Addressing $b \to s\ell\ell$ anomalies in minimally flavor-violating Z' scenario

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Based on

CW Chiang, XG He, JT, XB Yuan, arXiv:1706.02696 (PRD, in press)

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Outline

- Introduction
- $b \to s\ell\ell$ anomalies due to Z' in MFV framework
- Constraints on Z' couplings
- Allowed parameter space & predictions
- Conclusions

- Present $b\to s\ell\bar{\ell}$ data reveal intriguing tensions with the standard model:
  - LHCb measurements on $B\to K^{(*)}\mu^+\mu^-$ and $B_s\to\phi\mu^+\mu^-$ branching fractions favor values below their SM estimates. 1403.8044, 1506.08777
  - LHCb in angular analysis of $B^0\to K^{*0}\mu^+\mu^-$ found differences with SM predictions at the 3.4σ level. 1512.04442
    Belle saw a similar discrepancy, but with lower statistical confidence. 1612.05014
  - LHCb data on $R_K=\mathcal{B}(B^+\to K^+\mu^+\mu^-)/\mathcal{B}(B^+\to K^+e^+e^-)$ for $q^2_{\ell\ell}\in(1,6)\mathrm{GeV}^2$ and $R_{K^*}=\mathcal{B}(B\to K^*\mu^+\mu^-)/\mathcal{B}(B\to K^*e^+e^-)$ for $q^2_{\ell\ell}\in(0.045,1.1)\;[(1,6)]\mathrm{GeV}^2$ differ by 2.6σ and $2.1\,[2.4]\sigma$, respectively, from SM lepton universality. 1406.6482, 1705.05802
- These anomalies are not yet conclusive due to their low statistical significance but interestingly new physics beyond the SM can account for them.

Capdevila *et al.*, 2017
Altmannshofer *et al.*, 2017
D'Amico *et al.*, 2017
. . . .

- One of the best fits to the data results from NP contributing via

$$\mathcal{L}_{\rm eff}=\frac{\alpha_{\rm e}G_{\rm F}V^*_{ts}V_{tb}}{\sqrt{2}\,\pi}\,\bar{s}\gamma^\beta P_L b\,\bar{\ell}\gamma_\beta(C^\ell_9+C^\ell_{10}\gamma_5)\ell+\mathrm{H.c.}\,,\qquad C^\ell_i=C^{\rm SM}_i+C^{\ell,\rm NP}_i$$

mainly in the $\ell=\mu$ channel with $C^{\mu,\rm NP}_9=-C^{\mu,\rm NP}_{10}\sim-0.6$ and $C^{e,\rm NP}_{9,10}\sim 0$.

The SM contributes universally with $C^{\rm SM}_9\simeq-C^{\rm SM}_{10}\simeq 4.2$.

- Relevant effective operators respecting SM gauge symmetry

$$\mathcal{O}_1 = \bar{L}_L \gamma^\eta \Delta_\ell L_L \, \bar{Q}_L \gamma_\eta \Delta_q Q_L \,, \qquad \mathcal{O}_2 = \bar{L}_L \gamma^\eta \Delta'_\ell \tau_a L_L \, \bar{Q}_L \gamma_\eta \Delta'_q \tau_a Q_L$$

L_L (Q_L) contains the SM left-handed lepton (quark) doublets from the 3 families

$\Delta^{(\prime)}_{\ell,q}$ are generally complex 3×3 matrices in flavor space

- Operators with (pseudo)scalar or tensor structures are not favored by the data.

Hiller & Schmaltz, 2014
Alonso *et al.*, 2014
Altmannshofer *et al.*, 2017

- One could explore $\mathcal{O}_1$ and $\mathcal{O}_2$ within the framework of so-called minimal flavor violation (MFV)

Lee & JT, 2015

  - with MFV implemented in both their quark and lepton parts
  - without considering the underlying new physics.

- The standard model has been successful in describing the current data on flavor-changing neutral currents & *CP* violation in the quark sector.
- This motivates the hypothesis of MFV for quarks: Yukawa couplings are the only sources for the breaking of flavor & *CP* symmetries.
  - Effective field theory approach with MFV.

