A Natural Composite Higgs

via Universal Boundary Conditions

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MPIK

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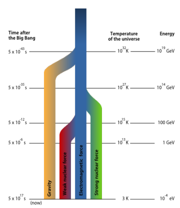
Blasi, Csáki, FG, 2004.06120

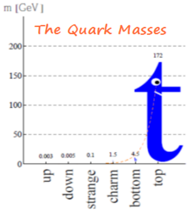
Blasi, FG, PRL **123**, 221801

The SM is an EFT

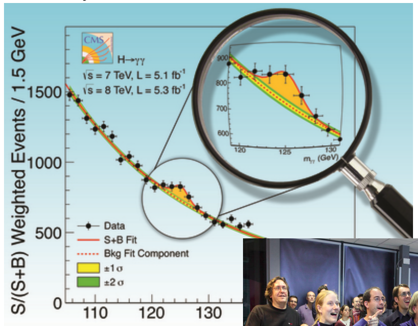


- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h \ll M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- Some Hints in Flavor/Precision Physics

.....

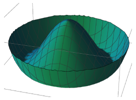


Use Higgs Sector as unique window to NP!



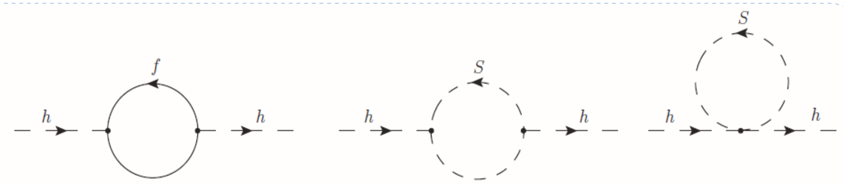
↓

many links to Higgs Sector



still least understood...

The Hierarchy Problem

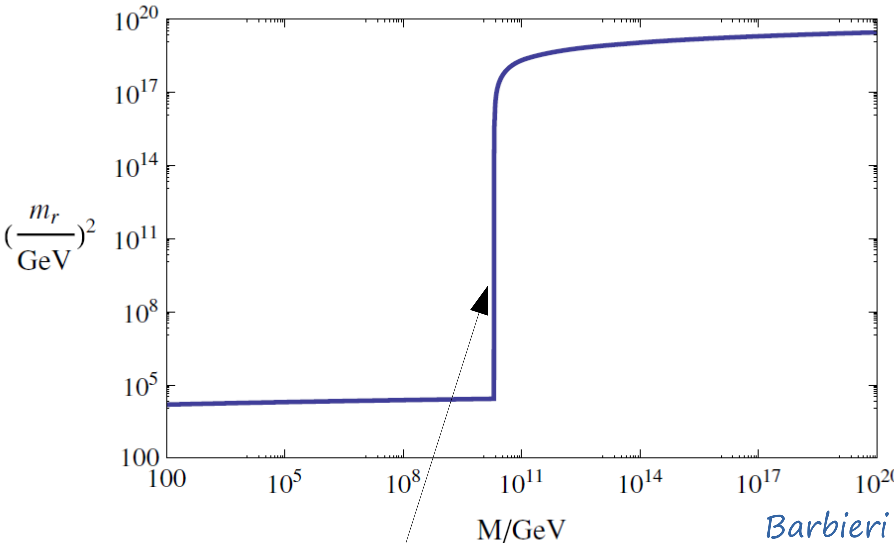
$\Delta m_h^2 \sim \Lambda^2$ 

$$\mathcal{L} \supset m_H^2 |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2}$$

$\Lambda^2 \gg m_H^2 \quad (??)$

Expect coefficient of unprotected D=2 operator H^2 to reside at cutoff: $m_H^2 \sim \Lambda^2 \gg 100\,\mathrm{GeV}$

Running Higgs Mass



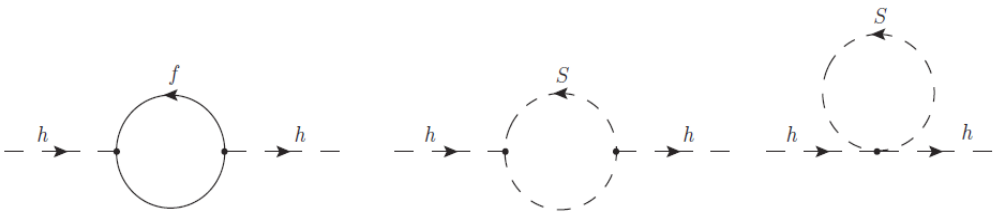
Barbieri
Phys. Scr. 2013 014006

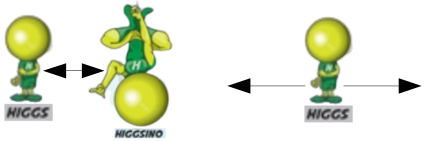
Jump at threshold of NP $\sim \frac{\lambda_{\rm NP}^2 M_{\rm NP}^2}{16\pi^2} \gg m_h^2$

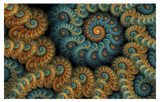
→ large fine-tuning to achieve $m_h \ll M_{\rm NP}$

Solving the Hierarchy Problem

Hierarchy Problem: $\Delta m_h^2 \sim \Lambda^2$







New Symmetry

- SUSY
- Goldstone Higgs: ⟺
  Composite/Little Higgs
- Conformal ?

$\Lambda \ll M_{Pl}$

Low Cutoff

- Large Extra Dim.
- Warped Extra Dim.
- Clockwork/LD
- Technicolor

$m_h \ll \Lambda$

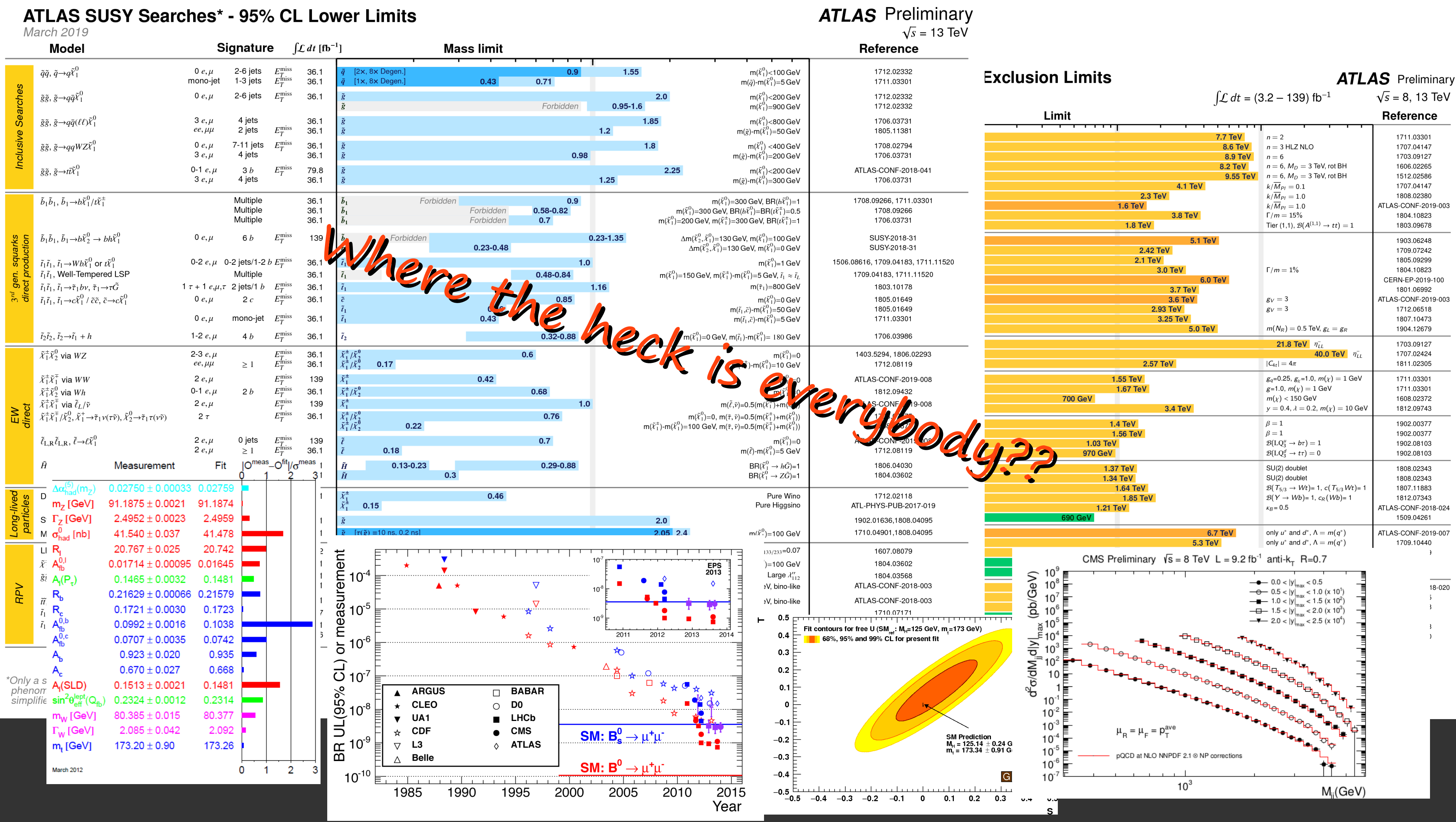
Vacuum Selection

- Relaxation
- NNaturalness

Agravity, WGC, ...

Solving the Hierarchy Problem

- SUSY, Composite Higgs, Extra Dim., … ➡ light (top) partners

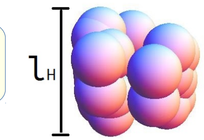


Composite Higgs Models

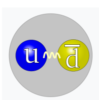
Kaplan, Georgi, Dimopoulos,. . .

