Probing feebly interacting dark matter with monojet searches

Jérôme Claude,* Maíra Dutra,† and Stephen Godfrey‡

Ottawa-Carleton Institute for Physics, Carleton University,
1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

(Dated: April 7, 2023)

Abstract

Dark matter may consist of feebly interacting massive particles (FIMPs) that never thermalized with the cosmic plasma. Their relic density is achieved via freeze-in for a wide range of masses, significantly expanding the model space that can be tested compared to other production mechanisms. However, testing the tiny couplings required by freeze-in is challenging. We show that FIMPs can be probed by LHC searches for new physics in monojet events with large missing energy. We study a $Z'$ portal model in which gluon annihilation produces FIMPs in the early universe and today at colliders. Monojet searches by LHC Run 3 might discover new physics accounted for by FIMPs with mass in the MeV-TeV range.

I. INTRODUCTION

The existence of dark matter (DM) particles is well-established from their gravitational interaction with ordinary matter [1–3]. However, their nature remains a major open problem. There are many ways to achieve the observed DM relic abundance ($\Omega h^2 \approx 0.120 \pm 0.001$ [4]). The most studied approach is via freeze-out, in which weakly interacting massive particles (WIMPs) are initially thermalized with the standard model (SM) particles. Viable WIMP candidates have electroweak scale couplings and masses typically in the few GeV to few TeV range. While simplified freeze-out models are mostly in tension with experimental bounds, WIMPs are still well-motivated DM candidates [5–8].

Another possibility for the origin of dark matter that has been gaining the community’s interest is the freeze-in mechanism, in which the SM bath produces feebly interacting massive particles (FIMPs) in out-of-equilibrium processes [9, 10]. An appealing feature of freeze-in is the possibility for viable DM candidates with masses from a few keV [11–13] up to the scale of the maximal temperature of the universe [14, 15].

Despite the fact that the SM-FIMP couplings must be feeble enough for freeze-in to work, FIMP phenomenology is possible. In extra $U(1)$ extensions of the SM in which new gauge bosons interact feebly with SM fermions, freeze-in is testable by direct detection [16–21], electron beam dump, neutrino-electron scattering [20], atomic parity violation, and collider experiments [22]. In models with mediators effectively coupled to photons, FIMP self-annihilation can generate keV X-ray lines [23, 24]. Moreover, an early matter-dominated era increases the testability of any FIMP model [25, 26].

Dark matter can be produced at colliders in association with detectable SM debris such as jets, leptons, and photons [27, 28]. In particular, monojet signatures have come to be at the forefront of DM searches, as production of a single jet alongside dark matter is a common feature of DM models [29–33]. Collider bounds on DM couplings and mass have the advantages of not depending on astrophysical uncertainties and being sensitive to very light DM candidates. The search for dark matter at colliders has focused on WIMPs due to their sizable couplings, but searches for FIMPs have garnered more attention over the last decade. The collider bounds on FIMPs rely on the macroscopic decay of long-lived particles which usually play a role in the freeze-in process [34–39].

In this work, we show that freeze-in can also be tested by monojet searches at hadron colliders that arise from the missing transverse momentum of the DM particles. In a model where the SM fermions are neutral under an extra $U(1)$ gauge symmetry, FIMPs can be produced at the Large Hadron Collider (LHC) from a promptly decaying $Z'$ in association with a monojet signal.

The paper begins in Section II with a description of the gluophilic $Z'$ model. In Section III we describe how the dark matter relic abundance is calculated. We give approximate expressions to help gain insights into freeze-in production although our results are found by numerically solving the full expressions. In Section IV we examine the out-of-equilibrium condition for the $Z'$ which puts limits on the allowed parameter space. Our results and discussion are given in Section V where we include the various constraints on the parameter space including theoretical constraints, indirect detection limits based on Fermi-LAT searches, and the constraints from monojet searches at the LHC. Our conclusions are given in Section VI.

II. THE GLUOPHILIC $Z'$ PORTAL MODEL

Extending the SM by a new $U(1)$ gauge group, $U(1)'$, is one of the simplest frameworks for physics beyond the standard model (BSM) to address dark matter. An interesting possibility for a viable yet minimal DM portal model is that BSM states, including a DM candidate, are charged under $U(1)'$ while all SM states are neutral. In this case, an effective portal between the visible and dark sectors arises when BSM fermions carry SM hypercharge [40–43] and/or color [44–46].