Chivukula & Georgi, 1987
Hall & Randal, 1990

Buras *et al.*, 2001
D'Ambrosio *et al.*, 2002

- The notion of MFV can be extended to the lepton sector
  - which may help pin down the origin of neutrino mass
  - but there are ambiguities in implementing leptonic MFV.

Cirigliano *et al.*, 2005

Davidson & Palorini, 2006
Gavela *et al.*, 2009
He, Lee, JT, Zheng, 2015
....

- We consider a *Z′* boson scenario with MFV in the *Z′* fermionic couplings
  - MFV is imposed in both the quark and lepton sectors
  - The lepton sector involves the type-I seesaw mechanism with 3 degenerate heavy right-handed neutrinos.

- The kinetic Lagrangian for SM fermions plus 3 right-handed neutrinos

$$\mathcal{L}_{\rm kin} = i\bar{Q}_{kL}\partial\!\!\!/ Q_{kL} + i\bar{U}_{kR}\partial\!\!\!/ U_{kR} + i\bar{D}_{kR}\partial\!\!\!/ D_{kR} + i\bar{L}_{kL}\partial\!\!\!/ L_{kL} + i\bar{\nu}_{kR}\partial\!\!\!/ \nu_{kR} + i\bar{E}_{kR}\partial\!\!\!/ E_{kR}$$

$k=1,2,3$ is summed over, $\quad Q_{jL} = \begin{pmatrix} U_{jL} \\ D_{jL} \end{pmatrix}, \quad L_{jL} = \begin{pmatrix} \nu_{jL} \\ \ell_{jL} \end{pmatrix}, \quad j=1,2,3$

$(U_1,U_2,U_3)=(u,c,t), \quad (D_1,D_2,D_3)=(d,s,b), \quad (E_1,E_2,E_3)=(\ell_1,\ell_2,\ell_3)=(e,\mu,\tau)$

- It's invariant under the global flavor rotations

$$Q_{jL} \to (V_Q)_{jk} Q_{kL}\,, \quad U_{jR} \to (V_U)_{jk} U_{kR}\,, \quad D_{jR} \to (V_D)_{jk} D_{kR}$$
$$L_{jL} \to (V_L)_{jk} L_{kL}\,, \quad \nu_{jR} \to (V_\nu)_{jk} \nu_{kR}\,, \quad E_{jR} \to (V_E)_{jk} E_{kR}\,, \qquad V_X \in {\rm SU}(3)_X$$

- The flavor symmetry of the theory is explicitly broken by fermion mass terms

$$\mathcal{L}_{\rm m} = -(Y_u)_{jk}\,\bar{Q}_{jL}\,U_{kR}\,\tilde{H} - (Y_d)_{jk}\,\bar{Q}_{jL}\,D_{kR}\,H$$
$$- (Y_\nu)_{jk}\,\bar{L}_{jL}\,\nu_{kR}\,\tilde{H} - (Y_e)_{jk}\,\bar{L}_{jL}\,E_{kR}\,H - \tfrac{1}{2}\,(M_\nu)_{jk}\,\overline{\nu^{\rm c}_{jR}}\,\nu_{kR} + \text{H.c.}$$

$Y_{u,d,\nu,e}$ are Yukawa coupling matrices, H is the Higgs doublet, $\tilde{H} = i\tau_2 H^*$

$M_\nu = \mathcal{M}\,{\rm diag}(1,1,1)$ is the Majorana mass matrix of the degenerate ν_{kR}

- $\mathcal{L}_{\rm m}$ is formally flavor-symmetric if the Yukawa couplings are spurions transforming as

$$Y_u \to V_Q Y_u V_U^\dagger\,, \quad Y_d \to V_Q Y_d V_D^\dagger\,, \quad Y_e \to V_L Y_e V_E^\dagger\,, \quad Y_\nu \to V_L Y_\nu \mathcal{O}_\nu^{\rm T}$$

