On the viable two leptoquark model for the B-physics anomalies*

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*D. Bečirević, I. D., S. Fajfer, D. A. Faroughy, N. Košnik, and O. Sumensari, arXiv:1806.05689.

I. D., S. Fajfer, D. A. Faroughy, and N. Košnik, arXiv:1706.07779.

I. D., S. Fajfer, and N. Košnik, arXiv:1701.08322.

OUTLINE

- **B-PHYSICS ANOMALIES**
- **VIABLE SCENARIOS OF NEW PHYSICS**
- **TWO LEPTOQUARK MODEL**
  $SU(5)$ **SET-UP**
- **FITS & PREDICTIONS**
- **CONCLUSIONS**

B-PHYSICS ANOMALIES [*]

$$R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})_{\ell\in(e,\mu)}$$

$$R_{D^{(*)}}^{\rm exp} > R_{D^{(*)}}^{\rm SM}$$

$$R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]}$$

$$R_{K^{(*)}}^{\rm exp} < R_{K^{(*)}}^{\rm SM}$$

[*] See talks by Stephen F. King, Monica Pepe-Altarelli, and Diego Guadagnoli.

B-PHYSICS ANOMALIES

$$\text{SCALE}_{\text{NEW PHYSICS}} = \mu_{\text{NP}} \lesssim 1\ \text{TeV}$$ ◎

$$R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}}$$

$$\text{SCALE}_{\text{NEW PHYSICS}} = \mu_{\text{NP}} \lesssim 30\ \text{TeV}$$ ◎

$$R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$$

◎L. Di Luzio and M. Nardecchia, arXiv:1706.01868.

B-PHYSICS ANOMALIES

The source of New Physics*:
LEPTOQUARKS, …

*See talk by Stephen F. King.

NOMENCLATURE FOR NEW PHYSICS ©

q(uark)–ℓ(epton)–L(epto)Q(uark)

LEPTOQUARK $\equiv (SU(3),\ SU(2),\ U(1))$	
SCALAR	VECTOR
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$V_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	$\tilde{V}_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, -1/6)$
$\tilde{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\tilde{U}_1 \equiv (\mathbf{3}, \mathbf{1}, 5/3)$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

©I. D., S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik, arXiv:1603.04993.

VIABLE B-PHYSICS ANOMALY SOURCES [©]

LEPTOQUARK $\equiv (SU(3),\ SU(2),\ U(1))$	
SCALAR	VECTOR
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$V_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	$\tilde{V}_2 \equiv (\overline{\mathbf{3}}, \mathbf{2}, -1/6)$
$\tilde{S}_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\tilde{U}_1 \equiv (\mathbf{3}, \mathbf{1}, 5/3)$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$

[©] A. Angelescu, D. Bečirević, D. A. Faroughy, and O. Sumensari, arXiv:1808.08179.

VIABLE SCENARIO OF NEW PHYSICS [⊚]

LEPTOQUARK	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$&$R_{K^{(*)}}$
$S_3 \equiv (\mathbf{\overline{3}}, \mathbf{3}, 1/3)$	×	✓	×
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	✓	✓	×
$S_1 \equiv (\mathbf{\overline{3}}, \mathbf{1}, 1/3)$	✓	×	×
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	×	✓	×
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓

[⊚] A. Angelescu, D. Bečirević, D. A. Faroughy, and O. Sumensari, arXiv:1808.08179.

VIABLE SCENARIO OF NEW PHYSICS [©]

LEPTOQUARK	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}\&R_{K^{(*)}}$
$S_3 \equiv (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\times$	$\checkmark$	$\times$
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	$\checkmark$	$\checkmark$	$\times$
$S_1 \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\checkmark$	$\times$	$\times$
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	$\times$	$\checkmark$	$\times$
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	$\checkmark$	$\checkmark$	$\checkmark$

[©] A. Crivellin, D. Müller, and T. Ota, arXiv:1703.09226; D. Marzocca, arXiv:1803.10972.

VIABLE SCENARIO OF NEW PHYSICS [◎]

LEPTOQUARK	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}\&R_{K^{(*)}}$
$S_3 \equiv (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	×	✓	×
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	✓	✓	×
$S_1 \equiv (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✓	×	×
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	×	✓	×
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓

[◎] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, arXiv:1706.07808.

VIABLE SCENARIO OF NEW PHYSICS [©]

LEPTOQUARK	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}\&R_{K^{(*)}}$
$S_3 \equiv (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	×	✓	×
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	✓	✓	×
$S_1 \equiv (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✓	×	×
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	×	✓	×
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓

[©] D. Bečirević, I. D., S. Fajfer, D. A. Faroughy, N. Košnik, and O. Sumensari, arXiv:1806.05689.

TWO LEPTOQUARK MODEL

$$\text{SCALE}_{\text{NEW PHYSICS}} = \mu_{\text{NP}} \lesssim 1 \text{ TeV}$$

$$R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}}$$

m_{R_2}

R_2

$$\text{SCALE}_{\text{NEW PHYSICS}} = \mu_{\text{NP}} \lesssim 30 \text{ TeV}$$

$$R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$$

m_{S_3}

S_3

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset \boxed{Y_R^{ij}\bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij}\bar{u}'_{Ri}(i\tau_2 R_2^*)^\dagger L'_j} + \boxed{Y^{ij}\bar{Q}'^C_i i\tau_2(\tau_k S_3^k) L'_j}$$

$R_{D^{(*)}}$

$R_{K^{(*)}}$

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

YUKAWA COUPLING MATRICES

$$Y_R = Y_R^T \qquad Y = -Y_L$$

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

UNITARY REDEFINITIONS *

$$u_{L,R} = U_{L,R} u'_{L,R}$$

$$d_{L,R} = D_{L,R} d'_{L,R}$$

$$\ell_{L,R} = E_{L,R} \ell'_{L,R}$$

$$\nu_L = N_L \nu'_L$$

*See talk by Gustavo Branco.

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij}\bar{Q}'_i\ell'_{Rj}R_2 + Y_L^{ij}\bar{u}'_{Ri}(i\tau_2 R_2^*)^\dagger L'_j + Y^{ij}\bar{Q}'^C_i i\tau_2(\tau_k S_3^k)L'_j$$

UNITARY REDEFINITIONS

$$u_{L,R} = U_{L,R}u'_{L,R}$$

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$$\ell_{L,R} = E_{L,R}\ell'_{L,R}$$

$$\nu_L = N_L\nu'_L$$

FLAVOUR ANSATZ

$$Y_R E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}$$

$$U_R Y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij}\bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij}\bar{u}'_{Ri}(i\tau_2 R_2^*)^\dagger L'_j + Y^{ij}\bar{Q}'^C_i i\tau_2(\tau_k S_3^k)L'_j$$

UNITARY MATRICES	FLAVOUR ANSATZ
U_L & D_L	$V = U_L D_L^\dagger \equiv U_L$
E_L & N_L	$U = E_L N_L^\dagger \equiv N_L^\dagger$
U_R	$\lvert U_R^{11}\rvert = 1$ $U_R^{22} = \cos\theta \equiv c_\theta$ $U_R^{23} = -\sin\theta \equiv -s_\theta$
E_R	$\lvert E_R^{33}\rvert = 1$ $E_R^{11} = c_\alpha \quad E_R^{12} = -s_\alpha$

