Phenomenological Constraints on Anomaly-Free Dark Matter Models

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Abstract

We study minimal benchmark models of dark matter with an extra anomaly-free U(1)\textsuperscript{'} gauge boson Z\textsuperscript{’}. We find model parameters that give rise to the correct cosmological dark matter density while evading the latest direct detection searches for dark matter scattering produced by the XENON1T experiment, including the effects of Z – Z\textsuperscript{’} mixing. We also find regions of parameter space that evade the constraints from LHC measurements of dileptons and dijets, precision electroweak measurements, and LHC searches for monojet events with missing transverse energy, $E_T$. We study two benchmark Z\textsuperscript{’} models with $Y$-sequential couplings to quarks and leptons, one with a vector-like coupling to the dark matter particle and one with an axial dark matter coupling. The vector-like model is extremely tightly constrained, with only a narrow allowed strip where $m_\chi \simeq M_{Z'}/2$, and the axial model is excluded within the parameter range studied. We also consider two leptophobic Z\textsuperscript{’} benchmark models, finding again narrow allowed strips where $m_\chi \simeq M_{Z'}/2$ as well as more extended regions where $\log_{10}(m_\chi/\text{GeV}) \gtrsim 3.2$.

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1 Introduction

The existence of the dark matter required by astrophysics and cosmology [1, 2, 3, 4] is one of the most pressing arguments for physics beyond the Standard Model, and its nature remains a mystery, despite many theoretical proposals and experimental searches. The simplest explanation is that the dark matter is some species of massive particle, and if this interpretation is correct the dark matter should be provided by some particle beyond the Standard Model. However, the range of possible dark matter particle masses is very broad, extending from the Planck mass down to \( \ll \text{eV} \). Within this range, one of the favoured possibilities is some type of weakly-interacting massive particle (WIMP) that was in thermal equilibrium with Standard Model particles during the early history of the Universe, but decoupled as it expanded and cooled. The typical range of WIMP masses that give rise to a good relic density today is in the GeV to TeV range, placing these particles potentially within reach of experiments at the LHC as well as direct and indirect searches for astrophysical dark matter. The prototypical WIMP candidate was a massive sequential neutrino [5, 6, 7], but this has been ruled out by a combination of accelerator (see, for example, [8]) and non-accelerator experiments. Many WIMP candidates from scenarios for physics beyond the Standard Model have been proposed subsequently [9], one of the most prominent being supersymmetry [10]. This theory has many potential experimental signatures beyond the WIMP particle itself, but also has many free parameters. Thus, although no experiment has found any evidence for supersymmetry, its appearance at the TeV scale cannot yet be ruled out. That said, interest has developed in exploring alternative WIMP scenarios.

In the absence of clear theoretical guidance, much activity has gone into the formulation and testing of simplified dark matter models that involve only a small number of relevant parameters, which can in principle be explored systematically. These simplified dark matter models may be divided into categories according to the way the dark matter candidates interact with Standard Model particles. The focus has evolved from effective field theories of these dark matter interactions [11, 12, 13] to more complete dynamical models featuring mediator particles, usually bosons of spin zero or one [14, 15, 16]. In principle, the mediator particle could be the Higgs or \( Z \) boson of the Standard Model, scenarios that are tightly constrained, but not excluded [17, 18, 19, 20].

Here we consider the alternative scenario in which the mediator is a boson that is not included in the Standard Model. These mediator particles could be produced at the LHC as well as the dark matter particles themselves, and the masses and couplings of the mediator particles are also constrained by the cosmological dark matter density, as well as by direct and indirect searches for astrophysical dark matter. We study here the possibility of a single mediator particle \( Z' \) with spin one. Extensions of the standard model containing a new \( Z' \) are extremely well studied in the literature going back several decades [21, 22, 23, 24, 25, 26, 27]. Such models feature the possibility of mixing with the \( Z \) boson, which is constrained by precision electroweak measurements. Moreover, they are strongly constrained by gauge invariance. In particular, the ultraviolet completions of these models should be free of triangle anomalies [23, 29, 30, 31].

A complete ‘simplified’ model of dark matter should include some mechanism for cancelling these triangle anomalies, which could in principle be achieved in different ways
The option we pursue in this paper is that the anomalies are cancelled by new physics at the TeV scale, which entails an interesting new set of phenomenological signatures and possible experimental constraints. Since there are, in total, six different gauge anomalies to be cancelled, the constraints on the beyond the Standard Model fermions needed to cancel them are non-trivial. Consequently, the minimal ‘simplified’ dark matter models cannot always be as simple as those originally considered, and the phenomenological signatures are correspondingly more complex and interesting.

In a previous paper we constructed systematically specific minimal anomaly-free dark matter models with a $U(1)'$ boson $Z'$ whose couplings to quarks and leptons are generation-independent. The simplest such models are leptophilic, and are subject to various powerful experimental constraints. In particular, the LHC constraint on resonances in dilepton mass spectra is now very strong, imposing important restrictions on $U(1)'$ models in which the $Z'$ boson couples to the charged leptons $e^+e^-$ and $\mu^+\mu^-$. Another powerful constraint comes from direct searches for dark matter scattering on nuclei, in which the market leader is now the XENON1T experiment. This constraint is particularly important for $U(1)'$ models in which the $Z'$ boson has vector-like couplings to Standard Model particles and/or dark matter, since coherent enhancement leads to an enhanced cross section in these situations. These considerations motivate specific studies of benchmark $U(1)'$ models in which the $Z'$ boson is either leptophobic and/or has axial couplings, as also discussed in.

We found in that models with a single dark matter particle necessarily contain a leptophilic $Z'$ with couplings to quarks and leptons that are proportional to those in the Standard Model - such models have become known as $Y$-sequential models. In such models, $Z' - Z$ mixing is unavoidable, inducing important contributions to precision electroweak observables that impose a powerful constraint on $M_{Z'}$. Moreover, the dark matter particle must have vector-like $Z'$ couplings. Because of these two features, the experimental constraints on this benchmark model are very strong, as we discuss in detail in Section 2 of this paper, and only a very small region of the model’s parameter space survives.

In Section 3 we then discuss a second $Y$-sequential benchmark model in which the dark matter particle has axial $Z'$ couplings, with the aim of reducing the impact of the direct dark matter search experiments. However, the dark matter density constraint is more important in this case, the $Z'$ is still leptophilic, and there is again an important constraint from precision electroweak data. Thus, even though the direct dark matter scattering constraint has less impact, the other constraints are still sufficiently powerful to exclude this model within the parameter range we explore.

Therefore, in Section 4 we also consider making the $Z'$ leptophobic, which requires at
least two additional particles in the dark sector, with non-zero Standard Model charges. We consider two benchmark scenarios proposed in [34], one with SU(2) doublet dark sector particles in which the $Z'$ couplings to quarks are suppressed, and LHC monojet constraints become important, and another with SU(2) triplet dark sector particles in which the quark couplings are less suppressed, so that the LHC dijet constraints are more important. In both cases the direct dark matter search constraint is more restrictive, but allows extended regions where $\log_{10}(m_\chi/\text{GeV}) \gtrsim 3.2$.

