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

Xiyuan Gao

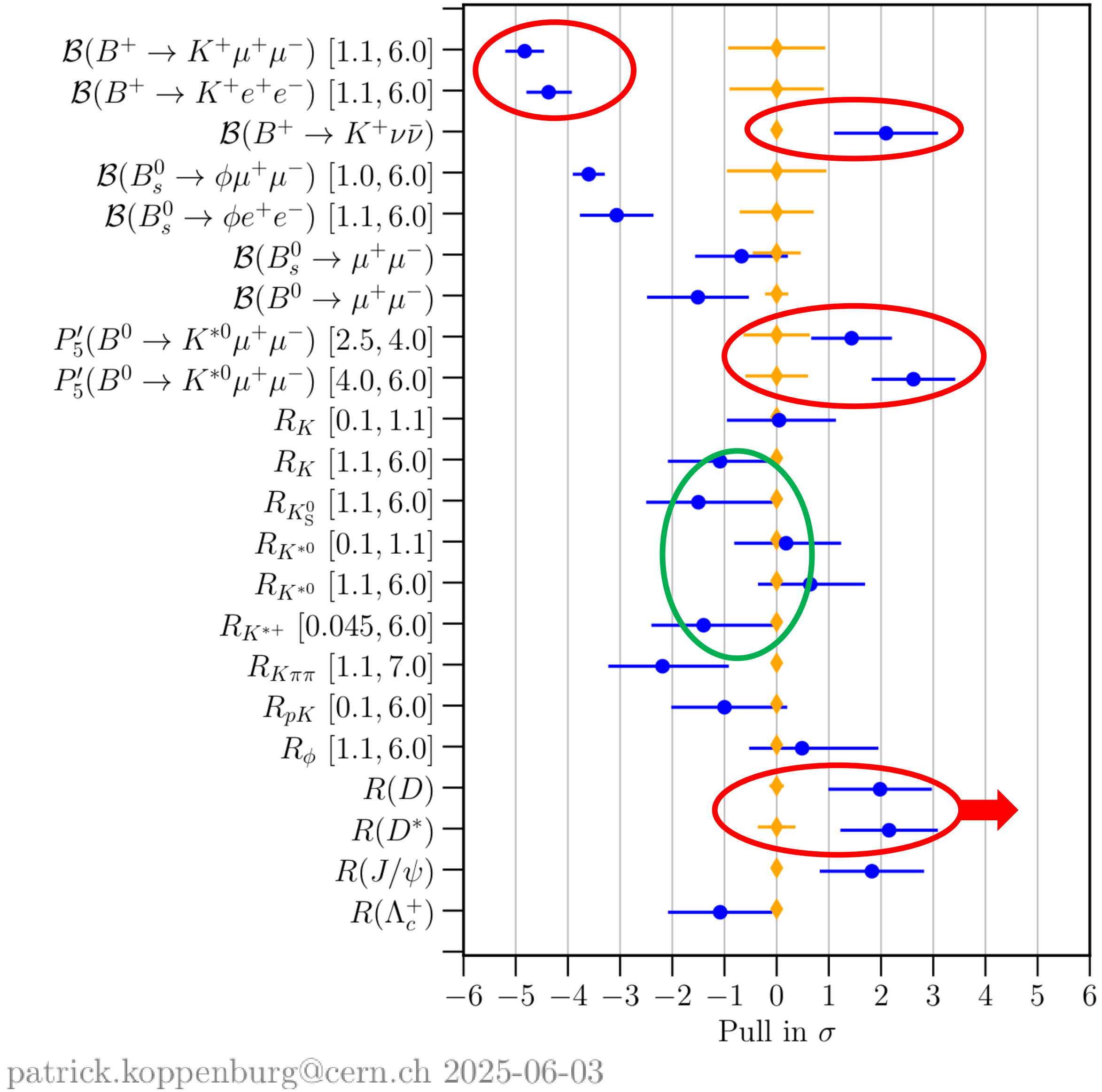
Institut für Theoretische Teilchenphysik (TTP),

Karlsruher Institut für Technologie (KIT), Germany

Based on: 2508.11745 with Ulrich Nierste

Motivation and Introduction

Karlsruher Institut für Technologie



- $b \to c\tau\nu$:
  - $R(D^{(*)}) = \frac{BR(B\to D^{(*)}\tau\nu)}{BR(B\to D^{(*)}\ell\nu)}$.
  - 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.