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

UNITARY REDEFINITIONS

$$u_{L,R} = U_{L,R} u'_{L,R}$$

$$d_{L,R} = D_{L,R} d'_{L,R}$$

$$\ell_{L,R} = E_{L,R} \ell'_{L,R}$$

$$\nu_L = N_L \nu'_L$$

FLAVOUR ANSATZ

U_L	$U_R(\theta)$
D_L	$\boxed{D_R}$
E_L	$\boxed{E_R(\alpha)}$
N_L	

TWO LEPTOQUARK MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

FIT PARAMETERS

$$\boxed{m_{R_2}, m_{S_3}, y_R^{b\tau}, y_L^{c\mu}, y_L^{c\tau}, \theta}$$

TWO LEPTOQUARK $SU(5)$ MODEL

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij} \bar{u}'_{Ri} (i\tau_2 R_2^*)^\dagger L'_j + Y^{ij} \bar{Q}'^C_i i\tau_2 (\tau_k S_3^k) L'_j$$

TWO SU(5) INVARIANT OPERATORS

$b^{ij} \mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}$

$a^{ij} \mathbf{10}_i \overline{\mathbf{5}}_j \underline{\overline{\mathbf{45}}}$

<u>$SU(5)$ MODEL</u>

$$b^{ij}\mathbf{10}_i\mathbf{10}_j\underline{\mathbf{50}}$$

$$a^{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\underline{\mathbf{45}}}$$

$$R_2 \in \underline{\mathbf{50}}$$

$$R_2,\ S_3 \in \underline{\mathbf{45}}$$

$SU(5)$ MODEL

$b^{ij}\,\mathbf{10}_i\,\mathbf{10}_j\,\underline{\mathbf{50}}$

$a^{ij}\,\mathbf{10}_i\,\overline{\mathbf{5}}_j\,\underline{\overline{\mathbf{45}}}$

$R_2 \in \underline{\mathbf{50}}$

$R_2,\ S_3 \in \underline{\mathbf{45}}$

$SU(5)$ MIXING OPERATOR

$m\,\underline{\mathbf{45}}\,\underline{\overline{\mathbf{50}}}\,\underline{\mathbf{24}}$

$SU(5)$ UNIFICATION *

FIELD CONTENT

$$\mathbf{10}_i,\ \overline{\mathbf{5}}_i,\ \underline{\mathbf{5}},\ \underline{\mathbf{24}},\ \underline{\mathbf{45}},\ \underline{\mathbf{50}}$$

*See talk by Graham Garland Ross.

$SU(5)$ UNIFICATION

FIELD CONTENT

$$\boxed{\boxed{\mathbf{10}_i,\ \overline{\mathbf{5}}_i,\ \underline{\mathbf{5}},\ \underline{\mathbf{24}},}\ ^{\circledcirc}\underline{\mathbf{45}},\ \underline{\mathbf{50}}}$$

◎H. Georgi and S. L. Glashow, Phys. Rev. Lett. (1974).

$SU(5)$ UNIFICATION

FIELD CONTENT

$$\boxed{\boxed{\mathbf{10}_i,\ \overline{\mathbf{5}}_i,\ \underline{\mathbf{5}},\ \underline{\mathbf{24}},\ \underline{\mathbf{45}},}\ ^{\circledcirc}\underline{\mathbf{50}}}$$

[©] H. Georgi and C. Jarlskog, Phys.Lett. 86B (1979).

$SU(5)$ UNIFICATION

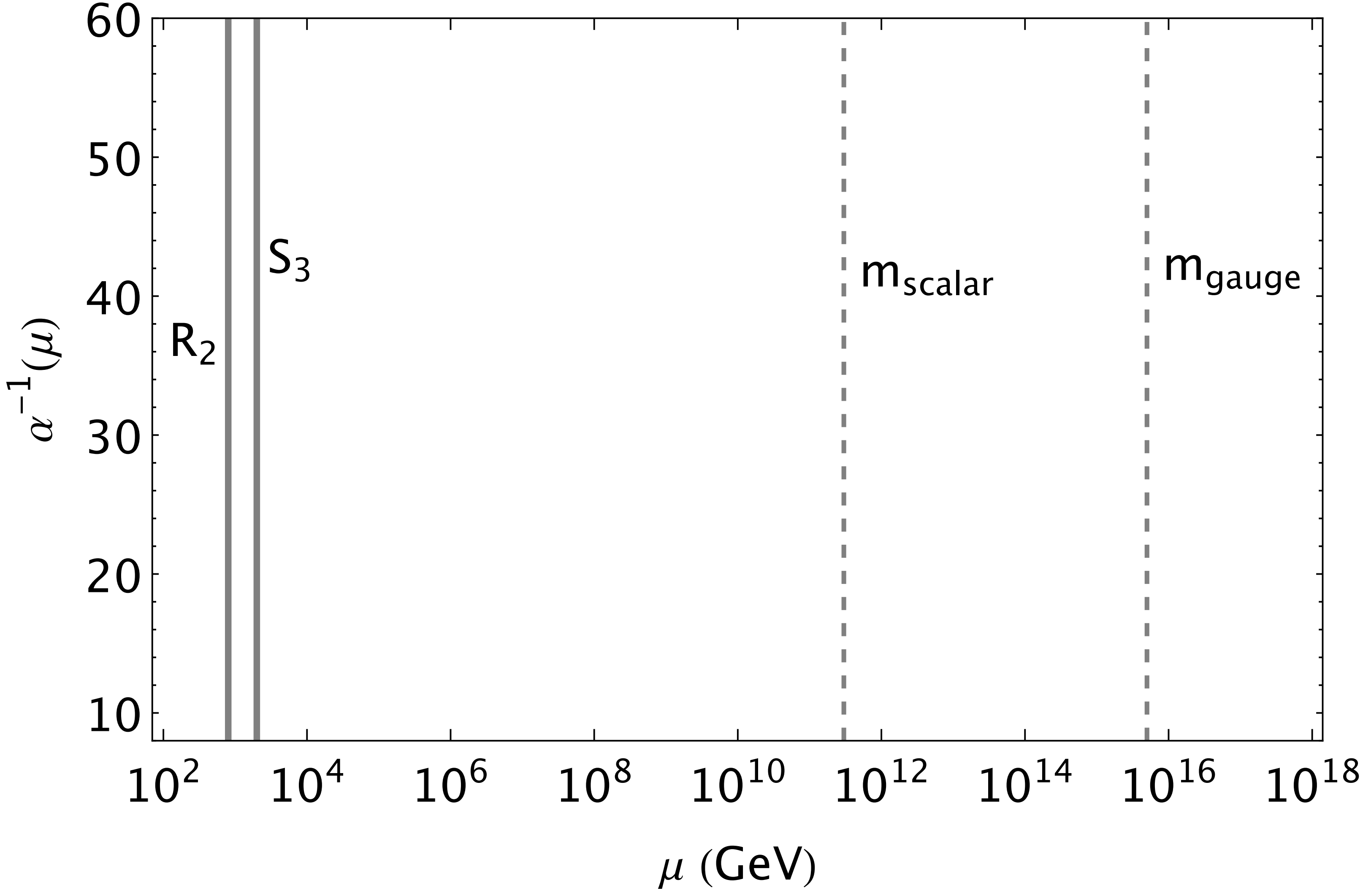
FIELD CONTENT

$$\mathbf{10}_i,\ \overline{\mathbf{5}}_i,\ \underline{\mathbf{5}},\ \underline{\mathbf{24}},\ \underline{\mathbf{45}},\ \underline{\mathbf{50}}$$

