



# Combined explanations of B-physics anomalies, $(g - 2)_{e,\mu}$ and neutrino masses by scalar leptoquarks

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Based on: Shao-Long Chen, Wen-wen Jiang, Ze-Kun Liu [2205.15794] Eur.Phys.J.C

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# Neutrino Mass

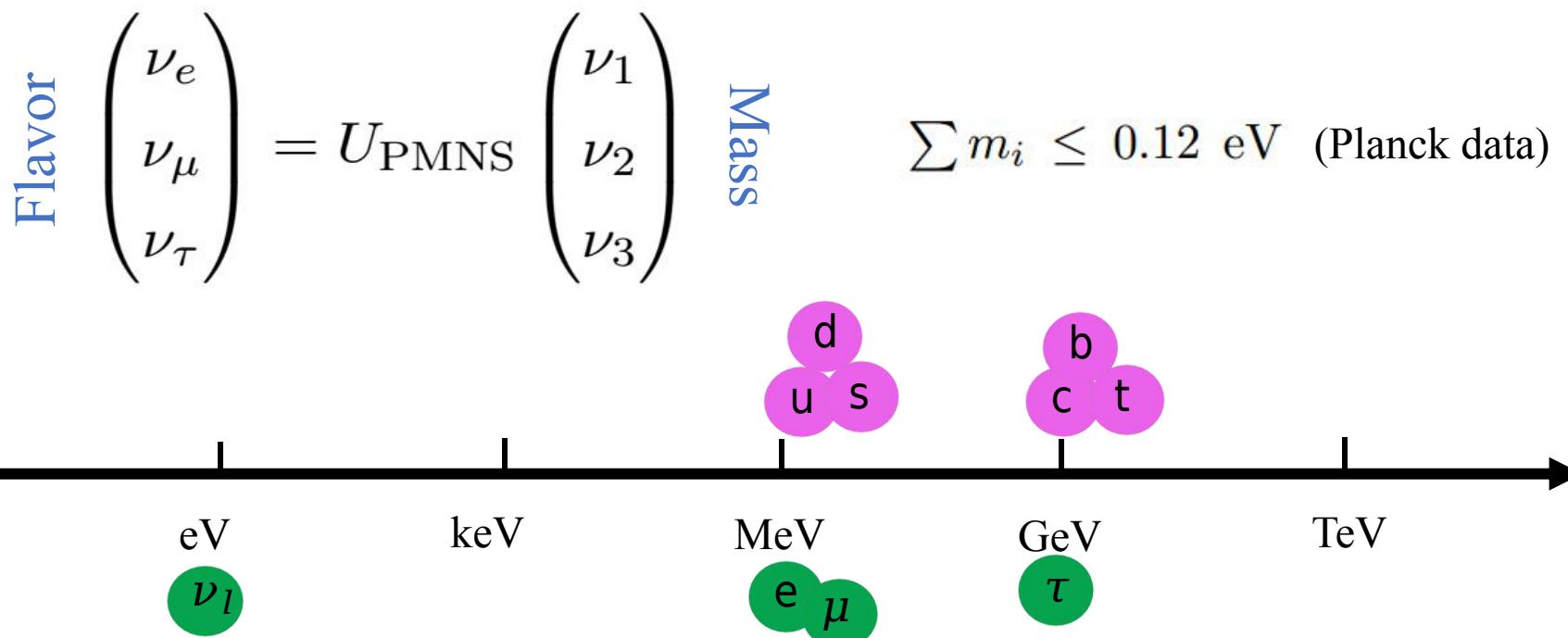
## Neutrino in SM

$$\mathcal{L}_{\text{Yukawa}} = \overline{q_L^i} Y_u u_R \tilde{H}^i + \overline{q_L^i} Y_d d_R H^i + \overline{\ell_L^i} Y_e e_R H^i + \text{h.c.}$$

$\nu_R$

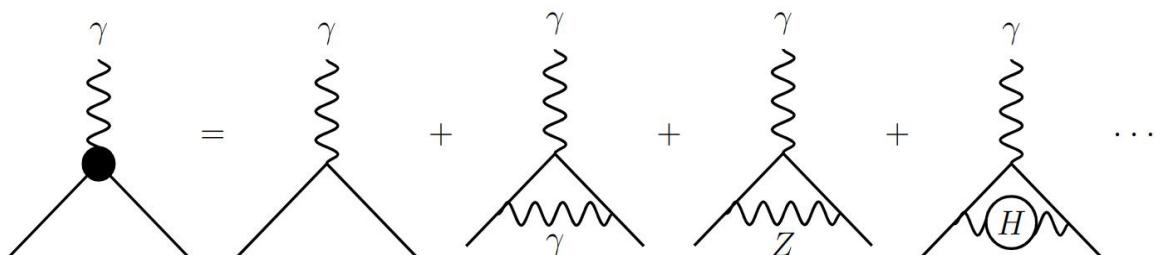
## Neutrino oscillations

$$P_{\alpha\beta}(t) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = U_{\alpha i}^* U_{\beta i} U_{\beta j}^* U_{\alpha j} e^{-i \frac{\Delta m_{ij}^2}{2E} L}$$

