Collider searches for Dark Matter (ATLAS+CMS)

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Abstract

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SEARCH FOR DARK MATTER AT THE LHC WITH THE ATLAS AND CMS DETECTORS

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Keywords: Dark Matter; LHC; HEP; ATLAS; CMS.

1. Introduction

The existence of dark matter (DM) is well established in modern physics, due to several astronomical observations [1,2]. Precise measurements from the Planck experiment [3] estimate that DM composes the 25% of the total Universe mass-energy budget, nevertheless its nature is still unknown. Several searches for DM have been put in place in the last decades, assuming it is made of particles which interact weakly with the known matter (weakly-interacting massive particles, or WIMPs). In this document the main searches performed using the CMS [5] and ATLAS [4] detectors, exploiting data collected during the first part of the Run 2 of the Large Hadron Collider (LHC) data taking are presented. The integrated luminosity collected by each experiment during this data-taking period is about 36 fb⁻¹.

2. Search for Dark Matter at the LHC

The LHC is a 27 km long circular hadron accelerator and collider located in the underground tunnel originally built for the Large Electron Positron collider (LEP). It currently represents the best machine to search for new physics, thanks to two characteristics:

- The unprecedented collisions center-of-mass energy (13 TeV during Run 2) allows to be sensitive to the production of new heavy mediators.
- Thanks to the high instantaneous luminosity (L = 2 × 10³⁴ cm⁻²s⁻¹), also rare processes with cross sections of the order of the fb can be inspected.

CMS and ATLAS, the two multipurpose detectors located along the LHC ring, at two of the beam interaction points, exploit similar analysis techniques in order to detect the presence of DM, which is not expected to interact in the detector:
• **In mono-X searches** a dark matter mediator is produced by the annihilation of a pair of quarks or gluons and then decays to a pair of WIMPs, which escape the experimental device undetected. To trigger this kind of events, the presence of a detectable SM particle in the event is required. The fact that the WIMPs cannot be recorded creates an imbalance in the momentum measured in the transverse plane, called *missing transverse energy* ($E_T^{miss}$) or *missing transverse momentum* ($p_T^{miss}$), which is a key property of these searches.

• **In mediator searches** the dark matter mediator decays to a pair of quarks or leptons, producing a localized excess of events in the invariant mass spectrum or in specifically chosen angular distributions.

A visual representation of the two approaches is shown in Figure 1.

![Figure 1. Schematic representation of the two search techniques presented in this document.](image)

3. Mono-X Searches

Mono-X searches at CMS and ATLAS follow the recommendations of the ATLAS/CMS Dark Matter Forum [6] for the choice of the models to inspect and their parameters. Particular attention is dedicated to the nature of the mediator, which can be a scalar, a pseudo-scalar, a vector, or an axial-vector, and to the couplings with quarks, leptons, and dark matter particles. Typically scans over the mediator and dark matter particle masses are performed, so that results are provided in terms of limits on the dark matter production cross section, as a function of the mediator and dark matter particle mass, and given a certain set of couplings. Several final states with different SM particles have been inspected: in mono-jet, mono-$\gamma$, and mono-Z searches the SM particle is emitted as initial state radiation (ISR), while in mono-top, mono-Higgs, and $t\bar{t}$+DM searches different kind of models are taken as reference. In this section the current mono-X analyses are described, giving basic details regarding the analysis strategy, the models inspected, and showing the main results.

