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Violation of lepton flavour universality in composite Higgs models

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ABSTRACT

We investigate whether the 2.6σ deviation from lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$ decays recently observed at the LHCb experiment can be explained in minimal composite Higgs models. We show that a visible departure from universality is indeed possible if left-handed muons have a sizable degree of compositeness. Constraints from Z-pole observables are avoided by a custodial protection of the muon coupling.

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1. Introduction

Rare B meson decays based on the quark-level transition $b \to s\ell^+\ell^-$, with $\ell = e, \mu, \tau$, are sensitive probes of physics beyond the Standard Model (SM) as these flavour-changing neutral currents are loop and CKM suppressed in the SM. In addition to probing flavour-violation in the quark sector, also lepton flavour universality (LFU) can be tested by comparing the rates of processes with different leptons in the final state. Recently, the LHCb Collaboration has measured the ratio R_K of the $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ branching ratios [1],

$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B^+ \to K^+e^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036\,, \tag{1}$$

which corresponds to a 2.6σ deviation from the SM value, which is 1.0 to an excellent precision. If confirmed, this deviation from unity would constitute an irrefutable evidence of new physics (NP).

Supposing the measurement (1) is indeed a sign of NP, it is interesting to ask which NP model could account for this sizable violation of LFU. It has been demonstrated already that in models where the $b \to s\ell^+\ell^-$ transition is mediated at the tree level by a heavy neutral gauge boson [2–8] or by spin-0 or spin-1 leptoquarks [3,9–12], it is possible to explain the measurement without violating other constraints. However, in more complete models, it often turns out to be difficult to generate a large enough amount of LFU violation. In the MSSM, it has been shown that it is not possible to accommodate the central value of (1) [7]. In composite Higgs models, which at present arguably constitute the most compelling solution to the hierarchy problem next to supersymmetry, one interesting possibility recently considered to explain (1) is to postulate the presence of composite leptoquarks [13]. This however comes at the price of a significant complication of the models. In more minimal models a thorough analysis of the possible size of LFU violation is still lacking and it is the purpose of this study to fill this gap.

2. FCNCs and partially composite muons

A departure from LFU in $b \to s\ell^+\ell^-$ transitions can be described in the weak effective Hamiltonian by a non-universal shift in the Wilson coefficients of the operators

$$O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)\,, \tag{2}$$

$$O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,. \tag{3}$$

A global analysis has shown that the data prefer a negative shift in C_9^μ, with a possible positive contribution to C_{10}^μ [7] (see also [14,15] for other recent fits). In the following, we will denote the shift in the Wilson coefficients with respect to their SM values by δC_i. Interestingly, for $\delta C_{10}^\mu = -\delta C_9^\mu$, which corresponds to the limit in which only the left-handed leptons are involved in the transition, a comparably good fit to the case of NP in δC_9^μ only is obtained.

In models with partial compositeness, there are two distinct tree-level contributions to the $b \to s\ell^+\ell^-$ transition (cf. [16,17]).

- Z exchange, facilitated by a tree-level flavour-changing Z coupling that arises from the mixing after EWSB of states with different $SU(2)_L$ quantum numbers; this effect is thus always parametrically suppressed by v^2/f^2, but not mass-suppressed.

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- Heavy neutral spin-1 resonance exchange. This effect does not require the insertion of a Higgs VEV, but is mass-suppressed by the heavy resonance propagator.

Concerning the heavy resonance exchange, one can distinguish two qualitatively different effects depending on how the coupling of the resonance to the final-state leptons comes about.

- There is a contribution stemming from the mixing of the heavy resonances with the Z boson; in this case, the coupling to the leptons is to a good approximation equal to the SM Z coupling of the leptons.
- Another contribution stems from the mixing of the leptons with heavy vector-like composite leptons. While the coupling of the resonance to composite leptons is expected to be strong, this contribution is suppressed by the (squared) degree of compositeness of the light leptons.

A crucial observation first made in [17] is that both the Z-mediated contribution and the resonance exchange contribution based on vector boson mixing lead to $\delta C_9^\mu/\delta C_{10}^\mu = (1-4s_w^2) \approx 0.08$ due to the (accidentally) small vector coupling of the Z to charged leptons in the SM. Such a pattern of effects is not supported by the global fit to $b \to s$ data.

