PROCEEDINGS OF SCIENCE

Searches for dark matter with CMS

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Determining the nature of dark matter is one of the most fundamental problems of particle physics and cosmology. This talk presents recent searches for dark matter particles in simplified and extended dark sectors from the CMS experiment at the Large Hadron Collider. The results are based on proton-proton collisions recorded at $\sqrt{s} = 13$ TeV with the CMS detector.

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1. Motivation

The standard model of particle physics (SM) is one of the most successful theories in physics. It is the current best description of fundamental particles and their interactions. Except for gravity, it describes all known fundamental forces of nature. Furthermore, the results of countless physical observations are described to a very high precision and accuracy, and therefore validate the SM over a large range of energy scales.

Nevertheless, several observations were made over the last decades that cannot be explained by the SM. One such important observation is the apparent invisible mass that our universe contains, which can be inferred from cosmological and astrophysical observations. This invisible mass is commonly called dark matter (DM). The SM, to this date, does not have an appropriate particle candidate to describe DM. Because of this, physicists search for possible DM particles in many experiments around the world in order to obtain a direct verification of what has been inferred from the formerly mentioned indirect observations.

Dark matter is mainly searched for with three different techniques. The direct detection experiments try to find DM particles by investigating their possible recoil from atomic nuclei. The second technique is called indirect detection and the experiments search for products of DM annihilation processes that might happen in dense regions of the universe.

The third technique is based on particle colliders. If an interaction between SM and DM particles exists and the collision energy is large enough, DM particles might be produced in high-energy collisions of protons at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). This paper presents recent results of searches for dark matter using data from the CMS experiment [1] at the LHC, which have been shown at the latest ICHEP conference in 2024.

2. Dark Matter searches at CMS

Dark matter searches that have been carried out over the last years can mainly be categorized in two classes motivated by their underlying theoretical models and their final states. These classes are called simplified and extended dark sectors. An illustration of these categories with further subdivision into different models is shown in Fig. 1.

First, searches and models in the simplified dark sector are characterized by the following properties:

- There is only one dark matter candidate.
- A new mediator exists, often called portal, that establishes the connection between the DM particles and the SM particles.

The searches in the simplified dark sector are commonly divided into visible and invisible searches. Visible searches concentrate on the production of the new mediator and the subsequent decay back into SM particles. Searches for heavy visible resonances, e.g. dijet searches, belong to the visible searches. Invisible searches concentrate on the decay of the new mediator into DM candidates. The well-known mono-X searches, in which the DM is assumed to recoil against SM particles, belong to the invisble searches.

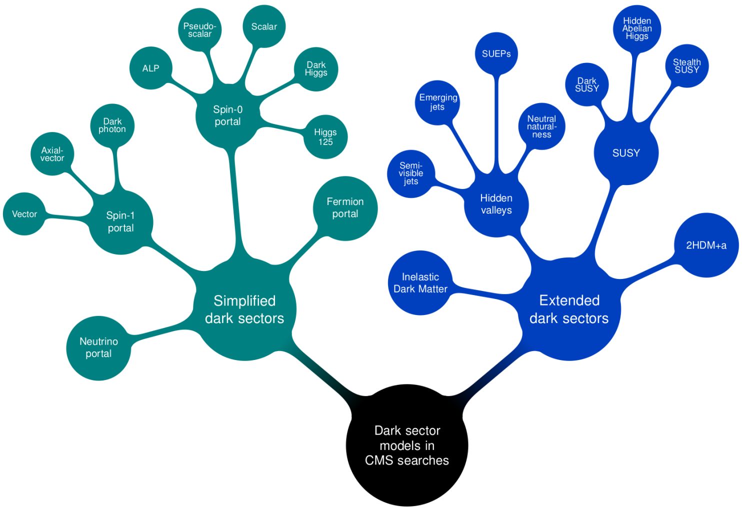


Figure 1: An illustration of the landscape of dark matter searches and models addressed by the CMS Collaboration [2].

Second, the extended dark sector comprises of models (and corresponding searches) with a

- more complex and UV complete structure,
- usually more than one new mediator or in general multiple new particles,
- and new kinds of interactions.

This results in richer final states compared to the simplified dark sector. Well-known models belonging to the extended dark sector are, for example, supersymmetric (SUSY) models or models with more than one Higgs doublet, such as two-Higgs-doublet models (2HDM).

