Gauge & matter unification in composite Higgs models

Sebastian Jäger (University of Sussex)

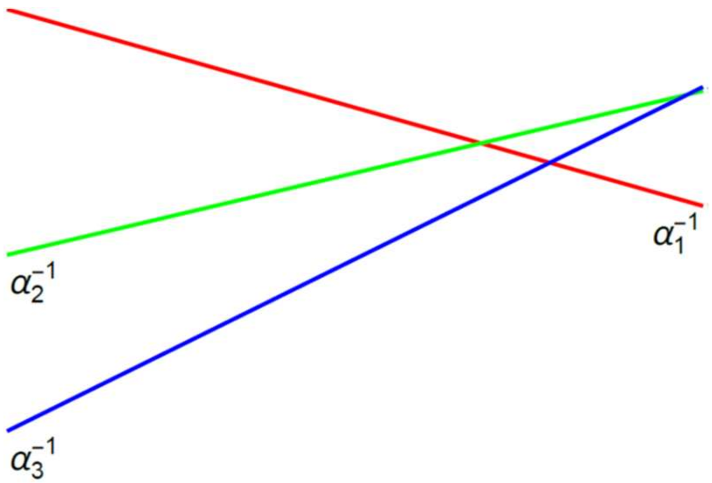
In collaboration with S Kvedaraite, G Lee, S J Lee, to appear

FLASY 2022, Lisbon 27/06/2022-01/07/2022

Outline

1) Motivation
2) Coupling unification, quark-lepton unification, proton decay and EPWT in composite Higgs
3) Phenomenology of a minimal model
4) Conclusions

Some possible clues to BSM



Apparent (near-)equality
of running couplings
at a scale ~ $10^{14..17}$ GeV

Possible interpretation through a unified, simple gauge group (GUT)

SM matter fills out complete multiplets of SU(5); this fixes the normalization of the U(1) coupling

Heavy vectors at the unification scale mediate quark-lepton transitions

Possible clues (2)

If the Weinberg operator

$$-\frac{1}{\Lambda_L}\bar{l}_L^c \phi c_\nu \phi^\dagger l_L$$

is responsible for neutrino mass, it points to a scale (for c = O(1))

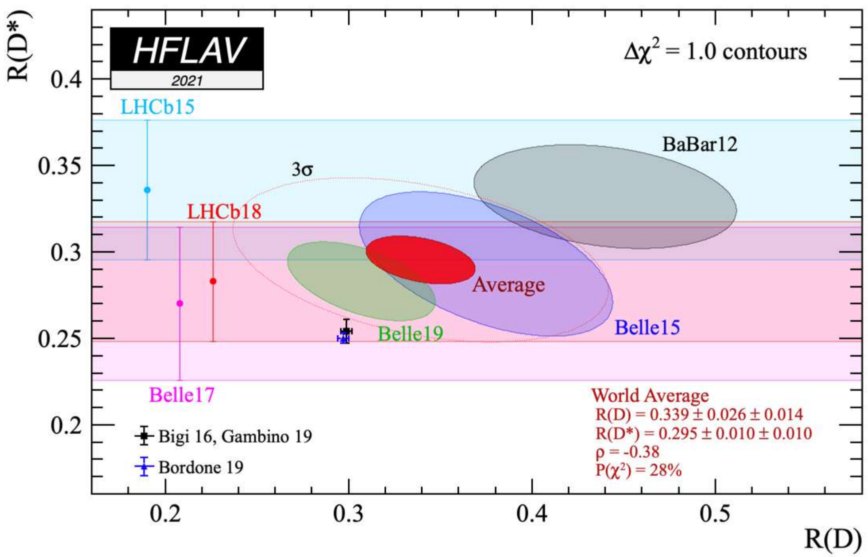
$$\Lambda_U \sim \frac{cv^2}{m_\nu} \sim 10^{14\ldots15}\mathrm{GeV}$$

Simplest picture is type-1 seesaw: Λ_U = Majorana mass of SM singlet fermions; 1 generation then fits into an irrep of SO(10)

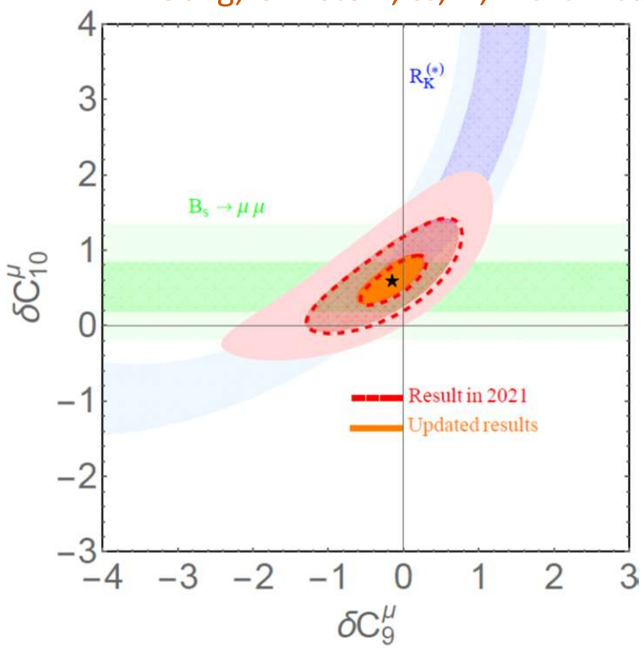
(but other heavy GUT states can generate the same operator)

Possible clues (3)

B-decay anomalies



Geng, Grinstein, SJ, Li, Martin Camlich, Shi



point to contact interactions

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

Λ ~ 4-5 TeV

$$\frac{1}{\Lambda^2}\left(\bar{s}_L \gamma^\mu b_L\right)\left(\bar{\mu}_L \gamma_\mu \mu_L\right)$$

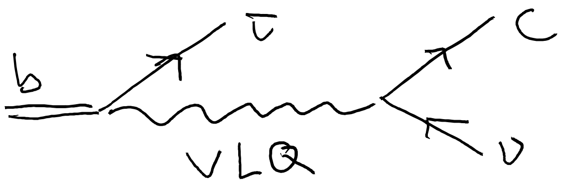
Λ ~ 40 TeV.