Motivation and Introduction

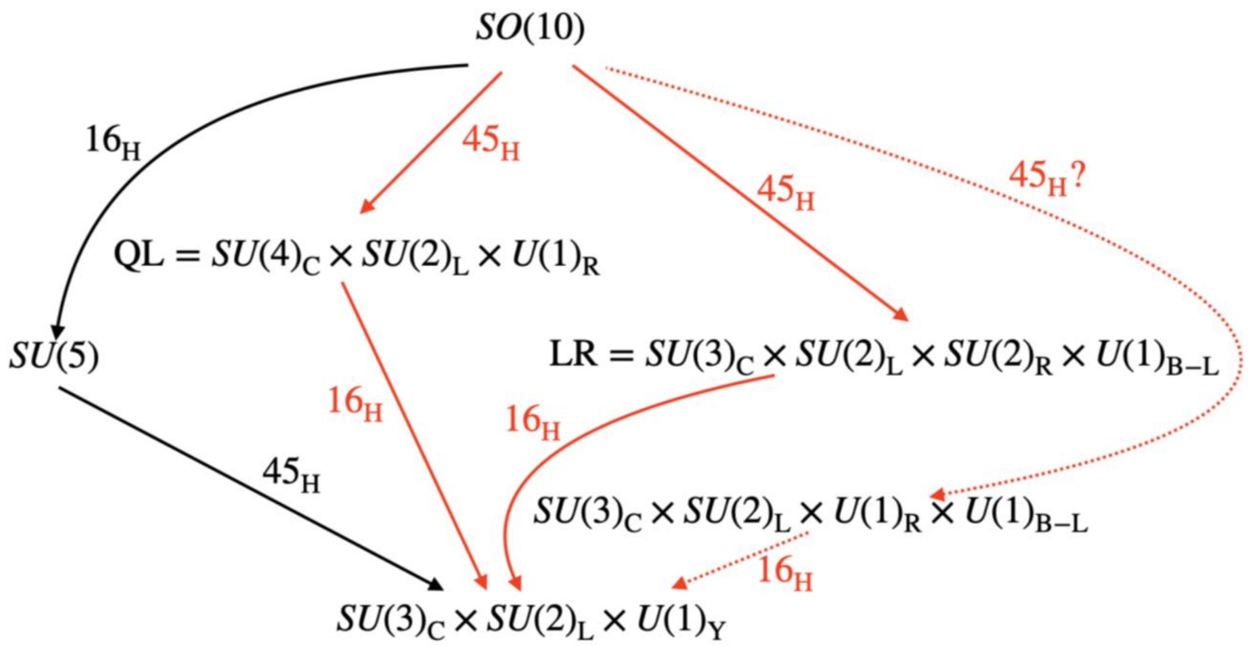
Leptoquark (LQ): leptons ↔ quarks

	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

Motivation and Introduction

- Why SO(10) GUT?
  - Charge quantization:
    Only Exp: $Q_n \lesssim 10^{-20} e.$
  - Quantization ← Unification:
    $(Q_L, u_R^c, d_R^c) + (l_L, \nu_R^c, e_R^c) = 16_F$
  - Prediction: proton-decay
  - Difficulty: flavor patterns



Babu, Mohapatra. ’89;
Foot, Lew, Volkas. ’93;
Bressi, et al. ’11;
Herms, Ruhdorfer. ’24.

Georgi, Glashow. ’74;
Fritzsch, Minkowski. ’75
Bertolini, Di Luzio, Malinsky.’10 ’12;
Preda, Senjanovic,
Zantedeschi.’22 ’24 (figure above);

Most Minimal SO(10)

Karlsruher Institut für Technologie

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.

