# On the interplay between flavour anomalies and neutrino properties

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Based on arXiv:2206.01674 [hep-ph]

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**BSM$^2$ - Beyond the Standard Model BrainStorming Meeting**

Despite its successes, the SM either **fails** or is **insufficient** in tackling various observations, with **anomalous results** popping up in recent years ...

- **$R_{D/D^*}$**

$$R_{D^{(*)}} \equiv \frac{\mathrm{Br}\left(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathrm{Br}\left(\bar{B} \to D^{(*)}l\bar{\nu}_l\right)} \quad \text{with} \quad l = \mu, e,$$

  $\mathbf{2.3\sigma}$ tension with the SM [Eur. Phys. J. C 81, 226 (2021)];

- **$R_{K/K^*}$**

$$R_K \equiv \frac{\mathrm{Br}\left(B^+ \to K^+\mu^-\mu^+\right)}{\mathrm{Br}\left(B^+ \to K^+e^-e^+\right)}, \quad R_{K^*} \equiv \frac{\mathrm{Br}\left(B^0 \to K^{*0}\mu^-\mu^+\right)}{\mathrm{Br}\left(B^0 \to K^{*0}e^-e^+\right)}$$

  $\mathbf{3.1\sigma}$ tension with the SM [Nat. Phys. 18, 277–282 (2022)];

- **$a_\mu$** $\mathbf{4.2\sigma}$ tension with the SM [Phys. Rev. Lett. 126, 141801 (2021)]. Although lattice results indicate consistency [Nature 593 (2021) 7857, 51-55].

- **$M_W$** $\mathbf{3.7\sigma}$ tension with the SM [2204.04204 [hep-ph]]. Tension primarily driven by the new CDF result [Science 376 (2022) 170–176].

**The goal:** Study the most minimal model that can simultaneously address **all** aforementioned problems while allowing for a good neutrino phenomenology

$$\mathbf{R_{D/D^*} + R_{K/K^*} + a_\mu + M_W + U_{PMNS} + m_\nu}$$

**The problem:** Improvement of different observables will cause problems in different sectors

- **Lepton number violation:** $\mu \to e\gamma$, $\tau \to \mu\gamma$, $h \to \tau\mu$, ...
- **Lepton number conservation:** $\mathrm{Z}^0 \to ee, \mu\mu, \tau\tau$, $\Gamma_Z$;
- **Meson mixing:** $\Delta M_D$, $\Delta M_S$;
- **CP sensitive observables:** $\epsilon_K$, $d_e/d_\mu/d_\tau$
- **Additional B-physics observables:** $R^{\nu\nu}_{K/K^*}$, $\mathrm{BR}(B^0 \to \mu\mu)$, $\mathrm{BR}(B_s \to \mu\mu)$

In the most minimal setup, we expect different parameters to correlate with distinct sectors. Can make for **a difficult fit to data**.

**The idea:** Introduce colored scalar fields to connect **leptons to quarks**, i.e. **Leptoquarks**! Neutrino mass in the same vain as the one-loop Zee model [Phys.Lett.B 95, 461 (1980)]

## The model:

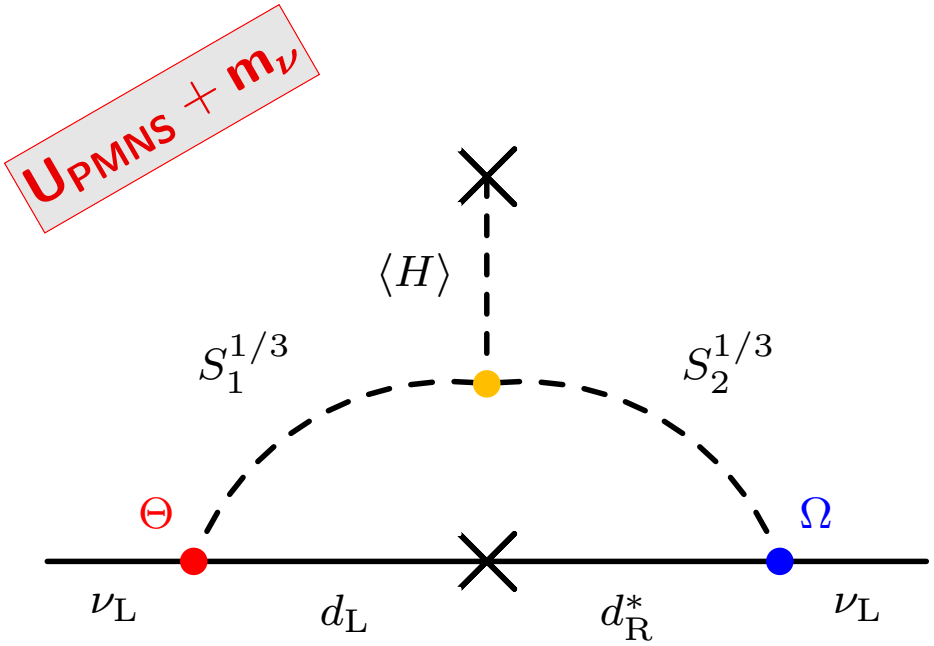
- **One** $\mathrm{SU}(2)$ singlet: $S \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)^-$;
- **One** $\mathrm{SU}(2)$ doublet: $R \sim (\bar{\mathbf{3}}, \mathbf{2}, 1/6)^-$;
- Yukawas that generate proton decay $\rightarrow y_1 \bar{Q}^c Q S^\dagger + y_2 \bar{d} u S + \mathrm{h.c.}$

$$\mathbb{Z}_2 \text{ symmetry: } \mathbb{P}_B = (-1)^{3B+2S} \quad \Longrightarrow \quad S^-,\, R^-,\, q^+_{L,R},\, \ell^-_{L,R},\, H^-$$

Group charges and particles are emergent in a gauge-flavour unification model based on $\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$ [Eur. Phys. J. C 80, 1162 (2020)].

