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Searches for Dark Matter with CMS in Mono-X Signatures

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Determination of the nature of dark matter is one of the most fundamental problems of particle physics and cosmology. These proceedings present recent searches for dark matter particles from the CMS experiment at the Large Hadron Collider, focusing on mono-X signatures.

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1. Introduction

The evidence for the presence of *Dark Matter* (DM) is based on numerous observations of its gravitational interaction on the large scale distance. The observations from strong lensing of galaxy clusters, and the rotation curve of many galaxies confirm its presence [1, 2]. The *Dark Sector* (DS) may be considered as a collection of quantum fields, force carriers to mediate the interactions with the Standard Model (SM) particles, and symmetries that are Beyond the SM (BSM) predictions. The main motivation for the DS is to explain the origin of DM and its nature. The *WIMPs* (Weakly Interacting Massive Particles), a class of particles, are considered to be the most favourable candidate for DM amongst the many others such as neutrinos and axions.

The Large Hadron Collider (LHC) is a prime lab for the production of such DS particles in proton-proton (pp) collisions (if they exist). Their searches in Compact Muon Solenoid (CMS) experiment [3, 4] could be classified into two broad categories: Simplified Dark Sector and Extended Dark Sector. The former one is characterized by a single species of final state dark sector particles or DM particles coupled (via vector or axial-vector couplings) with SM counterparts through a new mediator. The minimal main set of parameters of these simplified as well as extended models are: Mediator mass (M_{med}), their coupling g_q and g_χ (or g_{DM}) to SM and DM particles respectively, and mass of the DM (M_χ or M_{DM}). In most scenarios, the couplings are set to $g_q = 0.25$ and $g_\chi = 1.0$ as per LHC DM working group recommendations [5].

2. Mono-Photon

The simplified DS searches usually depend on some initial state radiation in order to identify them because DM particles will leave no signature in the detector due to their extremely weak interaction. Hence, such production will imprint a large momentum imbalance (P_T^{miss}) in the detector. In the mono-X searches, mono-γ has the advantage of identifying a clean high transverse momentum photon due to the very good energy resolution of the CMS ECAL detector. These photons are emitted from the incoming quarks, thus leading to $\gamma + P_T^{miss}$. The main SM background in this channel comes from $Z(\rightarrow \nu\nu) + \gamma$ production, while QCD multijet and W+γ are the subdominant backgrounds. Despite the very large QCD production cross section, the rate of jet faking a photon is severely reduced with the use of dedicated isolation and identification requirements. The simplified model considered here includes vector and axial-vector mediators which couple to the SM and decay to a pair of DM particles ($\chi\chi$) [6]. The signal region (SR) events are selected by requiring $P_T^{miss} > 200$ GeV and a photon with $E_T^\gamma > 225$ GeV within $|\eta^\gamma| < 1.4442$. Requiring ratio of $E_T^\gamma / P_T^{miss} < 1.4$ effectively reduces ~63% of SM γ+jet background. Events are vetoed if they contain isolated e/μ. This helps to reject $W(l\nu) + \gamma$ background. A minimal angular separation between P_T^{miss} and the direction of the first four highest P_T jets is used to further suppress multijet QCD events. To estimate dominant background single-electron (muon) and dielectron (dimuon) control regions (CR) are defined by requiring the presence of isolated electrons (muons) in addition to the SR selection. Additional requirements on $M_T < 160$ GeV (single electron CR) and 60< M_{ll} <120 GeV (dielectron CR) are used to enhance the purity of CRs. A simultaneous likelihood fit is performed over CRs and SRs to estimate the $Z(\nu\nu) + \gamma$ and $W(l\nu) + \gamma$ backgrounds. Fig. 1(left) shows the E_T^γ spectrum, and Fig. 1(centre) and 1(right) show corresponding 2D limits in M_{med} vs m_{DM} parameter space for vector and axial-vector couplings

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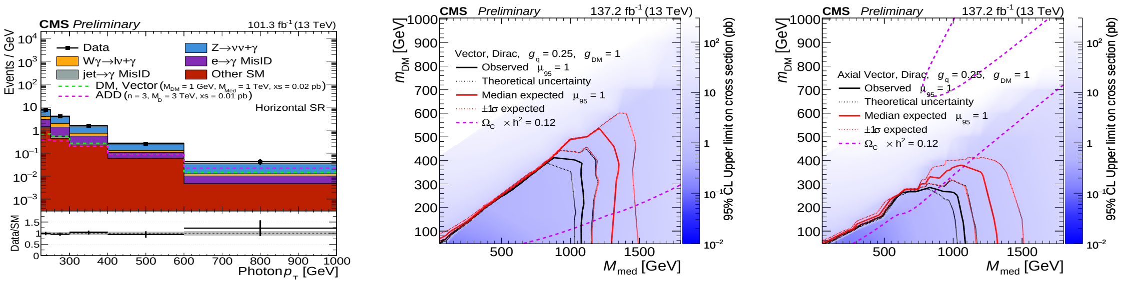

