A model with flavor dependent U(1) gauge symmetry

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collaborated with

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(Paper is under preparation)

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1. Introduction

Quark and lepton flavor dependent U(1) gauge symmetry

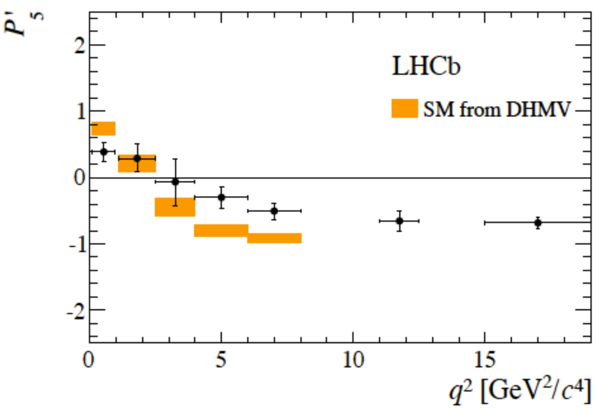
➡ Providing rich phenomenology

- Lepton flavor violation (LFV)
- Neutrino mass structure
- Collider physics
- Lepton flavor non-universality in meson decay
- Etc.

1. Introduction

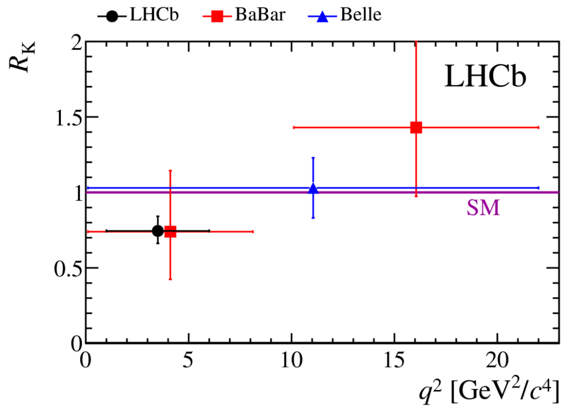
Recent interesting observations on B decay via $b \to s l^+ l^-$

❖ Observation of some anomalies in $B \to K^{(*)} l^+ l^-$



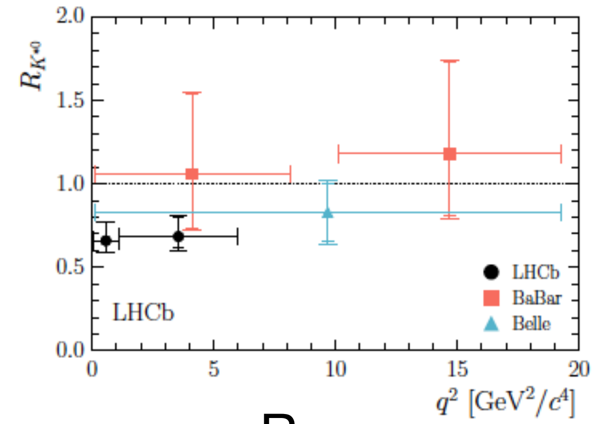
P'_5

LHCb, JHEP 1602 (2016) 104



R_K

LHCb, PRL 113 (2014) 151601



R_{K^*}

LHCb, JHEP 1708 (2017) 055

$$R_K \equiv \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \qquad R_{K^*} \equiv \frac{BR(B \to K^* \mu^+ \mu^-)}{BR(B \to K^* e^+ e^-)} \qquad \left(R_{K(K^*)}\right)^{SM} \approx 1$$

$$\left(R_K\right)^{\exp} = 0.745 \pm 0.09 \pm 0.036$$

[R. Aaij et al [LHCb] PRL 113, 151601 (2017)]

[S. Bifani, CERN seminar, April 18 (2017)]

$$\left(R_{K^*}\right)^{SM} = 1, \quad \left(R_K\right)^{\exp} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & (2m_\mu)^2 < q^2 < 1.1\,GeV^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & 1.1\,GeV^2 < q^2 < 6\,GeV^2 \end{cases}$$

~2.4 σ deviation from the SM

□ Angular distribution in $B \to K^{*}\mu^{+}\mu^{-}$ ($K^{*} \to K\pi$)

[S. Descotes-Genon et al, JHEP 1301, 048 (2013); LHCb JHEP 1602, 104]

The deviation in angular distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

θ_K : between K & B in K* rest frame

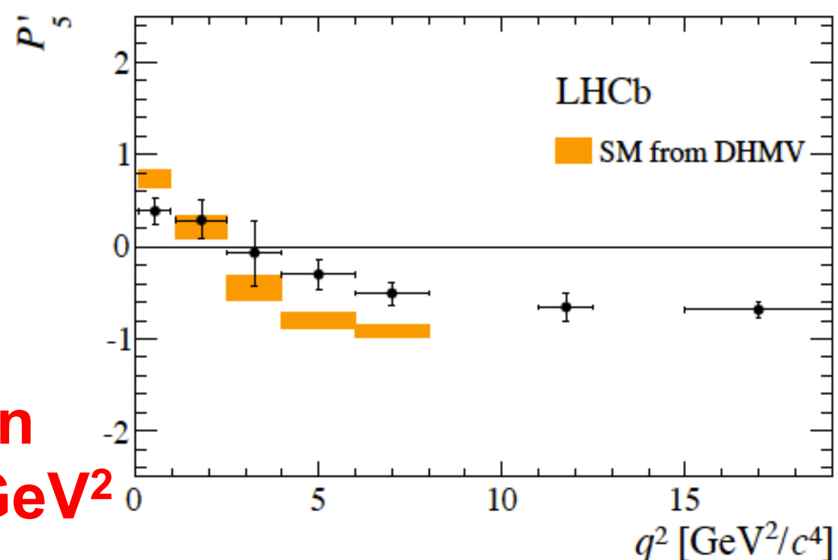
θ_l: between l and B in l^+l^- rest frame

