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Journal Article

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Search for Dark Matter and Supersymmetry with a Compressed Mass Spectrum in the Vector Boson Fusion Topology in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

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A first search for pair production of dark matter candidates through vector boson fusion in proton-proton collisions at $\sqrt{s} = 8$ TeV is performed with the CMS detector. The vector boson fusion topology enhances missing transverse momentum, providing a way to probe supersymmetry, even in the case of a compressed mass spectrum. The data sample corresponds to an integrated luminosity of 18.5 fb^{-1} , recorded by the CMS experiment. The observed dijet mass spectrum is consistent with the standard model expectation. In an effective field theory, dark matter masses are explored as a function of contact interaction strength. The most stringent limit on bottom squark production with mass below 315 GeV is also reported, assuming a 5 GeV mass difference with respect to the lightest neutralino.

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Cosmological measurements indicate that dark matter (DM) constitutes 85% of all matter in the Universe [1]. The identity of DM is one of the most fundamental open questions in both particle physics and cosmology. Many extensions of the standard model (SM) predict a DM candidate in the form of a weakly interacting massive particle (WIMP) at the electroweak symmetry breaking scale.

Previously, searches for WIMP DM at the CERN LHC have been performed in the context of complete renormalizable theories, such as supersymmetry (SUSY). For example, many searches for the lightest SUSY particle (LSP) in R -parity-conserving SUSY [2,3] rely on production through decays of heavier particles (e.g., squarks), accessible at the LHC that gives rise to signatures with energetic leptons, photons, and/or jets. Such searches [4–7] have limited sensitivity in scenarios with a compressed mass spectrum, which results in visible particles with too little energy to be detected efficiently.

This Letter describes the first search for direct pair production of DM through pure electroweak vector boson fusion (VBF) processes at a hadron collider. The VBF production mechanism provides a probe of DM that is agnostic to the accessibility of heavier-colored or electroweak sectors. In order to study DM-SM interactions with minimal assumptions, we consider an effective field theory (EFT) approach, which provides complementary information to other DM searches [8–11]. The benchmark model

used assumes the DM particle to be a Dirac fermion and its interaction with the electroweak gauge bosons to be mediated by a heavy particle (dimension 5a operator as in Ref. [12]). The EFT framework is examined with a contact interaction of scale $\Lambda = \mathcal{M}/g_{\text{eff}} = \mathcal{M}/\sqrt{g_\chi g_V}$, where \mathcal{M} is the mass of the heavy mediator, g_χ is its coupling to the DM particle, and g_V is its coupling to vector bosons $V = \gamma, Z, \text{ or } W$ [Fig. 1 (left)].

The EFT benchmark model can be used to compare the results in this Letter to other analyses considering V - V -DM-DM contact interactions, but it cannot be directly compared to searches which probe quark-DM interactions (e.g., in the monojet topology [13–15]). To demonstrate the effectiveness of this VBF analysis strategy relative to the monojet searches, we consider as a benchmark the strong production of squarks, which can satisfy the VBF selection when produced in association with two jets arising from initial-state radiation. Under the assumption that the squark and the LSP are nearly mass degenerate, the jets produced in the squark decays are typically too soft to be observed. Here, we consider bottom squarks [Fig. 1 (right)], and assume a 5 GeV mass difference with the LSP, where the

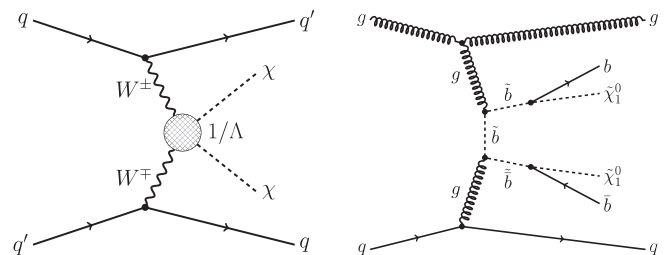


FIG. 1. Feynman diagrams for dark matter pair production in a vector boson fusion process (left) and for bottom squark pair production (right). Given a nearly degenerate bottom squark and LSP, the final-state b quarks are too soft to be observed.

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monojet analyses by ATLAS and CMS [13–15] exclude masses below ≈ 250 GeV, but the analysis is applicable to all generations of squarks.

