Unified Explanation of the Anomalies in Semi-Leptonic $B$ decays and the $W$ Mass

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The discrepancies between the measurements of rare (semi-)leptonic $B$ decays and the corresponding Standard Model predictions point convincingly towards the existence of new physics for which a heavy neutral gauge boson ($Z'$) is a prime candidate. However, the effect of the mixing of the $Z'$ with the SM $Z$, even though it cannot be avoided by any symmetry, is usually assumed to be small and thus neglected in phenomenological analyses. In this letter we point out that a mixing of the naturally expected size leads to lepton flavour universal contributions, providing a very good fit to $B$ data. Furthermore, the global electroweak fit is affected by $Z − Z'$ mixing where the tension in the $W$ mass, recently confirmed and strengthened by the CDF measurement, prefers a non-zero value of it. We find that a $Z'$ boson with a mass between $\approx 1 − 5$TeV can provide a unified explanations of the $B$ anomalies and the $W$ mass. This strongly suggests that the breaking of the new gauge symmetry giving raise to the $Z'$ boson is linked to electroweak symmetry breaking with intriguing consequences for model building.

I. INTRODUCTION

Even though the LHC has not discovered any particles beyond the ones of the Standard Model (SM) yet, in the last years intriguing hints for the violation of lepton flavour universality (LFU) have been accumulated (see e.g. Refs. [1–3] for recent reviews). Among them, the updated measurement of the ratios of semi-leptonic rare $B$ meson decay $R_{K^{\mu}} = \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+\ell^+\ell^-)$ [4] by LHCb [5] is particularly prominent since it provides first evidence for LFU violation (LFUV) in a single observable. Furthermore, when combining all tests of LFUV (like $R_{K^{\mu}}$) [6–9] with $B$ decays involving muon pairs (most prominently $P_{\tau}$) [10, 11] and $B_{s} \rightarrow \phi \mu^+ \mu^-$ [12, 13], one finds a preference for new physics (NP) hypotheses of more than $7 \sigma$ [14] compared to the SM [15]. Note that such a high significance is only possible since all measurements are compatible with each other, i.e. they form a coherent picture.

Simple patterns where NP couples solely to muons can in fact explain the discrepancies between the SM and experiment in rare semi-leptonic $B$ decays very well. However, it turns out that structures with additional LFU contributions can describe data even better [22, 23]. This means that allowing simultaneously for presence of LFUV and LFU NP effects, one can further improve the goodness of the global fits. Indeed, some of these hypotheses exhibit the highest significance among all studied scenarios [14, 16, 24, 25].

In this letter, we point out that, extending the SM by a new heavy neutral gauge boson ($Z'$), one has, in addition to the usually considered direct LFUV effect in $b \rightarrow s\ell^+\ell^-$ [31–34], also a LFU effect, which is generated via $Z − Z'$ mixing. In fact, because both bosons have the same quantum numbers, this mixing cannot be avoided by any symmetry. Furthermore, in the case that electroweak (EW) symmetry breaking and the breaking of the symmetry giving rise to the $Z'$ mass are connected, one even expects a mixing of the order of $m_Z/m_{Z'}$. Importantly, $Z − Z'$ mixing has also an impact on the global EW fit, in particular on $Z\ell^+\ell^-$ and $Z\nu\nu$ couplings and if the $Z'$ is an $SU(2)_L$ singlet (i.e. not the neutral component of an $SU(2)_L$ multiplet), in addition the prediction of the $W$ mass is altered compared to the SM. The latter is very important since the global EW fit displayed a tension of $1.8 \sigma$ [35] in this observable. This discrepancy was recently confirmed and strengthened by the CDF measurement [36] whose central value is $7 \sigma$ above the SM prediction [37]. Combining this new measurement with the existing ones from the LHC [38–41], one finds $m_{W} = (80.413 \pm 0.0080)\text{GeV}$ and $m_{W} = (80.413 \pm 0.015)\text{GeV}$, where in the second
the goal of this letter is to assess the size and impact of mixing has usually been assumed to be negligibly small if the $Z_b$ respectively.