Φ : between l^+l^- and $K\pi$ decay plane

The P_5' is deviated from SM

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

~3σ deviation @q^2= 4~8 GeV^2



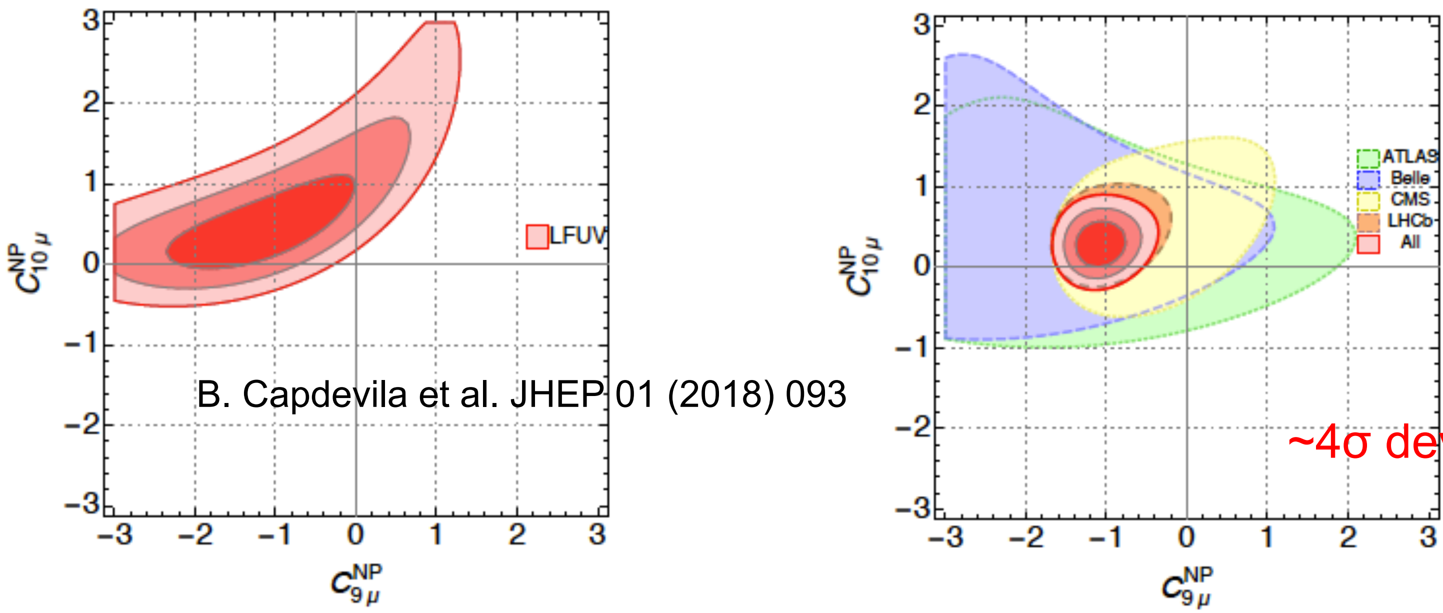
1. Introduction

✧ The relevant effective interaction terms

$\{C_9^{(')}, C_{10}^{(')}\}$: Wilson coefficients

$$H_{eff}^{l} \supset -\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}V_{tb}V_{ts}^{*}$$
$$\times\left[C_9^l\left(\bar{s}\gamma^{\mu}P_L b\right)\left(\bar{l}\gamma_{\mu}l\right)+\left(C_9^l\right)'\left(\bar{s}\gamma^{\mu}P_R b\right)\left(\bar{l}\gamma_{\mu}l\right)+C_{10}^l\left(\bar{s}\gamma^{\mu}P_L b\right)\left(\bar{l}\gamma_{\mu}\gamma^5 l\right)+\left(C_{10}^l\right)'\left(\bar{s}\gamma^{\mu}P_R b\right)\left(\bar{l}\gamma_{\mu}\gamma^5 l\right)\right]$$

Global fit for $b \to s l^+ l^-$ observables assuming NP



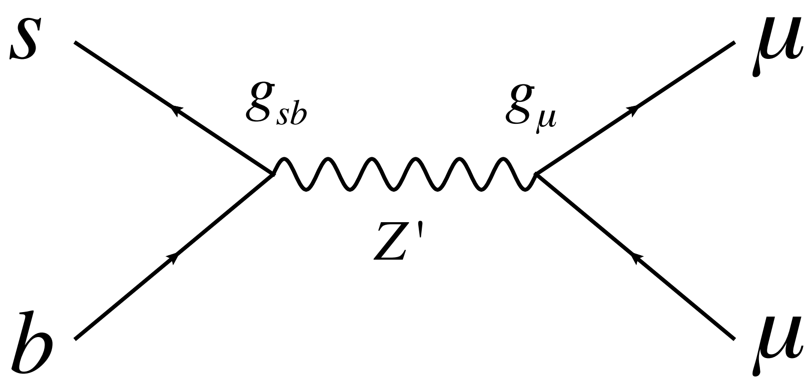
B. Capdevila et al. JHEP 01 (2018) 093

~4σ deviation from SM

❖ Indication to BSM from global fit : $C_9^{\mu(BSM)} \sim -1$

✧ Model with extra U(1) gauge symmetry

The effective interactions can be induced via Z' exchange at tree level



$$C_9^{\mu(Z')} \approx \frac{\pi}{\sqrt{2} V_{tb} V_{ts}^* \alpha G_F} \frac{g_{sb} g_\mu}{m_{Z'}^2}$$

✓ Flavor violating coupling in quark sector

- SM quarks have flavor dependent charge under extra local U(1)

  e.g. [A. Crivellin, G. D'Ambrosio, J. Heeck, PRD 91, 075006 (2015)]

- SM quarks mix with exotic quark with local U(1) charge

  e.g. [W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, PRD 89, 095033 (2014)]

- Loop induced Z'qq' interaction via exotic particles

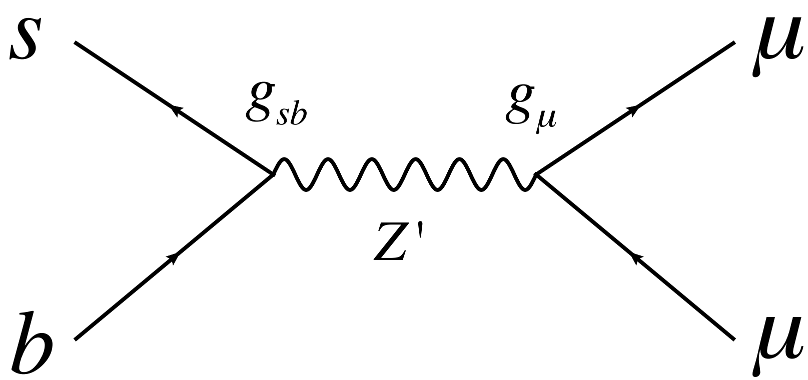
  e.g. Seunwon Baek arXiv:1707.04573

✓ Lepton flavor non-universality

- $U(1)_{\mu-\tau}$ (-like) gauge symmetry works

✧ Model with extra U(1) gauge symmetry

The effective interactions can be induced via Z' exchange at tree level



$$C_9^{\mu(Z')} \approx \frac{\pi}{\sqrt{2} V_{tb} V_{ts}^* \alpha G_F} \frac{g_{sb} g_\mu}{m_{Z'}^2}$$

