Frugal $U(1)_X$ models with non-minimal flavor violation for $b \to s\ell\ell$ anomalies and neutrino mixings

Disha Bhatia
The Institute of the Mathematical Sciences, India
work done in collaboration with Nishita Desai and Amol Dighe

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Summary of the talk:

- Several $b \to s\ell\ell$ anomalies pointing towards lepton flavor universality violations.
- Z' solutions $\Rightarrow$ potential explanations for these anomalies.
- The $U(1)_X$ symmetries are determined using principle of frugality and following bottom-up approach.
- The allowed solutions favour non-minimal mixings in the d-type left handed quark sector.
- $+$ non-zero charges for all three generations of fermions.
- The symmetries could be well-tested at the future runs of the LHC.

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- Exists for gauge interactions mediated by Z, W and γ

$$\begin{aligned}\mathrm{BR}(Z \to ee) &= (3.3662 \pm 0.0066)\,\%\,,\mathrm{BR}(Z \to \mu\mu) = (3.3632 \pm 0.0042)\,\%\\ \mathrm{BR}(W \to e\nu) &= (10.71 \pm 0.16)\,\%\,,\mathrm{BR}(W \to \mu\nu) = (10.63 \pm 0.15)\,\%\end{aligned}$$

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Why rare B decays in the Standard Model are important?

- In SM, all generations of quarks and leptons carry identical gauge charges $\Rightarrow$ no tree-level flavor changing neutral currents (FCNC).

$$\mathcal{L}_{\rm int} \propto V_{\rm rot}^{\dagger} \mathcal{X}_{\rm Charge} V_{\rm rot} = \mathcal{X}_{\rm Charge} \quad (\text{as } V_{\rm rot}^{\dagger} V_{\rm rot} = \mathcal{I}) \,.$$

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- Amplitudes of the FCNC process sensitive to the mass of the fermion mediating in the loop and is $\propto f(m_i^2/m_W^2)$.
- FCNC's with the top as internal propogators are less suppressed $\Rightarrow$ rare decays of d-type quarks a good testing ground for the SM.
- Decays of B are furthermore special because the physics contributions are largely dominated by the short distance physics (as $m_B > \Lambda_{\mathrm{QCD}}$), and this decays opens up many phenomenological channels.
- The decays concerning $b \to s$ more enhanced (V_{ts}) in comparison with $b \to d$ (V_{td}).
- The decays involving ratios for example

$$R_X = \frac{\mathrm{BR}(B \to X_s \mu\mu)}{B \to X_s ee}$$

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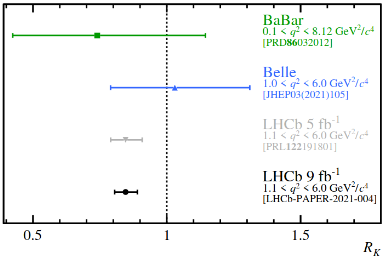
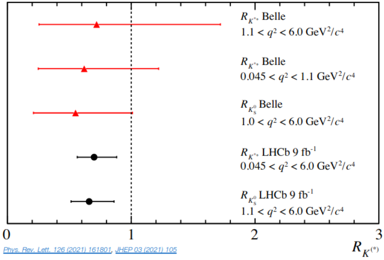
Current status of $b \to s\ell\ell$ anomalies from LHCb





LHCb has performed computations in following $b \to s$ channels:

- $B^+ \to K^+\mu\mu / B^+ \to K^+ee$, $B^0 \to K^0_S\mu\mu / B^0 \to K^0_S ee$.
- $B^0 \to K^{*0}\mu\mu / B^0 \to K^{*0}ee$, $B^0 \to K^{*+}\mu\mu / B^0 \to K^{*+}ee$.
- $\Lambda_b \to K\pi\mu\mu / \Lambda_B \to K\pi ee$
- Angular observables in: $B^0 \to K^{*0}\mu\mu$ and $B^+ \to K^{*+}\mu\mu$
- Several BR measurements

Current $b \to s\ell\ell$ anomalies

- Anomalies in combination point towards some new physics beyond the SM.
- Dominated by statistical uncertainties, systametics under control.
- Belle-2 would soon be able to match with the LHCb predictions.
- LHCb will provide more updates on new ratios.

