Dark Matter Searches at Colliders

Antonio Boveia,[1] Caterina Doglioni, [2]

[1]The Ohio State University + address
[2]Lund University + address

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Contents

1. INTRODUCTION

Define Standard Model (SM), Dark Matter (DM). There is also an "acronym" section we could use. Need to decide whether Dark Matter or dark matter.

Most recent reviews of DD and ID (in absence of anything better?) (1) (2) I prefer these ones also because they have arXivs but they are older (3), (4). There is also a VERY old AR: (5)

2. REACTIONS FOR INVISIBLE PARTICLE SEARCHES AT THE LHC

In this chapter, we will link the observations on DM to its particle properties. We then enumerate the possible reactions of DM at the LHC within certain grounding assumptions, building from simple to more complex models in terms of particle content.

2.1. Observations on DM as a guide for its particle properties

The observations mentioned in Section 1 require the dark matter particle to be stable on a cosmological timescale. This has important consequences for the prediction and observation of dark matter reactions at colliders.

Firstly, a simple theoretical way to stabilize DM is the introduction of a global Z_2 symmetry, as in Ref. (6). A realization of this symmetry can be found in R-parity in the MSSM. Under this symmetry, the parity of the DM particle is odd, while the parity of SM particles is even. Z_2-parity is multiplicative and conserved: this implies that an odd-parity DM particle (charge -1) cannot decay into any lighter even-parity SM particles (charge +1) and it is therefore stable. Additionally, DM particles will be produced in pairs from the decay of other particles that are charged under the same gauge group as the SM.

A simplified diagram of an s-channel process at colliders satisfying Z_2 symmetry is shown in panel (b) of Fig. 1. If the particle mediating the SM-DM interaction is a SM particle, no additional particles beyond the DM need to be invoked, leading to the simplest DM production mode at the LHC. The only theoretically viable SM portal particles within the grounding assumptions of this revew are the Z and the Higgs bosons, described in Section 2.3.

Transverse momentum is denoted as p_{T} in this review, and the magnitude of the missing transverse momentum is termed $\not{E}_T$.

Secondly, dark matter particles are invisible to detectors. However, the rest of the event is not: one can observe DM particles produced in the event and escaping the detector due to their missing momentum in the transverse plane, if they recoil against one or more visible SM particles.

Collider experiments have a nearly unlimited choice of theoretically motivated DM targets to search for. Theoretical arguments alone are not sufficient for a DM model to be tested at the LHC: couplings to SM particles need to feature in the model and be sufficiently large to produce new particles and observe their signatures in the detectors.

Models of particle dark matter include SM couplings to satisfy cosmological observations in the freeze-out case. These couplings need to be weak enough that there is no visible signal of DM particles, as there is no evidence for DM interacting strongly with baryonic matter, nor for its emission or absorption of light. A typical DM-SM coupling satisfying relic density is of the order of XXX.

The only SM particle that satisfies the requirement of being sufficiently weakly interacting is the neutrino. However, neutrinos cannot make up the totality of DM as they are relativistic particles and cannot explain the galaxy structures that formed in the universe (7).

Unlike previous accelerators that either yielded large datasets (e.g. B-factories) or high center-of-mass energy (e.g. Tevatron), the LHC gives unprecedented access to both rare processes and high scale processes at the same time, planning to collect 3/ab by 2035 reaching the design center-of-mass energy of 14 TeV. For this reason, it is worth speculating whether the portal particles could be observed at the LHC for the first time. Models that include one or more very massive new particles beyond the SM in addition to the DM particle are also an LHC search target, and are described in Section 2.4.

Portal models and models of simple BSM mediation are only motivated by the observation of DM. They keep the SM and the DM sectors separate, and make no claim to being a solution of other shortfalls of the SM. However, the coincidence that hierarchy problem, gauge coupling unification and DM particle nature could be solved with a single theory with observable consequences at the electroweak scale, has been one of the driving reasons to develop and consider SuperSymmetry (SUSY) as one of the main search targets for LHC searches. These models are discussed in Section 2.5.

Finally, let us return on the concept of observability of the search target mentioned above. Even general purpose particle detectors may miss certain classes of phenomena, as the initial design choices privileged searches for the Higgs boson and for particles that generally decay promptly, as predicted by models discussed so far. However, there is tension when confronting data with portal models, BSM mediation models and supersymmetric models that are compatible with the standard freeze-out scenarios. This encourages us to look for other classes of models, especially those including particles with long lifetimes, as a way to shine the search lamppost beyond the classic WIMP scenario. Reaction including those particles and their connections to DM are sketched in Section 2.6

2.2. Caveats and grounding assumptions

The observation of a signal of visible or invisible particles at an LHC experiment that could be identified as being generated by one of the reactions described in this chapter cannot lead to claim that DM has been discovered. This is because DM is stable on a cosmological scale, while LHC experiments are limited to the observation of particles with a lifetime that is longer than the time needed to escape the detector (i.e. DM candidate particles could still decay into other particles outside the detector and leave a signal of missing transverse momentum). This is not a reason to discount searches for DM at the LHC, as such a signal would still be a groundbreaking discovery, regardless of its interpretation. This statement highlights the importance of the comparison of LHC results, where DM would be produced in the lab, with the results of complementary experiments that look for signals of DM coming from space. This comparison can only take place if the same theoretical model is used to interpret both results. This motivates the enumeration of possible models in this chapter.

To define the scope of the reactions for invisible particles at colliders considered in this review, we make a number of grounding assumptions:

1. We describe models where the DM particle interacts with SM particles, either directly or indirectly;
2. We restrict our list to models that include a Z_2 symmetry to stabilize DM;
3. We privilege models that respect Minimal Flavour Violation (MFV), which imposes that the flavor structure of couplings between DM and ordinary particles follows that of the SM.
4. We primarily consider models where DM is a Dirac fermion, relying on existing theory material developed for early Run-2 searches. Other cases yield similar phenomenology for LHC searches, with some exceptions that we describe in this chapter.
5. We privilege models that have a connection with thermal relic from freeze-out. We remark however that there are other models from other cosmological histories (e.g. freeze-in) that can be considered and would lead to interesting LHC signatures (8).

In the following sections will describe models from the perspective of experimental collider physicists, focusing on a selection of models that provide distinct and testable LHC signatures, without the ambition of theoretical completeness. For other perspectives on the models used for early LHC searches for DM, see (9, 10, 11, 12).

2.3. Higgs and Z boson portals

Even if we cannot observe DM itself at colliders, we can look for visible particles that are associated to Dark Matter. The LHC alone cannot solve the strong CP problem through observation of the axion, but it can still observe e.g. scalar resonances that appear in the theory.

This raises the question of whether any of the SM particles could be associated to DM, for example in a similar fashion as the W and Z bosons mediate the weak interaction and produce neutrino pairs in the reaction. Models where the SM particle sector is coupled to the dark sector through an existing or a new particle are called *portal models*. This kind of model leads to the most economical particle content for reactions at the LHC, as one only needs to add a neutral DM particle to the SM content if one of the SM particles is the portal particle. SM fermions cannot be portal particles under the assumption of a Z_2 symmetry, as they would allow the decay of DM. Photons, W bosons and gluons can't be portal particles either, as DM does not absorb nor emit light, nor it does it have electromagnetic or strong charge. The only viable SM portal particles remaining are the Z and the Higgs bosons.

There are strong theoretical and experimental arguments to explore SM portal models at the LHC. Processes involving mediators at the electroweak scale are among the first to be investigated, in DM theories that predict new weakly interacting particles (13). This kind of portals are also present in a number of other theories (14). However, it is only the recent generations of collider and direct detection experiments that have started being able to probe the range of small couplings and relatively large scales required to observe this kind of models.

2.3.1. Z portal models.

The **Z portal** model, where the DM particle has vector and axial vector interactions with a Z boson, is a minimal extension of the SM as it only requires a single new particle to be added to the SM particle content. In $SU(2)_L \times U(1)$ extensions of the SM, the axial and vector couplings of the Z boson to DM are generally required to be of the same order. If no other couplings are present, this model is not $SU(2) \times U(1)$ invariant, unless couplings to the DM to the Higgs boson are added as well (15). In the minimal case where the couplings do not depend on the Lorentz structure of the interaction, large couplings are required for this model to satisfy the relic density. In the case of equal vector and axial couplings, this model is heavily constrained by LEP and direct detection experiments (see e.g. Refs. (14, 16)). This model can still be viable wherever no relations between the vector and axial couplings are present. A review of Z portal models with different couplings can be found in Ref. (14).

2.3.2. Higgs portal models.

The discovery of a SM-like Higgs boson (17, 18) has sparked theoretical and experimental interest in **Higgs portal** models, where DM particles can interact with SM particles only through the Higgs boson (see e.g. Refs. (19, 20, 21)). In Higgs portal models, DM couples to the SM operator connecting two Higgs fields and could dominate the interactions between SM and DM sectors. This interaction is renormalizable and leads to a UV-complete, minimal theory in the case of scalar and vector DM, while a self-consistent theory requires the presence of further particles mediating the interaction in the case of fermion DM (22, 16, 23).

The properties of the Higgs boson are modified in the presence of decays to invisible particles. Precision measurements of the Higgs width and couplings offer a probe for these models complementary to direct searches for the invisible particles, as described in the next chapter.

2.4. Effective Field Theories and Simplified models of BSM mediators

Having completed the survey of the possible minimal DM models that only add a single new DM particle to the SM, we move to the next class of models, where the SM particle spectrum is complemented by the DM particle as well as by other BSM particles. In this case, the LHC search targets expand from the excess of missing transverse momentum to a wide variety of observable signatures from e.g. the decays of the new BSM particles.

The large body of theoretical literature on DM models featuring additional BSM particles drives the design of experimental searches in two complementary directions. In the case of self-consistent models of DM such as fully-developed SUSY models, all experimental handles are exploited for targeted searches that are sensitive to specific model features. These models will be described in the next section. However, the desire to make no assumptions on the DM phenomenology and to cast a net as wide as possible remains. The adoption of much simpler model as first LHC Run-2 DM benchmarks led to the design of more generic searches targeting the broad features of those models. The success of such simple, at times incomplete and not always theoretically sound models has been due to their ability to predict the key features and observables related to DM production at the LHC with only a limited number of new particles and theory parameters, factoring out the more complex processes that do not affect LHC phenomenology as they e.g. occur at higher energy scales. As proven by the history of SM discoveries, this simple approach can be used to discover the most prominent DM-SM interaction processes in the wake of the LHC start-up.

