B decays and lepton flavour (universality) violation

A. Crivellin

CERN Theory Division - CH-1211 Geneva 23, Switzerland

Summary. — LHCb found hints for physics beyond the standard model in $B \to K^* \mu^+ \mu^-$, $B \to K^* \mu^+ \mu^- / B \to K^* e^+ e^-$ and $B_s \to \phi \mu^+ \mu^-$. In addition, the BABAR results for $B \to D^{(*)} \tau \nu$ and the CMS excess in $h \to \tau^\pm \mu^\mp$ also point towards lepton flavour (universality) violating new physics. While $B \to D^{(*)} \tau \nu$ and $h \to \tau^\pm \mu^\mp$ can be naturally explained by an extended Higgs sector, the probably most promising explanation for the $b \to s\mu\mu$ anomalies is a Z' boson. Furthermore, combining a 2HDM with a gauged $L_\mu - L_\tau$ symmetry allows for explaining the $b \to s\mu^+ \mu^-$ anomalies and $h \to \tau^\pm \mu^\mp$ simultaneously, with interesting correlations to $\tau \to 3\mu$. In the light of these deviations from the SM we also discuss the possibilities of observing lepton flavour violating B decays (*e.g.* $B \to K^{(*)} \tau^\pm \mu^\mp$ and $B_s \to \tau^\pm \mu^\mp$) in Z' models.

PACS `11.30.Hv` – Flavor symmetries.
PACS `12.60.Cn` – Extensions of electroweak gauge sector.
PACS `12.60.Fr` – Extensions of electroweak Higgs sector.
PACS `13.25.Hw` – Decays of bottom mesons.

1. – Introduction

With the discovery of the Brout-Englert-Higgs boson [1] the LHC completed the standard model (SM) of particle physics. While no new particles have been discovered at the LHC so far, some "hints" for indirect effect of new physics (NP) in the flavor sector appeared: $B \to K^* \mu^+ \mu^-$, $B_s \to \phi \mu^+ \mu^-$, $R(K) = B \to K \mu^+ \mu^- / B \to K e^+ e^-$, $B \to D^{(*)} \tau \nu$ and $h \to \mu \tau$ deviate from the SM predictions by $2 - 3\,\sigma$, each. While for the first three anomalies only quark flavour must be violated by NP, the last three processes require the violation on lepton flavour (universality).

1'1. *Experimental hints for NP in the flavour sector*. – LHCb reported deviations from the SM predictions [2] (mainly in an angular observable called P_5' [3]) in $B \to K^* \mu^+ \mu^-$ [4,5] with a significance of 2–3 σ depending on the assumptions of hadronic uncertainties [6-8]. Also in the decay $B_s \to \phi \mu^+ \mu^-$ [9] LHCb uncovered differences

compared to the SM prediction from lattice QCD [10, 11] of $3.1\,\sigma$ [7]. Furthermore, LHCb [12] found indications for the violation of lepton flavour universality in

$$(1) \qquad R(K) = \mathrm{Br}[B \to K\mu^+\mu^-]/\mathrm{Br}[B \to Ke^+e^-] = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

in the range $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$ which disagrees with the theoretically clean SM prediction $R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$ [13] by $2.6\,\sigma$. Combining these anomalies with all other observables for $b \to s\mu^+\mu^-$ transitions, it is found that a scenario with NP in $C_9^{\mu\mu}$ only is preferred compared to the SM by $4.3\,\sigma$ [14].

CMS recently also searched for the decay $h \to \tau\mu$ [15] finding a non-zero result of $\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)$ which disagrees by about $2.4\,\sigma$ from 0, *i.e.* from the SM value.

Hints for lepton flavour universality violating (LFUV) NP also comes from the BABAR collaboration who performed an analysis of the semileptonic B decays $B \to D^{(*)}\tau\nu$ [16]. They find for the ratios $R(D^{(*)}) = \mathrm{Br}(B \to D^{(*)}\tau\nu)/\mathrm{Br}(B \to D^{(*)}\ell\nu)$:

$$(2) \qquad R(D) = 0.440 \pm 0.058 \pm 0.042, \qquad R(D^*) = 0.332 \pm 0.024 \pm 0.018.$$

Here the first error is statistical and the second one is systematic. Comparing these measurements to the SM predictions

$$(3) \qquad R_{\mathrm{SM}}(D) = 0.297 \pm 0.017, \qquad R_{\mathrm{SM}}(D^*) = 0.252 \pm 0.003,$$

we see that there is a discrepancy of $2.2\,\sigma$ for $\mathcal{R}(\mathcal{D})$ and $2.7\,\sigma$ for $\mathcal{R}(\mathcal{D}^*)$ and combining them gives a $3.4\,\sigma$ deviation from the SM [16]. Due to the heavy tau lepton in the final state, these decays are sensitive to charged Higgses [17].

