

10th Symposium on Prospects in the Physics of Discrete Symmetries

Bratislava, Slovakia
16 Nov 2026

TeV-scale leptoquarks and Yukawa unification in SO(10)

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DFG Collaborative Research Center TRR 257 PPH Particle Physics Phenomenology after the Higgs Discovery

Flavour anomalies

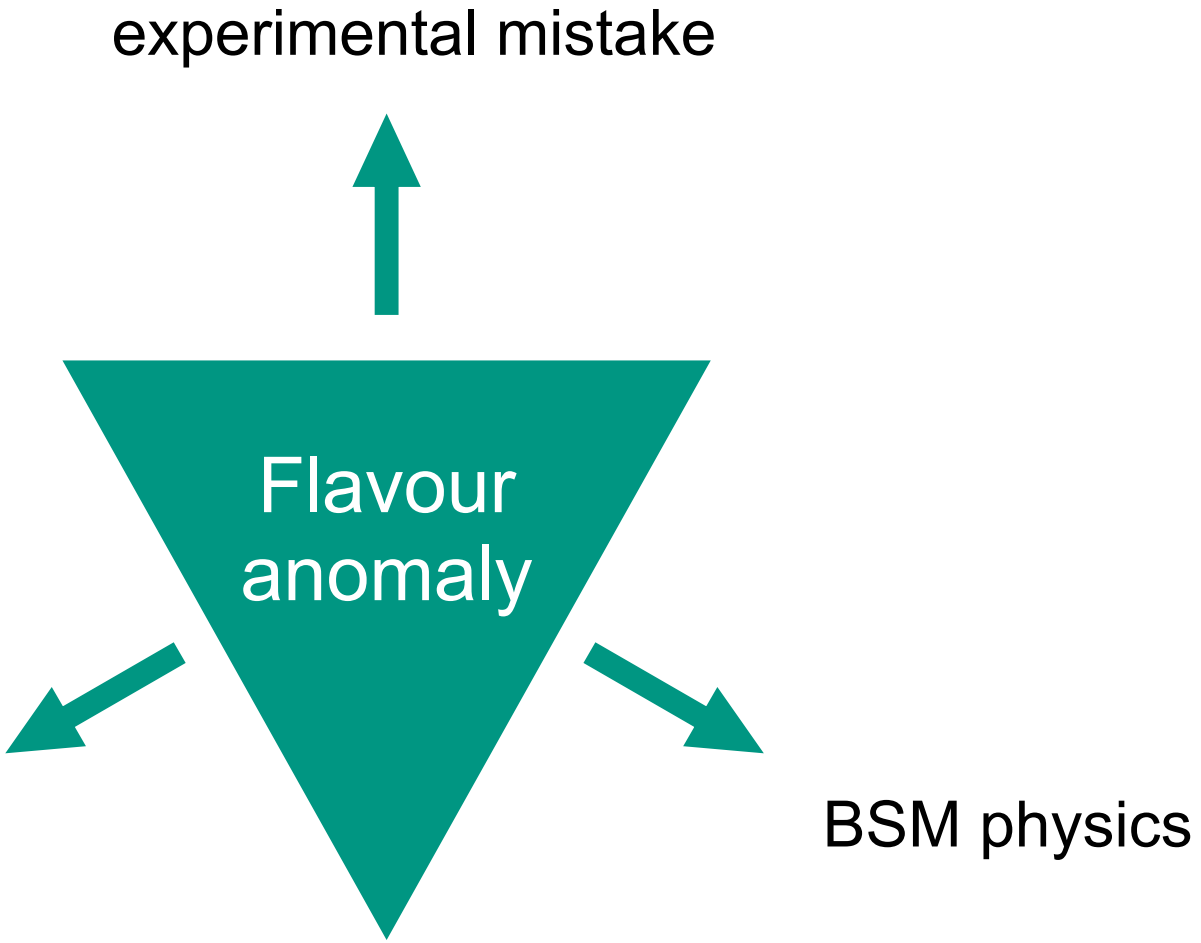
- $R(D^{(*)}) = \dfrac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}$, $R(J/\psi) = \dfrac{B(B_c \to J/\psi\tau\nu)}{B(B_c \to J/\psi\ell\nu)}$, $\ell = e, \mu$,
  are measured too high,

- low-q^2 deficit in several $b \to s\ell^+\ell^-$, $\ell = e, \mu$, decay distributions,
  compatible with a reduction of C_9^e and C_9^μ by $\mathcal{O}(25\%)$,

- $B(B \to K\nu\bar{\nu})$ is measured too high.