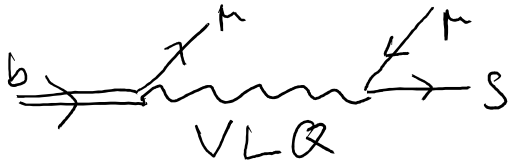
suggestive of vector mediator(s)

Possible tree-level mediators

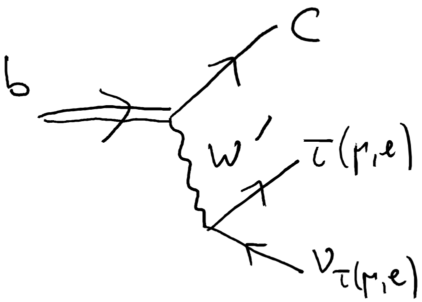
$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right) \qquad \frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

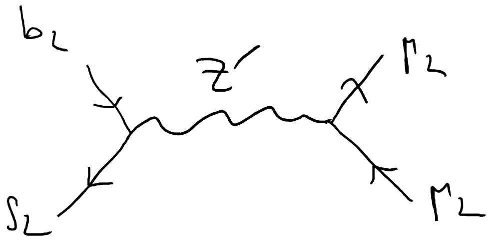
Vector leptoquarks $(3, 1, 2/3)$





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





Either mediator generates both operators (but pure W'/Z' problematic)
Less minimal possibilities exist

Composite Higgs

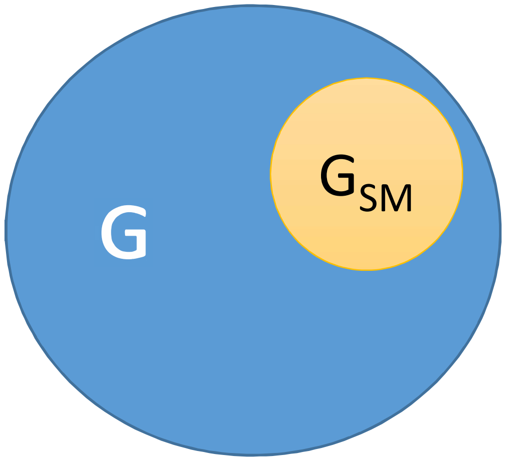
Higgs = bound state of some near-conformal new sector

(Relevant perturbations of) CFT's are **precisely** the UV-complete quantum field theory models (limit $\Lambda_{UV} \to \infty$ exists)

Symmetry of CFT must include $G_{SM} = SU(3) \times SU(2)_L \times U(1)_Y$

conformal symmetry broken at scale M ~ few TeV $\ll \Lambda_{UV}$

Higgs may be NGB (preferable for little hierarchy & suppresses $H \to \gamma\gamma$)



weak gauging of G_{SM} explicitly breaks G,

generates Higgs potential (but no EWSB)

Partial compositeness

Generate Yukawas through linear mixing:

SM fermions are mixtures of elementary and composite particles, eg

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

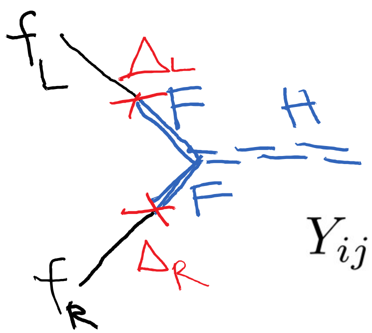
by virtue of $\mathcal{L}_{\rm mix} \supset -\lambda_{tL}\bar{t}_L T_L$ $\quad (\sin\phi_{t_L} = \lambda_{t_L}/(1+\lambda_{t_L}^2))$

where T_L is a CFT spin ½ operator with dimension ~ 5/2 and $|T_L\rangle$ its lightest excitation (a Dirac fermion)

Alleviates flavour problem (relative to bilinear mixing)

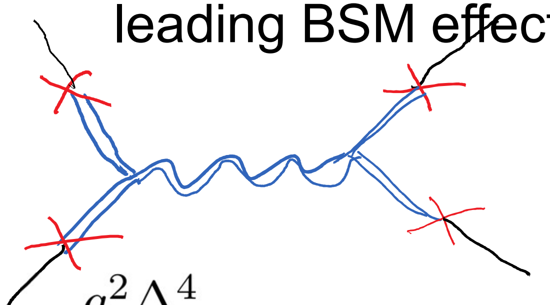
Can destabilize a pNGB Higgs potential & cause EWSB

can generate flavour hierarchy



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

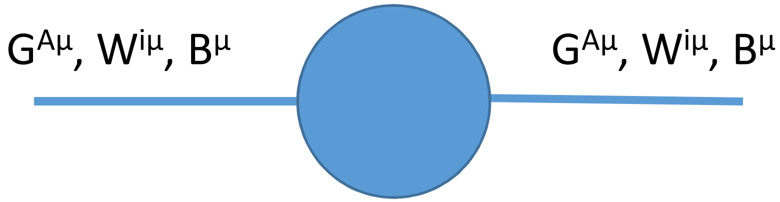
leading BSM effects:

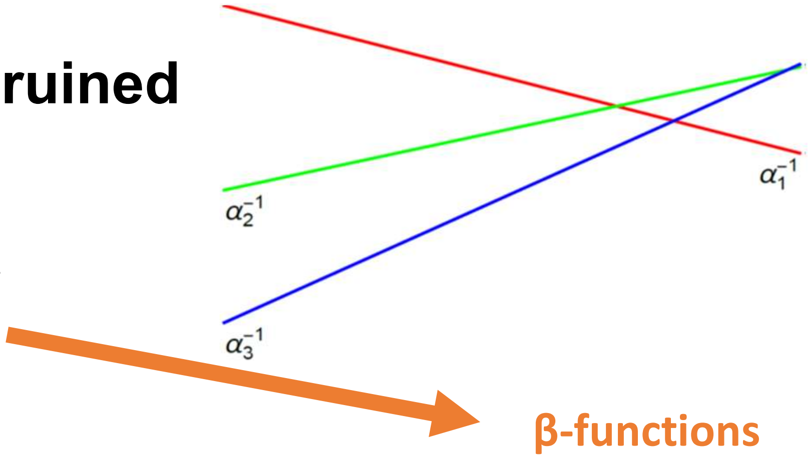


$$\sim \frac{g_*^2\Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

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)

EWPT clues

To suppress the T-parameter; as usual will assume

$$SO(4) \sim SU(2)_L \times SU(2)_R \stackrel{\langle H\rangle = v}{\longrightarrow} SU(2)_C$$

with Higgs in (2,2)

Z_{bb} coupling also problematic, particularly if b_L has substantial composite component

→ can extend symmetry to

$$O(4) \sim [SU(2)_L \times SU(2)_R] \rtimes P_{\rm LR}$$

Agashe-Contino-Da Rold-Pomarol 2006

Requires embedding (t_L, b_L) in (2,2)

Hypercharge requires additional $U(1)_X$ with $Y = T_{3R} + X$

implies $X(t_L) = X(t_R) = 2/3$

Unification condition becomes

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

Partner unification & proton stability

Generically, without B-conservation TeV-scale proton decay

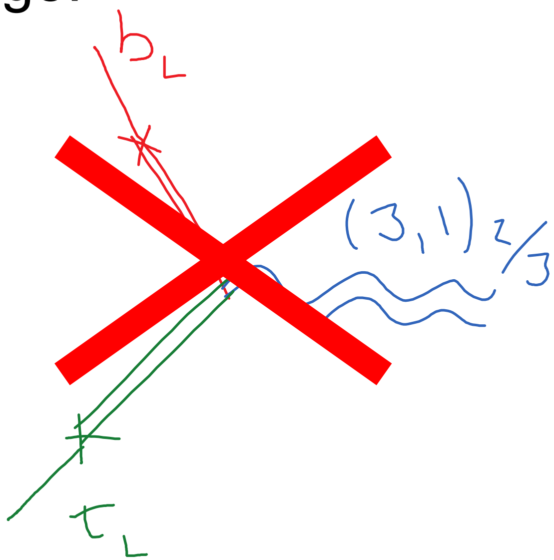
Agashe & Servant 2004

"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 want a leptoquark then $B \propto X$

and we must have X=0 for the lepton partners

A concrete assignment

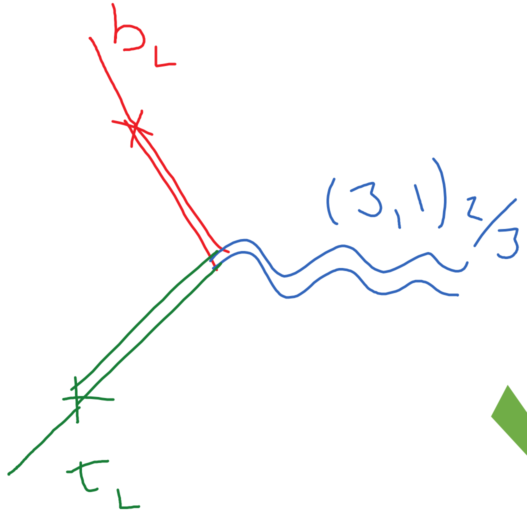
We can embed s.t. under SO(10) > SU(4) x SU(2)xSU(2),

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

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

$(15,2,2)_L$ 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 $O(11) \times U(1)_F / [O(10) \times U(1)_F]$ 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:

top mass and top partner masses
pNGB potential and masses
electroweak S and T parameters