Finally, we present our conclusions and some discussion in Section 5.

## 2 Benchmark with a Single Dark Matter Particle

We consider first the possibility that the only dark sector particles are fermions that are uncharged singlets of the Standard Model gauge group. Restricting our attention to generation-independent $U(1)'$ charge assignments, denoting the left-handed lepton doublets by $l$, the right-handed lepton singlets by $e$, the right-handed quark singlets by $u,d$ and the left-handed quark doublets by $q$, and choosing the normalisation $Y_q' = 1$, we found [34] the following unique solution:

$$
Y_l' = -3, \quad Y_e' = -6, \quad Y_d' = -2, \quad Y_u' = 4, \quad Y_H' = -3, \quad (2.1)
$$

which is known in the literature as the $Y'$-sequential model [40, 30]. Its free parameters include the $U(1)'$ gauge coupling $g$ and the masses of the $Z'$ and the dark matter particle $\chi$. If there is a single particle in the dark sector, it must be vector-like under $U(1)'$: $Y_{\chi,L}' = Y_{\chi,R}'$ [34], but the magnitude of the $U(1)'$ charge of this dark matter particle is arbitrary, introducing a fourth parameter into this minimal model.

We consider next the constraints on the $Y$-sequential model that are imposed by precision electroweak measurements, specifically the constraints from the oblique parameters $S$ and $T$. As seen in Eq. (2.1), this and other $Y$-sequential models have the feature that the Higgs doublet has a non-zero $U(1)'$ charge. Consequently, tree-level $Z' - Z$ mixing is unavoidable, and is calculable as a function of the $U(1)'$ gauge coupling $g$ and the $Z'$ mass, increasing as $g$ increases and/or $M_{Z'} \rightarrow M_Z$. Therefore the precision electroweak constraint is stronger in these cases, as seen in Fig. 1. This mixing also has important implications for the calculations of the relic density of the dark matter particle, $\Omega_\chi h^2$, and of the dark matter scattering cross section, which we discuss below.

If the dark sector contains more than one particle, it is possible that $Y_{\chi,L}' \neq Y_{\chi,R}'$. As already advertised, in order to minimise the impact of direct dark matter searches, the case where the dark matter particle has a purely axial $Z'$ coupling, $Y_{\chi,L}' = -Y_{\chi,R}'$, is of particular interest. The electroweak precision constraint shown in Fig. 1 is applicable to that model as well as to the vector-like model, since it depends only on the coupling of the $Z'$ to the SM Higgs. More constraints on the axial model are discussed in Section 3, whereas the rest of this Section is devoted to the minimal, vector-like case.

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5In this Section we neglect kinetic mixing, since mass mixing is much more important in these leptophobic models. The details of mass and kinetic mixing are described further in Appendix A.
Figure 1: The \((M_{Z'}, g)\) plane in the \(U(1)'\) Y-sequential model, showing the impact of the constraints on the oblique parameters \(S\) and \(T\) imposed by precision electroweak measurements.

We show below the standard formulae for DM annihilation, which we reproduce here so as to illuminate the plots we show below\(^6\). Away from the direct-channel \(Z'\) and \(Z\) resonances, a generic \(\chi\chi \to \bar{f}f\) annihilation cross-section multiplied by the \(\chi\) velocity, \(\sigma v\), may be expanded as a power series in \(v^2\):

\[
\sigma v = a + bv^2 + \mathcal{O}(v^4),
\]

where \(a\) and \(b\) arise from \(s\)- and \(p\)-wave annihilations respectively, and have the following leading-order expressions \(^{[44]}\)

\[
a = \frac{3m_{\chi}^2}{2\pi(M_{Z'}^2 - 4m_{\chi}^2)^2} \left( g_{\chi}^{V}(g_{f}^{V}(2 + \frac{m_{f}^2}{m_{\chi}^2}) + 2g_{f}^{A}(1 - \frac{m_{f}^2}{m_{\chi}^2})) + g_{\chi}^{A} g_{f}^{A} \frac{m_{f}^2}{m_{\chi}^2} \frac{(4m_{\chi}^2 - M_{Z'}^2)^2}{M_{Z'}^4} \right),
\]

\[
b = \frac{g_{\chi}^{A} g_{f}^{A} m_{f}^2}{2\pi(M_{Z'}^2 - 4m_{\chi}^2)^2} (1 - \frac{m_{f}^2}{m_{\chi}^2})^{3/2},
\]

where \(g_{\chi,f}^{V,A}\) are the vector and axial couplings of the dark matter particle and the final-state fermion, respectively. Close to resonance where \(m_{\chi} \sim M_{Z'}/2\), the denominators in Eq. (2.2) are modified: \((M_{Z'}^2 - 4m_{\chi}^2)^2 \to (M_{Z'}^2 - 4m_{\chi}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2\). As already mentioned, we include \(Z' - Z\) mixing, and there are analogous modifications when \(m_{\chi} \sim M_{Z}/2\). However care must be taken with the expansion of \(\sigma v\) close to resonance, so we always calculate the relic density numerically with Micromegas \(^{[42]}\), with model files generated with FeynRules \(^{[43]}\).

In general, there are regions of any model’s parameter space where the relic density exceeds the cold dark matter (CDM) density inferred from measurements by the Planck

\(^{[42]}\)In models where the dark sector contains more than one particle, such as the axial \(Y'\)-sequential model discussed in Section \(\text{[3]}\) and the leptophobic model discussed in Section \(\text{[4]}\) one or more of other ‘dark’ particles may coannihilate with the dark matter particle. However, this complication is absent in the vector-like \(Y'\)-sequential model discussed in this Section, and we neglect it for the other models.
satellite and other experiments, $\Omega_{CDM} h^2 \simeq 0.12$. We regard these regions as excluded, while noting that modified evolution in the early Universe could change the calculation of $\Omega_\chi$ so that it is $\leq \Omega_{CDM}$, in which case such models could be acceptable \cite{16}. The other generic possibility is that $\Omega_\chi < \Omega_{CDM}$, which is acceptable if there is some other source of dark matter (for example axions, primordial black holes or sterile neutrinos). However, in this case the strength of the constraint from the direct search for dark matter scattering is reduced by the density fraction $\Omega_\chi/\Omega_{CDM}$, a correction that we apply throughout this paper. Between these over- and under-dense regions there is a narrow boundary subspace where $\Omega_\chi \simeq \Omega_{CDM}$, and no correction factor is needed. If $\Omega_\chi > \Omega_{CDM}$, we consider the parameter point to be excluded by the relic density, but for the sake of presenting the direct detection bound we apply no rescaling.

