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Abstract

In this work, we consider a model independent Lepton-Flavor violating Z' gauge boson at TeV scale, which can be probed at LHC in the near future. The lepton-flavor-changing neutral currents originated from non-universal couplings to charged leptons and non-diagonal charge lepton mass matrix. We assume that the left-handed charged-lepton mixing matrix equals to the PMNS matrix and no mixing in the neutrino sector to make this phenomenological Z' model more predictive. There are indeed some parameter regions, where the Z' can generate a large enough $e^{\pm}\mu^{\mp}$ production cross section at the LHC, while at the same time satisfies various observables from lepton-flavor violation and other constraints from the LHC.

I. INTRODUCTION

The additional Z' gauge boson has been vastly discussed in the literatures. The simple way to have new gauge boson is introducing a $U'(1)$ gauge symmetry additional to standard model group. This extra $U'(1)$ may comes from symmetry breaking from larger gauge group, for example in the grand unified theory (GUT). Or it may comes from promoting some global symmetry to local symmetry, like $U(1)_{L_\mu - L_\tau}$ and $U(1)_{B-L}$.

In this work, we consider a model independent Lepton-Flavor violating (LFV) Z' gauge boson at TeV scale, which corresponds to an extra $U'(1)$. The lepton-flavor-changing neutral currents originated from non-universal couplings to charged leptons and non-diagonal charge lepton mass matrix. The particle couples to both quarks and leptons, hence it can be produced by quark-antiquark fusion at the LHC. With regard to the leptonic couplings, it violates the universality and has different strengths for different flavors. The non-universal couplings to charged leptons are also inspired from a recent observation of $b \to sl^+l^-$ in Ref. [2]. The gauge anomaly can be avoided by adding more fermions in the theory [3, 4].

If we further assume that the mass matrix of the charged leptons is not diagonal under the interaction basis and the couplings to Z' are non-universal, flavor-changing neutral currents (FCNC) can be induced at tree level in the charged-lepton sector after diagonalizing their mass matrix [5–8]. After a unitary transformation on the basis, non-zero $Z'e\mu$ coupling can be generated. However, complete informations of the unitary transformation on left- and right-handed charged leptons, U_{lL} and U_{lR}, are still ambiguous, since the neutrino oscillation observations always measure the product of the left-handed charged lepton and neutrino unitary matrices, i.e the PMNS matrix is $U_{PMNS} = U_{lL}^\dagger U_\nu$.

In order to make the couplings of Z' more predictive, we further postulate that the PMNS lepton-mixing matrix entirely comes from the charged-lepton sector [6, 7], i.e. $U_\nu = \mathbf{1}$ and $U_{lL}^\dagger = U_{PMNS}$. Based on this framework, we stress that the Z' boson can generate large enough $\sigma(pp \to X) \times B(X \to e^\pm\mu^\mp)$, meanwhile still evades the constraints from various kinds of observations. If the mass of the Z' is around 2 TeV, the $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp)$ can be larger than 1 fb.

The ATLAS collaboration recently reported the opposite-sign different-flavor dilepton $e^\pm\mu^\mp$ pairs, using 3.2 fb^{-1} data at $\sqrt{s} = 13$ TeV in Ref. [1]. In the plot of the spectrum of electron-muon invariant mass ($m_{e\mu}$), there is one event at $m_{e\mu} = 2.1$ TeV, where the expected background is almost zero. The largest local significance is 1.7σ at $m_{e\mu} = 2.1$ TeV. From the difference between the observed and expected limits at 2.1 TeV in Ref. [1], we estimated that the cross section $\sigma(pp \to X) \times B(X \to e^{\pm}\mu^{\mp}) \simeq 1 - 2$ fb is required to generate the event.

We organize this work as follows. In Sec. II, we introduce the notation, then consider possible constraints from other leptonic and dijet channels at the LHC in Sec. III. Bounds from various low-energy observables relevant to the lepton sector itself, or both lepton and quark sector will be considered in Sec. IV and V, respectively. Numerical results are in Sec. VI, and we summarize in Sec. VII.

II. FORMALISM

Here we trail the heavy resonance as a new gauge boson Z' from an extra $U'(1)$ additional to the SM gauge groups. The gauge couplings of the Z' to different generations of fermions may not be universal from some hints of the recent observations of $b \to s l^+ l^-$ in Ref. [2]. Flavor-changing neutral currents (FCNC) can be induced at tree level in both quark and leptonic sectors after diagonalizing their mass matrices [5–7]. We follow the formalism in Ref. [5]. In the interaction basis, the neutral-current Lagrangian from Z' can be written as

$$\mathcal{L}_{\rm NC} = -g' J^{(2)\mu} Z'_\mu \ , \tag{1}$$

where there is no mixing between Z' and Z boson from $SU(2) \times U(1)$ for simplicity, or because the mixing is small and naturally of order $(m_Z/m_{Z'})^2 \simeq 10^{-3}$ for a 2.1 TeV Z' boson. The g' is the gauge coupling of $U'(1)$. The current associated with the $U'(1)$ is

$$J^{(2)}_\mu = \sum_{i,j} \bar{\psi}_i \gamma_\mu \left[\epsilon^{\psi}_{Lij} P_L + \epsilon^{\psi}_{Rij} P_R \right] \psi_j \ , \tag{2}$$

where $\epsilon^{\psi}_{L,R_{ij}}$ are the chiral charges of $U'(1)$ with fermions i and j running over all quarks and leptons in the interaction basis.