Figure 1: (left)The photon E_T spectrum in SR after all the selection applied [6]. (centre) Upper 95 %CL limits on σ/σ_{th} for vector mediator [6], (right) and axial-vector mediator [6].

respectively. This search excludes mediator mass up to 1085 GeV for a 1 GeV DM mass for both vector and axial-vector couplings.

3. Extended Dark Sector

The extended dark sector framework generalizes the standard cold dark matter paradigm by introducing additional hidden states and interactions beyond a single stable DS particle and can communicate with the SM through different portals such as the Higgs portal or Fermion portal. The following section discusses a few such models and related searches by CMS.

3.1 Mono-Higgs

There are several BSM models where the Higgs boson acts as a portal to DM and could probe its coupling with the SM. Mono-Higgs searches have been performed by CMS in various channels. Here, mono-Higgs results [7] are interpreted in terms of two simplified DS models, namely two Higgs-doublet plus a pseudo scalar model [8], i.e. 2HDM+a (Fig. 2(left)) and Baryonic-Z'. In the 2HDM+a model, the additional light pseudoscalar boson a (of mass M_a) mixes with the scalar and heavy pseudoscalar partner A (with mass M_A) of the observed Higgs boson and decays to a $\chi\chi$ pair. On the other hand, in the Baryonic-Z' model, Z' is a new vector mediator corresponding to a new baryon number symmetry. Here, the Z' decays to a DM pair before radiating a Higgs boson. Due to the Lorentz boost effect, events are categorized into boosted (high P_T Higgs) and resolved (low P_T Higgs) categories. For the boosted category, AK8 (size R=0.8) jets are used, and the ParticleNet algorithm [9] is used to identify b-tagged subjets inside an AK8 jet. For the resolved category AK4 (R=0.4) jets are used, and b jets are tagged using *DeepJet* algorithm [10]. Events failing the boosted category selection are included in the resolved category. The SR is required to have $P_T^{miss} > 250$ (200) GeV for the boosted (resolved) category. Selections for the two models are similar after identifying the Higgs boson candidate in the event. To suppress $t\bar{t}$ and W+jets backgrounds, events are vetoed if they contain an isolated lepton. For both SRs, four different CRs are constituted, containing either a single lepton (e or μ) or dilepton (e or μ). The enriched Z(ll)+jets CR is used to estimate Z($\nu\nu$)+jets contribution in SR. The hadronic recoil $\mathcal{U}$ (defined as the vector sum of $\vec{P_T}^{miss}$ and $\vec{P_T}$ of identified leptons) is used as a proxy for P_T^{miss} and required > 250 (200) GeV in all CRs for the boosted (resolved) region. For the boosted (resolved) category, the soft-drop mass m_{SD} (M_{bb}) for the AK8 (AK4) jet is required to be between 70-160 GeV. A maximum likelihood fit is performed simultaneously over two SRs and eight CRs to extract signal and background yields.

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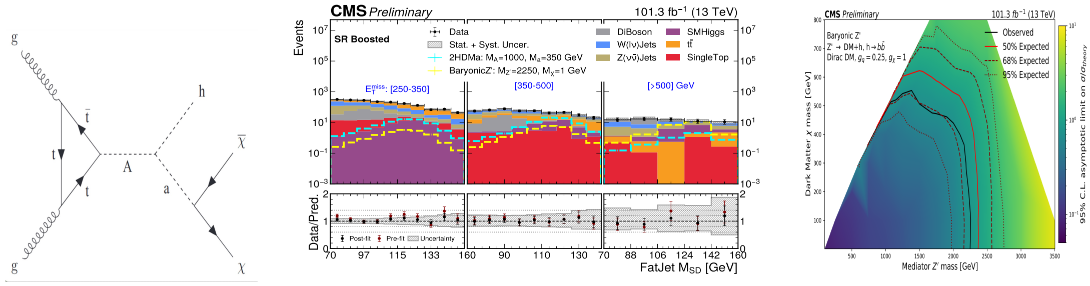

Figure 2: (left) The Feynman diagram for mono-Higgs production from the 2HDM+a model. (centre) The Fatjet M_{SD} distributions in the bins of missing transverse momentum [7]. (right) The expected and observed limits at 95 % CL on signal strength $\mu = \frac{\sigma}{\sigma_{th}}$ in the Z'-M_χ mass plane [7].