- Higgs is composite at small distances

➡ m_H saturated in IR ➡ Hierarchy Problem solved

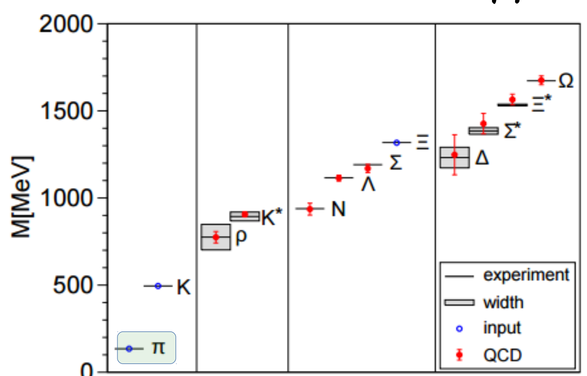


- Higgs = (pseudo) Goldstone Boson ➡ $m_H \ll m_\rho$

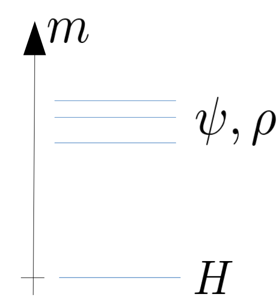


like pions in QCD

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q}q \rangle \neq 0} SU(2)_V$$



0906.3599



- MCHM: SO(5)→SO(4) Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

$\dim[SO(5)/SO(4)] = 4$ GB

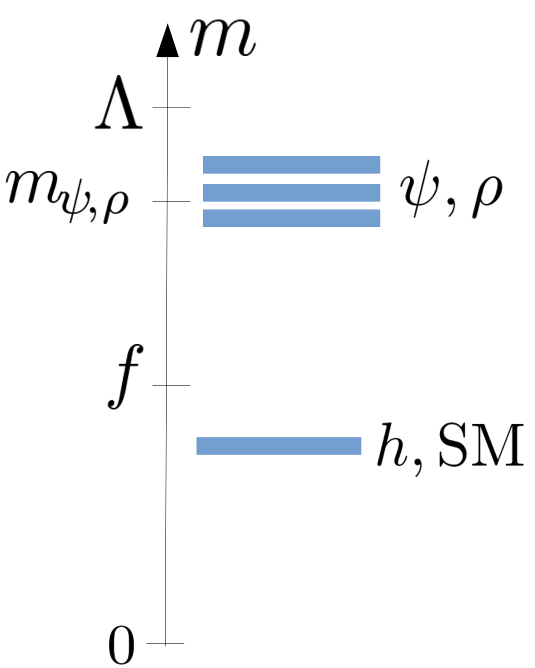
$\to$ Higgs $h_{1,..,4}$

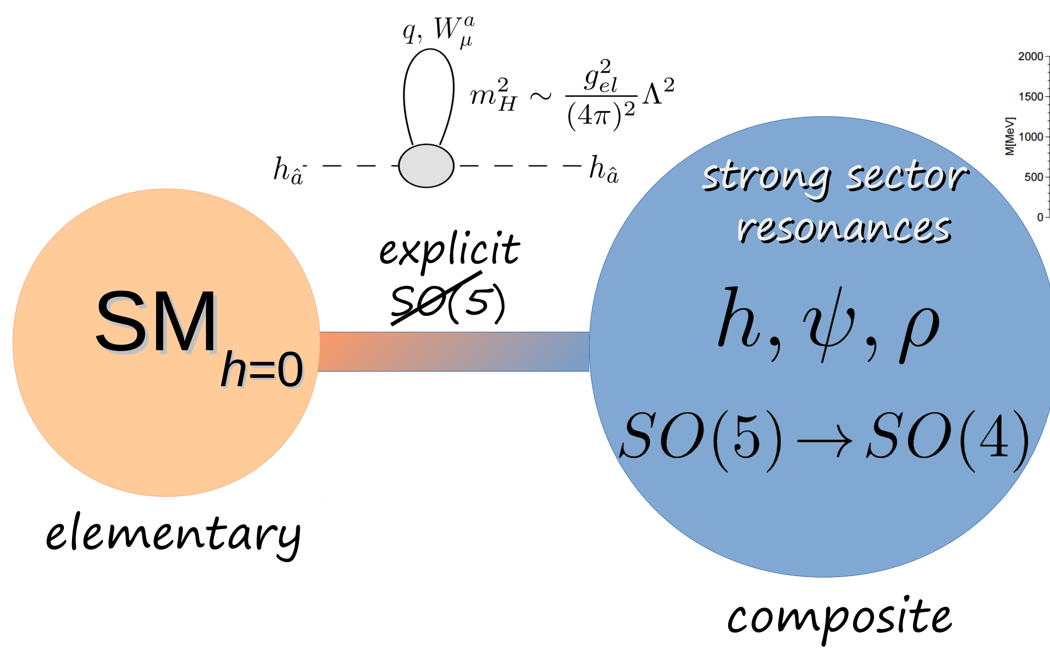
Naturally address

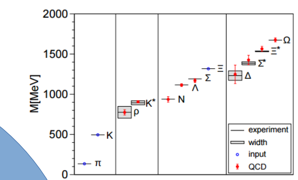
- Hierarchical Flavor Structure
- Dynamical EWSB
- Tiny Neutrino Masses
   - Dark Matter
   - Baryogenesis ...

custodially symmetric

Higgs Mass via Explicit SO(5) Breaking







$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f) \neq 0$$

Couplings to SM break SO(5):

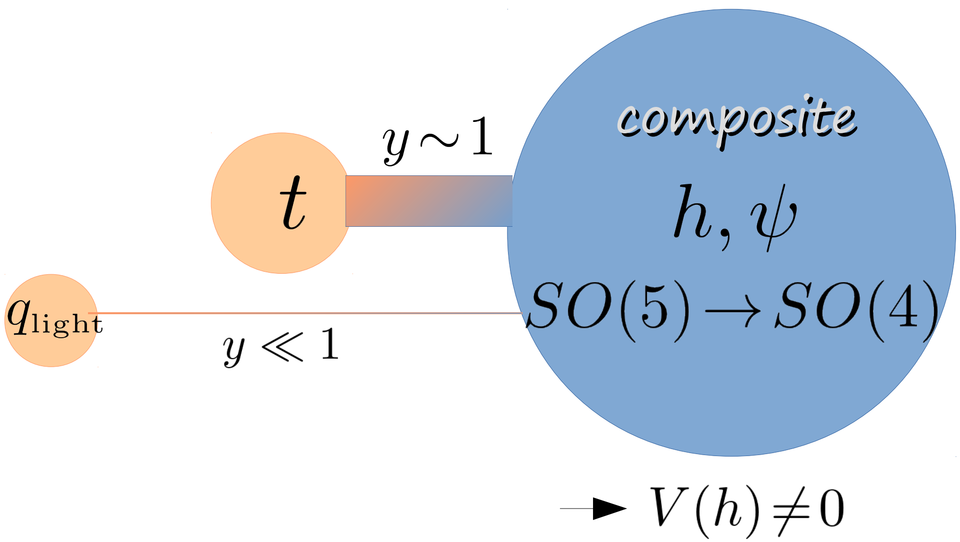
- Only subgroup of $\mathcal{G}$ gauged
- Fermions don't fill full $SO(5)$ reps

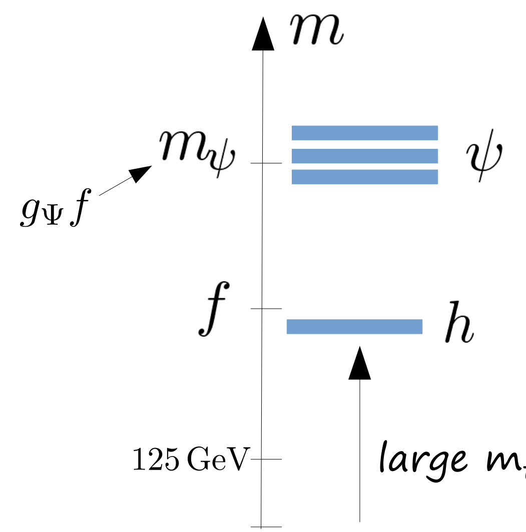
$f \sim \mathrm{TeV}: SO(5)$ breaking scale determines residual tuning, corrections to SM predictions

$$m_h^2 = 2\beta/f^2 \sin^2(2v/f)$$

Partially Composite Fermions

Kaplan; Agashe, Contino, Nomura, Pomarol

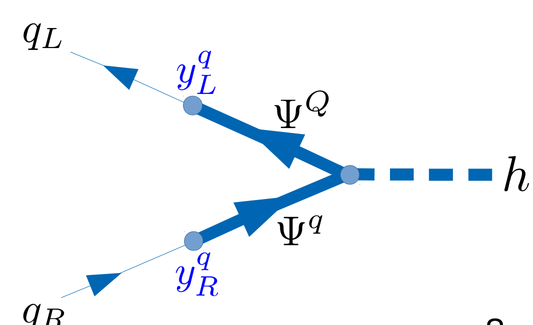




$$\mathcal{L} \supset -(y_L^q \, \bar{q}_L \cdot \Psi_R^Q + y_R^q \, \bar{q}_R \cdot \Psi_L^q) f$$

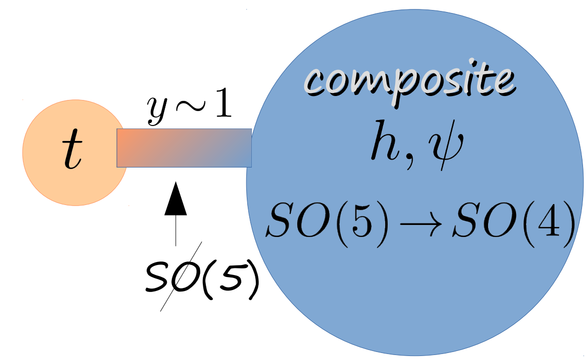
5 of $SO(5)$
10 of $SO(5)$
. . .

→ induce m_q



The Higgs Potential and the Tuning

- *Most important SO(5) breaking: top quark*



$$\to V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f) \neq 0$$

$$\text{Minimum}: \quad \sin(v/f)^2 \approx -\frac{\alpha}{2\beta} \quad \to \text{minimal tuning: } \Delta^{-1} \sim \sin(v/f)^2$$

$v \equiv \langle h \rangle$

- *Minimal explicit models (MCHM$_5$, MCHM$_{10}$):*

$$\alpha \sim y_t^2/g_\Psi^2\,, \quad \beta \sim (y_t^2/g_\Psi^2)^2 \ll \alpha \quad \to \text{double tuning: } \Delta^{-1} \sim \frac{y_t^2}{g_\Psi^2} \sin(v/f)^2 \ll 1$$

$\to O(1\%)$

$y_t \equiv y_L^t \sim y_R^t\,, \quad g_\Psi \sim 3$

Light Top Partners

- Large top yukawa → large m_h

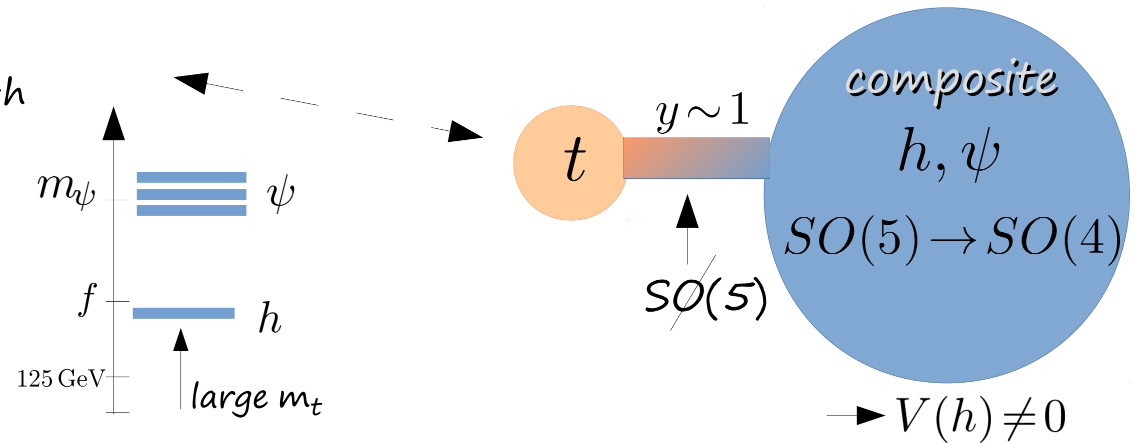
$$m_h \sim y_t^2\, v \;\sim\; m_T/f\; m_t$$