FIT & LHC DATA OUTPUT

$$m_{R_2} = 800\,\mathrm{GeV},\ m_{S_3} = 2\,\mathrm{TeV}$$

UNIFICATION



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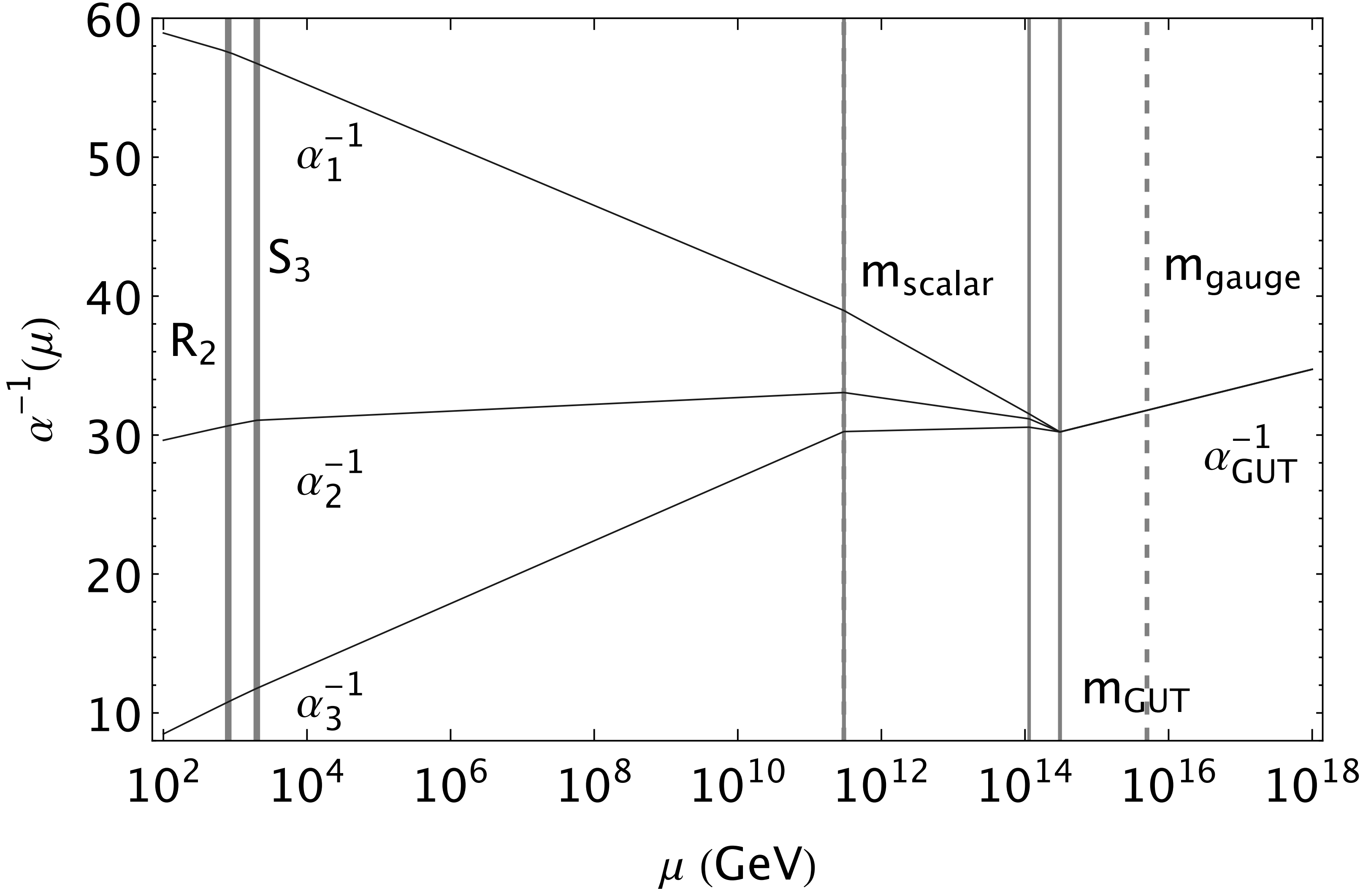

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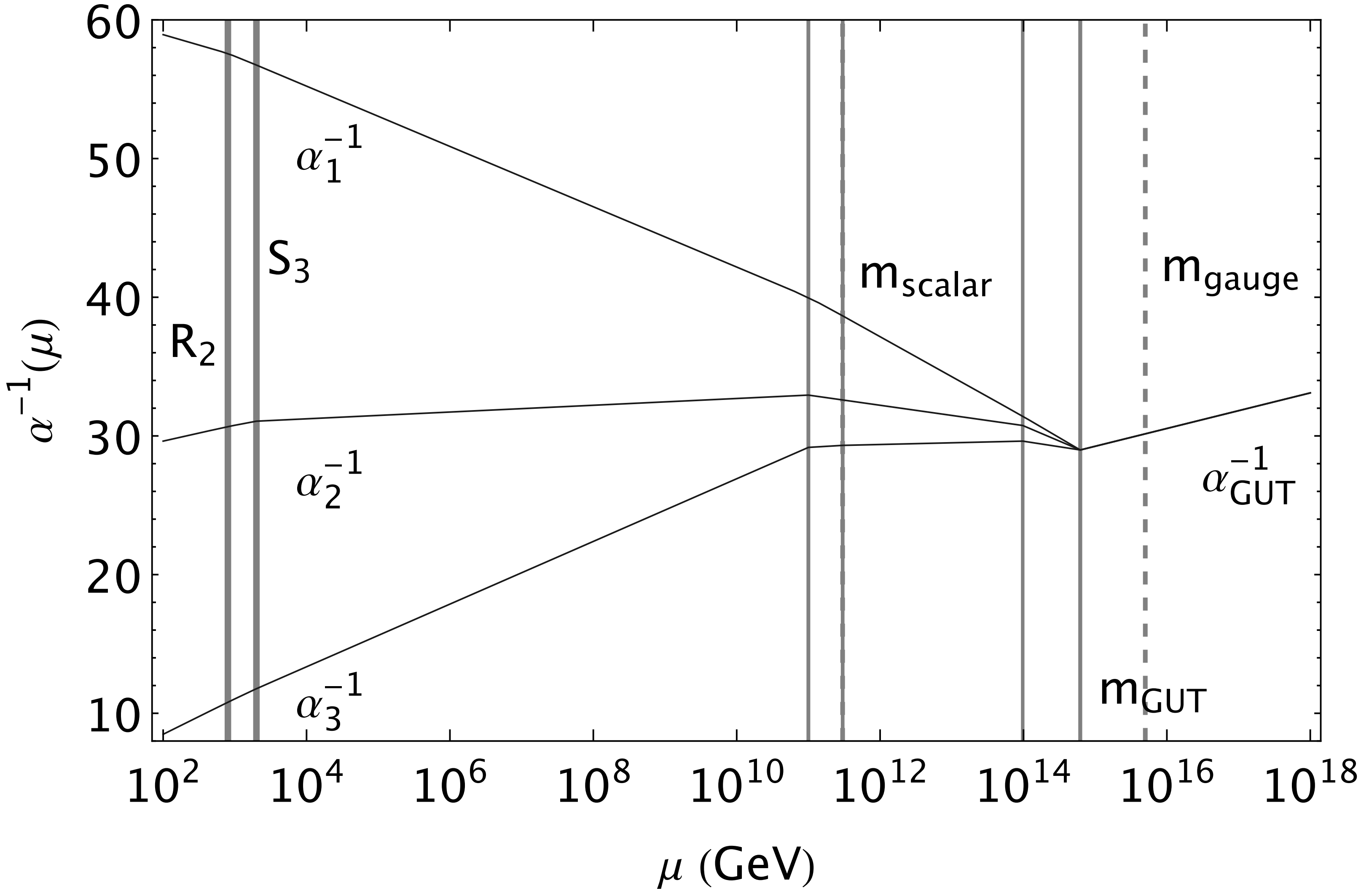