- Yukawa Lagrangian: $\boxed{\mathcal{L}_Y = \Theta_{ij} \bar{Q}^c_j L_i S + \Omega_{ij} \bar{L}_i d_i R^\dagger + \Upsilon_{ij} \bar{u}^c_j e_i S + \mathrm{h.c.}}$
- Relevant scalar potential:

$$\boxed{\begin{aligned} V \supset\ & -\mu^2 |H|^2 + \mu_S^2 |S|^2 + \mu_R^2 |R|^2 + \lambda (H^\dagger H)^2 + g_{HR} (H^\dagger H)(R^\dagger R) + \\ & g'_{HR} (H^\dagger R)(R^\dagger H) + g_{HS} (H^\dagger H)(S^\dagger S) + \left( a_1 R S H^\dagger + \mathrm{h.c.} \right) . \end{aligned}}$$

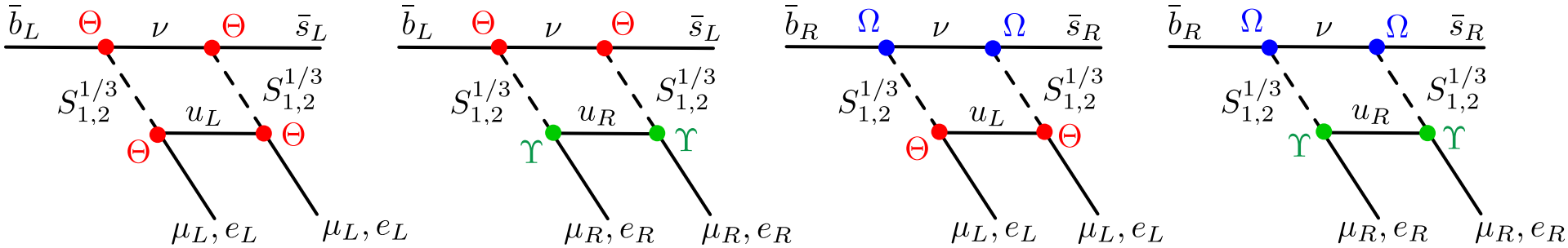



- Majorana neutrino mass and mixing generated at **one-loop** level. [JHEP 07, 069 (2021)]; [Phys. **5**, 63 (2017),]
- Relevant operators:
  $\Theta_{ij}\bar{Q}_j^c L_i S + \Omega_{ij}\bar{L}_i d_i R^\dagger + a_1 RSH^\dagger$
- Both $\Theta_{ij}$ and $\Omega_{ij}$ need to be generic matrices for valid PMNS. **No flavour ansatz**.

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m^2_{S_2^{1/3}} - m^2_{S_1^{1/3}})}\frac{v a_1}{\sqrt{2}}\ln\left(\frac{m^2_{S_2^{1/3}}}{m^2_{S_1^{1/3}}}\right)\sum_{m,a}(m_d)_a V_{am}(\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia})$$

Neutrino mass and mixing proportional to **down quark masses and the CKM**, $V$. Leptoquark mixing is a **necessary** ingredient, since $M_\nu = 0$ in the limit $a_1 \to 0$.

$\mathbf{R_{K/K^*}}$

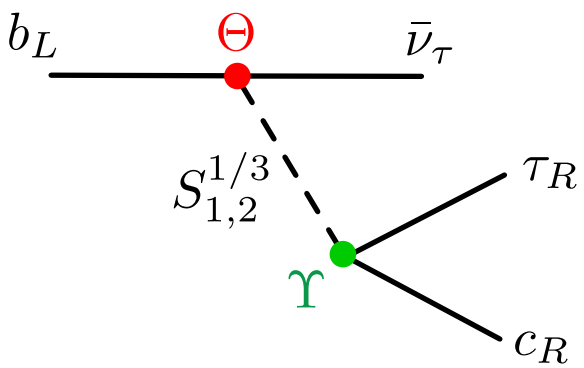



- New contributions to $\mathbf{R_{K/K^*}}$ generated at **one-loop** level. Involves **all** Yukawa couplings, $\Theta_{ij}$, $\Omega_{ij}$ and $\Upsilon_{ij}$;

$$C_9^{bs\ell\ell}(\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu \ell) \qquad C_9^{\prime\, bs\mu\mu}(\bar{s}\gamma^\mu P_R b)(\bar{l}\gamma_\mu \ell)$$
$$C_{10}^{bs\ell\ell}(\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu \gamma^5 \ell) \qquad C_{10}^{\prime\, bs\mu\mu}(\bar{s}\gamma^\mu P_R b)(\bar{l}\gamma_\mu \gamma^5 \ell)$$

