Anomalous Z' and diboson resonances at the LHC

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ABSTRACT: We propose novel collider searches which can significantly improve the LHC reach to new gauge bosons Z' with mixed anomalies with the electroweak (EW) gauge group. Such a Z' necessarily acquires a Chern-Simons coupling to the EW gauge bosons and these couplings can drive both exotic Z decays into $Z'\gamma$ if the new gauge boson is sufficiently light, as well as Z' decays into EW gauge bosons. While the exotic decay rate of the heavy Z into $Z'\gamma$ is too small to be observed at the LHC, for a light Z', we show the potential of a lepton jet search in association with a photon to probe the rare decay $Z \to Z'\gamma$.

Contents

1 Introduction

The motivations for new Z' gauge bosons, both heavier and lighter than the EW scale, are ubiquitous [1, 2]. These theoretical expectations stimulated multiple experimental searches at the LHC as well as earlier colliders including LEP and the Tevatron, in addition to B-factories, fixed target experiments and other facilities.

New Z's lighter than the mass of the SM Z-boson (that we will dub "light Z's") have been proposed in the context of theories of light dark matter (DM) [3, 4], various attempts to explain perceived anomalies in data, e.g. the 511 keV line [5], the muon anomalous magnetic dipole moment [6], the proton charge radius [7, 8], flavor measurements [9, 10] and many others. While the strengths of particular motivations for this type of scenario might depend on one's taste, a light and weakly coupled Z' is a necessary ingredient of many realistic BSM scenarios, and deserves careful dedicated studies.

Currently most experimental bounds on the light Z' scenario arose from low energy experiments, LEP and astrophysical observations (see [11] for a comprehensive review). In particular, to probe this particle one would rely on exotic flavor-changing neutral current (FCNC) processes, measurements of the electron and muon magnetic dipole moments, beam dump experiments and energy emission observation by supernovae. In the more massive region of the parameter space, i.e. between the MeV scale and the Z mass, the former two classes of constraints dominate the exclusions, while beam dump experiments are important only in the case of Z's that are extremely feebly coupled to the SM, such that their displaced decays can be observed. Therefore, the constraints that one usually quotes as the dominant constraints on the light Z's are mostly due to the *leptonic couplings of the Z'*, with a noticeable exception of the rare meson processes.

Because the couplings of the Z' are highly model dependent, constraints on new gauge bosons are often phrased in terms of the benchmark dark photon model, where the only

parameters are the Z' mass and its kinetic mixing with the photon. One can argue on general grounds that for any Z' which is not completely sequestered from the SM, this kind of kinetic mixing will be present, and even if it is absent at tree level, will necessarily be formed radiatively [12]. While this approach is relatively generic, it implicitly makes an extremely important assumption, that SM matter is not directly charged under the force mediated by the light Z'. Clearly, many models that we have listed above do not satisfy this assumption.

In this work we focus on a broad class of models, in which at least some of the SM fermions are charged under the dark $U(1)'$. Of course, if we assume no extra fermions charged under the SM and the dark $U(1)'$, the choice of allowed Abelian symmetries is strictly limited to linear combinations of the $B - L$, Y-sequential, and inter-generational symmetries. However, it is possible, and, in fact, desirable to extend the scope of Z' searches to theories that appear to be *anomalous* with the field content of the SM. As has been emphasized long ago [13–15], these naively anomalous theories can be formulated as Effective Field Theories (EFTs) well below the scale of the masses of the exotic fermions, the "spectators". Systematic integration out of the spectators yields Chern-Simons terms. These terms naively appear to be renormalizable, yet correspond to derivative couplings of longitudinal gauge bosons. They are not gauge invariant, and below the EFT cutoff produce amplitudes that grow with energy. Recently these kind of effective theories have been studied in detail both in the context of anomalous DM mediators [16], and in the context of light Z's [17, 18].

In this paper we point out that due to the Chern-Simons terms, light anomalous Z's can induce new distinctive LHC signatures, that can potentially significantly improve the reach, compared to existing constraints. Most noticeably, the Chern-Simons terms induce the exotic Z decays, $Z \to Z'\gamma$. This decay mode, followed by a subsequent leptonic Z' decay can be a spectacular signature even at a hadron collider.

We will further concentrate on the light Z' in the mass range between $1\,\mathrm{GeV}$ and the Z boson mass. We demonstrate that the LHC, and especially the high luminosity LHC (HL-LHC) can potentially probe $U(1)'$ couplings at or even below the 10^{-2} level via searches for these exotic Z decays. As we will later see, this $g_{Z'} \sim 10^{-2}$–10^{-3} reach is comparable to the LHC reach to similar scenarios due to the direct production of the Z' [19] as well as to the LEP and Tevatron sensitivities to similar scenarios [20, 21]. We emphasize however that the search that we propose is complementary to the existing searches, because exotic Z decays searches can also probe $U(1)'$ symmetries that do not couple to the first generation SM fermions at all and which are therefore inaccessible to existent direct production searches.

