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

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Based on: JHEP02(2026)082 [2508.11745]
with Ulrich Nierste

Motivation and Introduction

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- Why SO(10) GUT?
  - Charge quantization:

    Babu, Mohapatra. '89;
    Foot, Lew, Volkas. '93;

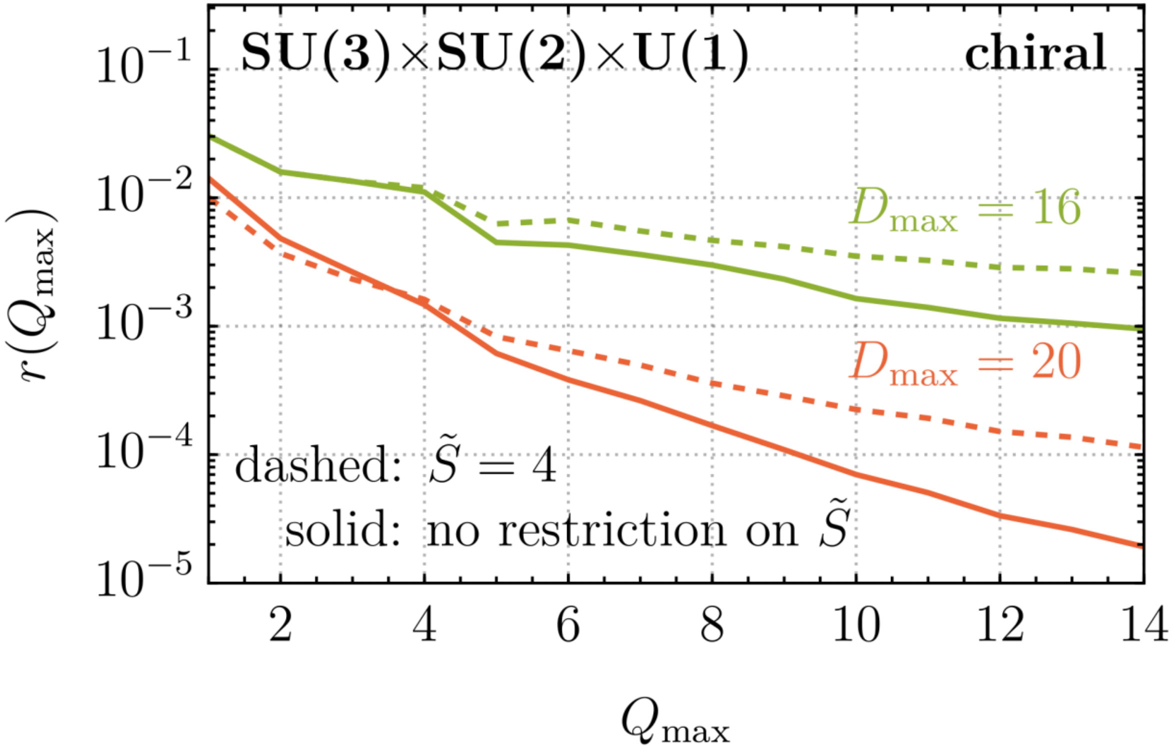
    Only Exp: $Q_n \lesssim 10^{-20} e$.

    Bressi, et al. '11;

  - Unification is rare:

    $(Q_L, u_R^c, d_R^c\ ) + (l_L, \nu_R^c, e_R^c) = 16_F$

    Herms, Ruhdorfer. '24. (the figure)



$\tilde{S}$: # of identical reps

SO(10) as a theory for flavor

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Most minimal: One Yukawa coupling

$10 = \binom{10}{1} = \binom{10}{9}$,

$120 = \binom{10}{3} = \binom{10}{7}$,

$126 = \frac{1}{2}\binom{10}{5}$.

i) $-\mathcal{L}_{Y_{10}} = Y_{10} 10_H \overline{16_F} 16_F^c, \quad 10_H = \Gamma_i \phi_i.$

Degenerate t, b, τ, ν_τ mass.

ii) $-\mathcal{L}_{Y_{120}} = Y_{120} 120_H \overline{16_F} 16_F^c, \quad 120_H = \Gamma_i \Gamma_j \Gamma_k \phi_{[ijk]}.$

Y_{120} antisymmetric: no 2-3 gen hierarchy.

Nature loves self-dual?

iii) $-\mathcal{L}_{Y_{126}} = Y_{126} 126_H \overline{16_F} 16_F^c, \quad 126_H = \Gamma_i \Gamma_j \Gamma_k \Gamma_l \Gamma_m \phi_{[ijklm]}.$

- High-scale vacuum: tiny neutrino masses.
- Two-Higgs-doublets: hierarchical $\frac{m_t}{m_b} = tan\beta$.
- All good at $\mathcal{O}(1)$, except for $\frac{m_\tau}{m_b} = 3$ is wrong.

