Flavour symmetry in partially composite unification

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based on w.i.p. with S Kvedaraite, G Lee, SJ Lee
and on w.i.p. with W Leung and M Starbuck

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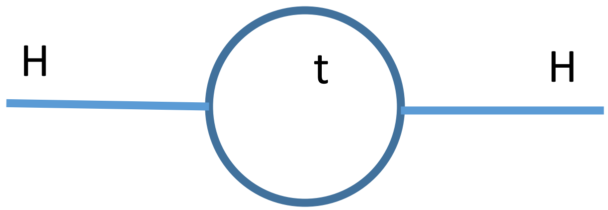
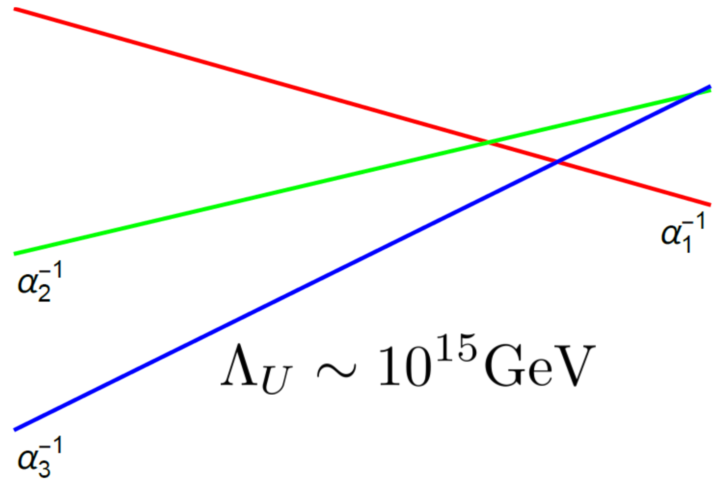
Outline

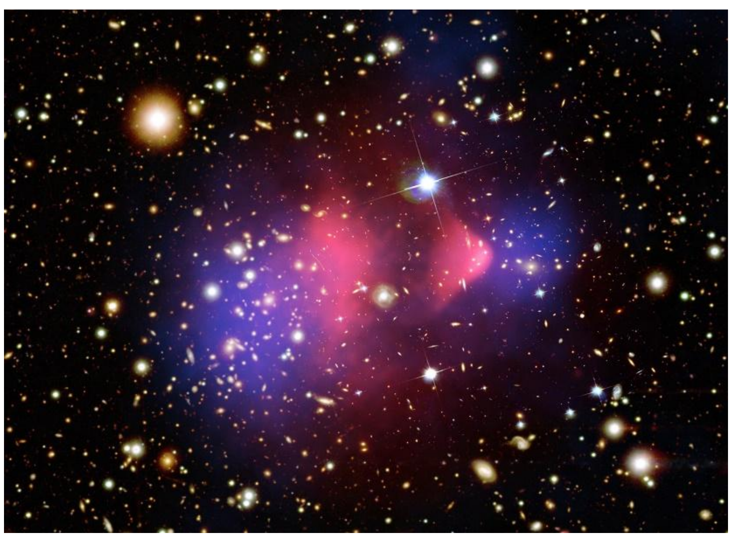
1) Motivation
2) Partial compositeness
3) Unification
4) Flavour symmetry
5) Putting things together
6) Conclusions

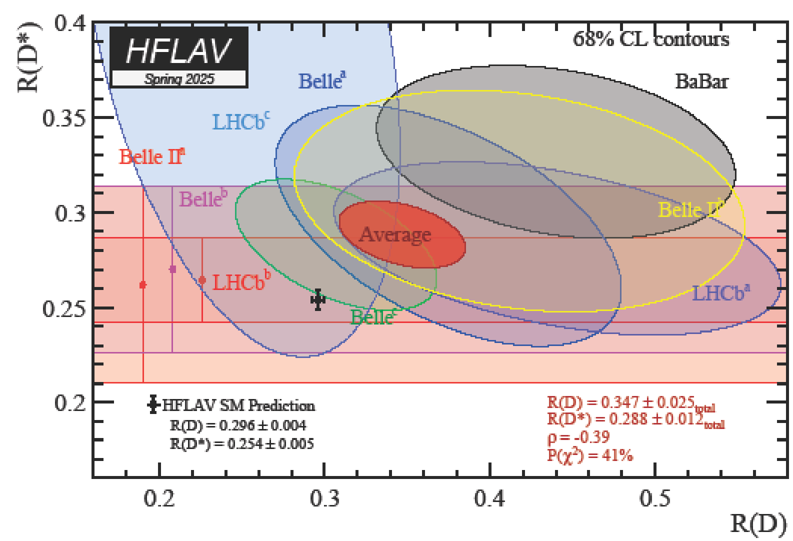
Some motivations for BSM



$$\Delta m_H^2 \propto y_t^2 \Lambda_{\rm UV}^2$$







Composite Higgs

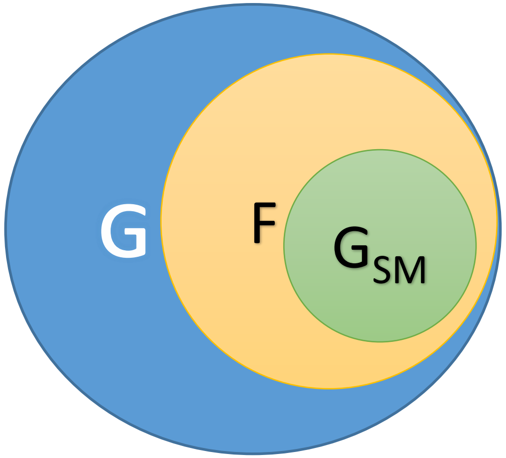
Basic idea: Higgs = bound state of a new sector

To have a large UV cutoff (without tuning) should be close to a CFT

Symmetry of CFT should include

$G_{SM} = SU(3) \times SU(2)_L \times U(1)_Y$

conformal sym. broken at scale M ~ few TeV <<Λ, massive states



Higgs **may** be NGB - preferable for little hierarchy & to suppress $H \to \gamma\gamma$

Giudice, Grojean, Pomarol, Rattazzi 2007

weak gauging of G_{SM} explicitly breaks G,

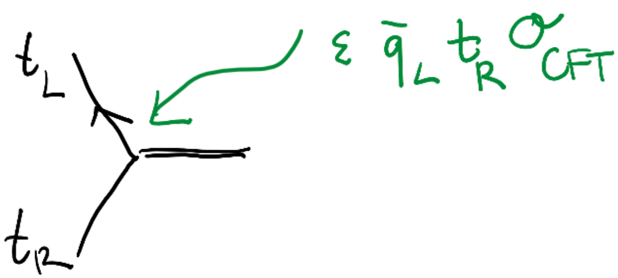
generates a Higgs potential (but typically no EWSB)

One realization: Randall-Sundrum (for NGB: gauge-Higgs unification)

Whence the flavour ?

