Searching for Dark Matter with the ATLAS Detector

Caterina Doglioni and Dan Tovey

1 Introduction

Experiments [1] at particle accelerators have revealed much about the nature of visible (ordinary) matter, starting from the first prototypes that aided the discovery of the proton and the antiproton [2] to the recent discovery of the Higgs boson [3, 4]. All of the particles observed so far are part of the Standard Model of Particle Physics, describing the fundamental components of matter and their non-gravitational interactions.

As discussed in the Introduction chapter, the most powerful accelerator ever built is the Large Hadron Collider (LHC) at CERN in Geneva [5, 6], accelerating protons and colliding them with a total energy of 13 TeV. According to Einstein's most famous equation, $E = mc^2$, the more energy (E) the more massive particles (with a mass m) one can create (13 TeV corresponds to roughly 14 thousand times the rest mass of a proton). The hope is that at the LHC we can create massive dark matter particles by colliding known particles, in the same way we create the Higgs boson in proton-proton collisions.

Particles are regularly accelerated to very high energies in the universe in "natural" particle accelerators, such as supernovae explosions, and then collide with other particles in our atmosphere. Cosmic rays, for example, are particles that are generated in outer space and make it to Earth. However, the advantage of laboratory particle accelerators such as the LHC is that there we know the initial conditions of the collisions - namely the type and energy of the particles being collided. We can

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C. Doglioni (✉)
University of Manchester, Manchester, UK
e-mail: caterina.doglioni@cern.ch

Lund University, Lund, Sweden

D. Tovey
University of Sheffield, Sheffield, UK
e-mail: dan.tovey@cern.ch

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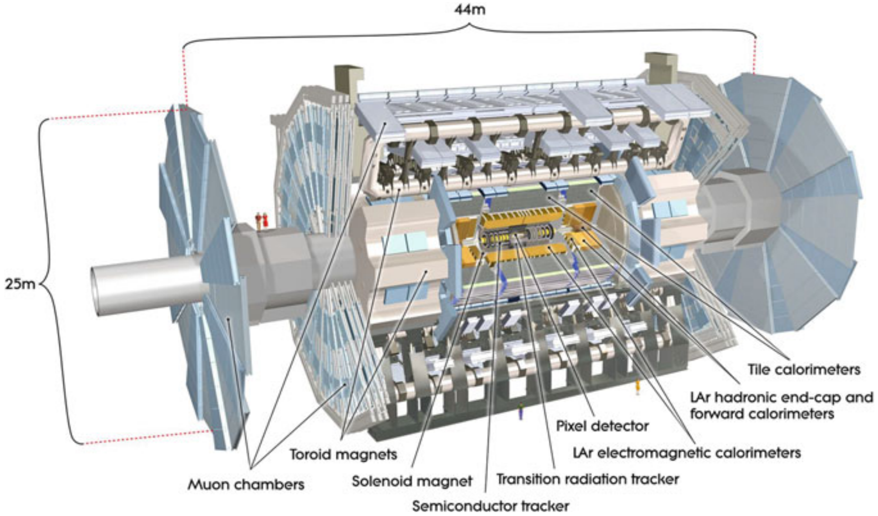

Fig. 1 Computer generated image of the whole ATLAS detector [9]. ©CERN

also create a large (and known) number of collisions and observe them in a controlled environment. These are essential features for detecting dark matter particles at collider experiments like ATLAS (Fig. 1).

> With experiments at the Large Hadron Collider like ATLAS, we hope to further understand the nature of dark matter by producing and observing it in controlled laboratory conditions.

The ATLAS experiment depicted in Fig. 2 [7, 8] is located at one of the collision points of the Large Hadron Collider, and it is one of the largest particle detectors ever built.

The layout and design of the ATLAS experiment allow the detection of the LHC collision products, in the form of particles with sizable interactions with the detector material. Scientists use ATLAS data to study a wide variety of physics processes.

2 How Dark Matter Appears in the ATLAS Detector

Since dark matter is *dark*, it will not interact significantly with instruments made of ordinary matter. For this reason, the underlying signature of dark matter production at the LHC, used by ATLAS searches, is the presence of new invisible particles in proton-proton collisions. One might reasonably ask how invisible particles can be

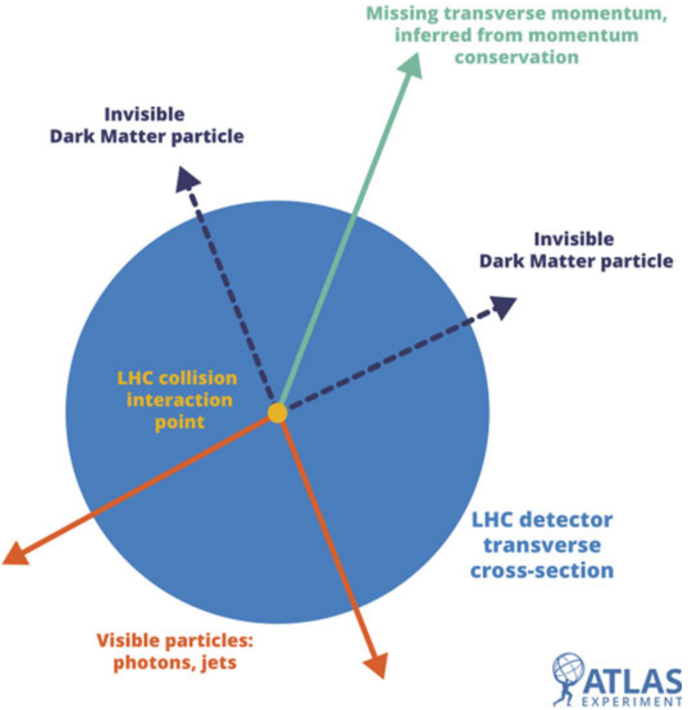

Fig. 2 Diagram showing how missing transverse momentum (ETmiss) is determined in the transverse cross-section of a LHC detector. The LHC beams are entering/exiting through the plane. (Image: C. Doglioni, L.T. Wang and E. Ward/ATLAS Collaboration, ©CERN)

observed, since they are by definition undetectable! We solve this problem with a little ingenuity.