These simple models have generally been organized according to their interactions and observable consequences (24, 10), used as building blocks for more complex theories in models of DM and elsewhere, see e.g (25, 26, 27, 28, 29), and employed for building a prioritized set of LHC search scenarios that is only loosely connected to specific theories of DM. Even in the case of simple models, this review lays grounding assumptions on what is covered, similarly to what has been done for the first LHC searches. In addition to the grounding assumptions discussed in Section 2.2, we restrict to models where the leading process is tree-level, leaving cases where the dominant contributions are of higher order for later study (see e.g. Ref. (30)).

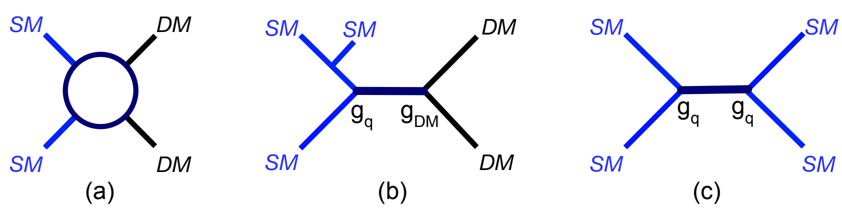


Figure 1

Sketches of (a) the basic Standard Model (SM) - Dark Matter (DM) interaction at colliders in an effective field theory (EFT), (b) its extension as a basic simplified model where a new mediator particle is exchanged in the s-channel (including an additional energetic object radiated from one of the initial state quarks) and (c) the same simplified model where the mediator decays back into SM quarks. The coupling constant characterizing the mediator-quark interaction strenght is denoted as g_{q}, while the mediator-DM coupling constant is denoted as g_{χ}. From (31).

2.4.1. Effective Field Theories.

Effective field theories (EFTs) (24, 32) are the simplest possible models of DM production at the LHC beyond those described in Section 2.3. A four-point interaction is used to describe the DM production at the LHC in a low-energy approximation of a full theory, similarly to what done when describing the weak interaction through a Fermi process before the introduction of the W and Z bosons (33). EFT operators were first widely employed to describe DM reactions at colliders at the Tevatron (34, 35). They were found advantageous because of their model-independence, and since each of the operators encapsulates the phenomenological characteristics of most known types of SM-DM interaction. A sketch of an EFT process at the LHC is shown in panel (a) of Fig. 1.

The only parameter characterizing an EFT operator, in addition to the type of DM particle and to the type of SM-DM interaction, is the scale of the contact interaction Λ. In the case of a $s-$channel completion of the EFT, this interaction scale is proportional to the mass of the mediator particle. If the scale of the DM interaction is sufficiently low with respect to the mediator mass, the phenomenology is the same for the EFT as for its $s-$channel completion. This may not always be the case at the LHC, given the high center-of-mass energy collisions: a better description of both theory and phenomenology can be reached when explicitly including the new particles in the model considered (36, 37, 38). Certain EFT operators also may suffer from gauge invariance issues at the electroweak scale (39). However, if no completion is available, EFTs are still a good benchmark to motivate the exploration distinct kinematic regions and signatures at the LHC.

Run-1 LHC searches privileged EFT operators, while Run-2 searches are limited to using EFT models with a SM singlet and a boson pair, coupled to DM through a contact interaction (see e.g. (44, 38)). These models provide a direct SM-DM interaction and motivates searches in final states with a vector boson accompanied by $\not\!\!E_T$.

If a completion of the EFT is not available, procedures describing how to truncate the events where the EFT description is not valid are available (40, 41, 42, 43). A recommendation on how to present EFT results from LHC searches can be found in (10).

2.4.2. Simplified models. Simplified models of BSM mediation are a natural step beyond effective operators and still map well to the different types of interactions.

Simplified models resolve the issue of whether a model-independent EFT description is valid at the LHC, even though they are not complete models themselves (e.g. not all the models used are gauge invariant (15)). Simplified models can be used for comparisons with non-collider DM searches within a clearly specified theory framework. Their use as benchmark models for Run-2 searches also highlights the strength of the LHC in searching for the visible decays of the mediator particle alongside its decays in DM particles, as detailed in the next chapter.

For a comprehensive review of WIMP simplified models of DM at the LHC, we refer to (11), while (10) presents a prioritized list of simplified models that have been used in early LHC Run-2 searches. The prioritized, compact set of benchmark simplified models in (10), as well as their parameters, have been discussed and agreed upon during a joint experimental and theory effort called the Dark Matter Forum (DMF), now Dark Matter Working Group within the LHC Physics Centre at CERN (LPCC) (45).

The DMF was built starting from the discussion of various communities in Refs. (46, 47, 48). All models covered in (10) are available on the DMF git repository. Add reference.

In the simplified models chosen as benchmarks for the first LHC Run-2 searches, only one extra particle is added to the the DM and SM particle spectra. In general, this particle mediates the DM-SM interactions. If neutral, the mediator particle is singly-produced at the LHC, and decays in pairs of DM particles due to the Z_2 symmetry as well as in pairs of SM particles. If the mediator is colored, it can lead to a $t-$channel exchange between an incoming LHC parton and the DM particle. The phenomenology of colored mediators of DM is akin to that of SUSY models with a squark exchange (49, 50, 51) with some differences that we will review later in this section.

Early LHC searches have initially privileged $s-$channel resonances as benchmark models, as a generalization of the simplest portal models described in the previous section. Resonances decaying in two bodies are a simple, attractive benchmark to be directly produced at particle collider that has just increased its center-of-mass energy. These resonances can be classified according to their spin: spin-1 vector or axial vector mediators (also called Z'), scalar mediators (termed ϕ in the following) and spin-2 vector mediators. This review does not cover in detail spin-2 mediators as they have not yet been adopted as benchmark models by LHC searches, even though they produce diboson signatures that are not present in other models. More information on spin-2 mediators can be found in e.g. Refs. (52, 53).

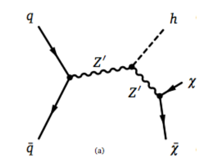
Massive spin-1 bosons with axial or axial vector couplings to SM and DM particles (32) are common in many theories, beyond those of DM mediation. They can be considered as heavy copies of the SM Z boson that arise from breaking of larger gauge groups, and as such they can be contained in larger models. A relevant characteristic of this model for LHC phenomenology is that if the Z' couples to quarks (as it needs to, in order to be produced at the LHC), then it must have visible decays back into quarks. This opens a new avenue for searches of this new particle in dijet signatures with sensitivity in early LHC data, complementing searches for excesses of missing transverse momentum.

The simplest incarnation of kind of model, where the Z' only couples equally to each kind of quarks and to DM, is fully defined given the nature of the Z' couplings (vector, axial vector or mixed), their magnitude (g_{q} and g_{χ}), the mass of the DM particle m_{χ} and the mediator mass M_{med}. The nature of the Z' couplings (vector, axial vector or mixed) does not change the LHC phenomenology, but changes the comparison of LHC results to DD and ID searches. Axial vector are the most widely used LHC benchmarks as DD rates are suppressed. [CD: specify more?].

Vector and axial vector mediator models can include couplings of the Z' to the Higgs boson, so that the Z' boson can acquire mass through a new baryonic Higgs h_B (38). This collapses to the simpler vector model in the limit of very heavy Z' mass. When the interaction between the Z' and the SM Higgs is relevant, it can be parameterized using the Z'-SM Higgs coupling $g_{hZ'Z'}$ and the mixing angle between the SM Higgs and the baryonic Higgs, $sin(\theta_B$. This model can also lead to mono-Z signals, if the Z' is allowed to interact with the Z and the photon through kinetic mixing, but this interaction has so far been neglected in LHC Run-2 searches. A Z' can also be embedded in a Type-II Two-Higgs Doublet Model (2HDM), where it does not decay directly into DM but instead decays into a new pseudoscalar A^0 and a SM Higgs boson with a coupling $g_{Z'}$ (38, 54). Here the model parameter space is more complex, even when the one of the Higgs from the doublets is the SM Higgs (alignment limit). This model includes a mixing between the Z' and the SM Z boson that is proportional to the ratio between the vacuum expectation values of the new Higgs doublets ($tan\beta$).

In certain region of this parameter space, especially at low mediator masses, the leptophobic Z' model can satisfy the relic density constraints (55). However, if taken in isolation, these models are non-renormalizable, and the axial vector model violates perturbative unitarity in certain regions of the off-shell parameter space, if $m_{\chi}^2 g_{\chi}^2/(\pi M_{\mathrm{med}}^2) < 1/2$ (55, 15, 56).

If the mediator is a real scalar or a pseudoscalar singlet, it can have tree-level interactions with DM. **Color-neutral scalar and pseudoscalar bosons** mediating SM-DM interactions (see e.g. Refs. (57)) take advantage of the theoretical and experimental body of knowledge that led to the recent discovery of another scalar boson, the Higgs boson. Minimal Flavor Violation dictates that the coupling of these new bosons to fermions should be proportional to those of the Higgs boson to escape flavor constraints (see Ref. (58) for a description of remaining constraints for pseudoscalar searches), and therefore that their visible decays should be dominated by heavy-flavor quarks. Other parallels with LHC Higgs phenomenology are the importance of loop-induced couplings to gluons in the production of scalar and pseudoscalar mediators (59, 60) and the associated production of the mediator together with heavy flavour quarks (57). Scalar and pseudoscalar models have much lower cross-sections than their vector and axial vector counterparts in the same fashion as the Higgs production cross-section is suppressed with respect to the Z cross-section in the SM, but the associated heavy quarks provide experimental handles that make those models testable at the Run-2 LHC. Single top signatures are also in reach of LHC searches (61), as they are kinematically favored even though their production cross-section is generally lower with respect to the associated production of a pair of top quarks.



Feynman diagram testing things. We could do this and it's informative, but positioning will be a pain.

Color-neutral scalar and pseudoscalar models are fully defined given the masses of the DM particle and of the mediator, the nature of the ϕ-DM couplings (g_χ) and ϕ-fermion (g_q) couplings. Following the convention in (10), g_q is a pre-factor to the Yukawa couplings of the mediator to fermions and it is considered equal for all quarks in early LHC searches. The LHC kinematics of models with scalar and pseudoscalar mediators assuming the same couplings is degenerate. Since the pseudoscalar model has been favoured for the interpretation of the DAMA and galactic center excess (62, 63) and collider searches are favored when comparing to DD (64), LHC searches have privileged this choice and considered the associated scalar boson as decoupled at higher energies.