We consider a model which includes a fermionic DM candidate $\chi$ and a set of BSM fermions $\Psi_i$ that are...
charged under $U(1)'$ and are electroweak singlets. If the $\Psi_i$ are also charged under $SU(3)_c$ and are heavy enough, the new gauge boson $Z'$ will only interact with gluons via a dimension-6 operator. Unlike in simplified $Z'$ portal models, our $Z'$ does not interact with SM fermions directly. The relevant Lagrangian for this gluophilic $Z'$ portal model is given by [44]

$$
\mathcal{L} \supset \frac{g_{Z'}}{2} \bar{\chi} \gamma^\mu (1 - \gamma_5) \chi Z'_\mu - \frac{\epsilon^{\mu\nu\rho\sigma}}{\Lambda^2} \left( \partial^\alpha Z'_\alpha \text{Tr}[G_{\mu\nu} G_{\rho\sigma}] - 2 Z'_\mu \text{Tr}[G_{\nu\lambda} \partial^\lambda G_{\rho\sigma}] \right),
$$

where $g_{Z'}$ is the gauge coupling associated with $U(1)'$, $\Lambda$ is the cut-off scale of the theory, and $G_{\mu\nu}$ is the gluon field strength.

Values of $\Lambda$ at intermediate scales are well-motivated by GUT theories and provide an elegant explanation for small FIMP couplings [46]. However, in order to study the testability of the model, we consider $\Lambda$ to be as small as possible for freeze-in to work. Assuming there are $N_\Psi$ nearly degenerate $\Psi_i$ fermions with mass $\tilde{M}$ and dark chiral charges satisfying $q_{\Psi_i} - q_{\Psi_{i'}} = 1$, $\Lambda$ is related to the parameters of the UV complete theory by

$$
\Lambda \simeq \sqrt{\frac{24\pi}{N_\Psi \alpha_s g_{Z'}}} \tilde{M},
$$

where $\alpha_s$ is the strong coupling constant evaluated at the $Z$ mass. The actual value of $N_\Psi$ is not relevant in our effective analysis, as it only re-scales the $Z'$ coupling to gluons. The only limit that we are aware of for an electroweak singlet color triplet Dirac fermion is derived from the running of $\alpha_s$ in high energy collisions at the LHC [47]. Ref. [47] finds $M \gtrsim \mathcal{O}(100)$ GeV for three degenerate fermions, although that limit can be off by a factor of 2 due to theoretical uncertainties. This merits future study which lies outside the scope of the present work.

In order to make explicit the implications of our results, in what follows we treat $M$ as a free parameter. The other free parameters in our analysis are the dark matter and $Z'$ masses, $m_\chi$ and $m_{Z'}$, the number of heavy fermions $N_\Psi$, and the $U(1)'$ gauge coupling $g_{Z'}$. Although we parametrize this model in terms of quantities that are physically meaningful for the UV theory, we present results at scales where the effective model remains valid.

An important feature of this model is the momentum dependence of the interaction between gluons and the $Z'$. For $Z'_\mu$, $G_{\mu\nu}$, and $G_{\nu\lambda}$ with four-momenta $k$, $p_1$, and $p_2$, respectively, the $Z'gg$ vertex is given by

$$
\frac{N_\Psi \alpha_s g_{Z'}}{12\pi M^2} \delta^{ab} (A_{Z'}^{\lambda\mu
u} + A_g^{\lambda\mu
u}),
$$

with the momentum-dependent terms $A_{Z'}^{\lambda\mu\nu}$ and $A_g^{\lambda\mu\nu}$ defined as

$$
A_{Z'}^{\lambda\mu\nu} \equiv -2k\lambda \epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma},
$$

$$
A_g^{\lambda\mu\nu} \equiv (p_1 \cdot p_2) \epsilon^{\mu\nu\rho\sigma} (p_1 - p_2)\alpha + p_1 \rho p_2\sigma (p_2 \mu \epsilon^{\lambda\rho\sigma} - p_1 \nu \epsilon^{\lambda\rho\sigma}).
$$

The contraction between one of the momenta and the corresponding polarization vector is exactly zero for an on-shell particle. As a consequence, in processes involving the vertex $Z'gg$, at least one of the three gauge bosons must be off-shell.

