Natural Composite Higgs, Top Partners, and Flavor

LIO Conference on Composite Connections of Higgs, Dark Matter and Neutrinos

21.9.2020

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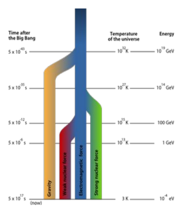
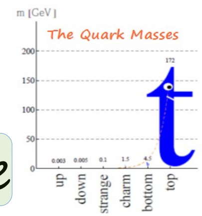
MPIK

Max-Planck-Institut für Kernphysik Heidelberg

The SM is an EFT



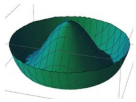
- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h << M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\notin$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- Some Hints in Flavor/Precision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



.....

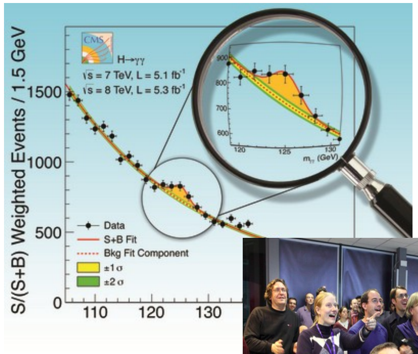
↓

many links to Higgs Sector



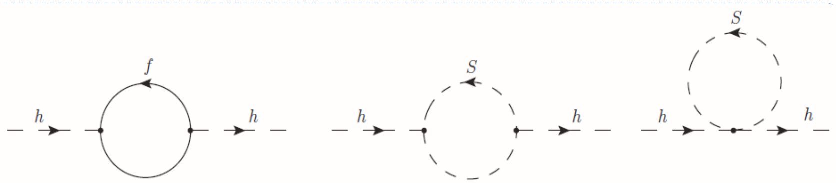
still least understood...

Use Higgs Sector as unique window to NP!



The Hierarchy Problem

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

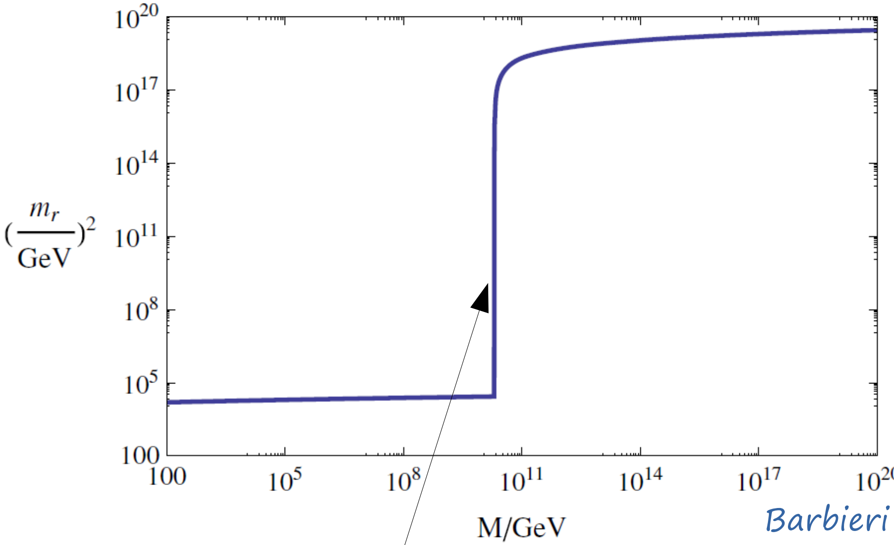


$$\mathcal{L} \supset m_H^2 |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2}$$

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

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



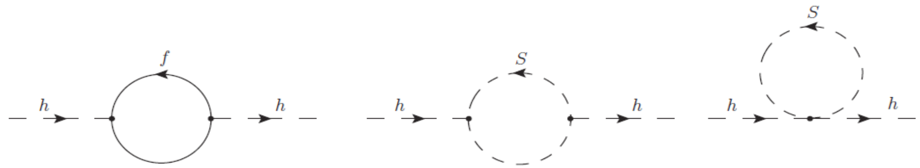
Barbieri
Phys. Scr. 2013 014006

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

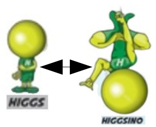
→ large fine-tuning to achieve $m_h \ll M_{\mathrm{NP}}$

Solving the Hierarchy Problem

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



New Symmetry	Low Cutoff	Vacuum Selection
	$\Lambda \ll M_{Pl}$	$m_h \ll \Lambda$



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

Low Cutoff ($\Lambda \ll M_{Pl}$)
- Large Extra Dim.
- Warped Extra Dim.
- Clockwork/LD
- Technicolor

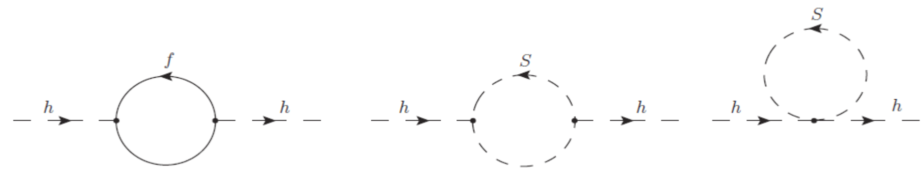
Vacuum Selection ($m_h \ll \Lambda$)
- Relaxation
- NNaturalness

Agravity, WGC, ...

→ often light (top) partners

Solving the Hierarchy Problem

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



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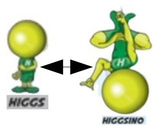

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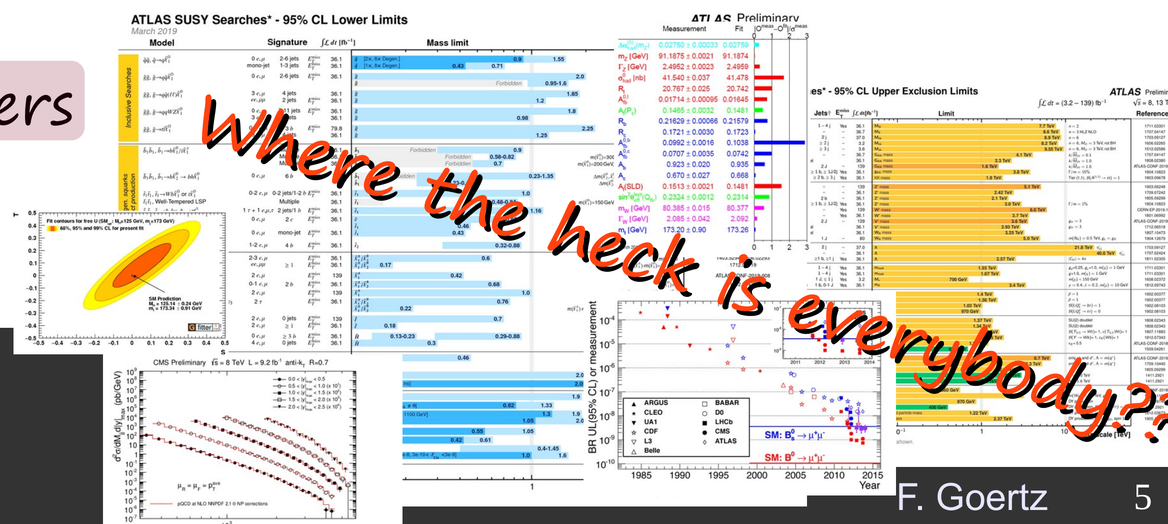
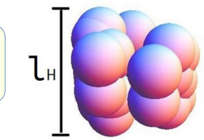


Composite Higgs Models

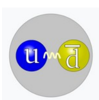
Kaplan, Georgi, Dimopoulos,. . .

- Higgs is composite at small distances

  ➡ m_H saturated in IR ➡ Hierarchy Problem solved

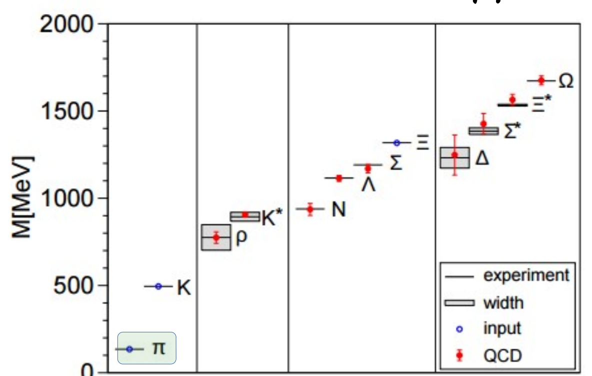


- Higgs = (pseudo) Goldstone Boson ➡ m_H<<m_ρ



like pions in QCD

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



0906.3599

Naturally address

- Hierarchical Flavor Structure
- Dynamical EWSB
- Tiny Neutrino Masses

- Dark Matter
- Baryogenesis ...

- MCHM: SO(5)→SO(4)

  Contino, Nomura, Pomarol, ph/0306259
  Agashe, Contino, Pomarol, ph/0412089

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

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

custodially symmetric

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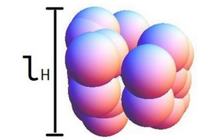

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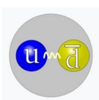

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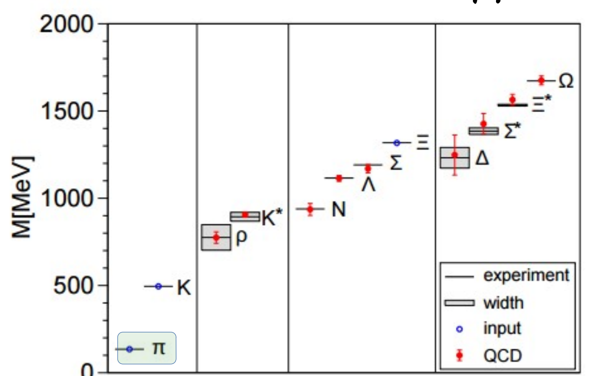

0906.3599

Naturally address

- Hierarchical Flavor Structure
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UV completions??

Barnard, Gherghetta, Ray 1311.6562,
Ferretti, Karateev, 1312.5330
Cacciapaglia, Sannino 1402.0233,
Vecchi, 1506.00623,
Ma, Cacciapaglia, 1508.07014

- MCHM: SO(5)→SO(4)