Fig. 2 displays this boundary in the $(m_\chi, M_{Z'})$ plane in the vector-like $Y'$-sequential model. The solid contours are at the boundaries where $\Omega_\chi = \Omega_{CDM}$, for $Y'_{\chi,L} = Y'_{\chi,R} = 1$ and fixed values of the gauge coupling $g = 0.03$ (green curve), 0.1 (orange) and 0.3 (blue) \cite{16}. The narrow-width approximation assumed in our analysis would no longer be applicable for $g > 0.3$, so we do not display results for larger $g$. Also shown are dashed lines where $m_\chi = M_{Z'}/2$ (red), $m_\chi = M_{Z'}$ (purple) and $m_\chi = m_t$ (brown), $m_\chi = M_{Z'}/2$ (grey) and $M_{Z'} = M_Z$ (black).

The relic $\chi$ density is reduced below the relic CDM density by rapid annihilation $\chi\chi \rightarrow Z' \rightarrow$ SM SM, for SM a Standard model particle, in wedge-shaped regions where $m_\chi \sim M_{Z'}/2$, whose widths increase with $g$. Larger values of $\Omega_\chi$ arise when the dark matter annihilation rate decreases as $M_{Z'}$ increases. We note that the wedge-shaped contours exhibit outward-pointing glitches when $m_\chi \simeq M_{Z'}/2$, where the relic density is suppressed by rapid $\chi\chi$ annihilations via the $Z$ to Standard Model particles, and when $M_{Z'} \simeq M_Z$, where $Z' - Z$ mixing is enhanced. As already mentioned, for parameter sets inside the wedges we rescale the constraint from the direct dark matter scattering rate by a factor $\Omega_\chi/\Omega_{CDM}$, whereas the regions outside these wedges are disallowed because $\Omega_\chi > \Omega_{CDM}$.

Fig. 3 displays $(m_\chi, M_{Z'})$ planes in the vector-like $U(1)’$ Y-sequential model for three selected values of the gauge coupling: $g = 0.03$ (upper left), $g = 0.1$ (upper right) and $g = 0.3$ (lower), implementing the following constraints. In each panel the blue contour is where $\Omega_\chi = \Omega_{CDM}$ and the blue shaded regions are excluded because $\Omega_\chi > \Omega_{CDM}$. The horizontal olive lines at fixed values of $M_{Z'}$ that rise with increasing $g$ bound the olive shaded regions at lower $M_{Z'}$ that are excluded by the constraints imposed by precision electroweak measurements induced by the effects of $Z' - Z$ mixing. For large $g \gtrsim 0.1$, this constraint is stronger than the ATLAS dilepton search at the LHC \cite{16}, which excludes the orange shaded regions \cite{16}. Finally, the purple shaded regions are excluded by the direct search for the scattering of dark matter by the XENON1T experiment \cite{16}, where the appropriate reduction factor $\Omega_\chi/\Omega_{CDM}$ has been applied to the experimental upper limit. Here and throughout we use the approximations in \cite{16} to calculate direct detection limits. In the $g = 0.03$ and 0.1 cases there is no visible region that is allowed by all these constraints. On the other hand, when $g = 0.3$ we see a tiny region that is only just

\footnote{The curves for other parameter choices with the same values of $g^2|Y'_{\chi,L}|$ would be identical away from resonance.}

\footnote{We have used MadGraph \cite{16} to calculate the dilepton, dijet, and monojet constraints.}
Figure 2: The \((m_\chi, M_{Z'})\) plane in the U(1)' Y-sequential model with a vector-like dark matter coupling \(Y'_{\chi,L} = Y'_{\chi,R} = 1\). The solid lines are contours where \(\Omega_\chi = \Omega_{CDM}\) for fixed values of the gauge coupling \(g = 0.03\) (green), 0.1 (orange) and 0.3 (blue), and the red/purple/brown/grey/black dashed lines are where \(m_\chi = M_{Z'}/2, m_\chi = M_{Z'}, m_\chi = m_t, m_\chi = M_Z/2, M_{Z'} = M_Z\), respectively.

consistent with the relic density and precision electroweak constraints, while being more comfortably consistent with the dark matter scattering and ATLAS dilepton constraints.

Finally, we present in Fig. 4 an analysis of the vector-like U(1)' Y-sequential model in which \(g\) is varied so as to maintain \(\Omega_\chi = \Omega_{CDM}\) across the \((m_\chi, M_{Z'})\) plane. In the left panel the values of \(g\) required by the relic density are indicated by the indicated shadings, and the red shaded regions correspond to \(\Gamma_{Z'}/M_{Z'} > 0.5\) which are excluded from our analysis. The right panel of Fig. 4 shows the interplay of the LHC (brown shading) and dark matter search (purple) constraints in this plane with varying \(g\), as well as the precision electroweak constraint (olive). As in the left panel, we exclude the red shaded regions where \(\Gamma_{Z'}/M_{Z'} > 0.5\). There is a visible area where the vector-like U(1)' Y-sequential model is compatible with all the constraints, in the high mass resonance region where \(M_{Z'} \approx 2m_\chi\) around \(\log_{10}(m_\chi/\text{GeV}) \gtrsim 3.3\) and \(\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.7\). This small allowed region at larger \(\log_{10}(m_\chi/\text{GeV}) \sim 3.5\) and \(\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.7\) is squeezed by the requirement that \(\Gamma_{Z'}/M_{Z'} < 0.5\).

In addition to this visible allowed region, there is also a narrow sliver of parameter space where \(M_{Z'} \sim 2m_\chi\) that is also compatible with all the constraints, which is invisibly thin in Fig. 4. The left panel of Fig. 5 displays the relevant constraints on the vector-like U(1)' Y-sequential model along the line \(M_{Z'} = 2m_\chi\) for a range of values of \(g\). The relic density \(\Omega_\chi = \Omega_{CDM}\) along the blue line, and the blue-shaded region below it is excluded because the relic particle is overabundant. The ATLAS dilepton constraint [46] is shown as a brown line extending over the range \(2.3 \lesssim \log_{10}(M_{Z'}/\text{GeV}) \lesssim 3.7\), with the
Figure 3: The \((m_\chi, M_{Z'})\) planes in the \(U(1)'\) \(Y\)-sequential model with a vector-like dark matter coupling \(Y'_{X,L} = Y'_{X,R} = 1\) for a gauge coupling \(g = 0.03\) (upper left), \(g = 0.1\) (upper right) and \(g = 0.3\) (lower). The solid blue lines are the contours where \(\Omega_\chi = \Omega_{CDM}\), and \(\Omega_\chi > \Omega_{CDM}\) in the regions shaded blue. The bands shaded orange are excluded by the ATLAS dilepton search \[46\], the regions shaded olive are excluded by precision electroweak measurements, and the direct XENON1T constraint \[38\] on dark matter scattering are shown as purple lines.
Figure 4: Left panel: The $(m_{\chi}, M_{Z'})$ plane in the $U(1)'$ Y-sequential model with a vector-like dark matter coupling $Y'_{\chi,L} = Y'_{\chi,R} = 1$ and the value of the gauge coupling $g$ allowed to vary so as to yield $\Omega_{\chi} = \Omega_{CDM}$ everywhere in the plane. Right panel: The same $(m_{\chi}, M_{Z'})$ plane with varying gauge coupling $g$, now showing the band excluded by the ATLAS dilepton search (shaded orange) [46], the regions excluded by the direct XENON1T search for dark matter scattering (shaded purple) [38], the region excluded by precision electroweak data (shaded olive) [39] and the regions where $\Gamma_{Z'}/M_{Z'} > 0.5$ (shaded red). Note the small allowed region with $\log_{10}(m_{\chi}/\text{GeV}) \gtrsim 3.3$ and $\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.7$. Note that there is a very narrow region on resonance that is not visible on this plot but is explored in Fig. 5.
Figure 5: The interplays of the constraints on the vector-like (left panel) and axial (right panel) $U(1)'$ Y-sequential models along the line $m_\chi = M_{Z'}/2$, for a range of values of the gauge coupling $g$. The relic density $\Omega_\chi = \Omega_{CDM}$ along the blue lines, and the relic density is too high in the blue-shaded region below it. The ATLAS dilepton constraint [46] is shown as brown lines: regions above are excluded. The purple lines are the upper limits on $g$ from direct dark matter searches, and the green lines show the upper bound from precision electroweak data.