- Need to couple top (and other fermions to the Higgs)
- How does CKM come about (and perhaps non-minimal flavour)?

If top is a composite state, or it is not but it is bilinearly coupled (as in basic technicolor-type constructions)



then generically also

& severe flavour problem, unless further engineering (walking; extended symmetries, …)

Partial compositeness

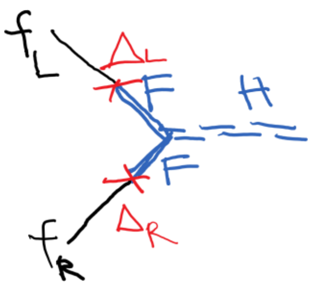
SM fermions are mixtures of elementary and composite particles,

$$|t_L^{\rm phys}\rangle \approx \cos\phi_{t_L}|t_L\rangle + \sin\phi_{t_L}|T_L\rangle$$

by virtue of linear mixing $\mathcal{L}_{\rm mix} \supset -\lambda_{tL}\bar{t}_L T_L \qquad (\sin\phi_{t_L} = \lambda_{t_L}/(1+\lambda_{t_L}^2))$

T_L = CFT spin ½ operator with dimension ~ 5/2 and $|T_L\rangle$ its lightest excitation (a Dirac fermion). Alleviates flavour problem (w.r.t. bilinear)

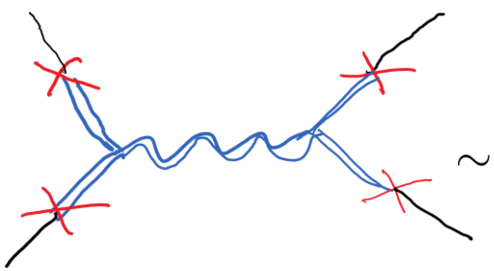
Can destabilize a pNGB Higgs potential & cause EWSB



$$Y_{ij} = (\Delta_L^\dagger M_L^{-1} \hat{Y} M_R^{-1} \Delta_R)_{ij}$$

Viable flavour from "anarchy"

Huber; Grossman & Neubert; Gherghetta & Pomarol; …



$$\sim \frac{g_*^2 \Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

for M ~ few TeV **requires some further symmetry**

Redi & Weiler; Barbieri, Isidori, Straub, …

EW precision & minimal model

To avoid tree-level T-parameter contributions

$\rightarrow \Delta\rho \sim \frac{M_W^2}{f^2} \ldots$

require a custodial symmetry;
minimal choice: $SU(2)_L \rightarrow SU(2)_L \times SU(2)_R \sim SO(4)$

$\rightarrow$ $G = SU(3) \times SO(5) \times U(1)_X$, $F = SU(3) \times SO(4) \times U(1)$,

$G \rightarrow F$ at scale $f < M$

for hypercharge

$\rightarrow$ NGB Higgs in $(0,2,2)_0$ representation
Minimal composite Higgs model

Agashe, Contino, Pomarol 2004

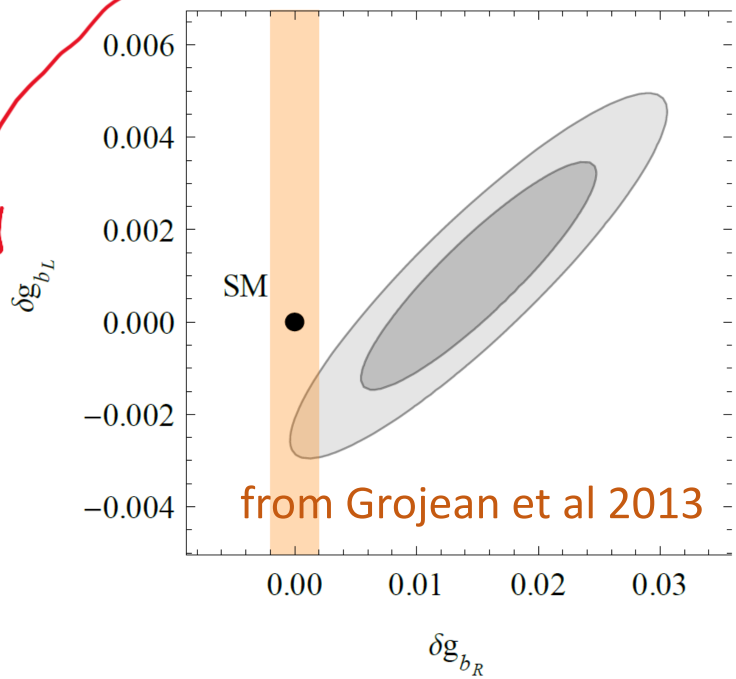
Various possible representations for top (and other matter) operators

Zqq coupling and P_{LR}

Generically, corrections to Z couplings of the form

$$\mathcal{L} = c_1 \,\mathrm{Tr}\left[\bar{Q}_L \gamma^\mu Q_L \hat{V}_\mu\right] + c_2 \,\mathrm{Tr}\left[\bar{Q}_L \gamma^\mu V_\mu Q_L\right] + c_3 \,\mathrm{Tr}\left[\bar{Q}_L \gamma^\mu i D_\mu U\right] \mathrm{Tr}[U^\dagger Q_L] + h.c.$$

$$\frac{g}{\cos\theta_W}\left[\frac{c_2 - c_1}{2}\,\bar{b}_L\gamma^\mu b_L - \frac{c_1 + c_2 + 2c_3}{2}\,\bar{t}_L\gamma^\mu t_L\right] Z_\mu - \frac{g}{\sqrt{2}}\,(c_2 + c_3)\,\bar{t}_L\gamma^\mu b_L W^+_\mu + h.c.$$



