Dark matter search in CMS

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Abstract

The dark matter search program at the LHC covers a wide range of final states and targets a variety of possible interactions between dark matter and standard model particles. A summary of the dark matter searches performed at the CMS experiment, using proton-proton collision data collected at a center of energy of 13 TeV, is presented. Searches performed in various final states are described, and results interpreted in terms of several dark matter models are presented. These results are also compared to the results from direct and indirect dark matter searches.

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The dark matter search program at the LHC covers a wide range of final states and targets a variety of possible interactions between dark matter and standard model particles. A summary of the dark matter searches performed at the CMS experiment, using proton-proton collision data collected at a center of energy of 13 TeV, is presented. Searches performed in various final states are described, and results interpreted in terms of several dark matter models are presented. These results are also compared to the results from direct and indirect dark matter searches.

1 Introduction

The existence of dark matter (DM) in the universe has been established through various astrophysical observations\(^1,2,3\). However, there exists no compelling evidence of a non-gravitational interaction between DM and standard model (SM) particles. If DM consists of weakly interacting massive particles (WIMPs), it may be possible to produce pairs of DM particles in the TeV-scale proton-proton collisions at the CERN LHC. The DM particles, if produced at the LHC, are not expected to leave an observable signal in the detector. However, if these particles recoil against an observable system of particles (X), they may produce a large transverse momentum imbalance \(E_T^{\text{miss}}\) in a collision event. Several DM searches have been performed in these \(E_T^{\text{miss}} + X\) final states at the LHC. The DM searches based on \(E_T^{\text{miss}} + X\) signatures, performed using a data set of proton-proton collisions at \(\sqrt{s} = 13\) TeV, collected with the CMS detector in 2015 and the first half of 2016, are discussed in this document.

2 Simplified dark matter models

The results of the DM searches at CMS have been interpreted in terms of certain simplified DM models that assume a single pair or fermionic DM particles, and a massive spin-0 or spin-1 particle that mediates the interaction between DM and SM particles. The spin-0 mediator is assumed to be either a scalar or a pseudoscalar particle, whereas the spin-1 mediator is assumed to be either a vector or an axial vector particle. The parameters of these simplified models include the DM particle mass \(m_{\text{DM}}\), the mediator mass \(m_{\text{med}}\), the strength of the coupling
between the mediator and SM quarks \((g_q)\), and the strength of the coupling between the mediator and DM particles \((g_{DM})\). Certain benchmark values are chosen for \(g_q\) and \(g_{DM}\) as per the LHC Dark Matter Working Group recommendations. In all cases, \(g_{DM} = 1.0\). In the case of the spin-1 mediators, \(g_q = 0.25\). This value was found to be consistent with the constraints from the dijet resonance searches performed in Run-1 of the LHC. The spin-0 mediators are assumed to couple to the SM quarks through SM-like Yukawa interactions. For these Yukawa interactions \(g_q\) represents the coupling strength modifier, and is assumed to be 1.0, i.e. the interaction between the spin-0 mediators and the SM quarks is assumed to be the same as that involving the SM Higgs boson.

3 Event reconstruction

A detailed description of the CMS detector can be found elsewhere. The proton-proton collision events collected with the CMS detector are reconstructed using the particle-flow (PF) algorithm, which reconstructs and identifies individual particles with an optimized combination of information from the various elements of the detector. A muon is reconstructed from a track in the silicon and pixel tracker that is geometrically matched to signals in the muon spectrometer. An electron is reconstructed from a track in the tracker that is geometrically matched to an energy cluster in the electromagnetic calorimeter (ECAL). The charged hadron is reconstructed when a track in the tracker can be associated with energy deposits in both the ECAL and the hadron calorimeter (HCAL). A photon is reconstructed from an energy cluster in the ECAL that cannot be matched to a track in the tracker. Finally, a neutral hadron is reconstructed when energy deposits in the ECAL and HCAL cannot be matched to a track in the tracker.

The \(E_T^{\text{miss}}\) in an event is computed as the negative vector sum of the transverse momenta of all the PF candidates produced in an event. Jets are reconstructed by clustering the PF candidates using the anti-\(k_t\) algorithm. Jets reconstructed with a distance parameter of 0.4, and are referred to as AK4 jets. Certain final states target large radius jets produced by the hadronic decays of heavy particles. These large radius jets are reconstructed using the anti-\(k_t\) algorithm with a distance parameter of 0.8 and a referred to as AK8 jets.