The $U'(1)$ charge assignment for left- and right-handed quarks are universal, i.e $\epsilon^u_{L,R} = Q'^{(u)}_{L,R}\, diag(1,1,1)$, $\epsilon^d_{L,R} = Q'^{(d)}_{L,R}\, diag(1,1,1)$. However, the $U'(1)$ charges for the charged-lepton sector could be non-universal, i.e. $\epsilon^l_L = diag(Q'^{(e)}_L, Q'^{(\mu)}_L, Q'^{(\tau)}_L)$. Finally, for the $U'(1)$ charges for the right-handed leptons, we simply assume they are zero, $\epsilon^l_R = 0$.

The fermions in Eq. (2) in the interaction basis will be rotated to the mass eigen-basis through a set of unitary matrices, e.g V_{u,d_L}, V_{u,d_R} for left-, right-handed up- and down-type quarks, respectively; U_{lL}, U_{lR}, and U_ν for leptons and neutrinos. Therefore, the interactions between Z' and fermions in mass eigen-basis become

$$\begin{aligned}
\mathcal{L}_{\rm NC} = & -g' Z'_\mu (\bar u, \bar c, \bar t)_M \gamma^\mu (V^\dagger_{uL} \epsilon^u_L V_{uL} P_L + V^\dagger_{uR} \epsilon^u_R V_{uR} P_R)\,(u,c,t)^T_M \\
& -g' Z'_\mu (\bar d, \bar s, \bar b)_M \gamma^\mu (V^\dagger_{dL} \epsilon^d_L V_{dL} P_L + V^\dagger_{dR} \epsilon^d_R V_{dR} P_R)\,(d,s,b)^T_M \\
& -g' Z'_\mu (\bar e, \bar \mu, \bar \tau)_M \gamma^\mu (U^\dagger_{lL} \epsilon^l_L U_{lL} P_L + U^\dagger_{lR} \epsilon^l_R U_{lR} P_R)\,(e,\mu,\tau)^T_M \ , \qquad (3) \\
\Rightarrow \mathcal{L}_{\rm NC} = & -Z'_\mu (\bar u, \bar c, \bar t)_M \gamma^\mu (g^u_L P_L + g^u_R P_R)\,(u,c,t)^T_M \\
& -Z'_\mu (\bar d, \bar s, \bar b)_M \gamma^\mu (g^d_L P_L + g^d_R P_R)\,(d,s,b)^T_M \\
& -Z'_\mu (\bar e, \bar \mu, \bar \tau)_M \gamma^\mu (g^l_L P_L + g^l_R P_R)\,(e,\mu,\tau)^T_M \ , \qquad (4)
\end{aligned}$$

where $g^{u,d,l}_{L,R}$ are 3×3 matrices describing the Z' couplings to the SM fermions. Since $\epsilon^u_{L,R}$, $\epsilon^d_{L,R}$, and ϵ^l_R are proportional to the identity matrix, no off-diagonal terms will be generated after sandwiched by the unitary matrices. On the other hand, since the diagonal elements in the ϵ^l_L are non-universal, it will generate non-zero off-diagonal terms after sandwiched by the unitary matrices. The non-zero off-diagonal elements can induce the FCNC of Z'.

In the leptonic sector, the PMNS matrix is $U_{PMNS} = U^\dagger_{lL} U_\nu$ and we assume that all the neutrino mixings come from the charged-lepton sector [6, 7], i.e $U_\nu = \mathbf{1}$, then

$$V_{PMNS} = U^\dagger_{lL} \ . \qquad (5)$$

Therefore, the couplings of the left-handed leptons is $g^l_L = g' U_{PMNS} \epsilon^l_L U^\dagger_{PMNS}$, such that g^l_L can be determined using the experimentally measured U_{PMNS} matrix and thus gives meaningful predictions.

III. CONSTRAINTS FROM $e^\pm\mu^\mp$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, AND jj PRODUCTION AT THE LHC

There are several constraints and upper limits for $e^\pm\mu^\mp$ [9], $e^\pm\tau^\mp$, $\mu^\pm\tau^\mp$ [1], e^+e^-, $\mu^+\mu^-$ [10–12], and $\tau^+\tau^-$ channels from ATLAS and CMS already. In Ref [12], the observed 95% upper limits at $\sqrt{s} = 13$ TeV at $m_{Z'} = 2.1$ TeV are $\sigma(pp \to Z') \times B(Z' \to e^+e^-) \lesssim 1.5$ fb and $\sigma(pp \to Z') \times B(Z' \to \mu^+\mu^-) \lesssim 2$ fb. For channels of different flavors [1], at 2.1 TeV, $\sigma(pp \to Z') \times B(Z' \to e^\pm\tau^\mp) \lesssim 5$ fb, and $\sigma(pp \to Z') \times B(Z' \to \mu^\pm\tau^\mp) \lesssim 9$ fb.