3.1. Mono-Jet

The mono-jet channel is currently the most sensitive Mono-X search, due to the high probability of emitting an ISR jet. The analysis strategy is similar for CMS and ATLAS, and consists of requiring one energetic jet recoiling against large amount of $E_T^{miss}$. Both the experiments select events with $p_T^{miss} > 250$ GeV, while the jet $p_T$ thresholds are different: 100 GeV for CMS [7], and 250 GeV for ATLAS [8]. The leading jet and the $p_T^{miss}$ are expected to be produced back-to-back, so that an angular separation in the transverse plane of 0.5 (0.4) radians is required by CMS (ATLAS). Events with additional leptons or photon are rejected. The main backgrounds are the represented by the production of $Z\rightarrow \nu\bar{\nu} +$ jets and $W\rightarrow \ell\nu +$ jets, which are estimated in dedicated control regions (CRs). The $Z$+jets process is estimated in a di-lepton control region, enriched in $Z\rightarrow \ell^+\ell^-$ events, in which the momenta of the leptons are used in the computation of the $p_T^{miss}$. In addition, CMS includes a $\gamma$+jets control region, in which the photon transverse energy is included in the $E_T^{miss}$ computation. Similarly,
the W+jets background is estimated in a single-lepton control region, where the lepton momentum is used in the \( p_T^{\text{miss}} \) computation. The signal extraction is performed through a simultaneous fit to the \( p_T^{\text{miss}} \) spectrum in the signal region and in the control regions, and is interpreted in terms of vector or axial-vector mediators. In Figure 2 the expected and observed \( p_T^{\text{miss}} \) distributions in the signal regions for CMS and ATLAS are shown. In both cases, no significant discrepancies with respect to the SM predictions are observed, so that limits on the DM mediator and final state particle masses are set, as shown in Figure 3. Assuming a coupling of the DM mediator to quarks of 0.25, and a coupling of the mediator to the WIMP particles \( \chi \), mediators of masses up to 1.8 TeV, and DM particles of masses up to 700 GeV are excluded.

![Figure 2](image)

**Figure 2.** Data-MC distributions of the mono-jet signal regions for the CMS [7] (left) and ATLAS [8] (right) analyses.

### 3.2. Mono-\( \gamma \)

The mono-\( \gamma \) search is similar to the mono-jet one, with the difference that the probability to emit a photon from ISR is lower than the probability to emit a jet, so that the analysis is slightly less sensitive. Also in this case the basic selection consists in requiring one energetic photon, with a transverse energy larger than 175 GeV (150 GeV) for CMS [9] (ATLAS [10]), and rejecting events with reconstructed leptons or jets. An additional selection on \( p_T^{\text{miss}} \) larger than 170 GeV is set by CMS, while ATLAS introduces the quantity \( \sqrt{E_T^{\text{miss}} \sum E_T} \), which must be larger than 8.5 GeV 1/2, and effectively rejects \( \gamma+\text{jets} \) events. The main backgrounds are, similarly to the mono-jet case, the \( Z \to \nu\bar{\nu} + \gamma \) and the \( W \to \ell\nu + \gamma \) processes, but also the production of single electrons or jets reconstructed as photons. The contaminations of the first two background are estimated in dedicated control regions with one (for \( W \to \ell\nu + \gamma \)) or two leptons (for \( Z \to \nu\bar{\nu} + \gamma \)). The estimation of the electron-induced background and the jet-induced background are performed by both experiments measuring the probability of reconstructing an electron or a hadronic jet as a photon, and then reweighting events in \( e+ E_T^{\text{miss}} \) or loosely-identified photons + \( E_T^{\text{miss}} \) regions. The results are obtained via a simultaneous fit to the signal and control regions and are illustrated in Figure 4. Also in this case they are interpreted in terms of vector or axial-vector mediators, and assuming the same couplings as in the mono-jet analysis. In the vector-mediator interpretation, mediator masses up to 1200 GeV, and DM particle masses up to 500 GeV are excluded. In the axial-vector interpretation, the same mediator masses are ruled out, while the exclusion of \( m_\chi \) reaches 350 GeV.
Figure 3. Exclusion limits for the CMS [7] (top), and ATLAS [8] (bottom) mono-jet analyses. On the left-side plots, results are interpreted in terms of vector mediator, on the right-side plots in terms of axial-vector mediator. In both cases the DM particles are considered as Dirac fermions. The coupling of the mediator to quarks ($g_q$) is set to 0.25, and the coupling of the mediator to DM ($g_{DM}$ or $g_{\chi}$) is fixed to 1.
Figure 4. Exclusion limits for the CMS [9] (top), and ATLAS [10] (bottom) mono-γ analyses. On the left-side plots, results are interpreted in terms of vector mediator, on the right-side plots in terms of axial-vector mediator. In both cases the DM particles are considered as Dirac fermions. The coupling of the mediator to quarks ($g_q$) is set to 0.25, and the coupling of the mediator to DM ($g_{\chi}$ or $g_{\chi}$) is fixed to 1.
3.3. Mono-Z