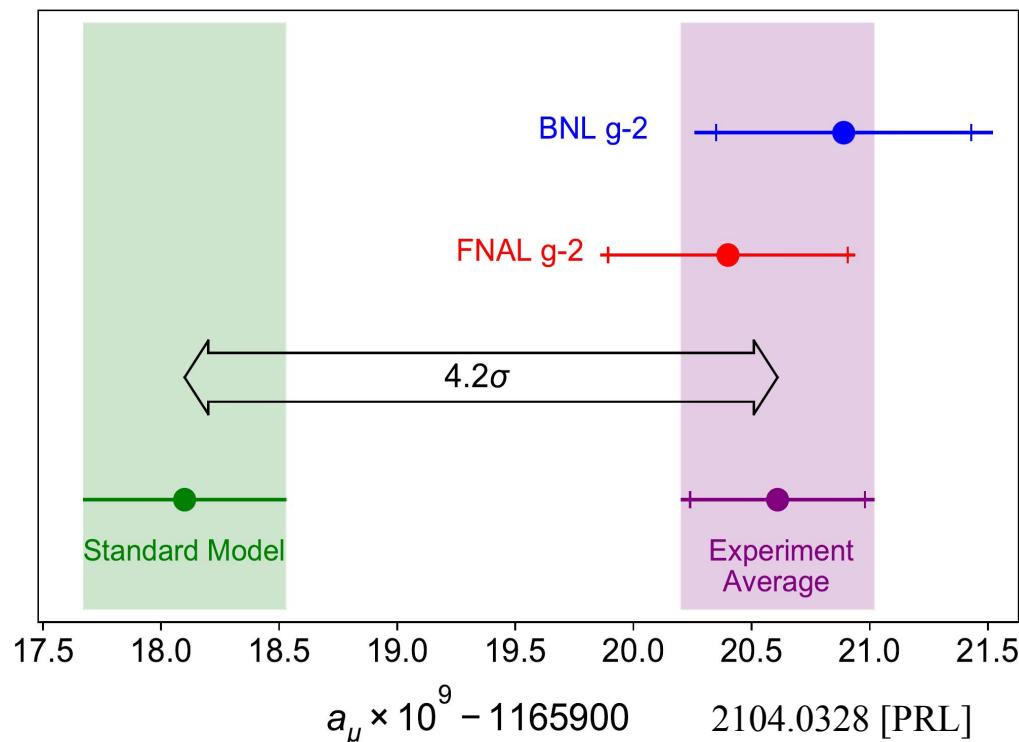


# Charged Leptons Anomalous Magnetic Moment

$$\text{AMM: } a_\ell \equiv \frac{(g_\ell - 2)}{2}$$



$$a_\ell = a_\ell(\text{QED}) + a_\ell(\text{Weak}) + a_\ell(\text{Hadron})$$



$$a_e^{\text{SM}} = 1159652181.61(23) \times 10^{-12}$$

$$a_\mu^{\text{SM}} = 116591810(43) \times 10^{-11}$$

$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -(8.7 \pm 3.6) \times 10^{-13}$$

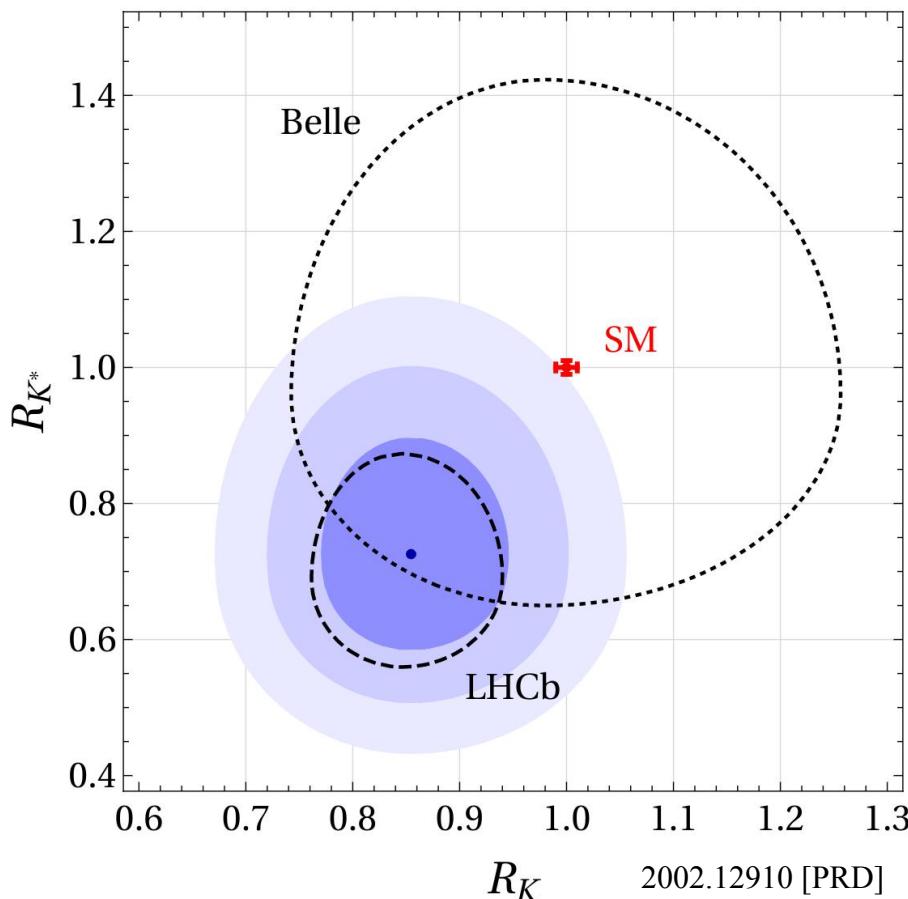
2.4  $\sigma$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.51 \pm 0.59) \times 10^{-9}$$

