$(g\text{-}2)_\mu$ versus Flavor Changing Neutral Current Induced by the Light $(\mathrm{B\text{-}L})_{\mu\tau}$ Boson

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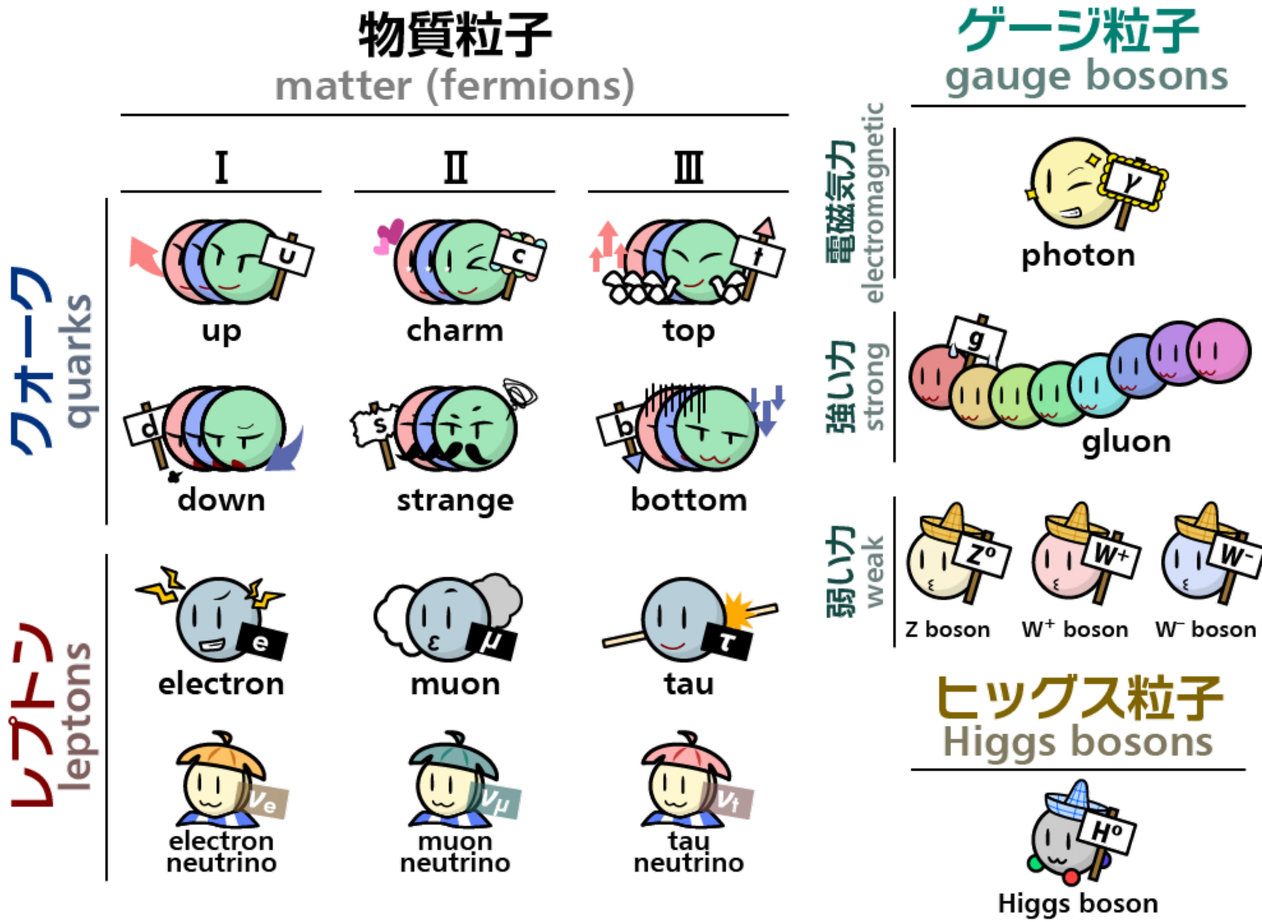
Based on arXiv:1905.11018 [hep-ph]

Introduction

- Standard Model (SM): gauge G_{SM} = SU(3)$_C$ × SU(2)$_L$ × U(1)$_Y$



http://higgstan.com/

Introduction

- We should solve and explain some mysteries

  ex. neutrino masses: massless in SM (no right-handed neutrinos)

  ⇕ **Extended model is needed**

- Neutrino masses are confirmed in some experiments

  Key: neutrino oscillation

$$P(\nu_e \to \nu_\mu) \propto \sin^2\left(\frac{|m_{\nu_1}^2 - m_{\nu_2}^2|}{4E}L\right)$$

- Super-Kamiokande → Neutrinos are oscillated!

  Nobel Prize (2015): T. Kajita, A. B. McDonald

- Tiny neutrino masses

$$\sum m_\nu < 0.12 \text{ eV}$$

Planck Collab., arXiv:1807.06209 [astro-ph.CO]

Parameter	best-fit	3σ
Δm_{21}^2 [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m_{31(23)}^2$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)

Introduction

- One of the interesting models → B-L model

  charges: +1 (+1/3) for Baryons (quarks), -1 for Leptons

- New U(1) gauge sym.

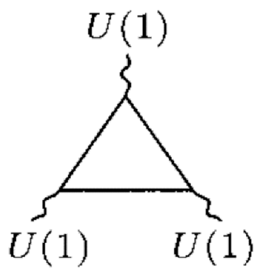


Figure from Peskin, Schroeder

	Q_L	u_R	d_R	L_L	e_R	ν_R
$U(1)_{B-L}$	$+1/3$	$+1/3$	$+1/3$	-1	-1	-1
d.o.f	3×2	3	3	2	1	1

$-6 \times 1/3 + 3 \times 1/3 + 3 \times 1/3 - 2 \times (-1) + 1 \times (-1) = 1$

$-6 \times 1/3 + 3 \times 1/3 + 3 \times 1/3 - 2 \times (-1) + 1 \times (-1) + 1 \times (-1) = 0$

Note:
$U(1)_{B-L}^3$ also cancels

- RHν is needed for gauge anomaly

- It appears from some high-energy theories

  ex. Grand Unified Theory : SO(10) → $G_{SM} \times U(1)_{B-L}$

Introduction

- New terms with RHν

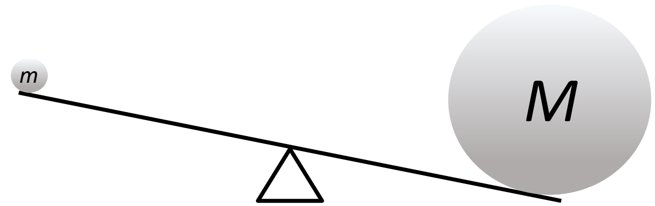
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underline{Y \overline{L_L} \widetilde{H} \nu_R} + \underline{\frac{\lambda_\nu}{2} \Phi \overline{\nu_R^c} \nu_R}$$

<H^0> ≠ 0 → Dirac mass term, *m*

Φ: new scalar (charge 2)

<Φ> ≠ 0 → Majorana mass term, *M*

Seesaw mechanism: $\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$

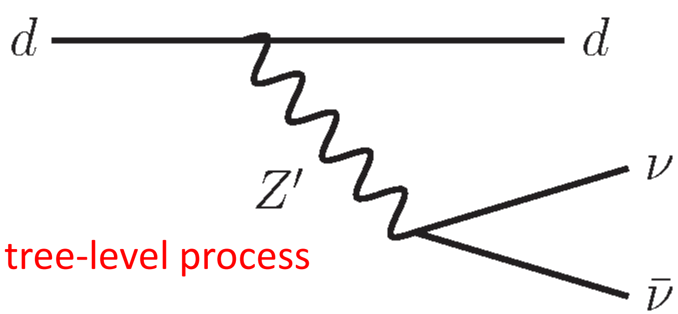


Minkowski, PLB **67**, 421 (1977);
Gell-Mann, Ramond, Slansky (proceedings) (1979);
Yanagida (proceedings) (1979);
Glashow, *"Quarks and Leptons"*;
Mohapatra, Senjanovic, PRL **44**, 912 (1980)