=> light top partners:

$$m_T \sim f \sim 800\,\mathrm{GeV}$$

lightest fermionic resonance

EWPT

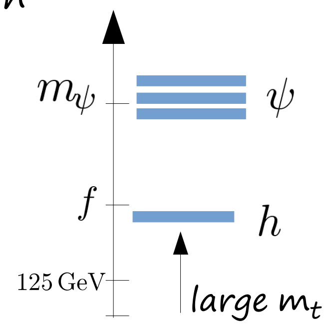


Matsedonskyi, Panico, Wulzer, 1204.6333;
Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954;
De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434

Light Top Partners

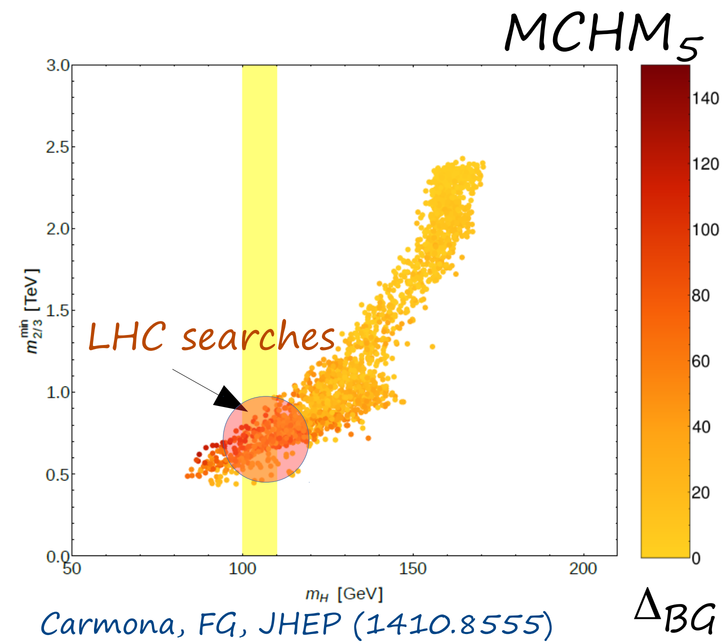
- Large top yukawa → large m_h

$$m_h \sim y_t^2\, v \;\sim\; m_T/f\;\, m_t$$



=> light top partners:

$$m_T \sim f \sim 800\,\mathrm{GeV}$$



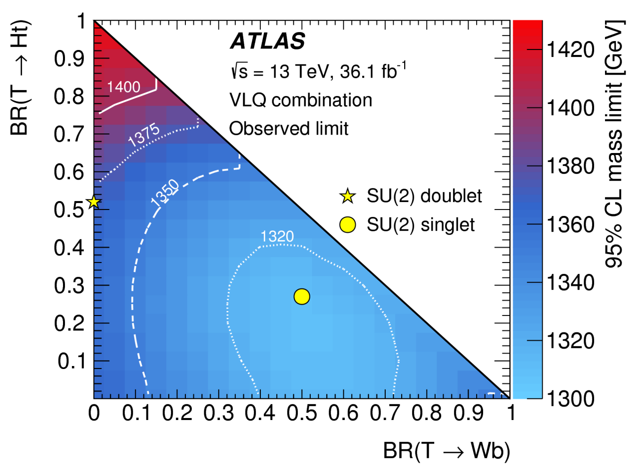
Carmona, FG, JHEP (1410.8555)

$f = 800\,\mathrm{GeV}$

↕

LHC Searches

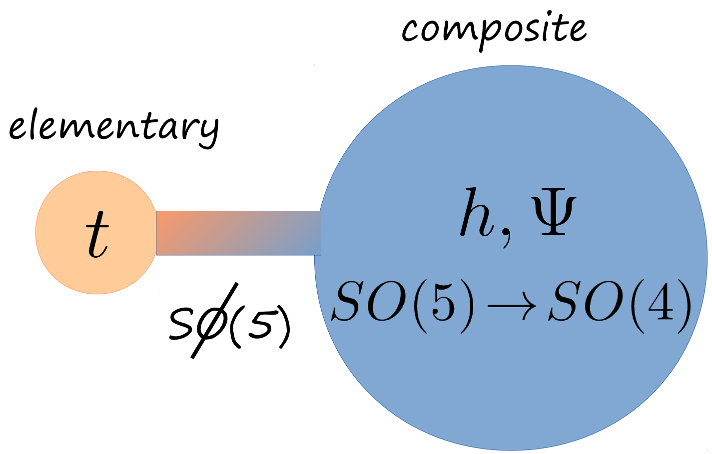
$\rightarrow m_T \gtrsim 1300\,\mathrm{GeV}$

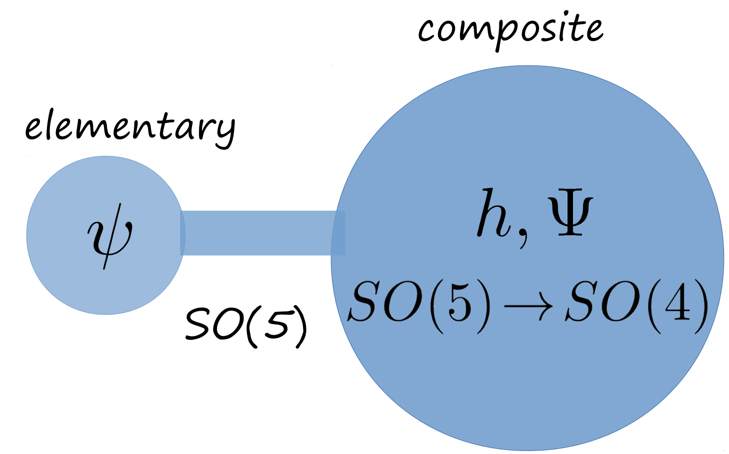


potentially strongest constraints on CH

Avoiding Light Top Partners

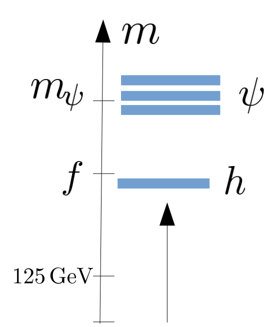
Change the nature of explicit Goldstone-symmetry breaking





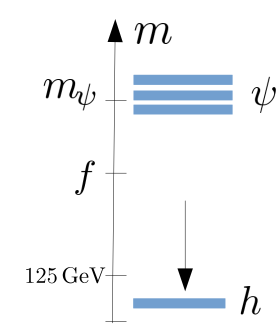
$$\bar{q}_L \cdot \Psi_R^T$$

5 of $SO(5)$



$$\bar{\psi}_L \cdot \Psi_R^T$$

$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$

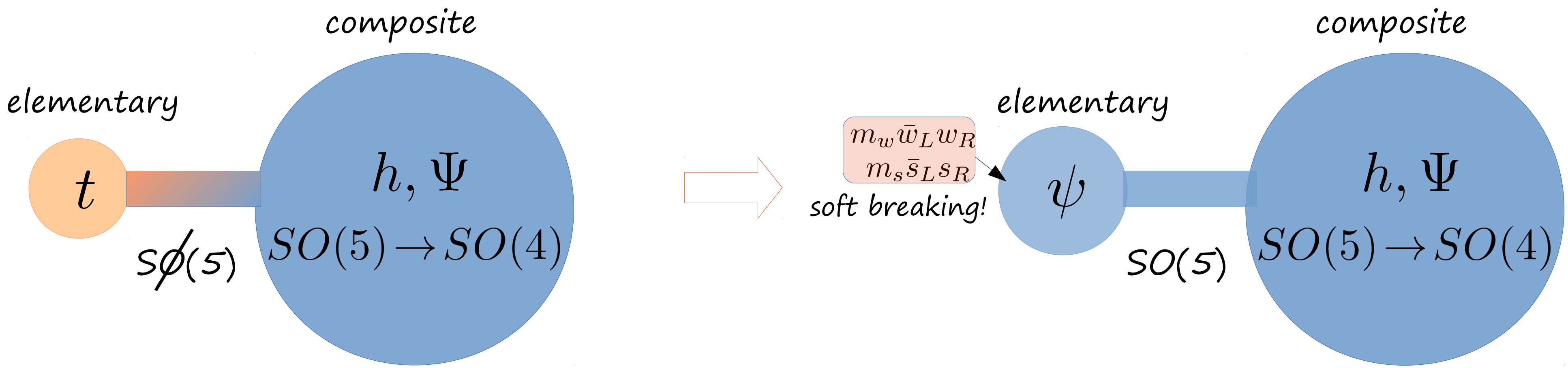


+ similar for RH

See Panico, Redi, Tesi, Wulzer, JHEP (1210.7114)
Carmona, FG, JHEP (1410.8555) for other approaches

