Composite unification and top physics

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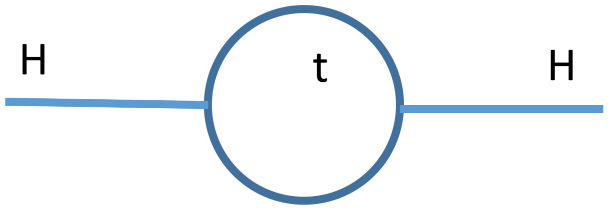
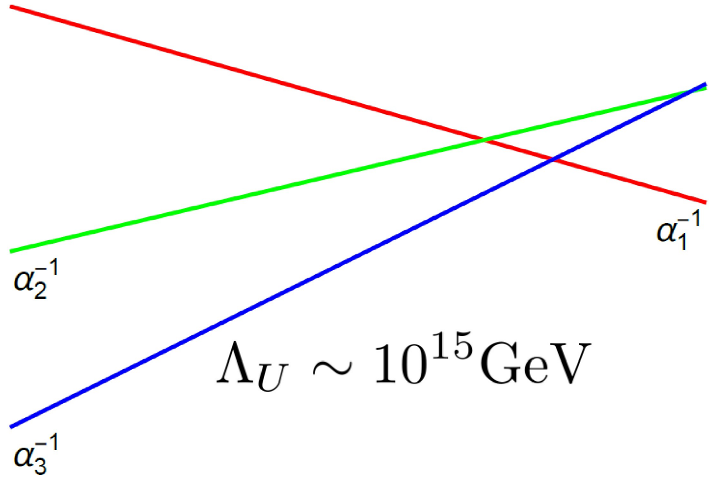
Outline

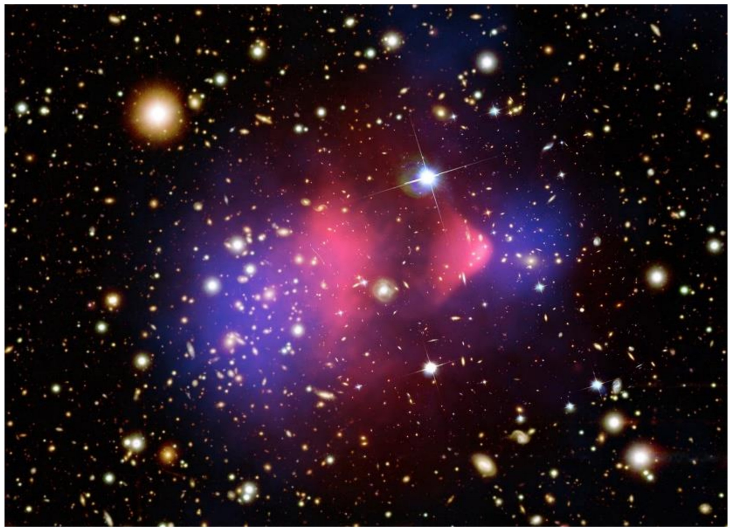
1) Motivation
2) Composite Higgs
3) Top partners
4) Composite Higgs, unification, leptoquarks
5) Conclusions

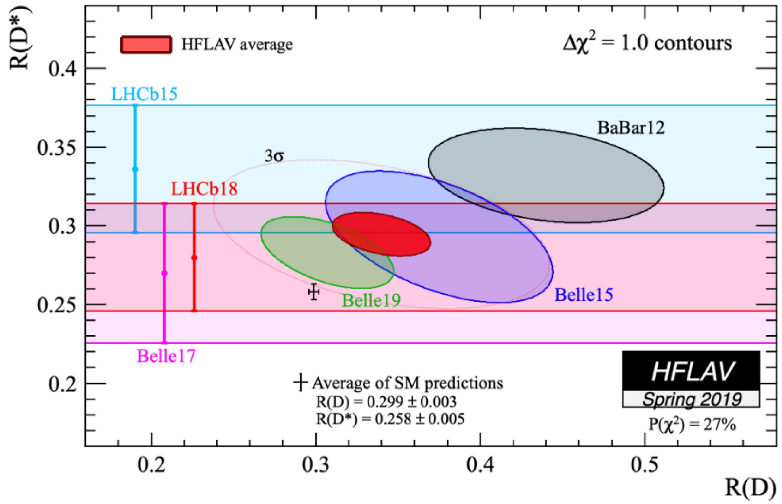
Some motivations for BSM



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





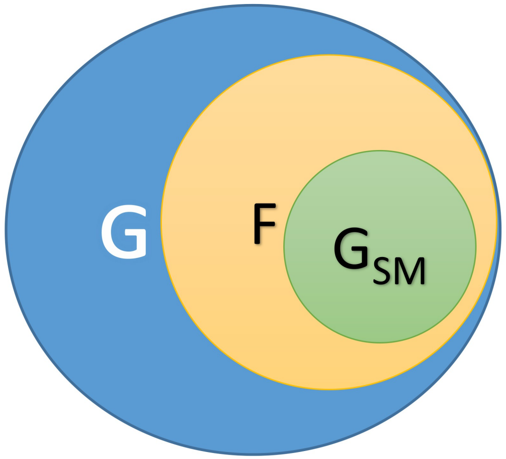


Composite Higgs

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

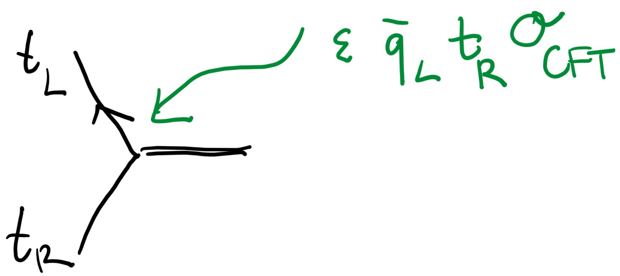
weak gauging of G_{SM} explicitly breaks G,
  generates a Higgs potential (but typically no EWSB)

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

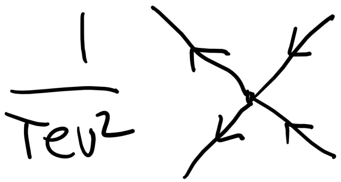
Whence the flavour ?

