SEARCHES FOR DARK MATTER AT THE LHC

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Astrophysical measurements show that around 85% of the universe consists of dark matter, the origin of which is unknown. Dedicated experiments search for dark matter in the cosmos interacting directly and through annihilation. Particle colliders may also be used to search for the origin of dark matter and may provide complementary information. This paper reviews searches for dark matter performed by the ATLAS and CMS Collaborations at the Large Hadron Collider at CERN.

1 Introduction

Astrophysical measurements show that around 85% of the universe consists of dark matter (DM), the origin of which is unknown [1]. All direct evidence for DM is of a purely gravitational nature, however the most studied model of DM predicts weakly interacting particles which, in order to account for the observed relic density of particles from the early universe, would be accessible at the electroweak scale and would have significant couplings to standard model (SM) particles [2]. The Large Hadron Collider (LHC) at CERN collides beams of protons at centre-of-mass energies up to 13 TeV, allowing electroweak scale interactions to be probed thoroughly.

Searches for DM at colliders such as the LHC provide a complementary approach by searching for evidence of the production of DM particles instead of the scattering and annihilation processes probed by underground direct detection experiments and astronomical indirect detection searches, as illustrated in Fig. 1. The three different approaches also have different sources of systematic uncertainty. Direct and indirect searches are affected by astrophysical uncertainties, such as the velocity and density of DM in the universe, while the collider environment is more controlled and would permit the study of DM in the laboratory, provided that the energy of the collider is high enough to allow the production process.

Current searches for DM from the ATLAS [3] and CMS [4] collaborations, and prospects for future searches, are reviewed in this paper.

2 Interpretation

Effective field theory interpretations are typically used for (in)direct searches, where the momentum of the interactions with SM particles is small. For collider searches however, with high momentum transfer, such interpretations have validity concerns. The LHC community has developed a phenomenological framework for interpretation, based on *simplified models* as used

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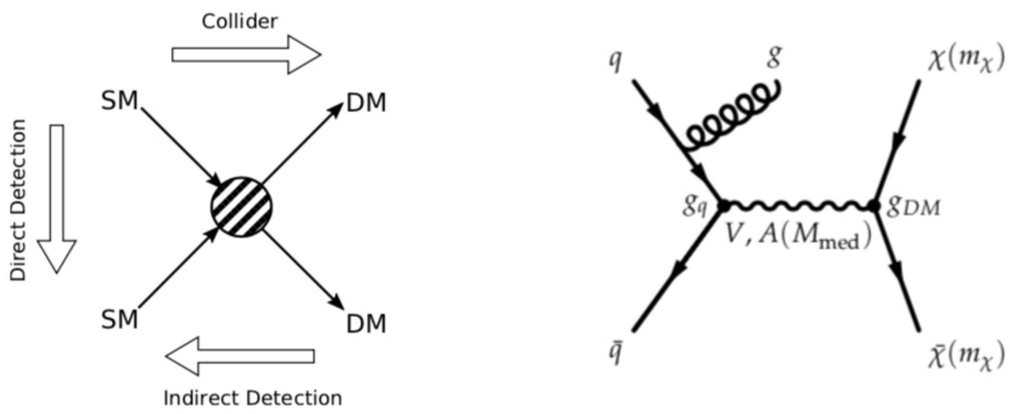


Figure 1 – Illustration of DM scattering, annihilation and production in direct, indirect and collider interactions, respectively (left). Feynman diagram illustrating DM production, with initial state gluon radiation, at the LHC (right).

commonly in other searches at the LHC. This approach aims to capture generic signatures, common to many complete theories, giving a more complete description of interactions. Benchmark models have been developed within the context of the LHC Dark Matter Working Group [5 6] and are used widely to express LHC search results.

The simplified models most widely used assume the DM candidate particle is a Dirac fermion and the particle mediating the interaction is a boson. The models introduce four parameters: the couplings of the mediator to DM (g_{DM} or g_χ) and SM (g_q) particles, and the masses of the mediator (M_{med}) and DM (m_χ or m_{DM}) particles. The width of the mediator is then calculated as the minimum allowed by the parameter values. Figure 1 illustrates the definition of these models.

