Letter

Toward excluding a light Z' explanation of $b \to s\ell^+\ell^-$

Andreas Crivellin[*] and Claudio Andrea Manzari[†]
Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH–8057 Zürich, Switzerland, and Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland

Wolfgang Altmannshofer[‡]
Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, California 95064, USA

Gianluca Inguglia[§] and Paul Feichtinger[∥]
Institute of High Energy Physics, 1050 Vienna, Austria

Jorge Martin Camalich[¶]
Instituto de Astrofísica de Canarias, C/ Vía Láctea, s/n E38205—La Laguna, Tenerife, Spain, and Universidad de La Laguna, Departamento de Astrofísica, La Laguna, Tenerife, Spain

(Received 4 March 2022; accepted 27 July 2022; published 15 August 2022)

The discrepancies between $b \to s\ell^+\ell^-$ data and the corresponding Standard Model predictions constitute one of the most significant hints for new physics currently available. In fact, many scenarios that can account for these anomalies have been proposed in the literature. However, only a single light new physics explanation, i.e., with a mass below the B meson scale, is possible: a light Z' boson. In this article, we aim at excluding any light Z' model as a solution to $b \to s\ell^+\ell^-$ data, using a minimal and conservative setup. Considering the improved limits on $B \to K^{(*)}\nu\nu$, including the experimental sensitivities required for a proper treatment of the necessarily sizable Z' width, together with the forthcoming Belle II analyses of $e^+e^- \to \mu^+\mu^- +$ invisible, can rule out a Z' explanation of $b \to s\ell^+\ell^-$ data with a mass below ≈4 GeV. Importantly, such a light Z' is the only viable single particle solution to the $b \to s\ell^+\ell^-$ anomalies predicting $R(K^{(*)}) > 0$ in high q^2 bins, therefore providing an essential consistency test of data.

DOI: 10.1103/PhysRevD.106.L031703

I. INTRODUCTION

In recent years, multiple hints for the violation of lepton flavor universality (LFU), which is satisfied by the Standard Model (SM) gauge interactions, have been accumulated (see Refs. [1,2] for recent reviews). Among them, the discrepancies between $b \to s\ell^+\ell^-$ data and the corresponding SM predictions are statistically most significant (see Refs. [3–5] for an overview). Combining the current measurements of the LFU ratios $R(K^{(*)})$ one observes that several new physics (NP) scenarios are statistically preferred over the SM hypothesis with significances close to 5σ [6–10]. Furthermore, global analyses including also muon-specific observables, like the branching ratio of $B_s \to \phi\mu^+\mu^-$ and angular observables in $B \to K^*\mu^+\mu^-$, like P_5', show preferences compared to the SM hypothesis with pulls of up to 7σ (and even more), depending on theoretical assumptions and data included in the fits [6–9,11–13].

Because the $b \to s\ell^+\ell^-$ anomalies constitute such tantalizing hints for NP, a plethora of SM extensions have been proposed in the literature, including leptoquarks [14–42], models with loop effects of new scalars and fermions [43–49] and in particular models with new neutral gauge bosons, i.e., Z's [50–108]. Because all of these solutions, except the Z' one, involve charged particles they must be realized at the electroweak scale, or even significantly above, due to the constraints from direct searches. However, a Z' boson can be light and, in fact, such solutions to the $b \to s\ell^+\ell^-$ anomalies have been proposed and studied in the literature [109–117]. Importantly, this is the only NP model addressing the $b \to s\ell^+\ell^-$ anomalies

[*]andreas.crivellin@cern.ch
[†]claudioandrea.manzari@physik.uzh.ch
[‡]waltmann@ucsc.edu
[§]gianluca.inguglia@oeaw.ac.at
[∥]paul.feichtinger@oeaw.ac.at
[¶]jcamalich@iac.es

which predicts $R(K^{(*)}) > 0$ in the high q^2 bins, i.e., above the charm resonances, where precise experimental data is still missing but expected in the near future.

While a light Z' explanation of $b \to s\ell^+\ell^-$ data is experimentally well constrained, it still remains viable if it is assumed that the Z' decays dominantly to invisible final states. This avoids direct searches such as $e^+e^- \to 4\mu$ and provides the sizable width necessary for the Z' to affect multiple q^2 bins in $b \to s\ell^+\ell^-$ observables and thus give a good fit to data. However, also processes with invisible final states are constrained experimentally, such as the dimuon invariant mass distribution in Drell-Yan production close to the Z mass [114] or $e^+e^- \to \mu^+\mu^- +$ invisible at Belle II [118]. In this paper, we analyze these processes together with $B \to K^{(*)}\nu\bar{\nu}$ [119] using a proper treatment of the Z' contribution, including the effects of its sizable width and the mass of the invisible states it decays to. We assess the possibility that a light Z' can in fact be responsible for the $b \to s\ell^+\ell^-$ anomalies and how this option can be tested in the future with the forthcoming Belle II analyses.

II. SETUP AND OBSERVABLES

We want to extend the SM by a light Z' boson in an agnostic and minimal way. This means we include the couplings necessary to explain $b \to s\ell^+\ell^-$ data but do not consider theoretical constraints such as $SU(2)_L$ invariance or anomaly freedom. Note that since we are aiming at excluding a light Z' explanation of $b \to s\ell^+\ell^-$ data, this is a conservative approach in the sense that any additional constraint could only lead to additional bounds but cannot remove the limits we will consider.

Therefore, we consider a Z', with a mass below the B-meson mass scale ($m_{Z'} \lesssim 6$ GeV) with the (simplified and minimal) Lagrangian

$$\mathcal{L}_{Z'} \supset (\bar{\mu}(g^V_{\mu\mu}\gamma^\mu + g^A_{\mu\mu}\gamma^\mu\gamma_5)\mu + g^{L,R}_{sb}\bar{s}\gamma^\mu P_{L,R} b)Z'_\mu. \quad (1)$$

We solely include couplings to muons because the ones to electrons are not necessary to explain the $b \to s\ell^+\ell^-$ anomalies and are experimentally well constrained, in particular when they appear simultaneously with muon couplings. Furthermore, we do not consider couplings to muon neutrinos as they are very stringently constrained by neutrino trident production. Note that this is a conservative assumption as we aim at excluding any light Z' models, i.e., taking into account neutrino couplings could only further limit the parameter space.

