Natural Composite Higgs Model

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Based on: ***Phys.Rev.Lett.*** **124 (2020) 25, 251801**

Collaborators:

Csaba Csaki, Guan Congsheng, Jing Shu

Little Hierarchy Problem

- The pNGB Higgs potential $V(h) = V_g + V_f$

D. B. Kaplan and H. Georgi, Phys. Lett. **136B**, 183 (1984).

K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B **719**, 165 (2005) [hep-ph/0412089].

Gauge loop: $V_g = \gamma_g \sin^2(\frac{h}{f})$ Fermion loop: $V_f = -\gamma_f \sin^2(\frac{h}{f}) + \beta_f \sin^4(\frac{h}{f})$

- Electroweak Symmetry Breaking

J. de Blas, O. Eberhardt and C. Krause, JHEP **1807**, 048

C. Grojean, O. Matsedonskyi and G. Panico, "Light top partners and precision physics," *JHEP* **10** (2013) 160, [1306.4655].

$$\xi \equiv (\frac{\langle h \rangle}{f})^2 = \frac{\gamma_f - \gamma_g}{2\beta_f} < 0.1$$

- Little Hierarchy Problem:

$$\gamma_f \sim \frac{N_c M_f^4}{16\pi^2 g_f^2}\mathcal{O}(\epsilon^2) \gg \beta_f \sim \frac{N_c M_f^4}{16\pi^2 g_f^2}\mathcal{O}(\epsilon^4) \rightarrow \xi_{Natural} > 1$$

Little Hierarchy Problem

- Solution: Independent Positive Higgs quartic coupling $\xi = \frac{\gamma_f - \gamma_g}{2\beta_f}$

Many extra pNGBs & Complicated set up :

Little Higgs,	N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP **0207**, 034 (2002) [hep-ph/0206021];
Extra dimension	C. Csáki, M. Geller and O. Telem, JHEP **1805**, 134 (2018) [arXiv:1710.08921 [hep-ph]].

- Existing Solutions still introduce a lot of fine tuning due to its complication and unsuppressed Higgs quartic!

$$m_h^2 = \frac{8\beta\xi(1-\xi)}{f^2}$$

Fixed!!

- Simplest mechanism with only one Higgs doublet and can be implemented in any pNGB Higgs models?

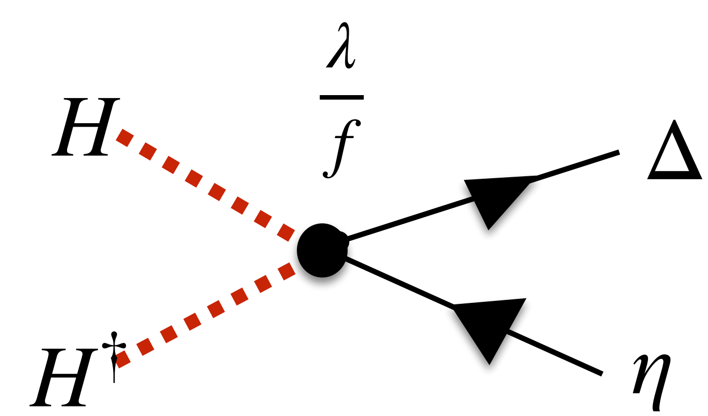
Generating Higgs quartic

- Simplest Solution: Higgs quartic from singlet (η) and triplet (Δ) fermion mixing.

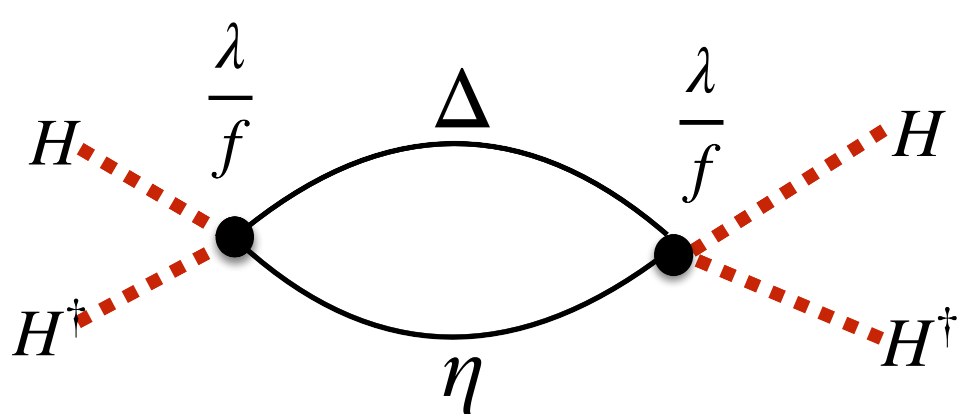
Case I: Effective Yukawa mixing

$$\mathcal{L} = \mathrm{Tr}[\bar{\Delta}\not{p}\Delta] + \bar{\eta}\not{p}\eta - (\frac{\lambda}{f} H^\dagger \bar{\Delta} H \eta + h.c.)$$

Higgs independant kinetic term
Realized by maximal symmetry



- A Higgs quartic can be generated by integrating out the fermions



$$V(H) \sim \frac{i}{2}\int \frac{d^4p}{(2\pi)^4}\frac{\lambda^2(H^\dagger H)^2}{f^2}\mathrm{Tr}[\frac{i\not{p}}{p^2}\frac{i\not{p}}{p^2}]$$
$$= -\frac{\lambda^2(H^\dagger H)^2}{f^2}\int\frac{d^4p_E}{(2\pi)^4}\frac{2}{p_E^2},$$

Negative!!!

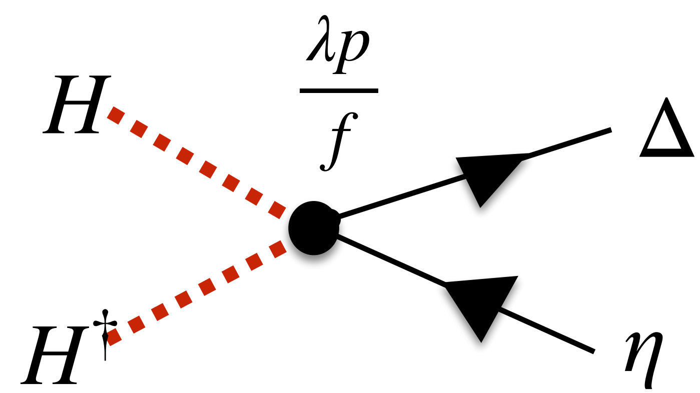
Generating Higgs quartic

Case II: Effective kinetic mixing

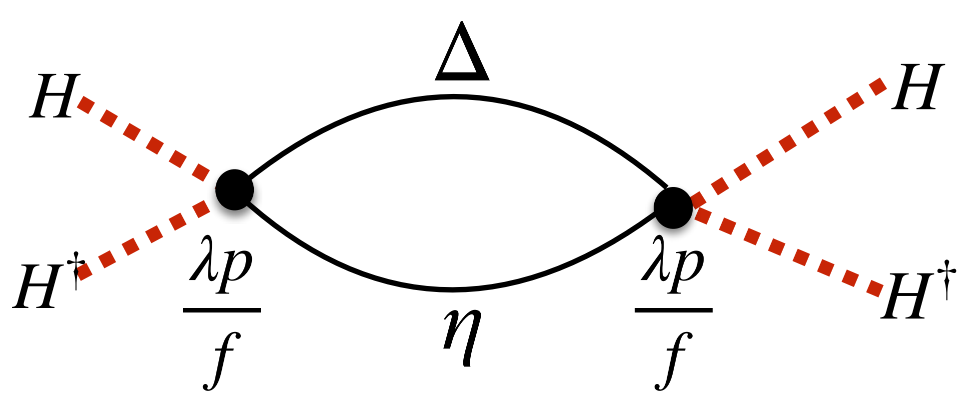
$$\mathcal{L} = \underbrace{\mathrm{Tr}[\bar{\Delta}\not{p}\Delta] + \bar{\eta}\not{p}\eta}_{\text{Independant of Higgs}} - \left(\frac{\lambda}{f^2} H^\dagger \bar{\Delta} H \underbrace{\not{p}}_{\text{Momentum factor}}\eta + h.c.\right)$$

Independant of Higgs

Momentum factor



- A Higgs quartic can be generated by integrating out the fermions



$$V(H) \sim \frac{i}{2}\int \frac{d^4p}{(2\pi)^4}\frac{\lambda^2(H^\dagger H)^2}{f^4}\mathrm{Tr}\left[\frac{i(\not{p})}{p^2}\not{p}\frac{i(\not{p})}{p^2}\not{p}\right]$$

$$= \frac{2\lambda^2(H^\dagger H)^2}{f^4}\int \frac{d^4p_E}{(2\pi)^4}.$$

Positive!!!

$p^2 = -p_E^2$

- Positive Higgs quartic conditions

1. The effective kinetic terms must be Higgs independent;
2. The triplet-singlet mixing must be momentum dependent.

Maximal symmetry can realize!!!

C. Csáki, T. Ma and J. Shu, Phys. Rev. Lett. **119** (2017) no.13, 131803 [arXiv:1702.00405 [hep-ph]].
C. Csáki, T. Ma, J. Shu and J. H. Yu, [arXiv:1810.07704 [hep-ph]].

UV Completion

- Toy model: a vector-like doublet fermion $\Psi_{\mathbf{2}}$

$$\mathcal{L}_{\rm int} = \lambda_{1L}\bar{\Psi}_{2_R}\Delta_L H + \lambda_{2L}\bar{\Psi}_{2_R} H\eta_L + (L \leftrightarrow R) + h.c.$$

- Effective Lagrange

$$\mathcal{L}_{\rm eff}^{\rm mix} = \frac{-1}{M^2 - p^2}\left(\lambda_{1L}\lambda_{2L}H^\dagger\bar{\Delta}_L H \not{p}\eta_L + M\lambda_{1L}\lambda_{2R}H^\dagger\bar{\Delta}_L H\eta_R\right)$$

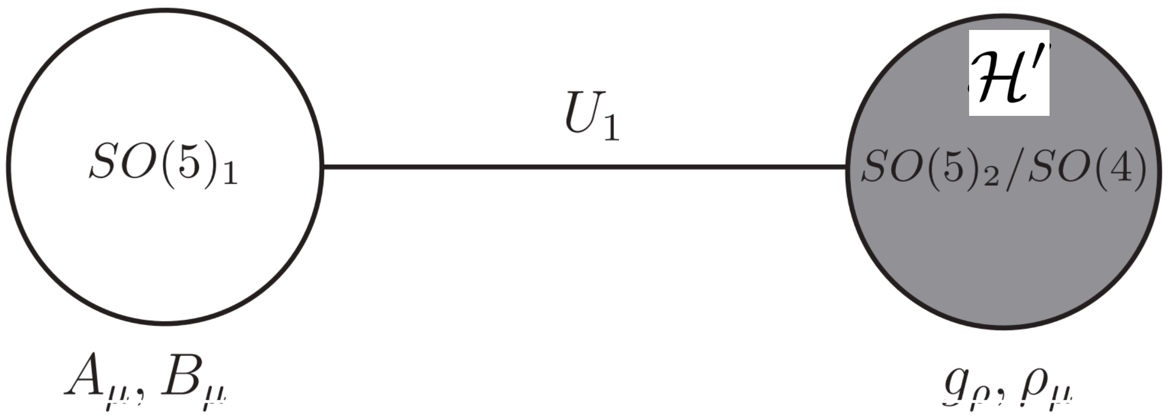
Positive Negative

- For pure chiral coupling, Higgs quartic is positive.