2. – New physics explanations

In this section we review NP models which can explain the deviations from the SM discussed in the last section with focus on models with a Z' boson and/or additional Higgs doublets.

2˙1. *Tauonic B decays*. – While a 2HDM of type II (like the MSSM at tree-level) cannot explain the deviations from the SM in tauonic B decays (due to the necessarily destructive interference) without violating bounds from other observables [18] (see left plot in fig. 1). However, a 2HDM with generic Yukawa coupling (*i.e.* type III) and large flavour violation in the up-sector can account for $B \to D\tau\nu$ and $B \to D^*\tau\nu$ simultaneously, respecting the constraints from all other observables [19]. For getting the desired effect in $B \to D^{(*)}\tau\nu$, in addition to the parameters already present in the standard type II model ($\tan\beta$ and the heavy Higgs mass m_H), only one addition free parameter (ϵ_{32}^u), coupling left-handed top quarks to right-handed charm quarks, is necessary (see right plot in fig. 1).

2˙2. *Anomalies in $b \to s\mu\mu$*. – A rather large contribution to operator $(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$, as required by the model independent fit [14], can be achieved in models containing a heavy Z' gauge boson [21,22]. If one aims at explaining also $R(K)$, a contributing to $C_9^{\mu\mu}$
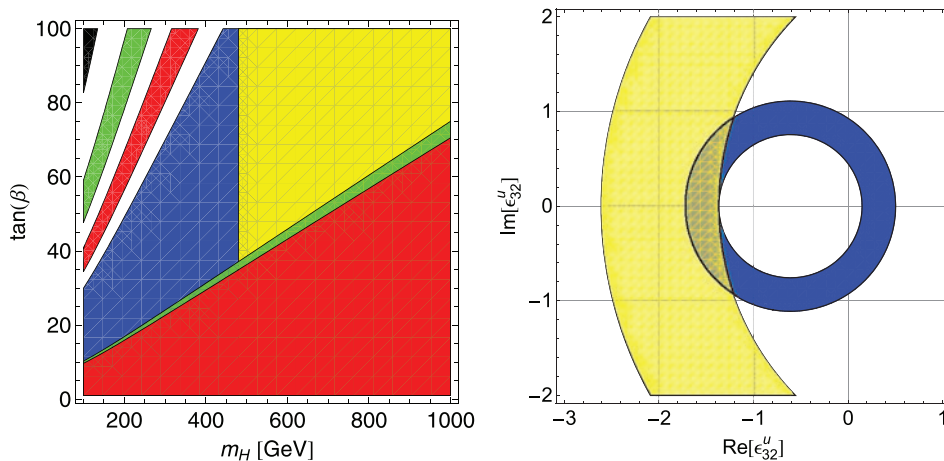
Fig. 1. – Left: Updated constraints on the 2HDM of type-II parameter space. The regions compatible with experiment are shown (the regions are superimposed on each other): $b \to s\gamma$ (yellow) [20], $B \to D\tau\nu$ (green), $B \to \tau\nu$ (red), $B_s \to \mu^+\mu^-$ (orange), $K \to \mu\nu/\pi \to \mu\nu$ (blue) and $B \to D^*\tau\nu$ (black). Note that no region in parameter space is compatible with all processes since explaining $B \to D^*\tau\nu$ would require very small Higgs masses and large values of $\tan\beta$ which is not compatible with the other observables. To obtain this plot, we added the theoretical uncertainty of the SM linearly on the top of the 2σ experimental error. Right: Allowed regions in the complex ϵ_{32}^u-plane from $\mathcal{R}(\mathcal{D})$ (blue) and $\mathcal{R}(\mathcal{D}^*)$ (yellow) for $\tan\beta = 40$ and $m_H = 800\,\mathrm{GeV}$.

involving muons, but not to C_9^{ee} with electrons is necessary [23-25]. This is naturally the case in models with gauged muon minus tauon number ($L_\mu - L_\tau$) [22,26,27]([1]).