- 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

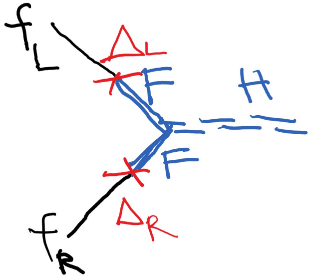
SM fermions are mixtures of elementary and composite particles,

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

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)

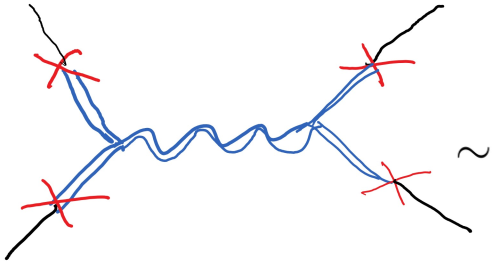
Can destabilize a pNGB Higgs potential & cause EWSB



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

Viable flavour from "anarchy"

Huber; Grossman & Neubert; Gherghetta & Pomarol; …



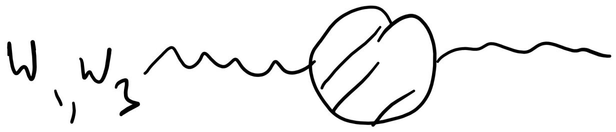
$$\sim \frac{g_*^2\Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

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) x SO(5) x U(1), F = SU(3) x SO(4) x U(1),

G → 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 operators

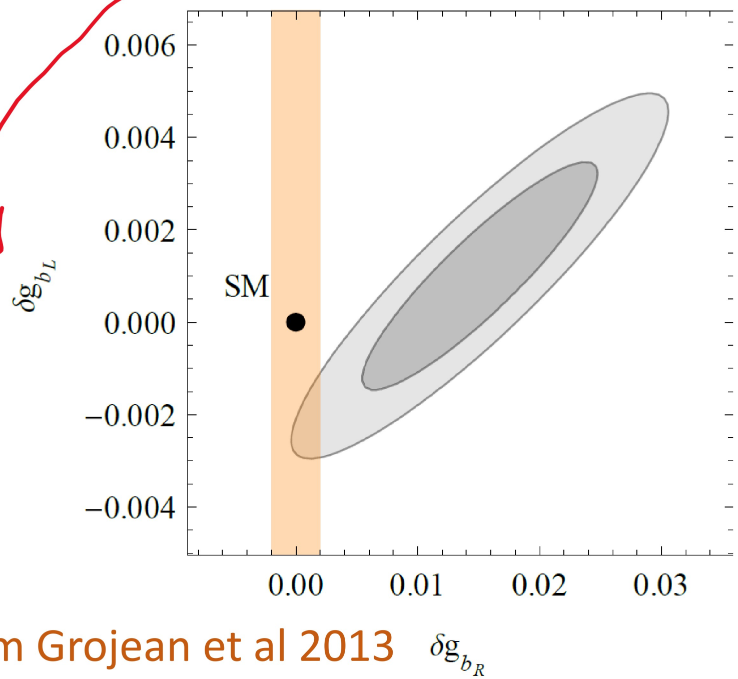
original choice was (4, 2, 1) & (4,1,2) (spinors under SO(4))
" $MCHM_4$ "

Zqq coupling

Generically, corrections to Z couplings of the form

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

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



from Grojean et al 2013

Targets for LHC top physics

can kill Zb_Lb_L by enlarging SO(4) to O(4) provided $T_{3L}(b_L) = T_{3R}(b_R)$

Agashe, Contino, DaRold, Pomarol 2006

Then $\quad \delta g_{t_L} \gtrsim \frac{y_t^2}{g_\psi^2}\frac{v^2}{f^2}$

Top partners

To protect Zbb via P_{LR}, tL should be in $(3, 2, 2)_{2/3}$ & tR in $(3, 1,1)_{2/3}$ (both can fit in 5 of SO(5): $MCHM_{5+5}$)

Gives top partner states B, T, $X_{2/3}$, $X_{5/3}$ (from 2 x SU(2) doublet) and $\tilde{T}$ (SU(2) singlet) , various decays involving tops

Table 7: Expected and observed lower limits on the T and B quark masses.

$\mathcal{B}$(bW)	$\mathcal{B}$(tZ)	$\mathcal{B}$(tH)	Expected Limit (TeV)	Observed limit (TeV)
1.0	0	0	1.44	1.54
0	1.0	0	1.47	1.48
0	0	1.0	1.55	1.50
0.50	0.25	0.25	1.41	1.49
0	0.50	0.50	1.50	1.50

$\mathcal{B}$(tW)	$\mathcal{B}$(bZ)	$\mathcal{B}$(bH)	Expected Limit (TeV)	Observed Limit (TeV)
1.0	0	0	1.51	1.56
0	1.0	0	1.08	1.12
0	0	1.0	1.12	1.11
0.50	0.25	0.25	1.38	1.47
0	0.50	0.50	1.09	1.12

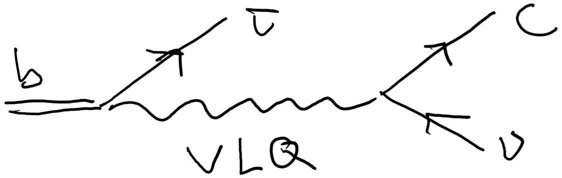
CMS PAS B2G-20-011

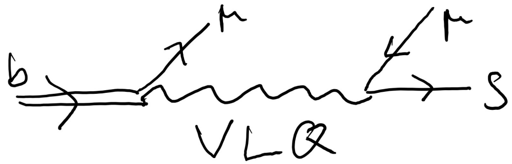
Leptoquarks & unification

Flavour anomalies:

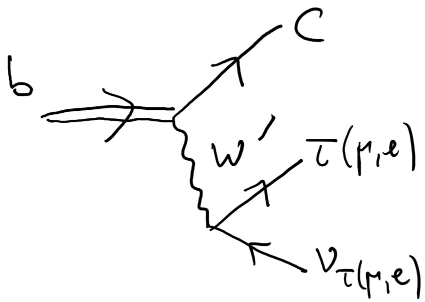
$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right) \qquad \frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