Explicit Realisation in CHMs

- Realisation in minimal maximal symmetric CHM based on $SO(5)/SO(4)$

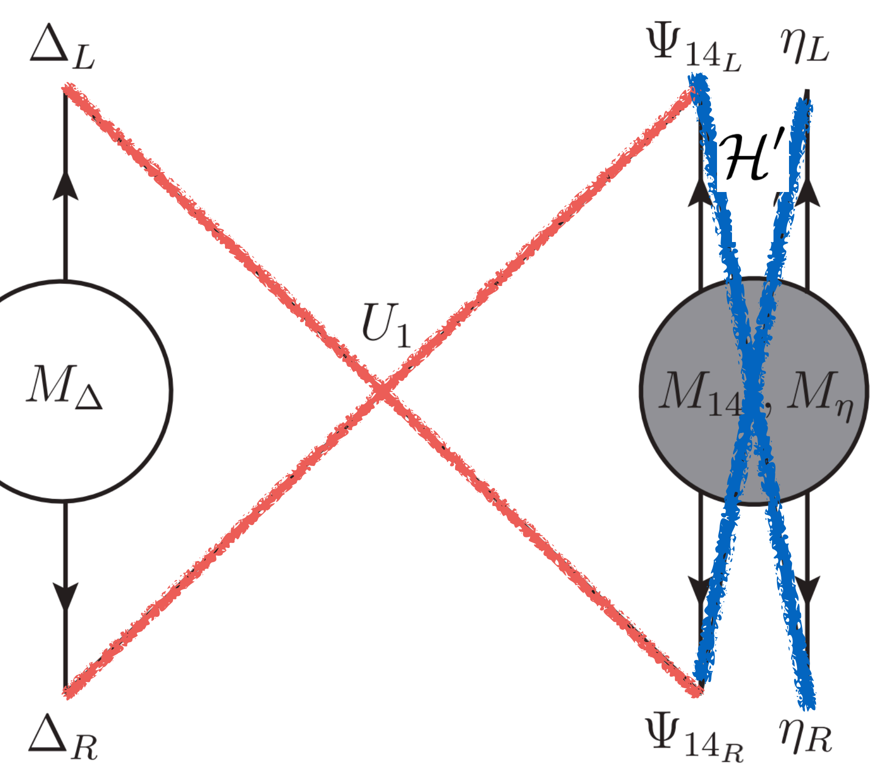
$$SO(5)_1 \times SO(5)_2$$



$$\mathcal{H} = U_1\mathcal{H}' = (0,0,0,s_h,c_h)$$

$$s_h \equiv \sin(h/f)$$

- Δ and η mix with composite partners $\Psi_{14} \in 14$ at second site



Explicit Realisation in CHMs

- The interactions

$$\mathcal{L}_{\Delta\eta} \sim -\left(\lambda_{\Delta_L}\mathrm{Tr}[\bar{\Psi}_{\Delta_L}U_1\Psi_{14_R}U_1^T] + \lambda_{\eta_L}\mathcal{H}'^{\dagger}\bar{\Psi}_{14_R}\mathcal{H}'\eta_L + h.c.\right) + (L \leftrightarrow R)$$

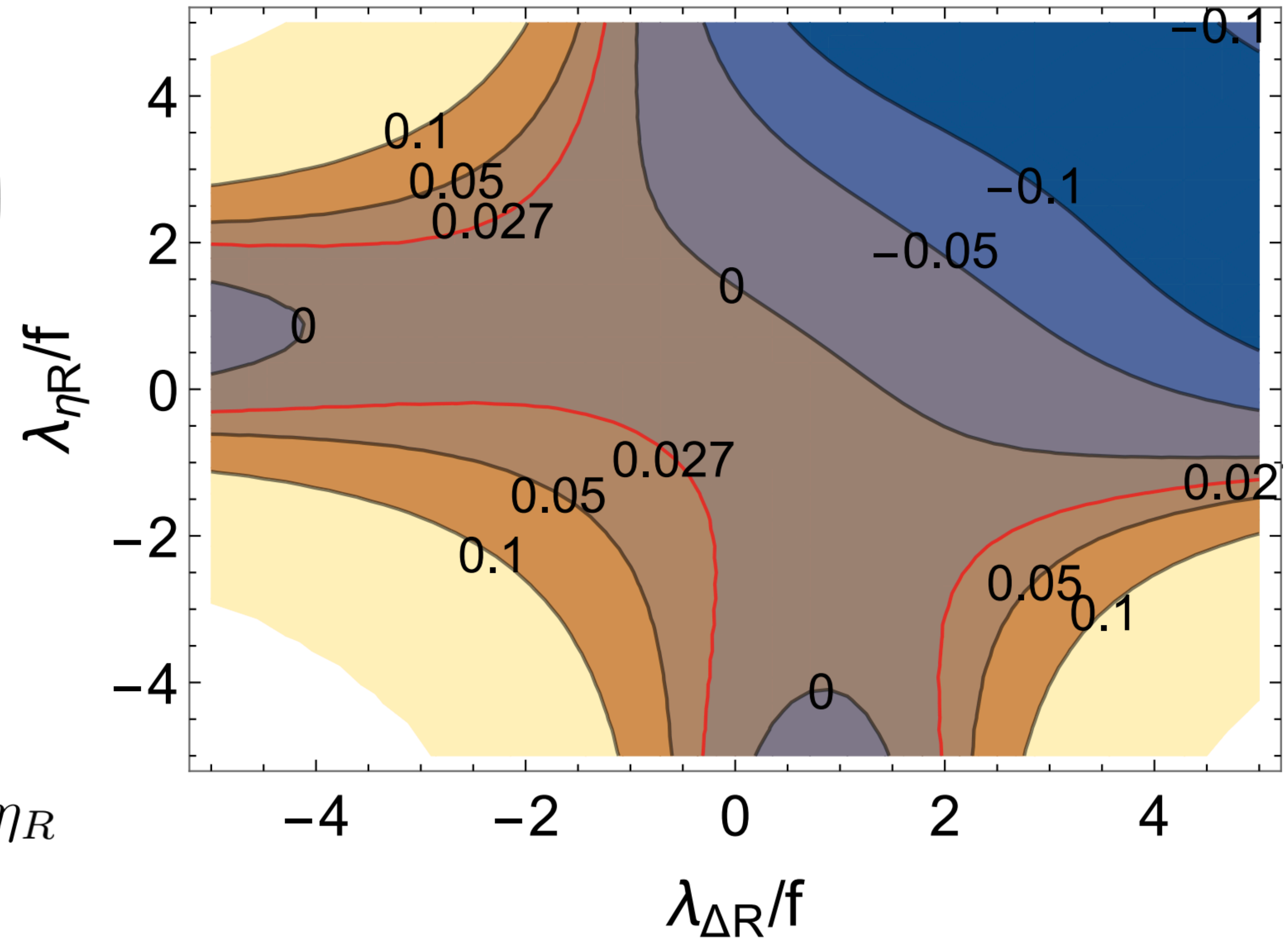
Triplet embedding:

$$\Psi_\Delta = \frac{1}{2\sqrt{2}}\begin{pmatrix} -\sqrt{2}\Delta^0\mathbb{1}_2 & \Delta^{+-} & \mathbf{0} \\ (\Delta^{+-})^T & \sqrt{2}\Delta^0\mathbb{1}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 \end{pmatrix}$$

$$\Delta^{+-} = \begin{pmatrix} -\Delta^+ - \Delta^- & i(\Delta^- - \Delta^+) \\ i(\Delta^- - \Delta^+) & \Delta^+ + \Delta^- \end{pmatrix}$$

- Effective interactions

$$\mathcal{L}_{\text{eff}} = \Pi_L^1 \mathcal{H}^\dagger \bar{\Psi}_{\Delta_L}\mathcal{H}\not{p}\eta_L + M_1^{\Delta\eta}\mathcal{H}^\dagger\bar{\Psi}_{\Delta_L}\mathcal{H}\eta_R + (L \leftrightarrow R) + h.c.$$



$$M_\Delta = M_\eta = M_{14} = 4 \text{ TeV} \quad \lambda_{\Delta_L} = 2f,\ \lambda_{\eta_L} = 2f$$

Application I

- Minimal maximal symmetric CHMs

$$V(h) = -\gamma s_h^2 + \beta s_h^4 \qquad \gamma = \gamma_f - \gamma_g \qquad \beta = \beta_f + \beta_\Delta$$

$$s_h \equiv \sin(h/f)$$

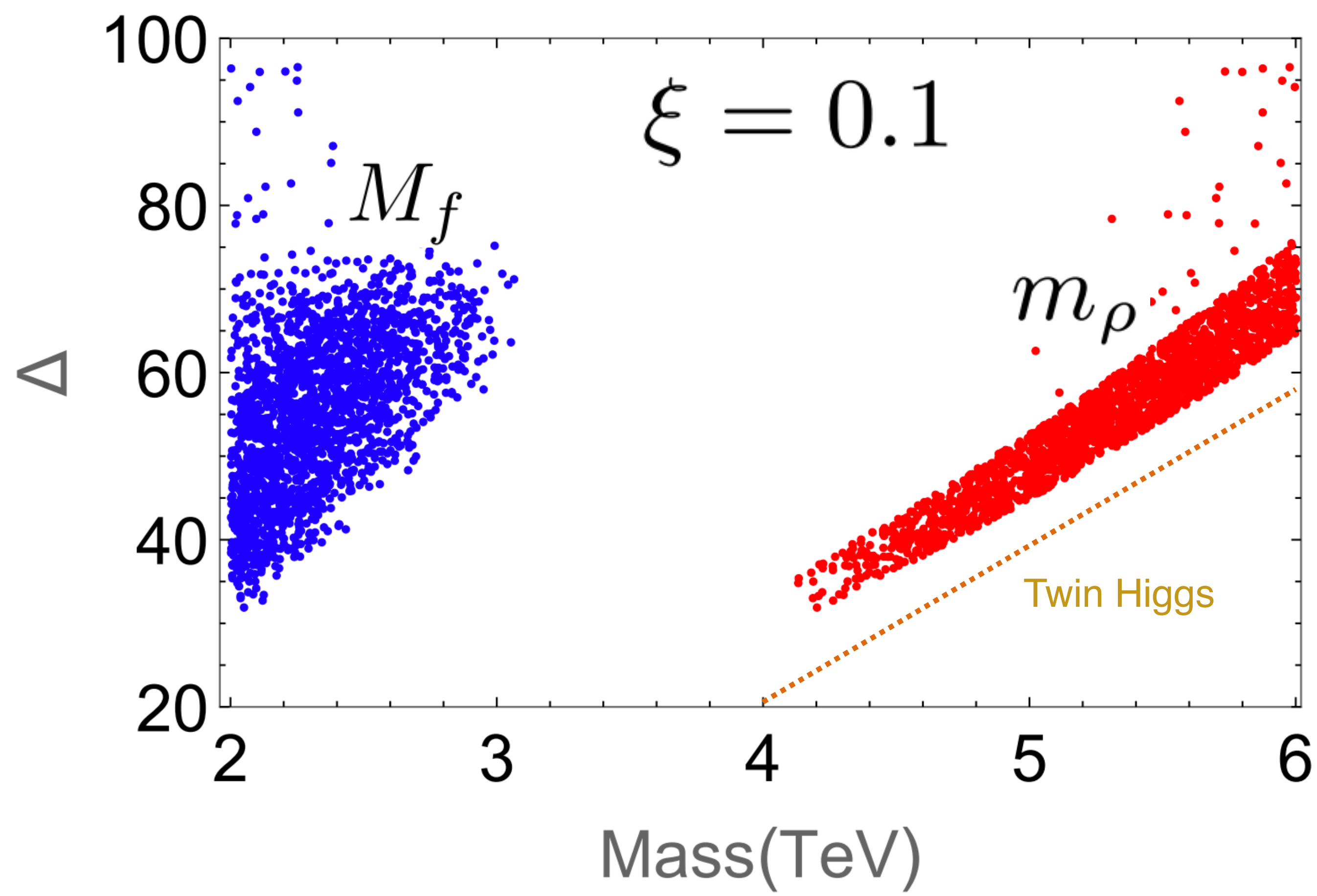
Top (γ_f), Gauge (γ_g); Top (β_f), Extra (β_Δ)

- Higgs mass and vacuum

$$m_h^2 = \frac{8\beta\xi(1-\xi)}{f^2} \quad s_h^2 = \frac{\gamma}{2\beta} \equiv \xi$$

- Higgs mass is suppressed and too light (around 100 GeV)

$$\beta_f \simeq \frac{N_c y_t^4 f^4}{(4\pi)^2} \ln \frac{M_f^2}{m_t^2}$$



$$\gamma_f \simeq \frac{2 N_c y_t^2 M_f^2 f^2}{(4\pi)^2} \Rightarrow \Delta = \left| \frac{\partial \ln \xi}{\partial \ln M_f} \right| \approx \frac{\gamma_f}{\xi \beta_f} \gtrsim 95/\xi$$

