1 Introduction

A wide range of astrophysical measurements point to the presence of a non-baryonic form of matter\(^1\) in our Universe. Observations of galactic rotation curves, gravitational lensing and colliding galaxy clusters, to name a few, strongly support the theory of dark matter (DM). However, all of these compelling measurements have something in common: they all infer the existence of dark matter through observations of gravitational interactions. If this elusive form of matter is to be properly identified and understood, it must be observed undergoing non-gravitational interactions with Standard Model (SM) particles. Many experiments contribute to this effort using distinct techniques which may be categorised as the following:

- direct detection (DD), where the elastic scattering of DM with nuclei is measured;
- indirect detection (ID), where Standard Model particles produced through the annihilation of DM are detected;
- and collider searches, where DM is produced in high energy particle interactions and subsequently undergoes measurable interactions with SM particles.
Figure 1 illustrates the complementarity of these three approaches. Analysis of the data obtained through these methods must be anchored through some theory of the nature of DM, and many theoretical models are considered in the ongoing searches. Weakly Interacting Massive Particles (WIMPs) are an attractive and popular candidate. In this framework, DM particles are thought to have been produced in the hot early Universe before self-annihilating, leaving behind a number of so-called “thermal relics”. WIMPs stand out in particular due to the observation that the relic abundance of a stable particle species with a typical weak-scale self-annihilation cross section and electroweak scale mass matches the observed cosmological density of DM ($\Omega_x \sim \mathcal{O}(0.1)$).

The popularity of these candidates is bolstered by the fact that new physics is expected at the WIMP scale according to a wealth of independent theories, such as supersymmetry (SUSY) and theories of extra spatial dimensions. Searches at colliders have a particular preference for WIMPS, since they could be produced in high energy collisions and have measurable non-gravitational interactions with the SM. As of yet, none of the above DM detection methods have proven the WIMP hypothesis. In lieu of a discovery, they continue to put mounting pressure upon it.

2 The Large Hadron Collider

The Large Hadron Collider (LHC) is a hadron-hadron synchrotron built by the European Organisation for Nuclear Research (CERN) between 1998 and 2008. It lies in a tunnel 26.7 km in circumference, 45 – 170 m below the Franco-Swiss border (see Figure 2), and is the largest particle physics experiment ever to be built. The counter-rotating hadronic beams which collide therein usually consist of protons, though heavy ions, such as lead nuclei, are used on a less frequent basis. The beam in one pipe circulates clockwise while the beam in the other circulates anti-clockwise. They are guided round the circumference of the accelerator by 1232 super-conducting dipole magnets and are accelerated by 8 RF cavities per ring until each beam reaches an energy of 6.5 TeV. There are four interaction points (IPs) where hadron bunches cross and collisions take place, about which the four main experiments are situated. Three of these experiments, namely, ATLAS, CMS and LHCb, have dark matter search programs which will be discussed in this document.

ATLAS$^4$, CMS$^5$ and LHCb$^6$ exploit distinct technologies to conduct complementary searches for new physics. ATLAS and CMS are independently designed hermetic general-purpose detectors which aim to cover the broadest possible range of physics by detecting and measuring all particles produced at the IP using cylindrical layers of specialised sub-detectors. Many BSM searches at these detectors exploit the fact that the missing transverse momentum ($E_{T,\text{miss}}$) can be reconstructed using all of the visible decay products from an interaction. In contrast, LHCb is a single arm forward spectrometer which exclusively probes the forward rapidity region and specialises in triggering on particles with low transverse momentum ($p_{T}$). This means that it can explore relatively small boson masses compared to the general purpose detectors.
3 LHC Dark Matter Searches