The mono-Z signature can be easily tagged by requiring events with two same-sign leptons with invariant mass compatible with $m_Z$, and large $E_T^{\text{miss}}$ (at least 100 GeV for CMS [11], or 90 GeV for ATLAS [12]). Additionally, events with more than two reconstructed leptons, or with at least one reconstructed b-jet are rejected. The main backgrounds are represented by the $ZZ \to \ell^+ \ell^- \nu \bar{\nu}$ and $WZ \to \ell \nu \ell^+ \ell^-$ processes. The former is estimated by ATLAS directly using MC simulation, while in CMS a control region with a tightly-identified same-sign lepton pair, and a loosely-identified same-sign lepton pair, both compatible with the decay of a Z boson, is used to describe the $E_T^{\text{miss}}$ of the process. Here the loose lepton pair is included in the $E_T^{\text{miss}}$ computation. For the latter both experiments define a control region with three leptons to estimate the contamination in the signal region. The results are extracted through a fit to the $E_T^{\text{miss}}$, and are interpreted in terms of limits on the production of vector and axial-vector mediator by CMS, and in terms of axial-vector mediator for ATLAS, as shown in Figure 5. The same couplings as in the mono-jet and mono-$\gamma$ analyses are used in this search. Vector-mediator mediator of mass up to 680 GeV, and DM particle of mass up to 250 GeV are excluded. In the axial-vector interpretation, mediator masses up to 700 GeV, and $m_\chi$ up to 150 GeV are excluded.

![Figure 5](image_url)

**Figure 5.** Exclusion limits for the CMS [11] (top), and ATLAS [12] (bottom) mono-Z analyses. CMS interpreted the results in terms of vector mediator (top-left), and axial-vector mediator (top-right), while ATLAS provided interpretation only for axial-vector mediator. In both cases the DM particles are considered as Dirac fermions. The coupling of the mediator to quarks ($g_q$) is set to 0.25, and the coupling of the mediator to DM ($g_{\text{DM}}$ or $g_\chi$) is fixed to 1.

3.4. Mono-Top

The search for mono-top has been carried out only by the CMS collaboration [13]. The model inspected differs from the previous ones, since a flavour-changing neutral current (FCNC) is introduced in this case. The analysis selects events with an energetic jet ($p_T > 250$ GeV) with a mass compatible with a top quark, and tagged as produced by a top quark by a dedicated BDT. The jet has to recoil
against a large amount of $E_T^{\text{miss}}$ (at least 250 GeV). Several control regions are defined to estimate the background contamination in the signal region using data. The main background, $Z \rightarrow \nu \bar{\nu} + \text{jets}$, is estimated using a di-electron, a di-muon, and a $\gamma + \text{jets}$ control regions, where the momenta of the muons or of the electrons, or the transverse energy of the photon are included in the $E_T^{\text{miss}}$ computation. Secondary backgrounds, $W \rightarrow \ell \nu + \text{jets}$ and semi-leptonic $t\bar{t}$ decays, are estimated in single leptons control regions, which can include a $b$-jet (top CR), or require $b$-veto ($W$+jets CR). The results are extracted through a simultaneous fit to the signal region and the control region, on the $E_T^{\text{miss}}$, and are interpreted as limits on the mass of the flavour-changing vector boson and on the DM particle mass (see Figure 6). In particular, the exclusion reaches 1.8 TeV for the mediator mass, and 750 GeV for DM particle mass, fixing the coupling of the mediator to quarks to 0.25, and the coupling to DM particles to 1.

3.5. Mono-Higgs

The emission of a Higgs boson from ISR is strongly suppressed, due to the low coupling with light quarks, and due to the loop-mediated interaction with massless gluons. This implies that models typically inspected in mono-X searches are not valid in the mono-Higgs case. Instead, $Z'$-2HDM model, and a $Z'$-Baryonic model, shown in Figure 7, are studied. Here the Higgs boson directly interacts with the mediator, so that Higgs-mediator coupling is accessible with these models. Different Higgs decay channels are inspected by CMS ($h \rightarrow b\bar{b}$ [14,15], and combination of $h \rightarrow \gamma\gamma$ and $h \rightarrow \tau\tau$ [16]) and ATLAS ($h \rightarrow b\bar{b}$ [17] and $h \rightarrow \gamma\gamma$ [18]). The analysis strategy is similar in all the cases: tag the Higgs boson through invariant mass requirements, and require it to recoil against significant amount of $E_T^{\text{miss}}$.