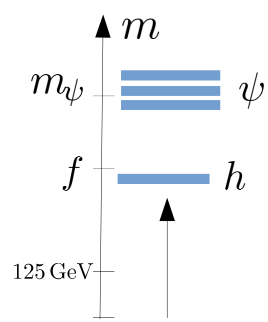
Avoiding Light Top Partners

Change the nature of explicit Goldstone-symmetry breaking



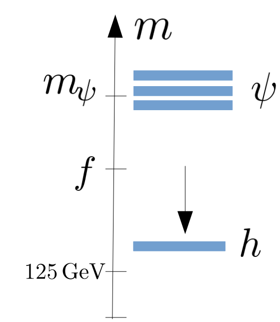
$$\bar{q}_L \cdot \Psi_R^T$$

5 of $SO(5)$



$$\bar{\psi}_L \cdot \Psi_R^T$$

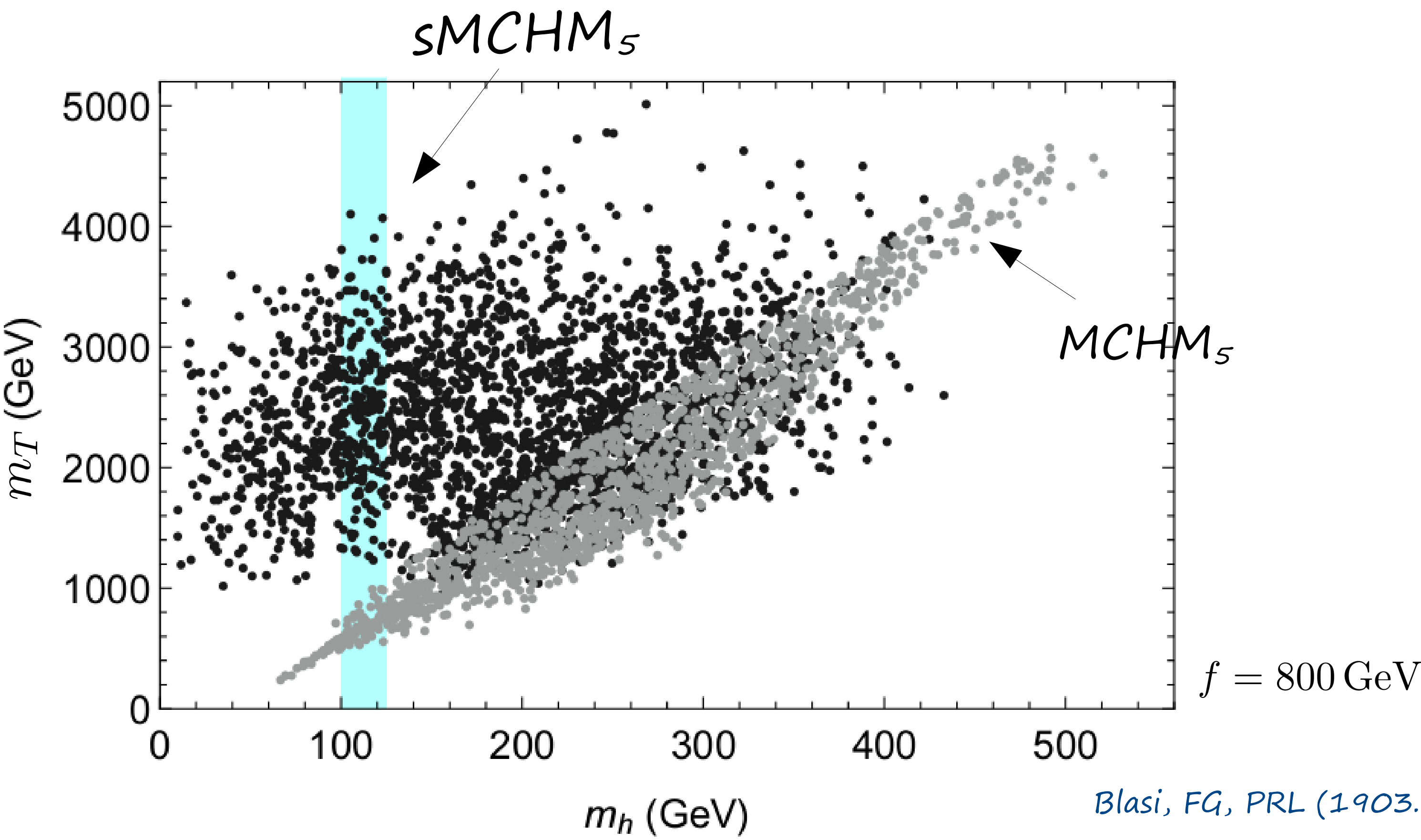
$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$



+ similar for RH

$m_w, m_s \gtrsim \text{TeV}$

Results



Blasi, FG, PRL (1903.06146)

$$1 \leq |y_{L,R}| \leq 2\,,\;\; 5 \leq |\tilde{m}_T/\mathrm{TeV}| \leq 10\,,\;\; -2 \leq m_Q/\tilde{m}_T \leq -0.3\,,\;\; 1.5 \leq |\tilde{m}_T/m_s| \leq 5\,,\; 2 \leq |m_{w,v}/m_s| \leq 4$$

Tuning

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right)$$

MCHM$_5$: $f \sim m_T$

$$\Delta_{\mathbf{5}} \simeq 90 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

$$\Delta_{\mathbf{5}}^{\text{soft}} \simeq 90 \left(\frac{m_T}{1\,\text{TeV}}\right)$$

sMCHM$_5$: $f \sim \text{const.}, \ \beta \sim f/m_T$

quadratic → linear; but double-tuning remains

➡ further increase symmetry

$f = 800\,\text{GeV}$

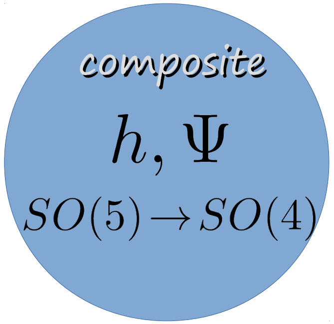
‘Maximal Symmetry’

Enhanced global symmetry eliminates double-tuning

Csaki, Ma, Shu, PRL (1702.00405), 1810.07704 (+Yu)

$$SO(5)_L \times SO(5)_R \xrightarrow{m_Q,\,\tilde{m}_T} SO(5)_{V'} \supset SO(4)$$

chiral symmetry in composite sector



$$\mathcal{L}_{\text{mass}} = \underbrace{-m_Q \bar{Q}_L Q_R - \tilde{m}_T \bar{\tilde{T}}_L \tilde{T}_R}_{} + \cdots$$
$$-\bar{\Psi}_L \left((m_Q + \tilde{m}_T) + (m_Q - \tilde{m}_T) V \right) \Psi_R$$

$$\Psi = (Q,\, \tilde{T})^T$$

4 **1** of $SO(4)$

$m_Q = -\tilde{m}_T \to SO(5)_{V'} \to V(h) \neq 0$

$SO(5)_{V'}: \; L^\dagger V R = V$ ‘Maximal Symmetry’

$$V = \begin{pmatrix} \mathbf{1}_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

Higgs-Parity Operator

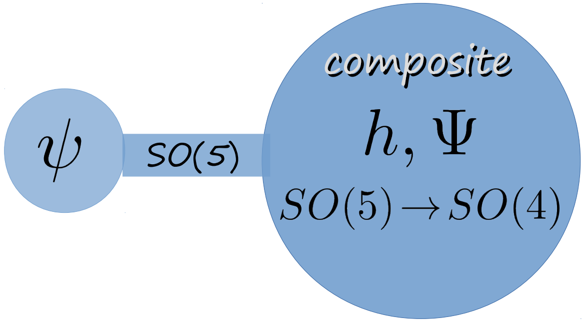
$V T^a V^\dagger = T^a \,, \; V T^{\hat{a}} V^\dagger = -T^{\hat{a}}$

Maximal Symmetry + Soft Breaking

$$SO(5)_L \times SO(5)_R \longrightarrow SO(5)_{V'}$$

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$\text{Minimum}: \quad \sin^2(v/f) = -\frac{\alpha}{2\beta}$$



$SO(5)_{V'}$: $\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta$ → No double tuning :)

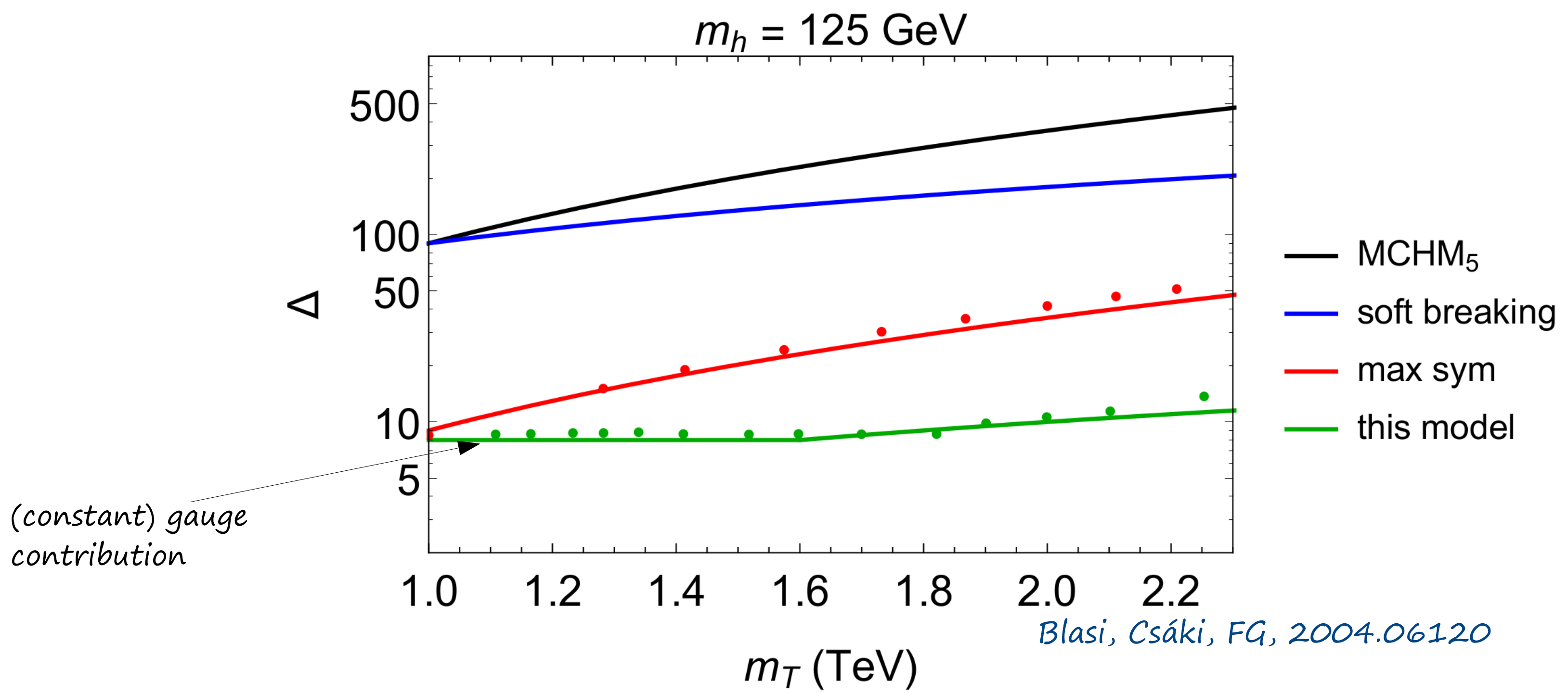
$\alpha + \beta = 0$ → $\sin^2(v/f) = 1/2$ → cancel with gauge contr.

soft breaking: $\alpha + \beta \sim y_L^2 y_R^2 m_{w_1}^2 (m_v^2 - m_{w_2}^2) \neq 0$ → $\sin^2(v/f) \neq 1/2$

$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L - w_{1L}^1 \\ -ib_L - iw_{1L}^1 \\ t_L + w_{1L}^2 \\ it_L - iw_{1L}^2 \\ -i\sqrt{2}\, s_L \end{pmatrix}$$

$$\psi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} v_R^2 - w_{2R}^1 \\ -iv_R^2 - iw_{2R}^1 \\ v_R^1 + w_{2R}^2 \\ iv_R^1 - iw_{2R}^2 \\ -i\sqrt{2}\, t_R \end{pmatrix}$$

