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Search for dark matter produced in association with a pair of bottom quarks in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for dark matter (DM) particles produced in association with bottom quarks is presented. The analysis uses proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. The search is performed in the final state with large missing transverse momentum and a pair of jets originating from bottom quarks. No significant excess of data is observed with respect to the standard model expectation. Results are interpreted in the context of a type-II two-Higgs-doublet model with an additional light pseudoscalar (2HDM+a). An upper limit is set on the mass of the lighter pseudoscalar, excluding masses up to 260 GeV at 95% confidence level. This is the first search at the LHC to probe DM produced in association with two nonresonant bottom quarks in the 2HDM+a model. Sensitivity to the parameter space with the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, greater than 15 is achieved, capitalizing on the enhancement of couplings between pseudoscalars and bottom quarks with high $\tan\beta$.

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*See Appendix A for the list of collaboration members

1 Introduction

So far, the evidence for the existence of dark matter (DM) has come from astrophysics. According to the lambda cold dark matter (ΛCDM) model of cosmology [1], the high-precision Planck satellite map of the cosmic microwave background [2] indicates that DM constitutes about 26% of the total mass-energy of the known universe [3], however, the particle nature of DM has not been elucidated yet. If it is composed of subnuclear particles, then these could potentially be produced at the LHC. Such particles, whether elementary or composite, are weakly interacting with standard model (SM) particles, which means they might escape detection in collider experiments. Since these DM candidates are expected to be electrically neutral and long-lived, their presence could be inferred through an observed imbalance in transverse momentum vectors of particles in the detector, known as missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) with magnitude represented by $p_{\mathrm{T}}^{\mathrm{miss}}$.

Many beyond-the-SM (BSM) theories hypothesize the particle nature of DM [4, 5]. Based on astrophysical and cosmological indications and the observed relic density of the universe, weakly interacting massive particles (WIMPs) [6], with masses in the range from a few GeV to a few TeV, are a popular type of DM candidates that can be searched for at colliders. Such searches can be performed by looking for the pair production of WIMPs through a mediator that recoils against one or more visible SM particles. WIMPs can give a detector signature of the type $\mathrm{X} + p_{\mathrm{T}}^{\mathrm{miss}}$ [7], where X is one or more SM particles, e.g. a heavy-quark pair, produced in association with DM.

In this paper, we perform a search for DM particles produced in association with a pair of bottom quarks ($\mathrm{b\overline{b}} + p_{\mathrm{T}}^{\mathrm{miss}}$) using the proton-proton (pp) collision data collected with the CMS detector in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. The search for DM produced in association with heavy-flavor quarks is complementary to other $\mathrm{X} + p_{\mathrm{T}}^{\mathrm{miss}}$ searches and to searches for DM production in cascades in the context of supersymmetry (SUSY) at the LHC. The ATLAS and CMS Collaborations have performed DM searches using heavy-flavor jets as tags, such as single top quarks ($\mathrm{t}/\bar{\mathrm{t}}$) [8], top quark pairs ($\mathrm{t\bar{t}}$) [9], and $\mathrm{b\overline{b}}$ [10–12].

2 Signal and background simulations

The model used for the interpretation of the results of this analysis is a type-II two-Higgs-doublet model with an additional pseudoscalar singlet interacting with DM particles, referred to as 2HDM+a [13, 14]. The model contains a scalar Higgs boson (h, assumed to be the observed Higgs boson with mass $m_{\mathrm{h}} = 125\,\mathrm{GeV}$), a pair of charged Higgs bosons ($\mathrm{H}^{\pm}$), a heavy scalar boson (H), a heavy pseudoscalar boson (A), a light pseudoscalar boson (a), and a Dirac fermion (χ), which is assumed to be the DM particle. Figure 1 shows the leading Feynman diagrams for the production of the $\mathrm{b\overline{b}} + \chi\overline{\chi}$ process within the 2HDM+a model.

The choice of the fixed and free parameters in this model follows the recommendations of Ref. [15]. The model contains the following parameters: the electroweak vacuum expectation value ($v \approx 246\,\mathrm{GeV}$), the mass of the DM candidate m_{χ}, the masses of the Higgs bosons ($m_{\mathrm{h}}, m_{\mathrm{H}}, m_{\mathrm{H}^{\pm}}$), the masses of the pseudoscalar bosons ($m_{\mathrm{a}}, m_{\mathrm{A}}$), the mixing angle between the two CP-even weak spin-0 eigenstates (α), the mixing angle between the two CP-odd weak spin-0 eigenstates (θ), the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$), and the quartic couplings ($\lambda_3, \lambda_{P1}, \lambda_{P2}$).

In the decoupling limit, where $\sin(\beta - \alpha) = 1$ and $\lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3$ ensure the boundedness of the Higgs potential, electroweak precision constraints give $m_{\mathrm{A}} = m_{\mathrm{H}} = m_{\mathrm{H}^{\pm}}$, and the DM coupling y_χ is set to 1. This results in five free parameters, namely, $\tan\beta$, $\sin\theta$, m_A, m_a, and m_χ. This choice is adopted in many 2HDM+a interpretations of heavy spin-0 resonances searches performed at the LHC [16–20]. Furthermore, the motivation for using the 2HDM+a model is that the couplings of both the heavier pseudoscalar ($g_{Ab\bar{b}}$) and the lighter pseudoscalar ($g_{ab\bar{b}}$) to bottom quarks are proportional to $\tan\beta$, resulting in increased interaction rates in the high-$\tan\beta$ region.