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

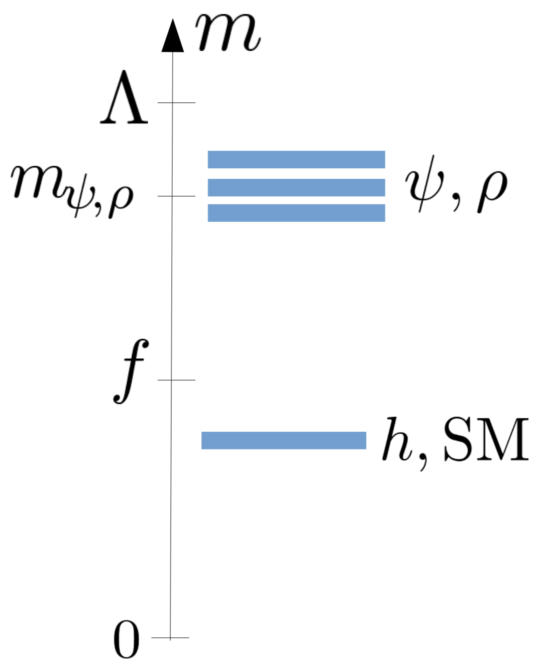
$\rightarrow$ Higgs $h_{1,..,4}$

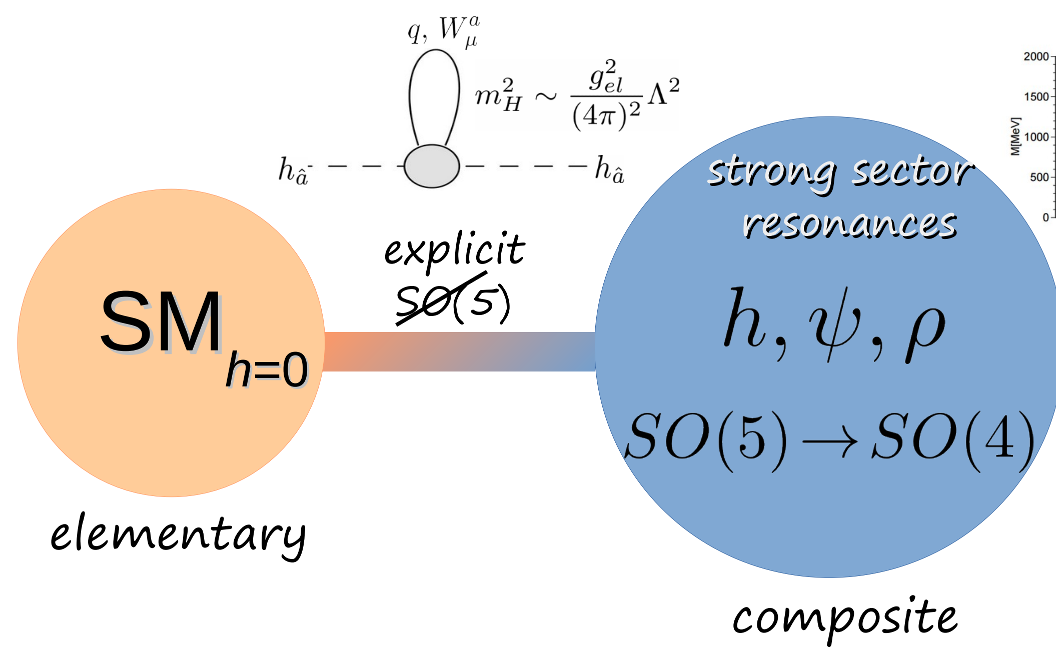
Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

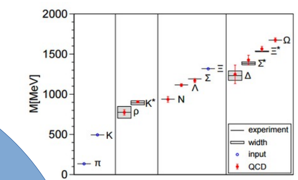
holographic construction / EFT

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):

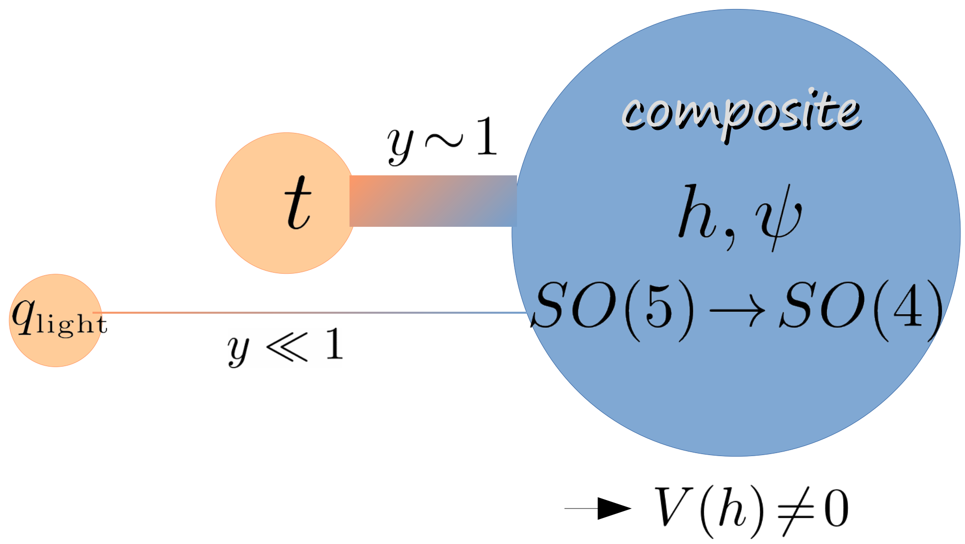
- Only subgroup of $\mathcal{G}$ gauged
- Fermions don't fill full $SO(5)$ reps

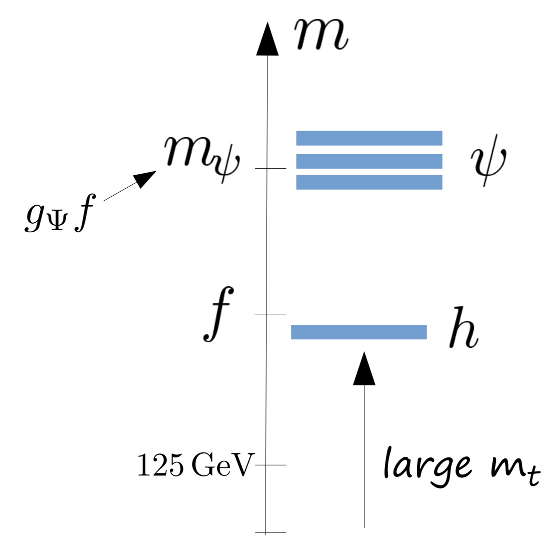
$f \sim \mathrm{TeV}: SO(5)$ breaking scale determines residual tuning, corrections to SM predictions

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

Partially Composite Fermions

Kaplan; Agashe, Contino, Nomura, Pomarol

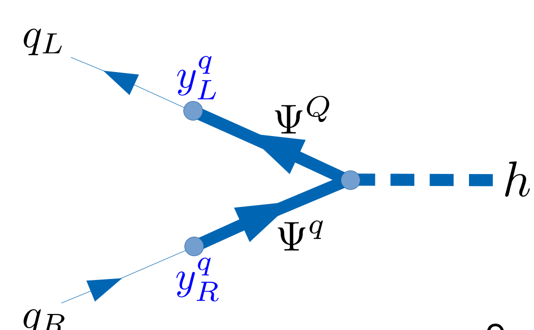




$$\mathcal{L} \supset -\left(\boxed{y_L^q}\,\bar{q}_L\cdot\Psi_R^Q + \boxed{y_R^q}\,\bar{q}_R\cdot\Psi_L^q\right)f$$

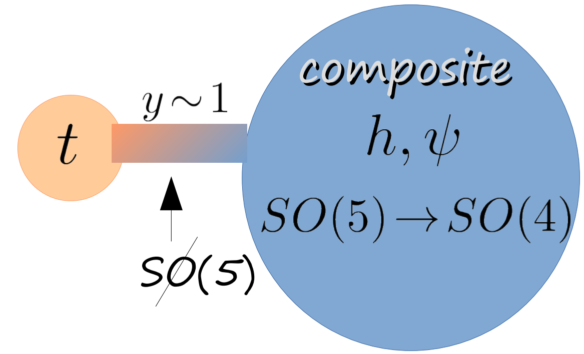
$\mathbf{5}$ of $SO(5)$
$\mathbf{10}$ of $SO(5)$
$\ldots$

$\to$ induce m_q



The Higgs Potential and the Tuning

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



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

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

$v \equiv \langle h \rangle$

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

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

$\rightarrow \mathcal{O}(1\%)$

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

Light Top Partners

Large top yukawa → large m_h

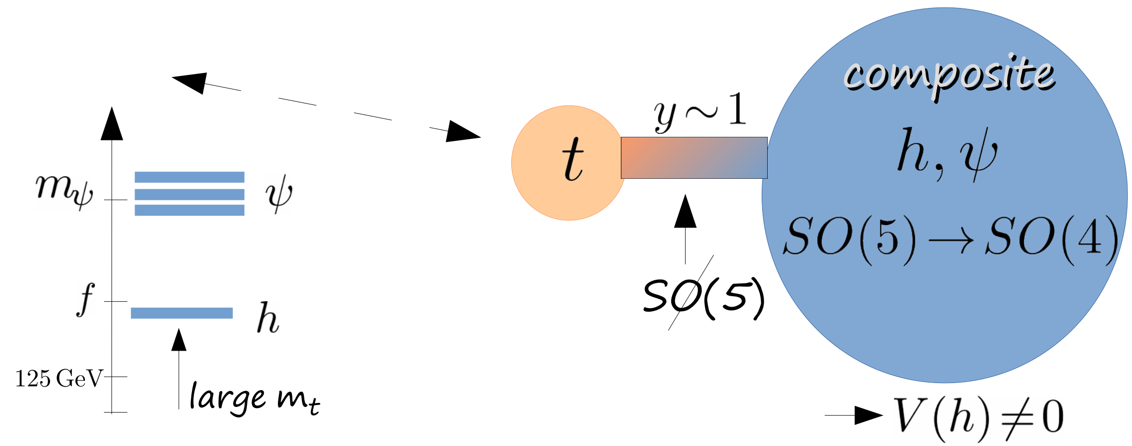
$$\boxed{m_h} \sim y_t^2\, v \;\sim\; \boxed{m_T/f\;\, m_t}$$

=> light top partners:

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

lightest fermionic resonance

EWPT

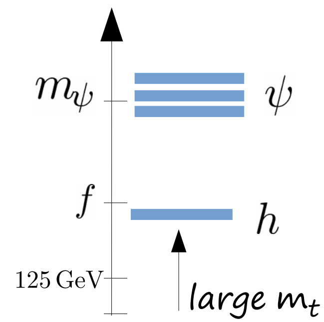


Matsedonskyi, Panico, Wulzer, 1204.6333;
Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954;
De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434

Light Top Partners

Large top yukawa → large m_h

$$\boxed{m_h} \sim y_t^2\, v \sim \boxed{m_T/f\ m_t}$$



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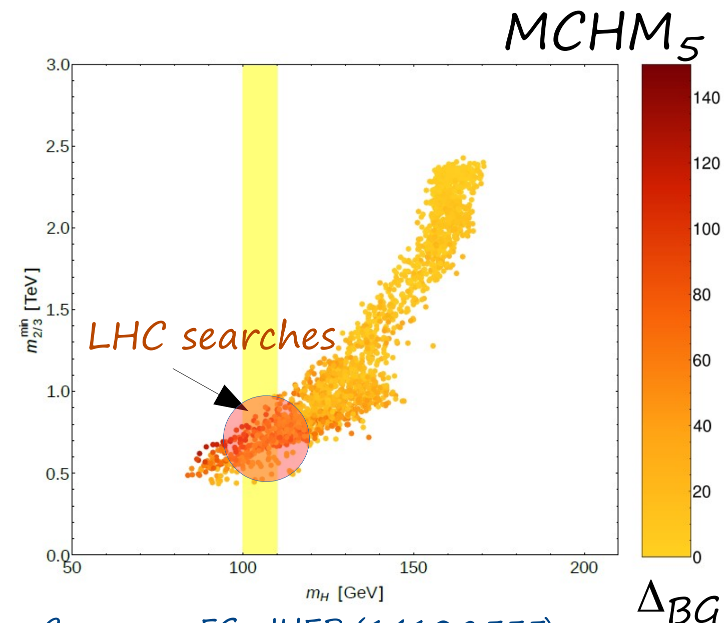
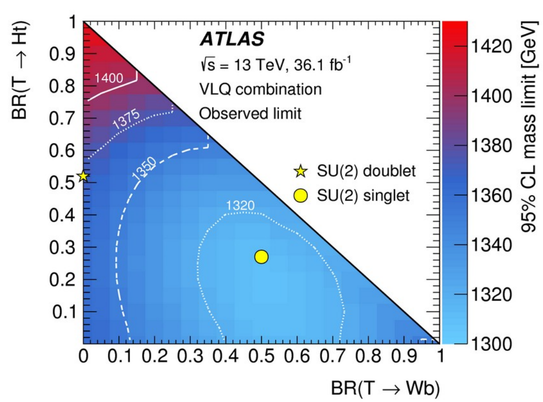