Flavour anomalies

Explanations:



Will we discuss this forever?

Flavour anomalies

No! Future measurements can discriminate between these different explanations. E.g.

- The sum rule $\frac{R(\Lambda_b)}{R(\Lambda_b)_{\rm SM}} \simeq 0.262 \frac{R(D)}{R(D)_{\rm SM}} + 0.738 \frac{R(D^*)}{R(D^*)_{\rm SM}}$ holds in any BSM model, its falsification will reveal an experimental or theoretical mistake as the source of the flavour anomaly.

  Blanke et al. *Phys.Rev.D* 99 (2019) 7, 075006, *Phys.Rev.D* 100 (2019) 3, 035035; Fedele at al. *Phys.Rev.D* 107 (2023) 5, 055005; Duan et al. *JHEP* 07 (2025) 166; Endo et al. *JHEP* 05 (2025) 112, *Eur.Phys.J.C* 85 (2025) 9, 961, *Phys.Rev.D* 113 (2026) 1, 014021

- Polarisation observables distinguish between BSM explanations and incorrect form factor calculations in $B \to D^* \mu \nu$. Fedele, Blanke, Crivellin, Iguro, Nierste, Simula, Vittorio

- Sizable mixing-induced CP asymmetries in $B_s \to \phi \mu^+ \mu^-$ will be a “smoking gun” signal of BSM physics.

Outline

- Scalar leptoquarks and SO(10)
- Yukawa unification
- Summary

Xiyuan Gao, UN,

TeV-scale scalar leptoquarks motivated by B anomalies improve Yukawa unification in SO(10) GUT

JHEP 02 (2026) 082

Leptoquarks and semileptonic decays

Scalar leptoquarks are a popular explanation of flavour anomalies.

S_1 or R_2 for

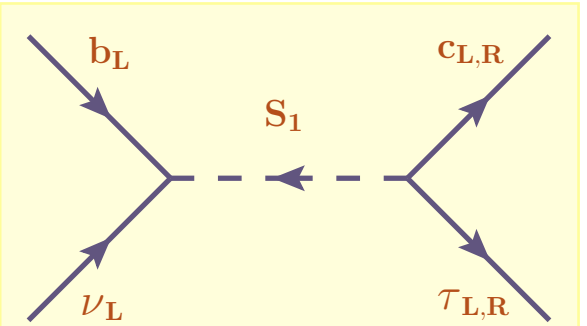
$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)}, \quad \ell = e, \mu,$$

S_3 for low-q^2 deficit in several

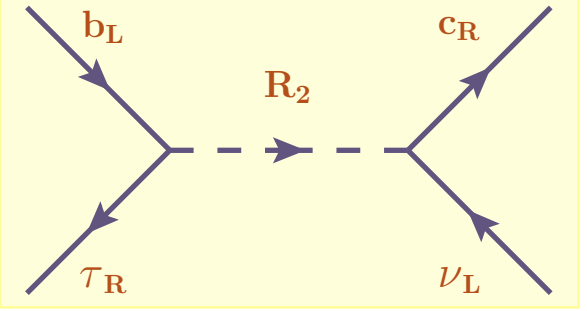
$$b \to s\ell^+\ell^-, \qquad \ell = e, \mu,$$

decay distributions.