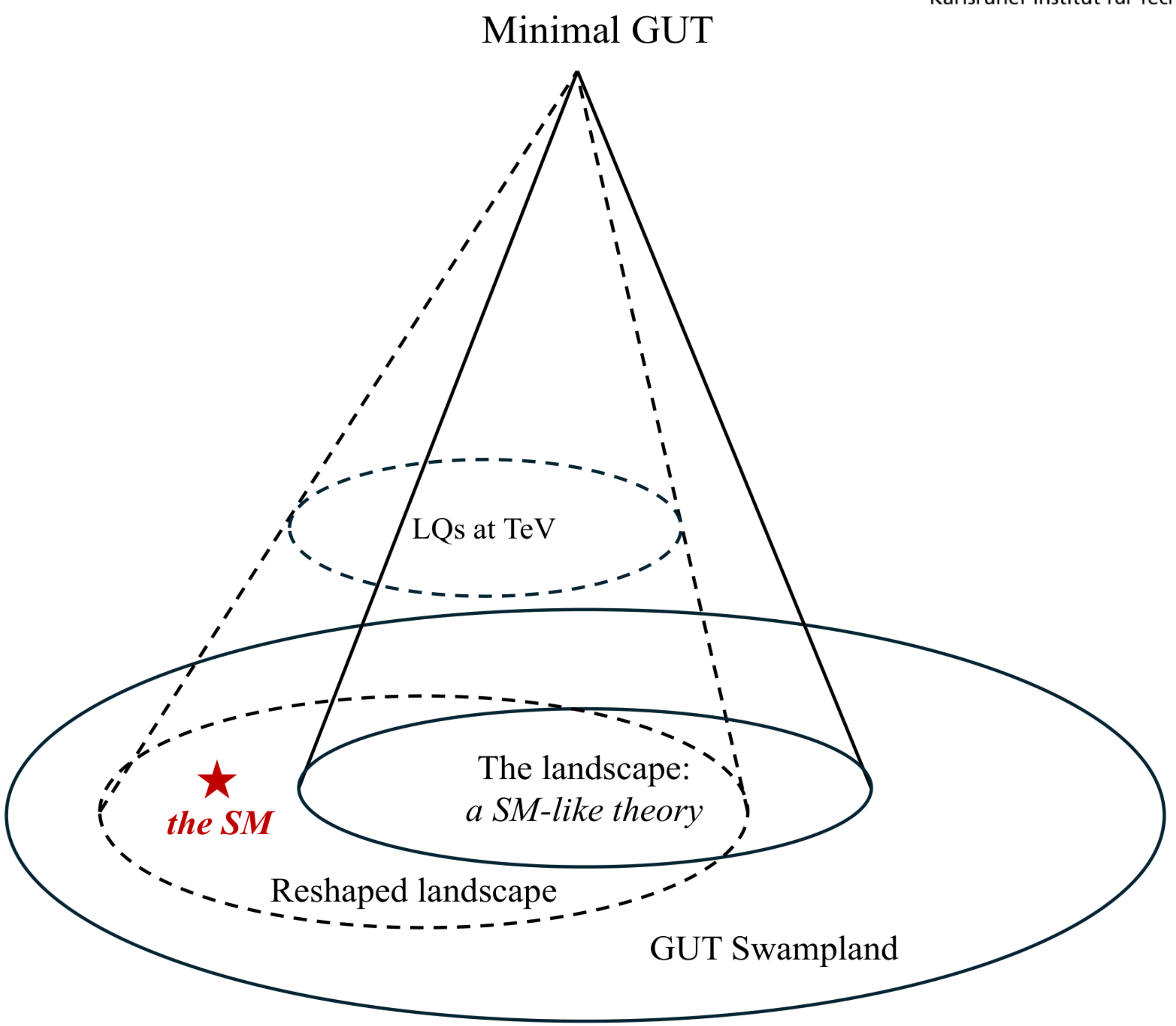
SM RGE: $\frac{m_\tau}{m_b} = 1.67$ at 10^{16} GeV.
Martin, Robertson 19'.

Most Minimal SO(10)

SM RGE: a loop-hole

- Non-minimal GUT?
- Particle desert fails.
- Data driven:

  TeV-scale LQs from 126_H.



Gauge coupling unification:
See-backup

Most Minimal SO(10)

Karlsruher Institut für Technologie

General LQ summary: Doršnera, Fajferd, Greljo, Kamenik, Košnik. 16'.

LQs in 126_H:

$$126_H \begin{cases} (6_c, 1_L, 1_R) \supset S_1(3,1,-1/3) + S_1'(\overline{3},1,1/3), \\ (10_c, 3_L, 1_R) \supset S_3(3,3,-1/3), \\ (\overline{10_c}, 1_L, 3_R) \supset \bar{S}_1(\overline{3},1,-2/3) + S_1''(\overline{3},1,1/3) + \widetilde{S}_1(\overline{3},1,4/3), \\ (15_c, 2_L, 2_R) \supset R_2(\overline{3},2,-7/6) + \widetilde{R}_2(\overline{3},2,-1/6) + R_2'(3,2,7/6) + \widetilde{R}_2'(3,2,1/6). \end{cases}$$

SO(10) → Pati-Salam → $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

Interactions: follow gauge and chiral sym, see back-up.