In these Z' model the couplings to quarks can be written generically as

$$(4) \qquad L \cup g' \left(\bar{d}_i \gamma^\mu P_L d_j Z'_\mu \Gamma_{ij}^{dL} + \bar{d}_i \gamma^\mu P_R d_j Z'_\mu \Gamma_{ij}^{dR} \right).$$

where g' is the new $U'(1)$ gauge coupling constant. Unavoidable contributions to $B_s - \overline{B}_s$ are generated which constrain the coupling to muons to be much larger than the one to $\bar{s}b$. In the left plot in fig. 2 the regions in the Γ_{sb}^L-Γ_{sb}^R plane are shown which are in agreement with B_s-$\overline{B}_s$ mixing and comply with $b \to s\mu^+\mu^-$ data within 2σ. Note that in the symmetry limit $\Gamma_{sb}^R = 0$, B_s-$\overline{B}_s$ mixing puts a upper bound on Γ_{sb}^L.

2'3. $h \to \tau\mu$. – LFV SM Higgs couplings are induced by a single operator up to dim-6. Considering only this operator $\mathrm{Br}[h \to \mu\tau]$ can be up to 10% [29]. However, it is in general difficult to get dominant contributions to this operator in a UV complete model, as for example in models with vector-like leptons [30]. Therefore, among the several attempts to explain this $h \to \mu\tau$ observation [31], most of them are relying on models with extended Higgs sectors. One particularly elegant solution employs a two-Higgs-doublet model (2HDM) with gauged $L_\mu - L_\tau$ [32].

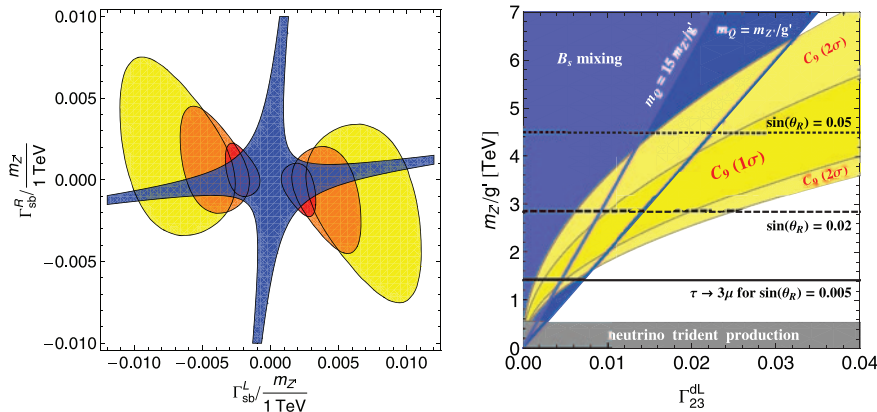([1]) Z' bosons with the desired couplings can also be obtained in models with extra dimensions [28].

Fig. 2. – Left: Allowed regions in the $\Gamma_{sb}^L/M_{Z'} - \Gamma_{sb}^R/M_{Z'}$ plane for $g' = 1$ from B_s-$\overline{B}_s$ mixing (blue), and from the $C_9^{\mu\mu} - C_9^{(')\mu\mu}$ fit of ref. [7] to $b \to s\mu^+\mu^-$ data, with $\Gamma_{\mu\mu}^V = \pm1$ (red), $\Gamma_{\mu\mu}^V = \pm0.5$ (orange) and $\Gamma_{\mu\mu}^V = \pm0.3$ (yellow). Note that the allowed regions with positive (negative) Γ_{sb}^L correspond to positive (negative) $\Gamma_{\mu\mu}^V$. Right: Allowed regions in the $\Gamma_{23}^{dL}-m_{Z'}/g'$ plane from $b \to s\mu^+\mu^-$ data (yellow) and B_s mixing (blue). For B_s mixing (light) blue corresponds to $(m_Q = 15m_{Z'}/g')$ $m_Q = m_{Z'}/g'$. The horizontal lines denote the lower bounds on $m_{Z'}/g'$ from $\tau \to 3\mu$ for $\sin(\theta_R) = 0.05$, 0.02, 0.005. The gray region is excluded by NTP.