Our paper is organized as follows. In the next section we will briefly review the theoretical background, calculate the exotic BR of the Z boson and present several simplified benchmark models, that can be probed by the techniques that we propose. In section 3 we review the existing constraints on light Z's that come from direct searches in earlier colliders and B factories (including BaBar, KLOE and LEP), exotic decays of B mesons, beam dump experiments and astrophysical observations. We describe the search that we propose and estimate its potential reach in section 4. Finally, in the last section we conclude.

2 Benchmark models

2.1 Theory background

Consider a U(1)′ symmetry that has a mixed anomaly with the EW group SU(2) × U(1). Clearly this theory cannot be extended up to arbitrary high scales [15]. However, it can be formulated as a low energy effective theory with a cutoff

$$\Lambda \lesssim \frac{64\pi^3 m_{Z'}}{3g_{Z'}g_{\mathrm{SM}}^2} \,, \tag{2.1}$$

where g_{SM} is usually the largest coupling of the SM gauge group with which the U(1)′ has an anomaly, unless the effective theory has a very big anomaly coefficient. The full theory should be augmented with the "spectators", the new fermions, charged both under the SM and the U(1)′ that eventually cancel the anomaly caused by the SM fermions. However, the masses of the "spectators" can be as heavy as Λ without compromising the validity of the theory. Note also that we assume that these fermions are chiral under the U(1)′ and vector-like under the SM, thus getting their masses from the U(1)′ breaking. While the opposite pattern is possible conceptually, it is very challenging to reconcile with experimental bounds on new fermions that are chiral under the SM.

We will further assume that the "spectators" are beyond the experimental reach of the colliders, whether the Z' is heavy or light, and integrate them out. After integrating them out one finds that the anomalous EFT possesses new Chern-Simons terms, that couple the Z' to the gauge fields of the groups with which it has a mixed anomaly:

$$\mathcal{L} \sim C_B \epsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu \partial_\rho B_\sigma + C_W \epsilon^{\mu\nu\rho\sigma} Z'_\mu \left(W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3}\epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma \right) \tag{2.2}$$

Strictly speaking the sizes of the counterterms corresponding to C_B and C_W can be completely arbitrary and depend on the momentum shift between the triangle loop diagrams when a full matrix element is calculated (see [22] for a detailed explanation and [16, 23, 24] for more recent overviews). However, for the purposes of the calculations there are two different gauges that turn out to be particularly useful. In one of them, one can simply set the counterterm coefficients C_B and C_W to zero and absorb all of the anomaly effects into the momentum shift between the diagrams. These momentum shifts, in turn, are chosen to satisfy the Ward identities for the anomaly-free gauge groups, SU(2) × U(1)$_Y$. This is the approach that we have recently adopted in [16].

In this paper we find another approach to be particularly useful. We choose a gauge such that there is no contribution from the momentum shift between the anomaly triangle diagrams, which then exactly cancel one another. In this case, to preserve SU(2) × U(1)$_Y$ gauge invariance the counterterms of (2.2) are given by

$$C_B = \frac{\mathcal{A}_{Z'BB}}{12\pi^2}g_{Z'}g^2, \quad C_W = \frac{\mathcal{A}_{Z'WW}}{12\pi^2}g_{Z'}g'^2 \,, \tag{2.3}$$

with the anomaly coefficients

$$\mathcal{A}_{Z'BB} = \mathrm{Tr}(Q'Y^2), \quad \mathcal{A}_{Z'WW} = \mathrm{Tr}(Q'T^aT^a) \,. \tag{2.4}$$
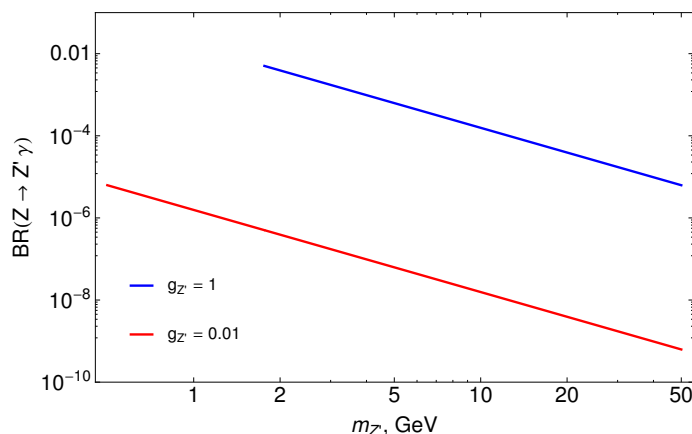
Figure 1. The exotic $\mathrm{BR}(Z \to Z'\gamma)$ as a function of the Z' mass. We assume $g_{Z'} = 1$ for the blue line and $g_{Z'} = 0.01$ for the red line. The anomaly coefficients are chosen to be $\mathcal{A}_{Z'BB} = -\mathcal{A}_{Z'WW} = 1$. We assume the cutoff of the theory (2.1) to be $\Lambda = 5\,\mathrm{TeV}$ and draw the BR line only in the region where the EFT is well defined.

With either of the gauge choices above, the physical observables are of course unchanged. However, the latter prescription fully captures the effect of the spectator masses in the Chern-Simons terms, and is simple to implement in the calculations here.