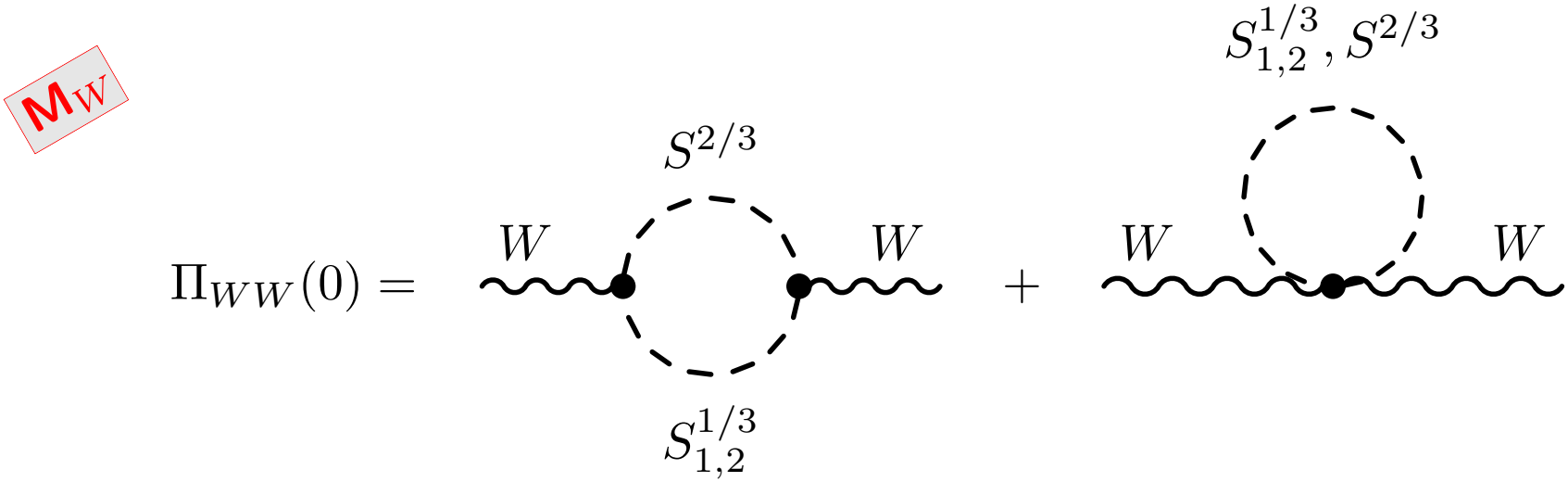
- Both **electron and muon** modes contribute. Wilson coefficients $C_{9,10}^{bs\ell\ell}$ lead to $\mathbf{R_{K/K^*}} < 1$, whereas $C_{9,10}^{\prime\, bs\ell\ell}$ lead to $\mathbf{R_K} < 1/\mathbf{R_{K^*}} > 1$ or vice-versa [Eur. Phys. J. C. 81 (2021), 10, 952];

$R_{D/D^*}$




- Contributions for $\mathbf{R_{D/D^*}}$ at **tree-level**, via the exchange of the $S$ leptoquark, through $\Theta_{ij}$ and $\Upsilon_{ij}$;
- $\mathbf{R_D}$ is dominated by the scalar operator $(\bar{c}b_L)(\bar{\tau}_R\nu_\tau) \rightarrow$ **Prefers real couplings**; [JHEP 01 (2017) 125]
- $\mathbf{R_{D^*}}$ is dominated by the pseudo-scalar operator $(\bar{c}\gamma_5 b_L)(\bar{\tau}_R\nu_\tau) \rightarrow$ **Prefers imaginary couplings**; [JHEP 01 (2017) 125]

Identical diagram with $\Upsilon \rightarrow \Theta$ leads to additional contributions to $R^{\nu\nu}_{K,K^*}$ [Phys.Rev.D 96, 091101 (2017)]. **Competition** between these observables.

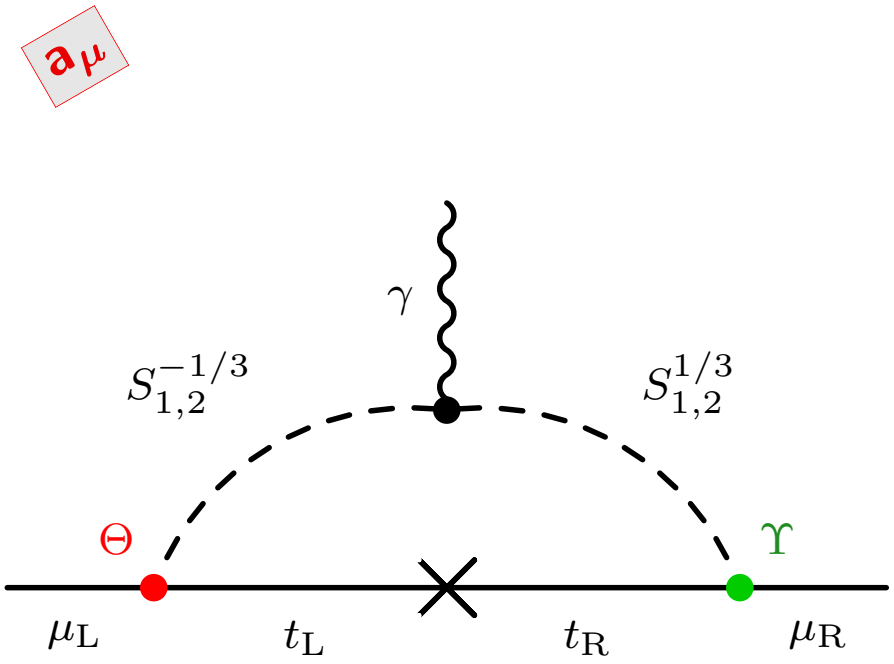



Corrections to the $W$ vacuum polarization self-energy $\Pi_{WW}$ through virtual LQs [JHEP 11 (2020) 094]. The $T$ parameter scale as