Before each collision, the protons travel along the direction of the LHC beams, and not in directions perpendicular to the beams. This means that their momenta in these perpendicular directions – their "transverse momentum" – is zero. A fundamental principle of physics is that momentum is conserved and so, after the collision, the sum of the transverse momenta of the products of the collision should still be zero. Therefore, if we add up the transverse momenta of all the visible particles produced in the collision and find it not to be zero, then this could be because we have missed the momentum carried away by invisible particles. This happens routinely in ATLAS, in the case of physics processes involving neutrinos. We refer to this missed transverse momentum as "*ETmiss*" or *MET*.

LHC searches for dark matter look for collisions with large values of ETmiss, where the dark matter is produced in association with other visible particles from the Standard Model, such as photons, quarks or gluons (forming "jets" of particles), or electrons, muons or tau leptons. While ETmiss can be difficult to measure because it relies on accurate measurements of all the other particles in the collision, it is a powerful tool for observing otherwise invisible particles such as dark matter.

LHC searches for dark matter look for collisions with large values of ETmiss, where the dark matter is produced in association with other visible particles from the Standard Model

A further requirement for the identification of dark matter particles in collisions is that the invisible particles should not decay as they travel through the ATLAS detector. In order for an invisible particle to be a candidate of the "relic" dark matter produced in the Big Bang, it should have a lifetime of at least the age of the Universe - of the order of 1 billion years. Particles created in LHC collisions take about 40 nanoseconds to cross the ATLAS detector, so requiring that their lifetime be longer than this is not enough, on its own, to prove they constitute the dark matter. Complementary information from astroparticle experiments searching for relic dark matter is required, as described in Sect. 5. However, hints of an invisible particle detected at one of the LHC experiments would provide very good hints for more targeted searches.

It is worth noting that other particles that are connected to dark matter might also be detected at the LHC, for example new short-lived particles that can decay both into dark matter and into known matter, or new particles that are predicted to be present together with the dark matter ones. Observing those would be an important complement to an observation of dark matter particles from space, as it would allow us to better understand the full landscape of dark matter interactions.

3 What Kinds of Dark Matter Could ATLAS Detect?

Experimentally, there are very few indications of what dark matter might be. We can, however, make theoretical hypotheses on the nature of dark matter, which are useful to experimentalists, as discussed in detail in Chap. 4. The theorist and experimentalist communities often collaborate. For example, the community of theorists and experimentalists looking for dark matter at the LHC has joined forces, forming first the Dark Matter Forum and then the Dark Matter Working Group. The goal and results of those group are described in Ref. [10].

Theoretical models of dark matter can tell us more about how the interaction of dark matter with ordinary matter may take place. From that, we can predict what to expect in our detectors if that model were realised in nature.

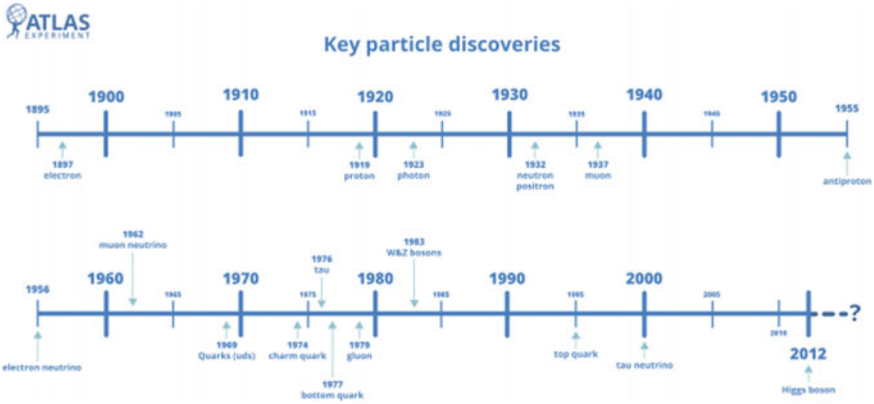

Fig. 3 A timeline showing the key discoveries of known particles (Image: E. Ward/ATLAS Collaboration, ©CERN)

Theory predictions for dark matter models is relevant for detector design, and for deciding how to record and analyse the products of the collisions. It is generally useful to know what to look for in advance, as we would not be able to collect LHC data in its entirety and must decide in real-time which collision events to record - this is done using the ATLAS trigger system. A solid theoretical framework is also necessary to put LHC searches into context, and compare them with dark matter searches from other instruments.

Searches for dark matter at the LHC are commonly guided by theoretical models that would allow us to explain the relic density of dark matter with one or a few kinds of particles. A class of models that satisfies these requirements includes a dark matter particle that only interacts weakly with ordinary particles and has a mass within the energy range that can be probed at the LHC - a Weakly Interacting Massive Particle (WIMP). Using WIMP models as our starting point for LHC searches doesn't mean that we are bound to the idea that dark matter should be described with a single particle and a single interaction. This is especially important when one considers that the content of dark matter in the Universe is five times the content of ordinary matter, and ordinary matter is described by a variety of different particles and interactions.

At the LHC, we are looking for a variety of possible theoretical models of dark matter hoping that the few most prominent components and interactions of dark matter will be detected first, just as the electron, proton and electromagnetic interaction were discovered before all other particles of the Standard Model, as shown in Fig. 3.

The simplest models one can build in terms of particle content are those where only a new kind of dark matter particle is added to the Standard Model. In these models, the interaction between visible and dark matter must proceed through existing particles, such as the Z or Higgs boson. This means that the Z or Higgs boson could decay into two dark matter particles,[1] in addition to their ordinary decay modes involving Standard Model particles.

These models are called “portal” models of dark matter, as known particles act as the portal between what we know (ordinary matter) and what we don’t know (dark matter). While models with a Z boson portal are fairly constrained by precision measurements, including those done at the LEP collider at CERN during the 1990s, now is the first time in the history of particles that we can study the properties of the Higgs boson in detail. We could discover whether one or more of those properties leads to a connection to dark matter. Searches for dark matter interacting with Standard Model particles through the Higgs portal are described in Sect. 4.1.