region above being excluded. The purple line shows the upper limit on $g$ provided by direct dark matter searches as a function of $M_{Z'}$. Finally, the green line reproduces the constraint from precision electroweak data. We see that there is a region to the right of this line, below the direct search and ATLAS dilepton lines and above the blue line that is compatible with all the constraints. Points above the blue line would have $\Omega_\chi < \Omega_{CDM}$, but the relic density could be brought up to the limit $\Omega_\chi = \Omega_{CDM}$ by taking $m_\chi$ slightly below or above $M_{Z'}/2$, so that the $\chi\chi$ annihilation cross-section is suitably reduced by sliding down one of the sides of the $Z'$ Breit-Wigner peak.

The conclusion of this analysis of the vector-like $U(1)'$ Y-sequential model is similar to what was foreseen in [34]. It is very tightly constrained by the ATLAS dilepton search and direct searches for dark matter scattering, as well as the precision electroweak data, with the only allowed region (apart from the very narrow resonance region discussed in the previous paragraph) appearing when with $\log_{10}(m_\chi/\text{GeV}) \gtrsim 3.3$ and $\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.7$.

3 Benchmark with an Axial Dark Matter Coupling

In this Section we consider another variant of the Y'-sequential model, assuming again that any exotic fermions are SM singlets such that the $U(1)'$ charges of the Standard Model particles are guaranteed to be:

$$Y'_{q} = 1, \quad Y'_{l} = -3, \quad Y'_{e} = -6, \quad Y'_{d} = -2, \quad Y'_{u} = 4, \quad Y'_{H} = -3.$$ (3.1)

However, in contrast to the previous Section, we now consider a case where the dark matter particle $\chi$ has an axial $U(1)'$ coupling: $Y'_{\chi_L} = -Y'_{\chi_R}$. As in the vector-like case
discussed in the previous Section, the model has as free parameters the $U(1)'$ coupling $g$, $m_\chi$, $M_{Z'}$, and the magnitude of the $U(1)'$ charge of the dark matter particle. In addition, this benchmark must have at least one additional dark sector particle so as to cancel the triangle anomalies, as discussed in [34]. However, here we do not discuss further the possible phenomenology of such an extended dark sector.

Fig. 6 displays the $(m_\chi, M_{Z'})$ plane in this model with $Y'_\chi,L = -Y'_\chi,R = 1$, analogous to the vector-like case shown in Fig. 2. We show as solid green (orange) (blue) lines the contours where $\Omega_\chi = \Omega_{\text{CDM}}$ for the same choices $g = 0.03(0.1)(0.3)$ considered above and the relations $m_\chi = M_{Z'}/2, m_\chi = M_{Z'}, m_\chi = m_t$, $m_\chi = M_{Z'}/2$ and $M_{Z'} = M_Z$ are again shown by dashed lines with the same colours as in the vector-like case. As in that case, the dark matter contour exhibits a wedge around $m_\chi = M_{Z'}/2$, which is asymmetric and extends to large $m_\chi$ when $\log_{10}(M_{Z'}/\text{GeV}) \lesssim 2$. This extension is due to the opening of the $\chi\chi \to t\bar{t}$ threshold when $m_\chi > m_t$. Below this threshold, annihilations into pairs of Standard Model fermions are suppressed by mass factors (helicity suppressed), as can be seen in the second line of Eq. (2.2). For this reason, the dominant $\chi\chi$ annihilation channel is into pairs of mediator bosons, $Z'Z'$, when $m_t \gtrsim m_\chi \gtrsim M_{Z'}$. The relic density contours also exhibit glitches associated with enhanced annihilation when $\chi\chi \to Z$ on resonance, induced by $Z - Z'$ mixing, and when $M_{Z'} \simeq M_Z$ this mixing is enhanced.

Fig. 7 displays the $(m_\chi, M_{Z'})$ planes in the axial $U(1)'$ Y-sequential model for the following fixed values of $g$, assuming $Y'_{\chi,L} = -Y'_{\chi,R} = 1$: $g = 0.03$ (upper left), 0.1 (upper right) and 0.3 (lower). As in the vector-like case, we do not consider larger values of $g$, because the narrow-width approximation for the $Z'$ breaks down. As in Fig. 3 the regions of the planes where $\Omega_\chi > \Omega_{\text{CDM}}$ are shaded blue, those excluded by the ATLAS dilepton search are shaded brown, those excluded by the (suitably rescaled) direct dark matter

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\[ g^2 |Y'_{\chi,L}| \]
Figure 7: The \((m_\chi, M_{Z'})\) planes in the \(U(1)'\) Y-sequential model with an axial-like dark matter coupling \(Y'_{X,L} = -Y'_{X,R} = 1\) for a gauge coupling \(g = 0.03\) (upper left), \(g = 0.1\) (upper right) and \(g = 0.3\) (lower). The solid blue lines are the contours where \(\Omega_\chi = \Omega_{CDM}\), and \(\Omega_\chi > \Omega_{CDM}\) in the regions shaded blue. The bands shaded brown are excluded by the ATLAS dilepton search, the regions shaded purple are excluded by direct searches for dark matter scattering, and the regions shaded olive are excluded by precision electroweak data.

Searches are shaded purple, and those excluded by precision electroweak measurements are shaded green. When \(g = 0.03\) and 0.1 the dark matter density constraint is in general more powerful than the ATLAS constraint, but they are more complementary when \(g = 0.3\). The direct dark matter search constraint is important at low \(m_\chi\) and \(M_{Z'}\), and is relatively similar in the three panels, strengthening slightly as \(g\) increases. However, the most important constraint for \(M_{Z'} \lesssim 3\) to 4 TeV is that from precision electroweak data. In combination with the relic density constraint that excludes larger \(M_{Z'}\), it excludes all the displayed region of the \((m_\chi, M_{Z'})\) plane.