### III. FREEZE-IN PRODUCTION OF DARK MATTER

In this model, dark matter can be produced in the early universe from gluon self-annihilation via the $s$-channel exchange of $Z'$ bosons. The reduced cross-section for this process reads

$$
\hat{\sigma}_{gg \rightarrow \chi\chi} = \frac{2 N_\Psi^2 \alpha_s^2 g_{Z'}^4}{32 \pi^3} \frac{m_{Z'}^2}{m_\chi^2 M^4} \sqrt{s} \frac{s^2 (s - m_{Z'}^2)^2}{(s - m_{Z'}^2)^2 + m_{Z'}^2 T^2} \sqrt{1 - \frac{4m_{Z'}^2}{s}},
$$

where $\sqrt{s}$ is the center-of-mass energy, $m_{Z'}$ the total decay width of $Z'$, and the approximation holds for $\Gamma_{Z'} \ll m_{Z'}^2/2$. Close to the $Z'$ pole, this cross-section is suppressed instead of enhanced because the $Z'$ must be off-shell [46]. It is worth mentioning that only the axial coupling between $\chi$ and $Z'$ contributes to this process. In the limit $\Gamma_{Z'} \ll m_{Z'}^2$, and $s \gg 4m_{Z'}^2$, the reaction rate density for the $gg \rightarrow \chi\chi$ process is given by

$$
\gamma_{gg \rightarrow \chi\chi}(T) \approx 6.4 \times 10^{-3} N_\Psi^2 \alpha_s^2 g_{Z'}^4 \frac{m_\chi^2 T_{10}}{m_{Z'}^4 M^4} e^{-\frac{m_\chi}{T}}.
$$

In this expression, we have approximated the effect of the Boltzmann suppression on the dark matter number density when $T < m_\chi$ by an exponential decrease.

The freeze-in production takes place when dark matter is initially absent and is produced from thermal bath species in out-of-equilibrium processes. The high temperature dependence of this reaction rate means that the freeze-in process starts to be effective as soon as a thermal bath is established, at the maximal temperature of the universe $T_{\text{MAX}}$. We can determine the region of our parameter space in which the out-of-equilibrium condition is satisfied, and thus the freeze-in regime holds, by requiring that the reaction rate $\gamma_{gg \rightarrow \chi\chi}(T)/n_{g}(T)$, with $n_{g}$ the gluon number density, be smaller than the Hubble rate $H(T)$ at $T = T_{\text{MAX}}$:

$$
0.013 N_\Psi^2 \alpha_s^2 g_{Z'}^4 \frac{g_6(T_{\text{MAX}})}{g_6(T_{\text{RH}})} \frac{m_\chi^2 T_{10}^2 T_{\text{MAX}}^3 M_{Pl}}{M^4 m_{Z'}^4} e^{-\frac{m_\chi}{T_{\text{MAX}}}} \lesssim 1,
$$

where $g_6(T_{\text{RH}})$ and $g_6(T_{\text{MAX}})$ are the gauge coupling constants at freeze-in and thermalization, respectively.
where \( T_{\text{RH}} \) is the inflationary reheat temperature, \( g_\text{e}(T) \) and \( g_\text{s}(T) \) are respectively the energetic and entropic relativistic degrees of freedom at a given temperature, and \( M_{\text{Pl}} \approx 2.43 \times 10^{18} \text{ GeV} \) is the reduced Planck mass.

