# flavor dependent U(1) gauge symmetry and related phenomenology

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P.Ko (KIAS), T.N, C.Yu (Korea Univ.) JHEP 1904, 1902.06107

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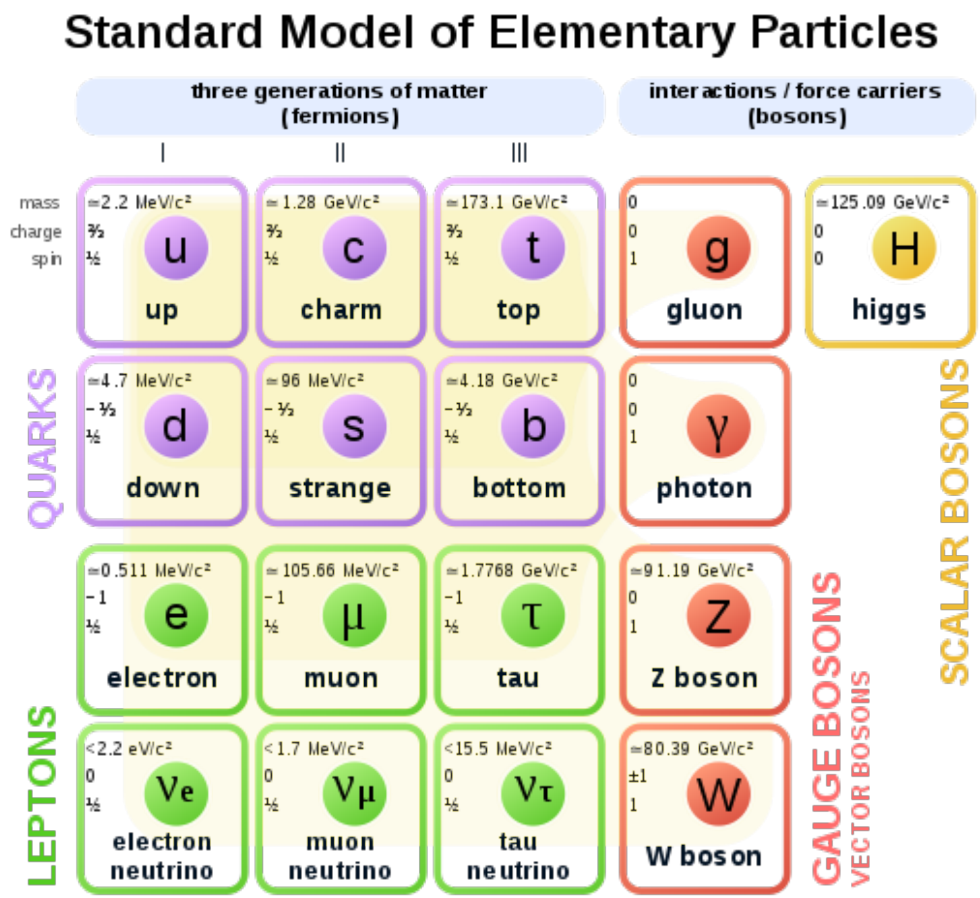
# The standard model (SM) of particle physics is successful



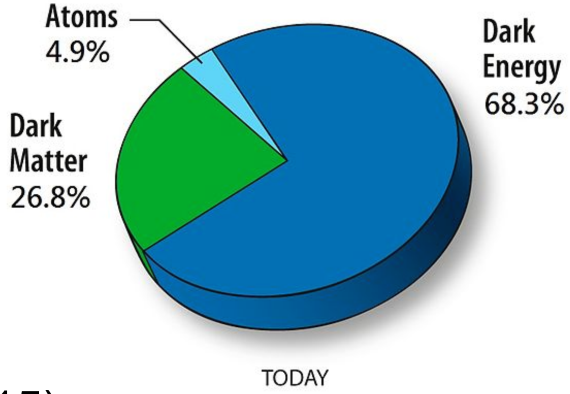

The SM is based on gauge symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$

However there should be beyond the SM (BSM) physics

1. Introduction

## Some issues suggesting BSM physics

### ☐ Existence of dark matter in our Universe




- ❖ **Rotation of spiral galaxies**
- ❖ **Formation of Large scale structure**
- ❖ **CMB anisotropy : WMAP, Planck**

➡ $\Omega_{DM}h^2 = 0.1188 \pm 0.0010$ Planck (2015)

### ☐ Non-zero neutrino mass

- ❖ **We need a mechanism to generate neutrino mass**
- ❖ **Also smallness of the mass should be explained**

### ☐ Some indication related to flavor

- ❖ **Anomalous muon magnetic moment (muon g-2)**
- ❖ **Lepton non-universality in B-meson decay observations**

1. Introduction

One simple extension of the SM

⇨ A model with extra U(1) gauge symmetry

◆ The SM is based on gauge symmetry

⇨ **The BSM would be also described by a gauge symmetry**

◆ It restricts interactions :
good for phenomenological model building

- Forbid neutrino mass at tree level
- Stabilizing dark matter
- Application to flavor structure
- U(1) breaking scalar VEV → Higgs physics
- Etc.

## An extra U(1) would appear from higher scale

- From grand unified theory (GUT)