Let us start first from a light Z' and consider a situation in which the exotic decays of the SM Z are allowed. Starting from the couplings (2.3) and (2.4) it is straightforward to project the gauge fields W^3_μ and B_μ onto the mass eigenstates and calculate the Z exotic decay width into $Z'\gamma$. One finds, assuming $m_{Z'} \ll m_Z$:[1]

$$\Gamma(Z \to Z'\gamma) = \frac{|g'^2 \mathcal{A}_{Z'BB} - g^2 \mathcal{A}_{Z'WW}|^2}{3456\pi^5} g_{Z'}^2 \sin^2\theta_W \cos^2\theta_W \frac{m_Z^3}{m_{Z'}^2} \ . \tag{2.5}$$

As expected this expression is enhanced by the ratio $(m_Z/m_{Z'})^2$, manifestly signaling that the theory is not renormalizable and that the coupling between the gauge bosons grows with the energy.

We show the exotic Z BR in figure 1. There for simplicity we assume $\mathcal{A}_{Z'BB} = -\mathcal{A}_{Z'WW} = 1$, where the first equality is expected to be true in any vector-like U(1)$'$, such that there is no mixed anomaly with U(1)$_{EM}$ or the SM color group SU(3)$_c$. In order to define the range of validity of the theory we should also address the issue of the cutoff as defined in (2.1). Hereafter we assume the cutoff of 5 TeV, making sure that the spectators can be safely pushed to scales that are inaccessible to the LHC. Because of the enhancement at low Z' masses, the main gains of our proposed LHC searches will be in the light Z' case.

For completeness we also consider here the case in the which the Z' is heavier than the mass of the Z. In this case it is straightforward to calculate the decay width of the Z'

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[1]Note the factor of 9 discrepancy in the denominator with ref. [18] due to the slightly different definitions of the $\mathcal{A}_{Z'BB}$, $\mathcal{A}_{Z'WW}$ coefficients.

into $Z\gamma$. This expression, assuming $m_{Z'} \gg m_Z$, is qualitatively different from (2.5):

$$\Gamma(Z' \to Z\gamma) = \frac{|g'^2 \mathcal{A}_{Z'BB} - g^2 \mathcal{A}_{Z'WW}|^2}{13824\pi^5} g_{Z'}^2 \sin^2\theta_W \cos^2\theta_W \frac{m_Z^2}{m_{Z'}} \ . \qquad (2.6)$$

Unlike (2.5) this expression is in fact suppressed by the lighter Z mass. This behaviour occurs because the effects of the integrated out spectators are suppressed by the cutoff of the theory, which is proportional to the Z' mass (2.1) due to the spectators being chiral under U(1)$'$. This renders the exotic width of the heavy Z' into $Z\gamma$ practically unobservable and therefore we do not pursue this direction any further.

2.2 Light Z' models

Here we survey models that could have relevant signatures for a Z' that is lighter than the mass of the SM Z.

While the LHC produces an immense quantity of Z bosons — at $\sqrt{s} = 13\,\text{TeV}$ we have $\sigma(Z+X) \approx 60$ nb [25] — we are interested in very small BRs with non-trivial background. Therefore, we will further concentrate on the theories, where the Z' has appreciable leptonic BRs and consequently the associated U(1)$'$ will be related to lepton number. In addition, as explained in the introduction, we will be interested in theories that have mixed anomalies with the SM SU(2) $\times$ U(1)$_Y$. Here we describe a handful of symmetries that we have in mind for these searches.

Lepton number. A classical example of a theory along these lines would be a lepton number gauge symmetry. Under this symmetry we give positive charge to the left-handed leptons and negative charge to the right-handed ones: $Q(L) = -Q(e^c) = 1$. Of course the neutrino mass operator violates this symmetry, suggesting a relatively low energy mechanism for the neutrino masses (below the EFT cutoff Λ). However, scenarios along these lines have been proposed and we believe that neutrino masses do not pose conceptual problems to the gauged lepton number.

One of the main advantages of this symmetry is that all of the SM Yukawa couplings (though not the Weinberg operator) respect this symmetry even if the SM Higgs is uncharged under U(1)$'$. Consequently there is no mixing between the Z and Z', and EW precision measurements are not affected. As expected in all theories that keep the Yukawa couplings gauge invariant, this symmetry has no mixed anomaly with SU(3)$_c$ $\times$ U(1)$_{EM}$. The anomaly coefficients are given by $\mathcal{A}_{Z'BB} = -\mathcal{A}_{Z'WW} = -N_g/2$, where N_g stands for the number of generations.

The dominant constraints on such a leptophilic Z' come from direct production and exotic Z decays at LEP; the former is typically much stronger. For lighter Z's with mass $\lesssim 10\,\text{GeV}$, one is also subject to stringent constraints from direct production at KLOE [26] and BaBar [27]. The second class of constraints on this scenario is exotic heavy meson decays, similar to those for light mesons that were first emphasized in [28]. While naively it would seem that we should have no coupling between the Z' and hadrons, because we postulate a lepton number symmetry, this kind of coupling does emerge due to the kinetic

mixing between the Z' and hypercharge. A priori we do not know how big this coupling is, however on naturalness grounds we expect it to be at least of order

$$\kappa \sim \frac{g' g_{Z'}}{16\pi^2} \log\left(\frac{M}{m_l}\right) , \qquad (2.7)$$

where M is some high scale where this mixing is formed, and m_l is the mass of the lightest fermions, that are charged both under the the $U(1)'$ and the hypercharge.

