Dark Matter Searches at Colliders

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Contents

1. INTRODUCTION

Define Standard Model (SM), Dark Matter (DM). There is an "acronym" section we could use.

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. (1). 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.

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.

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

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 (2).

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 (3).

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 (4, 5, 6, 7).

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 (8). This kind of portals are also present in a number of other theories (9). 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 (10). 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. (9, 11)). 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. (9).

2.3.2. Higgs portal models.

The discovery of a SM-like Higgs boson (12, 13) 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. (14, 15, 16)). 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 (17, 11, 18).

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 (19, 5), used as building blocks for more complex theories in models of DM and elsewhere, see e.g (20, 21, 22, 23, 24), 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. (25)).

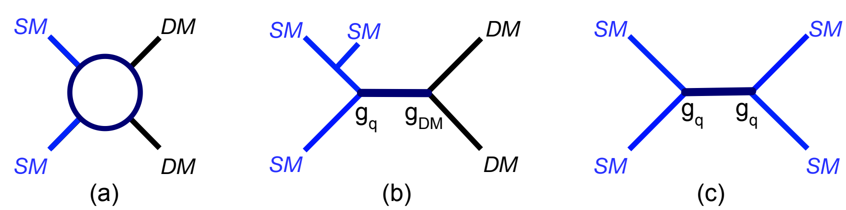


Figure 1

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 (26).

2.4.1. Effective Field Theories. **Effective field theories** (EFTs) (19, 27) 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 (28). EFT operators were first widely employed to describe DM reactions at colliders at the Tevatron (29, 30). 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 (31, 32, 33). Certain EFT operators also may suffer from gauge invariance issues at the electroweak scale (34). However, if no completion is available, EFTs are still a good benchmark to motivate the exploration distinct kinematic regions and signatures at the LHC.

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 (35, 36, 37, 38). A recommendation on how to present EFT results from LHC searches can be found in (5).

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. (39, 33)). These models provide a direct SM-DM interaction and motivates searches in final states with a vector boson accompanied by $\not{E}_T$.

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 (10)). 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.

The DMF was built starting from the discussion of various communities in Refs. (41, 42, 43). All models covered in (5) are available on the DMF git repository. Add reference.

For a comprehensive review of WIMP simplified models of DM at the LHC, we refer to (6), while (5) 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 (5), 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) (40).

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 (44, 45, 46) 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. (47, 48).

Massive spin-1 bosons with axial or axial vector couplings to SM and DM particles (27) 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?].

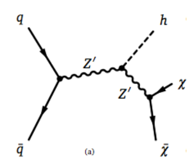
Vector and axial vector mediator models can include couplings of the Z' to the Higgs boson, so that the Z' boson can acquire mass through a new baryonic Higgs h_B (33). This collapses to the simpler vector model in the limit of very heavy Z' mass. When the interaction between the Z' and the SM Higgs is relevant, it can be parameterized using the Z'-SM Higgs coupling $g_{hZ'Z'}$, the mixing angle between the SM Higgs and the baryonic Higgs, $sin(\theta_B$, the vacuum expectation value of h_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 been negleccted in LHC Run-2 searches so far.

In certain region of this parameter space, especially at low mediator masses, the leptophobic Z' model can satisfy the relic density constraints (49). However, if taken in isolation, these models are non-renormalizable, and the axial vector model violates perturbative unitarity in certain regions of the parameter space (see Ref. (50) and references therein) if m_{χ} is larger than M_{med}.

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. (51)) 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. (52) 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 (53, 54) and the associated production of the mediator together with heavy flavour quarks (51). 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 (55), 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.

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 (5), 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 (56, 57) and collider searches are favored when comparing to DD (58), LHC searches have privileged this choice and considered the associated scalar boson as decoupled at higher energies.



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

In the most general scalar potential, the scalar can couple to DM through a Higgs portal (33). 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 (59, 60). 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 $SU(2)_L$ (61). 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 (62, 44, 45, 46) 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 (5). 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 (46).

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 (5).

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 (46). 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. (63). The parameters and couplings of this model have also been tuned to explain the gamma ray excess and motivate searches with a single $b-$quark in the final state (57), 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. (64, 65).

Dijet searches are sensitive to vector and axial vector DM mediators decaying exclusively to jets with couplings that would satisfy relic density constraints (49), 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 (66, 67).

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. (68) and references therein). A simple extension of the leptophobic vector and axial vector models allows the mediator to decay into leptons at tree level. 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 (68).

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. (69, 70, 71). The strong interaction between these two DM states drives the cosmological history (2), 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 (69). 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 (71). 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 (59, 33). A further refinement is to embed the scalar/pseudoscalar model in a more complete theory, namely a Two-Higgs Doublet Model (2HDM) (72, 73, 74, 75, 61). 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 (74), 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

[left for AB, see ooutline]

Other BSM theories including DM particle candidates that are not covered in this review are extra dimensions (76), and DM as sterile neutrino (77). 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 targeting those non-standard decays. These will be discussed in Chapter FUTURE.

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 $m_\chi > M_{\rm med}$), 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 (78), and its visible decays into SM particles or associated production with a SM boson provide the main collider handle (79). There is a large possible dark boson mass range that is still compatible with thermal freeze-out, from 1.5 GeV to 40 TeV (80), 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. (81, 3)), 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 (82) 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 (83, 84, 85). 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 and in Section 3.4 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 3.5.

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 pair of neutrinos, 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.

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.

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 (86) 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 (87). New physics effects modify direct and/or indirect Z width (88). The LEP precision measurements [1], as well as direct detection experiments, rule out the majority of the Z-mediated DM scenarios (9, 11). 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 (89) rule out most of the other simplified model scenarios compatible with freeze-out relic density up to multi-TeV DM masses.