We are therefore led to the conclusion that the vector resonance exchange with the resonance-lepton coupling induced by the mixing of muons with heavy vector-like partners is the only way to explain the R_K anomaly in our framework in accordance with the data. While the product of degrees of compositeness of the left- and right-handed muon needs to be small to account for the smallness of the muon mass, one of the two could be sizable. In the case of left-handed muons, as mentioned above, this would lead to a pattern $\delta C_9^\mu = -\delta C_{10}^\mu$, while right-handed muons would imply $\delta C_9^\mu = +\delta C_{10}^\mu$. The latter however is not preferred by the global fit to $b \to s$ data, so we require the *left-handed muons* to be significantly composite. The main questions are then:

- How large does the degree of compositeness of left-handed muons have to be to explain (1)?
- How large do precision measurements allow this degree of compositeness to be?

Concerning the first question, an important point is that the quark flavour-changing coupling to the vector resonances cannot be too large since it would otherwise lead to a large NP effect in B_s–$\bar{B}_s$ mixing that is not allowed by the data [7] (see also [17–21]). Combining the B_s mixing constraint with the requirement to get a visible effect in R_K leads to a lower bound on the coupling of the vector resonances to muons. Estimating this coupling in our case as $g_\rho s_{L\mu}^2$, where g_ρ is a generic (strong) coupling between the composite lepton partners and the vector resonances and $s_{L\mu}$ is the degree of compositeness of left-handed muons, and writing a common vector resonance mass as $m_\rho \equiv g_\rho f/2$,[1] one finds that a visible effect in R_K requires, up to a model-dependent $\mathcal{O}(1)$ factor, $s_{L\mu} \gtrsim 0.15\,\xi^{-1/4}$, where $\xi = v^2/f^2$.

Such a sizable degree of compositeness is problematic at first sight. In general, the left-handed muons mix after EWSB with composite states that have different $SU(2)_L$ quantum numbers. This leads to a shift in the Z coupling to left-handed muons that is generically of the size $\delta g^L_{Z\mu\mu} \sim \xi s^2_{L\mu}$. Given the LEP precision measurements which require $|\delta g^L_{Z\mu\mu}| \lesssim 10^{-3}$ implies, again up to a model-dependent $\mathcal{O}(1)$ factor, $s_{L\mu} \lesssim 0.03\,\xi^{-1/2}$. Even if just a rough estimate, this shows clearly that a model satisfying this naive estimates is not viable. However, it is well-known that models exist where certain couplings of the Z boson do not receive any corrections at tree level due to discrete symmetries: in the same way as this *custodial protection* prevents the $Z\bar{b}_L b_L$ coupling from large corrections [22], the $Z\bar{\mu}_L\mu_L$ coupling could be protected [23], opening the possibility of significantly composite left-handed muons.

3. Model setup

Composite Higgs models generally allow for many possibilities in model building. To make our results less model-dependent, our guideline will be to use the simplest model including partial compositeness. Indeed as we will see, very much is already fixed by demanding compatibility with electroweak precision tests.

In general, composite Higgs models feature a SM-like elementary sector and a strongly interacting BSM sector with a global symmetry H. It is well-known that in order to avoid critical tree-level corrections to the T parameter one has to impose custodial symmetry, which is most easily done by choosing $H = SO(4) \sim SU(2)_L \times SU(2)_R$. We further assume that the global symmetry in the composite sector contains a $U(1)_X$ such that hypercharge is given by $Y = T_{3R} + X$ where T_{3R} is the third component of right-handed isospin.