⋆ In the basis where Y_d and Y_e are diagonal

$$Y_d = \mathrm{diag}(y_d, y_s, y_b)\,, \qquad Y_e = \mathrm{diag}(y_e, y_\mu, y_\tau)\,, \qquad y_f \equiv \frac{\sqrt{2}\,m_f}{v}\,, \qquad v = \sqrt{2}\langle H\rangle$$

and U_k, D_k, and E_k refer to the mass eigenstates. Thus

$$Q_{j,L} = \begin{pmatrix} (V_{\rm CKM}^\dagger)_{jk} U_{k,L} \\ D_{j,L} \end{pmatrix}, \qquad Y_u = V_{\rm CKM}^\dagger \,\mathrm{diag}(y_u, y_c, y_t)\,, \qquad L_{j,L} = \begin{pmatrix} (U_{\rm PMNS})_{jk}\,\nu_{k,L} \\ E_{j,L} \end{pmatrix}$$

For degenerate heavy νs $\quad Y_\nu = \dfrac{i\sqrt{2\mathcal{M}}}{v} U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O \quad$ with complex orthogonal O

Casas & Ibarra, 2001

For light νs $\quad m_\nu = -\dfrac{v^2}{2\mathcal{M}} Y_\nu Y_\nu^{\rm T} = U_{\rm PMNS}\,\hat{m}_\nu\, U_{\rm PMNS}^{\rm T}\,, \qquad \hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$

⋆ The Yukawa combinations of interest

$$\mathsf{A}_q = Y_u Y_u^\dagger = V_{\rm CKM}^\dagger\, \mathrm{diag}(y_u^2, y_c^2, y_t^2)\, V_{\rm CKM}\,, \qquad \mathsf{B}_q = Y_d Y_d^\dagger = \mathrm{diag}(y_d^2, y_s^2, y_b^2)$$

$$\mathsf{A}_\ell = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2} U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger\,, \qquad \mathsf{B}_\ell = Y_e Y_e^\dagger = \mathrm{diag}(y_e^2, y_\mu^2, y_\tau^2)$$

⋆ Since $y_t^2 \gg y_b^2$ and large enough $\mathcal{M}$ is chosen so that $|(\mathsf{B}_\ell)_{jk}| \ll |(\mathsf{A}_\ell)_{jk}| \lesssim 1$ the pertinent spurion building blocks are

$$\Delta_q = \zeta_0 \mathbb{1} + \zeta_1 \mathsf{A}_q + \zeta_2 \mathsf{A}_q^2\,, \qquad \Delta_\ell = \xi_0 \mathbb{1} + \xi_1 \mathsf{A}_\ell + \xi_2 \mathsf{A}_\ell^2$$

Colangelo *et al.*, 2009

- The desired NP operators need to be invariant under the flavor rotations and SM gauge symmetry.

- Minimally flavor violating Z' interactions

$$\mathcal{L}_{Z'} = -\left(\overline{Q}\gamma^\eta \Delta_q P_L Q + \overline{L}\gamma^\eta \Delta_\ell P_L L\right) Z'_\eta$$

$$\Delta_q = \zeta_0 \mathbb{1} + \zeta_1 \mathsf{A}_q + \zeta_2 \mathsf{A}_q^2 , \qquad \Delta_\ell = \xi_0 \mathbb{1} + \xi_1 \mathsf{A}_\ell + \xi_2 \mathsf{A}_\ell^2$$

$$\mathsf{A}_q = Y_u Y_u^\dagger \simeq V_{\rm CKM}^\dagger {\rm diag}(0,0,y_t) V_{\rm CKM} , \qquad \mathsf{A}_\ell = Y_\nu Y_\nu^\dagger , \quad Y_\nu = \frac{i\sqrt{2}}{v} U_{\rm PMNS} \hat{m}_\nu^{1/2} O M_N^{1/2}$$

- Of the operators for $q \to q'\ell\ell'$

$$\mathcal{O}_1 = \bar{L}_L \gamma^\eta \Delta_\ell L_L \, \bar{Q}_L \gamma_\eta \Delta_q Q_L , \qquad \mathcal{O}_2 = \bar{L}_L \gamma^\eta \Delta'_\ell \tau_a L_L \, \bar{Q}_L \gamma_\eta \Delta'_q \tau_a Q_L$$

only $\mathcal{O}_1$ can be induced by $\mathcal{L}_{Z'}$, as $\mathcal{O}_2$ contains charged currents.

- The Z' couplings to SM fermions also generate 4-quark and 4-lepton effective interactions which are subject to various constraints.