In addition to dark matter, one can also conceive another particle not included in the Standard Model that acts as a portal particle. These are also called “portal” or “mediator” particles, since they mediate a new interaction between ordinary matter and dark matter. In the simplest versions of these models, the mediator is an unstable heavy particle that is produced directly from the interaction of Standard Model particles, such as quarks at the LHC or electrons in a secondary interaction [11]. Therefore, the mediator must also be able to decay into those same particles that were responsible for its production, in addition to into a pair of dark matter particles (see e.g. Refs. [12–14]). If a model of this kind occurs in nature, we have a chance to directly discover this mediator particle at the LHC, as we would be able to detect its Standard Model decay products. This is only an example of a *simplified model* that is commonly used to interpret the results of many LHC searches in terms of dark matter, even though it is often deemed too simple to represent the full complexity of a dark matter theory. However, simplified models are still useful as building blocks for more complete theories with more ingredients. Examples of ATLAS searches for dark matter interacting with Standard Model particles through a new mediator particle are described in Sects. 4.2 and 4.3.

The most popular example of a more complete theory that includes a dark matter candidate is supersymmetry (SUSY). SUSY was one of the first dark matter models to be studied extensively at the LHC. An appealing feature of supersymmetry is that it also solves a stability problem of the relatively low mass of the Higgs boson and other electroweak particles of the Standard Model (around 100 GeV) compared to the Planck scale (1019 GeV), at which gravity is expected to become strong and the Standard Model must break down. Quantum field theories like the Standard Model naturally prevent such large differences in energy scale from developing, so a physical mechanism is required to generate them. SUSY models provide such a mechanism and, in many cases, predict the existence of a new stable, invisible particle - the lightest supersymmetric particle (LSP) - which has exactly the right properties to be a WIMP dark matter particle. The search for particles predicted by SUSY is a major focus of the ATLAS physics programme. If produced in LHC collisions, these particles could decay to produce a variety of Standard Model particles that can be observed in the ATLAS detector, together with two escaping LSP dark matter particles that generate

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[1] This can happen if the dark matter particle mass is less than half of that of the Z or the Higgs boson.

the characteristic ETmiss signature discussed above. Examples of ATLAS searches for supersymmetric dark matter are described in Sect. 4.4.

Many other theories, of various degrees of completeness and complexity, contain dark matter particle candidates. Some of them predict new particles similar to the Higgs boson that can decay into dark matter, while others go beyond the WIMP paradigm and include mediators with extremely feeble interactions with known particles that only decay after travelling significant distances inside (or outside!) the detector, or more complex sectors of particles mirroring the Standard Model. It is important for LHC searches to cover all this ground, while also preparing for unexpected, not-yet-theorised discoveries. No stone must be left unturned, and some example searches for dark matter particles beyond the WIMP and SUSY paradigms are described in Sect. 4.5.

4 ATLAS Experimental Techniques and Results

4.1 Searches for Dark Matter Particles Associated to the Higgs Boson

Since the addition of the Higgs boson to the Standard Model after its discovery in 2012, an interesting question to ask is whether the Higgs boson has a privileged role in propagating the interactions between ordinary and dark matter. This would make LHC experiments an ideal ground to test such interactions, as the study of Higgs properties and decays is one of the physics priorities for the next decade. In the simplest scenario, the Higgs boson could be the only particle in the Standard Model that is able to decay into dark matter, leading to a minimal extension of the Standard Model that only requires the addition to a dark matter particle. More complex scenarios involve multiple Higgs-like bosons with a variety of interactions with both dark and ordinary matter in addition to the Standard Model one (see e.g. [15, 16]).

Since the discovery of the Higgs boson, we seek whether the Higgs boson has a privileged role in propagating the interactions between ordinary and dark matter.

We have two handles to understand whether the Higgs boson decays into dark matter particles. Firstly, decays of the Higgs boson into invisible particles in the Standard Model (neutrinos) are extremely rare. Therefore, if Higgs decays to invisible particles are observed, for example via an excess of missing transverse momentum in events identified as containing a Higgs boson, they could be attributed to dark matter.[2] Secondly, Higgs decays to dark matter particles would change the rates at which the Higgs boson decays into other particles, since the total probability of the Higgs decaying into any other particle must be equal to unity. The most recent ATLAS results to date have not observed any signs of extra invisible decays of the Higgs boson in either of these two approaches, and can place strong constraints on dark matter particles interacting exclusively with the Higgs boson [17].

4.2 From Measuring Invisible Particles to MET+X Searches

ATLAS measures many processes involving invisible Standard Model particles: neutrinos. Figure 4 shows the results of the measurement of the number of Z bosons decaying into a pair of neutrinos (about one fifth of all Z boson decays).

As shown in the diagram in Fig. 5, we use a particle that interacts with the detector and is therefore visible (in this case a photon) to detect the presence of invisible particles and measure their missing transverse energy, as explained in the previous section.

A very similar technique can be used for detecting the presence of dark matter particles. If we take the process in Fig. 5, replace the neutrinos with dark matter particles, replace the Z boson with a generic mediator between ordinary matter and dark matter, then we have the diagram in Fig. 6.

What appears in the ATLAS detector (also called detector *signature*) for the two processes shown in Figs. 5 and 6, and it is shown in Fig. 8: energy deposited by the photon and nothing else, leading to MET back-to-back with the photon (Fig. 7).

A variety of techniques, including machine learning algorithms, are used to precisely measure the properties of the particles contained in the collision events (including the MET). Since we cannot distinguish the processes on a collision-by-collision basis, we have to take a different approach. We start by collecting a large number of events that have a large amount of missing transverse momentum and a highly energetic particle (or group of particles). Then, we estimate precisely the number of expected events from known Standard Model processes (the *backgrounds*), and look for an excess of additional events that could be due to dark matter processes. This kind of search is called a “MET+X” search, where MET stands for missing transverse momentum and X stands for what the dark matter recoils against.

This kind of MET+X search makes no specific assumption about the nature of the invisible particles, other than that they are produced in association with a Standard Model particle. It is therefore well-suited to cast a wide net on a variety of dark matter models, as long as the model’s signature includes invisible particles and includes dark matter-Standard Model interactions. Conversely, the very large Standard Model

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[2] One of the physics targets for the high luminosity LHC era and future colliders is still to measure the rate of the decays of the Higgs boson into neutrinos and compare it to theoretical predictions, but since those decays make up less than a thousandth of the total possible Higgs decays, we will need to wait until enough Higgs bosons are collected!