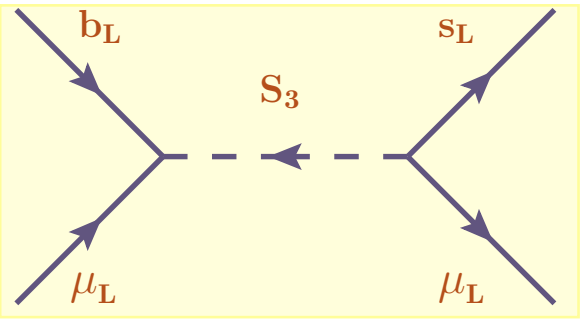
Spin 0,
SU(2) singlet



Spin 0,
SU(2) doublet

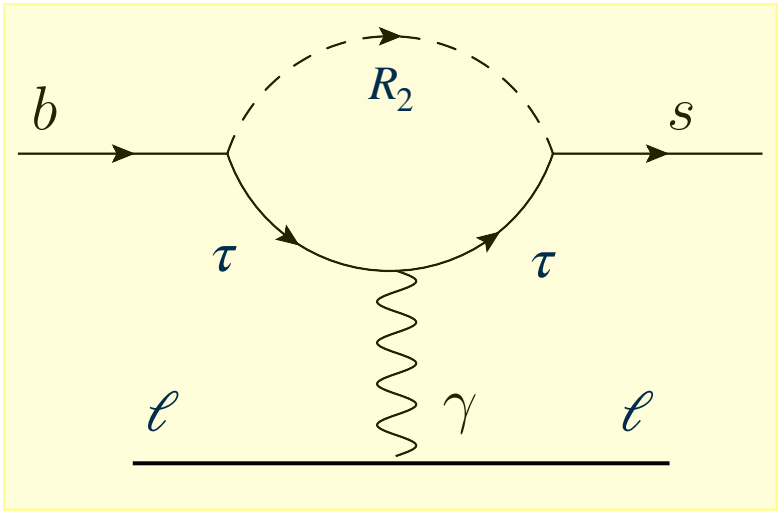


Spin 0,
SU(2) triplet



$b \to s\ell^+\ell^-$ from leptoquark loop

Tau loop contribution to
$b \to s\ell^+\ell^-$:



Crivellin et al. *Phys.Rev.Lett.* 122 (2019) 1, 011805, *JHEP* 06 (2020) 020

Criticism from model builders

The postulated leptoquarks are completely “ad-hoc”, masses and couplings are fixed to explain data without justification in other contexts.

Leptoquarks appear in theories with quark-lepton unification, so-called Pati-Salam (PS) theories, in which lepton number is the “fourth color”. E.g. the gauge group can be

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

with the possibility to further restore parity symmetry.

SO(10)

- The SM and PS gauge groups are subgroups of SO(10):

  $\mathrm{SU(3)}\times\mathrm{SU(2)}_L\times\mathrm{U(1)}_Y \subset \mathrm{SU(4)} \times \mathrm{SU(2)}_L \times \mathrm{SU(2)}_R \subset \mathrm{SO(10)}$

- SO(10) explains the quantum numbers of the SM fermions, in particular the quantisation of the hypercharge Y (and thus of electric charge) in units of the weak isospin:

$$Q(\nu_L) = I^3_{ew}(\nu_L) + Y(\nu_L) = \frac{1}{2} - \frac{1}{2} = 0,$$

  experimentally confirmed to 20 digits behind the decimal point.

- If all non-SM particles have masses around $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, i.e. if there is a "grand desert" between m_t and M_{GUT}, neither the three SM gauge couplings nor the t, b, and τ, Yukawa couplings unify.

SO(10)

- Adding superpartners (to get the MSSM) cures this but this is certainly not the minimal solution to the unification problem.

- In a minimal SO(10) theory one assumes in a first step that only one Higgs field couples to fermions, aiming at an explanation of the third-generation Yukawa couplings. There are only three possibilities, with the Higgs field in the SO(10) representations $\underline{10}$, $\underline{120}$, or $\underline{126}$. In all cases Yukawa unification fails if one has the SM or a two-Higgs doublet model below $M_{\rm GUT}$.

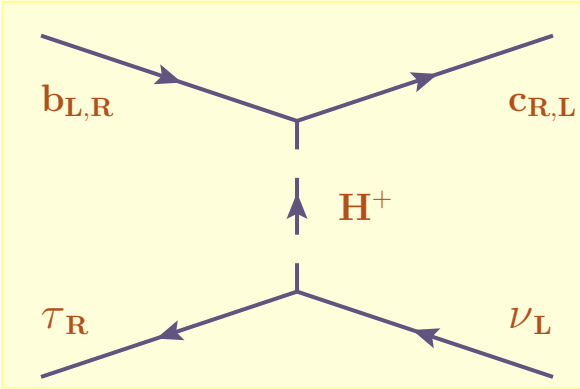
- But $\underline{126}$ contains all leptoquarks proposed as remedies of the flavour anomalies. What happens to Yukawa unification if these leptoquarks are much lighter than $M_{\rm GUT}$, with masses of a few TeV?