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

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

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

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

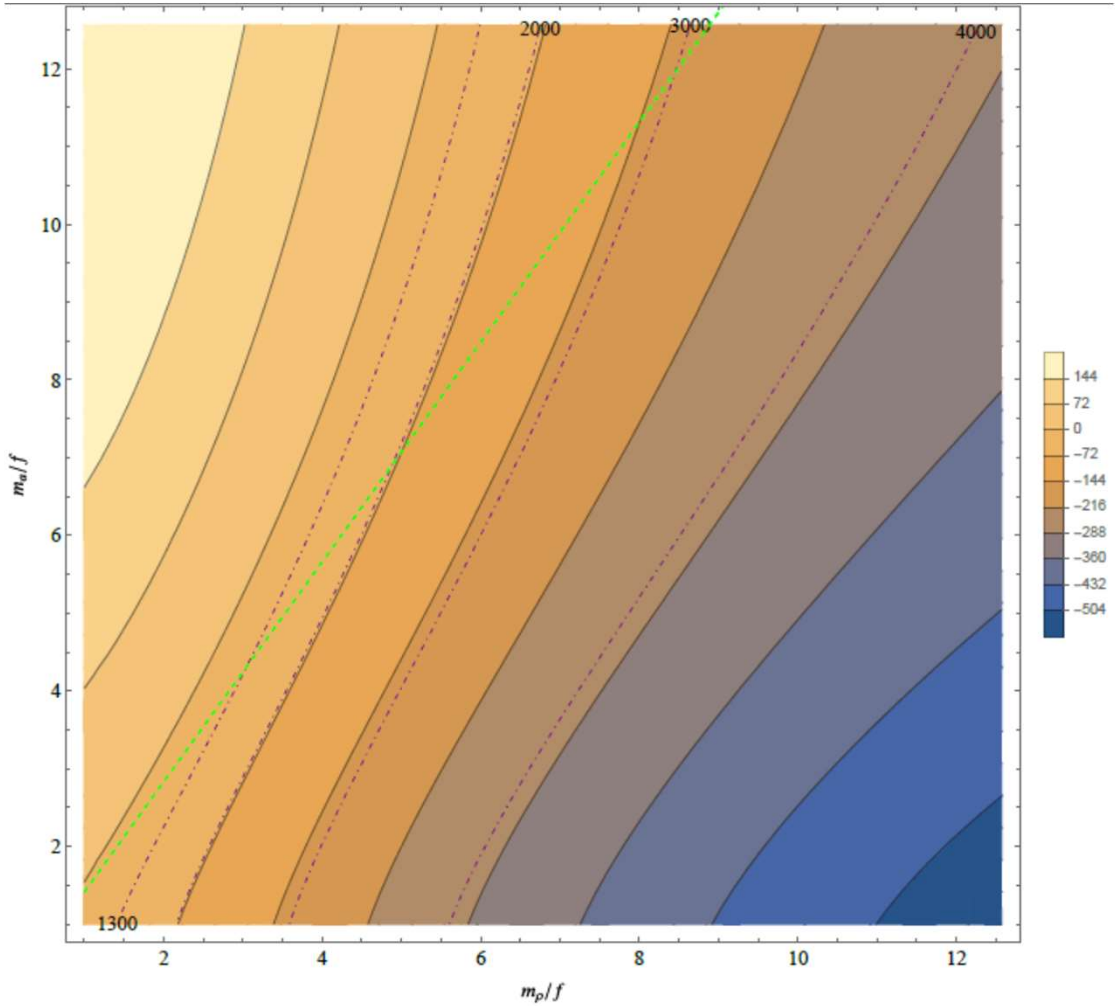
$f_\rho = f$

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

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

Dash-dotted:

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



Vector contribution to pNGB potential

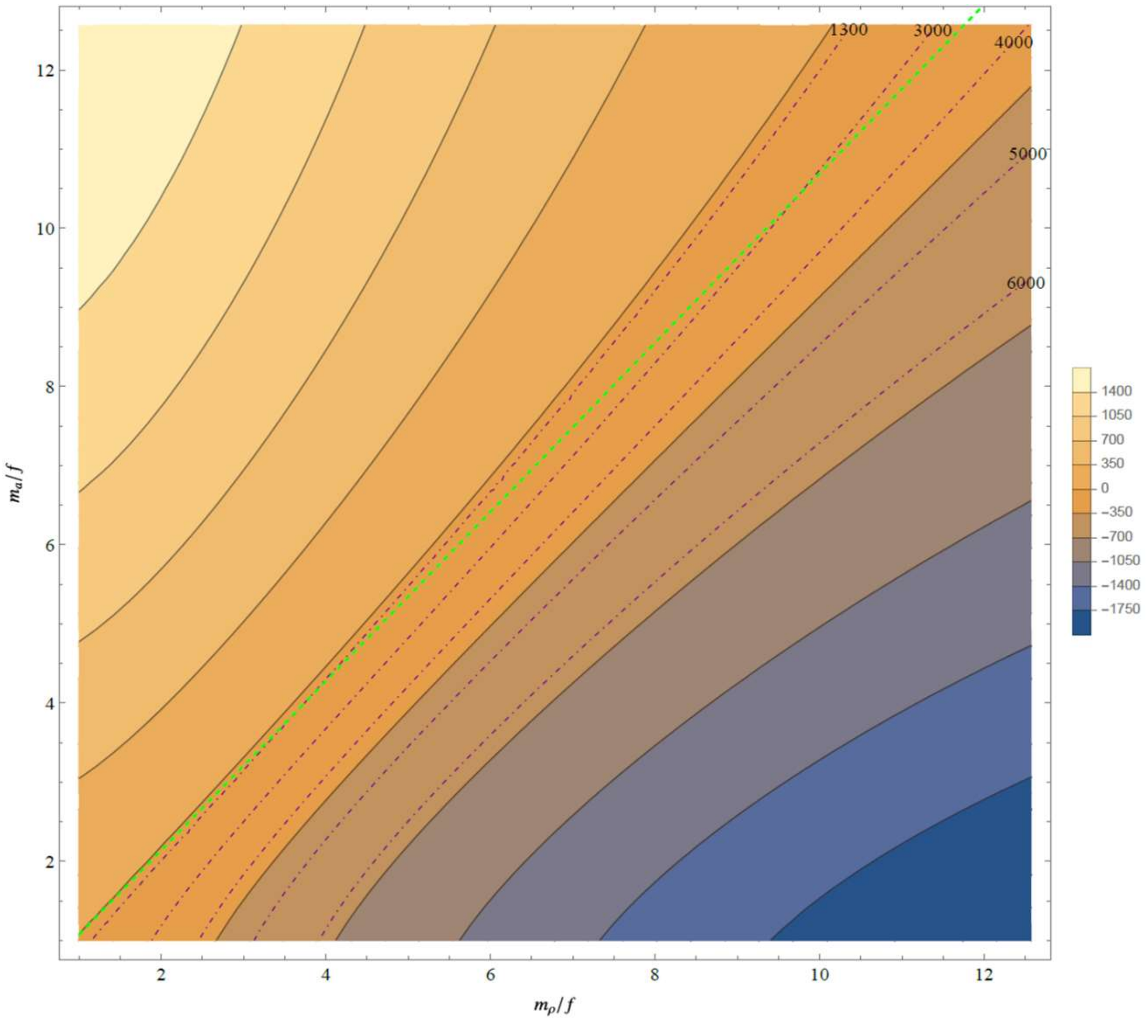
$f_\rho = 2\,f$

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.

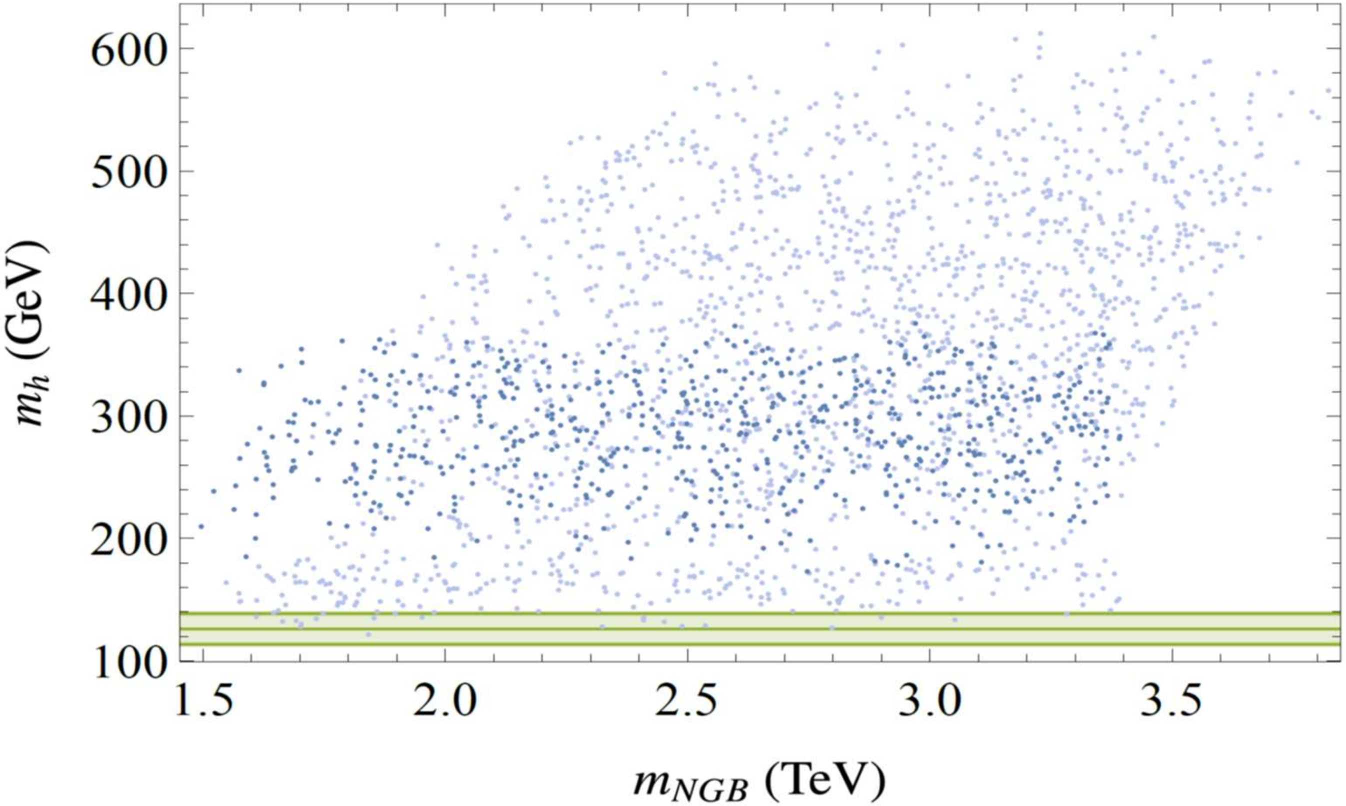
One constraint from reproducing correct top mass.

