A model of loop induced Z’ coupling explaining $B \to K^{(*)} \ell^+ \ell^-$ anomalies and dark matter

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Collaborated with P. Ko and H. Okada

Based on: PRD 95 no.11 111701 (2017) [Rapid Communications]

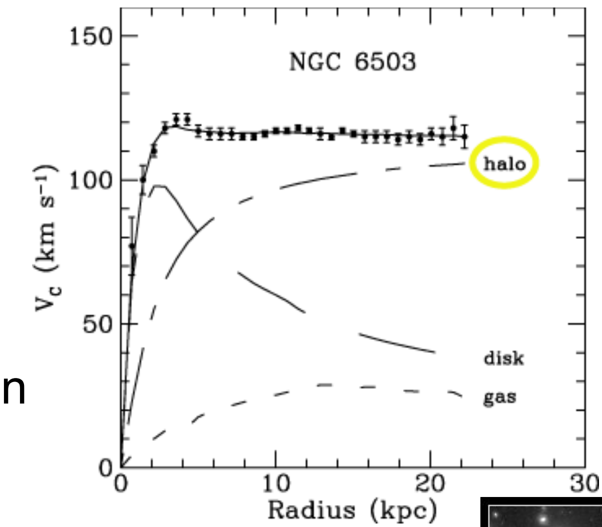
1. Introduction

Many observation indicate the existence of dark matter

❖**Rotation of spiral galaxies**

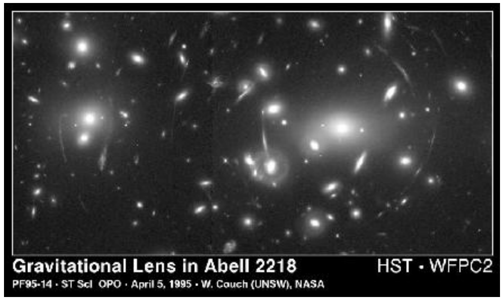
$$v(r) \propto \sqrt{M(r)/r}$$

M(r) ∝ r in outside of visible region



❖**Clusters of galaxies**

❖**Gravitational lensing**

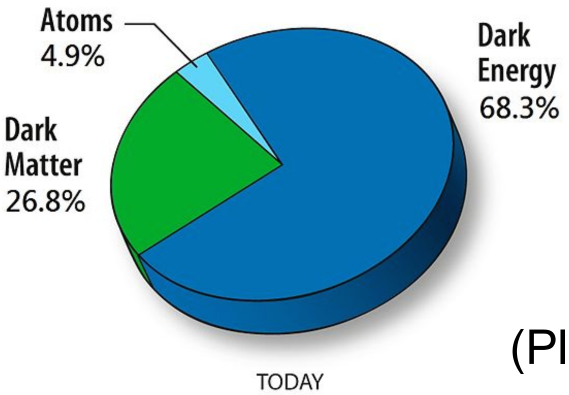


❖**Formation of Large scale structure**

❖**CMB anisotropy : WMAP, Planck**

$$\Omega_{DM} h^2 \approx 0.12$$

By Planck observation



(Planck)

One motivation to consider new physics

1. Introduction

Some anomalies in B→K(*)l+l- decay process

□ Lepton universality in b→sl+l- : R_K, R_{K^*}

$$R_K \equiv \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

$$\left(R_K\right)^{SM} = 1, \quad \left(R_K\right)^{\exp} = 0.745 \pm 0.09 \pm 0.036$$