Most Minimal SO(10)

Karlsruher Institut für Technologie

Addressing anomalies:

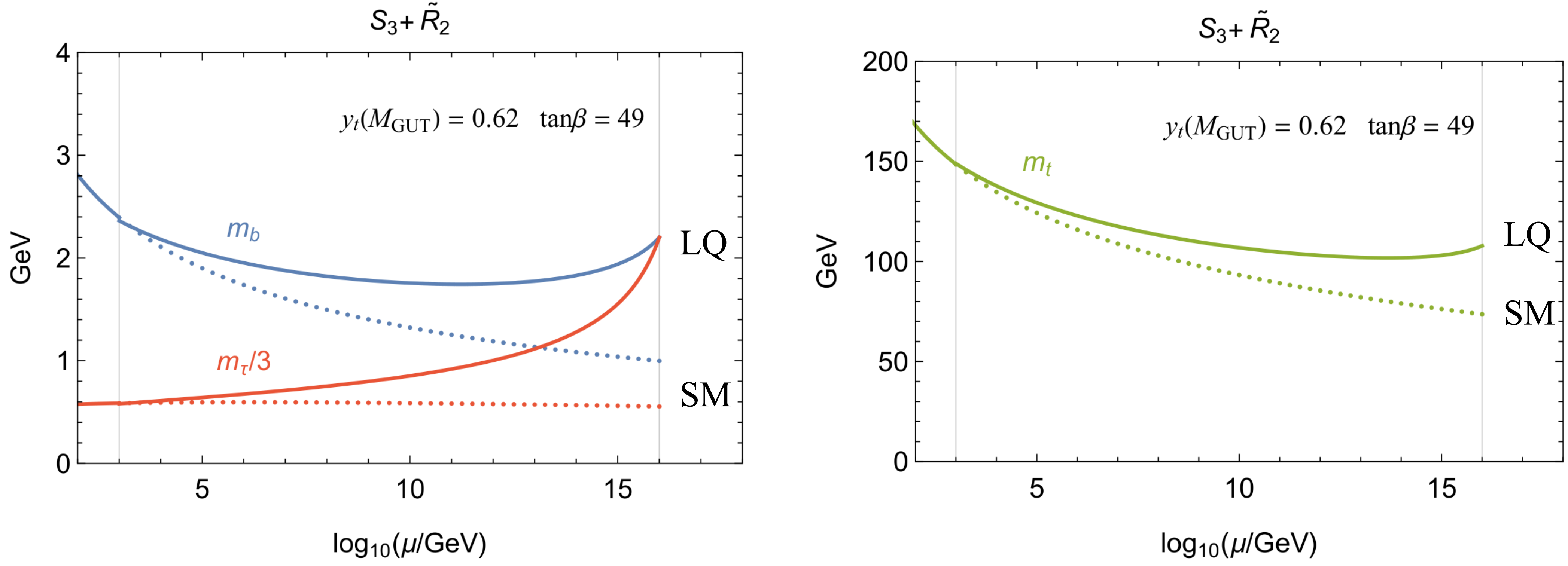
- S_3 for $R(D^{(*)})$.
- $S_3, \tilde{R}_2$ together for $B \to K\nu\nu$.
- $S_3, \tilde{R}_2$ cancel for $B \to K^*\nu\nu$.
- τ loop for $B \to K\ell\ell$, LFU.
- R_2 carries too large $U(1)_Y$.
- S_1 mediates P decay.
- S_3 no P decay with $U(1)_{PQ}$.
- $U(1)_{PQ}$ requires low scale 2HDM.

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

Improved RG equations

Charged fermion masses:

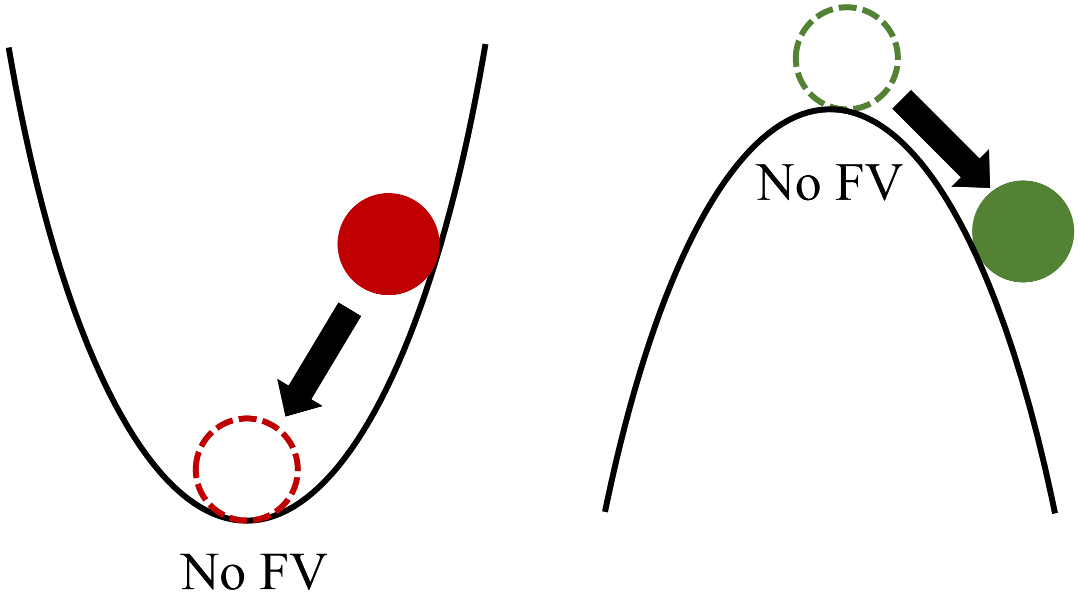


- Quark loop for Leptons = Lepton loop for Quarks × number of colors.
- Model independent: $S_3, \tilde{R}_2, \tilde{S}_1$ or $S_3, \tilde{S}_1$ also reasonably good – see backup.

Emerging flavour mixing?

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

- Always flavour diagonal?
- Need UV seeds for FV.
- A sensitive dependence on initial conditions.
- See back-up for plots.



SM RGE: Stable   With LQ: Unstable

Conclusion and Outlook

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

Thanks

Additional Slides

Karlsruher Institut für Technologie

Light theory: SM with 2HDM+LQs

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

Approximately 3rd generation specific.

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

Updated RGEs, see backup

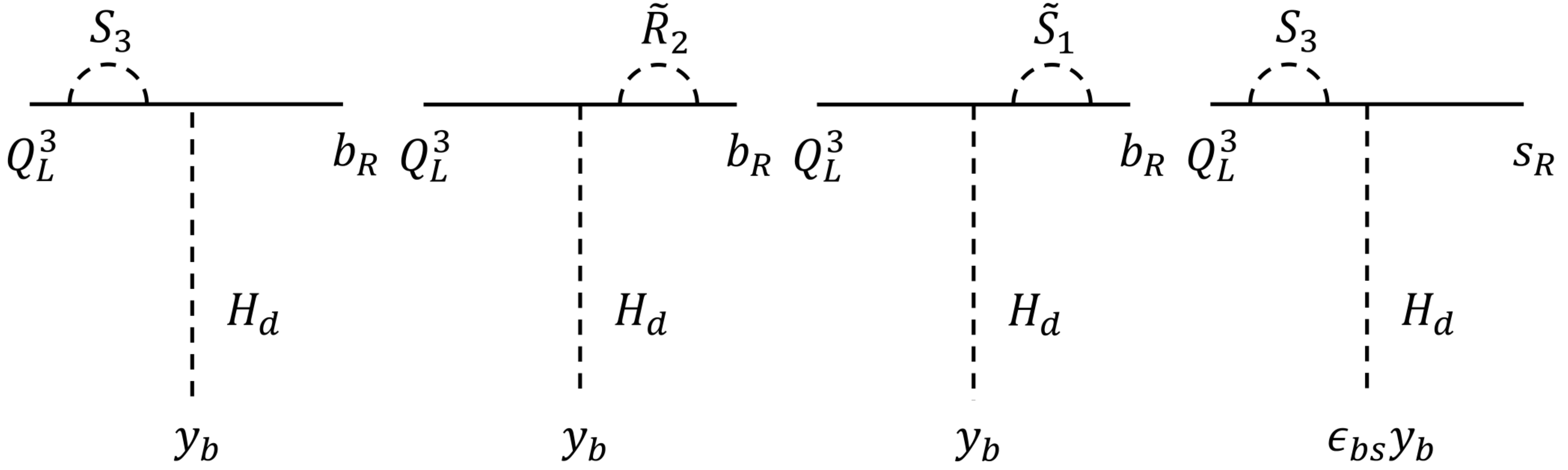
$$
m_t = \frac{1}{\sqrt{2}} y_t v \sin\beta, \quad m_b = \frac{1}{\sqrt{2}} y_b v \cos\beta, \quad m_\tau = \frac{1}{\sqrt{2}} y_\tau v \cos\beta, \quad v \equiv 246\ \text{GeV}.
$$