Tuning: Max Symmetry + Soft Breaking



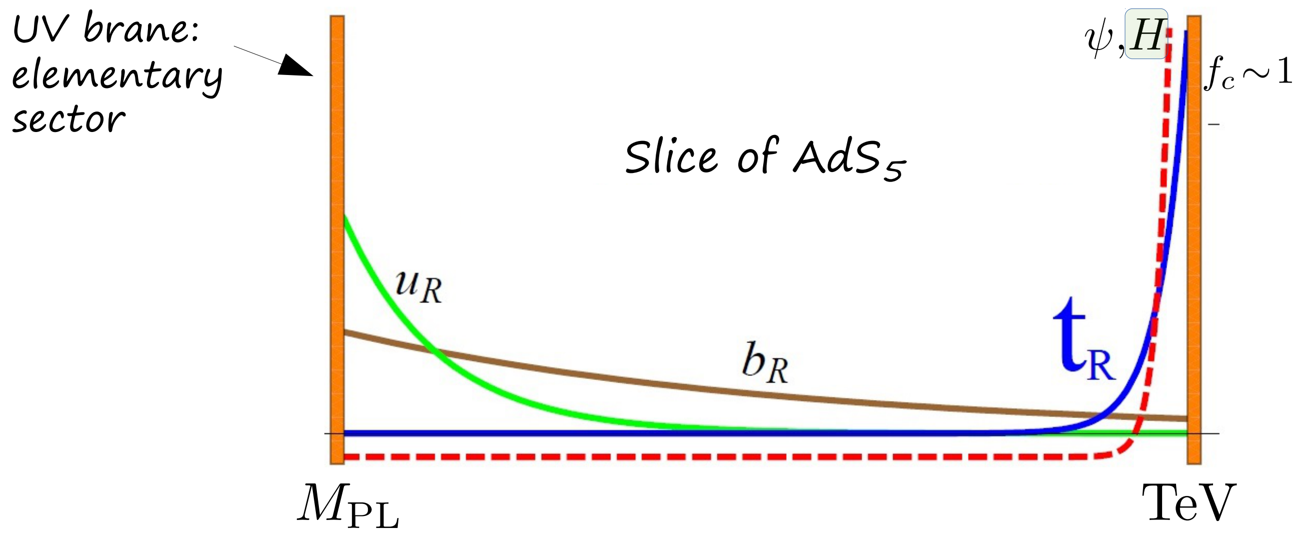
Blasi, Csáki, FG, 2004.06120

$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right) \rightarrow \Delta_5 \simeq 90 \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

$$\rightarrow \Delta \simeq 5 \left(\frac{m_T}{1\,\text{TeV}}\right)$$

quadratic → linear + double-tuning gone!

Very Natural 5D Picture



MCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[-,+] & t[+,+] \\ w_1^2[-,+] & b[+,+] \end{pmatrix} \oplus s[-,+]$$

SO(5) broken hardly by Dirichlet UV-boundary conditions

sMCHM$_5$

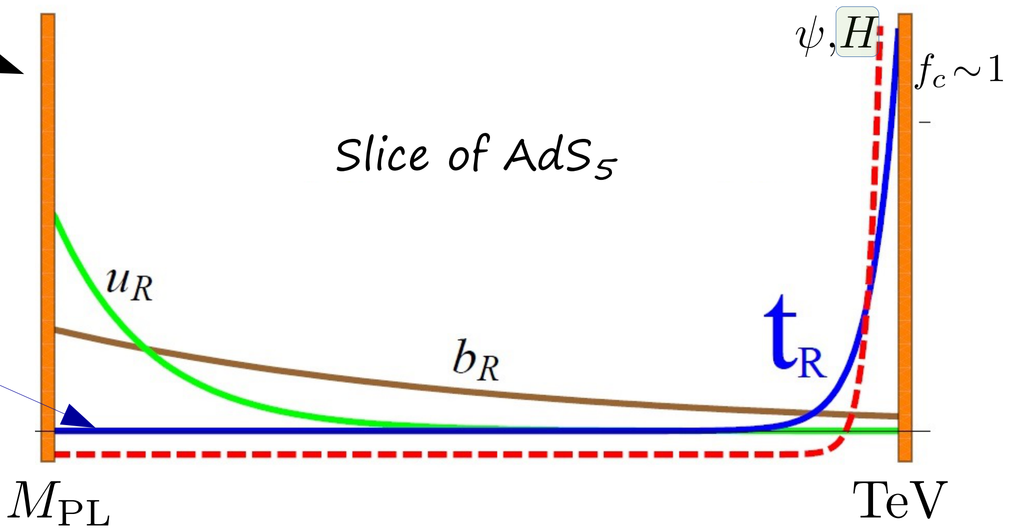
$$\psi_L = \begin{pmatrix} w_1^1[+,+] & t[+,+] \\ w_1^2[+,+] & b[+,+] \end{pmatrix} \oplus s[+,+]$$

SO(5) preserving universal BCs, breaking by *finite* UV-brane masses

$$\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$$

Very Natural 5D Picture

UV brane: elementary sector



Effective $m_{w1}, m_{w2}, m_v, m_s \sim$ TeV emerge naturally from GUT/Planck-scale masses via wave-function suppression!

MCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[-,+] & t[+,+] \\ w_1^2[-,+] & b[+,+] \end{pmatrix} \oplus s[-,+]$$

SO(5) broken hardly by Dirichlet UV-boundary conditions

sMCHM$_5$

$$\psi_L = \begin{pmatrix} w_1^1[+,+] & t[+,+] \\ w_1^2[+,+] & b[+,+] \end{pmatrix} \oplus s[+,+]$$

SO(5) preserving universal BCs, breaking by finite UV-brane masses

$$\mathbf{5} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1})$$

Conclusions

- Composite Higgs models challenged by missing light top partners (discovered Higgs too light)
- New, soft way of breaking Goldstone symmetry allows to reduce Higgs mass at constant partner mass
- Combination with ‘Maximal Symmetry’ leads to minimally ($\mathcal{O}(10\%)$) tuned model without ultra-light partners!

→ Back to level of tuning of LEP era, hope for discovery at HL-LHC or FCC!

Backup

Restore Global Symmetry in Linear Mixings

$$\mathcal{L} \supset -f\left(y_L \, \bar{\psi}_L \cdot \tilde{\Psi}^T_R + y_R \, \bar{\psi}_R \cdot \tilde{\Psi}^t_L \right)$$

MCHM_5 : Just one doublet/singlet filled in $\mathbf{5} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{1}, \mathbf{1})$

↳ Explicitly breaks SO(5)

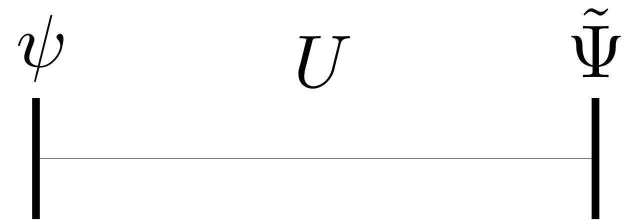
$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \qquad \psi_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -it_R \end{pmatrix}$$

sMCHM_5 : Consider complete elementary multiplets

↳ SO(5) restored, broken softly via vector-like masses

$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L - w^1_L \\ -ib_L - iw^1_L \\ t_L + w^2_L \\ it_L - iw^2_L \\ -i\sqrt{2}\, s_L \end{pmatrix} \qquad \psi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} v^2_R - w^1_R \\ -iv^2_R - iw^1_R \\ v^1_R + w^2_R \\ iv^1_R - iw^2_R \\ -i\sqrt{2}\, t_R \end{pmatrix}$$

Two-Site Model Lagrangian



$\mathbf{4}$ $\mathbf{1}$ of $SO(4)$

Resonances $\tilde{\Psi} = U(Q,\, \tilde{T})^T$

$$U = e^{-i\frac{\sqrt{2}}{f} h_a(x) T^a}$$

Partial Compositeness:

$$\mathcal{L}_{\rm mass} = - m_Q \bar{Q}_L Q_R - \tilde{m}_T \bar{\tilde{T}}_L \tilde{T}_R$$

$$- y_L f\, \bar{\psi}_{LI} \left(U_{Ii} Q^i_R + U_{I5} \tilde{T}_R \right)$$

$$- y_R f\, \bar{\psi}_{RI} \left(U_{Ii} Q^i_L + U_{I5} \tilde{T}_L \right) + \text{h.c.}$$

Vector-like elementary masses:

$$m_w \bar{w}_L w_R + m_v \bar{v}_L v_R + m_s \bar{s}_L s_R + m_1 \bar{s}_L t_R + m_2 \bar{q}_L v_R + \text{h.c.}$$

SO(5)-Breaking Spurions

Standard MCHM$_5$

$$\psi_L = \Delta_L^\dagger q_L \qquad \Delta_L = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 & -i & 0 \\ 1 & i & 0 & 0 & 0 \end{pmatrix}$$

$$\psi_R = \Delta_R^\dagger t_R \qquad \Delta_R = -i\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{L}_{\text{mass}} \supset - y_L f \; \bar{q}_L \Delta_L \tilde{\Psi}_R^T - y_R f \; \bar{t}_R \Delta_R \tilde{\Psi}_L^t$$

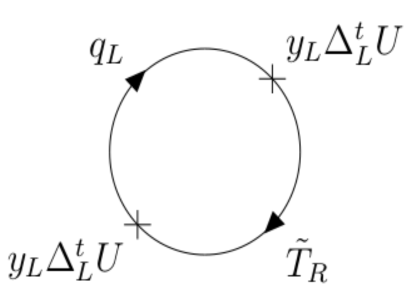
sMCHM$_5$

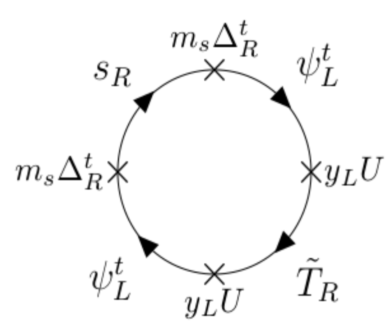
$$\psi_L \sim \mathbf{5}$$

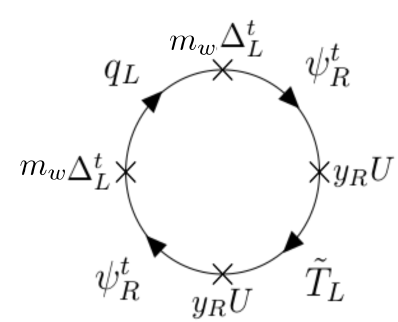
$$\psi_R \sim \mathbf{5}$$

$$-\mathcal{L}_{\text{el}} = m_w \bar{\psi}_L \psi_R + m_v \bar{v}_L \Delta_L \psi_R + m_s \bar{s}_R \Delta_R \psi_L - m_w \bar{q}_L \Delta_L \psi_R - m_w \bar{\psi}_L \Delta_R{}^* t_R + \text{h.c.}$$

$V(h) \sim$







$m_1 = m_2 = 0$

The Top Mass and the Higgs Potential

$$m_t^2 = y_L^2 y_R^2 f^4 \frac{m_s^2 m_v^2 (m_Q - \tilde{m}_T)^2}{8 m_{T_+}^2 m_{T_-}^2 \; m_{\tilde{T}_+}^2 m_{\tilde{T}_-}^2} \sin^2(2v/f)$$

Q, v $\quad$ $\tilde{T}, s$

$m_s, m_v \to \infty$ MCHM$_5$

$$y_L^2 y_R^2 f^4 \frac{(m_Q - \tilde{m}_T)^2}{8 m_T^2 m_{\tilde{T}}^2} \sin^2(2v/f)$$

$$m_T^2 = m_Q^2 + y_L^2 f^2$$
$$m_{\tilde{T}}^2 = \tilde{m}_T^2 + y_R^2 f^2$$

$$V(h) = -\frac{2N_c}{8\pi^2} \int_0^\infty \mathrm{d}p\, p^3 \ln\left\{\det[p^2 \mathbf{1} + m^\dagger m(h)]\right\}$$

$$\approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$m_h^2 = 2\beta/f^2 \sin^2(2v/f)$$

...

