Available on CMS information server

CMS CR -2024/293

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

29 October 2024 (v2)

Searches for BSM in top final states in CMS

Victor Shang for the CMS Collaboration

Abstract

Many open questions remain that require physics beyond the Standard Model. Results of two recent searches for physics beyond the Standard Model in top final states from the CMS Collaboration are presented. The first result is a search for dark matter produced in association with top quarks. The second result is a search for R-parity violating and stealth supersymmetric signatures in a final state with top quarks, multiple jets, and little to no missing transverse momentum.

Presented at *LHCP2024 12th Large Hadron Collider Physics Conference*

Searches for BSM in top final states in CMS

VICTOR SHANG on behalf of the CMS Collaboration[a,*]

[a] *University of Wisconsin-Madison,*
1150 University Ave, Madison, United States of America

E-mail: victor.shang@cern.ch

Many open questions remain that require physics beyond the Standard Model. Results of two recent searches for physics beyond the Standard Model in top final states from the CMS Collaboration are presented. The first result is a search for dark matter produced in association with top quarks. The second result is a search for R-parity violating and stealth supersymmetric signatures in a final state with top quarks, multiple jets, and little to no missing transverse momentum.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

*Speaker

1. Introduction

Though the Standard Model (SM) of particle physics has been extraordinarily successful at describing the fundamental interactions that govern our universe, many open questions still remain. These include, but are not limited to, questions about matter-antimatter asymmetry, gravity, neutrino masses, and dark matter. Answers to these questions require physics beyond the Standard Model (BSM). Results of two recent searches for BSM in top final states in CMS [1] are presented. The first result is a search for dark matter produced in association with a single top quark or a pair of top quarks [2]. The second result is a search for top squarks in final states with many light flavor jets and 0, 1, or 2 leptons [3] that are signatures of both R-parity violating (RPV) and stealth SY$\overline{\text{Y}}$ supersymmetry (SUSY).

2. Search for dark matter

A large body of evidence for dark matter (DM) comes from astrophysical observations, which include the mass of the Coma Cluster and gravitational lensing measurements of the Bullet Cluster [4, 5]. From these observations, various constraints have been set on the properties of DM. These properties include the fact that DM is stable, with a lifetime at the scale of the age of the universe, it interacts gravitationally, and it has no color or electromagnetic charge. Though there are many possible candidates for DM, one of the most well studied class of candidates are Weakly Interacting Massive Particles (WIMPs).

To look for WIMPs at high energy colliders such as the Large Hadron Collider (LHC) using the CMS detector, one can study various models, including effective field theories with few parameters all the way up to UV complete models with many parameters. This search focuses on a benchmark simplified model developed by the ATLAS/CMS Dark Matter Forum [6] where a single mediator describes the interaction between DM and the SM. This simplified model has a minimal set of four parameters, those being the mass of the mediator (m_{med}), mass of the DM particle (m_{DM}), and the couplings of the mediator to top quarks and DM (g_q, g_{DM}). The mediator is also assumed to be spin-0, with both scalar and pseudoscalar mediators being considered. Along with the assumption of minimal flavor violation, this directly implies a Yukawa coupling structure of the mediator to the SM, which means that the coupling of the mediator is strongest to the heaviest quark, which is the top quark.

Therefore, this search looks for production of a mediator from top quarks that then decay into two DM particles using the full Run II (2016-2018) data collected at CMS. Since the DM particles are not expected to interact strongly with the SM, the presence of DM in the CMS detector is instead inferred from the presence of missing transverse momentum ($\text{p}_{\text{T}}^{\text{miss}}$). Both top quark pair ($t\bar{t}$) and single top ($t/\bar{t}$) signal processes are considered, whose tree-level Feynman diagrams are shown in Fig. 1. For the $t/\bar{t}$ signal process, only the t-channel and tW-channel processes are considered since the cross section for the s-channel $t/\bar{t}$ signal process is at least an order of magnitude lower than for the other signal processes across the mediator mass spectrum. Depending on how the W boson from the top quark decays, there are three possible types of final states: all hadronic (AH), single lepton (SL) and dilepton (DL final states. This search is the first in CMS to consider all three possible channels for both the $t\bar{t}$+DM and $t/\bar{t}$+DM signal processes.