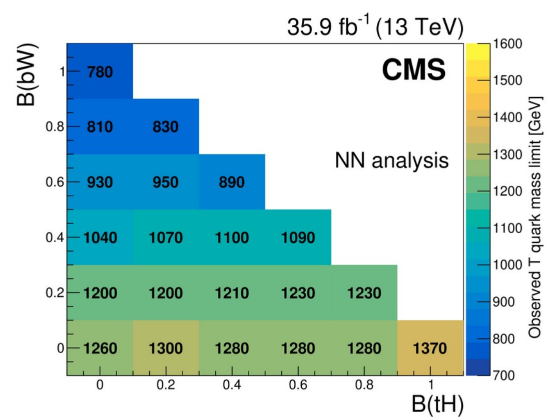
Carmona, FG, JHEP (1410.8555)

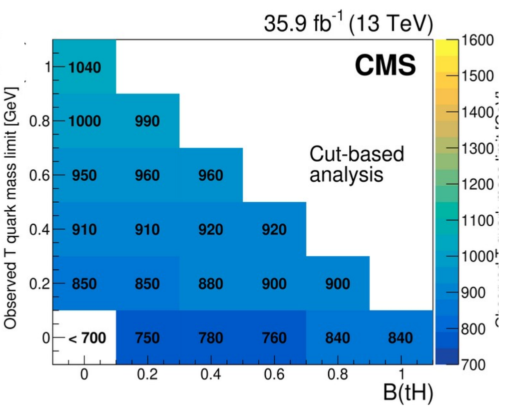
$f = 800\,\mathrm{GeV}$

LHC Searches

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







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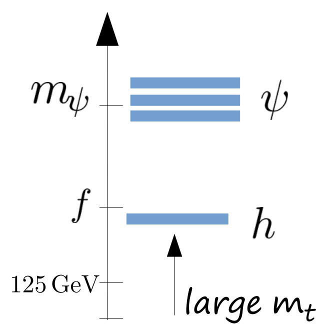
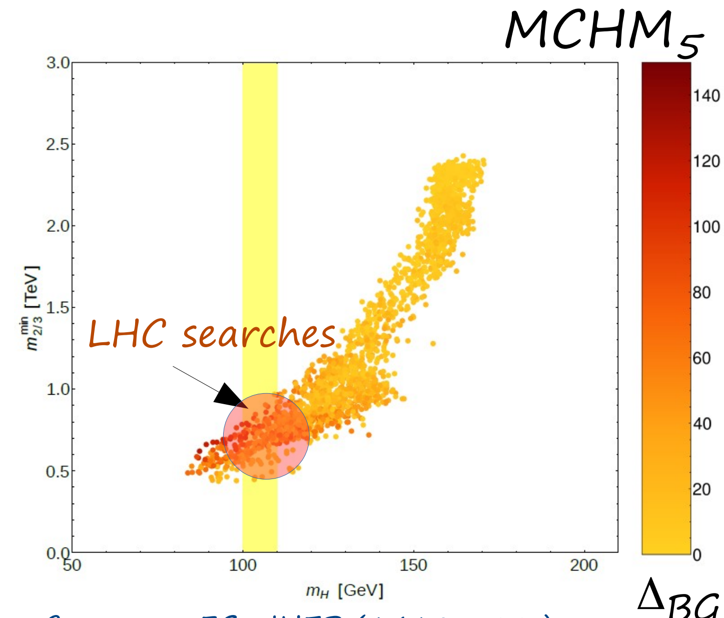
$$\boxed{m_h} \sim y_t^2\, v \;\sim \boxed{m_T/f\ m_t}$$





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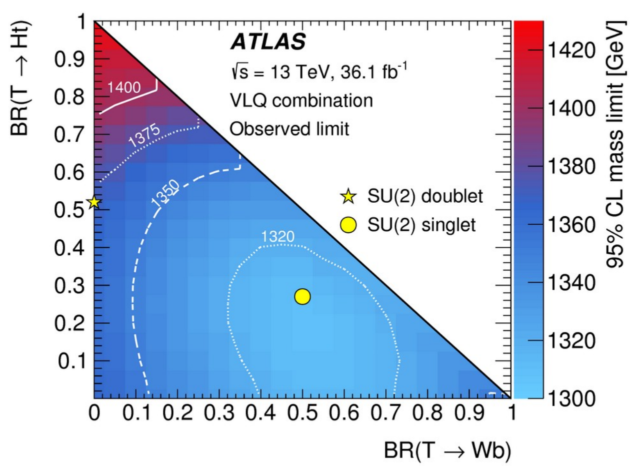

potentially strongest constraints on CH

→ raise f

→ increase tuning

Avoiding Light Top Partners I

- *Larger quark representations:* $\mathbf{14}$ of $SO(5)$ Panico, Redi, Tesi, Wulzer, JHEP (1210.7114)
  → strong correlation broken
- $\mathbf{14}$ *fits naturally in the (RH) lepton sector* (keep quark sector [even more] minimal)

$$\xi_{2\tau} = \boxed{\tau_2'[-,-]} \oplus \begin{pmatrix} \boxed{\begin{matrix} \nu_2^\tau[+,-] \\ \tau_2[+,-] \end{matrix}} & \begin{matrix} \tilde{\tau}_2[+,-] \\ \tilde{Y}_2^\tau[+,-] \end{matrix} \end{pmatrix} \oplus \begin{pmatrix} \boxed{\begin{matrix} \hat{\lambda}_2^\tau[-,-] \\ \hat{\nu}_2^\tau[-,-] \\ \hat{\tau}_2[-,-] \end{matrix}} & \begin{matrix} \nu_2^{\tau\prime\prime}[+,-] \\ \tau_2^{\prime\prime}[+,-] \\ Y_2^{\tau\prime\prime}[+,-] \end{matrix} & \begin{matrix} \tau_2^{\prime\prime\prime}[+,-] \\ Y_2^{\tau\prime\prime\prime}[+,-] \\ \Theta_2^{\tau\prime\prime\prime}[+,-] \end{matrix} \end{pmatrix}$$

Carmona, FG, JHEP (1410.8555)

- Just requires one **5** and one **14**: 'unification' of RH leptons
- Type-III seesaw, scale $\Lambda_{\rm seesaw} \ll M_{\rm PL}$ motivates modest lepton compositeness
- & Contribution to Higgs mass at leading order in Yukawa → leptons matter!

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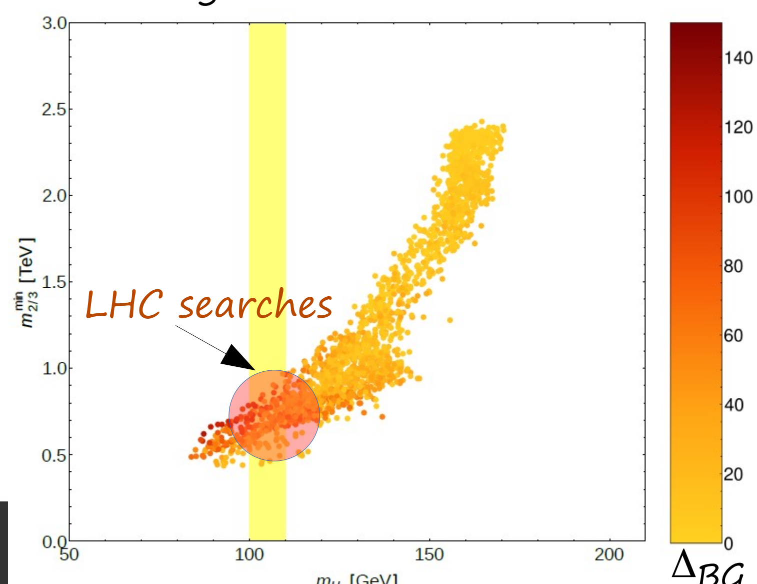
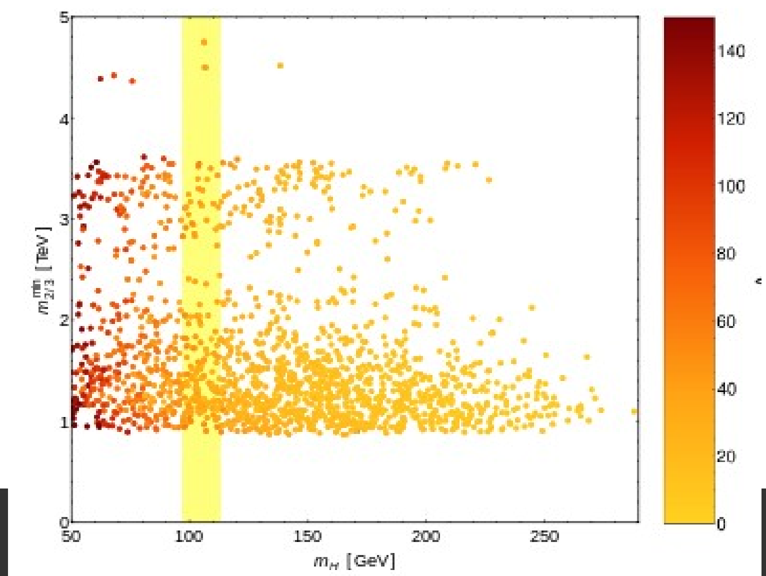
Carmona, FG, JHEP (1410.8555)

MCHM_5





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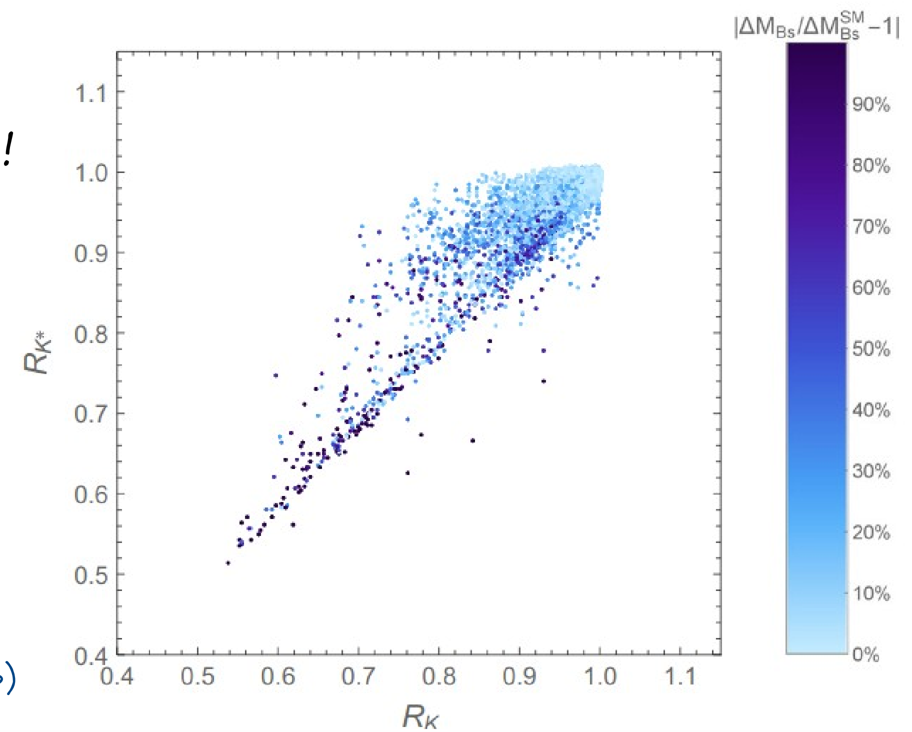
Carmona, FG, JHEP (1410.8555)

  - Predicts lepton-flavor universality violation (different RH lepton compositeness)!