The dijet limits from ATLAS [13, 15] are about $\sigma(pp \to Z') \times B(Z' \to jj) \times A \lesssim 0.5$ pb for a narrow-width Z', and $\lesssim 1$ pb for $\Gamma_{Z'}/m_{Z'} = 0.15$ at $M_{Z'} \simeq 2.1$ TeV. From the

CMS [14], $\sigma(pp \to Z') \times B(Z' \to jj) \times A \lesssim 1$ pb for the narrow-width case. Here A is the acceptance ratio due to selection cuts, and ranges between $40 - 60\%$.

IV. CONSTRAINTS FROM THE FCNC IN THE LEPTONIC SECTOR

In this section, we focus on the observables relevant to the flavor-changing Z'-charged-lepton couplings, such as $\mu \to e\gamma$ or $\mu \to 3e$. The experimental limits from these processes are listed in Table I. This Z' boson may contribute to the muon $g-2$, and a more detailed study can be found in Ref. [16]. However, the Z' mass here is much heavier than that considered in Ref. [16], such that it would not make any sizeable contribution to the muon $g-2$. Numerically, the contribution of the 2.1 TeV Z boson with the size of the couplings considered here is only 2×10^{-11}, which is negligible compared with the experimental result: $\Delta a_\mu = (288 \pm 80) \times 10^{-11}$. Therefore, we do not attempt to explain the muon $g-2$ or use it as a constraint.

A. $l_j \to l_i \gamma$

The expression for the branching ratio $l_j \to l_i\gamma$ is [17] is given by

$$B(l_j \to l_i\gamma) = \frac{\alpha_e \tau_j m_j}{9(4\pi)^4}\left(\frac{m_j}{m_{Z'}}\right)^4 \left(\left|\sum_k (g^l_L)_{jk}(g^l_L)_{ki} - \frac{3m_k}{m_j}(g^l_L)_{kj}(g^l_R)_{ki}\right|^2 + (L \leftrightarrow R)\right) , \quad (6)$$

where fine structure constant $\alpha_e \equiv e^2/4\pi = 1/137.036$ at very low energy [18], $m_{i,j,k}$ are mass of charged leptons ($m_{e,\mu,\tau}$ =0.0005, 0.10567, 1.77682 GeV), and τ_j is the life time of the charged lepton j ($\tau_\mu = 3.34 \times 10^{18}$, and $\tau_\tau = 4.42 \times 10^{11}$ GeV^{-1} [18]). Here we adopt the recent results from MEG Collaboration [23], i.e. $B(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% CL.

From the expression in Eq.(6), if there are only left-handed couplings g^l_L, the mass insertion only occurs at external lepton legs in the Feynman diagram. However, when both left- and right-handed couplings are nonzero, the mass insertion can happen in the internal fermion loop in the Feynman diagram and its flavor can be different from the external leptons. In the latter case, mass ratio m_k/m_j in Eq.(6) may enhance the decay rate of $l_j \to l_i\gamma$. For instance, among the current experimental limits the most stringent one is from $\mu \to e\gamma$. If both left- and right-handed couplings are nonzero, the diagram with the mass insertion in the τ running in the loop will be enhanced by the factor m_τ/m_μ. Therefore, in order to dodge the experimental limit of $B(\mu \to e\gamma)$, we assume $g_R^l = 0$.

B. $l_j \to l_i l_k \bar{l}_l$

The expressions for the branching ratios $l_j \to l_i l_k \bar{l}_l$ are given by [17]

$$B(l_j \to l_i l_k \bar{l}_l) = \frac{\tau_j m_j}{1536\pi^3}\left(\frac{m_j}{m_{Z'}}\right)^4 \times \left(\left|(g_L^l)_{ij}(g_L^l)_{kl} + (g_L^l)_{kj}(g_L^l)_{il}\right|^2 + \left|(g_L^l)_{ij}(g_R^l)_{kl}\right|^2 + \left|(g_L^l)_{kj}(g_R^l)_{il}\right|^2 + (L \leftrightarrow R)\right) ,$$

$$B(l_j \to l_i l_i \bar{l}_l) = \frac{\tau_j m_j}{1536\pi^3}\left(\frac{m_j}{m_{Z'}}\right)^4 \left(2\left|(g_L^l)_{ij}(g_L^l)_{il}\right|^2 + \left|(g_L^l)_{ij}(g_R^l)_{il}\right|^2 + (L \leftrightarrow R)\right) . \quad (7)$$

The observed limit of $\mu^- \to e^- e^- e^+$ is less than 1.0×10^{-12} [18], which not only constrains the flavor-changing coupling $(g_L^l)_{12}$, but also the flavor-conserving one $(g_L^l)_{11}$. So we have to suppress the $Z'ee$ coupling as well in our numerical study.

V. CONSTRAINTS FROM THE FCNC IN THE LEPTON-QUARK SECTOR

In this section, we focus on the $\mu - e$ conversion processes in heavy nuclei, which are relevant to the Z'-charged-lepton and Z'-quark couplings. For the vector-like Z' interactions, these processes will be enhanced through coherent scattering with the entire nucleus, therefore putting strong bounds on the Z' couplings. The experimental limits from these processes are listed in Table I.