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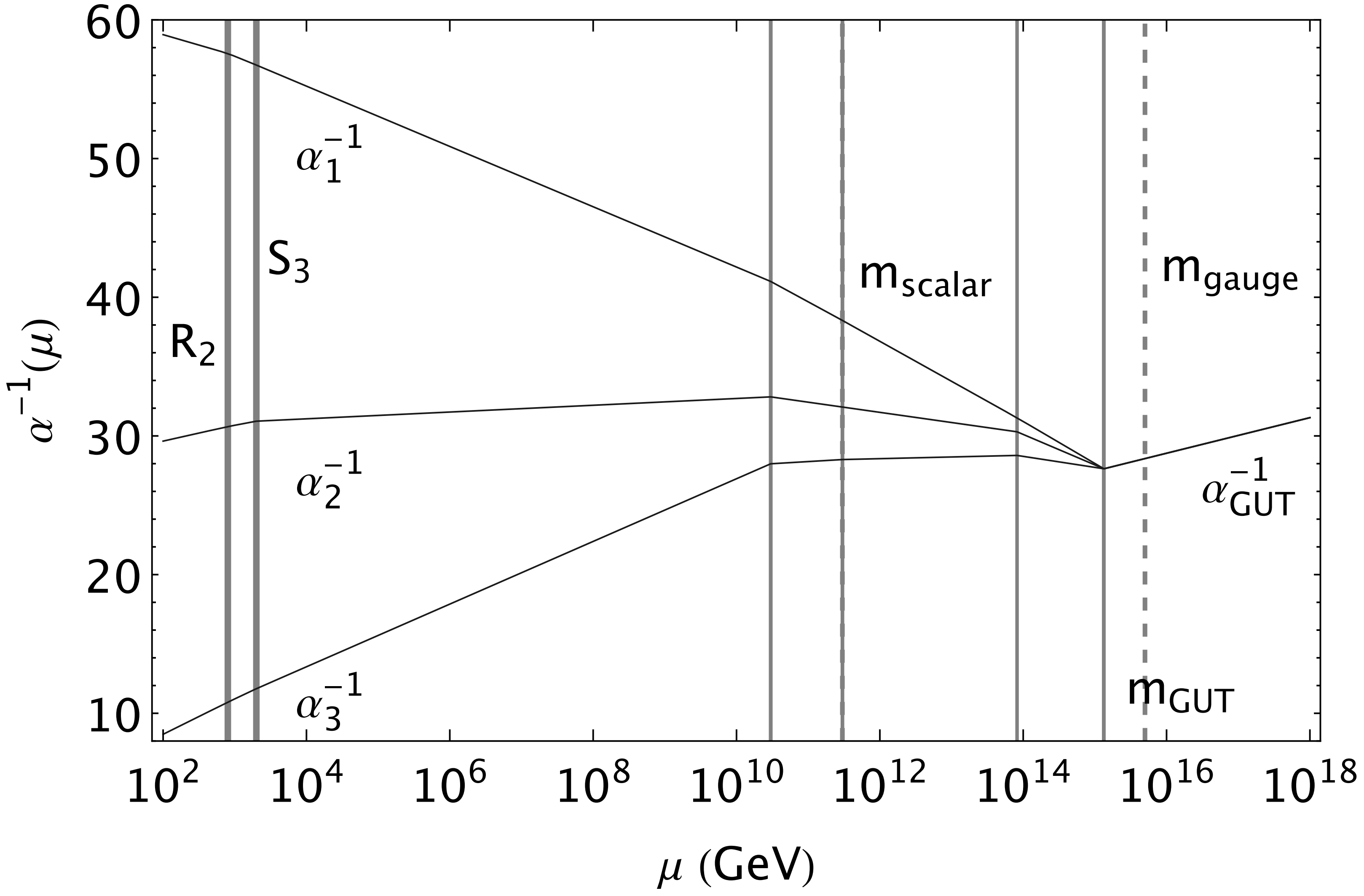

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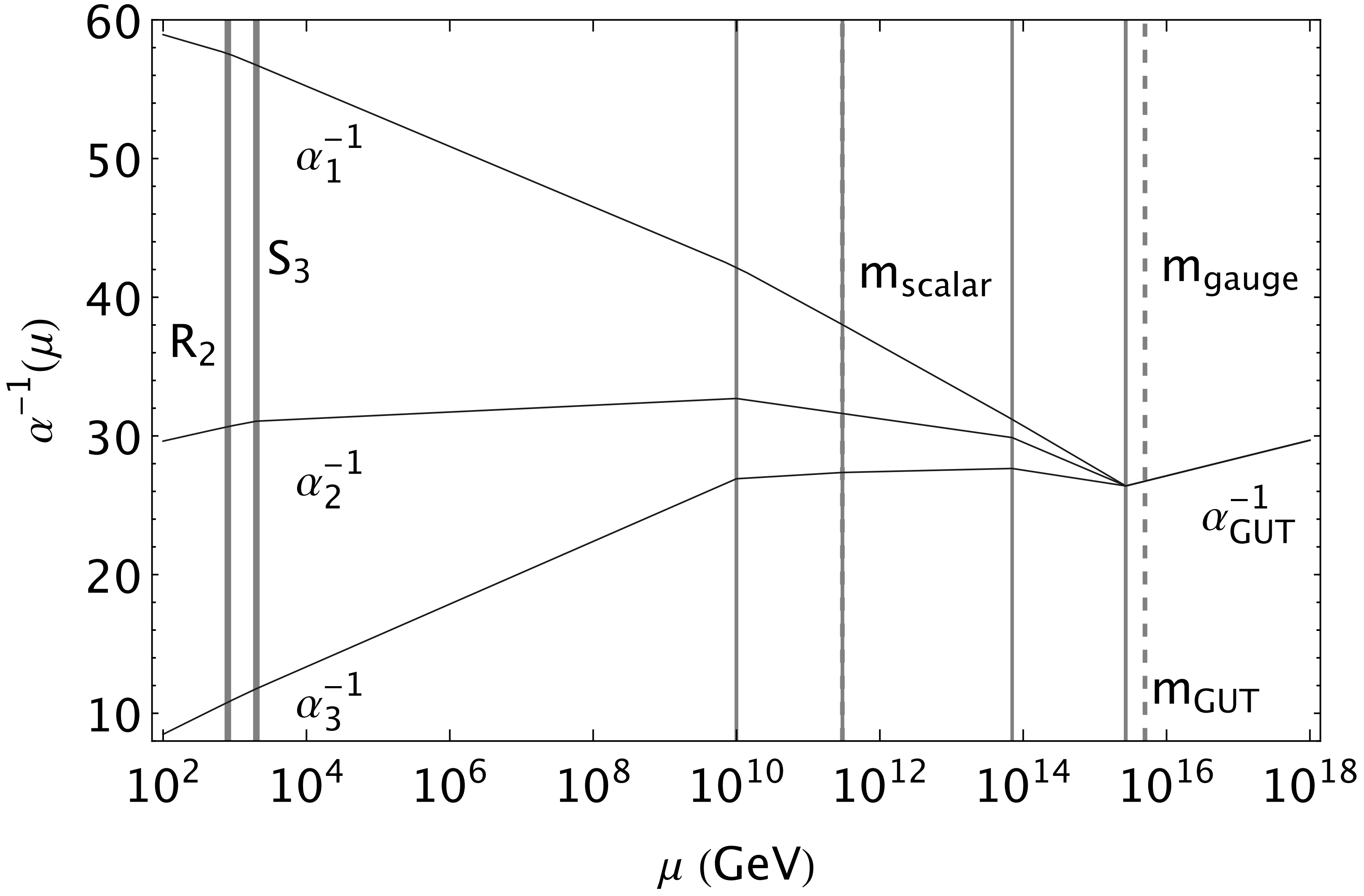