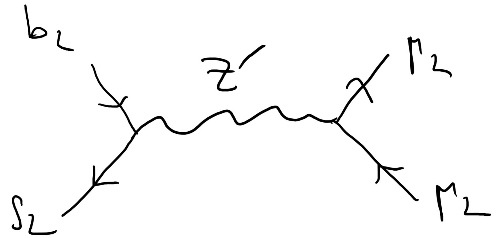
Vector leptoquarks $(3, 1, 2/3)$





W'/Z' triplet $(0, 3, 0)$

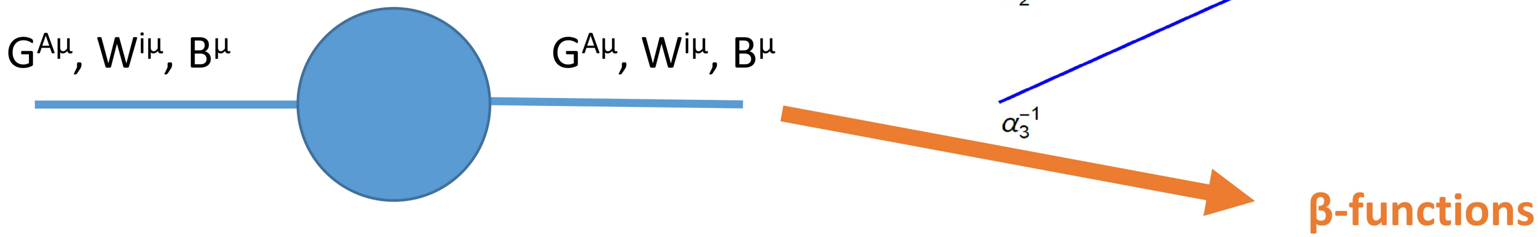


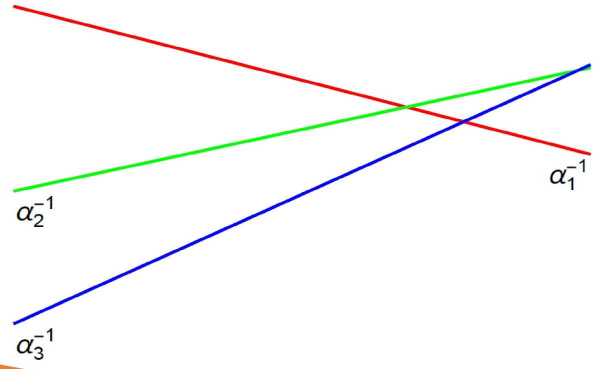


Can we have a composite vector leptoquark ?

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, meaning

$$\frac{3}{5}\mathrm{tr}Y^2 = \mathrm{tr}(T^2)$$ (T any SU(3)xSU(2) generator)

(not always satisfied in the literature)

Partner unification & proton stability

Generically, without B-conservation TeV-scale proton decay

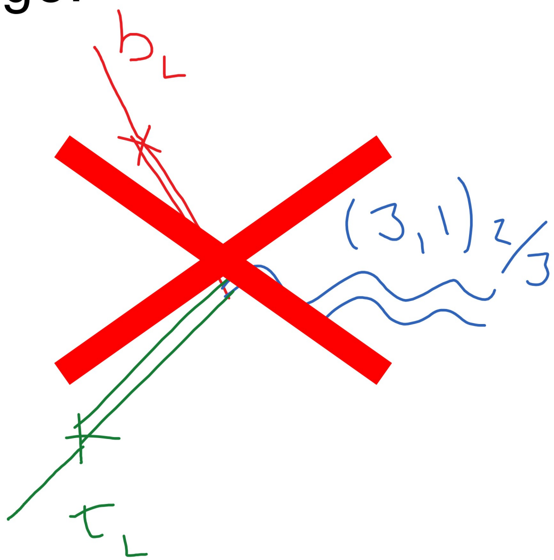
Agashe & Servant 2004

“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) 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

- If we have P_{LR} symmetry we know X=2/3 for the top, which together with the condition $\mathrm{tr}X^2 = \frac{2}{3}\mathrm{tr}(T_{3L}^2)$ restricts the possible fermion representations.

- If we have $B \propto X$ with X=0 for the lepton partners then we can unify quark and lepton partners

A concrete assignment

We can embed s.t. under SO(10) > SU(4) x SU(2)xSU(2),

$$t_L \in (15, 2, 2), \quad t_R \in (15, 1, 1)$$

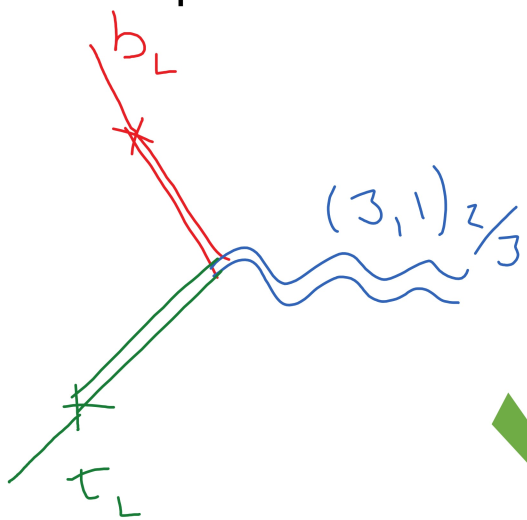
Under SU(3) x U(1)$_X$, $\quad 15 = 8_0 + 3_{2/3} + \bar{3}_{-2/3} + 1_0$

(15,2,2)$_L$ contains colour singlet with the correct quantum numbers to embed left-handed leptons

τ_L naturally unified with t_L, b_L.

X must be a symmetry of entire model: assign X = B to elementary fields

Proton stable. Vector in $(3,1)_{2/3}$ become genuine vector leptoquark!



(See also [Da Rold & Lamagna 2019], though their model does not seem to unify.)