The analysis is performed using data collected with the CMS experiment at the LHC in proton-proton (pp) collisions at a center-of-mass energy of 8 TeV. The data sample corresponds to an integrated luminosity of 18.5 fb^{-1} . The VBF topology is characterized by the presence of two forward jets (i.e., jets near the beam axis) in opposite hemispheres, leading to a large dijet invariant mass [16–21]. The two jets boost the decay products of new particles, similar to requiring a jet from initial state radiation, which aids event selection and enhances rejection of multijet background. We analyze the dijet mass spectrum to search for new physics in events consistent with the VBF topology and with missing transverse momentum (p_T^{miss}).

The central feature of the CMS apparatus [22] 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, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors up to $|\eta| < 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used (including the azimuthal angle ϕ), and the relevant kinematic variables can be found in Ref. [22].

The data sample was collected using an online event selection requiring events with $p_T^{\text{miss}} > 65$ GeV and at least two jets with $p_T > 35$ GeV, with a VBF topology. This online selection has an efficiency of more than 98% for the analysis.

For the offline analysis, the events are reconstructed from particle candidates found by the particle-flow (PF) algorithm [23,24], which uses reconstructed objects in an event to build candidate muons, electrons, photons, and charged and neutral hadrons. The anti- k_T algorithm [25], with a distance parameter of 0.5, is used for jet clustering. Jets are required to pass identification criteria designed to reject particles from other interactions in the same bunch crossing (pileup) and spurious energy measurements in the calorimeters. For jets with $p_T > 30$ GeV and $|\eta| < 2.5$ (> 2.5), the identification efficiency is about 99% (95%), with 90–95% (60%) of pileup jets rejected [26]. Jets originating from the hadronization of bottom quarks are tagged using the combined secondary vertex algorithm [27,28]. For b -tagged jets with $p_T > 20$ GeV, the identification efficiency is $\approx 85\%$, with a $\approx 10\%$ (20%) misidentification probability for light quarks and gluons (charm quarks) [28]. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker [29]. Muons are identified as a

track in the central tracker, consistent with either a track or several measurements in the muon system, associated with an energy deficit in the calorimeters [30]. Taus are reconstructed using the hadron plus strips algorithm [31].

We require exactly two jets with $p_T > 50$ GeV and $|\eta| < 5$ in a VBF configuration, which corresponds to jets in opposite hemispheres ($\eta_1 \eta_2 < 0$), with large separation in pseudorapidity ($|\Delta\eta| > 4.2$), and large dijet mass ($m_{jj} > 750$ GeV). Events with additional jets of $p_T > 30$ GeV (jet veto) or b -tagged jets of $p_T > 20$ GeV are rejected. Since there are no bottom quarks in Fig. 1 (left), and the bottom quarks in Fig. 1 (right) are too soft to identify efficiently, the rejection of events which contain a b -tagged jet with $p_T > 20$ GeV is optimized to maintain high signal efficiency while reducing $t\bar{t}$ and single-top backgrounds to negligible levels. Similarly, events with isolated leptons of $p_T > 10$ GeV (> 15 GeV for tau leptons) and $|\eta| < 2.5$ are rejected. For electrons and muons, we define the isolation variable as the p_T sum of the reconstructed PF charged and neutral particles within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, centered around the electron or muon track. We require that this isolation variable divided by the lepton's p_T be less than 0.20. Isolation for tau candidates is imposed by applying a dedicated multivariate discriminator, which combines the surrounding energy deposits with the median energy density flow in the event. The analysis selects events with $p_T^{\text{miss}} > 250$ GeV. To reduce contributions from jet mis-measurements, an azimuthal separation between the sub-leading jet and the direction of the missing transverse momentum vector, $|\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_2)| > 0.5$, is required. This set of requirements defines the signal region.

After this selection, the main SM contributions are from the production of $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \ell\nu) + \text{jets}$ (where $\ell = e, \mu, \tau$), with smaller contributions from QCD multijet, $t\bar{t}$, and diboson production. The $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ background has the same topology as the DM or LSP signals, and is therefore mostly irreducible. Because of contribution to p_T^{miss} from neutrinos, $W(\rightarrow \ell\nu) + \text{jets}$ events can enter the signal region if the accompanying charged lepton fails the lepton veto criteria.