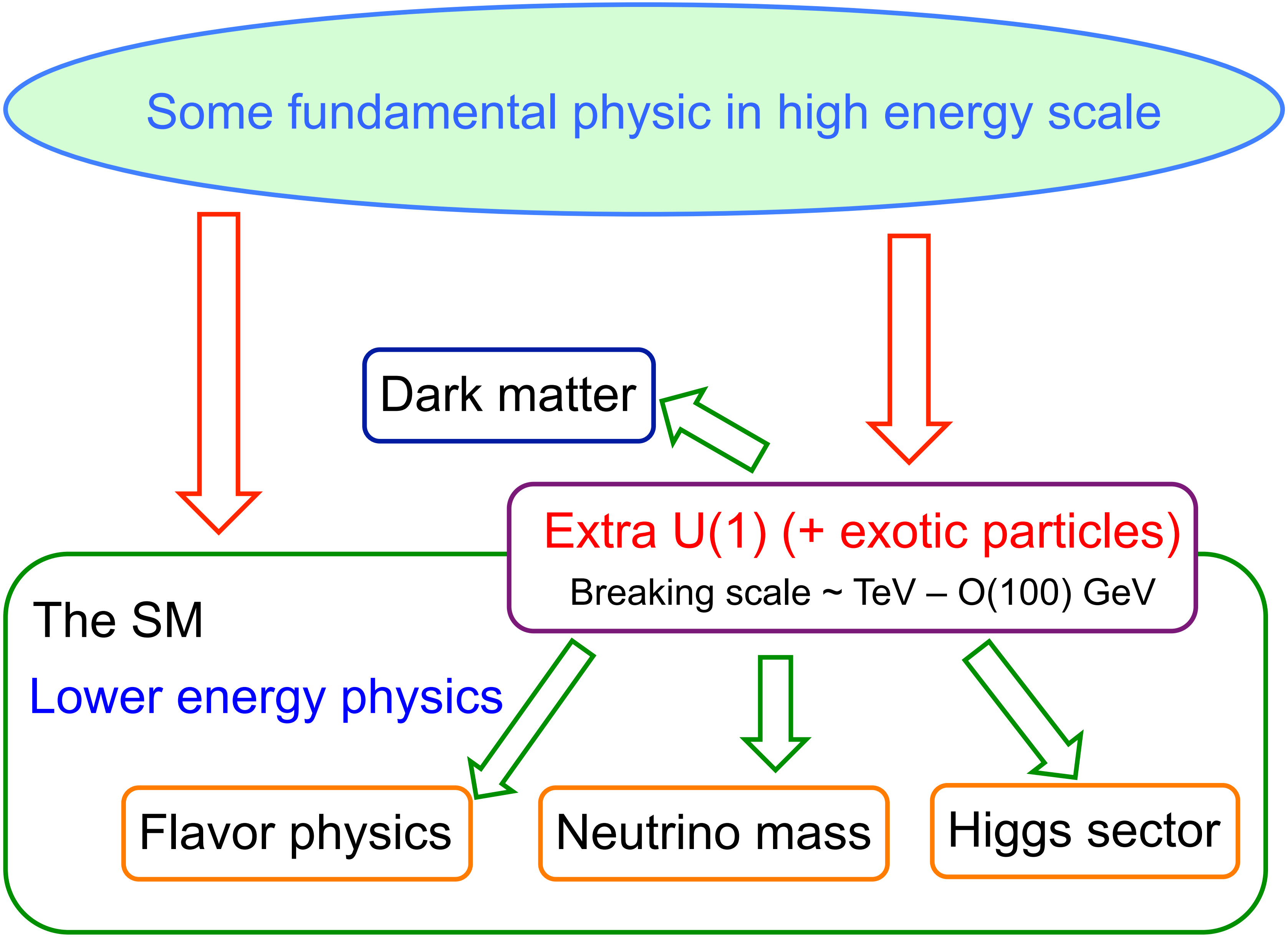
$$SO(10) \supset SU(3)\times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \supset SU(3)\times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

$$E_6 \supset SO(10)\times U(1)_\psi \supset SU(5)\times U(1)_\psi \times U(1)_\chi$$

- From other gauge extended theories
- From string theory
- Etc.

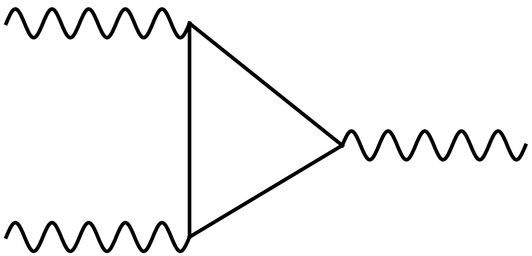
**In ~TeV scale we may just see the SM + extra U(1) gauge symmetry**

# 1. Introduction



## Gauge anomaly free conditions

In constructing a consistent extra $U(1)_X$ gauge symmetric model charge assignment of fermion contents should be anomaly free



$$\sum_f \left( Tr[T_i T_j T_k]_R - Tr[T_i T_j T_k]_L \right) = 0$$

$T_i$ : generator of gauge group

$[SU(3)_c]^2\, U(1)_X$ $\quad [SU(2)_L]^2\, U(1)_X$

$[U(1)_Y]^2\, U(1)_X$ $\quad [U(1)_X]^2\, U(1)_Y$

$[U(1)_X]^3$ $\quad [\text{gravity}]^2\, U(1)_X$

**Conditions in addition to the SM gauge anomaly free conditions**

1. Introduction

## Possibilities of anomaly free U(1) model

### Flavor dependent charge assignment

Simple case: $U(1)_{e-\mu},\quad U(1)_{e-\tau},\quad U(1)_{\mu-\tau}$

Two generation of leptons has opposite U(1) charge

→ Anomaly cancellation between generations

Light Z' boson has been discussed in this framework

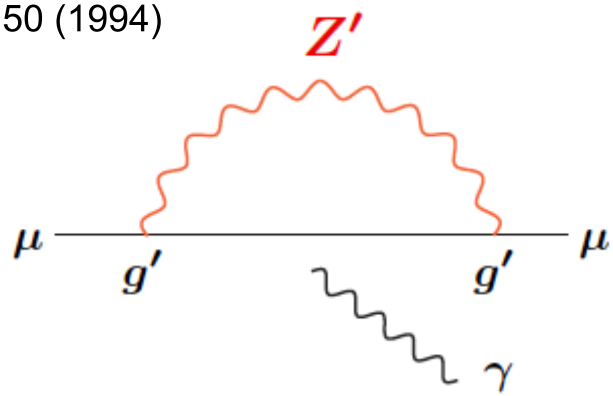
→ In particular $U(1)_{\mu-\tau}$ is motivated by muon g-2

He, Joshi, Lew, Volkas PRD 43 (1991)
He, Lew, Volkas PRD 50 (1994)

$$\Delta a_\mu \equiv \Delta a_\mu^{\exp} - \Delta a_\mu^{th} = (27.1 \pm 7.3) \times 10^{-10}$$

(1802.02995)

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



# Possibilities of anomaly free U(1) model

## More general anomaly free flavor dependent case

$$U(1)_X : X = \sum_i c_i (B-L)_i + A(L_e - L_\tau) + B(L_e - L_\mu) + C(L_\mu - L_\tau)$$

Ex) $U(1)_X : X = B_i - x_e L_e - x_\mu L_\mu - x_\tau L_\tau$ (i=1,2,3)

Anomaly free for $x_e + x_\mu + x_\tau = 1$

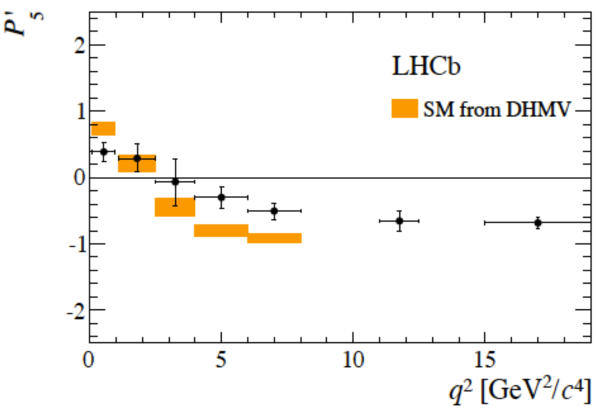
Both lepton and quark flavor dependent U(1)

- Applications to flavor physics
- **Explanation of b→sμμ anomalies**
- Neutrino mass structure is constrained
- Specific signature at collider experiments
- Muon g-2 explanation
- Etc.