In order to evaluate the relic abundance of dark matter in this scenario, we numerically solve a coupled set of Boltzmann fluid equations for the number density of \( \chi \) and the energy densities of radiation and of the inflaton field [46]. However, as explained in detail in Ref. [48], one can find an approximate expression for the relic density which takes into account freeze-in during reheating. In the present case, we find

\[
\frac{\Omega h^2}{0.12} \approx \left( 76 g_{\text{eff}} \right)^{3/2} \left( N_\text{q} \right)^2 \left( g_\text{z}/0.01 \right)^4 \left( \frac{m_\chi}{0.6 \text{GeV}} \right)^3 \left( \frac{2 \text{TeV}}{M} \right)^4 \left( 1 \text{GeV} \right)^4 \left( \frac{T_{\text{RH}}}{1 \text{GeV}} \right)^5 \left[ 1 + 8.13 r \left( \frac{T_{\text{RH}}}{1 \text{GeV}} \right)^2 \left( \frac{0.6 \text{GeV}}{m_\chi} \right)^2 \right].
\]

(7)

\[\text{FIG. 1. Processes leading to monojet signals. The thick lines represent gluons (g) and quarks (q = u, d, c, and s).}\]

\[\text{V. RESULTS AND DISCUSSION}\]

We are now in a position to present the constraints on the viable parameter space of feebly interacting dark matter in the context of the gluophilic \( Z' \) portal model discussed above.

We start with the theoretical constraints that ensure the consistency of the model. Since we are working in the effective regime, the scale of new physics, \( \Lambda \), must be above all relevant energy scales. This condition is satisfied by the allowed values of \( M \) via Eq. 2. Additionally, the presence of axial couplings lead to the violation of unitarity of the process \( \chi \chi \rightarrow \chi \chi \) at high energies [49]. As a consequence, dark matter cannot be arbitrarily heavier than \( Z' \):

\[
m_\chi \lesssim \sqrt{2\pi \frac{m_{Z'}}{g_\text{z}'}}.
\]

(9)

We now consider the experimental constraints on our model. Proton-proton collisions at the LHC can produce \( Z' \) bosons which promptly decay into dark matter. The Feynman diagrams allowing for monojet signals are depicted in Fig. 1. The ATLAS collaboration searched for new physics in events with an energetic jet and large missing transverse energy (\( E_{\text{T}}^{\text{miss}} \)) using 139 fb\(^{-1}\) of data collected at \( \sqrt{s} = 13 \text{ TeV} \) [32]. Since no excess over the SM background was found, they provided model-independent upper limits on the visible cross section for different \( E_{\text{T}}^{\text{miss}} \) event selection criteria. In this work, we use the limit with the strictest selection criteria to optimize signal-to-background ratio and, in turn, sensitivity. For \( E_{\text{T}}^{\text{miss}} > 1200 \text{ GeV} \), values of \( \sigma \times A \times \epsilon \) above 0.3 fb are excluded at 95\% confidence level. Using MadGraph5_aMCNLO [50], we generated events featuring a single jet with transverse momentum \( p_T > 1200 \text{ GeV} \) and pseudorapidity \( |\eta| < 2.4 \), which accounts for the
our parameter space where the freeze-in is testable and equilibrium with gluons. Therefore, the viable region of which \( T_{\chi} \) for DM, as the viable region of our parameter space in driven by gluon annihilation relies on low-scale reheating.

With Eq. 7, one can easily understand the features of the relic density contours and how they would change with different values of the free parameters. The first term of Eq. 7 is a good approximation when \( m_\chi < T_{\text{RH}} \), whereas the second term is a good approximation when \( m_\chi > T_{\text{RH}} \). However, when \( m_\chi > T_{\text{MAX}} \), one can see the Boltzmann suppression of the relic density, which is not considered by our approximation. To compensate for this suppression, light mediators \( Z' \) and \( \Psi_i \) are needed. Because of the high temperature dependence of the production rate, for a given value of \( m_\chi \), the higher the reheat scale, the more dark matter is produced. Therefore, the heavier the mediators must be to produce the same amount of \( \chi \).

The theoretical bounds set strong upper limits on the

![Graphical representation](image-url)
dark matter mass. In the upper panel of Fig. 2, we set $M = 2 \, \text{TeV}$, corresponding to $\Lambda \approx 291.4 \, \text{TeV}$. We observe that the unitarity bound excludes the limits from Fermi-LAT. Lower values of $M$ would enhance the Fermi-LAT limit and make it complementary to the ATLAS limit. However, such low values of $M$ cause the $Z'$ to thermalize with gluons. Higher values of $M$ are nevertheless of phenomenological interest. In the lower panel of Fig. 2, we set $M = 5 \, \text{TeV}$ ($\Lambda \approx 728.5 \, \text{TeV}$). In this case, the process $gg \rightarrow \bar{\chi}\chi$ is suppressed with respect to the upper panel case, and lower values of $m_{Z'}$ become viable.