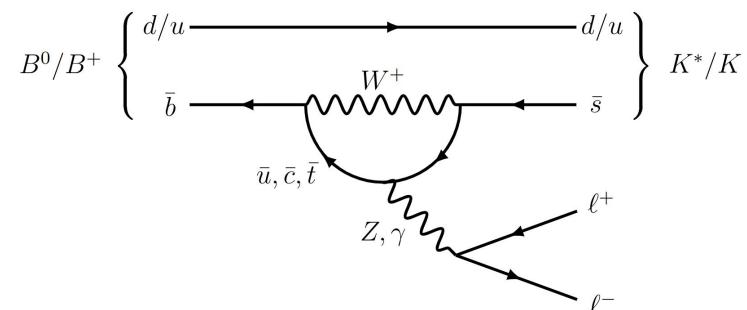
4.2  $\sigma$

# B-physics Anomalies: $R_{K^{(*)}}$

$$R_K = \frac{\text{Br}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{Br}(B^+ \rightarrow K^+ e^+ e^-)}, \quad R_{K^*} = \frac{\text{Br}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\text{Br}(B^0 \rightarrow K^{*0} e^+ e^-)}.$$



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Loop induced in the SM

$$R_K^{\text{SM}} = 1.0003 \pm 0.0001, \quad R_{K^*}^{\text{SM}} = 1.00 \pm 0.01$$

$$R_K^{\text{LHCb}} = 0.846^{+0.042}_{-0.039} {}^{+0.013}_{-0.012}$$

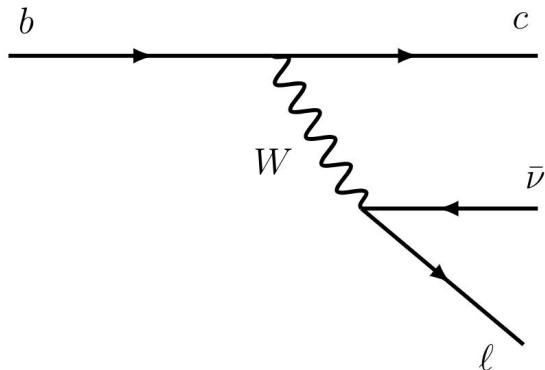
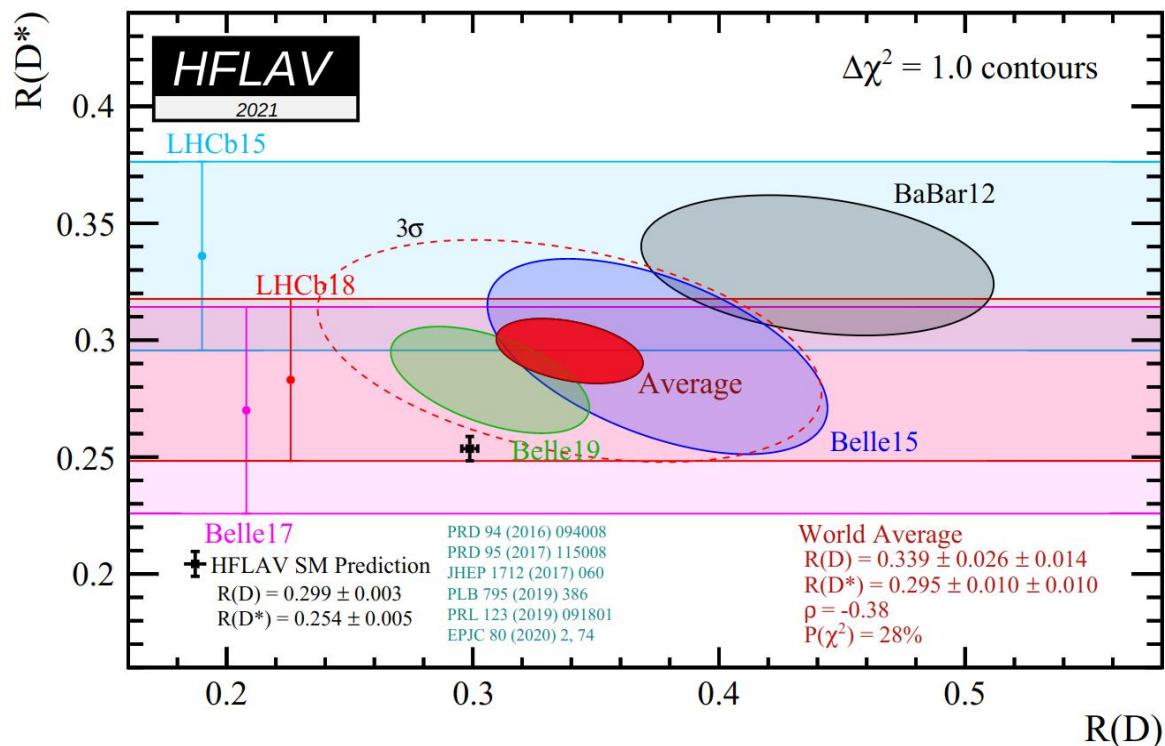
$$R_{K^*}^{\text{LHCb}} = 0.685^{+0.113}_{-0.069} \pm 0.047$$