$$T \sim \frac{1}{\alpha M_W^2} \frac{\ln\left(\frac{m_{S^{2/3}}}{m_{S_a^{1/3}}}\right)}{\frac{m_{S^{2/3}}}{m_{S_a^{1/3}}} - 1} \Longrightarrow m_{S^{2/3}} \neq m_{S_a^{1/3}} \text{ to have non-zero } T$$

The quartic parameters of the potential $g_{HR}(H^\dagger H)(R^\dagger R)$, $g'_{HR}(H^\dagger R)(R^\dagger H)$, and $g_{HS}(H^\dagger H)(S^\dagger S)$ lift the degeneracy

- $g_{HR}$, $g'_{HR}$ and $g_{HS}$ of $\mathcal{O}(1)$ for sizable effects




- Dominant one-loop contributions via chirality flip of the top quark [JHEP 07 (2021) 069];
- Relevant operators:
  $\Theta_{ij}\bar{Q}_j^c L_i S + \Upsilon_{ij}\bar{u}_j^c e_i S$
- Sub-leading contribution from the $R$ LQ: $a_\mu \sim (m_\mu^2/m_{S^{2/3}}^2)|\Omega_{\mu q}|^2$.

$$(\Delta a_\mu^{S^{1/3}}) \sim -\frac{N_c m_\mu m_t}{16\pi^2 m_{S^{1/3}}^2}\mathrm{Re}\left(\Theta_{\mu t}\Upsilon_{\mu t}^*\right)\ln\left(\frac{m_{S^{1/3}}^2}{m_t^2}\right) + \mathcal{O}\left(m_\mu^2\left(|\Theta_{\mu t}|^2 + |\Upsilon_{\mu t}|^2\right)\right)$$

Other pairings induce **LFV's** e.g. $\Theta_{\mu t}\Upsilon_{et}^*$ induces $\mu \to e\gamma$, so there must some **hiearchy in the Yukawa couplings**.

## Main observables

| Observable | Experimental measurement |
|---|---|
| $a_\mu$ | $(251 \pm 59) \times 10^{-11}$ |
| $\hat{T}$ | $(0.88 \pm 0.14) \times 10^{-3}$ |
| $R_K[1.1, 6.0]$ | $0.846^{+0.042+0.013}_{-0.039-0.012}$ |
| $R_{K*}[1.1, 6.0]$ | $0.685^{0.113+0.047}_{-0.069-0.047}$ |
| $R_K[0.045, 1.1]$ | $0.660^{0.110+0.024}_{-0.070-0.024}$ |
| $R_D$ | $0.340 \pm 0.027 \pm 0.013$ |
| $R_{D^*}$ | $0.295 \pm 0.011 \pm 0.008$ |
| **LFVs** | |
| $\mathrm{BR}(h \to e\mu)$ | $< 6.1 \times 10^{-5}$ [95% CL] |
| $\mathrm{BR}(h \to e\tau)$ | $< 4.7 \times 10^{-3}$ [95% CL] |
| $\mathrm{BR}(h \to \mu\tau)$ | $< 2.5 \times 10^{-3}$ [95% CL] |
| $\mathrm{BR}(\mu \to e\gamma)$ | $< 4.2 \times 10^{-13}$ [90% CL] |
| $\mathrm{BR}(\mu \to eee)$ | $< 1.0 \times 10^{-12}$ [90% CL] |
| $\mathrm{BR}(\tau \to e\gamma)$ | $< 3.3 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \mu\gamma)$ | $< 4.4 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to eee)$ | $< 2.7 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to e\mu\mu)$ | $< 2.7 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \mu ee)$ | $< 1.5 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(Z \to \mu e)$ | $< 7.5 \times 10^{-7}$ [95% CL] |
| $\mathrm{BR}(Z \to \tau e)$ | $< 9.8 \times 10^{-6}$ [95% CL] |
| $\mathrm{BR}(Z \to \mu\tau)$ | $< 1.2 \times 10^{-5}$ [95% CL] |
| $\mathrm{BR}(\tau \to \pi e)$ | $< 8.0 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \pi\mu)$ | $< 1.1 \times 10^{-7}$ [90% CL] |
| $\mathrm{BR}(\tau \to \phi e)$ | $< 3.1 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \phi\mu)$ | $< 8.4 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \rho e)$ | $< 1.8 \times 10^{-8}$ [90% CL] |
| $\mathrm{BR}(\tau \to \rho\mu)$ | $< 1.2 \times 10^{-8}$ [90% CL] |
| **EDMs** | |
| $d_e$ | $< 1.1 \times 10^{-29}$ e.cm [90% CL] |
| $d_\mu$ | $< 1.8 \times 10^{-19}$ e.cm [95% CL] |
| $d_\tau$ | $< (1.15 \pm 1.70) \times 10^{-17}$ e.cm [95% CL] |
| **QFVs** | |
| $\mathrm{BR}(B^0 \to \mu\mu)$ | $(0.56 \pm 0.70) \times 10^{-10}$ |
| $\mathrm{BR}(B_s \to \mu\mu)$ | $(2.93 \pm 0.35) \times 10^{-9}$ |
| $\mathrm{R}(B \to \chi_s\gamma)$ | $1.009 \pm 0.075$ |
| $R_K^{\nu\nu}$ | 4.65 [95% CL] |
| $R_{K^*}^{\nu\nu}$ | 3.22 [95% CL] |
| **LFCs** | |
| $\lvert\mathrm{Re}\ \delta g_R^e\rvert$ | $\leq 2.9 \times 10^{-4}$ |
| $\lvert\mathrm{Re}\ \delta g_L^e\rvert$ | $\leq 3.0 \times 10^{-4}$ |
| $\lvert\mathrm{Re}\ \delta g_R^\mu\rvert$ | $\leq 1.3 \times 10^{-3}$ |
| $\lvert\mathrm{Re}\ \delta g_L^\mu\rvert$ | $\leq 1.1 \times 10^{-3}$ |
| $\lvert\mathrm{Re}\ \delta g_R^\tau\rvert$ | $\leq 6.2 \times 10^{-4}$ |
| $\lvert\mathrm{Re}\ \delta g_L^\tau\rvert$ | $\leq 5.8 \times 10^{-4}$ |