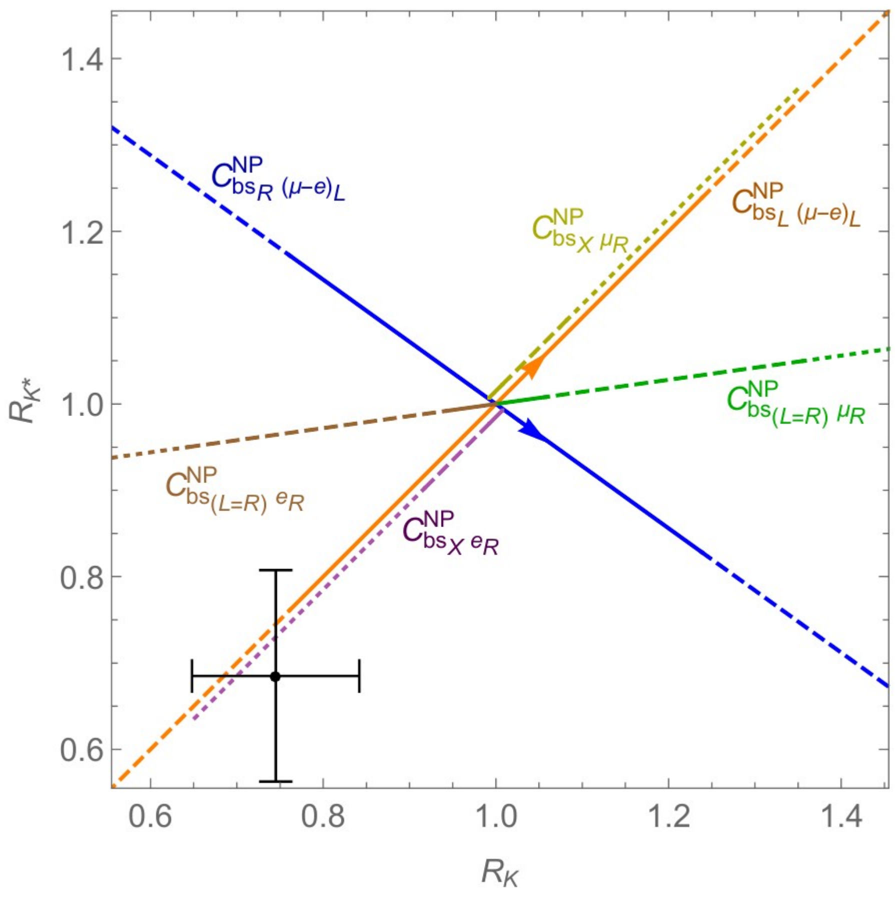
$$R_K = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}\right|_{q^2\in[1,6]\ \mathrm{GeV}}$$

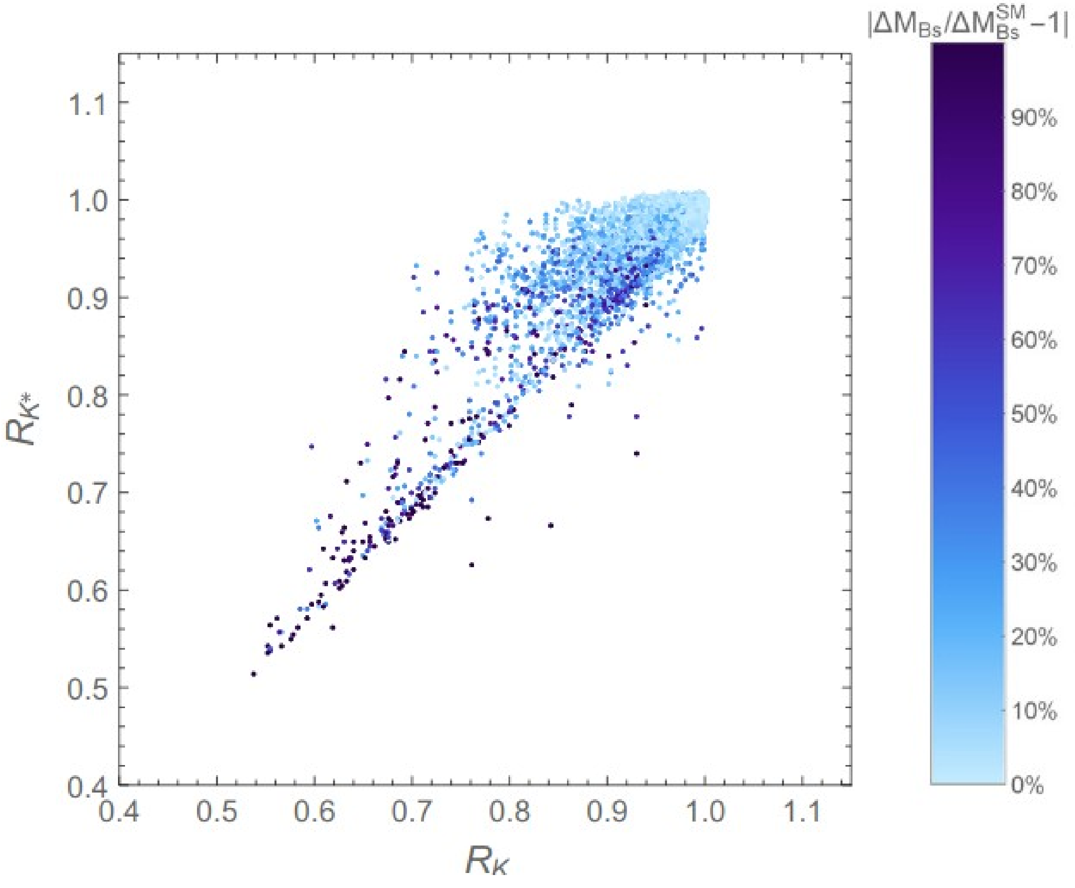
$$R_{K^*} = \left.\frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}\right|_{q^2\in[1.1,6]\mathrm{GeV}}$$



Carmona, FG, PRL (1510.07658)
Carmona, FG, EPJC (1712.02536)

R_K and R_{K^*}: possible solutions



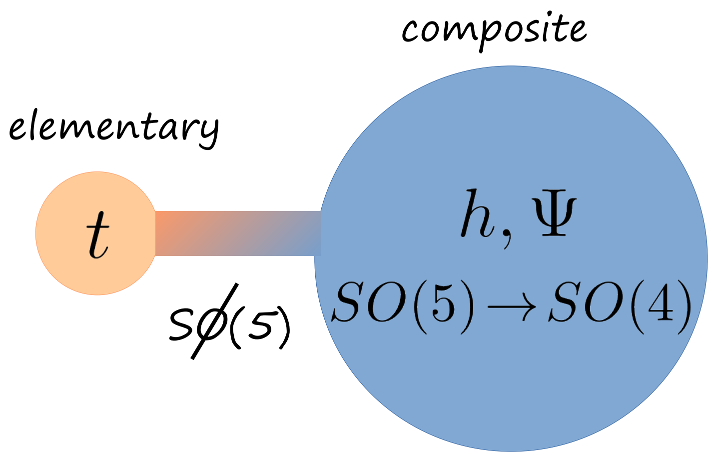


Carmona, FG, EPJC (1712.02536)

Avoiding Light Top Partners II

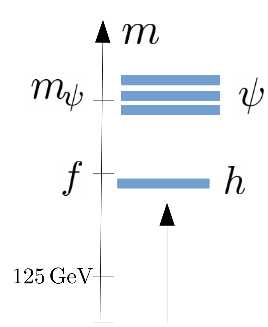
Change the nature of explicit Goldstone-symmetry breaking

Blasi, FG, PRL (1903.06146)



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

$\mathbf{5}$ of $SO(5)$



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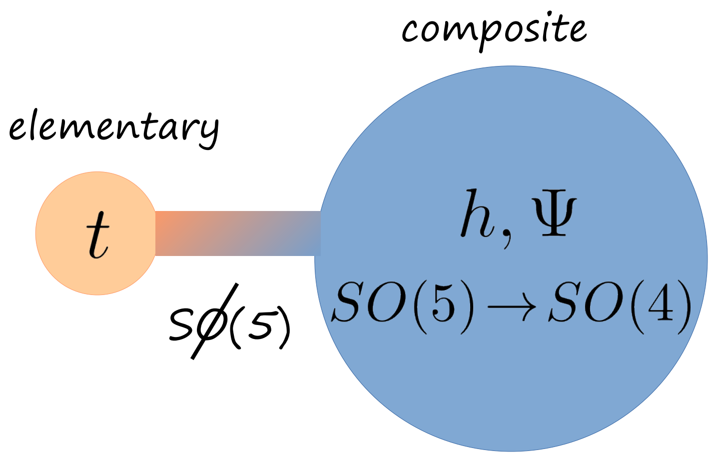
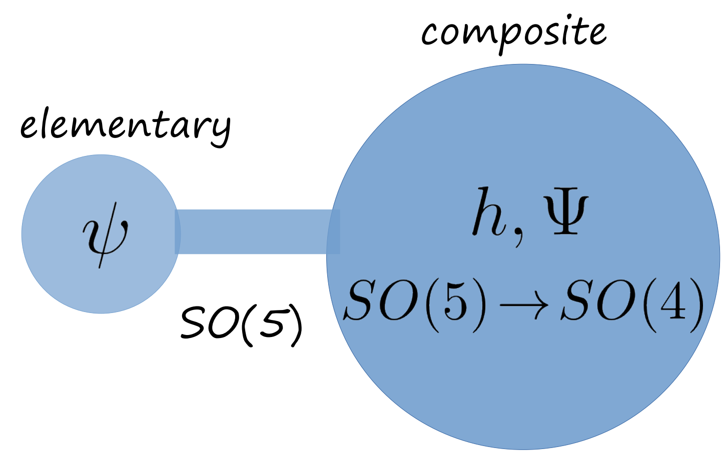
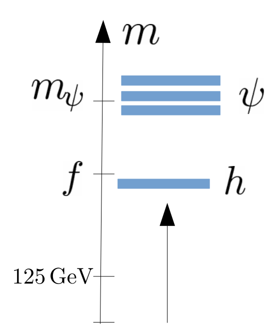




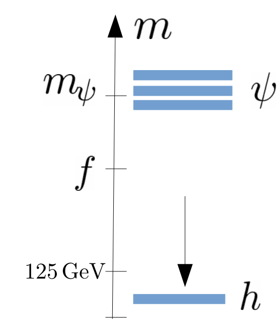
$$\boxed{\bar{q}_L} \cdot \boxed{\Psi_R^T}$$