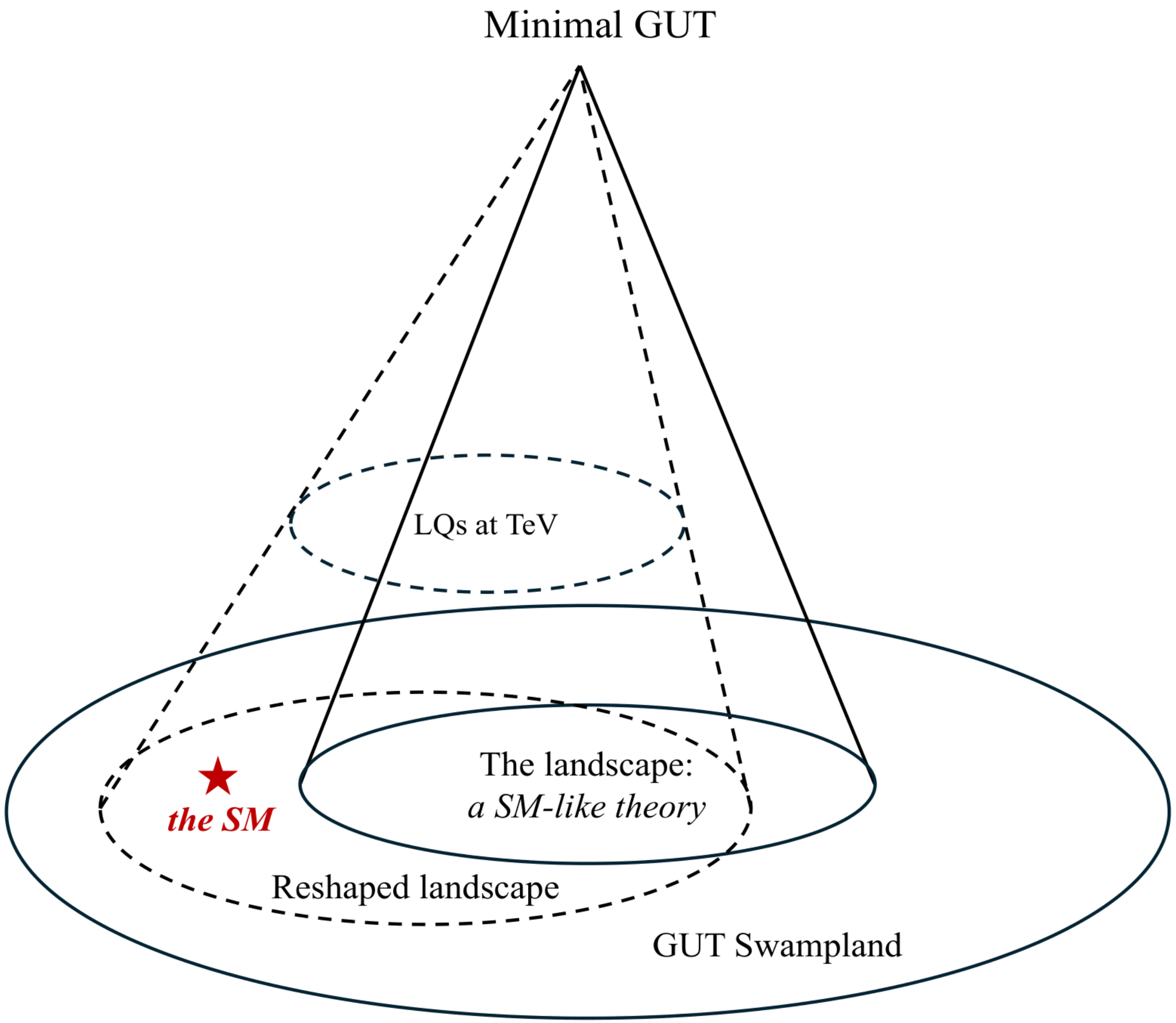
See also talk by Zi-Qiang Chen

SO(10) as a theory for flavor

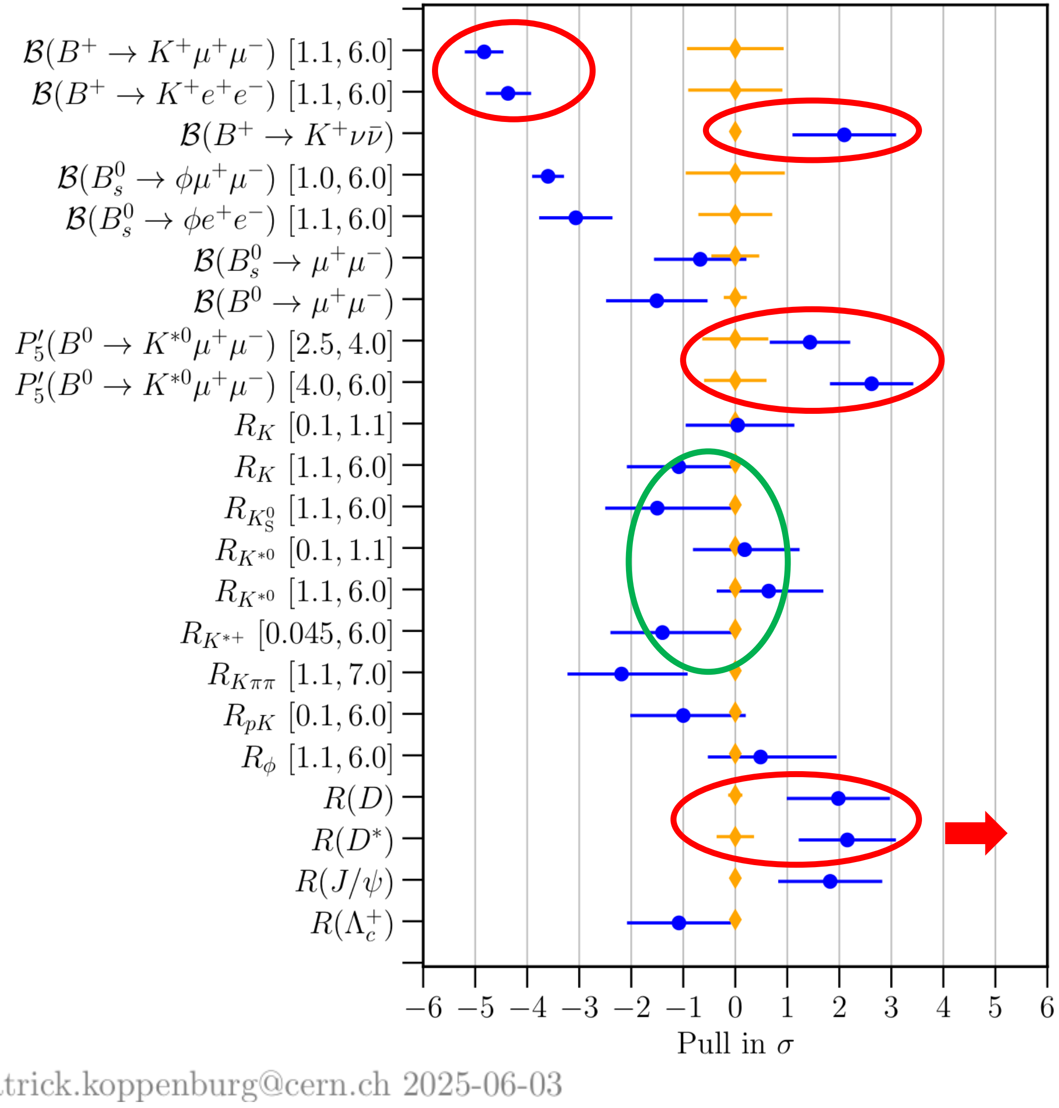
Towards a realistic theory:

- UV model building:
  - Beyond the most minimal GUT.
- Reshaping the Infrared:
  - Oasis in the particle desert.

    See also talk by Saurabh K. Shukla
  - TeV-scale particles from 126_H.
  - Also motivated by gauge coupling unification (See-backup).



Reshaping the Infrared



- $b \to c\tau\nu$:
  - $R(D^{(*)}) = \frac{BR(B\to D^{(*)}\tau\nu)}{BR(B\to D^{(*)}\ell\nu)}$.
  - With experimental information on the form factors: 4σ: Iguro, Kitahara, Watanabe 24'
- $b \to s\ell\ell$:
  - $R(K^{(*)})$ disappear. LHCb 22'
  - Low q^2, P_5'.
  - Highest significance.
- $b \to s\nu\nu$:
  - $B \to K + \text{inv}$ excess. Belle-II 23'.

Statistically, unlikely all disappear.

Reshaping the Infrared

Postulating TeV-scale LQs ad-hoc → Embedding them into a meaningful theory

Generic LQ review:
Doršnera, Fajferd, Greljo, Kamenik, Košnik. 16'.

Addressing B anomalies:
Crivellin, Müller, Ota 17'; Crivellin, Müller, Saturnino 19; Fedele, Wuest, Nierste 23'; Bause, Gisbert, Hiller, 23'; He, Ma, Valencia 23'; Crivellin, Iguro, Kitahara 25'; and more…

$SO(10)$	$SU(4)_C \times SU(2)_L \times SU(2)_R$	$SU(3)_c \times SU(2)_L \times U(1)_Y$
ϕ_{126}	$(\mathbf{6}_C, \mathbf{1}_L, \mathbf{1}_R)$	$S_1(\mathbf{3}, \mathbf{1}, -1/3)$
		$S_1'(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
	$(\mathbf{10}_C, \mathbf{3}_L, \mathbf{1}_R)$	$S_3(\mathbf{3}, \mathbf{3}, -1/3)$
	$(\overline{\mathbf{10}_C}, \mathbf{1}_L, \mathbf{3}_R)$	$\bar{S}_1(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
		$S_1''(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
		$\widetilde{S}_1(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$
	$(\mathbf{15}_C, \mathbf{2}_L, \mathbf{2}_R)$	$R_2(\bar{\mathbf{3}}, \mathbf{2}, -7/6)$
		$\widetilde{R}_2(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$
		$R_2'(\mathbf{3}, \mathbf{2}, 7/6)$
		$\widetilde{R}_2'(\mathbf{3}, \mathbf{2}, 1/6)$

Reshaping the Infrared

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- S_3: $R(D^{(*)})$ partly.
- $S_3, \tilde{R}_2$ together: $B \to K\nu\nu$ (enhancement) and $B \to K^*\nu\nu$ (cancellation).
- τ loop: $B \to K\ell\ell$, LFU.
- R_2: $R(D^{(*)})$ as well, but it carries too large $U(1)_Y$.
- S_1: always mediates P decay.
- $\bar{S}_1$: only couple to ν_R.
- $S_3, \tilde{S}_1$: no P decay with $U(1)_{PQ}$.
- 2HDM required by $U(1)_{PQ}$: $R(D^{(*)})$ as well.

	S_3	S_1	$\widetilde{S}_1$
$b \to c\tau\nu$	$(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$	$(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)$ $(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$ $(\overline{c_R}b_L)(\bar{\tau}_R\nu_L)$	–
$b \to s\tau\tau$	$(\bar{s}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\tau_L)$	–	$(\bar{s}_R\gamma^\mu b_R)(\bar{\tau}_R\gamma_\mu\tau_R)$
$b \to s\nu\nu$	$(\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_L\gamma_\mu\nu_L)$	$(\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_L\gamma_\mu\nu_L)$	–

	R_2	$\widetilde{R}_2$	$\bar{S}_1$
$b \to c\tau\nu$	$(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)$ $(\overline{c_R}b_L)(\bar{\tau}_R\nu_L)$	–	–
$b \to s\tau\tau$	$(\bar{s}_L\gamma^\mu b_L)(\bar{\tau}_R\gamma_\mu\tau_R)$	$(\bar{s}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\tau_L)$	–
$b \to s\nu\nu$	–	$(\bar{s}_R\gamma^\mu b_R)(\bar{\nu}_L\gamma_\mu\nu_L)$	–

Improved RG equations

Light theory: SM with 2HDM+LQs (approx 3rd gen specific:)