In the most general scalar potential, the scalar can couple to DM through a Higgs portal (38). The scalar mediator mixes with the SM Higgs boson with a mixing angle $sin(\theta_{hS}$ and with a new physics coupling b that can be set to unity, and to DM through a Yukawa term as above. This model adds mono-Higgs signals to the signatures of the scalar model without Higgs couplings. The mixing angle is constrained from current Higgs precision measurements to be $sin(\theta_{hS} < 0.4$, and the LHC kinematics does not depend on this mixing angle. Couplings to other MS particles, notably EW gauge bosons, can also be added as a consequence of electroweak symmetry breaking as in (65, 66). The signatures of this latter model include invisible decays of the Higgs boson if the DM particle is lighter than the SM Higgs, as well as signals of Higgs and vector bosons plus missing transverse momentum at tree level.

If the mediators are pure SM singlets, the model is not invariant under $SU(2)_L$ (67). To restore gauge invariance, the mediator needs to mix with the Higgs sector, introducing further complexity of interactions. However, as we will see in Sec. 2.4.4, this complexity does not translate into significant changes in the LHC kinematics of the simplest models, but rather adds extra signatures for LHC searches.

Scalar and pseudoscalar bosons that possess a Z_2 charge take simplified models used at the LHC beyond $s-$channel SM-DM interactions (68, 49, 50, 51) as they mediate the interaction between a DM particle and a SM quark. Models including color triplets of this kind have historically been called $t-channel$ models, but their diagrams are not exclusively of simple $t-$channel mediation. In these particular diagrams, a scalar that is colored under SU(3) is exchanged, analogously to a squark exchange in the MSSM where only squarks and neutralino are light. With respect to the $s-$channel mediator models, models with a colored scalar mediator have a broader set of multi-jet signatures and kinematic features that make it interesting in terms of LHC phenomenology (10). Another handle for LHC searches is the radiation of a Z boson by the right- and left-handed mediators, as well as a W boson by the left-handed mediator (51).

The definition of the parameter space for colored mediator models requires setting the mass of the mediators and of the DM particle. The mediator mass is set equal for all mediators due to the MFV assumption, and the mediator must be heavier than the DM particle to ensure DM stability. The coupling between DM and quarks $g_{\chi q}$ in LHC searches have been set to be universal but only to the first two quark generations, violating MFV.

However, if only right-handed, down-type quarks are considered, flavour constraints still do not exclude a significant part of the parameter space (10).

As opposed to the MSSM, the coupling between DM and quarks in this simplified model is not a priori fixed or constrained by the necessity of fitting within a more complex, self-consistent particle spectrum. The couplings required for this model to satisfy the relic density are generally higher than what used by SUSY models. Couplings to vector bosons also allow the mediator to radiate a W or a Z, leading to LHC signatures that can be targeted by specific searches (51). More sophisticated models that satisfy the full SM gauge symmetry and MFV include third generation couplings and lead to two independent mediators and couplings are described in Ref. (69). The parameters and couplings of this model have also been tuned to describe the gamma ray excess and motivate searches with a single $b-$quark in the final state (63), leading to a similar phenomenology as the MSSM with a light bottom squark and neutralino.

2.4.3. Consequences of $s-$channel mediated models: visible decays. As mentioned in the earlier section, if the mediator particle is produced from from interactions of quarks and gluons, it will also decay in quarks and gluons. For this reason, it is worthwhile that collider experiments not only search for the invisible Dark Matter particles, but also probe directly the interaction between Standard Model and Dark Matter particles by searching for the visible decays of the particles that mediate it, as shown in Figure 1 (c) and summarized in e.g. Refs. (54, 70).

Dijet searches are sensitive to vector and axial vector DM mediators decaying exclusively to jets with couplings that would satisfy relic density constraints (55), but also to new, unknown particles that might be created when crossing the threshold of a new energy scale. For the same reason, it is not possible to claim a discovery of DM mediators at the LHC without corresponding excesses in invisible channels and non-collider experiments. Nevertheless, these benchmark models have motivated novel search techniques to look for low-coupling, low-mass resonances below the TeV scale that would have otherwise not been explored in early Run-2 data due to experimental difficulties (71, 72).

The leptophobic vector and axial vector simplified models described in 2.4.2 are however not always theoretically viable, as lepton decays are needed for gauge invariance or are included through radiative corrections leading to a mixing between the Z' and the Z (see Ref. (73) and references therein). A simple extension of the leptophobic vector and axial vector models allows the mediator to decay into leptons at tree level, with a coupling g_l. As explained in the next sections, dilepton resonances are often more sensitive than dijet resonances at the LHC. Decays of the spin-1 mediator into neutrinos are also required by gauge invariance, and add an invisible decay channel that can enhance signatures of missing transverse momentum, depending on the size of the couplings (73).

2.4.4. Less simplified models. The initial list of models recommended to the experimental collaboration by the Dark Matter Forum described above is a first set of simple, mostly tree-level processes targeting early Run-2 searches. Targeting one simplified model at a time however does not cover the full complexity of LHC signatures and kinematic distributions in more complete models. Exclusively considering simplified models therefore presents the risk of missing important search targets. Moreover, UV-complete models are important and interesting as they offer solutions to SM problems beyond DM, as in the case of SUSY that will be discussed in the following section.

There are a large number of these "less-simplified" models in literature, and very few of them have been explored directly by LHC searches considering them as benchmarks. In this review we will only sketch the main characteristic of a small selection of models within our grounding assumptions. This selection has different kinematic consequences and different signatures with respect to the simplified models used by Run-2 LHC searches so far.

Co-annihilation models add one extra particle to the dark sector, generally close in mass to the DM particle. Examples can be found in Refs. (74, 75, 76). The strong interaction between these two DM states drives the cosmological history (7), as processes involving both DM particles can efficiently annihilate DM into SM particles. In terms of LHC phenomenology, coannihilation models produce signatures of missing transverse energy and multiple hadronic jets accompanied by multiple resonant or non-resonant hadronic jets, in some cases untested by current searches (74). In other cases, the small mass splitting between the two particles forces the decay of the next-to-lightest particle into the lightest particle to be kinematically suppressed, in turn leading to a sizable lifetime for the next-to-lightest particle (76). The late decays of the coannihilation partner give an additional experimental handle that can be used for LHC searches, as described in the next chapter.

The **evolution of scalar models** has also attracted the attention of both theory and experimental LHC community. The simplified scalar and pseudoscalar models described in Sec. 2.4.2 are not self-consistent, if considered as stand-alone models they only focus on one experimental signature at a time. They are not considered the best benchmark model to make the most of the search opportunity offered by a machine that is sensitive to scalar particles with couplings of the order of those of the Higgs boson. The first step towards more consistent scalar and pseudoscalar models is the addition of Higgs couplings and coupling to vector bosons that naturally stem from gauge invariance, as described above and in (65, 38). A further refinement is to embed the scalar/pseudoscalar model in a more complete theory, namely a Two-Higgs Doublet Model (2HDM) (77, 78, 79, 80, 67). In these models, the new scalar or pseudoscalar mediator mixes with the Higgs partners rather than with the SM Higgs, so that the model is still compatible with Higgs measurements. 2HDM+scalar/pseudoscalar have an interesting phenomenology that is not dominated by jet+missing transverse momentum searches but rather by the results of searches of Higgs or EW bosons+MET. A richer span of experimental signatures permits to expose uncovered regions in the parameter space of the model, as well as to highlight the complementarity between final states. 2HDM models developed for LHC searches focus on a Yukawa structure of Type-II, where the couplings are the same as the MSSM. The particle content of this model includes two CP-even bosons (one of which is the SM Higgs boson), two CP-odd bosons (of which one is the pseudoscalar DM mediator, privileged because it escapes DD constraints), two charged Higgs boson and the DM particle. Masses and couplings of these models are chosen to respect vacuum stability (79), electroweak and flavour constraints, as well as to highlight the complementarity of the various experimental signatures. Depending on the parameter chosen, this model can satisfy the relic DM density, in general with values of m_χ above 100 GeV.

2.5. Supersymmetric models and other theories

A complete review of supersymmetric DM models can be found in (81).

[left for AB, see ooutline]

R-parity conservation makes the neutralino a viable DM particle candidate.

Other BSM theories including DM particle candidates that are not covered in this review are extra dimensions (82), and DM as sterile neutrino (83). For AB who has book: See Bertone's book for non-SUSY candidates at the EW scale.

2.6. Long-lived particle models

As discussed in the introduction to this chapter, the LHC does not directly detect DM, but rather uses visible objects to signal the presence of non-interacting, long-lived particles that escape detection. If the particle does not decay, then it is a good DM candidate. In many non-WIMP, dark sector models, one can postulate the existence of DM particles as well as other particles with lifetimes not long enough to be cosmologically stable. Those particles would escape conventional detection by collider experiments, as they e.g. decay half-way through the detector, and still lead to signatures of missing transverse momentum. However, these dark sector particles usually do not carry sufficient energy to be observed in this way, so experiments must devise methods that specifically target those non-standard decays. These will be discussed in Chapter (**?**).

The main mechanisms for a partner particle to acquire a long lifetime are related to the suppression of its tree-level decays when:

- the partner particle has a large mass compared to its parents and decay products, so the decay proceeds off-shell, as in the case of e.g. the W-mediated pion decay in the SM;
- the partner particle can decay to the DM particle but won't do so frequently due to the small mass splitting, as in the case of coannihilation;
- when the couplings between the partner particle and either SM or DM particles are small, as in the case of the Cabibbo-suppressed B-meson decays in the SM.

In this review, we only sketch two examples of the third case, as it connects directly with the simplified models described in Sec. 2.4.2. If the only connection between the DM and SM is the new mediator particle, and DM can annihilate directly to BSM mediators and not viceversa (as $m_\chi > M_{\mathrm{med}}$), then the couplings of the mediator to the SM can be arbitrarily small. This happen for example when introducing a U(1)' symmetry mediated by a vector boson (a "dark boson"), leading to coupling ϵ through kinetic mixing, or when adding a scalar boson (a "dark Higgs") that only couples to the SM via a Higgs portal or via mixing with a heavy pseudoscalar in 2HDMs with a coupling k. In both these cases, the mediator (a "dark boson") can be long-lived (84), and its visible decays into SM particles or associated production with a SM boson provide the main collider handle (85). There is a large possible dark boson mass range that is still compatible with thermal freeze-out, from 1.5 GeV to 40 TeV (86), and it can be probed by complementary experiments including present and future colliders. Another mechanism for generating the relic density that is compatible with very weak SM interactions such as those of dark photons is the freeze-in scenario (see e.g. (87, 8)), where DM is produced from the thermal bath but never reaches equilibrium. CD: I don't understand this yet.