$\mathbf{5}$ of $SO(5)$



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

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

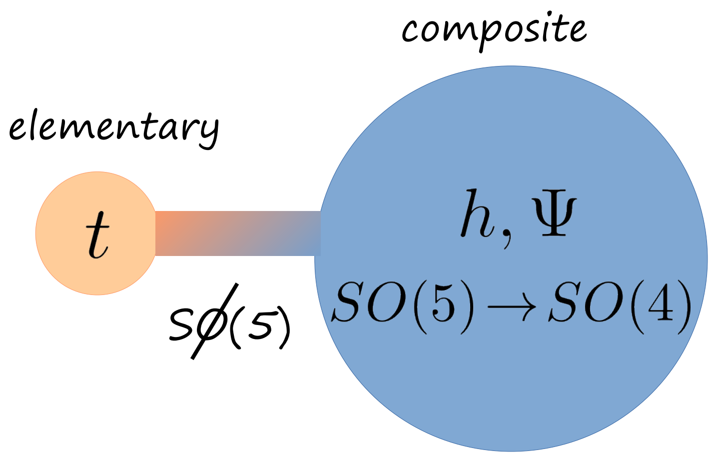


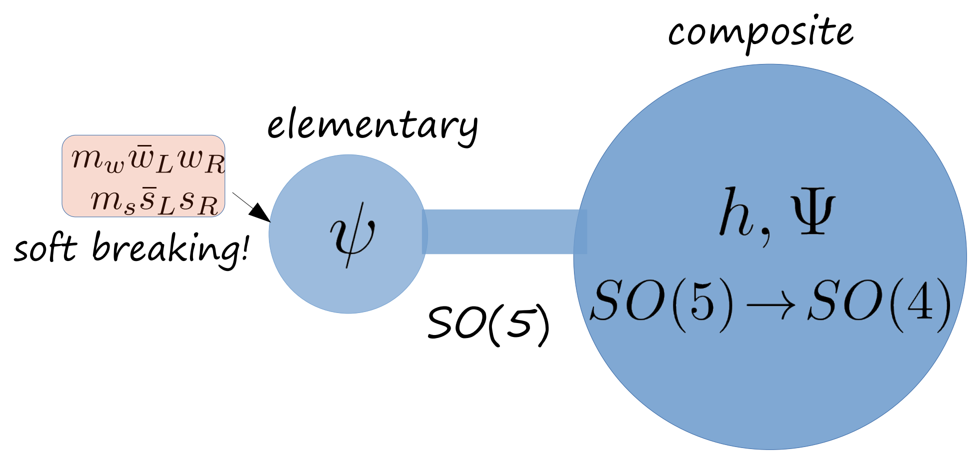
+ similar for RH

Avoiding Light Top Partners II

Change the nature of explicit Goldstone-symmetry breaking

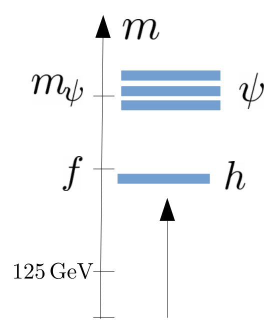
Blasi, FG, PRL (1903.06146)





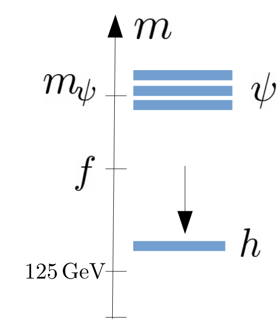
$$\bar{q}_L \cdot \Psi_R^T$$

5 of $SO(5)$



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

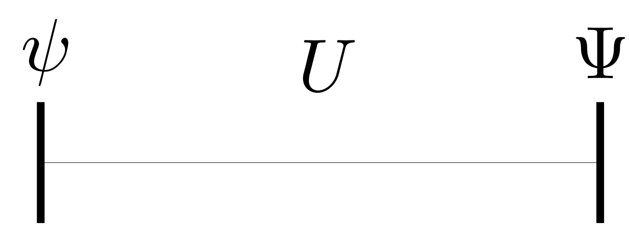
$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$



+ similar for RH

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

Two-Site Model Lagrangian



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

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

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

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:

$$-\mathcal{L}_{\rm el} = m_s \bar{s}_L s_R + m_v \bar{v}_L v_R + m_w \bar{w}_L w_R + \text{h.c.}$$

SO(5) Breaking Spurions

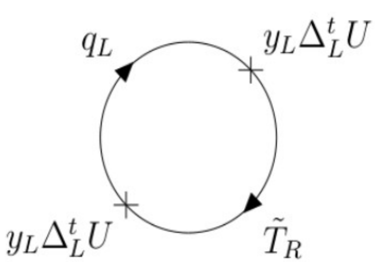
Standard MCHM$_5$

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

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

$$\begin{aligned}\mathcal{L}_{\text{mass}} \supset &- y_L f\ \bar{q}_L \boxed{\Delta_L} U \Psi_R^T \\ &- y_R f\ \bar{t}_R \boxed{\Delta_R} U \Psi_L^t\end{aligned}$$

$V(h) \sim$

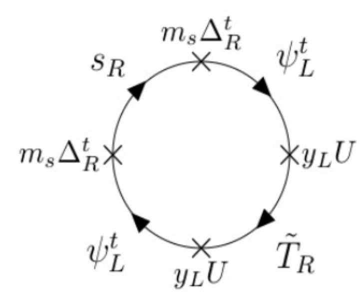


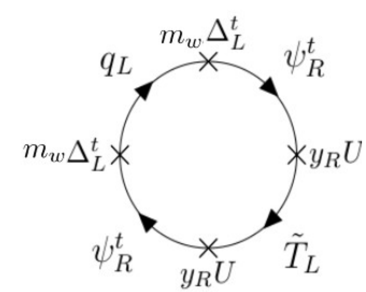
sMCHM$_5$

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

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

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





SO(5) Breaking Spurions

Standard MCHM$_5$

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

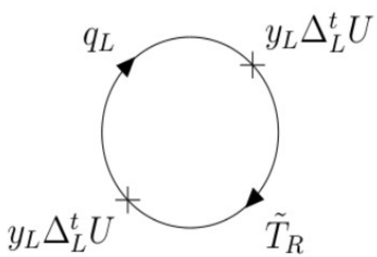
$$\psi_R = \Delta_R^\dagger t_R \qquad \Delta_R = -i\begin{pmatrix} 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

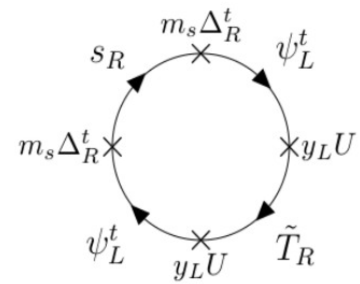
sMCHM$_5$

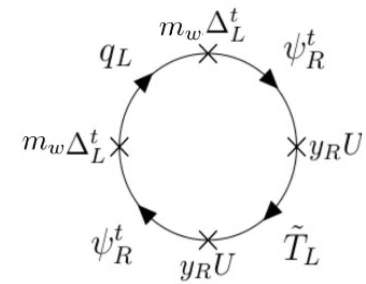
$$\psi_L \sim \mathbf{5}$$

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

$$V(h) \sim$$







$$m_h \simeq \frac{m_T}{f} m_t \boxed{\frac{\sqrt{\epsilon}}{2(1-\epsilon/4)}}$$

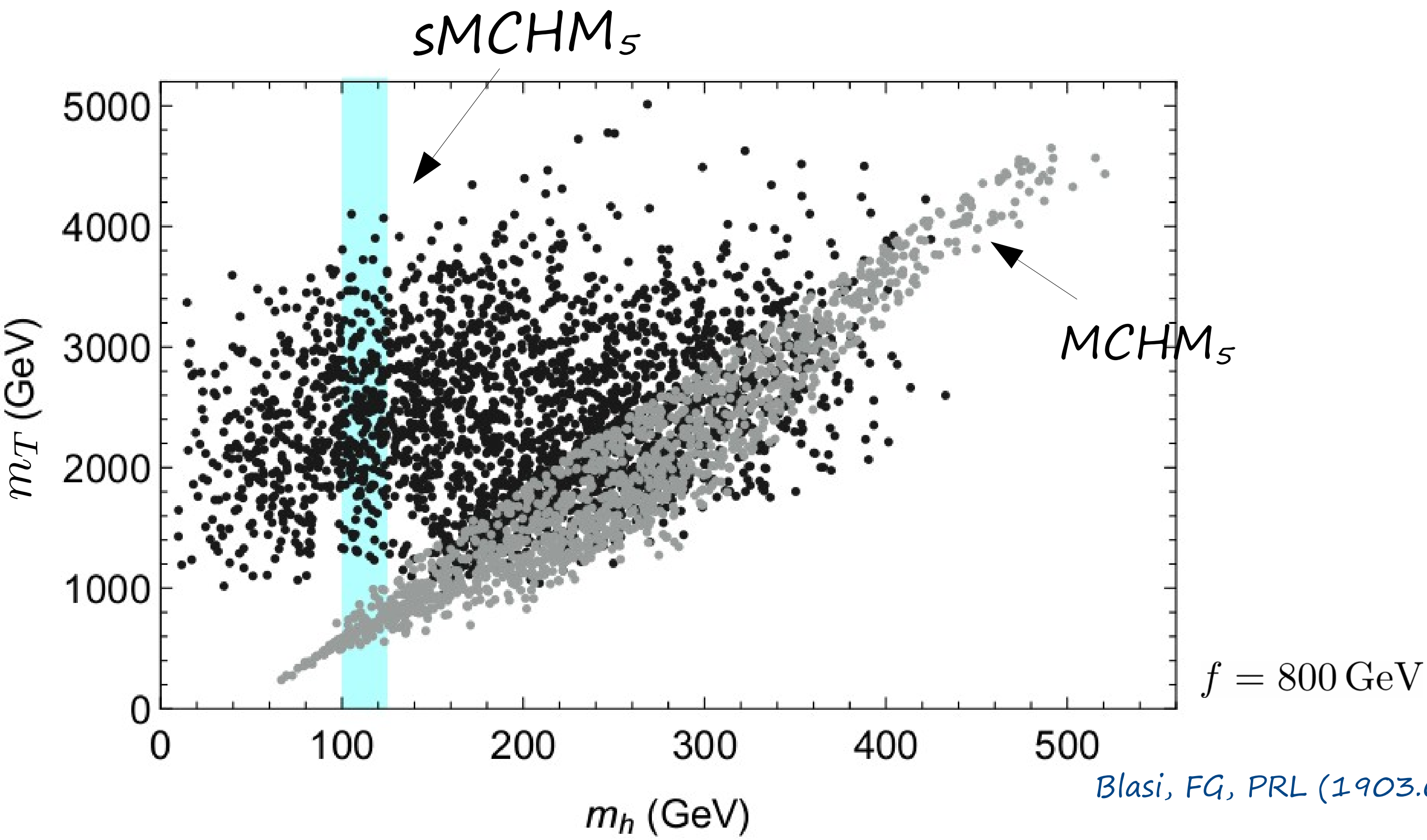
$$< 1$$

$$\boxed{\epsilon \equiv 1 - M/m_s}$$

$$m_Q = -\, m_{\tilde{T}} \equiv M$$

$$m_s \ll m_w, m_v$$

Full 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 in $MCHM_5$

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

$$\Delta \simeq \frac{f^2}{v^2} \times \boxed{\left(\frac{\alpha}{2\beta}\right)} \xrightarrow{MCHM_5:\ f \sim m_T} \Delta_5 \simeq \boxed{100} \left(\frac{m_T}{1\,\text{TeV}}\right)^2$$

double-tuning ➡ further increase symmetry

'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

$h,\,\Psi$

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

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

$$-\bar{\Psi}_L \left((m_Q + \tilde{m}_T) + (m_Q - \tilde{m}_T) V \right) \Psi_R$$

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

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

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

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

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

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

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

Higgs-Parity Operator

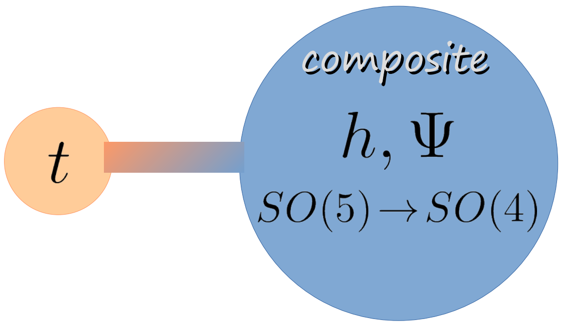
$V T^a V^\dagger = T^a\,,\ V T^{\hat{a}} V^\dagger = -T^{\hat{a}}$

Maximal Symmetry

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

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

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



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

$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right) \xrightarrow[\alpha \sim \beta]{f \sim m_T} \boxed{10} \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

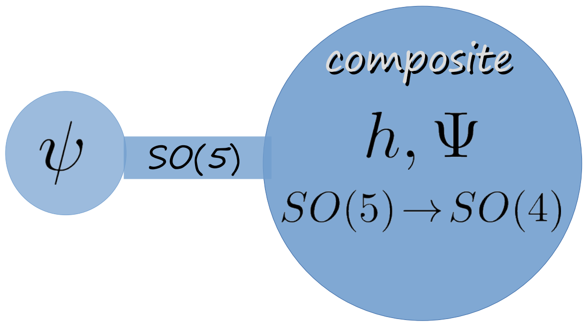
$\alpha + \beta = 0 \rightarrow \boxed{\sin^2(v/f) = 1/2}$ ↯ $\rightarrow$ cancel with gauge contr.