- Effective interactions responsible for $b \to s\ell\bar{\ell}'$

$$\mathcal{L}_{\rm eff} \supset \frac{\sqrt{2}\,\alpha_{\rm e}\,\lambda_{sb}\,G_{\rm F}}{\pi}\, C_{\ell\ell'}\,\overline{s}\,\gamma^\eta P_L b\,\overline{\ell}\gamma_\eta P_L \ell'$$

$$\lambda_{q'q} = V_{tq'}^* V_{tq}\,, \qquad C_{\ell\ell'} = \delta_{\ell\ell'}\,C_9^{\rm SM} + \mathsf{c}_{\ell\ell'}\,, \qquad C_{10}^{\rm SM} \simeq -C_9^{\rm SM}$$

In terms of elements of $\Delta_{q,\ell}$

$$\mathsf{c}_{\ell_j\ell_k} = \frac{-\pi\,(\Delta_q)_{23}\,(\Delta_\ell)_{jk}}{\sqrt{2}\,\alpha_{\rm e}\,\lambda_{sb}\,G_{\rm F}\,m_{Z'}^2} \simeq -25.3\,{\rm TeV}^2\,\frac{(\zeta_1 y_t^2 + \zeta_2 y_t^4)(\Delta_\ell)_{jk}}{m_{Z'}^2}$$

$(\Delta_q)_{23} = \lambda_{sb}(\zeta_1 y_t^2 + \zeta_2 y_t^4)$ after neglecting $y_{u,c}$ terms

- Analogous formulas for $b \to d\ell\ell'$ and $s \to d\ell\ell'$

- We adopt the global fit result (at 2σ)

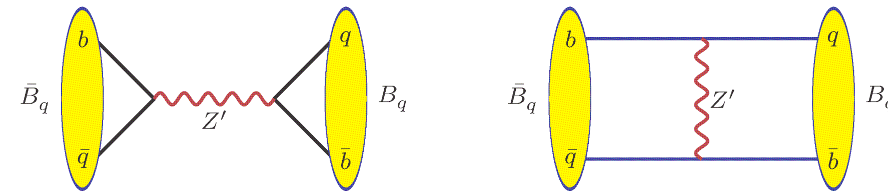
$$c_{ee} = 0\,, \qquad -1.00 \le c_{\mu\mu} \le -0.32$$

Altmannshofer *et al.*, 2017

implying $(\Delta_\ell)_{11} = 0$

- Nuclear $\mu \to e$ conversion may restrict the *uuμe* and *ddμe* couplings, but the current experimental bounds are not yet stringent enough.
- Constraints from LEP data on $e^+e^- \to qq$ are evaded because $(\Delta_\ell)_{11} = 0$.
- LHC measurements on $pp \to \ell^+\ell^-$ are not yet restrictive.

- At tree level, the Z' contributes to $|\Delta F|=2$ meson mixing



- The sum of SM and Z' contributions to $B_{d(s)}$ mixing yields

$$\Delta M_{d(s)} = \Delta M_{d(s)}^{\rm SM} \left| 1 + \frac{S_{d(s)}^{Z'}}{S_0(x_t)} \right| , \qquad S_{d(s)}^{Z'} \simeq \frac{4(\Delta_q)_{13(23)}^2}{\lambda_{db(sb)}^2\, g_{\rm SM}^2\, m_{Z'}^2} = \frac{4\left(\zeta_1 y_t^2 + \zeta_2 y_t^4\right)^2}{g_{\rm SM}^2\, m_{Z'}^2}$$

$S_0(x_t) \sim 2.4$ due to SM loop diagrams, $g_{\rm SM}^2 \sim 2 \times 10^{-7}\,{\rm GeV}^{-2}$

- Experimental & SM values

$$\Delta M_d^{\rm exp} = 0.5064 \pm 0.0019\,, \qquad \Delta M_d^{\rm SM} = 0.575^{+0.093}_{-0.090}$$

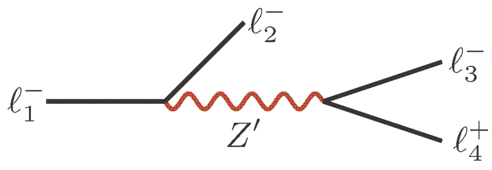
$$\Delta M_s^{\rm exp} = 17.757 \pm 0.021\,, \qquad \Delta M_s^{\rm SM} = 18.6^{+2.4}_{-2.3}$$