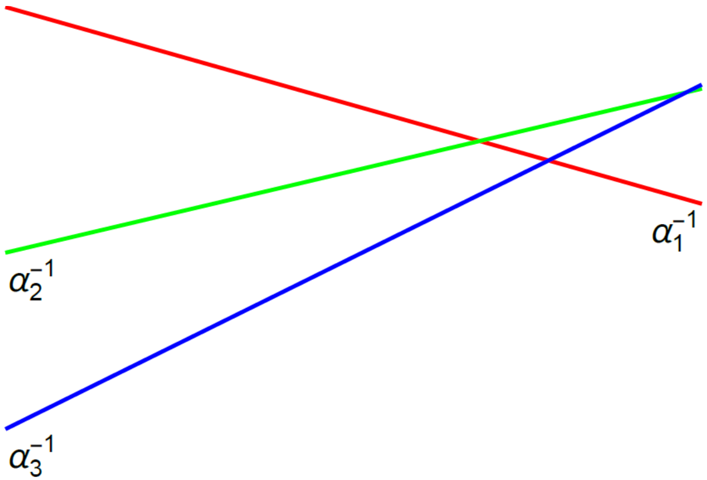
can kill Zb_Lb_L by enlarging SO(4) to O(4)

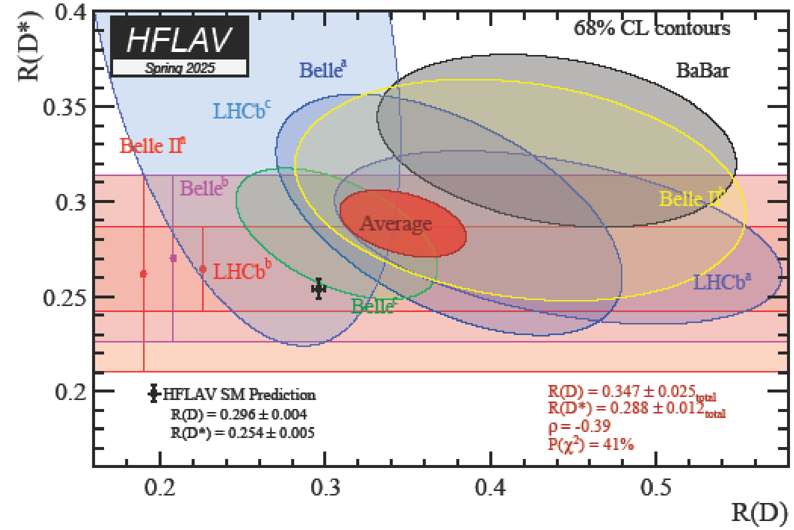
embed s.t. $T_{3L}(b_L) = T_{3R}(b_R)$

Agashe, Contino, DaRold, Pomarol 2006

The P_{LR} = O(4)/SO(4) can help with suppressing Bs -> mu mu, too.

Looking at the clues more closely



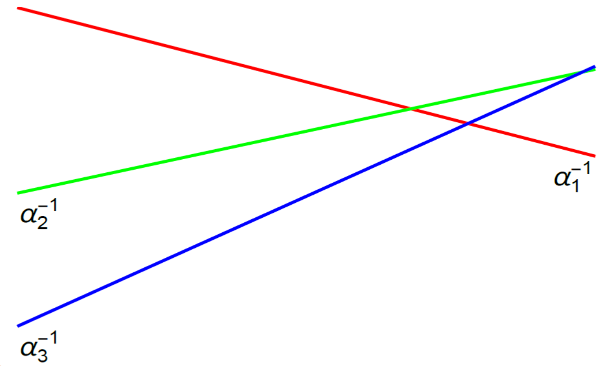


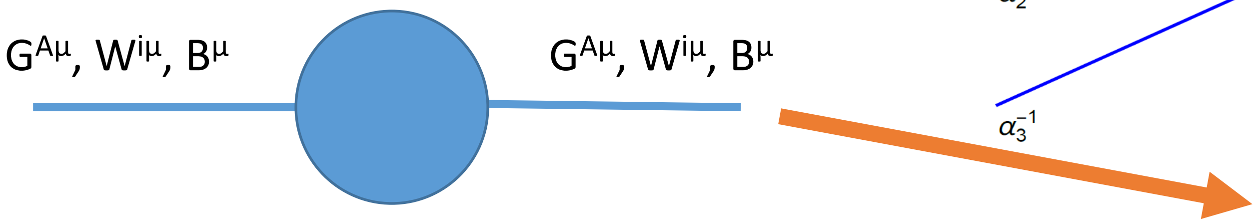
Imposes further requirements on the strong-sector symmetry and the embedding of the SM

suggests a vector leptoquark

Running couplings

Coupling unification **generally ruined** by strong sector contributions.





To preserve gauge coupling unification, strong-sector symmetry should be simple.

Agashe,Contino,Sundrum 2005
Frigerio,Serra,Varagnolo 2011

To preserve elementary matter unification, should have “GUT” U(1) normalisation; this translates to

$$\mathrm{tr} X^2 = \frac{2}{3}\mathrm{tr}(T_{3L}^2)$$

(extends to any SU(3)xSU(2) generator)

Kvedaraite, Lee, Lee, SJ, w.i.p.

(not always satisfied in the literature)

Partner unification & proton stability

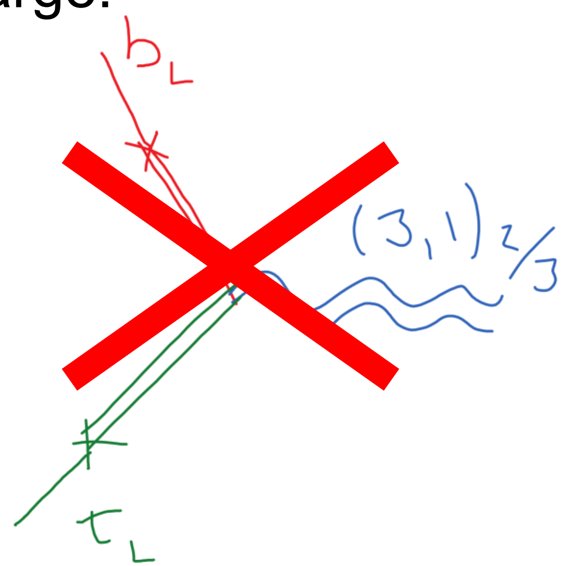
Generically, without B-conservation TeV-scale proton decay

Agashe & Servant 2004

“Standard” solution: $U(1)_B$ symmetry

Agashe & Servant 2004; Frigerio,Serra,Varagnolo 2011; Da Rold & Lamagna 2019

Generically lepton partners carry B-charge:
Prevents composite partner unification



Vector resonances corresponding to extra G-currents are **not** leptoquarks (even if they carry the correct SM quantum numbers)

SO(10) solutions

G' = SU(3) x SU(2) x SU(2) x $U(1)_X$ has rank 5.