| Observable | Experimental measurement |
|---|---|
| $F_L(B^+ \to K\mu\mu)$ | $0.34 \pm 0.10 \pm 0.06$ |
| $S_3(B^+ \to K\mu\mu)$ | $0.14^{+0.15+0.02}_{-0.14-0.02}$ |
| $S_4(B^+ \to K\mu\mu)$ | $-0.04^{+0.17+0.04}_{-0.16-0.04}$ |
| $S_5(B^+ \to K\mu\mu)$ | $0.24^{+0.12+0.04}_{-0.15-0.04}$ |
| $A_{FB}(B^+ \to K\mu\mu)$ | $-0.05 \pm 0.12 \pm 0.03$ |
| $S_7(B^+ \to K\mu\mu)$ | $-0.01^{+0.19+0.01}_{-0.17-0.01}$ |
| $S_8(B^+ \to K\mu\mu)$ | $0.21^{+0.22+0.05}_{-0.20-0.05}$ |
| $S_9(B^+ \to K\mu\mu)$ | $0.28^{+0.25+0.06}_{-0.12-0.06}$ |
| $P_1(B^+ \to K\mu\mu)$ | $0.44^{+0.38+0.11}_{-0.40-0.11}$ |
| $P_2(B^+ \to K\mu\mu)$ | $-0.05 \pm 0.12 \pm 0.03$ |
| $P_3(B^+ \to K\mu\mu)$ | $-0.42^{+0.20+0.05}_{-0.21-0.05}$ |
| $P_4'(B^+ \to K\mu\mu)$ | $-0.092^{+0.36+0.12}_{-0.35-0.12}$ |
| $P_5'(B^+ \to K\mu\mu)$ | $0.51^{+0.30+0.12}_{-0.28-0.12}$ |
| $P_6'(B^+ \to K\mu\mu)$ | $-0.02^{+0.40+0.06}_{-0.34-0.06}$ |
| $P_8'(B^+ \to K\mu\mu)$ | $-0.45^{+0.50+0.09}_{-0.39-0.09}$ |
| $F_L(B^0 \to K\mu\mu)$ | $0.255 \pm 0.032 \pm 0.007$ |
| $S_3(B^0 \to K\mu\mu)$ | $0.034 \pm 0.044 \pm 0.003$ |
| $S_4(B^0 \to K\mu\mu)$ | $0.059 \pm 0.050 \pm 0.004$ |
| $S_5(B^0 \to K\mu\mu)$ | $0.227 \pm 0.041 \pm 0.008$ |
| $A_{FB}(B^0 \to K\mu\mu)$ | $-0.004 \pm 0.040 \pm 0.004$ |
| $S_7(B^0 \to K\mu\mu)$ | $0.006 \pm 0.042 \pm 0.002$ |
| $S_8(B^0 \to K\mu\mu)$ | $-0.003 \pm 0.051 \pm 0.001$ |
| $S_9(B^0 \to K\mu\mu)$ | $-0.055 \pm 0.041 \pm 0.002$ |
| $P_1(B^0 \to K\mu\mu)$ | $0.090 \pm 0.119 \pm 0.009$ |
| $P_2(B^0 \to K\mu\mu)$ | $-0.003 \pm 0.038 \pm 0.003$ |
| $P_3(B^0 \to K\mu\mu)$ | $-0.073 \pm 0.057 \pm 0.003$ |
| $P_4'(B^0 \to K\mu\mu)$ | $-0.135 \pm 0.118 \pm 0.003$ |
| $P_5'(B^0 \to K\mu\mu)$ | $-0.521 \pm 0.095 \pm 0.024$ |
| $P_6'(B^0 \to K\mu\mu)$ | $-0.015 \pm 0.094 \pm 0.007$ |
| $P_8'(B^0 \to K\mu\mu)$ | $-0.007 \pm 0.122 \pm 0.002$ |
| $\epsilon_k^{\mathrm{NP}}/\epsilon_k^{\mathrm{SM}}$ | $1.00 \pm 0.14$ |
| $\Delta M_d^{\mathrm{NP}}/\Delta M_d^{\mathrm{SM}}$ | $1.00 \pm 0.11$ |
| $\Delta M_s^{\mathrm{NP}}/\Delta M_s^{\mathrm{SM}}$ | $1.000 \pm 0.0054$ |