Furthermore, in order to achieve the sizable width necessary to affect multiple $q^2 = s$ bins in $b \to s\ell^+\ell^-$ observables such that a good fit to data is possible, we will assume that the Z' has a sizable decay rate to invisible final states χ with $m_\chi < m_{Z'}/2$. Again, we are agnostic about the details of the dark sector and disregard (in our conservative approach) any constraints related to it. As the couplings to $\bar{s}b$ and $\bar{\mu}\mu$ turn out to be small, we will assume that the branching ratio to invisible final states is to a good approximation 100%. Furthermore, for specificity χ is taken to be a fermion with vectorial couplings to the Z' [120].

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

Using the standard parametrization of semileptonic B decays, the effect of a light Z' can be described by a q^2 dependent contribution to the effective Wilson coefficients,

$$C_{9(10)} = \frac{g^L_{sb} g^{V(A)}_{\mu\mu}}{q^2 - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}},$$
$$C'_{9(10)} = \frac{g^R_{sb} g^{V(A)}_{\mu\mu}}{q^2 - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}}, \quad (2)$$

defined at the B meson scale. Here $\Gamma_{Z'}$ is the width of the light vector boson which we approximate here to be q^2 independent and checked that the final result is not significantly affected by this assumption. For the phenomenological analysis, we implemented these contributions into FLAVIO [121] to perform the global fit of our model to data. This includes e.g., the measurement of the LFU ratios R_K [122], $R_{K^{(*)}}$ [123], $R_{K^0_S}$ [124] and $R_{K^{*+}}$ [124], as well as the branching ratio for $B_s \to \mu^+\mu^-$ [125–127], the angular observables of $B \to K^*\mu^+\mu^-$ [128] and the branching ratio and angular distribution of $B_s \to \phi\mu^+\mu^-$ [129,130] which exhibit the most significant deviations from SM predictions.

B. $B \to K^{(*)}$ + invisible

The most important constraints on $Z' - b - s$ couplings, in case the Z' decays dominantly to invisible final states, can be obtained from the processes $B \to K^{(*)}\nu\bar{\nu}$ measured most precisely at *BABAR* [131] and Belle [119]. However, only the latest Belle II analysis [132] with the bound

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5} \quad (3)$$

provides the necessary q^2 dependence of the experimental efficiency necessary to easily recast it in terms of the decay $B^+ \to K^+\chi\bar{\chi}$ [133].

In the case of a sizable Z' width, the branching ratio $\mathcal{B}(B \to K^{(*)}\chi\bar{\chi})$ can be approximated by

$$\mathcal{B}(B \to K^{(*)}\chi\bar{\chi}) = \int_{s_{\min}}^{s_{\max}} ds\Gamma_{Z'}(s)\mathrm{BW}(s)\mathcal{B}(B \to K^{(*)}Z')(s), \quad (4)$$

with $s_{\min} = 4m^2_\chi$, $s_{\max} = (m_B - m_{K^{(*)}})^2$ and $\mathrm{BW}(s) = \pi^{-1}\sqrt{s}/((s - m^2_{Z'})^2 + \Gamma_{Z'}(s)^2 m^2_{Z'})$. In these expressions we have kept the s dependence of the Z' width obtained from our fermionic model of the dark sector, $\Gamma_{Z'}(s) = g^2_V/(12\pi\sqrt{s})(1 - 4m^2_\chi/s)^{1/2}(s + 2m^2_\chi)$, with g_V adjusted

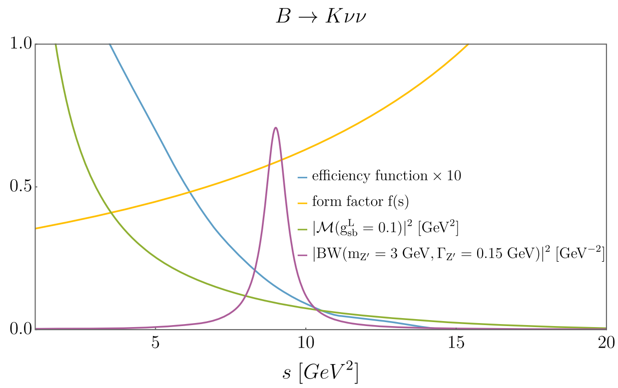

FIG. 1. Components of the calculation of $\mathcal{B}(B \to K\nu\bar{\nu})$ for a light Z' with a width of 15%. The final result is obtained by integrating the product of these functions starting at $s_{\min} = 4m_\chi^2$. As the Breit-Wigner leaks to the left where the experimental efficiency and the matrix element (squared) are enhanced, the bounds are stronger for a larger width.

such that $\Gamma_{Z'}(m_{Z'}^2)$ gives the desired width $\Gamma_{Z'}$. The reason for keeping the s dependence is that it can affect significantly the limits obtained from $B \to K^{(*)}\nu\bar{\nu}$ searches for large m_χ.

With the SM predictions for the differential decay width. $d\Gamma(B^+ \to K^+\nu\bar{\nu})/dq^2$ [135], the relevant form factors [136] and the experimental efficiency function reported by Belle II [137], we can translate Eq. (3) into a limit on our Z' model, given the masses $m_{Z'}$ and m_χ as well as the width $\Gamma_{Z'}$. The experimental signal efficiency [137] is shown in Fig. 1 together with the form factor, the Breit-Wigner distribution of the Z' and the squared matrix element of the amplitude (excluding the form factor). The resulting branching ratio is obtained by integrating the product, starting at $s_{\min}$. As the amplitude and the efficiency function increase at small $s = q^2$, the bounds on g_{sb} are stronger in case of a sizable width compared to a narrow one.

Finally, let us remark that $B \to K\chi\bar{\chi}$ is only sensitive to the vector current $g_{sb}^L + g_{sb}^R$ such that data from $B \to K^*\chi\bar{\chi}$ would be required to probe the axial-vector coupling $g_{sb}^R - g_{sb}^L$. However, the former process is sufficient to constrain the NP scenarios needed to explain the $b \to s\ell^+\ell^-$ anomalies as right-handed bs couplings are bounded by the fits to data.