✓

015)]

(2014)]

In this talk we discuss flavor dependent U(1) for both quark and lepton sector

$$U(1)_{B_3 - x_\mu L_\mu - x_\tau L_\tau}$$

e.g. Seunwon Baek arXiv:1707.04573

✓ **Lepton flavor non-universality**

- U(1)$_{\mu-\tau}$ (-like) gauge symmetry works

1. Introduction
2. A model
3. Phenomenology
4. Summary

2. A model

SM fermions + right-handed neutrino under $U(1)_X$

Fermions	Q_L^a	u_R^a	d_R^a	Q_L^3	t_R	b_R	L_L^1	L_L^2	L_L^3	e_R	μ_R	τ_R	ν_R^1	ν_R^2	ν_R^3
$SU(3)_C$	**3**	**3**	**3**	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	0	0
$U(1)_X$	0	0	0	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	$-x_\mu$	$-x_\tau$	0	$-x_\mu$	$-x_\tau$	0	$-x_\mu$	$-x_\tau$

Anomaly cancellation condition: $x_\mu + x_\tau = 1$

We fix the charge as $x_\mu = -\dfrac{1}{3}, \quad x_\tau = \dfrac{4}{3}$

Fields	Φ_1	Φ_2	φ_1	φ_2	χ
$SU(2)_L$	**2**	**2**	**1**	**1**	**1**
$U(1)_Y$	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0
$U(1)_X$	$-\frac{1}{3}$	0	$\frac{1}{3}$	1	$\frac{5}{6}$

Scalar + DM candidate (Dirac fermion)

Two-Higgs doublet + two singlet scalars

VEVs: $\langle \Phi_{1,2} \rangle = v_{1,2}/\sqrt{2}, \quad \langle \varphi_{1,2} \rangle = v_{\varphi_{1,2}}/\sqrt{2},$

2. A model

Yukawa couplings and mass for quarks

$$-\mathcal{L}_Q = y_{ij}^u \bar{Q}_{iL}\tilde{\Phi}_2 u_{jR} + y_{ij}^d \bar{Q}_{iL}\Phi_2 d_{jR} + y_{33}^u \bar{Q}_{3L}\tilde{\Phi}_2 t_R + y_{33}^d \bar{Q}_{3L}\Phi_2 b_R$$
$$+ \tilde{y}_{3i}^u \bar{Q}_{3L}\tilde{\Phi}_1 u_{iR} + \tilde{y}_{i3}^d \bar{Q}_{iL}\Phi_1 b_R + \text{h.c.},$$

$\langle \Phi_{1,2} \rangle = v_{1,2}/\sqrt{2}$ ⇒

$$M^u = \frac{1}{\sqrt{2}}\begin{pmatrix} v_2 y_{11}^u & v_2 y_{12}^u & 0 \\ v_2 y_{21}^u & v_2 y_{22}^u & 0 \\ v_1 \tilde{y}_{31}^u & v_1 \tilde{y}_{32}^u & v_2 y_{33}^u \end{pmatrix}, \quad M^d = \frac{1}{\sqrt{2}}\begin{pmatrix} v_2 y_{11}^d & v_2 y_{12}^d & v_1 \tilde{y}_{13}^d \\ v_2 y_{21}^d & v_2 y_{22}^d & v_1 \tilde{y}_{23}^d \\ 0 & 0 & v_2 y_{33}^d \end{pmatrix}$$

Mass matrices are diagonarized by $u_{L,R} \to U_{L,R}^\dagger u_{L,R} (d_{L,R} \to D_{L,R}^\dagger d_{L,R})$

When elements with v_1 are much smaller than those with v_2

$V_{CKM} \approx D_L, \quad D_R(U_L) \approx 1$ e.g. [A. Crivellin, G. D'Ambrosio, J. Heeck, PRD 91, 075006 (2015)]

⇒ Left-handed quark has flavor changing Z' interaction

Yukawa couplings and mass for leptons

$$-\mathcal{L} \supset y^e_{aa}\bar{L}_{aL}e_{aR}\Phi_2 + y^\nu_{aa}\bar{L}_{aL}\nu_{aR}\tilde{\Phi}_2 + \tilde{y}^e_{12}\bar{L}_{1L}\mu_R\Phi_1 + \tilde{y}^\nu_{21}\bar{L}_{2L}\nu_{1R}\tilde{\Phi}_1 + M\bar{\nu}^c_{1R}\nu_{1R} + Y_{12}\bar{\nu}^c_{1R}\nu_{2R}\varphi^*_1 + Y_{23}\bar{\nu}^c_{2R}\nu_{3R}\varphi^*_2 + h.c.,$$

Charged lepton mass

$$\langle \Phi_{1,2} \rangle = v_{1,2}/\sqrt{2}$$

$$M^e = \frac{1}{\sqrt{2}}\begin{pmatrix} y^e_{11}v_2 & \tilde{y}^e_{12}v_1 & 0 \\ 0 & y^e_{22}v_2 & 0 \\ 0 & 0 & y^e_{33}v_2 \end{pmatrix} \equiv \begin{pmatrix} m^e_{11} & \delta m^e_{12} & 0 \\ 0 & m^e_{22} & 0 \\ 0 & 0 & m^e_{33} \end{pmatrix}$$

diagonalize

$$\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \simeq V^e_L M^e (V^e_R)^\dagger \qquad V^e_R \simeq 1, \quad V^e_L \simeq \begin{pmatrix} 1 & -\epsilon & 0 \\ \epsilon & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\left(\varepsilon = \frac{\delta m^e_{12}}{\delta m^e_{22}} < 1 \right)$$

Yukawa couplings and mass for leptons

$$-\mathcal{L} \supset y^e_{aa}\bar{L}_{aL}e_{aR}\Phi_2 + y^\nu_{aa}\bar{L}_{aL}\nu_{aR}\tilde{\Phi}_2 + \tilde{y}^e_{12}\bar{L}_{1L}\mu_R\Phi_1 + \tilde{y}^\nu_{21}\bar{L}_{2L}\nu_{1R}\tilde{\Phi}_1$$
$$+ M\bar{\nu}^c_{1R}\nu_{1R} + Y_{12}\bar{\nu}^c_{1R}\nu_{2R}\varphi^*_1 + Y_{23}\bar{\nu}^c_{2R}\nu_{3R}\varphi^*_2 + h.c.,$$