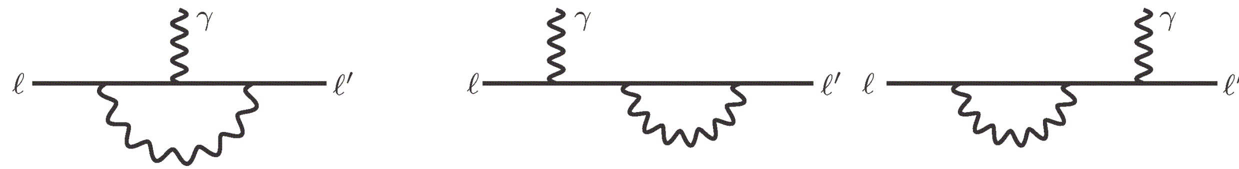
- Assuming 2σ ranges leads to

$$\frac{\left|\zeta_1 y_t^2 + \zeta_2 y_t^4\right|}{m_{Z'}} \le \frac{0.13}{\rm TeV}$$

- Kaon-mixing data yield a somewhat weaker bound.

- The Z' induces charged-lepton-flavor violation at the tree and loop levels.





  - The experimental bounds on $\mu \to e\gamma$ and $\tau \to 3\mu$ can be important

- The loop-level Z' contribution cannot explain the muon g-2 anomaly, but does not lead to a strong constraint.

$$a_{\ell_j}^{Z'} = \frac{-m_{\ell_j}^2}{12\pi^2\, m_{Z'}^2} \sum_k \left|(\Delta_\ell)_{jk}\right|^2$$

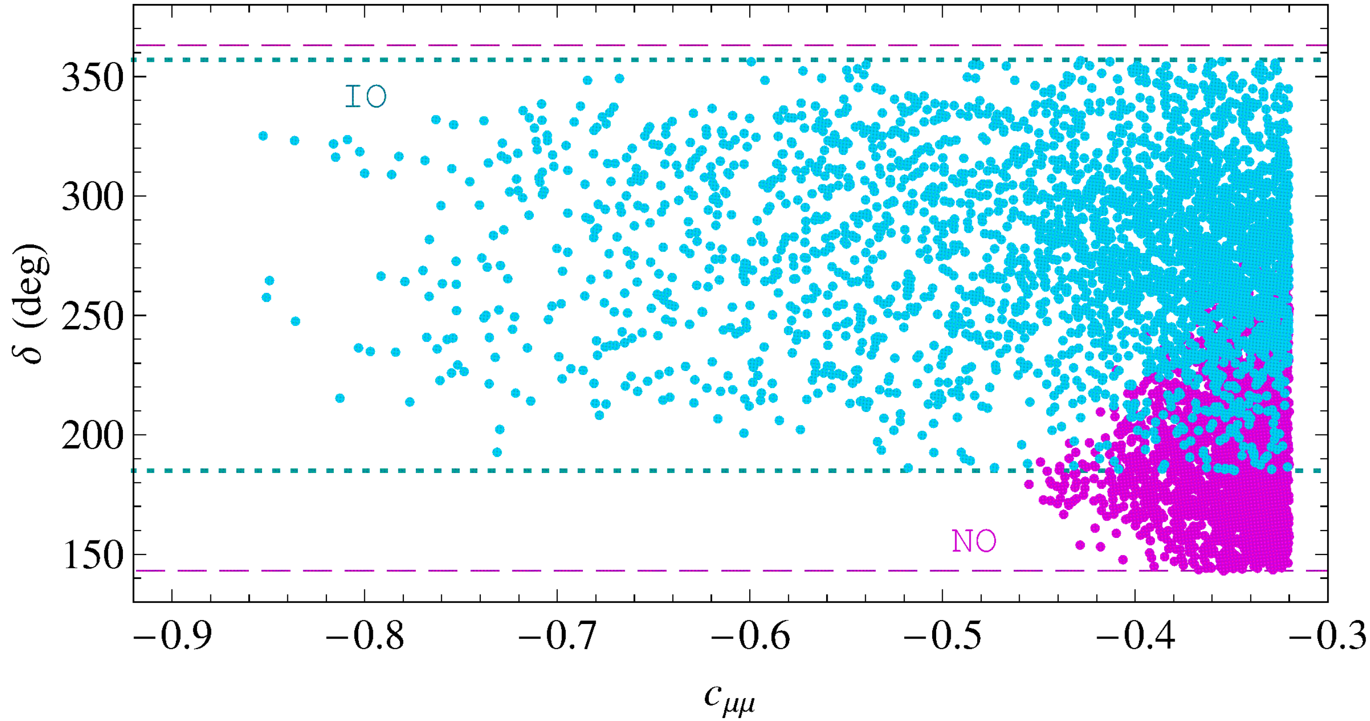
- With 3 degenerate right-handed neutrinos, $M_N = \mathcal{M}\,\text{diag}(1,1,1)$