C. $B_s - \bar{B}_s$ mixing

Tree-level exchange of the Z' contributes to $B_s - \bar{B}_s$ mixing. For light Z' masses one can set up an operator product expansion in $m_{Z'}/m_b$ to calculate this new physics contribution to the mixing amplitude and obtain bounds on g_{sb} [134]. However, these limits turn out to be much weaker than the ones from $B \to K^{(*)}\nu\nu$. While in principle for higher Z' masses there could be a (close to) resonant enhancement, it is not clear how to calculate these effects reliably and we will therefore not use $B_s - \bar{B}_s$ mixing as a constraint in our analysis.

D. $(g-2)_\mu$

The anomalous magnetic moment of the muon receives one-loop corrections from the Z'. With the results given e.g., in Ref. [138] we find

$$\Delta a_\mu = \frac{m_\mu^2}{12\pi^2 M_{Z'}^2} \mathrm{Re}[(g_{\mu\mu}^V)^2 - 5(g_{\mu\mu}^A)^2]. \tag{5}$$

This expression has to be compared with the experimental value [139,140] and the SM prediction [141,142], resulting in $\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-11}$.

E. $pp \to \mu^+\mu^-$ (+anything)

Reference [114] pointed out that Drell-Yan (DY) searches for muon pairs at the LHC place relevant limits on the parameter space. The Z' can be radiated from the final state muons and significantly modify the dimuon invariant mass distribution close to the Z pole. It is found that for a Z' mass between 1–5 GeV the muon coupling should be smaller than ≈0.1 in the case of a dominant branching ratio to invisible.

F. $e^+e^- \to \mu^+\mu^-$ + invisible

The Belle II experiment released a search of invisible Z' decays in the process $e^+e^- \to \mu^+\mu^- +$ invisible [118] using the commissioning run data. Although limited by the size of the data sample analyzed (276 pb^{-1}), 90% confidence level limits on the coupling $g_{\mu\mu}^V$ of the order of $10^{-2} - 10^{-1}$ were obtained. Belle II has also provided sensitivity projections for this model for integrated luminosities up to 50 fb^{-1} [168]; in addition, we obtain projections of the sensitivity up to 5 ab^{-1} by accounting for a scaling factor equivalent to $L^{1/4}$. While Ref. [118] gives bounds on the vectorial coupling, the cross section for $e^+e^- \to \mu^+\mu^- + Z'$ scales as $(g_{\mu\mu}^V)^2 + (g_{\mu\mu}^A)^2$ and thus can be easily adjusted to the case of other chiralities. Note that the analysis of Ref. [118] was done for a Z' with a narrow width. We therefore recast the analysis such that it applies to our case with a sizable Z' width by recalculating the expected signal yield in each bin of the original analysis, assuming a Breit-Wigner with $\Gamma_{Z'} = 0.1M_{Z'}$ (Fig. 3, left) and $\Gamma_{Z'} = 0.15M_{Z'}$ (Fig. 3, right) convoluted with a Gaussian resolution function for the signal. We then set up a binned likelihood fit and used the profile likelihood ratio method to extract the 90% CL intervals.

III. PHENOMENOLOGY

First of all, as already noted in Ref. [109], a sizable width for the Z' is necessary such that it does not only affect a single bin of P_5', $R(K^{(*)})$ etc. This can be achieved by assuming that the Z' decays dominantly into invisible final states χ which at the same time avoids constraints from searches like $e^+e^- \to 4\mu$. Recasting the $B^+ \to K^+\nu\bar{\nu}$

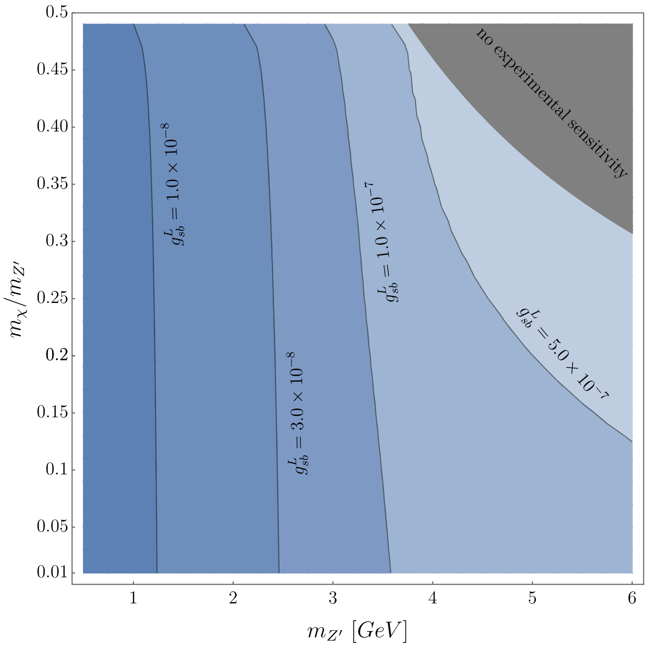

FIG. 2. Contour lines of the bounds on g^L_{sb} in the $m_{Z'} - m_\chi/m_{Z'}$ plane for a Z' width of 10%. The region to the top right is not constrained as in this case the experimental sensitivity vanishes due $s_{\min} = (2m_\chi)^2$.

analysis of Belle II the limits on g^L_{sb} for a 100% branching ratio to undetected final states [169] are shown in Fig. 2. In this plot we see that a large $m_\chi \leq m_{Z'}/2$ weakens the bound on g^L_{sb} such that for $2m_\chi^2 \gtrsim 15$ GeV^2 no limit can be obtained because the experimental sensitivity vanishes.

Let us now turn to the couplings of the Z' to leptons. For purely vectorial couplings, the bound from $(g-2)_\mu$ would be so strong that it would exclude a Z' explanation of $b \to s\ell^+\ell^-$. However, the effect vanishes for $g_V = -\sqrt{5}g_A$. As this scenario (i.e., $C_9^{\text{eff}} = -\sqrt{5}C_{10}^{\text{eff}}$) gives a good fit to $b \to s\ell^+\ell^-$ data (as any scenario between the limiting cases C_9 and $C_9 = -C_{10}$) we will use it as a benchmark scenario here. Note that if we choose g_V slightly bigger, we could account for the tension in $(g-2)_\mu$ while leaving the $b \to s\ell^+\ell^-$ fit unchanged to a very good approximation.