Neutrino mass

$$\langle\Phi_{1,2}\rangle = v_{1,2}/\sqrt{2}, \quad \langle\varphi_{1,2}\rangle = v_{\varphi_{1,2}}/\sqrt{2},$$

Dirac mass matrix | Majorana mass matrix

$$M_D = \begin{pmatrix} (M_D)_{11} & 0 & 0 \\ (M_D)_{21} & (M_D)_{22} & 0 \\ 0 & 0 & (M_D)_{33} \end{pmatrix}, \quad M_{\nu_R} = \begin{pmatrix} (M_{\nu_R})_{11} & (M_{\nu_R})_{12} & 0 \\ (M_{\nu_R})_{21} & 0 & (M_{\nu_R})_{23} \\ 0 & (M_{\nu_R})_{32} & 0 \end{pmatrix}$$

$$m_\nu \simeq -M_D M^{-1}_{\nu_R} M^T_D$$
$$= \begin{pmatrix} \frac{(M_D)^2_{11}}{(M_{\nu_R})_{11}} & \frac{(M_D)_{11}(M_D)_{21}}{(M_{\nu_R})_{11}} & -\frac{(M_D)_{11}(M_D)_{33}(M_{\nu_R})_{12}}{(M_{\nu_R})_{11}(M_{\nu_R})_{32}} \\ \frac{(M_D)_{11}(M_D)_{21}}{(M_{\nu_R})_{11}} & \frac{(M_D)^2_{21}}{(M_{\nu_R})_{11}} & \frac{(M_D)_{33}(M_D)_{22}}{(M_{\nu_R})_{32}}\left(1 - \frac{(M_D)_{21}(M_{\nu_R})_{12}}{(M_{\nu_R})_{11}(M_D)_{22}}\right) \\ -\frac{(M_D)_{11}(M_D)_{33}(M_{\nu_R})_{12}}{(M_{\nu_R})_{11}(M_{\nu_R})_{32}} & \frac{(M_D)_{33}(M_D)_{22}}{(M_{\nu_R})_{32}}\left(1 - \frac{(M_D)_{21}(M_{\nu_R})_{12}}{(M_{\nu_R})_{11}(M_D)_{22}}\right) & \frac{(M_D)^2_{33}(M_{\nu_R})^2_{12}}{(M_{\nu_R})_{11}(M_{\nu_R})^2_{23}} \end{pmatrix}$$

Flavor dependent Z' interaction

- Quark sector

$$\frac{g_X}{3}\bar{t}\gamma^\mu t Z'_\mu + \frac{g_X}{3}\left(\bar{d}_\alpha\gamma^\mu P_L d_\beta \Gamma^{d_L}_{\alpha\beta} + \bar{d}_\alpha\gamma^\mu P_R d_\beta \Gamma^{d_R}_{\alpha\beta}\right) Z'_\mu$$

$$\Gamma^{d_L} \simeq \begin{pmatrix} |V_{td}|^2 & V_{ts}V^*_{td} & V_{tb}V^*_{td} \\ V_{td}V^*_{ts} & |V_{ts}|^2 & V_{tb}V^*_{ts} \\ V_{td}V^*_{tb} & V_{ts}V^*_{tb} & |V_{tb}|^2 \end{pmatrix}, \quad \Gamma^{d_R} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Charged lepton sector

$$\mathcal{L} \supset -\frac{g_X}{3}\bar{\ell}_i\gamma^\mu \left[V_L \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 4 \end{pmatrix} V_L^\dagger \right]_{ij} P_L \ell_j Z'_\mu - \frac{g_X}{3}\bar{\ell}_i\gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 4 \end{pmatrix}_{ij} P_R \ell_j Z'_\mu,$$

$$V_L \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 4 \end{pmatrix} V_L^\dagger \simeq \begin{pmatrix} -\epsilon^2 & \epsilon & 0 \\ \epsilon & -1 & 0 \\ 0 & 0 & 4 \end{pmatrix}.$$

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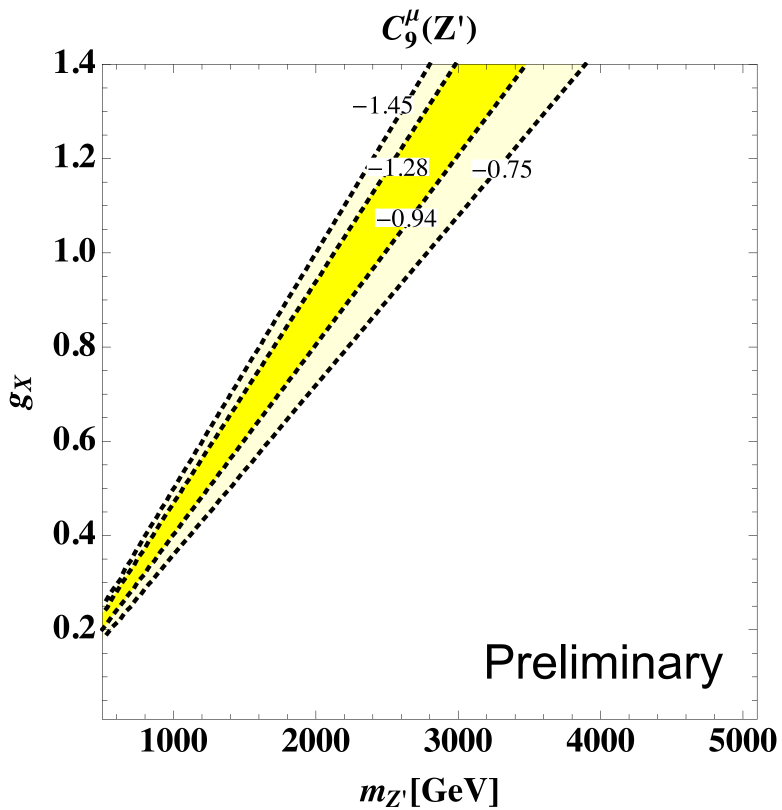
$C_9(\mu)$ from Z' exchange

$$\Delta H_{\rm eff} = -\frac{x_\mu g_X^2 V_{tb} V_{ts}^*}{3 m_{Z'}^2} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu) + h.c.,$$
$$= \frac{x_\mu g_X^2}{3 m_{Z'}^2} \left(\frac{\sqrt{2}\pi}{G_F \alpha_{em}} \right) \left(\frac{-4 G_F}{\sqrt{2}} \frac{\alpha_{em}}{4\pi} V_{tb} V_{ts}^* \right) (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu) + h.c.,$$

$$\Delta C_9^\mu = \frac{x_\mu g_X^2}{3 m_{Z'}^2} \left(\frac{\sqrt{2}\pi}{G_F \alpha_{em}} \right),$$
$$\simeq 0.174 \times x_\mu \left(\frac{g_X}{0.1} \right)^2 \left(\frac{1\ \mathrm{TeV}}{m_{Z'}} \right)^2$$



