On the interplay between flavour anomalies and neutrino properties

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Workshop on Multi-Higgs Models - IST Lisbon

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

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

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

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

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

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

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

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

- $\mathbf{M_W}$ $\mathbf{3.7\sigma}$ 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

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

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:** $Z^0 \to ee, \mu\mu, \tau\tau$, Γ_Z;
- **Meson mixing:** ΔM_D, ΔM_S;
- **CP sensitive observables:** ϵ_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 $\rightarrow y_1 \bar{Q}^c Q S^\dagger + y_2 \bar{d} u S + \mathrm{h.c.}$

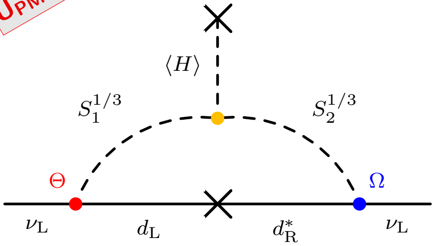
  $\mathbb{Z}_2$ symmetry: $\mathbb{P}_B = (-1)^{3B+2S} \quad \Longrightarrow \quad S^-,\ R^-,\ q^+_{L,R},\ \ell^-_{L,R},\ H^-$

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

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

$\mathbf{U_{PMNS} + m_\nu}$

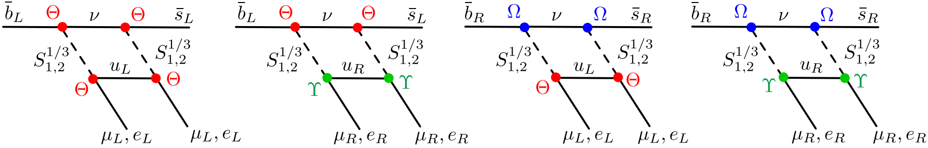


- Majorana neutrino mass and mixing generated at **one-loop** level. [JHEP 07, 069 (2021)]; [Phys. **5**, 63 (2017),]
- Relevant operators:
  $\Theta_{ij}\bar{Q}_j^c L_i S + \Omega_{ij}\bar{L}_i d_i R^\dagger + a_1 RSH^\dagger$
- Both Θ_{ij} and Ω_{ij} need to be generic matrices for valid PMNS. **No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

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m^2_{S_2^{1/3}} - m^2_{S_1^{1/3}})}\frac{va_1}{\sqrt{2}}\ln\left(\frac{m^2_{S_2^{1/3}}}{m^2_{S_1^{1/3}}}\right)\sum_{m,a}(m_d)_a V_{am}(\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia})$$

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 $a_1 \to 0$.

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



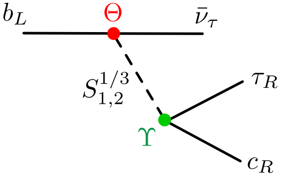
- New contributions to $\mathbf{R_{K/K^*}}$ generated at **one-loop** level. Involves **all** Yukawa couplings, Θ_{ij}, Ω_{ij} and Υ_{ij};

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

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

- 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];

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

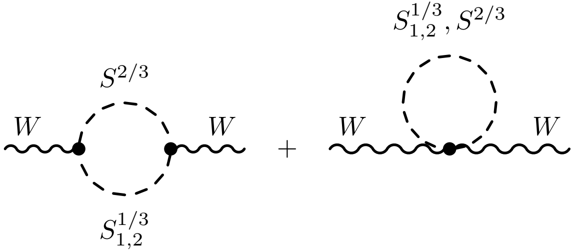


- Contributions for $\mathbf{R_{D/D^*}}$ at **tree-level**, via the exchange of the S leptoquark, through Θ_{ij} and Υ_{ij};
- $\mathbf{R_D}$ is dominated by the scalar operator $(\bar{c}b_L)(\bar{\tau}_R\nu_\tau) \rightarrow$ **Prefers real couplings**; [JHEP 01 (2017) 125]
- $\mathbf{R_{D^*}}$ is dominated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

M_W

$\Pi_{WW}(0) =$



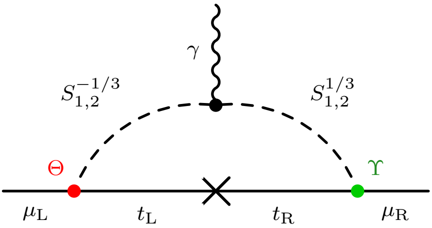
Corrections to the W vacuum polarization self-energy Π_{WW} through virtual LQs [JHEP 11 (2020) 094]. The T parameter scale as