Performing the $b \to s\ell^+\ell^-$ fit under these assumptions, we have three free parameters, $m_{Z'}$, $\Gamma_{Z'}$ and $g^L_{sb} \times g^V_{\mu\mu}$ (with $g^V_{\mu\mu} = -\sqrt{5}g^A_{\mu\mu}$). First of all, note that a width ≈15% gives the best fit to data with $\Delta\chi^2 = \chi^2 - \chi^2_{\text{SM}} \approx 40$ which is however still smaller than what can be achieved with heavy NP that give a q^2 independent effect in the same scenario. Furthermore, $\Delta\chi^2$ does not change significantly for $0.1m_{Z'} < \Gamma_{Z'} < 0.2m_{Z'}$.

In order to minimize the effect in direct searches for the Z' (i.e., DY and $e^+e^- \to \mu^+\mu^-$invisible), given that it provides an explanation to $b \to s\ell^+\ell^-$ data, we can assume that g^L_{sb} takes its maximal value allowed by $B^+ \to K^+\nu\bar{\nu}$. The resulting regions preferred by $b \to s\ell^+\ell^-$ data in the $m_{Z'}$ and $g^V_{\mu\mu} = -\sqrt{5}g^A_{\mu\mu}$ plane are shown in Fig. 3. From there, one can see that the constraints from DY searches at the LHC and $e^+e^- \to \mu^+\mu^-+$ invisible cannot exclude a light Z' explanation of the $b \to s\ell^+\ell^-$ anomalies, yet. However, the forthcoming Belle II analysis of $e^+e^- \to \mu^+\mu^-+$ invisible has the potential of excluding a mass below 4 GeV depending on m_χ and the width of the Z'. Alternatively, we can use the $e^+e^- \to \mu^+\mu^-+$ invisible to derive an upper limit on $g^V_{\mu\mu} = -\sqrt{5}g^A_{\mu\mu}$ and show the exclusions from $B^+ \to K^+\nu\bar{\nu}$ in the $m_{Z'} - g^L_{sb}$ as depicted in Fig. 4, where the 50 fb^{-1} prospects of Belle II have been used. Note that for a width of 15% a Z' with 4 GeV $< m_{Z'} < 4.5$ GeV gives a good fit to data and cannot be excluded due to the vanishing experimental sensitivity in

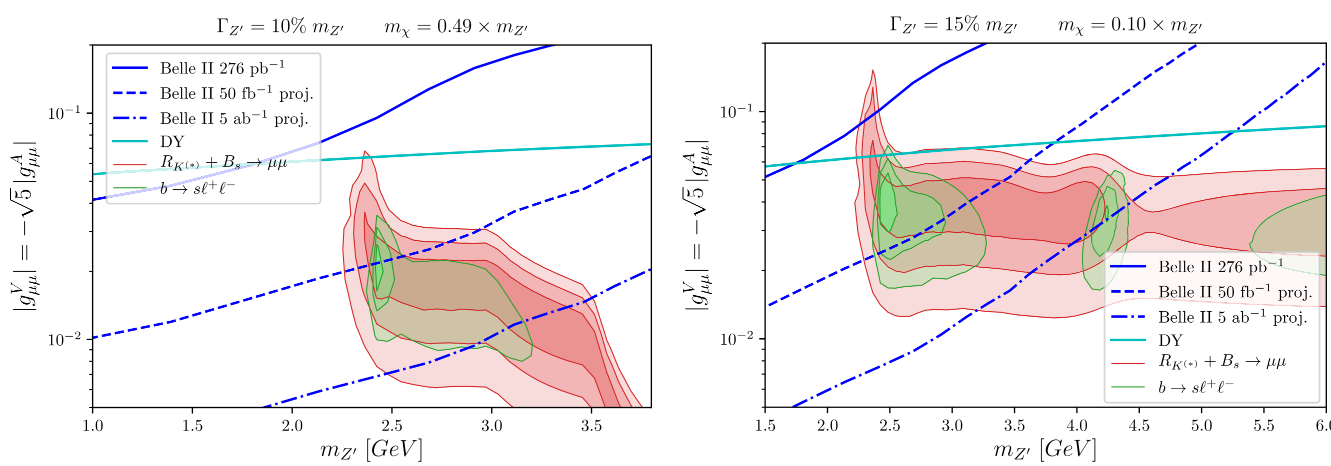

FIG. 3. Preferred regions in the $m_{Z'} - g^V_{\mu\mu}$ plane from $b \to s\ell^+\ell^-$ (whole dataset, green) and the fit to the LFU ratios $R(K)$ and $B_s \to \mu^+\mu^-$ (red) at the $1\sigma, 2\sigma$ and 3σ level for $g^V_{\mu\mu} = -\sqrt{5}g^A_{\mu\mu}$ assuming that g^L_{sb} takes its maximally allowed value from $B \to K\nu\bar{\nu}$ for different Z' widths and χ masses. The regions above the solid lines are excluded by the current DY (cyan) and $e^+e^- \to \mu^+\mu^-$invisible searches (blue) while the dashed lines indicate future sensitivities. Note that a smaller width and a larger χ mass lead to weaker constraints on the model.

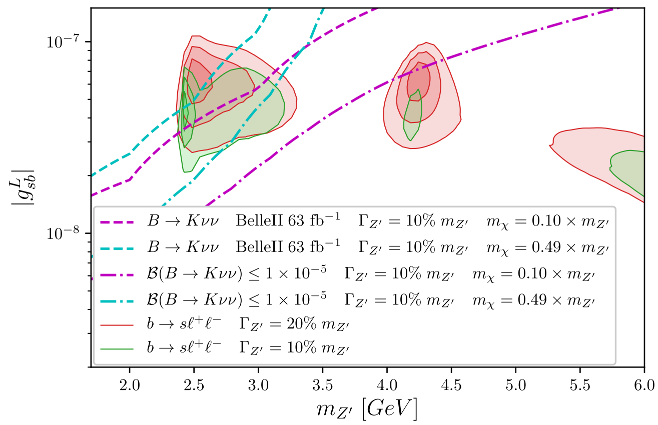

FIG. 4. Preferred regions from $b \to s\ell^+\ell^-$ ($1\sigma, 2\sigma$ and 3σ) in the $m_{Z'} - g_{sb}^L$ plane for the scenario with $g_{\mu\mu}^V = -\sqrt{5} g_{\mu\mu}^A$ assuming that $g_{\mu\mu}^V = -\sqrt{5} g_{\mu\mu}^A$ takes its maximally allowed value allowed by the 50 fb^{-1} sensitivity of Belle II for $e^+e^- \to \mu^+\mu^-$invisible. The regions above the lines, depending on the width and m_χ, can be excluded by future $B \to K\nu\nu$ bounds.