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

~2.4 σ deviation from the SM

$$R_{K^*} \equiv \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}$$

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

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

~2.4 σ deviation from the SM

Indicating lepton non-universality from new physics contribution

□ 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

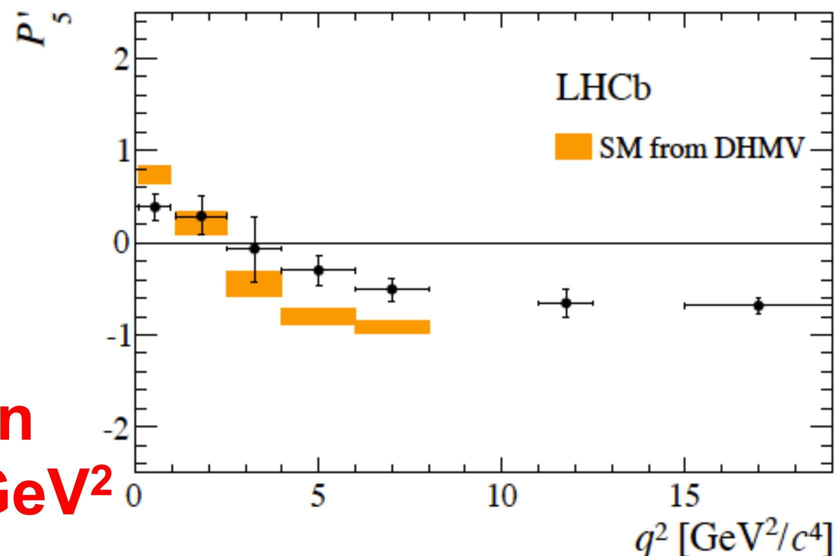
θ_l: between l and B
in l+l- rest frame

Φ : between l+l-
and 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

$$H^{l}_{eff} \supset -\frac{4G_F}{\sqrt{2}} \frac{e^2}{(4\pi)^2} V_{tb} V^{*}_{ts}$$
$$\times\left[C^{l}_{9} \left(\bar{s}\gamma^{\mu} P_L b\right)\left(\bar{l}\gamma_{\mu} l\right) + \left(C^{l}_{9}\right)' \left(\bar{s}\gamma^{\mu} P_R b\right)\left(\bar{l}\gamma_{\mu} l\right) + C^{l}_{10} \left(\bar{s}\gamma^{\mu} P_L b\right)\left(\bar{l}\gamma_{\mu}\gamma^{5} l\right) + \left(C^{l}_{10}\right)' \left(\bar{s}\gamma^{\mu} P_R b\right)\left(\bar{l}\gamma_{\mu}\gamma^{5} l\right)\right]$$

Or

$$H^{l}_{eff} \supset -\frac{4G_F}{\sqrt{2}} \frac{e^2}{(4\pi)^2} V_{tb} V^{*}_{ts} \sum_{X,Y=L,R} \left[C_{XY} \left(\bar{s}\gamma^{\mu} P_X b\right)\left(\bar{l}\gamma_{\mu} P_Y l\right)\right]$$

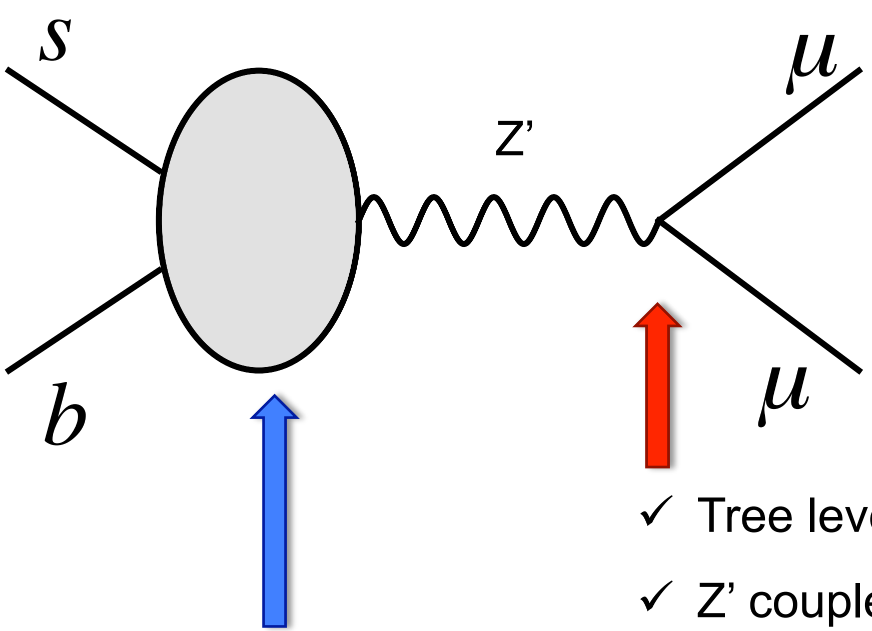
$\{C^{(')}_{9}, C^{(')}_{10}, C_{XY}\}$: Wilson coefficients