The main backgrounds are estimated using data in the invariant mass side-bands, or in specific control regions, and the results are extracted through a fit to significant variables, as the invariant mass, the $E_T^{\text{miss}}$, or the transverse mass, defined as:

$$m_T = \sqrt{2 \cdot p_T^{\ell\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta \phi(\ell\ell, E_T^{\text{miss}}))}$$

The most significant interpretations of the results, from CMS and ATLAS, and for the two models, are shown in Figure 9. For the $Z'$-Baryonic model, assuming the coupling between the mediator and quarks to be 0.25, and the coupling of the mediator to DM particles to be 1, $Z'$ mediator lighter than 1.6 TeV, and DM particles lighter than 450 GeV are excluded. For the $Z'$-2HDM model, the $Z'$ coupling...
strength is 0.8, and the mass of the DM particles is fixed to 100 GeV. With these parameters, Z' masses up to 3.2 TeV, and DM masses up to 800 GeV are excluded.

3.6. $t\bar{t}$ + Dark Matter

The production of Dark Matter in association with a pair of top quarks is favoured in models in which Yukawa coupling between the mediator and SM particles is expected, due to the large mass of the top. The three possible final states, with 0, 1 or 2 leptons are inspected, and CMS combined the results together [19], while ATLAS did not perform a full combination [20,21]. Depending on the final state, events with top quarks are selected by requiring the presence of b-tagged (0 or 1 lepton)
or top-tagged jets (fully hadronic final state). Additionally, events must present a large amount of $E_T^{miss}$. Different definitions of the transverse mass of the event, depending on the number of leptons in the final state, are used to discriminate the signal from the dominant $t\bar{t}$ background. The presence of undetectable DM particles tends in fact to produce $m_T$ distributions with larger tails in the signal, with respect to the background. The results are obtained through a fit to the $E_T^{miss}$ variable, and are shown in Figure 9 both for CMS and ATLAS. In the case of the scalar mediator interpretation, mediator masses up to 165 GeV, and DM particle masses up to 75 GeV are excluded, while in the case of the pseudoscalar mediator, mediators with mass up to 225 GeV, and DM particles of mass up to 105 GeV are ruled out.

![Figure 9. Main results for the $t\bar{t}$ +DM analyses in CMS [19] (top), and ATLAS [21] (bottom). On the left, the results for a scalar mediator are shown, on the right the results for a pseudoscalar mediator. Both the coupling of the mediator to quarks ($g_q$), and the coupling to DM ($g_{\chi}$) are set to 1. CMS presented the results of the combination of three $t\bar{t}$ final states as limits on the mediator mass versus DM particle mass. ATLAS fixed the $m_\chi$ to 1 GeV and showed the limits on the mediator mass, without combining the results of the different final states.](image)

### 4. Mediator Searches

Assuming that a DM mediator can be produced by quark-quark annihilation implies that it can also decay to a pair of quarks. Mediator searches focus on final states with two jets, typically looking for a bump in the di-jet invariant mass spectrum, due to the presence of a new resonance. The di-jet production at the LHC is very abundant, so that these searches are usually able to inspect high mass ranges, and put stringent limits. On the other hand, due to the very high rate of production, particularly of pairs of low-$p_T$ jets, traditional di-jet searches are not sensitive to low-mass mediators, since typically high jet-$p_T$ threshold have to be set to avoid the saturation of the trigger band width. Trigger-level
analysis, making use of events with limited amount of information, and searches for boosted mediators recoiling against hard ISR jets have been implemented to increase the sensitivity to lighter mediators. Finally, to search for broad resonances, which would be impossible to distinguish from the SM QCD $m_{jj}$ falling spectrum, analyses based on di-jet angular distribution have been designed: SM jet pairs are usually produced in the forward region of the detector, while heavy mediators would preferentially emit jets in the barrel. Since these searches involve only the coupling between mediator and quarks, they can be used to put constraints on this parameter or, fixing the coupling value, to put upper limits to the mediator mass.