- New gauge boson: Z'

interactions with fermions: $\mathcal{L}_{Z'} = g_{B-L} \left[\left(\frac{1}{3} \right) \bar{q} \gamma^\mu q + (-1)\, \bar{\ell} \gamma^\mu \ell \right] Z'_\mu$

⇨ Contributes to some predictions



tree-level process

Introduction

- μ couples to new gauge particles → $(g\text{-}2)_\mu$

Hamiltonian: $H = -\mu \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$

q: charge, *m*: mass, **s**: spin

→ Magnetic moment: $\mu = g \left(\frac{q}{2m} \right) \mathbf{s}$

- $a_\mu = \frac{g-2}{2}$ → $a_\mu = 0$ (tree level)
- 1-loop QED: $a_\mu = \alpha/(2\pi)$ (Schwinger)
- SM prediction: $a_\mu^{\rm SM} = (11659182.04 \pm 3.56) \times 10^{-10}$

A. Keshavarzi *et al.*, PRD **97**, 114025 (2018)

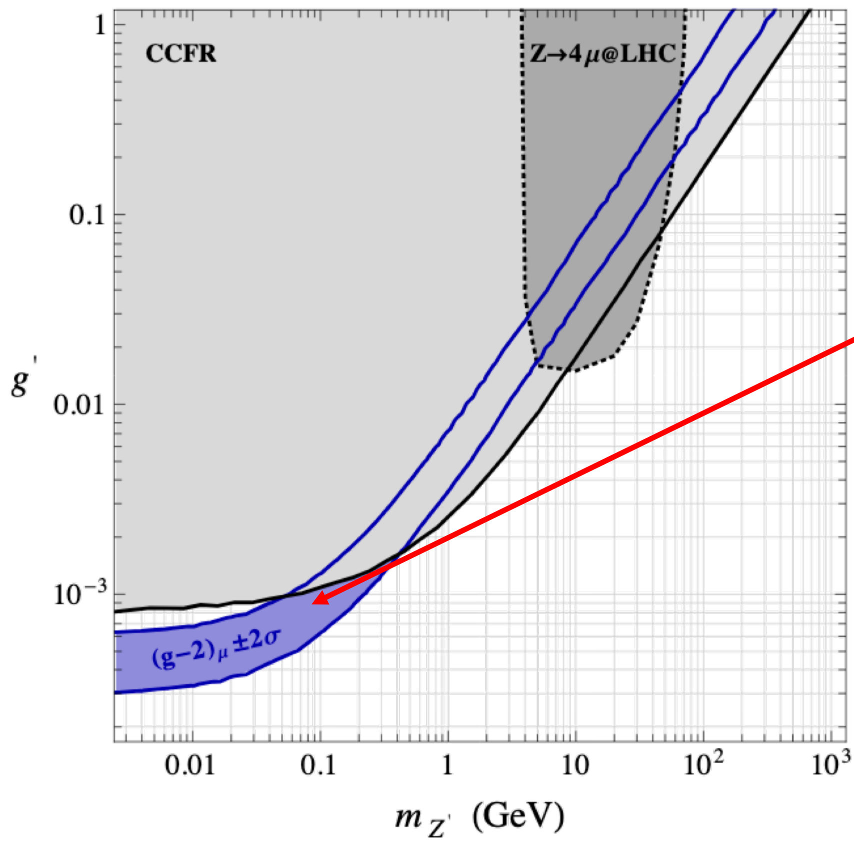
⇕ 3.7σ deviation!

- Experimental result: $a_\mu^{\rm exp} = (11659208.9 \pm 6.3) \times 10^{-10}$

PDG

Introduction

- New physics explanation: B-L model, L_μ-L_τ model, …
- There is favored parameter space in light Z' mass region



$M_{Z'} \sim$ 10-400 MeV & $g' \sim$ (3-15) × 10^{-4}

main focus of this work

W. Altmannshofer *et al.*, PRL **113**, 091801 (2014)

Introduction

K. Zhaofeng and YS, arXiv:1905.11018 [hep-ph]

- Our setup: 2nd and 3rd generations have $U(1)_{B\text{-}L}$ charges

Z' interactions: $\mathcal{L}_{Z'} = \frac{g_{B-L}}{3} \sum_{i=2,3} \bar{q}_i \gamma^\mu q_i Z'_\mu$

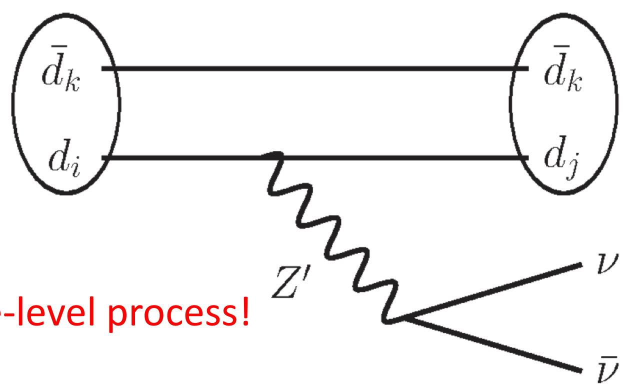
- In mass basis,

elements of diagonalizing matrix for Yukawas

$$\mathcal{L}_{Z'} = \frac{g_{B-L}}{3} \sum_{a,b=1,2,3} C^q_{ab} \bar{q}_a \gamma^\mu q_b Z'_\mu$$

→ Flavor Violating Couplings (FVCs)

- New contributions: $t \to q\, Z'$, $P_1 \to P_2\, Z'$ ($Z' \to \nu\nu$)

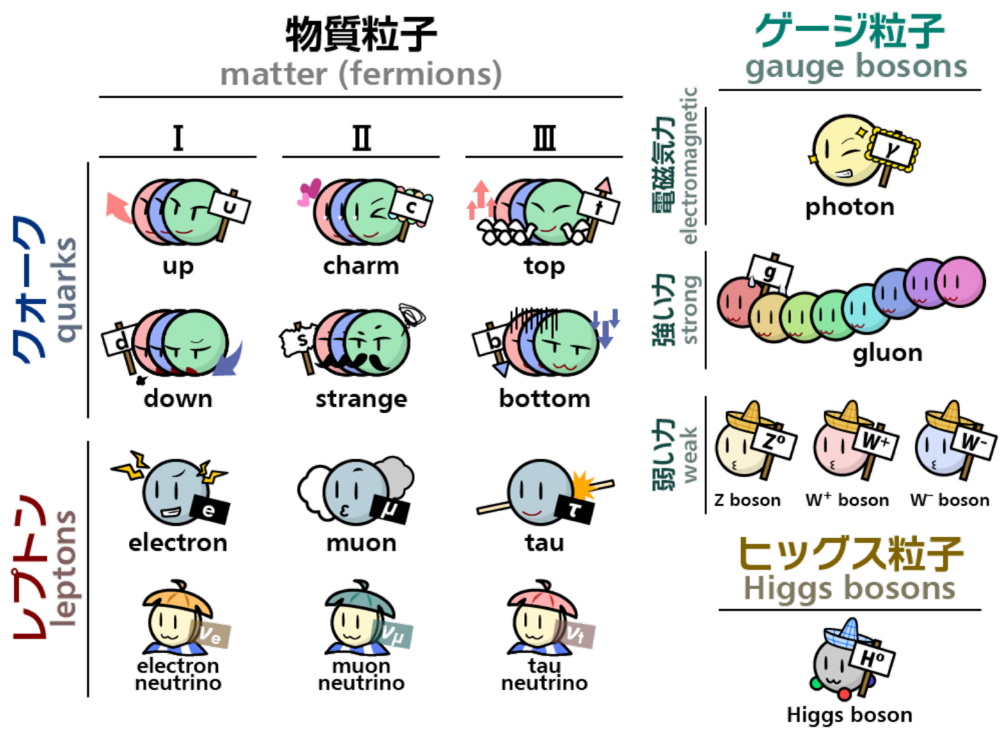


tree-level process!

light Z' → decays to $\nu\bar{\nu}$

Contents

- Introduction (7) → ✓ done!
- Model details (4)
- $(g\text{-}2)_\mu$ (3)
- Quark FCNCs (6)
- Summary (1)



+ which New Physics? → Light Z'!