“Calculable” model & phenomenlogy

Minimal model

Consider O(11) x $U(1)_F$ / [O(10) x $U(1)_F$] pNGB Higgs realization

[$U(1)_F$ “fermion number”: forbid TeV-scale Weinberg operator]

Embed, t_L, b_L, e_L and v_L in a single SO(11) irrep 165 (per generation)

Embed t_R either in 165 (“33 model”) or 55 (“23 model”)

(d_R, e_R can go in 330 but will be irrelevant here)

Higgs will be a pNGB in 10 of O(10) together with a **colour triplet**

Compute (in “2-site” approximation)

top mass and top partner masses

top partners now in SO(10) multiplets: includes
colour octet “gluino” states (expt > 1.96 TeV)

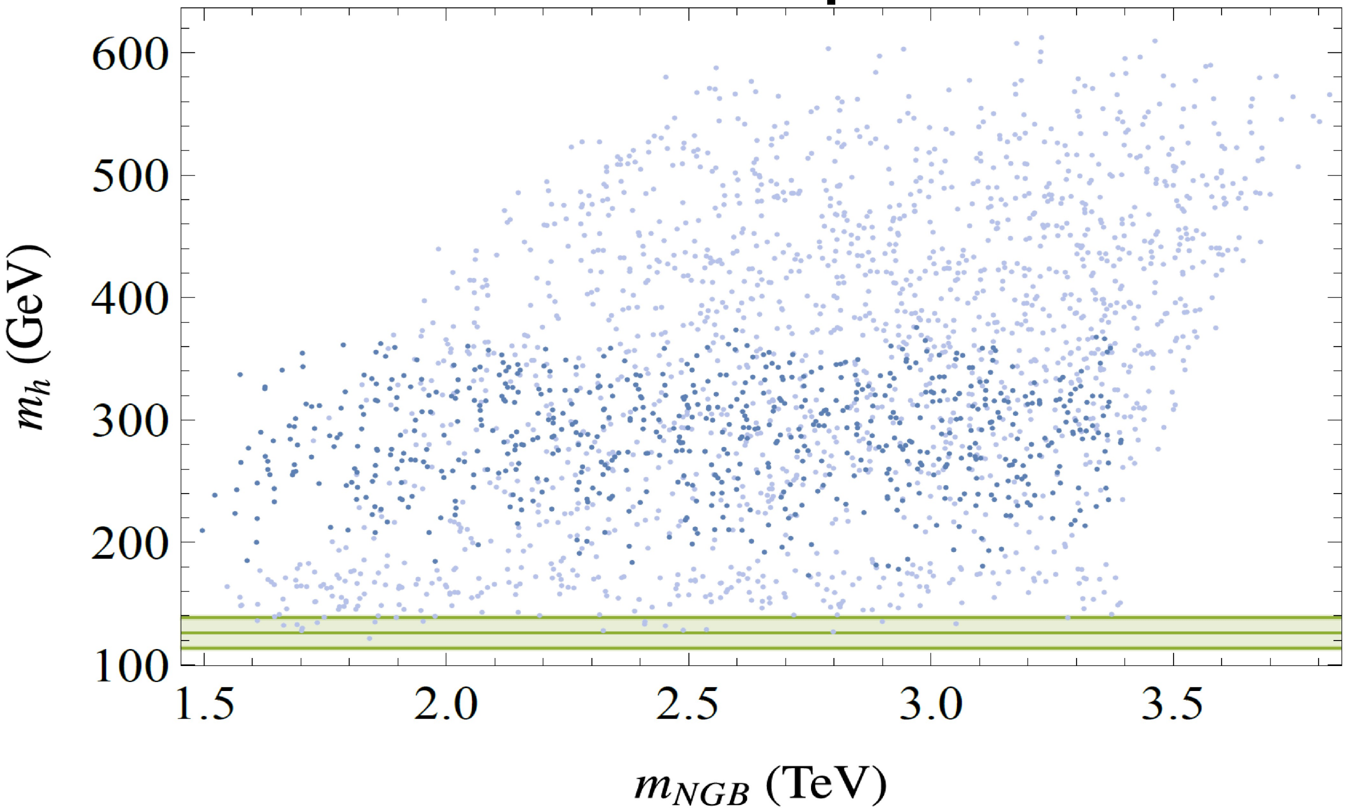
pNGB potential and masses

electroweak S and T parameters

Higgs mass vs colour triplet mass

33 model

f=2 TeV



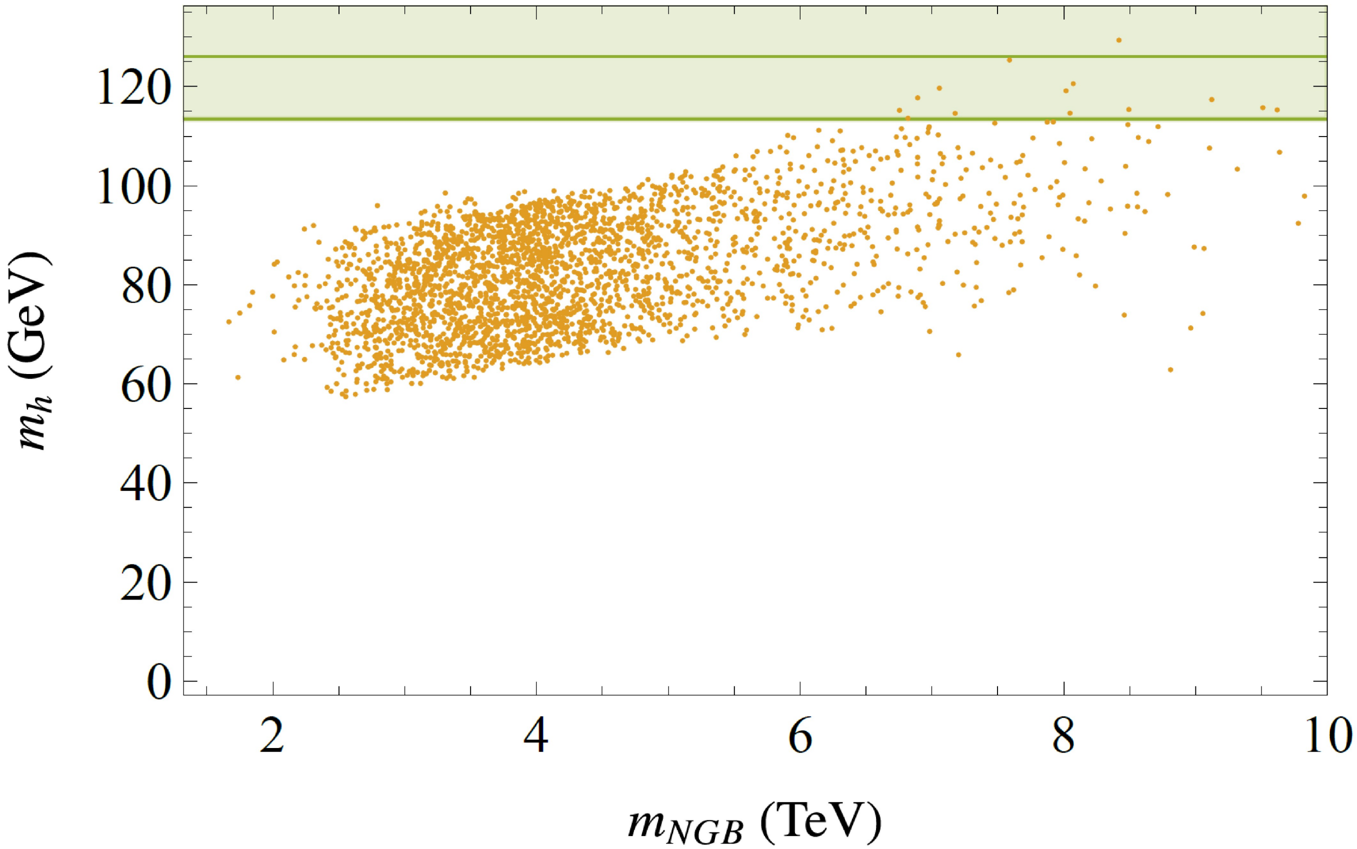
Tends to overshoot Higgs mass but can be viable (just as in $MCHM_{5+5}$)