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 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

[1] Bounds on Z to invisible decays obtained from LHC searches are not yet competitive (18).

[2] For the case of heavier DM particles, see Ref. (16).

using Run-1 and Run-2 data (90, 91) employ and combine the $qq \rightarrow Hqq$, $qq \rightarrow VH$, $gg \rightarrow HZ$, $gg \rightarrow Hg$ 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 $qq \rightarrow Hqq$ 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 $gg \rightarrow Hg$ 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 (92, 15, 91).

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 (11, 16). 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 (93, 30, 29). 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 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 (94). For this reason, the most recent LHC searches for MET with jets (95, 96) 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. 3.4.2.

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) is rejected with specific quality criteria discussed in Sec. 3.4.1. 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 ($Z \to ll, W \to l\nu + jets$, 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. 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 (97). 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 Sec. 3.4.3. 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 (5), 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_{med} plane fixing the couplings to g_{q} =0.25 and g_χ =1.0 for vector and axial vector mediated models, g_{q} =g_χ =1.0 for scalar and pseudoscalar models and $g_{\chi q}$ =1.0 for colored scalar models.

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_χ >0.3 TeV at m_χ =1.8 TeV for the vector mediator, and for 0.65<m_χ <0.75 TeV at m_χ =1.8 TeV for the axial vector mediator. 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_χ = 10 GeV are excluded for $g_{\chi q}$ =1. Considering this exclusion limit, this model still provides a viable DM relic density for M_{med} m_χ above roughly 500 GeV at M_{med} =1.7 TeV[3].

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

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 (98). Additionally, a simplified likelihood function (99), which under certain assumptions approximates the full likelihood using a reduced set of information, is provided for the CMS result (95) and has been used for reinterpretation (100). 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 (101), 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 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 (102, 103). Moreover, the sensitivity hierarchy of $\not\!\!E_T$ +X searches does not privilege the jet+$\not\!\!E_T$ final state if there is a direct new physics coupling between the vector boson and the DM, as in the case of the EFT model mentioned in Section 2.4.1.

ATLAS and CMS have pursued searches for missing transverse momentum produced in association with a photon(104, 105), vector boson decaying hadronically (95, 106) or leptonically (107, 108).

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 provided by either the photon object 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 (108) as opposed to 200 GeV for the jet+$\not\!\!E_T$ search (95).

The background estimation technique for the main γ/V+$\not\!\!E_T$ search backgrounds mirrors that of the jet+$\not\!\!E_T$ search, where $\not\!\!E_T$ is emulated by removing visible boson decays from the event energy balance in control regions, and transferring the number of measured events to the signal region.

Another approach is to follow a mono-Higgs event selection and reinterpret the results.

Jets faking leptons or photons, as well as pions that convert to photons within the detector volume, are reducible backgrounds for these searches.

The main experimental uncertainties for V+$\not\!\!E_T$ searches and the sensitivity to specific

Searches in the $\not\!\!E_T$ +leptonic Z final state provide constraints on $M_{\rm med} < 650$ GeV for vector and axial vector mediators, while they are not yet sensitive to scalar and pseudoscalar mediated models.

Talk about t-channel and radiation.

Hadronic decays of the Z constrain

Leptonic decays W bosons have also been used in the past for this kind of searches, but due to the additional experimental challenges (invisible decays)

3.2.3. Searches with heavy-flavor quarks.

3.2.4. Search signatures including the Higgs boson.

3.2.5. Two-body mediator searches.

Table 1 Summary of searches for BSM mediators at the LHC

Signature	Model	$M_{\rm med}$ limit (m_χ =100 GeV)	m_χ limit ($M_{\rm med}$ =100 GeV)	Cit.
Jets+$\not\!\!E_T$	$s-$channel, AV[a]	Column3	Column4	(95, 96)
Z (lep)+$\not\!\!E_T$ 1	$s-$channel, AV[a]	Column3	Column4	(107, 108)
Photon+$\not\!\!E_T$	$s-$channel, AV[a]	Column3	Column4	(104, 105)
Jets+$\not\!\!E_T$	colored scalar	Column3	Column4	(95, 96)
Jets+$\not\!\!E_T$	pseudoscalar	Column3	Column4	(95, 96)
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: $g_{\rm q}$ =0.25, g_χ =1.0; [b]second table footnote.

3.2.6. Comparison of sensitivity of visible and invisible LHC searches.

3.3. Searches for SUSY DM

3.3.1. Searches for sparticles.

3.3.2. pMSSM scans.

3.3.3. Searches for electroweakinos.

3.4. Experimental challenges for DM searches at the LHC

Now that we have seen the searches for invisible particles and their sensitivity to DM models, we will cover the experimental challenges more in detail, as those will be the key to fully exploit the Run-2 and Run-3 datasets.

3.4.1. Missing transverse momentum. Main points:

- The measurement of $\not\!\!E_T$ relies on the precise measurement of all reconstructed physics objects.
- Some description of $\not\!\!E_T$ significance may be needed, but it may also be too academic.
- Fake $\not\!\!E_T$ is rejected using quality cuts.
- Pile-up needs specific techniques because of the soft terms.
- $\not\!\!E_T$ at the trigger level is the driving reason why we can't go lower, see next section.

3.4.2. Event selection: triggering on visible and invisible particles.

3.4.3. Precise background estimation.

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

4. EXTRAPOLATION OF COLLIDER RESULTS

5. FUTURE EVOLUTION OF COLLIDER SEARCHES

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

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

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