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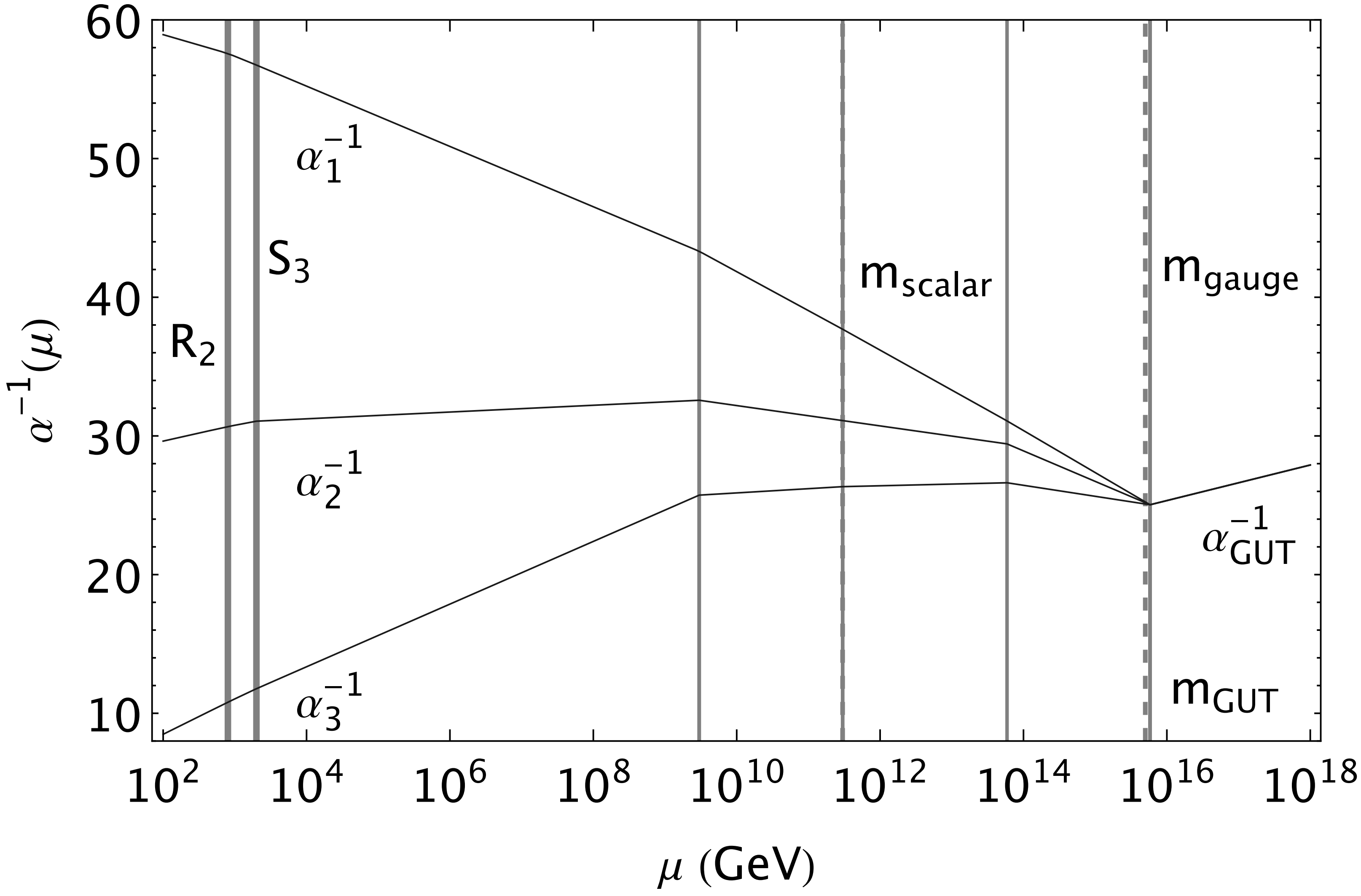
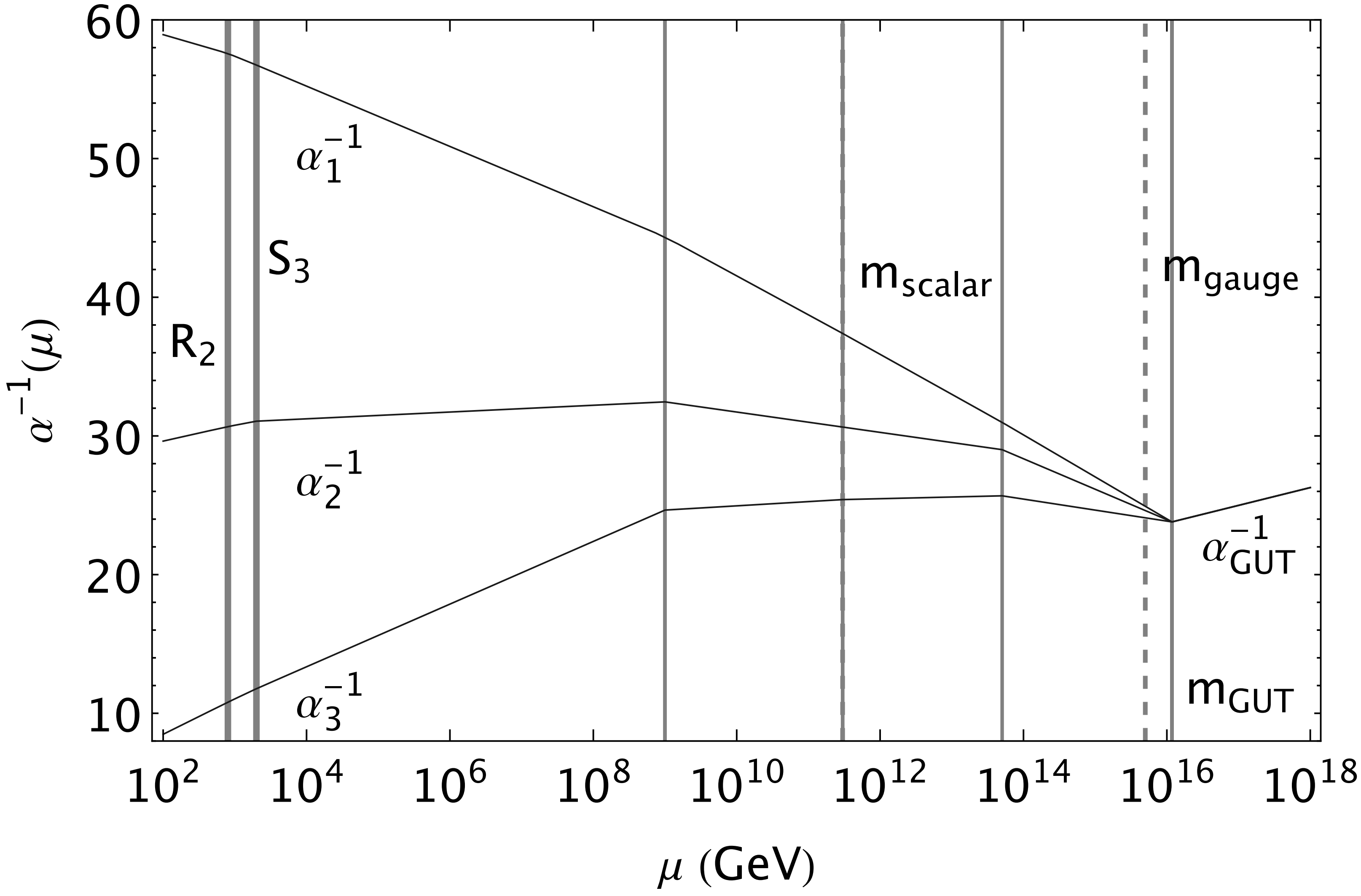


