Direct Search Implications for a Custodially-Embedded Composite Top

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Summary

The following work is based on research performed by R. Sekhar Chivukula, R. Foadi, D. Foren, E. Simmons.

We update and extend the analysis of a model presented in **arXiv:1105.5437v3 [hep-ph]**.

∼Outline∼

- ⋆ Motivation
- ⋆ Bi-Doublet + Singlet Model → DESM + Singlet
- ⋆ Updated Precision EW Constraints
- ⋆ Direct Search Limits

Why is the Top Quark Heavy?

- Maybe...

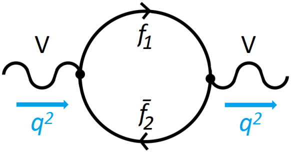
$$\star\textbf{top quark} = \textbf{heavy}\star$$
$$\Updownarrow$$
$$\star\textbf{top quark} = \textbf{substantially composite}\star$$

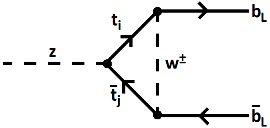
- Particularly, add vector-like "top partners"...

$$\textbf{top quark} = \textbf{(SM, Yukawa)} + \sum_i \textbf{(VL, Dirac)}_i$$

We'll alter the top sector and leave rest of SM unchanged.

$\hat{T}$-parameter, g_{Lb}





$$\hat{T} \equiv \frac{\Pi^{new}_{WW}(0)}{m_W^2} - \frac{\Pi^{new}_{ZZ}(0)}{m_Z^2}$$

0 in SM AND experimentally $\Longrightarrow$ OK!

$g_{Lb} \equiv$ coupling of Zb_Lb_L

SM: -0.42114
Exp: -0.4182 ± 0.0015
$\Longrightarrow \approx 2\sigma$ **discrepancy!**

Bi-Doublet + Singlet: New Particles

∼New (Vector-Like) Particles∼

1	$+\frac{5}{3}$	quark	(exotic)	Ω
3	$+\frac{2}{3}$	quarks	(top-like)	$t_1^q,\ t_1^\Psi,\ t_1$
1	$-\frac{1}{3}$	quark	(bottom-like)	b_1

To control corrections to $\hat{T}$ and g_{Lb}, embed new fermions in **custodial multiplets** $(SU(2)_L \times SU(2)_R \to SU(2)_c)$:

$$Q_1 \equiv (q_1, \Psi_1) \equiv \begin{pmatrix} t_1^q & \Omega_1 \\ b_1 & t_1^\Psi \end{pmatrix} \quad \text{and} \quad t_1$$

Also, embed the usual Higgs in a custodial bi-doublet:

$$\Phi \equiv (i\sigma_2\varphi^*, \varphi)$$

Bi-Doublet + Singlet: Lagrangian

$$
\begin{aligned}
\mathcal{L}_{bi\text{-}doublet+singlet} = {} & \overline{q}_{0L} i\not{D} q_{0L} + \overline{t}_{0R} i\not{D} t_{0R} + \overline{b}_{0R} i\not{D} b_{0R} \\
& + \overline{t}_1 i\not{D} t_1 + \mathrm{Tr}\left(\overline{Q}_1 i\not{D} Q_1\right) \\
& - M_t \overline{t}_1 t_1 - M_q \mathrm{Tr}\left(\overline{Q}_1 Q_1\right) \\
& - \mu_q \left(\overline{q}_{0L} q_{1R} + \text{h.c.}\right) - \mu_t \left(\overline{t}_{1L} t_{0R} + \text{h.c.}\right) \\
& - y_q \left[\mathrm{Tr}\left(\overline{Q}_{1L}\Phi\right) t_{0R} + \text{h.c.}\right] - y_t \left[\mathrm{Tr}\left(\overline{Q}_{1L}\Phi\right) t_{1R} + \text{h.c.}\right]
\end{aligned}
$$

6 variables!

To reduce this...