We show in the left panel of Fig. 7 the \((m_\chi, M_{Z'})\) plane in the axial \(U(1)'\) Y-sequential model with \(g\) allowed to vary as indicated by the colour coding shown in the legend, so as to obtain \(\Omega_\chi = \Omega_{CDM}\) throughout the plane. As in the vector-like case shown in the left panel of Fig. 4, there is a region at large \(M_{Z'}\) where the required value of \(g\) becomes large and even non-perturbative. Shaded in red is the region where \(\Gamma_{Z'}/M_{Z'} > 0.5\). One difference from the vector-like case is the series of ‘steps’ in the contours of \(g\) at \(\log_{10}(m_\chi/\text{GeV}) \sim 2.7\) where the onset of the \(t\bar{t}\) threshold increases the annihilation rate.
for fixed $g$, so that a smaller value of $g$ is needed to obtain $\Omega_\chi = \Omega_{CDM}$.

This feature is reflected in the right panel of Fig. 8, where we see that the exclusion by the direct search for dark matter scattering (purple shading) runs out of steam when $\log_{10}(m_\chi/\text{GeV}) \gtrsim 3$ and $g$ is small. For the same reason, it is also weakened along the diagonal line where $m_\chi \simeq M_{Z'}/2$. We also note the region at large $M_{Z'}$ where $\Gamma_{Z'}/M_{Z'} > 0.5$, and that the ATLAS dilepton constraint again enforces $\log_{10}(M_{Z'}/\text{GeV}) \lesssim 2.3$. Lower values of $M_{Z'}$ are excluded by the precision electroweak data, as in the vector-like case.

However, we see in the right panel of Fig. 8 that there is no part of the displayed region of the $(m_\chi, M_{Z'})$ plane in the Y-sequential model with an axial $Z'$ dark matter coupling that is consistent with all the constraints. In particular, in this instance, unlike in the vector-like case, there is no allowed strip when $m_\chi \simeq M_{Z'}/2$, as there was in the left panel of Fig. 5. This is mainly a result of the fact that the annihilation cross section is p-wave suppressed (resulting in a $v^2$ suppression), which requires the gauge coupling $g$ to be larger to match the observed value of the relic density.

## 4 Benchmarks with a Leptophobic $Z'$

We now consider two benchmark leptophobic models that were also originally proposed in [34]. By construction, they both have $Y_{l', e'} = 0$, which is possible only if there are additional particles beyond the dark matter particle. The first model we study contains an additional SU(2) doublet of fermions $B$. In the visible sector it has universal U(1)'}
charges for the quarks:

\[ Y'_q = Y'_u = Y'_d, \]  

and hence \( Y'_H = 0 \). Normalizing the U(1)' coupling so that \( Y'_{\chi,L} = 1 \), the following are the U(1)' charges of the quarks and the \( \chi_R \):

\[ Y'_q = -\frac{1}{27}, \quad Y'_{\chi,R} = 0, \]  

and the U(1)' charges of the left- and right-handed components of the additional SU(2) doublet \( B \) are

\[ Y'_{B,L} = -\frac{1}{3}, \quad Y'_{B,R} = \frac{4}{3}. \]  

The leptophobia of this model implies that the ATLAS dilepton search constraint is irrelevant. However, one must still consider the (weaker) constraint from searches for structures in the dijet spectrum. In addition, the small size of the quark charges in Eq. (4.2) compared to the charge of the dark matter particle implies that the LHC monojet + \( E_T \) constraint is also important. The absence of leptonic U(1)' charges implies that the Higgs multiplet must also have vanishing \( Y' \), which implies that tree-level \( Z - Z' \) mixing through the Higgs sector is absent. However, the presence of particles with both Standard Model and U(1)' charges implies that kinetic \( Z - Z' \) mixing is induced at the loop level (we assume \( \epsilon = 0 \) at tree level), as we discuss in Appendix A.

The second leptophobic \( Z' \) model that we consider contains instead an additional SU(2) triplet of fermions. It has the following universal U(1)' charges for the quarks:

\[ Y'_q = -\frac{2}{9}, \quad Y'_u = 0, \]  

where we have again normalized the U(1)' coupling so that \( Y'_{\chi,L} = 1 \), and vanishing Higgs charge. In addition, this model has \( Y'_{\chi,R} = 1/2 \) and the following charges for the left- and right-handed components of the additional SU(2) triplet:

\[ Y'_{B,L} = -\frac{1}{2}, \quad Y'_{B,R} = \frac{1}{2}. \]  

In this model the quark charges in Eq. (4.4) are less suppressed relative to the charge of the dark matter particle than in the first leptophobic benchmark model, so that the LHC monojet + \( E_T \) constraint is correspondingly less important.

Fig. 9 displays in the left panel the \((m_\chi, M_{Z'})\) plane in the first leptophobic U(1)' model with the U(1)' charges shown in Eq. (4.2), and in the right panel plane the corresponding \((m_\chi, M_{Z'})\) plane in the second leptophobic U(1)' model (Eq. (4.4)). The solid lines are contours where \( \Omega_\chi = \Omega_{CDM} \) for the indicated fixed choices of the U(1)' coupling \( g \). The choices of \( g \) are different because the larger quark U(1)' charges in the second model imply that its total decay width is larger than in the first model for the same value of \( g \), causing the narrow-width approximation to break down for a smaller value of \( g \) than is the case in the first leptophobic model Eq. (4.2).

In both cases, we see the familiar feature that larger values of \( m_\chi \) and \( M_{Z'} \) are compatible with the \( \Omega_\chi = \Omega_{CDM} \) constraint along the dashed red diagonal line where
Figure 9: The \((m_\chi, M_{Z'})\) planes in the leptophobic \(U(1)'\) models (Eq. (4.2) (left panel) and Eq. (4.4) (right panel)). The solid lines are contours where \(\Omega_\chi = \Omega_{CDM}\) for the indicated choices of the \(U(1)'\) coupling \(g\), and the red/purple/orange/grey/black dashed lines are where \(m_\chi = \frac{M_{Z'}}{2}, m_\chi = M_{Z'}, m_\chi = m_t, m_\chi = M_Z\) and \(M_{Z'} = M_Z\), respectively.

\(m_\chi = \frac{M_{Z'}}{2}\). Below this diagonal line, the contours in the two models are quite different when \(m_\chi > M_{Z'}\) (below and to the right of the diagonal purple dashed line), reflecting the greater importance of \(\chi\chi\) annihilations into pairs of \(Z'\) bosons relative to annihilations into SM particles. This is because the first leptophobic model has a smaller quark \(U(1)'\) charge (shown in Eq. (4.2) while the dark matter charges are somewhat similar. We also note glitches in the relic density contours where \(M_{Z'} = M_Z\) (black dashed lines).