allows relatively light pNGB, less tuning of Higgs mass/EWSB

Higgs mass vs colour triplet mass

23 model

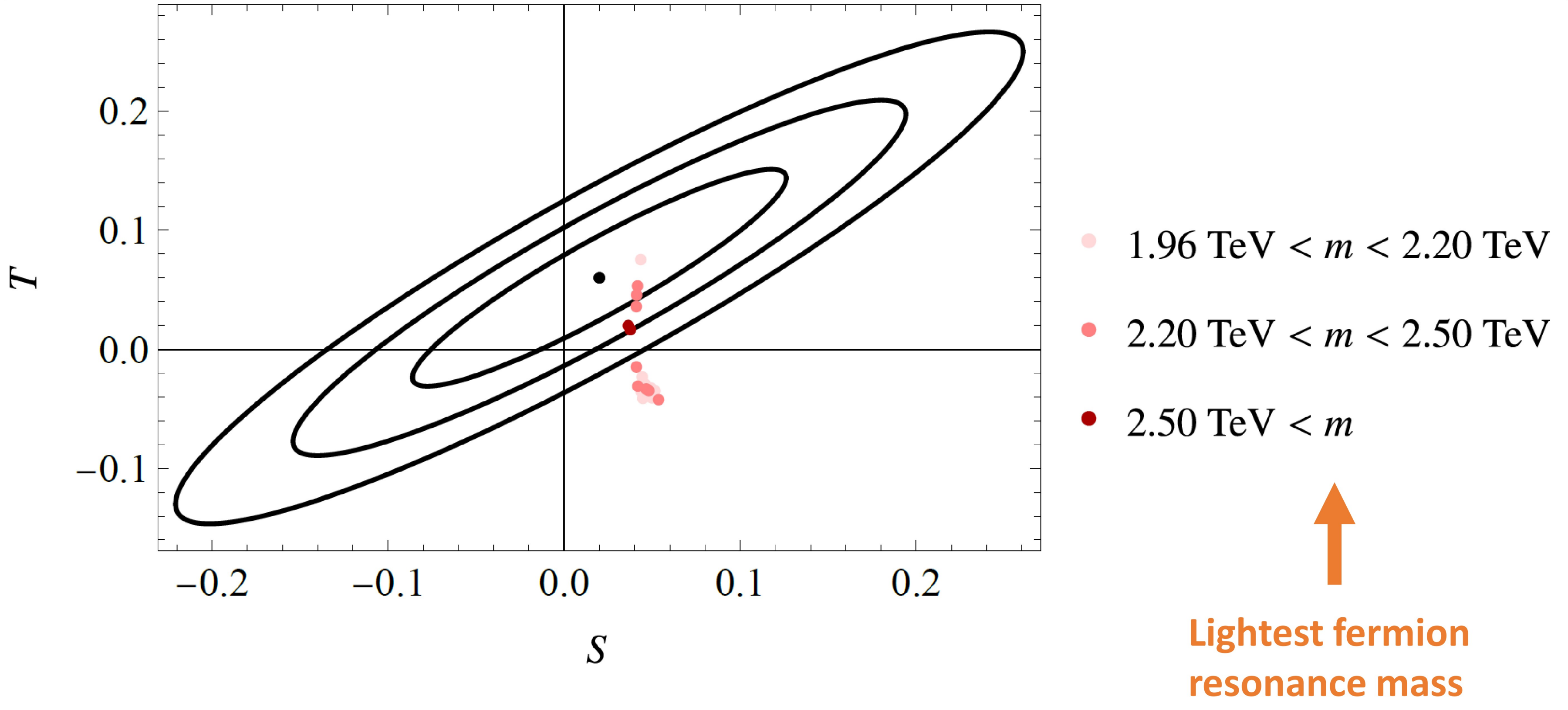
f=2 TeV



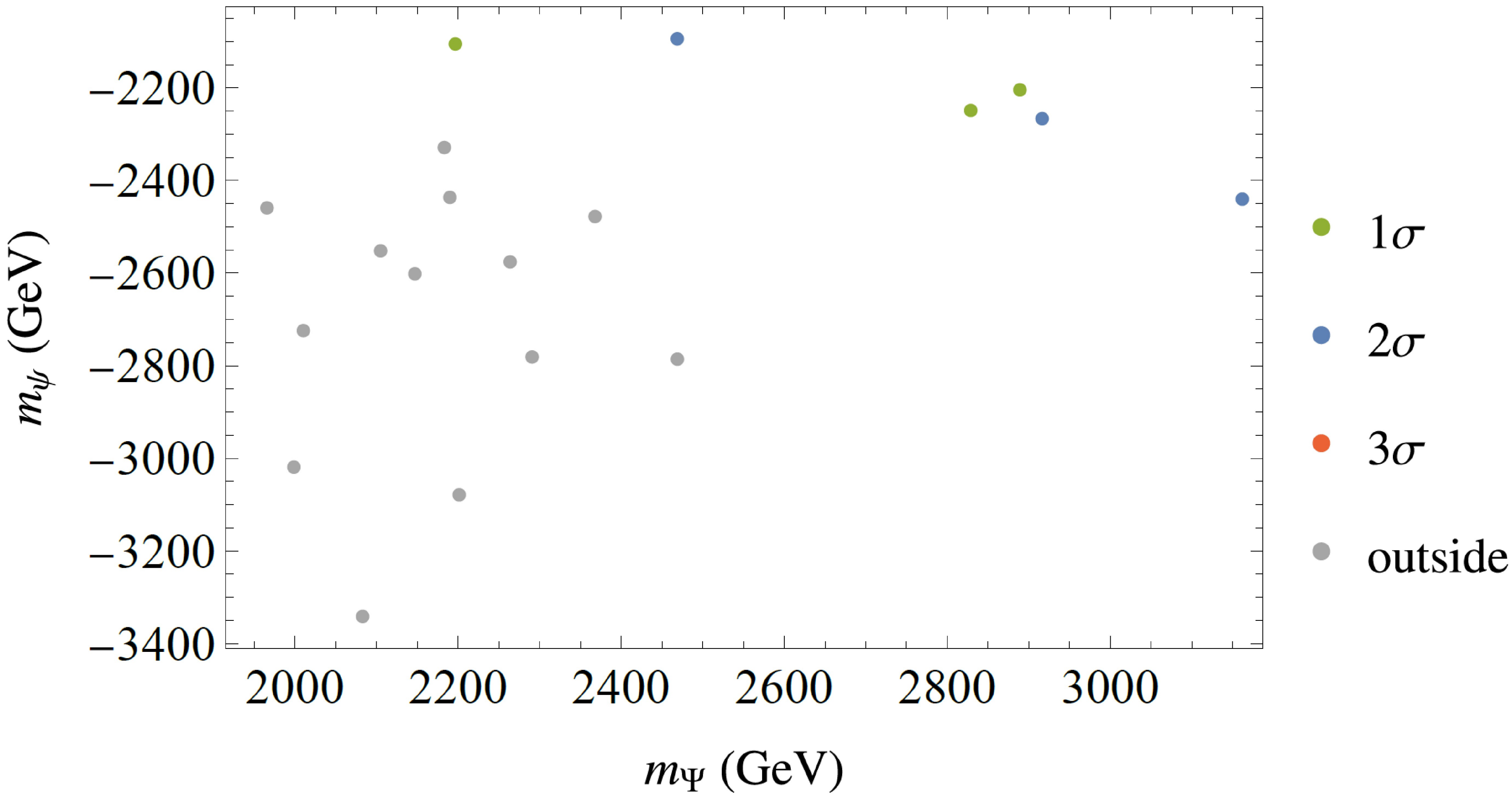
Physical Higgs mass requires implies heavy pNGB (and enhanced tuning of weak scale)

EW oblique corrections

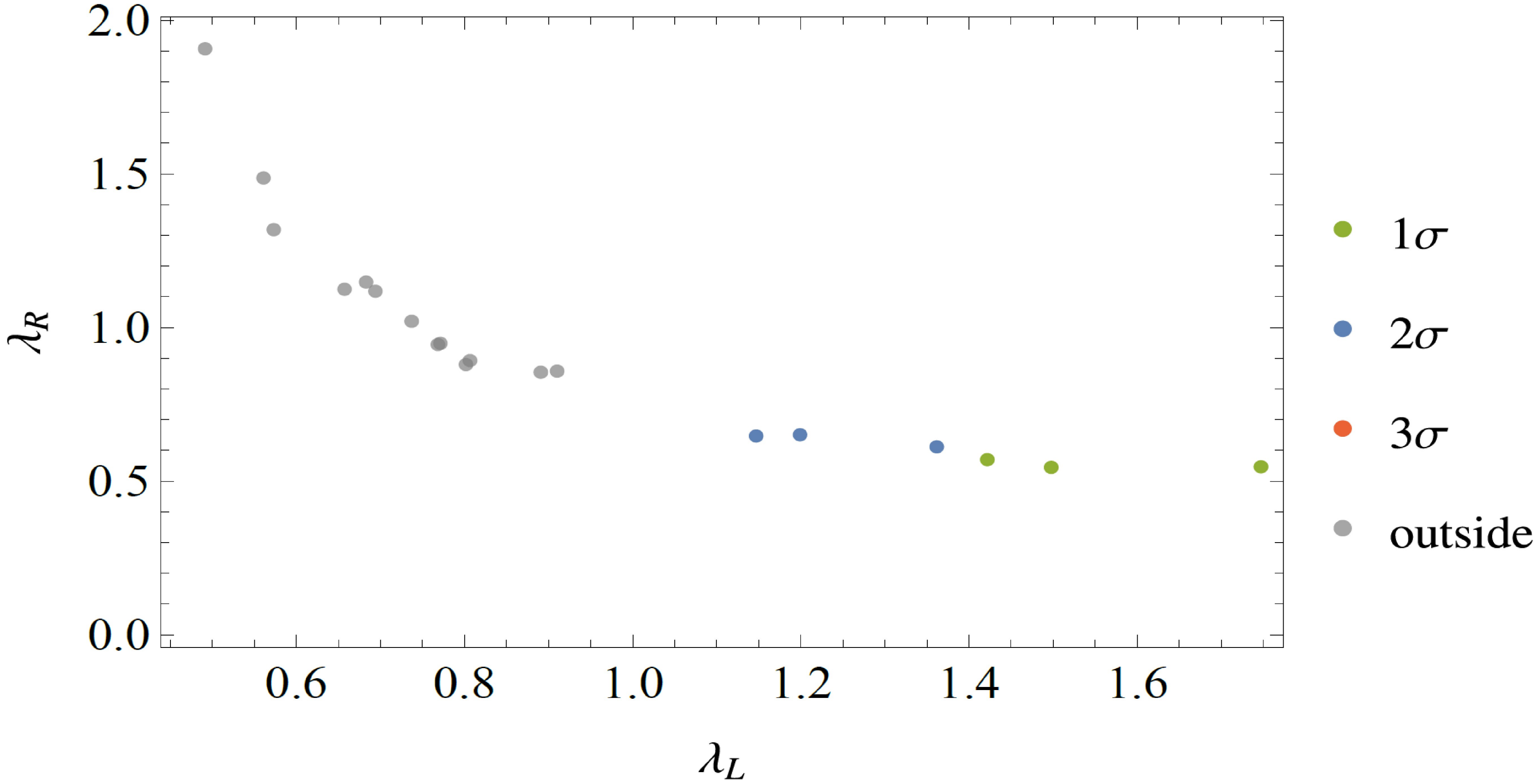
33 model, all points acceptable Higgs, top and NGB mass



top partner mass parameters vs EWPT



left/right top compositeness vs EWPT

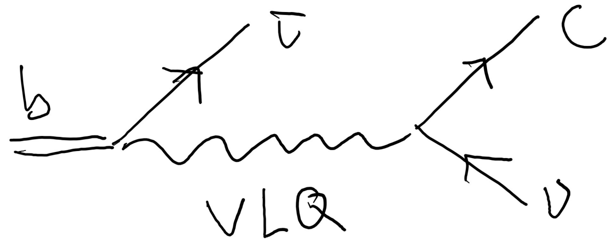


EWPT favour large left-handed compositeness

Flavour

The 33 model favours relatively light resonances (fermions close to 2 TeV, vectors ~ 3-4 TeV possible) with stong left-handed compositeness.