Application II

- Natural twin Higgs with $\beta_\Delta s_h^4$ as Twin parity breaking source

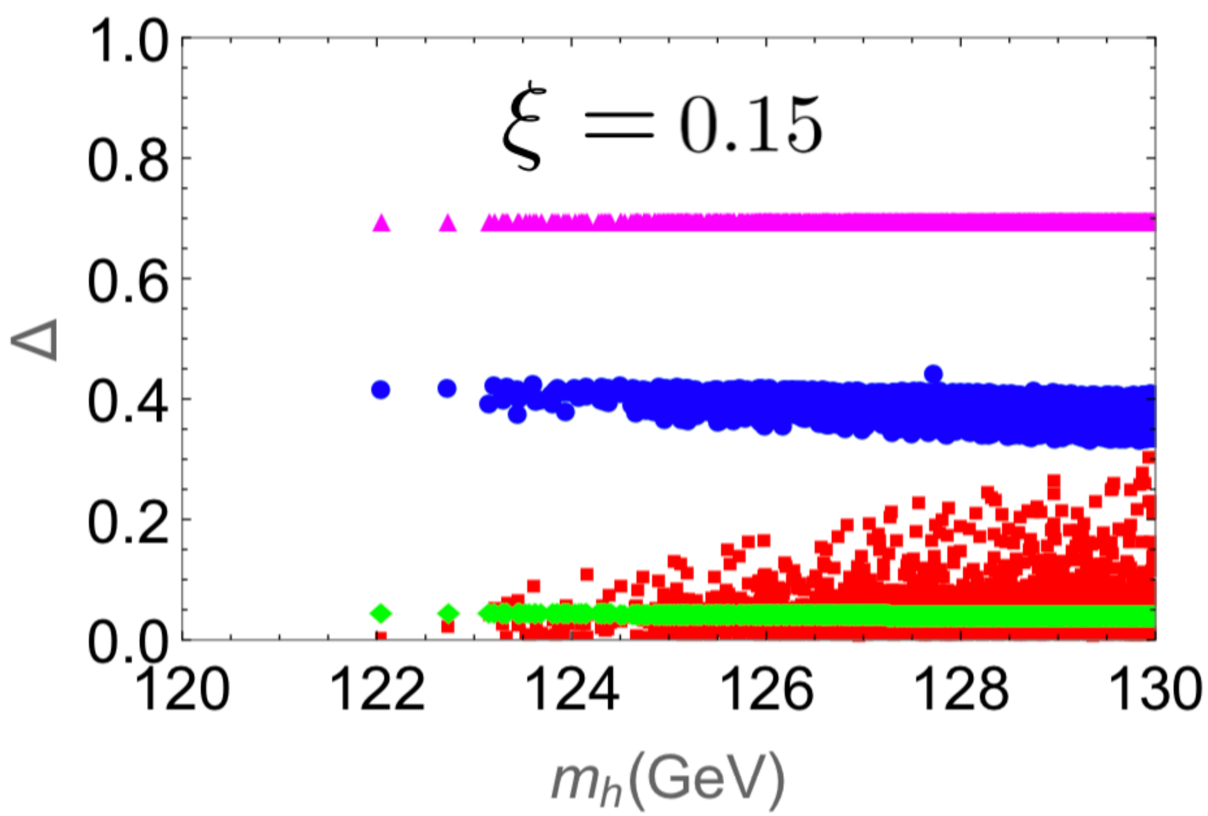
$$V(h) \approx (\beta_f - \beta_g)(s_h^4 + c_h^4) + \beta_\Delta s_h^4$$

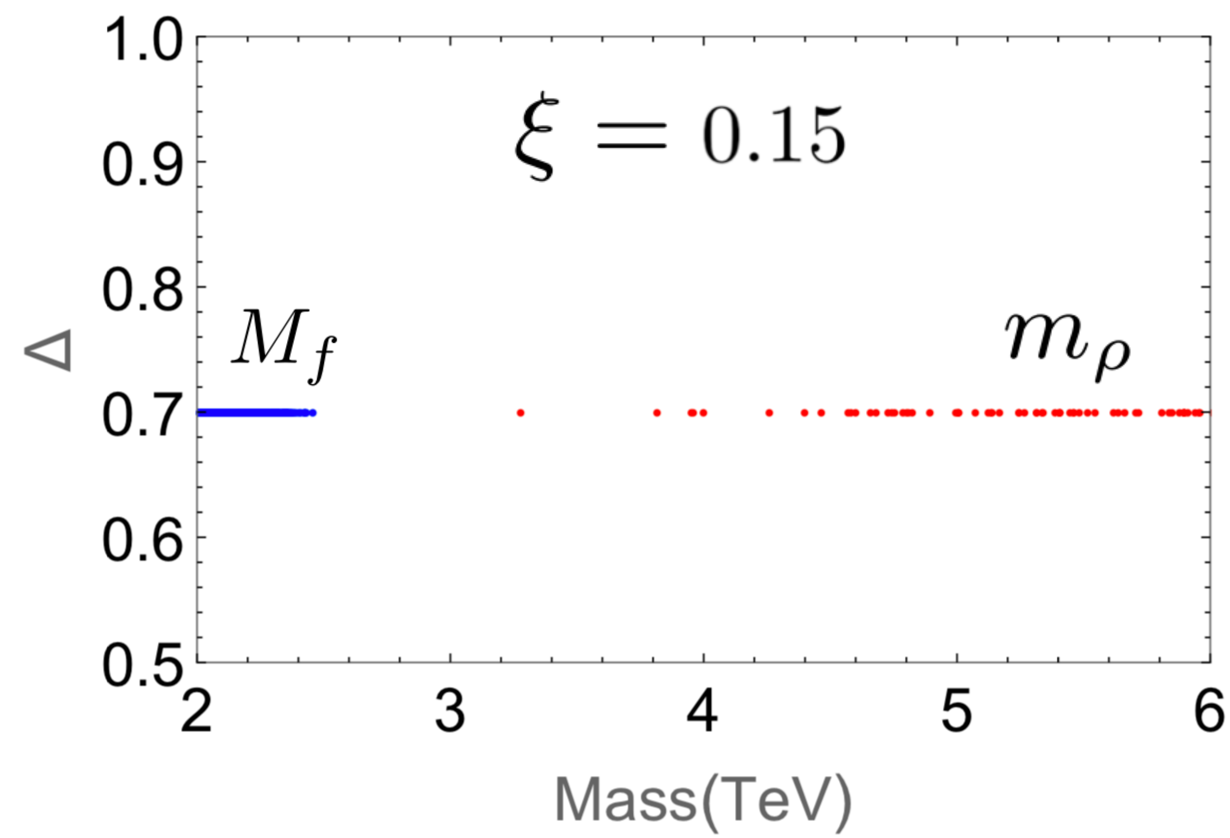
$$\beta_f \simeq c_f' \frac{N_c y_t^4 f^4}{(4\pi)^2} \ln \frac{M_f^2}{m_t^2} \qquad \beta_g \simeq c_g' \frac{9 f^4 g^4}{1024\pi^2} \ln \frac{m_\rho^2}{m_W^2}$$

- Vacuum is fixed (Current bound $\xi < 0.2$)

$$\xi \simeq c_f' \frac{N_c y_t^2}{2\pi^2} \left(\frac{m_t}{m_h}\right)^2 \ln\left(\frac{M_f^2}{m_t^2}\right) = 0.15$$

$$\Delta = \max(\Delta_i), \quad \Delta_i = \frac{\partial \ln \xi}{\partial \ln x_i}$$





Summary

- ☑ Simplest Higgs quartic generating mechanism that can be implemented in any pNGB Higgs Model

- ☑ This independent quartic can significantly suppress the tuning in minimal CHMs and achieve natural Twin Higgs.

- ☑ the triplet and singlet Dirac fermions and unbroken twin parity are the main predictions

BACK UP

N-Suppression

- Gauge contribution can be significant

$$V_g(h) \approx \boxed{\frac{9g^4 f^4}{32(4\pi)^2} \log(\frac{\Lambda_g^2}{m_W^2})} \left(s_h^2 - s_h^4\right),$$

- The full Potential

$$V(h) \approx -(\frac{\gamma_f}{N^2} - \gamma_g) s_h^2 + \frac{4}{3}\gamma_f s_h^4$$

$$\frac{\gamma_f}{\gamma_g} \approx \mathcal{O}(10) \Rightarrow N \approx 3.$$

N-Suppression

- Tuning

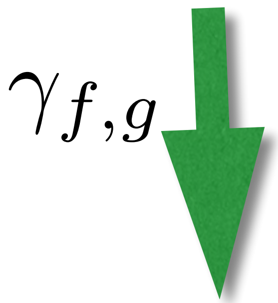
$$\gamma_g \sim \frac{9g^4 f^4}{32(4\pi)^2} \log(\frac{\Lambda_g^2}{m_W^2}) \quad \gamma_f \sim \frac{2N_c y_t^4 f^4}{(4\pi)^2} \log(\frac{\Lambda_f^2}{m_t^2})$$

$$\xi \approx \frac{\frac{\gamma_f}{N^2} - \gamma_g}{8\gamma_f/3}$$

$$\Delta = \left|\frac{\partial \ln \xi}{\partial \ln \Lambda_\rho}\right| \approx \frac{1}{\log \frac{\Lambda_\rho^2}{m_W^2}} (\frac{3}{4\xi N^2} - 2)$$

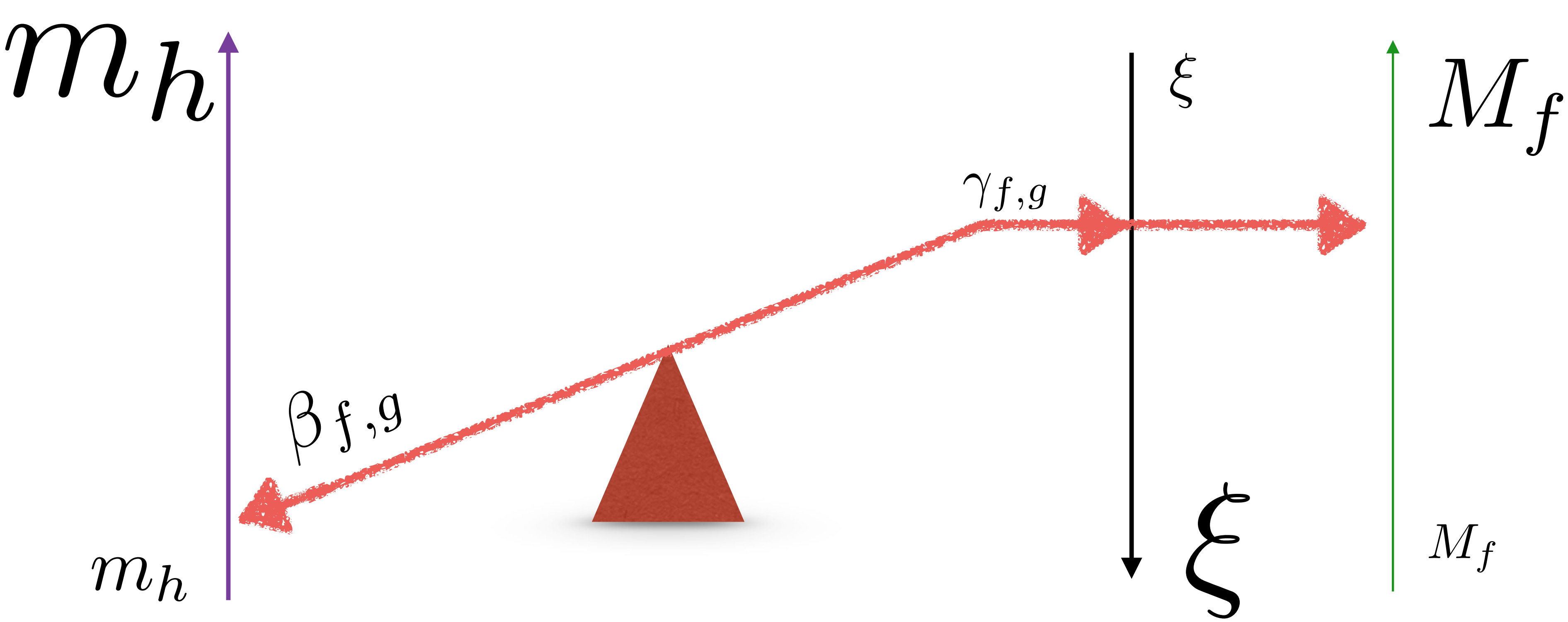
Little Hierarchy Problem

Solution B



$$\xi = \frac{v_{SM}^2}{f^2} = \frac{(\gamma_f - \gamma_g)}{2\beta_f}$$

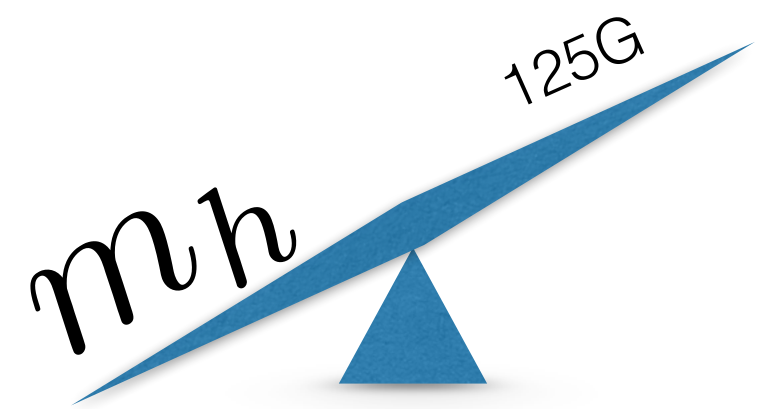
$$m_h^2 = \frac{8\beta_f \xi (1-\xi)}{f^2}$$