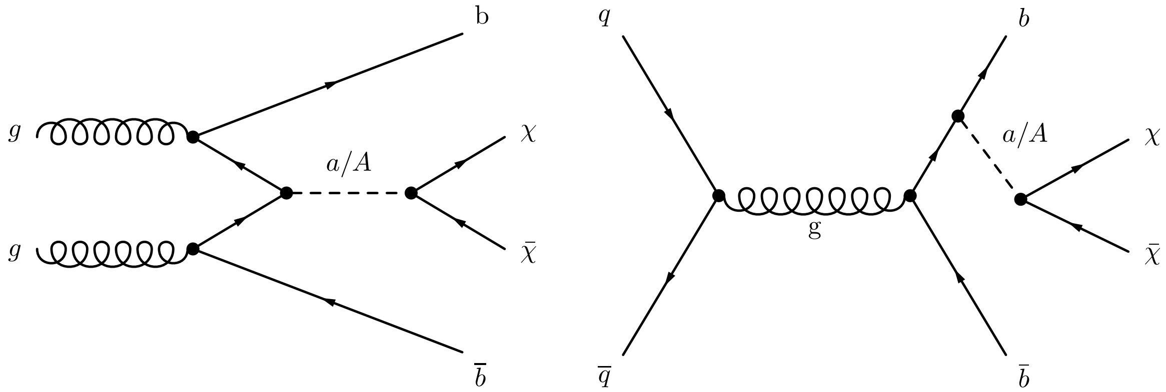

Figure 1: Leading Feynman diagrams for the $b\bar{b} + \chi\bar{\chi}$ process in the 2HDM+a model.

The production cross section is dominantly driven by the lighter mediator a as well as $\tan\beta$ and $\sin\theta$, and does not depend on the mass of A. Furthermore, as shown in Fig. 2, the distribution of p_T^{miss} strongly depends on m_a. On the other hand, $\tan\beta$, $\sin\theta$, and m_χ marginally change the p_T^{miss} distribution, as also shown in Fig. 2 for m_χ. Hence, signal events are generated with $m_A = 600$ GeV, $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_\chi = 1$ GeV for different m_a values using MADGRAPH5_aMC@NLO v2.6.0 [21] and the 5-flavor scheme at leading order (LO) in quantum chromodynamics (QCD) with no additional jets at the matrix element level.

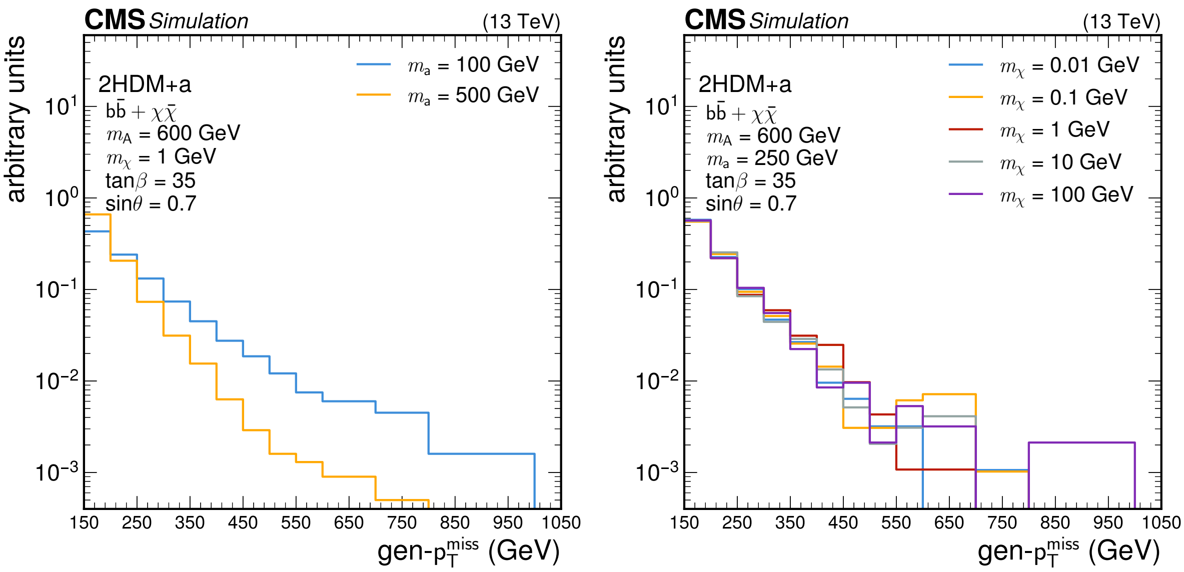

Figure 2: Normalized (to unity) shape of generator-level p_T^{miss} distribution for two illustrative lighter pseudoscalar masses m_a (left) and for five illustrative DM masses m_χ (right).

A lower threshold of 150 GeV is set on p_T^{miss} at the generator level to constrain the kinematic phase space of simulated events to the region where the analysis is conducted. Various SM processes have a similar final state and higher production cross sections. The dominant background comes from the $Z(\nu\nu) + \text{jets}$ production (≈60–70% of the total background), when the Z boson is produced in association with one or two b jets and decays to neutrinos. The $t\bar{t}$ (lepton + jets) and $W(\ell\nu) + \text{jets}$ backgrounds are the next largest backgrounds, where a lepton coming from these processes is either lost or not reconstructed properly in the detector. Dileptonic and hadronic $t\bar{t}$ decays, as well as single top quark and diboson (WW, WZ, ZZ) production events, are smaller contributions to the total background.