Together with the “automatic” U_1 vector leptoquark, is qualitatively what is needed to explain the $R_{D(*)}$ anomalies



$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right)$$

Satisfying other constraints (such as B_s mixing) puts additional requirements on the flavour structure of the elementary composite mixing and the flavour symmetry (or lack thereof) of the strong sector – add’l model dependence

Conclusions

1) Composite Higgs can address the hierarchy problem and may underly the observed flavour hierarchies/mixings
2) Generic prediction of top partners with interesting LHC phenomenology
3) Sketched pNGB GUT model which embodies gauge coupling unification, matter unification and custodial protection of T and Zbb
4) Within unification, a generic prediction of a vector leptoquark with impact on collider and flavour – though reaching the level hinted at by $R_{D(*)}$ is a challenge.

pNGB potential - generalities

$$V(H,\mathcal{T}) = -\alpha' f^2 \sin^2 \frac{H}{f} + \beta' f^2 \sin^4 \frac{H}{f} + \gamma' f^2 \sin^2 \frac{|\mathcal{T}|}{f} + \epsilon' f^2 \sin^2 \frac{H}{f} \sin^2 \frac{|\mathcal{T}|}{f}$$

$$\alpha' = 2\,\beta'\,\xi \qquad \xi = v^2/f^2$$

$$m_H^2 = 8\,\xi(1-\xi)\beta'$$

Must reproduce measured values

$$m_{\rm NGB}^2 = \gamma' + \epsilon\xi$$

Stable colour triplet – must exceed LHC bound

Compute as Coleman-Weinberg potential from strong-sector current-current (vector) and fermion 2-point functions (modelled with a small number of resonances)

pNGB potential - qualitative

$$m_H^2 = 8\,\xi(1-\xi)\beta' \qquad\qquad m_{\mathrm{NGB}}^2 = \gamma' + \epsilon\xi$$

Each coefficient is the sum of a vector and a fermion contribution

- Very strong, almost linear correlation between α'_{vec} and γ'_{vec}, with $\gamma'_{\mathrm{vec}} \sim -(15..16)\,\alpha'_{\mathrm{vec}} > 0$
- $\xi \ll 1$ hence $\alpha'_{\mathrm{ferm}} \approx -\alpha'_{\mathrm{vec}} > 0$
- Hence γ' dominated by vector contribution
- β' dominated by fermion contribution (>0)

Vector contribution

$$V_{\rm vec}(h) = \frac{9}{32\pi^2}\int_0^{\Lambda} dp^2 p^2 \ln\left(1 + \frac{h^2}{4}\frac{\Pi_1(p^2)}{\Pi_0(p^2)}\right)$$

where $\Pi_0,\, \Pi_1$ parameterize the strong sector current-current two-point functions

Model in terms of a single resonance for the unbroken generators (ρ) and broken generators (a), with corresponding decay constants

Impose first Weinberg sum rule (corresponding to a condition on dimension of a CFT operator, reduces UV divergence from quadratic to logarithmic)