Case I: Decoupled w,v

Standard $MCHM_5$

$$\beta \simeq \beta_0 \frac{(1-q)^2}{q^2} F(q^2)$$

$sMCHM_5$

$$\beta(r^2) \simeq \beta_0 \frac{(1-q)^2}{1-q^2 r^2} \left[(r^2 + \tfrac{1}{q^2}) F(q^2) - 2F(r^2) \right]$$

$< \beta(0)$

$$\beta_0 \equiv \frac{N_c}{16\pi^2} y_L^2 y_R^2 f^4$$

$$m_t^2 \simeq \frac{y_L^2 y_R^2 f^4}{8 m_Q^2} (q-1)^2 \sin^2(2v/f)$$

$$q = m_Q / \tilde{m}_T$$

$$r = \tilde{m}_T / m_s$$

$$F(x^2) = \frac{x^2}{1-x^2} \ln \frac{1}{x^2}$$

$$m_Q^2 \simeq \frac{1}{16} y_L^2 y_R^2 f^2 \frac{(1-q)^2}{\beta(r^2)} \left(\frac{m_h}{m_t} \right)^2$$

$$\beta \xrightarrow{q \to 1} 0$$

$$m_t \xrightarrow{q \to 1} 0$$

$$\beta \xrightarrow{q^2 r^4 \to 1} 0$$

$$m_t \xrightarrow{q^2 r^4 \to 1} \text{finite}$$

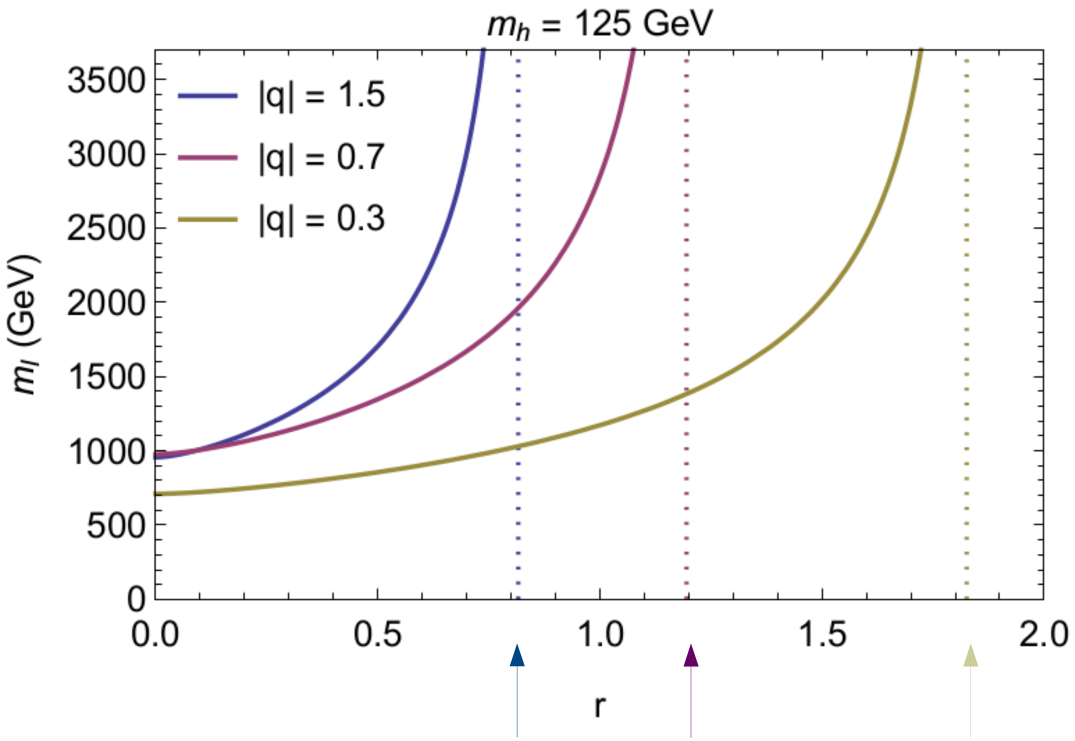
$$m_Q \xrightarrow{q^2 r^4 \to 1} \infty$$

Suggests possibility of light Higgs with heavy resonances

Case I: Top Partners

Lightest top partner in sMCHM$_5$

$$m_l^2 \simeq \min\{m_Q^2, \tilde{m}_T^2, m_s^2\} = m_Q^2 \times \min\left\{1, \frac{1}{q^2}, \frac{1}{q^2 r^2}\right\} = m_Q^2 \times \min\left\{1, \frac{1}{q^2}\right\}$$



$$m_Q^2 \simeq \frac{1}{16} y_L^2 y_R^2 f^2 \frac{(1-q)^2}{\beta(r^2)} \left(\frac{m_h}{m_t}\right)^2$$

$q = m_Q/\tilde{m}_T$

$r = \tilde{m}_T/m_s$

$q^2 r^4 \to 1$: s about to become lightest state $\to \beta < 0$

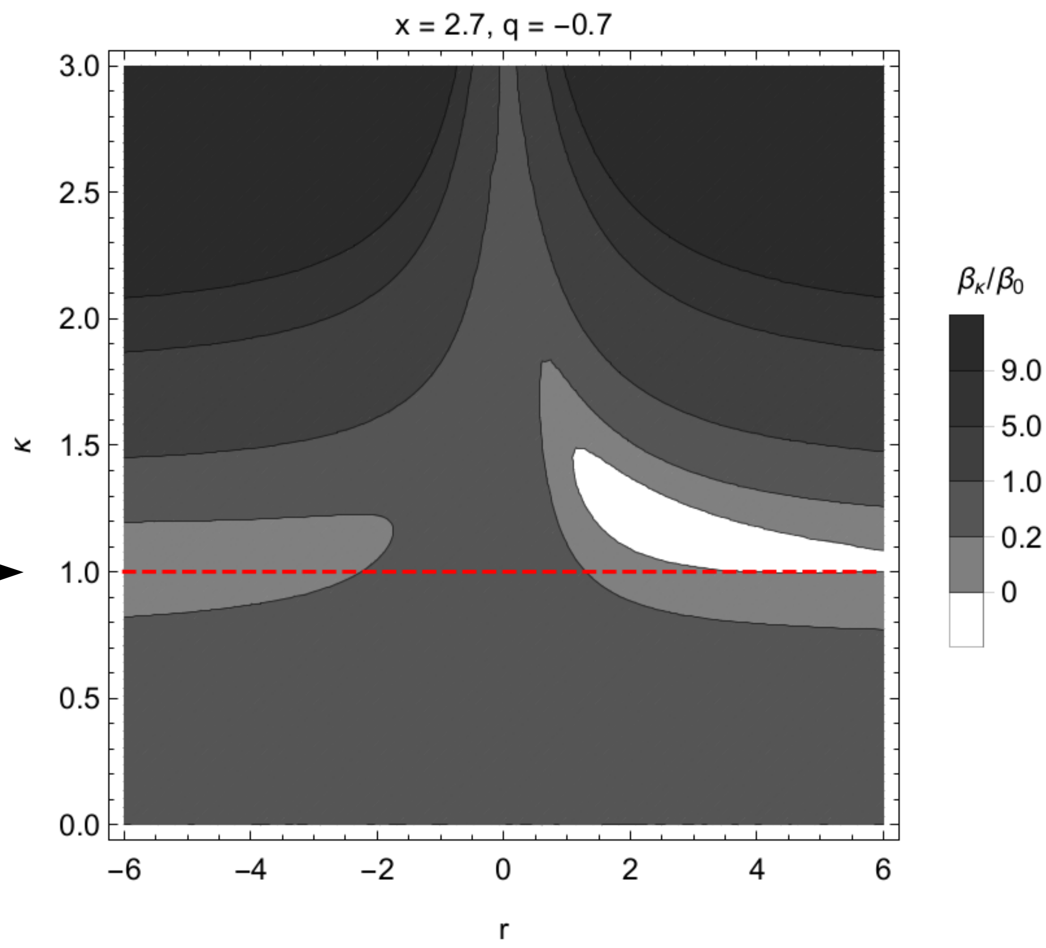
Goldstone Restoration as Source of Effect