The $Z(\nu\nu) + \text{jets}$, $Z(\ell\ell) + \text{jets}$, and $W(\ell\nu) + \text{jets}$ background processes ($\ell = e, \mu, \tau$) are simulated using MadGraph5_aMC@NLO v2.4.2 [21] at next-to-LO (NLO) in QCD. The $t\bar{t}$ and single top quark production events are simulated using the POWHEG v2 generator [22, 23] at NLO in QCD. Diboson events are generated at LO in QCD using the PYTHIA 8.212 generator [24]. The SM Higgs boson with a mass of 125 GeV produced in association with a vector boson is considered as a background and is simulated using the POWHEG generator at NLO in QCD. The NNPDF3.1 parton distribution functions (PDFs) [25] are used, depending on the QCD order of the generator for each physics process. Parton showering, fragmentation, and hadronization are simulated with PYTHIA 8.230 (8.212 for 2016) using the CP5 (CUETP8M1 for 2016) underlying event tune [26, 27].

Interactions of the resulting final state particles with the CMS detector are simulated using the Geant4 software [28] and reconstructed using the same algorithms used for the data. Additional inelastic pp interactions in the same or a neighboring bunch crossing (pileup) are included in the simulation. The pileup distribution is adjusted to match the corresponding distribution observed in data.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters, made of steel and quartz fibers, extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [29]. The first level, composed of custom hardware processors (L1), uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz in a fixed time interval of approximately 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, along with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [30].

4 Data samples and event reconstruction

This search uses data collected in pp collisions between 2016 and 2018. In particular, physics data sets for which the events pass the p_T^{miss} and single-electron triggers at the HLT, and electron-photon and calo-p_T^{miss} triggers at L1 are used for final analysis.

A global "particle-flow" (PF) algorithm [31] aims to reconstruct all individual particles in an event, combining information provided by the inner tracker ECAL, HCAL, and muon detectors. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum [32–34]. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [35].

Jets are clustered using the anti-k_{T} jet clustering algorithm [36] with a distance parameter ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) of 0.4 ("AK4 jets"). Jet calibration [33] is used to account for the energy deposits of neutral particles and full nonlinear hadronic response of the detector. Pileup effects from the charged hadrons are mitigated by removing them from pileup interactions, with a technique called "charged-hadron subtraction" (CHS) [37]. For mitigation of neutral PU particles, a new technique, pileup per particle identification (PUPPI) [38] is used, which builds on the existing CHS algorithm. Furthermore, to ensure that the energy and momentum of the reconstructed jet matches that of the quark/gluon-initiated jet, jet energy corrections are applied to the reconstructed jets. In this search, jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$ are considered. To remove any overlap with leptons, all jets within $\Delta R = 0.4$ with leptons are removed.

Jets originating from bottom quark hadronization, b jets, are identified with the DEEPCSV algorithm [39], which uses a deep neural network (DNN) with 4 hidden layers and exploits the discriminating power of variables such as the position of the secondary vertex, the lifetime of the bottom quark, and the mass of b hadrons. Three working points are defined on the basis of the output of the DeepCSV algorithm. The loose working point corresponds to a 10% misidentification ("mistag") rate with 84% efficiency. The medium working point gives a 1% mistag rate with 68% efficiency, and the tight working point gives a 0.1% mistag rate with 50% efficiency.

The hadron-plus-strips algorithm is employed to reconstruct hadronically decaying τ leptons, denoted as τ_{h} [32]. Jets reconstructed using AK4 jet clustering are used as an input to the algorithm and τ_{h} candidates are reconstructed on the basis of the number of charged hadrons and energy deposits in strips in the ECAL, which originate from the photon candidates and their electron-positron conversions. In order to minimize the misidentification rate of τ_{h} from quark and gluon jets, a convolutional discriminator based on a DNN called DeepTau [40] is employed. Events with a τ_{h} candidate with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.3$ are vetoed.

Shower shape and isolation variables, as defined in Section 7.1 of Ref. [41], are used to identify electrons and photons. Isolated electrons and photons used in this analysis have $p_{\mathrm{T}} > 10$ and $15\,\mathrm{GeV}$, respectively, and $|\eta| < 2.5$. Isolated muons have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$. Two parameters are considered while identifying the muons, namely the number of measurements in the tracker-muon system and the track reconstruction quality [42].

As mentioned in Section 1, the negative vectorial p_{T} sum of all PF candidates is used to calculate $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ with all jet energy corrections are applied. Events with anomalous $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ can occur because of reconstruction failures, detector artifacts, or noncollision backgrounds [34]. Dedicated event filters, which can identify more than 90% of such events, are used, with a mistagging rate of less than 0.1%.

5 Analysis strategy and event selection

The final states reconstructed in this analysis consist of one or two b-tagged jets and large $p_{\mathrm{T}}^{\mathrm{miss}}$, which could arise from DM particles. The data are split into two categories based on the number of b-tagged jets: the 1b category contains events with only one b-tagged jet and is composed of one signal region (SR), called SR1, and two control regions (CRs), while the 2b category contains events with two b-tagged jets and is composed of one SR (SR2) and two CRs. Events that contain at least one well identified and isolated electron and muon with $p_T > 10\,\text{GeV}$ are vetoed from the SRs to reduce the background from the $t\bar{t}$ and $W(\ell\nu)$ + jets processes. These regions are illustrated in Fig. 3. The three dominant background sources $Z(\nu\nu)$ + jets, $t\bar{t}(\ell\nu)$, and $W(\ell\nu)$ + jets are estimated by performing a simultaneous fit of the SRs and CRs, as detailed in Section 7.