The signal extraction in the boosted (resolved) category uses M_{SD} (M_{bb}) across three (five) P_T^{miss} bins. The normalization (shape) uncertainties are treated as a log-normal (Gaussian) distribution in the fit for various theoretical and experimental sources. The M_{SD} distribution for pre-fit and post-fit is shown in Fig. 2(centre). For the 2HDM+a model the $M_a < 350$ GeV is excluded at 95% CL for $M_A = 1$ TeV and $M_\chi = 10$ GeV. For the Baryonic-Z' model, $M_{Z'}$ is excluded below 2.10 TeV for $M_\chi = 1$ GeV as shown in Fig. 2(right).

3.2 Dark Higgs

In some of the extended theoretical frameworks, where DM particles are not the lightest, they could annihilate into a pair of the lightest DS states. One such BSM framework introduces a complex Higgs field together with a spin-1 gauge boson Z'. The vacuum expectation value of such a field breaks the gauge symmetry spontaneously in the DS, giving rise to a dark Higgs boson (H_D). In this model, the H_D is the lightest state in DS, and by mixing with the SM Higgs, it can decay to SM particles [11]. This is also the reason it decays dominantly to $b\bar{b}$ pair for H_D mass between 135 –160 GeV. The representative production mechanism is shown in Fig. 3(left). The SR is characterized by large hadronic recoil $\mathcal{U} > 250$ GeV and large size (R=1.5) AK15 jet from $H_D \to b\bar{b}$ decay [12]. The AK15 jets are required to have $P_T > 160$ GeV and $|\eta| < 2.4$. The modified mass drop tagger algorithm [13], known as the soft drop (SD) algorithm, is applied to remove wide-angle radiation from the AK15 jet. To check the consistency of the AK15 jet with those from $b\bar{b}$ pair DEEPAK15, a Deep *Neural Network* algorithm is used by requiring a certain score obtained from it [14]. The main backgrounds in this search are Z+jets, W+jets, $t\bar{t}$ and multijet QCD. The W+jets events are suppressed by rejecting events that contain a well-isolated lepton. The $t\bar{t}$ contribution is removed by rejecting events that contain a b-tagged AK4 jet. To suppress the QCD multijet background, an azimuthal separation between the direction of $\vec{\mathcal{U}}$ and each AK4 jet is required to be greater than 0.5 radians. Electroweak backgrounds, where a photon is radiated as ISR, are also rejected by vetoing events having loose isolated photons. To characterize and constrain the remaining background contamination in the SR, dedicated CRs are constructed. The enriched Z+jets CR is formed by requiring the same selection as SR, but inverting the selection on the DEEPAK15 score. The W+jets CR is formed requiring full SR selection with the exception of an electron or muon veto. The same single-electron CR is used to constrain the $t\bar{t}$ events (as

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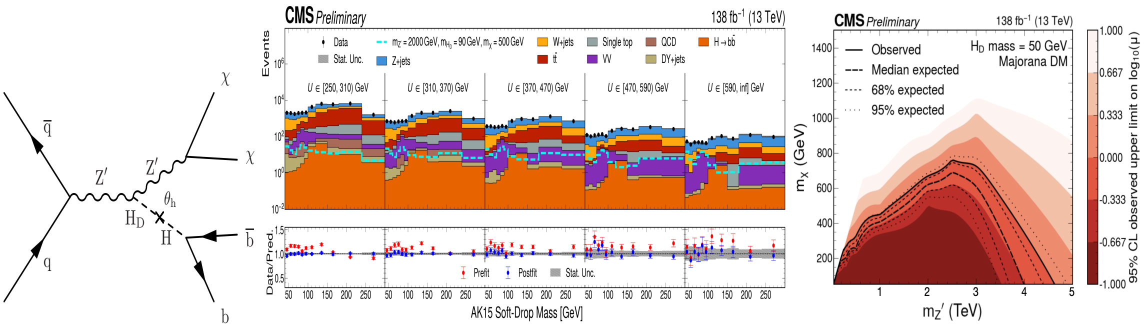

Figure 3: (left)Feynman diagram for the associated production of H_D with χ. (centre) Post-fit m_{SD} distributions in bins of $\mathcal{U}$ [12]. (right) The expected and observed limits at 95% CL on signal strength $\mu = \frac{\sigma}{\sigma_{Th}}$ as function of Z'-M_χ mass plane for H_D mass of 50 GeV [12].