The CMS Collaboration has provided results addressing all of the models shown in Fig. 1 and extensive information about the corresponding analyses and their results can be found in the latest CMS dark sector searches review paper [2]. In the following a small subset of recent results is presented. Analyses based on new data collection and reconstruction techniques such as scouting and parking that enhance sensitivity or open the possibility to search for completely new signatures cannot not be shown in this paper but are part of the given reference.

2.1 Simplified dark sector searches

2.1.1 Search for dark matter production in association with a single top quark

A preliminary search for the non-resonant production of a single top quark in association with two DM candidates via a flavor-changing neutral current process using the full Run-2 data [3] was recently published by CMS. A newly introduced spin-1 mediator allows for the electrically neutral change of flavor by coupling first and third generation quarks. The DM particles are consequently produced by the decay of the mediator. The complete final state is then determined by the decay of the top quark. This analysis is focused on the hadronic decay of the top quark. The analysis strategy is based on a large amount of missing transverse momentum and a fat jet produced by the hadronic top quark decay. To differentiate fat jets originating from pure QCD radiation and

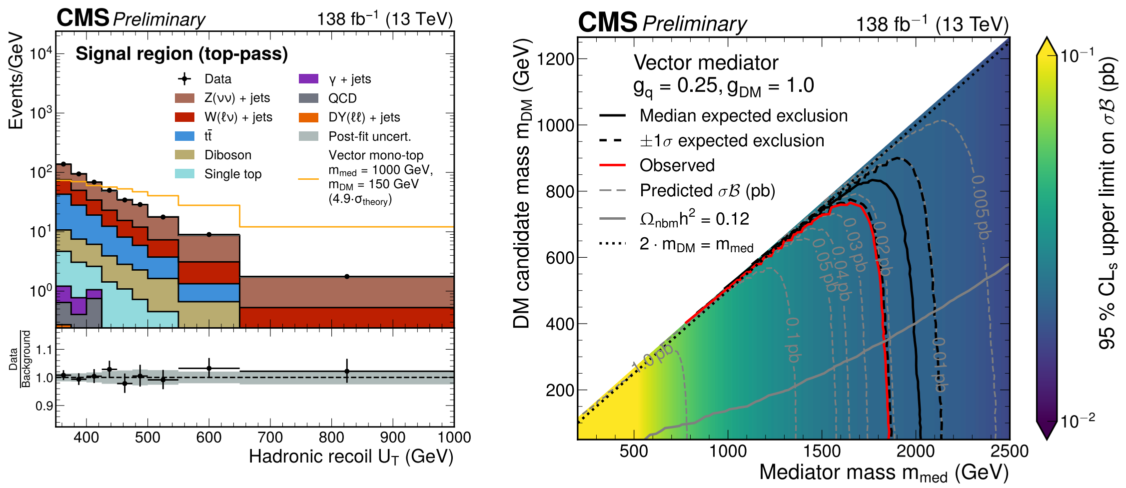
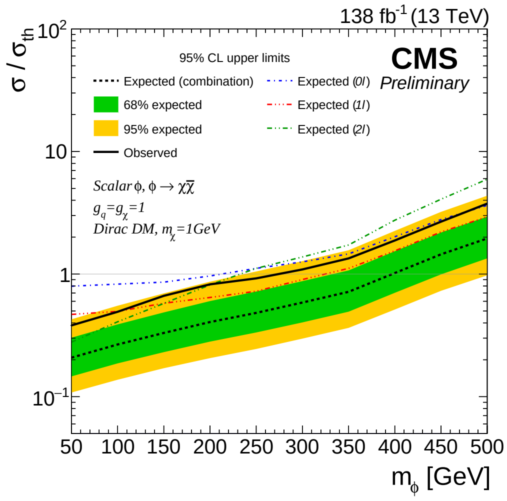


Figure 2: Postfit distribution of the signal-sensitive observable assuming the background-only hypothesis (left) and upper exclusion limits on the cross section times branching fraction of a vector coupling scenario of the mediator (right) [3].