While dark matter produced at the LHC would be almost invisible to the detectors, it may recoil with large $p_T$ against detectable SM particles, resulting in a measurable overall momentum imbalance. Such imbalances, if detected, must be described by a theoretical model of DM production at colliders, of which there are many examples\textsuperscript{7,8}, ranging in complexity. Considered models range from the simplest and most generic, such as operators in effective field theories (EFTs) with a very reduced set of model parameters, to minimal extensions to the SM involving new boson fields which mediate SM-DM interactions, up to UV complete theories such as SUSY, which rely heavily on model assumptions. While the LHC aims to cover the most diverse possible range of interpretations, including the more specific and targeted models, the large number of available theories has driven the focus of the most recent searches to be more model agnostic, with the aim of detecting excesses of $E_{T,\text{miss}}$ over the SM background with minimal assumptions applied to the visible recoil. For this reason, searches for signatures with initial state radiation (ISR) and $E_{T,\text{miss}}$ have garnered much popularity at the LHC in recent years. These are often referred to as ‘mono-$X$’ searches, where the ‘$X$’ denotes the species of initial state radiation targeted, though it should be noted that radiation of a single object is only the leading process in the simplest scenario. In the run-II phase of the LHC, a high momentum transfer squared ($Q^2$) of 13 TeV is reached and EFTs become invalid, so searches instead opt for simplified models involving production of DM pairs through a mediator. In this framework, the process can be described in terms of the Lorentz structure, the mass of DM ($m_X$), mediator mass ($m_{\text{med}}$), the coupling to DM ($g_X$), and the couplings to the SM quarks ($g_q$) and leptons ($g_\ell$).

Searches at the LHC are subject to many difficulties arising from the harsh environment imposed by the large number of events which take place in the detectors. Only a fraction of the collision events which take place can be recorded for further processing, meaning a rigorous selection of these events, referred to as triggering\textsuperscript{9–11}, must be applied. Measurements of $E_{T,\text{miss}}$ require precise reconstruction\textsuperscript{12,13} of any visible objects originating from the hard scatter event in an environment where multiple interactions (pile-up) per bunch crossing can occur. The searches summarised in this document are all impacted by such obstacles, but use specific techniques (choice of visible objects for triggering, kinematic or event quality cuts) to make the most of the available data.
4 Mono-X Searches

Mono-X searches generally involve selecting events where the eponymous visible object ‘X’ is present (such as a jet/$\gamma/W/Z/t/H$), vetoing other objects, precisely modelling SM backgrounds and checking the distribution of $E_{T,\text{miss}}$ for any excess over the SM expectation. In the absence of a discovered excess, limits on the mediator mass and DM mass are calculated for different possible couplings. Even when only the mono-X methodology is considered, a wealth of available final states is available at the LHC, with various production mechanisms (e.g. $q\bar{q}, gg$), (axial-)vector or (pseudo-)scalar mediators and different couplings possible, depending on the chosen benchmark. In this section, the different types mono-X searches currently pursued at the LHC are summarised.

4.1 Searches with jets (mono-jet)

The jet+$E_{T,\text{miss}}$, or mono-jet, search is a key mono-X channel due to the prevalence of gluon ISR at hadron colliders. Mono-jet searches are conducted by both ATLAS and CMS. They typically involve selecting $pp$ collision events which have large $E_{T,\text{miss}}$ ($>250$ GeV) and at least one jet with high $p_T$ (100 – 250 GeV) in the central region of the detector ($|\eta| < 2.4$). The high $E_{T,\text{miss}}$ thresholds are necessary in order to trigger on events of interest at a manageable rate.

The dominant backgrounds for mono-jet searches arise from events with a vector boson and jets, while sub-dominant backgrounds include top processes ($t=\bar{t}$) and di-boson events. These backgrounds are constrained in the signal region using various control regions enriched with the relevant SM background processes, constructed through the application of further restrictions on relevant visible particles, such as lepton vetoes. A simultaneous background-only likelihood fit is performed on the $E_{T,\text{miss}}$ distributions for these regions, yielding normalisation factors which are applied to the Monte Carlo (MC) backgrounds in the signal region. QCD multijet processes, where one or more jets are mis-measured, and non-collisional events (such as beam-gas interactions, cosmic rays and calorimeter problems) can also result in spurious $E_{T,\text{miss}}$. Both are quantified using data-driven methods and can be mitigated with more stringent requirements on the leading jets, with the latter further rejected using event quality filters based on hardware performance and collision timing criteria. The $E_{T,\text{miss}}$ distribution for the mono-jet signal region selection from the CMS search is shown in the left plot of Figure 3.