This effect is also visible in Fig. 10, where the gauge coupling \(g\) is allowed to vary across the \((m_\chi, M_{Z'})\) planes so as to maintain \(\Omega_\chi = \Omega_{CDM}\) in the leptophobic \(U(1)'\) models with the quark charges (4.2) (left panel) and (4.4) (right panel). In the red shaded regions \(\Gamma_{Z'}/M_{Z'} > 0.5\) so that the narrow-width approximation breaks down.

The upper panel of Fig. 11 displays the constraint imposed by precision measurements of the oblique parameters \(S, T\) in the \((M_{Z'}, \epsilon)\) plane \([39]\), where \(\epsilon\) is the magnitude of (tree-level) kinetic mixing. For our models however, we will assume that at tree level \(\epsilon = 0\), but we cannot avoid generating it at loop-level. In the lower left panel of Fig. 11 we show the constraint in the \((M_{Z'}, g)\) plane that is imposed by the oblique parameters \(S, T\) in the first leptophobic model with \(Y'_q = -1/27\) (Eq. (4.2)), and in the lower right panel the corresponding constraint in the second leptophobic model with \(Y'_q = -2/9\) (Eq. (4.4)), assuming in both cases that the loop-induced mixing vanishes at the scale of 100 TeV \([10]\).

For further details on the electroweak precision constraints, see Appendix A.

This constraint is much weaker than the mass mixing constraint in the \(Y'_q\)-sequential models that was shown in Fig. 1, due to both the loop-suppression and the small quark charges present in both models. In particular, in the case of the second leptophobic model we see in the lower right panel of Fig. 11 that for \(M_{Z'} < M_Z\) only \(g \gtrsim 0.5\) is

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\[10\] For consistency, the scale at which the mixing vanishes should not lie within the range of \(M_{Z'}\) displayed in the figures. By choosing the mixing to vanish at the boundary of the displayed range of \(M_{Z'}\), we are applying it in the most conservative possible way.
Figure 10: The \((m_\chi, M_{Z'})\) planes in the leptophobic U(1)' models Eq. (4.2) (left panel) and Eq. (4.4) (right panel), with the value of the gauge coupling \(g\) varying across the planes so as to enforce \(\Omega_\chi = \Omega_{CDM}\), as indicated by the colours and solid contours.

Disallowed, and that any value of \(g < 1\) is allowed for \(\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 2.1\). Since the first leptophobic model has a smaller quark charge, namely \(Y'_{q} = -1/27\) (Eq. (4.2)), the constraint on \(g\) for any fixed value of \(M_{Z'}\) is weaker by a factor 6, and hence of even less importance, as seen in the lower left panel of Fig. 11.

We consider next the dijet bounds on these leptophobic models, which are shown in Fig. 12. This shows the constraints on the quark coupling \(g \times Y'_{q}\) when \(m_\chi > M_{Z'}/2\), so that the invisible width vanishes. The irregularities in the limit contour arise because several different 13-TeV experimental analyses are combined:

- An ATLAS search for resonances decaying into boosted quark pairs + a \(\gamma\) or a jet with 36.1/fb for \(M_{Z'} < 220\) GeV [55],
- An ATLAS search for dijets + an ISR \(\gamma\) with 15.5/fb for \(220 \text{ GeV} < M_{Z'} < 350\) GeV [56],
- An ATLAS search for dijets + an ISR jet with 15.5/fb for \(350 \text{ GeV} < M_{Z'} < 450\) GeV [56],
- An ATLAS dijet search with 3.6 to 29.7/fb for \(450 \text{ GeV} < M_{Z'} < 1500\) GeV [57],
- An ATLAS dijet search with 37.0/fb for \(1.5 \text{ TeV} < M_{Z'} < 3.5 \text{ TeV}\) [58].

We have also explored the constraints on the leptophobic models coming from mono-jet searches at the LHC. To this end, we have modelled the published results from ATLAS [62] using a rapid recasting procedure that reproduces the published experimental results within the quoted \(\pm 1\sigma\) uncertainty, the main deviations being associated with

\[\text{The glitches seen in the upper and lower right panels of Fig. 11 arise from a mismatch between our treatments of the precision electroweak constraints using } S \text{ and } T \text{ at large } M_{Z'} \text{ and the } \rho \text{ parameter at smaller } M_{Z'}, \text{ and are without consequence for our global analysis.}\]
Figure 11: Upper panel: The constraint on kinetic mixing $\epsilon$ as a function of $M_{Z'}$ imposed by precision measurements of the oblique parameters $S$ and $T$ (and $\rho$). Lower left panel: The kinetic mixing constraint in the $(M_{Z'}, g)$ plane in the first leptophobic model (Eq. (4.2)), taking account of the logarithmic variation of $\epsilon$ and assuming that it vanishes at a renormalization scale of 100 TeV. Right panel: The corresponding kinetic mixing constraint in the $(M_{Z'}, g)$ plane in the second leptophobic model (Eq. (4.4)).
binning effects in the experimental analysis and theoretical modelling. Practical details are described in Appendix B.

Next we show summary plots of all relevant constraints for fixed gauge couplings, in which we treat the relic density as an upper limit rather than a strict requirement, for leptophobic model 1 in Fig. 13 and for leptophobic model 2 in Fig. 14. We see that relic density considerations along with the direct detection constraint rule out much of the parameter space, with LHC searches being less important. In particular, the monojet constraint is unimportant for $g = 0.3$, but makes an appearance for $g = 1$ and becomes more important for $g = 3$. At low $m_\chi$ and $M_{Z'}$ the monojet signal would fall into the low $E_{T,\text{miss}}$ selection, whereas at higher masses the signal is best constrained by the higher $E_{T,\text{miss}}$ selection. The band structure of the region excluded by the LHC dijet searches arises because of the irregularity in the combined constraint seen in Fig. 12.

Finally, we show in the left and right panels of Fig. 15, respectively, compilations of the various phenomenological constraints in the $(m_\chi, M_{Z'})$ planes for the first and second leptophobic models (Eqs. (4.2, 4.4)), varying $g$ so as to obtain the correct total cold dark matter density. The monojet constraints (black lines and grey shading) are quite similar in the two models, despite the differences in their $Z'$-quark couplings and limited to $\log_{10}(M_{Z'}/\text{GeV}) \lesssim 3.3$ to 3.4. We see that the dijet constraint (orange lines and shading) is generally weaker in the first model, as was to be expected in view of its smaller $Z'$-quark couplings. We also see that in both cases the direct DM detection constraints (purple lines and shading) are stronger than those from the dijet and monojet constraints. In the first leptophobic model, when $\log_{10}(m_\chi/\text{GeV}) \lesssim 4$ the direct DM scattering constraint enforces $\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.2$, which is attained along the diagonal line where $M_{Z'} = 2m_\chi$ and rapid resonant annihilation requires a smaller value of the