Background samples for $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, $W(\rightarrow \ell\nu) + \text{jets}$, $t\bar{t}$, and diboson production are generated with MADGRAPH (v5.1.3) [32]. Events with a Higgs boson produced through VBF are generated with POWHEG (v1.0r1380) [33,34]. Signal samples, DM pair production ($\chi\chi jj$), and bottom squark pair production ($\tilde{b}\tilde{b} jj$) are generated with MADGRAPH (v5.1.5). The momentum distribution of the partons is taken from CTEQ6L1 (MADGRAPH) and CTEQ6M (POWHEG) [35], except for the VBF Higgs boson samples where CT10 [36] is used. The parton showering, fragmentation, hadronization, and various decays are performed with PYTHIA (v6.4.22) [37]. For background samples, the response of the CMS

apparatus is simulated using GEANT4 (v9.4p03) [38], while for the signal samples, a fast simulation program [39] is used. The signal acceptance and dijet mass distribution are cross checked with the GEANT4-based simulation, and the acceptance is corrected for the small differences ($< 5\%$) observed. To simulate the effect of pileup, additional pp collisions with the multiplicity distribution matching that in data are superimposed on the hard-scattering event. Event yields are normalized to the integrated luminosity of the collision data using next-to-next-to-leading order cross section calculations, except in the case of signal samples for which next-to-leading order ($\tilde{b}\tilde{b}jj$) [40] and leading order ($\chi\chi jj$) cross sections [32] are used.

The strategy for the background estimation is to use Monte Carlo (MC) simulations to model the p_T^{miss} distributions, and jet and lepton vetoes. The background yields predicted by the MC simulations are corrected for observed differences, with respect to the data in control regions, and scaled to the fraction of events passing the VBF topology selection, derived from data. The modeling of the dijet mass distribution is checked in the control regions. For the $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ background, we use three control regions to verify the MC simulation, estimate acceptance corrections used to scale the MC yields, and measure the fraction of events passing the VBF topology selection. The control regions are defined by treating muons as neutrinos in the $Z \rightarrow \mu^+\mu^-$ decay mode. The first control region (CR_{Z1}) is a $Z(\rightarrow \mu^+\mu^-) + \text{two jets}$ sample, used to validate modeling of geometric and kinematic acceptance of leptons. We find a data-to-MC correction of $0.98 \pm 0.01(\text{stat})$. For the CR_{Z2} control region, which is a subset of CR_{Z1}, we treat the two muons as neutrinos, subtract the muon p_T vectors from \vec{p}_T^{miss} , and require $p_T^{\text{miss}} > 250$ GeV together with a veto on b -tagged jets and additional leptons, as in the analysis selection. We measure a data-to-MC correction factor of $0.95 \pm 0.06(\text{stat})$. For CR_{Z2}, the non- $Z(\rightarrow \mu^+\mu^-)$ contributions, about 4%, are treated as an uncertainty. Adding the VBF topology selection defines CR_{Z3}. The ratio of CR_{Z3} to CR_{Z2} events in the data gives the fraction of $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ events passing the VBF topology selection. Table I details the contributions of the major backgrounds.

To determine the contribution of $W(\rightarrow \ell\nu) + \text{jets}$ background to the analysis, we use a similar procedure. We substitute the lepton veto with a one muon requirement to obtain a $W(\rightarrow \mu\nu)$ plus two jets sample, CR_{W1}. The data-to-MC correction factor for the sample is $0.97 \pm 0.01(\text{stat})$. Treating the muon as undetected and requiring $p_T^{\text{miss}} > 250$ GeV, and the veto on b -tagged jets and additional leptons, as in the analysis selection, defines CR_{W2}. We measure a data-to-MC correction factor of $0.80 \pm 0.04(\text{stat})$. The control region CR_{W3} is obtained by adding the VBF topology selection.

From MC simulation, we expect the fraction of events passing the lepton and jet vetoes and p_T^{miss} selection that also satisfies our VBF topology selection to be the same for the $Z + \text{jets}$ and $W + \text{jets}$ events. To increase the statistical precision, we combine the two samples and obtain a prediction of $0.008 \pm 0.002(\text{stat})$.