Finally let us note that in our subsequent analysis we will also address the gauging of a lepton number symmetry that acts only on one or two generations (e.g. muon number or muon-plus-tau number). While there is no conceptual problem in defining these symmetries and they do not lead to FCNCs in isolation,[2] these symmetries will be especially interesting in the context of our study because one cannot produce the Z' directly in $e^+ e^-$ collisions (except for the kinetic mixing-suppressed production), and therefore exotic Z decays are one of the only accessible ways to probe these models experimentally.

$B+L$ symmetry.   We introduce this symmetry because both the leptons and the hadrons are charged under it and therefore it is subject both to LEP and LHC direct production constraints. We assign the $U(1)'$ charges as follows:

$$Q(L_i) = -Q(e_i^c) = 1, \qquad Q(\mathcal{Q}_i) = -Q(u_i^c) = -Q(d_i^c) = 1 \qquad (2.8)$$

Exactly as in the previous scenario, we will further consider a $B+L$ symmetry that acts on all the generations, along with a $B+L$ model that acts only on the heavy flavors, thus avoiding the most stringent constraints from direct searches. Like the previous symmetry it is also vector-like and therefore does not have any mixed anomalies with the $SU(3)_c \times U(1)_{EM}$ subgroup of the SM. The anomaly coefficients for this group are $\mathcal{A}_{Z'BB} = \mathcal{A}_{Z'WW} = -2N_g$. Finally we notice that we expect the kinetic mixing between the hypercharge and the $U(1)'$ symmetry to be the same as (2.7) except that instead of m_l in the logarithm we can have either the lepton or the quark mass, whichever is lighter. However, unlike in the previous scenario, this mixing does not have any important consequences on the detectability of the Z'.

Right-handed lepton number.   This is the only model that we consider that is not vector-like under $U(1)_{EM}$ and therefore contains the anomalous coupling $\gamma\gamma Z'$ does not vanish (although the decay rate $Z' \to \gamma\gamma$ still vanishes due to the Landau-Yang theorem). We assign (some or all of) the right-handed leptons e_i^c charge $+1$, while leaving the rest of the SM fermions uncharged. The only non-vanishing anomaly coefficient is $\mathcal{A}_{Z'BB} = -N_g$, and the minimal mixing with hypercharge in the absence of fine-tuning is expected to be identical to (2.7). It is also worth emphasizing, that because this symmetry does not have a mixed anomaly with $SU(2)_L$, it evades some flavor physics bounds that we discuss in the next section.

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[2]Through its anomalies with $SU(2)$, such a Z' can still contribute to FCNCs mediated by W loops and proportional to the CKM matrix elements. We will review these processes in the next section.

3 Existing constraints on light Z's and the LHC searches

While the experimental bounds on a heavy Z' are in most cases straightforward and set by LHC resonance searches, which by now largely supersede older LEP and Tevatron bounds, the situation with a Z's lighter than the SM Z is more subtle. A light Z' has been previously searched for at various collider experiments, including LEP, BaBar and the LHC. As we will see, most of the existing bounds that are relevant for the scenarios that we have outlined in section 2 are still coming from these searches. In this section we will review these bounds, as well as various other constraints that arise from other searches, most notably flavor measurements.

In the low mass range, the strongest bounds are coming from the BaBar experiment, and, for masses below 1 GeV, from KLOE. The latter mostly searched for a Z' with flavor-blind couplings to the SM, motivated by a hidden $U(1)'$ under which the SM particles are not directly charged, so that the couplings come from kinetic mixing between the SM photon and the Z'. The relevant searches of KLOE for a Z' decaying into electrons [26] (that excludes the Z' masses below 500 MeV, with the exclusions often not exceeding those of NA48/2 [29]) and charged pions [30] constrain the kinetic mixing parameter $\kappa \lesssim 10^{-3}$ in the mass range between 500 MeV and 1 GeV. As we have noted, we will be interested in the Z' mass range above 1 GeV because of the practical difficulty in resolving resonances lighter than 1 GeV at the LHC, and, therefore, these constraints are of limited interest for us.

The mass range between 1 and 10 GeV currently enjoys the best coverage from the BaBar experiment. BaBar has both searches for a Z' that couples directly to electrons [31], and for a Z' that only couples to the second and third generations of leptons [32]. In the former case BaBar looks for $e^+e^- \to \gamma Z'$ events with a subsequent decay of the Z' into a pair of electrons or muons. The bounds are quoted by BaBar in terms of the kinetic mixing $\kappa \lesssim 10^{-3}$–10^{-4} assuming that the coupling between the SM fermions and the Z' is merely due to the kinetic mixing. If we interpret these results in terms of the lepton number gauge boson, such that the electron and muon are directly charged under the hidden $U(1)'$, we constrain the gauge coupling $g_{Z'} \lesssim 10^{-4}$. We show these constraints explicitly on figure 4 together with the other relevant bounds. These are the dominant constraints on the leptophilic Z' in the range between 1 and 6 GeV. This search for a universal leptophilic Z' is extremely robust and the bounds are unlikely to be improved at the LHC.