4 Monojet search

The monojet DM search targets processes in which DM is produced in association with a jet or a weak boson \(V\) which is either a \(W\) or \(Z\) boson decaying hadronically, resulting in ‘monojet’ and ‘mono-V’ final states, respectively. The Feynman diagrams for the monojet and mono-V signal processes in the case of a spin-1 mediator are shown in Fig. 1.

![Feynman diagrams](image.png)

Figure 1 – Leading order Feynman diagrams of monojet (left) and mono-V (right) production and decay of a spin-1 mediator.

Events are required to have \(E_T^{\text{miss}} > 200\) GeV, and at least one AK4 jet with \(p_T > 100\) GeV in the central region of the detector \((|\eta| < 2.5)\). Furthermore, events are required to have no prompt, isolated leptons (electrons, muon or taus), no isolated photons, and no b jets. These requirements help to significantly backgrounds such as Z+jets, W+jets, and \(t\bar{t}\). The mono-V category targets events in which the \(V\) boson has \(p_T > 250\) GeV. The hadronic decays of such
a boosted V boson are predominantly reconstructed as an AK8 jet. The mass of the AK8 jet is required to lie between 65 and 105 GeV. The ratio of the N-subjettiness variables $\tau_2/\tau_1$ is required to be less than 0.6 since large radius jets emerging from two prong decays are expected to have low values of $\tau_2/\tau_1$.

The DM signal is extracted by fitting the $E_T^{\text{miss}}$ distribution of events passing the mono-jet or mono-V requirements. The main backgrounds in this search consist of $Z(\nu\bar{\nu})$+jets and $W(\ell\nu)$+jets processes. These backgrounds are estimated by performing a simultaneous fit across several control regions in data consisting of dimuon, dielectron, single muon, single electron and $\gamma$+jets events. Figure 2 shows the $E_T^{\text{miss}}$ distributions in the monojet and mono-V signal regions. The background prediction is obtained from a combined fit in all the control samples, excluding the signal region. Data are found to be consistent with the estimated background from the SM processes.

Figure 2 – Observed $E_T^{\text{miss}}$ distribution in the monojet (left) and mono-V (right) signal regions compared with the background expectations for various SM processes evaluated after performing a combined fit to the data in all the control samples. Expected signal distributions for a 125 GeV Higgs boson decaying exclusively to invisible particles, and for a 1.6 TeV axial-vector mediator decaying to 1 GeV DM particles, are overlaid. The ratio of data and the post-fit background prediction is shown. The gray bands in these ratio plots indicate the post-fit uncertainty in the background prediction. Finally, the distributions of the pulls, defined as the difference between data and the post-fit background prediction relative to the post-fit uncertainty in the prediction, are also shown in the lower panels.

Figure 3 shows the exclusion contours in the $m_{\text{med}}$–$m_{\text{DM}}$ plane for the vector and axial-vector mediators. Mediator masses up to 1.95 TeV and DM masses up to 750 and 550 GeV are excluded for the vector and axial-vector models, respectively, at 95% CL.

5 $t\bar{t}$+DM search

Since the spin-0 mediators couple to the SM quarks through SM-like Yukawa interactions, they interact most strongly with the top quark. The spin-0 mediators can be produced at the LHC in association with a $t\bar{t}$ pair as shown in Fig. 4. This results in a final state consisting of a pair of top quarks and large $E_T^{\text{miss}}$. Each top quark may further decay either hadronically or
Figure 3 – Exclusion limits at 95% CL on the signal strength $\mu = \sigma / \sigma_{\text{th}}$ in the $m_{\text{med}}$–$m_{\text{DM}}$ plane assuming vector (left) and axial-vector (right) mediators. The solid (dotted) red (blue) line shows the contour for the observed (expected) exclusion. The solid contours around the observed limit and the dashed contours around the expected limit represent one standard deviation theoretical uncertainties in the signal cross section and the combination of the statistical and experimental systematic uncertainties, respectively. Constraints from the Planck satellite experiment are shown with the dark green contours and associated hatching. The hatched area indicates the region where the DM density exceeds the observed value.

leptonically with the lepton being either an electron or a muon. This results in final states involving 0, 1, or 2 leptons, multiple jets, two b-jets, in addition to large $E_T^{\text{miss}}$.

Figure 4 – Leading order Feynman diagrams of the production and decay of a spin-0 mediator in association with a top quark pair.