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

Higgs mass vs colour triplet mass

33 model

f=2 TeV



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

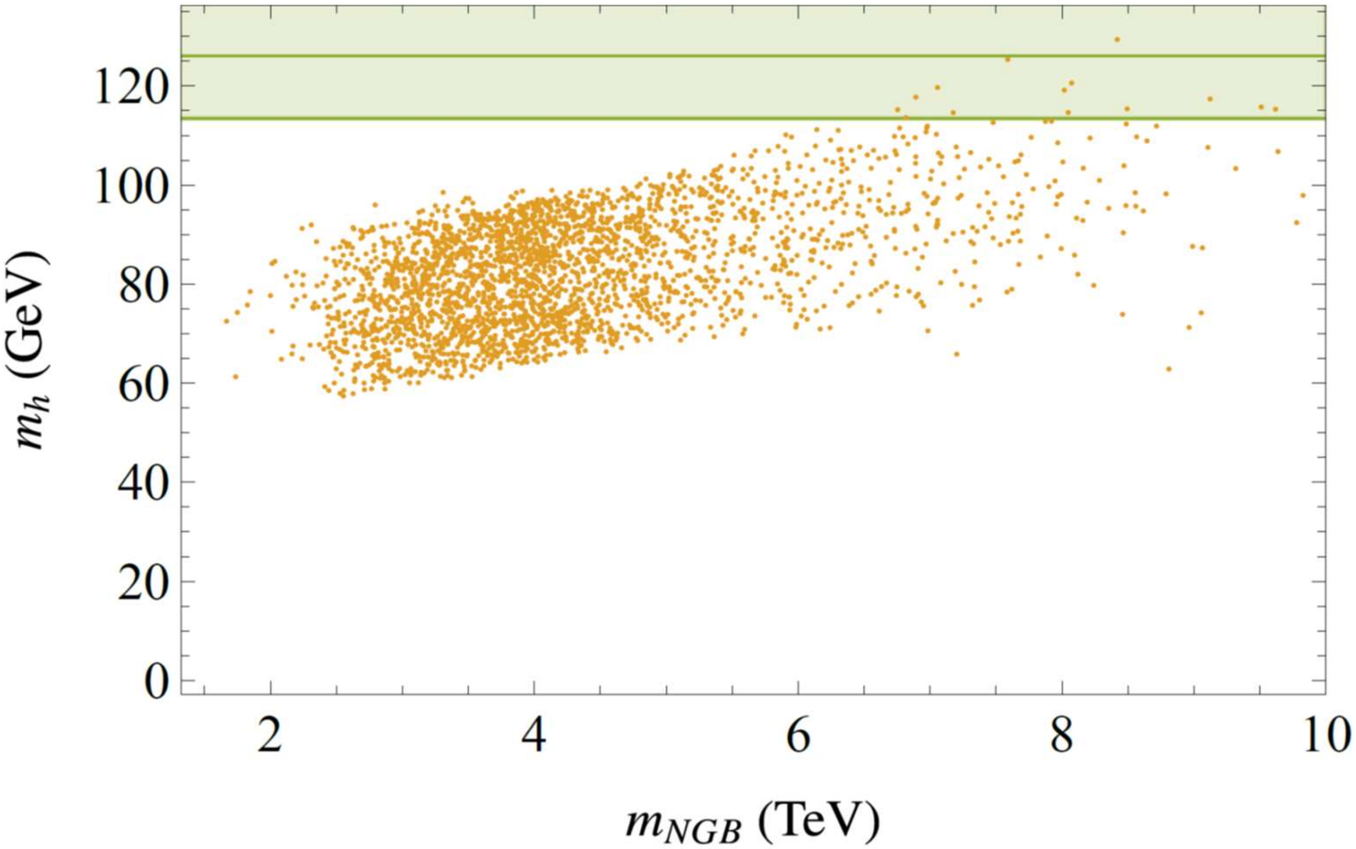
$\alpha'_f/f^2 \times 10^3 \sim 50\text{-}200$