Both give deviation about  $3\sigma$  from the SM

# B-physics Anomalies: $R_{D^{(*)}}$

$$R_D = \frac{\text{Br}(B \rightarrow D\tau\bar{\nu})}{\text{Br}(B \rightarrow D\ell\bar{\nu})} \quad R_{D^*} = \frac{\text{Br}(B \rightarrow D^*\tau\bar{\nu})}{\text{Br}(B \rightarrow D^*\ell\bar{\nu})} \quad \ell = e, \mu$$

[2206.07501]

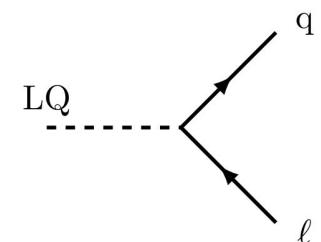


Tree-level process in the SM

Both give deviation about  $3.4\sigma$  from the SM

# Solution: Leptoquarks

- Leptoquarks (LQs) are hypothetical particles.  
SU(5) GUT model, SU(4) Pati-Salam model, supersymmetric models, etc.
- LQs are coupled to both leptons and quarks  
SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers
- LQs can be spin 0 or spin 1  
scalar LQs or vector LQs



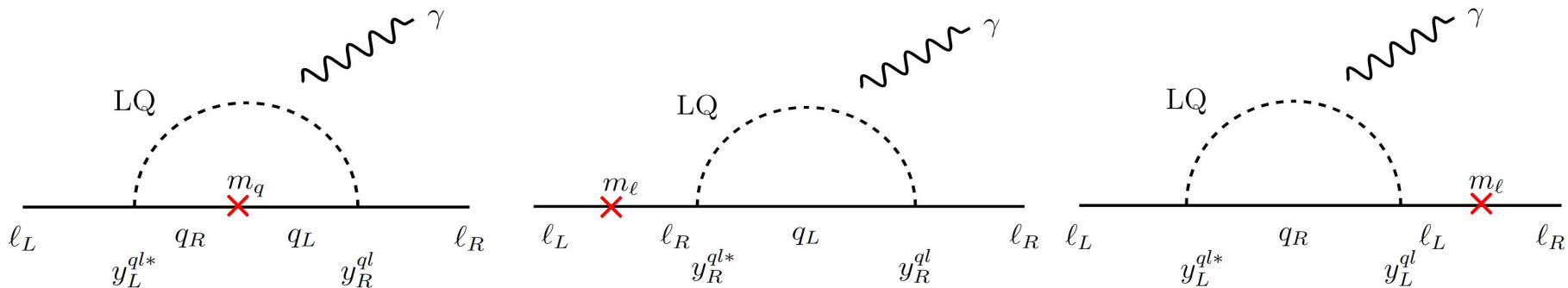
Leptoquark	Spin	$(SU(3), SU(2), U(1))$	Charge
$S_1$	0	$(\bar{3}, 1, 1/3)$	$+1/3$
$\tilde{S}_1$	0	$(\bar{3}, 1, 4/3)$	$+4/3$
$R_2$	0	$(3, 2, 7/6)$	$+2/3, +5/3$
$\tilde{R}_2$	0	$(3, 2, 1/6)$	$-1/3, +2/3$
$S_3$	0	$(\bar{3}, 3, 1/3)$	$-2/3, +1/3, +4/3$

# g-2: Chiral Enhancement

General interactions:

$$\mathcal{L}^{F=0} = \bar{q}_i (y_L^{ij} P_L + y_R^{ij} P_R) \ell_j S + \text{h.c.}, \quad \mathcal{L}^{|F|=2} = \overline{q_i^C} (y_L'^{ij} P_L + y_R'^{ij} P_R) \ell_j S + \text{h.c.}.$$