Three category of events are considered in the $t\bar{t}$+DM search targeting top quark decays resulting in no leptons, one lepton, or a pair of leptons in the final state. The largest background in the 0-lepton category consists of $t\bar{t}$ events in which one of the two top quarks decays leptonically, the lepton either falls out of the detector acceptance, or fails to be the identified, and the neutrino produces the requisite $E_T^{\text{miss}}$. The largest background in the 1-lepton category consists of $t\bar{t}$ events in which both the top quarks decay leptonically, and one of the leptons either falls out of detector acceptance, or fails to be identified. The largest background in the 2-lepton category consists of $t\bar{t}$ events with both the top quarks decayaing leptonically, with the two leptons being identified.

Events in the 0-lepton are required to have $E_T^{\text{miss}} > 200$ GeV, at least four AK4 jets with $p_T > 30$ GeV, and at least b tagged jet. A dedicated multivariate tagger called the ‘resolved top tagger’ (RTT) is used to identify a triplet of AK4 jets associated with the decay of a top quark. Events are further classified depending on whether two top tagged AK4 jet triplets are found in the event or not. Events in the 1-lepton category are required to have $E_T^{\text{miss}} > 160$ GeV, at least three AK4 jets with $p_T > 30$ GeV, and at least b tagged jet. In the 1-lepton category, the transverse mass ($m_T$) of the lepton-$E_T^{\text{miss}}$ system, and the $m_T^W$ variable is used to suppress the W+jets, and the $t\bar{t}$ backgrounds, respectively. More specifically, $m_T > 160$ GeV, and $m_T^W > 200$ GeV requirements are imposed. Events in the 2-lepton category are required
to have $E_T^{\text{miss}} > 50 \text{ GeV}$, at least two AK4 jets with $p_T > 30 \text{ GeV}$, and at least one b tagged jet. The invariant mass of the dilepton system is required to be greater than 20 GeV. If the two leptons have the same flavor, their invariant mass is required to lie outside the 76–106 GeV range in order to reduce the $Z+\text{jets}$ background.

The DM signal is extracted by performing a fit to the $E_T^{\text{miss}}$ distribution observed in data in each of the above event categories. The estimates of the main backgrounds in this search which consist of the $Z(\nu \overline{\nu})+\text{jets}$, $W(\nu)+\text{jets}$, and $t\bar{t}$ processes, are obtained from several control regions in data. Figure 5 shows the $E_T^{\text{miss}}$ distributions in the signal regions with one or no leptons. The event categories with one or no leptons are found to be the most sensitive categories in this search. No excess of events is observed compared to the predicted SM backgrounds. Upper limits are computed at 95% CL for both scalar and pseudoscalar mediators, assuming a DM particle of 1 GeV. These limits, obtained by combining the results from the zero and one lepton categories are shown in Fig. 6.

**Figure 5** – Distributions of $E_T^{\text{miss}}$ expected from SM backgrounds and observed data in the zero lepton event category with two RTT tagged AK4 jet triplets, and the one lepton category of the $t\bar{t}+\text{DM}$ search. The expected background distributions are shown after fitting the observed data simultaneously across several control regions and the signal region. The overall post-fit uncertainties are shown in the blue band on the lower panel.

**Figure 6** – 95% CL upper limits on the ratio of the DM production cross section to the simplified model expectation as a function of scalar and pseudoscalar mediator mass with the zero and one lepton event categories. The DM mass is assumed to be 1 GeV.
6 Mono-Z and monophoton searches

The mono-\(Z\) and monophoton searches target DM production in association with the initial state radiation of a \(Z\) boson and a photon respectively. The mono-\(Z\) search specifically targets the decays of the \(Z\) boson to a pair of electrons or muons. Events are required to have two prompt, isolated, well identified, oppositely charged electrons or muons. The invariant mass of the dilepton pair is required to lie between 76 and 101 GeV, and the \(p_T\) of the dilepton pair is required to be larger than 60 GeV. Events with one or more b tagged jets are rejected in order to suppress the top quark background. Events with a third lepton are rejected in order to suppress the WZ background. The largest background in this search consists of ZZ events in which one of the \(Z\) boson decays to a pair of electrons or muons, and the other \(Z\) boson decays to a pair of neutrinos. The second largest background consists of WZ events in which both the W and Z bosons decays leptonically, and the lepton from the W boson fails to get identified or falls out of the detector acceptance. The mono-\(Z\) signal is extracted by fitting the observed \(E_T^{\text{miss}}\) distribution.