Talk by Yoshihiro Shigekami

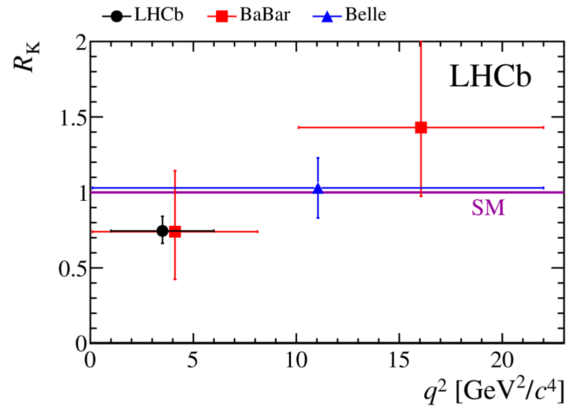
# Recent interesting observations on B decay via $b \to s l^+ l^-$

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



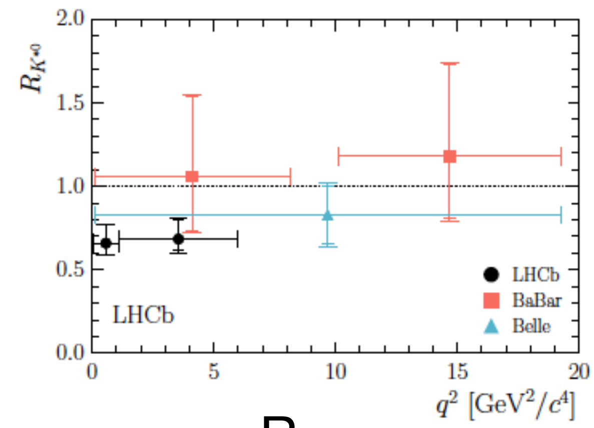

$P'_5$

LHCb, JHEP 1602 (2016) 104




$R_K$

LHCb, PRL 113 (2014) 151601




$R_{K^*}$

LHCb, JHEP 1708 (2017) 055

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

$$\left(R_K\right)^{\exp} = 0.846^{+0.060\,+0.016}_{-0.054\,-0.014} \qquad 1.1\,GeV^2 < q^2 < 6\,GeV^2$$

[R. Aaij et al [LHCb] PRL 122, 191801 (2019)]

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

**~2.5 σ deviation from the SM**

LHCb, JHEP 1708 (2017) 055

## ☐ 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

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

$\theta_K$ : between K & B in K* rest frame

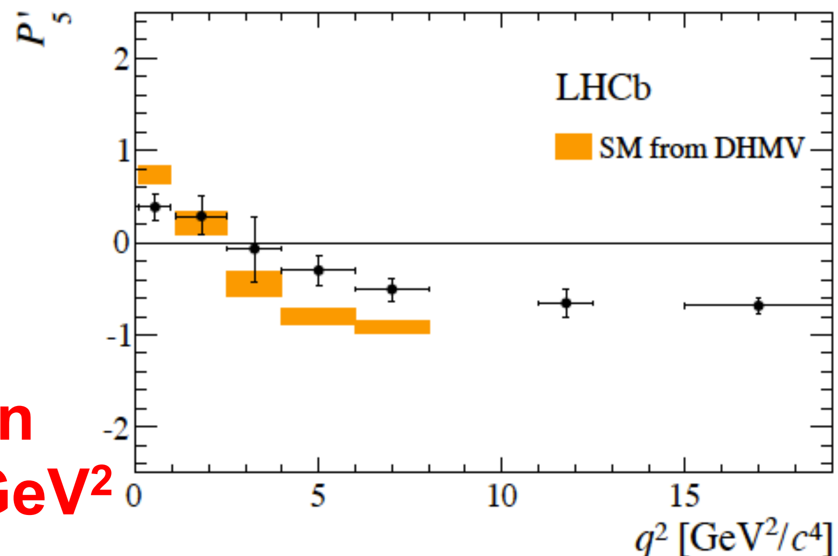
$\theta_l$: between l and B in $l^+l^-$ rest frame

Φ : between $l^+l^-$ and Kπ 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 $GeV^2$**



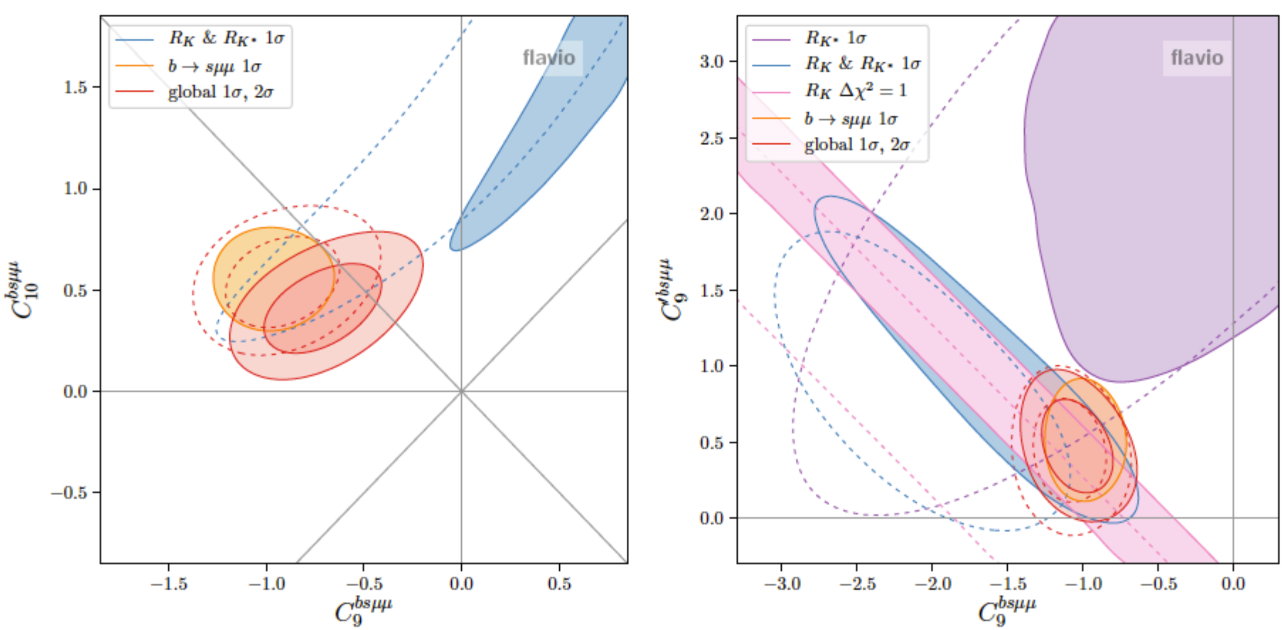
1. Introduction

# ✧ The relevant effective interaction terms

$\{C_9^{(\prime)}, C_{10}^{(\prime)}\}$ : 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 $b\to sl^+l^-$ observables assuming NP