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Dominant effective Hamiltonian for $b \to s\ell\ell$ in SM

- The effective Lorentz structures generated for vector-currents at one loop, can be understood in terms of Gordon's identity,

$$\Gamma^\mu = \gamma^\mu A + \frac{1}{m}\sigma^{\mu\nu} q_\nu B$$

- The leading order effective $b \to s$ Hamiltonian in SM:

$$\mathcal{H}_{\rm eff} \;=\; -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \times \left(C_{7\gamma}\mathcal{O}_{7\gamma} + \sum_{i=9,10} C_i \mathcal{O}_i \right)$$

with following operators:

$$\mathcal{O}_{7\gamma} \;=\; \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\mu\nu} P_R b\right) F^{\mu\nu} \;,\; \mathcal{O}_9 = \frac{\alpha_e}{4\pi}\left[\bar{s}\gamma_\mu P_L b\right]\left[\bar{\ell}\gamma^\mu \ell\right] \;,$$
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Preferred new physics directions using global fits

- Global fits : Simultaneous explanation if NP in **vector-axial** operators

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- R_K is observed to be less than one, either destructive interference in muon sector, or constructive interference in electrons, or combinations of both.
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Our choice to have new physics effects in pure vector-currents

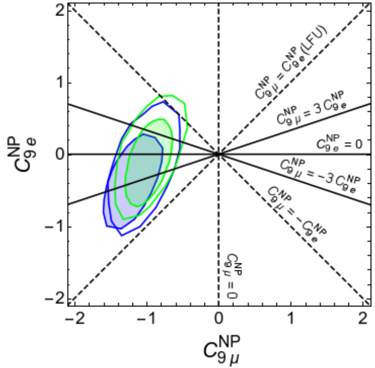

Figure: 2 σ favored contours from J. Matias et. al (1903.09578, 2104.08921) and F. Mahmoudi et al (1904.08399, 2104.10058)

Comparing 2019's prediction with 2021 now $|C_{9e}| < |C_{9\mu}|$
Global fits prefer negative $C_{9\mu}^{\mathrm{NP}}$.

Model building by taking RK anomaly at face value

- Introduce NP in vector currents i.e. atleast in $\mathcal{O}_9^\mu$ and $\mathcal{O}_9^e$.
- Can be done either using Z' or leptoquark $\Rightarrow$ We pick on the $U(1)_X$ solutions.
  - $R_K \Rightarrow$ diff X-charges for e and μ, certainly $|X_\mu| > |X_e|$
  - dominant Z' effects $\Rightarrow$ unequal X-charges atleast for d-type quarks.
- The gauge charges of $U(1)_X$ symmetry (or the X-charges) determined following a bottom-up approach
- First assign random charges to SM fields:

Quarks	Q_1	u_R	d_R	Q_2	c_R	s_R	Q_3	t_R	b_R
$U(1)_X$	x_{1_L}	$x_{1_{uR}}$	$x_{1_{dR}}$	x_{2_L}	$x_{2_{cR}}$	$x_{2_{sR}}$	x_{3_L}	$x_{3_{tR}}$	$x_{3_{bR}}$
Leptons	L_1		e_R	L_2		μ_R	L_3		τ_R
$U(1)_X$	y_{1_L}		$y_{1_{eR}}$	y_{2_L}		$y_{2_{\mu R}}$	y_{3_L}		$y_{3_{\tau R}}$

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$U(1)_X$	$y1_L$		$y1_{eR}$	$y2_L$		$y2_{\mu R}$	$y3_L$		$y3_{\tau R}$

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- Can be done either using Z' or leptoquark $\Rightarrow$ We pick on the $U(1)_X$ solutions.
  - $R_K \Rightarrow$ diff X-charges for e and μ, certainly $|X_\mu| > |X_e|$
  - dominant Z' effects $\Rightarrow$ unequal X-charges atleast for d-type quarks.
- The gauge charges of $U(1)_X$ symmetry (or the X-charges) determined following a bottom-up approach
- First assign random charges to SM fields:

Quarks	Q_1	u_R	d_R	Q_2	c_R	s_R	Q_3	t_R	b_R
$U(1)_X$	$x1_L$	$x1_{uR}$	$x1_{dR}$	$x2_L$	$x2_{cR}$	$x2_{sR}$	$x3_L$	$x3_{tR}$	$x3_{bR}$
Leptons	L_1		e_R	L_2		μ_R	L_3		τ_R
$U(1)_X$	$y1_L$		$y1_{eR}$	$y2_L$		$y2_{\mu R}$	$y3_L$		$y3_{\tau R}$

- X-charge of $\Phi_{SM} = a_{\Phi_{SM}}$

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Determination of X-charges

They are determined using the theoretical and experimental considerations.