$B^+ \to K^+\nu\bar{\nu}$ for a DM mass close to one half of $m_{Z'}$. However, a Z' with such a mass would not lead to $R(K^{(*)}) > 1$ in the high q^2 bins above the J/Ψ resonances.

IV. CONCLUSIONS AND OUTLOOK

In this paper we pointed out that a light Z' explanation (with a mass below 4 GeV) of the $b \to s\ell^+\ell^-$ anomalies can be confirmed or disproved by combining the forthcoming Belle II searches for $e^+e^- \to \mu^+\mu^+ +$ invisible and $B \to K^{(*)}\nu\bar{\nu}$. Concerning the latter, it is imperative to properly take into account the sizable Z' width and the experimental efficiencies. This endeavor is very important to limit the number of viable models addressing $b \to s\ell^+\ell^-$, in particular in the absence of a signal in direct searches. Furthermore, a light Z' is the only remaining viable NP explanation of $b \to s\ell^+\ell^-$ for which the high q^2 bin (above the charm resonances) in e.g., $R(K^{(*)})$ could lie above unity (assuming that the situation in the low q^2 bins remains unchanged). While a light Z' with a mass between ≈4–6 GeV, which enhances the SM amplitude at high q^2, cannot be excluded for $m_\chi \approx m_{Z'}/2$ due to the limited experimental sensitivity of the $B \to K^{(*)}\nu\nu$ analysis to low energetic $K^{(*)}$, this gap could be closed in the future, e.g., with a reliable calculation of $B_s - \bar{B}_s$ mixing for such Z' masses.

ACKNOWLEDGMENTS

We thank Luc Schnell for checking the heavy NP fit for the $g_{\mu\mu}^V = -\sqrt{5} g_{\mu\mu}^A$ scenario. Support by the Swiss National Science Foundation of the Project *B decays and lepton flavor universality violation* (PP00P21_76884) is gratefully acknowledged by A. C. and C. A. M. G. I. and P. F. acknowledge support by the European Research Council under the Grant Agreement No. 947006—*InterLeptons*. The research of W. A. is supported by the U.S. Department of Energy Grant No. DE-SC0010107. J. M. C. acknowledges Spanish MINECO Grant No. PGC2018-102016-A-I00 and "Ramón y Cajal" No. RYC-2016-20672.

APPENDIX: $B \to K^{(*)}Z'$ BRANCHING RATIO

For the decay width of a B meson into $K^{(*)}$ and a vector of invariant mass s, the operator product expansion analysis of Refs. [136,170] gives

$$\mathcal{B}(B \to KZ') = \frac{(g_{sb}^L + g_{sb}^R)^2 f^2(s)}{64\pi s m_B^3} \lambda(m_B^2, m_K^2, s)^{3/2}, \quad \text{(A1)}$$

$$\begin{aligned}\mathcal{B}(B \to K^* Z') = {} & \frac{(g_{sb}^L + g_{sb}^R)^2 V^2(s)}{8\pi m_B^3 (m_B + m_{K^*})^2} \lambda(m_B^2, m_{K^*}^2, s)^{3/2} + \frac{(g_{sb}^R - g_{sb}^L)^2 A_2^2(s)}{64\pi m_B^3 m_{K^*}^2 s (m_B + m_{K^*})^2} \lambda(m_B^2, m_{K^*}^2, s)^{5/2} \\ & + \frac{(g_{sb}^R - g_{sb}^L)^2 A_1^2(s)(m_B^4 + m_{K^*}^4 + s^2 + 10 s m_{K^*}^2 - 2m_B^2(m_{K^*}^2 + s))}{64\pi m_B^3 m_{K^*}^2 s} \lambda(m_B^2, m_{K^*}^2, s)^{1/2} \\ & + \frac{(g_{sb}^R - g_{sb}^L)^2 A_1(s) A_2(s)(m_B^2 - m_{K^*}^2 - s)}{32\pi m_B^3 m_{K^*}^2 s} \lambda(m_B^2, m_{K^*}^2, s)^{3/2}, \end{aligned} \quad \text{(A2)}$$

where $f(s), V(s), A_1(s)$ and $A_2(s)$ are the form factor given in Refs. [136,170] and λ is the Källén function $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. Note the $1/s$ dependence of the branching ratios which is characteristic for Z' bosons coupled to nonconserved currents [171].