- *What if VL fermions are added with arbitrary couplings?*
- *Couple new elementary states with strength κ to strong sector*

$$\kappa = 0 : \mathrm{MCHM}_5$$

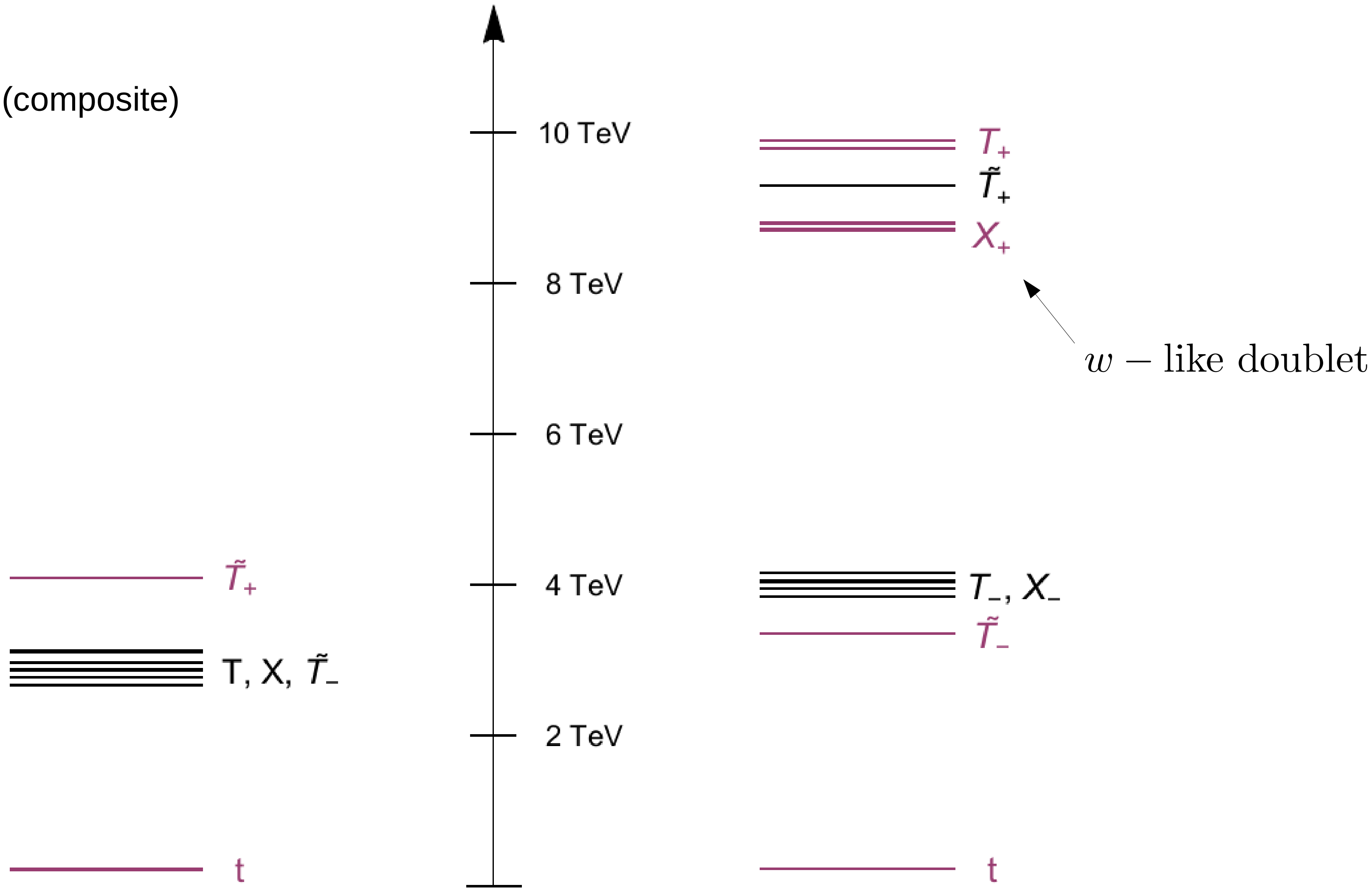
$$\kappa = 1 : \mathrm{sMCHM}_5$$

➡ *sMCHM_5 clearly singled out concerning Higgs-mass reduction*



Benchmark Points

purple (black):
mostly elementary (composite)



$B_s: \{y_L = 1.4, y_R = 1.3, \tilde{m}_T = 3\,\mathrm{TeV}, m_s = 3.8\,\mathrm{TeV}\}$ $B_f: \{y_L = 1.8, y_R = 1.8, x = 2.8, y = 2.5, \tilde{m}_T = 9\,\mathrm{TeV}, m_s = 3.5\,\mathrm{TeV}\},$

Maximal Symmetry

- Symmetric coset → can envisage enlarged global symmetry $G_L \times G_R \to G_{V'}$ that reduces the tuning (eliminates double tuning)

Csaki, Ma, Shu, PRL (1702.00405)

⬇

$$[T^{\hat{a}}, T^{\hat{a}}] \sim T^a$$

broken generator

⬇

$$\psi_L \to L\psi_L$$
$$\psi_R \to R\psi_R$$
$$G_{V'} : \; L^\dagger \Sigma' R = \Sigma'$$

- Modified Goldstone matrix $\Sigma' = U^2 V$ transforms linearly under $G : \Sigma' \to g\Sigma' g^\dagger$

Higgs-Parity Operator
$VT^aV^\dagger = T^a \, , \; VT^{\hat{a}}V^\dagger = -T^{\hat{a}}$

Maximal Symmetry

Enhanced global symmetry eliminates double-tuning

Csaki, Ma, Shu, PRL (1702.00405), 1810.07704 (+Yu)

$$SO(5)_L \times SO(5)_R \xrightarrow{m_Q,\tilde{m}_T} SO(5)_{V'} \supset SO(4)$$

chiral symmetry in composite sector

composite

h, Ψ

$SO(5) \to SO(4)$

$$\mathcal{L}_{\text{mass}} = \underbrace{-m_Q \bar{Q}_L Q_R - \tilde{m}_T \bar{\tilde{T}}_L \tilde{T}_R}_{} + \cdots$$
$$-\bar{\Psi}_L \left((m_Q + \tilde{m}_T) + (m_Q - \tilde{m}_T) V\right) \Psi_R$$

$$\Psi = (Q,\, \tilde{T})^T$$

$\mathbf{4}$ $\mathbf{1}$ of $SO(4)$

$$\text{I}: \; m_Q = \tilde{m}_T \to SO(5)_V \to V(h) = 0$$

$$\text{II}: \; m_Q = -\tilde{m}_T \to SO(5)_{V'} \to V(h) \neq 0$$

$SO(5)_V: \; L = R$

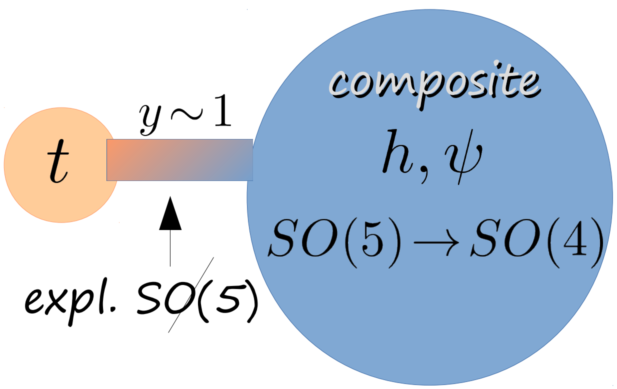
$SO(5)_{V'}: \; L^\dagger V R = V$ 'Maximal Symmetry'

$$V = \begin{pmatrix} \mathbf{1}_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

Higgs Potential: Reduced Tuning

$$SO(5)_L \times SO(5)_R \to SO(5)_{V'}$$

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$



$$\text{Minimum}: \quad \sin^2(v/f) = -\frac{\alpha}{2\beta}$$

$$\Delta_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & -i & 0 \\ 1 & i & 0 & 0 & 0 \end{pmatrix}$$

$$\Delta_R = -i \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Spurion Analysis

$SO(5)$ breaking combinations respecting $G_{\rm SM}$: $\Gamma_{L,R} \equiv \Delta^\dagger_{L,R}\Delta_{L,R}$

transform as $\Gamma_L \to L\Gamma_L L^\dagger\,,\ \Gamma_R \to R\Gamma_R R^\dagger$

$$\Sigma' R \to L\Sigma' R^\dagger$$

$$\to V(h) \sim y_L^2 y_R^2 f^4 \mathrm{Tr}[\Sigma'^\dagger \Gamma_L \Sigma' \Gamma_R] \sim y_L^2 y_R^2 f^4 \sin^2(h/f)\cos^2(h/f)$$

$\alpha = -\beta \to$ No double tuning :)

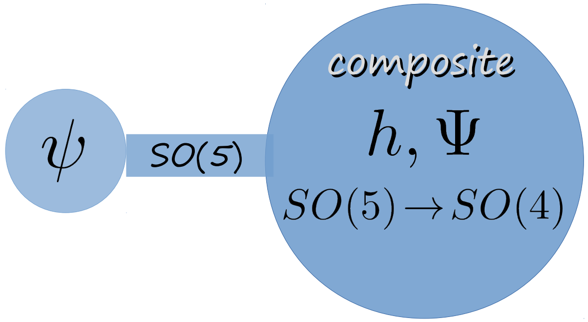
$\sin^2(v/f) = 1/2$:(

→ tune with gauge contribution

Maximally Symmetric sMCHM$_5$

$$V(h) \approx \alpha \sin^2(h/f) + \beta \sin^4(h/f)$$

$$\text{Minimum}: \quad \sin^2(v/f) = -\frac{\alpha}{2\beta}$$



$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L - w_{1L}^1 \\ -ib_L - iw_{1L}^1 \\ t_L + w_{1L}^2 \\ it_L - iw_{1L}^2 \\ -i\sqrt{2}\, s_L \end{pmatrix} \quad \psi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} v_R^2 - w_{2R}^1 \\ -iv_R^2 - iw_{2R}^1 \\ v_R^1 + w_{2R}^2 \\ iv_R^1 - iw_{2R}^2 \\ -i\sqrt{2}\, t_R \end{pmatrix}$$

need to split w-doublet

Spurion Analysis

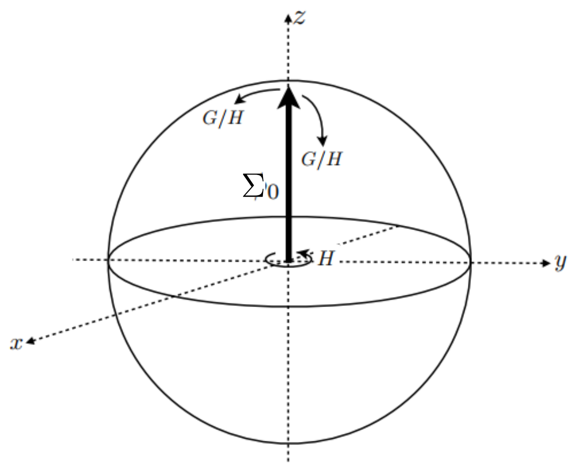
$$\to V(h) \sim y_L^2 y_R^2 f^4 M_\Psi^2 \sum_{i,j} a_{ij} \mathrm{Tr}[\Sigma'^\dagger \Gamma_L^i(m_\psi^2) \Sigma' \Gamma_R^j(m_\psi^2)]$$