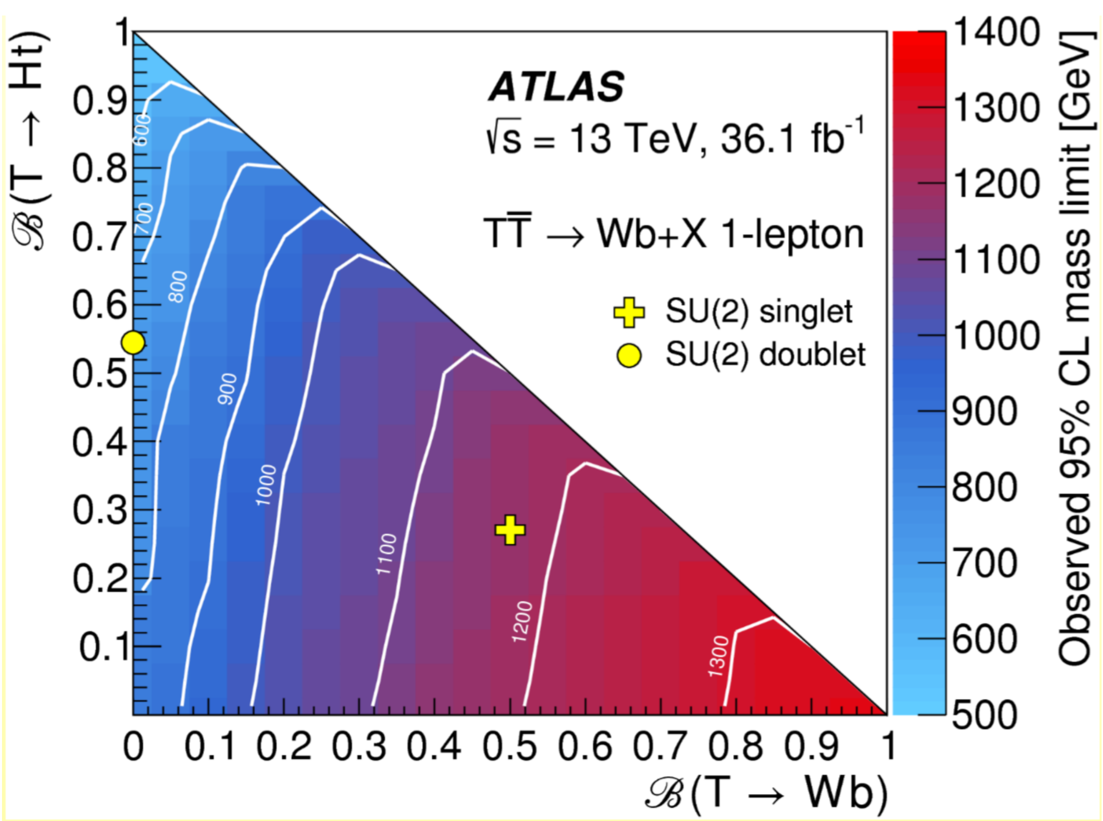


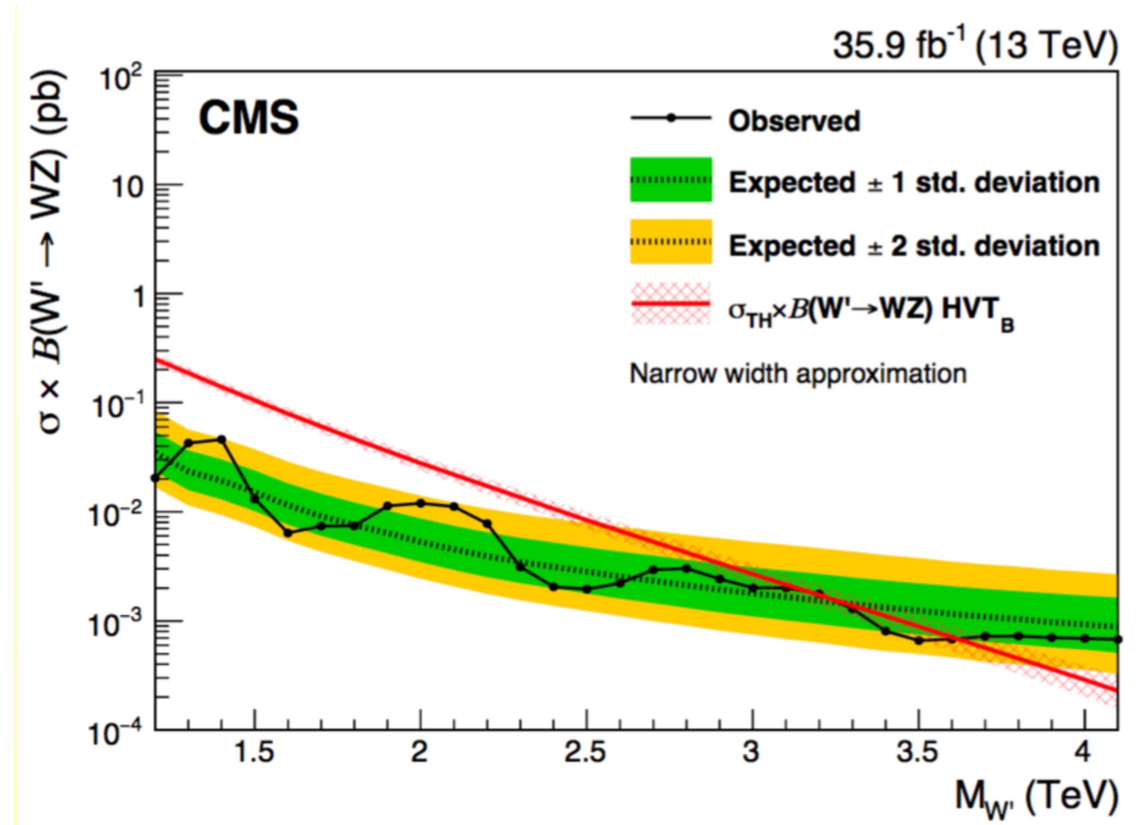
Higgs as pNGB

- **Direct Detection**

Spin-1/2 partners Bound >~1.3 TeV
Spin-1 partners Bound >~ 3 TeV







Neutral Naturalness

- **The Higgs Potential** $V(h) = -\gamma s_h^2 + \beta s_h^4$

$$\sin\frac{\pi^i}{f} \leftrightarrow \cos\frac{\pi^i}{f}$$

Fixed by Z2

$$m_{\tilde{t}} = y_t f$$

$$\gamma_f = \beta_f \sim \frac{N_C y_t^2 f^2 m_{\tilde{t}}^2}{(4\pi)^2} \log(\frac{\Lambda^2}{m_t^2})$$

$$\xi = \sin^2(\frac{\pi}{4}) = 0.5$$

N-Suppression

$$\mathcal{L}_g = gW_\mu^a W_\mu^a \sin(\frac{h}{f})^2 + g\tilde{W}_\mu^a \tilde{W}_\mu^a \cos(\frac{h}{f})^2$$

$$m_W = \frac{g}{2} f \sin(\frac{h}{f}) \qquad m_t = y_t' f \sin(\frac{Nh}{f})$$

The Coupling Deviation

$$\frac{g'_{WWh}}{g^{SM}_{WWh}} = \sqrt{1-\xi} \approx 0.97$$

$$\frac{y'_{tth}}{y_t^{SM}} = N\sqrt{\xi}\cot(N\sqrt{\xi}) \approx 0.75.$$

N-Suppression

- SO(8)/SO(7)

$$U = e^{i\frac{\sqrt{2}}{f}h^{\hat{a}}T^{\hat{a}}} = \begin{pmatrix} \mathbb{1}_3 & 0 & 0 & 0 \\ 0 & \cos\frac{h}{f} & 0 & \sin\frac{h}{f} \\ 0 & 0 & \mathbb{1}_3 & 0 \\ 0 & -\sin\frac{h}{f} & 0 & \cos\frac{h}{f} \end{pmatrix}$$

- Get $\sin(Nh/f)$ $(\cos(Nh/f))$

$$U^N = U(\frac{h}{f} \to \frac{Nh}{f}).$$

Little Hierarchy Problem

Little Hierarchy Problem Always Exists

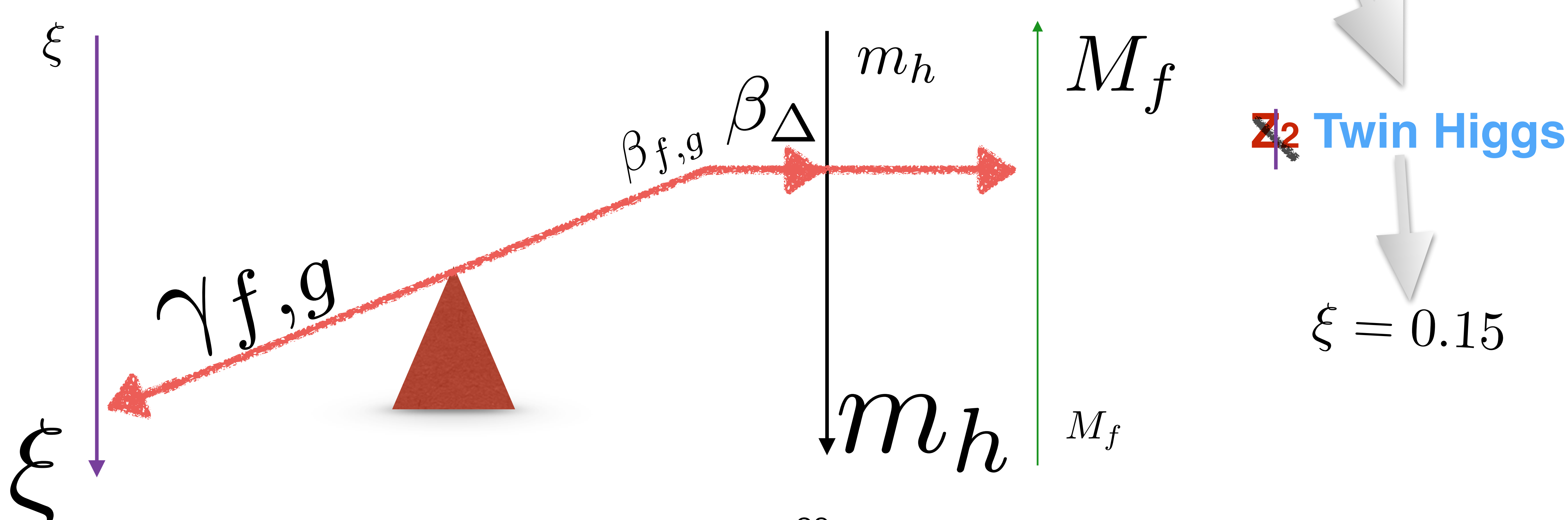
$$V(h) = -(\gamma_f - \gamma_g)\sin^2\frac{h}{f} + \beta_f \sin^4\frac{h}{f}$$

$$\xi = \frac{v_{SM}^2}{f^2} = \frac{(\gamma_f - \gamma_g)}{2\beta_f}$$

$$\xi \equiv \sin^2\frac{\langle h\rangle}{f}$$

Solution A $\quad \Delta V(h) = \beta_\Delta \sin^4\frac{h}{f}$

- *Little Higgs* **hep-ph/0206020**
- *6D 2HD* **arXiv:1710.08921**
- **Triplet-singlet Mixing arXiv:1904.03191**