Karlsruher Institut für Technologie

Updated RGEs with LQs

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

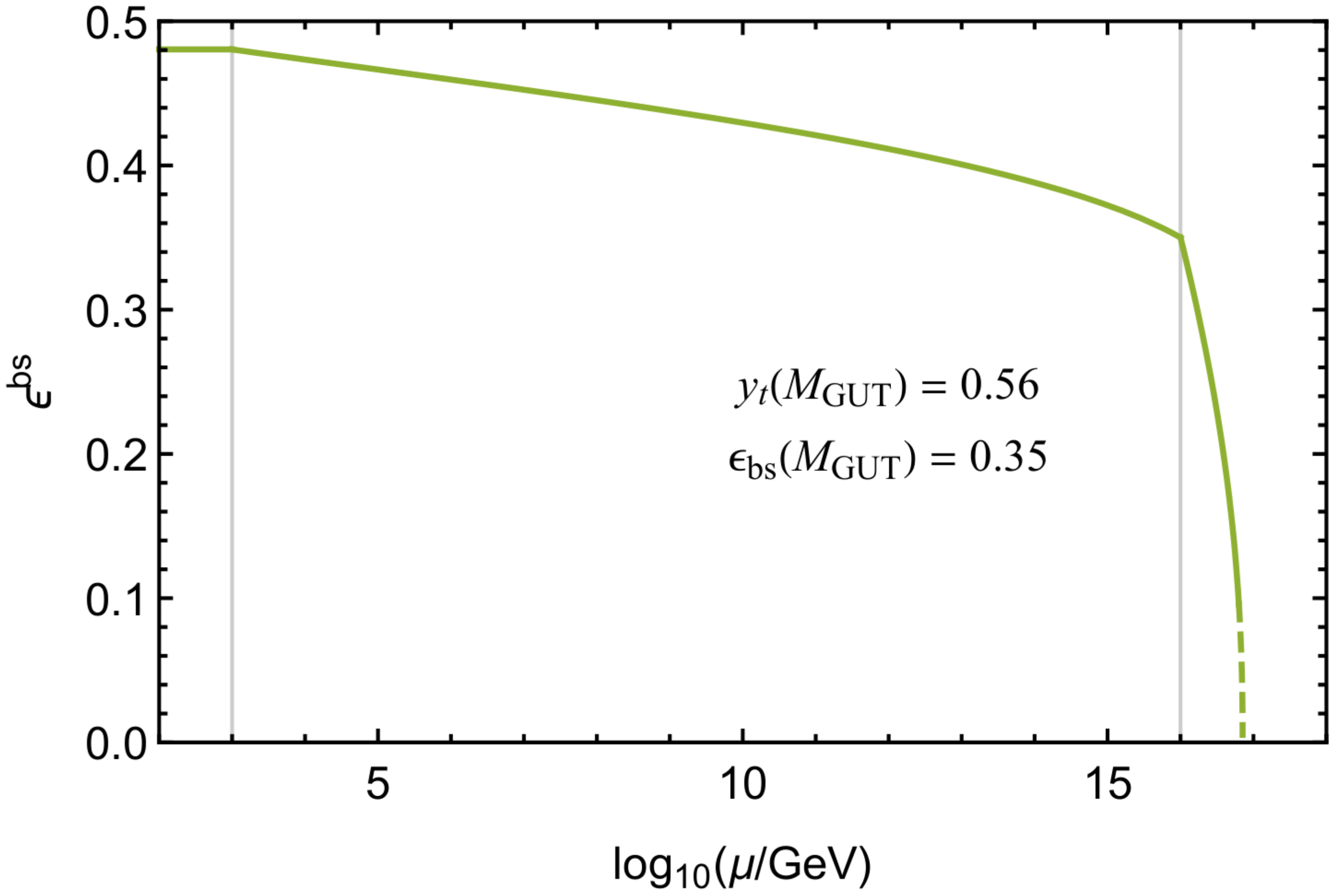
Why unstable?