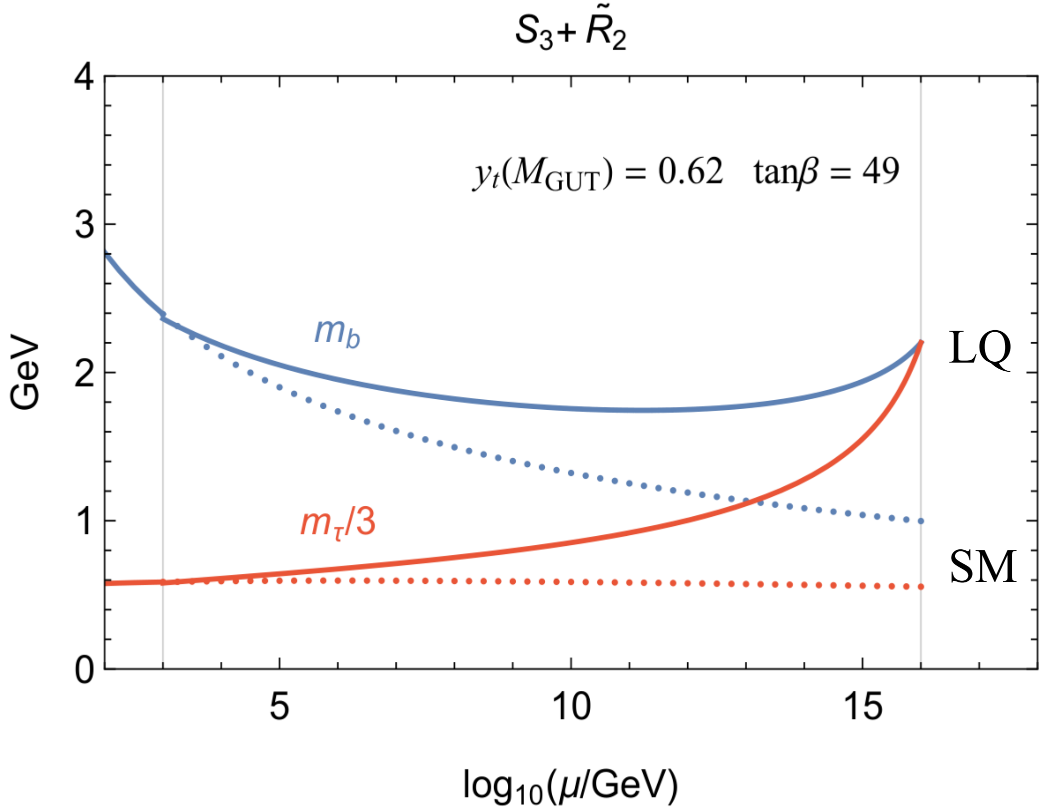
$$
\begin{aligned}
-\mathcal{L}_Y \; &= y_t \overline{Q_L^3} t_R H_u + y_b \overline{Q_L^3} b_R H_d + y_\tau \overline{L_L^3} \tau_R H_d \\
&+ y_1 \overline{b_R^c} \tau_R \widetilde{S}_1 + y_2 \overline{b_R^c} L_L^{3c} \widetilde{R}_2 + y_3 \overline{Q_L^{3c}} L_L^3 S_3 + \text{h.c.}
\end{aligned}
$$

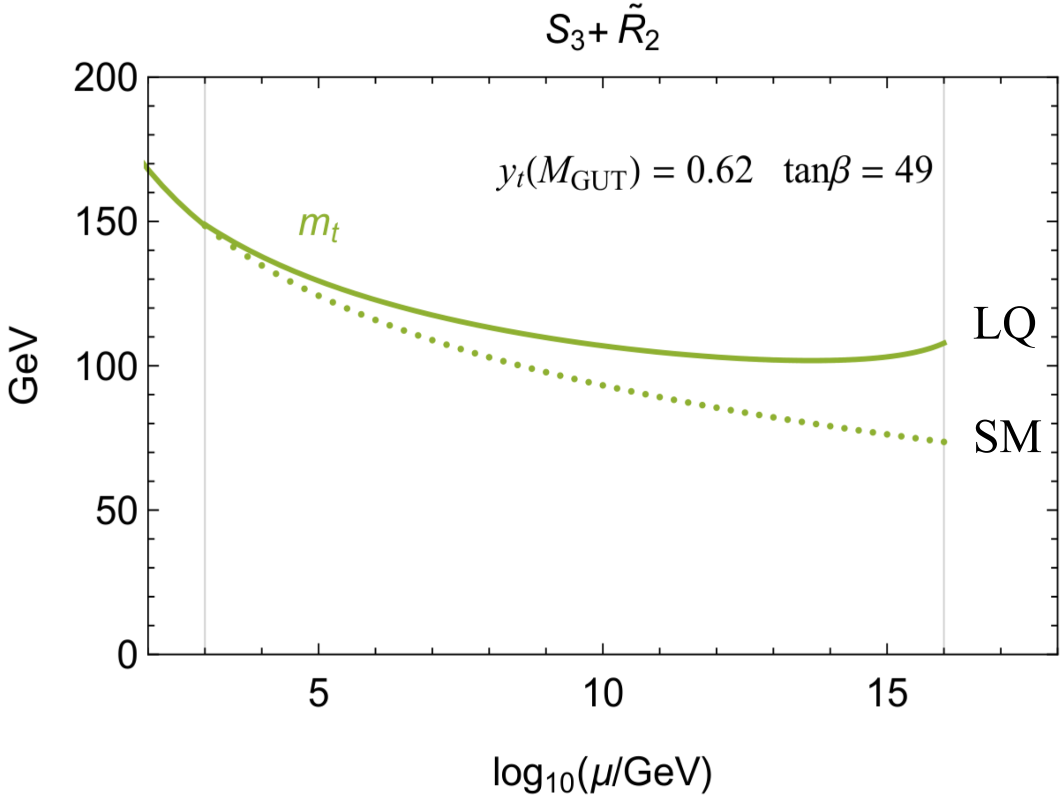
TeV-scale: m_t, m_b, m_τ → Updated RGEs → GUT scale: y_t and tanβ

$$
\begin{aligned}
16\pi^2 \frac{d}{d\ln\mu} y_b \; &= y_b \left(-\frac{5g_1^2}{12} - \frac{9g_2^2}{4} - 8g_3^2 + \frac{y_t^2}{2} + \frac{9y_b^2}{2} + y_\tau^2 + \frac{y_1^2}{2} + y_2^2 + \frac{3y_3^2}{2} \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_\tau \; &= y_\tau \left(-\frac{15g_1^2}{4} - \frac{9g_2^2}{4} + \frac{5y_\tau^2}{2} + 3y_b^2 + \frac{3y_1^2}{2} + \frac{3y_2^2}{2} + \frac{9y_3^2}{2} \right),
\end{aligned}
$$