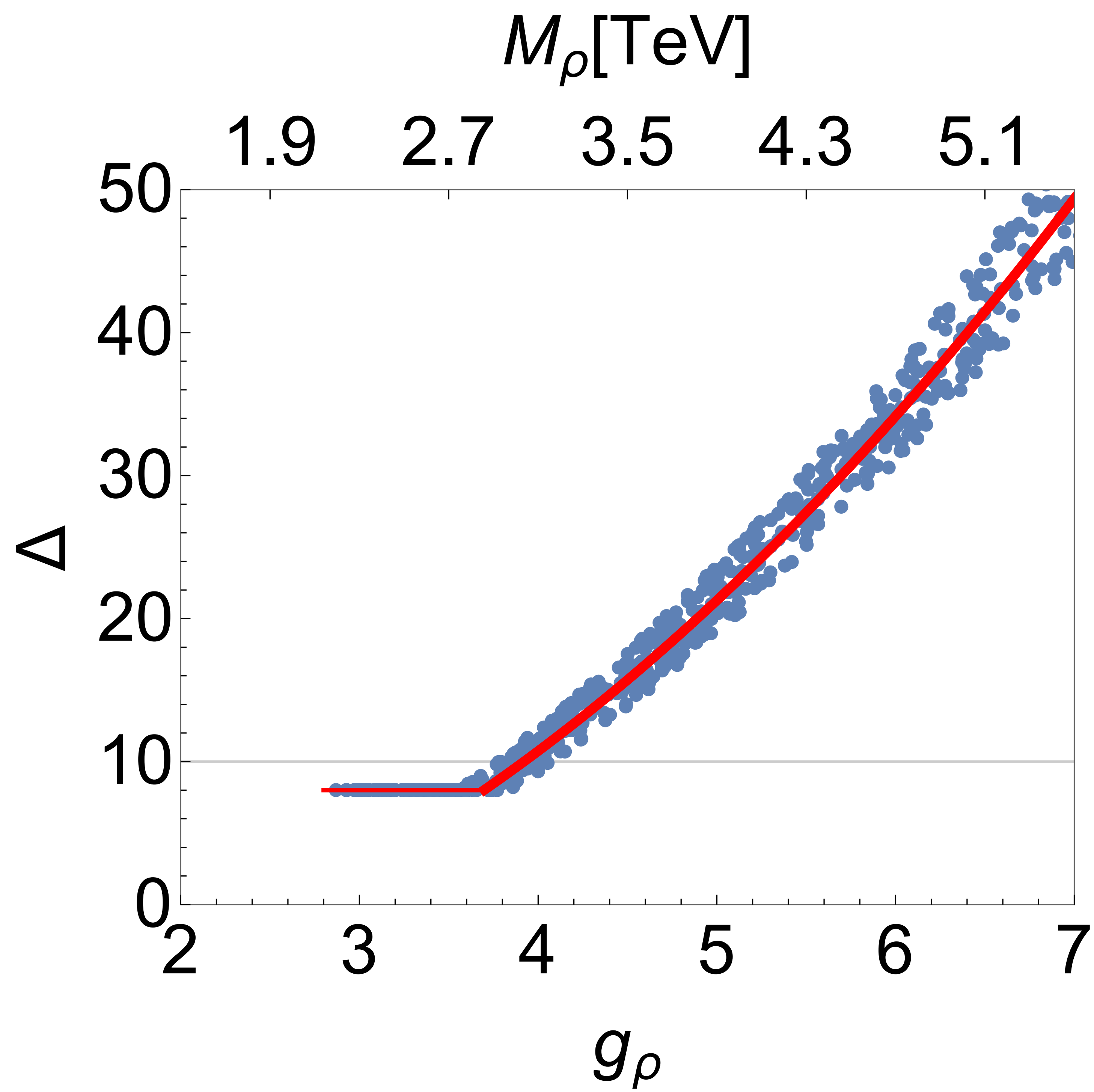


Neutral Naturalness

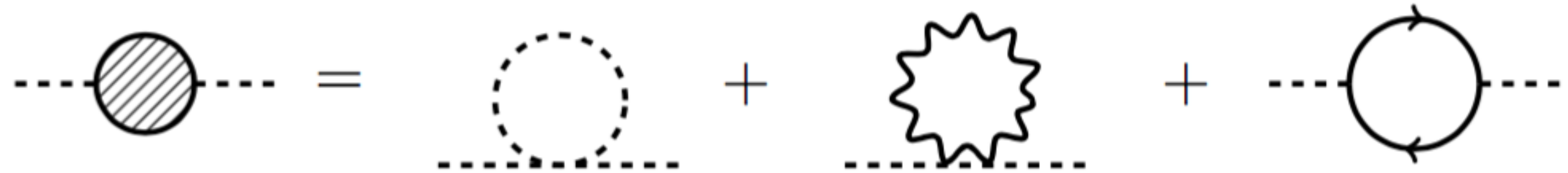
~~Z_2~~

$$\gamma_g \sim \frac{g^2 f^2 \Lambda^2}{(4\pi)^2}$$

$$\xi = \frac{\gamma_f - \gamma_g}{2\beta_f}$$ ↓



Higgs Big Hierarchy Problem



$$\delta m_h^2 \sim \frac{g^2}{(4\pi)^2}\Lambda^2$$

$\sim H^\dagger H$ Singlet

N-Suppression

- Realisation: SO(8)/SO(7) coset space → N-Suppression

$$\mathcal{L}_t^{\text{Yuk.}} = y_t' f \bar{t}_L t_R \sin(\frac{Nh}{f}) + y_{\tilde{t}}' f \bar{\tilde{t}}_L \tilde{t}_R \cos(\frac{Nh}{f}) + h.c.$$

- Symmetry in UV completion

$$t \leftrightarrow \tilde{t} \qquad \frac{h}{f} \to -\frac{h}{f} + \frac{\pi}{2} \qquad \sin(\frac{h}{f}) \leftrightarrow \cos(\frac{h}{f})$$

- N is odd

$$t \leftrightarrow \tilde{t} \qquad \sin(\frac{Nh}{f}) \leftrightarrow \cos(\frac{Nh}{f})$$

$$|y_t'| = |y_{\tilde{t}}'|$$

Z. Chacko, H. S. Goh and R. Harnik, Phys. Rev. Lett. **96**, 231802 (2006) [hep-ph/0506256].

M. Low, A. Tesi and L. T. Wang, Phys. Rev. D **91**, 095012 (2015) [arXiv:1501.07890 [hep-ph]].
R. Barbieri, D. Greco, R. Rattazzi and A. Wulzer, JHEP **1508**, 161 (2015) [arXiv:1501.07803 [hep-ph]].

C. Csáki, T. Ma and J. Shu, Phys. Rev. Lett. **121**, no. 23, 231801 (2018) [arXiv:1709.08636 [hep-ph]].

M. Geller and O. Telem, Phys. Rev. Lett. **114**, 191801 (2015) [arXiv:1411.2974 [hep-ph]]; C. Csaki, M. Geller, O. Telem and A. Weiler, JHEP **1609**, 146 (2016) [arXiv:1512.03427 [hep-ph]].

N-Suppression

- Higgs potential from (twin) top Sector

$$V_f(h) \sim -\frac{(y_t')^4 f^4}{(4\pi)^2}\log(\frac{\Lambda_f^2}{m_t^2})\sin^2(\frac{2Nh}{f})$$

- Electroweak Symmetry Breaking

$$\xi_{Natural} = (\frac{\langle h\rangle}{f})^2 = (\frac{\pi}{4N})^2 \ll 1, \quad N \geq 3$$

- The coupling deviation N = 3

$$\frac{g'_{WWh}}{g^{SM}_{WWh}} = \sqrt{1-\xi} \approx 0.97$$

A. M. Sirunyan *et al.* [CMS Collaboration], Eur. Phys. J. C **79**, no. 5, 421 (2019) doi:10.1140/epjc/s10052-019-6909-y [arXiv:1809.10733 [hep-ex]].

$$\frac{y'_{tth}}{y_t^{SM}} = N\sqrt{\xi}\cot(N\sqrt{\xi}) \approx 0.75.$$

G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **101**, no. 1, 012002 (2020) doi:10.1103/PhysRevD.101.012002 [arXiv:1909.02845 [hep-ex]].

- Gauge sector

$$V_g = \gamma_g \sin^2(\frac{h}{f}) \qquad \gamma_g \sim \frac{g^4 f^4}{(4\pi)^2}\log(\frac{\Lambda_\rho^2}{m_W^2})$$

N-Suppression

- Suppression $$y_t' \approx \frac{y_t}{N}$$
- The potential in term of $\sin(\frac{h}{f})$ and SM top Yukawa y_t

$$V(h) = -(\frac{\gamma_f}{N^2} - \gamma_g)\sin^2(\frac{h}{f}) + \gamma_f \sin^4(\frac{h}{f})$$

$$\gamma_g \approx 0.1\gamma_f \longrightarrow N \approx 3$$

- Get Yukawa coupling $\sin(Nh/f)\ (\cos(Nh/f))$

$$U = e^{ih^a T^a/f} \longrightarrow U^N = U(\frac{h}{f} \to \frac{Nh}{f}).$$

N-Suppression

- UV completion: introduce m (hidden) Dirac fermions

$$\Psi_i(\tilde{\Psi}_i) \in \mathbf{8} \qquad\qquad M_i \bar{\Psi}_i V' \Psi_i$$

- Twisted mass $\quad V' = \mathrm{diag}(1,1,1,1,-1,-1,-1,-1)$

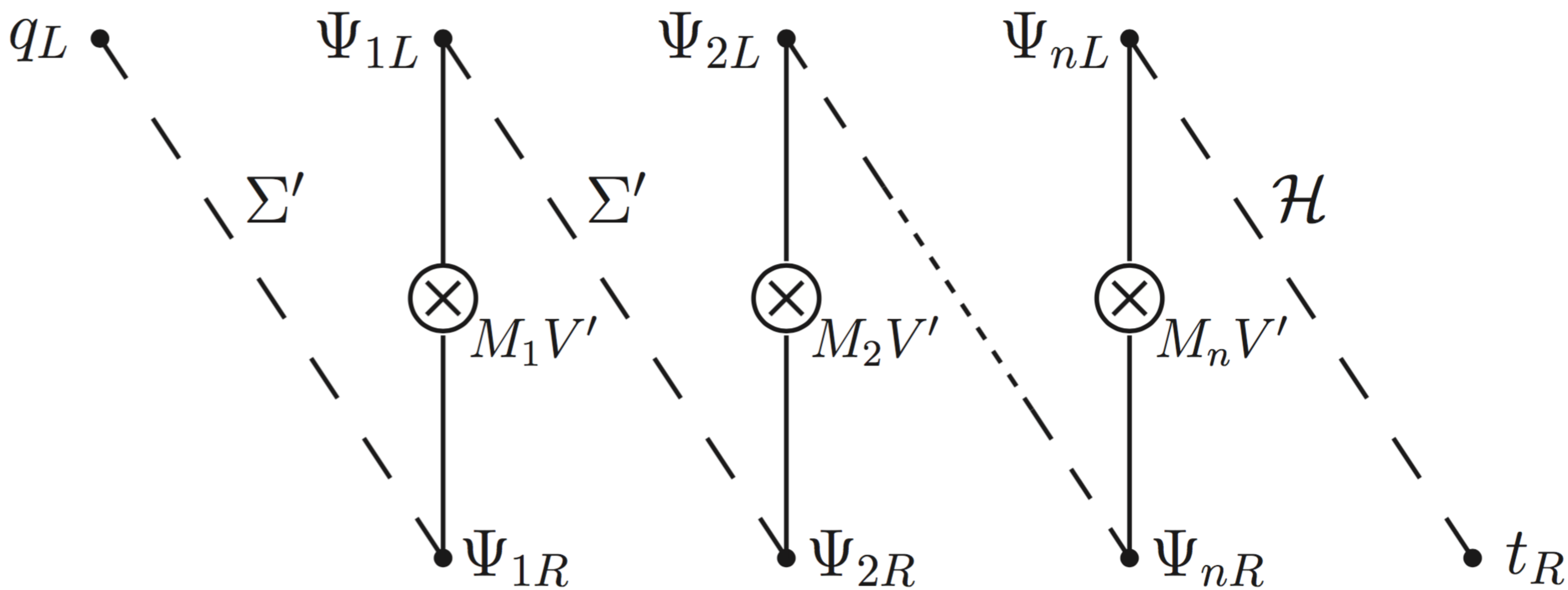
$$SO(8)_L \times SO(8)_R \to SO(8)_{V'}.$$