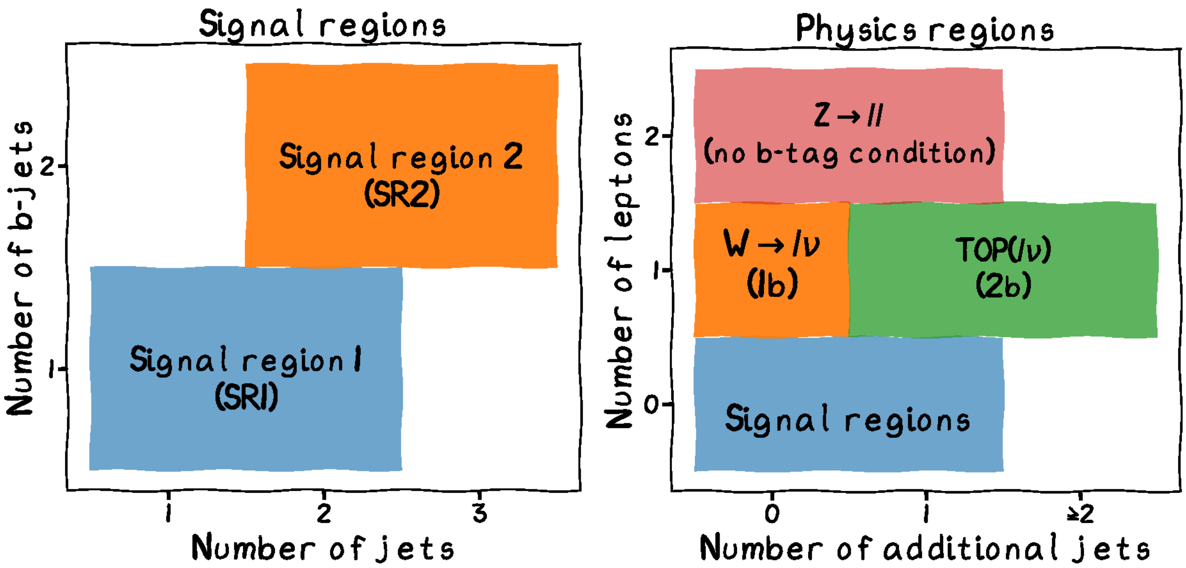

Figure 3: Definition of SR1 and SR2 in terms of jet multiplicity (left), and CR and SR definition in the lepton multiplicity and additional jet multiplicity plane (right). The categories depend on the number and flavor of leptons, and the number of jets in an event.

In the CRs, p_T^{miss} is replaced by the the absolute value of the transverse momentum recoil, $\vec{U}$, to mimic the variation observed in p_T^{miss} within the SRs because of the presence of leptons. The recoil is defined as:

$$U = |\vec{U}| = \left| - \left(\vec{p}_T^{\,miss} + \sum \vec{p}_T^{\,lep} \right) \right| \quad (1)$$

In the 2b category, the p_T^{miss} distribution for signal events is similar to that of background events, such that there is little separation power for signal and background. The angular variable $\cos\Theta^*$ [43], defined as

$$\cos\Theta^* = \left| \tanh\left(\frac{\eta_1 - \eta_2}{2} \right) \right|, \quad (2)$$

where η_1 and η_2 are the pseudorapidities of the leading and subleading jets, gives an optimal discrimination between the signal and backgrounds in this category. In the longitudinally boosted frame, $\cos\Theta^*$ is the cosine of the polar angle between each jet and the beam axis, where the pseudorapidities of the jets are equal and opposite.

Events in the SRs and CRs are selected such that they are mutually exclusive. The events in the SRs and muon-based CRs are selected by a logical 'OR' of p_T^{miss} triggers with different thresholds (90, 100, 110, 120, or 140 GeV), whereas events in the electron-based CRs are selected by using a logical 'OR' of single electron triggers with minimum threshold of 27, 32, or 35 GeV [29]. Events are preselected using a set of requirements common to the SRs and CRs. In the CRs, the selection criteria incorporate U to mimic the variation observed in $p_{\mathrm{T}}^{\mathrm{miss}}$ within the SRs because of the presence of leptons.

The event selection procedure starts with the preselection, which requires events passing trigger thresholds, followed by an offline selection of $p_{\mathrm{T}}^{\mathrm{miss}}$ or recoil $> 250\,\mathrm{GeV}$. Events must include at least one jet, with the leading jet having $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, as optimized based on signal sensitivity. Events with a photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$ are rejected to suppress photon-induced backgrounds ($\mathrm{Z}(\ell\ell) + \gamma + \mathrm{jet}$, $\mathrm{W}(\ell\nu) + \gamma + \mathrm{jet}$).

QCD multijet events can mimic the signal signature when the jet momentum is mismeasured, giving rise to high $p_{\mathrm{T}}^{\mathrm{miss}}$. The QCD multijet background is reduced by requiring the minimum $\Delta\phi$ between any jet and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ ($\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))$) to be higher than 0.5 radians. This ensures that $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is not aligned with any jet, which is a common feature in events with mismeasured jets. The QCD multijet background is further reduced by requiring the relative difference in the value of $p_{\mathrm{T}}^{\mathrm{miss}}$ measured with the PF algorithm and with calorimeter only information to be less than 0.5. This quantity is defined as

$$\Delta p_{\mathrm{T}}^{\mathrm{miss}}(\text{PF - calorimeter}) = \begin{cases} \left|p_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{PF})\,/\,p_{\mathrm{T}}^{\mathrm{miss}}(\text{calorimeter}) - 1\right|, & \text{in the SRs and} \\ \left|p_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{PF})\,/\,U(\text{calorimeter}) - 1\right|, & \text{in the CRs.} \end{cases}$$

Table 1 summarizes the requirements to preselect the events for all three data-taking years. A dedicated event selection for the SRs and CRs is applied on top of the preselection.