- ❖ Indication to BSM from global fit : $C_9^{\mu(BSM)} \sim -1$
- ❖ R_K, R_{K^*} data can be fitted with Wilson coefficients for electron

➡ P$_5$' data prefer non-zero BSM contribution to Wilson coefficients for **muon**
We thus prefer muon coupling than electron

We consider Z' exchange to generate the effective int.

➡ **U(1)μ-τ (-like) gauge symmetry** (L_μ, μ_R : charge 1; L_τ, τ_R : charge -1)



$$\left|C_9^{\mu(Z')}\right| \sim 1$$

$$\left|\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}V_{tb}V_{ts}^{*}C_{9,LL}^{\mu(BSM)}\right| \sim \frac{0.003}{TeV^2}$$

- ✓ Tree level coupling
- ✓ Z' couples to μ and τ, not to e

- ✓ Flavor changing b→s
- ✓ We consider one loop level coupling
- ✓ DM propagates inside a loop

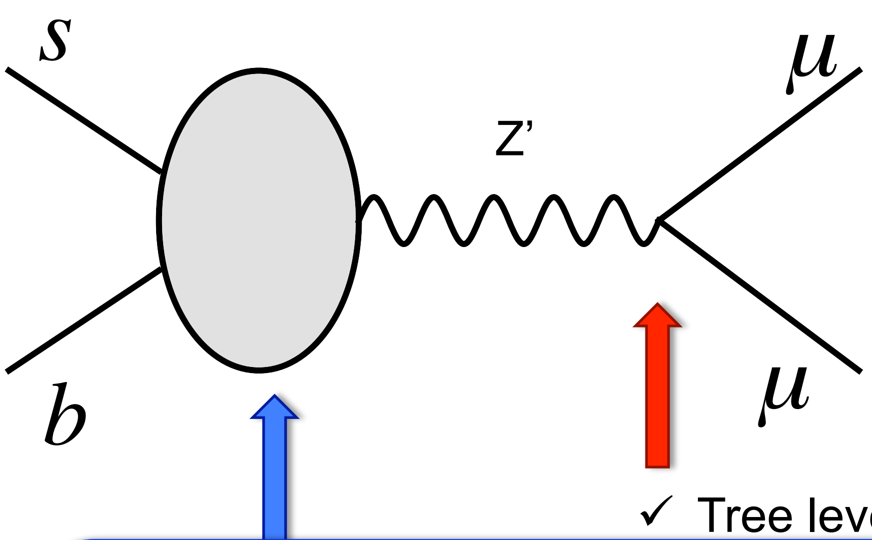
Our model explains b→sl⁺l⁻ anomalies and DM

1. Introduction

We consider Z' exchange to generate the effective int.