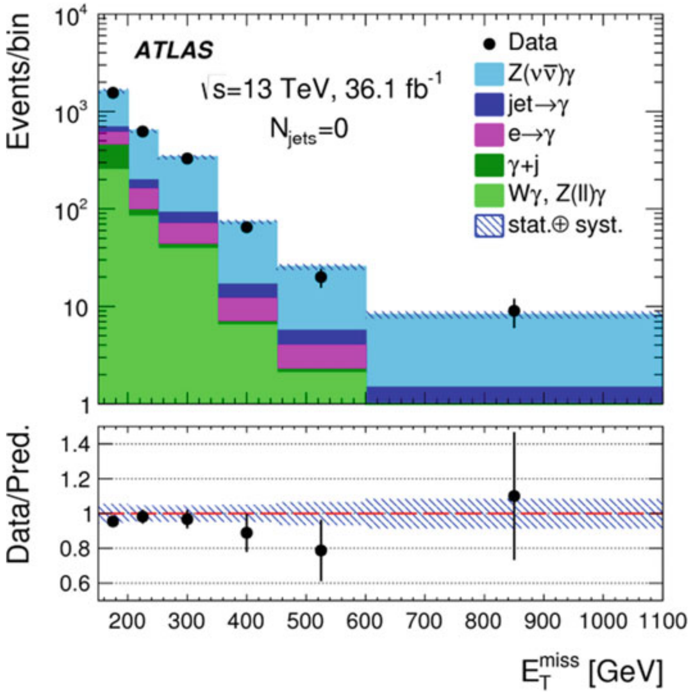

Fig. 4 Measurement of the number of events in data for each range of missing transverse momentum, compared to the sum of different physics processes that produce this signature in the detector, from simulation. Figure from [18] and ©CERN

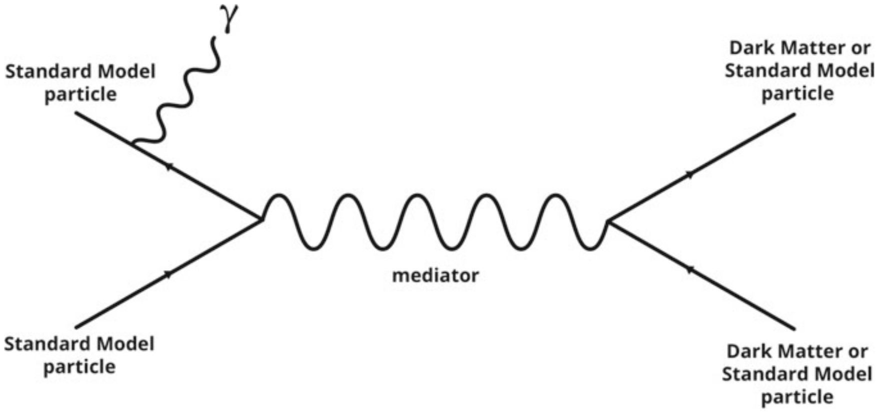

Fig. 5 Diagram of a Z boson decaying into a neutrino-antineutrino pair where the Z boson is produced in association with a photon. ©CERN

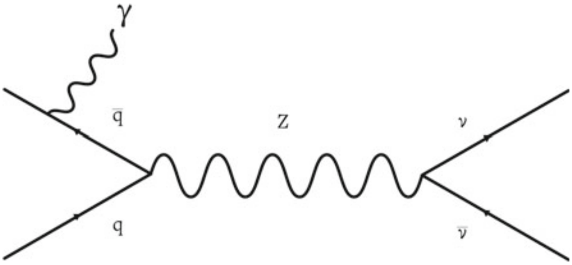

Fig. 6 Diagram of a new mediator particle decaying into a pair of dark matter particles, produced in association with a photon. ©CERN

backgrounds in MET+X searches can be reduced by giving up some of their generality, for example by requiring distinctive particles (e.g. top quarks, the Higgs boson or related particles) to be produced in association with the dark matter.

MET+X searches make no specific assumption about the nature of the invisible particles, other than that they are produced in association with a Standard Model particle. They are therefore well-suited to cast a wide net on a variety of dark matter models.

ATLAS has searched for excesses of invisible particles recoiling against photons [19], jets [20, 21], both photons and jets [22], Z and W bosons [17, 23] as well as in association with heavy flavour quarks [24–26].

So far, we have not found any excess with respect to backgrounds in any of these searches, as shown in Fig. 9 for the MET+photon search, where the data agrees with the Standard Model-only prediction. Still, the journey of MET+X searches at the LHC is far from over. Adding data and improving the experimental precision of future searches will enable us to search for even weaker dark matter interactions yielding processes that are even rarer than the processes we are sensitive to right now.

4.3 From MET+X Searches to Searches for Visible Mediator Decays

The mediator in Fig. 6 can also decay to visible particles, leading to a peak or "resonance" in the total (invariant) mass of those particles, as in Fig. 9.

Searches for new particles using resonances in the total mass of visible particles have led to numerous discoveries at colliders, including, most recently, the Higgs boson at the LHC. Given that the LHC is the highest-energy laboratory particle collider, the most obvious goal is to search for extremely massive particles that could not have been produced before.