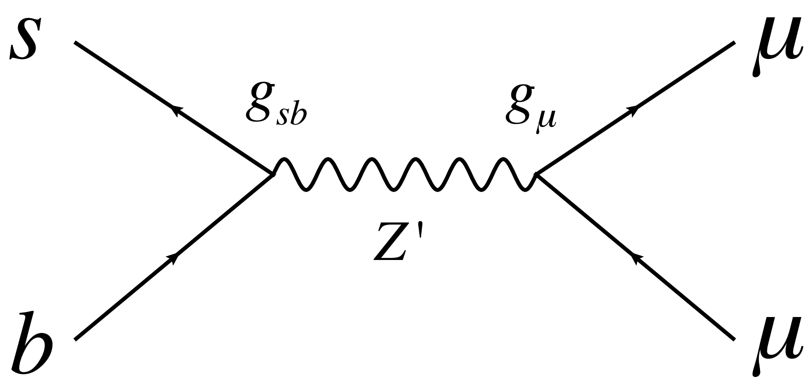



Aebischer et. al. 1903.10434

❖ 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

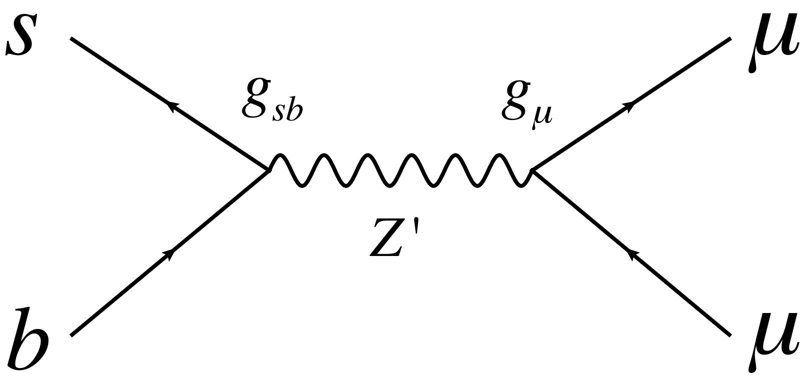
  e.g. Seunwon Baek arXiv:1707.04573

✓ **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**




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

✓

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

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

(P.Ko, T.N, C.Yu JHEP 1904, 1902.06107)

015)]

(2014)]

e.g. Seunwon Baek arXiv:1707.04573

✓ **Lepton flavor non-universality**

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

1. Introduction
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3. Phenomenology
4. Summary

2. A model

# Model with $SU(3)\times SU(2)_L\times U(1)_Y\times U(1)_X$

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

| Fermions | $Q_L^a$ | $u_R^a$ | $d_R^a$ | $Q_L^3$ | $t_R$ | $b_R$ | $L_L^1$ | $L_L^2$ | $L_L^3$ | $e_R$ | $\mu_R$ | $\tau_R$ | $\nu_R^1$ | $\nu_R^2$ | $\nu_R^3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_C$ | **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 | $\Phi_1$ | $\Phi_2$ | $\varphi_1$ | $\varphi_2$ | $\chi$ |
|---|---|---|---|---|---|
| $SU(2)_L$ | **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: $\langle \Phi_{1,2} \rangle = v_{1,2}/\sqrt{2}, \quad \langle \varphi_{1,2} \rangle = v_{\varphi_{1,2}}/\sqrt{2},$

## ☐ Interactions in the model

### Yukawa interactions of quarks

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

### Z' interaction with fermion

$$L \supset -g_X\left(x_\mu \bar{\mu}\gamma^\alpha \mu + x_\tau \bar{\tau}\gamma^\alpha \tau + x_\mu \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu + x_\tau \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau + x_\mu \bar{\nu}_\mu \gamma^\alpha P_R \nu_\mu + x_\tau \bar{\nu}_\tau \gamma^\alpha P_R \nu_\tau\right) Z'_\alpha + \frac{g_X}{3}\bar{t}\gamma^\alpha t Z'_\alpha + \frac{g_X}{3}\bar{b}\gamma^\alpha b Z'_\alpha$$

This is in flavor basis

Flavor changing Z' interaction appears in mass basis

2. A model

# Quark mass and Flavor changing interactions

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

$$M^u = \frac{1}{\sqrt{2}}\begin{pmatrix} v_2 y^u_{11} & v_2 y^u_{12} & 0 \\ v_2 y^u_{21} & v_2 y^u_{22} & 0 \\ 0 & 0 & v_2 y^u_{33} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ (\xi_u)_{31} & (\xi_u)_{32} & 0 \end{pmatrix}$$

$$(\xi_{u,d})_{ij} \equiv \tilde{y}^{u,d}_{ij} v_1/\sqrt{2}$$

$$M^d = \frac{1}{\sqrt{2}}\begin{pmatrix} v_2 y^d_{11} & v_2 y^d_{12} & 0 \\ v_2 y^d_{21} & v_2 y^d_{22} & 0 \\ 0 & 0 & v_2 y^d_{33} \end{pmatrix} + \begin{pmatrix} 0 & 0 & (\xi_d)_{13} \\ 0 & 0 & (\xi_d)_{23} \\ 0 & 0 & 0 \end{pmatrix}.$$

Mass matrices are diagonalized by Unitary transformation

$$u_L \to U_L u_L, \quad u_R \to U_R u_R \quad d_L \to D_L d_L, \quad d_R \to D_R d_R$$

The mass matrices can be approximated (for small ξ)

$$U_{L,R} \approx 1, \quad D_R \approx 1, \quad D_L \approx V_{CKM}$$

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

## Quark mass and Flavor changing interactions

### In flavor basis

$$L \supset g_X \begin{pmatrix} \bar{u} \\ \bar{c} \\ \bar{t} \end{pmatrix}^T \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix} Z'_\mu + g_X \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}^T \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} Z'_\mu$$

### In mass basis

$$u_L \to U_L u_L, \quad u_R \to U_R u_R \quad d_L \to D_L d_L, \quad d_R \to D_R d_R$$

$$U_{L,R} \approx 1, \quad D_R \approx 1, \quad D_L \approx V_{CKM}$$

$$\Rightarrow \begin{cases} \dfrac{g_X}{3} \bar{t} \gamma^\mu t Z'_\mu + \dfrac{g_X}{3} \left( \bar{d}_\alpha \gamma^\mu P_L d_\beta \Gamma^{d_L}_{\alpha\beta} + \bar{d}_\alpha \gamma^\mu P_R d_\beta \Gamma^{d_R}_{\alpha\beta} \right) Z'_\mu \\ \Gamma^{d_L} \simeq \begin{pmatrix} |V_{td}|^2 & V_{ts} V_{td}^* & V_{tb} V_{td}^* \\ V_{td} V_{ts}^* & |V_{ts}|^2 & V_{tb} V_{ts}^* \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & |V_{tb}|^2 \end{pmatrix}, \quad \Gamma^{d_R} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{cases}$$

# Neutrino mass

- Lepton Yukawa interactions

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

Dirac mass | Majorana mass

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

$$(M_D)_{aa} = \frac{1}{\sqrt{2}}y^\nu_{aa}v_2, \quad (M_D)_{21} = \frac{1}{\sqrt{2}}\tilde{y}_{21}v_1,$$

$$(M_{\nu_R})_{11} = M, \quad (M_{\nu_R})_{12(21)} = \frac{1}{\sqrt{2}}Y_{12}v_{\varphi_1}, \quad (M_{\nu_R})_{23(32)} = \frac{1}{\sqrt{2}}Y_{23}v_{\varphi_2}.$$