3. – Simultaneous explanation of $b \to s\mu\mu$ and $h \to \tau\mu$ and predictions for $\tau \to 3\mu$

In [26, 27] two models with gauged $L_\mu - L_\tau$ symmetry were presented which can be explain $h \to \tau\mu$ simultaneously with the anomalies in $b \to s\mu\mu$ data (including $R(K)$) giving rise to interesting correlated effects in $\tau \to 3\mu$. While in both models the Z' couplings to leptons originate from a gauged $L_\mu - L_\tau$ symmetry, the coupling to quarks is either generated effectively with heavy lepto-quarks charged under $L_\mu - L_\tau$ or directly by assigning horizontal changes to baryons(²).

3.1. *2 Higgs doublets with vector-like quarks*. – Here the model is 2HDM with a gauged $U(1)_{L_\mu - L_\tau}$ symmetry [32]. The $L_\mu - L_\tau$ symmetry is broken spontaneously by the vacuum expectation value of a scalar Φ (beeing singlet under the SM gauge group) with $Q_{L_\mu - L_\tau}^\Phi = 1$, leading to the Z' mass $m_{Z'} = \sqrt{2}g'\langle\Phi\rangle \equiv g'v_\Phi$. Two Higgs doublets are introduced which break the electroweak symmetry: Ψ_1 with $Q_{L_\mu - L_\tau}^{\Psi_1} = -2$ and Ψ_2 with $Q_{L_\mu - L_\tau}^{\Psi_2} = 0$. Therefore, Ψ_2 gives masses to quarks and leptons while Ψ_1 couples only off-diagonally to $\tau\mu$:

$$(5) \qquad \mathcal{L}_Y \supset -\bar{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu}\bar{\ell}_3 \Psi_1 e_2 - \overline{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \overline{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.}$$

Here Q (ℓ) is the left-handed quark (lepton) doublet, u (e) is the right-handed up-quark (charged-lepton) and d the right-handed down quark while i and f label the three generations. The scalar potential is the one of a $U(1)$-invariant 2HDM [33] with additional

---

(²) For pioneering work on horizontal $U(1)$ gauge symmetries see ref. [35].

couplings to the SM-singlet Φ. We defined as usual $\tan\beta = \langle\Psi_2\rangle/\langle\Psi_1\rangle$ and α is the mixing angle between the neutral CP-even components of Ψ_1 and Ψ_2 (see for example [33]). Therefore, quarks and gauge bosons have standard type-I 2HDM couplings to the scalars. The only deviations from the type-I model are in the lepton sector: while the Yukawa couplings $Y_i^\ell \delta_{fi}$ of Ψ_2 are forced to be diagonal by the $L_\mu - L_\tau$ symmetry, $\xi_{\tau\mu}$ gives rise to an off-diagonal entry in the lepton mass matrix:

$$
(6) \qquad m_{fi}^\ell = \frac{v}{\sqrt{2}} \begin{pmatrix} y_e \sin\beta & 0 & 0 \\ 0 & y_\mu \sin\beta & 0 \\ 0 & \xi_{\tau\mu}\cos\beta & y_\tau \sin\beta \end{pmatrix}.
$$

It is this τ–μ element that leads to the LFV couplings of h and Z'. The mass basis for the charged leptons is obtained by rotations of (μ_R, τ_R) and (μ_L, τ_L) with the angles θ_R and θ_L. A non-vanishing angle θ_R not only gives rise to the LFV decay $h \to \mu\tau$ due to the coupling

$$
(7) \qquad \frac{m_\tau}{v} \frac{\cos(\alpha - \beta)}{\cos(\beta)\sin(\beta)} \sin(\theta_R)\cos(\theta_R)\bar{\tau}P_R\mu h \equiv \Gamma_{\tau\mu}^h \bar{\tau}P_R\mu h,
$$

in the Lagrangian, but also leads to off-diagonal Z' couplings to right-handed leptons

$$
(8) \qquad g' Z'_\nu (\bar\mu, \bar\tau) \begin{pmatrix} \cos 2\theta_R & \sin 2\theta_R \\ \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} \gamma^\nu P_R \begin{pmatrix} \mu \\ \tau \end{pmatrix},
$$