Therefore, in $Z'$ models an interesting interplay between $b \to s \ell^+\ell^-$ processes and the global EW fit arises if the $Z - Z'$ mixing angle is non-zero [31]. While this mixing has usually been assumed to be negligibly small [4] the goal of this letter is to assess the size and impact of $Z - Z'$ mixing via a combined analysis of flavour and EW data, providing a unified explanation of both anomalies.

II. SETUP

We extend the SM by adding a heavy neutral $SU(2)_L$ singlet gauge boson. Following the notation of Ref. [93] [94] the kinetic term and the mass term of this new boson, before EW symmetry breaking, are

$$L_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{\mu^2}{2} Z_{\mu0} Z'^{\mu0} + g Z' Z_0 Z'^\mu Z^{\mu0} + \frac{\phi^2}{2} Z^\mu Z_{\mu0} \phi + \frac{\phi^2}{2} D_\mu \phi,$$

where $Z'_{\mu\nu} \equiv \partial_\mu Z'_{\nu0} - \partial_\nu Z'_{\mu0}$ is the field strength tensor, $D_\mu = \partial_\mu - (D_\mu)_i$, $\phi$ is the SM Higgs $SU(2)_L$ doublet and we use $D_\mu = \partial_\mu + ig_2 W^{\mu T} + ig_1 Y B_\mu$ as the definition of the SM part of the covariant derivative and $g_{Z'}^2$ is real by hermicity. The physical $Z$ and $Z'$ masses are obtained from diagonalizing the mass matrix

$$\mathcal{M}^2 = \left( \begin{array}{cc} m_{Z_0}^2 & \frac{\mu}{2} \frac{\phi^2}{2} \\ \frac{\mu}{2} \frac{\phi^2}{2} & m_{Z'}^2 \end{array} \right), \quad y = \frac{\mu}{2} g_2 g_{Z'}^\phi,$$

in the $Z_0, Z_0'$ basis, where $Z_0$ coincides with the the SM $Z$ for $g_{Z'}^2 = 0$ with $m_{Z_0}^2 = \frac{1}{2} (g_1^2 + g_2^2), \frac{\mu}{2} \approx 174$ GeV and $c_{W}^2$ is the cosine of the Weinberg angle. At leading order in $v/m_{Z_0}$ we have

$$m_{Z'}^2 \simeq m_{Z_0}^2 - \frac{\mu^2}{c_W^2 m_{Z_0}^2} \equiv m_{Z_0}^2 (1 + \delta m_{Z}^2).$$

Note that the corrections to the mass of the $Z$ with respect to the SM value $m_{Z_0}$ can only be negative. The

### TABLE I

| $C_{\mu}^V$ | Best-fit point | 1 σ CI | 2 σ CI |
|-------------|----------------|--------|--------|
| $C_{10}^U$  | $-0.96$        | $[-1.11, -0.80]$ | $[-1.25, -0.64]$ |
| $C_{10}^U$  | $+0.30$        | $[+0.15, +0.45]$ | $[+0.00, +0.61]$ |

mass eigenstates $Z^{(i)}$ can then be expressed as

$$\left( \begin{array}{c} Z \cr Z' \end{array} \right) \rightarrow \left( \begin{array}{c} Z_0 \sin \xi + Z_0 \cos \xi \\ Z_0 \cos \xi - Z_0 \sin \xi \end{array} \right),$$

where $sin \xi \equiv \frac{y}{c_W m_{Z_0}^2}$ describes the $Z - Z'$ mixing.