[1] A. Crivellin and M. Hoferichter, Science **374**, 1051 (2021).
[2] O. Fischer *et al.*, arXiv:2109.06065.
[3] J. M. Camalich and M. Patel, Sci. Bull. **67**, 1 (2022).
[4] J. Albrecht, D. van Dyk, and C. Langenbruch, Prog. Part. Nucl. Phys. **120**, 103885 (2021).
[5] D. London and J. Matias, arXiv:2110.13270.
[6] W. Altmannshofer and P. Stangl, Eur. Phys. J. C **81**, 952 (2021).
[7] L.-S. Geng, B. Grinstein, S. Jäger, S.-Y. Li, J. Martin Camalich, and R.-X. Shi, Phys. Rev. D **104**, 035029 (2021).
[8] M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, and M. Novoa-Brunet, Eur. Phys. J. C **82**, 326 (2022).
[9] T. Hurth, F. Mahmoudi, D. M. Santos, and S. Neshatpour, Phys. Lett. B **824**, 136838 (2022).
[10] G. Isidori, D. Lancierini, P. Owen, and N. Serra, Phys. Lett. B **822**, 136644 (2021).
[11] K. Kowalska, D. Kumar, and E. M. Sessolo, Eur. Phys. J. C **79**, 840 (2019).
[12] M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, arXiv:2110.10126.
[13] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, and A. Urbano, J. High Energy Phys. 09 (2017) 010.
[14] R. Alonso, B. Grinstein, and J. Martin Camalich, J. High Energy Phys. 10 (2015) 184.
[15] L. Calibbi, A. Crivellin, and T. Ota, Phys. Rev. Lett. **115**, 181801 (2015).
[16] G. Hiller, D. Loose, and K. Schönwald, J. High Energy Phys. 12 (2016) 027.
[17] B. Bhattacharya, A. Datta, J.-P. Guévin, D. London, and R. Watanabe, J. High Energy Phys. 01 (2017) 015.
[18] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, J. High Energy Phys. 11 (2017) 044.
[19] R. Barbieri, G. Isidori, A. Pattori, and F. Senia, Eur. Phys. J. C **76**, 67 (2016).
[20] R. Barbieri, C. W. Murphy, and F. Senia, Eur. Phys. J. C **77**, 8 (2017).
[21] L. Calibbi, A. Crivellin, and T. Li, Phys. Rev. D **98**, 115002 (2018).
[22] A. Crivellin, D. Müller, A. Signer, and Y. Ulrich, Phys. Rev. D **97**, 015019 (2018).
[23] M. Bordone, C. Cornella, J. Fuentes-Martín, and G. Isidori, J. High Energy Phys. 10 (2018) 148.
[24] J. Kumar, D. London, and R. Watanabe, Phys. Rev. D **99**, 015007 (2019).
[25] A. Crivellin, C. Greub, D. Müller, and F. Saturnino, Phys. Rev. Lett. **122**, 011805 (2019).
[26] A. Crivellin and F. Saturnino, Proc. Sci. DIS2019 (**2019**) 163 [arXiv:1906.01222].
[27] C. Cornella, J. Fuentes-Martin, and G. Isidori, J. High Energy Phys. 07 (2019) 168.
[28] M. Bordone, O. Catà, and T. Feldmann, J. High Energy Phys. 01 (2020) 067.
[29] J. Bernigaud, I. de Medeiros Varzielas, and J. Talbert, J. High Energy Phys. 01 (2020) 194.
[30] J. Aebischer, A. Crivellin, and C. Greub, Phys. Rev. D **99**, 055002 (2019).
[31] J. Fuentes-Martín, G. Isidori, M. König, and N. Selimović, Phys. Rev. D **101**, 035024 (2020).
[32] O. Popov, M. A. Schmidt, and G. White, Phys. Rev. D **100**, 035028 (2019).
[33] S. Fajfer and N. Košnik, Phys. Lett. B **755**, 270 (2016).
[34] M. Blanke and A. Crivellin, Phys. Rev. Lett. **121**, 011801 (2018).
[35] I. de Medeiros Varzielas and J. Talbert, Eur. Phys. J. C **79**, 536 (2019).
[36] I. de Medeiros Varzielas and G. Hiller, J. High Energy Phys. 06 (2015) 072.
[37] A. Crivellin, D. Müller, and F. Saturnino, J. High Energy Phys. 06 (2020) 020.
[38] S. Saad, Phys. Rev. D **102**, 015019 (2020).
[39] S. Saad and A. Thapa, Phys. Rev. D **102**, 015014 (2020).
[40] V. Gherardi, D. Marzocca, and E. Venturini, J. High Energy Phys. 01 (2021) 138.
[41] L. Da Rold and F. Lamagna, Phys. Rev. D **103**, 115007 (2021).
[42] J. Heeck and A. Thapa, Eur. Phys. J. C **82**, 480 (2022).
[43] B. Gripaios, M. Nardecchia, and S. A. Renner, J. High Energy Phys. 06 (2016) 083.
[44] P. Arnan, L. Hofer, F. Mescia, and A. Crivellin, J. High Energy Phys. 04 (2017) 043.
[45] B. Grinstein, S. Pokorski, and G. G. Ross, J. High Energy Phys. 12 (2018) 079.
[46] S.-P. Li, X.-Q. Li, Y.-D. Yang, and X. Zhang, J. High Energy Phys. 09 (2018) 149.
[47] C. Marzo, L. Marzola, and M. Raidal, Phys. Rev. D **100**, 055031 (2019).
[48] A. Crivellin, D. Müller, and C. Wiegand, J. High Energy Phys. 06 (2019) 119.
[49] P. Arnan, A. Crivellin, M. Fedele, and F. Mescia, J. High Energy Phys. 06 (2019) 118.
[50] A. J. Buras and J. Girrbach, J. High Energy Phys. 12 (2013) 009.
[51] R. Gauld, F. Goertz, and U. Haisch, Phys. Rev. D **89**, 015005 (2014).
[52] R. Gauld, F. Goertz, and U. Haisch, J. High Energy Phys. 01 (2014) 069.
[53] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. D **89**, 095033 (2014).
[54] A. Crivellin, G. D'Ambrosio, and J. Heeck, Phys. Rev. Lett. **114**, 151801 (2015).
[55] A. Crivellin, G. D'Ambrosio, and J. Heeck, Phys. Rev. D **91**, 075006 (2015).
[56] C. Niehoff, P. Stangl, and D. M. Straub, Phys. Lett. B **747**, 182 (2015).
[57] D. Aristizabal Sierra, F. Staub, and A. Vicente, Phys. Rev. D **92**, 015001 (2015).
[58] A. Carmona and F. Goertz, Phys. Rev. Lett. **116**, 251801 (2016).
[59] A. Falkowski, M. Nardecchia, and R. Ziegler, J. High Energy Phys. 11 (2015) 173.
[60] A. Celis, W.-Z. Feng, and D. Lüst, J. High Energy Phys. 02 (2016) 007.
[61] A. Celis, J. Fuentes-Martin, M. Jung, and H. Serodio, Phys. Rev. D **92**, 015007 (2015).
[62] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski, and J. Rosiek, Phys. Rev. D **92**, 054013 (2015).
[63] S. M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente, and J. Virto, Phys. Lett. B **760**, 214 (2016).

