PROCEEDINGS OF SCIENCE

# Dark Matter searches with CMS

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Numerous cosmological observations support the existence of a large amount of non-radiating matter in the universe which cannot originate from any Standard Model (SM) particle. This non-visible mass is called Dark Matter (DM) and its nature is still unknown. Should it exist in the form of particles, it may be possible to produce DM at the LHC. Finding such particles could explain many of the deviations between SM predictions and cosmological observations. Now that the Higgs boson has been discovered, Dark Matter is one of the main targets of the physics program of the CMS Collaboration. We present some of the latest searches for DM particles with the CMS detector in the most sensitive final states.

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## 1. Introduction

Through gravitational effects, we see evidence that luminous matter cannot be the only type of matter in the universe. Another type of non-visible matter, Dark Matter (DM), must exist that interacts only weakly with standard matter. In reference [2], the history of the quest for DM is reviewed and the main possible solutions are presented.

In the scenario where DM would exist in the form of particles, cosmological observations strongly suggest it should be weakly interacting and massive. These Weakly Interacting Massive Particles (WIMPs) could be searched for with the CMS experiment [1] at the CERN LHC. Two main strategies are used to analyze the CMS data. A new mediator connecting the SM to the dark sector is introduced that could be produced in proton-proton collisions. In the first scenario, the mediator decays to DM particles that escape detection as illustrated by the diagram in figure 1. The only way to observe such a signal is to trigger on events in which a SM object is produced as an Initial State Radiation (ISR). We refer to these searches as "mono-X" searches as the final state is made of missing transverse energy $E_T^{miss}$ and the ISR as the only detected object. Missing transverse energy is defined as the norm of the vectorial sum of the transverse momentum $\vec{p}_T$ of all the objects in the event. It is a measure of what is missing from the event description. In the second scenario, the mediator decays back to SM particles. The search strategy is then to look for a resonant signal in the invariant mass spectrum of the two SM particles. We do not cover this type of searches in this review.

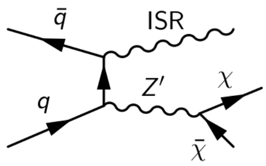


**Figure 1:** Diagram for the co-production of invisible DM particles $\chi$ along with a detectable object radiated from the initial state. This leads to the so-called "mono-X" searches.

## 2. Monojet and mono-V (hadronic)

This analysis targets events with jets and missing transverse energy [3]. It is a combination of two categories: the monojet per se and the mono-V hadronic. The first category is made of events in which the ISR is a gluon or a light quark that hadronizes to form a jet. In the second category, the ISR is a weak vector boson that decays hadronically. Events are selected if they pass an $E_T^{miss}$ trigger with a threshold at 110 or 120 GeV (depending on the data-taking year). The main selection is to require at least one jet with a $p_T$ larger than 100 GeV, a large $E_T^{miss}$ ($>$ 250 GeV, trigger motivated) and a veto on all other objects (leptons, photon, b-jets). The two categories are then distinguished by $p_T$ and shape requirements on the jets. An event falls in the mono-V category if the jet $p_T$ is larger than 250 GeV, its invariant mass falls in the [65,105] GeV window and it has a N-subjettiness ratio $\tau_2/\tau_1$ smaller than 0.6. The N-subjettiness is a variable that catches the substructure of the jet. If the event fails the mono-V requirements, it is counted in the monojet category. The two main backgrounds, the Z($\nu\nu$) and W(l$\nu$) processes, are estimated using five control regions (CR) in data: dielectrons, dimuons and $\gamma$+jets (for Z($\nu\nu$)) and single-electron and single-muon for W(l$\nu$). The number of events passing the analysis selection is estimated in each CR and transfered to the signal region using transfer factors derived from simulations. In each of the CR, the recoil (i.e. the $p_T$ of the lepton pair, the single lepton, or the photon) plays the role of the $E_T^{miss}$. Finally, the five CRs are fitted to data in a combined likelihood.

No excess of events is observed in the $E_T^{miss}$ spectrum as shown in figure 2 (left). Upper limits on the signal cross-section are set at 95 % confidence level using the CLs method in the context of simplified models [4]. They are shown in the summary figure 5.

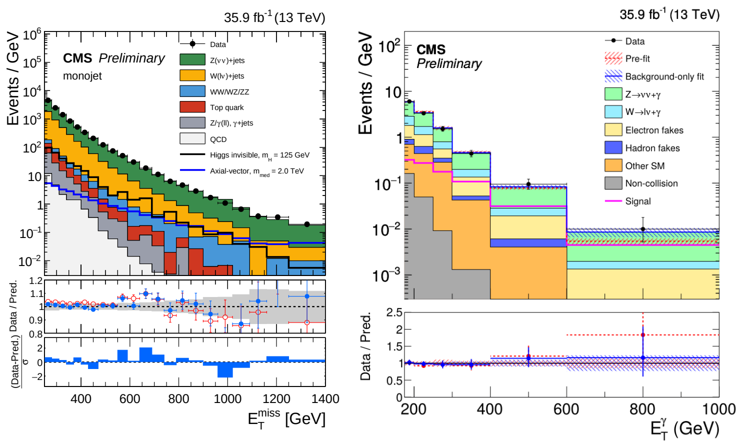


**Figure 2:** Left: expected $E_T^{miss}$ spectrum from SM background and observations in the full 2016 CMS dataset for the monojet category of the monojet search [3]. Right: expected $E_T^{\gamma}$ spectrum from SM background and observations in the full 2016 CMS dataset for the monophoton search [6].