Another bottom-up approach adopted in (88) is to impose masses and couplings for the models described in 2.4.2 so that they include a long-lived particle. The categorization of the models by production operator and final state permits a more systematic set of benchmarks for this kind of signatures. These models can then be mapped onto more complete theories. No attempts have yet been made however to connect these models to cosmological history.

3. EXPERIMENTAL RESULTS

Now that we have a handle on the reactions of DM observable at collider experiments, we turn to a description of the searches and experimental constraints for DM at colliders, privileging LHC searches as they generally set the most stringent constraints. For a detailed description of the LHC and the ATLAS, CMS and LHCb experiments, we refer to (89, 90, 91). The first period of LHC running (2010-2012) at 7 and 8 TeV center-of-mass energy ($\sqrt{s}$) is termed Run-1, while the second period (2015-2018) is called Run-2. The categorization of these searches follows loosely the description of the benchmark models. We start describing searches for DM interacting through SM bosons 3.1, then move to generic searches for signals with missing transverse momentum 3.2, and outline the searches for complete models with DM candidates in Section 3.3. Throughout this chapter we will highlight the experimental challenges and the novel experimental techniques used to overcome them, motivated by the strong interest in dark matter searches. We then conclude with searches for long-lived particles within models of DM in Section 3.4.

3.1. Searches for DM in interactions mediated by SM-boson

The invisible decays of the Z and Higgs boson are the main direct targets of searches for SM-boson-mediated interactions between SM and DM particles, if the DM particle is lighter than half the mass of the boson. Above this region, Direct Detection experiments are generally more sensitive than collider experiments. In the SM, the Z boson can decay to a neutrino-antineutrino pair, while the Higgs boson decays into a pair of Z bosons each decaying to neutrinos. Additional decays of the Z and Higgs boson to particles beyond the SM modify the properties of the vector boson, such as width and couplings.

Decays of the Z boson into invisible particles can be constrained using the invisible Z width. It can be measured directly in Z decays in association with a photon emitted as initial state radiation. Events are selected containing a single photon, missing transverse momentum and no other sizable event activity. This selection is also used for identifying events from possible DM reactions at colliders. The total Z width has been measured indirectly at LEP (92) leading to a measurement of the number of light neutrino families compatible with cosmology; if the partial widths of the decays into visible particles are subtracted from the total width, the invisible width can be measured to 499.1 $\pm$ 1.5 MeV (93). New physics effects modify direct and/or indirect Z width (94). The LEP precision measurements [1], as well as direct detection experiments, rule out the majority of the Z-mediated DM scenarios (14, 16). The LEP invisible width is well below the width one would expect if vector and axial vector models of DM were realized, for all couplings satisfying the relic density with a DM mass below 25 GeV. Direct detection experiments such as Xenon1T (95) rule out most of the other simplified model scenarios compatible with freeze-out relic density up to multi-TeV DM masses.

Direct and indirect Z width measurements must agree if the decay of the Z to a pair of invisible new particles is to be the main mechanism responsible for the deviation from the SM values.

Invisible decays of the H boson within the SM only contribute to less than 0.1% of the total decay width. For this reason, an observation of even a small contribution to the Higgs width from invisible particles would signal the presence of new physics phenomena that could be linked to DM if $2m_\chi < m_H$ [2].

Pre-LHC constraints on the invisible Higgs width are derived from measurements of the

[1] Bounds on Z to invisible decays obtained from LHC searches are not yet competitive (23).
[2] For the case of heavier DM particles, see Ref. (21).

ZH production channel at LEP in searches for new neutral Higgs-like bosons, where only the visible decays of the Z are observed. This is a common procedure to select events in LHC DM searches. It is not feasible to directly or indirectly measure the total and partial Higgs widths at a hadron collider and then extract the invisible contribution as done for the Z at LEP, as some of the decays (e.g. gluons and lighter quarks) have too large a background to be measured, the experimental resolution even for leptonic decays is large compared to the intrinsic Higgs SM width, and the kinematics of the ZH process is not fully determined as in lepton colliders. Instead, searches at the LHC either attempt to directly observe the invisible decays of the Higgs boson, or compare measurements with precise theoretical calculations of SM parameters, to reveal discrepancies signaling new physics or indirectly place constraints on new physics phenomena. Higgs to invisible LHC searches using Run-1 and Run-2 data (96, 97) employ and combine the $qq \to Hqq$, $qq \to VH$, $gg \to HZ$, $gg \to Hg$ Higgs production modes. In all cases, in addition to a requirement of sizable missing transverse momentum, auxiliary visible objects are used to select the events. The events are divided in exclusive categories targeting specific production modes. The associated boson (VH) searches target the decays of Z bosons to electrons, muons light or heavy flavour quarks, while the W bosons can decay into light-flavour jets. The $qq \to Hqq$ production mode is dominated by Vector Boson Fusion (VBF) processes, where the Higgs boson is produced in association with two hadronic jets that have a large pseudorapidity (η) separation in the detector, and a large invariant mass. This topology is used to select events and discriminate between signal and background. The jet+MET search, described in more detail in the next section, is reinterpreted for the $gg \to Hg$ mode.

Precision measurements of the Higgs boson properties and the comparison with SM theory also play a role in constraining the possible contributions to new physics, as decays into invisible particles would reduce the SM Higgs production and decay coupling strengths (98, 20, 97).

The most stringent observed upper limit on the fraction of invisible decays of the Higgs boson, combining direct and precision measurements is 23%. In the case of light fermion DM with scalar couplings to the Higgs, direct detection experiment rule out most of the parameter space where the model can provide the measured relic density (16, 21). Due to the suppression of the cross-section for DD in the pseudoscalar case, the model is still not constrained around a small region for DM masses corresponding to half the Higgs mass and above.

3.2. Generic searches for DM with missing transverse momentum

WIMP DM particles at colliders escape detection, and their observation requires one or more visible objects in the same event. Searches that only rely on this feature are for the most part model-agnostic, as they only need to detect an excess of missing transverse momentum left by the DM particles recoiling against SM objects, without making any extra assumption on the DM particles or on their production mechanism. Similar search strategies have been employed as center-of-mass energy and dataset size increased, from LEP to Tevatron to the most recent LHC searches (99, 35, 34). A generic event selection for excesses of $\not{E}_T$ also provides an inclusive sample for more targeted searches as it will be discussed in Chapter 5.

We begin this section by describing the LHC searches for missing transverse momentum in association with one or more hadronic jets. The jet+$\not{E}_T$ search allows us to illustrate

Details of $\not{E}_T$ reconstruction and fake $\not{E}_T$ rejection

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many of the techniques used in invisible particle searches, and it is one of the most powerful to constrain BSM-mediated simplified models of dark matter. We then move on to outlining searches using different associated objects, and continue with searches for visible mediators that are the consequences of the DM production mechanism. Finally, we compare and discuss the sensitivity of invisible DM and visible mediator searches at the LHC.

3.2.1. Searches with jets. Events containing invisible particles can be identified and selected at colliders if initial state radiation (ISR) is present. For e^+e^- colliders, the most frequently radiated object is a photon, while for hadron colliders gluon radiation dominates. These searches have been called "Mono-X", where X is the radiated object, although the radiation of a single object is only the leading process in a SM-DM $s-$channel interaction (100). For this reason, the most recent LHC searches for MET with jets (101, 102) allow for events containing more than one jet in the final state. Since the presence of highly energetic invisible particles would manifest as an excess of events with a significant $\not{E}_T$, the main observable for this search is the number of events in $\not{E}_T$ *signal regions*, either exclusive (in bins of $\not{E}_T$) or inclusive (considering all events above a given $\not{E}_T$ threshold). The discovery of a signal originating from one of the benchmarks DM models presents different challenges, depending on the DM particle mass and boost. If the mediator is heavy, any light DM particle will receive a boost and appear as an excess in the tails of the SM $\not{E}_T$ distribution. If instead the DM particle pair originates from a light mediator, of the same mass range as the Higgs boson, it will manifest itself at low $\not{E}_T$. The low $\not{E}_T$ suffers from a much higher rate of both instrumental and SM backgrounds. As a consequence, it is impossible to record and store all events with a low-$\not{E}_T$ for further analysis, since at the data-taking stage (within the *trigger* and data acquisition systems) it is difficult to obtain further handles to discriminate signal and background, and the sensitivity to low-$\not{E}_T$ signals is compromised. This challenge will be discussed further for both visible and invisible particle searches in Sec. 3.2.5.

Trigger: a detector system that decides which LHC collision events are to be recorded for physics analysis. For a description of the trigger systems of the ATLAS and CMS experiments, see (103, 104, 105).

Events are selected to enter the $\not{E}_T$ signal regions if they contain at least one jet in the central region of the detector ($\eta < 2.4$) with $p_{\mathrm{T}} > 250$ GeV (ATLAS) or $p_{\mathrm{T}} > 100$ GeV (CMS) and $\not{E}_T > 250$ GeV (ATLAS) or $\not{E}_T > 200$ GeV (CMS). This selection ensures that all events with these characteristics are recorded by the trigger system for further analysis.

A lepton veto is used to suppress background from leptonically decaying W bosons. QCD background where large $\not{E}_T$ originates from mismeasured jets is rejected by requiring that the ϕ direction of the missing transverse momentum vector does not align with the direction of the four-momentum of the jets with the highest p_{T} (leading jets). The remaining QCD background estimated from data amounts to a maximum of 0.4% of the total background. The large number of events containing fake $\not{E}_T$ due to non-collision background (e.g. cosmic rays, beam-gas interactions, calorimeter problems), shown in Fig. 2 is rejected with specific quality criteria discussed in the relative Sidebar.

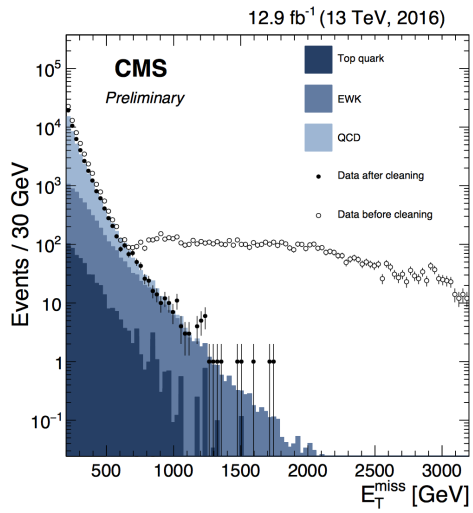

Figure 2

The $\not{E}_T$ distribution of the data events passing the [define selection] without any cleaning criteria applied on the leading jet. The Standard Model background indicated in the plots corresponds to the estimates obtained for the analysis signal region, including jet quality requirements. This demonstrates the necessity of a strong non-collision background suppression for this analysis. From (**?**).