Table 1: Preselection criteria applied to all the events entering the SRs and CRs.

Selection	Cut Value
Trigger	$p_{\mathrm{T}}^{\mathrm{miss}}$ or single electron
$p_{\mathrm{T}}^{\mathrm{miss}}$ (U in CR)	$>250\,\mathrm{GeV}$
Jets	multiplicity ≥ 1, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
Leading jet	$p_{\mathrm{T}} > 100\,\mathrm{GeV}$
Overlap removal	no overlap with e, μ, τ_{h}, γ
γ	veto photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$
$\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))$	>0.5
$\Delta p_{\mathrm{T}}^{\mathrm{miss}}(\text{PF - calorimeter})$	<0.5

Events in SR2 have two jets tagged as originating from bottom quarks (using the medium working point) and large $p_{\mathrm{T}}^{\mathrm{miss}}$. Furthermore, up to one additional jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, not b-tagged, is allowed in events entering this region. SR1 is foreseen to catch signal events where one of the b jets is lost because it is outside of the detector acceptance or is not tagged correctly, requiring exactly one b-tagged jet and up to one additional jet. This category helps to recover some lost signal efficiency at the cost of a relatively higher background.

6 Background estimation

To estimate the $\mathrm{Z}(\nu\nu) + \mathrm{jets}$ background, two CRs, targeting the $\mathrm{Z} \to \mathrm{e}^-\mathrm{e}^+$ and $\mathrm{Z} \to \mu^-\mu^+$ processes, are defined. In these CRs, out of exactly two leptons in the event, the leading lepton must have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, the invariant mass of the dilepton candidate must be between 70 and 110 GeV, and there is no b tagging requirement on the jets. The CRs dedicated to the $\mathrm{W}(\ell\nu) + \mathrm{jets}$ and $\mathrm{t\bar{t}}$ backgrounds are built for SR1 and SR2, respectively. They require a single lepton (electron or muon) with $p_T > 30\,\text{GeV}$ and a transverse mass $m_T = \sqrt{2 p_T^{miss} p_T^{l} (1 - \cos[\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{\,l})])}$ less than 160 GeV, together with the same b tagging requirements as in the SRs. In addition, events in the $t\bar{t}$ CR have at least 2 additional non b-tagged jets, while, for the $W(\ell\nu)$ + jets CR, exactly one additional non b-tagged jet is required and p_T^{miss} must be greater than 100 GeV.

To estimate the QCD multijet background, a QCD CR is defined using the same selection as the SR except for requiring $\min(\Delta\phi(\text{jet}, \vec{p}_T^{miss})) < 0.5$. The QCD background in the CR is estimated as the difference between data and other simulated backgrounds, and is plotted against the $\min(\Delta\phi)$ threshold, i.e., for each entry of $\min(\Delta\phi)$ on the x axis, the y axis corresponds to the number of events passing the $\min(\Delta\phi)$ requirement. This distribution is plotted for each bin of p_T^{miss} or $\cos\Theta^*$ and then fitted with a function that describes the behavior of the distribution. The QCD contribution exhibits an exponential decrease with $\min(\Delta\phi)$, as shown for one example in Fig. 4. The QCD background is fitted with an exponential in the $\min(\Delta\phi)$ range between 0 to 0.3, and the resulting function is validated in the $\min(\Delta\phi)$ range between 0.3 to 0.5. The QCD contribution in the SR is calculated as the integral of the function for $\min(\Delta\phi(\text{jet}, \vec{p}_T^{miss})) > 0.5$.

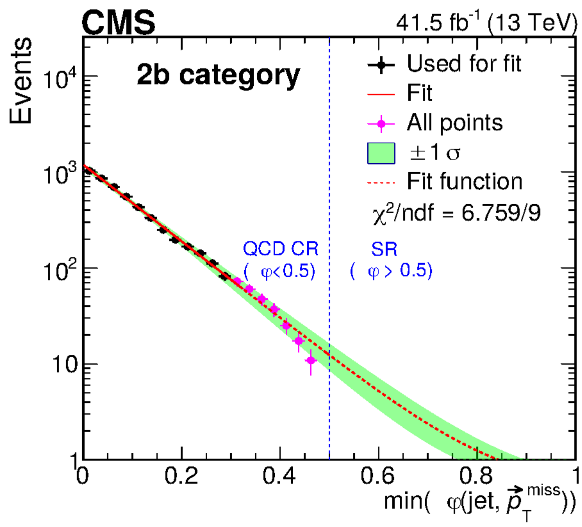

Figure 4: QCD background contribution in the QCD CR (black and pink dots) in the 2b category using 2017 data. The exponential is fitted in the range $\min(\Delta\phi(\text{jet}, \vec{p}_T^{miss})) < 0.3$, checked to fit well in the range $0.3 < \min(\Delta\phi(\text{jet}, \vec{p}_T^{miss})) < 0.5$, and extrapolated to the SRs for $\min(\Delta\phi(\text{jet}, \vec{p}_T^{miss})) > 0.5$. The process is performed for the 1b as well as 2b categories for all years.

7 Signal extraction

The fit for the 1b category is performed using p_T^{miss} in SR1 and U in corresponding CRs as observables, therefore, both SR1 and the corresponding CRs enter simultaneously in a binned profile likelihood fit to estimate the signal. Each bin of p_T^{miss} in SR1 is tied to the corresponding bin of U in the CR via a scale factor, treating the systematic uncertainties as nuisance parameters in the fit. A variable binning is used for p_T^{miss} and U with bin edges 250, 300, 400, 550, and 1000 GeV.