We can obtain required C_9

1(2)σ region from global fit in 1704.0534

$$-1.28(-1.45) \le C_9^{NP} \le -0.94(-0.75)$$

Constraint from B_s – B_s bar mixing

❖ Effective Hamiltonian

$$H_{eff} = C_1(\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma_\mu P_L b) + C_2'(\bar{s}P_R b)(\bar{s}P_R b)$$

$$C_1 = \frac{1}{2}\frac{g_X^2}{9m_{Z'}^2}(\Gamma_{sb}^{d_L})^2 \qquad C_2' = \sum_{\eta=h,H,A}\frac{-1}{2m_\eta^2}(\Gamma_{sb}^\eta)^2$$

From Z' exchange

From scalar boson exchange (Γ_{sb} : Yukawa coupling)

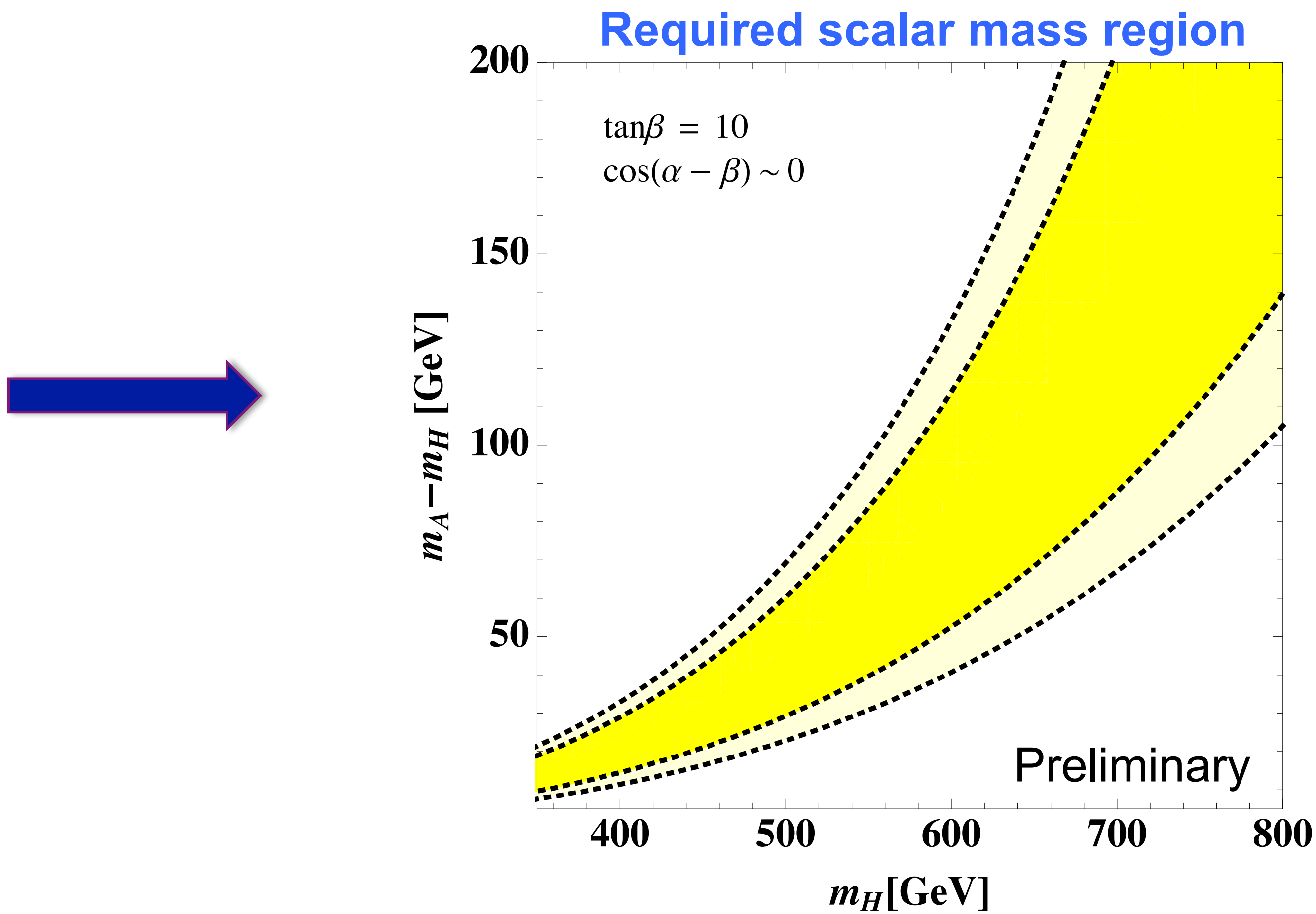
$$\begin{aligned} R_{B_s} &= \frac{\Delta m_{B_s}}{\Delta m_{B_s}^{SM}} \\ &\simeq \frac{g_X^2 (V_{tb}V_{ts}^*)^2}{9m_{Z'}^2}(8.2\times 10^{-5}\ \mathrm{TeV}^{-2})^{-1} \\ &+ \left[0.12\cos^2(\alpha-\beta)\tan^2\beta + 0.19\tan^2\beta\left(\frac{(200\ \mathrm{GeV})^2}{m_H^2} - \frac{(200\ \mathrm{GeV})^2}{m_A^2}\right)\right] \end{aligned}$$