UNIFICATION



FITS & PREDICTIONS

$$b \to c\tau\bar{\nu} \qquad \propto \frac{y_L^{c\tau} y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)\right]$$

$$b \to s\mu\mu \qquad \propto s_{2\theta}\frac{|y_L^{c\mu}|^2}{m_{S_3}^2}(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \nu_L)$$

$$\Delta m_{B_s} \qquad \propto s_{2\theta}^2 \frac{[(y_L^{c\mu})^2 + (y_L^{c\tau})^2]^2}{m_{S_3}^2}(\bar{s}_L \gamma^\mu b_L)^2$$

FIT OUTPUT

$$\theta \approx \pi/2,\; m_{R_2}^2 < m_{S_3}^2,\; y_R^{b\tau} \in \mathbb{C}$$

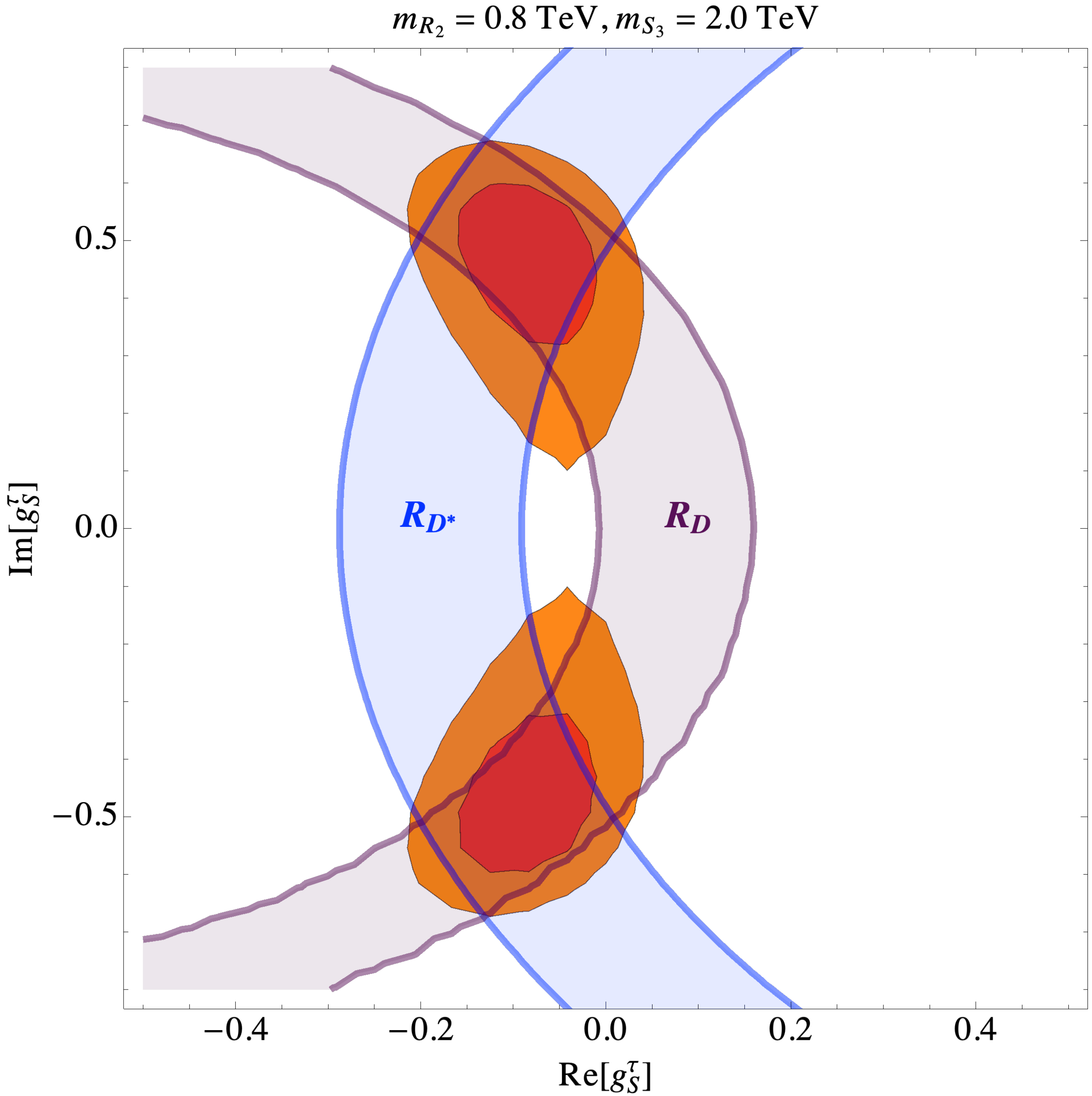
FITS & PREDICTIONS

$$g_S^\tau(\mu_{\rm NP}) = \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{4\sqrt{2}\, m_{R_2}^2\, G_F V_{cb}}$$