[64] W. Altmannshofer, M. Carena, and A. Crivellin, Phys. Rev. D **94**, 095026 (2016).
[65] S. M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente, and J. Virto, J. High Energy Phys. 12 (2016) 059.
[66] A. Crivellin, J. Fuentes-Martin, A. Greljo, and G. Isidori, Phys. Lett. B **766**, 77 (2017).
[67] I. Garcia Garcia, J. High Energy Phys. 03 (2017) 040.
[68] G. Faisel and J. Tandean, J. High Energy Phys. 02 (2018) 074.
[69] S. F. King, J. High Energy Phys. 08 (2017) 019.
[70] C.-W. Chiang, X.-G. He, J. Tandean, and X.-B. Yuan, Phys. Rev. D **96**, 115022 (2017).
[71] S. Di Chiara, A. Fowlie, S. Fraser, C. Marzo, L. Marzola, M. Raidal, and C. Spethmann, Nucl. Phys. **B923**, 245 (2017).
[72] P. Ko, Y. Omura, Y. Shigekami, and C. Yu, Phys. Rev. D **95**, 115040 (2017).
[73] F. Sannino, P. Stangl, D. M. Straub, and A. E. Thomsen, Phys. Rev. D **97**, 115046 (2018).
[74] S. Raby and A. Trautner, Phys. Rev. D **97**, 095006 (2018).
[75] R. Alonso, P. Cox, C. Han, and T. T. Yanagida, Phys. Rev. D **96**, 071701 (2017).
[76] J. M. Cline and J. Martin Camalich, Phys. Rev. D **96**, 055036 (2017).
[77] D. Bhatia, S. Chakraborty, and A. Dighe, J. High Energy Phys. 03 (2017) 117.
[78] A. Carmona and F. Goertz, Eur. Phys. J. C **78**, 979 (2018).
[79] A. Falkowski, S. F. King, E. Perdomo, and M. Pierre, J. High Energy Phys. 08 (2018) 061.
[80] R. H. Benavides, L. Muñoz, W. A. Ponce, O. Rodríguez, and E. Rojas, J. Phys. G **47**, 075003 (2020).
[81] P. Maji, P. Nayek, and S. Sahoo, Prog. Theor. Exp. Phys. **2019**, 033B06 (2019).
[82] S. Singirala, S. Sahoo, and R. Mohanta, Phys. Rev. D **99**, 035042 (2019).
[83] D. Guadagnoli, M. Reboud, and O. Sumensari, J. High Energy Phys. 11 (2018) 163.
[84] B. C. Allanach and J. Davighi, J. High Energy Phys. 12 (2018) 075.
[85] M. Kohda, T. Modak, and A. Soffer, Phys. Rev. D **97**, 115019 (2018).
[86] S. F. King, J. High Energy Phys. 09 (2018) 069.
[87] G. H. Duan, X. Fan, M. Frank, C. Han, and J. M. Yang, Phys. Lett. B **789**, 54 (2019).
[88] P. Rocha-Moran and A. Vicente, Phys. Rev. D **99**, 035016 (2019).
[89] S. Dwivedi, D. Kumar Ghosh, A. Falkowski, and N. Ghosh, Eur. Phys. J. C **80**, 263 (2020).
[90] P. Foldenauer, Ph.D. thesis, University of Heidelberg (main), 2019.
[91] P. Ko, T. Nomura, and C. Yu, J. High Energy Phys. 04 (2019) 102.
[92] B. C. Allanach and J. Davighi, Eur. Phys. J. C **79**, 908 (2019).
[93] J. Kawamura, S. Raby, and A. Trautner, Phys. Rev. D **100**, 055030 (2019).
[94] W. Altmannshofer, J. Davighi, and M. Nardecchia, Phys. Rev. D **101**, 015004 (2020).
[95] L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari, and L. Vernazza, Phys. Rev. D **101**, 095003 (2020).
[96] J. Aebischer, A. J. Buras, M. Cerdà-Sevilla, and F. De Fazio, J. High Energy Phys. 02 (2020) 183.
[97] J. Kawamura, S. Raby, and A. Trautner, Phys. Rev. D **101**, 035026 (2020).
[98] A. Crivellin, C. A. Manzari, M. Alguero, and J. Matias, Phys. Rev. Lett. **127**, 011801 (2021).
[99] B. C. Allanach, Eur. Phys. J. C **81**, 56 (2021); **81**, 321(E) (2021).
[100] B. Capdevila, A. Crivellin, C. A. Manzari, and M. Montull, Phys. Rev. D **103**, 015032 (2021).
[101] A. Greljo, P. Stangl, and A. E. Thomsen, Phys. Lett. B **820**, 136554 (2021).
[102] J. Davighi, J. High Energy Phys. 08 (2021) 101.
[103] B. C. Allanach, J. E. Camargo-Molina, and J. Davighi, Eur. Phys. J. C **81**, 721 (2021).
[104] M. F. Navarro and S. F. King, Phys. Rev. D **105**, 035015 (2022).
[105] P. Ko, T. Nomura, and H. Okada, J. High Energy Phys. 05 (2022) 098.
[106] R. Bause, G. Hiller, T. Höhne, D. F. Litim, and T. Steudtner, Eur. Phys. J. C **82**, 42 (2022).
[107] B. C. Allanach, J. M. Butterworth, and T. Corbett, Eur. Phys. J. C **81**, 1126 (2021).
[108] M. Algueró, A. Crivellin, C. A. Manzari, and J. Matias, arXiv:2201.08170.
[109] F. Sala and D. M. Straub, Phys. Lett. B **774**, 205 (2017).
[110] M. K. Mohapatra and A. Giri, Phys. Rev. D **104**, 095012 (2021).
[111] A. Datta, J. Kumar, J. Liao, and D. Marfatia, Phys. Rev. D **97**, 115038 (2018).
[112] W. Altmannshofer, M. J. Baker, S. Gori, R. Harnik, M. Pospelov, E. Stamou, and A. Thamm, J. High Energy Phys. 03 (2018) 188.
[113] F. Sala, Nucl. Part. Phys. Proc. **303–305**, 14 (2018).
[114] F. Bishara, U. Haisch, and P. F. Monni, Phys. Rev. D **96**, 055002 (2017).
[115] D. Borah, L. Mukherjee, and S. Nandi, J. High Energy Phys. 12 (2020) 052.
[116] L. Darmé, M. Fedele, K. Kowalska, and E. M. Sessolo, J. High Energy Phys. 03 (2022) 085.
[117] A. Greljo, Y. Soreq, P. Stangl, A. E. Thomsen, and J. Zupan, J. High Energy Phys. 04 (2022) 151.
[118] I. Adachi *et al.* (Belle-II Collaboration), Phys. Rev. Lett. **124**, 141801 (2020).
[119] J. Grygier *et al.* (Belle Collaboration), Phys. Rev. D **96**, 091101 (2017); **97**, 099902(A) (2018).
[120] This is relevant for calculating the width of the Z' as a function of q^2. However, we checked that this assumption has a minor impact on our final results.
[121] D. M. Straub, arXiv:1810.08132.
[122] R. Aaij *et al.* (LHCb Collaboration), Nat. Phys. **18**, 277 (2022).
[123] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 08 (2017) 055.
[124] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **128**, 191802 (2022).
[125] V. Khachatryan *et al.* (CMS, LHCb Collaborations), Nature (London) **522**, 68 (2015).
[126] M. Aaboud *et al.* (ATLAS Collaboration), J. High Energy Phys. 04 (2019) 098.