\[12\] This is because the gauge coupling determined via the relic density for model 1 is higher than that for model 2 because it has a smaller quark charge, compensating for the smaller quark charge that enters the monojet production cross-section. In addition, model 1 has a higher invisible branching fraction.
Figure 13: The $(m_X, M_{Z'})$ planes for leptophobic model 1, for a gauge coupling $g = 0.3$ (upper left), $g = 1.0$ (upper right) and $g = 3.0$ (lower). The solid blue lines are the contours where $\Omega_X = \Omega_{CDM}$, and $\Omega_X > \Omega_{CDM}$ in the regions shaded blue. The dark grey band is excluded by the most recent ATLAS monojet search and the bands shaded brown are excluded by ATLAS dijet searches. The regions shaded purple are excluded by direct searches for dark matter scattering, and the regions shaded green are excluded by precision electroweak data.
Figure 14: The \((m_X, M_{Z‘})\) planes for leptophobic model 2, for a gauge coupling \(g = 0.1\) (upper left), \(g = 0.3\) (upper right) and \(g = 1.0\) (lower). The solid blue lines are the contours where \(\Omega_X = \Omega_{CDM}\), and \(\Omega_X > \Omega_{CDM}\) in the regions shaded blue. The dark grey band is excluded by the most recent ATLAS monojet search and the bands shaded brown are excluded by ATLAS dijet searches. The regions shaded purple are excluded by direct searches for dark matter scattering, and the regions shaded green are excluded by precision electroweak data.
coupling $g$, reducing the scattering cross section. In the second leptophobic model the direct dark matter constraint imposes $\log_{10}(M_{Z'}/\text{GeV}) \gtrsim 3.2$ in all the plane displayed.

The importance of the direct DM scattering constraint in Fig. 15 arises from the vector nature of the coupling of the DM particle to quarks in the two minimal leptophobic models (Eqs. (4.2, 4.4)) proposed in [34]. It would be possible, in principle, to construct non-minimal leptophobic models in which the quark couplings are axial, in which case the impact of the direct DM scattering constraint would be reduced. In this hypothetical case indirect constraints on DM annihilations, e.g., from searches for $\chi\chi \rightarrow \gamma + X$ in dwarf spheroidal galaxies [59], would play a role for $m_\chi \lesssim 50$ GeV. However, we do not consider this case any further, and away from resonance these indirect searches play no role in constraining our benchmark vector-like leptophobic models.

As in the previous leptophilic models, in narrow strips of resonant annihilation near the $Z'$ peak where $m_\chi \simeq M_{Z'}/2$, the gauge coupling $g$ may be significantly smaller while also reproducing the observed relic density. To investigate to what extent, if at all, the other experimental constraints can exclude this region, we show the ($M_{Z'}, g$) plane for both leptophobic models in Fig. 16. We see that, in both cases, the correct total cold dark matter density can be obtained for any value of $M_{Z'}$ without coming into conflict with data from direct detection, the LHC and electroweak precision data. As in the case of the vector-like leptophobic model, this feature is too narrow to be visible in the ($m_\chi, M_{Z'}$) planes shown in Fig. 15.

5 Discussion and Conclusions

We have studied four benchmark models of dark matter taken from [34], whose interactions are mediated by an anomaly-free $Z'$ boson. Two of these models are leptophilic, one with a vector-like coupling of the dark matter particle to the $Z'$, and one with an axial coupling. The other two models are leptophobic, with the gauge anomalies can-
Figure 16: The \((M_{Z'}, g)\) planes for leptophobic model 1 (left) and 2 (right), with \(m_\chi = M_{Z'}/2\) for resonant annihilation. The solid blue lines are the contours where \(\Omega_\chi = \Omega_{CDM}\), and \(\Omega_\chi > \Omega_{CDM}\) in the regions shaded blue. The region above the dark grey line is excluded by the most recent ATLAS monojet search and the region above the line shaded brown is excluded by ATLAS dijet searches. The region above the purple line is excluded by direct searches for dark matter scattering, and the region above the green line is excluded by precision electroweak data.

celled by different sets of additional particles in the dark sector. We have considered the phenomenological constraints coming from the overall density of cold dark matter, direct searches for dark matter scattering, from LHC searches for dileptons, dijets and monojets, and from precision electroweak measurements.

We have found that the vector-like leptophilic model is extremely tightly constrained by both dilepton constraints, and especially modifications to the \(S\) and \(T\) electroweak parameters, which rule out almost completely the areas of parameter space where we obtain good relic abundance. There is, however, a very small region of parameter space still available where both \(m_\chi\) and \(M_{Z'}\) have masses of several TeV. This region may be accessible to improvements in future constraints on electroweak precision variables before future enhancements in direct detection constraints. In addition to this region, there is a continuous line of solutions constrained to a very narrow allowed strip where \(m_\chi \simeq M_{Z'}/2\).

The axial leptophilic model is excluded for \(M_{Z'} < 10\) TeV completely, again by dilepton constraints and modifications to the electroweak variables. Therefore, this model requires modifications if it is to survive in the energy window that we are considering, namely that of interest to the LHC.

The two leptophobic models both have larger allowed regions where \(\log_{10}(m_\chi/\text{GeV}) \gtrsim 3.2\), as well as narrow allowed strips where \(m_\chi \simeq M_{Z'}/2\). The interesting regions of these models are generally safe in terms of their effect upon electroweak precision variables, as well as evading the dilepton bounds that constrain tightly the previous models. The monojet constraints on both models are relatively weak compared to the other constraints. The leptophobic model with a triplet of ‘dark’ particles has a stronger \(Z'\) coupling to quarks, so that the dijet searches are stronger. However, despite this, the constraint from direct detection limits is the strongest constraint on the parameter spaces of both leptophi-
phobic models. Since the LHC centre-of-mass energy will not be increased substantially, whereas the integrated luminosity will increase by almost two orders of magnitude compared to that analyzed so far, we expect that the improvement in dijet constraints will be mainly in terms of coupling rather than $Z'$ mass. We therefore expect future direct dark matter detection experiments to continue to impose stronger constraints than future collider results.

We have shown that $Z'$ models similar to the spin-one simplified models widely studied in the literature are either very strongly constrained (the Y-sequential models) or must feature exotic fermions charged under the SM gauge group (including SU(2) multiplets). In the latter case, it would be interesting in the future to study novel experimental constraints that might arise from the presence of such exotic fermions. On the theoretical side, it would be of interest to come up with an anomaly-free theory that features a purely axial coupling to dark matter, since this would allow a greater deal of complementarity between LHC and direct detection constraints. For our benchmark models, we have found that complementarity between different experimental constraints is not so simple to achieve.

The great progress made in recent years in exploring new physics scenarios at colliders and in underground experiments still leaves uncovered regions of parameter space which will be probed by the next generation of colliders. In particular we have shown how dijet and dilepton searches can set the strongest constraints when the DM annihilation is on the $Z'$ resonance. We look forward to the continued exploration of simplified anomaly-free models of dark matter from both the theory community and future experimental data.