1. Criteria for vector-currents and anomaly cancellation at high scales

- This can be simply satisfied together by simply assigning vector-like charges to the fermions + adding three right handed neutrinos.
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$$X \equiv \alpha_1 B_1 + \alpha_2 B_2 + \alpha_3 B_3 + \alpha_e L_e + \alpha_\mu L_\mu + \alpha_\tau L_\tau \ ,$$

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X	$\alpha_1/3$	$\alpha_2/3$	$\alpha_3/3$	α_e	α_μ	α_τ

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2. Constraints from $K-\overline{K}$ oscillations

- Unequal X-charges of 1-2 generations of quarks and the large mixing angles stringently constrained by the $K-\overline{K}$ mixings $\Rightarrow$ push new physics to very high scales.

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\begin{aligned}
K:\ [V_{dL}^{\dagger}\cdot \mathbb{X}_q \cdot V_{dL}]_{12} &\propto (\alpha_1-\alpha_2)[V_{dL}]^*_{ud}[V_{dL}]_{us}+(\alpha_3-\alpha_2)[V_{dL}]^*_{td}[V_{dL}]_{ts}\ ,\\
[V_{dR}^{\dagger}\cdot \mathbb{X}_q \cdot V_{dR}]_{12} &\propto (\alpha_1-\alpha_2)[V_{dR}]^*_{ud}[V_{dR}]_{us}+(\alpha_3-\alpha_2)[V_{dR}]^*_{td}[V_{dR}]_{ts}
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- The choice $\alpha_1=\alpha_2$ and the small values of $[V_{dL/R}]_{td}$ and $[V_{dL/R}]_{ts}$ allows us to bypass the stringent constraints from Kaon-mixing.
- Consequently V_{ckm} in 1-2 sector as

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\mathcal{Y}_u^{\rm SM}=\begin{pmatrix}\times & \times & 0\\ \times & \times & 0\\ 0 & 0 & \times\end{pmatrix},\quad \mathcal{Y}_d^{\rm SM}=\begin{pmatrix}\times & \times & 0\\ \times & \times & 0\\ 0 & 0 & \times\end{pmatrix},
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Determination of X-charges

- Can be solved by adding $\Phi_{\rm NP}$ with X-charge, $\alpha_1 - \alpha_3$,

$$\mathcal{Y}_u^{\rm NP} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & 0 \end{pmatrix}, \quad \mathcal{Y}_d^{\rm NP} = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & 0 \end{pmatrix},$$

- The rotation angles can be then computed using

$$M_u^{\rm diag} = V_{uL}^\dagger M_u V_{uR} \ , \ M_d^{\rm diag} = V_{dL}^\dagger M_d V_{dR} \ .$$

with $V_{\rm CKM} = V_{uL}^\dagger V_{dL}$.

- Since the constraints from the up-sector less stringent, we can assume $V_{dL} = V_{\rm CKM}$.
V_{dR} mixing angles are suppressed.

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$$\begin{aligned} B_d: \ [V_{dL}^\dagger \cdot \mathbb{X}_q \cdot V_{dL}]_{13} &\propto [V_{\rm CKM}]_{td}^*[V_{\rm CKM}]_{tb} \ , \\ B_s: \ [V_{dL}^\dagger \cdot \mathbb{X}_q \cdot V_{dL}]_{23} &\propto [V_{\rm CKM}]_{ts}^*[V_{\rm CKM}]_{tb} \ . \end{aligned}$$

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Summary of charges so far:

Fields	u, d	c, s	t, b	e, ν_e	μ, ν_μ	τ, ν_τ	$\Phi_{\rm SM}$	$\Phi_{\rm NP}$
X	$\alpha_1/3$	$\alpha_1/3$	$\alpha_3/3$	α_e	α_μ	α_τ	0	$(\alpha_1 - \alpha_3)/3$

1. A Z' is introduced to induce FCNC's at tree-level.
2. 3 RHN's to account for vector-like charges for anomaly cancellation.
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Is the particle addition enough?