while the left-handed couplings are to a good approximation flavour conserving. In order to explain the observed anomalies in the B meson decays, a coupling of the Z' to quarks is required as well, not inherently part of $L_\mu - L_\tau$ models (aside from the kinetic Z-Z' mixing, which is assumed to be small). Following ref. [22], effective couplings of quarks to the Z' are generated by heavy vector-like quarks [34] charged under $L_\mu - L_\tau$. As a result, the couplings of the Z' to quarks are in principle free parameters. In the limit of decoupled vector-like quarks with the quantum numbers of right-handed quarks, only C_9 is generated, giving a very good fit to data. The results are shown in the right plot of fig. 2 depicting that for small values of Γ_{sb}^L and θ_R, $b \to s\mu^+\mu^-$ data can be explained without violating bounds from B_s-$\overline{B}_s$ mixing or $\tau \to 3\mu$. In the left plot of fig. 3 the correlations of $b \to s\mu^+\mu^-$ and $h \to \tau\mu$ with $\tau \to 3\mu$ are shown, depicting that consistency with $\tau \to 3\mu$ requires large values of $\tan\beta$ (not beeing in conflict with any data as the decoupling limit is a type I model) and future searches for $\tau \to 3\mu$ are promising to yield positive results.

3$\cdot$**2.** *Horizontal charges for quarks.* – In order to avoid the introduction of vector-like quarks, one can introduce flavour-dependent charges to quarks as well [27]. Here, the first two generations should have the same charges in order to avoid very large effects in K–$\overline{K}$ or D-$\overline{D}$ mixing, generated otherwise unavoidably due to the breaking of the symmetry necessary to generate the measured Cabibbo angle of the CKM matrix. If we require in addition the absence of anomalies, we arrive at the following charge assignment for baryons $Q'(B) = (-a, -a, 2a)$. Here $a \in \mathcal{Q}$ is a free parameter of the model with
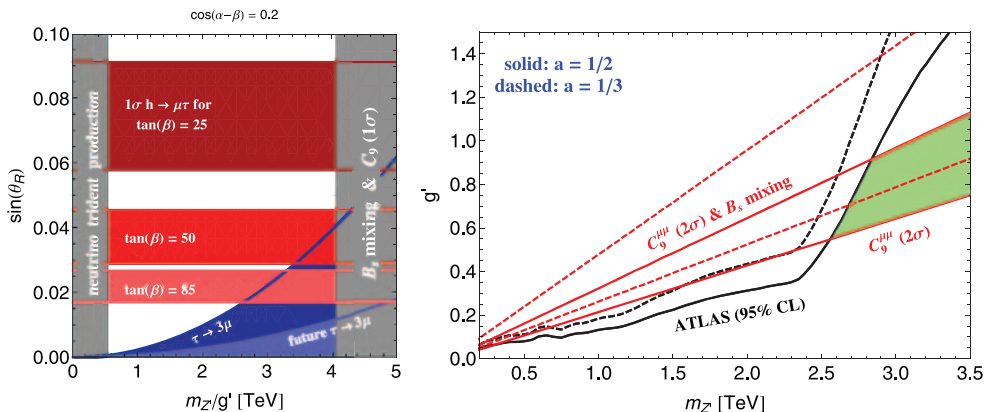
Fig. 3. – Left: Allowed regions in the $m_{Z'}/g' - \sin(\theta_R)$ plane: the horizontal stripes correspond to $h \to \mu\tau$ (1σ) for $\tan\beta = 85, 50, 25$ and $\cos(\alpha - \beta) = 0.2$, (light) blue stands for (future) $\tau \to 3\mu$ limits at 90% C.L. The gray regions are excluded by NTP or B_s-$\overline{B}_s$ mixing in combination with the 1σ range for C_9. Right: Limits on $q\overline{q} \to Z' \to \mu\overline{\mu}$ from ATLAS [36] (black, allowed region down right) and the 2σ limits on $C_9^{\mu\mu}$ to accommodate $b \to s\mu^+\mu^-$ data (red, allowed regions inside the cone). Solid (dashed) lines are for $a = 1/2$ ($a = 1/3$). For $a = 1/2$, the green shaded region is allowed (similar for $a = 1/3$ using the dashed bounds).

important phenomenological implications. In this model, at least one additional Higgs doublet which breaks the flavour symmetry in the quark sector is required, and one more is needed if one attempts to explain $h \to \tau\mu$. In case the mixing among the doublets is small, the correlations among $h \to \tau\mu$, $b \to s\mu^+\mu^-$ and $\tau \to 3\mu$ are the same is in the model with vector-like quarks discussed in the last subsection and shown in the left plot of fig. 3.