Model details

K. Zhaofeng and YS, arXiv:1905.11018 [hep-ph]

Model details

- We consider $G_{\mathrm{SM}} \times U(1)_{B\text{-}L}$
- 2^{nd} and 3^{rd} generations are charged under $U(1)_{B\text{-}L}$
- Contents (i = 2, 3):

	spin	$SU(2)_L$	$U(1)_Y$	$(B-L)_{\mu\tau}$
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

need for realization of CKM (U_L, U_R, $\mathcal{F}$)

← right-handed neutrinos ($N_{R,i}$)

tiny ν mass via seesaw mechanism

← $\langle\Phi\rangle$ breaks $U(1)_{B\text{-}L}$

Model details

- Yukawa couplings for quarks

$$-\mathcal{L} \supset Y^u_{11}\overline{Q}_1\widetilde{H}u_{R,1} + Y^u_{ij}\overline{Q}_i\widetilde{H}u_{R,j} + Y^d_{11}\overline{Q}_1 H d_{R,1} + Y^d_{ij}\overline{Q}_i H d_{R,j}$$

→ No Yukawas between 1st and the other generations: ~~CKM~~

- Vector-like quarks: Integrate out

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

⇨ $$-\mathcal{L} \supset Y^u_{ab}\overline{Q}_a\widetilde{H}u_{R,b} + Y^d_{11}\overline{Q}_1 H d_{R,1} + Y^d_{ij}\overline{Q}_i H d_{R,j}$$

a = 1, 2, 3; *i* = 2, 3

- If we introduce doublet flavons with $U(1)_{B-L}$ charge +1/3,

$$-\mathcal{L} \supset \widetilde{Y}^u_{1i}\overline{Q}_1\widetilde{H}_{\mu\tau}u_{R,i} + \widetilde{Y}^d_{i1}\overline{Q}_i H_{\mu\tau} d_{R,1} + h.c.$$

→ vector-like quarks are not needed

Model details

- Z' couplings of quarks

$$-\mathcal{L}_{Z'} \supset \frac{g_{B-L}}{3}\left[\overline{Q'}_i\gamma^\mu Q'_i + \overline{u'}_{R,i}\gamma^\mu u'_{R,i} + \overline{d'}_{R,i}\gamma^\mu d'_{R,i}\right] Z'_\mu$$

mass basis from flavor one: $q'^i_L = U_q^{ij} q_L^j$ and $q'^i_R = W_q^{ij} q_R^j$

U_q, W_q: diagonalizing matrices for Yukawa

$$-\mathcal{L}^q_{Z'} = \frac{g_{B-L}}{3}\bar{q}_i\gamma^\mu\left(V^q_{ij} - \gamma_5 A^q_{ij}\right) q_j Z'_\mu$$

: Flavor violating couplings (FVCs)

$$V^q_{ij} = \frac{1}{2}\sum_{k=2,3}\left[(U_q^\dagger)_{ik}(U_q)_{kj} + (W_q^\dagger)_{ik}(W_q)_{kj}\right] = \delta_{ij} - \frac{(U_q^\dagger)_{i1}(U_q)_{1j} + (W_q^\dagger)_{i1}(W_q)_{1j}}{2},$$

$$A^q_{ij} = \frac{1}{2}\sum_{k=2,3}\left[(U_q^\dagger)_{ik}(U_q)_{kj} - (W_q^\dagger)_{ik}(W_q)_{kj}\right] = -\frac{(U_q^\dagger)_{i1}(U_q)_{1j} - (W_q^\dagger)_{i1}(W_q)_{1j}}{2}.$$

Note: our FVCs are related to (1, i)-element of U_q and W_q

- Different type of quark FCNC:

  - Singlet flavon case → only up sector

$$Y_u = \begin{pmatrix} y^u_{11} & y^u_{12} & y^u_{13} \\ y^u_{21} & y^u_{22} & y^u_{23} \\ y^u_{31} & y^u_{32} & y^u_{33} \end{pmatrix}, \quad Y_d = \begin{pmatrix} y^d_{11} & 0 & 0 \\ 0 & y^d_{22} & y^d_{23} \\ 0 & y^d_{32} & y^d_{33} \end{pmatrix}$$

  - Doublet flavon case → up and down sectors

$$Y_u = \begin{pmatrix} y^u_{11} & y^u_{12} & y^u_{13} \\ 0 & y^u_{22} & y^u_{23} \\ 0 & y^u_{32} & y^u_{33} \end{pmatrix}, \quad Y_d = \begin{pmatrix} y^d_{11} & 0 & 0 \\ y^d_{21} & y^d_{22} & y^d_{23} \\ y^d_{31} & y^d_{32} & y^d_{33} \end{pmatrix}$$

Model details

- The size of FVCs: depend on $g_{\text{B-L}}$ and U_q, W_q
- $g_{\text{B-L}}$ → determine from $(g\text{-}2)_\mu$
- U_q → size from CKM matrix:

$$V_{\rm CKM} = U_u^\dagger U_d = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- No cancellation means

$$(U_u)_{c'u,u'c}, (U_d)_{s'd,d's} \lesssim \lambda, \quad (U_u)_{c't,t'c}, (U_d)_{s'b,b's} \lesssim \lambda^2, \quad (U_u)_{t'u,u't}, (U_d)_{b'd,d'b} \lesssim \lambda^3$$

and diagonal element ∼ 1

- For W_q, there are no concrete bound, but if $U_q \sim W_q$, similar inequalities are applied

$(g\text{-}2)_\mu$

$(g\text{-}2)_\mu$

- Our scenario has the possibility to solve $(g\text{-}2)_\mu$ deviation

  current result:

  $$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (27.06 \pm 7.26) \times 10^{-10}$$

  K. Hagiwara *et al.*, J. Phys. G **38**, 085003 (2011)
  A. Keshavarzi *et al.*, PRD **97**, 114025 (2018)
  G. W. Bennet *et al.*, PRD **73**, 072003 (2006)
  B. L. Roberts, Chin. Phys. C **34**, 741 (2010)

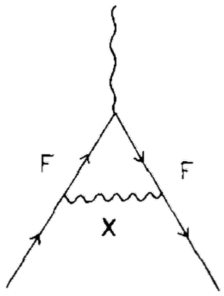
- Z' coupling with leptons:

  $$-\mathcal{L}_{Z'}^{l} = -g_{B-L}(\bar{\mu}\gamma^\mu\mu + \bar{\tau}\gamma^\mu\tau + \bar{\nu}_\mu\gamma^\mu\nu_\mu + \bar{\nu}_\tau\gamma^\mu\nu_\tau)Z'_\mu$$

- When $M_{Z'}$ is light, Δa_μ can be calculated by

  J. P. Leveille, NPB **137**, 63 (1978)

  $$\Delta a_\mu = \frac{g_{B-L}^2}{8\pi^2}\int_0^1 \frac{2x^2(1-x)}{x^2 + (M_{Z'}^2/m_\mu^2)(1-x)}dx$$



- In light mass region there are other constraints

  neutrino trident production, $e^+e^- \to 4\mu$, BBN, ...