We note in passing that for an extremely light leptophilic Z', there are additional constraints from neutrino-electron scattering that could be stronger than those that we have mentioned already below $m_{Z'} \sim 1$ GeV [33, 34]. Given our mass region of interest, we do not show these bounds in what follows.

The constraints are naturally more modest if we assume that only the second and third generation SM fermions are charged under the hidden $U(1)'$. This scenario has been analyzed by BaBar in ref. [32] by considering the process $e^+e^- \to \mu^+\mu^- Z'$, where the Z' is radiated off of a muon. Even though these constraints are slightly weaker than those that one gets in the case of the direct coupling to the electron, they are still extremely strong, excluding couplings of order $g_{Z'} \lesssim 10^{-2}$ and even slightly smaller. We also show these bounds on figure 4 together with the projected reach of the proposed LHC searches.

As we will further see, this bound can be significantly improved by the search for exotic Z decays that that we propose in section 4.

As expected, the direct searches from BaBar cannot be efficient above masses of approximately 6–7 GeV, and we are forced to switch to other experiments. Searches at LEP, which would produce the Z' in conjunction with the photon, give a generic bound around $g_{Z'} \lesssim 10^{-2}$ [20], provided that the mass of the Z' is not too close to the center-of-mass energy of any of the LEP runs, namely $\sqrt{s} = 130, 136, 161, 172, 183$ GeV, which is always true in the case of the light Z'. However, as we will immediately see, the existing LHC searches already outperform these results.

Unfortunately there is no dedicated search for a light Z' at ATLAS or CMS, except in the leptophobic case where a limit of the order of $g_{Z'} \lesssim 10^{-1}$ has recently been set [35]. However, a recast in the context of direct Z' production in the Drell-Yan process has been performed in [19]. The main conclusion of this reference is that the bounds that CMS puts on a light Z' from direct searches are meaningful and already improve on the existing LEP bounds.[3] Ref. [19] interprets these bounds again in terms of the kinetic mixing between the visible and the hidden photon. The bound that these searches put is around $\kappa \lesssim 10^{-2}$ in the range of masses between 10 and 30 GeV, rising to a few$\times 10^{-2}$ in the range between 30 and 80 GeV. This would impose a rather strong bound on a *lepton-baryon universal model* such as U(1)$_{B+L}$, of order $g_{Z'} \lesssim 10^{-3}$; however, the bounds on leptophilic models are much more modest and, assuming the kinetic mixing as in (2.7), does not even exceed $g_{Z'} \sim 0.1$, weaker than LEP.

Another important observation in the context of the LHC searches has been made in [36]. Once we have a light Z' that couples to the SM leptons (not necessarily the electrons), it can be radiated off of the final state in the decay $Z \to \ell^+\ell^-$, leading to an exotic Z decay into four leptons. Measurements of radiative Z decay [37] probe this final state, with the best acceptance attained in the 4μ channel. The resulting limit is unrelated to the coupling of the Z' to the electrons. It is not surprising that the bounds one gets from this process are generally strong, constraining values of $g_{Z'} \lesssim 10^{-2}$, and for high Z' masses this search is superior to the search that we propose. However, as one lowers the mass of the Z', the search for the muons starts suffering from poor acceptances, as ref. [37] vetoes events with dileptons below 5 GeV to suppress charmonium background. Simultaneously, the BR of the exotic decay mode $Z \to Z'\gamma$ grows, and as we will see in section 4, becomes more sensitive than the four muon search.

One can also consider the LHCb light Z' search [38], which focuses on a light Z' that is directly produced in the LHC pp collisions and further decays into $\mu + \mu^-$. No associated production is considered and no other decay channels except the dimuon decay modes. We also rescale the bound from this search and present it together with our projected reach on figure 4. Not surprisingly the bound on lepton-specific models is again relatively weak and comparable to the one that is expected from the search of [19], namely of order $g_{Z'} \lesssim 10^{-1}$.

Finally we comment on the flavor bounds. As we have noticed in section 2, none of our Z's is expected to *mediate* FCNCs. However, the *emission* of a light Z' can give an

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[3]The ATLAS data were not explicitly recasted, though they can arguably yield similar constraints.

important contributions to FCNC processes that are mediated by W bosons. In this sense all of the processes that we are analyzing here, are by definition minimally flavor violating in the quark sector, and nonetheless the effect can be appreciable. Most of the relevant processes have been analyzed already in ref. [18] and we will rely on the results of this paper. For a light Z', the dominant FCNC processes correspond to effective two-loop diagrams, such that the Z' is emitted from a virtual W; note that this is true even if the quarks have charge under U(1)$'$, which would give FCNCs arising at one loop but relatively suppressed by $m_{Z'}/m_t$. The most stringent constraints on this scenario come from the $B \to K Z'$ and, to a lesser extent, $B \to \pi Z'$ decays. There are additional bounds from the $K \to \pi Z'$ decays are not relevant in our mass range of interest $m_{Z'} > 1\,\text{GeV}$.