Vector contribution to pNGB potential

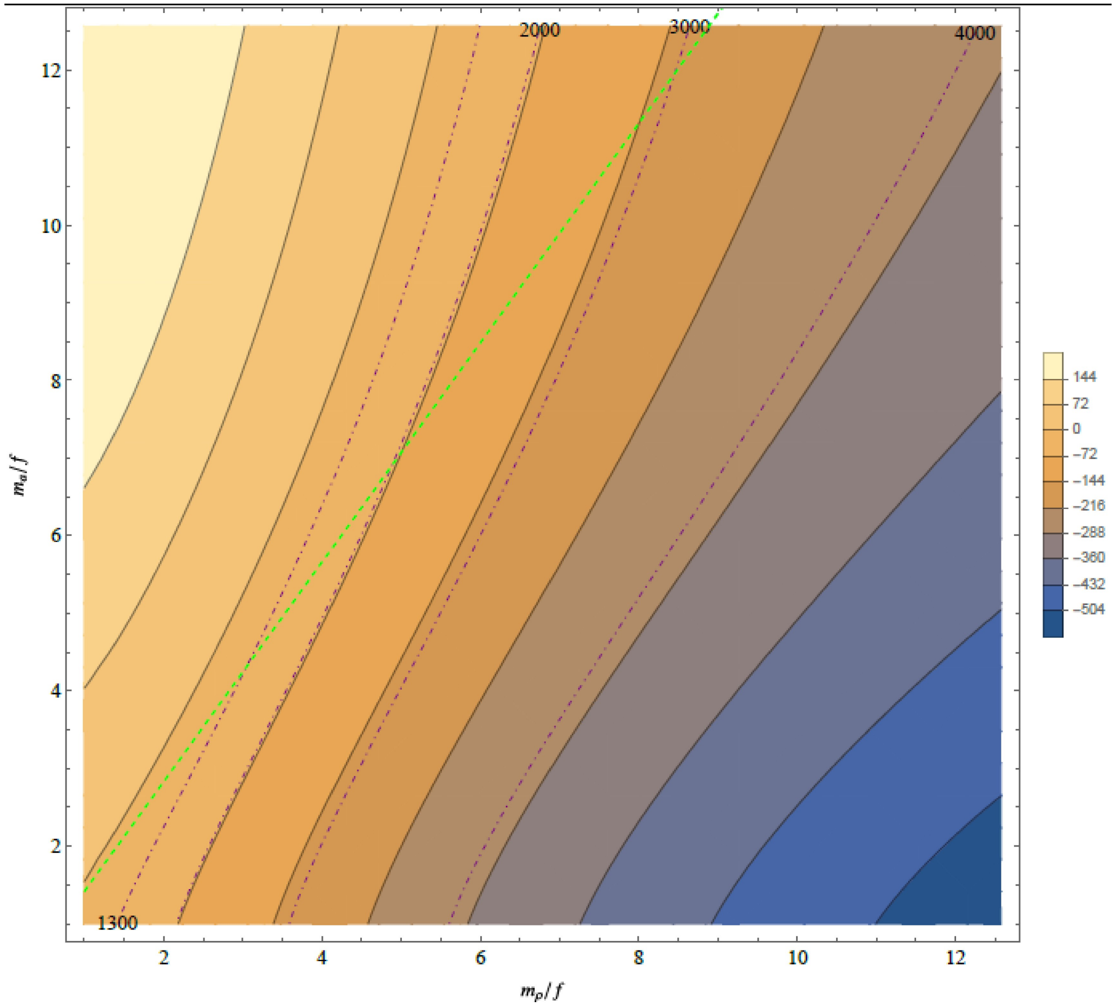
$f_\rho = f$

contours: $\alpha'/f^2 \times 10^3$

green: second Weinberg sum rule holds (UV-finite integral)

Dash-dotted:

$$\sqrt{\gamma'} \approx m_{\rm pNGB}$$



Vector contribution to pNGB potential

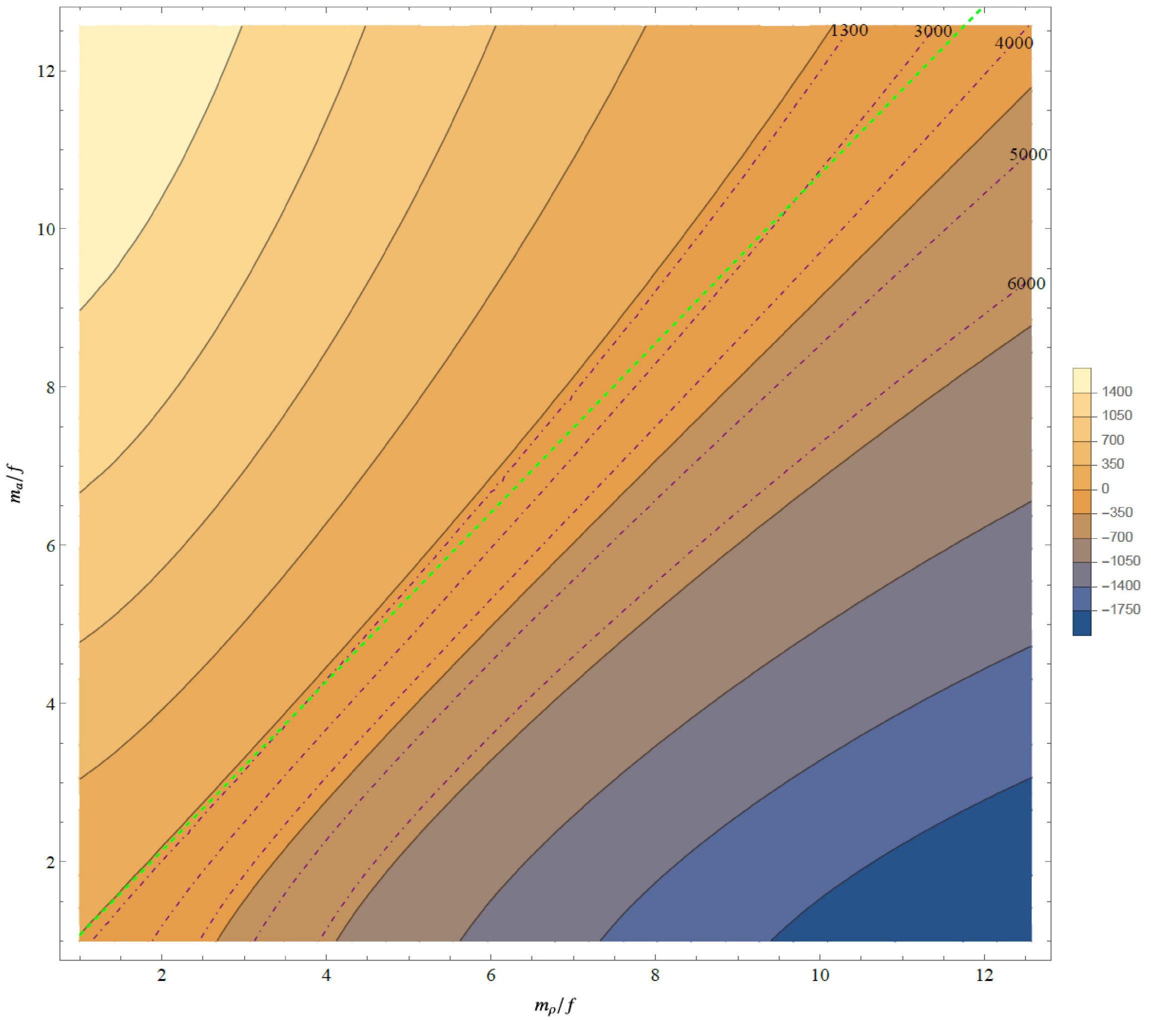
$f_\rho = 2\,f$

contours: $\alpha'/f^2 \times 10^3$

green: WSR2

Dash-dotted:

$$\sqrt{\gamma'} \approx m_{\mathrm{pNGB}}$$



Fermion contribution

Analogous to gauge contribution model with single resonance for each SO(10) fermion multiplet.

Impose first Weinberg sum rule.

One constraint from reproducing correct top mass.

Stringent experimental bounds on composite fermions masses – most stringent is from gluino searches (requires fermion resonance masses > 1.8 TeV)

Cosmology

The coloured NGB has a “weird” charge. In the 33 model all other resonances decay to it, plus SM stuff.

Apparence of such states is generic [Agashe & Servant 2004]

Unacceptable as a cosmological relic (affects BBN)

Pospelov 2007

However it might form ($\mathcal{T}\mathcal{T}\mathcal{T}$) bound states in the early universe

De Luca, Mitdidate, Redi, Smirnov, Strumia 2018

Gross, Mitridate, Redi, Smirnov, Strumia 2018

and sufficiently efficiently annihilate into SM particles via

$$\mathcal{T}\mathcal{T} \to \mathrm{VLQ} \to b_L \bar{\tau}$$

similarly to the long-lived stop scenario in [Gross, Mitridate, Redi, Smirnov, Strumia 2018]