Enhance by quark mass:



$$\Delta a_\ell = -\frac{3m_\ell}{8\pi^2 m_S^2} \sum_q \left[ m_\ell (|y_R^{q\ell}|^2 + |y_L^{q\ell}|^2) F(x) + m_q \text{Re}(y_L^{*q\ell} y_R^{q\ell}) G(x) \right]$$

Leptoquark	chirality	$(g-2)_{e,\mu}$ at one-loop
$S_1$	no-chiral	✓
$\tilde{S}_1$	chiral	✗
$R_2$	no-chiral	✓
$\tilde{R}_2$	chiral	✗
$S_3$	chiral	✗

# B-physics Anomalies: $R_{K^{(*)}}$

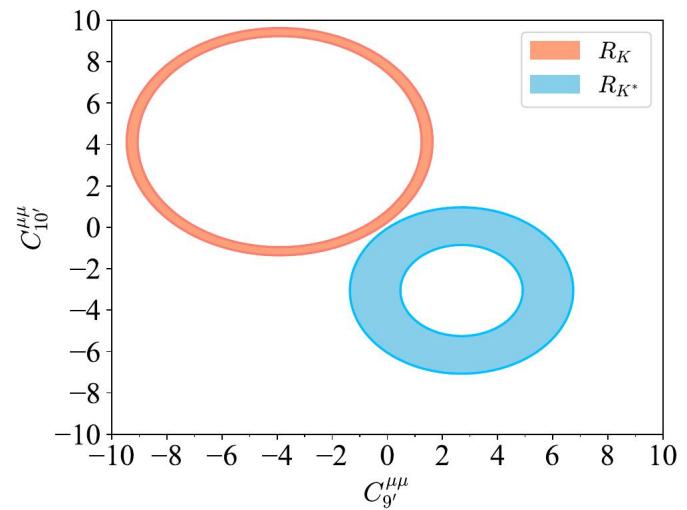
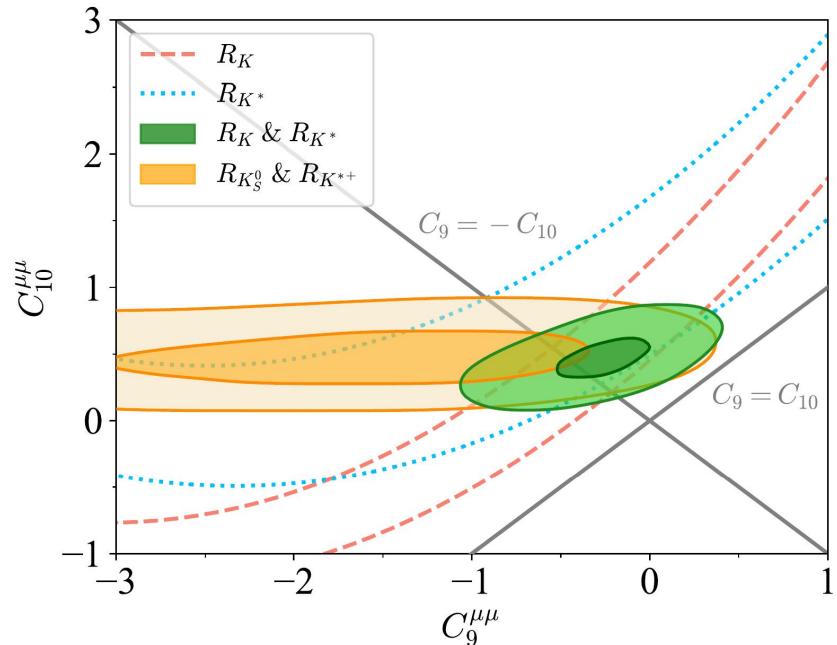
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{X=9,10} (C_X^{\ell\ell} \mathcal{O}_X^{\ell\ell} + C_{X'}^{\ell\ell} \mathcal{O}_{X'}^{\ell\ell}) \right] + \text{h.c.}$$

$$\mathcal{O}_9^{\ell\ell} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10}^{\ell\ell} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell),$$

$$\mathcal{O}_{9'}^{\ell\ell} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10'}^{\ell\ell} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