The interactions with the SM fields are given by

$$L_{\text{fermions}} = u_j \gamma_\mu (g_{3L}^{ijL} P_L + g_{3R}^{ijR} P_R) u_i Z_{\mu}^n + d_j \gamma_\mu (g_{3L}^{ijL} P_L + g_{3R}^{ijR} P_R) d_i Z_{\mu}^n + g_{3L}^{ijL} (i \gamma_\mu P_L \nu_i) Z_{\mu}^n + \dot{\epsilon}_j \gamma_\mu (g_{3L}^{ijL} P_L + g_{3R}^{ijR} P_R) \ell_i Z_{\mu}^n,$$

where, in the down basis, $g_{3L}^{ijL} = V_{jk} g_{3LL}^{jkL} V_{kj}$. Note that the couplings to left-handed charged leptons and neutrinos (up and down quarks) are the same (up to a CKM rotation), due to $SU(2)_L$ invariance and that only the relative phase between $sin \xi$ and $g_{L}^{jL}$ is physical, such that one can assume $sin \xi$ to be positive without loss of generality. In the following, we will assume flavour diagonal coupling to leptons and in the quark sector disregard all couplings except left-handed $b \to s$ couplings.

III. OBSERVABLES

A. $b \to s \ell^+\ell^-$

In $Z'$ models without $Z - Z'$ mixing, the simple one dimensional scenario with the best fit to data is obtained from a left-handed $b \to s$ coupling and a vectorial muon coupling, i.e. the $C_{\mu}^V$ scenario [43]. Allowing in addition for $Z - Z'$ mixing we have

$$c_{\mu}^V = -\frac{\pi^2}{e^2} \frac{4 \sqrt{2} g_{3L}^{ijL} g_{3L}^{ijL}}{G_F m_{Z'}^2 V_{tb} V_{ts}^*},$$

$$c_{10}^U = -k c_{10}^U = \frac{\sqrt{2} \pi^2}{e^2} \frac{g_{3L}^{ijL} g_{3R}^{ijR}}{c_W G_F m_{Z'}^2 V_{tb} V_{ts}^*},$$

using the effective Hamiltonian of Ref. [95, 96] where $g_{3L}^{ijL} = (g_{L}^{jL} + g_{L}^{jR})/2$. This corresponds to the scenario

$$\left\{ c_{\mu}^V, c_{10}^U \right\} = -k c_{10}^U,$$

with $k = 1/(1 - 4 e_w^2)$ (see the appendix for the definitions of the operators). The superscript V (U) in the Wilson coefficient stands for a LFUV (LFU) contribution.

We perform the most recent fit [13] to the scenario in Eq. (7), including 254 observables and the latest measurements by LHCb of LFUV observables, namely, $R_{K_S}^{III}$ [9]
is given by

g_{A} = -kC_{s}^{V}

and $R_{K^{*+}}$ as well as the new branching ratio and angular distribution of $B_{s} \rightarrow \phi \mu^{+}\mu^{-}$ [12] [13]. We obtain the best fit point and confidence level regions in Table I. The results of the global fit in our scenario are shown in Fig. 1.

FIG. 1. Preferred 1σ, 2σ and 3σ regions in the $(C_{s}^{V}, C_{10}^{V} = -kC_{s}^{V})$ plane for the scenario discussed in the paper, including all available $b \rightarrow s \ell^{+}\ell^{-}$ data and using the most updated version of ACDMN code [14]. Note that the SM case corresponds to the (0,0) point.

B. $B_{s} - \bar{B}_{s}$ Mixing

The most important constraint on $Z' - b - s$ couplings, i.e. $g_{Z'}^{LL}$, comes from $B_{s} - \bar{B}_{s}$ mixing where the contribution to the Hamiltonian $H_{\text{eff}} = C_{1} \mathcal{O}_{1}$, with

$$
\mathcal{O}_{1} = (\bar{b}\gamma_{\mu}P_{L}s) \times (\bar{b}\gamma_{\mu}P_{L}s),
$$

is given by

$$
C_{1} = 2 \frac{g_{Z'}^{LL}}{m_{Z'}}^{2} \left(1 + \frac{\alpha_{s}}{4\pi} \frac{11}{3}\right),
$$