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

Additional Slides

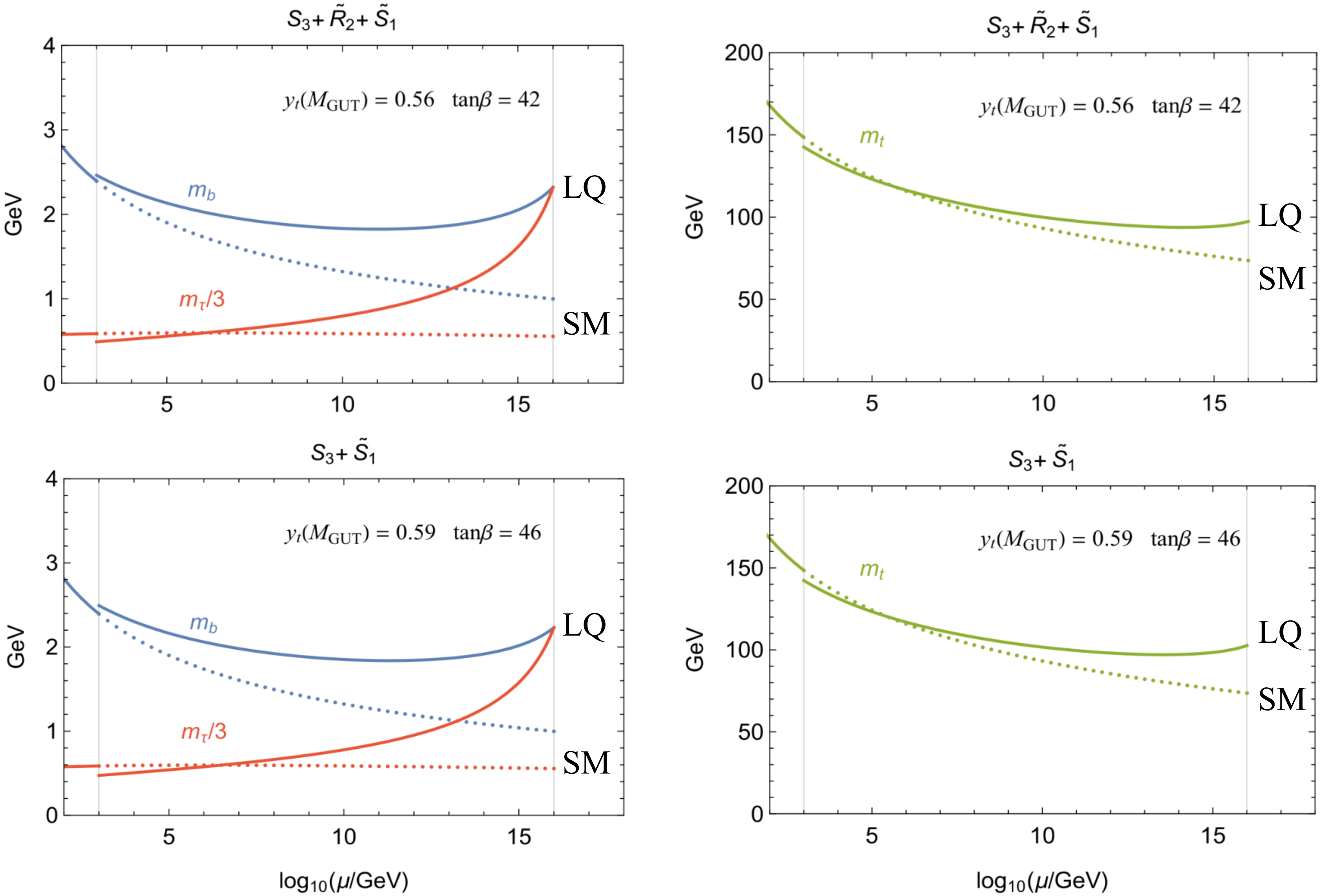
- Diquarks?
- $\Lambda \gtrsim 10 M_{GUT}$?