See back-up for complete RGEs

Improved RG equations

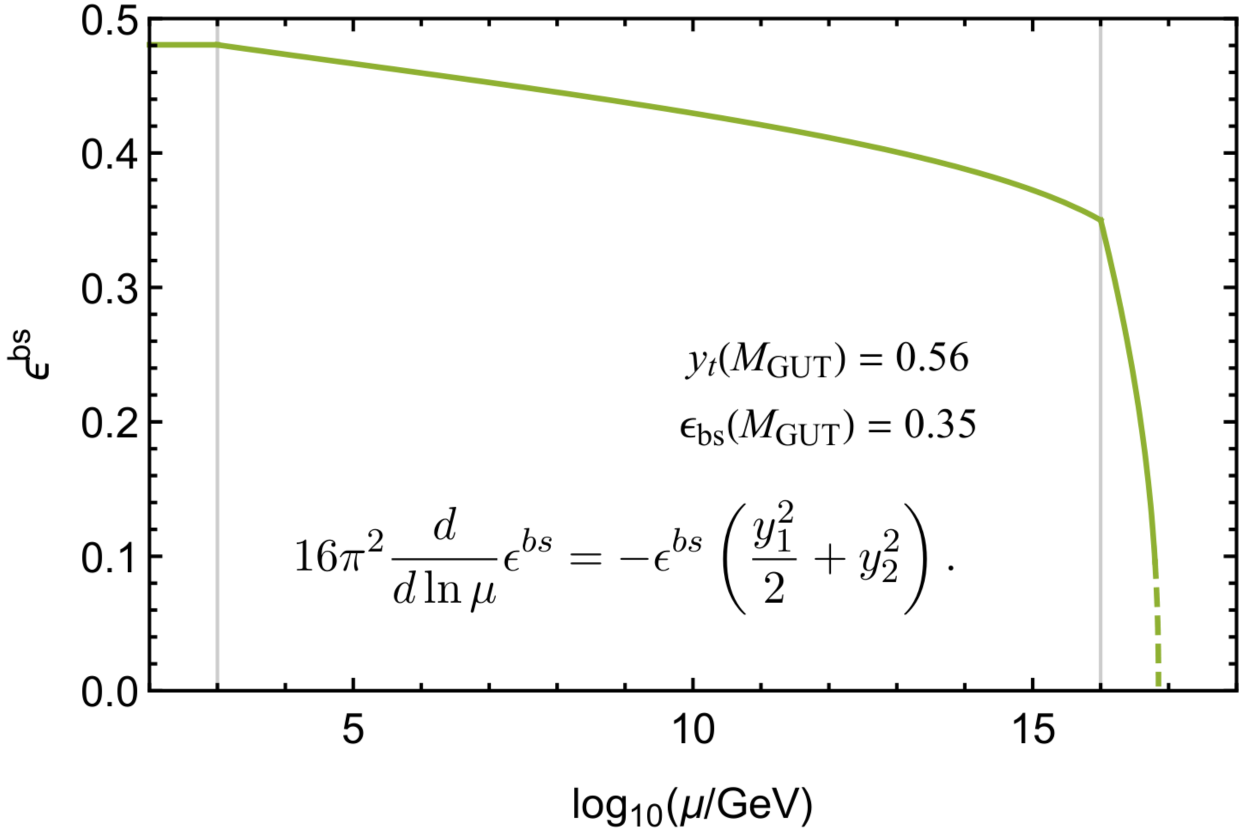




- Quark loop for Leptons = Lepton loop for Quarks × number of colors.
- Model independent: $S_3, \tilde{R}_2, \tilde{S}_1$ or $S_3, \tilde{S}_1$ also reasonably good – see backup.

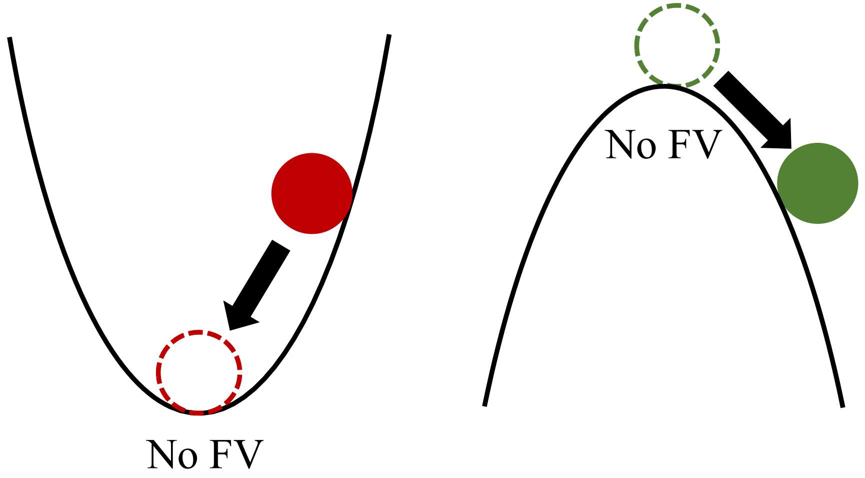
Improved RG equations

Emerging flavor mixing:



- Single Yukawa: always flavor diagonal.
- Need UV seeds for FV.
- A sensitive dependence on initial conditions.