Both ATLAS and CMS produce constraints for a series of mediator models and coupling choices. Both searches are able to probe (axial-)vector mediated processes, but are only more recently accessing sensitivity to (pseudo-)scalar mediator processes, which have lower cross-sections. For the simplified model with (axial–)vector mediators, mediator masses of up to 1.6 – 1.8 TeV are excluded for couplings of $g_\chi = 1$, $g_q = 0.25$ (CMS results are shown in the right plot of Figure 3). In the CMS search, pseudoscalar mediators with masses below 0.4 TeV are also excluded for couplings of $g_\chi = 1$, $g_q = 1$, while in the ATLAS search, coloured scalar mediator masses with these same couplings and low $m_\chi$ are excluded up to 1.67 TeV. The searches are interpreted in a series of alternative scenarios in addition to the simplified model, such as the Arkani-Hamed, Dimopoulos, and Dval (ADD) model of large extra dimensions and Higgs to invisible processes.

4.2 Searches with Vector Bosons (mono-V) and Photons (mono-photon)

While rates for photon and electroweak boson ISR are much lower than for gluon radiation, searches involving photons and vector bosons can be complementary to mono-jet searches. ATLAS and CMS both conduct mono-photon searches as well as mono-V searches in cases where the boson subsequently decays leptonically and hadronically. Since these channels have lower backgrounds than the mono-jet search, they are able to apply less stringent kinematic thresholds, giving access to a lower visible $p_T$ and $E_{T,\text{miss}}$ range. For example, in the
4.3 Searches with heavy flavour quarks (mono-HF)

Assuming minimal flavour violation, interactions between SM matter and any new neutral spin-0 state is proportional to fermion masses via Yukawa-type couplings. This means that colour-neutral (pseudo-)scalar mediators may be substantially produced in association with heavy flavour (HF) quarks. Motivated by this, many searches in ATLAS and CMS are dedicated to processes resulting in $E_{T,\text{miss}}$ and singly or doubly produced third generation quarks:\textsuperscript{23–27} Searches involving pairs of bottom or top quarks have similar signatures to searches for third-generation...
quark superpartners, meaning that they can either be part of dedicated SUSY searches or can be reinterpreted.

4.4 Searches with Higgs bosons (mono-H)

The rate of Higgs ISR is strongly suppressed by the boson’s heavy mass. As a result, mono-H searches target dark interactions in which the Higgs directly participates. Two common scenarios involving a $Z'$ mediator are often explored in mono-H analyses: one non-resonant and one resonant. The former introduces a new $U(1)$ group with baryon number symmetry, yielding a new baryonic Higgs boson which couples to the $Z'$. The latter is a type-II Higgs doublet model (2HDM), where a new pseudo-scalar $A$ is introduced. Many mono-H searches arise from the different possible decays of the Higgs boson, including $bb^{30,31}$, $\gamma\gamma^{32}$, $\tau\tau^{33}$ and $WW=ZZ^{34}$ have been performed at ATLAS and CMS.

5 Mediator Searches

The LHC can be described as a “mediator machine”, producing mediators with a wide range of masses ($\mathcal{O}100$ – 1000 GeV) which are targeted by many searches at its various experiments. The mediators involved in the mono-X DM searches may not always decay to invisible particles. If $2m_{\chi}$ is greater than the mediator mass, since the mediators also couple to the SM, they may preferentially decay to visible particles. In such cases, these mediators of dark interactions may actually be discovered in searches involving visible di-object signatures, such as di-jet$^{35,36}$ or di-lepton$^{37,38}$ pairs.

Both di-lepton and di-jet searches exploit the smoothly falling di-object invariant mass spectra expected in the SM, modelling it using parametrised fits to data. This minimises model and theory uncertainties which plague MC-based background models. The searches then seek out bumps in the measured spectra, probing the highest available mass range. In the absence of excesses over the SM expectation, they set exclusion limits in a series of interpretations. In the di-lepton search, mediator masses up to 4.5 TeV are excluded for one of the considered interpretations. The standard di-jet searches at the LHC lose sensitivity for masses below the TeV-scale due to the extremely high event rates: data collection rates for inclusive single-jet triggers are eclipsed by the high SM multijet production rate. This can be addressed using so-called ‘trigger-object level’ or ‘data-scouting’ analysis techniques, whereby a reduced data format is used to allow for high trigger rates with a low bandwidth. The left plot of Figure 4 shows a comparison between the number of di-jet events which are obtained using different triggering techniques. Sensitivity to even lower mediator masses is achieved by requiring hard ISR (either jet or photon) in addition to the light dijet resonance. An example of a dijet mass distribution obtained using a combination of these techniques can be seen in the right plot of Figure 4, where a clearly visible $W=Z$ is reconstructed.