The low-energy phenomenology is rather similar to the one of the model with vector like quarks considered in the last section, but the contributions to B_s-$\overline{B}_s$ mixing are directly correlated to B_d-$\overline{B}_d$ and K-$\overline{K}$ mixing as all flavour violation is due to CKM factor. However, concerning direct LHC searches, the implications are very different, as the Z' boson can be directly produced on-shell as a resonance in $p\overline{p}$ collisions since it couples to quarks of the first generation. The resulting strong bounds are shown in right plot of fig. 3 where they are compared to the allowed regions from B_s-$\overline{B}_s$ mixing and $b \to s\mu^+\mu^-$ data for different values of a.

3˙3. *Lepton flavour violating B decays.* – As lepton flavour universality is violated in $R(K)$ and $B \to D^{(*)}\tau\nu$, and $h \to \tau\mu$ even violates lepton flavour, it is interesting to examine the possibility of observing lepton flavour violating B decays [37]. Here we review $B \to K^{(*)}\tau^\pm\mu^\mp$ and $B_s \to \tau^\pm\mu^\mp$ in Z' models with generic couplings to fermions [38]. While in the UV complete model of refs. [26, 27] the branching ratios for LFV B decays are tiny, in general these processes are proportional to $\Gamma_{\mu\tau}\Gamma_{sb}$ and can be large in the presence of sizable flavour violation in the quark and in the lepton sector. As we can see from the left plot in fig. 2, Γ_{sb}^L can only be large if there are cancellations originating from Γ_{sb}^R having the same sign but being much smaller. Therefore, the branching ratios for LFV B decays are bounded by fine tuning together with $\tau \to 3\mu$ and $\tau \to \mu\nu\nu$ limiting $\Gamma_{\mu\tau}$. As a result, we find in a scenario in which NP contributions to $C_9^{\ell\ell'}$ only

are generated

$$(9) \qquad \mathrm{Br}\left[B \to K^{(*)}\tau^{\pm}\mu^{\mp}\right] \leq 2.2(4.4) \times 10^{-8}(1 + X_{B_s}),$$

$$(10) \qquad \mathrm{Br}\left[B_s \to \tau^{\pm}\mu^{\mp}\right] \leq 4.3 \times 10^{-8}(1 + X_{B_s}),$$

where X_{B_s} measures the degree of fine tuning in the B_s system. Note that these limits are obtained for $\Gamma_{\mu\mu} = 0$ (which corresponds to $C_9^{\mu\mu} = 0$) and are even stronger for non-vanishing values of $\Gamma_{\mu\mu}$. For μe final states the possible branching ratios are much smaller due to the stringent constraints from $\mu \to e\gamma$ and $\mu \to e\nu\nu$.

4. – Conclusion

In these proceedings we reviewed the impact of the indirect hint for physics beyond the SM in the flavour sector obtained by BABAR, LHCb and CMS on models of NP with focus on models with Z' bosons and/or additional Higgs doublets. While a prime candidate for the explanation of the anomalous $b \to s\mu^+\mu^-$ data is a Z' boson, $h \to \tau\mu$ as well as $B \to D^{(*)}\tau\nu$ can be most naturally explained by an extended scalar sector. Interestingly, models with gauged $L_\mu - L_\tau$ can explain $b \to s\mu^+\mu^-$ data and $h \to \tau\mu$ simultaneously, predicting sizable branching ratios of $\tau \to 3\mu$, potentially observable in future experiments. While the UV complete models [26,27] predict tiny branching ratios for LFV B decays, these decays can have sizable branching fractions for $\tau\mu$ final states in generic Z' models in the presence of significant fine-tuning in the B_s-$\overline{B}_s$ system.

$$* * *$$

REFERENCES

[1] AAD G. *et al.* (ATLAS COLLABORATION), *Phys. Lett. B*, **716** (2012) 1, arXiv:1207.7214 [hep-ex]; CHATRCHYAN S. *et al.* (CMS COLLABORATION), *Phys. Lett. B*, **716** (2012) 30, arXiv:1207.7235 [hep-ex].