including the NLO matching corrections of Ref. [97]. Note that the effect of the mixing induced $Z - b - s$ couplings can be neglected as it corresponds to a dimension 8 contribution. Employing the 2-loop renormalization group evolution [98] [99], this leads to an effect, normalized to the SM one, of

$$
\left(\frac{g_{Z'}^{LL}}{0.52}\right)^{2} \left(\frac{10\text{TeV}}{m_{Z'}}\right)^{2} = 0.110 \pm 0.090
$$

using the bag factor of Ref. [100] and the global fit to NP in $\Delta F = 2$ observables of Ref. [101].

C. LFUV in tau decays

Assuming lepton flavour conservation, $Z' - W$ boxes contribute to $\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\tau}$ as [35]:

$$
\mathcal{A}(\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\tau}) = 1 - 3 \frac{g_{Z'}^{LL}}{8\pi^{2}} g_{Z}^{LL} \ln \left(\frac{m_{Z'}}{m_{W}}\right) \left(1 - \frac{m_{Z}^{2}}{m_{W}^{2}}\right),
$$

and analogously for $\tau \rightarrow e \nu_{\tau} \bar{\nu}_{\tau}$ and $\mu \rightarrow e \nu_{\mu} \bar{\nu}_{\mu}$. Note that at vanishing momentum transfer the $Z'$ induced correction to the $W$-$\ell$-$\nu$ vertex vanishes as $SU(2)_{L}$ gauge invariance is not broken. This we compared to the experimental results [102] (see Ref. [103] for an overview on LFUV):

$$
\frac{\mathcal{A}_{\tau \rightarrow \mu \nu_{\tau}}}{\mathcal{A}_{\tau \rightarrow e \nu_{\tau}}} = 1.0029 \pm 0.0014,
$$

$$
\frac{\mathcal{A}_{\tau \rightarrow \mu \nu_{\tau}}}{\mathcal{A}_{\tau \rightarrow e \nu_{\tau}}} = 1.0018 \pm 0.0014,
$$

$$
\frac{\mathcal{A}_{\tau \rightarrow \mu \nu_{\tau}}}{\mathcal{A}_{\tau \rightarrow e \nu_{\tau}}} = 1.0010 \pm 0.0014,
$$

with the correlation matrix given in Ref. [102].

D. Electroweak fit

The EW sector of the SM has been tested with a very high precision at LEP [104] [105] but also at the Tevatron [106] and the LHC [88] [90]. Since it can be parametrized by only three Lagrangian parameters, we choose as usual the set with the smallest experimental error consisting of the Fermi constant ($G_{F} = 1.1663787(6) \times 10^{-5}$ GeV$^{-2}$ [107]), the mass of the $Z$ boson ($m_{Z} = 91.1875(21)$ GeV [105]) and the fine structure constant ($\alpha_{em} = 7.297525664(17) \times 10^{-3}$ [107] [110]).

In our model, the relation between the Lagrangian values and the measurements of $G_{F}$ and $m_{Z}$ is shifted with respect to the SM. While the effect in $\mu \rightarrow e \nu_{\tau}$ is analogous to the one in $\tau \rightarrow \mu \nu_{\tau}$ discussed above we have

$$
\frac{m_{W}^{2}}{m_{Z}^{2}} \approx 1 - \sin^{2} \frac{m_{Z}^{2}}{m_{W}^{2}}. \quad \text{However, since the Z mass is used as an input, this translates into a shift in the W mass prediction of approximately}
$$

$$
\frac{m_{W}^{2}}{m_{Z}^{2}} \approx 1 + \sin^{2} \frac{m_{Z}^{2}}{m_{W}^{2}}.
$$

Note that this shift is positive definite such that the corresponding tension can be explained.