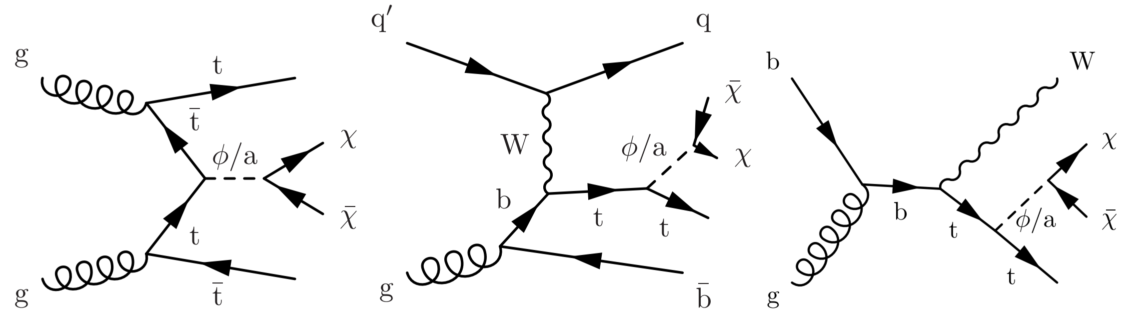

Figure 1: Tree-level Feynman diagrams for the $t\bar{t}$+DM (left), $t/\bar{t}$+DM t-channel (middle), and $t/\bar{t}$+DM tW-channel (right) signal processes considered in the DM search. Figures taken from [2].

The search strategy consists of looking for an excess in the final kinematic spectrum, which is either p_T^{miss} for the AH and SL channels or the output of a neutral network (NN) for the DL channel. Dedicated signal regions (SRs) for all three channels are constructed with different discriminating variable selections applied to optimize signal sensitivity. The main backgrounds include both $t\bar{t}$ and V+jet processes. In the AH and SL channels, a shape analysis is performed on the p_T^{miss} spectrum after selections for the 0 and 1 lepton final states, while the major SM backgrounds are determined in a simultaneous fit to data in orthogonal control regions (CRs) designed to be enriched in the main backgrounds. In the DL channel, p_T^{miss} turns out to be less effective as a discriminating variable because of the presence of an additional neutrino in the final state. Thus, a shape analysis is instead performed on the output of a NN that is trained to distinguish signal from background after selections for the 2 lepton final state. Various discriminating variables including p_T^{miss} are used to train the NN, while the SM background is predominantly estimated from Monte Carlo (MC) simulations.

In all three channels, SRs are defined based on the number of b-tagged jets (=1, $\geq$ 2) in order to target the $t/\bar{t}$ and $t\bar{t}$ signal processes, respectively. In the DL channel, the event is also required to contain at least 1 jet as well as pass a $t\bar{t}$ kinematic reconstruction algorithm in the $\geq$ 2 b-tagged jet region. In the AH and SL channels, an additional categorization based on the number of forward jets in the detector is defined in order to specifically target the t-channel $t/\bar{t}$ signal process. In addition, minimal selections of $p_T^{miss} > 250$ GeV and $\geq 3(\geq 2)$ jets in the AH(SL) channels are also imposed.

For the statistical analysis, a maximum likelihood binned fit is performed in both the SRs and CRs to the p_T^{miss} (AH, SL) or NN (DL) distributions. Normalization and shape effects of the systematic uncertainties are considered through constrained nuisance parameters, while the CRs are used to estimate the main background through unconstrained rate parameters linked to the SRs. Since no significant deviation from SM predictions was found for all mediator mass hypotheses, the estimated signal strength parameters from the fit were then used to set limits on DM production cross sections relative to theory predictions. These limits are shown in Fig. 2. Scalar and pseudoscalar mediator masses are excluded below 280(400) GeV and 290(380) GeV for observed (expected) limits at 95% confidence level (CL), respectively.