Ref. [18] puts a bound of order $g_{Z'} \sim 10^{-2}$–10^{-3} in the case where the Z' decays invisibly in the relevant mass range. For our light Z' models where the dominant decays are to leptons, we are instead interested in muonic decays. In this channel, the comparison to data is more laborious (see [39] for an experimental reference) due to the absence of the theoretical prediction and the necessity to compare bin-by-bin our predictions to the LHCb results. We prefer not to perform a full recast of this search in this paper, though the bound should not be very different from the one reported on the invisible decays in [18]. Parenthetically, we also note that these constraints can be further attenuated in right-handed lepton number models, because, as we have explained, the dominant contribution to the process comes from emission of a Z' from a virtual W through the anomaly. Evidently, if we gauge the RH lepton number, the corresponding one-loop coupling is absent.

4 Exotic Z decays at the LHC

In this section we describe the LHC analysis that we propose and roughly estimate its expected sensitivity to a light Z' in exotic Z decays. In order to avoid large QCD backgrounds, we will further concentrate on the leptonic decays of the Z', hence the choice of our benchmark models in section 2.

The signature that we focus on in this study is $Z \to Z'\gamma$, $Z' \to \ell^+\ell^-$ such that the invariant mass of the three final state objects reconstructs the Z mass. The dominant background is leptonic Z decay with a photon radiated off of a final state lepton. In our simulations we also generate the $\gamma^*/Z^* + \gamma$ background where the real photon comes from initial state radiation, but this process is subdominant to the three-body Z decays.

While the background is by no means small, it has a very different geometry from the signal events. In the signal events the Z' and the photon are back-to-back in the Z rest frame, and because the boost of the Z in the vast majority of the events is moderate, the picture in the lab frame is not vastly different. Moreover, because a light Z' tends to be somewhat boosted, the leptons from its decay will mostly follow the direction of the Z'. This behavior becomes more prominent for increasingly light Z's. Therefore, in the bulk of the signal events the photon and leptons will be in different detector hemispheres. In the background events, however, the photons typically have small p_T and are collinear with one of the leptons. We illustrate these properties of the signal and background, showing the distribution of the angular separation between the photon and the closest lepton $\Delta R_{\ell\gamma}$
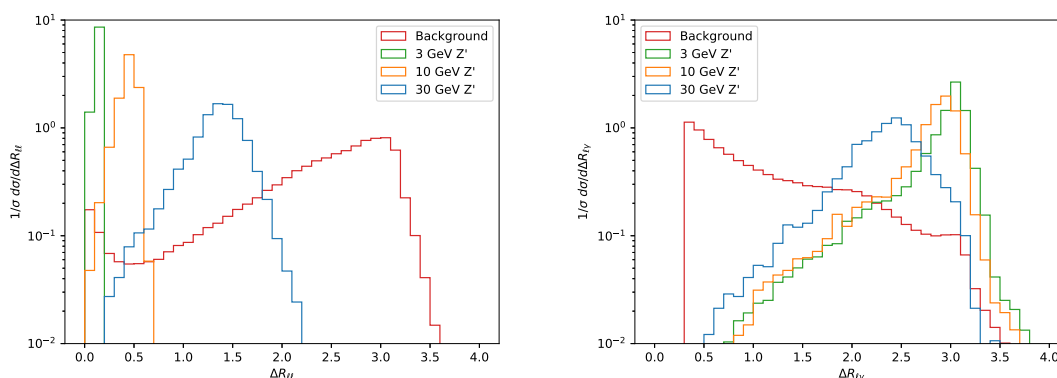
Figure 2. The separation ΔR between the leptons (left) and between the photon and the nearest lepton (right) as a function of the Z' mass in the signal events, compared to the background. All the distributions are normalized.

in figure 2.[4] The shoulder in the background $\Delta R_{\ell\gamma}$ distribution is due to $Z\gamma$ production, whose kinematics are more similar to our signal process than radiative Z decay. Note, however, that the invariant mass of the $\ell^+\ell^-\gamma$ system usually significantly exceeds the Z mass when the Z recoils against a hard photon.

Another kinematic variable that is relevant for the search is the angular distance between the two leptons $\Delta R_{\ell\ell}$. This variable is strongly correlated with $\Delta R_{\ell\gamma}$. In the background events the photon is usually soft and therefore the leptons are almost back-to-back and are very well separated from one another. In the signal events the leptons are coming from the decays of the Z', which is again boosted if $m_{Z'} \ll m_Z$. Therefore the signal leptons will often be spatially close to one another and even collimated in the extreme case of very light Z', leading to "lepton jets". On general grounds we expect

$$\Delta R_{\ell\ell} \sim \frac{4m_Z m_{Z'}}{(m_Z^2 - m_{Z'}^2)} \ . \tag{4.1}$$

For example, for $m_{Z'} = 15\,\mathrm{GeV}$, $\Delta R_{\ell\ell} \sim 0.3$. This point is also illustrated in figure 2. Again, $Z\gamma$ production leads to a small peak in the background at low $\Delta R_{\ell\ell}$. For any analysis requiring isolated leptons, however, this feature is irrelevant.