In the 2b category, the variable $\cos\Theta^*$ is used with bins of 0.25 width from 0.0 to 1.0, and a similar procedure is used to constrain the backgrounds using equivalent bins in the CRs. For each category, the electron and muon CRs are combined to form a single CR for each background estimated from data.

8 Systematic uncertainties

The background and signal predictions are affected by systematic uncertainties. Only the systematic uncertainties that have an impact of at least half a percent are taken into account in the signal extraction fit. Some uncertainties affect only the normalization of the various processes, while some affect their distributions too.

Shape-based uncertainties in the b tagging efficiency are calculated separately for true b jets (having b flavor at the particle level) and incorrectly b-tagged jets for each event. The uncertainty in the integrated luminosity amounts to 1.2–2.5%, depending on the data-taking year [44–46], while the overall uncertainty for the 2016–2018 period is 1.6%.

The $p_{\mathrm{T}}^{\mathrm{miss}}$-based trigger efficiency scale factors are measured in a phase space with single-muon and dimuon events, and the difference in the scale factors is considered as the systematic uncertainty. A shape-based systematic uncertainty of the order of 1% is applied to all the simulated samples in the SRs and muon CRs. The electron trigger efficiency scale factors are calculated using a tag-and-probe method [47] and a shape-based uncertainty is applied to all the simulated samples in the electron CRs. The overall effect is of the order of 2–3% on the normalization.

Shape uncertainties arising from jet energy corrections are applied to the simulations, separating different sources of uncertainty. The average effect is of the order of 2–3%.

An uncertainty in the total inelastic cross section of 4.6% [48] is used as a shape-based uncertainty to account for the effects of pileup modeling.

For the single top quark, diboson, and SM Higgs boson processes, a normalization uncertainty of 10%, 20%, and 20%, respectively, is used [49–51]. The systematic uncertainty in the SM Higgs boson cross section due to the renormalization and factorization scales is taken into account, using the envelope of the distributions treated as the shape uncertainty. The uncertainty related to the modeling of PDFs is estimated using the replicas provided in the corresponding PDF sets for the different backgrounds [25, 52–54].

For the QCD multijet background, the total uncertainty comes from the combination of the uncertainty obtained from the 95% confidence intervals of the fitted extrapolation function and a flat uncertainty of 20% that covers the statistical uncertainty. The total effect on the QCD background estimation is about 50%. The magnitude and categories of systematic uncertainties are detailed in Table 2.

9 Results

Figures 5 and 6 present the expected distributions of $p_{\mathrm{T}}^{\mathrm{miss}}$ for SR1 and U for the $\mathrm{Z}(\ell\ell)+\text{jets}$ and $\mathrm{W}(\ell\nu)+\text{jets}$ CRs in the 1b category, as well as $\cos\Theta^*$ for the SR and CRs in the 2b category. These distributions are shown both before (prefit) and after (postfit) the maximum likelihood fit, with the observed data superimposed. No excess with respect to the SM prediction is observed.

Upper limits on the signal strength modifier $\mu = \sigma/\sigma_{\text{theory}}$ are extracted, where σ_{theory} is the production cross section of DM candidates in association with two bottom quarks as predicted by the theoretical model, and σ represents the upper limit on the observed cross section. The upper limits are calculated at the 95% confidence level (CL) using a modified frequen-

Table 2: Systematic uncertainties affecting the shape and normalization (lnN) of the signal and background predictions with an impact greater than 0.5%.

Systematics	Type	Size
Pileup reweighting	shape	3%
b tag efficiency	shape	3–8%
Incorrectly b-tagged jets	shape	1–7%
Electron identification	shape	5–7%
Electron reconstruction efficiency	shape	3–5%
Muon identification	shape	$<$1%
Muon isolation	shape	$<$1%
Electron trigger	shape	1%
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger	shape	1%
Jet energy correction	shape	3%
L1 prefiring	shape	0.5%
Muon prefiring	lnN	0.5%
τ_{h} veto	lnN	6%
Integrated luminosity	lnN	2.5%
Cross section diboson	lnN	20%
Cross section Drell–Yan	lnN	5%
Cross section Higgs boson	lnN	20%
Cross section single top quark	lnN	10%
QCD normalization	lnN	20%
Renormalization and factorization scales	shape	16–42%
PDF	shape	25–50%