Type-I seesaw

$$m_\nu \simeq -M_D M^{-1}_{\nu_R} M^T_D$$

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

# Charged lepton mass and LFV interactions

- Charged lepton mass matrix

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

It can be diagonalized as (δm << m)

$$\begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \simeq V^e_L M^e (V^e_R)^\dagger, \quad V^e_R \simeq 1, \quad V^e_L \simeq \begin{pmatrix} 1 & -\epsilon & 0 \\ \epsilon & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \epsilon = \delta m^e_{12} / m^e_{22}$$

- Lepton flavor violating Z' interactions

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

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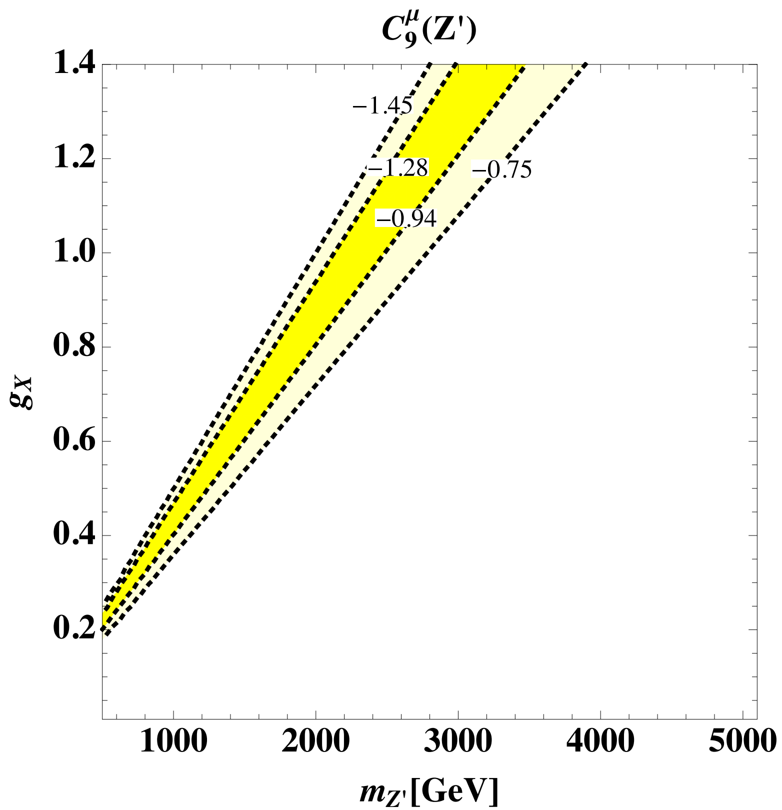
# $C_9(\mu)$ from Z' exchange

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

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




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 ($\Gamma_{sb}$ : Yukawa coupling)

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

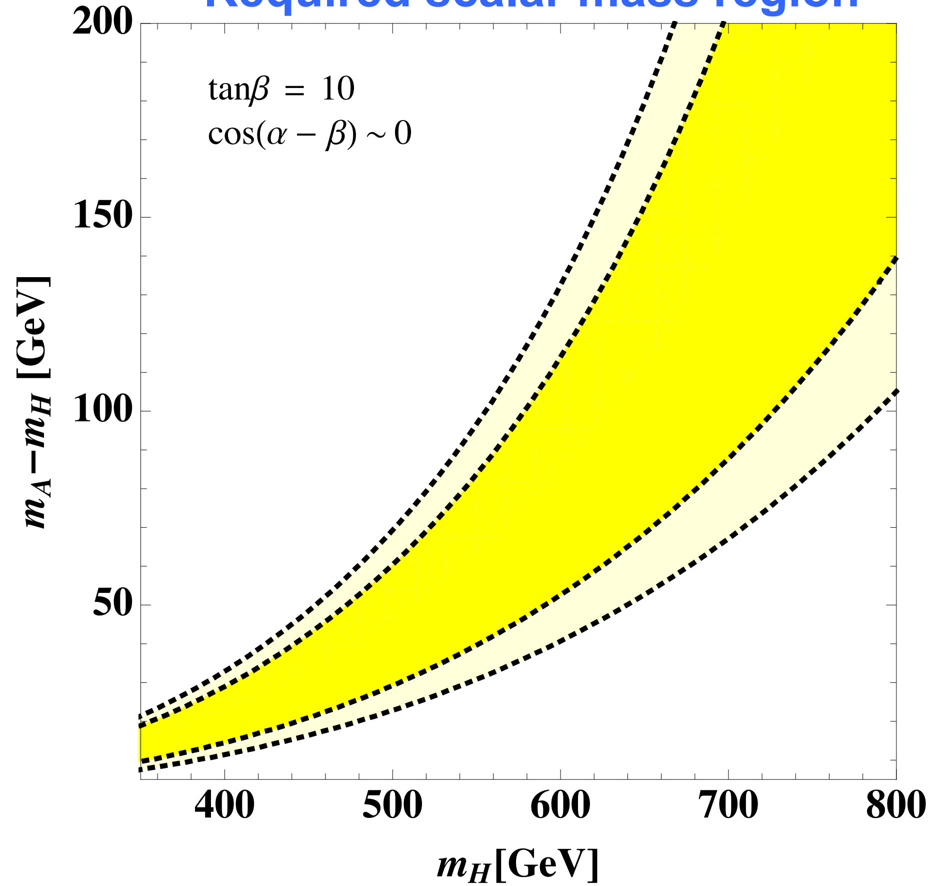
It is compared with experimental bound: $0.83 < R_{B_s} < 0.99$

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

# Constraint from $B_s$ – $B_s$ bar mixing

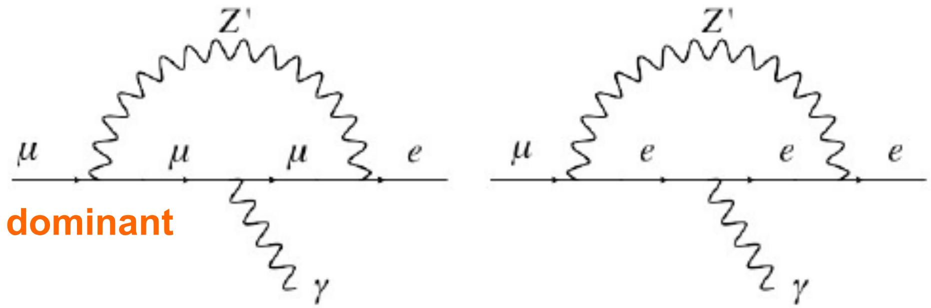
- ✓ When we obtain $C_9(Z')$ ~ −1, $R_{Bs}$ deviate from experimental bound
- ✓ Scalar contributions are necessary for compensation