Best fit:  $C_9^{\mu\mu} = -C_{10}^{\mu\mu} = -0.45$

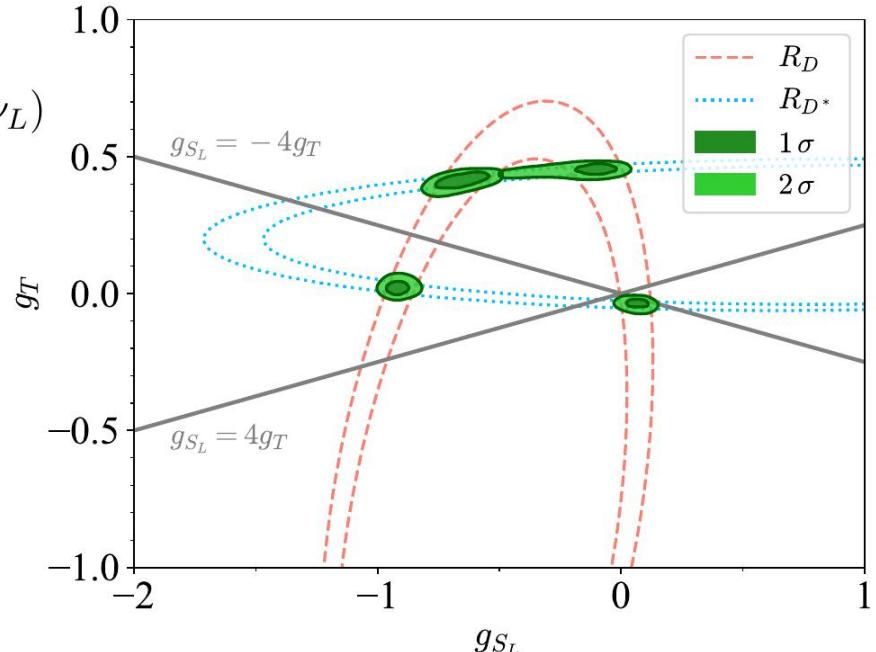
Leptoquark	Tree level	$R_{K^{(*)}}$
$S_1$	✗	✗
$\tilde{S}_1$	✗	✗
$R_2$	$C_{9'} = -C_{10'}$	✗
$\tilde{R}_2$	$C_9 = C_{10}$	✗
$S_3$	$C_9 = -C_{10}$	✓



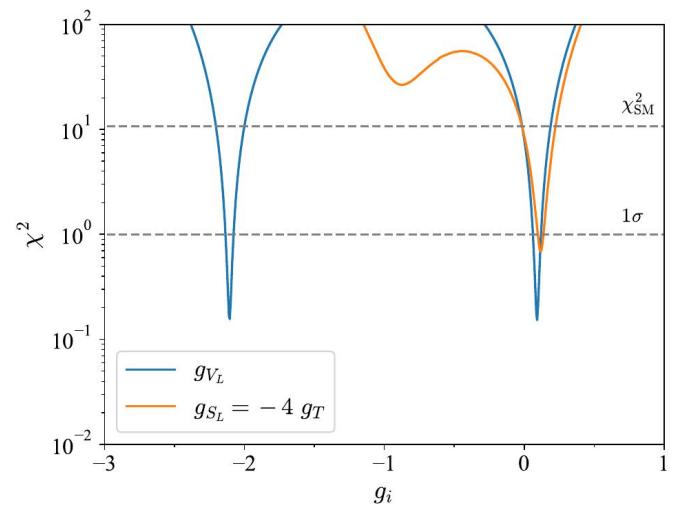
# B-physics Anomalies: $R_{D^{(*)}}$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ g_{V_L} (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) + g_{S_L} (\bar{c}_R b_L) (\bar{\tau}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.} .$$

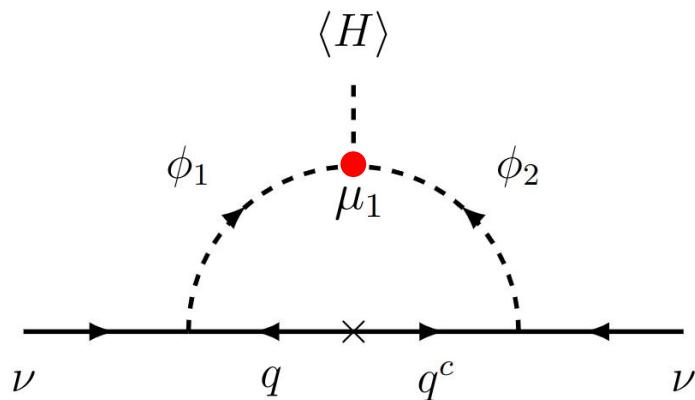
Best fit:  $g_{S_L} = -4g_T = 0.12$



Leptoquark	Tree level	$R_{D^{(*)}}$
$S_1$	$g_{S_L} = -4g_T, g_{V_L}$	✓
$\tilde{S}_1$	✗	✗
$R_2$	$g_{S_L} = 4g_T$	✓ (imag)
$\tilde{R}_2$	✗	✗
$S_3$	$g_{V_L}$	✗



# Neutrino Mass



Possible combinations:

$$S_1 - \tilde{R}_2 \quad S_3 - \tilde{R}_2$$

Neutrino mass matrix:

$$(\mathcal{M}_\nu)_{\alpha\beta} = (y_{1L}^T \Lambda y_{2L} + y_{2L}^T \Lambda^T y_{1L})_{\alpha\beta}$$

$$\Lambda \equiv \begin{pmatrix} \Lambda_d & 0 & 0 \\ 0 & \Lambda_s & 0 \\ 0 & 0 & \Lambda_b \end{pmatrix} \quad \Lambda_k \simeq \frac{3}{32\pi^2} m_k \frac{\sqrt{2}\mu_1 v}{m_{\phi_1}^2 - m_{\phi_2}^2} \log \left( \frac{m_{\phi_1}^2}{m_{\phi_2}^2} \right)$$