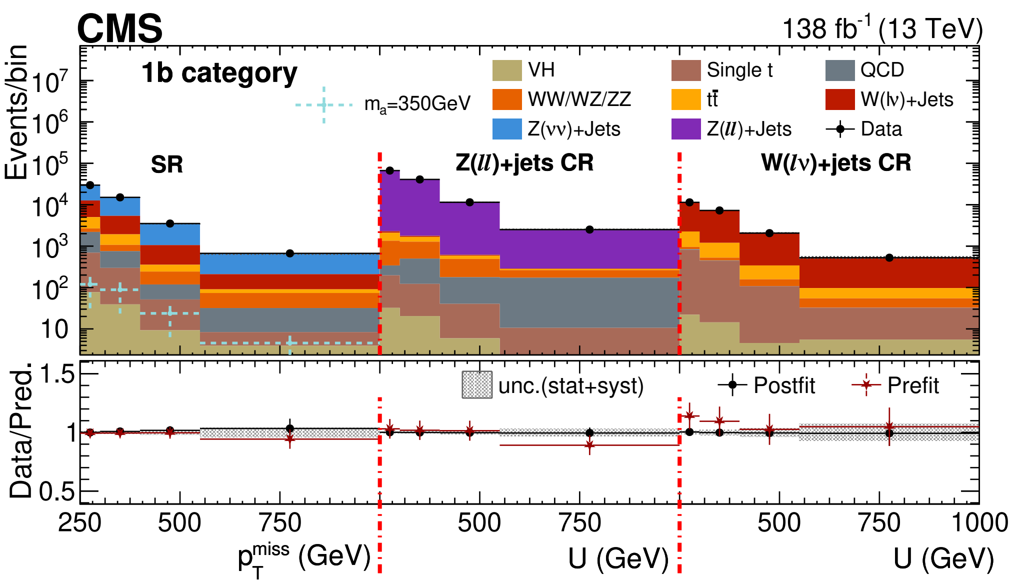

Figure 5: Observed and predicted $p_{\mathrm{T}}^{\mathrm{miss}}$ (U) distributions in the 1b category. The red lines divide the plot into three parts: the first part shows the SR, the second part the $\mathrm{Z}(\ell\ell)+\mathrm{jets}$ CR, and the third part the $\mathrm{W}(\ell\nu)+\mathrm{jets}$ CR. The bottom plot shows the ratio of observed and predicted (both postfit and prefit) distributions along with an uncertainty band that includes both the systematic and statistical components.

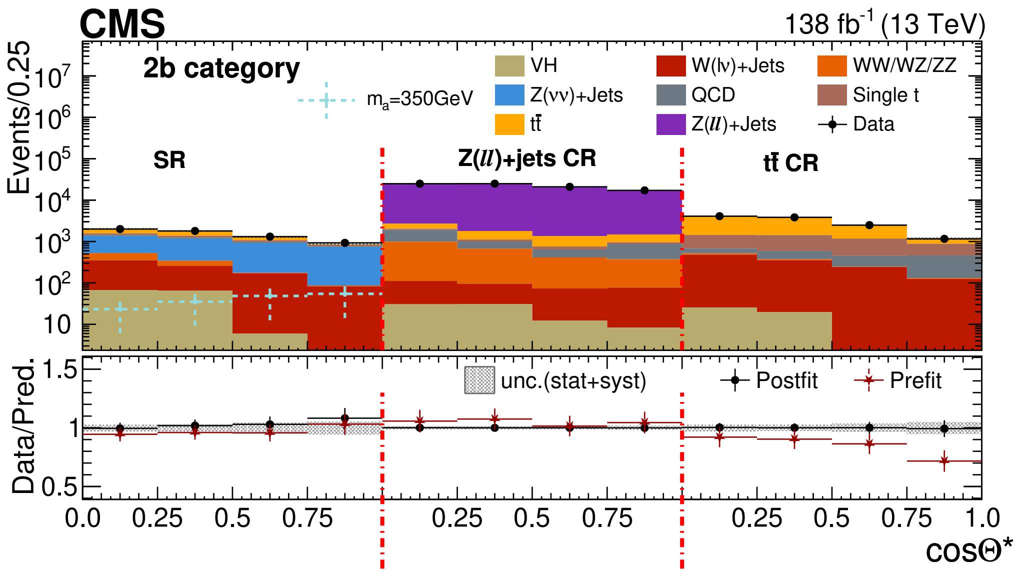

Figure 6: Observed and predicted $\cos\Theta^*$ distributions in the 2b category. The red lines divide the plot into three parts: the first part shows the SR, the second part the $Z(\nu\nu)+$jets CR, and the third part the $t\bar{t}$ CR. The bottom plot shows the ratio of observed and predicted (both postfit and prefit) distributions along with an uncertainty band that includes both the systematic and statistical components.

tist method [55–57] computed with an asymptotic approximation [58]. The combined limit is shown in Fig. 7. The observed exclusion range for m_a is up to 260 GeV, for $m_A = 600$ GeV, $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_\chi = 1$ GeV. The two-dimensional limit in the plane of m_a-$\tan\beta$, using $m_A = 600$ GeV, $\sin\theta = 0.7$ and $m_\chi = 1$ GeV, is shown in Fig. 8 (upper left). The two-dimensional limit in the plane of m_a-$\sin\theta$, using $m_A = 600$ GeV, $\tan\beta = 35$ and $m_\chi = 1$ GeV, is shown in Fig. 8 (upper right). The two-dimensional limit in the plane of m_a–m_χ, using $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_A = 600$ GeV is shown in Fig. 8 (lower).

Tabulated results are provided in the HEPData record for this analysis [59].

10 Summary

A search for dark matter produced in association with a pair of bottom quarks is performed using data collected by the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. The analysis searches for a possible signal by using two independent categories with different multiplicities of jets reconstructed as originating from a bottom quark. The results are interpreted in the framework of a simplified model, namely a type-II two-Higgs-doublet model with an additional pseudoscalar singlet (2HDM+a). It is the first search at the LHC to probe dark matter (DM) produced in association with two nonresonant bottom quarks in this model. This search performs best in the high-$\tan\beta$ phase space, where the signal production cross section is enhanced. This provides a complementary search to constrain the 2HDM+a model parameter phase space in the region where other DM searches are less sensitive. The lighter pseudoscalar mass below 260 GeV is excluded at 95% confidence level for $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_A = 600$ GeV.