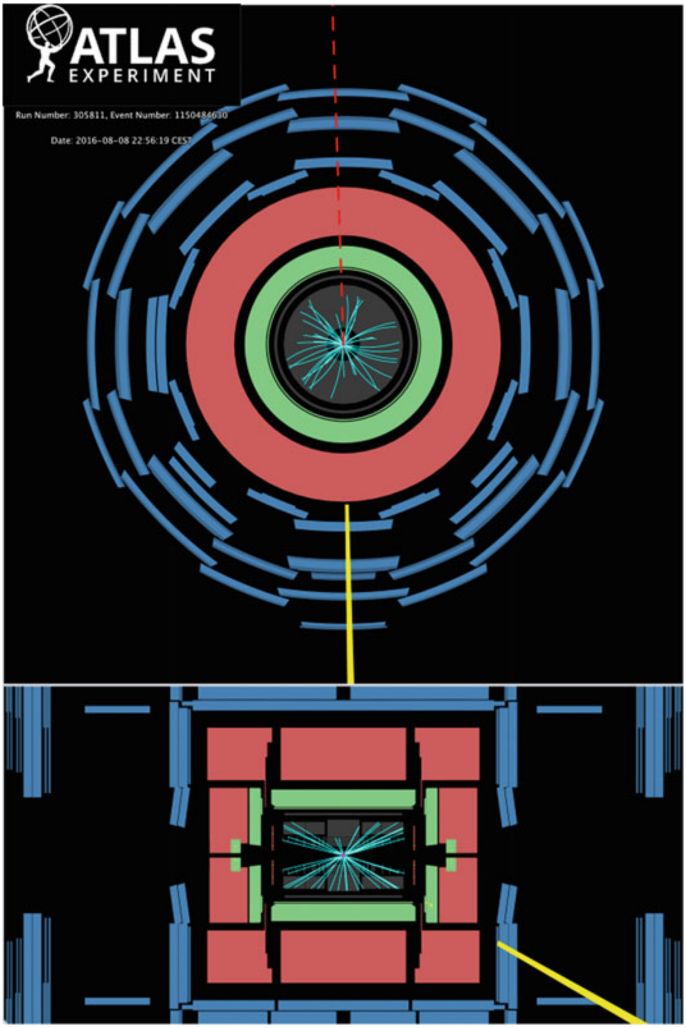

Fig. 7 A visualisation of a photon + ETMiss event recorded in 2016 (event 1150484630, run 3058110), is shown in two different sections of the ATLAS detector. A photon with transverse momentum of 265 GeV (yellow bar) is balanced by a ETmiss of 268 GeV (red dashed line in the opposite side of the detector). (Image: ATLAS Collaboration/CERN, ©CERN). Reference should be taken from https://inspirehep.net/literature/1591328

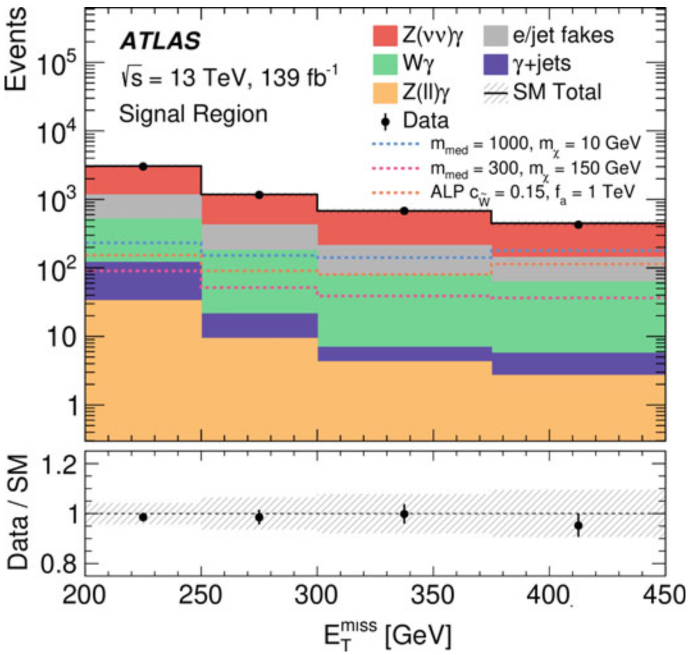

Fig. 8 Missing transverse momentum distribution in data after selecting events with an energetic photon and ETmiss, compared to the Standard Model predictions. The different background processes are shown in different colours. The expected spectra of an example WIMP dark matter scenario is illustrated with blue and red dashed lines. Figure from [19], ©CERN

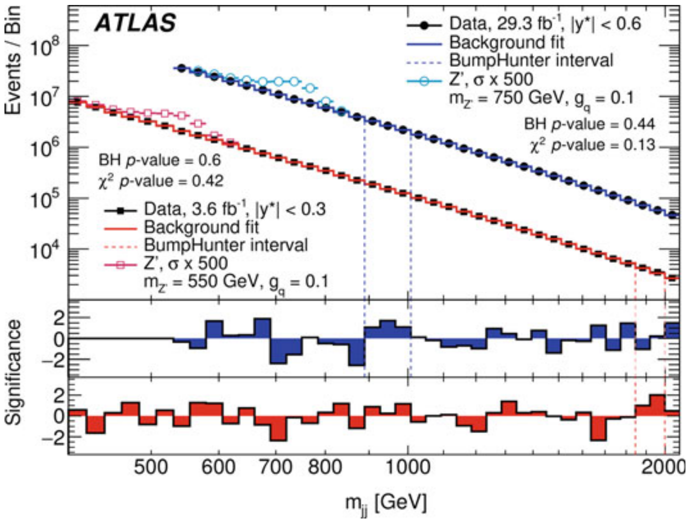

Fig. 9 Distribution of the invariant mass of two jets in ATLAS data (filled circles) with two different data analysis selections, with simulated resonance peaks for dark matter mediators overlaid in blue and red open circles lines. Figure from [27], ©CERN

Still, dark matter mediators could also appear at lower masses, escaping our eyes because of very low couplings to the protons' constituents. This is a region where it has been increasingly difficult to perform searches due to the overwhelming backgrounds that exceed the experiment's data capacity if recorded in their entirety. Since background events are indistinguishable from events coming from decays of dark matter mediators, there is a risk of discarding both. Being able to detect this kind of process has provided motivation for overcoming technical limitations. All the main LHC experiment now employ data-taking techniques that allow them to retain a smaller amount of information from the collision than in ordinary data taking, so that more events can be recorded (see Refs. [27, 28] for ATLAS). These searches have not yet yielded any new particles as one can see in Fig. 9, but improvements to the data acquisition and trigger systems may bring surprises for the next LHC run.

The state of the art of MET+X searches and searches for visible mediator decays in ATLAS as of 2018 was summarized in Ref. [29].

The results of searches for invisible and visible dark matter mediator decays bring complementary information on different parameters of dark matter models. Together, they could help to characterise the nature of a discovery.

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We must keep in mind, though, that the interpretation of those searches is in terms of the processes in Fig. 6, which stems from a very simple theoretical model. In this model, the only two new particles are the dark matter and the mediator of the interaction, and that may not describe the full complexity of the unknown matter in the universe.