4.1. Di-Jet Searches

The standard mediator-search approach consists in selecting events with two reconstructed jets in the final state, and plot their invariant mass. The distribution is fitted with a smooth function, since QCD predicts a smoothly-falling $m_{jj}$ spectrum, looking for excesses or deviations in data with respect to the fit results, as shown in Figure 10. Due to the abundant QCD production of events with jet pairs at the LHC, to avoid the saturation of the trigger band width, events with very energetic jets can be selected. For this reason this kind of analyses are sensitive to very high mass mediators, with masses larger than 1.6 TeV for CMS [22], and 1.5 TeV for ATLAS [23]. The results are interpreted as upper limits on the quark-mediator coupling, as a function of the mediator mass, and are displayed in Figure 11. The most stringent limit is given by ATLAS, for $m_{\text{med}} = 1.5$ TeV, and corresponds to $g_{q} = 0.08$.

4.2. Low-Mass Di-Jet Searches

The main limiting factor in the search for low-mass mediators in the finite trigger band width of the CMS and ATLAS experiments. In order to avoid this inconvenient, two techniques have been exploited in dedicated analyses:

- Save only limited relevant information at trigger level to enhance the rate of data acquisition. This means that events can be reconstructed faster, and occupy less space, allowing to lower the jet $p_{T}$ thresholds, and hence being sensitive to lighter mediators. In particular ATLAS [24] managed to push the sensitivity down to resonances of 450 GeV, and CMS [25] to 500 GeV.
- Select events in which the two jets are highly boosted and merged together, due to recoil against an additional hard ISR jet. This means that even for very light resonances, the event presents potentially three high-$p_{T}$ jets able to pass the standard trigger thresholds. This analysis has been performed by CMS [26], and is sensitive to di-jet invariant masses between 50 GeV and 300 GeV.
Figure 11. Results for the CMS [22] (left) and the ATLAS [23] (right) mediator searches. Limits on the mediator coupling to quarks ($g_q$) as a function of the mediator mass are set. The CMS plot shows also the results for low-mass mediator searches, for $m_{med} < 1.6$ TeV.

The results of these low-mass di-jet analyses are shown in Figure 11 (low-mass region in the left plot for CMS), and in Figure 12. They are interpreted as limits on the coupling between quarks and the DM mediator: couplings lower than 0.03 are excluded for $m_{med} = 800$ GeV by ATLAS, and couplings lower than 0.06 are excluded for $m_{med} = 60$ GeV by CMS.

Figure 12. Results for the CMS [26] (left) and the ATLAS [24] (right) low-mass mediator searches. Limits on the mediator coupling to quarks ($g_q$) as a function of the mediator mass are set. The CMS plot shows the results for the ISR-low-mass mediator search, while the ATLAS results refer to the trigger-level analysis.

4.3. Di-Jet $\chi$ Searches

In case of broad resonances, the classic bump search may not be the optimal analysis strategy, since it would be difficult to distinguish the peak of resonant events over the falling QCD spectrum. On the other hand, the jet angular distribution is not sensitive to the resonance width, but is a good variable to discriminate signal and background. In particular, it is common to define $\chi$ as:

$$\chi = e^{y_1 - y_2} = \frac{1 + \cos \theta^*}{1 - \cos \theta^*}$$

(2)

where $y_1$ and $y_2$ are the rapidities of the jets, and $\theta^*$ is the polar angle in the center-of-mass system. The definition has been chosen since QCD events are expected to present angular distributions independent of $\chi$, while heavy mediators would preferentially produce events with low values of $\chi$. The results are
interpreted in different frameworks by the CMS [25] and ATLAS [23] collaborations. In CMS limits are set on the mass of the mediator, assuming the coupling with quarks equal to 1: resonance masses between 2 TeV and 4.6 TeV are ruled out. The ATLAS interpreted as limits on the energy scale \( \Lambda \) of contact interactions: considering constructive (destructive) interference with QCD, values of \( \Lambda \) smaller than 21 TeV (13 TeV) are excluded. The results are presented in Figure 13.