For a given value of $M$, the lighter the $Z'$, the stronger the indirect detection and monojet cross sections. However, sub-GeV $Z'$ bosons are also of interest in our context. In Fig. 3, we set $g_{Z'} = 0.01$ and $m_{Z'} = 10 \, \text{MeV}$. For such a light $Z'$ boson, the upper limit on $m_{\chi}$ coming from unitarity is much stronger, ruling out the region of our parameter space probed by indirect detection. Interestingly, we find that for reheat scales much lower than hundreds of MeV, our dark matter candidate is completely ruled out by the monojet bounds. For reheat scales above hundreds of MeV, our dark matter candidate completely evades the current monojet limits.

Our results show that monojet searches strongly constrain the mass spectrum of a gluophilic $Z'$ portal model. In the region below the magenta dotted lines (where $m_{Z'} = 2m_{\chi}$), $Z'$ is resonantly produced and decays into dark matter. From Eq. 3, we note that this is allowed by the $A_{\mu}^{\lambda\mu}$ contribution to the $Z'gg$ vertex. The production rate of DM at the LHC becomes insensitive to the DM mass when the mediator is too heavy. The value at which this occurs depends on the interaction strength $g_{Z'}/M^2$. On the other hand, the off-shell mediator region ($m_{Z'} < 2m_{\chi}$) is strongly probed by monojet searches, unlike what we find in simplified $Z'$ portal models. At values of $m_{\chi}$ approaching $\sqrt{s}/2$, DM becomes kinematically inaccessible for monojet searches. Therefore, indirect detection bounds offer an opportunity to probe dark matter candidates too heavy to be produced at colliders.

Upcoming measurements by collider and indirect detection experiments will probe new viable regions of our parameter space. The recent launch of the LHC Run 3 and the planned High Luminosity runs will push both the energy and precision frontiers further than before [58, 59]. Future observatories such as the Cherenkov Telescope Array (CTA) and the Southern Wide field-of-view Gamma-ray Observatory (SWGO) will reach unprecedented sensitivity to DM particles in the 100 GeV – $10^6 \, \text{GeV}$ mass range [60]. Finally, it is worth mentioning that a reheating scale roughly below 150 MeV might lead to detectable effects [61].

VI. CONCLUSIONS

The freeze-in mechanism has become a popular explanation for the origin of dark matter. Frozen-in DM particles, the FIMPs, evade most of the current experimental bounds and motivate new searches for DM in a broad mass range. We have shown that monojet searches at the LHC are able to constrain the parameter space of a FIMP candidate. We considered a model in which gluons annihilate into FIMPs by exchanging a gluophilic $Z'$. Feeble DM interactions consistent with freeze-in are easily accomplished in this model, as the coupling between $Z'$ and gluons is loop-induced. The high momentum dependence of this effective coupling has a two-fold role in our results. On the one hand, it causes the freeze-in to occur during the post-inflationary reheating period. On the other hand, it leads to stringent monojet bounds, even in the off-shell mediator regime. A large region of our parameter space, for FIMP masses between the MeV scale and the collider threshold of 6.5 TeV, is already excluded by monojet limits. The LHC and future MeV gamma-ray telescopes will further test this model in the coming years, placing the usually elusive FIMPs at the edge of detection.

ACKNOWLEDGMENTS

We are grateful to Gopolang Mohlabeng and Olivier Mattelaer for their help with MadGraph5_aMCNLO. This work was supported by the Natural Sciences and Engineering Research Council of Canada under grant No. SAPIN- 2016-00041.

[1] Gianfranco Bertone, Dan Hooper, and Joseph Silk, “Particle dark matter: Evidence, candidates and constraints,” Phys. Rept. 405, 279–390 (2005), arXiv:hep-ph/0404175.
et al. (Planck), “Planck 2018 results. VI. Cosmological parameters,” Astron. Astrophys. 641, A6 (2020), [Erratum: Astron.Astrophys. 652, C4 (2021)], arXiv:1807.06209 [astro-ph.CO].