⇒ U(1)μ-τ (-like) gauge symmetry

L_μ, μ_R : charge 1
L_τ, τ_R : charge -1



$$\left|C_9^{\mu(Z')}\right| \sim 1$$

⇓

$$\left|\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}V_{tb}V_{ts}^{*}C_{9,LL}^{\mu(BSM)}\right| \sim \frac{0.003}{TeV^2}$$

✓ Tree level coupling

Other possibility to get relevant Z' interaction

Ex)

- **$U(1)_{\mu\text{-}\tau}$ (-like) symmetry with quark – vector like quark mixing**
  [W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, PRD 89, 095033 (2014)]
- **Quark flavor dependent U(1) model**
  [A. Crivellin, G. D'Ambrosio, J. Heeck, PRD 91, 075006 (2015)]

Our model explains $b \to s l^+ l^-$ anomalies and DM

2. Our model

2. Our model

- **$U(1)_{\mu-\tau}$ (-like) gauge symmetry with Z_2 odd particles**

	VLQ Q'_a	Scalar χ
$SU(3)_C$	**3**	**1**
$SU(2)_L$	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	0
$U(1)_{\mu-\tau}$	q_x	q_x

$$-L \supset f_{aj}\bar{Q}'_a P_L Q_j \chi + h.c.$$: Yukawa coupling

(Q_j : SM quark doublet)

Exotic Z_2 odd particles

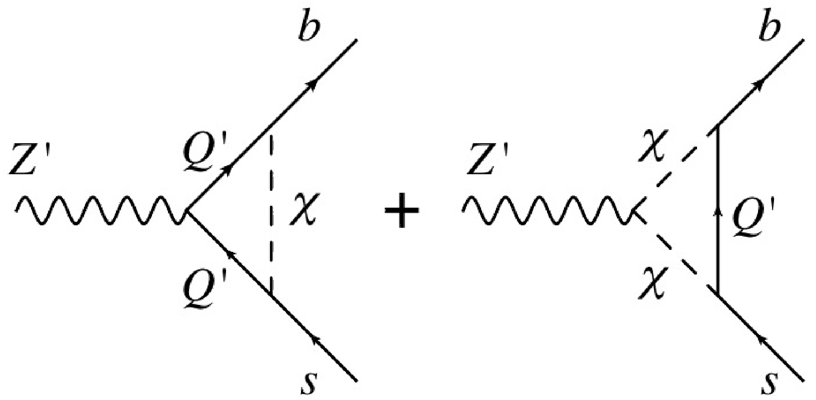
χ : DM candidate interacting with Z'

The extra U(1) is spontaneously broken by VEV of SM singlet scalar φ

$$\begin{cases} \langle \varphi \rangle = \dfrac{v'}{\sqrt{2}} \\ m_{Z'} = Q_\varphi g' v' \end{cases}$$

(Q_φ: U(1) charge of φ)

Z'-b-s coupling via loop effect



Z_2 odd particles propagate inside loops

The sum of loop diagram is finite

$$C_9^{\mu(Z')} \approx \frac{\sqrt{2}\pi}{V_{tb}V_{ts}^{*}\alpha G_F}\frac{q_x g'^2}{m_{Z'}^2}\sum_{a=1,2,3} f_{3a}^{*} f_{a2} F_{loop}(M_a, m_\chi)$$

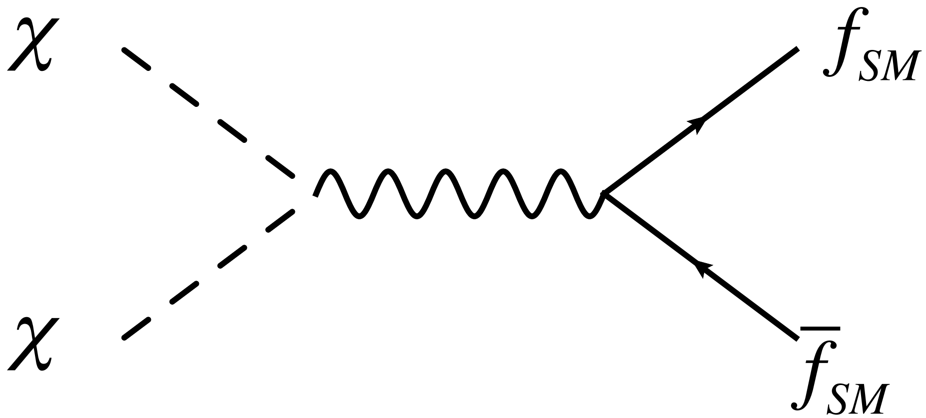
$$F_{loop}(M_a, m_\chi) = \int dX\, dY\, dZ\, \delta(1-X-Y-Z)\, Log\left[\frac{(X+Y-1)(Xm_b^2+Ym_s^2)+XM_a^2+(Y+Z)m_\chi^2}{(X+Y-1)(Xm_b^2+Ym_s^2)+Xm_\chi^2+(Y+Z)M_a^2}\right]$$