5 Here we neglected semi-leptonic tau decays as well as other probes of LFUV in the charged current which are not affected in the absence of quark coupling (see Ref. [103] for a recent review).
FIG. 2. Global fit to EW data, neutrino trident production, LEP bounds on 4-lepton contact interactions and \( \tau \to \mu \nu \nu \) data with vectorial flavour diagonal couplings \( g_{li} = g_{ri} = g_{vi} \). Here we marginalized over the \( Z - Z' \) mixing angle \( \xi \). The 68\% and 95\% confidence level regions are shown for a \( Z' \) mass of 2 TeV. Note that a preference for the \( L_\mu - L_\tau \) scenario emerges.

This modification of the \( W \) mass as well as \( Z_{\ell\ell} \) and \( Z_{\nu\nu} \) are implemented in HEPfit [111] (including the \( Z' \) vertex corrections [35, 112]). In addition, the Higgs mass \( m_H = 125.16 \pm 0.13 \) GeV [113, 114], the top mass \( m_t = 172.80 \pm 0.40 \) GeV [115–117], the strong coupling constant \( \alpha_s(m_Z) = 0.1181 \pm 0.0011 \) [107] and the hadronic contribution to the running of \( \alpha_\text{em} \) \( (\Delta \alpha_\text{had} = 276.1(11) \times 10^{-4}) \) [107] have been used as input parameters, since they enter EW observables indirectly via loop effects. The complete set of observables used are listed in the appendix.

E. Neutrino Trident Production

The production of a \( \mu^+ \mu^- \) pair from the scattering of a muon-neutrino off the Coulomb field of a nucleus, known as neutrino trident production, constitutes a sensitive probe of new neutral current interactions in the lepton sector [35, 118]. Generalizing the formula of Ref. [118] we find

\[
\frac{\sigma_{\text{SM}+\text{NP}}}{\sigma_{\text{SM}}} = 1 + 8 \frac{g_{LL}^2 m_W^2}{g_2^2 m_Z'^2} \left( 1 + 4s_W^2 \right) \left( g_{LL}^R + g_{RR}^R \right) + \frac{g_{LL}^L - g_{RR}^R}{(1 + 4s_W^2)^2 + 1}.
\]

This ratio is bounded by the weighted average \( \sigma_{\text{exp}}/\sigma_{\text{SM}} = 0.83 \pm 0.18 \) obtained from averaging the CHARM-II [119], CCFR [120] and NuTeV results [121].

F. Direct searches

LEP-II sets stringent bounds on 4-lepton contact interactions and \( \tau \to \mu \nu \nu \) data (orange) and \( b \to s \ell^+ \ell^- \) data (blue) in the \( g' - \sin \xi \) plane for \( m_{Z'} = 2 \) TeV and \( m_{Z'} = 3 \) TeV. One can see that both regions overlap nicely and that a non-zero value of the mixing angle is preferred.
TABLE II. Predictions for some of the most relevant observables in the \( b \to s \ell^+ \ell^- \) fit within the scenario of Eq. (6). The pulls are given in units of standard deviations.

| Observable | Scenario 1 | Experiment | Pull |
|------------|------------|------------|------|
| \( R_{K^0} \) | +0.79 ± 0.01 | +0.85 ± 0.04 | -1.3 |
| \( R_{K^+} \) | +0.79 ± 0.01 | +0.66 ± 0.20 | +0.7 |
| \( R_{K^0}^{D^*} \) | +0.87 ± 0.08 | +0.69 ± 0.12 | +1.3 |
| \( R_{K^{(*)}}^{D_0} \) | +0.84 ± 0.04 | +0.70 ± 0.18 | +0.8 |
| \( Q_3^{[1.6]} \) | +0.28 ± 0.02 | +0.66 ± 0.50 | -0.8 |
| \( \langle p_{1/2} \rangle^{[1.6]}_3 \) | -0.57 ± 0.11 | -0.44 ± 0.12 | -0.8 |
| \( \langle p_{1/2} \rangle^{[1.6]}_9 \) | -0.79 ± 0.11 | -0.58 ± 0.09 | -1.4 |
| \( 10^3 \times B_{B_s \to g_{23}^L} \) | +0.78 ± 0.15 | +0.62 ± 0.06 | +1.0 |
| \( 10^9 \times B_{B_s \to g_{23}^L} - p_{1/2} \) | +3.08 ± 0.14 | +2.85 ± 0.34 | +0.6 |