Howard Baer, Ki-Young Choi, Jihn E. Kim, and Leszek Roszkowski, “Dark matter production in the early Universe: beyond the thermal WIMP paradigm,” Phys. Rept. 555, 1–60 (2015), arXiv:1407.0017 [hep-ph].

Giorgio Arcadi, Maíra Dutra, Pradipita Ghosh, Manfred Lindner, Yann Mambro, Mathias Pierre, Stefano Pro-fumo, and Farinaldo S. Queiroz, “The waning of the WIMP? A review of models, searches, and constraints,” Eur. Phys. J. C 78, 203 (2018), arXiv:1703.07364 [hep-ph].

Leszek Roszkowski, Enrico Maria Sassolo, and Sebastian Tatar-Koanjan, “WIMP dark matter candidates and searches—current status and future prospects,” Rept. Prog. Phys. 81, 066201 (2018), arXiv:1707.06277 [hep-ph].

Tao Han, Zhen Liu, Lian-Tao Wang, and Xing Wang, “WIMP Dark Matter at High Energy Muon Colliders—A White Paper for Snowmass 2021,” in 2022 Snowmass Summer Study (2022) arXiv:2203.07351 [hep-ph].

Lawrence J. Hall, Karsten Jedamzik, John March-Russell, and Stephen M. West, “Freeze-In Production of FIMP Dark Matter,” JHEP 03, 080 (2010), arXiv:0911.1120 [hep-ph].

Nicolas Bernal, Matti Heikinheimo, Tommi Tenkanen, Kimmo Tuominen, and Ville Vaskonen, “The Dawn of FIMP Dark Matter: A Review of Models and Constraints,” Int. J. Mod. Phys. A 32, 1730023 (2017), arXiv:1706.07442 [hep-ph].

Jae Hyek Chang, Rouven Essig, and Annika Reinert, “Light(ly)-coupled Dark Matter in the keV Range: Freeze-In and Constraints,” JHEP 03, 141 (2021), arXiv:1911.03389 [hep-ph].

Cora Dvorkin, Tongyan Lin, and Katelin Schutz, “Cosmology of Sub-GeV Dark Matter Freeze-In,” Phys. Rev. Lett. 127, 111301 (2021), arXiv:2011.08186 [astro-ph.CO].

Ahmet Coskuner, Tanner Trickle, Zhengkang Zhang, and Kathryn M. Zurek, “Directional detectability of dark matter with single phonon excitations: Target comparison,” Phys. Rev. D 105, 015010 (2022), arXiv:2102.09567 [hep-ph].

Daniel J. H. Chung, Edward W. Kolb, and Antonio Riotto, “Nonthermal supersymmetric dark matter,” Phys. Rev. Lett. 81, 4048–4051 (1998), arXiv:hep-ph/9805473.

Daniel Carney et al., “Snowmass2021 Cosmic Frontier White Paper: Ultrahigh energy particle dark matter,” (2022) arXiv:2203.06508 [hep-ph].

Rouven Essig, Jeremy Mardon, and Tomer Volansky, “Direct Detection of Sub-GeV Dark Matter,” Phys. Rev. D 85, 076007 (2012), arXiv:1108.5383 [hep-ph].

Xiaoyong Chu, Thomas Hambye, and Michel H. G. Tytgat, “The Four Basic Ways of Creating Dark Matter Through a Portal,” JCAP 05, 034 (2012), arXiv:1112.0493 [hep-ph].

Rouven Essig, Marivi Fernandez-Serra, Jeremy Mardon, Adrian Soto, Tomer Volansky, and Tien-Tien Yu, “Direct Detection of sub-GeV Dark Matter with Semiconductor Targets,” JHEP 05, 046 (2016), arXiv:1509.01598 [hep-ph].

Thomas Hambye, Michel H. G. Tytgat, Jérôme Van-decasteele, and Laurent Vanderheyden, “Dark matter direct detection is testing freeze-in,” Phys. Rev. D 98, 075017 (2018), arXiv:1807.05022 [hep-ph].

Saniya Heeba and Felix Kahilo, “Probing the freeze-in mechanism in dark matter models with U(1) gauge extensions,” Phys. Rev. D 101, 035043 (2020), arXiv:1908.09834 [hep-ph].