Signal region: a region of phase space for a search that is enriched in signal events. Event counts in this region are used to compare background-only prediction to data in search for discrepancies signaling new physics.

Control region: a region of phase space for a search that is signal-free but with characteristics otherwise as close as possible to the signal region. Event counts in this region are used to estimate backgrounds in the signal region.

The CMS analysis also applies specific vetoes for photons and heavy flavour jets, to reject events with photon ISR or containing top quarks. The CMS analysis also includes a signal region targeting hadronic decays of the W and Z bosons using substructure techniques, which is considered separately in the case of ATLAS and will be discussed in Sec. 3.2.2.

The main background contributions that remain after the event selection are invisible decays of the Z boson into neutrinos (approximately 55-70% of the total background) and leptonic decays of the W boson where the lepton is not reconstructed (approximately 20-35% of the total background), in association with jets. In order to reduce theoretical and experimental uncertainties on the main V+jet backgrounds, the number of events in the signal region from each of these backgrounds are derived from data in signal-free *control regions* selecting V+jet processes where the W and Z bosons decay into visible particles ($Z \rightarrow ll, W \rightarrow l\nu + jets$, where $l = e, \mu$). The event selection follows that of the signal region, substituting a lepton requirement to the lepton veto. The visible decay products in events selected for the control regions are subtracted from the total transverse momentum balance, providing an estimate of the contribution of these backgrounds in the signal region.

Precision estimation of background for $\not\!\!E_T$ +X searches

In order to relate the number of events in the jet+$\not\!\!E_T$ signal regions (where $Z \to \nu\nu$ dominates) and control regions (where events with jets produced in association with $Z \to ll$, $W \to l\nu$ and γ are used to maximise the statistical power of the background estimation), one needs to rely on a precise theory prediction of the ratio of the V+jets cross-sections. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words. This is why this is important, this is 10 words.

CMS also uses a γ+jet control region where the photon is subtracted following the same procedure, to increase the statistical precision of the background estimate. The distribution of events in the main observable used for the search, the shape of the $\not\!\!E_T$ distribution, is simulated and reweighted for each of the control regions using the most recent perturbative calculations for NLO QCD and QED (106). The estimation of the number of $Z \to \nu\nu$events from the γ+jet and $W \to l\nu$+jets control region needs a specific treatment due to the difference in the processes. This is particularly important for a consistent treatment of the different processes used in the background estimation and of the main theoretical uncertainties, and it will be discussed further in the following textbox. The full information on the theoretical and experimental uncertainties and their correlations from this procedure is used in a simultaneous fit to control and signal regions, to determine the overall background estimate in each of the $\not\!\!E_T$ regions considered. Backgrounds from top processes in ATLAS are estimated using a dedicated control region with a requirement of a $b-$jet that is included in the fit, while CMS takes this background from simulation. Smaller diboson backgrounds are estimated from simulation.

The systematic uncertainties on the background estimate for the jet+MET search range from 2 to 7% (CMS) and 2 to 10% (ATLAS), depending on the $\not\!\!E_T$ region. The main uncertainties are due to the identification of leptons (CMS) and the understanding of the jet and $\not\!\!E_T$ calibration (ATLAS).

Since no significant excess is found in any of the signal regions, limits are set on the parameter space of Higgs portal models described in Sec. 2.3 and simplified models described in Sec. 2.4, namely where the SM-DM interaction is mediated by $s-$channel vector (V), axial vector (AV), scalar (S) and pseudoscalar (P) and colored scalar mediators. Since the simulation of the entire parameter space for these models by the experiments is computationally intensive, the Dark Matter Forum had agreed on a limited set of benchmark parameters to be tested (10), privileging those that change the LHC kinematics of the search (e.g. give a harder $\not\!\!E_T$ spectrum) rather than those that only change the cross-section of the process and can therefore be reinterpreted from the search results. For example, the kinematics and cross-section of the vector and axial vector mediators is very similar at the LHC, while the DD and ID cross-sections change. The parameter values used as benchmarks (e.g. couplings) have been selected considering the sensitivity of early Run-2 searches, precision constraints and general simplicity arguments. As described more in detail in Section 3.2.6, results are given in the m_χ, $M_{\rm med}$ plane fixing the couplings to $g_{\rm q}$ =0.25 and g_χ =1.0 for vector and axial vector mediated models, $g_{\mathrm{q}} = g_\chi = 1.0$ for scalar and pseudoscalar models and $g_{\chi q} = 1.0$ for colored scalar models. The simplified models employed by the experimental collaborations are known at NLO (107, 100, 108).

The most stringent 95% C.L. observed (expected) upper limits on the invisible branching fraction from jet+$\not\!\!E_T$ searches are 53% (40%). TODO look for ATLAS? Vector and axial vector mediators are excluded by LHC searches at values of m_χ up to 700 and 400 GeV respectively with M_{med} up to 1.8 TeV. This choice of model and couplings produces a relic density that is lower than the Planck measurement and it is still unconstrained by LHC searches for $m_\chi > 0.3$ TeV at $m_\chi = 1.8$ TeV for the vector mediator, and for $0.65 < m_\chi < 0.75$ TeV at $m_\chi = 1.8$ TeV for the axial vector mediator[3]. The LHC limit on the pseudoscalar mediator mass is lower due to the Yukawa-like couplings suppressing the cross-section with respect to spin-1 mediators, and it is 0.4 TeV in the CMS search for m_χ up to roughly 150 GeV. Jet+$\not\!\!E_T$ searches are not yet sensitive to scalar mediators with the chosen couplings. Colored scalar mediators with masses up to 1.7 TeV at values of $m_\chi = 10$ GeV are excluded for $g_{\chi q} = 1$ and $m_\chi = 100$ GeV. Considering this exclusion limit, this model still provides a viable DM relic density for M_{med} m_χ above roughly 500 GeV at $M_{\mathrm{med}} = 1.7$ TeV[4].

Other benchmark scenarios such as compressed SUSY scenarios, squark pair production, non-thermal singly-produced DM, and Large Extra Dimensions (ADD) are also constrained by the ATLAS and CMS searches, in some cases providing the most stringent constraints to date.

The jet+$\not\!\!E_T$ search can constrain a wide variety of reactions for invisible particles. Therefore, various approaches have been taken to allow model-builders and phenomenologists to easily reinterpret its results. As for most LHC searches, the published experimental data from the ATLAS and CMS collaborations is provided on the HEPData platform (109). Additionally, a simplified likelihood function (110), which under certain assumptions approximates the full likelihood using a reduced set of information, is provided for the CMS result (101) and has been used for reinterpretation (111). Moreover, the ATLAS Collaboration has used the ratio of cross sections of events containing a jet and $\not\!\!E_T$ and events containing a jet produced in association with an opposite-sign same-flavour dilepton pair from the decay of a $Z/\gamma*$ boson (112), corrected for detector effects. This is an observable sensitive to the anomalous production of events with jets and $\not\!\!E_T$, and uses many of the techniques from the the jet+$\not\!\!E_T$ search described above to estimate background. The constraints derived are comparable to those of the jet+$\not\!\!E_T$ search with the equivalent dataset. Unlike most other searches for new physics described in this review, detector effects are already accounted for (*unfolded*) when presenting results, so that there is no need to implement a detector simulation to reinterpret this search.

3.2.2. Searches with photons and vector bosons. Searches for invisible particles produced in association with a jet are the most sensitive among the searches employing an object radiated in the initial state, due to the large signal rates from the radiation of a gluon as opposed to the radiation of a photon or a W/Z/Higgs boson. The jet+$\not\!\!E_T$ final state is however also affected by the largest SM and instrumental background, and only covers signals

[3] Here and in the following, we quote observed limits at 95% C.L. and refer to the bibliography for expected limits and 90% C.L. limits.

[4] The ATLAS and CMS results do not use the same parameters, here we report the ATLAS result.

producing a high $\not\!\!E_T$ to comply with data-taking limitations at the trigger level, due to the high-rate backgrounds producing signal-like signatures. It is therefore worth considering other objects as ISR, as those searches will be subject to different backgrounds, different kinds of systematic uncertainties, lower $\not\!\!E_T$ thresholds, and can provide confirmation in case of an excess in the jet+$\not\!\!E_T$ final state (113, 114). The sensitivity hierarchy of $\not\!\!E_T$ +X searches does not necessarily privilege the jet+$\not\!\!E_T$ final state if there is a direct new physics coupling between a vector boson and the DM, as in the case of the EFT model mentioned in Section 2.4.1, or if the radiated object is a new particle (115).

ATLAS and CMS have pursued searches for missing transverse momentum produced in association with a photon(116, 117),vector boson decaying hadronically (101, 118) or leptonically (119, 120).

One of the advantages of these search signatures over the jet+$\not\!\!E_T$ one is the lower event selection threshold, thanks to the additional handles to suppress background provided by either the photon ISR or the leptonic decays. As an example, the lowest $\not\!\!E_T$ value for the search is 100 GeV for the leptonic Z+$\not\!\!E_T$ search (120) as opposed to 200 GeV for the jet+$\not\!\!E_T$ search (101).

The event selection and the background estimation strategy depends on the final state, but generally mirror those of the jet+$\not\!\!E_T$ search. The **photon+$\not\!\!E_T$ searches** use a photon to trigger the events to be recorded for analysis, and selects events containing an isolated photon above 150 GeV and no leptons. The number of events from Z decays to neutrinos in association with a photon can be estimated in events where the lepton veto is inverted and the contribution of visible Z and W boson decays is removed from the transverse momentum balance of the event, and transferred to the signal region. The total systematic uncertainty is dominated by the statistical uncertainty in the control regions, ranging from 4% to 10%. Jets and leptons faking photons are estimated directly from data, and the γ+jet background where the jet is mismeasured and produced $\not\!\!E_T$ is suppressed by the requirement that the photon and the direction of the $\not\!\!E_T$ vector do not overlap in the azimuthal plane.

The **W/Z+$\not\!\!E_T$ searches** where the vector boson (V) decays to a quark-antiquark pair specifically select events where the decay products from the high-p_T boson are collimated, to better discriminate signal and background. QCD jets will not present any *substructure*, while the decay products of vector bosons grouped into large-radius jets have a typical two-prong pattern from the hadronization of the quark-antiquark pair. The dominant background is still Z decays to neutrinos in association with jets, followed by W decays where the lepton is not identified, and top quark decays. The shapes of these backgrounds are estimated using simulation, while the normalization is determined in control regions, similarly to the jet+$\not\!\!E_T$ search. In the CMS search, the V+$\not\!\!E_T$ backgrounds are estimated in a simultaneous fit together with the jet+$\not\!\!E_T$ backgrounds. The main uncertainty for this search (up to 9% (101) and 13% (118)) is due to the modeling of the substructure observables.