A. $\mu - e$ conversion: $\mu + N \to e + N$

For coherent $\mu^- - e^-$ conversion, it only involves scalar- and vector-coupling contributions. In our Z' model, there is only the vector contribution, and no scalar couplings will be generated if RG running is restricted to QCD dressing only. The relevant expressions can be found in Ref. [19]

$$B(\mu^- N \to e^- N) = \frac{p_e E_e G_F^2}{8\pi}\left(|X_L(p_e)|^2 + |X_R(p_e)|^2\right)\frac{1}{\Gamma_{capt}} \quad (8)$$

where p_e and E_e is the momentum and energy of the electron, respectively, Γ_{capt} is the muon capture rate from the experiment, and

$$X_L(p_e) = \left(g_{LV}^{(0)} + g_{LV}^{(1)}\right) ZM_p(p_e) + \left(g_{LV}^{(0)} - g_{LV}^{(1)}\right)(A - Z)M_n(p_e) ,$$

TABLE I. Various experimental constraints coming from the LHC, rare lepton-flavor violating decays, and μ-e conversions, as well as the predictions of the benchmark point (Z' M-1): (NH) $g' = 1$, $\epsilon^u_L = -\epsilon^u_R = diag(0.2, 0.2, 0.2)$, $\epsilon^d_L = -\epsilon^d_R = diag(0.2, 0.2, 0.2)$, $\epsilon^l_L = 1/10 \times diag(-0.404, 0.912, -0.064)$, $\epsilon^l_R = 0$ with $m_{Z'} = 2.1$ TeV. The total width of the Z' is $\Gamma_{Z'} = 40.7$ GeV, and the Z' production cross section $\sigma(pp \to Z') = 367$ fb at the 13 TeV LHC.

observable	exp.	Z' M-1
$\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp)$ [fb]	$1 \sim 2$ [1]	1.03
$\sigma(pp \to Z') \times B(Z' \to e^+e^-)$ [fb]	$\lesssim$1.5 [12]	1.4×10^{-7}
$\sigma(pp \to Z') \times B(Z' \to \mu^+\mu^-)$ [fb]	$\lesssim$2 [12]	0.210
$\sigma(pp \to Z') \times B(Z' \to \tau^+\tau^-)$ [fb]	-	0.060
$\sigma(pp \to Z') \times B(Z' \to e^\pm\tau^\mp)$ [fb]	$\lesssim$5 [1]	0.782
$\sigma(pp \to Z') \times B(Z' \to \mu^\pm\tau^\mp)$ [fb]	$\lesssim$9 [1]	0.428
$\sigma(pp \to Z') \times B(Z' \to jj)$ [fb]	$\lesssim$500 [13]	362
$B(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$ [23]	4.4×10^{-13}
$B(\mu^- \to e^-e^-e^+)$	$< 1.0 \times 10^{-12}$ [18]	1.1×10^{-16}
$B(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [18]	1.2×10^{-13}
$B(\tau^- \to \mu^-\mu^-\mu^+)$	$< 2.1 \times 10^{-8}$ [18]	1.2×10^{-11}
$B(\tau^- \to \mu^-e^-e^+)$	$< 1.8 \times 10^{-8}$ [18]	2.7×10^{-11}
$B(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$ [18]	4.8×10^{-14}
$B(\tau^- \to e^-e^-e^+)$	$< 2.7 \times 10^{-8}$ [18]	1.5×10^{-17}
$B(\tau^- \to e^-\mu^-\mu^+)$	$< 2.7 \times 10^{-8}$ [18]	5.0×10^{-11}
$B(\mu\text{Ti} \to e\text{Ti})$	$< 6.1 \times 10^{-13}$ [27]	0
$B(\mu\text{Au} \to e\text{Au})$	$< 7.0 \times 10^{-13}$ [18]	0
$B(\mu\text{Al} \to e\text{Al})$	-	0

$$X_R(p_e) = \left(g^{(0)}_{RV} + g^{(1)}_{RV}\right) Z M_p(p_e) + \left(g^{(0)}_{RV} - g^{(1)}_{RV}\right) (A - Z) M_n(p_e) \ ,$$

where Z and A are, respectively, the proton and nucleon numbers of the nucleus. The $M_{p,n}$ are the transition nuclear matrix elements. Also,

$$g^{(0)}_{LV} = \frac{1}{2} \sum_{q=u,d,s} \left(g_{LV(q)} G^{(q,p)}_V + g_{LV(q)} G^{(q,n)}_V\right) \ ,$$

$$
\begin{aligned}
g_{RV}^{(0)} &= \frac{1}{2}\sum_{q=u,d,s}\left(g_{RV(q)}G_V^{(q,p)} + g_{RV(q)}G_V^{(q,n)}\right) \ , \\
g_{LV}^{(1)} &= \frac{1}{2}\sum_{q=u,d,s}\left(g_{LV(q)}G_V^{(q,p)} - g_{LV(q)}G_V^{(q,n)}\right) \ , \\
g_{RV}^{(1)} &= \frac{1}{2}\sum_{q=u,d,s}\left(g_{RV(q)}G_V^{(q,p)} - g_{RV(q)}G_V^{(q,n)}\right) \ ,
\end{aligned}
\tag{9}
$$

for vector currents $G_V^{(u,p)} = G_V^{(u,n)} = 2$, $G_V^{(d,p)} = G_V^{(u,n)} = 1$, and $G_V^{(s,p)} = G_V^{(s,n)} = 0$ from Ref. [20]. Comparing the effective operators in Ref. [19] with Eq.(4), the coefficients of these operators can be written in terms of Z' couplings