The $\underline{126}$ leptoquarks of SO(10)

The Higgs field $\underline{126}$ contains "ordinary" Higgs doublets and leptoquarks with these $SU(3)\times SU(2)_L\times U(1)_Y$ quantum numbers:

S_1: (3, 1, -1/3)
$\tilde{S}_1$: $(\bar{3}, 1, 4/3)$
R_2: $(\bar{3}, 2, -7/6)$
$\tilde{R}_2$: $(\bar{3}, 2, -1/6)$
S_3: (3, 3, -1/3)

Contribution of a charged Higgs to $b \to c\tau\nu$:



With two Higgs doublets one can arrange for bottom-top Yukawa unification through $\tan\beta \equiv \frac{v_2}{v_1}$. The non-trivial problem is bottom-tau unification.

SO(10) and flavour anomalies

The scenarios to modify $R(D^{(*)})$, the $b \to s\ell^+\ell^-$ polarisation observables and $B(B \to K\nu\bar{\nu})$ while obeying all constraints from other observables have been identified and studied exhaustively in the literature. The additional SO(10) constraints eliminate some of these solutions:

- S_1 has diquark couplings and mediates proton decay
  $\Rightarrow M_{S_1} = \mathcal{O}(M_{\text{GUT}})$ and S_1 cannot solve the flavour anomalies.
- R_2 comes with large threshold corrections to Yukawa couplings, so predictivity is lost.
- For the possible "light" TeV-scale leptoquarks we are left with S_3, $\tilde{S}_1$, $\tilde{R}_2$.

SO(10) and flavour anomalies

The Yukawa lagrangian responsible for the RG evolution between $M_{\rm GUT}$ and the electroweak scale is

$$-\mathscr{L}_Y = \underbrace{y_t \overline{Q_L^3} t_R H_u + y_b \overline{Q_L^3} b_R H_d + y_\tau \overline{L_L^3} \tau_R H_d}_{\text{couplings of Higgs doublets } H_u \text{ and } H_d \text{ to } Q_L^3 = (t_L, b_l),\ t_R,\ b_R,\ L_L^3 = (\nu_{\tau L}, \tau_l), \text{ and } \tau_R.} + \underbrace{y_1 \overline{b_R^c} \tau_R \widetilde{S}_1 + y_2 \overline{b_R^c} L_L^{3c} \widetilde{R}_2 + y_3 \overline{Q_L^{3c}} L_L^3 S_3}_{\text{couplings of leptoquarks to SM fermion fields}} + \text{h.c.}$$

Renormalisation group evolution

The formulae are known for an arbitrary BSM theory,

Machacek, Vaughn, Nucl. Phys. B 222 (1983) 83, Nucl. Phys. B 236 (1984) 221,

and have been specified to leptoquark models, Fedele, Wüst, UN, JHEP 11 (2023) 131.

Boundary condition at the GUT scale:

$$y_b = y_t, \quad y_\tau = -3y_b, \quad y_1 = y_2 = y_3 = 2\sqrt{3}y_t.$$

implies $\tan\beta = 42$

no free parameter to fix this

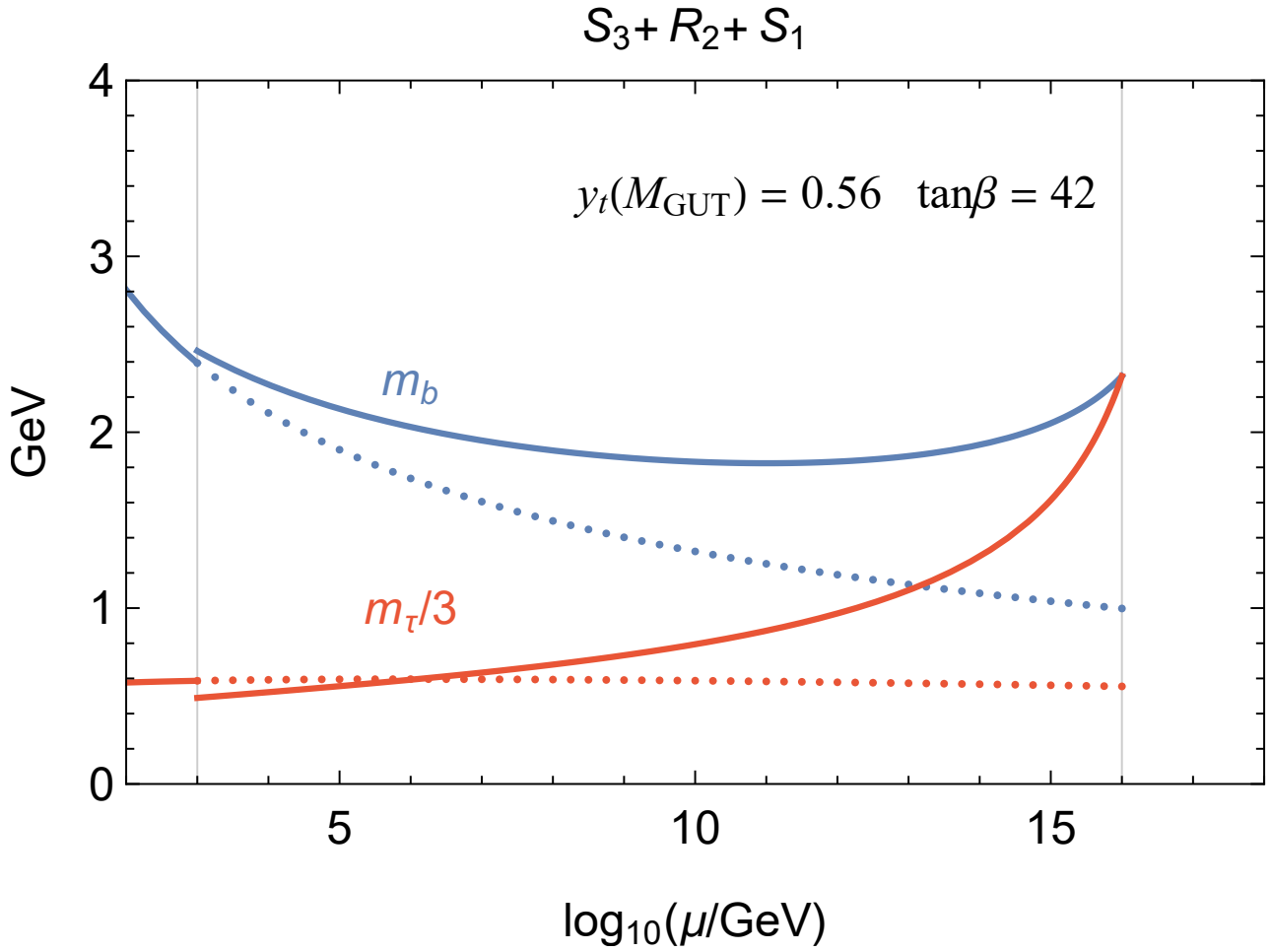
large leptoquark couplings, $2\sqrt{3} \approx 3.5$

Renormalisation group evolution

Overall normalisation of $m_b = y_b v_{\text{ew}}$, $m_t = y_t v_{\text{ew}}$, and $m_\tau = y_\tau v_{\text{ew}}$ determines $y_t(M_{\text{GUT}}) = 0.56$.