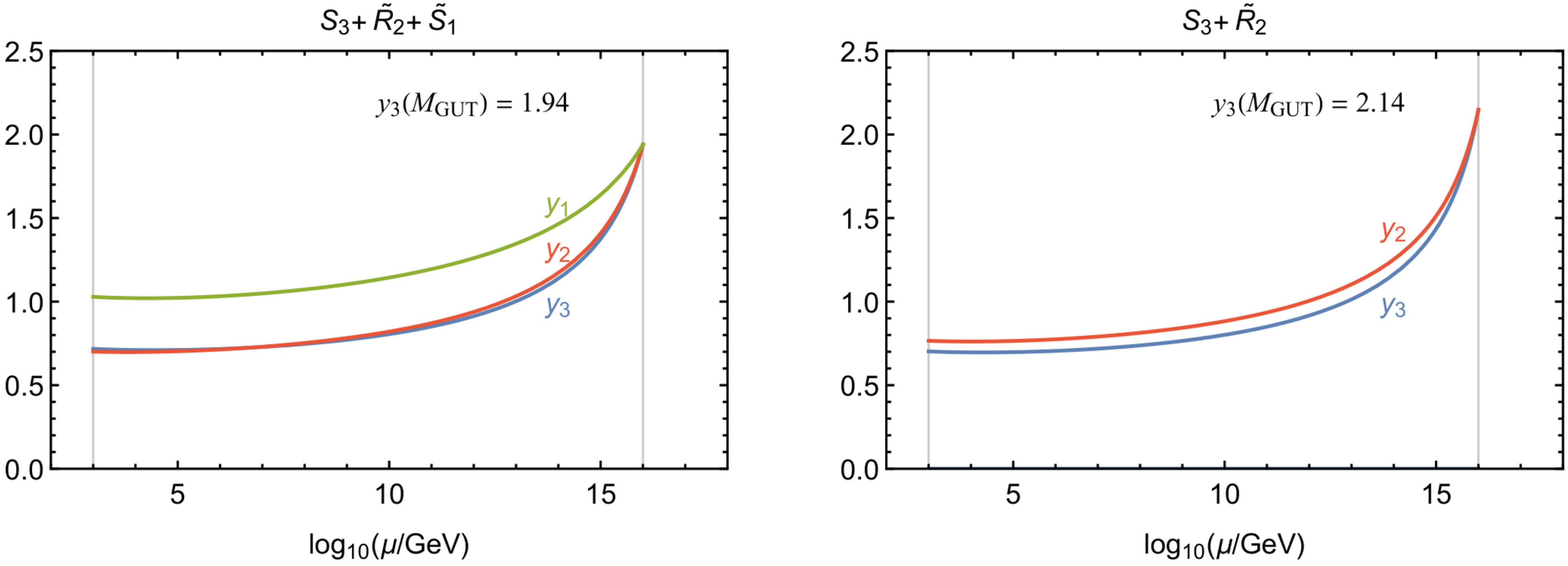
$$Y_{126} \sim \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & \epsilon' & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



SM RGE: Stable   With LQ: Unstable

Improved RG equations

LQ-fermion coupling strength:



- Fixed-point behavior similar to Fedele, Nierste, Wuest, 23'.
- Minimal GUT prediction: $y_2 \approx y_3$: $\tilde{R}_2, S_3$ cancellation less ad-hoc.

Conclusion and Outlook

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- Two key improvements:
  - $b-\tau$: successful unification.
  - Emerging flavor mixing possible.
- Outlook:
  - A generic behavior but examples ongoing.
  - Appliable for other deep-UV models.
  - Beyond Froggatt-Nielsen paradigm.

Thanks

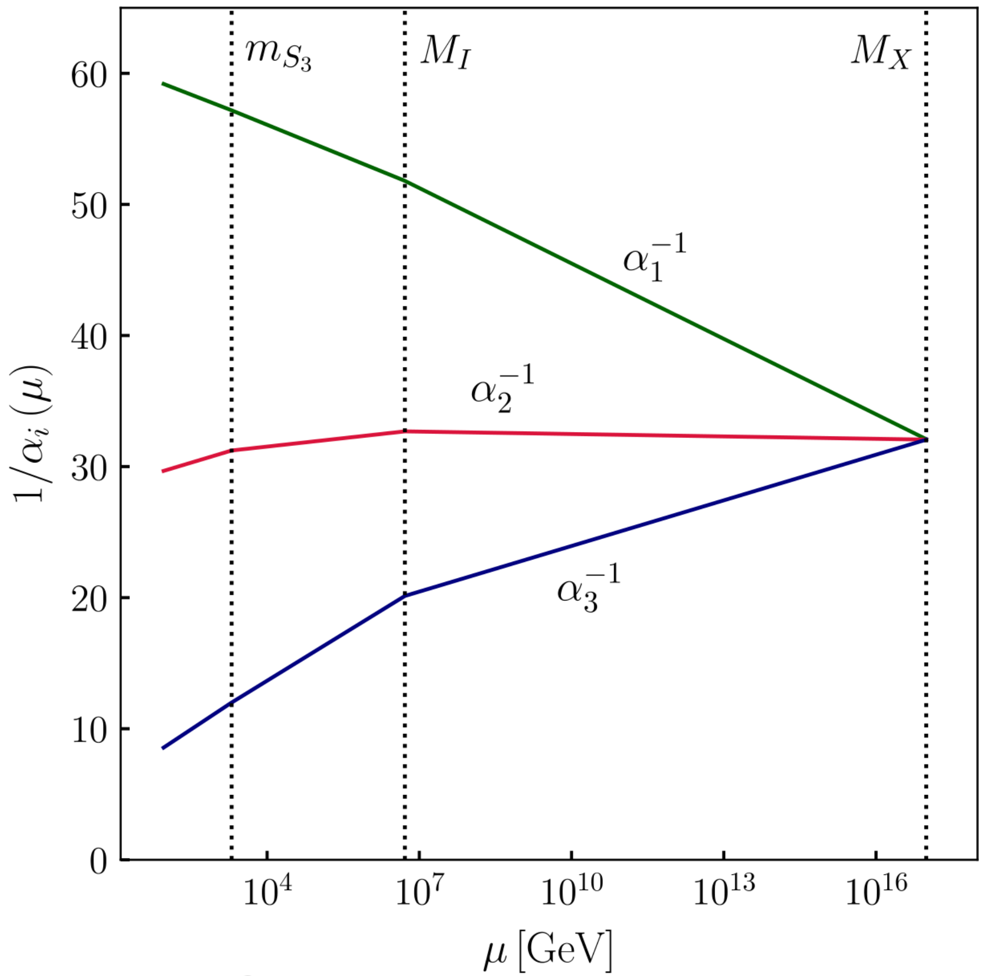
Additional Slides

Gauge coupling unification

- $\tilde{R}_2$ is good.

