Search for dark matter produced in association with a Higgs boson decaying to a pair of W bosons at CMS

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Introduction

Despite several pieces of evidence suggesting the existence of a large amount of invisible and gravitationally-interacting matter, known as dark matter (DM), its particle nature is still unknown. Assuming an interaction exists between DM and particles predicted by the Standard Model (SM) of particle physics, the possibility of search for it at hadron colliders open. Among the many DM particle candidates, Weakly Interacting Massive Particles (WIMPs) represent the benchmark for searches at the Large Hadron Collider (LHC). Since WIMPs are not expected to interact within the detector material, their presence in an event can be triggered if one or more SM particles are produced in the same event. This leads to an experimental signature with one or more SM particle and large missing momentum in the transverse plane (p_T^{miss}), known as Mono-X or p_T^{miss} + X signatures.

Mono-Higgs Physics Models

Mono-X searches in which the SM particle is a Higgs boson (h) are known as mono-Higgs [1]. While in typical p_T^{miss} + X the SM particle is emitted as initial state radiation, this possibility is strongly suppressed in the mono-Higgs case, due to the low coupling of the Higgs with light quarks and to the loop-mediated interaction of the Higgs with gluons. This means that the Higgs boson has to interact directly with the DM mediator, giving insight into the Higgs-mediator vertex. Following the recommendations of the LHC Dark Matter Working Group [2], two simplified models have been taken as benchmarks for this study. The first is a Z'-2HDM model [3], in which a new Z' mediator is produced through quark annihilation and resonantly decays to a heavy pseudoscalar A and a SM Higgs boson; the pseudoscalar A then decays to a pair of DM particles. The second one is a baryonic Z' model [4] and in this case the Z' mediator radiates a Higgs and then decays to a pair of DM particles.

Search for mono-Higgs signature in the WW final state

In this study, the fully leptonic h → WW decay is considered, producing a final state with one electron, one muon and large p_T^{miss} due to the presence of two neutrinos and two DM particles. The selected final state takes advantage from the large branching fraction: BR(h → WW) ~ 21%, the second largest, after BR(h → bb). Requiring the two W boson to decay leptonically partially reduces the amount of signal events, but ensures a significant background refection and a good control of systematic uncertainties. To define a phase space enriched in signal events, events containing two opposite sign, different flavor leptons (one electron and one muon) are selected. Additional requirements are introduced to enhance the signal significance, as listed in Table 1. In particular, while the first selections in Table 1 are valid to select a phase space enriched in events with two W bosons, the last two have been introduced to exploit the fact that the mono-Higgs signal typically presents low values of the di-leptonic invariant mass (m_{ll}), compatible with the Higgs resonance decaying to two leptons and two neutrinos, and low angular distance ΔR between the two leptons, since the Higgs boson is typically highly boosted.

Variable	Selection		Reason
$q_{\ell_1} \times q_{\ell_2}$	$<$	0	Higgs boson decays to W^+W^-
$p_T^{\ell_1}$ [GeV]	$>$	25	Couple to trigger selections
$p_T^{\ell_2}$ [GeV]	$>$	20	Suppress non-prompt leptons contamination
$p_T^{\ell_3}$ [GeV]	$<$	10	Suppress tri-boson events
$m_{\ell\ell}$ [GeV]	$>$	12	Suppress low-mass resonances
$p_T^{\ell\ell}$ [GeV]	$>$	30	Suppress non-prompt leptons contamination
pf E_T^{miss} [GeV]	$>$	20	Suppress $Z/\gamma^* \to \tau^+\tau^-$ contamination
mpmet [GeV]	$>$	20	Suppress $Z/\gamma^* \to \tau^+\tau^-$ contamination
$m_T^{\ell\ell E_T^{miss}}$ [GeV]	$>$	40	Suppress $Z/\gamma^* \to \tau^+\tau^-$ contamination
Jets cMVAv2	$<$	-0.5884	Suppress top quark contamination
$m_{\ell\ell}$ [GeV]	$<$	76	Suppress non-resonant processes
$\Delta R(\ell, \ell)$ [rad]	$<$	2.5	Suppress non-boosted events

Table 1: Summary of the signal region selections.

Multivariate analysis

After the signal region selections, the signal significance is still low, due to the presence of the two neutrinos in the final state, which spoils the two key variables of the signature: m_{ll} and p_T^{miss}. To recover sensitivity, two sets of boosted decision trees (BDTs) have been trained, one for each model. The BDTs are trained against the main background (Higgs, WW, and Top), using several significant kinematic variables. In order to obtain a BDT response independent of the signal mass point considered, different mass points entered the training:

- Z'-2HDM model: all mass points with m_A = 300 GeV;
- Baryonic Z' model: all mass points with m_χ = 1 GeV.

Additionally, the weights given to signal events used for the training are divided the expected number of events passing the pre-selections required for the training.