IV. PHENOMENOLOGY

Let us now study the combined phenomenological consequences of \( Z - Z' \) mixing in rare semi-leptonic \( B \) decays and the global EW fit with the aim of obtaining a combined explanation. For this purpose we will focus on an illustrative simplified scenario with an \( SU(2)_L \) singlet \( Z' \), such that \( Z - Z' \) mixing can account for the discrepancy in the \( W \) mass. Furthermore, \( b \to s \ell^+ \ell^- \) data motivates vectorial couplings to leptons, i.e. \( g_{13}^{LL} = g_{13}^{RR} = g_{13}^{VV} \) which also allow for simple configurations without gauge anomalies such as \( L_\mu - L_\tau \) [25, 44] or \( B_2 - L_2 \) [27]. In addition, \( g_{13}^{LL} = 0 \) and \( g_{13}^{RR} = -g_{13}^{VV} = g' \), i.e. a \( L_\mu - L_\tau \) symmetry [124, 125], is motivated by the EW fit since the effect of \( Z - Z' \) mixing in \( Z \to \nu \nu \) will cancel to leading order. Therefore, larger lepton couplings are possible (see Fig. 2) and \( \tau \to \mu \nu \nu \) receives the desired constructive contribution via \( W - Z' \) box diagrams. In addition to these couplings to leptons, we assume only the presence of left-handed \( Z' - b \to s \) couplings [1].

Importantly, as discussed in the introduction, the current experimental average for the mass of the \( W \) boson, shows at least a 3.7 \( \sigma \) discrepancy with the value predicted from the EW fit within the SM [92]. This prediction is changed in our model according to Eq. (11) such that one accounts for data with a non-zero mixing angle of \( \sin \xi \approx 3.5 \times 10^{-3} \times 1 \text{TeV}/m_{Z'} \). Moving to the complete EW fit (including also LFUV in tau decays, LEP bounds on 4-lepton operators and neutrino trident production) we have \( m_{Z'}, g' \) and \( \sin \xi \) as free parameters. However, since all expressions depend on \( g'^2/m_{Z'}^2 \), despite logarithmic terms we set \( m_{Z'} = 2 \text{TeV} \). The resulting preferred regions from the EW fit and LFUV in tau decays are shown in Fig. 8 for \( m_{Z'} = 2 \) and 3 TeV. Including \( b \to s \ell^+ \ell^- \) as well as \( B_s - \bar{B}_s \) mixing, in addition \( g_{23}^{LL} \) enters as a free parameter. Marginalizing over \( g_{23}^{LL} \) we find the 1 \( \sigma \) and 2 \( \sigma \) regions shown in blue in Fig. 3. Note that all 2\( \sigma \) regions nicely overlap, showing that both the EW fit and \( b \to s \ell^+ \ell^- \) data prefer a non-zero \( Z - Z' \) mixing angle such that the \( W \) mass can be explained.

V. CONCLUSIONS AND OUTLOOK

In this article we systematically studied the impact of \( Z - Z' \) mixing on the global fit to \( b \to s \ell^+ \ell^- \) data and EW precision observables. Concerning the former, we observe that a LFU effect is generated while in the latter the mixing leads to modified \( Z \) couplings and to an enhancement in the predicted \( W \) mass w.r.t. the SM, which accommodates the new experimental average (including the recent one from CDF). Therefore, while in previous analyses in the literature the effect of \( Z - Z' \) mixing was usually assumed to be small and was therefore mostly neglected, we stress that both \( b \to s \ell^+ \ell^- \) data and the EW fit even prefers a small but non-zero value of the order of \( 10^{-3} \) for \( m_{Z'} \approx 1 \text{TeV} - 5 \text{TeV} \). Note that this is in agreement with the expectation \( \sin \xi \approx g_2 g_{23}^L m_{Z'}^2/m_{Z}^2 \). A TeV scale \( Z' \) with order one couplings in case \( U(1)' \) and EW symmetry breaking are related.