Additional Slides

Karlsruher Institut für Technologie

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



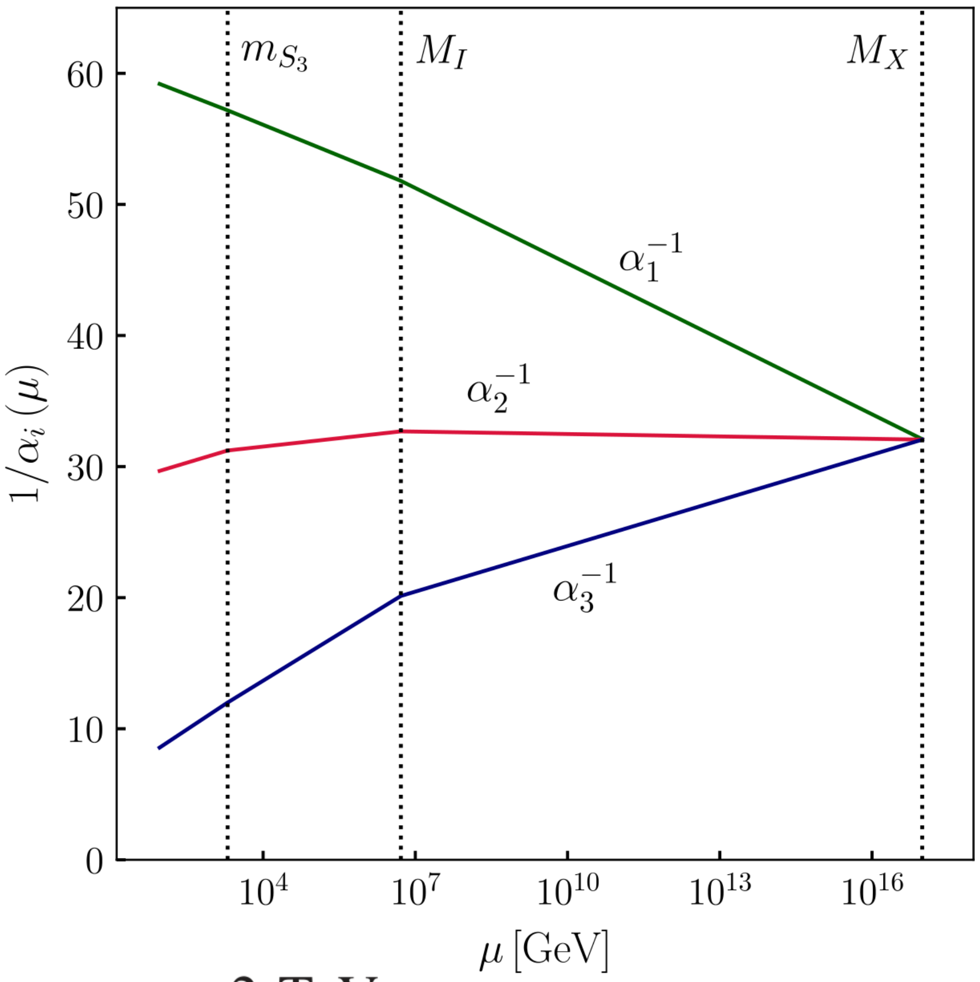
Gauge coupling unification

- $\tilde{R}_2$ 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).



$m_{S_3} = 2$ TeV,

$m_{S_6} = m_{S_8} = m_{\Sigma_8} \equiv M_I = 5.2 \times 10^6$ GeV

Karlsruher Institut für Technologie

LQs in 126_H: interactions

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

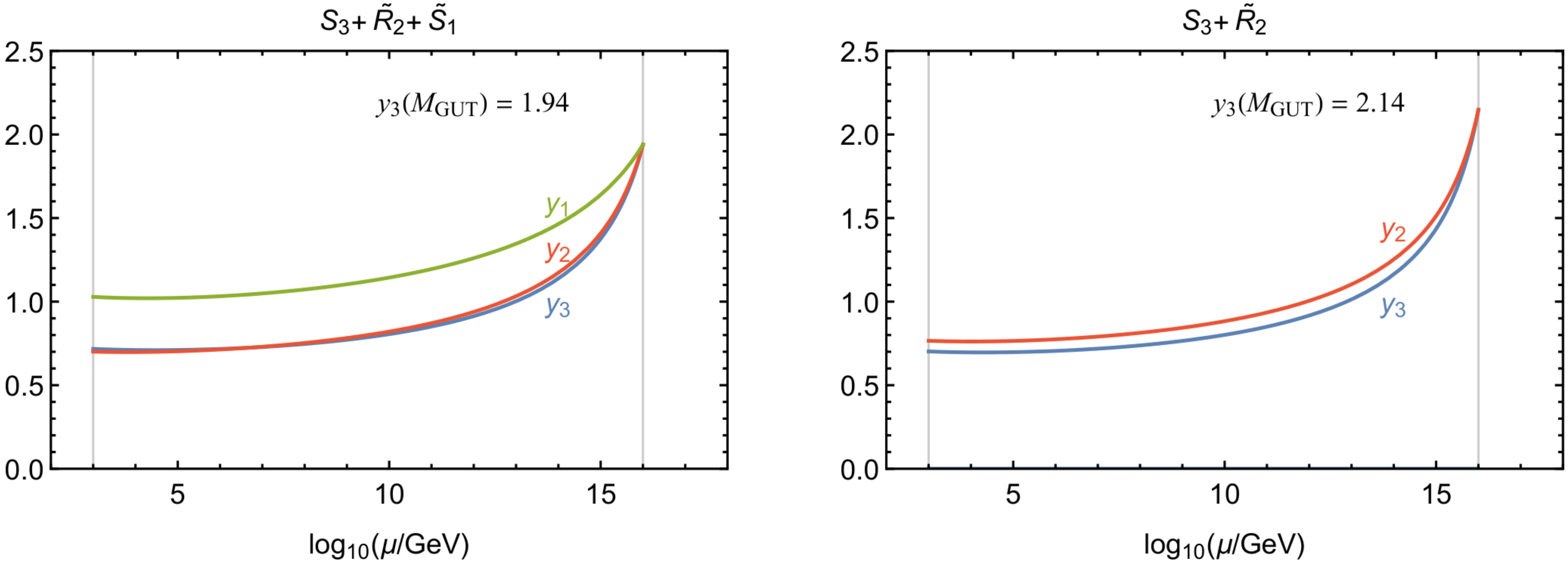
With $SU(2)_R$ multiplets:

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

$$Q_R = (u_R, d_R)$$
$$L_R = (\ell_R, \nu_R)$$

Additional Slides

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.