Required scalar mass region



# LFV processes via Z' interactions

- $\mu \to e\,\gamma$




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

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

- $\mu \to e$ conversion

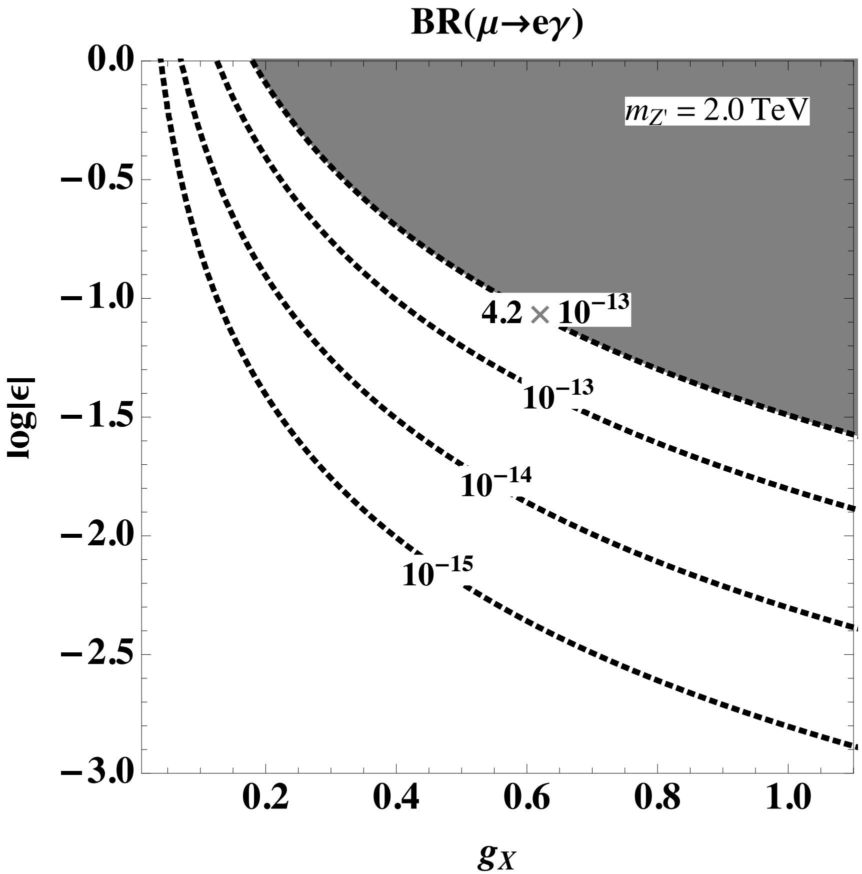
$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\sum_{N=p,n}\left[C_{VL}^{NN}\bar{e}\gamma^\alpha P_L \mu \bar{N}\gamma_\alpha N + C_{AL}^{NN}\bar{e}\gamma^\alpha P_L \mu \bar{N}\gamma_\alpha\gamma_5 N\right]$$

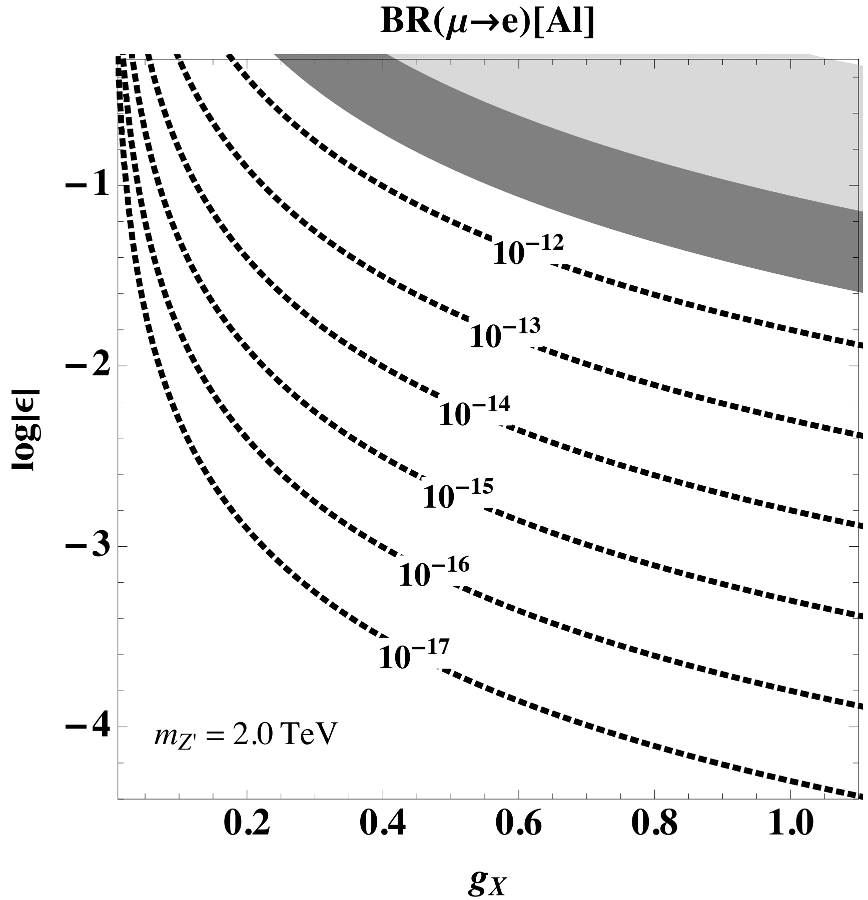
$$BR(\mu\to e) = \frac{32 G_F^2 m_\mu^5}{\Gamma_{cap}}\left|C_{VL}^{pp}V^{(p)} + C_{VL}^{nn}V^{(n)}\right|^2$$

$$\left(C_{VL}^{pp(nn)} = -C_{AL}^{pp(nn)} = (2)\frac{\sqrt{2}\epsilon g_X^2|V_{td}|^2}{216 G_F m_{Z'}^2}\right)$$