![Figure 13. Results for the CMS (left) and the ATLAS (right) di-jet \( \chi \) searches.](image)

5. Comparison of Results and Reinterpretation

The results of all the searches can be compared by fixing the mediator couplings and plotting the corresponding exclusion limits in terms of masses of mediator versus masses of DM particles which are ruled out. Summary plots for CMS [27] and ATLAS [28] are presented in Figure 14, assuming coupling of the mediator to DM (\( g_{\text{DM}} \)) to 1, to quarks (\( g_q \)) to 0.25, and to leptons (\( g_{\ell} \)) to 0. The CMS results presented in this document show the vector mediator interpretation, and the ATLAS results show the axial-vector mediator interpretation. The exclusion limits are dominated by the di-jet analyses, which take profit of the large di-jet production cross section, and do not depend on the mass of the DM particles, which are not directly involved in this kind of searches. The strong dependence of the results on the particular choice of the couplings is shown in Figure 15, where the same exclusion plots are displayed, but introducing a coupling of the mediator with leptons, and reducing the coupling to quarks. In this case stringent limits from di-lepton searches significantly reduce the phase space excluded by mono-X or mediator analyses. The results can be also reinterpreted in terms of DM-nuclei scattering cross section [29], to be compared with the results of direct-detection DM experiments. Axial-vector results can be interpreted as limits on spin-dependent scattering cross sections, while results of vector mediator searches are reinterpreted as limits on spin-independent scattering cross sections. The choice of the couplings strongly affects the comparison shown in Figure 16, where the same couplings as in Figure 14 are selected. Under this assumption, collider searches show to be particularly effective in inspecting light dark matter particles, with masses of the order of 10 GeV or lower.
Figure 14. Summary plots for the CMS [27] (left) and ATLAS [28] (right) dark matter searches. The coupling of the mediator to DM ($g_{\text{DM}}$) is set to 1, to quarks ($g_{q}$) to 0.25, and to leptons ($g_{\ell}$) to 0. The CMS results refer to vector-mediator interpretation, the ATLAS results to axial-vector mediator.

Figure 15. Summary plots for the CMS [27] (left) and ATLAS [28] (right) dark matter searches. The coupling of the mediator to DM ($g_{\text{DM}}$) is set to 1, to quarks ($g_{q}$) to 0.1, and to leptons ($g_{\ell}$) to 0.1 (0.01 for CMS). The CMS results refer to vector-mediator interpretation, the ATLAS results to axial-vector mediator.

Figure 16. Summary of the reinterpretation of dark matter searches as DM-nuclei scattering cross section, for CMS [27] (left) and ATLAS [28] (right). The coupling of the mediator to DM ($g_{\text{DM}}$) is set to 1, to quarks ($g_{q}$) to 0.25, and to leptons ($g_{\ell}$) to 0. The CMS results refer to spin-independent (vector-mediator) scattering, the ATLAS results to spin-dependent (axial-vector) interaction. The results from some of the main direct-detection, and indirect-detection searches are also shown for comparison.
6. Conclusions

The main searches for dark matter performed by the CMS and ATLAS collaborations have been presented. Making use of data collected during 2016 with proton-proton collisions with a center of mass energy of 13 TeV by the LHC, for a total integrated luminosity of 36 fb$^{-1}$ for each experiment, no significant discrepancies with respect to SM predictions have been found, so that the results have been interpreted as limits on the couplings of dark matter mediators to SM particles, or as limits on the masses of the mediator and the DM particles. A further interpretation of the results as limits on the DM-nuclei scattering cross section have been provided, in order to allow a comparison with results from experiments of direct-detection of dark matter. This comparison strongly depends on the choice of the couplings between DM and SM particles, and shows that collider searches are competitive in particular for low DM particles masses. Several searches are still limited by the low number of expected signal events, in particular mono-X searches, so that the sensitivity of the analyses will take profit of the luminosity of the full Run-2 LHC data taking, which will include data collected between 2015 and 2018, for a total luminosity of more than 100 fb$^{-1}$.