Jet substructure: a set of techniques employed to extract information from the radiation pattern of a jet, by analyzing its constituents or its reconstruction history. For a review, see (121).

The **Z+$\not\!\!E_T$ searches** where the Z boson decays leptonically [5] are sufficiently general to be sensitive to simplified models of DM with a Z radiation, as well as to Higgs decaying into new invisible particles and produced in association with a Z (120, 119). The event selection includes a constraint on the dilepton invariant mass, which limits the backgrounds

[5]Leptonic decays W bosons have also been employed in the past for this kind of searches, but due to the additional experimental challenges (e.g. the presence of an additional invisible particle, the neutrino in the W decay) and the reduced sensitivity with respect to the hadronic decays, they have not been specifically pursued as DM searches for the LHC Run-2.

to diboson, leptonically decaying top quarks, Drell-Yan production and a small amount of triboson processes. The estimation of the main $ZZ \rightarrow 2\nu 2l$ background (about 60% of the total backgrounds) uses simulation, as the data sample that could be used to constrain the normalization as in the jet+$\not\!\!E_T$ search is statistically-limited. The main uncertainty for this search (10% on the background estimation) comes from the theoretical uncertainties on this background. The CMS search uses a Boosted Decision Tree (BDT) applied to events with the missing transverse momentum between 100 and 130 GeV, to enhance the sensitivity to invisible Higgs decays.

The photon+$\not\!\!E_T$ searches provide the next-to-most stringent constraints after the jet+$\not\!\!E_T$ search, up to M_{med} < 1200 GeV for vector and axial vector mediators with g_χ =1.0 and g_{q} =0.25 for m_χ =100 GeV, in the region where the mediator can decay to DM. The ATLAS photon+$\not\!\!E_T$ search also sets limit on the EFT model where the DM couples directly to the photon, excluding EFT scales between 150 and 750 GeV for m_χ =100 GeV, assuming the maximal coupling value allowed by perturbativity. Searches in the $\not\!\!E_T$ +hadronic Z final state constrain vector and axial vector mediator masses of M_{med} < 650 GeV for m_χ =100 GeV[6]. Searches in the $\not\!\!E_T$ +leptonic Z final state provide constraints on M_{med} < 650 GeV for m_χ =100 GeV for vector and axial vector mediators. W/Z+$\not\!\!E_T$ searches are also uniquely sensitive to the radiation of a boson from the mediator particle in the case of colored scalar models (51), but the Run-2 searches do not present this interpretation.

3.2.3. Search signatures including the Higgs boson. The newly discovered Higgs boson is of particular interest for DM searches at the LHC. Higgs radiation is kinematically and PDF suppressed, but searches for a mono-Higgs have other strong theoretical motivations. Higgs portal models are the simplest incarnation of theories where the coupling between the dark sector and the SM is realized through a Higgs boson. Higgs couplings to at least a new scalar are necessary for the gauge invariance of simplified models described in the previous chapters towards more complete theories. Gauge symmetries link Higgs+$\not\!\!E_T$ signatures and signatures including W, Z bosons or jets as well as two-body mediator searches (54).

The search strategy depends on the decay mode of the Higgs boson. With the current LHC dataset (2015+2016 Run-2, 36 fb^{-1}), only the $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$ decay channels have been used to search for DM, due to their relative experimental simplicity and high rates. Other decay channels such as ZZ, WW and $\tau\tau$ are expected to contribute to DM searches as well in the future.

Searches in the decay channel $H \rightarrow \gamma\gamma$ in association with $\not\!\!E_T$ (123, 124) are sensitive to a variety of benchmark models regardless of the small branching fraction, thanks to the high precision in the reconstructed Higgs boson mass and the ability to probe low $\not\!\!E_T$ thresholds compared to other Higgs decay channel as the trigger rates are low. The SM background is estimated using a fit to the diphoton mass distribution, in events categorized according to their missing transverse momentum for CMS (50<$\not\!\!E_T$ <130 GeV and $\not\!\!E_T$ > 130 GeV) or according to specifications optimised for different signal categories.The main uncertainty for the $H \rightarrow \gamma\gamma$ searches using the 2015+2016 LHC Run-2 dataset is statistical. In the search

[6] As a side note that is useful to compare results from different LHC datasets, Run-1 V+$\not\!\!E_T$ searches used a version of the vector simplified model that enhanced W radiation because of the constructive interference due to different up- and down-quark mediator couplings, but that was not gauge invariant (39, 122).

where the Higgs boson decays into two bottom quarks (125) in association with $\not{E}_T$ >150 GeV, all backgrounds except for the QCD background are estimated using MC simulation and constrained in dedicated control regions. This search also employs jet substructure techniques for events with $\not{E}_T$ >500 GeV, to discriminate boosted Higgs decays from QCD processes. The main systematic uncertainty for the lower $\not{E}_T$ signal region is the modelling of the V+jets background, while higher $\not{E}_T$ signal region is still statistically limited with the 2015+2016 LHC dataset.

In absence of discrepancies between data and background, limits are set on the baryonic Higgs benchmark model outlined in Sec. 2.4.2 with g_{q} =1, g_χ =1, $g_{hZ'Z'}/m_Z$=1, $sin(\theta_B$ =0.3, and on a Z'-2HDM model with $tan\beta$=1, $g_{Z'}$ =0.8 and m_χ =100 GeV [7].

3.2.4. Searches with heavy-flavor quarks. Generic searches employing one single additional object produced in association with $\not{E}_T$ are powerful tools to probe simple models of DM. More complex models, however, bring more handles for discovery: the first step in this direction can be taken with searches using scalar and pseudoscalar models as benchmarks, where information about the production mechanism (e.g. the mediator is produced in association with two heavy flavor quark, complementing the gluon-fusion production mode of the $\not{E}_T$ +jet searches) is exploited in the search strategy.

The searches in (126, 127) are optimized for DM scalar and pseudoscalar mediators selecting events in the semileptonic and fully hadronic top quark decay channels, as well as events containing one or two bottom quarks, in association with $\not{E}_T$. The dominant backgrounds in (126) are estimated separately using MC in each of the signal regions, and their normalization constrained using control regions in a simultaneous fit. The main uncertainties for these searches are, depending on the signal region, theoretical and MC simulation related uncertainties, jet energy scale and resolution. and uncertainties related to the identification of heavy flavor quarks. Signatures including $\not{E}_T$ and two heavy flavor quarks are similar to signatures of third generation quark superpartners, leading to dedicated DM signal regions being included in SUSY searches or used for reinterpretation (128, 129). In SUSY-like searches, the dominant $t\bar{t}$ backgrounds are heavily suppressed using variables that combine visible and invisible mass (130) targeting the model sought. This step uses information that is model-dependent, but increases the sensitivity to specific processes. The remaining small backgrounds are estimated using simulation.

The sensitivity of searches of $\not{E}_T$ associated to top quarks is comparable for the two strategies. For a choice of m_χ =1 GeV, pseudoscalar mediator masses of 10-50 GeV (**?**) and scalar mediator masses up to 100 GeV (129) are excluded. The increased LHC dataset will allow these searches to be sensitive for other DM masses. Signatures with $b\bar{b}$ pairs are less sensitive to scalar and pseudoscalar mediators that do not explicitly privilege bottom quarks. Mediator masses for the b-flavored colored scalar model discussed in (63) are excluded up to 1.1 TeV for m_χ =35 GeV.

Other searches in the heavy flavor+$\not{E}_T$ category are those only including only one top or bottom quark (also called mono-top or mono-bottom searches) (127, 131), and place constraints on models that include singly-produced DM candidates through flavor-changing neutral currents, described in (132).

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[7] In the case of the Z'-2HDM model, CMS and ATLAS set different masses for the new Higgs bosons, so the constraints are not directly comparable. This has been rectified in the coming iteration of these analyses.

3.2.5. Two-body mediator searches. Decays into pairs of SM particles are an inevitable consequences of models where DM mediators are exchanged in the $s-$channel and have a SM coupling. This possibility to probe the SM-DM interaction through the visible decays of mediator is a unique feature of collider experiments and one that they are well-prepared for, with a wealth of generic searches for two-body resonances (see e.g. (133)). In the following, we will describe two of the most general examples, the searches for dijet and dilepton resonances, their challenges and the implication of their results for models of SM-DM mediation.

Searches for dijet resonances exploit the smoothness of the falling QCD background to derive their background directly from a fit to data. This minimizes modelling and theoretical uncertainties. Localized excesses are sought atop the fitted background estimation (134, 135). If the resonance is wider than 15%, as in the case of vector and axial vector mediator models with couplings roughly above g_{q} >0.5 [8], the fitted background estimation will be biased by the presence of signal. In this case, the **scattering angle of dijet events** can be exploited as a discriminating variable, since the QCD background is dominated by $t-$channel processes that privilege large angular separations between the two jets, as opposed to signals with an isotropic angular distribution in the center-of-mass frame that translates to the presence of more central jets in the detector (136, 134).

Standard LHC dijet searches lose sensitivity at masses below the TeV, where the high QCD rates force the experiments to randomly discard a large fraction of background and signal events alike (see sidebar). An example of such a technique is recording only **partial event information** for later analysis directly from the trigger system (called Data Scouting in CMS (135), Trigger-object Level Analysis in ATLAS (104), Turbo Stream in LHCb (137)), to overcome the data storage constraints. Dijet resonance searches that use this technique (135, 138) can record the full rate of dijet events to much lower dijet invariant masses than the standard dijet searches, but have to overcome a number of challenges that go beyond a seemingly simple search. The first challenge is demonstrating that the performance of the physics objects reconstructed at the trigger level is sufficiently good to perform a physics analysis and not just take a decision on whether to keep the event. Secondly, the extremely large background rates (above 10^5 events/GeV) grant a sufficient statistical precision to observe signals of the order of a few thousand events, but also per mille-level detector and SM contamination effects. An alternative data-taking strategy is to require a **high-p_{T} ISR object** to trigger on the event and reduce the QCD background, but the sensitivity is reduced by this requirement with respect to selecting the leading order dijet process. The ISR object can be either a jet and a photon, and it recoils against a dijet pair. The dijet pair can be either resolved (139) or collimated and reconstructed within a large-radius jet tagged with substructure techniques (140), depending on the ratio between mass and transverse momentum of the resonance that boost the decay products. If the mediator particle decays democratically to different quark flavours or preferentially into heavy flavour quarks (as in the case for a scalar mediator), searching for **$b\bar{b}$ or $t\bar{t}$ resonances** (141, 142) can overcome the data taking constraints at masses above roughly 500 GeV and have a sensitivity comparable to inclusive dijet searches for vector and axial vector mediators. An interesting feature of scalar and pseudoscalar particles decaying to $t\bar{t}$ is their interference with SM $gg \to t\bar{t}$ production (143) that has to be explicitly accounted

[8]This value assumes that the new particle can decay only to quarks and DM particles, with g_χ =1.0 and m_χ =1 GeV.