**CP-averaged angular obs.**

Access quality of the fit through the $\chi^2$ function [Eur.Phys.J.C 81 (2021) 10, 952]

$$\chi^2 = (\mathcal{O}_{\rm exp} - \mathcal{O}_{\rm th})^{\rm T}(\mathbf{\Sigma}_{\rm th} + \mathbf{\Sigma}_{\rm exp})^{-1}(\mathcal{O}_{\rm exp} - \mathcal{O}_{\rm th})$$

- The experimental correlations are also considered in $\mathbf{\Sigma}_{\rm exp}$, if available;
- Theoretical correlations are computed from simulated data set, using Pearson's method;
- Theoretical uncertainties are assumed gaussian. Determined from experimental errors on inputs (fermion masses, PMNS and CKM).

Analysis based on three distinct scenarios:

- Both $\mathbf{a_\mu}$ and $\mathbf{M}_W$ are SM-like (**Scenario a**);
- $\mathbf{a_\mu}$ requires new physics but $\mathbf{M}_W$ is SM-like (**Scenario b**);
- $\mathbf{a_\mu}$ and $\mathbf{M}_W$ require new physics (**Scenario c**).

**SM input** parameters: $\Delta m^2_{\nu_{ij}}, m_h, m_{u_i}, m_{d_i}, V_{\rm CKM}, V_{\rm PMNS}$.

The LQ mass matrix is $2 \times 2$ and can be easily inverted, such that the LQ physical masses are an input in the parameter scan

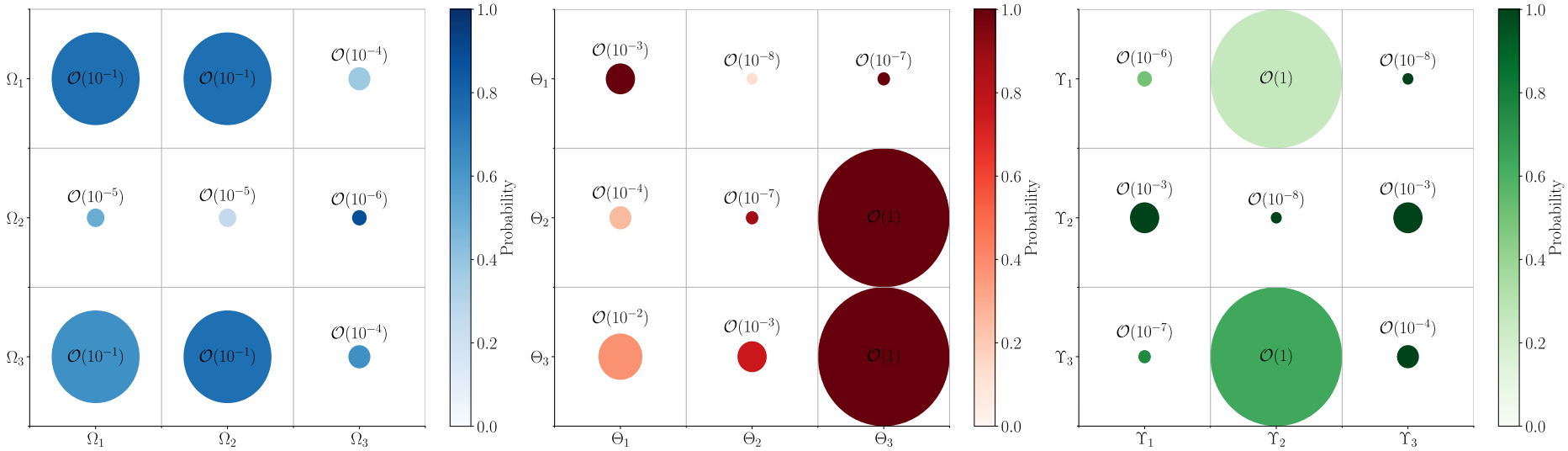
$$\mu_S^2 = \frac{1}{2}(m_{S_1}^2 + m_{S_2}^2 - g_{HS}v^2 + \sqrt{(m_{S_1}^2 - m_{S_2}^2)^2 - 2a_1^2 v^2}),$$
$$\mu_R^2 = \frac{1}{2}(m_{S_1}^2 + m_{S_2}^2 - (g_{HR} + g'_{HR})v^2 - \sqrt{(m_{S_1}^2 - m_{S_2}^2)^2 - 2a_1^2 v^2})$$