Maximal Symmetry + Soft Breaking

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

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

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



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

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

$$\Delta \simeq \frac{f^2}{v^2} \times \left(\frac{\alpha}{2\beta}\right) \xrightarrow[\alpha \sim \beta]{f \approx 800\,\mathrm{GeV} \nsim m_T} \boxed{10} \cancel{\left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2} > 1$$

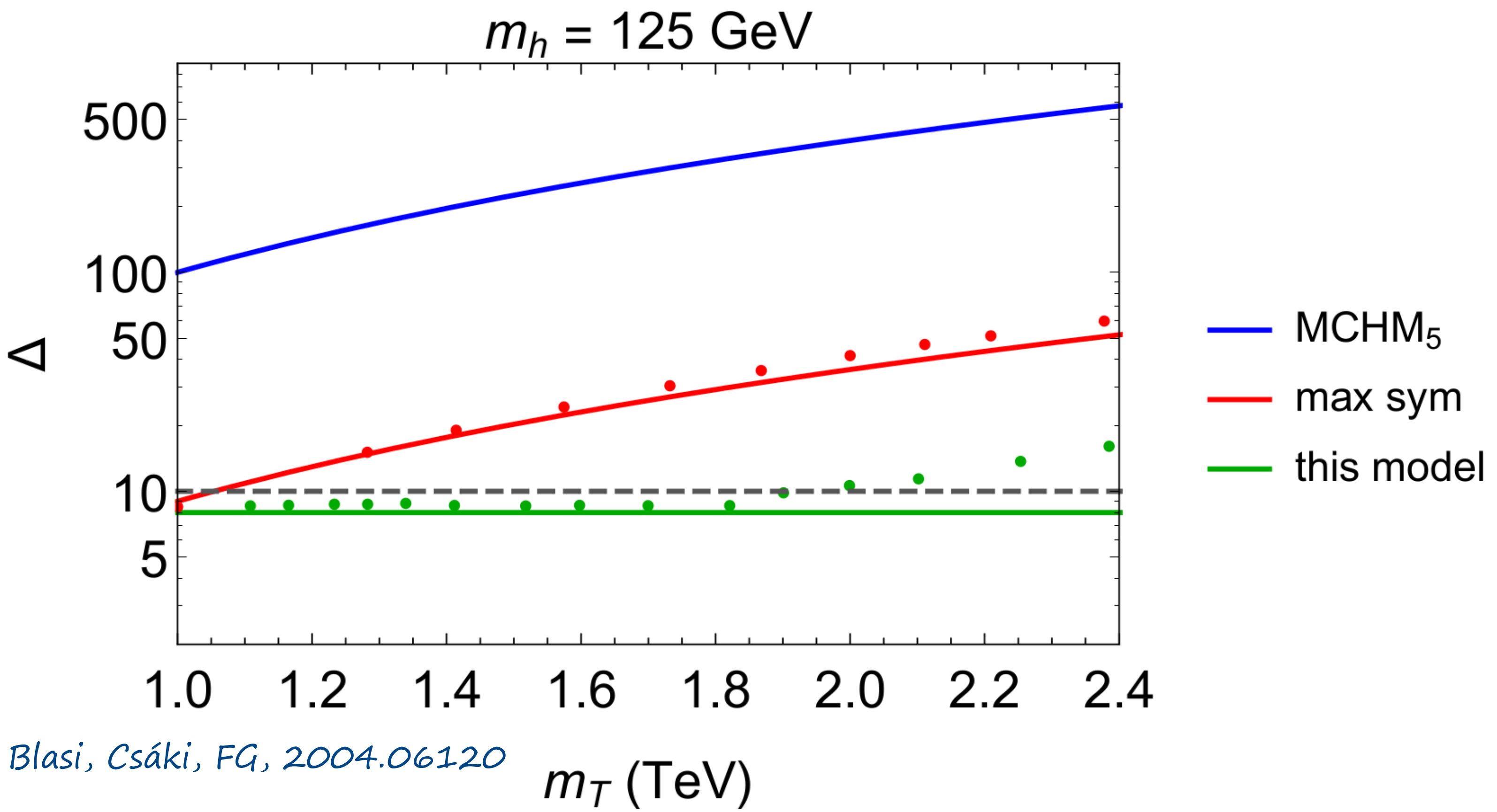
soft breaking

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

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

Blasi, Csáki, FG, 2004.06120

Tuning: Max Symmetry + Soft Breaking



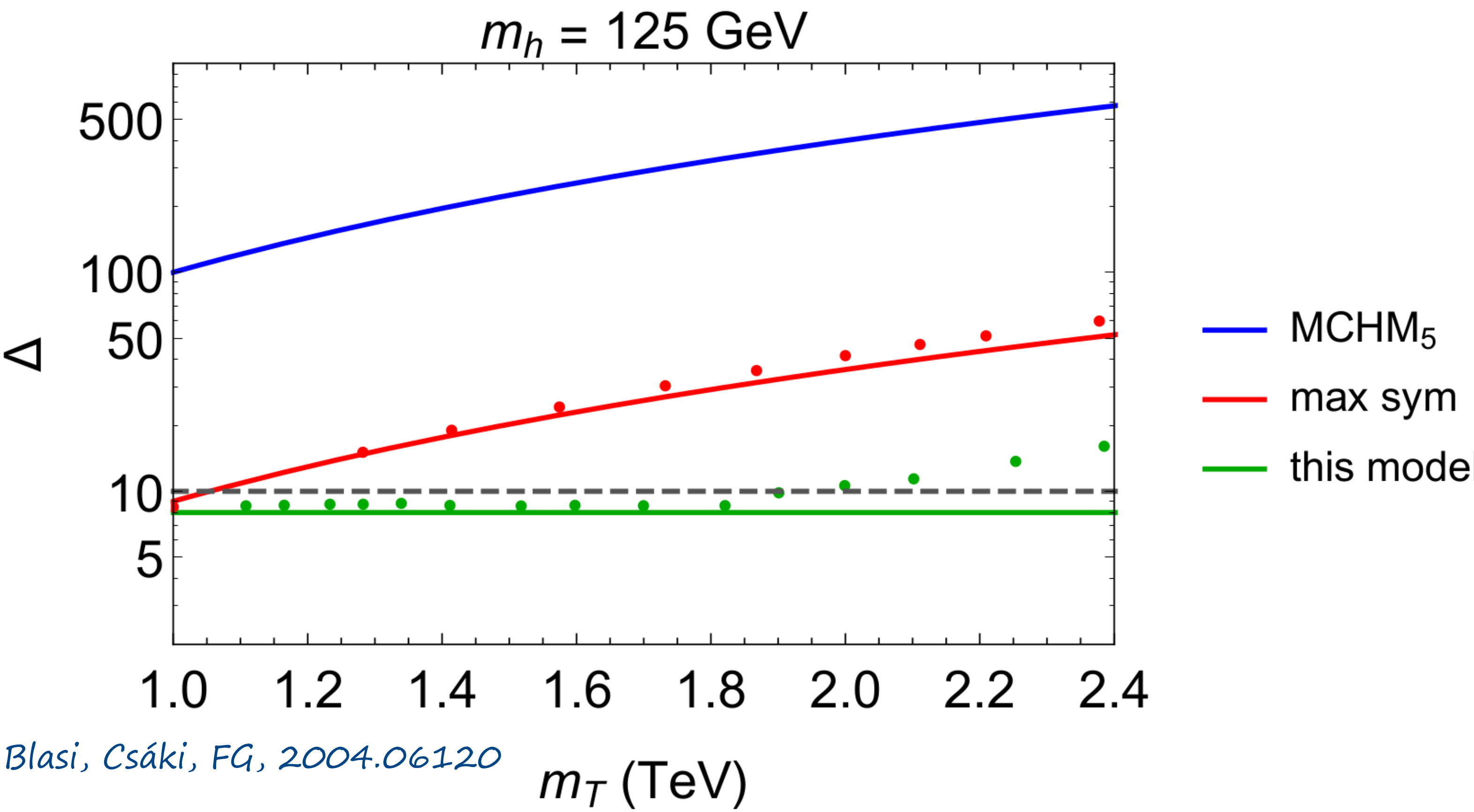
Blasi, Csáki, FG, 2004.06120

$$\Delta \simeq 100 \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

$$\Delta \simeq 10 \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

$$\Delta \simeq 10$$

Tuning: Max Symmetry + Soft Breaking



Blasi, Csáki, FG, 2004.06120

$$\Delta \simeq 100 \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

$$\Delta \simeq 10 \left(\frac{m_T}{1\,\mathrm{TeV}}\right)^2$$

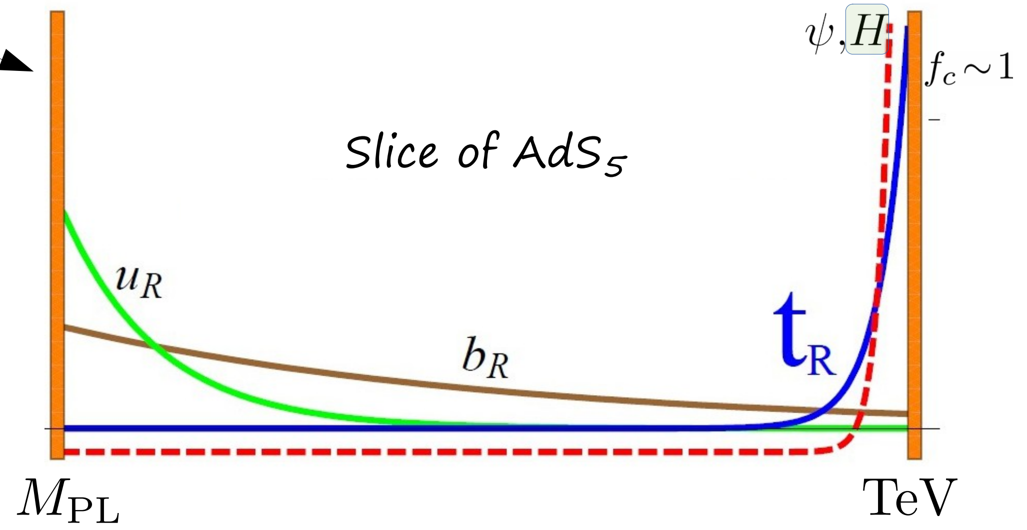
$$\Delta \simeq 10$$

- $m_T > 2\,\mathrm{TeV}$ possible without notable tuning
- beyond that, no longer flat $\leftrightarrow$ tuning in ϵ

$$m_h \simeq \frac{m_T}{f} m_t \, \frac{\sqrt{\epsilon}}{2(1-\epsilon/4)} \qquad \epsilon \equiv \; 1 - M/m_s$$