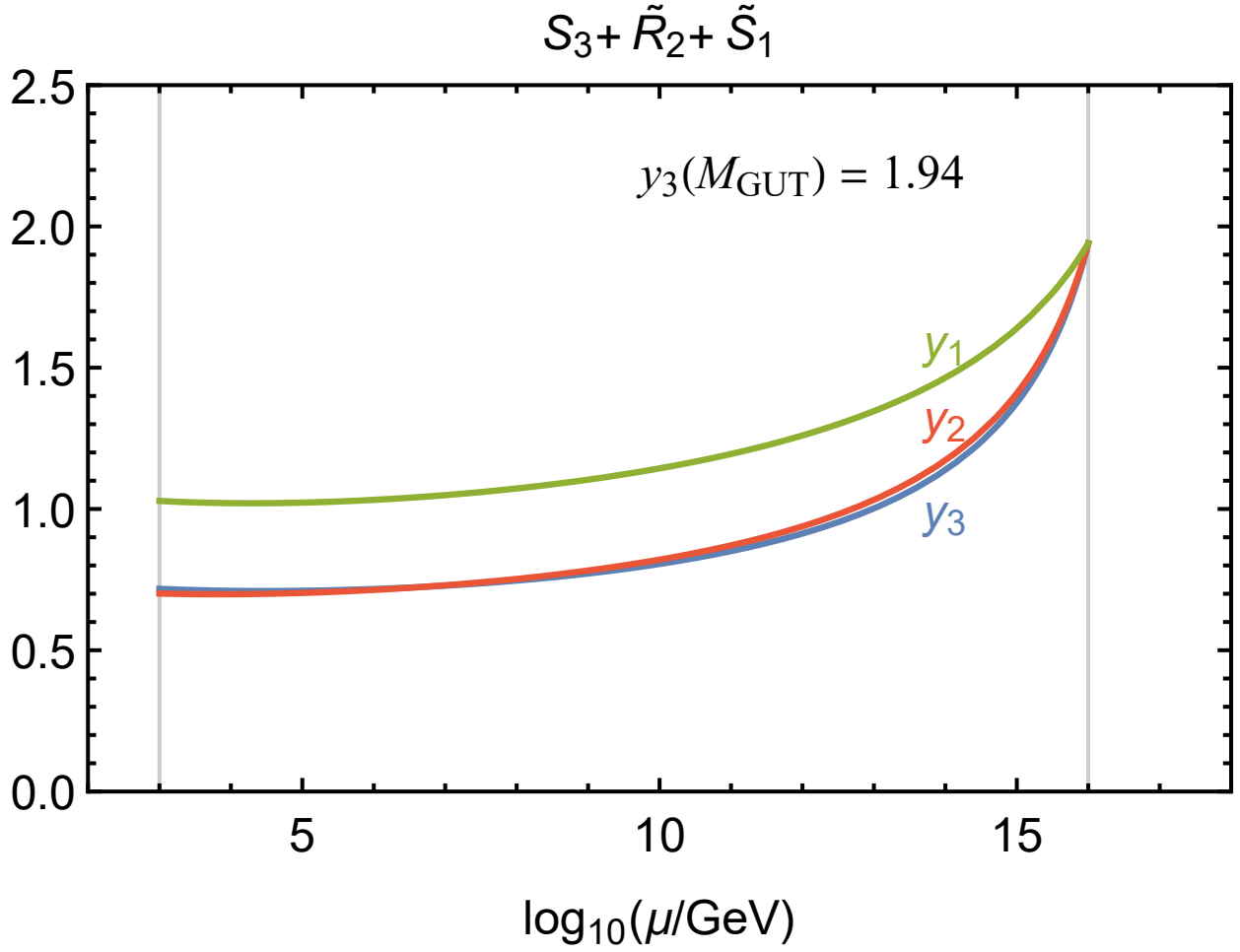
The reproduction of the correct value for m_b/m_τ is a successful prediction!

Dashed lines: evolution without the TeV-scale leptoquarks.



Renormalisation group evolution

Leptoquark couplings run into IR fixed points and have the desired $\mathcal{O}(1)$ couplings needed for the flavour anomalies.



