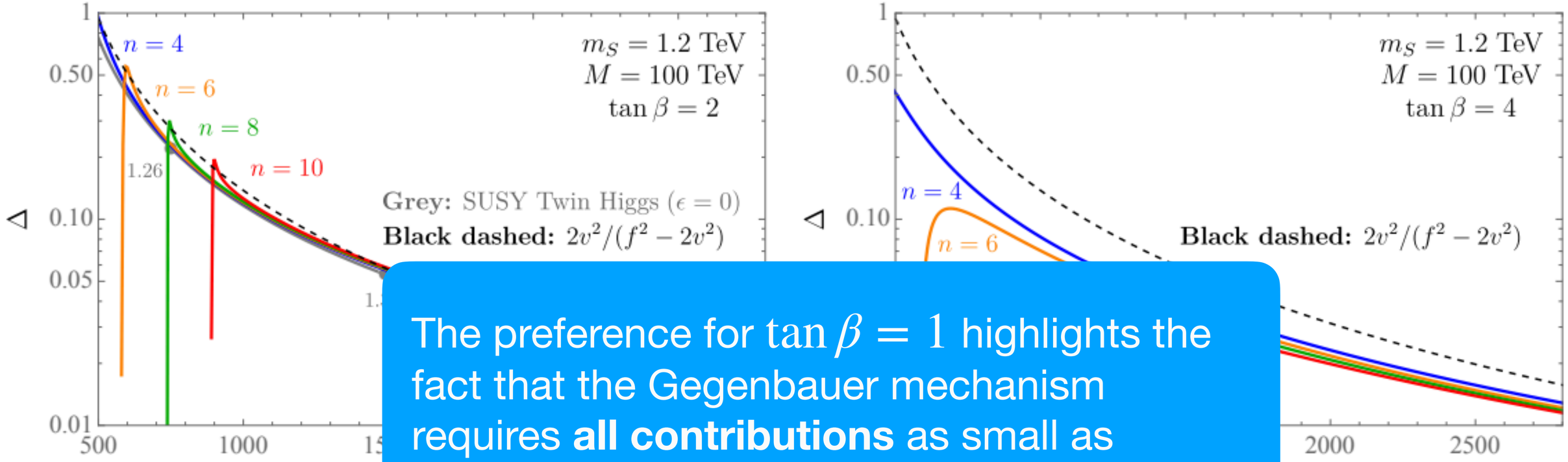
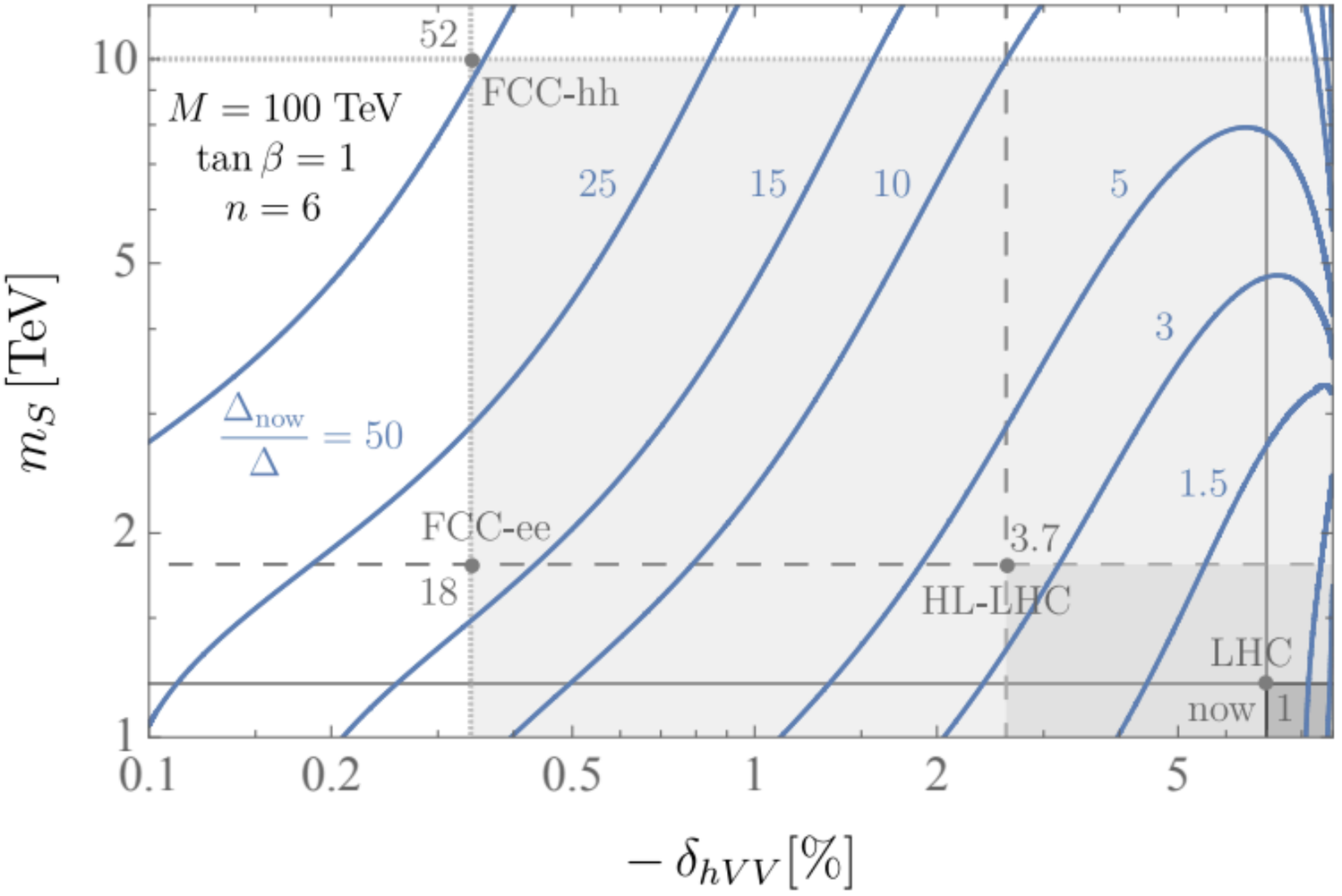
Black dashed: $2v^2/(f^2 - 2v^2)$
1
0.50
0.10
0.05
0.01
500
1000
1500
2000
2500
Δ
f [GeV]