Hence minimal rank for G is 5, in which case $U(1)_X$ is fixed as the commutant (centralizer) of SU(3) x SU(2) x SU(2) in G.

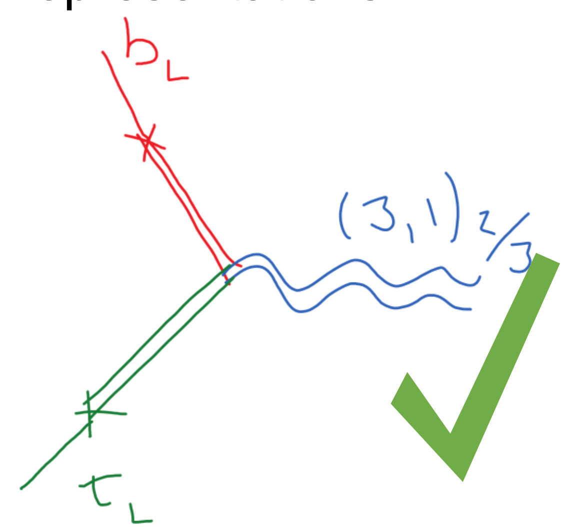
For G=SO(10) this is (up to normalization) the "B-L" generator

P_{LR} symmetry -> X=2/3 for the top

together with $\mathrm{tr} X^2 = \frac{2}{3} \mathrm{tr}(T_{3L}^2)$ restricts fermion representations.

Simplest solutions have X = 2 B.
X can be made a symmetry of the full model and we can unify some composite quark and lepton partners into multiplets, **making the $(3,1)_{2/3}$ vector a genuine leptoquark**

SO(11)/SO(10) pNGB models with viable EW sector can be constructed



Kvedaraite, Lee, Lee, SJ, w.i.p.

Two reference models

Two SO(10) embeddings that work (before considering flavour physics) are

Elementary fermion	Partner for 334 model "Model A"	Partner for 3355 model "Model B"
q_L^i	$\Psi^i \in \mathbf{120}$	$\Psi^i \in \mathbf{120},\ Q_D^i \in \mathbf{252}$
l_L^3	$\Psi^3 \in \mathbf{120}$	$\Psi^3 \in \mathbf{120}$
l_L^a	$L_L^a \in \mathbf{252}$	$L_L^a \in \mathbf{252}$
u_R^i	$U^i \in \mathbf{45}$	$U^i \in \mathbf{45}$
d_R^i	$D^i \in \mathbf{210}$	$D^i \in \mathbf{210}$
e_R^3	$E^3 \in \mathbf{45}$	$E^3 \in \mathbf{45}$
e_R^a	$E^a \in \mathbf{210}$	$E^a \in \mathbf{210}$

Flavour and flavour symmetry

Recall that without flavour symmetry in the strong sector, FCNC require NP scale in composite Higgs models to be tens of TeV. An example of the more generic NP flavour problem.

One approach: <u>Minimal Flavour violation</u>

Omitting the Higgs (and hence Yukawas), the SM Lagrangian reduces to what in partial compositeness is the "elementary" Lagrangian.

$$\mathcal{L}_{\rm el} = \sum_{f=q,l,u,d,e} i\bar{\psi}^i_f \not{D} \psi^i_f + \sum_a \frac{1}{g_a^2} \frac{1}{2} {\rm tr} \left(F^{(a)}_{\mu\nu} F^{(a)\mu\nu} \right)$$

L_{el} has a large flavour symmetry

$$\begin{aligned} {\rm G_{el}} &= {\rm U(3)}_q \times {\rm U(3)}_u \times {\rm U(3)}_d \times {\rm U(3)}_l \times {\rm U(3)}_e \\ &= G_{\rm quarks} \times G_{\rm leptons} \end{aligned}$$

Minimal flavour violation

Treating the Yukawas Y_U and Y_D as spurions of G_{quarks}

$$Y_U \ : \ (3, \bar{3}, 1) \qquad\qquad Y_D \ : \ (3, 1, \bar{3})$$

formally extends the G_{quarks} invariance to the full SM Langrangian including the Yukawa terms

$$\mathcal{L}_Y = \bar{q}_L Y_U u_R H + \bar{q}_L Y_D d_R H + \bar{l}_L Y_L e_R H$$

and as a result to the effective action. Allows to deduce the flavour structure of e.g. the weak Hamiltonian (CKM dependences and Yukawa suppressions).

postulate that also BSM Y_U and Y_D remain (the only) spurions of G_{quarks}-breaking.

Then one gets similarly strong suppressions of FCNC as in the SM (e.g., B-Bbar mixing ~ $(V_{td} V_{tb})^2$ and can have low BSM scale (TeV or lower).

D'Ambrosio, Giudice, Isidori, Strumia 2002

The sources of flavour breaking in a BSM model need to map to Y_U and Y_D (or at least these must be the only combinations that are relevant at low energies)

Left compositeness/left universality

Redi, Weiler 2011

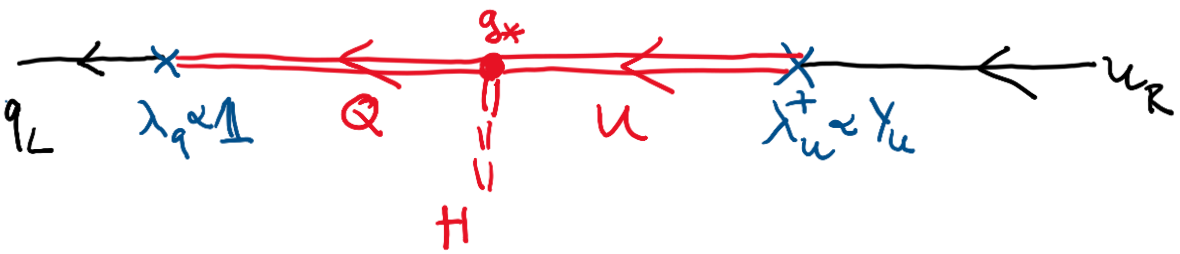
$$\mathcal{L}_{\text{mix}} = \bar{q}_L \lambda_q Q_R + \bar{u}_R \lambda_u U_R + \bar{d}_R \lambda_d D_R (+\text{possible leptonic terms})$$