It is compared with experimental bound: $0.83 < R_{B_s} < 0.99$

P. Arnan, L. Hofer, F. Mescia, A. Crivellin, JHEP 1704, 043 (2017)

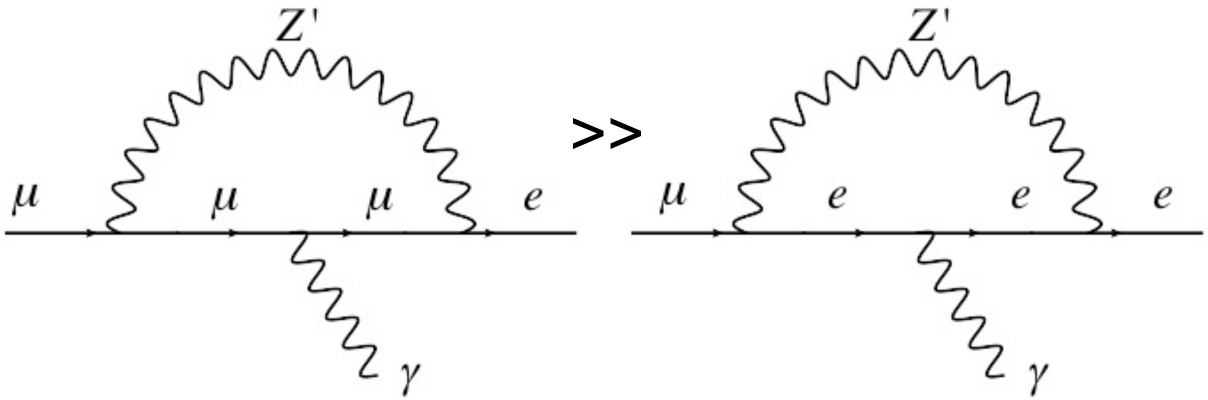
Constraint from B_s – B_s bar mixing

- ✓ When we obtain $C_9(Z')$ ~ −1, R_{Bs} deviate from experimental bound
- ✓ Scalar contributions are necessary for compensation



LFV constraint

LFV Z’ interaction induce μ→eγ decay



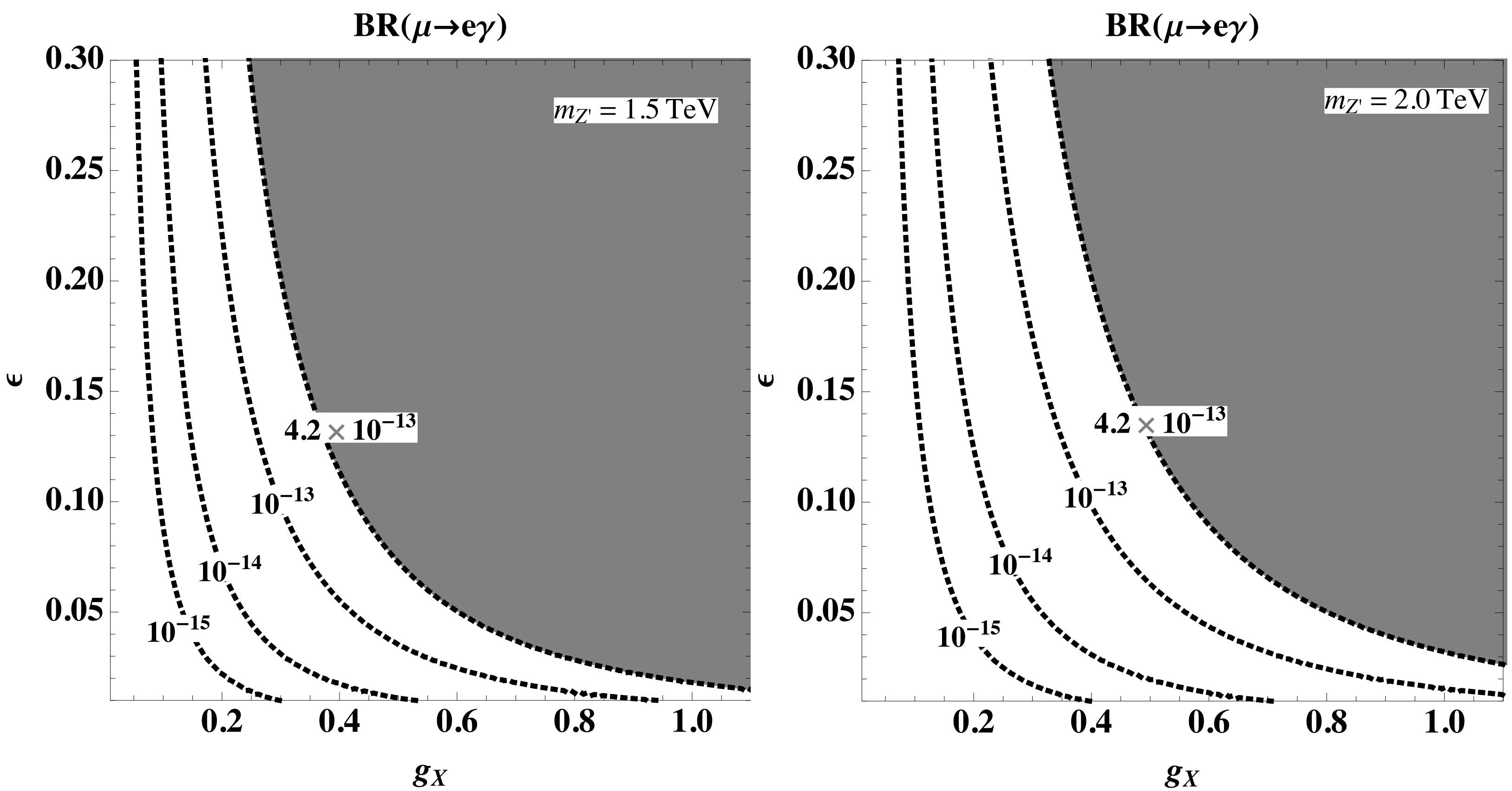
$$\Gamma_{\mu\to e\gamma} \simeq \frac{e^2 m_\mu^3}{16\pi}|a_R|^2,$$

$$a_R \simeq \frac{e\epsilon g_X^2 m_\mu}{144\pi^2}\int_0^1 dxdydz\delta(1-x-y-z)\frac{2x(1+y)}{[(x^2-x)+xz+y+z]m_\mu^2+xm_{Z'}^2}$$

➡ $$BR(\mu\to e\gamma) = \frac{\Gamma_{\mu\to e\gamma}}{\Gamma_{\mu\to e\bar{\nu}_e\nu_\mu}} \simeq \frac{12\alpha}{G_F^2 m_\mu^2}|a_R|^2$$