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Theoretical considerations: introducing scalar singlet S

- At present $U(1)_X$ breaks along with the electroweak symmetry.
  Concern 1: Scale of new physics highly constrained from collider searches.
- Accidental global symmetry in the scalar potential

$$V(\Phi_{\rm SM}\Phi_{\rm NP}) = -m^2_{\rm SM}\Phi^\dagger_{\rm SM}\Phi_{\rm SM} + \frac{\lambda_{\rm SM}}{2}(\Phi^\dagger_{\rm SM}\Phi_{\rm SM})^2 - m^2_{\rm NP}\Phi^\dagger_{\rm NP}\Phi_{\rm NP}$$
$$+\frac{\lambda_{\rm NP}}{2}(\Phi^\dagger_{\rm NP}\Phi_{\rm NP})^2 + \lambda(\Phi^\dagger_{\rm SM}\Phi_{\rm SM})(\Phi^\dagger_{\rm NP}\Phi_{\rm NP}) + \lambda'(\Phi^\dagger_{\rm SM}\Phi_{\rm NP})(\Phi^\dagger_{\rm NP}\Phi_{\rm SM}).$$

- Allows invariance of independent $\Phi_{\rm SM}$ and $\Phi_{\rm NP}$ rotations or $V \times A$ rotations i.e.

$$U(1)_V \times U(1)_A : \quad \Phi_{\rm SM} \rightarrow e^{i(\theta_V - \theta_A)}\Phi_{\rm SM}, \qquad \Phi_{\rm NP} \rightarrow e^{i(\theta_V + \theta_A)}\Phi_{\rm NP}.$$

- The vector symmetry gets identified with the $U(1)_Y$.
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Summarizing the bottom-up construction

Fields	u, d	c, s	t, b	e, ν_e	μ, ν_μ	τ, ν_τ	$\Phi_{\rm NP}, S$
X	$\alpha_1/3$	$\alpha_1/3$	$\alpha_3/3$	α_e	α_μ	α_τ	$(\alpha_1 - \alpha_3)/2 \equiv X_S$

- **Theory considerations:** The charges must satisfy the anomaly equation. add 3 ν_R's and assign vector-like charges.
- $K - \overline{K}$**:** $\alpha_1 = \alpha_2$
- **Global fits:** sign of C_{9_μ} to be negative.
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Taking hints from the neutrinos textures

- Presence of 3 ν_R's along with vev of S :

$$[M_R^S]_{ij} \;=\; [M_R]_{ij} + \frac{v_S}{\sqrt{2}}[\mathcal{Y}_R]_{ij} \neq 0 \quad \text{if} \;\; \alpha_i + \alpha_j = 0\,, \pm X_S\;.$$

- Using Type-I seesaw mechanism

$$m_{\nu_L} = -[m_D]^T [M_R^S]^{-1} [m_D] = U_{\rm PMNS}\, m_{\nu_L}^{\rm diag}\, U_{\rm PMNS}^T\;.$$

- Basis of diagonal m_D and charged lepton mass matrix $\Rightarrow$ determine allowed textures of m_{ν_L} or M_R^S (J. Heeck et al (1203.4951)).
- The experimental quantities are described by 9 parameters — three mixing angles, three phases, and three mass terms, among which we know 5 quantities $\Rightarrow$ can allow for two zeros at-max (owing to general mass matrix being complex).

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- Leptonic symmetries constructed using allowed textures:
  - $a\,(L_\mu - L_\tau)$ or aL_μ, with $X_S = \pm a$,
  - $a\,(L_e - 3L_\mu + L_\tau)$ or $a\,(L_e \pm 3L_\mu - L_\tau)$, with $X_S = \pm 2a$.
- Since $X_S = (\alpha_1 - \alpha_3)/3$, and charges are related by anomaly equation, turns out we can determine all charges in terms of a.
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Summarizing the particle content:

- First-two generations of quarks always charged under $U(1)_X$ $\Rightarrow$ stringent constraints from the collider direct searches.