Challenges in selecting events at the detector level (trigger)

The LHC collides protons every 25 ns, producing 40 billion of events per second at nominal conditions. This amount of data cannot be recorded in its entirety, and not all events are interesting for the experiments' physics programmes. A trigger system is used to decide whether an event is selected for further analysis. Its first level is realized in hardware and only uses partial detector information for fast decisions in a time of the order of μs, while its second level is software-based and uses more refined algorithms and information to make a decision in ms.

Challenge: triggering on low-p_{T} objects Since the rates of SM physics processes decrease with the transverse momentum of the objects involved, and processes with a high momentum transfer have a higher chance of containing interesting features or new particles, the trigger system records events above a certain threshold e.g. in leading jet p_{T} or in event $\not\!\!E_T$. Only a fraction of events that do not satisfy these thresholds is recorded. Searches for signals with high-rate backgrounds and MET or jet p_{T} below these thresholds are therefore penalized unless novel data recording techniques, such as only recording partial event information needed for the search, are employed.

Challenge: *pile-up* in trigger Simultaneous proton-proton interactions occurring within the detector readout time cannot be completely disentangled from the hard process of interest, especially if reconstructing the collision vertex is not possible at the trigger level due to CPU constraints. This *pile-up* increases the likelihood of passing the minimum threshold to record events, especially in the $\not\!\!E_T$ triggers. For this reason, the increase in the LHC instantaneous luminosity by virtue of increasing the number of simultaneous collisions leads to increases in the trigger thresholds to keep manageable event recording rates. Reconstruction algorithms that suppress the effects of pile-up can be employed by ATLAS and CMS directly at the trigger level, using information on the objects and energy density within the event (145, 146). In future LHC runs, track information to disentangle the provenance of the energy deposits from the collision vertex will be available for ATLAS and CMS from dedicated hardware systems (see e.g. Refs. (147, 148)).

for when estimating the background for these searches (144).

TODO: add coupling-mass summary plot for ATLAS

Searches for new particles decaying in opposite-sign, same-flavor lepton pairs (149, 150) can also be interpreted in terms of the simplified models of DM, if the mediator particle has sizable couplings to leptons. Although lepton couplings are not mandated by the quark-antiquark production at hadron colliders as dijet couplings are, lepton couplings feature in a variety of models that can embed the simplified models of DM used as benchmark for LHC searches.

The main backgrounds for the dilepton searches in electron and muon final states arise from Drell-Yan processes, and are estimated using simulation corrected for NNLO effects and normalized to the Z boson peak event yield in data. Reducible backgrounds where other objects are mismeasured as leptons are estimated using data. The main uncertainties on the background estimation are of theoretical nature, for the entire invariant mass range.

The same constraints from dijet and dilepton searches apply to both vector and axial vector mediators: the LHC phenomenology (rates and kinematics) is the same for both. Searches for visible mediator decays are sensitive to masses as low as 50 GeV (boosted dijet) and constrain SM-DM couplings g_{q} as low as 0.05 at 60 GeV. Jets from the mediator decay start being spatially separated above mediator masses of 250-300 GeV, and that is where the resolved dijet+ISR topology takes over in terms of sensitivity, with the γ ISR + dijet channel constraining g_{q} ¿0.15-0.2 up to 350 GeV, where the jet ISR + dijet channel is not limited by trigger thresholds anymore and is more sensitive due to the higher gluon radiation rates. Searches with jets at the trigger level are the most sensitive to low-mass mediators where available, excluding simplified models with g_{q} as low as 0.05 starting from 400 GeV. Standard dijet searches constrain models with DM mediators up to 3 TeV. Dilepton searches are more sensitive than dijet searches in case of equal couplings of the mediator to leptons and jets, due to the much reduced backgrounds. ATLAS and CMS searches with the 2015+2016 dataset probe signal masses starting from 150 and 400 GeV respectively.

3.2.6. Comparison of sensitivity of visible and invisible LHC searches. It is important to note that generic searches for new two-body resonances are by design sensitive to a broad range of theoretical benchmarks, and as such they alone can offer little information on whether a discovery would imply in terms of DM mediators. In absence of a signal and within a specific model scenario, searches for mediator particle with visible decays provide constraints that are complementary to those of searches for DM particles, in particular in the off-shell region $2m_{\chi} > M_{\mathrm{med}}$ where the mediator cannot decay to DM directly but can still decay into much lighter SM particles such as leptons and quarks. The relative sensitivity of the two kinds of searches is a model- and parameter-dependent statement: for $s-$channel simplified models searches for DM particles only dominate if the coupling to DM is much larger than the coupling to quarks, and even then reducing g_{q} reduces the LHC production cross-section and therefore the overall sensitivity of $\not{E}_T$ +X searches. One advantage of searches for invisible particles is their sensitivity to models with very light mediators (<50 GeV), since the reach of dijet and dilepton searches to low-mass resonances is still ultimately limited by data taking constraints.

A sketch of the comparison of the sensitivity of searches for visible decays of vector and axial vector mediator models, and invisible DM particles in the m_{χ} vs M_{med} plane is shown in Fig. 3, fixing the couplings. The choice of plane and the scenarios chosen follow the choices of the Dark Matter Working Group (73), to illustrate the complementarity of different LHC searches for $s-$channel-mediated model of DM and to convey the message that the sensitivity of LHC searches to simplified models of DM depends both on model choice and parameter choice.

The topmost left-hand side figure shows a leptophobic vector mediator with g_{l} =0, g_{χ} =1.0 and g_{q} =0.25, where dijet searches for visible decays of the mediator constrain both on-shell and off-shell region but are limited by data-taking constraints at masses above roughly 50 GeV, where $\not{E}_T$ +X searches take over in the on-shell region. The top-right figure shows the case of an axial vector mediator with reduced quark couplings and equal lepton couplings (g_{q} =g_{l} =0.1 and g_{χ} =1.0), where it can be seen that searches for dilepton resonances cover a larger range of parameter space with respect to dijet resonances but are still limited at low mediator masses; the region constrained by from $\not{E}_T$ +jet searches extends to lower DM and mediator masses with respect to the case of the model with g_{q} =0.25 due to the reduced production rate. The third panel in the bottom left shows the scenario of a vector mediator where lepton couplings are reduced with respect to quark couplings (g_{q} =0.1, g_{l} =0.01, g_{χ} =1.0), where the range of all regions constrained by visible mediator decay searches is considerably reduced with respect to the scenarios with larger couplings.

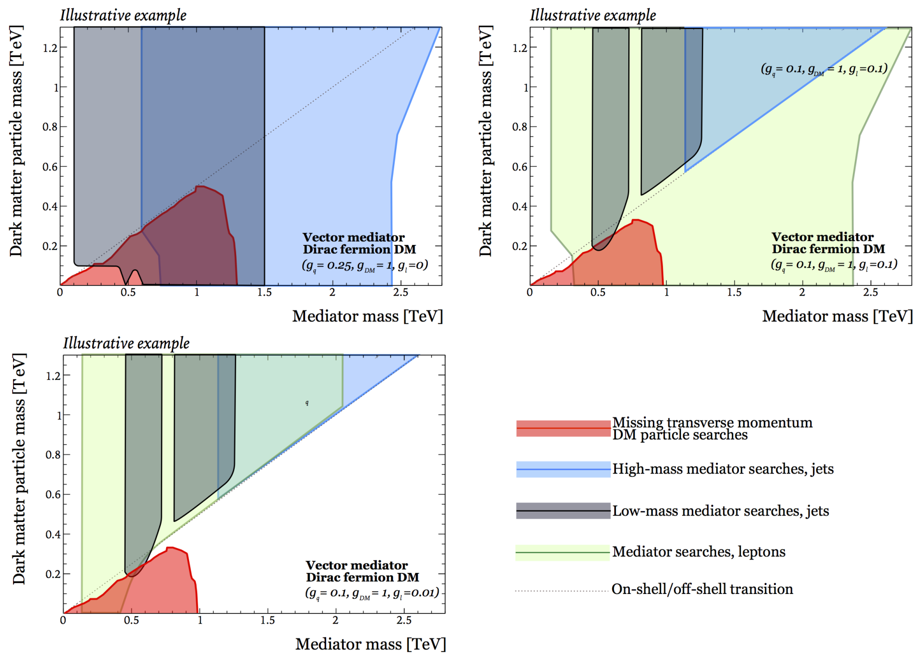

Figure 3

Illustrative examples of the comparison of the sensitivity of searches for visible and invisible mediators in the m_χ-M_{med} plane, for different coupling scenarios. No actual data has been used, but experimental observations have been used as inspiration for the figure. From (**?**).

Table 1 Summary of searches for BSM mediators at the LHC

Signature	Model	M_{med} limit (m_χ =100 GeV)	m_χ limit (M_{med} =100 GeV)	Cit.
Jets+$\not{E}_T$	$s-$channel, AV[a]	Column3	Column4	(101, 102)
Z (lep)+$\not{E}_T$ 1	$s-$channel, AV[a]	Column3	Column4	(119, 120)
Photon+$\not{E}_T$	$s-$channel, AV[a]	Column3	Column4	(116, 117)
Jets+$\not{E}_T$	colored scalar	Column3	Column4	(101, 102)
Jets+$\not{E}_T$	pseudoscalar	Column3	Column4	(101, 102)
Photon+$\not{E}_T$	Column 2	Column3	Column4	Column
W,Z (had)+$\not{E}_T$ 1	Column 2	Column3	Column4	Column
W,Z (lep)+$\not{E}_T$ 1	Column 2	Column3	Column4	Column
Higgs+$\not{E}_T$	Column 2	Column3	Column4	Column

[a] Coupling values: g_{q} =0.25, g_χ =1.0; [b]second table footnote.

3.3. Searches for SUSY DM

Left for AB.

3.3.1. Searches for sparticles.

3.3.2. pMSSM scans.