6 Combined Results

All of the above searches provide unique information about possible dark interactions. The various mono-X channels specialise in certain kinematic ranges and interpretations, while the fully visible di-object searches powerfully probe the regions of parameter space where the invisible particles may be too heavy to be directly produced. In order to show the complementarity of results from these searches, they are combined in the context of different benchmarks. In the absence of any clues as to the nature of DM, it is necessary to test as many models as possible. Such combinations are generally presented using exclusions in the $m_{\chi}$ vs. $m_{\text{med}}$ plane, as done for the individual mono-X results, for different mediator types and couplings. The top plot of Figure 5 shows an example of such a plot for a vector mediator with couplings $g_q = 0.1$, $g_\ell = 0.01$, $g_\chi = 1$. For this particular benchmark, since the dijet production and
Figure 4 – The figure on the left shows a comparison, as a function of dijet invariant mass $m_{jj}$, between the number of di-jet events in the data used by the ATLAS ‘trigger-level analysis’ (black points), the number of events selected by any of the experiment’s single-jet triggers (blue line) and the events selected by single-jet triggers and corrected by prescale factors (red line), where a prescale refers to a pre-defined number of events which are accepted for the given trigger in order to reduce rates (i.e. a prescale of $N$ means the system accepts $1/N$ events).

The figure on the right shows the ‘soft-drop’ (referring to a CMS jet algorithm) jet mass distribution for data and various sources of backgrounds, as well as a hypothetical $Z'$ signal with a mass of 135 GeV. The bottom panel shows the ratio of data to the background prediction, including uncertainties.

decay rates are lower, the mono-$X$ searches set the strongest exclusion limits for lower mediator masses where mediator decays to DM dominate.

It is also useful to compare the results from LHC DM searches to those performed by DD and ID experiments, in order to expose the complementarity of these different detection methods and identify any uncovered regions of parameter space to target in future searches. Connecting these very different results requires that one assumes a specific model and makes any assumptions abundantly clear. As previously stated, results from collider experiments are typically expressed as constraints on production cross-sections of specific processes, interpreted as statements about given model parameters, such as masses and couplings. Within the confines of these chosen parameters, these results may be extrapolated to statements about the observables measured by non-collider experiments, such as WIMP-nucleon scattering cross-sections (DD), DM annihilation cross-sections (ID) or the thermal relic density. In the bottom plot of Figure 5, results from LHC searches in the context of the aforementioned benchmark are re-interpreted as constraints on the spin-independent WIMP-nucleon scattering cross-section. The results are compared to those obtained from DD experiments. In this specific benchmark, the mono-$X$ searches provide the strongest constraints for low $m_X$, where the WIMP-nucleon elastic scattering cross-section is small. Though not shown here, results from the LHC may be particularly helpful in the case of pseudo-scalar interaction in the spin-dependent scenario, which are velocity suppressed. Many assumptions go into the translation of LHC results to parametrisations which can be directly compared to DD and ID limits, so these comparisons must not be taken at face value. The aim of these summary plots is to highlight the complementarity of these different forms of detection within a given model and its assumptions.