Results are usually expressed in terms of limits on the two masses in the model, which requires the couplings to be fixed to agreed values. The conventional values are $g_{DM} = 1$ and $g_{SM} = 0.25$ for spin-1 vector or axial-vector mediators and $g_{DM} = 1$ and $g_{SM} = 1$ and proportional to the mass of the SM particle for spin-0 scaler or pseudo-scaler mediators, to respect minimal flavour violation, giving stronger couplings to third generation fermions.

3 Detection at the LHC

The nature of DM, weakly interacting, stable and with no electric or colour charge, means that it is not expected to interact in the LHC detectors. In collider experiments the presence of invisible particles is usually inferred by the measurement of non-zero missing momentum in the transverse plane. In the case of a fully invisible dark matter final state, initial state radiation is necessary to allow analysis of the event. Since SM events may also have missing transverse momentum through the production of neutrinos and detector effects, searches for DM must search for excesses of events over the predicted SM background at large values of missing transverse momentum. Measurement of missing momentum is very challenging, requiring excellent detector calibration and understanding of noise and backgrounds.

In collider experiments, in addition to the dark matter particle itself the mediator may also be searched for. The mediator may have significant couplings to standard model particles, and in such cases the mediator may be produced and its decay to SM particles observed as a mass resonance.

A wide range of signatures are probed at the LHC in the search for dark matter. This paper covers a selection of results, some representative of key techniques, and some highlighting new results. Most of the analyses presented are based on the data taken in 2015 and 2016, corresponding to an integrated luminosity of 36 fb^{-1}. None of the searches to date have observed any significant deviations from the standard model predictions, and therefore the results constitute limits on the properties of dark matter.

3.1 Invisible searches

The first class of searches has a signature of initial state radiation and large missing transverse momentum.

The ATLAS collaboration has searched in events with initial state gluon radiation [7] (see Fig. 2). The main standard model background stems from Z-boson decays to neutrinos which represents about 60% of the total background. Over a large range of the phase space considered the search is limited by systematic uncertainties of 5-10% from the modelling of the Z-boson transverse momentum. Figure 2 shows the missing transverse momentum distribution for this signature. Figure 3 shows interpretations of this search, in terms of the masses of the dark matter and mediator particles, for fixed couplings and also converted into a spin-dependent cross section limit, to allow comparison with direct detection limits.

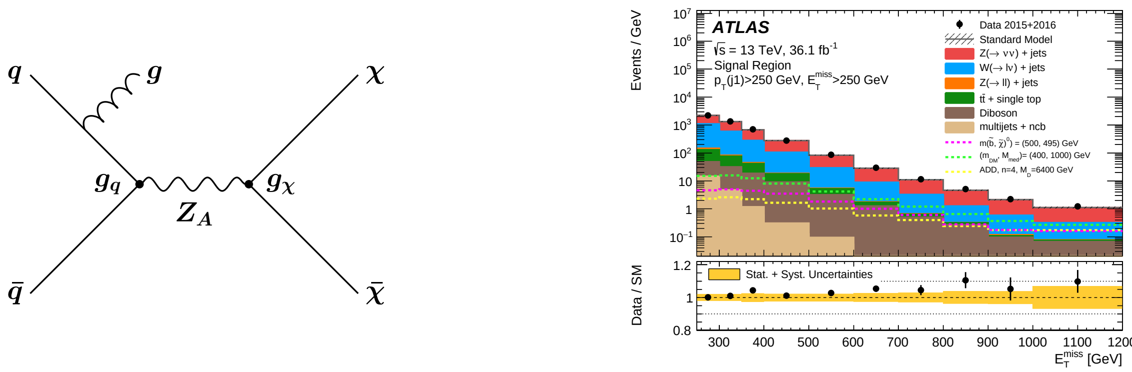


Figure 2 – Feynman diagram illustrating the DM production process in association with an initial state radiation gluon (left) and the missing transverse momentum distribution (right) showing the expected SM backgrounds and data yields [7].