(M_a : VLQ masses, m_χ : mass of χ)

Relic density of DM

✓ DM pair annihilate into SM fermions via Z' exchange

(We don't consider coannihilation with VLQ)



We assume Higgs portal interaction is much smaller than Z' interaction

❖ Relic density

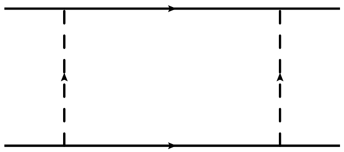
$$\Omega h^2 \approx \frac{1.07\times 10^9}{\sqrt{g_*(x_f)}M_{pl}J(x_f)[GeV]},$$

$$J(x_f)=\int_{x_f}^{\infty} dx\left[\frac{\int_{4m_\chi^2}^{\infty} ds\sqrt{s-4m_\chi^2}(\sigma v_{rel})K_1\left(\frac{\sqrt{s}}{m_\chi}x\right)}{16m_\chi^5 x[K_2(x)]^2}\right], \quad \sigma v_{rel}=\frac{g'^4 x^2 s(s-m_\chi^2)}{3\pi\left[(s-m_{Z'}^2)^2+m_{Z'}^2\Gamma_{Z'}^2\right]}$$

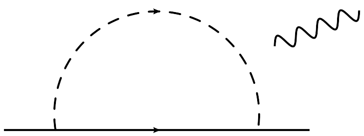
3. Results

Numerical calculation estimating C_9 and Ωh^2

Some constraints are also taken into account



- ✓ Meson – anti meson mixing
- ✓ b→sγ



We run free parameters in our model

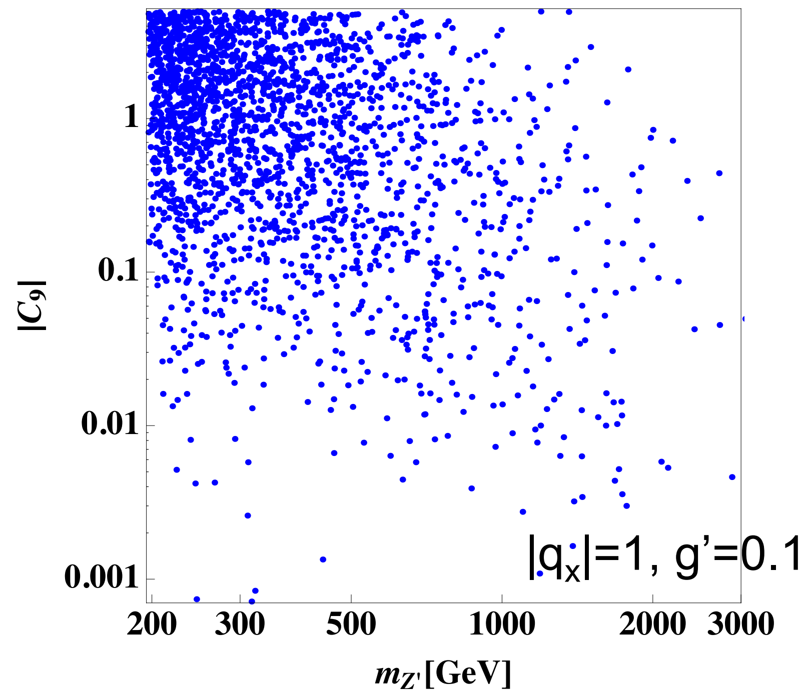
$$f \in [10^{-3}, 1],\ m_{Z'} \in [200, 3000]\ [\mathrm{GeV}],$$
$$m_\chi \in [1, 2000]\ [\mathrm{GeV}],\ M_a \in [1000, 3000]\ [\mathrm{GeV}].$$