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A $Z - Z'$ mixing

We follow the approach in [52, 32, 53], assuming a Lagrangian with both mass and kinetic mixing:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \hat{F}^\mu_{\nu} \hat{F}_{\mu\nu} + \frac{1}{2} m_Z^2 \hat{X}_\mu \hat{X}^\mu - \frac{1}{2} \sin \epsilon \hat{B}_{\mu\nu} \hat{F}^\mu_{\nu} + \delta m^2 \hat{Z}_\mu \hat{X}^\mu$$

(A.1)

where $\hat{Z} \equiv \cos \hat{\theta}_W \hat{W}^3 - \sin \hat{\theta}_W \hat{B}$ and $\hat{F}^\mu_{\nu} \equiv \partial^\mu \hat{X}_\nu - \partial^\nu \hat{X}_\mu$.

The Lagrangian can be transformed to the mass basis, with canonical kinetic terms,
via the following transformations:

\[
\begin{pmatrix}
\hat{B}_\mu \\
\hat{W}_\mu^3 \\
\hat{X}_\mu^\prime
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & -\tan \epsilon \\
0 & 1 & 0 \\
0 & 0 & 1/\cos \epsilon
\end{pmatrix}
\begin{pmatrix}
B_\mu \\
W_\mu^3 \\
X_\mu^\prime
\end{pmatrix}
\] (A.2)

\[
\begin{pmatrix}
B_\mu \\
W_\mu^3 \\
X_\mu^\prime
\end{pmatrix} =
\begin{pmatrix}
\cos \hat{\theta}_W & -\sin \hat{\theta}_W \cos \xi & \sin \hat{\theta}_W \sin \xi \\
\sin \hat{\theta}_W & \cos \theta_W \cos \xi & -\cos \hat{\theta}_W \sin \xi \\
0 & \sin \xi & \cos \xi
\end{pmatrix}
\begin{pmatrix}
A_\mu \\
Z_\mu \\
Z_\mu^\prime
\end{pmatrix}
\] (A.3)

where we identify \(A, Z\) and \(Z'\) as the physical fields, with \(\xi\) determined by

\[
\tan(2\xi) = -2 \cos \epsilon (\delta m^2 + m_Z^2 \sin \hat{\theta}_W \sin \epsilon)
\] (A.4)

The impact on electroweak precision observables can then be calculated using the \(S\) and \(T\) parameters\(^{13}\):

\[
\alpha S = 4 \cos \theta_W \sin \theta_W \xi (\epsilon - \sin \theta_W \xi)
\] (A.5)

\[
\alpha T = \xi^2 \left( \frac{m_Z^2}{m_Z^2} - 2 \right) + 2 \sin \theta_W \xi \epsilon
\] (A.6)

where \(\cos \theta_W\) is the cosine of the electroweak mixing angle and \(\alpha = e^2/4\pi\) is the electroweak coupling. We use for the numerical values of the \(S\) and \(T\) parameters the recent fit \[39\]. However, for smaller \(Z'\) masses it is more suitable to use the \(\rho\) parameter

\[
\rho - 1 = \frac{\cos^2 \theta_W \cos^2 \epsilon - \sin^2 \theta_W \sin^2 \epsilon}{\cos^2 \theta_W - \sin^2 \theta_W} \left( \frac{m_Z^2}{m_Z^2} - 1 \right)
\] (A.7)

and we use the \(\rho\) parameter instead of the \(S\) and \(T\) parameters when \(M_{Z'} < \sqrt{2} M_Z\). The reader who is paying attention may notice some glitches in some diagrams at those places in parameter space where we switch from using the \(S, T\) variables to \(\rho\).

For the Y-sequential models in Section 2 we neglect kinetic mixing, since the effect of mass mixing is much stronger. We then find

\[
\delta m^2 = \frac{1}{2 \sin \theta_W \cos \theta_W} \frac{e g Y_H'}{v^2}
\] (A.8)

where \(g\) is the \(U(1)'\) gauge coupling, \(Y_H'\) is the Higgs charge under \(U(1)'\), and \(v\) is the SM Higgs vev.

For the leptophobic models, \(Y_H' = 0\) so there is no mass mixing effect, and we assume also that tree-level kinetic mixing vanishes. However, it is unavoidably generated at loop level. Conservatively, we assume that \(\epsilon = 0\) at \(\Lambda = 100\) TeV, such that at a lower scale \[60\]

\[
\epsilon(\mu) = \frac{e g Y_q'}{2\pi^2 \cos \theta_W} \log \frac{\Lambda}{\mu}
\] (A.9)

In calculating our constraints we set \(\mu = M_{Z'}\).

\(^{13}\)To lowest order in \(\xi\), \(\cos \hat{\theta}_W = \cos \theta_W\) and \(\sin \hat{\theta}_W = \sin \theta_W\).
Figure 17: Left: the most sensitive search region, numbered 1-10 as the inclusive search regions IM1-10 defined by ATLAS \cite{62}. The most sensitive search region is the one that gives the largest $\mu$ factor. At low masses, IM1 is the most sensitive, whereas at high masses, IM9 is the most sensitive. Right: Contours of $\log_{10}\mu$ (see text for definitions) in the most sensitive search region.

B Monojet recast

In implementing the LHC monojet constraints, we adopt the rescaling procedure proposed in \cite{61}, generating monojet samples across a grid of $Z'$ and dark matter particle masses, and then rescaling to other points of parameter space.

For the constraints, we use the inclusive selection of the latest ATLAS monojet search with 36.1 $fb^{-1}$ of integrated luminosity \cite{62}. We calculate the exclusion using each of the missing energy selections defined by ATLAS, IM1 - IM10, corresponding to various $E_{T,\text{miss}}$ cuts: $E_{T,\text{miss}} > 250$ GeV for IM1 up to $E_{T,\text{miss}} > 1000$ GeV for IM10. We calculate $\mu$ as

$$\mu = \frac{\sigma(g = 1, \Gamma = 0.01 M_{Z'})}{\sigma_{95\%}} \quad (B.1)$$

for each separate $E_{T,\text{miss}}$ cut defined in each search region, where $\sigma_{95\%}$ is the cross section excluded by ATLAS at the 95\% CL. We show which search region is most constraining in the left panel of Fig. 17 and the corresponding $\mu$ factor in leptophobic model 1 is shown in the right panel of Fig. 17.

We then scale this $\mu$ to different points of parameter space by a factor (for fixed charges) $g^4/\Gamma$ for the on-shell region, and $g^4$ for the off-shell region, where $\Gamma$ is the width of the $Z'$ boson.

We note that the limit we obtain is approximate, since we do not simulate parton shower or detector effects, and we include the generation of only one hard jet at parton level in Madgraph \cite{47}. However we have validated our approach by reproducing the published results from ATLAS for the axial-vector simplified model, as seen in Fig. 18.
Figure 18: Parameter points excluded by our recast of the inclusive search (blue) compared to the published results from the exclusive monojet search [62] (red), for the axial-vector simplified model, with fixed couplings of $g_q = 0.25$ and $g_{DM} = 1.0$.

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