$$\Delta_\ell = \xi_1 \mathbb{1} + \xi_2 \mathsf{A}_\ell + \xi_4 \mathsf{A}_\ell^2, \qquad \mathsf{A}_\ell = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2} U_{\text{PMNS}} \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\text{PMNS}}^\dagger$$

- If O is real, the Z' parameter space cannot satisfactorily explain the $b \to s\mu^+\mu^-$ anomalies

- To get viable solutions requires a less simple structure of Y_ν, particularly with a complex O, so that $OO^\dagger = e^{2i\mathsf{R}}$, with $\mathsf{R} = \begin{pmatrix} 0 & r_1 & r_2 \\ -r_1 & 0 & r_3 \\ -r_2 & -r_3 & 0 \end{pmatrix}$ and $r_{1,2,3}$ real

- From scans over 2σ ranges



Required value

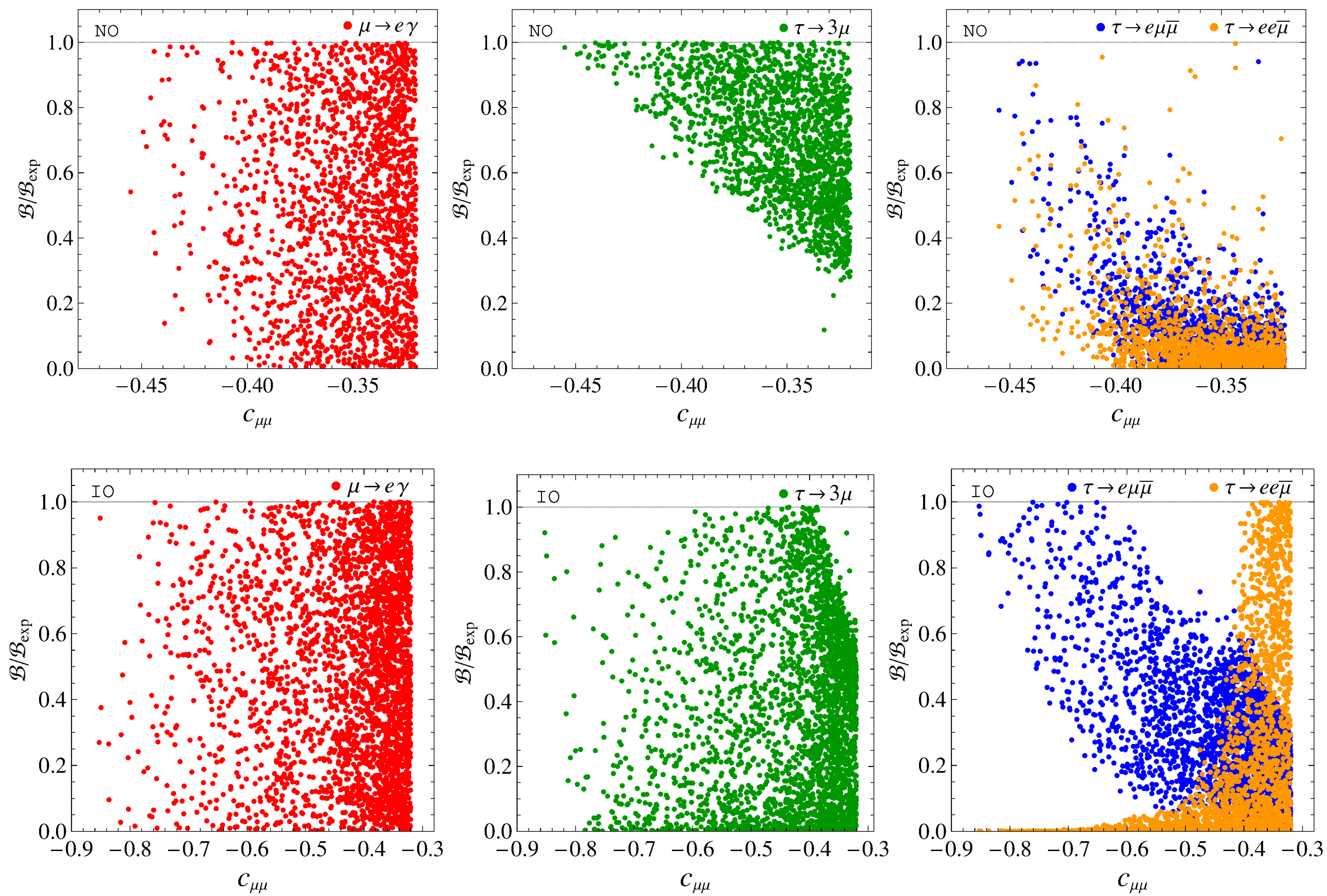
$$-1.00 \leq c_{\mu\mu} \leq -0.32$$

The IO scenario is preferred over NO

Parameter	NH	IH
$\sin^2\theta_{12}$	0.306 ± 0.012	0.306 ± 0.012
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.587^{+0.020}_{-0.024}$