3.3.3. Searches for electroweakinos.

3.4. Searches for DM in association with long-lived particles

4. EXTRAPOLATION OF COLLIDER RESULTS

Models of particle dark matter involving SM-DM interactions necessarily link searches for DM at collider and searches in direct and direct detection experiments. Figures 4 (a-c) show that, in the EFT paradigm, different search strategies are simply looking at the same process from different perspectives: DM can interact in the lab in DD experiments, it can be observed in space by ID experiments, and it can be created in the lab by colliders and observed by experiments such as ATLAS, CMS and LHCb. This complementarity of multiple search targets in different experiments is necessary to elucidate the nature of dark matter in case of a discovery. Collider experiments are unable to determine whether a new phenomenon with the signatures discussed in Sec. 3, originates from an invisible particle or from a DM mediator.

On the other hand, collider experiment can make a prediction for the signal strength of a particular model and test its consistency with relic density. This prediction can be verified in presence of a signal in DD and ID, and the connection with the galactic nature of the new phenomenon can be established. Colliders can also shed light on the physics processes that complement DM production, e.g. as in Fig. 4 (d) colliders can discover the new particle mediating the interaction and measure its coupling to SM particles other than quarks and gluons.

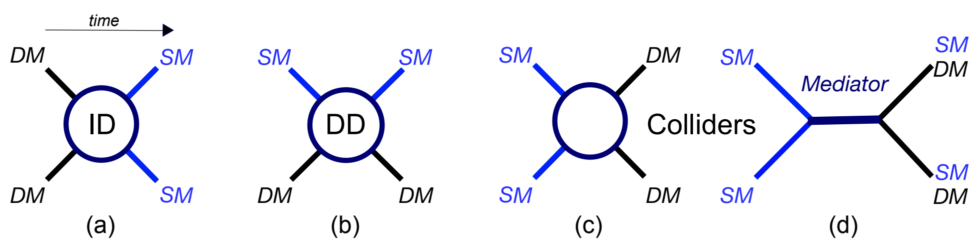

Figure 4

Schematic illustration of Dark Matter interactions and their corresponding experimental detection techniques, with time flowing from left to right. Fig. (a) shows DM annihilation to Standard Model particles, as sought by Indirect Detection (ID) experiments. Fig. (b) shows DM -¿ SM particle scattering, targeted by Direct Detection (DD) experiments. Fig. (c) shows the production of DM particles from the annihilation of SM particles at colliders. Fig. (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. From (31), inspired by (151).

It is also worth mentioning that, even though comparisons between collider, DD and ID have become, the comparison with LHC, DD and ID results with results from astrophysics is a growing field. This is particularly important since all the observational evidence of DM that we have is gravitational, so DM properties such as mass and density in our and other galaxies can be inferred from galaxy simulations or deviations in astrophysical observables, and signatures of DM self-interactions in rotation galaxies or cluster collisions can complement and verify any DD observations. Even though we do not cover this topic in detail in this review we refer to (152).

4.1. Comparing LHC constraints from visible and invisible searches with non-collider results

The comparison of results from complementary experiments needs a mechanism to relate the processes that will produce a signal in each type of detectors. This ultimately means that any comparison between LHC, DD and ID needs a fully specified theoretical benchmark to be predictive and consistent. Since there are a large possible number of options to choose from, it is always important to keep in mind that such comparisons are model-dependent and the choice of benchmark can have severe implications for the conclusions drawn.

Tevatron and Run-1 LHC searches mainly used EFTs as the common theoretical ground to compare their constraints on DM across experiments, or full models such as SUSY. EFTs are a good and flexible benchmark model to represent DM interactions in DD and ID experiment, since the momentum transfer of the collision is sufficiently low not to resolve the theory beyond the scale of the interaction and certainly below the electroweak scale. As discussed in Sec. 2.4.1, this is not always the case for high-energy collider experiments. The difference in interaction scales also requires that any operator in the model is evolved from the scale of the LHC collisions to the nuclear scale of DD through renormalization group expansion (RGE) (153) for full consistency of the results. An example of a comparison plot between collider and DD results using EFT operators in the WIMP-nucleon cross-section vs WIMP mass plane[9], without evolving the operators using RGE but showing the effects of the truncation of the events where the EFT is invalid, is shown for the LHC Run-1 results in Fig. 5. What can be inferred from the plot is that within this class of models and spin assumption the ideal region for the discovery of DM is that where WIMPs have masses above 10 GeV, as both collider and DD experiments are sensitive and could verify each other's claims. Next-generation DD experiments are expected to lower the minimum sensitivity thresholds in the next decade, see e.g. (154).

With the adoption of simplified models of DM by LHC searches in Run-2 (10), the constraints and caveats of the comparisons between DD and ID have been made clearer, even though the comparisons themselves have become more model-specific and so far privileged $s-$channel models with fixed coupling values. ATLAS and CMS follow a series of recommendations and well-defined procedure by the Dark Matter Working Group (56). LHC experimentalists and theorists have chosen to translate the collider results on visible mediator and invisible DM searches from the m_χ, $M_{\rm med}$ plane to the DD and ID planes, so that all information on the results that are reinterpreted are available and all assumptions can be clearly spelled out. An example of such a comparison including the most recent LHC and DD results is shown in Fig. **??**. In this kind of comparisons, it should be noted that the colliders limits do not include any constraint on the relic density, and that absolute exclusion of the different collider searches as well as their relative importance depend strongly on the benchmark scenario and its coupling. We also note that neither this procedure nor the benchmark models used are explicitly accounting for effects that may be important for

[9]The formulas to translate LHC limits to this plane can be found in Ref. (24)

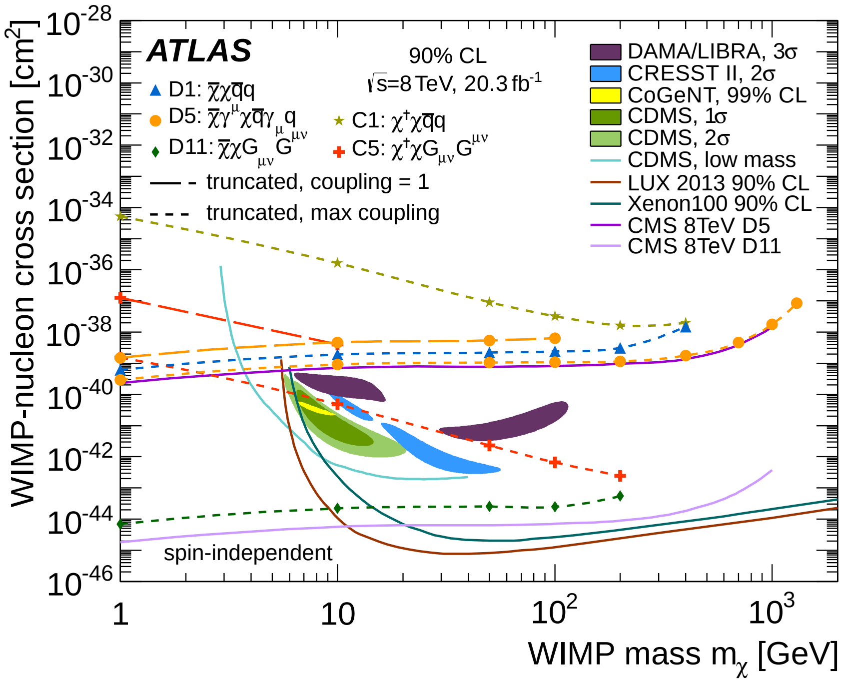

Figure 5

Inferred 90% CL limits on (left) the spin-independent and (right) spin-dependent WIMP–nucleon scattering cross section as a function of DM mass m? for different operators. Results from direct-detection experiments for the spin-independent and spin-dependent cross section, and the CMS (untruncated) results are shown for comparison. From (31).

mediators with masses below 100 GeV, such as interference and mixing with the X boson, quarkonia resonances and unitarity violation.

Recently, LHC results have also started to be utilized by DD collaboration for constraints of simplified models of DM, see e.g.(156, 157). IceCube and other experiments have used constraints from a MSSM scan, see e.g. (158).

The comparison of collider and ID results using simplified model benchmarks has received new attention since the publication of (56). In traditional comparisons, only one DM annihilation state at a time has been used for the comparison of collider and ID results (e.g. $b\bar{b}$, see for example (63)). The work in (159) considers multiple final state fermions and interprets ID and LHC results in simplified models with $s-$ and $t-$channel mediators.

4.2. Relic density

5. FUTURE EVOLUTION OF COLLIDER SEARCHES

Mention inclusive vs exclusive searches, monojet is the basic event selection then one selects more things on top of that.

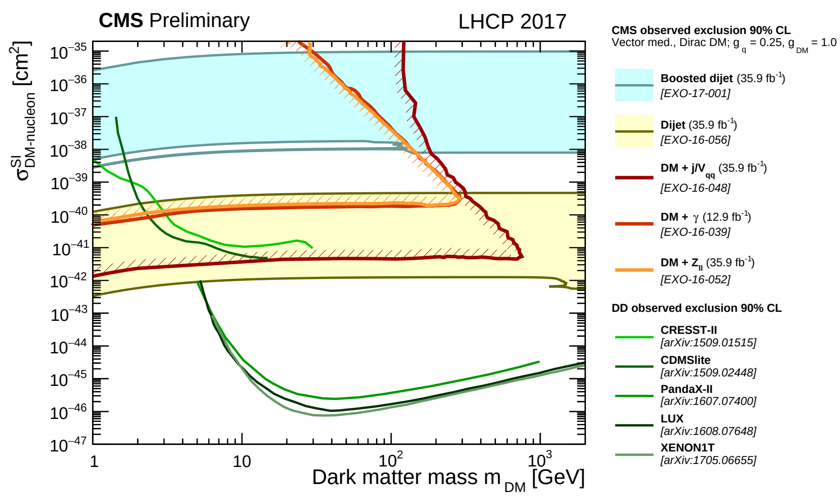

Figure 6

The 90% CL CMS constraints in the m_χ-spin-independent DM-nucleon plane, for a vector mediator, Dirac DM and couplings gq = 0.25 and gDM = 1.0, compared with DD experiments. From (155).

SUMMARY POINTS

1. Summary point Note. These should be full sentences.
2. Summary point 1. Both broad and targeted searches at the LHC are necessary
3. Summary point 2. The LHC is a mediator-producing machine
4. Summary point 3. DM is a good motivation to implement novel techniques
5. Summary point 4. DM connected people in the DMF and DMWG, LHC community effort
6. Summary point 5. Complementarity is important to elucidate DM

FUTURE ISSUES

1. Summary point Note. These should be full sentences.
2. Future issue 1. HL-LHC and precision searches
3. Future issue 2. Dark sectors and DM particles near the range of the SM are worth looking for, not just high-mass EW scale WIMPs
4. Future issue 3. Look out for community efforts, try to include DD and ID and low-mass experiments

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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