Category	Scenario	X_S	Leptonic symmetry	α_1	α_2	α_3	α_e	α_μ	α_τ
A	A1	-1	$L_\mu - L_\tau$	-1	-1	2	0	1	-1
	A2	-1	L_μ	$-\frac{4}{3}$	$-\frac{4}{3}$	$\frac{5}{3}$	0	1	0
B	B1	$-\frac{2}{3}$	$L_e - 3L_\mu + L_\tau$	$-\frac{7}{9}$	$-\frac{7}{9}$	$\frac{11}{9}$	$-\frac{1}{3}$	1	$-\frac{1}{3}$
	B2	$-\frac{2}{3}$	$L_e - 3L_\mu - L_\tau$	-1	-1	1	$-\frac{1}{3}$	1	$\frac{1}{3}$
C	C1	$-\frac{2}{3}$	$L_e + 3L_\mu - L_\tau$	-1	-1	1	$\frac{1}{3}$	1	$-\frac{1}{3}$
AA	AA1	1	$L_\mu - L_\tau$	1	1	-2	0	1	-1
	AA2	1	L_μ	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{7}{3}$	0	1	0
BB	BB1	$\frac{2}{3}$	$L_e - 3L_\mu + L_\tau$	$\frac{5}{9}$	$\frac{5}{9}$	$-\frac{13}{9}$	$-\frac{1}{3}$	1	$-\frac{1}{3}$
	BB2	$\frac{2}{3}$	$L_e - 3L_\mu - L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{5}{3}$	$-\frac{1}{3}$	1	$\frac{1}{3}$
CC	CC1	$\frac{2}{3}$	$L_e + 3L_\mu - L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	1	$-\frac{1}{3}$

Sign of $C_{9\mu}^{\rm NP}$ for $V_{dL} = V_{\rm CKM}$

The effective Hamiltonian relevant for the process $B \to K^{(*)}\ell\ell$ is

$$\begin{aligned}\mathcal{H}_{\rm eff} \;\; = \;\; & -\left(\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}[V_{\rm CKM}]_{tb}[V_{\rm CKM}]^*_{ts}\; C_{9\ell}^{\rm SM}\right)(\overline{s_L}\gamma^\mu b_L)\left(\overline{\ell}\gamma_\mu\ell\right) \\ & -\left(\frac{X_S\,\alpha_\ell\, g^2_{Z'}}{M^2_{Z'}}[V_{dL}]_{tb}[V_{dL}]^*_{ts}\right)(\overline{s_L}\gamma^\mu b_L)\left(\overline{\ell}\gamma_\mu\ell\right)\;\; .\end{aligned}$$

Since $C_{9\ell} = C_{9\ell}^{\rm SM} + C_{9\ell}^{\rm NP}$, the above equation is equivalent to

$$C_{9\ell}^{\rm NP} \;\; = \;\; \frac{4\sqrt{2}\,\pi^2\, g^2_{Z'}}{G_F\, M^2_{Z'}\, e^2}\cdot X_S\,\alpha_\ell\;.$$

Sign of C_{9_μ} hence sensitive to X_S (in the normalization $\alpha_\mu = 1$):

Scenarios considered for $V_{dL} = V_{\rm CKM}$

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C	C1	$-\frac{2}{3}$	$L_e + 3L_\mu - L_\tau$	-1	-1	1	$\frac{1}{3}$	1	$-\frac{1}{3}$

- The scenarios are same as considered in our previous papaer (1701.05825) expect category D, which consisted of $|\alpha_e| = |\alpha_\mu| \Rightarrow$ disfavored from global fits.
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Testing scenarios against experimental constraints: Case A: MFV-like mixings with $V_{dL} = V_{\mathrm{CKM}}$

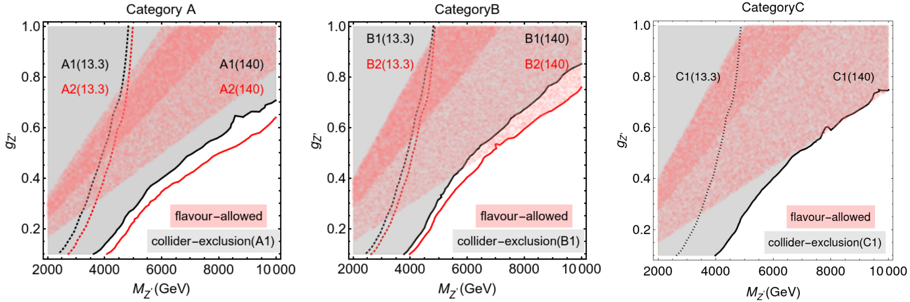

Figure: Collider constraints from: ATLAS(13.3 fb^{-1}): ATLAS-CONF-2016-045 and CMS(140 fb^{-1}):arXiv:2103.02708 and mixing constraints from UTfit collaboration

The symmetries are disfavored by combined constraints from global fits+ neutral-meson mixing and collider searches