$(g\text{-}2)_\mu$

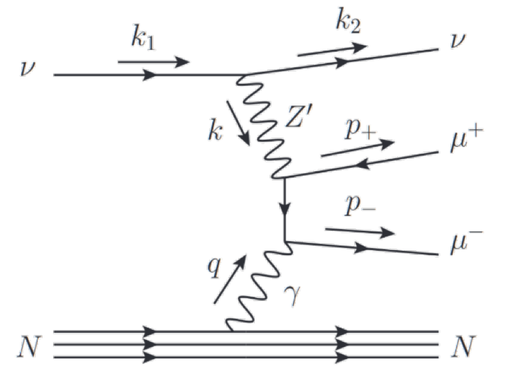


Figure from PRL 113, 091801 (2014)

- Neutrino trident production

  ruled out the mass range $M_{Z'} \gtrsim 400\ \mathrm{MeV}$

  CCFR Collab., PRL **66**, 3117 (1991)

- $e^+e^- \rightarrow 4\mu$ ($e^+e^- \rightarrow Z'\mu^+\mu^-$, $Z' \rightarrow \mu^+\mu^-$)

  ruled out the mass range $M_{Z'} \gtrsim 2m_\mu \simeq 210\ \mathrm{MeV}$ with $g' \sim O(10^{-3})$

  BaBar Collab., PRD **94**, 011102 (2016)

- BBN (Big Ban Nucleosynthesis): light Z' → effective relativistic d.o.f

  ruled out the mass range $M_{Z'} \lesssim O(1)\ \mathrm{MeV}$

  B. Ahlgren et al., PRL **111**, 199001 (2013)
  A. Kamada et al., PRD **92**, 113004 (2015)
  M. Escudero et al., JHEP **1903**, 071 (2019)

- *e*-*ν* scattering (Borexino)

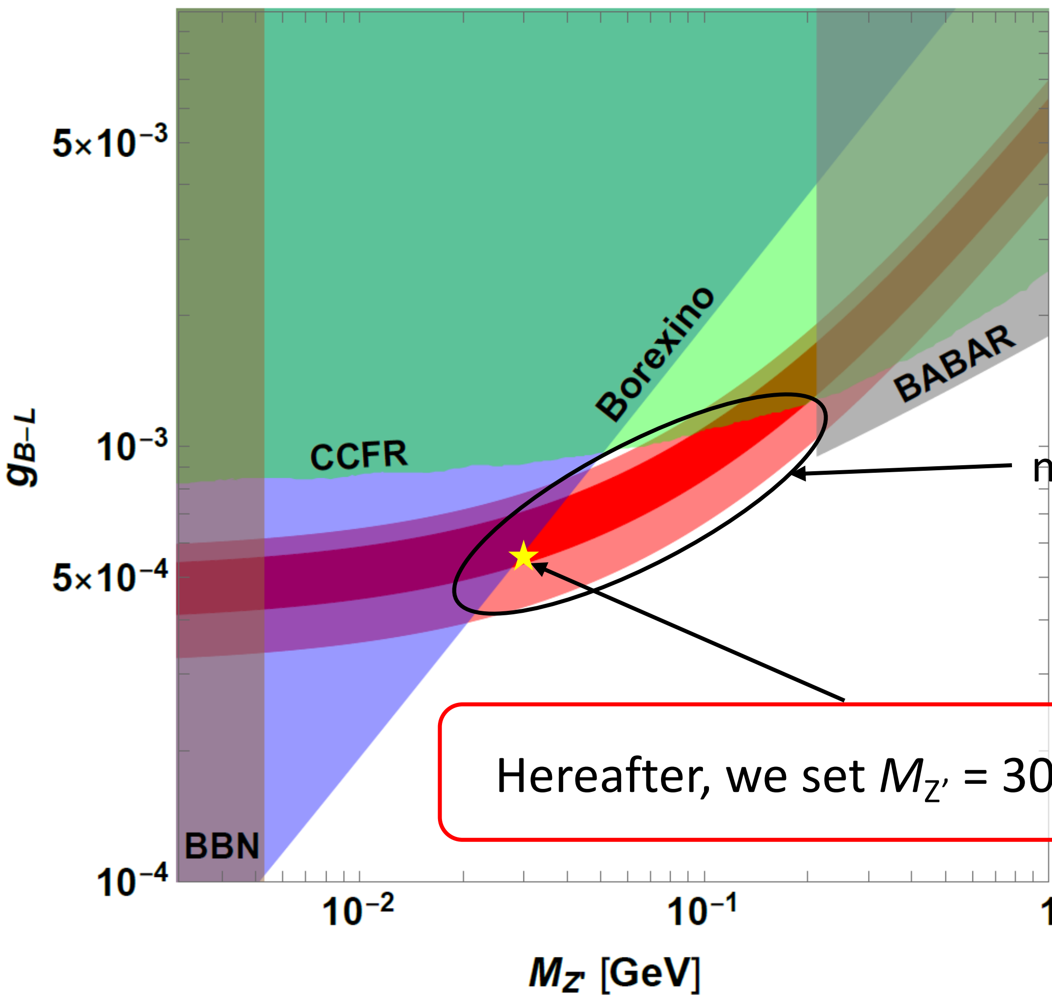
  G. Bellini et al., PRL **107**, 141302 (2011); R. Harnik et al., JCAP **1207**, 026 (2012); Borexino Collab., arXiv:1707.09279 [hep-ex]

  even when *e* doesn't couple to Z' at tree level, it does at loop level

  the bound is depend on model, especially kinetic mixing χ

$(g\text{-}2)_\mu$

- Bounds on Z' mass and coupling



narrow, but favored region here

Hereafter, we set $M_{Z'}$ = 30 MeV and $g_{B\text{-}L} = 5.5\times10^{-4}$

Quark FCNCs

Singlet and doublet flavon models

- $t \to q\, Z'$ decay

M. D. Goodsell *et al*, EPJC **77**, 758 (2017)

$$\Gamma(t \to qZ') = \frac{m_t}{32\pi}\lambda(1, x_q, x')^{1/2}\left[\left(1 + x_q - 2x' + \frac{(1-x_q)^2}{x'}\right)\left(|(g_L^u)_{qt}|^2 + |(g_R^u)_{qt}|^2\right) - 12\sqrt{x_q}\mathrm{Re}\left((g_L^u)_{qt}(g_R^u)^*_{qt}\right)\right]$$

$$\approx \frac{m_t^3}{32\pi}\lambda(1, x_q, x')^{1/2}\frac{|(g_L^u)_{qt}|^2 + |(g_R^u)_{qt}|^2}{M_{Z'}^2}$$

when $x_q \ll 1$, $x' \ll 1$

$x_q \equiv m_q^2/m_t^2,\ x' \equiv M_{Z'}^2/m_t^2$ and $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$

- FVCs: $(g_L^u)_{ij} = \frac{g_{B-L}}{3}(V_{ij}^u + A_{ij}^u) = -\frac{g_{B-L}}{3}(U_u^\dagger)_{i1}(U_u)_{1j},$