Haipeng An and Daneng Yang, “Direct detection of freeze-in inelastic dark matter,” Phys. Lett. B 818, 136408 (2021), arXiv:2006.15672 [hep-ph].

Catarina Cosme, Maíra Dutra, Stephen Godfrey, and Taylor R. Gray, “Testing freeze-in with axial and vector Z’ bosons,” JHEP 09, 056 (2021), arXiv:2104.13937 [hep-ph].

Vedran Brdar, Joachim Kopp, Jia Liu, and Xiao-Ping Wang, “X-Ray Lines from Dark Matter Annihilation at the keV Scale,” Phys. Rev. Lett. 120, 061301 (2018), arXiv:1710.02146 [hep-ph].

Anirban Biswas, Sougata Ganguly, and Sourov Roy, “Fermionic dark matter via UV and IR freeze-in and its possible X-ray signature,” JCAP 03, 043 (2020), arXiv:1907.07973 [hep-ph].

Nicola Bernal, Catarina Cosme, and Tommi Tenkanen, “Phenomenology of Self-Interacting Dark Matter in a Matter-Dominated Universe,” Eur. Phys. J. C 79, 99 (2019), arXiv:1803.08064 [hep-ph].

Catarina Cosme, Maíra Dutra, Teng Ma, Yongcheng Wu, and Litao Yang, “Neutrino portal to FIMP dark matter with an early matter era,” JHEP 03, 026 (2021), arXiv:2003.01723 [hep-ph].

Felix Kahilofo, “Review of LHC Dark Matter Searches,” Int. J. Mod. Phys. A 32, 1730006 (2017), arXiv:1702.02430 [hep-ph].

Nicolo Trevisani (ATLAS, CMS), “Collider Searches for Dark Matter (ATLAS + CMS),” Universe 4, 131 (2018).
[35] Andre G. Hessler, Alejandro Ibarra, Emiliano Molinaro, and Stefan Vogl, “Probing the scotogenic FIMP at the LHC,” JHEP 01, 100 (2017), arXiv:1611.09540 [hep-ph].

[36] Lorenzo Calibbi, Laura Lopez-Honorez, Steven Lowette, and Alberto Mariotti, “Singlet-Doublet Dark Matter Freeze-in: LHC displaced signatures versus cosmology,” JHEP 09, 037 (2018), arXiv:1805.04423 [hep-ph].

[37] G. Bélanger et al., “LHC-friendly minimal freeze-in models,” JHEP 02, 186 (2019), arXiv:1811.05478 [hep-ph].

[38] Jose Miguel No, Patrick Tunney, and Bryan Zaldivar, “Probing Dark Matter freeze-in with long-lived particle signatures: MATHUSLA, HL-LHC and FCC-hh,” JHEP 03, 022 (2020), arXiv:1908.11387 [hep-ph].

[39] Nobuchika Okada, Satomi Okada, and Qaisar Shafi, “Light Z’ and dark matter from U(1)\text{X} gauge symmetry,” Phys. Lett. B 810, 135845 (2020), arXiv:2003.02667 [hep-ph].

[40] Ignatios Antoniadis, Alexey Boyarsky, Sam Espahbodi, Oleg Ruchayskiy, and James D. Wells, “Anomaly driven signatures of new invisible physics at the Large Hadron Collider,” Nucl. Phys. B 824, 296–313 (2010), arXiv:0901.0639 [hep-ph].

[41] Emilian Dudas, Yann Mambrini, Stefan Pokorski, and Alberto Romagnoni, “Extra U(1) as natural source of a monochromatic gamma ray line,” JHEP 10, 123 (2012), arXiv:1205.1520 [hep-ph].

[42] Emilian Dudas, Yann Mambrini, Stefan Pokorski, and Alberto Romagnoni, “(In)visible Z-prime and dark matter,” JHEP 08, 014 (2009), arXiv:0904.1745 [hep-ph].

[43] Giorgio Arcadi, Pradipta Ghosh, Yann Mambrini, Mathias Pierre, and Farinaldo S. Queiroz, “Z’ portal to Chern-Simons Dark Matter,” JCAP 11, 020 (2017), arXiv:1706.04198 [hep-ph].