This is why ATLAS searches target many other experimental signatures in addition to MET-X and resonance searches. For example, models including putative new Higgs bosons yield an assortment of detector signals that can be targeted by different searches. All experimental results targeting the same model can be compared to see whether there are regions in the model parameter space where we haven't yet looked and, in some cases, they can be combined to strengthen the discovery potential or constraints on dark matter models.

4.4 Searches for Supersymmetric Dark Matter Particles

Compared with the MET+X searches described above, detector signatures from SUSY scenarios offer the possibility to make use of some additional tricks to identify a potential dark matter signal from the Standard Model background. In many models, SUSY particles are produced in pairs due to a requirement to conserve a quantity

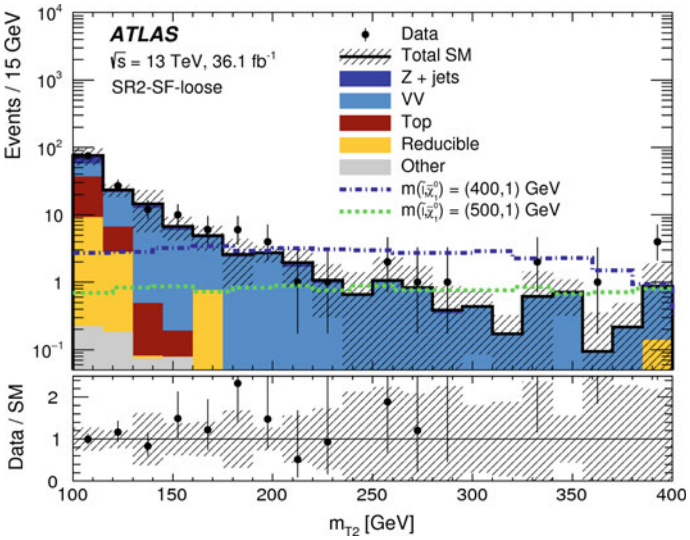

Fig. 10 Distribution in data of a quantity sensitive to the production of pairs of SUSY particles whose decays include dark matter particles, after selecting events with two electrons or muons and ETmiss, compared to the Standard Model predictions. The different background processes are shown in different colours. The expected spectra of example SUSY dark matter scenarios are illustrated with blue and green dashed lines. Figure from [31], ©CERN

called "R-parity" (sometimes also denoted "matter-parity").[3] Whenever a SUSY particle decays, the resulting decay products must include exactly one lighter SUSY particle. The decay chain ends when one of the lightest SUSY particles, which is a candidate dark matter particle, is produced. In contrast to many non-SUSY dark matter models, SUSY particle decays can generate many visible Standard Model particles of high energy. Hence events containing SUSY particles can be identified by requiring these particles as well as missing transverse momentum. A further trick is to make use of constraints on the momenta of the visible particles produced in the SUSY decays coming from the high masses of their SUSY particle parents. In particular, when two visible particles are produced from two identical decay chains in a SUSY event, we can measure properties of the event which can take on much larger values than those expected in Standard Model background events. An example result of a SUSY dark matter search after all analysis selections is shown in Fig. 10 and described in [30, 31].

With the help of these tools, SUSY searches are able to set tight requirements for events with a given set of characteristics, targeting specific models. This makes them less general than MET+X searches, but also less impacted by large numbers of background events.

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[3] R-parity ensures that in SUSY models protons, and hence all of the atoms in the universe, are unable to decay to other particles quickly by exchanging SUSY particles. In models without R-parity conservation, this can also be prevented. However, introducing R-Parity is the simplest possibility.

ATLAS has not yet found evidence of SUSY LSPs, and has strongly constrained many of the models that would simultaneously solve the dark matter puzzle and provide an explanation for the low mass of the Higgs boson. Nevertheless, many SUSY variants remain interesting and the search isn't over, as described in Ref. [32]; other recent results are mentioned in Ref. [33].

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4.5 Searches for Non-WIMP Dark Matter Particles

Many other searches for particles from more complex dark matter theories are also performed in ATLAS even though we don't cover them in detail in this chapter. Some of the characteristics of these particles make them behave very differently compared with the particles the LHC was built to observe [34, 35]. Therefore, searching for signs of these more complex theories is generally more challenging and requires dedicated techniques to identify and reconstruct candidate particles that would hint at the presence of dark matter. These searches are now at the forefront of the ATLAS and LHC quest for dark matter, and have gathered at least as much interest as searches for WIMPs and their associated particles.

> Searching for non-WIMP dark matter is well-motivated but generally more challenging than MET+X searches, as it requires dedicated techniques to identify and reconstruct candidate particles that would hint at the presence of dark matter.

One example search out of many, highlighted because of its connection with searches in the LHCb experiment (discussed in the relevant chapter of this book), is looking for a portal particle akin to those mentioned in Sect. 4.2, called dark boson or dark photon. This dark photon can be likened to a massive equivalent of the Standard Model photon (with which it interacts). It arises from a new dark force that mirrors the electromagnetic force we know, but this new dark force is much weaker. Many target models sought by ATLAS also contain other particles in addition to the dark photon, so care is needed when comparing results with other searches looking for minimal models containing dark photons only (as in the case of some of the LHCb searches mentioned in this book).

In some theoretical models, dark photons are radiated from new dark fermions and produced in association with other new particles that under certain circumstances could serve as dark matter candidates, or can arise from the decays of dark Higgs bosons [36]. ATLAS looks for the decay products of the dark photons predicted by these models, for example Standard Model leptons [37]. Since the dark photons have low masses (order of 1 GeV) and are produced from the decays of massive particles, their decay products are Lorentz-boosted and are collimated in the same detector area (in the case of decays into leptons, these are called lepton-jets). This is a useful feature for enhancing signal over background, since the other Standard Model processes that produce pairs of leptons very close to each other are relatively rare and can be suppressed further.

Searches involving even weaker interactions between the dark photon and the regular photon, and in general with very weakly coupled particles, lead to interesting features in terms of detector signatures. For example, the dark photon decay products can be displaced with respect to the collision vertex due to the long lifetime of the dark photon. This feature can be exploited in a targeted search for displaced lepton-jets [38].