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

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

a_μ



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

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

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_μ	$(251 \pm 59) \times 10^{-11}$
$\hat{T}$	$(0.88 \pm 0.14) \times 10^{-3}$
$R_K[1.1, 6.0]$	$0.846^{+0.042+0.013}_{-0.039-0.012}$
$R_{K*}[1.1, 6.0]$	$0.685^{0.113+0.047}_{-0.069-0.047}$
$R_K[0.045, 1.1]$	$0.660^{0.110+0.024}_{-0.070-0.024}$
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_μ	$< 1.8 \times 10^{-19}$ e.cm [95% CL]
d_τ	$< (1.15 \pm 1.70) \times 10^{-17}$ 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 ± 0.075
$R_K^{\nu\nu}$	4.65 [95% CL]
$R_{K^*}^{\nu\nu}$	3.22 [95% CL]
LFCs	
$\lvert\mathrm{Re}\ \delta g_R^e\rvert$	$\leq 2.9 \times 10^{-4}$
$\lvert\mathrm{Re}\ \delta g_L^e\rvert$	$\leq 3.0 \times 10^{-4}$
$\lvert\mathrm{Re}\ \delta g_R^\mu\rvert$	$\leq 1.3 \times 10^{-3}$
$\lvert\mathrm{Re}\ \delta g_L^\mu\rvert$	$\leq 1.1 \times 10^{-3}$
$\lvert\mathrm{Re}\ \delta g_R^\tau\rvert$	$\leq 6.2 \times 10^{-4}$

CP-averaged angular obs.

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 ± 0.14
$\Delta M_d^{\mathrm{NP}}/\Delta M_d^{\mathrm{SM}}$	1.00 ± 0.11
$\Delta M_s^{\mathrm{NP}}/\Delta M_s^{\mathrm{SM}}$	1.000 ± 0.0054

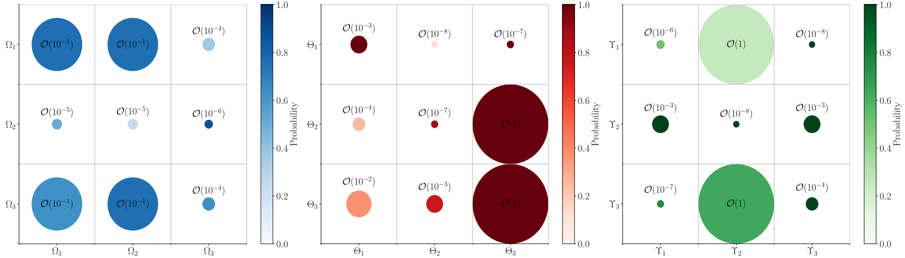
Access quality of the fit through the χ^2 function [Eur.Phys.J.C 81 (2021) 10, 952]

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

- 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:

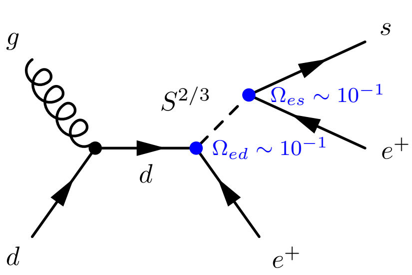
- Both $\mathbf{a}_{\boldsymbol{\mu}}$ and $\mathbf{M}_W$ are SM-like (**Scenario a**);
- $\mathbf{a}_{\boldsymbol{\mu}}$ requires new physics but $\mathbf{M}_W$ is SM-like (**Scenario b**);
- $\mathbf{a}_{\boldsymbol{\mu}}$ and $\mathbf{M}_W$ require new physics (**Scenario c**).



- **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;

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 $\chi^2/28$ **d.o.f = 1.83**.

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Thank you for your attention

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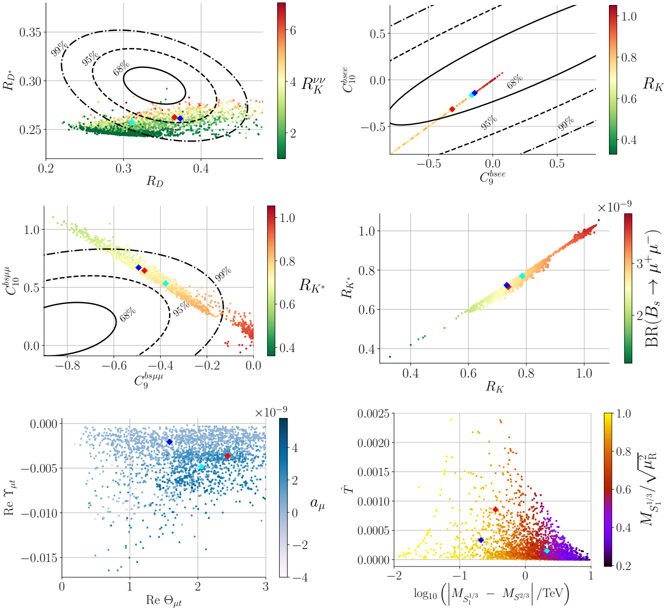
Backup slides


R_D
R_{D^*}
99%
95%
68%
$R_K^{\nu\nu}$
C_9^{bsee}
C_{10}^{bsee}
R_K
$C_9^{bs\mu\mu}$
$C_{10}^{bs\mu\mu}$
R_{K^*}
$\times 10^{-9}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$
Re $\Theta_{\mu t}$
Re $\Upsilon_{\mu t}$
a_μ
$\hat{T}$
$\log_{10}\left(\left|M_{S_1^{1/3}} - M_{S^{2/3}}\right|/\mathrm{TeV}\right)$
$M_{S_1^{1/3}}/\sqrt{\mu_R^2}$