Impose strong sector symmetry G_{strong} = $U(3)_Q$
implies flavour-universal partner masses and Higgs couplings
full (quark) flavour symmetry $G_{flavour}$ = $U(3)_Q$ x G_{quarks}

$$Q, U, D : (3,1,1,1) \quad \lambda_q : (\bar{3},3,1,1) \quad \lambda_u : (\bar{3},1,3,1) \quad \lambda_d : (\bar{3},1,1,3)$$

Require λ_q to preserve a $U(3)_{Q+q}$ i.e. $\lambda_q \propto \mathbf{1}_{3\times 3}$
Then $\lambda_u \propto Y_U^\dagger, \qquad \lambda_d \propto Y_D^\dagger$

Schematically,



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Partial universality (pLU)

Left compositeness implements MFV. FCNC processes allow partner masses ~ TeV.

Nevertheless, stringent constraints from CKM unitarity tests and from flavour-conserving contact interactions $\propto \lambda_q^4$

Requires mass scales O(10 TeV). Glioti, Rattazzi, Ricci, Vecchi 2024

Similar conclusion for ‘right compositeness/universality’ (where $\lambda_u, \lambda_d \propto \mathbf{1}$)

To alleviate, reduce the strong-sector symmetry. The price is nonminimal flavour violation and, in general, flavour constraints become **more stringent** compared to MFV.

Barbieri, Buttazzo, Sala, Straub, Tesi 2011-13
….. (many more)
Glioti, Rattazzi, Ricci, Vecchi 2024

Partial left universality

(Following setup of Glioti, Rattazzi, Ricci, Vecchi 2024)

Strong sector symmetry $U(2)_Q \times U(1)_Q$

Composite operators/states in 2+1 representations, singling out a set of "third generation" partners

$$\mathcal{L}_{\rm mix} = -\bar{q}_L \lambda_q^{(2)} Q_R - \bar{q}_L \lambda_q^{(1)} Q_{3R} - \bar{u}_R \lambda_u^{(2)} U_L - \bar{u}_R \lambda_u^{(1)} U_{3L} - \bar{d}_R \lambda_d^{(2)} D_L - \bar{d}_R \lambda_d^{(1)} D_{3L}$$

'Partial universality' of the quark doublet elementary-composite mixing:

$$\lambda_q^{(2)} \oplus \lambda_q^{(1)} = g_* \begin{pmatrix} \epsilon_q & 0 \\ 0 & \epsilon_q \\ 0 & 0 \end{pmatrix} \oplus g_* \begin{pmatrix} 0 \\ 0 \\ \epsilon_{q3} \end{pmatrix}$$

Leaves

$$G_{\rm flavour} = U(2)_{Q+q} \times U(1)_{Q+q} \times U(3)_u \times U(3)_d$$

under which

$$\lambda_u : (\bar{2} + \bar{1}, 3, 1) \qquad \lambda_d : (\bar{2} + \bar{1}, 1, 3)$$

Viable for partner masses as low as 3 TeV

Glioti, Rattazzi, Ricci, Vecchi 2024

pLU$_T$ Incorporating quark-lepton unification

SJ, Leung, Starbuck w.i.p.

Partial left universality can be extended to the SO(10) case, with unified bottom and tau. We replace

$$\mathcal{L}_{\rm mix} = -\bar{q}_L\lambda_q^{(2)}Q_R - \bar{q}_L\lambda_q^{(1)}Q_{3R} - \bar{u}_R\lambda_u^{(2)}U_L - \bar{u}_R\lambda_u^{(1)}U_{3L} - \bar{d}_R\lambda_d^{(2)}D_L - \bar{d}_R\lambda_d^{(1)}D_{3L}$$

$$\mathcal{L}_{\rm mix} = -\bar{q}_L\lambda_q^{(2)}Q_R - \bar{q}_L\lambda_q^{(1)}\Psi_R - \bar{u}_R\lambda_u^{(2)}U_L - \bar{u}_R\lambda_u^{(1)}U_{3L} - \bar{d}_R\lambda_d^{(2)}D_L - \bar{d}_R\lambda_d^{(1)}D_{3L}$$
$$-\lambda_\tau \bar{l}_{l3}\Psi_R$$

and (re)interpret the composite sector operators/fields as those of SO(10) model A. We have

$$G_{\rm flavour} = U(2)_{Q+q} \times U(1)_{\Psi+q} \times U(3)_u \times U(3)_d$$

under which again

$$\lambda_u : (\bar{2} + \bar{1}, 3, 1) \qquad \lambda_d : (\bar{2} + \bar{1}, 1, 3)$$

No LFV is generated. (The mechanism for generating lepton masses and neutrino mixings is left unspecified)

Spurion parameterization

Using G_{flavour} field redefinitions, one can achieve

$$\lambda_u = \lambda_u^{(2)} \oplus \lambda_u^{(1)} = \frac{1}{\epsilon_q}\begin{pmatrix} y_u & 0 \\ 0 & y_c \\ \theta_{u1} y_t & \theta_{u2} y_t \end{pmatrix} \left(U_u^{12}\right)^\dagger \oplus \frac{1}{\epsilon_{q3}}\begin{pmatrix} 0 \\ 0 \\ y_t \end{pmatrix}$$

$$\lambda_d = \lambda_d^{(2)} \oplus \lambda_d^{(1)} = \frac{1}{\epsilon_q}\begin{pmatrix} y_d & 0 \\ 0 & y_s \\ \bar\theta_{d1}^* y_b & \bar\theta_{d2}^* y_b \end{pmatrix} \oplus \frac{1}{\epsilon_{q3}}\begin{pmatrix} 0 \\ 0 \\ y_b \end{pmatrix}$$