Under the paradigm of partial compositeness the elementary leptons χ mix linearly with fermionic composite operators $\mathcal{O}^{(\chi)}_{\text{comp}}$ such that $\mathcal{L}_{\text{mix}} = \sum_\chi \bar{\chi}\mathcal{O}^{(\chi)}_{\text{comp}} + \text{h.c.}$ Demanding a custodial protection of the $Z\bar{\mu}_L\mu_L$ vertex by the introduction of a discrete P_{LR} symmetry restricts the possible choices for representations of the composite operators under the custodial symmetry [22]. We find that for the operator mixing with the left-handed lepton doublet, this leaves only one possibility, $(\mathbf{2},\mathbf{2})_0$ under $SU(2)_L \times SU(2)_R \times U(1)_X$. By the same reasoning the right-handed muon then has to mix with a $(\mathbf{1},\mathbf{3})_0$. On the composite side we thus embed the lepton partners into a representation $(\mathbf{2},\mathbf{2})_0 \oplus (\mathbf{1},\mathbf{3})_0 \oplus (\mathbf{3},\mathbf{1})_0$, where the $(\mathbf{3},\mathbf{1})_0$ is required by the P_{LR} symmetry. This implies that additionally to the bidoublet L and the $SU(2)_R$ triplet E there will also be an $SU(2)_L$ triplet E' appearing in the spectrum of composite resonances. This choice of representations is in fact unique unless one allows for $SU(2)_R$ representations with dimension higher than 3 (which would imply the presence of states with exotic electric charges greater than ± 2).

The second generation lepton sector Lagrangian then reads

$$\begin{aligned}\mathcal{L}_f = &\bar{l}_L(i\not{D})l_L + \bar{\mu}_R(i\not{D})\mu_R \\ &+ \bar{L}(i\not{D}-m_L)L + \bar{E}(i\not{D}-m_E)E + \bar{E}'(i\not{D}-m_E)E', \qquad (4)\end{aligned}$$

where the covariant derivative $\mathcal{D}_\mu$ contains the couplings to the composite vector resonances associated with the $SU(2)_L \times SU(2)_R \times U(1)_X$ global symmetry[2] for the composite leptons and the coupling to the elementary gauge bosons for the elementary fermions. The composite-elementary mixings can be written as[3]

[1] Here, $m_\rho \equiv g_\rho f/2$ is just a convenient definition because f is the suppression scale of dimension-6 operators mediated by vector resonance exchange. In models with a composite pseudo-Goldstone boson Higgs, f can be identified with the Goldstone boson's "decay constant".

[2] Contrary to [24], we will include resonances associated with $U(1)_X$ and $SU(3)_c$ in the following.

[3] In models where the Higgs boson is implemented as a pseudo Nambu–Goldstone boson these mixing terms correspond to an expansion in the Higgs nonlinearities. For example, in a dimensionally deconstructed model like [24] with coset structure $SO(5)/SO(4)$ these are only the leading terms in h/f. In this case the composite fermions should be embedded into the $SO(5)$ adjoint representation $\mathbf{10}_0 = (\mathbf{2},\mathbf{2})_0 \oplus (\mathbf{1},\mathbf{3})_0 \oplus (\mathbf{3},\mathbf{1})_0$ to achieve the custodial protection of the Z vertex.

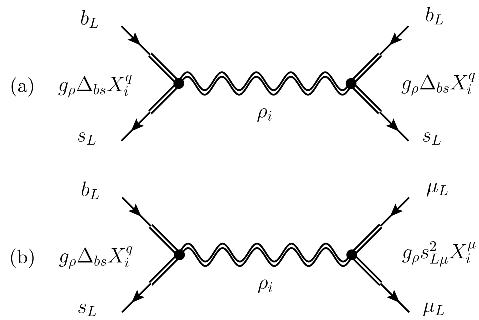

Fig. 1. Tree-level contribution to (a) B_s mixing and (b) $b \to s\mu^+\mu^-$ transitions. Double lines indicate composite fields, g_ρ is the coupling between composite fermion and vector resonances, $s_{L\mu}$ the left-handed muons' degree of compositeness, X_i^f is the charge of the composite fermion mixing with f under the global symmetry associated with vector resonance ρ_i, and Δ_{bs} is a parameter depending on the flavour structure and the degrees of compositeness of b and s quark.

$$\begin{aligned}\mathcal{L}_{\text{mix}} = {} & \lambda_L \operatorname{tr}[\bar{\chi}_L L_R] + \lambda_R \operatorname{tr}[\bar{\chi}_R E_L] \\ & + Y_L \operatorname{tr}[\bar{L}_L \mathcal{H} E_R] + Y'_L \operatorname{tr}[\mathcal{H} \bar{L}_L E'_R] \\ & + Y_R \operatorname{tr}[\bar{L}_R \mathcal{H} E_L] + Y'_R \operatorname{tr}[\mathcal{H} \bar{L}_R E'_L] \\ & + \text{h.c.}\end{aligned} \tag{5}$$

where χ_L and χ_R denote the embeddings of the SM leptons into $(\mathbf{2},\mathbf{2})_0$ and $(\mathbf{1},\mathbf{3})_0$, respectively, and $\mathcal{H}$ is the Higgs doublet transforming as a $(\mathbf{2},\mathbf{2})_0$.