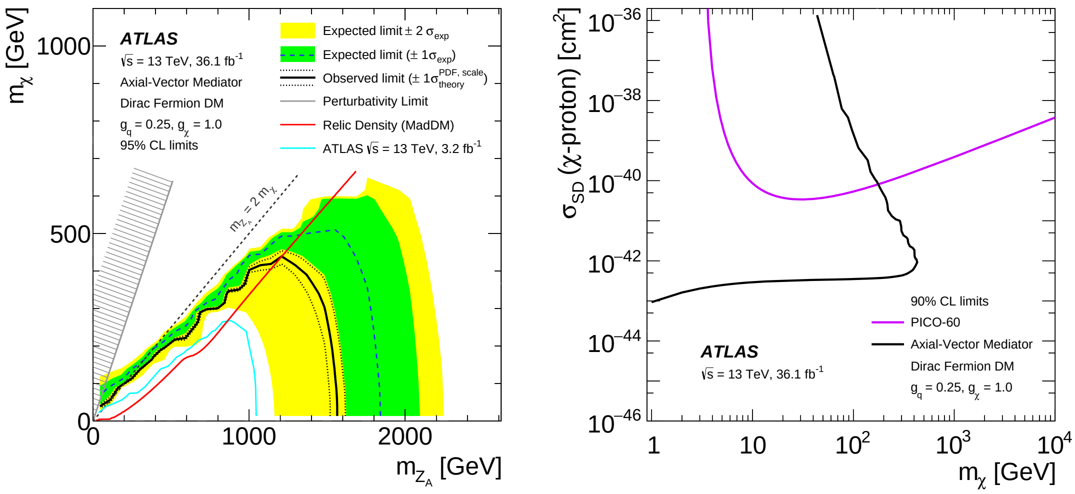


Figure 3 – Results of the ATLAS single jet and missing transverse momentum search [7], in terms of the masses of the dark matter and mediator particles, for fixed couplings (left), and converted into a spin-dependent cross section limit, to allow comparison with direct detection limits (right).

Similar searches with initial state radiation of a photon can also be performed. Figure 4 illustrates such a search by the CMS collaboration [8], showing the photon transverse energy distribution used to extract a limit on DM scattering cross sections. The photon process is suppressed compared to the gluon process by the difference in their coupling constants, but benefits from less background, allowing the search to extend to lower values of the momentum of the radiated particle. Searches with a Z boson in the place of the photon allow further reductions in the momentum at the price of lower yield overall.

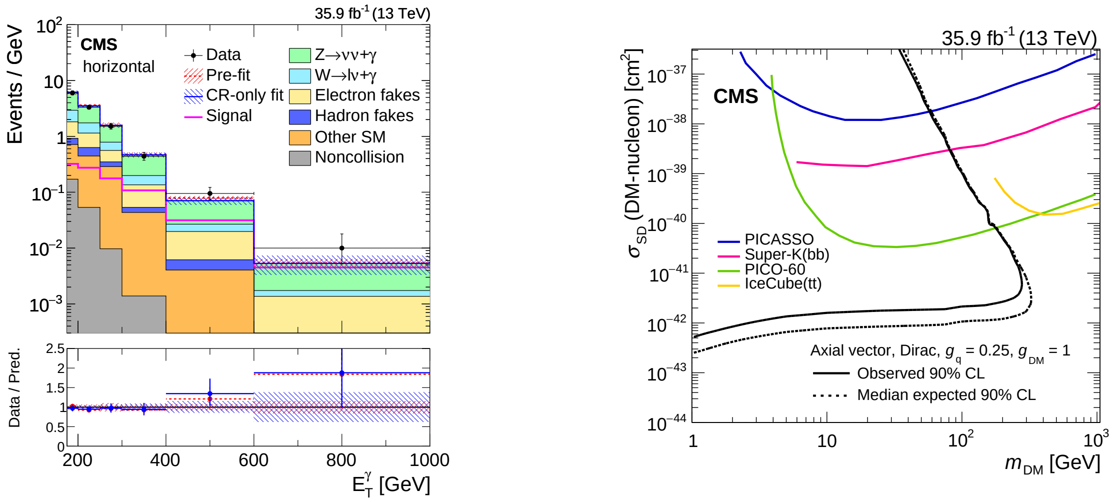


Figure 4 – The transverse energy of the photon in the CMS single photon and missing transverse momentum search (left) and the corresponding cross section limit plot, showing the LHC results extending to lower DM masses (right) [8].