7 Dark Sector Searches

The searches mentioned thus far cover a wide range of models in which DM particles undergo SM gauge interactions. However, this is not the only scenario covered in the LHC search programme. There is growing interest and effort towards cases where DM exists in a hidden sector. In such a sector, dark mediators, which couple to the SM via portal interactions, could arise. In dark
Figure 5 – The top plot shows the regions in a (mediator-mass, DM-mass) plane excluded at 95% confidence level by di-jet, di-lepton and mono-X searches for leptophilic vector mediator simplified models. The exclusions are computed for couplings of $g_1 = 1$, $g_q = 0.1$ and $g_\ell = 0.01$. Dashed curves labelled “thermal relic” correspond to combinations of DM and mediator mass values that are consistent with a DM density of $\Omega h^2 = 0.12$. Between these dashed curves, annihilation processes described by the chosen model deplete $\Omega h^2$ to below this value. The fine dotted line indicates the kinematic threshold below which the mediator can decay on-shell to DM particles. The bottom plot shows a comparison of the inferred limits from the same benchmark model with constraints from direct-detection experiments on the spin-independent WIMP-nucleon scattering cross-section. LHC limits are shown at 95% confidence level, while direct-detection limits are shown at 90% confidence level. While the DD experiments set upper limits on the scattering cross section, indicated by curves, the LHC results, which have been translated from a simplified model, are closed contours of excluded phase space. Both from reference 45.

sector models, the coupling of the new dark bosons to the SM are encoded in mixing terms in the Lagrangian. Searches involve looking for visible particles which result from decays which occur via these portals, and, in the absence of signal, exclusion limits are set as a function of this mixing. Searches can be categorised based on the size of this term: larger mixing terms lead to more prompt decays of the dark mediator, while smaller terms lead to longer lived particles. Prompt decays produce visible particles which originate at the interaction point; a scenario which the LHC experiments are optimised for. However, in the case of long-lived particles, decays can take place in different parts of the detectors, depending on the lifetime. In order
Figure 6 – A two-dimensional exclusion plot in the dark photon mass $m_{\gamma_d}$ and the kinetic mixing parameter $\epsilon$, taken from\textsuperscript{48}. The 90\% confidence-level exclusion region, for prompt $H \rightarrow 2\gamma_d + X$ production with various (colour-coded) branching fractions, is extracted using results for various combinations of subsequent dark photon decays involving electron-jets and muon-jets, using 8 TeV data at ATLAS for both the prompt and displaced analyses. Other shaded regions indicate the exclusions from various fixed-target and beam-dump experiments.

to cover the widest possible range of lifetimes, the experiments must adopt various techniques, using clues such as displaced vertices or disappearing tracks to identify non-prompt decays. The LHC detectors may contribute considerably to dark sector searches conducted by fixed-target and beam-dump experiments due to their ability to extend searches to very high masses and low couplings. ATLAS and CMS both conduct searches for dark photons in the prompt-like and long-lived regimes\textsuperscript{46,47}. Figure 6 shows the exclusion limits from a previous iteration of the ATLAS search\textsuperscript{48}. Results from other experiments are overlaid, exposing the complementary coverage achieved at the LHC.

LHCb takes advantage of its precise vertex reconstruction ($< 10$ \( \mu \)m vertex resolution in the transverse plane) and low $p_T$ trigger to probe lower masses and lifetimes, providing complementary coverage to ATLAS and CMS. Various searches at LHCb focus on di-muon final states, exploiting the excellent muon identification efficiency of the detector. One such effort\textsuperscript{49} looks for dark photons in the prompt-like (PL) regime, where $2(m_{\mu}) < m_{\gamma_d} < 70$ GeV, as well as the long-lived (LL) regime, where $214 < m_{\gamma_d} < 350$ MeV. The analysis is fully data-driven. The prompt-like search uses a special data sample which contains all di-muon decays recorded by the detector, made possible through novel trigger techniques whereby most lower-level event information is discarded. The top plot of Figure 7 shows the prompt-like mass spectrum. The prompt sample is contaminated by various resonant di-muon decays, whose mass-peaks are therefore vetoed in the search (indicated by grey bands in the spectrum), as well as various forms of mis-reconstruction: pairs of prompt hadrons misidentified as muons ($hh$), pairs of muons from heavy-flavour quark decays which are misidentified as prompt ($\mu\mu$) and combinations of such misidentified hadrons and muons ($h\mu\mu$). The prompt search produces the most stringent constraints to date for dark photons with $214 < m_{\gamma_d} < 740$ MeV and $10.6 < m_{\gamma_d} < 30$ GeV, as shown in the bottom plot of Figure 7. The long-lived search, which uses the same dataset as the prompt-like search with re-sampling of the decay topology into a long-lived one, is the first of its kind to achieve sensitivity using a displaced-vertex signature. It places world leading constraints for low mass dark photons with lifetimes $O(1)$ ps.