[2] EGEDE U., HURTH T., MATIAS J., RAMON M. and REECE W., *JHEP*, **11** (2008) 032, arXiv:0807.2589 [hep-ph]; ALTMANNSHOFER W., BALL P., BHARUCHA A., BURAS A. J., STRAUB D. M. and WICK M., *JHEP*, **01** (2009) 019, arXiv:0811.1214 [hep-ph].

[3] DESCOTES-GENON S., HURTH T., MATIAS J. and VIRTO J., *JHEP*, **05** (2013) 137, arXiv:1303.5794 [hep-ph].

[4] RAAIJ *et al.* (LHCB COLLABORATION), *Phys. Rev. Lett.*, **111** (2013) 191801, arXiv:1308.1707 [hep-ex].

[5] THE LHCB COLLABORATION (LHCB COLLABORATION), LHCb-CONF-2015-002, CERN-LHCb-CONF-2015-002.

[6] JGER S. and MARTIN CAMALICH J., arXiv:1412.3183 [hep-ph].

[7] ALTMANNSHOFER W. and STRAUB D. M., arXiv:1411.3161 [hep-ph].

[8] DESCOTES-GENON S., HOFER L., MATIAS J. and VIRTO J., *JHEP*, **12** (2014) 125, arXiv:1407.8526 [hep-ph].

[9] AAIJ R. *et al.* (LHCB COLLABORATION), *JHEP*, **07** (2013) 084, arXiv:1305.2168 [hep-ex].

[10] HORGAN R. R., LIU Z., MEINEL S. and WINGATE M., *Phys. Rev. Lett.*, **112** (2014) 212003, arXiv:1310.3887 [hep-ph].

[11] HORGAN R. R., LIU Z., MEINEL S. and WINGATE M., arXiv:1501.00367 [hep-lat].

[12] AAIJ R. *et al.* (LHCB COLLABORATION), *Phys. Rev. Lett.*, **113** (2014) 151601, arXiv:1406.6482 [hep-ex].

[13] BOBETH C., HILLER G. and PIRANISHVILI G., *JHEP*, **12** (2007) 040, arXiv:0709.4174 [hep-ph].

[14] ALTMANNSHOFER W. and STRAUB D. M., arXiv:1503.06199 [hep-ph].

[15] CMS COLLABORATION (CMS COLLABORATION),, CMS-PAS-HIG-14-005.

[16] LEES J. P. *et al.* (BABAR COLLABORATION), *Phys. Rev. Lett.*, **109** (2012) 101802, arXiv:1205.5442 [hep-ex].

[17] KRAWCZYK P. and POKORSKI S., *Phys. Rev. Lett.*, **60** (1988) 182.

[18] CRIVELLIN A., KOKULU A. and GREUB C., *Phys. Rev. D*, **87** (2013) 9, 094031, arXiv:1303.5877 [hep-ph].

[19] CRIVELLIN A., GREUB C. and KOKULU A., *Phys. Rev. D*, **86** (2012) 054014, arXiv:1206.2634 [hep-ph].

[20] MISIAK M., ASATRIAN H. M., BOUGHEZAL R., CZAKON M., EWERTH T., FERROGLIA A., FIEDLER P. and GAMBINO P. *et al.*, arXiv:1503.01789 [hep-ph].

[21] GAULD R., GOERTZ F. and HAISCH U., *Phys. Rev. D*, **89** (2014) 015005, arXiv:1308.1959 [hep-ph]; BURAS A. J., DE FAZIO F. and GIRRBACH J., *JHEP*, **02** (2014) 112, arXiv:1311.6729 [hep-ph], arXiv:1311.6729.

[22] ALTMANNSHOFER W., GORI S., POSPELOV M. and YAVIN I., *Phys. Rev. D*, **89** (2014) 095033, arXiv:1403.1269 [hep-ph].

[23] ALONSO R., GRINSTEIN B. and MARTIN CAMALICH J., *Phys. Rev. Lett.*, **113** (2014) 241802, arXiv:1407.7044 [hep-ph].