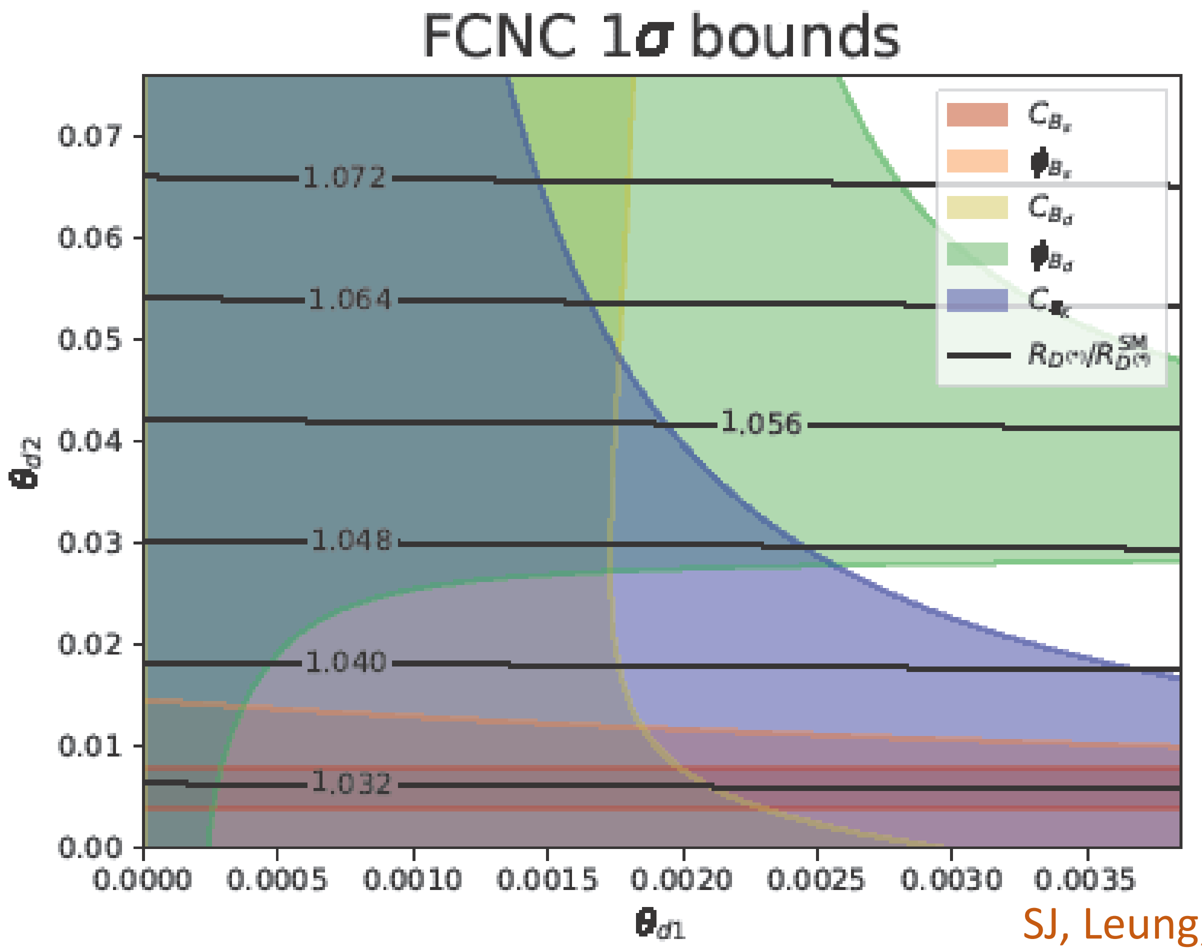
Spurion expressions for e.g. Delta F=2 agree with pLU

Computing the coefficient of $(\bar c_L \gamma^\mu b_L)(\bar\nu_\tau \gamma_\mu \tau_L)$ for the flavour observables $R_{D(*)}$ gives

$$C_{LL}^c \approx \frac{7}{12}\xi \epsilon_{q3}^2 \epsilon_{l3}^2 \left(1 - \frac{\theta_{d2}}{A\lambda^2} e^{i\phi_2 - i\gamma}\right)$$

(Apart from the normalization this would follow from a spurion analysis)

Partially left-universal case



SJ, Leung, Starbuck w.i.p.

Using Utfit results. Allows/prefers few-% effect in $R_{D(*)}$

Conclusions

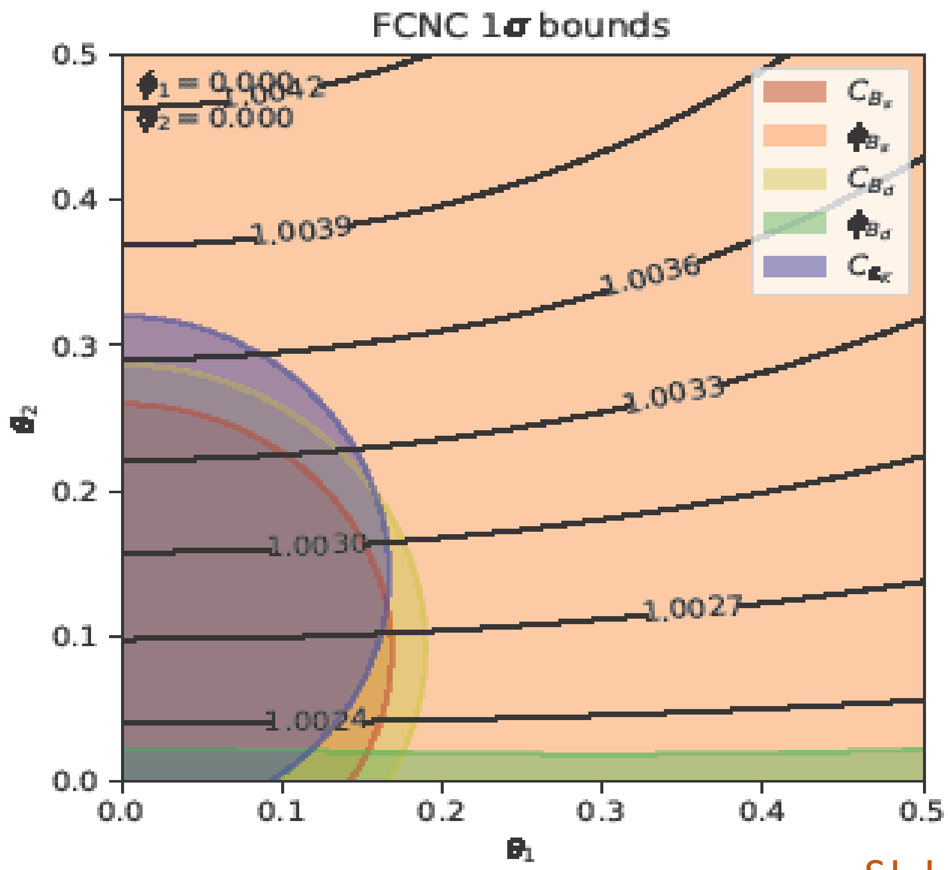
Composite Higgs with partial compositeness can stabilize the weak/GUT hierarchy.