Very Natural 5D Picture

UV brane:
elementary
sector



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$_5$

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

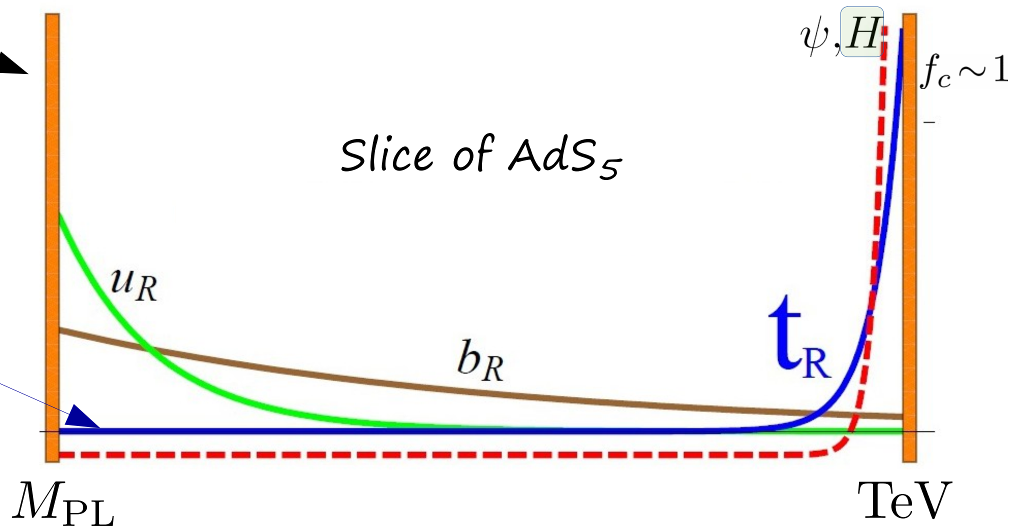
SO(5) preserving universal BCs,
breaking by *finite* UV-brane masses

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

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)
- Lepton sector might have interesting impact
- 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

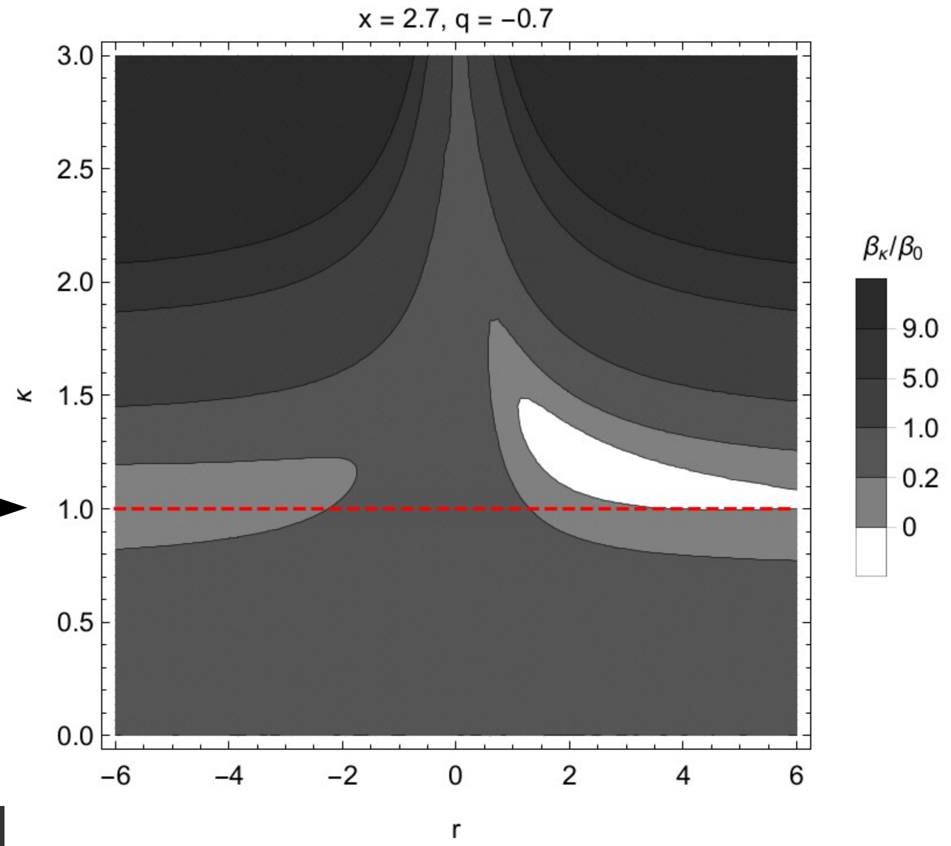
Goldstone Restoration as Source of Effect

- 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



Restore Global Symmetry in Linear Mixings

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

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

$$\psi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ -i\sqrt{2}\, s_L \end{pmatrix} \qquad \psi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} v_R^2 - w_R^1 \\ -iv_R^2 - iw_R^1 \\ v_R^1 + w_R^2 \\ iv_R^1 - iw_R^2 \\ -i\sqrt{2}\, t_R \end{pmatrix}$$

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 $\qquad$ $\tilde{T}, s$

$m_s, m_v \to \infty$ 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 $MCHM_5$

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

$sMCHM_5$

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

$< \beta(0)$

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

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

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

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

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

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

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

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

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

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

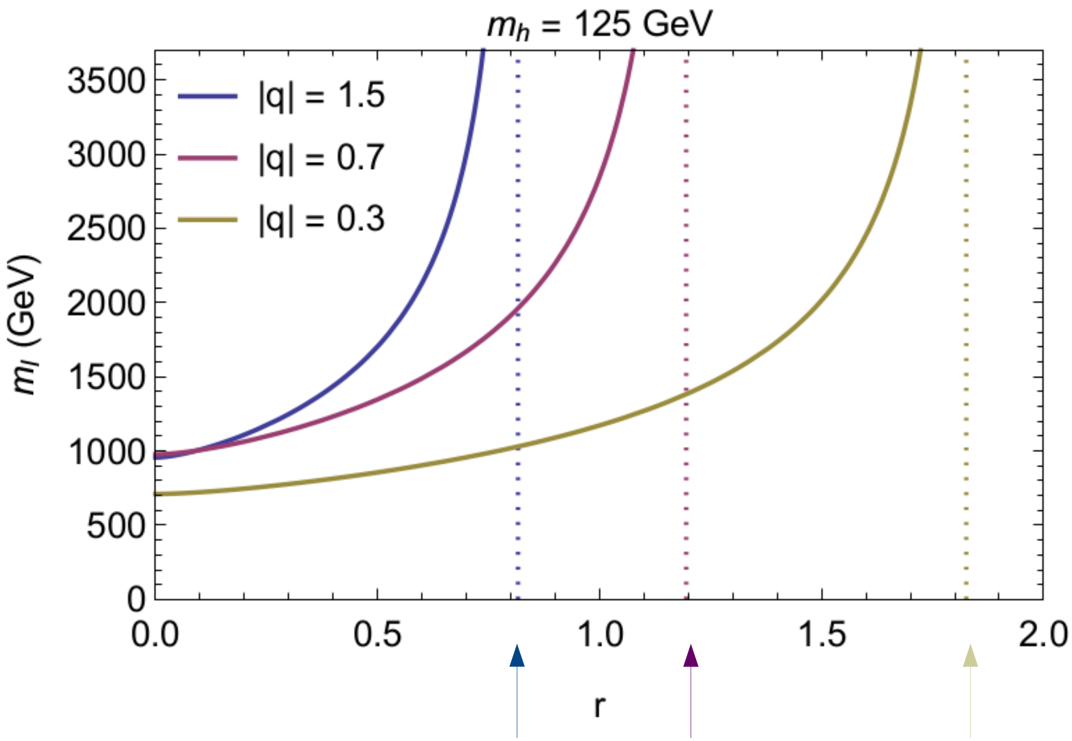
$$m_Q \xrightarrow{q^2r^4\to 1} \infty$$

Suggests possibility of light Higgs with heavy resonances

Case I: Top Partners

Lightest top partner in sMCHM_5

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



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

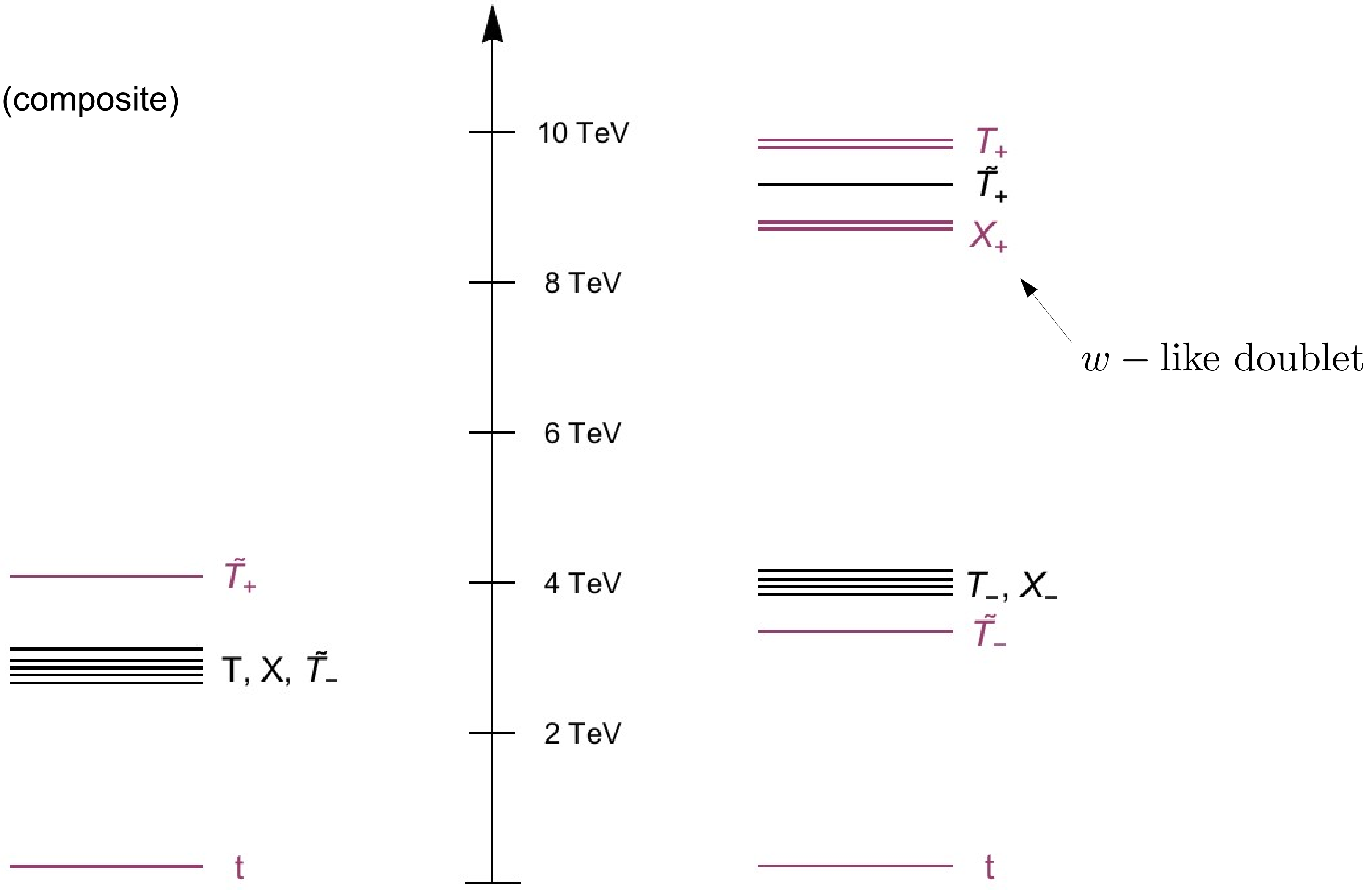
$q = m_Q/\tilde{m}_T$

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

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

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

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

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

$h,\,\Psi$

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

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

$$\Psi = \underset{\mathbf{4}}{(Q,}\ \underset{\mathbf{1}\text{ of }SO(4)}{\tilde{T})^T}$$