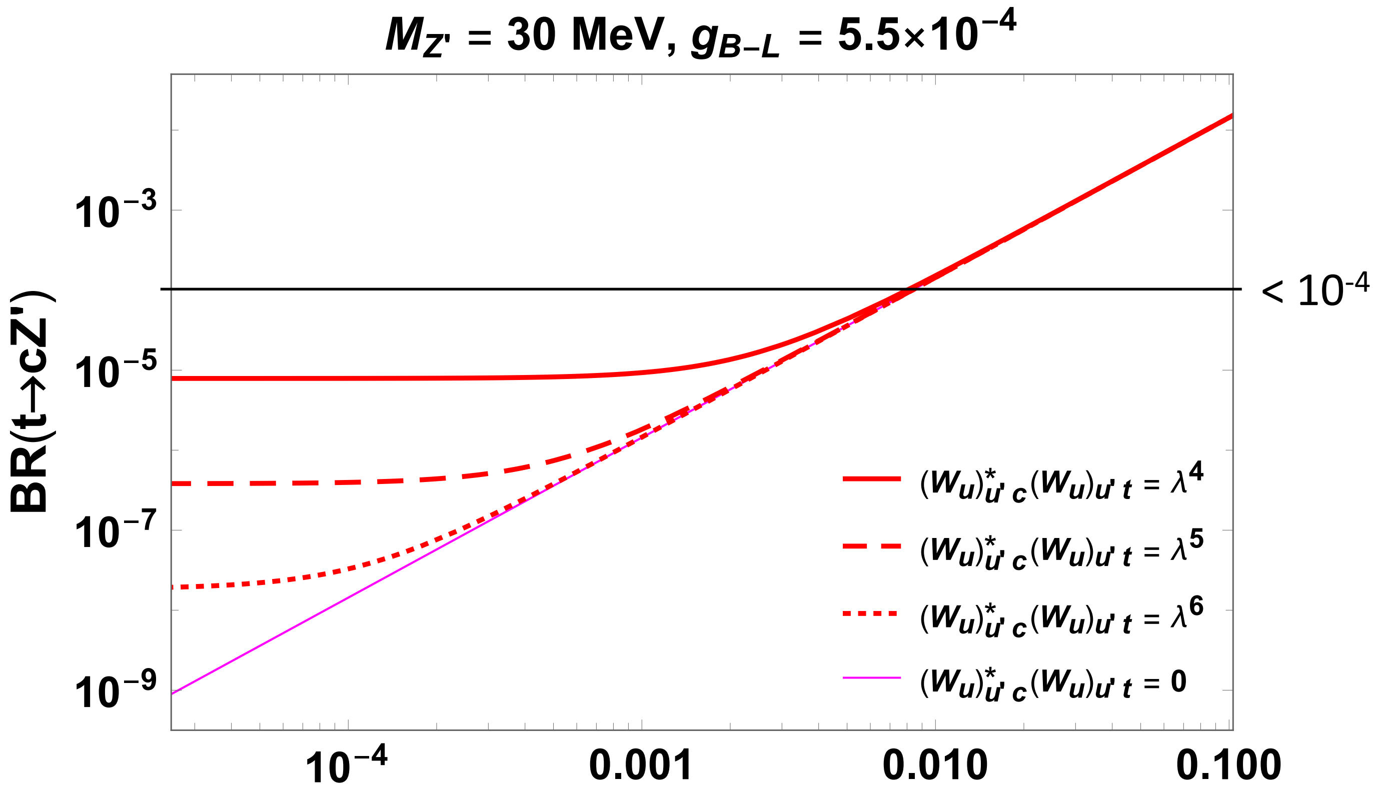
  $(g_R^u)_{ij} = \frac{g_{B-L}}{3}(V_{ij}^u - A_{ij}^u) = -\frac{g_{B-L}}{3}(W_u^\dagger)_{i1}(W_u)_{1j}$

- The results are proportional to $|g_{B-L}|^2/M_{Z'}^2$ when $M_{Z'} < \mathcal{O}(10)\ \mathrm{GeV}$

Singlet and doublet flavon models

- Result of $t \to c\, Z'$ decay

$t \to Wb$ is dominant mode in top quark decay



$(U_u)^*_{u'c}(U_u)_{u't} < 8 \times 10^{-3} \sim \lambda^{3.2}$

Note: our Z' decays mainly to ν-pair

→ no concrete bounds…

→ Consistent with the CKM matrix!

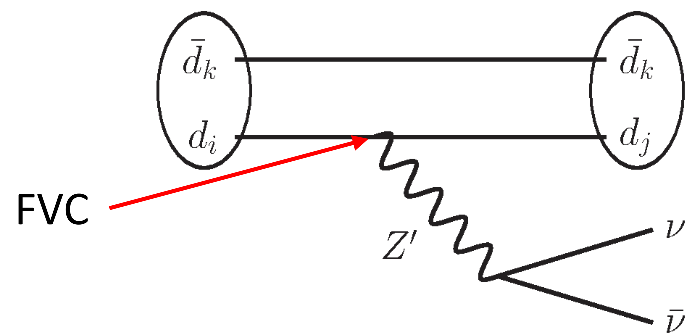
Doublet flavon model

- Up sector: predictions are not changed
- FCNC in down sector, especially focus on ν-pair in final state

  $Z' \to \nu \bar{\nu}$

- Meson decay such as $B \to K\nu\bar{\nu}$ and $K \to \pi\nu\bar{\nu}$

  these processes are tree level ones



- Since Z' is light, it is produced through meson decay directly

  → $\mathrm{BR}(B \to KZ') \times \underline{\mathrm{BR}(Z' \to \nu\bar{\nu})}$ and $\mathrm{BR}(K \to \pi Z') \times \underline{\mathrm{BR}(Z' \to \nu\bar{\nu})}$

  $\fallingdotseq 1$ $\fallingdotseq 1$

Doublet flavon model

- Branching ratios

$$\mathrm{BR}(B^+ \to K^+ Z') = \frac{|(g_L^d)_{sb} + (g_R^d)_{sb}|^2}{64\pi} \frac{\lambda(m_{B^+}, m_{K^+}, M_{Z'})^{3/2}}{M_{Z'}^2 m_{B^+}^3 \Gamma_{B^+}} \left[f_+^{B^+K^+}(M_{Z'}^2)\right]^2,$$

$$\mathrm{BR}(K^+ \to \pi^+ Z') = \frac{|(g_L^d)_{ds} + (g_R^d)_{ds}|^2}{64\pi} \frac{\lambda(m_{K^+}, m_{\pi^+}, M_{Z'})^{3/2}}{M_{Z'}^2 m_{K^+}^3 \Gamma_{K^+}} \left[f_+^{K^+\pi^+}(M_{Z'}^2)\right]^2,$$

$f_+^{M_1 M_2}(M_{Z'}^2)$: M1 → M2 form factor at $M_{Z'}$

P. Ball and R. Zwicky, PRD **71**, 014015 (2005)
F. Mescia and C. Smith, PRD **76**, 034017 (2007)

- FVCs: $$(g_L^d)_{ij} = \frac{g_{B-L}}{3}(V_{ij}^d + A_{ij}^d) = -\frac{g_{B-L}}{3}(U_d^\dagger)_{i1}(U_d)_{1j},$$

$$(g_R^d)_{ij} = \frac{g_{B-L}}{3}(V_{ij}^d - A_{ij}^d) = -\frac{g_{B-L}}{3}(W_d^\dagger)_{i1}(W_d)_{1j}$$

- Masses and decay widths:

m_{K^+}	493.677(16) MeV	τ_{K^+}	$1.2380(20) \times 10^{-8}$ s
m_{K_L}	497.611(13) MeV	τ_{K_L}	$5.116(21) \times 10^{-8}$ s
m_{B^+}	5279.32(14) MeV	τ_{B^+}	$1.638(4) \times 10^{-12}$ s
m_{π^+}	139.57061(24) MeV		
m_{π^0}	134.9770(5) MeV		