## 3. Monophoton

In this search [6], events are selected with the help of a single-photon trigger with a threshold at 165 GeV. Offline, the cut on the photon transverse energy $E_T^{\gamma}$ is set at 175 GeV and the cut on the $E_T^{miss}$ at 170 GeV. A good part of the work in this analysis consists in selecting events with "good" photons, discriminating them from calorimeter noise and beam halo. The ratio of the energy measured in the hadronic calorimeter to that in the electromagnetic calorimeter H/E must not exceed 0.05. Moreover, the shape variable $\sigma_{\eta\eta}$ must stay below 0.0102. This latter variable describes the shape of the shower in the $\eta$ direction and is used to discriminate a single photon-initiated shower from the elecromagnetic shower in a jet.

As opposed to the monojet analysis, the monophoton search looks for an excess in data in the $E_T^{\gamma}$ spectrum on which the resolution is better than on the $E_T^{miss}$ (see figure 2, right). No excess is observed and and upper limits are set on the signal cross-section as shown in the summary figure 5.

## 4. Mono-Higgs

Due to the fact that the SM Higgs boson couples proportionally to the mass of the particle (Yukawa interaction), an ISR from a initial quark is not the most sensitive way to produce a mono-

Higgs signature. The loop-suppressed coupling of the Higgs to the gluons yields the same conclusion. Instead, mono-Higgs final states rather involve Beyond the Standard Model (BSM) mediators in models such as Z'-HDM or baryonic Z'. In the former, the Z' meditator decays to a new scalar (that decays to invisible particles) and the SM Higgs, while in the latter the Higgs boson is radiated from the Z' itself. In the latest CMS result [7], all decay modes of the Higgs boson are combined to obtain the best possible sensitivity. The final states are H(bb), H($\gamma\gamma$), H($\tau\tau$), H(WW) and H(ZZ). Those channels show a nice complementarity as the bb signature has the largest branching fraction, the diphoton and di-Z signatures have the best resolution on the invariant mass of the Higgs boson and the di-$\tau$ channel has the lowest background from SM processes.

The result of the combination is shown in figure 3 for the Z'-2HDM model. It is clear that the H(bb) channel drives the limit sensitivity on most of the Z' mass range (above 700 GeV) but the other channels become competitive at lower mediator masses.

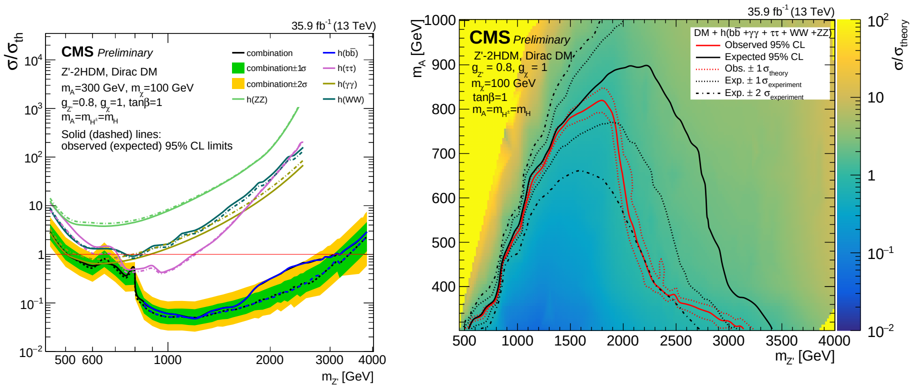


**Figure 3:** Left: upper limit on the signal cross-section for each individual channel and for the combination as a function of the mediator mass. Right: interpretation in the $m_A$-$m_{Z'}$ plane, where A is the new scalar particle [7].

## 5. Mono-top / $t\bar{t}$

The top final states in mono-X searches are interesting as they have the best sensitivity in models with a Yukawa-coupling type scalar mediator. Three types of signals are investigated in CMS: the production of $t\bar{t}$ pairs through a new scalar boson [8, 9], the production of boosted single top through Flavour Changing Neutral Currents (FCNC) or a charged colored scalar resonance [10] and the production of a single top along with a W boson or a b quark through a new scalar boson [9]. The standard $t\bar{t}$ analysis [8] combines all possible decay channels of the two top quarks, refered to as all-hadronic, leptons + jets and dileptons. The events are respectively triggered on $E_T^{miss}$, single-lepton and both single-lepton and dileptons. The affordable cut on the $E_T^{miss}$ gets lower and lower as the trigger threshold diminishes. It stands at 200 GeV (all-hadronic), 160 GeV (leptons + jets) and 50 GeV (dileptons). The three categories are subject to different requirements depending on the expected number of jets from light and b quarks.