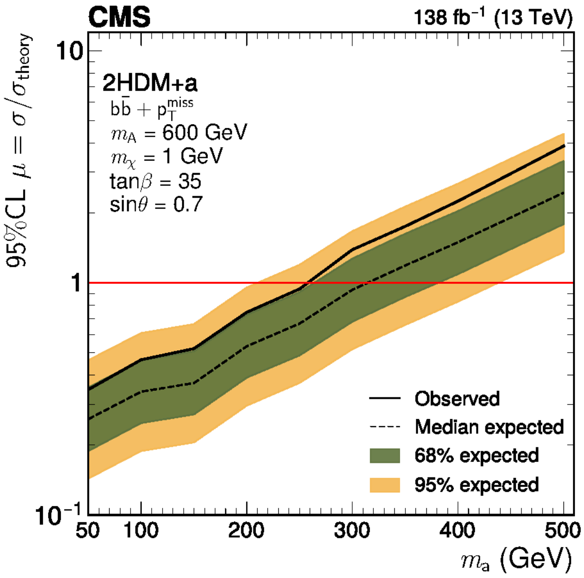

Figure 7: The 95% CL upper limit on the signal strength modifier of DM produced in association with a pair of bottom quarks for $m_A = 600\,\text{GeV}$, $\sin\theta = 0.7$, $m_\chi = 1\,\text{GeV}$, and $\tan\beta = 35$, for the combination of SR1 and SR2. The green and yellow bands show the ±1 and ±2 standard deviations from expected limits. The mass points below the red line are excluded.

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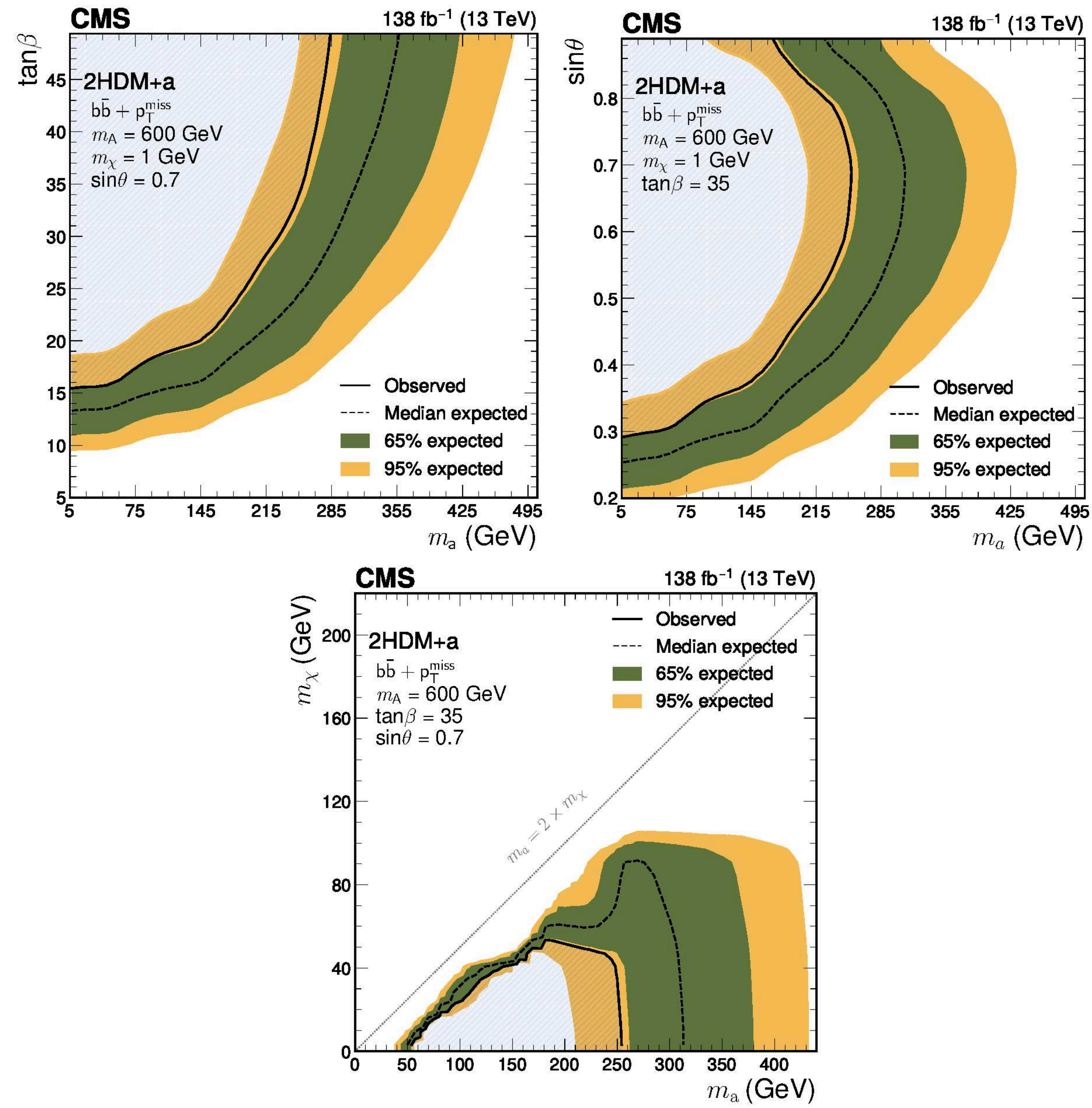

Figure 8: Observed and expected upper limits at 95% CL on the signal strength in the m_a– $\tan\beta$ (upper left), m_a– $\sin\theta$ (upper right), and m_a– m_χ (lower) planes. The shaded area bounded by solid black line is excluded, with, the dotted grey line ($m_a = 2m_\chi$) separating on-shell and off-shell productions for the lower plot.

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