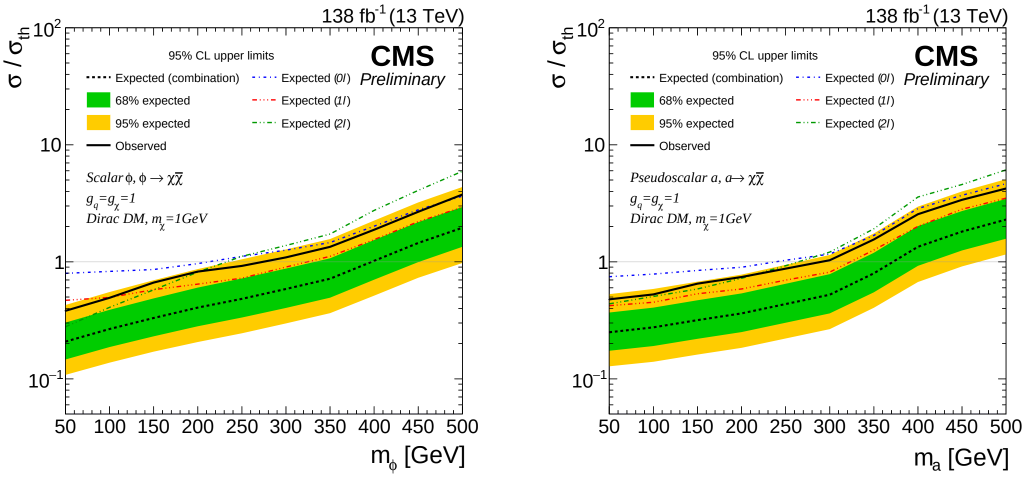

Figure 2: 95% CL upper limits on production cross section for combined $t\bar{t}$ and $t/\bar{t}$ DM signal processes for scalar (left) and pseudoscalar (right) interactions as a function of the mediator mass. The expected upper limit for the full channel combination is shown by the black dashed line with the 68% and 95% CL uncertainty bands in green and yellow, respectively, while the observed upper limit is shown by the solid black line. The dashed blue, red, and green lines also show the expected upper limits for the AH, SL, and DL channels alone, respectively. Figures taken from [2].

3. Stealth/RPV Stop Search

Many BSM physics models include versions of SUSY that predict the production of events with top quarks, low p_T^{miss}, and many additional quarks or gluons. This search for top squarks (stops) considers both RPV and stealth SY$\overline{\text{Y}}$ SUSY signatures whose main tree-level Feynman diagrams are shown in Fig. 3. The final state for both signal models include $t\bar{t}$ with at least 6 jets and little to no p_T^{miss}. Because of the high multiplicity of jets expected in the final state for the signal, the primary observable is the jet multiplicity (N_{jets}). Three possible channels are considered: zero lepton (0l), one lepton (1l) and two leptons (2L), depending on the decay of the top quarks in the final state.

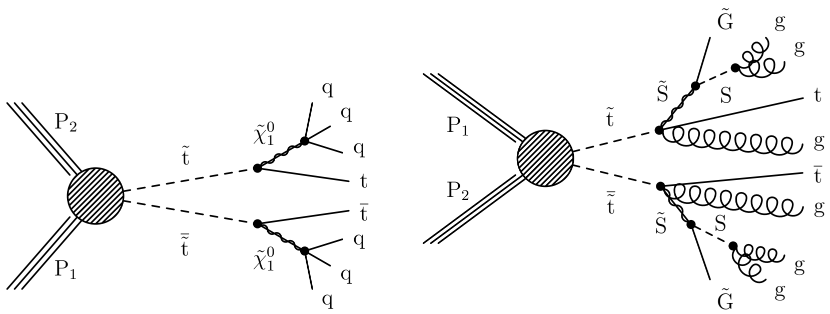

Figure 3: Tree-level Feynman diagrams for the RPV (left) and stealth SY$\overline{\text{Y}}$ (right) signal processes considered in the stop search. Figures taken from [3].