Other recent dark boson searches at LHCb include a search for $pp \rightarrow \phi \rightarrow \mu^+\mu^-$ in gluon-gluon fusion\textsuperscript{50} and a search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays\textsuperscript{51}. The former looks for narrow resonances in the $\Sigma$ mass region, setting limits in the previously unexplored $8.7 < m(\phi) < 11.5$ GeV region. The latter, motivated by hints of a resonance in $\Sigma^+$ decays from\textsuperscript{52}, observes the decays
Figure 7 – Results of the recent LHCb search for prompt-like dark photon decays to di-muons. The top plot shows the di-muon mass spectrum, where the contributions from prompt $\mu^+\mu^-$ and various forms of mis-reconstruction (described in the text) are shown. Grey boxes cover the regions with large SM resonances. The bottom plot shows regions of the $[m_{d}, \epsilon^2]$ parameter space excluded at 90% CL by the search compared to the best published and preliminary limits from other experiments. Both from reference 49.

to di-muons but finds no significant di-muon peak.

8 Additional Contributions to DM

BSM searches are not the only area where experiments at the LHC may contribute to the hunt for dark matter. Measurements made by the detectors could help to improve our understanding of the uncertainties which affect astrophysical measurements. A recent example is a measurement of the antiproton cross-section made by LHCb. The $\bar{p}/p$ fraction in cosmic rays is a sensitive probe of dark matter annihilation. The cosmic ray flux of antiprotons is measured with high precision by astroparticle experiments, but these measurements are subject to large uncertainties in the antiproton cross-section. Until recently, this cross-section has been extracted from $pp$ and $pC$ data, which fail to fully describe the dominant production process for antiprotons in our Galaxy, namely, the interaction of cosmic-ray protons and helium with the interstellar medium. In this new measurement, the addition of a noble-gas injection device transforms the LHCb detector into a fixed target experiment, with He as the target of choice. The device allows the 6.5 TeV protons from the LHC to collide with He in the interaction region. For the antiproton measurement, events containing primary vertices with good quality negative tracks are selected, and antiproton candidates in a range of momentum bins are discriminated from dominant backgrounds using two-dimensional fits of identification criteria for the different particle species involved. The results represent the first direct determination of the antiproton production cross-section in $p$He collisions, covering antiproton momenta between 12 and 110 GeV.

9 Conclusions & Outlook

An expansive DM search programme at the LHC, contributed to by the ATLAS, CMS and LHCb experiments, continues to put mounting pressure on the WIMP hypothesis, while also
expanding to cover other possible scenarios, such as new dark sectors. Searches for mediators in the context of simplified models, with both visible and invisible decay modes, put limits on DM mass for a series of benchmarks, and these constraints are compared to those obtained from DD and ID experiments in order to illustrate the complementary coverage of these different means of detection. These simplified searches are the most generic possible, setting optimistic limits in the most model-agnostic way. Searches targeting more complex models, such as SUSY, are also conducted, and will be developed further in the future in the interest of covering the largest possible range of theoretical models. Already, searches for dark bosons have been conducted by these three distinct experiments, with efforts in both the prompt-like and long-lived regimes, with the latter requiring special analysis techniques for which the general purpose detectors were not optimised. The results from these searches already show complementary coverage to fixed-target and beam-dump experiments, with LHCb providing world-leading constraints for dark photons.

Another unique result from LHCb, namely the new measurement of the anti-proton cross-section in \( p\text{He} \) collisions, provides valuable data for reducing uncertainties which astrophysical measurements are subject to. This exemplifies the benefit which the widening range of LHC activities can have on the DM community at large.

During the next phase of the LHC (run-III), the LHC is expected to deliver 300 fb\(^{-1}\) of data at 14 TeV, while the following High Luminosity phase of the LHC (HL-LHC) is expected to collect at least ten times that amount. Experiments will undergo various upgrades, not only to be capable of surviving the harshened running conditions, but also to improve the present detector and trigger performance. Though the LHC experiments are yet to find evidence for dark matter, this impressive increase in energy and luminosity, paired with the widening range of theoretical models and analysis techniques explored, will hopefully bring us closer to the answers we seek.

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