Background estimation

The estimation of the background contamination exploits data whenever possible. The evaluation of the non-prompt leptons (leptons produced by the decay of a heavy-flavor quark or by the hadronization of a light quark) contamination fully relies on data and uses the tight-to-loose method: the probability for a non-prompt lepton to be reconstructed as a prompt lepton is measured in a jet-enriched phase space and then applied to events with one tightly-identified lepton and one loosely-but-not-tightly identified lepton. The WZ and Wγ* processes, which can enter the signal region when one of the three leptons they produce is not reconstructed, are simulated using dedicated Montecarlo samples and normalized in specific three-leptons control regions. Also the WW, Top, and DY → ττ backgrounds estimation is based on simulation and normalized in specific control regions. In this case, however, the normalization scale factor is obtained by fitting simultaneously the signal region with the three control regions. Minor backgrounds (multibosons production) and backgrounds for which is not possible to define a sensible control region (SM Higgs production) are simulated using Montecarlo samples and normalized to the theoretical cross-section.

Signal extraction and interpretation of the results

The signal and background yields are obtained through a simultaneous fit to the signal region and the WW, Top, and DY → ττ control regions. The fit is performed on BDT output variable, binned in order to maximize the signal significance in each bin for the signal region, as shown in Figure 1 for the two models, while each control region enters the fit as just one bin, in order to adjust the normalization of the related process. No significant discrepancies with respect to the SM predictions are observed, such that they are interpreted in terms of upper limits for the dark matter production cross-section and the LHC, as shown in Figure 2.

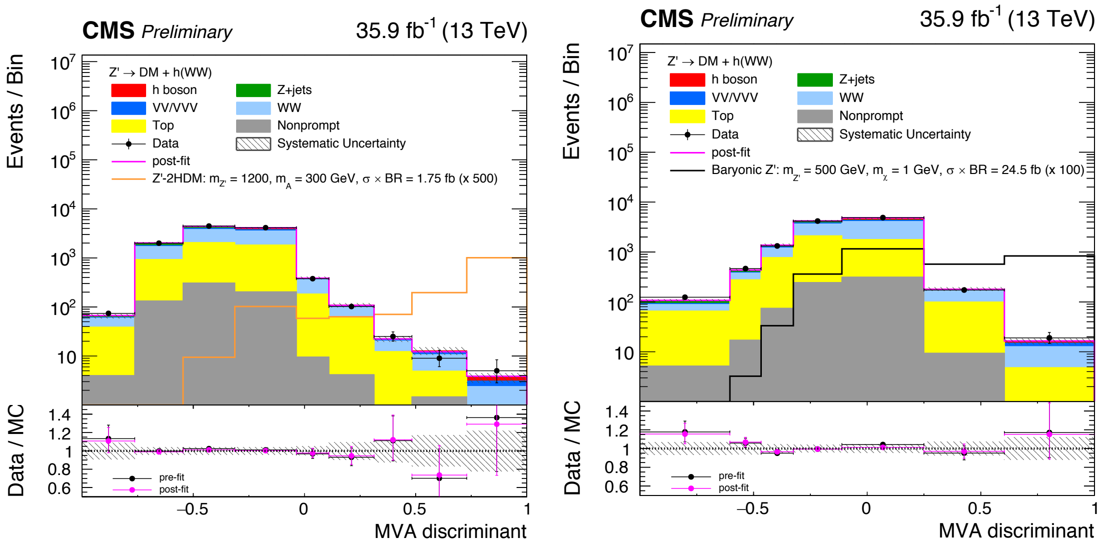

Figure 1: BDT output distribution for the Z'-2HDM model (left) and for the baryonic Z' model (right). The binning used in the fit is shown [5].

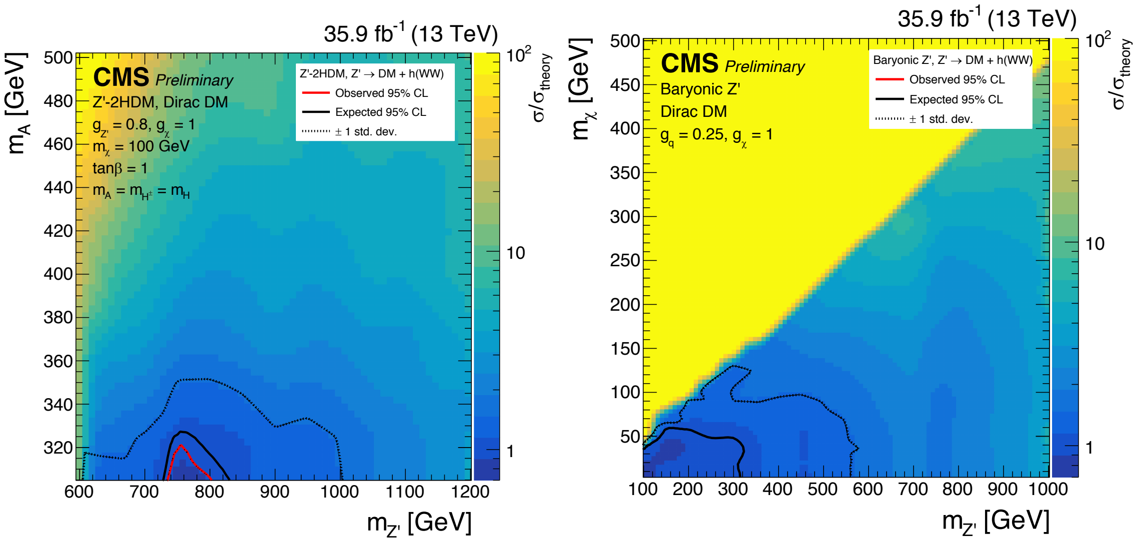

Figure 2: Exclusion limits for the Z'-2HDM model (left) and for the baryonic Z' model (right) using the WW final state [5].