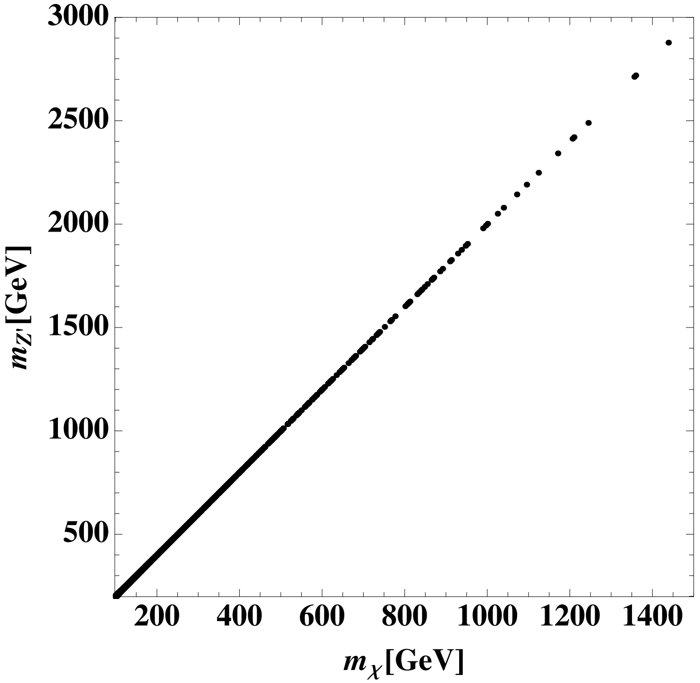
Additional requirement : $m_\chi < 1.2 \times M_a$

Observed relic density is required

$$0.11 \leq \Omega h^2 \leq 0.13$$

Results for C_9 and Z' - DM mass relation



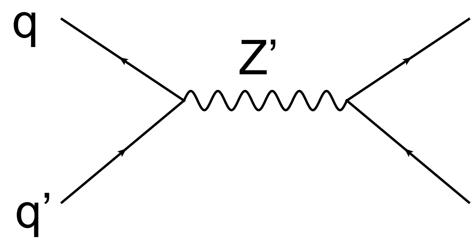


- ✓ C_9~-1 can be obtained for $m_{Z'}$ below ~ 2 TeV when g' =0.1
- ✓ DM mass is around half of Z' mass; resonant annihilation is required
- ✓ For larger g', heavier $m_{Z'}$ is possible

Z’ production cross section at the LHC

✓ **Lagrangian**

$$L \supset \left[g_{bs} \left(\bar{s} \gamma^{\mu} P_L b + h.c. \right) + g' \bar{\mu} \gamma^{\mu} \mu \right] Z'_{\mu}$$



The g_{bs} coupling induced at one-loop level

➡ Couplings to other quarks can also be induced at one loop level

Ex) $\{g_{\mu}, g_{bb,bs,ss,cc}\}=\{0.1, 0.002\}$: $\sigma_{pp\to Z'} \sim 1.0\times10^{-3}$ pb (m$_{Z'}$ = 500 GeV)

BR(Z’→μμ)~BR(Z’→ττ) ~BR(Z’→νν)~0.3

➡ Safe from current experimental constraint by the LHC data

arXiv:1706.04786 (ATLAS)

More parameter region will be tested with more integrated luminosity

Summary and Discussions

- A Model for explaining $b \to s l^+ l^-$ with $U(1)_{\mu-\tau}$(-like) symmetry
  - ✓ Models with Z' boson
  - ✓ Flavor violating b-s-Z' coupling from one-loop diagram
  - ✓ DM propagates in loop diagram
- Consequences of our model
  - ✓ C_9 Wilson coefficient to explain $b \to s l^+ l^-$ anomalies
  - ✓ Relic density of DM
  - ✓ Z' physics at the LHC

Thanks for listening !