The negligible contribution from QCD multijet production is checked using the number of events passing the analysis selection, except the jet veto and $|\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_2)|$ requirement. Nonmultijet background ($Z/W + \text{jets}$, $t\bar{t}$, diboson) is subtracted, and the number of events is scaled by the efficiency to inefficiency ratios of the jet veto and $|\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_2)|$ requirements. The two ratios are measured in low- p_T^{miss} multijet-enriched data samples. Other smaller background contributions [$Z(\rightarrow \ell^+\ell^-) + \text{jets}$, $t\bar{t}$, diboson] are taken from simulation.

The dominant source of systematic uncertainty in the background estimate for both $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \ell\nu) + \text{jets}$ comes from the event yields found in the control regions. The control sample statistics lead to an uncertainty in the data-to-MC correction factors of 5–6%, and 24% on the fraction of events passing the VBF topology selection. Additional sources of systematic uncertainties due to trigger efficiency (5%), background in the control regions (4–5%), jet energy resolution and scale (3%), and integrated luminosity measurement (3%) [41] are incorporated. The dominant source of systematic uncertainty in the signal expectation comes from the modeling of the two jets in simulation, i.e., the fraction of events passing the VBF topology selection. We take the largest value of the

TABLE I. Event yields predicted from MC in the control regions and observed in the signal region (SR). Only statistical uncertainties are shown. Dashes indicate cases where a background contribution is negligible. The units for the yields are given in the header row of the table.

| Sample | CR _{Z1} (10^3) | CR _{Z2} | CR _{Z3} | CR _{W1} (10^4) | CR _{W2} (10^2) | CR _{W3} | SR |
|---|-----------------------------|---------------------|------------------------|-----------------------------|-----------------------------|------------------------|---------------------|
| $W(\rightarrow \ell\nu) + \text{jets}$ | 0.10 ± 0.02 | $0.0_{-0.0}^{+2.4}$ | $0.0_{-0.0}^{+2.4}$ | 6647 ± 4 | 13.4 ± 0.6 | 8.0 ± 4.4 | 43.6 ± 10.3 |
| $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ | ... | ... | ... | ... | ... | ... | 88.2 ± 9.8 |
| $Z(\rightarrow \ell^+\ell^-) + \text{jets}$ | 5130 ± 5 | 675 ± 35 | 5.5 ± 2.3 | 594.9 ± 0.4 | 0.12 ± 0.04 | $0.0_{-0.0}^{+1.9}$ | $0.0_{-0.0}^{+0.2}$ |
| $t\bar{t}$ | 17.2 ± 0.2 | 1.3 ± 1.2 | $0.0_{-0.0}^{+0.7}$ | 40.5 ± 0.1 | 0.13 ± 0.04 | $0.0_{-0.0}^{+0.7}$ | $0.0_{-0.0}^{+0.7}$ |
| Diboson | 12.8 ± 0.1 | 23.8 ± 4.9 | $0.02_{-0.02}^{+0.25}$ | 10.33 ± 0.03 | 0.22 ± 0.01 | $0.07_{-0.07}^{+0.34}$ | $0.4_{-0.4}^{+0.7}$ |
| Σ MC | 5160 ± 5 | 700 ± 36 | 5.5 ± 2.3 | 7292 ± 5 | 13.8 ± 0.6 | 8.0 ± 4.4 | 132 ± 14 |
| Data | 5073 | 666 | 6 | 7075 | 11.1 | 9 | 118 |

observed difference between data and MC of this fraction from the $Z(\rightarrow \mu^+\mu^-) + \text{jets}$ and $W(\rightarrow \mu\nu) + \text{jets}$ control regions, and their uncertainties as an estimate of the signal uncertainty. For the uncertainty due to the choice of parton momentum distributions, we follow the PDF4LHC recommendations [42,43], using CTEQ6.6L, MRST2006, and NNPDF10 [44–46]. The dominant uncertainties that contribute to the signal dijet mass shape include the p_T^{miss} and jet energy scale uncertainties. The background dijet mass shape uncertainties, which vary between 7% and 42%, are determined by comparing the differences in the predicted and measured dijet mass distributions in various low- p_T^{miss} control regions for Z and $W + \text{jets}$ events.