The main background consists of $t\bar{t}$+jets background. This background is estimated using a novel machine learning method using decorrelated discriminators referred to as the ABCDisCoTEC technique [7]. First, two independent discriminators between signal and background ($S_{NN,1}$, $S_{NN,2}$) are generated to use as the basis variables for the ABCD background estimation technique. Then, signal and $t\bar{t}$+jets background are estimated separately in each N_{jets} bin in a simultaneous fit to data in four 'ABCD' bins (N_A, N_B, N_C, N_D) in the $S_{NN,1}$ vs $S_{NN,2}$ plane. An 'ABCD' constraint is then imposed, given by

$$N_A = \kappa \left(\frac{N_B N_C}{N_D} \right) \tag{1}$$

where κ is a correction factor calculated for each N_{jets} category to account for discrepancies between the number of $t\bar{t}$+jets events predicted and observed in region A in simulation. The other backgrounds are predicted either from MC simulation (tt+X, single top, Z+jets, multiboson) or extracted from a dedicated control region (QCD multijet).

Since no significant deviation from SM predictions was found for all stop mass hypotheses, the estimated signal strength parameters from the fit were then used to set limits on $\sigma_{\tilde{t}\bar{\tilde{t}}}$ relative to theory predictions. These limits are shown in Fig. 4. Stop mass exclusion limits were set at 700 GeV and 930 GeV for the RPV and stealth SY$\bar{\text{Y}}$ SUSY signal models, respectively.

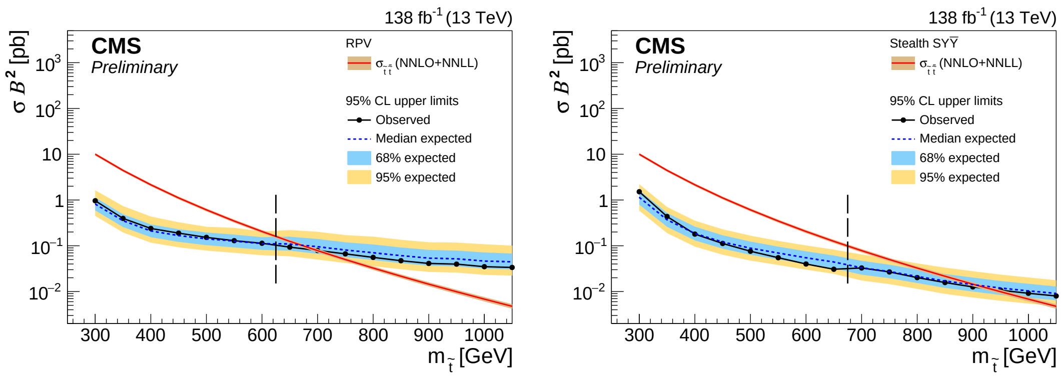

Figure 4: 95% CL upper limits on $\sigma_{\tilde{t}\bar{\tilde{t}}}$ for the RPV (left) and stealth SY$\bar{\text{Y}}$ SUSY (right) signal models as a function of $m_{\tilde{t}}$ for the full channel combination. The median expected upper limit is shown in the dashed blue line, with the 68% and 95% CL uncertainty bands shown in light-blue and yellow, respectively. The observed limit is shown in black. The vertical dashed line denotes the transition from the low-mass optimization to high-mass optimization ABCD boundaries. Additionally, the theoretical cross section ins shown in red with its uncertainty in light brown. Figures taken from [3].

References

[1] CMS Collaboration, *The CMS Experiment at the CERN LHC*, *JINST* **3**, S08004 (2008).

[2] CMS Collaboration, *Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at* $\sqrt{s}$ = 13 *TeV*, *CERN Technical Report* CMS-PAS-EXO-22-014 (2024), CDS URL.

[3] CMS Collaboration, *Search for top squarks in final states with many light flavor jets and 0, 1, or 2 leptons in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *CERN Technical Report* CMS-PAS-SUS-23-001 (2024), CDS URL.

[4] F. Zwicky, *Die Rotverschiebung von extragalaktischen Nebeln*, *Helv. Phys. Acta* **6** (1933).

[5] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, *A direct empirical proof of the existence of dark matter*, *The Astrophysical Journal Letters* **648** (2006).

[6] ATLAS/CMS Dark Matter Forum, *Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum*, *Phys. Dark Univ.* **27**, 100371 (2020).

[7] G. Kasieczka, B. Nachman, M. D. Schwartz, and D. Shih, *Automating the ABCD method with machine learning*, *Phys. Rev. D* **103**, 035021 (2021).