Appendix

M-Mbar mixing form VLQ box loop

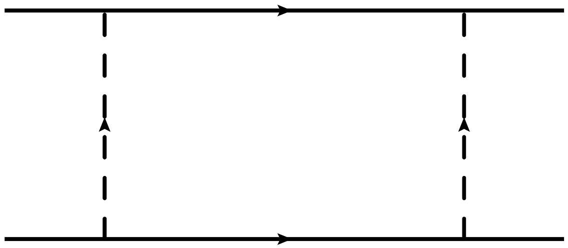
$$\Delta m_K \approx \sum_{a,b=1}^{3} f^\dagger_{1a} f_{a1} f^\dagger_{2b} f_{b2} G^K_{box}[m_\chi, M_a, M_b] \lesssim 3.48 \times 10^{-15}\ [\mathrm{GeV}], \quad (4)$$

$$\Delta m_{B_d} \approx \sum_{a,b=1}^{3} f^\dagger_{1a} f_{a1} f^\dagger_{3b} f_{b3} G^{B_d}_{box}[m_\chi, M_a, M_b] \lesssim 3.36 \times 10^{-13}\ [\mathrm{GeV}], \quad (5)$$

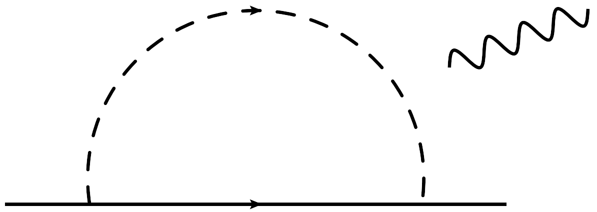
$$\Delta m_{B_s} \approx \sum_{a,b=1}^{3} f^\dagger_{2a} f_{a2} f^\dagger_{3b} f_{b3} G^{B_s}_{box}[m_\chi, M_a, M_b] \lesssim 1.17 \times 10^{-11}\ [\mathrm{GeV}], \quad (6)$$

$$\Delta m_D \approx \sum_{a,b=1}^{3} f^\dagger_{2a} f_{a2} f^\dagger_{1b} f_{b1} G^D_{box}[m_\chi, M_a, M_b] \lesssim 6.25 \times 10^{-15}\ [\mathrm{GeV}], \quad (7)$$

$$G^M_{box}(m_1, m_2, m_3) = \frac{m_M f_M^2}{3(4\pi)^2} \int_0^1 \frac{X[dX]}{X m_1^2 + Y m_2^2 + Z m_3^2}, \quad (8)$$



VLQ-DM contribution to b→sγ



$$\Gamma_{b\to s\gamma} \approx \frac{\alpha_{\rm em} m_b^3}{12(4\pi)^4}(m_b^2+m_s^2)\left|\sum_{a=1}^{3}\frac{f_{2a}^{\dagger}f_{3a}F(M_a,m_\chi)}{36(M_a^2-m_\chi^2)^4}\right|^2,$$

$$F(m_1,m_2) = 5m_1^6 - 27m_1^4m_2^2 + 27m_1^2m_2^4 - 5m_2^6 - 12m_2^4(-3m_1^2+m_2^2)\ln(m_1/m_2), \qquad (9)$$

Constraint from experiments

$$\mathrm{BR}(b\to s\gamma) \equiv \frac{\Gamma(b\to s\gamma)}{\Gamma_{\rm tot.}} \lesssim 3.29\times 10^{-4},$$

$$\Gamma_{\rm tot.} \approx 4.02\times 10^{-13}\ \mathrm{GeV}.$$