Finally we notice one more important feature of the background that will further largely determine our search strategy. After we impose an isolation cut on the photon (here we use the standard criterion of $\Delta R > 0.3$ between the photon and any other reconstructed object in the event), the background is *not* a smoothly falling function of the dilepton mass $m_{\ell\ell}$. In fact the cut on the spatial distance between the photon and the lepton introduces a hidden scale into the problem, because the the probability to emit an extra photon is proportional to the Sudakov double logarithm $\log^2 \delta p^2$, where δp is the change in the momentum of the emitting particle due to the bremsstrahlung. Therefore the angular cut

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[4]Both the signal and background events are simulated at leading order with `MadGraph 5` [40] and further showered and hadronized with `Pythia 6` [41], with matching up to one additional jet. No K-factors have been applied. The detector simulation has been performed with `Delphes 3` [42].
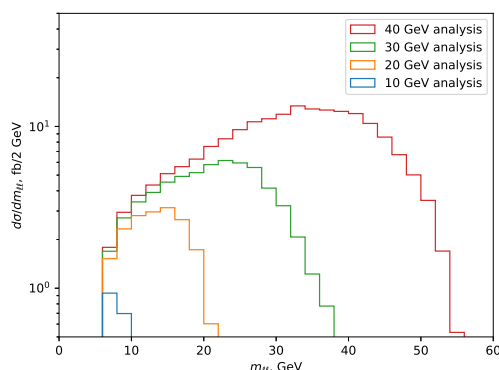
Figure 3. Dilepton mass distribution for the $\ell\ell\gamma$ background. All cuts in the text, except for the $m_{\ell\ell}$ resonance requirement, have been imposed, for various target Z' masses.

necessarily translates into the minimal energy fraction that the emitted photon can carry, and the corresponding maximal dilepton invariant mass. For a $\Delta R > 0.3$ cut one finds a broad hump in the background $dN/dm_{\ell\ell}$ distribution, around $50\,\mathrm{GeV}$. We emphasize again, that this is an expected feature of the background, carved by our cuts. This was also discussed in detail in a recent experimental analysis [43], although their feature was much closer to the Z mass due to much looser angular cuts than we propose. Clearly, as we tighten the cut on the $\Delta R_{\ell\gamma}$ (or, alternatively, $\Delta R_{\ell\ell}$) the hump moves further to lower invariant dilepton masses, but it is always present.

Because we suggest a search for a low mass resonance, bump hunting on top of the low-mass $m_{\ell\ell}$ background is a logical strategy. That said, the feature that we have just described will somewhat hamper these attempts. Not only does the background have a non-trivial feature, resulting from our own cuts, but the signal can be close to the background feature itself, depending on the Z' mass (although, for most of the target masses this is clearly not the case, as one can see from figure 3, and the situation improves as we are going to lower masses.) Therefore, rather than fitting the overall dilepton mass distribution, we choose to impose angular cuts for a given Z' mass and then look for a dilepton resonance. For the background, we expect that we can largely rely on the theoretical prediction, given that the differential Z production is theoretically known up to NNLO order, both singly-produced [44, 45] and in conjunction with a photon [46].

We proceed to perform a simple analysis for a given Z' mass with the following cuts:

- Exactly two leptons with $p_T > 25, 10\,\mathrm{GeV}$ and $|\eta| < 2.5$

- Exactly one photon with $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.5$

- $m_{\ell\ell\gamma} = m_Z \pm 5\,\mathrm{GeV}$

- $m_{\ell\ell} = m_{Z'} \pm 1\,\mathrm{GeV}$

- $\Delta R_{\ell\ell} < 4m_Z m_{Z'}/(m_Z^2 - m_{Z'}^2)$
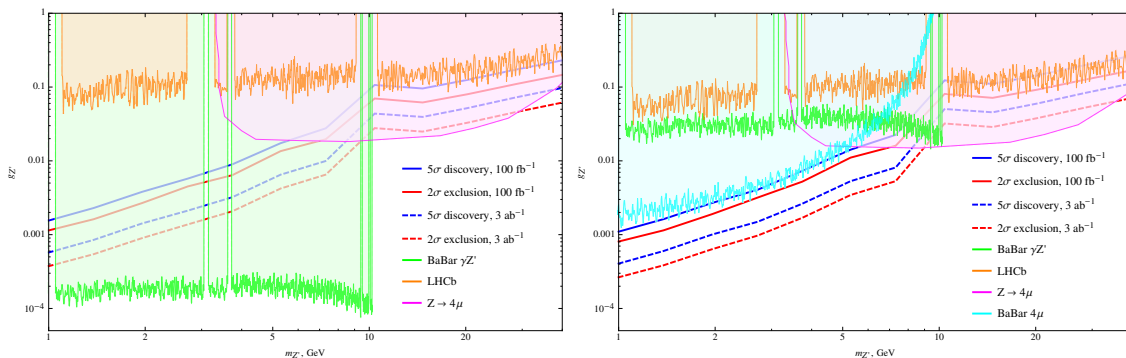
- $\Delta R_{\ell\gamma} > \pi - 4m_Z m_{Z'}/(m_Z^2 - m_{Z'}^2)$

Figure 4. Exclusion (2σ) and discovery (5σ) contours for the $\ell\ell\gamma$ searches described in the text. The lepton number model of section 2 is assumed, with $\mathcal{A}_{Z'BB} = -\mathcal{A}_{Z'WW} = -N_g/2$. The shaded regions indicate the (suggested) bounds from other experiments. The picture on the left hand side concerns with the lepton number theories, that couple indiscriminatingly to all the lepton generations. The picture on the RH side shows the situation, assuming that the Z' couples only to the second and the third generations of the leptons ($\mu + \tau$).