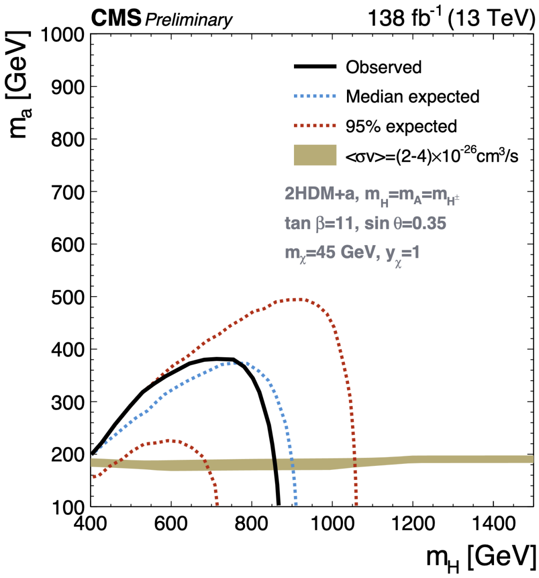
the hadronic decay of a top quark, a powerful discriminator based on a graph neural network [4] is used. The signal region is defined by vetoing any additional physics objects except for the previously explained signatures. Control regions are designed to determine the major background processes, $Z(\nu\nu)$ + jets, $W(\ell\nu)$ + jets, and $t\bar{t}$, directly from data in the control regions. Results and interpretations are provided for vector and axial-vector coupling scenarios of the mediator. Exclusion limits in the plane of the mediator mass and the DM candidate mass are given. On the left-hand side of Fig. 2 the postfit distribution of the signal-sensitive observable, the hadronic recoil, is shown, assuming the background-only hypothesis. No significant deviation from the SM is observed. On the right-hand side of Fig. 2 the upper limits on the product of cross section and branching fraction for a vector coupling scenario are given. The red curve represents the exclusion contour of this analysis with all parameter space inside the area enclosed by it being excluded within the given interpretation. More details and results can be found in [3].

2.1.2 Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s}$ = 13 TeV

In this recent preliminary publication [5] a search for DM in association with a $t\bar{t}$ pair or a single top quark is presented. In contrast to the analysis presented previously, the single top quark signatures are not produced by a flavor-changing neutral current but by the common single top quark production processes (t- and tW-channel) with an additional radiation of a spin-0 mediator off a top quark and the mediator then decaying into a pair of DM candidates. The new mediator couples to fermions, similarly to the Higgs boson, by a Yukawa-type coupling that is proportional to the mass of the fermion. Therefore, the coupling of the mediator is preferrably to heavy third-generation quarks. The final states are characterized by the typical $t\bar{t}$ and single top quark production final states in association with significant missing transverse momentum due to the DM candidates escaping detection. The analysis utilizes final states with zero, one, or two leptons, using the full Run-2



(a) Upper limits on the signal-strength modifier as a function of the mass of the scalar mediator [5] in a spin-0 portal model resulting in $t\bar{t}$ and single top quark production in association with DM.



(b) Exclusion contours in the plane of the mass of the additional pseudoscalar boson a and the mass of the heavy CP-even Higgs boson H in a 2HDM+a model obtained from a search for DM in association with b-quark and lepton pairs [6].

Figure 3

dataset. A first categorization is performed based on the multiplicity of b-tagged jets and a second categorization is done based on the number of forward jets to benefit from the different signatures of t- and tW-channel single top quark production. Similar to the previous analysis, the hadronic recoil is used as observable in the zero-lepton and single-lepton channels whereas a neural network discriminant is employed in the two-lepton channel. A signal-like excess with a significance smaller than 2σ above the background-only hypothesis is observed as can be seen in Fig. 3a in which upper limits on the signal-strength modifier are shown as a function of the mass of the new scalar mediator. More information and results are provided in [5].

2.2 Extended dark sector searches

2.2.1 Search for DM in association with b-quark and lepton pairs

An analysis belonging to the class of extended dark sector searches is the preliminary search for DM in association with b-quark and lepton pairs [6]. This analysis is motivated by a pseudoscalar link between the SM and DM that avoids existing DM-nucleon constraints from direct detection experiments and by a favored b-quark production in DM annihilation that is hypothesized to explain [7–9] the Fermi-LAT gamma-ray excess [10]. Both these properties can be obtained in a 2HDM+a model [11]. Such a model could produce a pair of b quarks, DM candidates, and a Z boson. By the decay of the Z boson into a pair of charged leptons, a clear signature is given. The analysis uses the number of leptons, the multiplicity of b-tagged jets, the missing transverse momentum and an analytical reconstruction of the $t\bar{t}$ dilepton system to select the events. Furthermore, a neural network is used to discriminate the signal from the remaining backgrounds and the major background processes are constrained from dedicated control regions. The results are interpreted in the previously mentioned 2HDM+a model, and shown in Fig. 3b.

3. Summary

A wide variety of dark matter searches at CMS are performed ranging from simple dark sector to extended dark sector searches correponding to simple and more complex final states. A very extensive review of CMS dark sector searchs can be found in [2]. So far no significant dark matter signals have been found; however, more data, higher center-of-mass energy, refined analysis techniques, and detector upgrades will push the sensitivity further in the future.

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