Small mixing:  $\mu_1 \sim 10 \text{ keV}$

# Combined Explanations

Leptoquark	$(g - 2)_{e,\mu}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$	Neutrino mass
$S_1$	✓	✗	✓	
$\tilde{S}_1$	✗	✗	✗	$S_1 - \tilde{R}_2$
$R_2$	✓	✗	✓	
$\tilde{R}_2$	✗	✗	✗	$S_3 - \tilde{R}_2$
$S_3$	✗	✓	✗	

Two scenarios: ①  $S_1 - \tilde{R}_2 - S_3$     ②  $R_2 - \tilde{R}_2 - S_3$

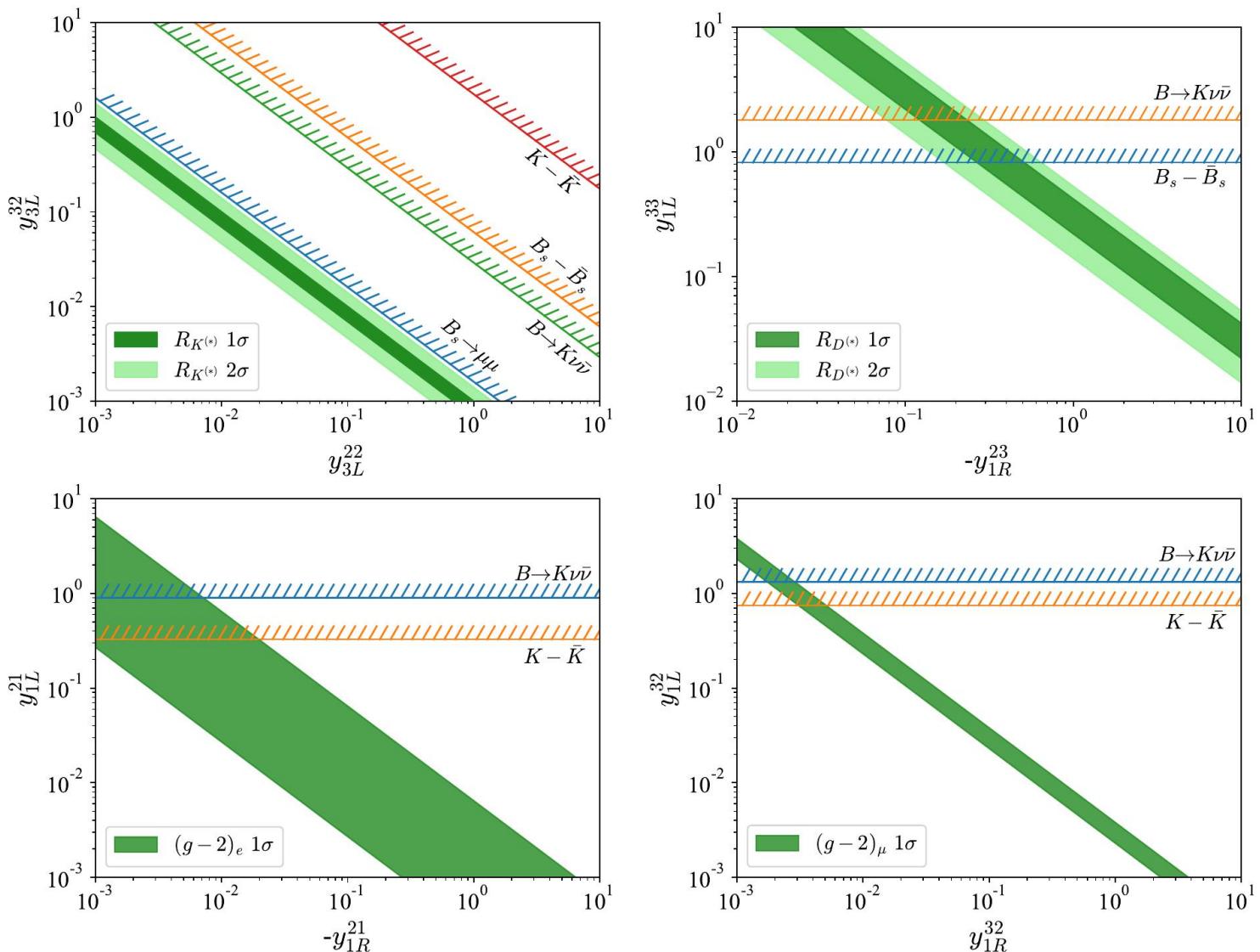
① Minimal Yukawa coupling textures:

$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ y_{1R}^{21} & 0 & y_{1R}^{23} \\ 0 & y_{1R}^{32} & 0 \end{pmatrix}, \quad y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ y_{1L}^{21} & 0 & y_{1L}^{23} \\ 0 & y_{1L}^{32} & y_{1L}^{33} \end{pmatrix}, \quad \begin{array}{l} \bullet (g - 2)_e \\ \bullet (g - 2)_\mu \\ \bullet R_D, R_{D^*} \\ \bullet R_K, R_{K^*} \end{array}$$

$$y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{3L}^{22} & y_{3L}^{23} \\ y_{3L}^{31} & y_{3L}^{32} & 0 \end{pmatrix}, \quad y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ y_{2L}^{21} & y_{2L}^{22} & y_{2L}^{23} \\ y_{2L}^{31} & y_{2L}^{32} & y_{2L}^{33} \end{pmatrix} \quad y_{1L} - y_{2L} \text{ Neutrino oscillation}$$

$$y_{3L} - y_{2L}$$

# Allowed Range



# Benchmark Points

Benchmark point 1:

$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ -0.37 & 0 & -0.70 \\ 0 & 0.054 & 0 \end{pmatrix}, \quad y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.029 & 0 \\ 0 & 0.023 & 0 \end{pmatrix},$$
$$y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.012 + 0.016i & 0 & -0.049 - 0.0042i \\ 0 & 0.57 + 0.0082i & 0.59 + 0.052i \end{pmatrix},$$
$$y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.043 - 0.042i & 0.044 & -0.048 \\ -0.00013 & 0.00038 & 0.00027 \end{pmatrix}.$$

Benchmark point 2:

$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ -0.014 & 0 & -0.93 \\ 0 & 0.012 & 0 \end{pmatrix}, \quad y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.37 & 0 & 0 \\ 0 & 0.21 & 0.38 \end{pmatrix},$$
$$y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.070 & 0.038 \\ 0.0019 & 0.0059 & 0 \end{pmatrix}, \quad y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ -0.015 & -0.0020 & 0.023 \\ 0.0015 & 0.0031 & -0.00078 \end{pmatrix}.$$

# Observable Values for Two Benchmark Points

Observables	Allowed range	BP1	BP2
$\Delta m_{21}^2 (10^{-5} \text{eV}^2)$	[6.82, 8.04]	7.44	7.40
$\Delta m_{32}^2 (10^{-3} \text{eV}^2)$	[2.435, 2.598]	2.50	2.51
$\sin^2 \theta_{12}$	[0.269, 0.343]	0.305	0.301
$\sin^2 \theta_{23}$	[0.405, 0.620]	0.569	0.570
$\sin^2 \theta_{13}$	[0.02064, 0.02430]	0.0226	0.0225
$\delta_{\text{CP}} / {}^\circ$	[169, 246]	194	180
$R_K$	[0.795, 0.901]	0.808	0.812
$R_{K^*}$	[0.569, 0.845]	0.794	0.817
$R_{K_S^0}$	[0.48, 0.88]	0.808	0.812
$R_{K^{*+}}$	[0.53, 0.91]	0.825	0.844
$R_D$	[0.310, 0.370]	0.358	0.351
$R_{D^*}$	[0.281, 0.309]	0.305	0.292
$\Delta a_e (10^{-13})$	[-12.3, -5.1]	-8.48	-9.89
$\Delta a_\mu (10^{-9})$	[1.93, 3.11]	2.52	2.06

# Observable Values for Two Benchmark Points

$\text{Br}(\mu \rightarrow e\gamma)$	$< 4.2 \times 10^{-13}$	$6.49 \times 10^{-21}$	$1.04 \times 10^{-17}$
$\text{Br}(\tau \rightarrow e\gamma)$	$< 3.3 \times 10^{-8}$	$2.98 \times 10^{-18}$	$6.09 \times 10^{-16}$
$\text{Br}(\tau \rightarrow \mu\gamma)$	$< 4.4 \times 10^{-8}$	$2.99 \times 10^{-18}$	$7.82 \times 10^{-16}$
$\text{Br}(\mu - e)_{\text{Au}}$	$< 7 \times 10^{-13}$	$4.84 \times 10^{-19}$	$2.62 \times 10^{-15}$
$\text{Br}(B_s^0 \rightarrow \mu\mu)$	$[2.58, 3.28] \times 10^{-9}$	$2.93 \times 10^{-9}$	$3.42 \times 10^{-9}$
$\text{Br}(B_s^0 \rightarrow \tau\tau)$	$< 6.8 \times 10^{-3}$	$7.82 \times 10^{-7}$	$7.95 \times 10^{-7}$
$\text{Br}(B_s^0 \rightarrow \mu\tau)$	$< 1.4 \times 10^{-5}$	$2.11 \times 10^{-14}$	$1.40 \times 10^{-10}$
$R_K^{\nu\nu}$	$< 3.9$	1.3	0.75
$R_{K^*}^{\nu\nu}$	$< 2.7$	1.4	0.76
$\Delta m_{B_s}^{\text{SM+NP}} / \Delta m_{B_s}^{\text{SM}}$	$[0.85, 1.15]$	1.03	1.01
$\Delta m_K^{\text{NP}} (10^{10} s^{-1})$	$< 0.95$	0.0016	0.52

# Summary

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- Analyze current observed deviations from the SM predictions
- Explain these anomalies by extending SM with three TeV-scale scalar leptoquarks
- Summarize the most stringent low-energy processes and give the relevant constraints
- Obtain the corresponding viable region of model

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Thanks