- SM fields(hidden partners)

$$q_L(\tilde{q}_L) \in \mathbf{8} \qquad\qquad t_R(\tilde{t}_R) \in \mathbf{1}$$

N-Suppression

- Collectively break Higgs shift in chain pattern



- Linearly realised sigma field

$$\Sigma' \rightarrow g\Sigma' g^\dagger \qquad \mathcal{H} \rightarrow g\mathcal{H}$$

N-Suppression

- The interactions for m = 1

- Effective Yukawa coupling

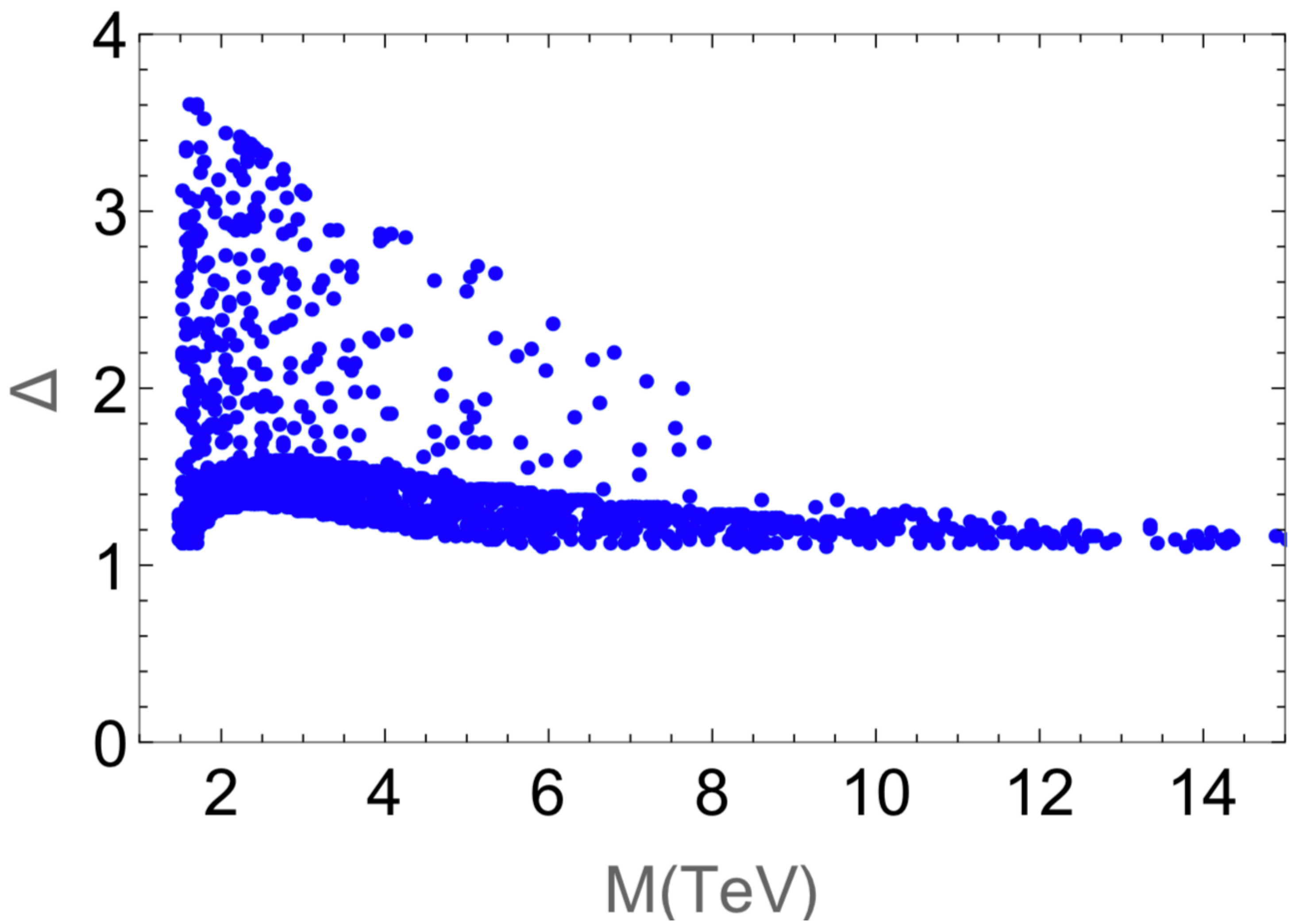
$$\mathcal{L}_t^{\text{Yuk.}} \sim M_1^t \bar{\Psi}_{q_L} \Sigma t_R + M_1^t \bar{\Psi}_{\tilde{q}_L} \Sigma \tilde{t}_R + h.c$$

$$\Sigma = U^{2m+1} \mathcal{V} = \begin{pmatrix} \mathbf{0} \\ \sin(\frac{Nh}{f}) \\ \mathbf{0} \\ \sin(\frac{Nh}{f}) \end{pmatrix}$$

$$N = 2m + 1$$

N-Suppression

- Numerical results   m=1 → N=3



$$\xi = 0.01$$

$$\frac{y_{tth}}{y_t^{SM}} = 0.97$$

$$\frac{g_{WWh}}{y_{WWh}^{SM}} = 0.995$$

$$\Delta = \left| \frac{\partial \ln \xi}{\partial \ln \Lambda_\rho} \right| \approx \frac{1}{\log \frac{\Lambda_\rho^2}{m_W^2}} \left(\frac{3}{4\xi N^2} - 2 \right)$$

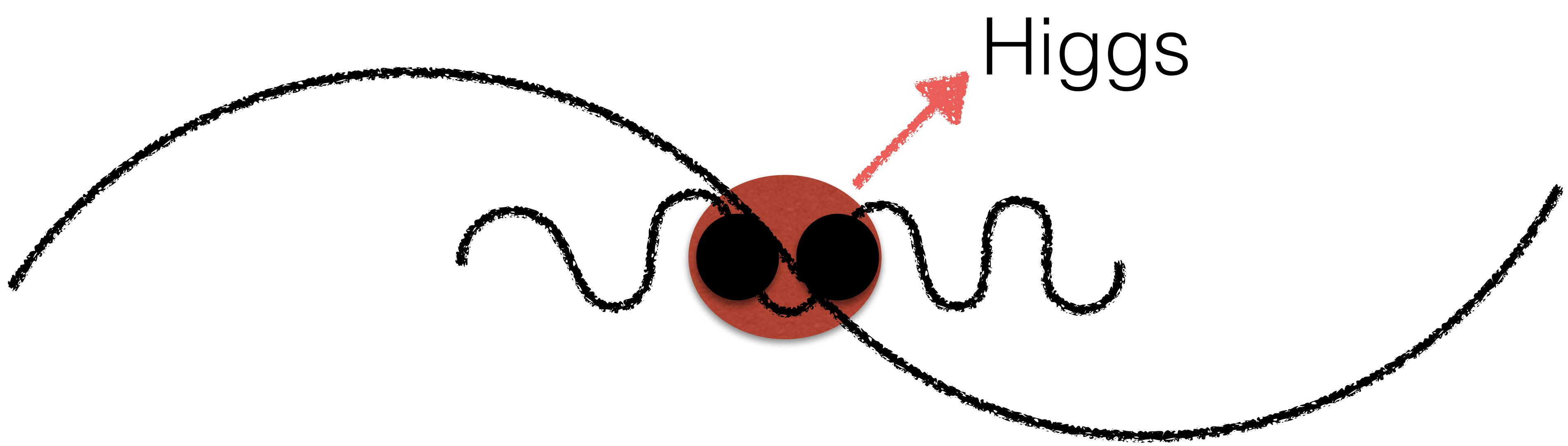
R. Barbieri and G. F. Giudice, Nucl. Phys. B **306** (1988) 63.

G. Panico, M. Redi, A. Tesi and A. Wulzer, JHEP **1303**, 051 (2013) [arXiv:1210.7114 [hep-ph]].

Composite Higgs Model

One simple solution to Hierarchy: Higgs

is Composite



Technicolor $m_h^2 \sim \Lambda^2$ $v_{SM} = f$

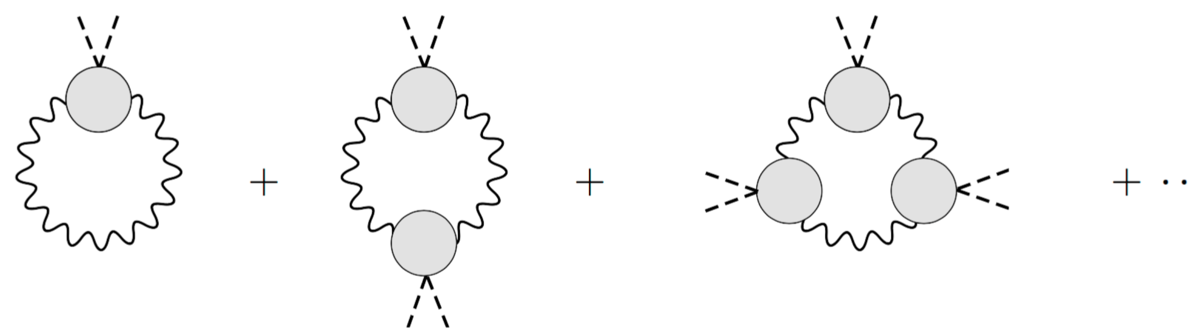
$$4\pi f \approx \Lambda \geq 5 - 10\, TeV$$

Higgs as pNGB

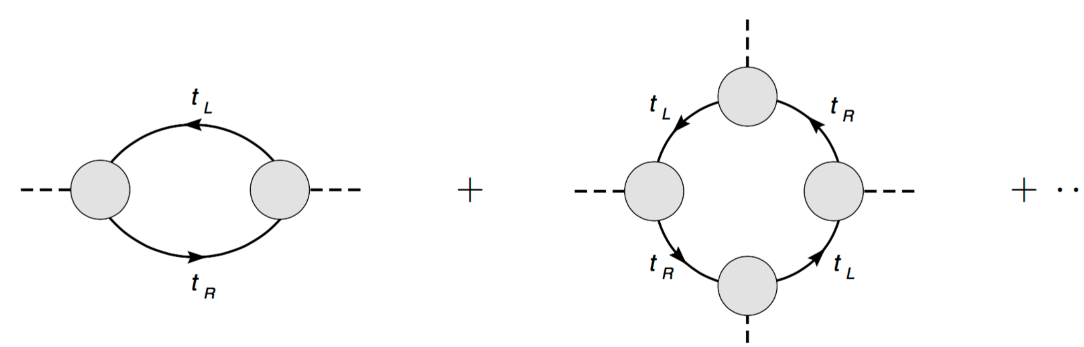
Lighter Higgs: pNGB from G ⟶ H breaking.