LFV constraint

LFV Z' interaction induce μ→eγ decay

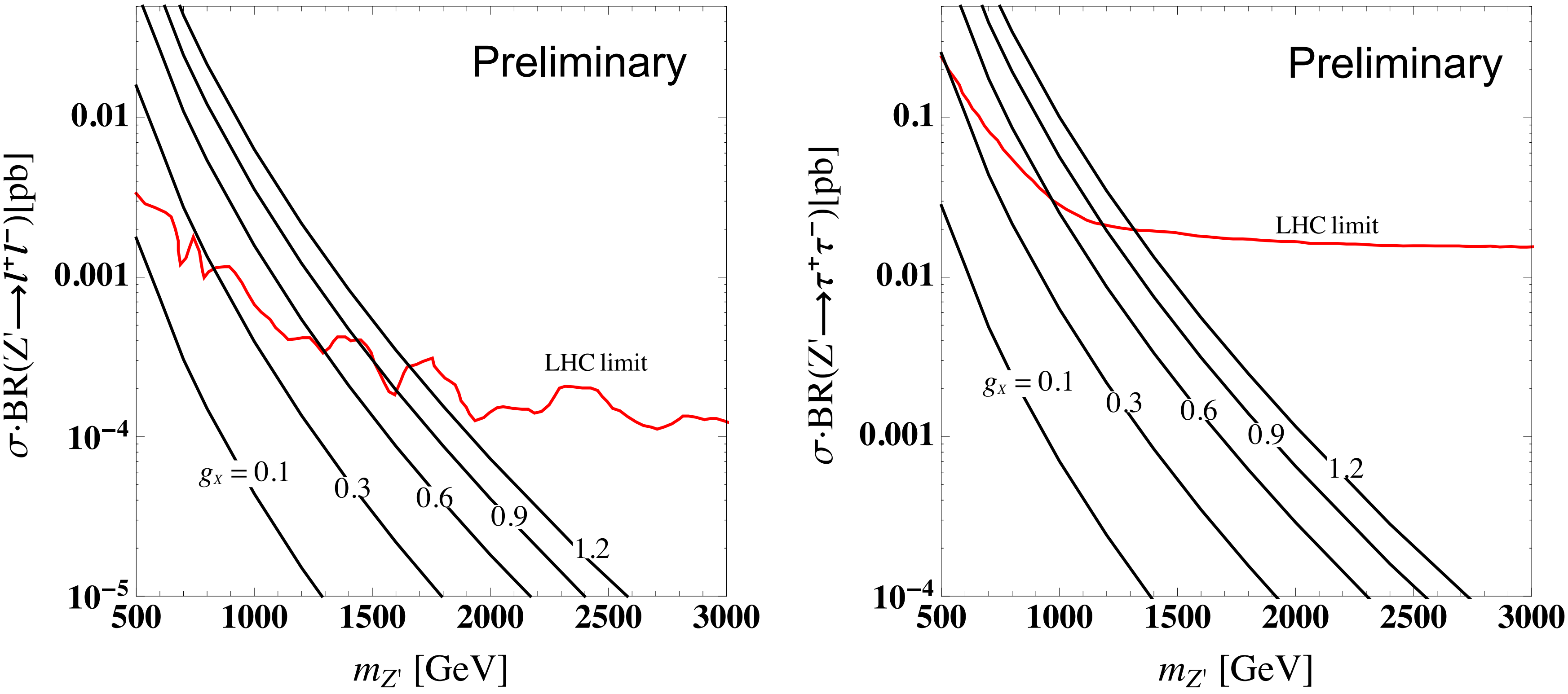


Experimental bound: $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$

[MEG Collaboration] EPJC 76, no.8, 434 (2016)

Z' production at the LHC

[ATLAS Collaboration] JHEP 1710, 182 (2017)
[CMS Collaboration] JHEP 1702, 048 (2017)

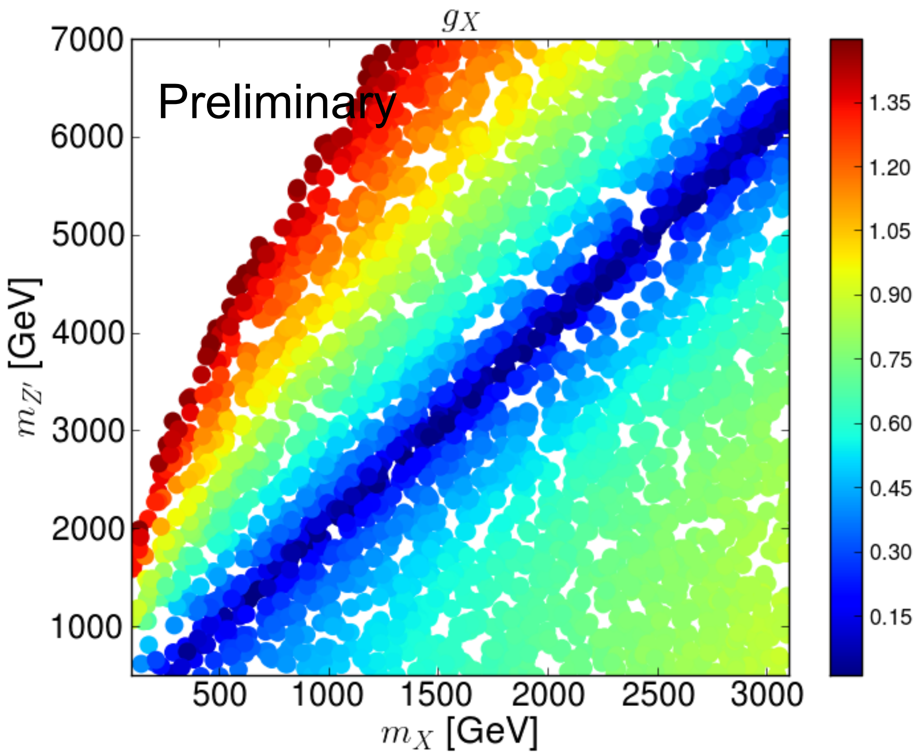


- ✓ Z' is produced via Z'-quark coupling
- ✓ Dominant decay mode is tau pair mode
- ✓ The strongest bound is from mu pair mode