$\sin^2\theta_{13}$	0.02166 ± 0.00075	0.02179 ± 0.00076
$\delta/^\circ$	261^{+51}_{-59}	277^{+40}_{-46}
$\Delta m^2_{21} = m^2_2 - m^2_1$	$\left(7.50^{+0.19}_{-0.17}\right) \times 10^{-5}$ eV^2	$\left(7.50^{+0.19}_{-0.17}\right) \times 10^{-5}$ eV^2
$\Delta m^2_{3\ell}$	$m^2_3 - m^2_1 = \left(2.524^{+0.039}_{-0.040}\right) \times 10^{-3}$ eV^2	$m^2_3 - m^2_2 = \left(-2.514^{+0.038}_{-0.041}\right) \times 10^{-3}$ eV^2

Data from Esteban *et al.*, 2017

- Ratio of calculated branching fraction to its experimental upper limit versus $c_{\mu\mu}$.



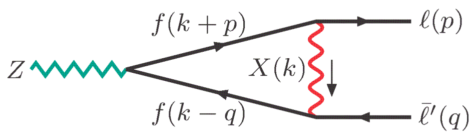
- Some of these examples are also predictions of the model potentially testable in the near future.

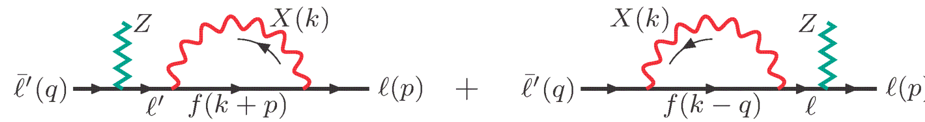
Predictions for lepton-flavor-violating B and K decays

Interestingly, the predictions for a few of the modes are within 2 orders of magnitude from their experimental bound and thus may be probed in near-future searches.

