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Search for dark matter and supersymmetry in the vector boson fusion topology in proton-proton collisions at CMS

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Abstract: A search for pair production of dark matter candidates and supersymmetry (SUSY) production with two jets in vector-boson fusion (VBF) topology is presented using data collected by the Compact Muon Solenoid (CMS) detector in proton-proton collisions at the Large Hadron Collider (LHC). Final states with no leptons are expected in pair production of dark matter particles or scalar quarks in SUSY compressed mass-spectra scenarios. Final states with low-energy leptons are expected in the production of charginos and neutralinos in SUSY compressed mass-spectra scenarios. Results for both zero and two lepton final states at 8 TeV are presented with brief prospects at 13 TeV.

1. Introduction

Understanding the nature of dark matter (DM) in the Universe would rank among the biggest leaps forward in the progress of fundamental physics. Supersymmetry remains perhaps the best motivated of possible theories to simultaneously describe the nature of DM and solve the gauge hierarchy problem in the Standard Model (SM). The lightest neutralino ($\tilde{\chi}_1^0$) in SUSY could be the lightest supersymmetric particle (LSP) and stable as the DM candidate. However, for all of its attractive features, there are no experimental signs yet of its existence. Current SUSY limits now reach as high as around 1.7 TeV for gluinos in certain scenarios [1]. It could be because SUSY has a more challenging nature. SUSY scenarios with compressed mass-spectra are of great interest. This motivates to conduct searches with vector-boson fusion (VBF) type events. In this paper, results from VBF searches in Run-1 along with prospects in Run-2 are presented.

The search strategy using events with dijet in the VBF topology at the LHC has been suggested in Refs. [2-4]. Two analyses reported here are the first searches for SUSY and DM with two jets in the VBF topology at the LHC: (i) two leptons with VBF dijet to search for charginos and neutralinos in the Minimal Supersymmetric Standard Model (MSSM) [5]; (ii) large momentum imbalance with VBF dijet to test DM-gauge boson couplings in a framework of an effective field theory (EFT) and also test SUSY in compressed mass-spectrum scenario [6]. Below are brief summaries of each analysis.

2. Search for charginos/neutralinos using the VBF processes

Figure 1 shows one of representative Feynman diagrams for pair production of charginos and neutralinos in VBF processes. Figure 2 (left) shows the invariant mass distributions of two jets (m_{jj}) in VBF topology for events with two leptons, comparing between the data and the SM expectation [5]. Upper limits are set on the cross sections for pair production of charginos and neutralinos with two



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associated jets, assuming the supersymmetric partner of the τ lepton to be the lightest slepton and to be lighter than the lighter chargino. The data sample corresponds to an integrated luminosity of 19.7 fb^{-1} at 8 TeV recorded by the CMS detector [7]. Figure 2 (right) shows the observed limit on cross sections for two scenarios. For a compressed mass-spectrum scenario in which the mass difference between the $\tilde{\chi}_1^0$ and the next lightest, mass-degenerate, gaugino particles $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ is 50 GeV, lower mass limit of 170 GeV is set for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$. This scenario was not excluded by the latest CMS analyses in the trilepton channel [8]. The VBF topology has been demonstrated to be complementary to a standard SUSY search in trilepton channel at the LHC.

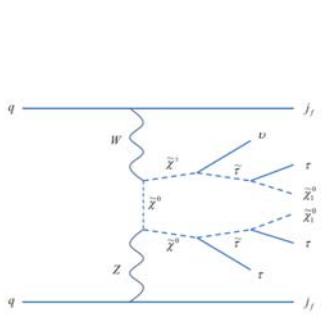


Figure 1. A representative Feynman diagram of pair production of charginos and neutralinos in the VBF processes [5].

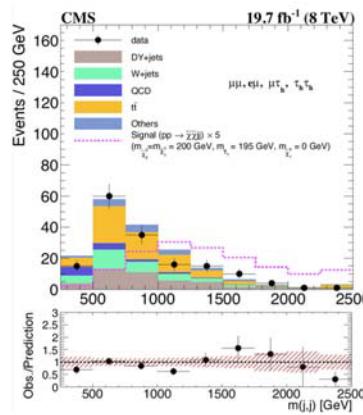
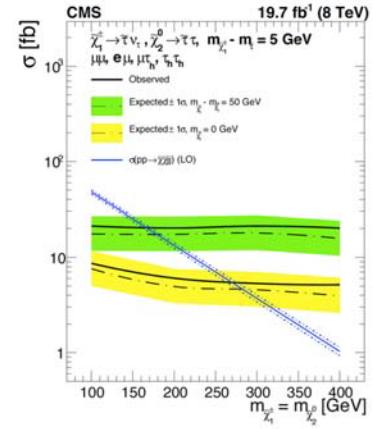


Figure 2. (Left) Dijet invariant mass distribution for the combination of all dilepton channels in missing transverse energy + VBF events, comparing data and the SM expectation [5]. (Right) 95% C.L. upper limits on the cross section as a function of $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$ for the scenario where $m(\tilde{\tau}) = m(\tilde{\chi}_1^\pm) - 5 \text{ GeV}$ in two different $m(\tilde{\chi}_1^0)$ definitions: $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm) - 50 \text{ GeV}$ (compressed mass spectra) and $m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ (large mass gap) [5].