$$\mathcal{L} \sim \frac{P_t^{\mu\nu}}{2} g^2 f^2 W_\mu^a W_\nu^a \frac{\sin^2(h/f)}{4} + y_t \bar{t}_L t_R f \sin(h/f)$$

$$V_g(h) = \gamma_g \sin^2 \frac{h}{f} + \ldots$$



$$V_f(h) = -\gamma_f \sin^2 \frac{h}{f} + \beta_f \sin^4 \frac{h}{f} \ldots$$



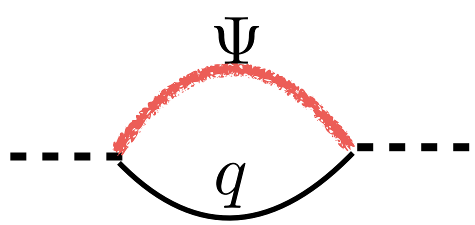
$$\gamma_g \sim \frac{g^2 f^2 \Lambda^2}{16\pi^2} \qquad \gamma_f \sim \frac{N_c y_t^2 f^2 \Lambda^2}{16\pi^2}, \qquad \beta_f \sim \frac{N_c y_t^4 f^4}{16\pi^2} \log(\frac{\Lambda^2}{m_t^2})$$

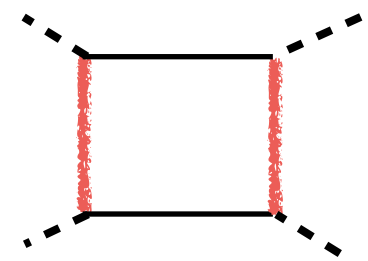
Higgs as pNGB

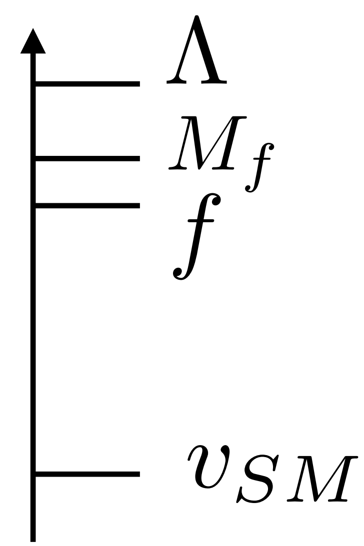
Much Lighter Higgs: Composite Partners Collectively

Break Shift symmetry

$$\mathcal{L} \sim y_q f \bar{q} U \Psi_R + M_f \bar{\Psi}\Psi + h.c.$$







$$\gamma_f \sim \frac{\epsilon^2 N_C f^2 M_f^2}{16\pi^2} \qquad \beta_f \sim \frac{\epsilon^4 N_C f^4}{16\pi^2}$$

$$\xi_{na} \sim \frac{\gamma_f}{2\beta_f} \gg 1 \qquad m_h^2 \sim \frac{y_t^2 N_c M_f^2}{2\pi^2}\xi$$

125 GeV → $\frac{M_f}{f} \approx \mathcal{O}(1)$

Higgs as pNGB

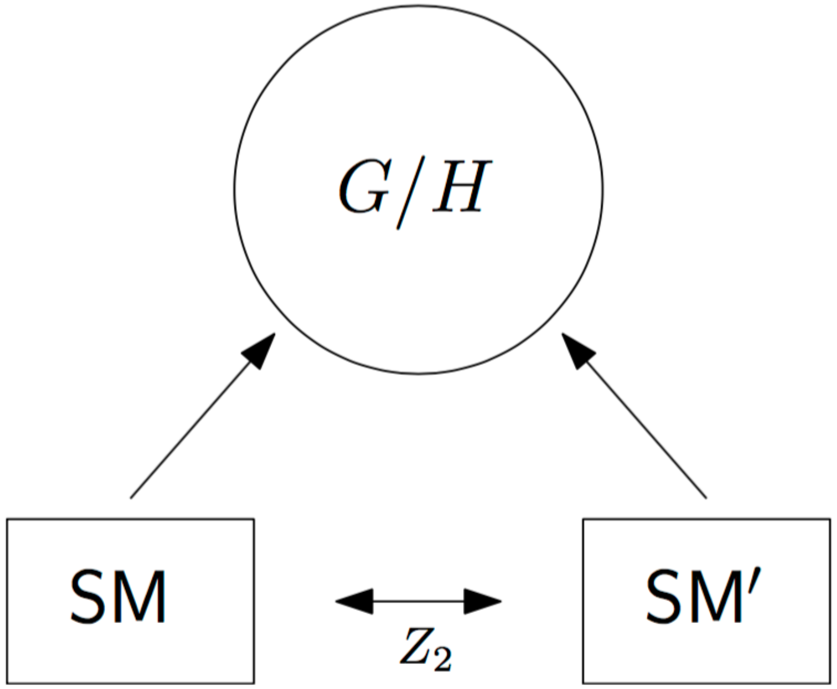
- **Higgs Coupling Measurement**

Model	Collider	LHC now	HL-LHC
	L [ab^{-1}]	0.06	3
CHM-5	ξ [$\times 10^{-3}$]	120	42
	f [GeV]	710	1200

From JHEP 1807 (2018) 048

Neutral Naturalness

- **Neutral Naturalness in pNGB Higgs**



$$\frac{\pi^i}{f} \to -\frac{\pi^i}{f} + \frac{\pi}{2} \quad \longrightarrow \quad \sin\frac{\pi^i}{f} \leftrightarrow \cos\frac{\pi^i}{f}$$

Neutral Naturalness

- **Neutral Naturalness**

$$Z_2 : \quad t \leftrightarrow \tilde{t} \quad s_h \leftrightarrow c_h$$

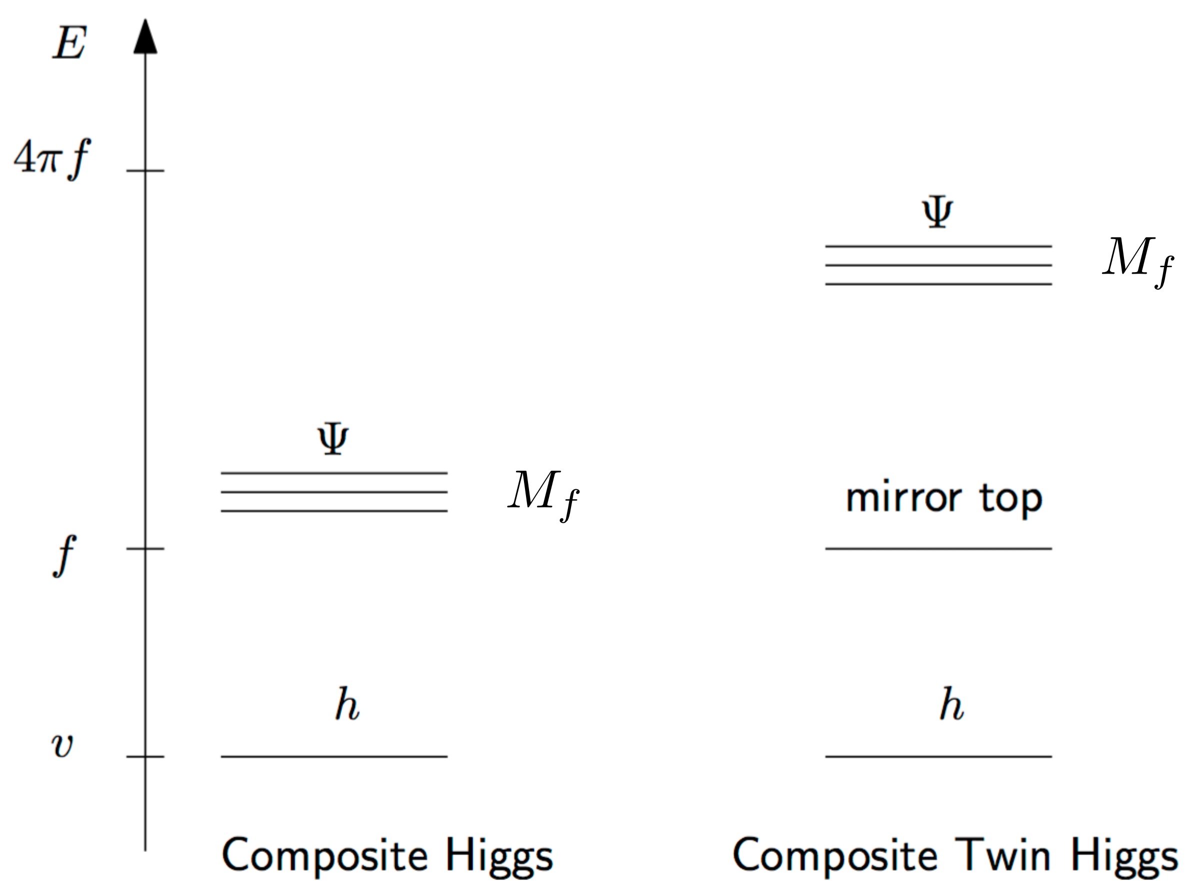
$$\mathcal{L}_f = y_t f \bar{t} t \sin(h/f) + y_t f \bar{\tilde{t}} \tilde{t} \cos(h/f)$$

$$y_t^2 f^2 \Lambda^2 (s_h^2 + c_h^2) = y_t^2 f^2 \Lambda^2$$

Neutral Naturalness

- **Light Higgs**

$$m_h^2 \sim \frac{y_t^2 m_{\tilde{t}}^2}{16\pi^2} \text{Log} \frac{\Lambda^2}{m_t^2}, \qquad m_{\tilde{t}} = y_t f$$



N-Suppression

Successful EWSB

$$N\sqrt{\xi} \ll 1$$

N-Suppression

$$m_t = y_t' f \sin(\frac{Nh}{f})$$

$$y_t' \approx \frac{y_t}{N}$$

Higgs as pNGB

$$V(h) = -(\gamma_f - \gamma_g)\sin^2\frac{h}{f} + \beta_f \sin^4\frac{h}{f}$$

- EWSB

$$\xi \equiv \sin^2\left(\frac{\langle h\rangle}{f}\right) = \frac{\gamma_f - \gamma_g}{2\beta_f}$$

- Ordinary

$$\gamma_{f,g} \sim \epsilon^2 f^2 \Lambda^2, \quad \beta_f \sim \epsilon^4 f^4 \log(\Lambda^2)$$

$\gamma \gg \beta$

- Neutral Naturalness

$$\gamma_{f,g} = \beta_{f,g} \sim \epsilon^2 f^2 \tilde{\Lambda}^2$$

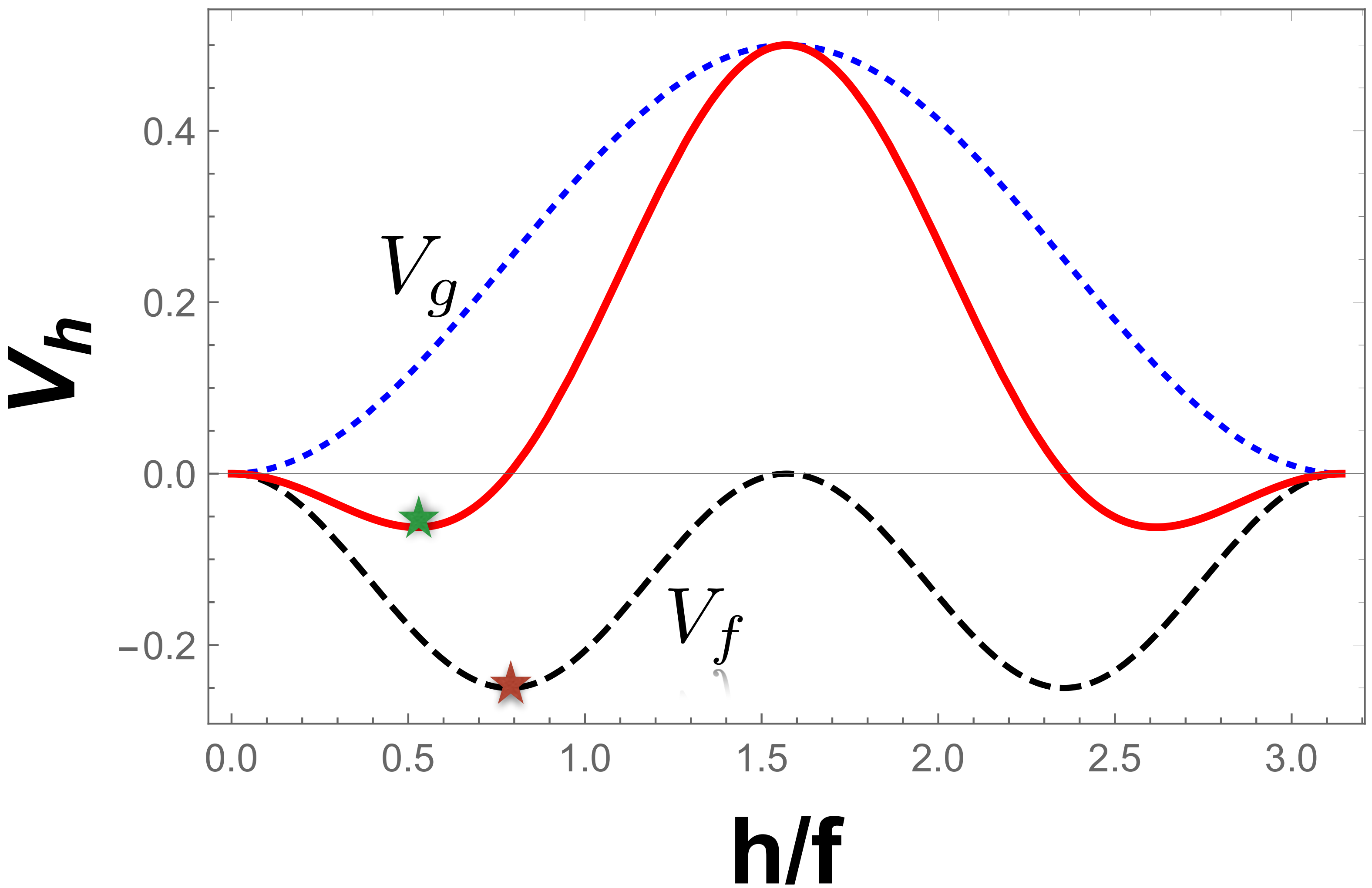
- Deviation:

$$\delta \sim \xi \lesssim 0.1$$

→ Little Hierarchy

Little Hierarchy Problem

- General Higgs Potential



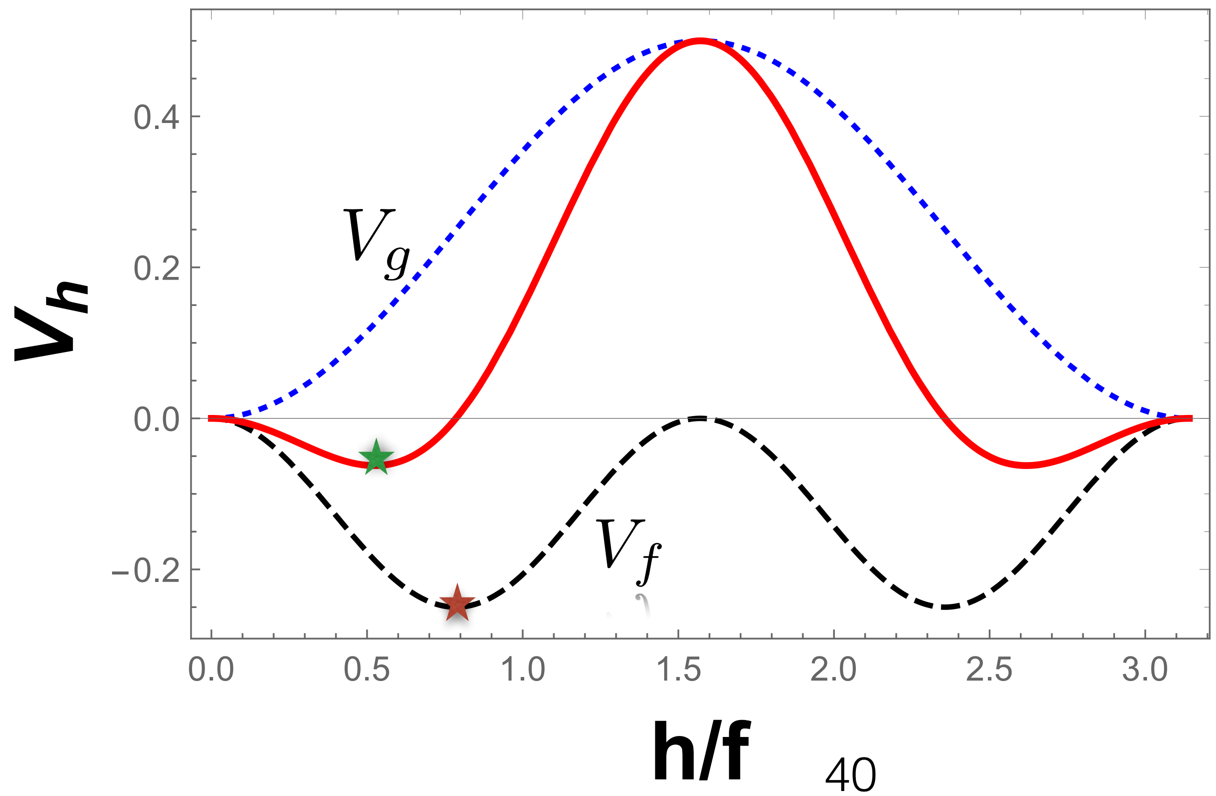
Higgs as pNGB

$$V(h) = -(\gamma_f - \gamma_g)\sin^2\frac{h}{f} + \beta_f \sin^4\frac{h}{f}$$

- EWSB

$$\xi \equiv \sin^2\left(\frac{\langle h\rangle}{f}\right) = \frac{\gamma_f - \gamma_g}{2\beta_f}$$

- Bounds: $\xi < 0.1$



N-Suppression

- SO(8)/SO(7) coset space

$$t \leftrightarrow \tilde{t} \qquad \frac{h}{f} \to -\frac{h}{f} + \frac{\pi}{2}$$

$$\sin(\frac{h}{f}) \leftrightarrow \cos(\frac{h}{f})$$

- Interactions
- The Potential In Term of

$$\mathcal{L}_t^{\text{Yuk.}} = y_t' f \bar{t}_L t_R \sin(\frac{Nh}{f}) + y_{\tilde{t}}' f \bar{\tilde{t}}_L \tilde{t}_R \cos(\frac{Nh}{f}) + h.c.$$

- N is odd

$$t \leftrightarrow \tilde{t} \qquad \sin(\frac{Nh}{f}) \leftrightarrow \cos(\frac{Nh}{f})$$

$$|y_t'| = |y_{\tilde{t}}'|$$

N-Suppression

- SO(8)/SO(7) $\Sigma' = UVU^\dagger$ $\mathcal{H} = U\mathcal{V}$

$$V = \mathrm{drag}(1,1,1,1,1,1,1,-1), \quad \mathcal{V} = (0,0,0,0,0,0,0,1)$$

$$\Sigma' \rightarrow g\Sigma' g^\dagger \qquad \mathcal{H} \rightarrow g\mathcal{H}$$

- Introduce m Dirac Fermions(Hidden)

$$\Psi_i(\tilde{\Psi}_i) \in \mathbf{8} \qquad M_i \bar{\Psi}_i V' \Psi_i$$

- Twisted Mass $V' = \mathrm{diag}(1,1,1,1,-1,-1,-1,-1)$

$$SO(8)_L \times SO(8)_R \rightarrow SO(8)_{V'}.$$

N-Suppression

- Numerical Results m=1 → N=3

$$\xi = 0.01 \qquad \frac{y_{tth}}{y_t^{SM}} = 0.97 \qquad \frac{g_{WWh}}{y_{WWh}^{SM}} = 0.995$$

- Natural Little Hierarchy

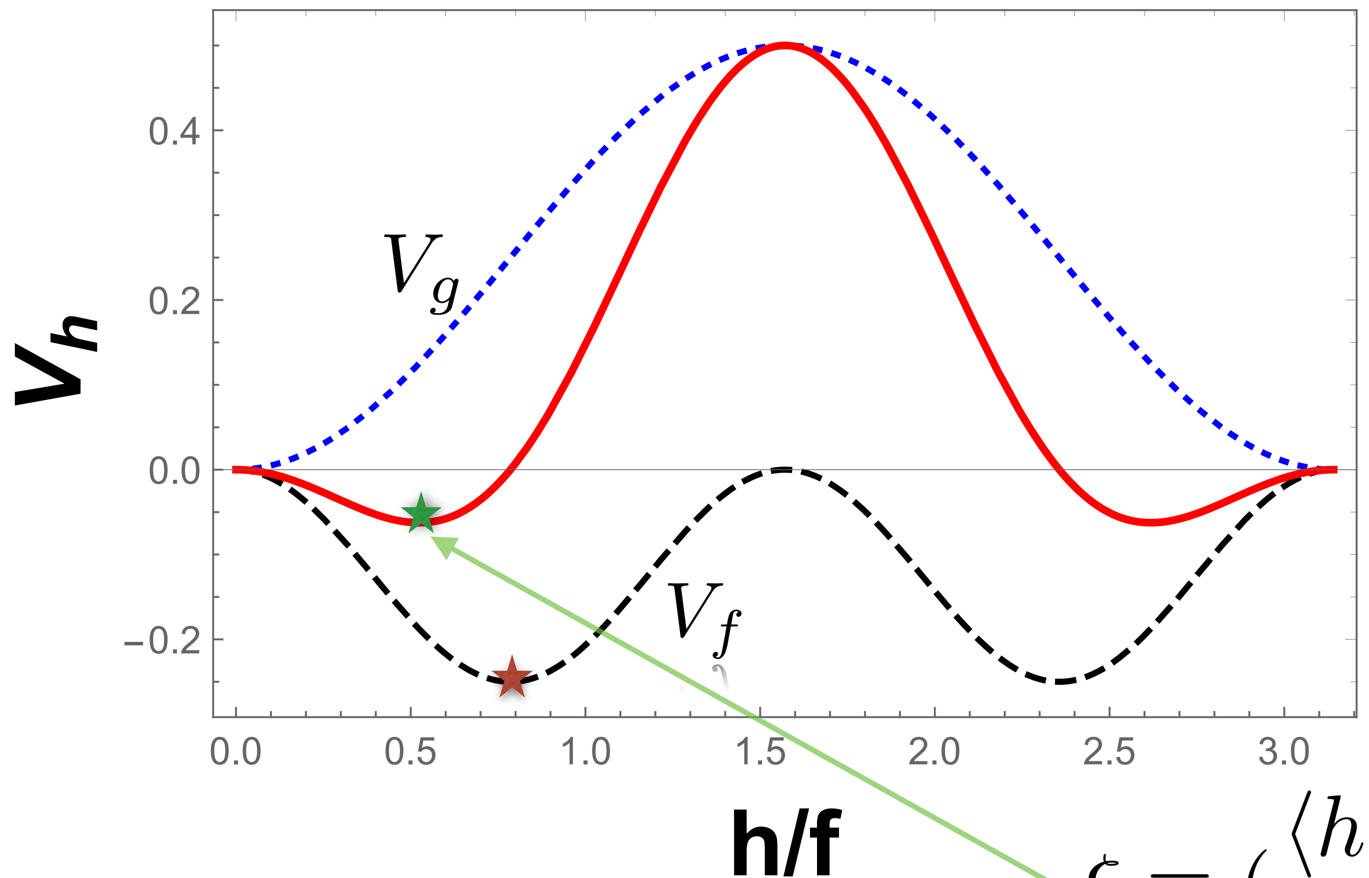
$$\Delta = \left| \frac{\partial \ln \xi}{\partial \ln \Lambda_\rho} \right| \approx \frac{1}{\log \frac{\Lambda_\rho^2}{m_W^2}} \left(\frac{3}{4\xi N^2} - 2 \right)$$

G. Panico, M. Redi, A. Tesi and A. Wulzer, JHEP **1303**, 051 (2013) [arXiv:1210.7114 [hep-ph]].

Little Hierarchy Problem

- The Higgs Potential $V(h) = V_g + V_f$

$$V_g = \gamma_g \sin^2(\frac{h}{f}) \qquad V_f = -\gamma_f \sin^2(\frac{h}{f}) + \beta_f \sin^4(\frac{h}{f})$$



$\xi_{Natural} \gg 0.1$

Little Hierarchy Problem!!

$$\xi \equiv (\frac{\langle h \rangle}{f})^2 = \frac{\gamma_f - \gamma_g}{2\beta_f}$$

- Electroweak Symmetry Breaking

- Bounds: $\xi < 0.1$

C. Grojean, O. Matsedonskyi and G. Panico, "Light top partners and precision physics," *JHEP* **10** (2013) 160, [1306.4655].

J. de Blas, O. Eberhardt and C. Krause, JHEP **1807**, 048