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

Higgs mass vs colour triplet mass

23 model

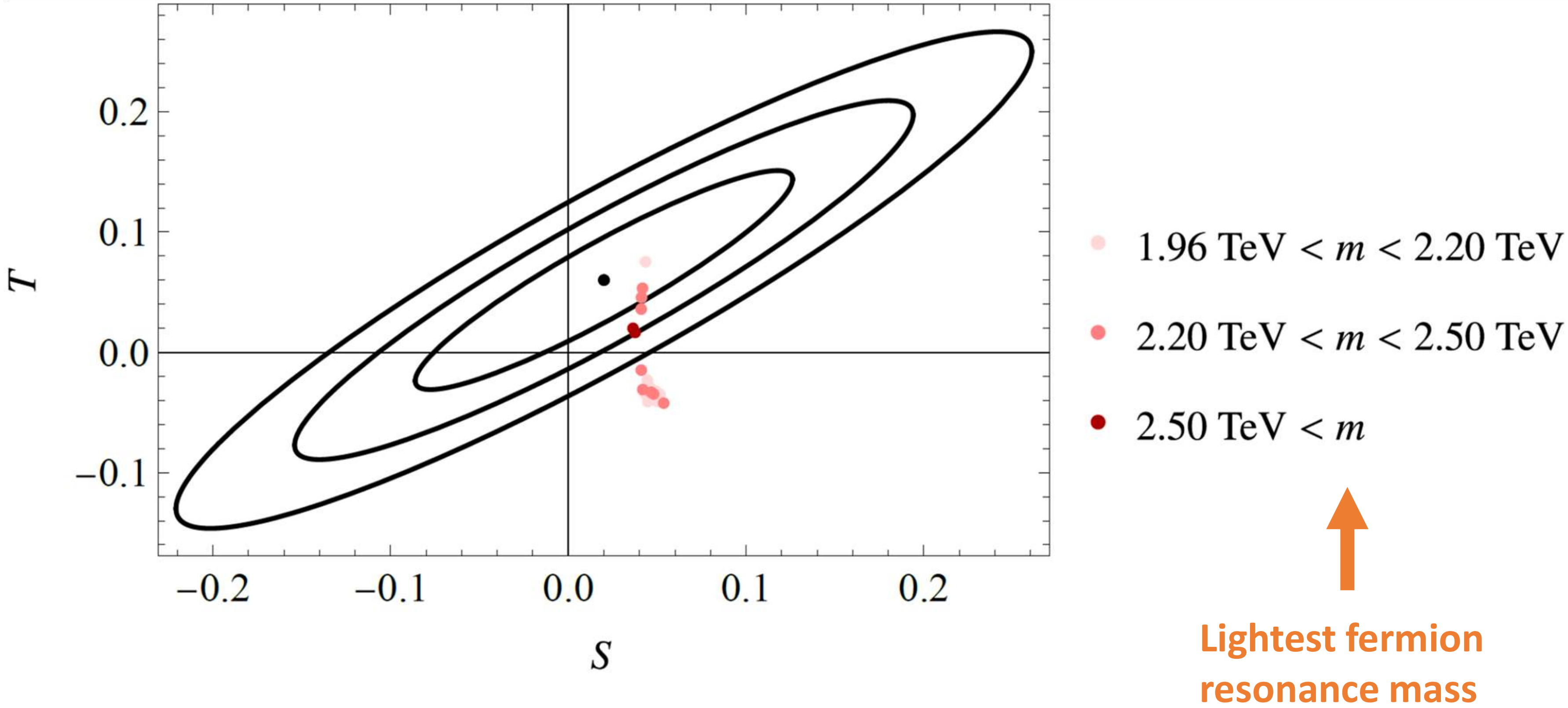
f=2 TeV



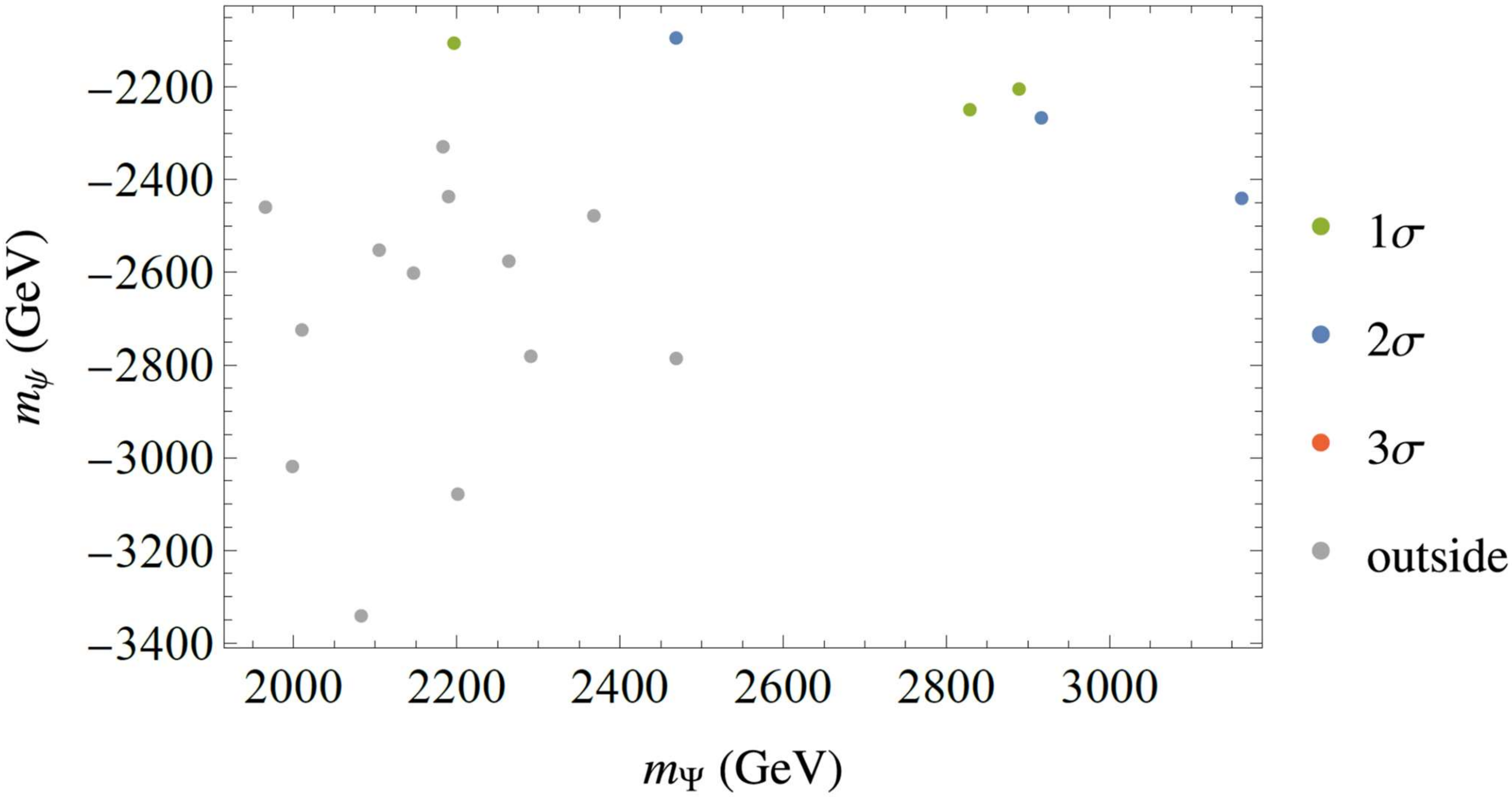
Physical Higgs mass requires implies heavy pNGB (and enhanced tuning of weak scale)