3. DM and Compressed Mass-Spectra SUSY

Events with transverse momentum imbalance and two jets in VBF topology is used for the first time to search for pair production of (i) DM candidates (figure 3 top) and (ii) compressed mass-spectra squarks (figure 3 bottom). The data sample corresponds to an integrated luminosity of 18.5 fb^{-1} of pp collision at 8 TeV recorded by the CMS detector. The observed dijet mass spectrum is consistent with the SM expectation (figure 4).

The results are used to test DM-gauge boson coupling (g_{eff}) in an EFT framework. DM masses (m_χ) are explored as a function of contact interaction strength (Λ) (figure 5 left). The EFT approach is defined to be valid for each parameter point of m_χ and Λ if the fraction of MC signal events (R_Λ) classified as not having large momentum transfer is 80% or more. Here the MC signal event is considered 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, $M = \Lambda g_{\text{eff}}$. Truncated limits are calculated by adding the requirement $E_{\text{cm}}^{\chi\chi} < \Lambda g_{\text{eff}}$ to the signal acceptance, following Refs. [9, 10]. More signal events are removed in higher DM mass regions where R_Λ curves tend to go up and truncated limits go down. The curve of the DM relic abundance $\Omega h^2 = 0.12$ is calculated using the MadDM program [11], assuming that DM pairs annihilate to electroweak gauge boson pairs. The DM is more abundant than observed in the regions above and left from the $\Omega h^2 = 0.12$ line.

The results are also used to set the most stringent limit on third-generation squark production mass below 315 GeV is found (figure 5 right), assuming a 5 GeV mass difference with respect to the lightest neutralino. The result can be compared to the "monojet" searches with a mass limit of 250 GeV in a compressed scenario of bottom squark and top squark [12]. It is demonstrated as a powerful tool for DM and SUSY searches at the LHC.

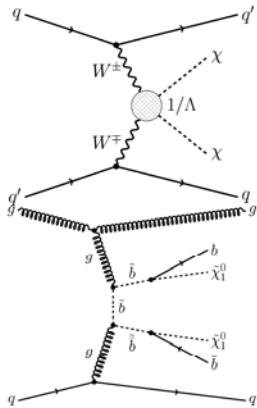


Figure 3. Feynman diagrams for dark matter pair production in a VBF process (top) and for bottom squark pair production (bottom) [6]. Given a nearly degenerate bottom squark and the lightest neutralino (LSP), the final state b -quarks are too soft to be observed.

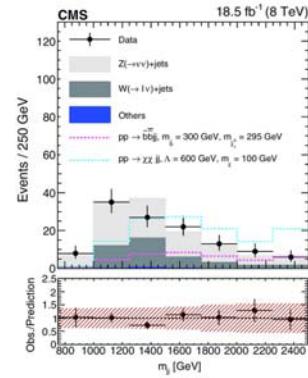


Figure 4. Dijet mass distribution of the data (dots), estimated background (stacked histograms), and signal samples (dashed lines) after the event selection. The last bin includes all events above 2250 GeV. The ratio plot (below) shows the yields in data divided by predicted yields for each bin. The shaded band includes systematic and statistical uncertainties in the background prediction [6].

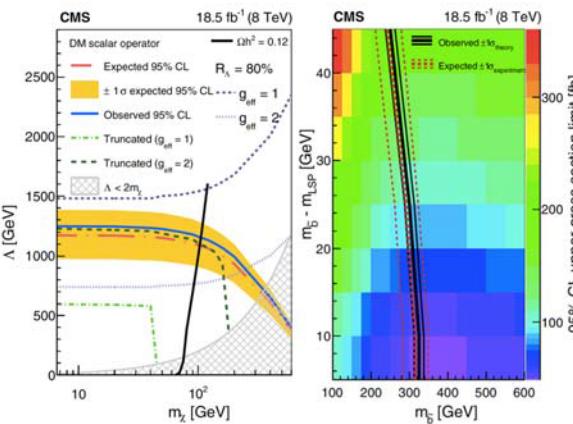


Figure 5. (left) Contact interaction scale (Λ) limit at 95% C.L. as a function of the DM mass (m_χ). Values of (m_χ , Λ) below the curve are excluded. The validity of the effective field theory is quantified by (i) $R_\Lambda = 80\%$ contours and (ii) truncated limits for different values of the effective coupling (g_{eff}). The DM relic abundance $\Omega h^2 = 0.12$ is calculated as described in the text [6]. (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 [6].

4. Summary

The searches for events with 0 and 2 leptons plus two jets in the VBF topology at 8 TeV are presented, using the data of 8-TeV pp collisions recorded by the CMS detector. The dijet mass distributions are consistent with the SM expectations, testing the DM-gauge boson coupling for the first time and setting the stringent limits on squark mass in compressed mass-spectra scenarios. It demonstrates a new approach using VBF for SUSY and DM searches at the LHC.

In Run 2 of the LHC, the CMS experiment recorded so far (2015, 2016) a data sample correspond to an integrated luminosity of about 40 fb^{-1} . This dataset will allow to substantially extend the sensitivity of analyses with events containing 0, 1 or 2 leptons and two jets in the VBF topology in compressed mass-spectra scenario.

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