If \( b \to s \ell^+ \ell^- \) data is in fact explained by a \( Z' \) with non-vanishing \( Z - Z' \) mixing, one predicts a pattern for the main observables driving the anomaly as shown in Table 1. We observe that all tensions with experiment reduce significantly below the 1.5 \( \sigma \) level in the scenario analyzed. Because \( b \to s \ell^+ \ell^- \) ratios testing LFUV depend naturally (and almost entirely) on \( g_{23}^L \) and thus do not carry information on \( \sin \xi \), angular observables are necessary for a distinctive study of \( Z' \) models. It will therefore be important to verify with more precise LHCb data together with future Belle II analysis if this scenario gets reinforced.

Furthermore, forthcoming LHC measurements of the \( W \) mass may reinforce the current tension and any improvement in the global EW fit (e.g. in the top mass or in \( Z \) decays) would lead to a more precise \( W \) mass predictions which could be very precisely measured with future lepton colliders such as FCC-ee [27], ILC [28], CEPC [29] or CLIC [30]. Importantly, if a non-zero \( Z - Z' \) mixing is established in the future, like e.g. predicted in the model of Ref. 27, this would imply that \( SU(2)_L \) and \( U(1)' \) are broken by a field charged under both symmetries with important consequences for model building.

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6 Note that our analysis would to a good approximation also apply to other scenarios, such as \( B_3 - L_2 \).

7 Note that such a scenario could be generated in models with vector-like quarks [20, 25], where absence of \( Z' \) couplings to light quarks avoids problems with direct LHC searches as well as larger effects in the total \( W \) width from mixing.
APPENDIX

We write the interactions of the SM Z with fermions as:

\[ \mathcal{L}_{Zff} = \bar{f}_i \gamma_\mu (\Delta_{ij} \mathcal{L}_{PL} + \Delta_{ij}^{R} \mathcal{L}_{PR}) f_j Z^\mu + \bar{f}_i g_{ij} \Delta^{\nu \mu} \mathcal{L}_{P L} v_i Z^\mu \]

\[ + \bar{f}_j \gamma_\mu (\Delta_{ij} \mathcal{L}_{PL} + \Delta_{ij}^{R} \mathcal{L}_{PR}) u_i Z^\mu \]

\[ + \bar{f}_j \gamma_\mu (\Delta_{ij} \mathcal{L}_{PL} + \Delta_{ij}^{R} \mathcal{L}_{PR}) d_i Z^\mu , \]

with \( i, j = 1, 2, 3 \) and

\[ \Delta_{ij}^{LL(R)} = \sin \xi \left( g_{ij}^{LL(R)} + g_{SM}^{LL(R)} \delta_{ij} \right) , \]

\[ \Delta_{ij}^{\nu L} = \sin \xi \left( g_{ij}^{\nu L} + g_{SM}^{\nu L} \delta_{ij} \right) , \]

\[ \Delta_{ij}^{W L} = \sin \xi \left( V_{jk} g_{ik}^{W} V_{i\nu} + g_{SM}^{W} \delta_{ij} \right) , \]

\[ \Delta_{ij}^{W R} = \sin \xi \left( g_{ij}^{W R} + g_{SM}^{W R} \delta_{ij} \right) , \]

\[ \Delta_{ij}^{dL(R)} = \sin \xi \left( \bar{g}_{ij}^{dL(R)} + g_{SM}^{dL(R)} \delta_{ij} \right) , \]