Searches with a single Higgs boson in the place of the photon from ATLAS [9], based on 80 fb^{-1} of data, and CMS [10] based on 36 fb^{-1} of data, have also been performed, probing the coupling between the DM mediator and the Higgs boson. The searches use a combination of channels including Higgs decays to paris of τ-leptons, b-quarks, photons, and W and Z bosons, with the sensitivity driven by the $b\bar{b}$ channel.

Finally, DM may be produced in association with a single or pair of top quarks, as illustrated in Fig. 5. A spin-0 mediator would couple strongly to the third generation quarks, making this a senstive search channel. The CMS result [11] shown in Fig. 5 uses both (semi) leptonic and hadronic top decays to search for this process, combining the channels to extract the limit shown in Fig. 6 excluding scalar and pseudo-scalar DM mediator particles below around 300 GeV.

3.2 Mediator searches

In addition to searching for evidence of the dark matter particles themselves, at colliders it is also possible to search for mediator particle decays to SM particles. Such searches are complementary to the invisible searches and are experimentally cleaner and easier to perform. If the DM particle itself is too heavy to produce or has a very weak coupling to the mediator, then searches for the mediator may be preferred to direct searches.

Figure 7 illustrates the production and decay processes for a DM mediator and shows a summary of searches from ATLAS [12]. The results include a wide variety of channels, mainly searches for mass resonances, including dijet resonances, top-quark resonances etc. Limits on the mass of the mediator extend over 2 TeV but depend strongly on the couplings of the meditor to SM particles.

It is also possible that the mediator is not a new, exotic particle but a SM particle, such as the Higgs boson (referred to as Higgs portal models). Both ATLAS [13] and CMS [14] experiments search for invisible decays of the Higgs boson, which may be interpreted in Higgs portal models of DM. The SM branching ratio for Higgs to invisible particles is around 0.1% (via ZZ decays to neutrinos) but may be significantly enhanced by decays to DM particles. The dominant

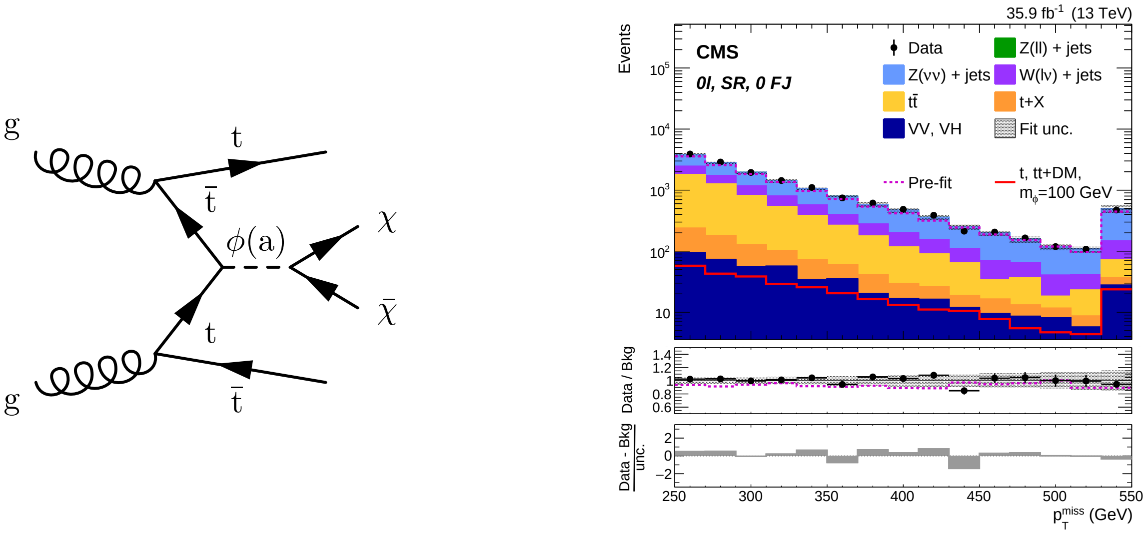


Figure 5 – Feynman diagram for DM production in association with top-quark pair-production (left) and the missing transverse energy distribution for the hadronic top search sample (right), showing the expected SM backgrounds and the data. [11]