$$
\begin{aligned}
g_{LV(q)} &= \frac{\sqrt{2}}{m_{Z'}^2 G_F}(g_L^l)_{12}\left[(g_R^q)_{11} + (g_L^q)_{11}\right]/2 \ , \\
g_{RV(q)} &= \frac{\sqrt{2}}{m_{Z'}^2 G_F}(g_R^l)_{12}\left[(g_R^q)_{11} + (g_L^q)_{11}\right]/2 \ , \\
g_{LA(q)} &= \frac{\sqrt{2}}{m_{Z'}^2 G_F}(g_L^l)_{12}\left[(g_R^q)_{11} - (g_L^q)_{11}\right]/2 \ , \\
g_{RA(q)} &= \frac{\sqrt{2}}{m_{Z'}^2 G_F}(g_R^l)_{12}\left[(g_R^q)_{11} - (g_L^q)_{11}\right]/2 \ ,
\end{aligned}
\tag{10}
$$

where $q = u, d$. Here we shall consider those experiments with three different nuclei $N =$ ^{27}Al, ^{48}Ti, ^{197}Au. Useful values for these experiments are listed in Table 1 of Ref. [20].

Note that in our Z' model only the vector couplings in the quark sector significantly contribute to the $\mu - e$ conversion. We can easily evade the current experimental limits by choosing $U'(1)$ charges as $\epsilon_L^u = -\epsilon_R^u$ and $\epsilon_L^d = -\epsilon_R^d$, such that the Z' couplings to quarks are almost axial-vector-like. However, even under this $U'(1)$ charge assignment, vector-like couplings can be induced from non-universal couplings of the Z' in the quark sector by performing the unitary rotation into the quark mass basis. Then, the Z' will suffer from the strong limits of $\mu - e$ conversion. Therefore, in order to escape from this once and for all, later in our numerically analysis, the Z' has universal couplings in quark sector, and we assign opposite $U'(1)$ charges to the left- and right-handed quarks in order to evade the stringent $\mu - e$ conversion limits.

Another advantage of the assumption that the Z' has universal couplings in the quark sector is that we do not need to take into account the flavor-changing observables in the quark sector, such as $B - \bar{B}$ or $K - \bar{K}$ mixing.

Now we address the mechanism of the fermion mass generation. For the quark sector in the scheme of the universal and axial-vector-like couplings, the type-II model of two Higgs doublets of opposite hypercharges and opposite Z' charges is able to have the gauge compatible Higgs-Yukawa couplings that generate the required quark masses. However, the lepton masses require more technical structures in the Higgs sector due to the non-universal $U'(1)$ charges of leptons. In this paper, we are only concerned about the phenomenological study of the Z' interaction and put aside the Higgs interaction.

VI. NUMERICAL RESULTS

Here we shall demonstrate step by step how to assign the $U'(1)$ charges for the charge leptons and quarks, so as to make the model consistent with all the observables, and then to check if there is any parameter space left that can be tuned to generate large enough $\sigma(pp \to Z') \times B(Z' \to e^{\pm}\mu^{\mp}) \simeq 1$ fb.

The PMNS matrix with the best-fit values of matrix elements is given in Particle Data Book [18] as (assuming zero values for the two Majorana CP violation phases):

$$U_{PMNS} = \begin{pmatrix} 0.822 & 0.548 & -0.0518 + 0.144i \\ -0.388 + 0.0791i & 0.643 + 0.0528i & 0.653 \\ 0.399 + 0.0898i & -0.528 + 0.0599i & 0.742 \end{pmatrix},$$

in the normal hierarchy(NH), and

$$U_{PMNS} = \begin{pmatrix} 0.822 & 0.548 & -0.0525 + 0.146i \\ -0.380 + 0.0818i & 0.634 + 0.0546i & 0.666 \\ 0.407 + 0.0895i & -0.540 + 0.0597i & 0.729 \end{pmatrix},$$

in the inverse hierarchy(IH).

In Table I, we show an example of the $U(1)'$ charge assignment for quarks and leptons, such that it can give a large enough cross section for $\sigma(pp \to Z') \times B(Z' \to e^{\pm}\mu^{\mp}) \simeq 1$ fb, and meanwhile satisfies the limits from all other observations.

The steps in assigning the $U(1)'$ charges are as follows.

(i) Considering in the leptonic sector very strong experimental limits come from $B(\mu \to e\gamma)$ and $B(\mu^- \to e^-e^-e^+)$. The latter limit can be satisfied by suppressing the