where \( g_{SM}^{L(R)} \) are the SM couplings given by

\[ g_{SM}^{L} = - \frac{e}{2 s_{W} c_{W}}, \]

\[ g_{SM}^{\nu L} = \frac{e}{2 s_{W} c_{W}} \left( 1 - 2 s_{\nu}^2 \right) , \quad g_{SM}^{R} = - \frac{e}{2 s_{W} c_{W}}, \]

\[ g_{SM}^{W L} = - \frac{e}{2 s_{W} c_{W}} \left( \frac{1}{3} - \frac{2}{3} s_{W}^2 \right) , \quad g_{SM}^{W R} = - \frac{1}{3} s_{W}. \]

with \( e = g_{1} g_{2} / \sqrt{g_{1}^{2} + g_{2}^{2}} = g_{1} c_{W} = g_{2} s_{W} \) being the electric charge. Moreover, taking into account the \( Z - Z' \) mixing in Eq. (14) and the vertex corrections \( [35, 112] \), we have the following modified \( Z \) couplings to leptons

\[ \Delta_{ij}^{LL} = \frac{\bar{f}_{SM}^{LL}}{s_{W} c_{W}} \left( \delta_{ij} + \sin \xi \frac{g_{ij}^{LL} + \sum_{k} g_{ik}^{LL, \nu L} K_{F} \left( \frac{m_{Z}^{2}}{m_{Z'}^{2}} \right)}{(4 \pi)^{2}} \right) , \]

\[ \Delta_{ij}^{\nu L} = \frac{g_{SM}^{\nu L}}{s_{W} c_{W}} \left( \delta_{ij} + \sin \xi \frac{g_{ij}^{\nu L} + \sum_{k} g_{ik}^{LL, \nu L} K_{F} \left( \frac{m_{Z}^{2}}{m_{Z'}^{2}} \right)}{(4 \pi)^{2}} \right) , \]

\[ \Delta_{ij}^{W L} = \frac{g_{SM}^{W L}}{s_{W} c_{W}} \left( \delta_{ij} + \sin \xi \frac{g_{ij}^{W L} + \sum_{k} g_{ik}^{W L, \nu L} K_{F} \left( \frac{m_{Z}^{2}}{m_{Z'}^{2}} \right)}{(4 \pi)^{2}} \right) , \]

at the \( Z \) pole with

\[ K_{F}(x) = - \frac{2(x + 1)^{2}(L_{12}(-x) + \ln(x) \ln(x + 1))}{x^{2}} \]

\[ - \frac{7x + 4}{2x} \left( 3x^{2} + 2x \right) \ln(x). \]

The effective Hamiltonian \( [35, 98] \) in which heavy degrees of freedom have been integrated out is given by

\[ \mathcal{H}_{\text{eff}} = - \frac{4 G_{F}}{\sqrt{2}} V_{ib} V_{ic}^{*} \sum_{i} C_{i} O_{i} \]

The relevant operators for this paper are:

\[ O_{9r} = \frac{e^{2}}{16 \pi^{2}} (\bar{\nu}_{\gamma} P_{L} \nu_{L} \bar{\nu}_{\gamma} \nu_{L} \ell), \]

\[ O_{9} = \frac{e^{2}}{16 \pi^{2}} (\bar{\nu}_{\gamma} P_{R} \nu_{L} \bar{\nu}_{\gamma} \nu_{L} \ell), \]

\[ O_{10} = \frac{e^{2}}{16 \pi^{2}} (\bar{\nu}_{\beta} P_{R} \nu_{L} \bar{\nu}_{\gamma} \nu_{L} \ell), \]

\[ O_{10} = \frac{e^{2}}{16 \pi^{2}} (\bar{\nu}_{\gamma} P_{R} \nu_{L} \bar{\nu}_{\gamma} \nu_{L} \ell), \]

where \( P_{L, R} = (1 \mp \gamma_{5}) / 2 \).

The set of observables used in the EW fit are given in Table III.
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