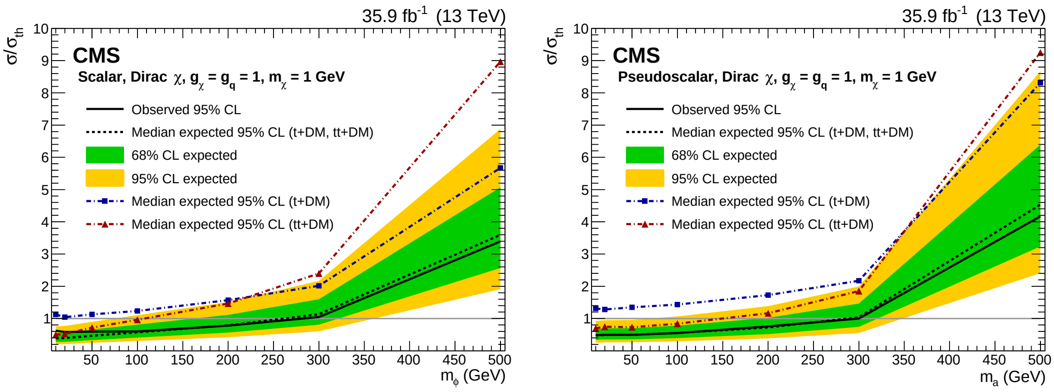


Figure 6 – Limits on the ratio of production cross section to the SM prediction, for scalar (left) and pseudo-scalar (right) DM mediators for single top and top pair-production processes and the combination of both [11].

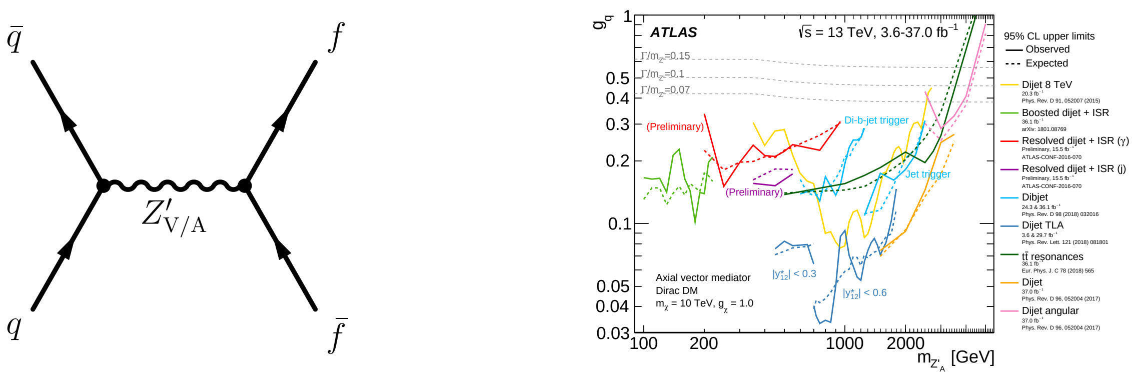
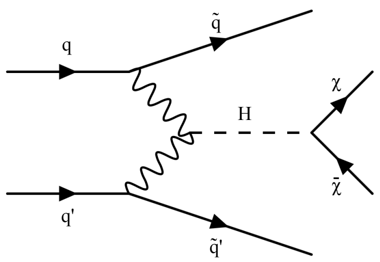


Figure 7 – Feynman diagram for dark matter mediator production and decay to SM particles (left) and a summary of ATLAS searches in this channel, in the plane of mediator mass and coupling to SM particles (right) [12].

process for these searches is the vector-boson fusion production process shown in Fig. 8. Both collaborations use the invariant mass distribution of the jets in this process to search for a potential signal above the SM background from W and Z boson decays (see Fig. 8). This channel is combined with other channels, shown in Fig. 9, to set limits on the branching ratio of $BR(H \to \text{invs.}) < 0.26$ obs. (0.17 exp.) for ATLAS and $BR(H \to \text{invs.}) < 0.19$ obs. (0.15

exp.) for CMS. The result may also be interpreted as a cross section limit for DM scattering off a nucleon, and compared to direct detection limits, as shown in Fig. 9, where the LHC results extend coverage to lower DM masses.