Figure 2 shows the dijet mass distribution after the analysis selection for the backgrounds and the two signal models. Because of the harder scattering required for DM and bottom squark pair production, we expect a harder dijet mass spectrum than for the SM backgrounds. We fit the dijet mass distribution to calculate upper limits on the cross sections at a 95% confidence level (C.L.), using the CL_s criterion [47,48], with the one-sided (LHC-style) profile likelihood ratio as the test statistic. Systematic uncertainties are represented by nuisance parameters, assuming a gamma or log-normal prior probability for normalization parameters and Gaussian priors for dijet mass shape uncertainties.

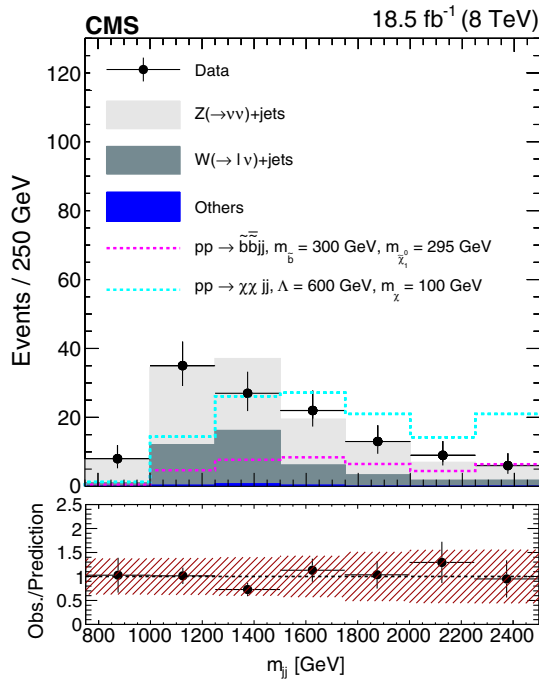


FIG. 2. Dijet mass distribution of the data (dots), estimated background (stacked histograms), and signal samples (dashed lines) after the analysis selection. The last bin includes all events above 2250 GeV. The ratio plot (below) shows the yields in data divided by predicted yields for each bin. The shaded band in the ratio plot includes systematic and statistical uncertainties in the background prediction.

The result of the fit for the 95% C.L. limit in the DM effective theory is given by the solid blue line in Fig. 3 (left); values of (m_χ, Λ) below the curve are excluded. Although EFT is a good approximation in the regime of small momentum transfers, such as direct DM detection experiments, its validity needs to be quantified for LHC experiments where interactions may occur with large momentum transfer. For this purpose, an event in the MC signal sample is classified as having large momentum transfer if the center-of-mass energy of the DM pair ($E_{\text{cm}}^{\chi\chi}$) is larger than the mediator mass parameter of the EFT, $\mathcal{M} = \Lambda g_{\text{eff}}$. In the EFT approach, each parameter point of m_χ and Λ is classified as valid if the fraction of MC signal events (R_Λ) classified as not having large momentum transfer is 80% or more. Truncated limits are calculated by adding the requirement $E_{\text{cm}}^{\chi\chi} < \Lambda g_{\text{eff}}$ to the signal acceptance, following Refs. [49,50]. More signal events are removed in higher DM mass regions where R_Λ curves tend to go up and truncated limits go down. Figure 3 (left) shows curves corresponding to $R_\Lambda = 80\%$ and truncated limits for different values of g_{eff} , along with the DM relic abundance $\Omega h^2 = 0.12$, calculated using the MADDM program [51], assuming that DM pairs annihilate to electroweak boson pairs. The DM is more abundant than observed in the regions above or left from the $\Omega h^2 = 0.12$ line.

The observed cross section upper limit on bottom squark pair production in association with two partons ($p_T > 30 \text{ GeV}$, $|\Delta\eta| > 4.2$) is shown as a function of $m_{\bar{b}}$ and its difference from m_{LSP} in Fig. 3 (right). The contours show observed and expected limits on the masses. The excluded mass values are taken at the intersection of the observed cross section limit, with the theoretical cross section less one standard deviation of its uncertainty.