Y. Kuno and Y. Okada, Rev. Mod. Phys. **73**, 151 (2001) [hep-ph/9909265].

# LFV processes via Z' interactions



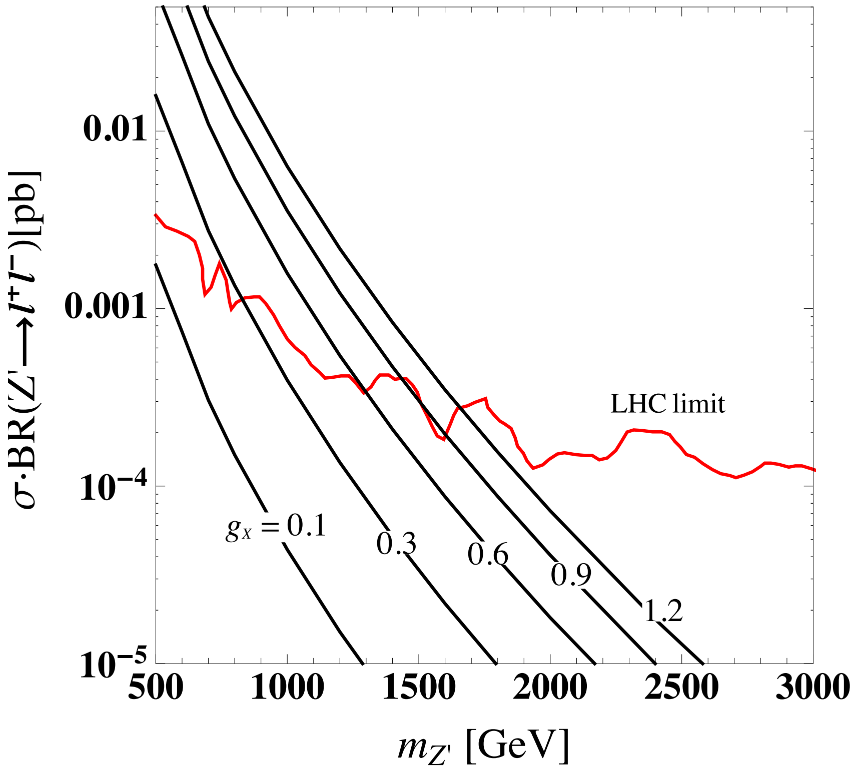



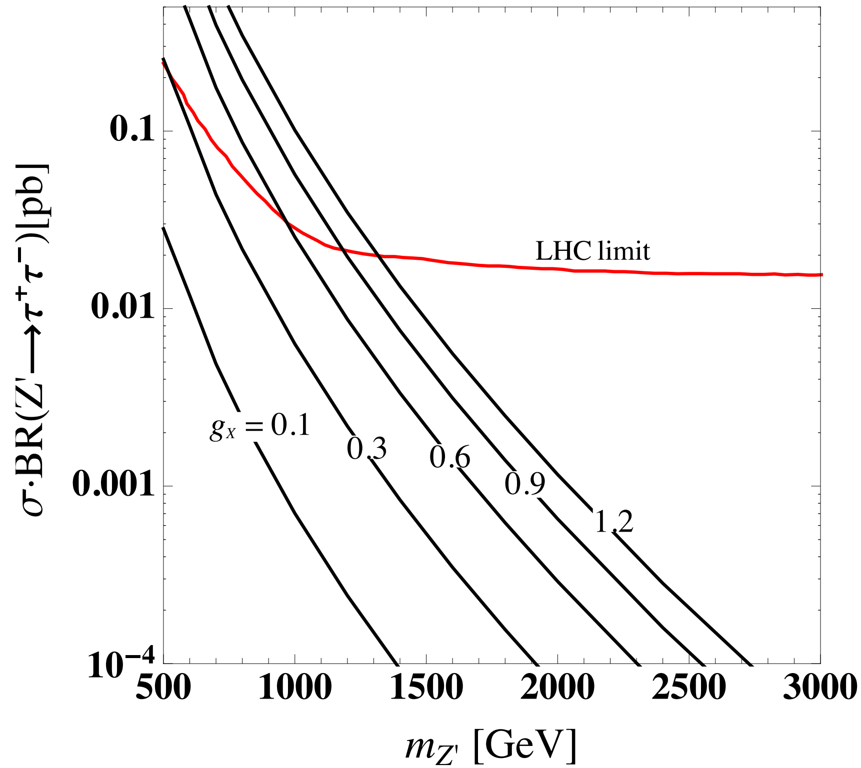

| Nucleus ${}^A_Z N$ | $V^p$ | $V^n$ | $\Gamma_{\rm capt}$ [$10^6$sec$^{-1}$] |
|---|---|---|---|
| ${}^{27}_{13}$Al | 0.0161 | 0.0173 | 0.7054 |
| ${}^{197}_{79}$Au | 0.0974 | 0.146 | 13.07 |

R. Kitano, M. Koike and Y. Okada, Phys. Rev. D **66**, 096002 (2002) Erratum: [Phys. Rev. D **76**, 059902 (2007)] [hep-ph/0203110].

# 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

# Dark matter relic density in the model

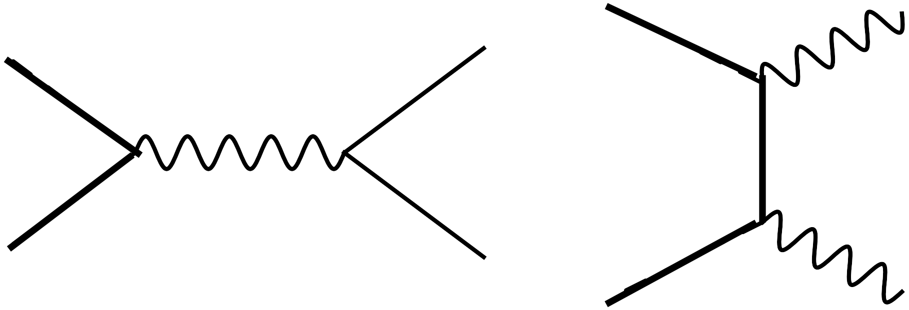
We focus on Z' interaction of DM

$$L \supset i\frac{5}{6} g_X Z'_\mu \bar{\chi}\gamma^\mu \chi$$

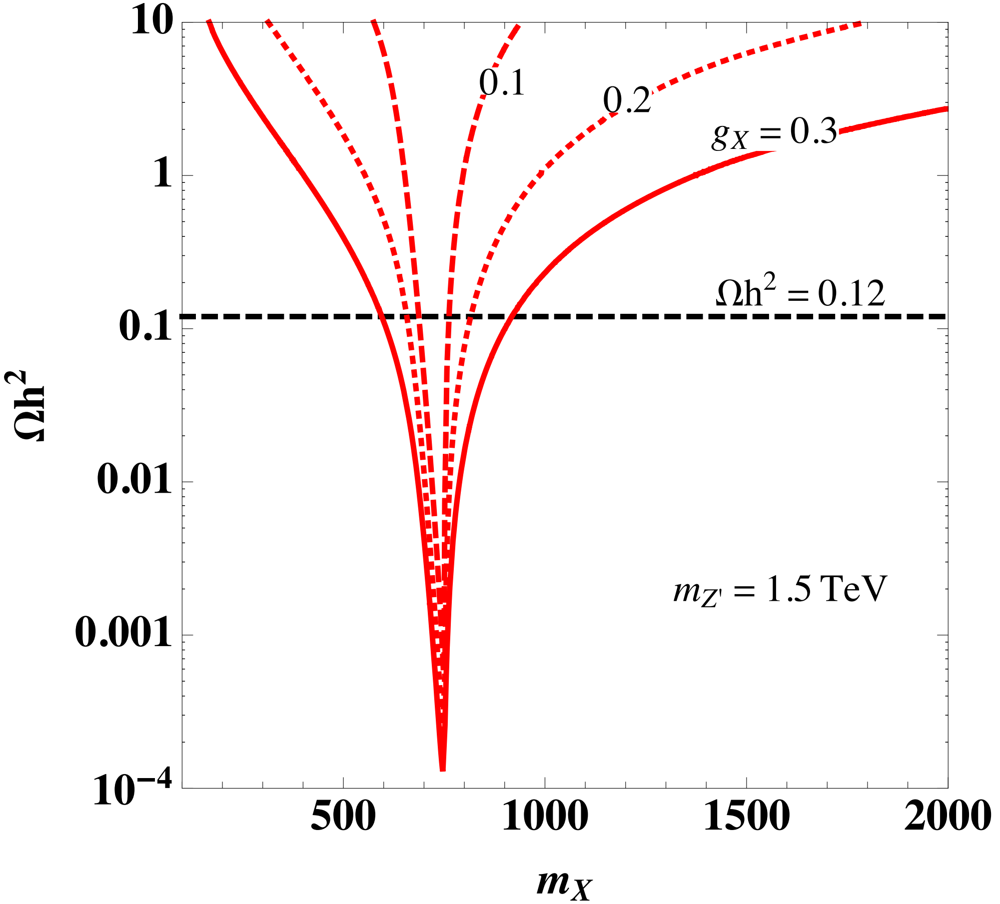
(Higgs portal interaction is highly constrained by direct detection constraint)