- Reproduce top quark mass to eliminate one variable.
- Take $\mu_q \to \infty$ to obtain the **DESM + singlet limit**. (This eliminates q_{0L} and q_{1R}, and removes y_q as well.)

DESM + Singlet

The $\mu_q \to \infty$ limit of the Bi-doublet + Singlet model is,

$$\mathcal{L}_{top} = \bar{t}_{0R} i \not{D} t_{0R} + \bar{t}_1 i \not{D} t_1 + \text{Tr}\left(\overline{Q}_{1L} i \not{D} Q_{1L}\right) + \overline{\Psi}_{1R} i \not{D} \Psi_{1R}$$
$$- M_t \bar{t}_1 t_1 - M_q \left(\overline{\Psi}_{1L} \Psi_{1R} + \text{h.c.}\right)$$
$$- \mu_t \left(\bar{t}_{1L} t_{0R} + \text{h.c.}\right) - y_t \left[\text{Tr}\left(\overline{Q}_{1L} \Phi\right) t_{1R} + \text{h.c.}\right]$$

3 Remaining Parameters

$$M_q \qquad M_t \qquad \sin\beta \equiv \frac{\mu_t}{\sqrt{M_t^2 + \mu_t^2}}$$

The three remaining top-like gauge eigenstates will mix to form **three top-like mass eigenstates:** t, T, T^{Ψ}.

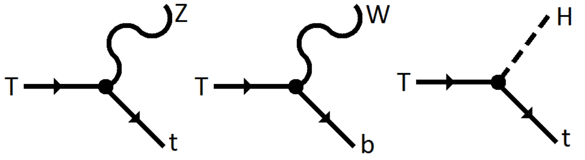
Application of Direct Search Limits

Note

T^{Ψ} is always heavier than direct limits,
limits on $+5/3$ quark Ω are less stringent.

$\Downarrow$

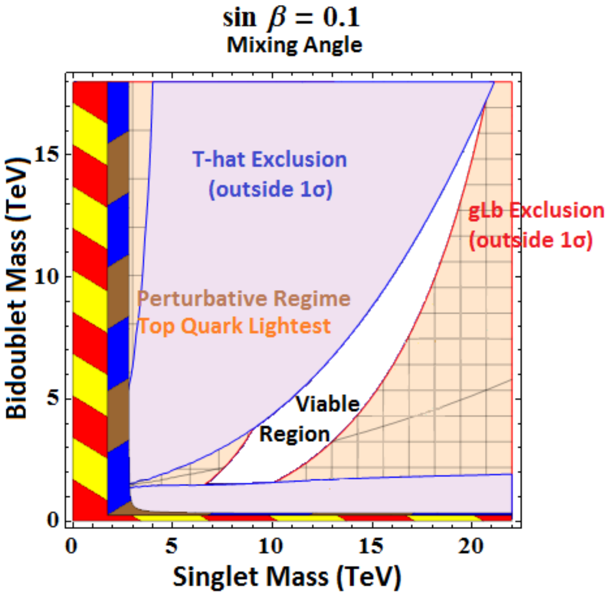
⋆**Focus on lighter top partner T**⋆



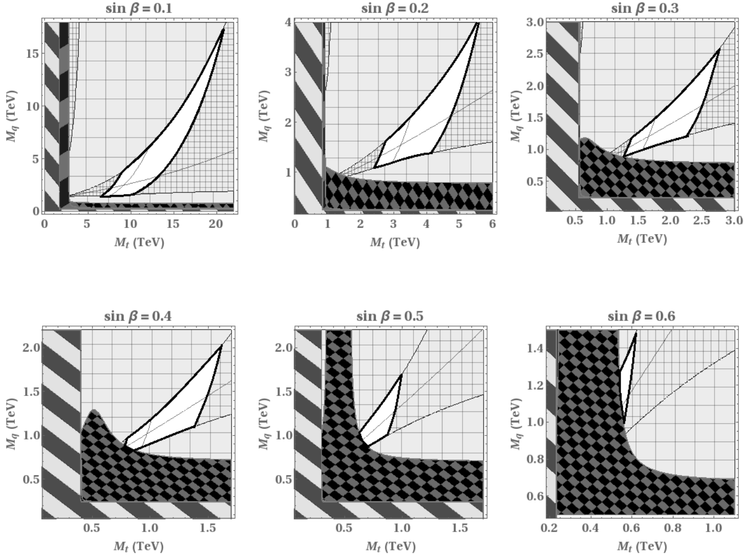
A point of $(M_q, M_t, \sin\beta)$ space is **viable** if:

- reproduces experimental $\hat{T}$, g_{Lb} to within 1σ
- T evades experimental **direct limits**.

Illustration of Updated EW Constraints



EW Constraints + Direct Search Limits



Checkerboard = Eliminated by **Direct Search Limits**

Conclusion

DESM + Singlet is **viable** for:

$$0.05 \lesssim \sin\beta \lesssim 0.65$$

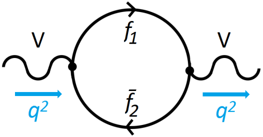
(by reproducing $\hat{T}, g_{Lb}$ & satisfying direct limits)

This strongly suggests that **the full bi-doublet + singlet model is similarly viable** across a significant subset of parameter space.

Thank You for your Attendance!
Questions?

BONUS SLIDES

$\hat{T}$, $\hat{S}$-parameters

$i\Pi^{12}_{VV}(q^2) =$ 

$$\hat{T} \equiv \frac{\Pi^{new}_{WW}(0)}{m_W^2} - \frac{\Pi^{new}_{ZZ}(0)}{m_Z^2}$$

$\approx$ measures **custodial isospin violation**

$$\hat{S} \equiv 4c^2 s^2 \left[\frac{\Pi^{new}_{ZZ}(m_Z^2) - \Pi^{new}_{ZZ}(0)}{m_Z^2} - \frac{c^2 - s^2}{cs} \frac{\Pi^{new}_{ZZ}(0)}{m_Z^2} - \frac{\Pi^{new}_{\gamma\gamma}(m_Z^2)}{m_Z^2} \right]$$

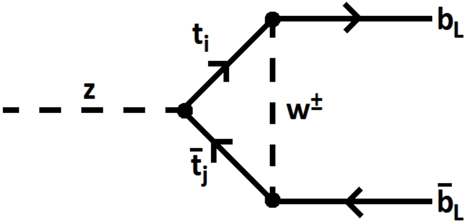
$\approx$ measures **presence of new chiral fermions**

(*much weaker constraint for our model*)

$\hat{T} = \hat{S} = 0$ **in SM AND experimentally**

g_{Lb}

$g_{Lb} \equiv$ coupling of $Zb_L b_L$



∼Interesting∼

Standard Model:	-0.42114
Experiment:	-0.4182 ± 0.0015

There's a discrepancy!

Addressing Potential Concerns

$$m_t = \sin\beta \frac{y_t v}{\sqrt{2}} \sqrt{\frac{(M_q^2 - 2m_t^2)(M_t^2 - m_t^2 \cot^2\beta)}{(M_q^2 - m_t^2)(M_t^2 - m_t^2 \cos^2\beta)}} \sim \sin\beta \frac{y_t v}{\sqrt{2}}$$

Therefore, y_t has to (roughly) increase like $1/\sin\beta$ to maintain m_t.

$$g_L[Ht\bar{t}] = -\frac{1}{\sqrt{2}} y_t R_{t2j}(L^*_{ti1} + L^*_{ti2})$$

$L, R =$ essentially mixing angles, so y_t is twice-suppressed by mixing, yielding overall a weaker $Ht\bar{t}$ coupling.

The Bi-Doublet + Singlet Model can arise as an EFT of new strong dynamics or extra dimensions, which would ensure vacuum stability via additional new physics.