Preserving grand unification imposes requirements on the embedding of the SM into the strong sector symmetry group. May or may not allow unifying composite partners connected by vector leptoquarks

Showed how to incorporate quark/lepton composite unification into an MFV-inspired flavour-symmetric scenario, resulting in non-negligible effects in semileptonic B decays.

BACKUP

Partially up-right-universal case



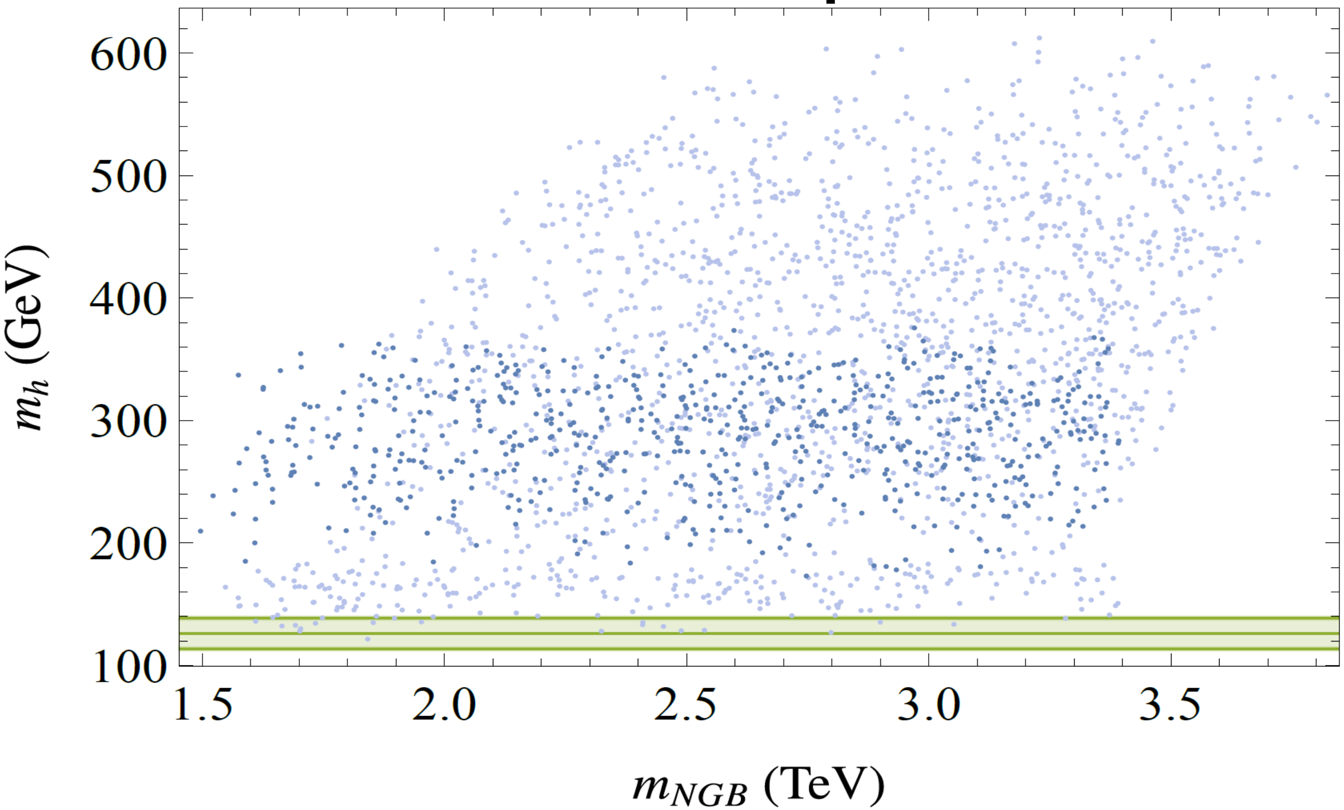
SJ, Leung, Starbuck w.i.p.

Only allows permille-level effects in $R_{D^{(*)}}$

Higgs mass vs colour triplet mass

"33 model"