Decay mode	Branching fractions		
	Measured upper limit at 90% CL [8, 84]	Prediction maximum [or range]	
		NO	IO
$B \to K e^\pm \mu^\mp$	3.8×10^{-8}	2.9×10^{-9}	3.0×10^{-9}
$B \to K^* e^\pm \mu^\mp$	5.1×10^{-7}	7.8×10^{-9}	7.8×10^{-9}
$B_s \to e^\pm \mu^\mp$	1.1×10^{-8}	8.6×10^{-12}	9.0×10^{-12}
$B \to \pi e^\pm \mu^\mp$	9.2×10^{-8}	1.2×10^{-10}	1.3×10^{-10}
$B \to \rho e^\pm \mu^\mp$	3.2×10^{-6}	3.1×10^{-10}	3.2×10^{-10}
$B^0 \to e^\pm \mu^\mp$	2.8×10^{-9}	2.6×10^{-13}	2.7×10^{-13}
$B^+ \to K^+ e^\pm \tau^\mp$	3.0×10^{-5}	8.1×10^{-9}	5.9×10^{-9}
$B^+ \to K^{*+} e^\pm \tau^\mp$	–	1.6×10^{-8}	1.2×10^{-8}
$B_s \to e^\pm \tau^\mp$	–	8.0×10^{-9}	5.8×10^{-9}
$B^+ \to \pi^+ e^- \tau^+$	2.0×10^{-5}	1.9×10^{-10}	1.4×10^{-10}
$B^+ \to \rho^+ e^\pm \tau^\mp$	–	7.1×10^{-10}	5.2×10^{-10}
$B^0 \to e^\pm \tau^\mp$	2.8×10^{-5}	2.4×10^{-10}	1.7×10^{-10}
$B^+ \to K^+ \mu^\pm \tau^\mp$	4.8×10^{-5}	$[0.3, 3.1] \times 10^{-9}$	2.6×10^{-9}
$B^+ \to K^{*+} \mu^\pm \tau^\mp$	4.8×10^{-5}	$[0.7, 6.1] \times 10^{-9}$	5.1×10^{-9}
$B_s \to \mu^\pm \tau^\mp$	–	$[0.3, 3.1] \times 10^{-9}$	2.6×10^{-9}
$B^+ \to \pi^+ \mu^\pm \tau^\mp$	7.2×10^{-5}	$[0.2, 1.5] \times 10^{-10}$	1.2×10^{-10}
$B^+ \to \rho^+ \mu^\pm \tau^\mp$	7.2×10^{-5}	$[0.3, 2.7] \times 10^{-10}$	2.3×10^{-10}
$B^0 \to \mu^\pm \tau^\mp$	2.2×10^{-5}	$[1, 9] \times 10^{-11}$	7.7×10^{-11}
$K_L \to e^\pm \mu^\mp$	4.7×10^{-12}	1.4×10^{-12}	1.5×10^{-12}

TABLE II: The maximum predictions for the branching fractions of exclusive b-meson (kaon) decays involving $e\mu$, $e\tau$, and $\mu\tau$ ($e\mu$) in the final states. The lower end of a prediction is also displayed if exceeding one per mill of its upper end. For comparison, the data are quoted if available.





$X \equiv Z'$

Decay mode	Branching fractions				
	Measured upper limit at 95% CL [49]	Prediction maximum [or range]			
		NO		IO	
		0.6 TeV	1 TeV	0.6 TeV	1 TeV
$Z \to e^{\pm}\mu^{\mp}$	7.5×10^{-7}	8.3×10^{-10}	1.8×10^{-11}	8.3×10^{-10}	1.8×10^{-11}
$Z \to e^{\pm}\tau^{\mp}$	9.8×10^{-6}	3.2×10^{-6}	7.0×10^{-8}	4.7×10^{-7}	1.0×10^{-8}
$Z \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	$[0.8, 8.5] \times 10^{-7}$	$[0.2, 1.9] \times 10^{-8}$	8.8×10^{-7}	1.9×10^{-8}

TABLE III: The maximum predictions of the branching fractions of $Z \to e\mu, e\tau, \mu\tau$ due to loop contributions of the Z' with mass $m_{Z'} = 0.6$ and 1 TeV, compared to the experimental limits. The lower end of a prediction is also displayed if exceeding one per mill of its upper end.

The $e\tau$ and $\mu\tau$ predictions can be less than 20 times below their respective experimental bounds and hence may be within the reach of upcoming searches

Conclusions

- If the recently observed $b \to s\ell\ell$ anomalies are new physics signals, it is possible that they arise from a Z' boson which interacts nonuniversally with SM fermions according to the hypothesis of minimal flavor violation.
- The application of MFV allows us to establish links among various lepton-flavor-violating decays, as well as the neutrino sector, and make predictions for some of these decay modes which may be testable soon.