PDG

Doublet flavon model

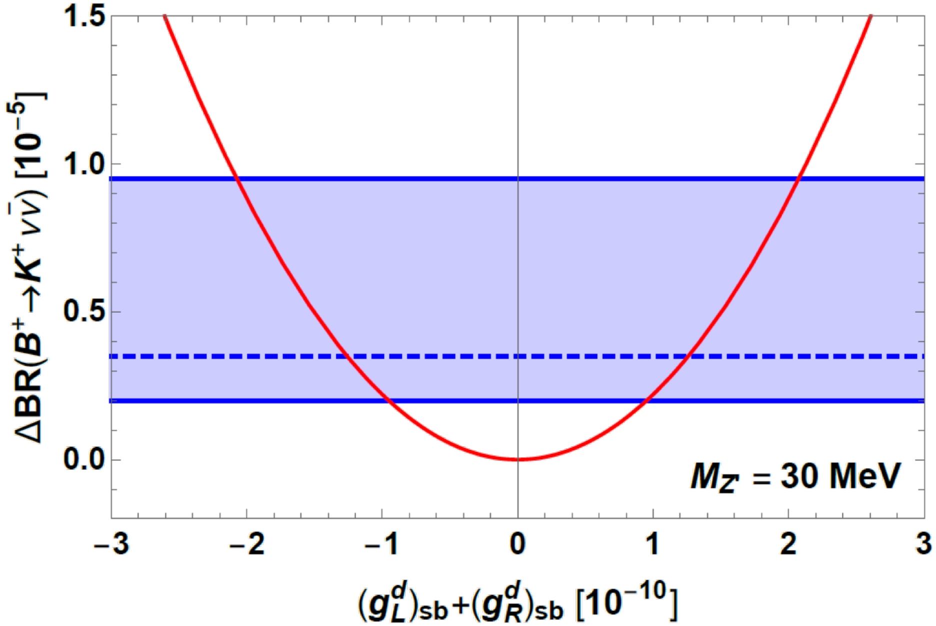
- Constraint: $\Delta\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{exp}} = (0.35^{+0.60}_{-0.15}) \times 10^{-5}$

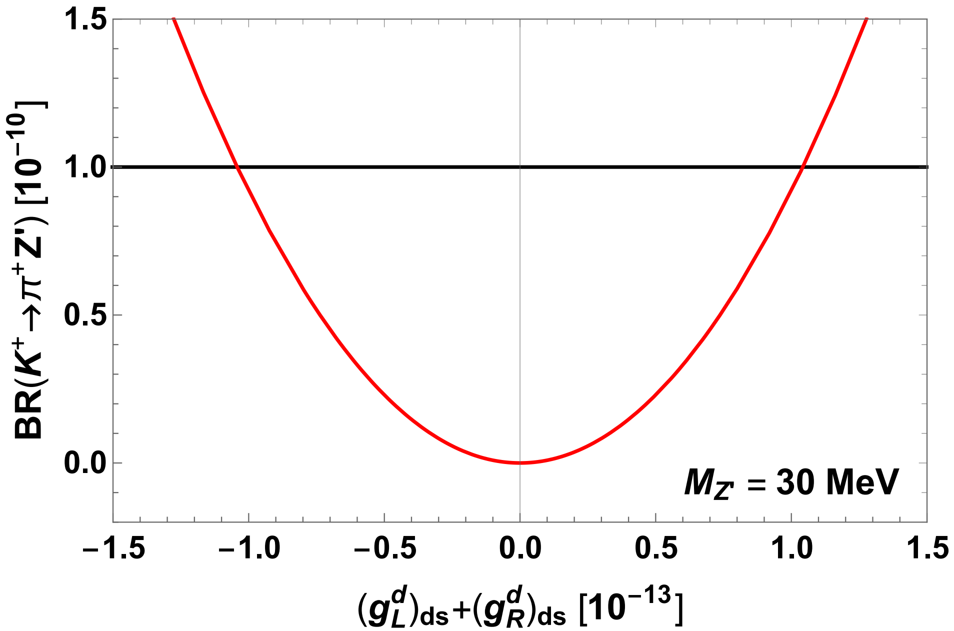
J. P. Lees *et al.*[BaBar Collab.], PRD **87**, 112005 (2013)

$$\mathrm{BR}(K^+ \to \pi^+ Z') < 1.0 \times 10^{-10} \text{ for } M_{Z'} = 30 \text{ MeV}$$

A. V. Artamonov *et al.*[BNL-E949 Collab.], PRD **79**, 092004 (2009)

- Results





$$0.95 \times 10^{-10} \leq |(g_L^d)_{sb} + (g_R^d)_{sb}| \leq 2.1 \times 10^{-10}$$

$$|(g_L^d)_{ds} + (g_R^d)_{ds}| < 0.11 \times 10^{-12}$$

Doublet flavon model

- Summary of bounds:

$$0.95 \times 10^{-10} \leq |(g_L^d)_{sb} + (g_R^d)_{sb}| \leq 2.1 \times 10^{-10}$$

$$|(g_L^d)_{ds} + (g_R^d)_{ds}| < 0.11 \times 10^{-12}$$

$\times$ 3/(5.5 $\times$ 10^{-4}) (= 3/$g_{B\text{-}L}$)

$$5.2 \times 10^{-7} \leq |(U_d)^*_{d's}(U_d)_{d'b}| \leq 1.1 \times 10^{-6}, \quad |(U_d)^*_{d'd}(U_d)_{d's}| < 6.2 \times 10^{-10}$$

- Taking unitary condition into account, $|(U_d)_{d'd}|^2 + |(U_d)_{d's}|^2 + |(U_d)_{d'b}|^2 = 1$ allowed patterns are

$|(U_d)_{d'd}|$	$|(U_d)_{d's}|$	$|(U_d)_{d'b}|$
$< 10^{-9}$	~ 1	$\simeq \mathcal{O}(10^{-6})$
$< 10^{-3}$	$\simeq \mathcal{O}(10^{-6})$	~ 1

Cannot be $O(1)$

⇨ Inconsistent with CKM structure!

Summary

Summary

- We consider B-L extended model

    2nd and 3rd generations are charged under $U(1)_{B\text{-}L}$

- We should introduce some flavon (singlet, double)
- In singlet flavon case, only up sector has FVCs of Z', and FCNC top decay is interesting:

    $\mathrm{BR}(t \to c\, Z') \sim O(10^{-4})$, which consistent with CKM bounds

- In doublet flavon case, down sector also have FVCs of Z', so strong bound from meson decay with ν-pair:

    excluded unless highly tuned cancellation between $g_L{}^d$ and $g_R{}^d$

- We can expect that our scenario (especially singlet case) can be tested by future experiments

    $(g\text{-}2)_\mu$, ν physics: NA64, DUNE, ...; top FCNC: CLIC, FCC, ...