Adding flavour

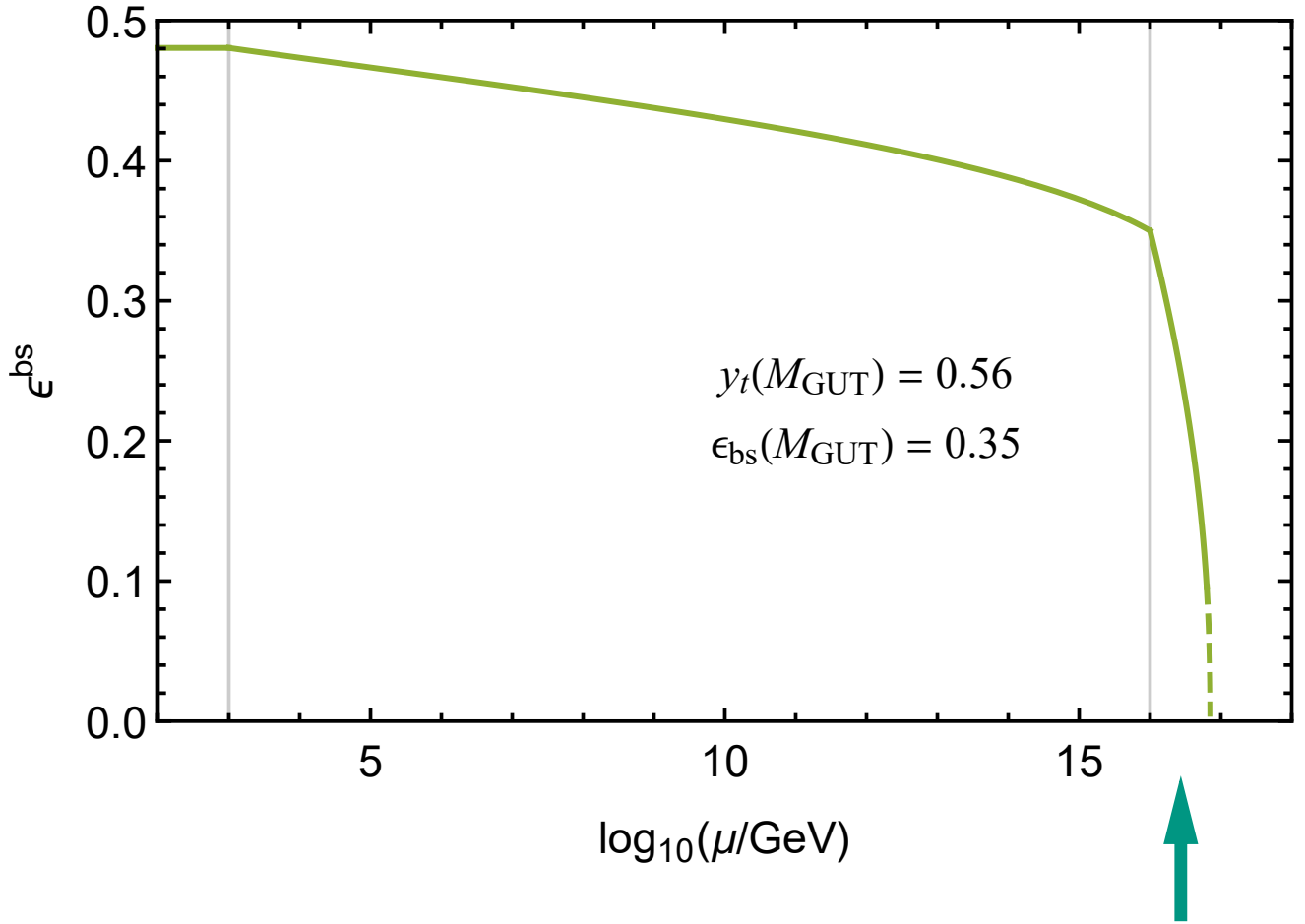
Perturb the successful Yukawa lagrangian with the most general terms involving both third- and second-generation fermions.

$$\mathscr{L}_Y^{\epsilon} = \epsilon^{ct} y_t \overline{Q_L^2} t_R H_u + \epsilon^{sb} y_b \overline{Q_L^2} b_R H_d + \epsilon^{bs} y_b \overline{Q_L^3} s_R H_d + \epsilon_1^{bs} y_1 \overline{s_R^c} \tau_R \widetilde{S}_1 + \text{h.c.}$$

Flavour violation

The smallness of the CKM-like flavour violation in the SM couplings is protected by SU(2) gauge symmetry.

For the leptoquark couplings, however, the point $\epsilon_{bs} = 0$ (meaning no flavour violation) is unstable w.r.t. the RG evolution, so that large flavour-changing leptoquark couplings are natural.



Here the 126 components of the Higgs field contribute.

Summary

- Scalar leptoquarks previously postulated *ad hoc* to explain flavour anomalies naturally occur in grand unified theories (GUTs).

- Third-generation Yukawa unification is known to fail in minimal SO(10) theories with just one Higgs multiplet coupling to fermions. We have found that this is remedied if either $\tilde{S}_1$, $\tilde{R}_2$, and S_3 or just $\tilde{S}_1$, $\tilde{R}_2$ are "light", with TeV-scale masses.

- The low-energy values of the leptoquark couplings $y_{1,2,3}$ are sizable, as needed for the flavour anomalies, due to the GUT scale boundary condition $y_1 = y_2 = y_3 = 2\sqrt{3}y_t$.

- Perturbing the solution with small flavour-changing parameters in the most general way introduces four parameters ϵ^{bs}, ϵ^{sb}, ϵ^{ct}, and ϵ_1^{bs} for transitions between second and third generation. Their RG evolution enhances the flavour-changing couplings of the leptoquarks, while the smallness of CKM-like flavour violation is protected.

Backup

Renormalisation group evolution

The IR fixed-point behaviour seems to be generic. Right plot: scenario with only S_3 and $\tilde{R}_2$.

The fixed-point feature was discovered before in phenomenologically motivated leptoquark scenarios, it can lead to lepton flavour universality in $b \to s\ell^+\ell^-$ dynamically, so no symmetries are needed for this.

Fedele, Wüst, UN, JHEP 11 (2023) 131.