Recall that the one-loop neutrino mass matrix is given as

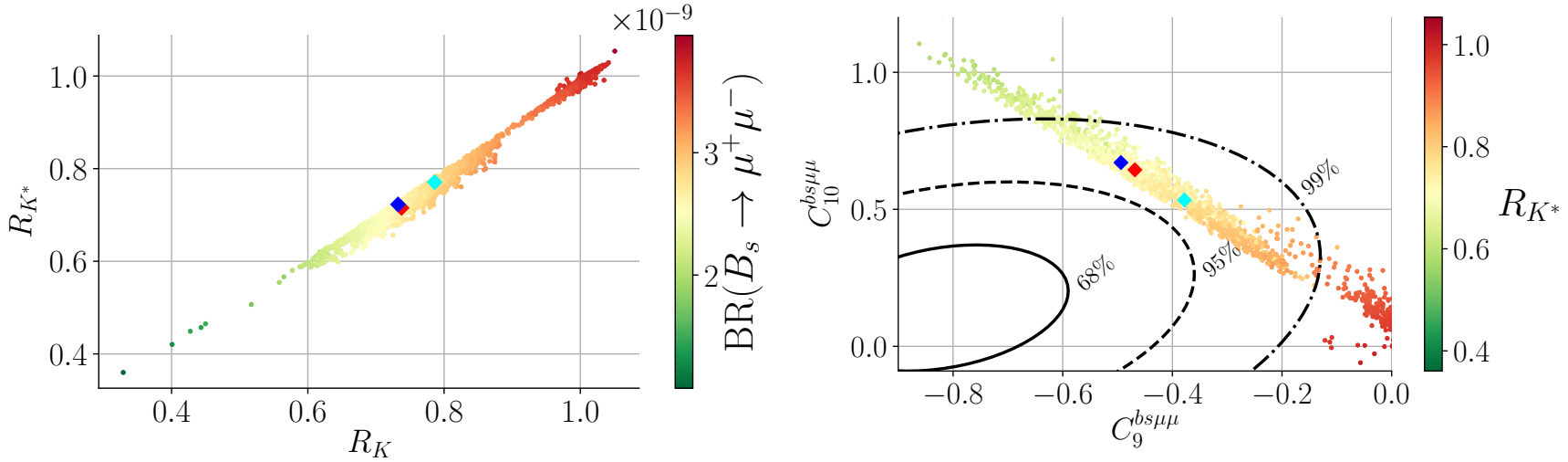
$$(M_\nu)_{ij} = \mathcal{C}(a_1, m_{S_1}, m_{S_2}) \sum_{m,a} (m_d)_a V_{am} (\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia})$$

The matrix is inverted, such that the physical/mixing of the neutrinos is input. $9$ elements of $\Omega$ and $\Theta$ are fixed by the neutrinos, leaving $9$ Yukawas as free parameters.

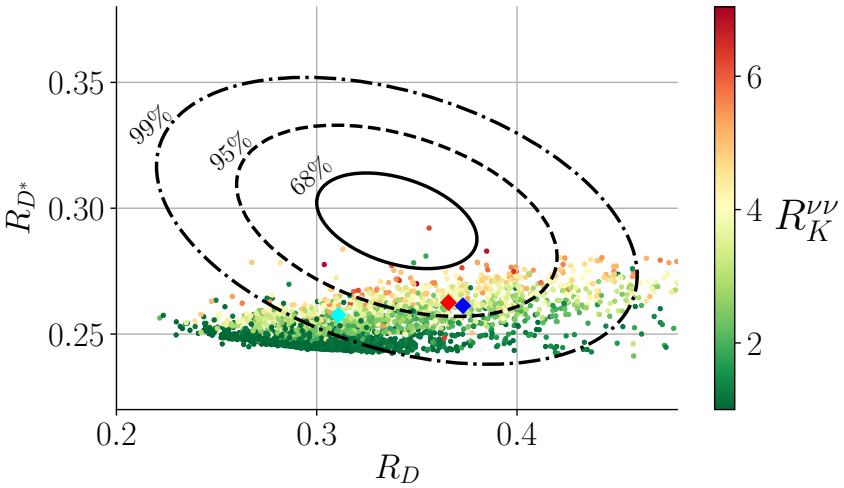
**BSM input** parameters: $9 \times \Omega, \Theta$, $9 \times \Upsilon$, $a_1$, $m_{S_1}$, $m_{S_2}$, $g_{HR}$, $g'_{HR}$, $g_{HS}$