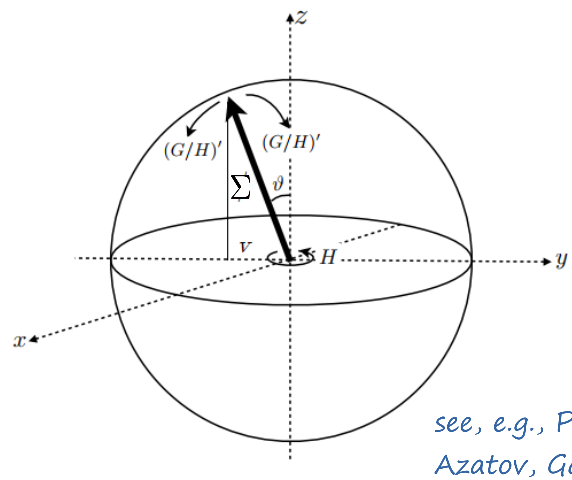
$$\alpha \sim y_L^2 y_R^2 f^4 M_\Psi^2 m_{w_1}^2 (m_v^2 - m_{w_2}^2) a_{11} \neq 0$$

$\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta$ → No double tuning :)

$\sin^2(v/f) \neq 1/2$:)

Vacuum Misalignment





see, e.g., Panico, Wulzer, 1506.01961, Azatov, Galloway, 1212.1380

Explicit $\mathcal{G}$ breaking $\to \langle h \rangle > 0 \Rightarrow$ breaks $G_{\rm EW} \subset \mathcal{H}$:
misalignment of true $\langle \Sigma \rangle$ vs. $\mathcal{H}$-preserving Σ_0, anlge $\vartheta \equiv \langle h \rangle / f$

EW breaking: $v = f \sin\vartheta\,, \;\; f = |\Sigma_0|$

Challenge: $\xi \equiv v^2/f^2 = \sin^2\vartheta \ll 1$
without excessive tuning

$$\Sigma(x) = \Sigma_0\, e^{-i\frac{\sqrt{2}}{f} h_a(x) T^a}$$

$$\Sigma_0 = (0,0,0,0,1) : SO(5) \to SO(4)$$

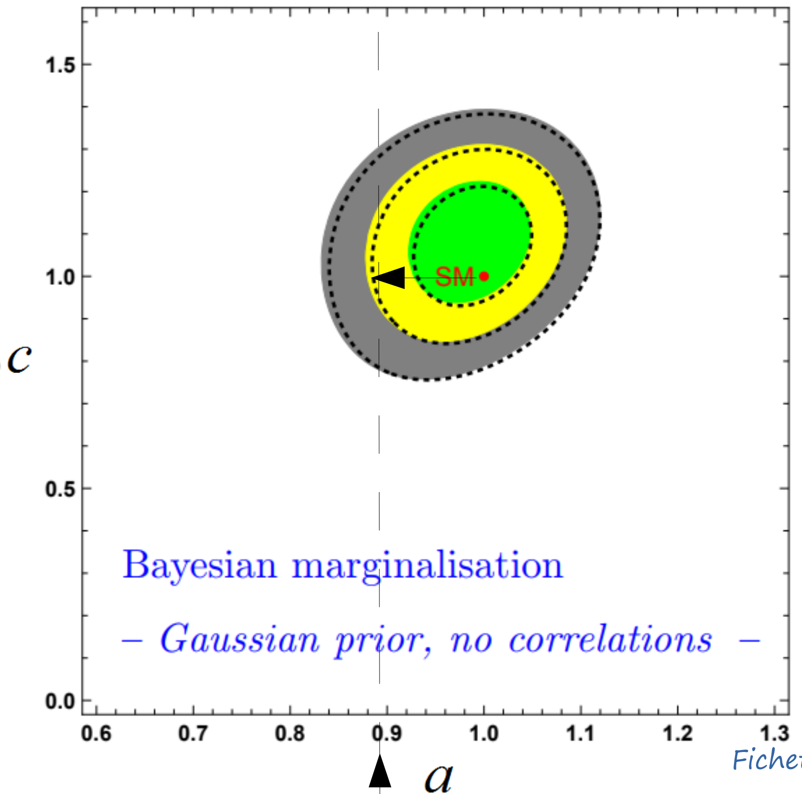
$$\mathcal{L}_\Sigma = \frac{f^2}{2}(D_\mu \Sigma)^T (D^\mu \Sigma)$$

Higgs Couplings

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}(\bar{u}_L^{(i)}\ \bar{d}_L^{(i)})\Sigma(1 + c\frac{h}{v} + \cdots)\begin{pmatrix} Y_{ij}^u u_R^{(j)} \\ Y_{ij}^d d_R^{(j)} \end{pmatrix} + \mathrm{h.c.}$$

depends on fermion embedding



Fichet, Moreau, 1509.00472

→ $a = \sqrt{1-\xi}\,,\quad b = (1-2\xi)$

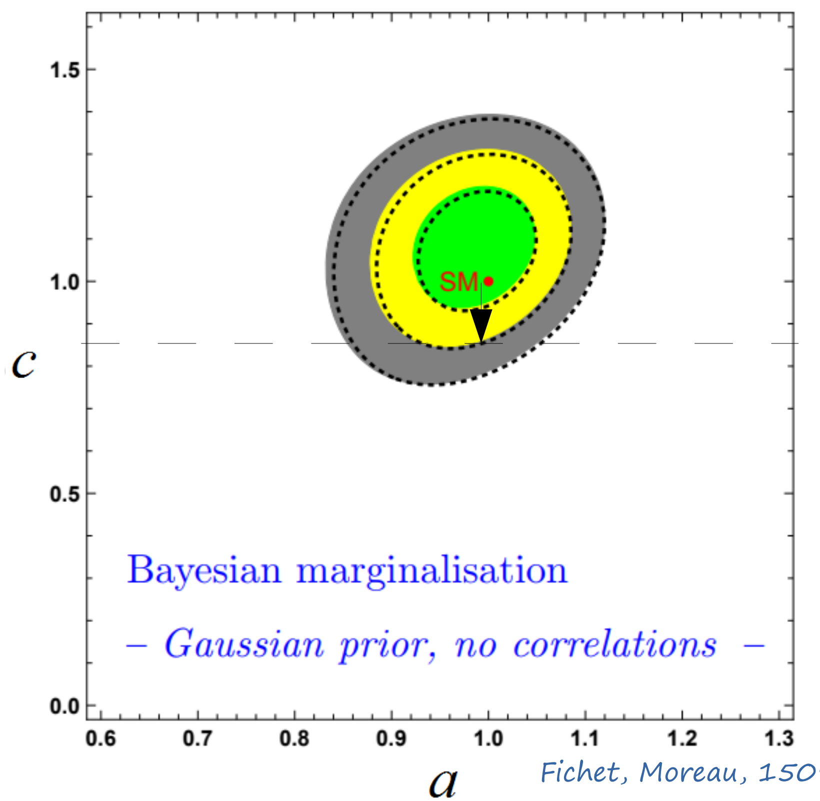
$\xi \approx 0.2 \rightarrow f \approx 550\,\mathrm{GeV}$

Higgs-Fermion Couplings

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}(\bar{u}_L^{(i)}\,\bar{d}_L^{(i)})\Sigma(1 + c\frac{h}{v} + \cdots)\begin{pmatrix} Y_{ij}^u u_R^{(j)} \\ Y_{ij}^d d_R^{(j)} \end{pmatrix} + \text{h.c.}$$

depends on fermion embedding



Fichet, Moreau, 1509.00472

Rather model dependent:

Representations of $\Psi^{Q,q}$ under SO(5)

$c = \sqrt{1-\xi}$: MCHM_4 (spinorial)

$c = \frac{1-2\xi}{\sqrt{1-\xi}}$: MCHM_5 (fundamental)

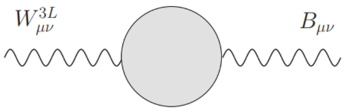
...

$c \approx 0.85 \rightarrow f \approx 500\,(780)$ GeV for $\mathrm{MCHM}_4(\mathrm{MCHM}_5)$

Electroweak Precision Tests

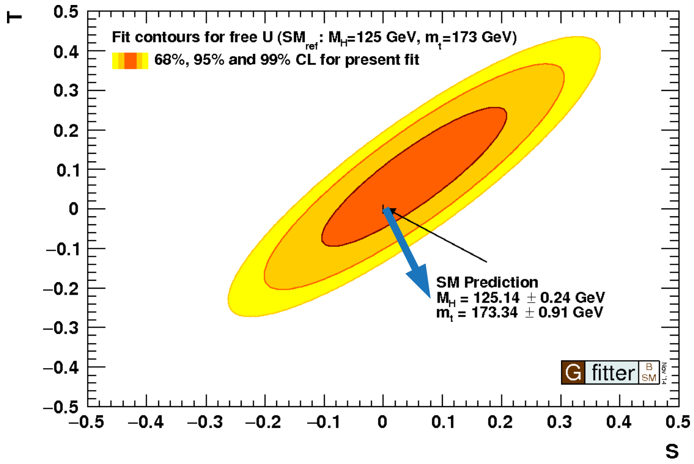
- Tree Level (SO5/SO(4)) :

$$S = 2\pi\xi\,\Pi_1'(0)$$



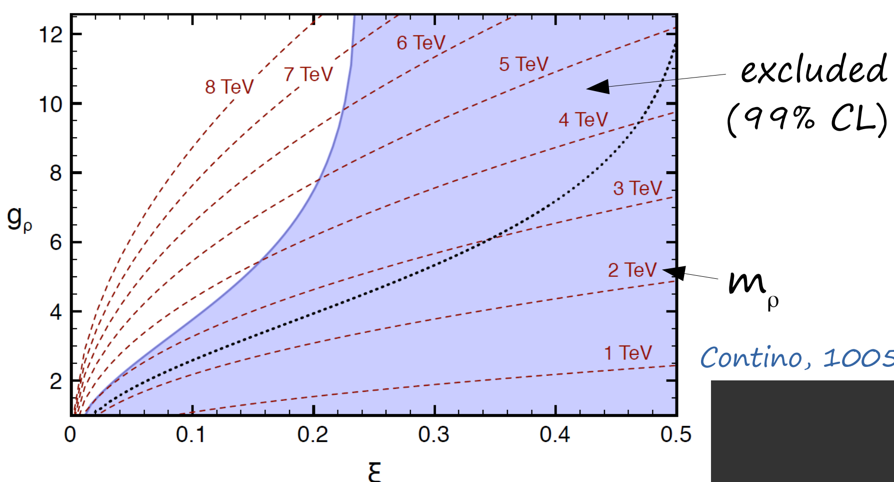
$$T = 0 \text{ (custodial)}$$

$$\approx 4\pi\,(1.36)\left(\frac{v}{m_\rho}\right)^2 \to 0 \text{ for } \xi \to 0$$



- 1-loop: modified Higgs-Gauge couplings

$$\sim \cos(\langle h\rangle/f) = \sqrt{1-\xi} \qquad \to \Delta S > 0,\ \Delta T < 0$$



Contino, 1005.4269

$$\xi \lesssim 0.1 \to f \gtrsim 800\text{ GeV} \,@\, 95\%\text{CL}$$

Thamm, Torre, Wulzer, 1502.01701

Ghosh, Salvarezza, Senia, 1511.08235