Throughout, we impose a minimum separation between physics objects $\Delta R_{\ell\ell}, \Delta R_{\ell\gamma} > 0.3$. For $m_{Z'} \gtrsim 10\,\mathrm{GeV}$, the leptons are sufficiently well separated from each other that such isolation cuts do not significantly affect the acceptance.

The impact of the angular cuts on the background dilepton mass distribution is shown explicitly in figure 3. This plot shows the $m_{\ell\ell}$ distribution for the $\ell\ell\gamma$ background after all of the cuts above except for the $m_{\ell\ell}$ requirement have been imposed, with the angular cuts chosen to target a selection of Z' masses. Clearly the background is shaped by the analysis cuts, and is neither a smoothly falling function of the dilepton mass nor peaked at the Z mass. The latter behavior would be approached if very soft photons aligned with the outgoing leptons were allowed by the cuts.

For resonances below approximately $10\,\mathrm{GeV}$, the decay products of the Z' are collimated and a lepton-jet search becomes appropriate. To avoid photon fakes, we do not consider the electrons in this mass range and search for two muons within $\Delta R_{\ell\ell} < 0.5$ [47], as well as a well-separated photon $\Delta R_{\ell\gamma} > \pi - 0.5$. At such low masses, meson resonances become important background sources, and so we take a tighter dilepton mass window $m_{\ell\ell} = m_{Z'} \pm 20\,\mathrm{MeV}$ [48].

We present the expected reach of the searches that we propose in figure 4, for both a leptophilic Z' as well as a $L_\mu + L_\tau$ gauge boson. For comparison, the dominant constraints from section 3 are also shown. We see that for direct couplings of the electron to the Z', the BaBar limit from $e^+e^- \to Z'\gamma$ is quite stringent for Z' masses that are kinematically accessible, and at higher masses the existing LHC $Z \to 4\mu$ search already excludes the parameter space that would be probed by our analysis. Nevertheless, we emphasize that rare Z decays constitute an independent check of the mixed anomaly coefficients once a Z' is discovered, without requiring the observation of all of the couplings in the low-energy anomalous EFT. The lack of such decays could be construed as evidence for an anomaly-free gauge group with the SM matter field content, such as $B - L$, sequential hypercharge or $L_\mu - L_\tau$.

When $L_\mu + L_\tau$ is gauged, our proposed lepton jet search is already competitive with only $100\,\mathrm{fb}^{-1}$ of LHC data, which should be achievable next year. Belle II [49], with a large increase in integrated luminosity over BaBar, would be able to improve the BaBar $e^+e^- \to 4\mu$ bound in the light Z' region. For intermediate Z' masses in the 5–10 GeV range, several existing searches show roughly similar sensitivity, including both BaBar searches for hidden gauge bosons and LHC rare Z decays. With more data, the lepton jet analysis proposed in this work should be able to outperform existing analyses, though a full study with systematics would be worthwhile. At higher Z' masses, the $Z \to 4\mu$ search is expected to remain dominant, although, as we have pointed out, the searches for the exotic Z decays can carry valuable information.

5   Conclusions

Because generic U(1)′ theories contain mixed anomalies with the SM at collider energy scales, most gauged Abelian extensions of the SM include Chern-Simons terms coupling the new gauge boson to a pair of SM bosons. Knowing only the charges of the low energy fermionic content of the theory under a new U(1)′ allows one to determine these Chern-Simons terms unambiguously up to fermion mass effects, assuming the absence of new sources of electroweak symmetry breaking.

In this study we have examined the exotic decay mode $Z \to Z'\gamma$ induced by such anomalous terms. Because the associated operators are simply higher dimensional operators of an EFT, their influence rises with $m_Z/m_{Z'}$. In particular, the BR for the exotic decay can be detectable at the LHC for a sufficiently light Z'. We have demonstrated a simple analysis that could be used to search for exotic Z decays, including using lepton jets in the region where the decay products of the Z' are collimated. The resulting limits can be competitive with existing searches, owing to the large Z production cross section at the LHC.

While our toy search relied on the existence of a leptonic Z' coupling, Z' production in Z decays does not depend on any particular interaction other than the anomalous Chern-Simons terms. It is thus conceivable that a low mass dijet resonance search could also be performed in events with photons. Because the dijet resonance would be boosted, it would be crucial to manage the QCD background well and have a good understanding of substructure variables.

No matter how a new gauge boson is discovered, the searches for rare decays which we have outlined can be instrumental in revealing the underlying structure of new physics. In a fashion completely orthogonal to traditional dijet or dilepton resonance analyses, gauge boson resonance searches offer insight into the anomaly coefficients of a gauge theory at one or more energy scales. Such information constitutes an independent probe of the physics associated with a new gauge symmetry that could lie just beyond the SM.

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