$Z'ee$ coupling, i.e $(g_L^l)_{11}$. The Z' couplings are $g_L^l = g' U_{PMNS} \epsilon_L^l U_{PMNS}^\dagger$, where $\epsilon_L^l = diag(Q_L'^{(e)}, Q_L'^{(\mu)}, Q_L'^{(\tau)})$. The coupling $(g_L^l)_{ij}$ depends linearly on $Q'^{(e)}_L, Q'^{(\mu)}_L, Q'^{(\tau)}_L$ with coefficients $(\vec{A}_{ij})_l$,

$$(g_L^l)_{ij} = g'(\vec{A}_{ij})_l \, Q'^{(l)}_L \ , \text{ or } \ g'\vec{A}_{ij} \cdot \vec{Q}'_L \ ,$$

where

$$(\vec{A}_{ij})_l = (U_{PMNS})_{il}(U^*_{PMNS})_{jl} \ .$$

We attempt to assign the $U(1)'$ charges, such that maximize the $e-\mu$ coupling $(g_L^l)_{12}$, while minimize the $e-e$ one $(g_L^l)_{11}$. In NH, two $U(1)'$ charge assignments along the directions $\vec{A}_{12} \simeq (-0.319, 0.353, -0.034)$ and $\vec{A}_{11} \simeq (0.676, 0.301, 0.023)$ will maximize the $e-\mu$ and $e-e$ couplings, respectively. In order to eventually suppress the $e-e$ coupling, we keep the components of $\vec{A}_{12}$ that are perpendicular to $\vec{A}_{11}$, i.e

$$\vec{A}_{12} - \vec{A}_{11}\frac{\vec{A}_{11}\cdot\vec{A}_{12}}{|\vec{A}_{11}|^2} = \vec{A}_{12} + 0.201\vec{A}_{11} \propto (-0.404, 0.912, -0.064) \ .$$

We normalize the charges by marginalizing the limit of $B(\mu \to e\gamma)$, shown in Table I, then obtain $(Q_L'^{(e)}, Q_L'^{(\mu)}, Q_L'^{(\tau)}) = 1/10 \times (-0.404, 0.912, -0.064)$ and so $B(\mu \to e\gamma) = 4.4 \times 10^{-13}$. Furthermore, if the right-handed charge-lepton couplings g_R^l are nonzero, the tau-mass insertion terms in Eq. 6 will enhance $B(\mu \to e\gamma)$. We therefore simply set $g_R^l = 0$.

(ii) Considering the quark-lepton sector strong experimental limits come from $\mu - e$ conversion, such as $B(\mu\text{Ti} \to e\text{Ti})$. Nevertheless, these constraints can be alleviated by choosing the couplings of $Z'q\bar{q}'$ to be axial-vector-like from the expressions of $\mu - e$ conversion in Sec. V A. Therefore, we choose $\epsilon_L^u = -\epsilon_R^u$ and $\epsilon_L^d = -\epsilon_R^d$. As the $U(1)'$ charges for the quark sector are flavor-universal, the couplings of $Z'q\bar{q}'$ remain axial-vector-like under an unitary transformation of quark basis. Recently, the LHCb Run-I data showed some deviations in B-meson decays from the SM predictions: $R_K \equiv B(B \to K\mu^+\mu^-)/B(B \to Ke^+e^-) = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ [2] has 2.6σ departure from unity. The angular observables in $B \to K^*\mu^+\mu^-$ deviate from the SM expectation by about 3σ [24]. Several Z' models with non-universal charged-lepton and down-type quark couplings can explain these anomalies [25, 26]. Nevertheless, these anomalies are beyond the scope of this work and we do not attempt to explain them.