Case B: NMFV mixings

- Scenarios with $V_{dL} = V_{\rm CKM}$ ruled out by combined constraints.
- To bring collider constraints compatible with global fit, one needs to compensate for the ratio $g_{Z'}^2/M_{Z'}^2$ meaning move towards the decoupling regime.

$$C_{9\mu}^{\rm NP} = \frac{4\sqrt{2}\,\pi^2\,g_{Z'}^2}{G_F\,M_{Z'}^2\,e^2} \cdot X_S \cdot \frac{[V_{dL}]_{tb}[V_{dL}^*]_{ts}}{[V_{\rm CKM}]_{tb}[V_{\rm CKM}]_{ts}^*} .$$

- Possible when $|\mathcal{R}_{\rm mix}| \equiv |\frac{[V_{dL}]_{tb}[V_{dL}^*]_{ts}}{[V_{\rm CKM}]_{tb}[V_{\rm CKM}]_{ts}^*}| > 1.$

  This is capable of generating scenarios with positive X_S

- Consider a simple scenario, where V_{dL} describes mixing of only second-third generation left handed d-type quarks.

$$\mathcal{R}_{\rm mix} \approx \frac{[\sin 2\theta_{23}]_{dL}}{[\sin 2\theta_{23}]_{\rm CKM}} .$$

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- Hence $[\sin(2\theta_{23})]_{dL}$ cannot be too large.
  - For symmetries with $X_S < 0$, $\theta_{23,dL}$ lies in the first quadrant.
  - For symmetries with $X_S > 0$, $\theta_{23,dL}$ lies in the second quadrant.

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- $C_{9\mu}$ sensitive to $X_S \cdot \mathcal{R}_{\rm mix}$, while $B_s - \overline{B_s}$ sensitive to $X_S^2 \cdot \mathcal{R}^2_{\rm mix}$
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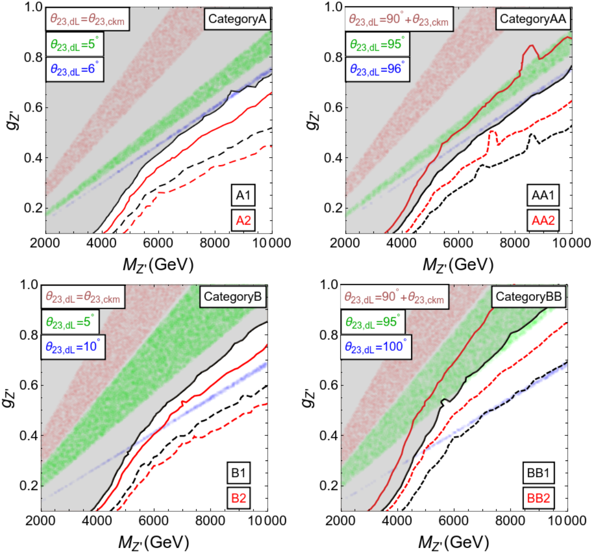

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- As the flavor constraints depend on $X_S \mathcal{R}_{\rm mix}$, they can be identical for the scenarios that have the same value of $|X_S|$ but opposite sign, with $\theta_{23,dL}$ values differing by 90°.
- Thinning of bands with large $\sin(2\theta_{23,dL})$ indicates that overlap between global fits and neutral meson mixing is fading away.
- The symmetries belonging to categories A and AA, where new physics contributes only in the muon (and/or) tau sector, stay ruled out.
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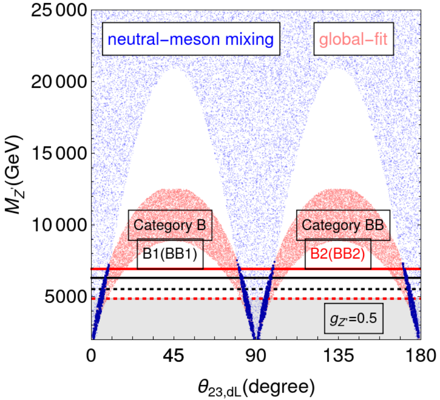

The idea of incompatibility of the neutral meson mixing with global fits for large $\sin(2\theta_{23,dL})$ is shown.

Summarizing...

- Several $b \to s\ell\ell$ anomalies pointing towards lepton flavor universality violations.
- Z' solutions $\Rightarrow$ potential explanations for these anomalies.
- The $U(1)_X$ symmetries are determined using principle of frugality and following bottom-up approach.
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