Back up slides

$(g\text{-}2)_\mu$

- Experimental results so far:

BNL-E821 final report, PRD 73, 072003 (2006)

Experiment	Years	Polarity	$a_\mu \times 10^{10}$	Precision [ppm]
CERN I	1961	μ^+	11 450 000(220 000)	4300
CERN II	1962-1968	μ^+	11 661 600(3100)	270
CERN III	1974-1976	μ^+	11 659 100(110)	10
CERN III	1975-1976	μ^-	11 659 360(120)	10
BNL	1997	μ^+	11 659 251(150)	13
BNL	1998	μ^+	11 659 191(59)	5
BNL	1999	μ^+	11 659 202(15)	1.3
BNL	2000	μ^+	11 659 204(9)	0.73
BNL	2001	μ^-	11 659 214(9)	0.72
Average			11 659 208.0(6.3)	0.54

Model details

- Yukawa couplings for quarks

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

→ No Yukawas between 1st and the other generations: ~~CKM~~

- Vector-like quarks: Integrate out

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

⇩

$$\mathcal{L}_{eff} \supset c_{ab}\bar{u}_a i\gamma_\mu \partial^\mu P_R u_b + Y_{ib}\bar{Q}_i \widetilde{H} P_R u_b + h.c.$$

$$c_{ab} = \frac{M_{Ua}M_{Ub}^*}{M_U^2}, \quad Y_{ib} = \lambda_i \frac{M_{Ub}}{M_U}.$$

$M_{U1} = \lambda_1 v_f/\sqrt{2}$: *a* = 1, 2, 3; *i* = 2, 3

choose canonical basis by $u_R \to \widetilde{W}_u u_R$

$$-\mathcal{L} \supset Y_{ab}^{u}\overline{Q}_a\widetilde{H}u_{R,b} + Y_{11}^{d}\overline{Q}_1 H d_{R,1} + Y_{ij}^{d}\overline{Q}_i H d_{R,j}$$

Model details

- Comparison between singlet and doublet flavons
  - Yukawas in singlet case

$$Y_u = \begin{pmatrix} y^u_{11} & y^u_{12} & y^u_{13} \\ y^u_{21} & y^u_{22} & y^u_{23} \\ y^u_{31} & y^u_{32} & y^u_{33} \end{pmatrix}, \quad Y_d = \begin{pmatrix} y^d_{11} & 0 & 0 \\ 0 & y^d_{22} & y^d_{23} \\ 0 & y^d_{32} & y^d_{33} \end{pmatrix}$$

diagonalizing matrices for Y_d: $U_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta^d_u & -\sin\theta^d_u \\ 0 & \sin\theta^d_u & \cos\theta^d_u \end{pmatrix}, \quad W_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta^d_w & -\sin\theta^d_w \\ 0 & \sin\theta^d_w & \cos\theta^d_w \end{pmatrix}$

$$\Rightarrow \quad -\mathcal{L}_{Z'} \supset \frac{g_{B-L}}{3}\left[\overline{d'}_{L,i}\gamma^\mu d'_{L,i} + \overline{d'}_{R,i}\gamma^\mu d'_{R,i}\right] Z'_\mu$$

$$\to \frac{g_{B-L}}{3}\left[\bar{d}_{L,i}\gamma^\mu d_{L,i} + \bar{d}_{R,i}\gamma^\mu d_{R,i}\right] Z'_\mu$$

No FVCs

- Only up sector has FVCs of Z’

Model details

- Comparison between singlet and doublet flavons

  - Yukawas in doublet case

$$Y_u = \begin{pmatrix} y^u_{11} & y^u_{12} & y^u_{13} \\ 0 & y^u_{22} & y^u_{23} \\ 0 & y^u_{32} & y^u_{33} \end{pmatrix}, \quad Y_d = \begin{pmatrix} y^d_{11} & 0 & 0 \\ y^d_{21} & y^d_{22} & y^d_{23} \\ y^d_{31} & y^d_{32} & y^d_{33} \end{pmatrix}$$

  diagonalizing matrices for Y_d: arbitrary 3 × 3 unitary matrices

$$\Rightarrow -\mathcal{L}_{Z'} \supset \frac{g_{B-L}}{3}\left[\overline{d'}_{L,i}\gamma^\mu d'_{L,i} + \overline{d'}_{R,i}\gamma^\mu d'_{R,i}\right] Z'_\mu$$

$$\to \frac{g_{B-L}}{3}\left[\overline{d}_{L,a}(U_d^\dagger U_d)_{ab}\gamma^\mu d_{L,b} + \overline{d}_{R,a}(W_d^\dagger W_d)_{ab}\gamma^\mu d_{R,b}\right] Z'_\mu$$

- Both up and down sectors have FVCs of Z'

Note: in both cases, there are no FVCs in charged leptons sector

Model details

- Comments on scalar sector

  - singlet flavon case

$$|D_\mu \mathcal{F}|^2 + |D_\mu \Phi|^2 \supset \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu$$

$$\Rightarrow \quad M_{Z'}^2 = g_{B-L}^2 \left(1/9 v_f^2 + 4 v_\phi^2\right) \sim \mathcal{O}(0.01\mathrm{GeV})^2 - \mathcal{O}(0.1\mathrm{GeV})^2$$

- $g_{B\text{-}L}$ should be $O(10^{-3})$ for $(g\text{-}2)_\mu$, then $v_f < 30 - 300$ GeV

  → $M_{U1} = \lambda_1 v_f / \sqrt{2}$ ~ 100 GeV

  ⇩

$Y_{ib} = \lambda_i \dfrac{M_{Ub}}{M_U}$ can be large enough to accommodate CKM when $M_U \sim O(10^{3\text{-}4})$ GeV

  - doublet flavon case → enough for CKM:

$$(m_u^0)_{1i} = \widetilde{Y}_{1i}^u v_{\mu\tau}/\sqrt{2} \quad \Rightarrow \quad v_{\mu\tau}/v_h \lesssim 1$$

Model details

- Comments on gauge sector

  - singlet flavon case → no mass mixing

    since there is no scalar which have both SM and $U(1)_{B\text{-}L}$ charges

  - doublet flavon case → $H_{\mu\tau}$ contributes to Z and Z' mass

$$M_G^2 = \frac{v_h^2}{4}\begin{pmatrix} g_Y^2(1+r_{\mu\tau}) & -g_Y g_2(1+r_{\mu\tau}) & \frac{2}{3}g_Y g_{B-L} r_{\mu\tau} \\ -g_Y g_2(1+r_{\mu\tau}) & g_2^2(1+r_{\mu\tau}) & -\frac{2}{3}g_2 g_{B-L} r_{\mu\tau} \\ \frac{2}{3}g_Y g_{B-L} r_{\mu\tau} & -\frac{2}{3}g_2 g_{B-L} r_{\mu\tau} & g_{B-L}^2\left(\frac{4}{9}r_{\mu\tau}+16 r_\phi\right) \end{pmatrix}$$

$r_{\mu\tau} \equiv \frac{v_{\mu\tau}^2}{v_h^2}$ and $r_\phi \equiv \frac{v_\phi^2}{v_h^2}$ in (B, W^3, Z') basis

- Because of the size of $g_{B\text{-}L}$ and $M_{Z'}$, we ignore mass mixing

  we also choose $r_{\mu\tau} \ll 1$ without loss of realization of $M_{Z'} \sim O(10)$ MeV

- In addition, there is kinetic mixing: $\mathcal{L} \supset -\frac{\chi}{2}F^{\mu\nu}Z'_{\mu\nu}$

  $\chi \sim O(10^{-4}\text{-}10^{-5})$ in our scenario

Kinetic mixing

- Kinetic mixing term can be written as $\mathcal{L} \supset -\frac{\chi}{2} F^{\mu\nu} Z'_{\mu\nu}$
- χ is estimated by calculation of vacuum polarization diagram

$$\chi = -\frac{e g_{B-L}}{12\pi^2} \sum_f Q_f Q_f^{B-L} \left[6 \int_0^1 dx\, x(1-x) \ln \left(\frac{m_f^2 - k^2 x(1-x)}{\mu^2} \right) \right]$$

- In doublet flavon model, χ is

$$\chi = -\frac{e g_{B-L}}{18\pi^2} \ln \left(\frac{m_c^2 m_t^2 m_\mu^3 m_\tau^3}{m_s m_b M_U^8} \right)$$

we assume $\chi = 0$ @ M_U

for singlet flavon case, simply set $M_U = m_t$

- If M_U = 1 TeV, $\chi = 4.6 \times 10^{-5}$ with $g_{B\text{-}L} = 5.5 \times 10^{-4}$