EW oblique corrections

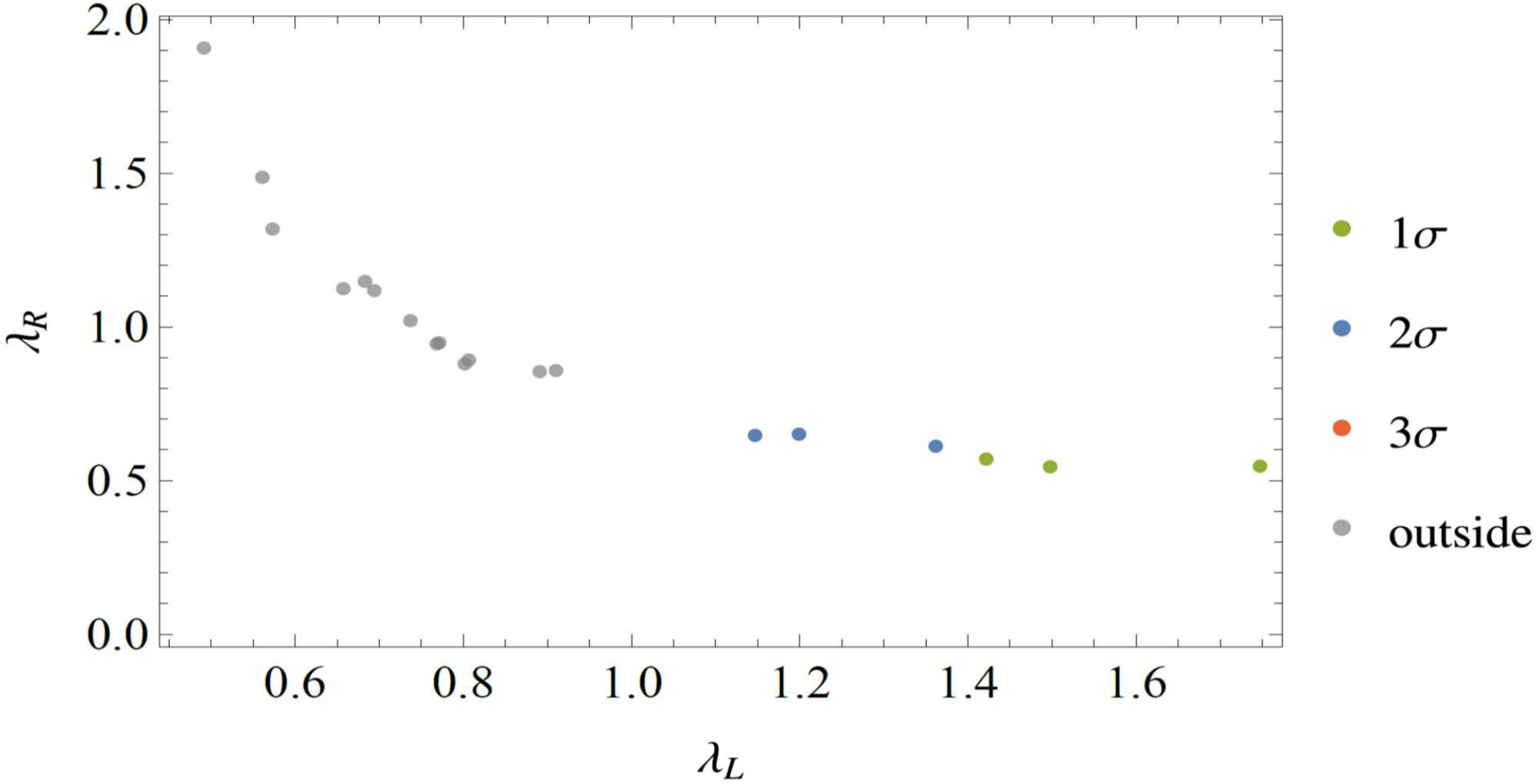
33 model, all points acceptable Higgs, top and NGB mass



top partner mass parameters vs EWPT



left/right top compositeness vs EWPT

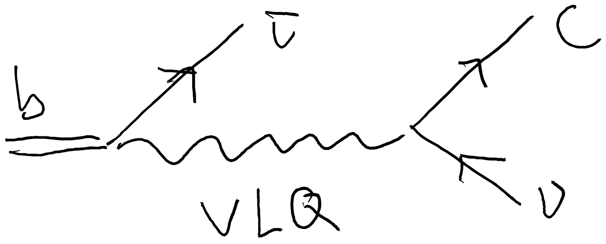


EWPT favour large left-handed compositeness

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

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]

Conclusions

1) Constructed a composite pNGB GUT model which embodies gauge coupling unification, matter unification and custodial protection of T and Zbb
2) Studies quantitatively the NGB potential, EWPT and mass spectrum – nontrivial but possible to satisfy requirements
3) Generic prediction of vector leptoquark with impact on collider and flavour – though reaching the level hinted at by $R_{D(*)}$ is a challenge.