[127] A. M. Sirunyan *et al.* (CMS Collaboration), J. High Energy Phys. 04 (2020) 188.
[128] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **126**, 161802 (2021).
[129] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 11 (2021) 043.
[130] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **127**, 151801 (2021).
[131] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **87**, 112005 (2013).
[132] F. Abudinén *et al.* (Belle-II Collaboration), Phys. Rev. Lett. **127**, 181802 (2021).
[133] The bounds obtained using the full Belle [119] and *BABAR* [131] datasets are slightly more stringent than Eq. (3) but are more difficult to use for our purposes (see, however, Ref. [134] for a recast of the *BABAR* limits in terms of a QCD axion).
[134] J. Martin Camalich, M. Pospelov, P. N. H. Vuong, R. Ziegler, and J. Zupan, Phys. Rev. D **102**, 015023 (2020).
[135] A. J. Buras, J. Girrbach-Noe, C. Niehoff, and D. M. Straub, J. High Energy Phys. 02 (2015) 184.
[136] J. A. Bailey *et al.*, Phys. Rev. D **93**, 025026 (2016).
[137] F. Abudinén *et al.* (Belle-II Collaboration), Phys. Rev. Lett. **125**, 161806 (2020).
[138] A. J. Buras, A. Crivellin, F. Kirk, C. A. Manzari, and M. Montull, J. High Energy Phys. 06 (2021) 068.
[139] G. W. Bennett *et al.* (Muon $g-2$ Collaboration), Phys. Rev. D **73**, 072003 (2006).
[140] B. Abi *et al.* (Muon $g-2$ Collaboration), Phys. Rev. Lett. **126**, 141801 (2021).
[141] T. Aoyama *et al.*, Phys. Rep. **887**, 1 (2020).
[142] This result is based on Refs. [143–162]. The recent lattice result of the Budapest-Marseilles-Wuppertal collaboration (BMWc) for the hadronic vacuum polarization (HVP) [163], on the other hand, is not included. This result would render the SM prediction of a_μ compatible with experiment. However, the BMWc results are in tension with the HVP determined from $e^+e^- \to$ hadrons data [157–162]. Furthermore, the HVP also enters the global EW fit [164], whose (indirect) determination is below the BMWc result [165]. Therefore, the BMWc determination of the HVP would increase tension in the EW fit [166,167] and we opted for using the community consensus of Ref. [141].
[143] T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, Phys. Rev. Lett. **109**, 111808 (2012).
[144] T. Aoyama, T. Kinoshita, and M. Nio, Atoms **7**, 28 (2019).
[145] A. Czarnecki, W. J. Marciano, and A. Vainshtein, Phys. Rev. D **67**, 073006 (2003); **73**, 119901(E) (2006).
[146] C. Gnendiger, D. Stöckinger, and H. Stöckinger-Kim, Phys. Rev. D **88**, 053005 (2013).
[147] A. Kurz, T. Liu, P. Marquard, and M. Steinhauser, Phys. Lett. B **734**, 144 (2014).
[148] K. Melnikov and A. Vainshtein, Phys. Rev. D **70**, 113006 (2004).
[149] P. Masjuan and P. Sanchez-Puertas, Phys. Rev. D **95**, 054026 (2017).
[150] G. Colangelo, M. Hoferichter, M. Procura, and P. Stoffer, J. High Energy Phys. 04 (2017) 161.
[151] M. Hoferichter, B.-L. Hoid, B. Kubis, S. Leupold, and S. P. Schneider, J. High Energy Phys. 10 (2018) 141.
[152] A. Gérardin, H. B. Meyer, and A. Nyffeler, Phys. Rev. D **100**, 034520 (2019).
[153] J. Bijnens, N. Hermansson-Truedsson, and A. Rodríguez-Sánchez, Phys. Lett. B **798**, 134994 (2019).
[154] G. Colangelo, F. Hagelstein, M. Hoferichter, L. Laub, and P. Stoffer, J. High Energy Phys. 03 (2020) 101.
[155] T. Blum, N. Christ, M. Hayakawa, T. Izubuchi, L. Jin, C. Jung, and C. Lehner, Phys. Rev. Lett. **124**, 132002 (2020).
[156] G. Colangelo, M. Hoferichter, A. Nyffeler, M. Passera, and P. Stoffer, Phys. Lett. B **735**, 90 (2014).
[157] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C **77**, 827 (2017).
[158] A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D **97**, 114025 (2018).
[159] G. Colangelo, M. Hoferichter, and P. Stoffer, J. High Energy Phys. 02 (2019) 006.
[160] M. Hoferichter, B.-L. Hoid, and B. Kubis, J. High Energy Phys. 08 (2019) 137.
[161] M. Davier, A. Hoecker, B. Malaescu, and Z. Zhang, Eur. Phys. J. C **80**, 241 (2020); **80**, 410(E) (2020).
[162] A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D **101**, 014029 (2020).
[163] S. Borsanyi *et al.*, Nature (London) **593**, 51 (2021).
[164] M. Passera, W. J. Marciano, and A. Sirlin, Phys. Rev. D **78**, 013009 (2008).
[165] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer, and J. Stelzer, Eur. Phys. J. C **78**, 675 (2018).
[166] A. Crivellin, M. Hoferichter, C. A. Manzari, and M. Montull, Phys. Rev. Lett. **125**, 091801 (2020).
[167] A. Keshavarzi, W. J. Marciano, M. Passera, and A. Sirlin, Phys. Rev. D **102**, 033002 (2020).
[168] Belle-II (2020), https://docs.belle2.org/record/2028?ln=en.
[169] Of course, the actual branching ratio cannot be 100% since decays to muons must be possible where kinematically allowed. However, as long as $Z' \to$ invisible is the dominant decay mode, the bounds depend weakly on the branching ratio.
[170] A. Bharucha, D. M. Straub, and R. Zwicky, J. High Energy Phys. 08 (2016) 098.
[171] J. A. Dror, R. Lasenby, and M. Pospelov, Phys. Rev. D **96**, 075036 (2017).