f=2 TeV

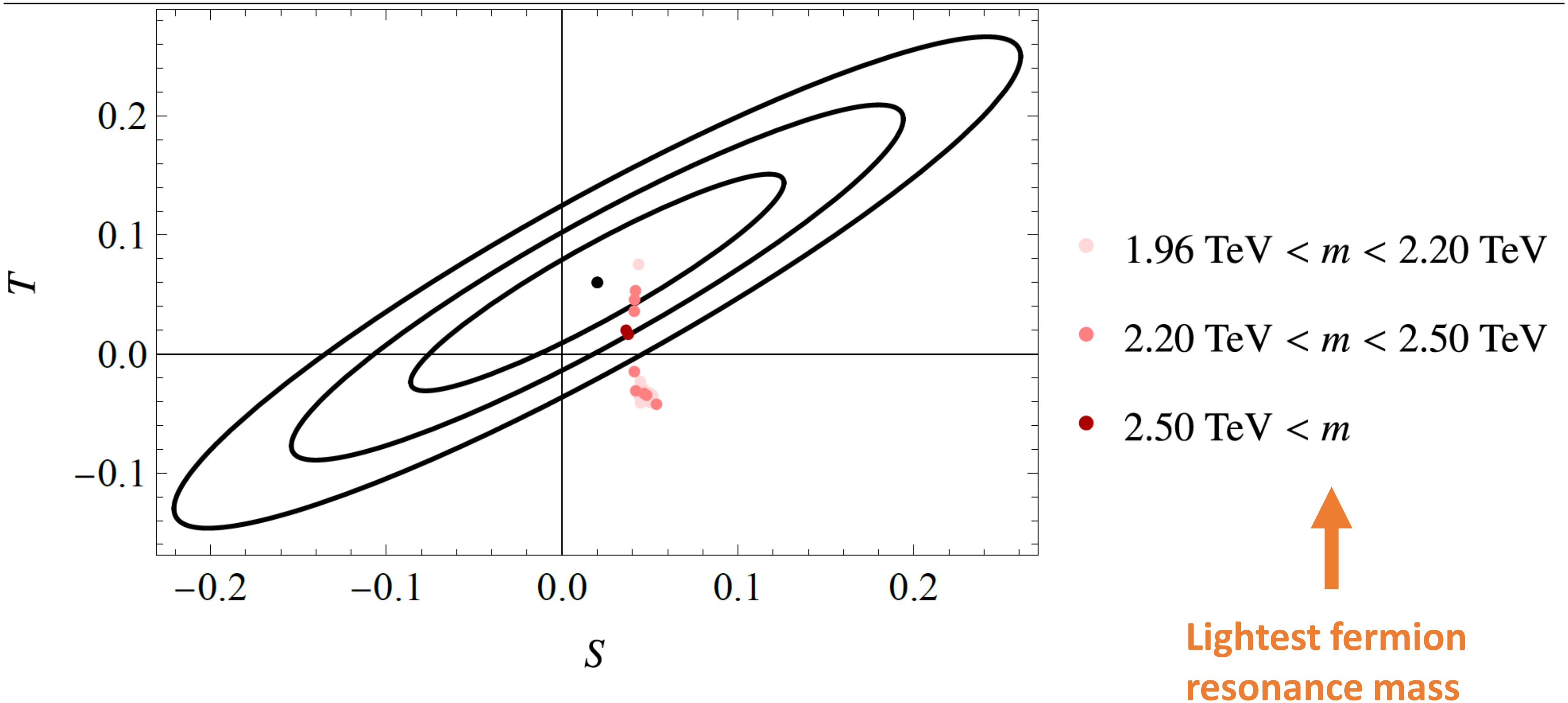


Tends to overshoot Higgs mass (similarly to $MCHM_{5+5}$)

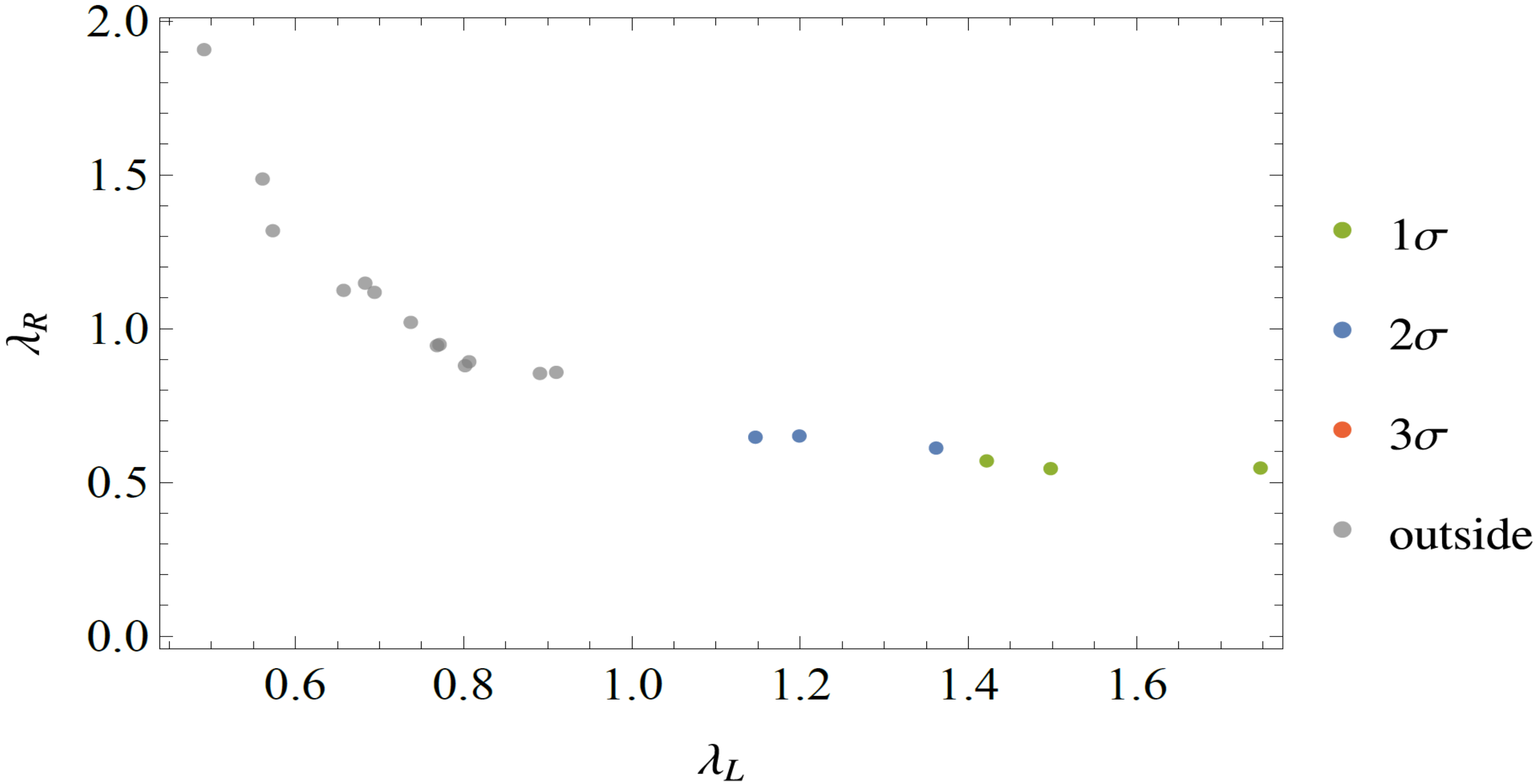
However, allows relatively light Higgs and colour triplet, reduing tuning of Higgs mass/EWSB compared to other fermion embeddings

EW oblique corrections

33 model, all points acceptable Higgs, top and NGB mass



left/right top compositeness vs EWPT



EWPT favour large left-handed compositeness