In the mass basis, we obtain a muon with mass

$$m_\mu = \frac{Y_L}{2\sqrt{2}} \langle h \rangle\, s_{L\mu} s_{R\mu}\,, \tag{6}$$

where $\langle h \rangle$ is the VEV of the Higgs field and $s_{L,R} \equiv \sin\theta_{L,R}$ are the degrees of compositeness of left- and right-handed muons, determined by $\tan\theta_L = \lambda_L/m_L$ and $\tan\theta_R = \lambda_R/m_E$.

At this point, the muon neutrino is still massless and we have not introduced any mixing between the different lepton families to avoid constraints from charged lepton flavour violating processes. We do not attempt to construct a full model accounting for neutrino masses and mixing but instead focus on the constraints on muon compositeness that are present even without lepton mixing.

4. Numerical analysis

4.1. Quark flavour physics

To generate a visible NP effect in the $b \to s\mu^+\mu^-$ transition, there must be sufficiently large flavour violating interactions involving left-handed quarks. But apart from this requirement, other details of the (composite) quark sector, such as the representations of composite quarks or the presence of flavour symmetries or flavour anarchy, are not important for our conclusions. This is because the same flavour-changing coupling that enters the $b \to s\ell^+\ell^-$ transition also enters B_s–$\bar{B}_s$ mixing and is thus constrained from above.

The NP contribution to B_s–$\bar{B}_s$ mixing is encoded in the dimension-6 $\Delta B = 2$ operator $O_V^{dLL} = (\bar{s}_L \gamma^\mu b_L)^2$ that arises from tree-level vector resonance exchange (see Fig. 1a). Its Wilson coefficient can be written as

$$C_V^{dLL} = \frac{g_\rho^2}{m_\rho^2} \Delta_{bs}^2\, c_V^{dLL}\,, \tag{7}$$

where c_V^{dLL} is an $O(1)$ numerical factor that arises from the sum over the quantum numbers of the composite quark partners under the global symmetries associated with the exchanged vector resonances (indicated by X_i^q in Fig. 1a). For both of the two choices of composite quark representations that feature a custodial protection of the $Z\bar{b}_L b_L$ coupling, one finds $c_V^{dLL} = -23/36$ [25]. The flavour violating parameter Δ_{bs} depends on the quark degrees of compositeness, but a typical size (both in flavour anarchic models and in models with a $U(2)^3$ flavour symmetry) is $\mathcal{O}(1) \times V_{ts}^2$.

The Wilson coefficient of the $\Delta B = 1$ operator $O_{dl} = (\bar{s}_L \gamma^\nu b_L) \times (\mu_L \gamma_\nu \mu_L)$, that arises in an analogous way (see Fig. 1b), reads instead

$$C_{dl} = \frac{g_\rho^2}{m_\rho^2} \Delta_{bs} s_{L\mu}^2\, c_{dl}\,, \tag{8}$$

where Δ_{bs} is the same coupling as above and $c_{dl} = -1/2$ for our choice of representations.

We can then write a numerical formula for the deviation of R_K from 1, as a function of the left-handed muons' degree of compositeness and the allowed deviation of the mass difference in B_s mixing from the SM,

$$R_K - 1 \approx \pm 0.10 \left[\frac{1\,\text{TeV}}{f}\right] \left[\frac{s_{L\mu}}{0.3}\right]^2 \left[\frac{|\Delta M_s - \Delta M_s^{\text{SM}}|}{0.1\,\Delta M_s^{\text{SM}}}\right]^{1/2}, \tag{9}$$

where the negative sign holds for positive Δ_{bs} and we have used $m_\rho/g_\rho = f/2$ (see footnote 1).