The results of the search are combined with other Higgs boson final states (bb, γγ, ττ, and ZZ) to enhance the sensitivity. The exclusion obtained, shown in Figure 3, is driven by the bb final state, which takes advantage of the larger branching fraction. The limits on the baryonic Z' are further interpreted in terms of spin-independent cross-section for DM scattering off a nucleus [6], allowing a comparison with direct detection experiment. The results are shown in Figure 4.

Conclusions

The current CMS [7] searches for mono-Higgs have been presented, with main focus on the fully leptonic WW final state. The results of the combination of five different Higgs boson decay channels are presented, using two simplified models have been used as benchmarks. The results show no significant differences with respect to the Standard Model expectations and are interpreted in terms of upper limits on the dark matter production cross-section at the LHC. In particular, for the Z'-2HDM mode, masses of the Z' mediator from 1 TeV to 3 TeV and masses of the pseudoscalar A up to 800 GeV are excluded; for the baryonic Z' model, Z' mediator masses up to 1.5 TeV and dark matter particle masses up to 420 GeV are excluded. The results are also reinterpreted in terms of spin-independent interaction cross-section between dark matter and nuclei, excluding values larger than 10^{-42} cm^2 for light dark matter particles.

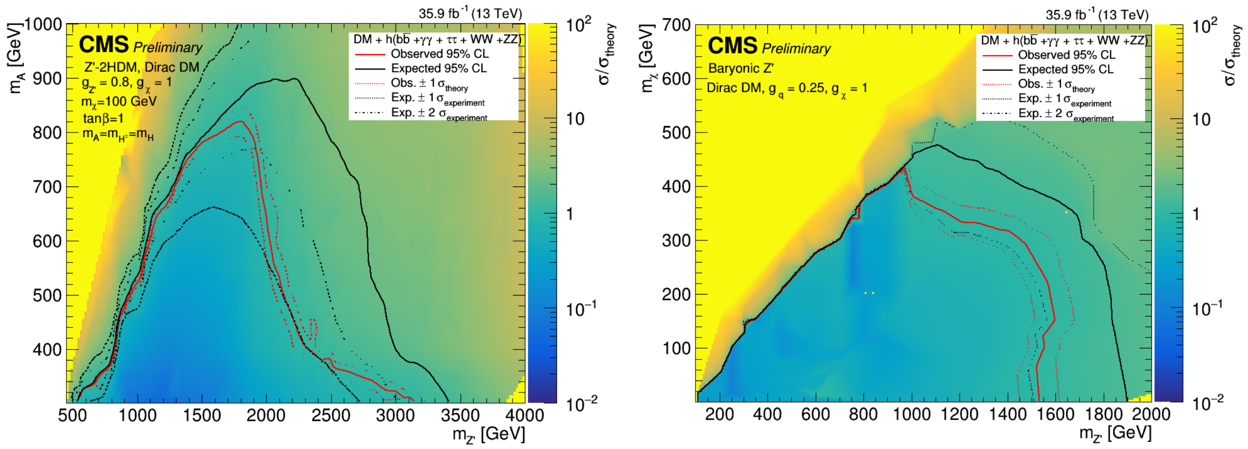

Figure 3: Exclusion limits obtained with the combination of 5 Higgs decay channels for the Z'-2HDM model (left) and for the baryonic Z' model (right) [5].

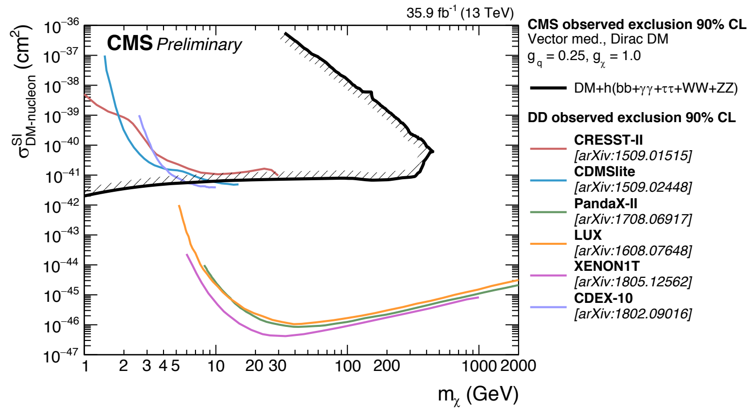

Figure 4: Upper limits on the spin-independent nucleus dark matter interaction cross-section [5].

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