  Preda, Senjanovic, Zantedeschi.’22; ’25.
- S_3 increases $g_{SU(2)_L}$ too much.
- Need light diquarks and color-octets.

  Goto, Mishima, Shindo. 23’ (the figure).
- Potential corrections from reps **irrelevant** to the Yukawa couplings.



$$m_{S_3} = 2 \text{ TeV},$$
$$m_{S_6} = m_{S_8} = m_{\Sigma_8} \equiv M_I = 5.2 \times 10^6 \text{ GeV}$$

Updated RGEs with LQs

$$
\begin{aligned}
16\pi^2 \frac{d}{d\ln\mu} y_t &= y_t \left(-\frac{17g_1^2}{12} - \frac{9g_2^2}{4} - 8g_3^2 + \frac{9y_t^2}{2} + \frac{y_b^2}{2} + \frac{3y_3^2}{2} \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_b &= y_b \left(-\frac{5g_1^2}{12} - \frac{9g_2^2}{4} - 8g_3^2 + \frac{y_t^2}{2} + \frac{9y_b^2}{2} + y_\tau^2 + \frac{y_1^2}{2} + y_2^2 + \frac{3y_3^2}{2} \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_\tau &= y_\tau \left(-\frac{15g_1^2}{4} - \frac{9g_2^2}{4} + \frac{5y_\tau^2}{2} + 3y_b^2 + \frac{3y_1^2}{2} + \frac{3y_2^2}{2} + \frac{9y_3^2}{2} \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_1 &= y_1 \left(-2g_1^2 - 4g_3^2 + y_b^2 + \frac{y_\tau^2}{2} + 3y_1^2 + y_2^2 \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_2 &= y_2 \left(-\frac{13g_1^2}{20} - \frac{9g_2^2}{4} - 4g_3^2 + y_b^2 + \frac{y_\tau^2}{2} + \frac{y_1^2}{2} + \frac{7y_2^2}{2} + \frac{9y_3^2}{2} \right), \\
16\pi^2 \frac{d}{d\ln\mu} y_3 &= y_3 \left(-\frac{g_1^2}{2} - \frac{9g_2^2}{2} - 4g_3^2 + \frac{y_t^2}{2} + \frac{y_b^2}{2} + \frac{y_\tau^2}{2} + \frac{3y_2^2}{2} + 8y_3^2 \right).
\end{aligned}
$$

Additional Slides

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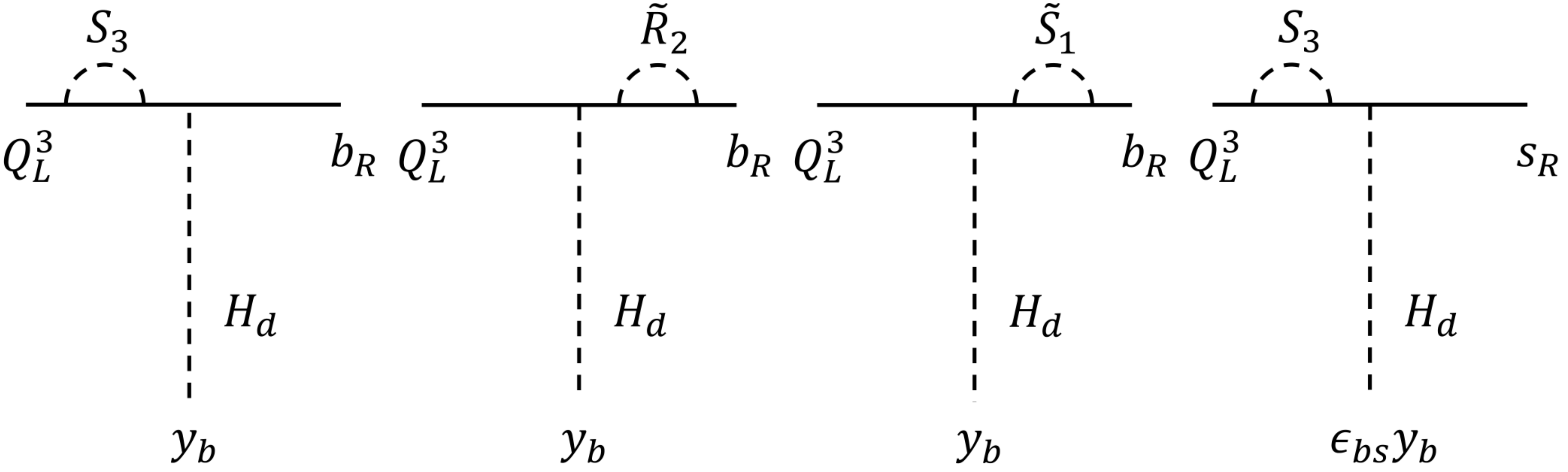
Leptoquark (LQ): leptons ↔ quarks