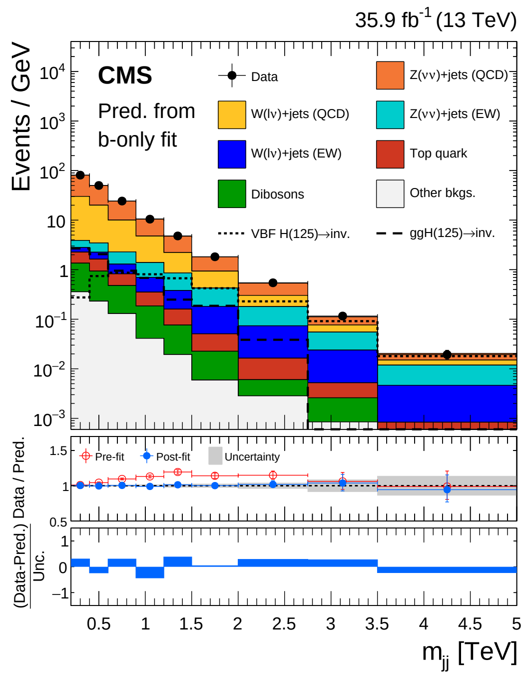
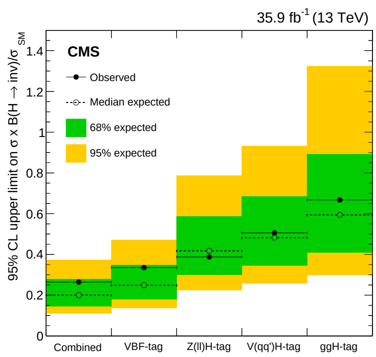


Figure 8 – Feynman diagram for the vector-boson fusion production of a Higgs boson and subsequent decay to dark matter particles (left) and the invariant mass distrbution used to set limits on this process, showing the expected SM background and observed data (right) [14].



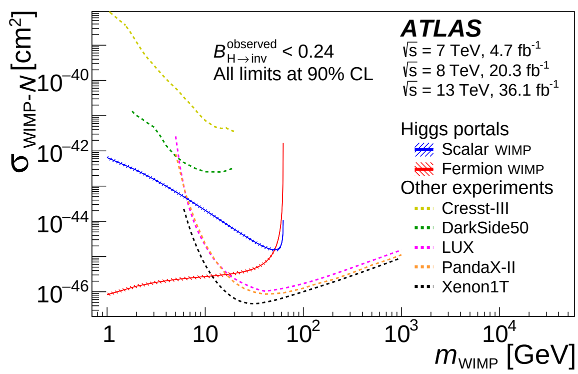


Figure 9 – Limits on the cross section for Higgs decays to invisible particles, showing the relative contributions of different channels [14] (left) and cross section limits for DM particles scattering off nucleons (right) [13].

4 Future prospects

The results of a selection of current searches have been projected to future data samples. Two datasets were considered, 300 fb^{-1} corresponding to the dataset expected to be available before the next large upgrade of the LHC experiments, and 3 ab^{-1} corresponding to the ultimate LHC dataset.

The ATLAS collaboration have studied the projection of the single jet and missing transverse momentum analysis discussed above[15]. Figure 10 shows the results expected for the two datasets. The limits increase by around 500 GeV in mediator mass, between the two datasets. Different scenarios for how systematic uncertainties evolve with the dataset size are also shown and play a role in the sensitivity.