In summary, we have searched for new physics that results in large p_T^{miss} and jets with a VBF topology. The data sample used corresponds to an integrated luminosity of 18.5 fb^{-1} , collected by the CMS detector in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$. The low multijet background demonstrates the power of the VBF topology approach for DM and compressed mass spectrum SUSY searches. This is the first search for DM production through pure electroweak VBF processes at a hadron collider. The production of DM via VBF, with masses below 420 GeV, is excluded at a 95% confidence level for a chosen contact interaction scale $\Lambda = 600 \text{ GeV}$, extending the reach by other DM searches probing similar operators (e.g., Λ exclusions up to $\approx 100 \text{ GeV}$ for similar DM mass in [8–11]). Limits for different values of Λ can be obtained by scaling the $\chi\chi jj$ cross section, which is proportional to $1/\Lambda^2$. For a nearly mass-degenerate bottom squark and LSP, this analysis sets the most stringent limits reported to date, excluding scalar bottom quarks up to masses of 315 GeV at a 95% confidence level.

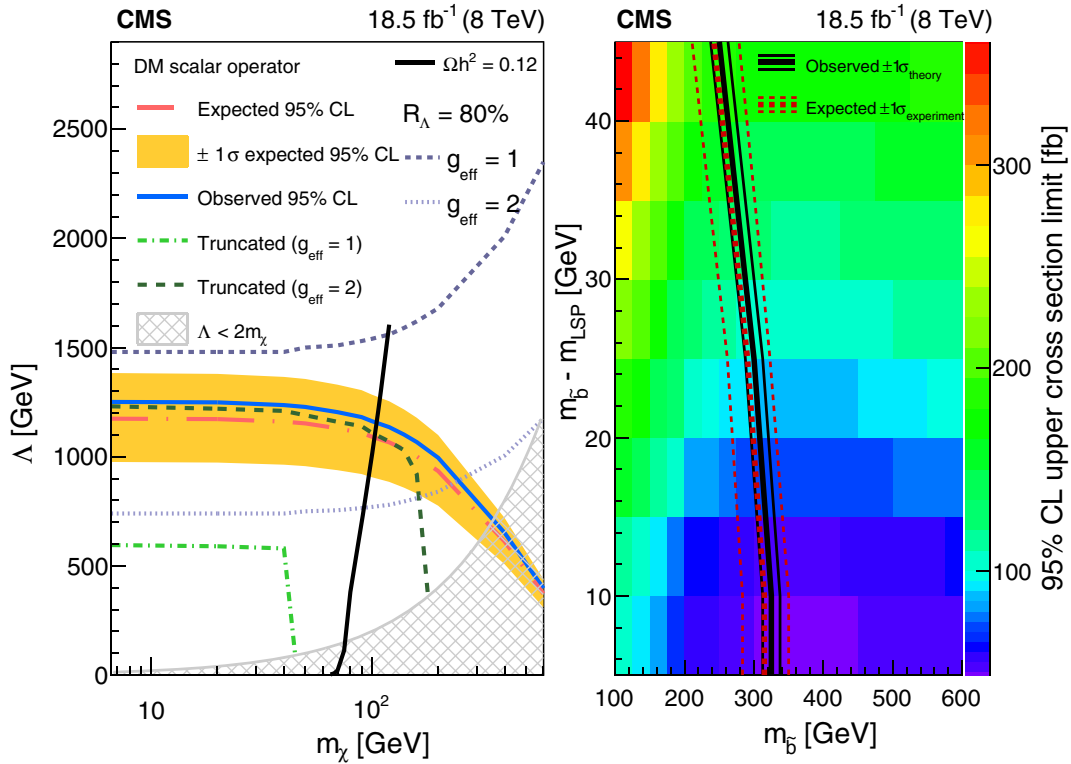


FIG. 3. (left) Contact interaction scale limit at 95% C.L. as a function of the DM mass. The validity of the effective field theory is quantified by (i) $R_\Lambda = 80\%$ contours and (ii) truncated limits for different values of the effective coupling. The DM relic abundance $\Omega h^2 = 0.12$ is calculated as described in the text. (right) Bottom squark pair production 95% C.L. upper cross section limit as a function of the bottom squark mass and the mass difference between the bottom squark and the LSP. The observed (expected) cross section limit includes one standard deviation bands for the theoretical (experimental) uncertainty.

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