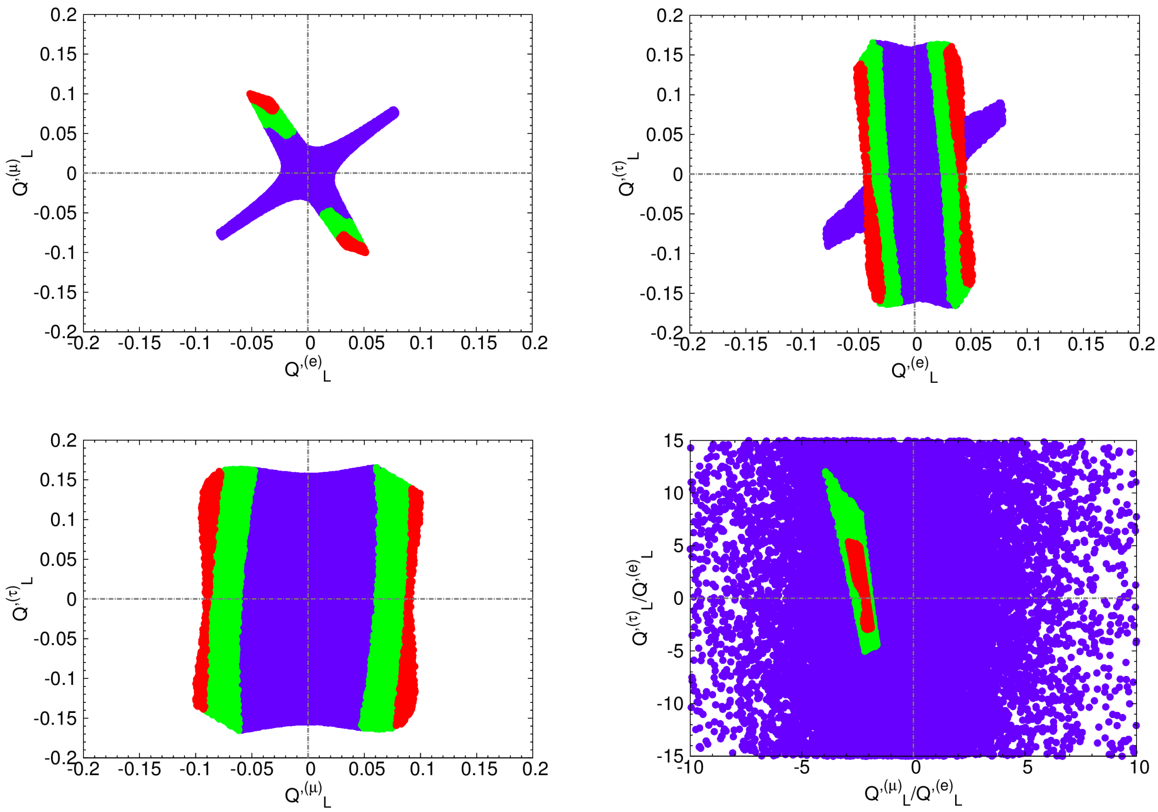

FIG. 1. Scanning over $Q_L^{\prime(e)}$, $Q_L^{\prime(\mu)}$, and $Q_L^{\prime(\tau)}$, while fixing $g' = 1$, $\epsilon_L^{u,d} = -\epsilon_R^{u,d} = diag(0.2, 0.2, 0.2)$, and $\epsilon_R^l = 0$ with $m_{Z'} = 2.1$ TeV. The colored points satisfy all the experimental limits listed in Table I, except for $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \simeq 1 \sim 2$ fb. Blue points: $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 0.5$ fb, are the majority. Green points: $0.5 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 1.0$ fb. Red points: $1.0 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 2.0$ fb are the minority.

(iii) Attempting to produce a large enough $e^\pm\mu^\mp$ cross section at the LHC we tune the $g_{L,R}^q$ couplings, meanwhile satisfy the dijet limits. Fixing $g' = 1$, when $Q_L^{\prime u,d} = -Q_R^{\prime u,d} \subset [0.02, 0.23]$, we have $0.5 \leq \sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \leq 1$ fb and $1.5 \leq \sigma(pp \to Z') \times B(Z' \to jj) \leq 500$ fb. If $Q_L^{\prime u,d} = -Q_R^{\prime u,d}$ were larger than 0.23, then the dijet cross section would be too large, but the $e\mu$ production cross section would saturate around 1 fb. On the other hand, if $Q_L^{\prime u,d} = -Q_R^{\prime u,d}$ were less than 0.02, the $e\mu$ production cross section would be too small. In Table I, we show that $Q_L^{\prime u,d} = -Q_R^{\prime u,d} = 0.2$ can produce the $\sigma(pp \to Z') \times B(Z' \to e^\pm\mu^\mp) \simeq 1$ fb, while at the same time the ee, $\mu\mu$, $\tau\tau$, and dijet channels satisfy the current LHC limits at 13 TeV.

Checking whether $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}, Q_L^{\prime(\tau)}) = 1/10 \times (-0.404, 0.912, -0.064)$ is the only solution or not, we perform a scan over the parameter space of the three $U(1)'$ charges for the charge leptons, $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}, Q_L^{\prime(\tau)})$, meanwhile fix $g' = 1$, $\epsilon_L^{u,d} = -\epsilon_R^{u,d} = diag(0.2, 0.2, 0.2)$, and $\epsilon_R^l = 0$. The resulting scan is shown in Fig. 1. The Z' production cross section is only relevant to g' and $Q_{L,R}^{\prime(u,d)}$. From the upper-left panel in Fig. 1, projecting onto the $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)})$ plane, we find that two preferred directions can satisfy the experimental limits: one is along $(\mp 0.404, \pm 0.912)$, which gives a large enough $\sigma(pp \to Z') \times B(Z' \to e^{\pm}\mu^{\mp})$ at $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}) \simeq (\mp 0.404, \pm 0.912)$; and the other one is along $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}) \propto (1, 1)$. If we further combine with the information of the upper-right panel in Fig. 1, the latter one corresponds to the universal $U'(1)$ charges, i.e $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}, Q_L^{\prime(\tau)}) \propto (1, 1, 1)$, explaining why $\sigma(pp \to Z') \times B(Z' \to e^{\pm}\mu^{\mp})$ would not be large along this direction. The former one covers the benchmark point in Table I and justifies the above steps in assigning the $U(1)'$ charges. There are two solution regions, $(Q_L^{\prime(e)}, Q_L^{\prime(\mu)}) \simeq (-0.404, +0.912)$ and $(+0.404, -0.912)$, which give the $e^{\pm}\mu^{\mp}$ production cross section larger than 1 fb but have weaker correlation with $Q_L^{\prime(\tau)}$. The bottom-right panel of Fig. 1 shows the ratios of $Q_L^{\prime(\mu)}/Q_L^{\prime(e)}$ and $Q_L^{\prime(\tau)}/Q_L^{\prime(e)}$. Requiring the production cross section $e^{\pm}\mu^{\mp}$ larger than 1 fb strongly confines the ratio between $U(1)'$ charges of e and μ, $Q_L^{\prime(\mu)}/Q_L^{\prime(e)} \subset [-3.0, -1.8]$, but the ratio between $U(1)'$ charges of e and τ can vary a lot, $Q_L^{\prime(\tau)}/Q_L^{\prime(e)} \subset [-3.0, 5.5]$.