No excess is observed in the $E_T^{miss}$ spectrum and upper limits are set on the signal cross-section, combining the three channels as shown in the summary figure 5.

## 6. Higgs to invisible final states

The first four analyses that were shown above belong to the "mono-X" type of search. We now present a different type of analysis in which the decay of the Higgs to invisible final states in studied [11]. As the Higgs boson may decay to a pair of experimentally invisible DM particles, this is another way of investigating the existence of such a signal. The most sensitive channel to study this signature is Vector Boson Fusion (VBF), in which two electroweak bosons radiated from initial quarks fuse to form a Higgs boson that then decays to an invisible state. This is explained by the low background from SM processes and the peculiar kinematics of the VBF process. The two main features of the VBF process are the large invariant mass and pseudorapidity difference between the two "VBF jets" (originating from the quarks that radiated the VBF bosons). They are the consequence of the fact that the two VBF jets are not color-connected, i.e. there is no gluon exchange in the process. Two complementary analysis strategies are carried out: a shape analysis on the dijet invariant mass spectrum and a cut-and-count analysis. Finally, the VBF analysis is combined with the VH and ggH channels to optimize the sensitivity.

No excess is observed in the dijet invariant mass as shown in figure 4. Upper limits are set on the Higgs to invisible final state branching fraction B(H→inv) in all channels and for the combination.

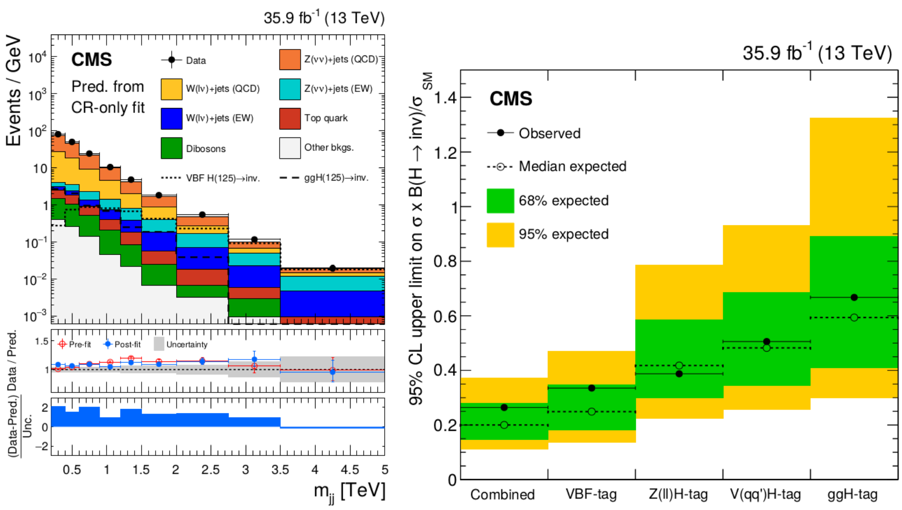


**Figure 4:** Left: invariant mass spectrum of the two VBF jets. Right: upper limit on the signal cross-section for the single channels and for the combination [11].

## 7. Summary

Latest CMS results in the search for Dark Matter particles have been presented. Figure 5 compares the obtained upper limits on the signal cross-section for several DM searches in the case of a vector (left) and a scalar (right) mediator. The results for the monojet, monophoton and $t\bar{t}$ analyses are compared with dijet searches (in the vector mediator scenario) and cosmological observations. With the results from the ATLAS Collaboration, they are amongst the best limits on the existence of DM as weakly interacting massive particles. All CMS public results can be found in reference [12].

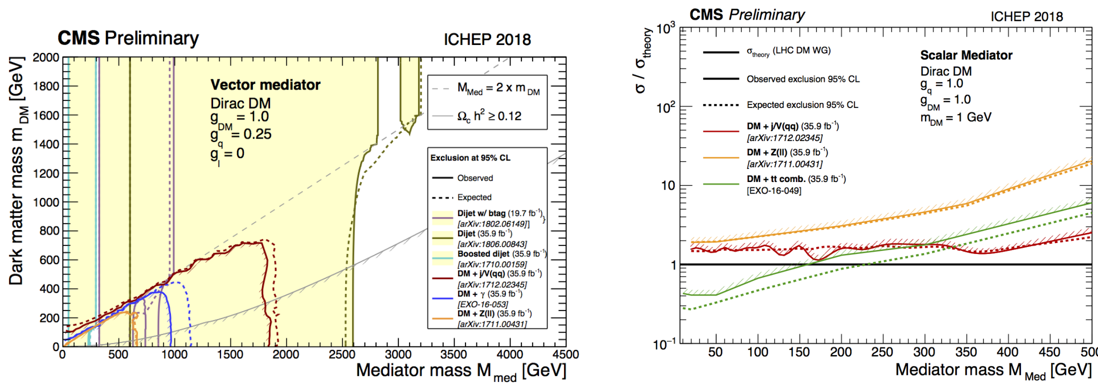


**Figure 5:** Upper limits on the signal cross-section in the DM-mediator mass plane for a vector (left) and a scalar (right) mediator [12].

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