$\tan\beta$

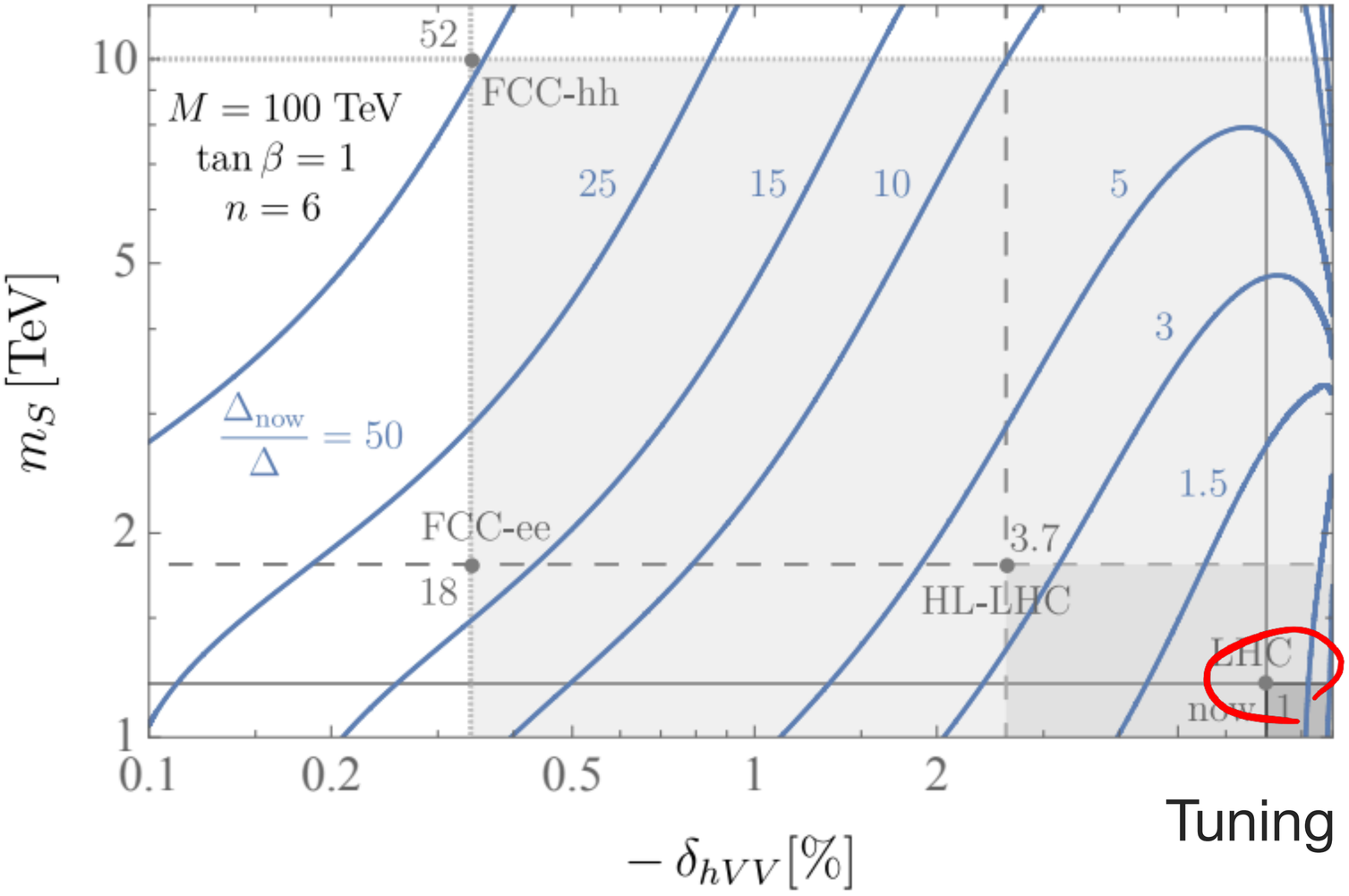


The preference for $\tan\beta = 1$ highlights the fact that the Gegenbauer mechanism requires **all contributions** as small as possible.

