$(g\text{-}2)_\mu$ Versus $K \to \pi + E_{miss}$ Induced by the $(B\text{-}L)_{23}$ Boson

Speaker: Yoshihiro Shigekami   Collaborator: Zhaofeng Kang   based on: JHEP04(2021)238

Abstract:
To address the long-standing $(g-2)_\mu$ anomaly via a light boson, in ref. [JHEP11(2019)049] we proposed to extend the standard model (SM) by the local $(B-L)_{23}$, under which only the second and third generations of fermions are charged. It predicts an invisible Z' with mass O(100) MeV, and moreover it has flavor-changing neutral current (FCNC) couplings to the up-type quarks at tree level. Such a Z', via $K_L \to \pi_0 + Z' (\to \nu\bar{\nu})$ at loop level, may be a natural candidate to account for the recent KOTO anomaly. In this article, we investigate this possibility, to find that Z' can readily do this job if it is no longer responsible for the $(g-2)_\mu$ anomaly. We further find that both anomalies can be explained with moderate tuning of the CP violation, but may contradict the B meson decays.

Introduction

The Standard Model (SM): not a full model of Nature ⇨

- Massless neutrinos
- Muon anomalous magnetic moment $(g\text{-}2)_\mu$
- No dark matter (DM) candidates
- …

Extensions are needed!

$(B\text{-}L)_{23}$ model
$\mathcal{Q}_1^f = 0, \quad \mathcal{Q}_{2,3}^f = (B-L)$

✓ 2 right-handed neutrinos are introduced
✓ Light Z' can explain the discrepancy of $(g\text{-}2)_\mu$

Other new fields (for CKM):
(i) singlet flavon + vector-like quarks
(ii) doublet flavon

→ Quark FCNCs induced by light Z'!
e.g. $t \to qZ', \; B \to KZ', \; K \to \pi Z'$

Our Model

i = 2,3	spin	$SU(2)_L$	$U(1)_Y$	$(B\text{-}L)_{23}$
Q_i	1/2	2	1/6	1/3
$u_{R,i}$	1/2	1	2/3	1/3
$d_{R,i}$	1/2	1	−1/3	1/3
U_L	1/2	1	2/3	1/3
U_R	1/2	1	2/3	1/3
$\mathcal{F}$	0	1	0	1/3
L_i	1/2	2	−1/2	−1
$e_{R,i}$	1/2	1	−1	−1
$N_{R,i}$	1/2	1	0	−1
H	0	2	1/2	0
Φ	0	1	0	2

- Yukawa interactions: $-\mathcal{L}_q \supset Y_{ij}^d \overline{Q}_i H d_{R,j} + Y_{11}^d \overline{Q}_1 H d_{R,1} + Y_{ij}^u \overline{Q}_i \widetilde{H} u_{R,j} + Y_{11}^u \overline{Q}_1 \widetilde{H} u_{R,1}$

Additional interaction: $-\mathcal{L}_U = M_U \overline{U}_L U_R + M_{Ui} \overline{U}_L u_{R,i} + \lambda_1 \overline{U}_L u_{R,1} \mathcal{F} + \lambda_i \overline{Q}_i \widetilde{H} U_R + h.c.$

After integrating out U,

$$m_u^0 = \frac{v_h}{\sqrt{2}} \begin{pmatrix} Y_{11}^u & y_{12}^u v_f/\Lambda & y_{13}^u v_f/\Lambda \\ y_{21}^u v_f/\Lambda & Y_{22}^u & Y_{23}^u \\ y_{31}^u v_f/\Lambda & Y_{32}^u & Y_{33}^u \end{pmatrix}, \quad m_d^0 = \frac{v_h}{\sqrt{2}} \begin{pmatrix} Y_{11}^d & 0 & 0 \\ 0 & Y_{22}^d & Y_{23}^d \\ 0 & Y_{32}^d & Y_{33}^d \end{pmatrix}$$