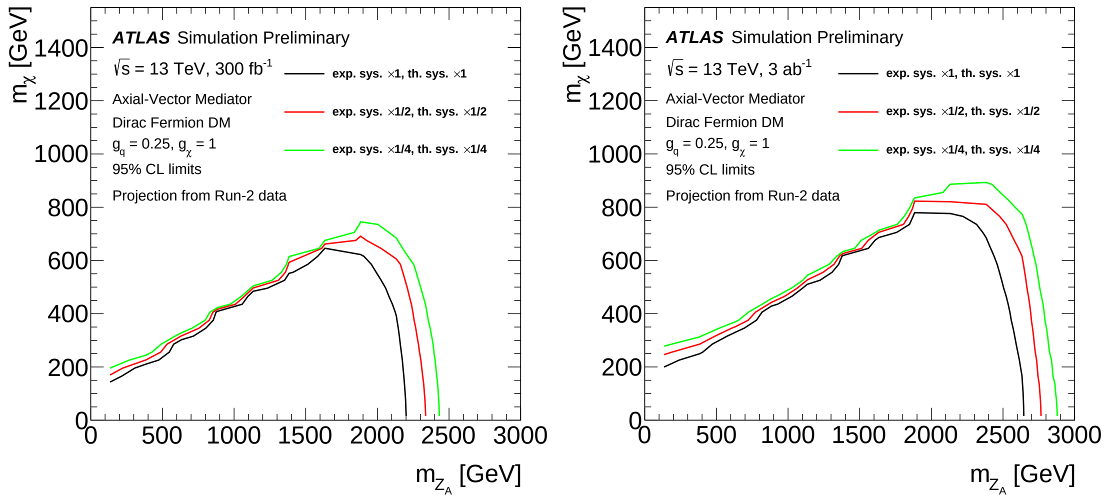


Figure 10 – Limits in the mediator and dark matter particle mass plane, at fixed values of the couplings, for 300 fb^{-1} (left) and 3 ab^{-1} (right), illustrating the increased sensitivity and the effect of systematic uncertainties on the sensitivity [15].

The CMS experiment has studied the evolution of a search for events with a Z boson and large missing transverse momentum [16]. Figure 11 shows the potential DM production process and the limits expected for 3 ab^{-1}. It can be seen that the level of systematic uncertainties has a significant impact on the mediator mass range probed.

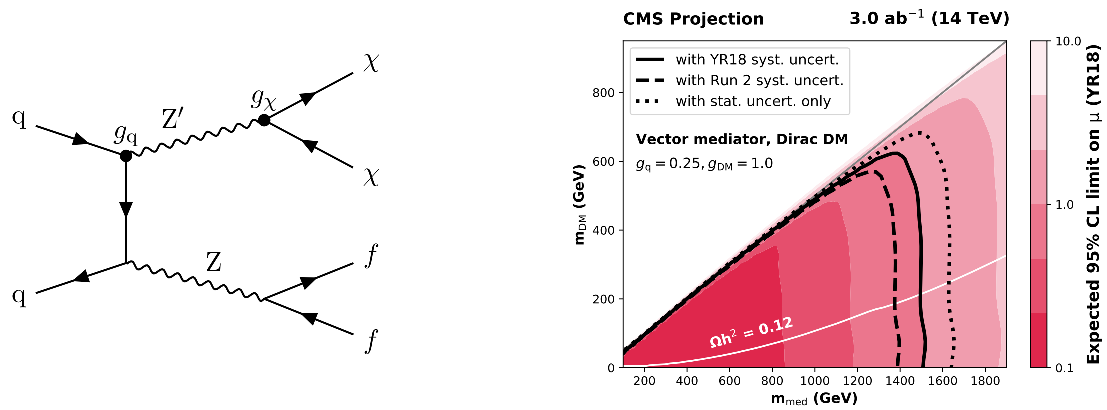


Figure 11 – Feynman diagram for DM production with a single Z boson (left) and limits in the mediator and dark matter particle mass plane for this analysis with 3 ab^{-1} of data (right), illustrating the effect of systematic uncertainties on the sensitivity [16].

5 Summary and conclusions

A broad programme of searches for dark matter is being pursued by the experiments at the LHC, which are complementary to direct and indirect search experiments. Completed analyses, mainly based on 36 fb^{-1} of data, have found no significant discrepancies with respect to standard model predictions and therefore limits on dark matter masses and couplings have been set within the framework of simplified models. A dataset of some 140 fb^{-1} is in hand and further analyses are in progress. Projections for 300 fb^{-1} and 3 ab^{-1}, the expectations for the next epoch and the ultimate LHC dataset have been studied, and motivate improvements in the analysis techniques alongside the collection of larger datasets, to extend sensitivity.

Acknowledgments

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