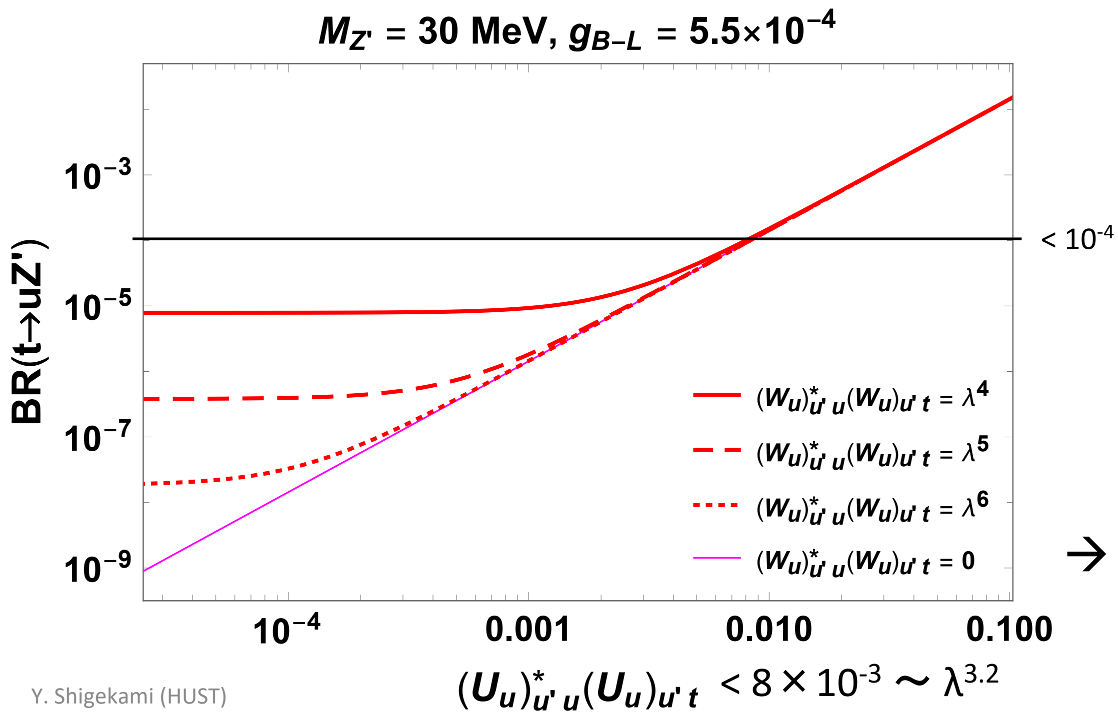
Singlet flavon model

- Comment on $t \to u\, Z'$ decay

  the difference only comes from x_q:

$$\Gamma(t \to qZ') \approx \frac{m_t^3}{32\pi} \underbrace{\lambda(1, x_q, x')^{1/2}}_{\fallingdotseq 1} \frac{|(g_L^u)_{qt}|^2 + |(g_R^u)_{qt}|^2}{M_{Z'}^2}$$

- We obtain (almost) same result for $t \to u\, Z'$ decay

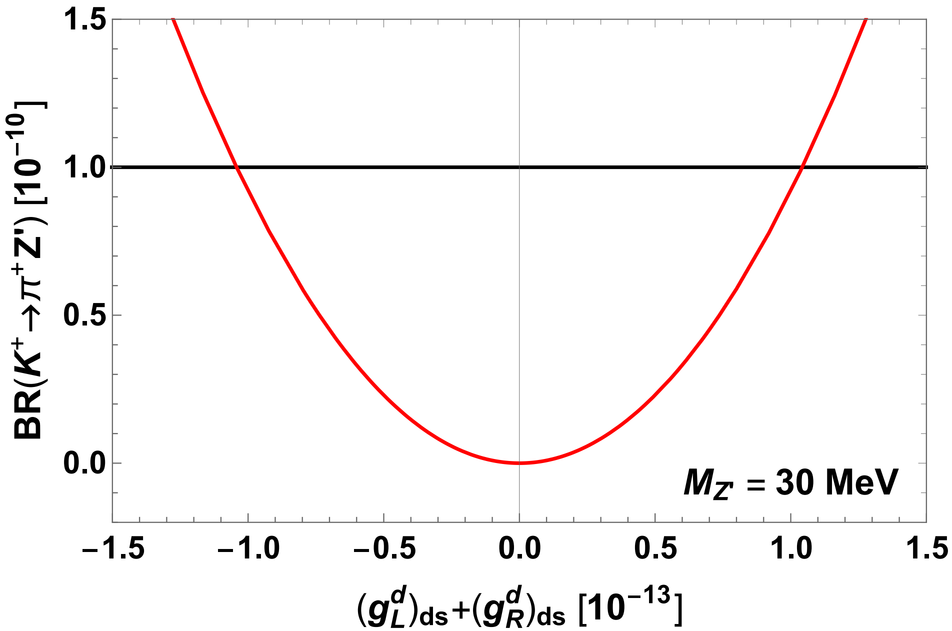


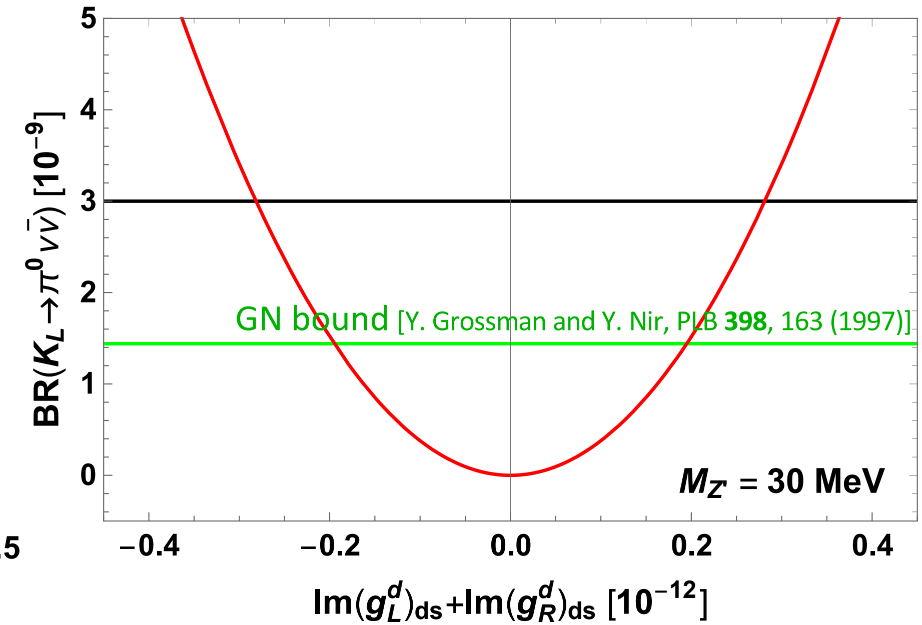
→ Consistent with the CKM matrix!

Doublet flavon model

A. V. Artamonov *et al.*[BNL-E949 Collab.], PRD **79**, 092004 (2009)
J. K. Ahn et al. [KOTO Collab.], PRL 122, 021802 (2019)

- Constraints: $\mathrm{BR}(K^+ \to \pi^+ Z') < 1.0 \times 10^{-10}$ for $M_{Z'} = 30$ MeV
$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} < 3.0 \times 10^{-9}$
- Results





$$|(g^d_L)_{ds} + (g^d_R)_{ds}| < 0.11 \times 10^{-12},$$
$$|\mathrm{Im}(g^d_L)_{ds} + \mathrm{Im}(g^d_R)_{ds}| < 0.28 \times 10^{-12} \quad (0.20 \times 10^{-12}\ (\text{GN bound}))$$