- Z' interactions: $-\mathcal{L}_{Z'}^u = \bar{u}_i \gamma^\mu \left[(g_L^u)_{ij} P_L + (g_R^u)_{ij} P_R \right] u_j Z'_\mu$ (i, j = 1, 2, 3)

Note: Down-type quark sector → No flavor violation

By using diagonalization matrices $m_q^{\rm diag} = U_q^\dagger m_q^0 W_q$, Z' couplings are

$$(g_L^u)_{ij} = \frac{g_{B-L}}{3} \left[\delta_{ij} - (U_u)_{1i}^* (U_u)_{1j} \right], \quad (g_R^u)_{ij} = \frac{g_{B-L}}{3} \left[\delta_{ij} - (W_u)_{1i}^* (W_u)_{1j} \right]$$

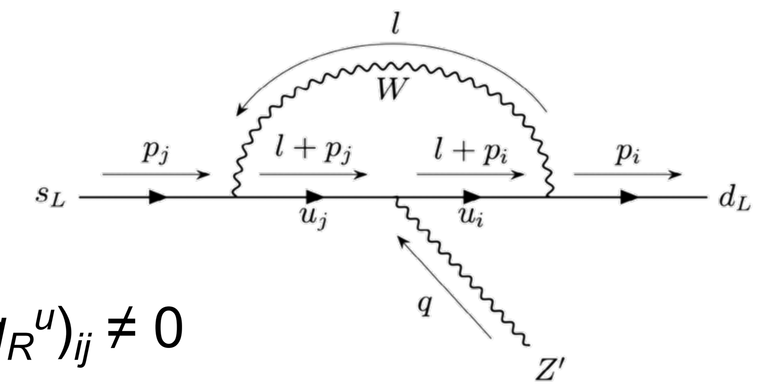
(1,i)-elements of U_q and W_q are important for FCNCs

✓ Because of CKM relation, $U_u^\dagger U_d = V_{\rm CKM}$, LH Z' couplings become
$(U_u)_{1i} = (U_d V_{\rm CKM}^\dagger)_{1i} = (V_{ud}^*, V_{cd}^*, V_{td}^*)$

$$g_L^u \simeq g_{B-L} \begin{pmatrix} 0.017 & 0.073 - 0.000046i & -0.0027 - 0.0011i \\ 0.073 + 0.000046i & 0.32 & 0.00062 + 0.00025i \\ -0.0027 + 0.0011i & 0.00062 - 0.00025i & 0.33 \end{pmatrix}$$

- FCNC in down-type quark sector $-\mathcal{L}_{Z'} \supset g_{dsZ'}^{\rm eff} \bar{d} \gamma^\mu P_L s Z'_\mu$

"Z'-penguin diagram"