The monophoton search targets events with one photon having \(p_T > 175\) GeV, and \(E_T^{\text{miss}} > 170\) GeV. Events with one or more well reconstructed leptons are vetoed. The main backgrounds consist of \(Z\gamma\) events in which the \(Z\) boson decays to neutrinos, and \(W\gamma\) events in which the \(W\) boson decays leptonically and the lepton is not identified. Further requirements are imposed on the timing of the ECAL energy deposit corresponding to the photon, and on the possible contributions to the reconstructed photon energy from beam halo particles, in order to suppress the background arising from instrumental noise or non-collision sources. The analysis is performed by counting the number events passing the selection requirements, and evaluating the consistency of this event count with background expectations.

Fig. 7 shows the observed \(E_T^{\text{miss}}\) distributions in the mono-\(Z\) and monophoton searches. Data are found to be consistent with the background predictions, and hence limits are set on the DM production cross section assuming a spin-1 mediator, as shown in Fig. 8.

![Figure 7](image-url) - Distributions of \(E_T^{\text{miss}}\) expected from SM backgrounds and observed data are shown for the mono-\(Z\) search (left) and monophoton search (right). The lower panel shows the ratio of the observed data yield to the predicted background yield along with the estimated uncertainty.
9.2 Limit on invisible Higgs boson decays

Figure 1: Left: Distribution of the $E_{\text{miss}} T$ after the full selection except that $50 \text{ GeV} < E_{\text{miss}} T < 100$ GeV. Right: The $E_{\text{miss}} T$ in the signal region. The error bars represent statistical uncertainty, and the shaded bands represent systematic uncertainty. The histogram stack correspond to the sum of all background predictions, the dots are the data, the red line is the prediction for the $Z(\text{``})H(m_H=125 \text{ GeV})$ signal, and the dashed green line is the prediction for the DM signal for the simplified model with vector mediator with $(m_c, M_V)=(150, 500)$ GeV. The DM signal yield is multiplied by a factor three.

Figure 2: The 95% CL observed limits on signal strength $s_{\text{obs}}/s_{\text{th}}$ in both vector (left) and axial-vector (right) coupling scenario, for coupling $g_q = 0.25$. The expected exclusion curves for unity signal strength are shown as a reference.

7 Comparison with direct and indirect searches

The limits obtained from the DM searches at the LHC can be translated to limits on the DM-nucleon scattering cross section as measured by the direct detection experiments. Figure 9 shows the limits from the monojet, mono-Z and monophoton searches for the vector mediator model cast into limits on the spin-independent DM-nucleon scattering cross section. The collider limits depend on the choice of the coupling parameters $g_q$ and $g_{\text{DM}}$. The direct detection results are significantly more sensitive compared to the CMS DM searches for DM masses larger than about 5 GeV. However, the limits from the CMS DM searches are stronger for DM masses smaller than 5 GeV. Figure 9 shows the limits from the monojet, mono-Z and monophoton searches for the axial vector mediator model cast into limits on the spin-dependent DM-nucleon scattering cross section. The CMS DM searches are significantly more sensitive compared to the direct and indirect DM searches for DM masses up to about 500 GeV. Figure 10 shows the limits from the monojet search assuming a pseudoscalar mediator in terms of the DM annihilation cross section. In this case, the only other constraints are set by the Fermi–LAT observations.

8 Summary

The CMS experiment has performed an extensive search for dark matter (DM) in high energy proton-proton collisions at the LHC. Several final states with $E_{\text{T}}^{\text{miss}}$ based signatures have been explored. Some of the key searches have been described in this document. Some searches have not been described for the sake of brevity but form an important and integral part of the DM search program. No significant excess has been observed compared to the standard model backgrounds in any of the searches. Results of the DM searches have been interpreted in terms of certain simplified models that capture different possible types of interactions between DM and standard model particles.
Figure 9 – Limits on the spin-independent DM-nucleon scattering cross section from the CMS experiment compared with the results from the direct DM detection experiments (left), and limits on the spin-dependent DM-nucleon scattering cross section from the CMS experiment compared with the results from the direct and indirect DM detection experiments (right). The CMS results are shown assuming a vector mediator and couplings $g_q = 0.25$, and $g_{DM} = 1.0$.

Figure 10 – Limits on the velocity averaged DM annihilation cross section from the CMS monojet search assuming a pseudoscalar mediator compared with the results from Fermi–LAT. The CMS results are shown assuming an axial vector mediator.
References