Other constraints in the flavour sector, such as K^0–$\bar{K}^0$ mixing, that typically represents a strong bound in models with flavour anarchy, are more model-dependent. In models with Minimal Flavour Violation, for instance, $b \leftrightarrow s$ transitions are the most constraining and K physics is not relevant in this respect.

4.2. Electroweak precision constraints

Due to the discrete P_{LR} symmetry of the fermion representations, the tree-level coupling of left-handed muons to the Z boson is custodially protected and thus SM-like by construction. An additional loop-correction to this coupling might be relevant in a complete analysis of a specific model [26]. However, this is beyond the scope of the present study whose intention is mainly a proof of concept. We will thus neglect the loop-contributions and focus solely on the tree-level effects.

In contrast to the neutral current coupling, the custodial protection is not active for the charged current coupling $W\mu_L\nu_{\mu L}$. A shift in this coupling would affect the muon lifetime and the extraction of the Fermi constant. To determine the allowed room for new physics in this coupling, a global fit to electroweak precision observables has to be performed. Importantly, the constraint on this coupling is strongly correlated with the constraint on the electroweak T parameter, which receives loop contributions in composite Higgs models that depend on the details of the quark sector. Following [27], we find the constraint shown in Fig. 2. To leading order in $s_{L\mu}$ and ξ, the correction to the Fermi constant, as illustrated by the diagram in Fig. 3, reads

$$\frac{\delta G_F}{G_F} = \frac{\delta g_{W\mu\nu}^L}{g_{W\mu\nu}^L} = -\frac{1}{4}\xi s_{L\mu}^2 \left(1 + \frac{m_L^2}{m_E^2}\right). \tag{10}$$

The first term in the bracket originates from the mixing of the W boson with the composite vector resonances, the second one from the mixing of the left-handed leptons with the composite fermion triplets. In the most favourable case of $m_L \ll m_E$ and a negative NP contribution to the T parameter, the constraint in Fig. 2 implies $s_{L\mu} \lesssim 0.08\,\xi^{-1/2}$. Inserting this maximum value of $s_{L\mu}$ back into eq. (9), one finds, choosing the sign preferred by (1),

$$1 - R_K \lesssim 0.12 \left[\frac{f}{1\,\text{TeV}}\right] \left[\frac{|\Delta M_s - \Delta M_s^{\text{SM}}|}{0.1\,\Delta M_s^{\text{SM}}}\right]^{1/2}. \tag{11}$$

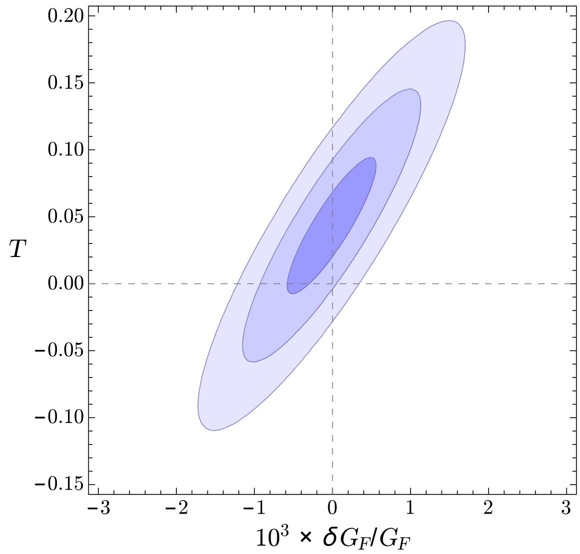

Fig. 2. Constraint at 1, 2, and 3σ on the modification of the Fermi constant in muon decay with respect to the SM versus a NP contribution to the electroweak T parameter.

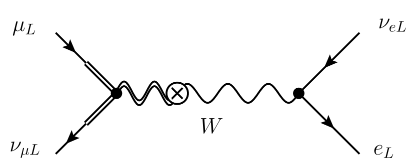

Fig. 3. Tree-level correction to the Fermi constant due to a shift in the tree-level coupling $W\mu_L\nu_{\mu L}$ coupling. The circled cross symbolized a double Higgs VEV insertion.

Consequently, the anomaly (1) can be explained at the 1σ level for $f \gtrsim 1.3$ TeV and $s_{L\mu} \gtrsim 0.4$.