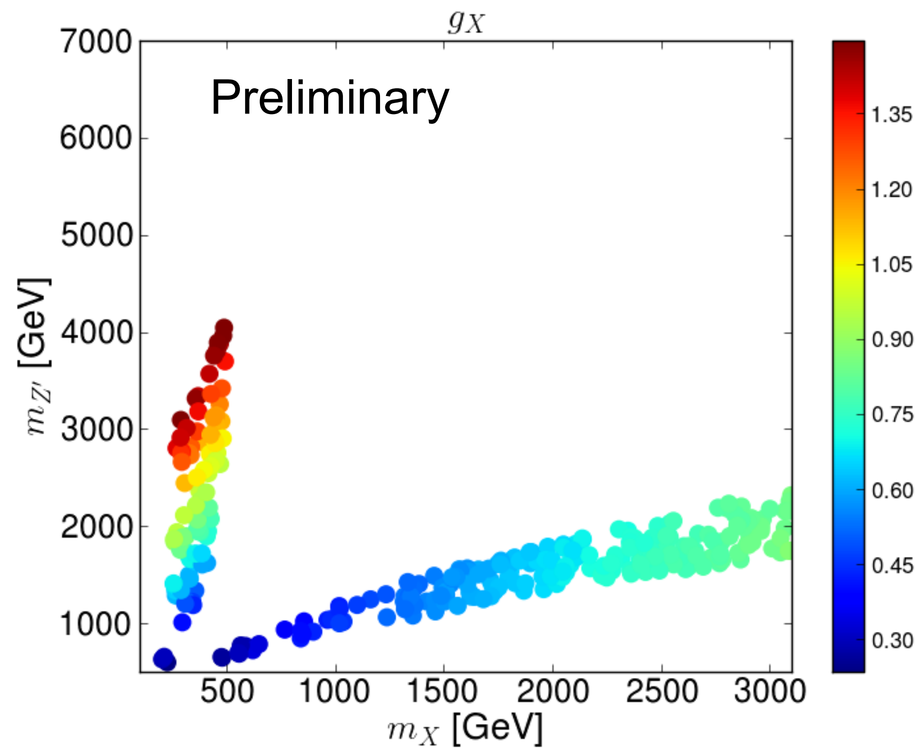
DM relic density

Relic density is obtained by DM DM $\rightarrow$ Z' $\rightarrow$ f f
DM DM $\rightarrow$ Z' Z'

Relic density is estimated by micrOMEGAs



Region explain DM relic density



Region explain DM relic density + C_9

The region is consistent with collider constraint for $m_{Z'} \gtrsim 1000$ GeV

Summary and Discussions

- A model with flavor dependent gauge symmetry
  - ✓ Introducing $U(1)_{B3 - x\mu L\mu - x\tau L\tau}$ gauge symmetry
  - ✓ DM candidate is introduced: Dirac fermion with fractional U(1) charge
  - ✓ Neutrino mass matrix from type-I seesaw mechanism

- DM physics
  - ✓ $B \to K^{(*)} l^+ l^-$ anomalies can be explained by Z' interaction
  - ✓ Flavor constraints are considered
  - ✓ Z' production at the LHC
  - ✓ DM relic density is explained by Z' interaction

Appendix

Higgs potential

$$V = \mu(\Phi_1^\dagger \Phi_2 \varphi_1^* + \text{h.c.}) + \mu_{11}^2|\Phi_1|^2 + \mu_{22}^2|\Phi_2|^2 - \mu_{\varphi_1}^2|\varphi_1|^2 + \mu_{\varphi_2}^2|\varphi_2|^2$$
$$+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \lambda_{\varphi_1}|\varphi_1|^4 + \lambda_{\varphi_2}|\varphi_2|^4$$
$$+ \lambda_{\Phi_1\varphi_1}|\Phi_1|^2|\varphi_1|^2 + \lambda_{\Phi_2\varphi_1}|\Phi_2|^2|\varphi_1|^2 + \lambda_{\Phi_1\varphi_2}|\Phi_1|^2|\varphi_2|^2 + \lambda_{\Phi_2\varphi_2}|\Phi_2|^2|\varphi_2|^2 + \lambda_{\varphi_1\varphi_2}|\varphi_1|^2|\varphi_2|^2$$
$$- \lambda_X(\varphi_1^3\varphi_2^* + h.c.) \qquad \text{(II.11)}$$

$$\langle \varphi_{1,2} \rangle = v_{\varphi_{1,2}} / \sqrt{2}$$

$$V_{2HDM} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2,$$
$$m_{1(2)}^2 = \mu_{11(22)}^2 + \frac{1}{2}\lambda_{\Phi_{1(2)}\varphi_1}v_{\varphi_1}^2 + \frac{1}{2}\lambda_{\Phi_{1(2)}\varphi_2}v_{\varphi_2}^2, \quad m_3^2 = \frac{1}{\sqrt{2}}\mu v_{\varphi_1}$$

Two-Higgs doublet type scalar potential

Yukawa interactions with Two-Higgs doublets

$$
\begin{aligned}
\mathcal{L}_Y = & -\bar{u}_L\left(\frac{\cos\alpha}{v\sin\beta}m_u^D - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^u\right)u_R h - \bar{d}_L\left(\frac{\cos\alpha}{v\sin\beta}m_d^D - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right)d_R h \\
& -\bar{u}_L\left(\frac{\sin\alpha}{v\sin\beta}m_u^D - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^u\right)u_R H - \bar{d}_L\left(\frac{\sin\alpha}{v\sin\beta}m_d^D - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right)d_R H \\
& -i\bar{u}_L\left(\frac{m_u^D}{v\tan\beta} - \frac{1}{\sqrt{2}\sin\beta}\tilde{\xi}^u\right)u_R A + i\bar{d}_L\left(\frac{m_d^D}{v\tan\beta} - \frac{1}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right)d_R A \\
& -\left[\bar{u}_R\left(\frac{\sqrt{2}}{v\tan\beta}m_u^D V - \frac{1}{\sin\beta}(\tilde{\xi}^u)^\dagger\right)d_L + \bar{u}_L\left(\frac{\sqrt{2}}{v\tan\beta}V m_d^D - \frac{1}{\sin\beta}V\tilde{\xi}^d\right)d_R\right]H^+ \\
& + h.c.\,, \qquad \text{(V.1)}
\end{aligned}
$$

$$
\tilde{\xi}^d \simeq V^\dagger \xi^d \simeq \frac{\sqrt{2}}{\cos\beta}\frac{m_b}{v}\begin{pmatrix} 0 & 0 & -V_{td}^* V_{tb} \\ 0 & 0 & -V_{ts}^* V_{tb} \\ 0 & 0 & 1-|V_{tb}|^2 \end{pmatrix}
$$