Relic density is determined by annihilation processes:

$$\chi^* \chi \to Z' \to f_{SM}\bar{f}_{SM}, HA, H^+H^-, \quad \chi^* \chi \to Z'Z'$$

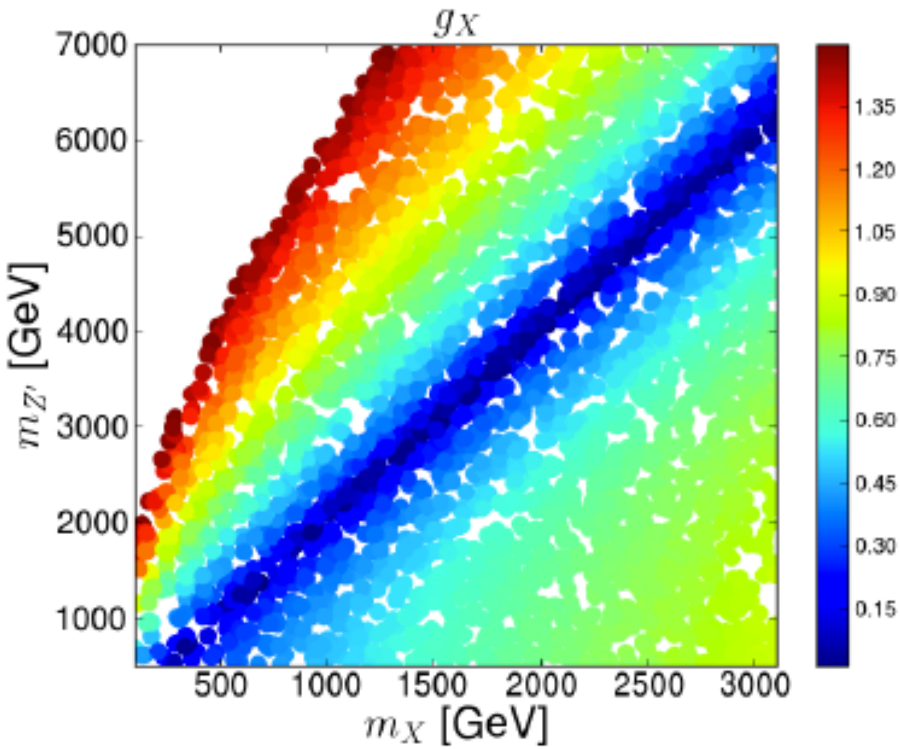


# Behavior of relic density of DM

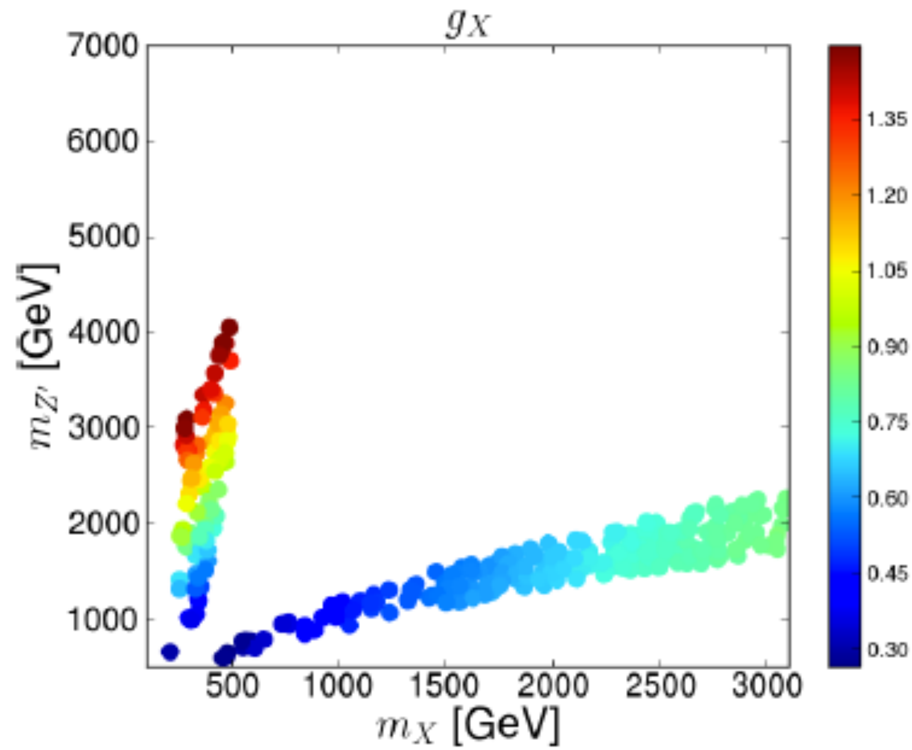



- Small relic density for $m_{Z'} \sim 2\ m_X$ due to resonant effect
- We get allowed parameter region requiring $\Omega h^2 \sim 0.12$

# Parameter region accommodating with observed relic density




$0.11 < \Omega h^2$ 0.13 only




Relic density + $\Delta C_9 \sim -1$

- ✓ Non resonant region is rather preferred including $\Delta C_9 \sim -1$ requirement
- ✓ The region is consistent with collider constraint for $m_{Z'} > 1000$ 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

- **Z' and 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

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

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

$$
\begin{aligned}
V_{2HDM} =& m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + h.c.) \\
&+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2,
\end{aligned}
$$

$$m_{1(2)}^2 = \mu_{11(22)}^2 + \frac{1}{2}\lambda_{\Phi_{1(2)}\varphi_1}v_{\varphi_1}^2 + \frac{1}{2}\lambda_{\Phi_{1(2)}\varphi_2}v_{\varphi_2}^2, \quad m_3^2 = \frac{1}{\sqrt{2}}\mu v_{\varphi_1}$$

Two-Higgs doublet type scalar potential

# Yukawa interactions with Two-Higgs doublets

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

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