VII. SUMMARY

We have performed an analysis by considering a model independent LFV Z' boson with universal couplings to quarks but non-universal couplings to left-handed charged leptons. The flavor-changing interactions of the Z' in the charged-lepton sector originate from non-universal couplings in the interaction basis and the mass matrix is not diagonal under the flavor basis. In order to make this Z' model more predictive, we have assumed that the entire lepton mixing comes from the charged-lepton sector, instead of the neutrino sector. The Z' boson with universal and axial-vector-like couplings to quarks is for simplicity and for dodging the stringent constraints from the $\mu - e$ conversion in heavy nucleus experiments. Therefore, the only degrees of freedom are the gauge coupling g', three $U'(1)$ charges for charge-leptons, and one universal $U'(1)$ charges for quarks.

We assign the $U'(1)$ charges, $\epsilon_L^l = 1/10 \times diag(-0.404, 0.912, -0.064)$, for the left-handed charged leptons to enhance the $Z'\mu e$ but suppress $Z'ee$ couplings. Other strategies are used to dodge the observational bounds, like setting the couplings to right-handed charged leptons to zero, and opposite $U'(1)$ charges between left- and right-handed quarks. We have shown a solution in Table I for the normal hierarchy (NH) that a narrow-width Z' boson can produce a large enough cross section for $\sigma(pp \to X) \times B(X \to e^{\pm}\mu^{\mp})$ and at the same time satisfies several stringent constraints from flavor-violating processes. Similar solutions can be found for the inverse hierarchy(IH) case. In the near future, LHC is able to probe this parameter region by searching dilepton channel with different flavor. If the Z' mass is about 2 TeV, the cross section of $\sigma(pp \to Z) \times B(Z' \to e^{\pm}\mu^{\mp})$ can be larger than 1 fb.

We have performed a scan over three $U(1)'$ charges for the charged leptons and fixed other parameters in Fig 1. It turns out that the solution in Table I is quite representative. Requiring the $e^{\pm}\mu^{\mp}$ production cross section larger than 1 fb will restrict the ratios among $U(1)'$ charges, $Q_L'^{(\mu)}/Q_L'^{(e)} \subset [-3.0, -1.8]$ and $Q_L'^{(\tau)}/Q_L'^{(e)} \subset [-3.0, 5.5]$.

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[1] The ATLAS collaboration, ATLAS-CONF-2015-072.

[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **113**, 151601 (2014), [arXiv:1406.6482 [hep-ex]].

[3] P. Batra, B. A. Dobrescu and D. Spivak, J. Math. Phys. **47**, 082301 (2006), [hep-ph/0510181].

[4] A. Ismail, W. Y. Keung, K. H. Tsao and J. Unwin, arXiv:1609.02188 [hep-ph].

[5] A. Arhrib, K. Cheung, C. W. Chiang and T. C. Yuan, Phys. Rev. D **73**, 075015 (2006), [hep-ph/0602175].

[6] S. M. Boucenna, J. W. F. Valle and A. Vicente, Phys. Lett. B **750**, 367 (2015), [arXiv:1503.07099 [hep-ph]].

[7] G. Altarelli, F. Feruglio and I. Masina, Nucl. Phys. B **689**, 157 (2004), [hep-ph/0402155].

[8] P. Langacker, Rev. Mod. Phys. **81**, 1199 (2009), [arXiv:0801.1345 [hep-ph]].

[9] V. Khachatryan *et al.* [CMS Collaboration], arXiv:1604.05239 [hep-ex].

[10] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1504**, 025 (2015), [arXiv:1412.6302 [hep-ex]].

[11] The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2014-030.

[12] The ATLAS collaboration, ATLAS-CONF-2015-070.

[13] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **754**, 302 (2016), [arXiv:1512.01530 [hep-ex]].

[14] V. Khachatryan *et al.* [CMS Collaboration], Phys. Rev. Lett. **116**, no. 7, 071801 (2016), [arXiv:1512.01224 [hep-ex]].

[15] M. Aaboud *et al.* [ATLAS Collaboration], arXiv:1603.08791 [hep-ex].

[16] W. Altmannshofer, C. Y. Chen, P. S. B. Dev and A. Soni, arXiv:1607.06832 [hep-ph].

[17] C. S. Kim, X. B. Yuan and Y. J. Zheng, arXiv:1602.08107 [hep-ph].

[18] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).

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

[20] T. S. Kosmas, S. Kovalenko and I. Schmidt, Phys. Lett. B **511**, 203 (2001), [hep-ph/0102101].

[21] A. J. Buras, F. De Fazio and J. Girrbach, JHEP **1302**, 116 (2013), [arXiv:1211.1896 [hep-ph]].

[22] M. Blanke, A. J. Buras, A. Poschenrieder, C. Tarantino, S. Uhlig and A. Weiler, JHEP **0612**, 003 (2006), [hep-ph/0605214].

[23] [MEG Collaboration], arXiv:1605.05081 [hep-ex].

[24] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **111**, 191801 (2013), [arXiv:1308.1707 [hep-ex]].

[25] R. Gauld, F. Goertz and U. Haisch, Phys. Rev. D **89**, 015005 (2014), [arXiv:1308.1959 [hep-ph]].

[26] W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. D **89**, 095033 (2014), [arXiv:1403.1269 [hep-ph]].

[27] D. K. Papoulias and T. S. Kosmas, Phys. Lett. B **728**, 482 (2014), [arXiv:1312.2460 [nucl-th]].