Fig. 4 shows the values of $\delta G_F/G_F$ and of R_K according to (9), assuming the flavour violating coupling Δ_{bs} to saturate a 10% correction to ΔM_s and setting $m_L/m_E = 0.3$.

5. Conclusions

We have demonstrated that a departure from lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$ decays, as hinted by the recent LHCb measurement, could be explained in minimal composite Higgs models if left-handed muons have a sizable degree of compositeness. Assuming a generic composite Higgs with a global custodial symmetry $SO(4)$,[4] the requirement to satisfy LEP bounds on departures from lepton flavour universality in $Z\ell\ell$ couplings uniquely fixes the representations of the composite lepton partners. The strongest constraint on the model then comes from modified W couplings. Depending on the size of the loop corrections to the electroweak T parameter, a departure at the level of 10–20% from $R_K = 1$ is possible for $f \sim 1$ TeV.

If this model is realized in nature, there are several ways to test it beyond R_K.

- It predicts $\delta C_9^\mu \approx -\delta C_{10}^\mu$, which can be tested by global fits to measurements of $b \to s$ transitions, including in particular angular observables in $B \to K^*\mu^+\mu^-$. This relation also implies a suppression of $B_s \to \mu^+\mu^-$ at the same level of the suppression in $B^+ \to K^+\mu^+\mu^-$ (cf. [4]);

[4] But one should keep in mind that the results also remain valid for more realistic models e.g. with a pNG Higgs.

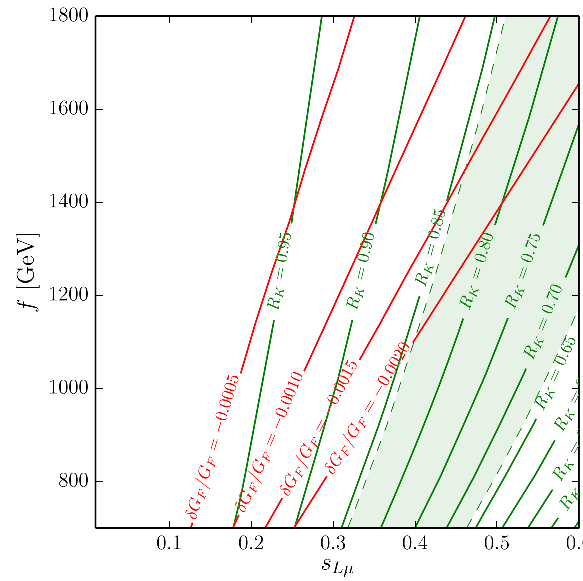

Fig. 4. Predictions for R_K (green) and the relative shift in the Fermi constant (red) for a benchmark point with $m_L/m_E = 0.3$. The flavour-changing coupling Δ_{bs} has been fixed to its maximum value allowing a 10% shift in ΔM_s. The green shaded region corresponds to the 1σ region allowed by (1). We do not show contours for $|\delta G_F/G_F| > 0.002$, which is disfavoured (cf. Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Deviations from LFU are also expected in other branching ratios and in the forward–backward asymmetry in $B \to K^*\mu^+\mu^-$ at low q^2 (cf. [7]);
- It implies an enhancement of both $B \to K\bar{\nu}\nu$ and $B \to K^*\bar{\nu}\nu$ correlated with, but roughly a factor of 5 smaller than, the suppression of R_K. Larger effects in these decays could be generated if taus are significantly composite as well (cf. [3]);
- In principle, vector resonances could be too heavy to be in the reach of the LHC. But if they are light enough, neutral electroweak resonances are expected to have a sizable branching ratio into muons and could show up as peaks in the dimuon invariant mass distribution;
- The model predicts a positive contribution to the B_s meson mass difference ΔM_s, which could be seen when the precision on the relevant lattice parameters and the tree-level determination of the CKM matrix improve in the future.

Finally, we note that our model is incomplete as it does not address neutrino masses or give a rationale for the absence of charged lepton flavour violation. If the anomaly (1) holds up against further experimental scrutiny, it will be interesting to investigate whether our model can be combined with a realistic mechanism for lepton flavour. Also, loop effects not considered in this letter may lead to additional constraints that should be included in a more complete analysis.

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