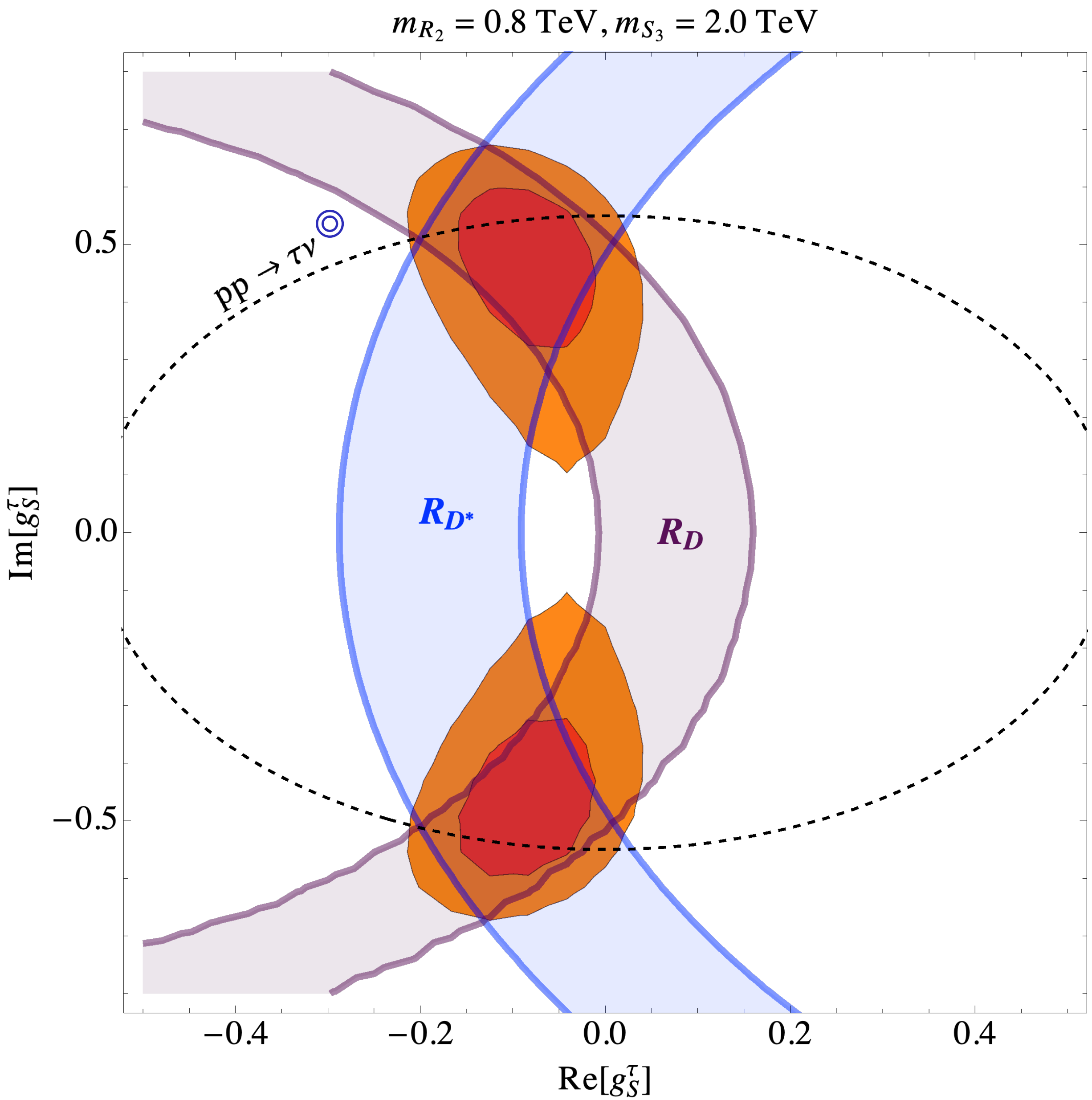
FIT & LHC DATA OUTPUT

$$m_{R_2} = 800\,\mathrm{GeV},\; m_{S_3} = 2\,\mathrm{TeV}$$

FITS & PREDICTIONS

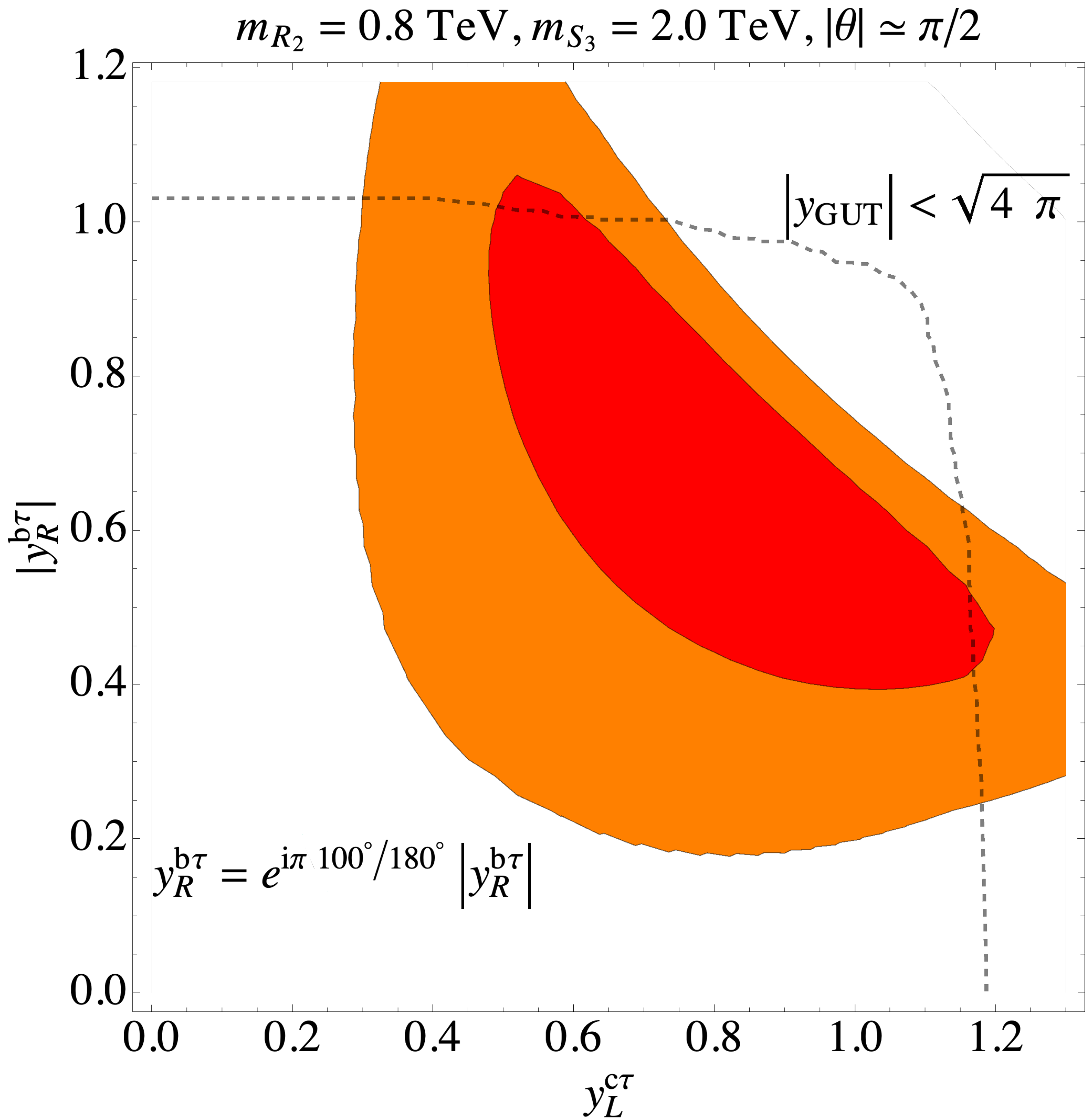


FITS & PREDICTIONS

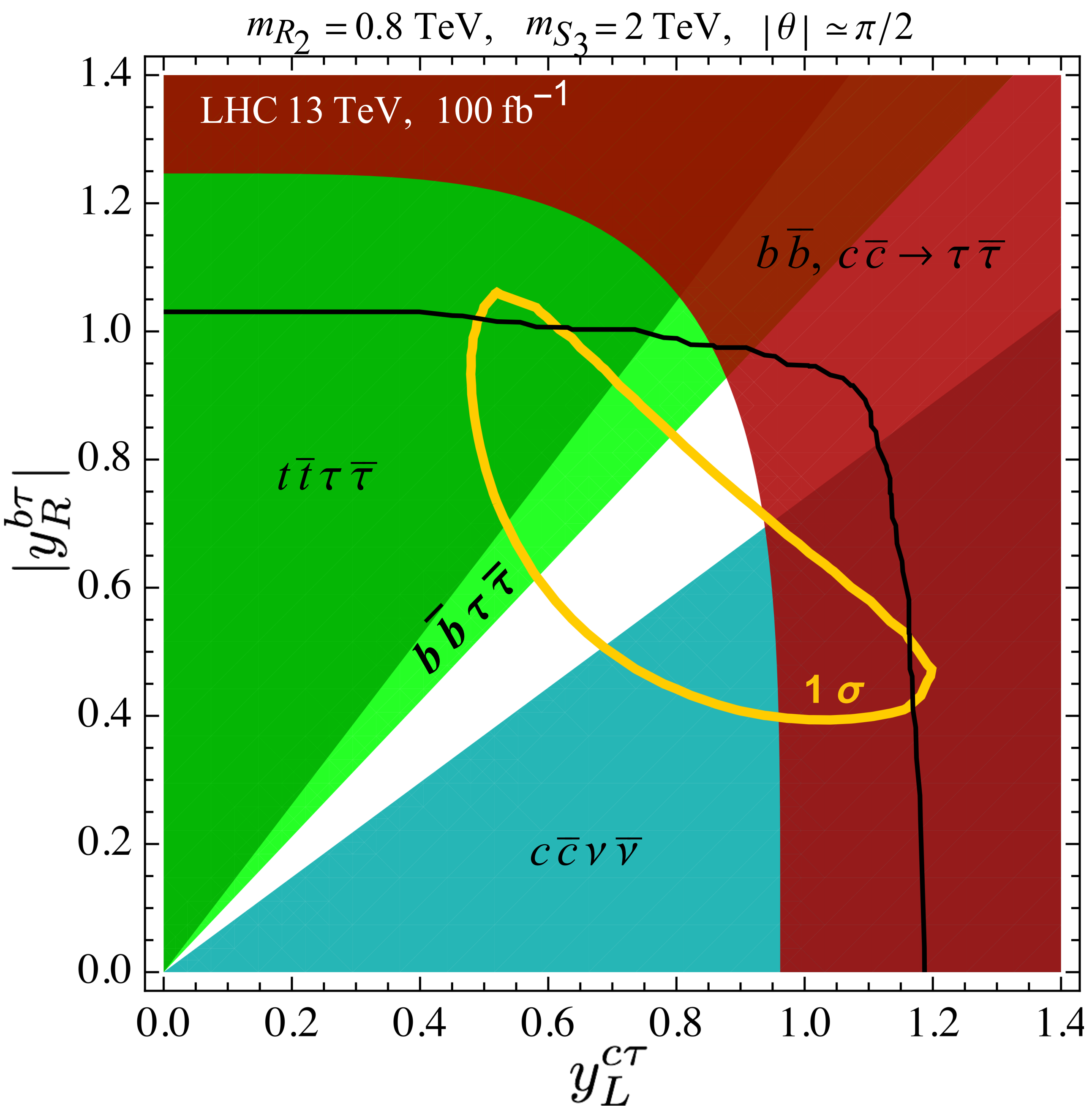


◎A. Greljo, J. M. Camalich, and J. D. Ruiz-Ávarez, arXiv:1811.07920.

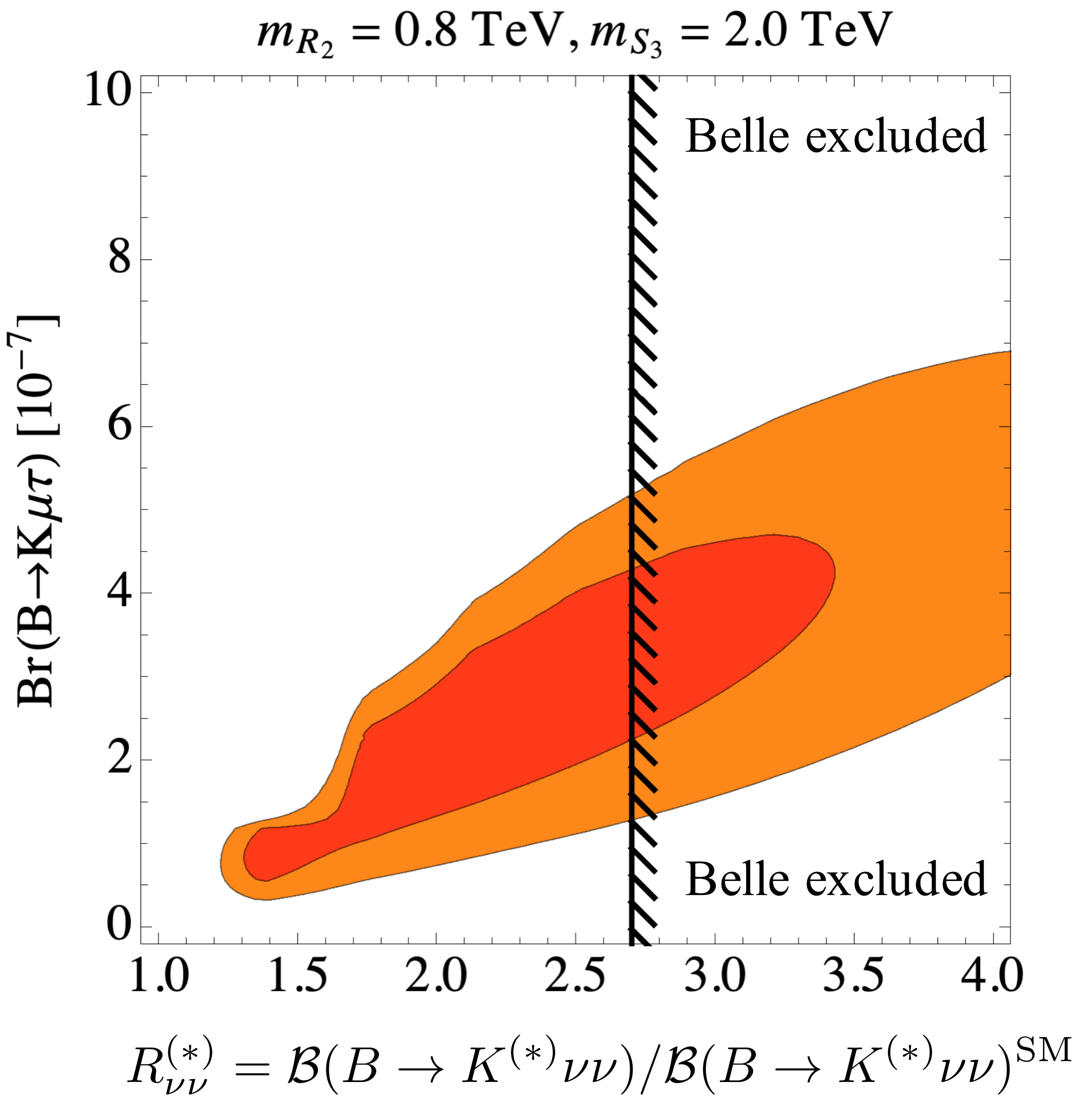
FITS & PREDICTIONS



FITS & PREDICTIONS



FITS & PREDICTIONS



CONCLUSIONS

There is a <u>two</u> leptoquark model based on *SU*(5) gauge symmetry that can address the *B*-physics anomalies.

The entire low-energy flavour structure of the set-up originates from <u>two</u> *SU*(5) operators.

The proposed scenario accommodates all measured lepton flavour universality ratios in *B*-meson decays, is consistent with related flavour observables, and is compatible with direct searches at the LHC.

The model is self-consistently perturbative, provides gauge coupling unification, and predicts several yet-to-be-measured flavour observables.

THANK YOU

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$SU(5)$ MODEL*

$b^{ij}\mathbf{10}_i\mathbf{10}_j\underline{\mathbf{45}}$

$a^{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\underline{\mathbf{45}}}$

$R_2,\ S_3 \in \underline{\mathbf{45}}$

$R_2,\ S_3 \in \underline{\mathbf{45}}$

*I. D., S. Fajfer, and N. Košnik, arXiv:1701.08322.

$SU(5)$ MODEL

$$b^{ij}\,\mathbf{10}_i\mathbf{10}_j\underline{\mathbf{45}} \qquad\qquad a^{ij}\,\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\underline{\mathbf{45}}}$$

$$R_2,\ S_3 \in \underline{\mathbf{45}} \qquad\qquad R_2,\ S_3 \in \underline{\mathbf{45}}$$

PROTON DECAY

$SU(5)$ MODEL

$b^{ij}\mathbf{10}_i\mathbf{10}_j\underline{\mathbf{50}}$

$a^{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\overline{\underline{\mathbf{45}}}$

$R_2 \in \underline{\mathbf{50}}$

$R_2,\ S_3 \in \underline{\mathbf{45}}$

PROTON DECAY