in the case of W+jets background), but veto on b-tagged AK4 jets is inverted. A joint maximum likelihood fit is performed simultaneously across SR and all CRs for each year of data taking to estimate backgrounds and extract signal. The bins of m_{SD} of AK15 jet and hadronic recoil were used to construct a likelihood function to model the background contribution. The various systematic uncertainties are passed as nuisance parameters to the likelihood function in the fit. The post-fit m_{SD} distribution is shown in Fig. 3(centre) for a given set of parameters of the model in different bins of $\mathcal{U}$. The mediator masses in the range of 2.4 – 4.5 TeV are excluded for H_D masses of 50 –150 GeV at 95% CL. Fig. 3(right) shows the expected and observed exclusion limits at 95% CL on the $\mu = \frac{\sigma}{\sigma_{th}}$ in 2D mass plane.

3.3 Pencil Jets

In this search [15], a simplified model associated with DM has a hypothetical Z' boson which couples to both SM and DM and has a mass range from 0.3 -3 GeV only [16]. The mediator mass is considered in the range of 2-3 TeV. The light Z' gives a signature of a narrow cone jet (hence called pencil jets) in the detector with only a few charged multiplicity, similar to a 2-prong object. The Fig. 4(left) shows one of the production mechanisms. For the $M_{Z'} < 2\ M_{DM}$ the Z' can decay only to SM particles while the scenario with $M_{Z'} \geq 2\ M_{DM}$ is similar to traditional mono-jet search. The limit of 3 GeV in $M_{Z'}$ is to avoid the charm threshold otherwise charge multiplicity will be high enough to make the narrow pencil-like jet feature unusable. Candidate events are required to have a hadronic recoil $\mathcal{U} > 250$ GeV and at least one pencil jet, reconstructed using the Hadron-Plus-Strip (HPS) algorithm (originally developed for SM τ lepton reconstruction [17]), with $P_T >$ 120 GeV and $|\eta| < 2.3$. The jet is also required to pass several identification selections. Events with well identified electrons, muons, and photons are rejected to reduce various electroweak backgrounds. To suppress the top background, events with a b-tagged jet are also rejected. To reduce the contribution from multijet QCD background, arising due to mis-measured momenta of jets, the angular separation between P_T^{miss} and the candidate pencil jet is required to be > 0.5 radian. After requiring SR selection, the Machine Learning (ML) techniques with a two-stage sequential approach, *Neural Network* (NN) followed by *Boosted Decision Tree* (BDT), are deployed to discriminate signal from background. The ML score obtained from these techniques is shown in Fig. 4(centre) for two different sets of mass parameters. Several variables, from simulation,

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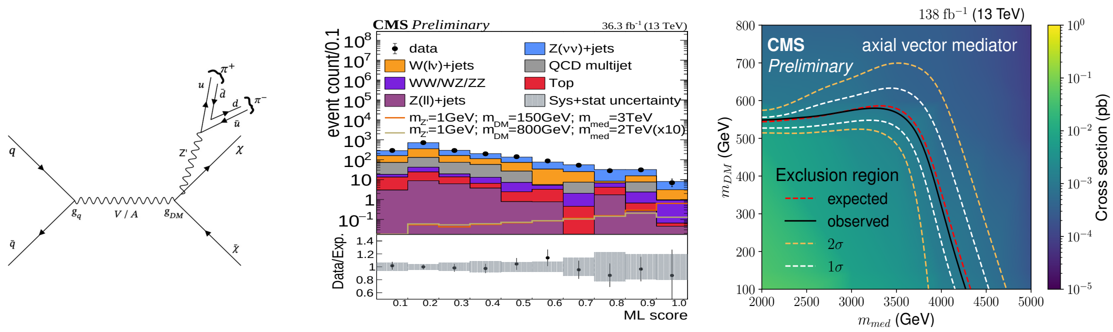

Figure 4: (left) The Feynman diagram for the production mechanism. (centre) Distribution of ML scores from data and estimated backgrounds [15]. (right) The expected and observed limits [15].

which give separation between signal and background are used for training in ML, e.g., ratio of leading track P_T in pencil jet and the pencil jet P_T, angular separation between pencil jet direction and recoil, fractional energies of charged hadrons, neutral hadrons and photons in the associated jets, etc. Various experimental and theoretical uncertainties, including those related to higher order corrections for QCD and electroweak processes, were accounted for final result. A binned maximum likelihood fit is performed on the ML output to obtain the final results. The mediator masses upto 4350 GeV are excluded at 95% CL for a DM mass of 100 GeV as shown in Fig. 4(right).

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