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

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

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

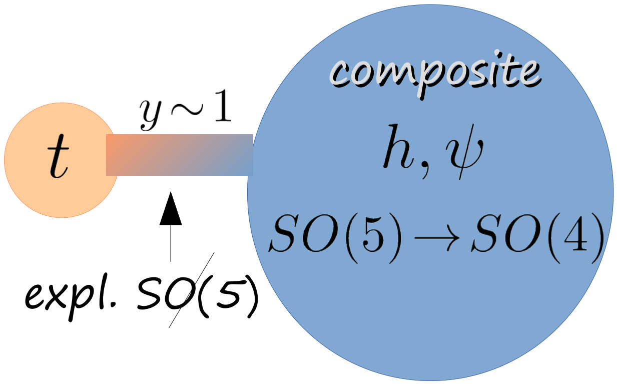
$\boxed{SO(5)_{V'}:\ L^\dagger V R = V}$ 'Maximal Symmetry'

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

Higgs Potential: Reduced Tuning

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

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



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

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

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

Spurion Analysis

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

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

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

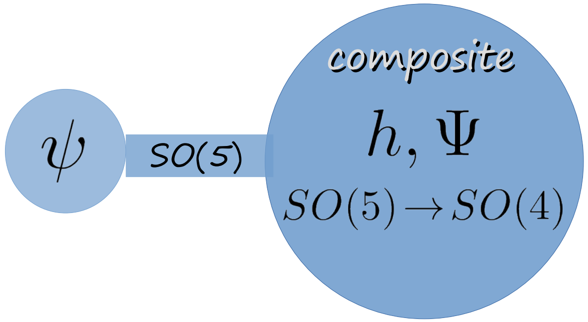
$$\to V(h) \sim y_L^2 y_R^2 f^4 \mathrm{Tr}[\Sigma'^\dagger \Gamma_L \Sigma' \Gamma_R] \sim \boxed{y_L^2 y_R^2 f^4 \sin^2(h/f) \cos^2(h/f)}$$

$\boxed{\alpha = -\beta \to \text{No double tuning :)}}$ $\boxed{\sin^2(v/f) = 1/2 \quad :(}$ $\to$ tune with gauge contribution

Maximally Symmetric sMCHM$_5$

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

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



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

need to split w-doublet

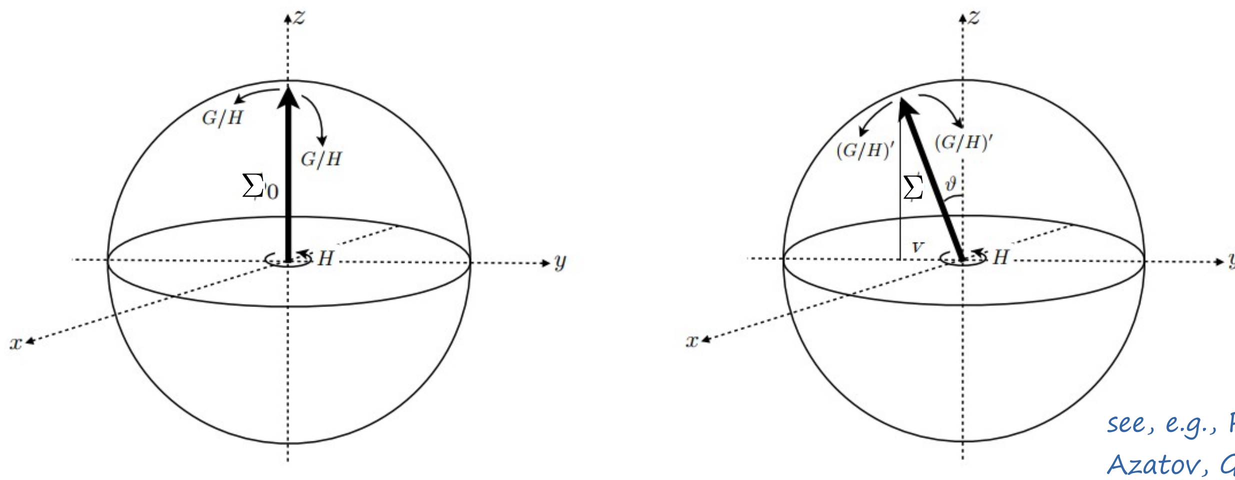
Spurion Analysis

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

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

$\boxed{\alpha \sim \mathcal{O}(y_L^2 y_R^2) \sim \beta \to \text{No double tuning :)}}$ $\boxed{\sin^2(v/f) \neq 1/2 \;\; :)}$

Vacuum Misalignment



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

Explicit $\mathcal{G}$ breaking $\rightarrow \langle h \rangle > 0 \Rightarrow$ 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: $v = f \sin\vartheta\,, \quad f = |\Sigma_0|$

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

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

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

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

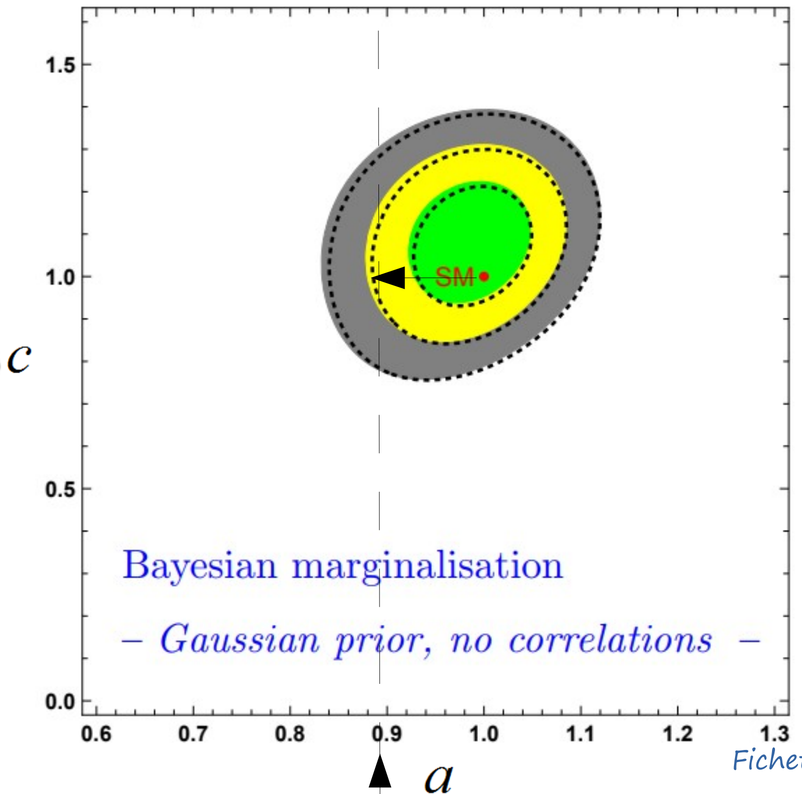
Higgs Couplings

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

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

depends on fermion embedding

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



Fichet, Moreau, 1509.00472

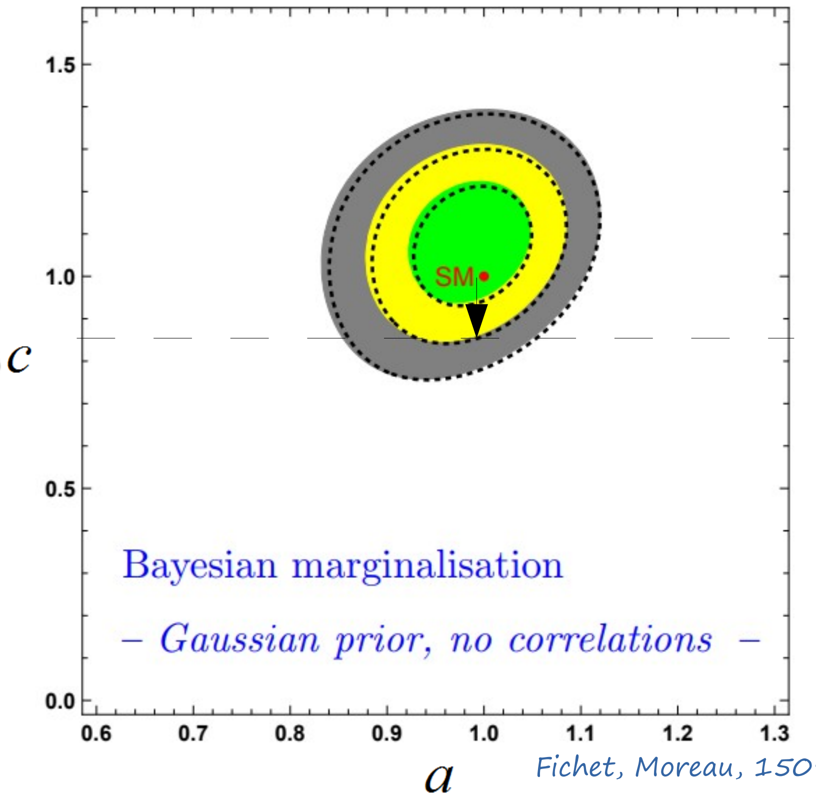
$\xi \approx 0.2 \to f \approx 550\,\mathrm{GeV}$

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)

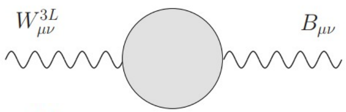
. . .

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

Electroweak Precision Tests

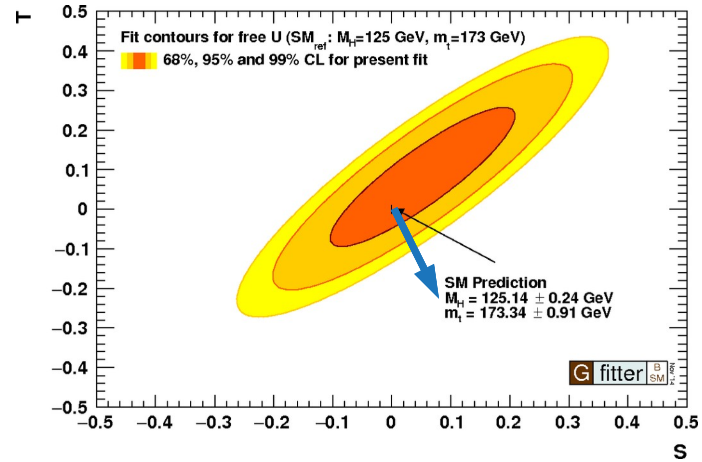
- Tree Level (SO5/SO(4)) :

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



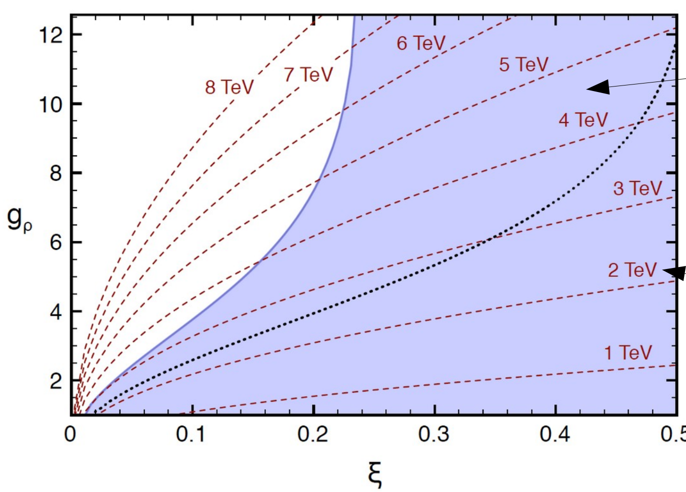
$$T = 0 \text{ (custodial)}$$

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



- 1-loop: modified Higgs-Gauge couplings

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



excluded (99% CL)

m_ρ

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