	Vector LQ Di Luzio, Greljo, Nardecchia 17'; Bordone, Cornella, Fuentes-Martin, Isidori 17'; Calibbi, Crivellin, Li 17'; Greljo, Stefanek 18'; Fuentes-Martin, Isidori, Lizana, Selimovic, Stefanek, 22';Davighi, Isidori, Pesut 23'; and more…	Scalar LQ Crivellin, Müller, Ota 17'; Crivellin, Müller, Saturnino 19; Fedele, Wuest, Nierste 23'; Bause, Gisbert, Hiller, 23'; He, Ma, Valencia 23'; Crivellin, Iguro, Kitahara 25'; and more…
Mass: TeV-scale	Protected (gauge inv)	Fine-tuned
Coupling: $U(2)^n$	'Next-to' minimal	Automatic (chiral sym)

Our idea: Fine-tuning → Consistency requirement

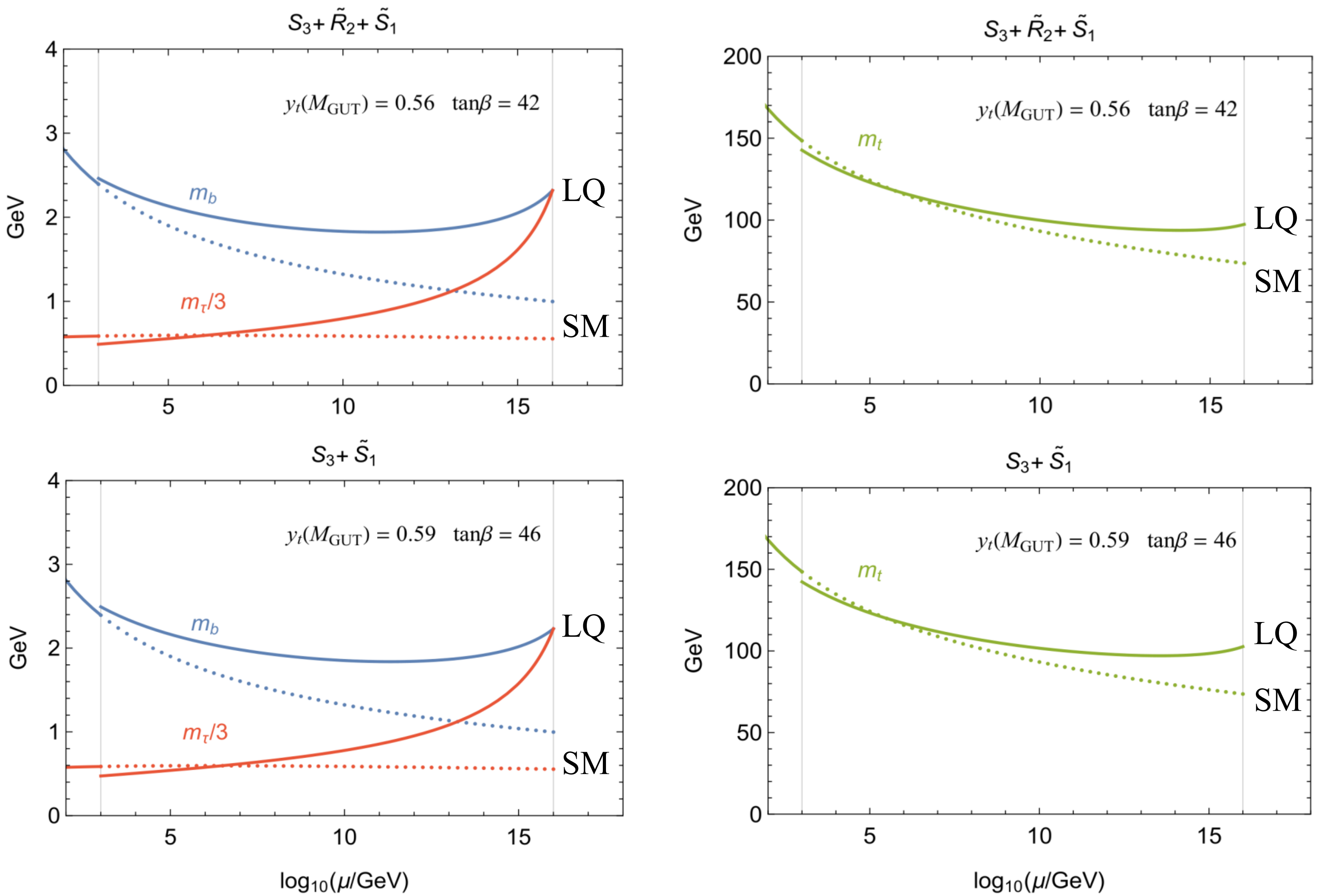
Why unstable?



$$16\pi^2 \frac{d}{d\ln\mu}\epsilon^{bs} = -\epsilon^{bs}\left(\frac{y_1^2}{2} + y_2^2\right).$$

Additional Slides

- Model-independent.
- $\mathcal{O}(\epsilon)$ gap at 1 TeV.
- Fair as leading-log estimation.



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LQs in 126_H: interactions

$$
\begin{aligned}
-\mathcal{L}_Y^{\text{LQ}} &= Y_3^{LL}\overline{Q_L}S_3L_L^c + Y_3^{RR}\overline{Q_R^c}\widehat{S}_3L_R + Y_1^{LL}\overline{Q_L}S_1L_L^c + Y_1^{RR}\overline{Q_R^c}\widehat{S}_1L_R \\
&+ Y_2^{LR}\overline{Q_L}(R_2', \widetilde{R}_2')L_R + Y_2^{RL}\overline{Q_R^c}(R_2, \widetilde{R}_2)L_L^c + \text{h.c.}
\end{aligned}
$$

With $SU(2)_R$ multiplets:

$$
\widehat{S}_3 = \begin{pmatrix} \overline{S}_1 & S_1''/\sqrt{2} \\ S_1''/\sqrt{2} & \widetilde{S}_1 \end{pmatrix} \qquad \widehat{S}_1 = \begin{pmatrix} 0 & S_1'/\sqrt{2} \\ -S_1'/\sqrt{2} & 0 \end{pmatrix}
$$

$$
Q_R = (u_R, d_R)
$$

$$
L_R = (\ell_R, \nu_R)
$$