[44] Emilian Dudas, Lucien Heurtier, Yann Mambrini, and Bryan Zaldivar, “Extra U(1), effective operators, anomalies and dark matter,” JHEP 11, 083 (2013), arXiv:1307.0005 [hep-ph].

[45] Otilia Ducu, Lucien Heurtier, and Julien Maurer, “LHC signatures of a Z’ mediator between dark matter and the SU(3) sector,” JHEP 03, 006 (2016), arXiv:1509.05615 [hep-ph].

[46] Gautam Bhattacharyya, Maira Dutra, Yann Mambrini, and Mathias Pierre, “Freezing-in dark matter through a heavy invisible Z′,” Phys. Rev. D 98, 035038 (2018), arXiv:1806.00016 [hep-ph].

[47] Javier Llorente and Benjamin P. Nachman, “Limits on new coloured fermions using precision jet data from the Large Hadron Collider,” Nucl. Phys. B 936, 106–117 (2018), arXiv:1807.06894 [hep-ph].

[48] Maira Dutra, Ph.D. thesis, Orsay, LPT (2019).

[49] Felix Kahlhoefer, Kai Schmidt-Hoberg, Thomas Schwetz, and Stefan Vogl, “Implications of unitarity and gauge invariance for simplified dark matter models,” JHEP 02, 016 (2016), arXiv:1510.02110 [hep-ph].

[50] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations,” JHEP 07, 079 (2014), arXiv:1405.0301 [hep-ph].

[51] Louis E. Strigari, “Dark matter in dwarf spheroidal galaxies and indirect detection: a review,” Rept. Prog. Phys. 81, 056901 (2018), arXiv:1805.05883 [astro-ph.CO].

[52] Marco Cirelli, Gennaro Corella, Andi Hektor, Gert Hutsi, Mario Kadastik, Paolo Panci, Martti Raidal, Filippo Sala, and Alessandro Strumia, “PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection,” JCAP 03, 051 (2011), [Erratum: JCAP 10, E01 (2012)], arXiv:1012.4515 [hep-ph].

[53] Federico Ambrogi, Chiara Arina, Mihailo Backovic, Jan Heisig, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, and Gopalong Mohlabeng, “MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies,” Phys. Dark Univ. 24, 100249 (2019), arXiv:1804.00044 [hep-ph].

[54] Steen Hannestad, “What is the lowest possible reheating temperature?” Phys. Rev. D 70, 043506 (2004), arXiv:astro-ph/0403291.

[55] Karsten Jedamzik, “Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles,” Phys. Rev. D 74, 103509 (2006), arXiv:hep-ph/0604251.

[56] Masahiro Kawasaki, Kazunori Kohri, Takeo Moroi, and Yoshitaro Takaesu, “Revisiting Big-Bang Nucleosynthesis Constraints on Long-Lived Decaying Particles,” Phys. Rev. D 97, 023502 (2018), arXiv:1709.01211 [hep-ph].

[57] Gian Francesco Giudice, Edward W. Kolb, and Antonio Riotto, “Largest temperature of the radiation era and its cosmological implications,” Phys. Rev. D 64, 023508 (2001), arXiv:hep-ph/0005123.

[58] Sebastian Baum, Riccardo Catena, Jan Conrad, Katherine Freese, and Martin B. Krauss, “Determining dark matter properties with a XENONnT/LZ signal and LHC Run 3 monojet searches,” Phys. Rev. D 97, 083002 (2018), arXiv:1709.06051 [hep-ph].

[59] ATLAS Collaboration, “Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors,” (2022).

[60] Aion Viana, Andrea Albert, J. Patrick Harding, Jim Hinton, Harm Schoorlemmer, and Vitor de Souza (SWGO), “Searching for Dark Matter with the Southern Wide-field Gamma-ray Observatory (SWGO),” PoS ICRC2021, 555 (2021).

[61] M. S. Delos and Tim Linden, “Dark matter microhalos in the solar neighborhood: Pulsar timing signatures of early matter domination,” Phys. Rev. D 105, 123514 (2022), arXiv:2109.03240 [astro-ph.CO].