It's also important to note that general-purpose experiments are only one of the many ways to search for dark photons and for other long-lived and feebly interacting particles belonging to dark sectors at colliders - for more, see e.g. Ref. [39] and the BASE, FASER, CAST and NA64 chapters. Often there is a trade-off between being able to search for the largest possible number of interactions and detector signatures and being able to target specific models with unusual detector signatures with the best possible sensitivity. This means that both approaches, both general-purpose and specialised detectors, are needed for a broad coverage of dark matter hypotheses at colliders.

5 Connecting ATLAS Searches to Astrophysical Searches in WIMP Scenarios

Searches for dark matter at the LHC are typically searches for the production, rather than the interaction or annihilation, of potential dark matter particles. As such, data from ATLAS would not provide proof that a new particle constitutes the dark matter - the sensitivity to dark matter lifetimes is just too short (see above). Nevertheless, ATLAS data could establish consistency with the predictions of dark matter models, and within those models ATLAS can provide complementary information to a broad range of astroparticle searches for the interaction of relic WIMP dark matter particles being carried out around the world.

This complementarity can be illustrated taking as example the simple dark matter-mediator model illustrated in Fig. 6.

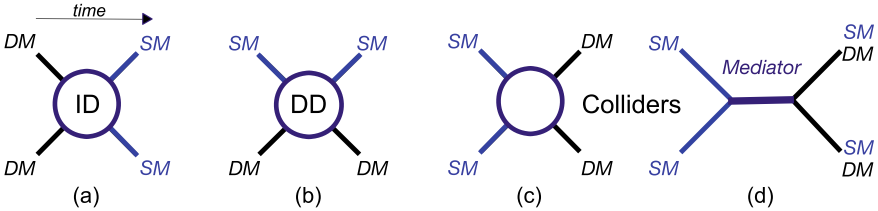

Fig. 11 Schematic illustration of Dark Matter (DM) interactions and their corresponding experimental detection techniques, with time flowing from left to right. Figure **a** shows DM annihilation to Standard Model (SM) particles, as sought by Indirect Detection (ID) experiments. Figure **b** shows DM -> SM particle scattering, targeted by Direct Detection (DD) experiments. Figure **c** shows the production of DM particles from the annihilation of SM particles at colliders. Figure **d** shows again the pair production of DM at colliders as in **c**, but in this case the interaction occurs through a mediator particle between DM and SM particles. *Source* and ©: Wikimedia commons, C. Doglioni and A. Boveia

ATLAS can provide complementary information to a broad range of astroparticle searches for the interaction of relic WIMP dark matter particles being carried out around the world.

Within this model, in order for dark matter particles to be produced in pairs at the LHC, two strongly interacting quarks or gluons from the colliding protons must interact to produce the two dark matter particles (Fig. 11b). These same interactions could enable relic dark matter particles trapped in the Milky Way galaxy to scatter off atomic nuclei on Earth, generating the nuclear recoil signature exploited by “direct” astroparticle searches for dark matter such as XENON in Europe, LUX in North America, PANDA-X in China and IceCube at the South Pole (see the chapter about underground searches in this book). Constraints from ATLAS searches can therefore be translated, albeit with assumptions on the mediator-proton and mediator-dark matter interaction, into constraints on the possible signals in those experiments. Figure 12 shows that recent ATLAS searches and astroparticle searches for dark matter have a complementary reach when plotted in terms of interactions with nucleons (y axis) and dark matter mass (x axis), in the case of the simple dark matter-mediator model of Fig. 6.

Furthermore, the same interactions also enable relic dark matter particles produced in the early Universe to annihilate and create Standard Model particles (Fig. 11a). This leads to the signatures for dark matter sought by “indirect” dark matter search experiments - typically high-energy photons (observed by telescopes such as HESS, MAGIC and VERITAS), neutrinos (observed by neutrino telescopes such as IceCube) or anti-particles (detected by space experiments such as AMS on the International Space Station, described in this book). Results from collider searches can therefore also be compared with results from those experiments.

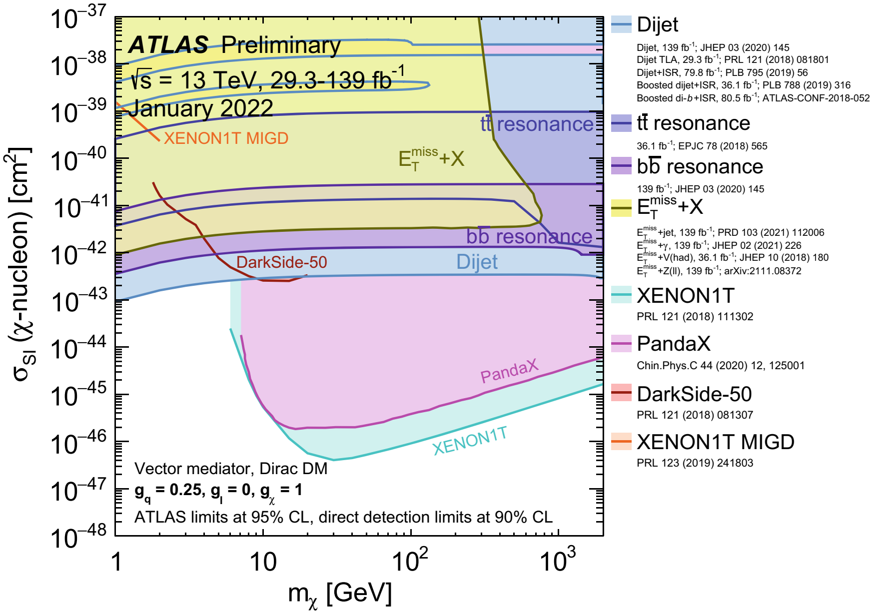

Fig. 12 A comparison of the inferred limits from ATLAS data, including those from both MET+X and mediator resonance searches, to the constraints from direct detection experiments on the WIMP-proton scattering cross section in the context of a model with a new vector particle mediating the standard model - dark matter interaction, fixing the given mediator-quark (g_q) and mediator-dark matter (g_{DM}) coupling strengths to the value in the plot. Figure from [40], ©CERN

It is important to note that the plots as in Fig. 12 only provide a single, limited snapshot of the complementarity between collider experiments and direct detection experiments. This is because in the results from collider searches the interaction strengths between mediator, dark matter and Standard Model particles (noted as $g_D M$, g_q and g_l in Fig. 12), as well as the kind of dark matter and mediator particles, are fixed. We don't know whether those exact couplings and particles are realised in nature. For example, if the interaction strength between quarks and mediator was much weaker than the value chosen for displaying results, the LHC constraints on this kind of model would also become weaker. As pointed out in the last section of this chapter, work is ongoing to display cases of weaker-coupled mediators as well, also to be able to compare collider results with other experiment at accelerators - for example, see the NA64 and FASER chapters of this book.