Evolution of the tuning

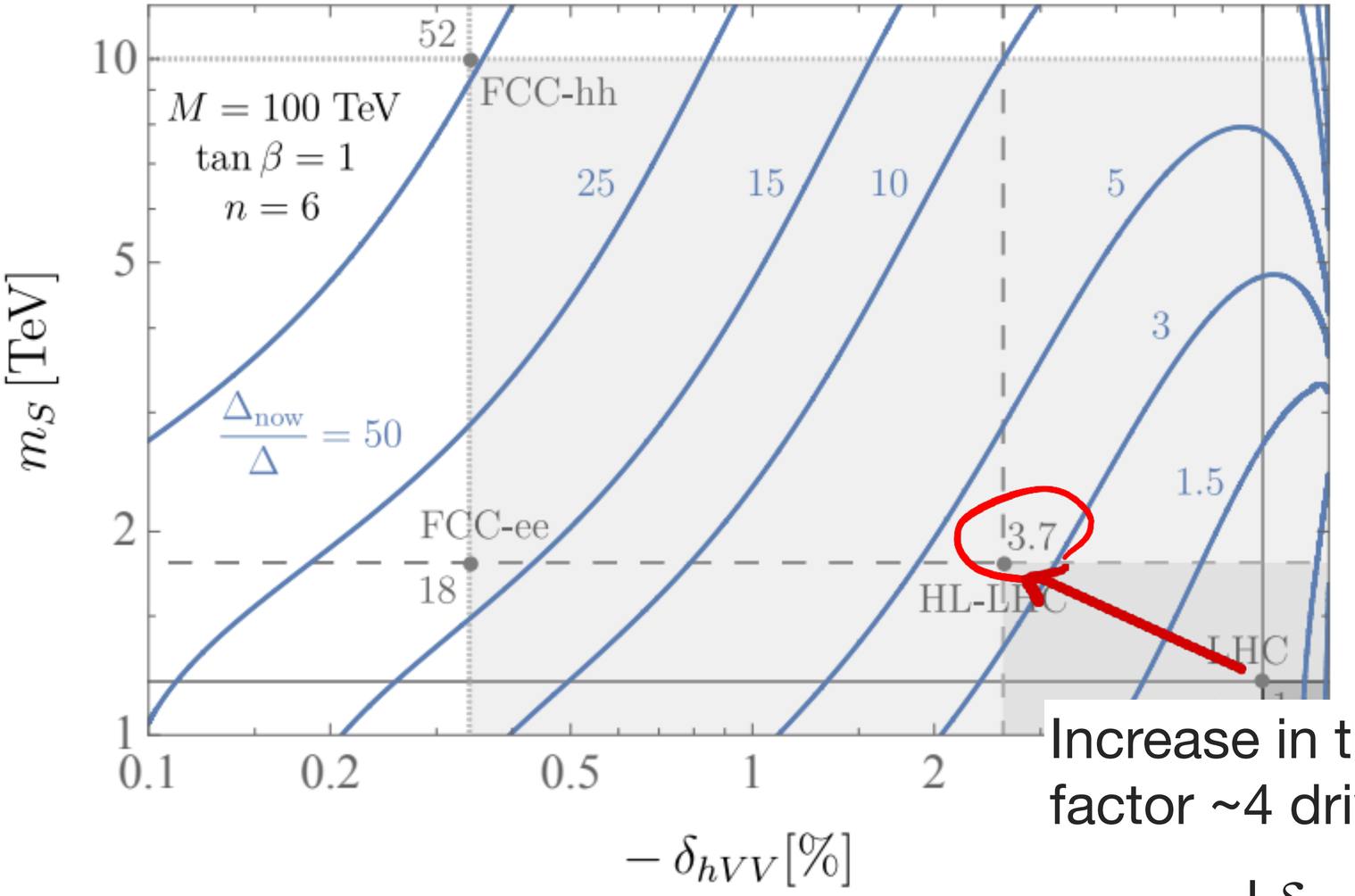


Evolution of the tuning



Tuning driven by **v/f**

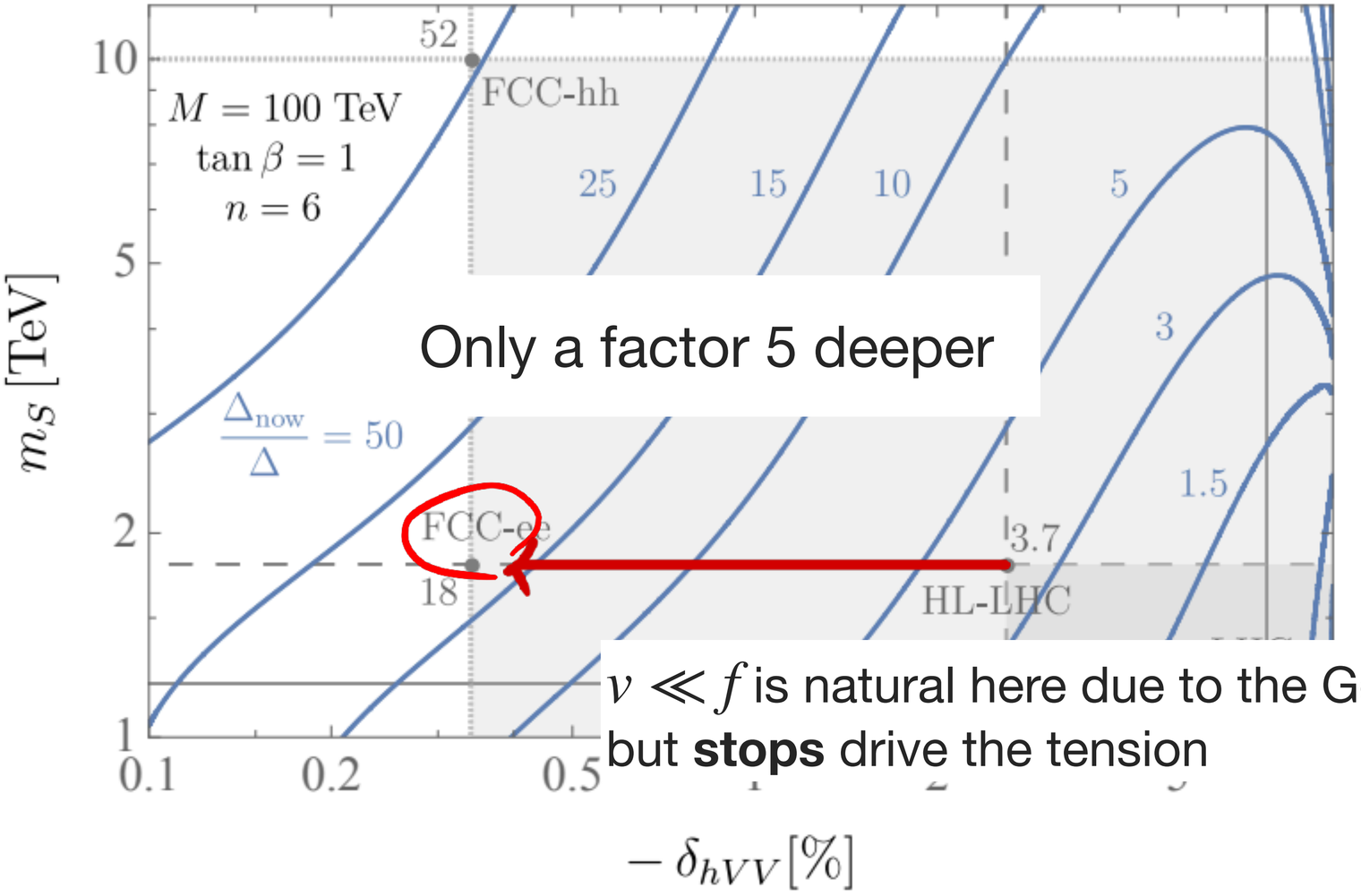
Evolution of the tuning



Increase in the tuning by a factor ~4 driven by

$$|\delta_{hVV}| < 2.6\,\%$$

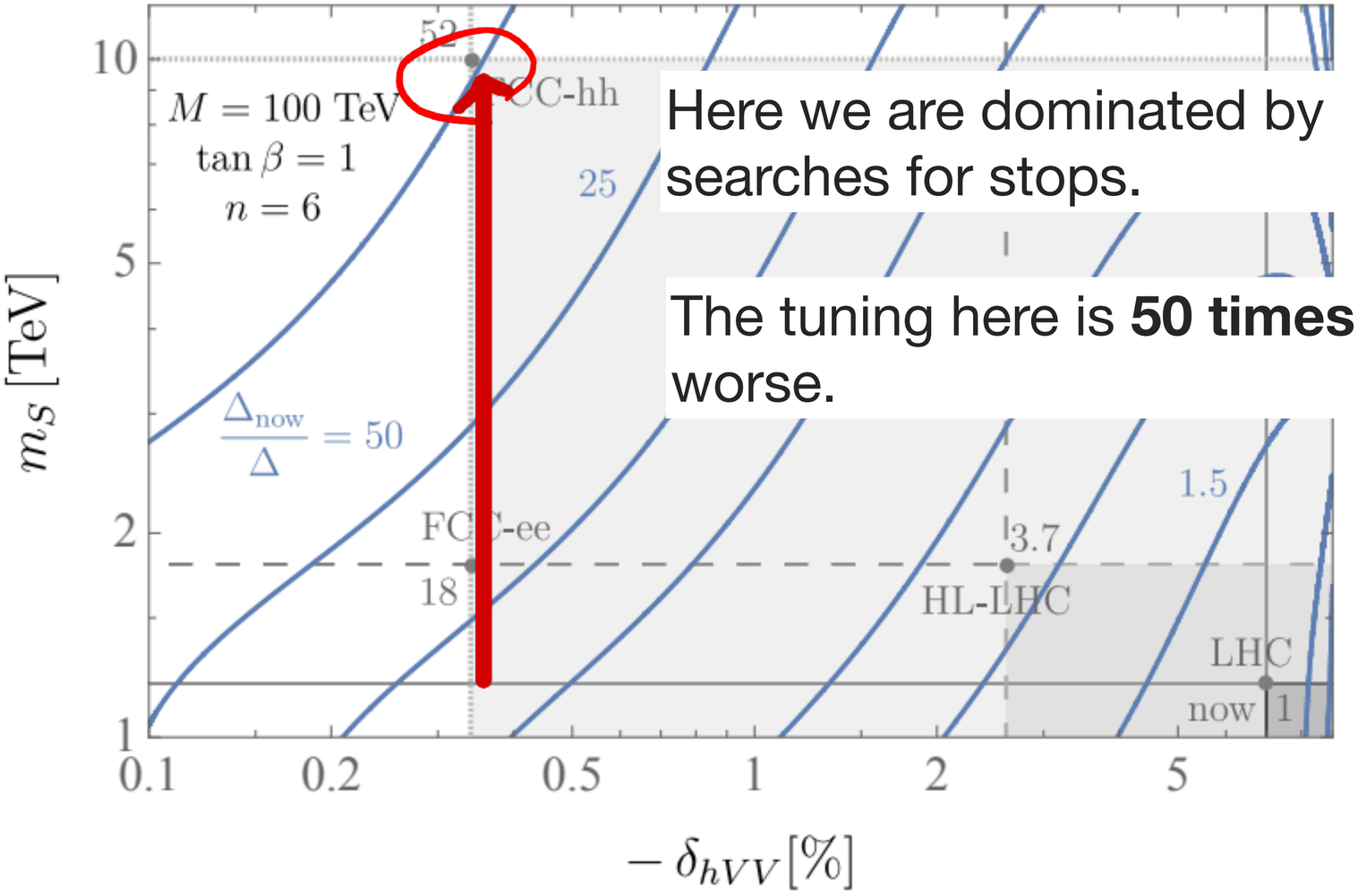
Evolution of the tuning



Only a factor 5 deeper

$v \ll f$ is natural here due to the Gegenbauer, but **stops** drive the tension

Evolution of the tuning



Here we are dominated by searches for stops.

The tuning here is **50 times** worse.

Conclusions

- For pNGb approaches to Higgs naturalness we are presently astride the ‘**direct search’** and **‘indirect precision’** eras.

- Precision will dominate progress in the near- and mid-term.

Pessimistically: If all measurements continue to be SM like, even the Kitchen Sink can’t escape tuning.

Optimistically: if evidence of naturalness is to arise, it may show first in the form of Higgs coupling deviations.