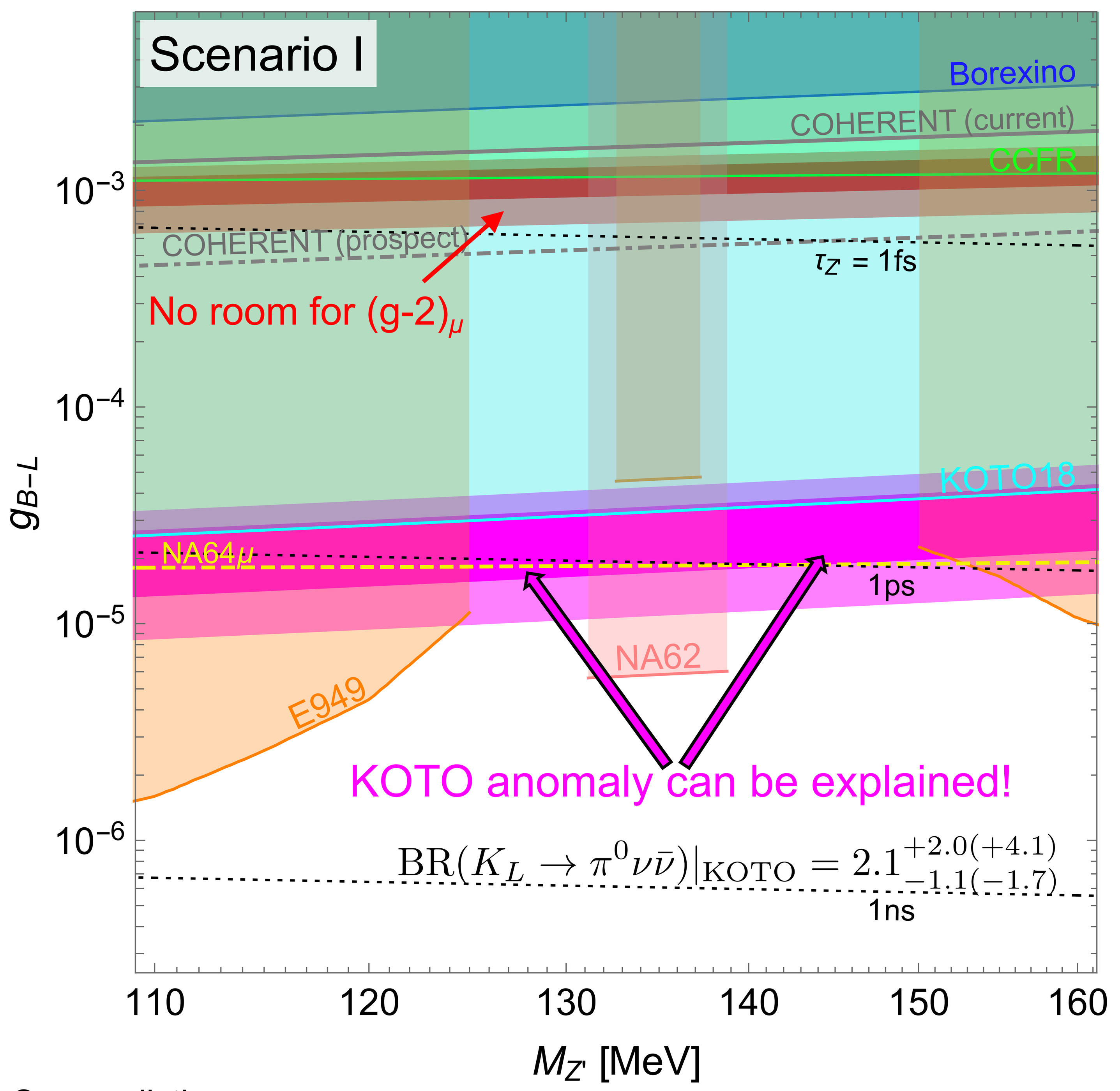
⇨ $g_{dsZ'}^{\rm eff} = -\frac{1}{16\pi^2} \sum_{i,j=1}^{3} \left[(C_L^{ds})_{ij} (g_L^u)_{ij} + (C_R^{ds})_{ij} (g_R^u)_{ij} \right]$

Flavor-violating Z' couplings will give important contributions
e.g. u_i = up, u_j = charm → there is no CKM suppression in $C_{L,R}$