[24] HILLER G. and SCHMALTZ M., *Phys. Rev. D*, **90** (2014) 054014, arXiv:1408.1627 [hep-ph].

[25] GHOSH D., NARDECCHIA M. and RENNER S. A., *JHEP*, **12** (2014) 131, arXiv:1408.4097 [hep-ph].

[26] CRIVELLIN A., D'AMBROSIO G. and HEECK J., *Phys. Rev. Lett.*, **114** (2015) 151801, arXiv:1501.00993 [hep-ph].

[27] CRIVELLIN A., D'AMBROSIO G. and HEECK J., *Phys. Rev. D*, **91** (2015) 7, 075006, arXiv:1503.03477 [hep-ph].

[28] NIEHOFF C., STANGL P. and STRAUB D. M., arXiv:1503.03865 [hep-ph].

[29] DAVIDSON S. and VERDIER P., *Phys. Rev. D*, **86** (2012) 111701, arXiv:1211.1248 [hep-ph]; ARHRIB A., CHENG Y. and KONG O. C. W., *Phys. Rev. D*, **87** (2013) 1, 015025, arXiv:1210.8241 [hep-ph]; ARHRIB A., CHENG Y. and KONG O. C. W., *Europhys. Lett.*, **101** (2013) 31003, arXiv:1208.4669 [hep-ph]; BLANKENBURG G., ELLIS J. and ISIDORI G., *Phys. Lett. B*, **712** (2012) 386, arXiv:1202.5704 [hep-ph]; HARNIK R., KOPP J. and ZUPAN J., *JHEP*, **03** (2013) 026, arXiv:1209.1397 [hep-ph].

[30] FALKOWSKI A., STRAUB D. M. and VICENTE A., *JHEP*, **05** (2014) 092, arXiv:1312.5329 [hep-ph].

[31] KOPP J. and NARDECCHIA M., *JHEP*, **10** (2014) 156, arXiv:1406.5303 [hep-ph]; DERY A., EFRATI A., NIR Y., SOREQ Y. and SUSI V., *Phys. Rev. D*, **90** (2014) 115022, arXiv:1408.1371 [hep-ph]; CAMPOS M. D., HERNNDEZ A. E. C., PS H. and SCHUMACHER E., arXiv:1408.1652 [hep-ph]; CELIS A., CIRIGLIANO V. and PASSEMAR E., arXiv:1409.4439 [hep-ph]; SIERRA D. ARISTIZABAL and VICENTE A., *Phys. Rev. D*, **90** (2014) 11, 115004, arXiv:1409.7690 [hep-ph]; LEE C. J. and TANDEAN J., *JHEP*, **04** (2015) 174, arXiv:1410.6803 [hep-ph]; DORSNER I., FAJFER S., GRELJO A., KAMENIK J. F., KOSNIK N. and NISANDZIC I., arXiv:1502.07784 [hep-ph].

[32] HEECK J., HOLTHAUSEN M., RODEJOHANN W. and SHIMIZU Y., arXiv:1412.3671 [hep-ph].

[33] BRANCO G. C., FERREIRA P. M., LAVOURA L., REBELO M. N., SHER M. and SILVA J. P., *Phys. Rep.*, **516** (2012) 1, arXiv:1106.0034 [hep-ph].

[34] LANGACKER P., *Rev. Mod. Phys.*, **81** (2009) 1199, arXiv:0801.1345 [hep-ph]; BURAS A. J., DE FAZIO F. and GIRRBACH J., *JHEP*, **02** (2013) 116, arXiv:1211.1896 [hep-ph].

[35] TERAZAWA H., AKAMA K. and CHIKASHIGE Y., *Phys. Rev. D*, **15** (1977) 480; TERAZAWA H., *Prog. Theor. Phys.*, **57** (1977) 1808.

[36] AAD G. *et al.* (ATLAS COLLABORATION), *Phys. Rev. D*, **90** (2014) 5, 052005, arXiv:1405.4123 [hep-ex].

[37] GLASHOW S. L., GUADAGNOLI D. and LANE K., *Phys. Rev. Lett.*, **114** (2015) 091801, arXiv:1411.0565 [hep-ph].

[38] CRIVELLIN A., HOFER L., MATIAS J., NIERSTE U., POKORSKI S. and ROSIEK J., arXiv:1504.07928 [hep-ph].