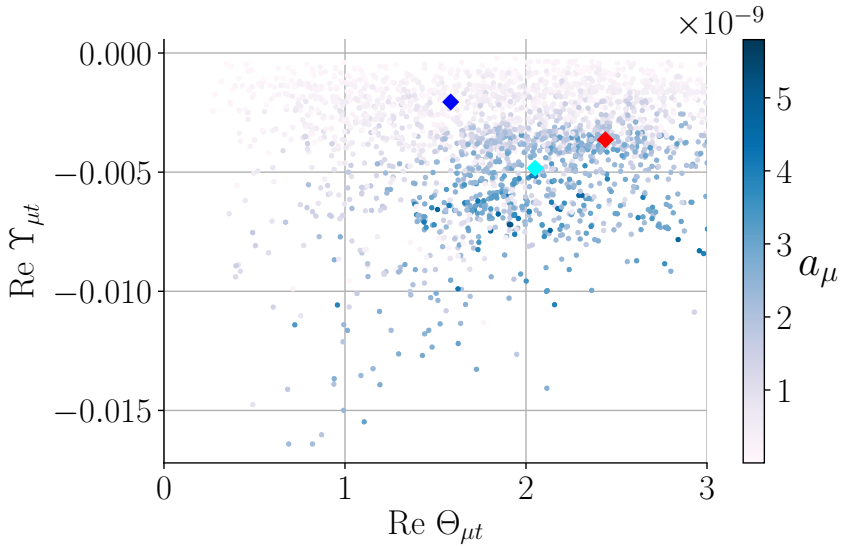



- **Scenario a):** $\boldsymbol{\chi^2/28\ \text{d.o.f} = 1.78}$, with $m_{S_1^{1/3}} = 2.57$ TeV, $m_{S_2^{1/3}} = 2.76$ TeV and $m_{S_2^{2/3}} = 2.78$ TeV;
- **Scenario b):** $\boldsymbol{\chi^2/28\ \text{d.o.f} = 1.76}$, with $m_{S_1^{1/3}} = 2.33$ TeV, $m_{S_2^{1/3}} = 4.48$ TeV and $m_{S^{2/3}} = 4.46$ TeV;
- **Scenario c):** $\boldsymbol{\chi^2/28\ \text{d.o.f} = 1.83}$, with $m_{S_1^{1/3}} = 2.46$ TeV, $m_{S_2^{1/3}} = 2.86$ TeV and $m_{S^{2/3}} = 2.81$ TeV;




- Linear relation between $R_K$ and $R_{K^*}$ is observed. Consistent with previous literature using effective field theories [Eur. Phys. J. C. 81 (2021), 10, 952];
- Strong correlation between $R_K$ and $\mathrm{BR}(B_s \to \mu\mu)$. Both are heavily impacted by $C_{9,10}^{bs\mu\mu}$. Muon mode is the preferred channel for solving these anomalies.



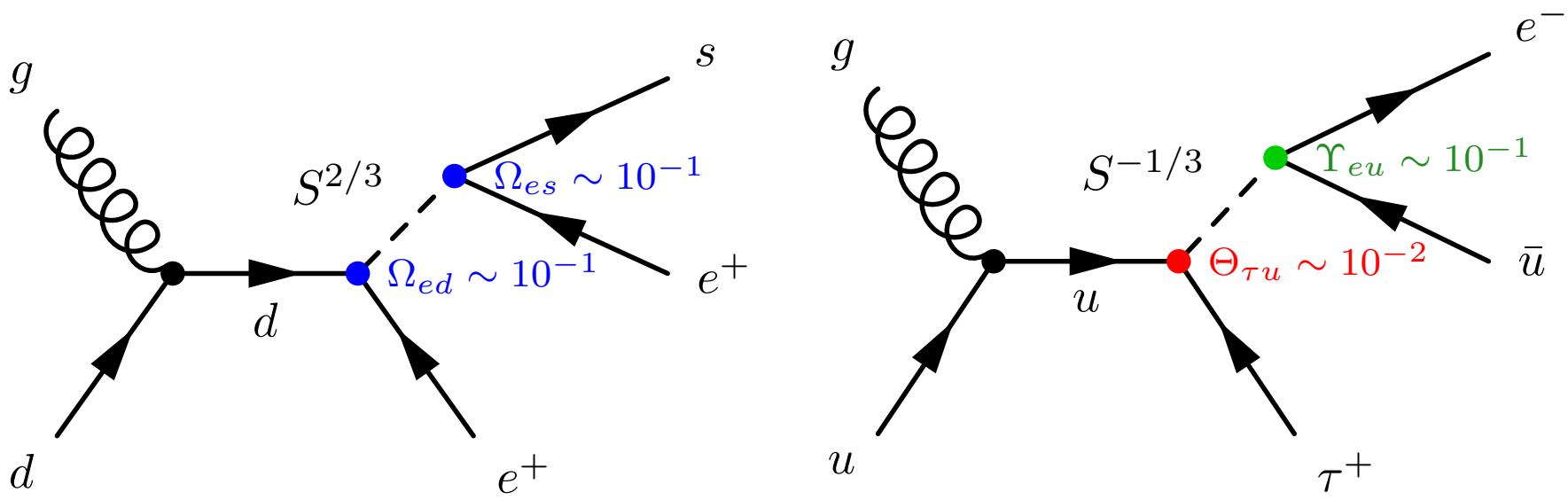




- Both the $R_{D,D^*}$ and $R^{\nu\nu}_{K,K^*}$ can be accommodated simultaneously. Competition between both observables is noted;
- $\Upsilon_{\mu t}$ controls the size of anomalous magnetic moment. Needs to always be **negative** to cancel the overall minus sign in $a_\mu$.

$$(\Delta a_\mu^{S^{1/3}}) \sim -\frac{N_c m_\mu m_t}{16\pi^2 m^2_{S^{1/3}}} \mathrm{Re}\left(\Theta_{\mu t}\, \Upsilon^*_{\mu t}\right) \ln\left(\frac{m^2_{S^{1/3}}}{m_t^2}\right) + \mathcal{O}\left(m_\mu^2 \left(|\Theta_{\mu t}|^2 + |\Upsilon_{\mu t}|^2\right)\right)$$

To conclude ...

- Discussed a simple economical model and showed prefered Yukawas for solving the anomalies;
- Textures of the Yukawas imply preference for channels involving, for example, 1st/3rd or 1st/2nd generation of fermions




- Can explain B-physics, $\mathbf{a_\mu}$, $\mathbf{m_\nu}$ and $\mathbf{M}_W$, while consistent with all relevant constraints with $\boldsymbol{\chi^2/28\ \text{d.o.f} = 1.83}$.

# On the interplay between flavour anomalies and neutrino properties

**Thank you for your attention**

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