Moreover, these plots do not take into account other astrophysical or theoretical uncertainties affecting any kind of experiments.

5.1 Considerations on Dark Matter Relic Density for the Comparison of Astrophysics Searches and Collider Searches

When interpreting and combining ATLAS results and those from astroparticle dark matter searches, we can also consider whether the dark matter model being tested is consistent with the observed density of relic dark matter particles (note that this is not done for the ATLAS results in Fig. 13, while it is an assumption that enters the WIMP-proton scattering cross section). This relic density has been measured with a precision better than 1% through observations of the cosmic microwave background by satellites such as Planck [41]. When considering a particular dark matter model, this can help setting an upper limit on the amount of dark matter the model should produce. This is because, in principle, the dark matter could consist of multiple types of particles, with any one type only contributing a fraction of the measured amount. However, other interaction mechanisms that are not considered in the particular model but are still compatible with it could also deplete the dark matter abundance, motivating searches that are only loosely tied to the relic density target. The relic dark matter density constraint is considered particularly important for more complete (e.g. SUSY) dark matter models, given that they are consistent models that can

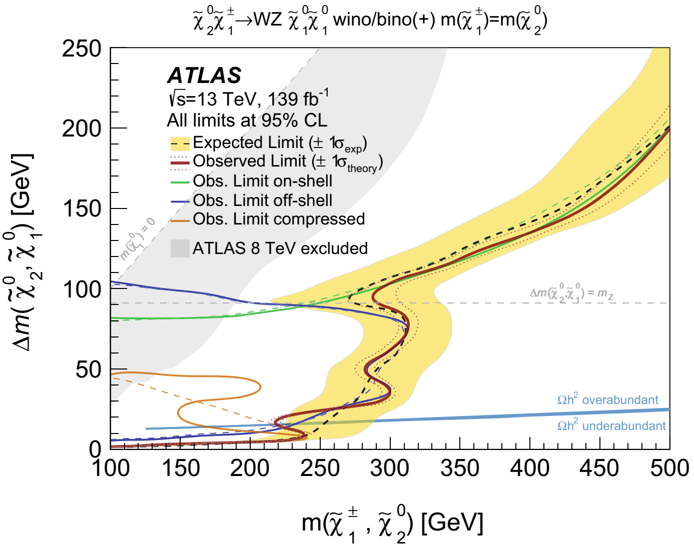

Fig. 13 Exclusion limits (shown as continuous and dashed lines) in terms of SUSY particle masses and mass differences between the two particles for a specific SUSY model. Certain light particles predicted by SUSY are able to give us the amount of dark matter abundance equal to the observed relic density, given the set of SUSY parameter models described in the paper. The area above (below) the blue line represents a dark-matter relic density larger (smaller) than the observed one. Figure from [42], ©CERN

provide answers for multiple questions in the Standard Model of particle physics. These models can often predict more dark matter than the Planck satellite observed. Special characteristics of the model, such as closely-spaced SUSY particle masses or increased dark matter interactions, can reduce this density to values consistent with observations, and searches for models with these characteristics are a high priority for ATLAS. An example of a plot displaying the relic density and pointing the way to parameter space where the model sought would produce the observed abundance is shown in Fig. 13.

6 Outlook: Where Do We Go From Here?

- ATLAS is searching for dark matter at the LHC in synergy with other experimental collaborations, such as CMS and LHCb. LHC experiments haven't yet discovered dark matter candidates but there is a large number of proton-proton collisions ahead to make the most of. The upcoming LHC data-taking period (2022–2024, known as Run 3) is expected to more than double the current dataset, and the high-luminosity period beginning 2027 will deliver at least another factor of 10 more data. The experiments will be able to probe dark matter processes that are rarer and more challenging to reconstruct than the ones studied today. In view of the upcoming data-taking, experiments are also making use of more advanced data collection and data analysis techniques, such as machine learning.[4]
- Direct and indirect searches for signals of the existing dark matter in our galactic neighbourhood are important complementary strategies to LHC searches, since astrophysical experiments are able to detect relic dark matter and they are necessary to confirm that a new invisible particle discovered at the LHC could make up dark matter. We will continue the dialogue with these experiments, exchanging scientific results and perspectives, share theoretical models, and extend the discussion to the broader astrophysics community. A number of cross-experiment and cross-field initiatives have been created for this purpose. For example, the Initiative for Dark Matter in Europe and Beyond (iDMEu) is a joint initiative supported by the European communities for accelerator, astroparticle and nuclear physics (JENAA) that works towards this purpose (see http://www.idmeu.org).
- Many other beyond-collider experiments can probe dark matter models to which the LHC experiments are not sensitive, for example models where the interactions between dark matter and ordinary matter are too feeble for dark matter to be produced in collisions of known particles. These experiments are being discussed in the Physics Beyond Colliders effort at CERN (see https://pbc.web.cern.ch and [39]).

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[4] For more information on ongoing collaborative efforts on Machine Learning in Dark Matter, see the DarkMachines research collective webpage: http://darkmachines.org/. For general perspectives on data acquisition and collection see the HEP Software Foundation webpage: https://hepsoftwarefoundation.org/.

- As one of the main outstanding questions in fundamental physics, the identification of the nature of dark matter is a key scientific driver for the future of particle physics. For this reason dark matter searches are a main focus of the discussions, including both experimentalists and theorists, which have taken place in recent initiatives to draw up roadmaps for the future of the field (see [43] and https://snowmass21.org). While the nature of dark matter is currently still unknown, it is clear that the quest to better understand it will be a highlight of humanity's study of the fundamental constituents of the universe for many years to come.

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