Note: our Z' decays mainly to neutrino pair

Results

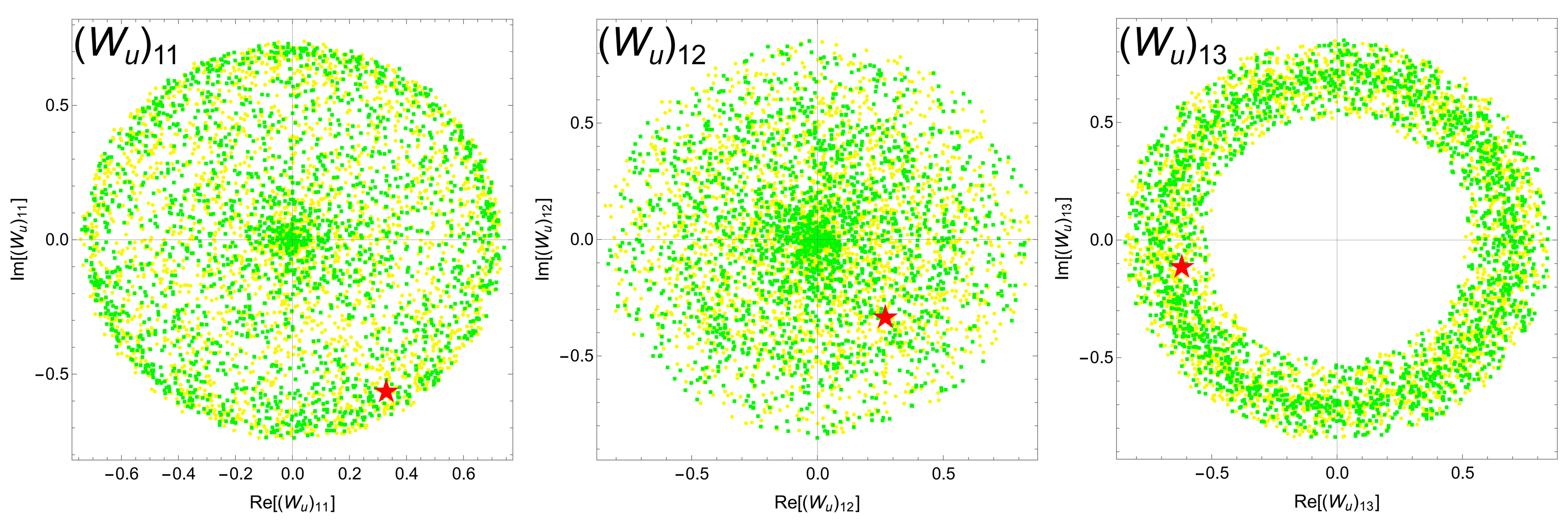
We consider two scenario: I $(g_R^u)_{ij} = 0$ & II $(g_R^u)_{ij} \neq 0$



Our prediction:

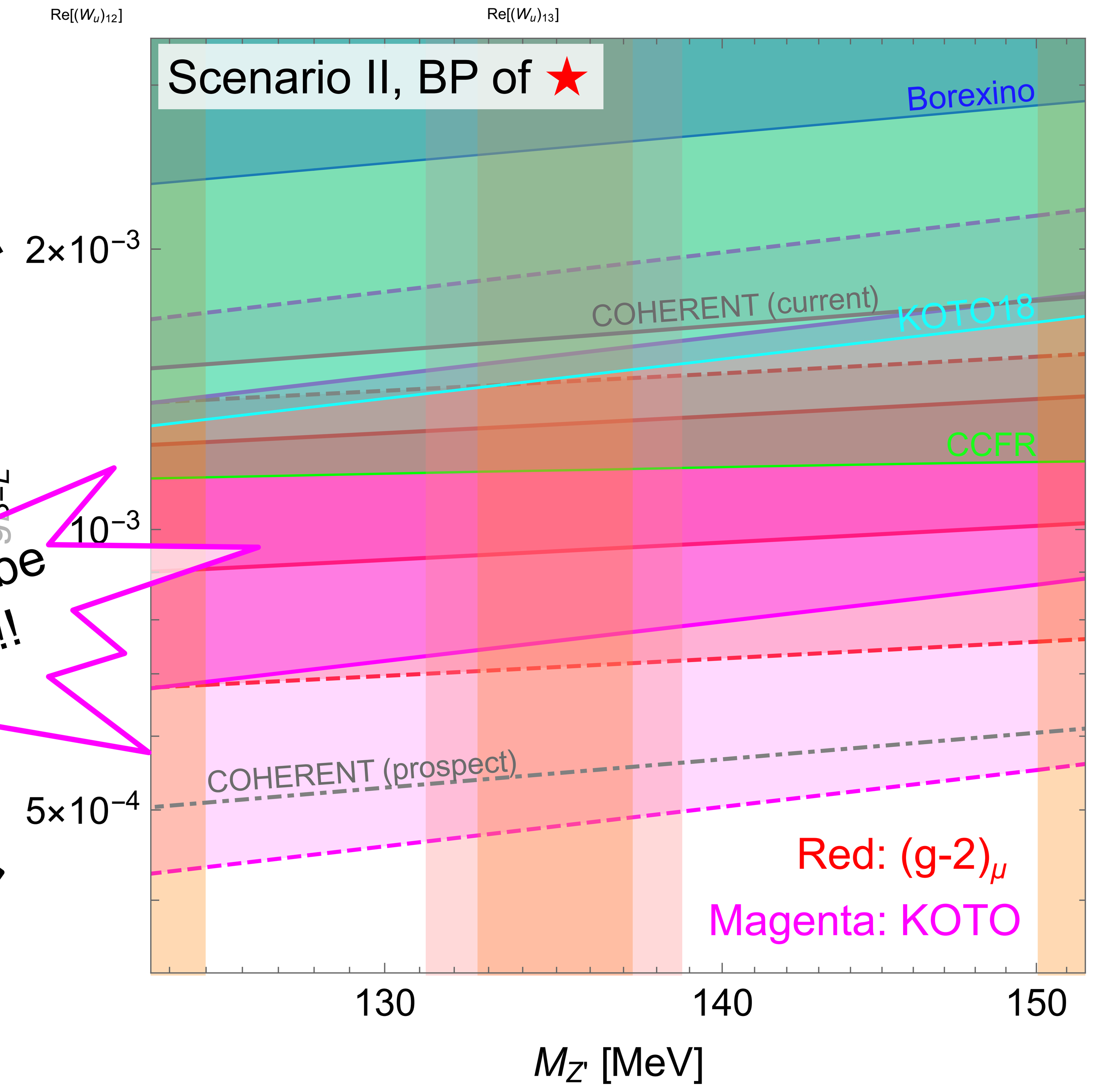
$$\mathrm{BR}(K_L \to \pi^0 Z') = \frac{\left(\mathrm{Im}\, g_{dsZ'}^{\rm eff}\right)^2}{64\pi} \frac{\lambda\left(m_{K_L}^2, m_{\pi^0}^2, m_{Z'}^2\right)^{3/2}}{m_{Z'}^2 m_{K_L}^3 \Gamma_{K_L}} \left[f_+^{K^0\pi^0}(m_{Z'}^2) \right]^2$$

- Distribution for W_u elements in Scenario II [explain anomalies 1σ (green), 2σ (yellow)]



$|(W_u)_{13}|$ ~ 0.5-0.8 is needed for the explanation

Add RH contributions ⇨



Both anomalies can be explained by our Z'!!!

B meson decay processes

- We also have B meson decay processes induced by Z'

e.g. BP of ★

$(m_{Z'}, g_{B-L})$	$(128\,\mathrm{MeV}, 1.02\times10^{-3})$	$(140\,\mathrm{MeV}, 1.15\times10^{-3})$
$B^0 \to \pi^0 Z'$	8.12×10^{-7}	8.59×10^{-7}
$B^+ \to \pi^+ Z'$	1.75×10^{-6}	1.85×10^{-6}
$B^0 \to \rho^0 Z'$	1.00×10^{-6}	1.06×10^{-6}
$B^+ \to \rho^+ Z'$	2.16×10^{-6}	2.28×10^{-6}
$B^0 \to K^0 Z'$	1.44×10^{-2}	1.53×10^{-2}
$B^+ \to K^+ Z'$	1.56×10^{-2}	1.65×10^{-2}
$B^0 \to K^{*0} Z'$	1.65×10^{-2}	1.75×10^{-2}
$B^+ \to K^{*+} Z'$	1.78×10^{-2}	1.89×10^{-2}

Current bounds: O(10^{-5})

⇨✓ More smaller g_{B-L} is required…

⇦ But… ⇨

Summary and Discussion

- Our Z' has a possibility to explain both anomalies by adding RH contributions
- B meson decay processes severely constrain the parameter space
  Further analysis helps to find parameter space without conflicting with the constraints
- However, KOTO events are now considered by BG consistent…

See e.g., PRL126(2021)121801