Validation of the MadAnalysis 5 implementation of the CMS search for supersymmetry in the multilepton channel with 35.9 fb^{-1} of 13 TeV LHC data

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We present the MadAnalysis 5 implementation and validation of the CMS-SUS-16-039 (arXiv:1709.05406) analysis. This analysis looks for multileptonic final states as could arise from the production of a pair of gauginos, and investigates 35.9 fb^{-1} of 13 TeV LHC collision data. The validation of our analysis is based on inputs provided by the CMS collaboration for definite MSSM benchmark scenarios, and we detail in this note extensive cutflow results for various signal regions that we compare with the CMS results.

I. INTRODUCTION

In this note, we summarise the validation of our implementation of the CMS saerch for supersymmetry in the multilepton plus missing energy channel that has been presented in Ref. [1]. Our implementation relies on the version v1.6 of the MadAnalysis 5 framework [2, 3] and its associated public analysis database [4]. The search strategy investigates final-state configurations featuring two same-sign, three or at least four leptons and a significant amount of missing transverse energy. The main search variables consist in the transverse mass of a system comprised of one of the leptons and the missing momentum (M_T), the invariant mass of dilepton systems ($M_{\ell\ell}$), the missing transverse energy $\not\!\!E_T$ and the system stransverse mass M_{T2}.

For the validation of our analysis, we have considered a class of simplified models with a light electroweakino sector and heavy colored sparticles for which the CMS collaboration has provided detailed cutflows. We have compared the efficiencies obained with MadAnalysis 5 with those provided by CMS for various selections and on a cut-by-cut basis. This has allowed us to consider our analysis as validated.

II. DESCRIPTION OF THE ANALYSIS

A. Investigated signals

The considered CMS search targets the direct production of associated pairs of charginos $\widetilde\chi_1^\pm$ and neutralinos $\widetilde\chi_2^0$ which are assumed to be mass-degenerate and wino-like. The $\widetilde\chi_1^0$ neutralino is the lightest supersymmetric particle (LSP) and is taken bino-like. In addition, the CMS-SUS-16-039 analysis also studies scenarios with a gravitino $\widetilde G$ LSP, the next-to-lightest supersymmetric particles being higgsino-like neutralinos. In practice, three classes of simplified models are considered, with a specific production process in mind.

- $pp \to \widetilde\chi_1^\pm\widetilde\chi_2^0$ **decaying via sleptons**. The gaugino pair decays into a final state made of charged leptons, neutrinos and neutralinos through intermediate sleptons and sneutrinos. For decays mediated by left-handed sleptons ($\widetilde\ell_L$), the gaugino properties are fixed so that they decay into any lepton flavor with the same branching fraction. This setup is therefore coined "flavor-democratic". For decays mediated by right-handed slepton ($\widetilde\ell_R$), a preference for tau lepton production is implemented. In this case, left-handed sleptons and sneutrinos are assumed to be decoupled from the rest of the spectrum, and this class of models is dubbed "τ-enriched". A third category of models, known as "τ-dominated", is finally considered. In this case, all left-handed sleptons and sneutrinos as well as the first and second generations of right-handed sleptons are decoupled, so that winos can only decay via a $\widetilde\tau_R$. In all these simplified scenarios, the mass(es) of all relevant sleptons is (are) assumed to lie within the bino-wino mass window, $m_{\widetilde\ell} = m_{\widetilde\nu} = m_{\widetilde\chi_1^0} + x(\widetilde\chi_2^0 - \widetilde\chi_1^0)$, where $x = 0.05$, 0.5 or 0.95.
- $pp \to \widetilde\chi_1^\pm\widetilde\chi_2^0$ **decaying into gauge and Higgs bosons**. All sleptons and sneutrinos are assumed decoupled, so that charginos and neutralinos directly decay into a neutralino LSP and an electroweak gauge or Higgs boson. Apart from the Standard-Model-like Higgs boson, all Higgs states are considered heavy and decoupled.
- $pp \to \widetilde\chi_1^0\widetilde\chi_1^0$ **decaying into gauge and Higgs bosons**. One focuses here on a specific gauge-mediated supersymmetry breaking (GMSB) model, in which the light part of the spectrum is comprised of four almost mass-degenerate higgsinos ($\widetilde\chi_2^0$, $\widetilde\chi_1^\pm$ and $\widetilde\chi_1^0$) and an effectively massless gravitino LSP $\widetilde G$. Since the heavier $\widetilde\chi_2^0$ and $\widetilde\chi_1^\pm$ states decay into the lighter $\widetilde\chi_1^0$ state and very soft particles which escape detection, all possible production processes ($pp \to \widetilde\chi_1^\pm\widetilde\chi_2^0 + \widetilde\chi_2^0\widetilde\chi_1^0 + \widetilde\chi_1^\pm\widetilde\chi_1^\mp + \widetilde\chi_1^\pm\widetilde\chi_1^0$) effectively contribute to the $\widetilde\chi_1^0\widetilde\chi_1^0$ production rate. The $\widetilde\chi_1^0$ higgsino then promptly decays into a Z-boson or a Higgs boson and a gravitino $\widetilde G$.

B. Same-sign dilepton signal regions

The same-sign dilepton analysis strategy relies on an event preselection imposing the presence of at least two isolated same-sign light-flavor leptons ($\ell = e,\ \mu$) with a transverse momentum $p_T > 25$ (20) GeV for the leading lepton and $p_T > 15$ (10) GeV for the next-to-leading lepton if it is an electron (a muon). Moreover, the pseudorapidity of these two leading lepton has to satistify $|\eta_\ell| < 2.5$ or 2.4 in the electron and muon case, respectively. Events exhibiting a third lepton with a $p_T > 20$ GeV (in the case of an electron or a tau) or 10 GeV (in the case of a muon) are vetoed, together with events featuring a third loose lepton forming an opposite-sign same-flavour (OSSF) dilepton system compatible with a Z-boson ($|m_{\ell\ell} - m_Z| < 15$ GeV) or a light hadronic resonance ($m_{\ell\ell} < 12$ GeV). In addition, events are required to contain some transverse missing energy $\not{E}_T > 60$ GeV.

Considered jets candidates have a $p_T > 25$ GeV and a pseudorapidity $|\eta| < 2.4$, and they are required to be well separated from any lepton candidate located at a distance in the transverse plane of $\Delta R < 0.4$. b-jets are identified according to the medium working point of the CMS CSV algorithm [5], and any event featuring at least one b-tagged jet and more than one jet is rejected.

The events are then categorized in 30 'SS' signal regions depending on the number of jets ($N_j = 0$ or 1), the minimum transverse mass of the systems comprised of one of the leptons and the missing energy, the amount of missing transverse energy and the transverse momentum of the dilepton system.

C. Trileptonic signal regions

In this case, events featuring three leptons including at most two hadronic taus are selected. The leading electron or muon must satisfy the same requirements as in section II B, as for the next-to-leading electron and muon if present. Tau candidates must have a $p_T > 20$ GeV and a pseudorapidity satisfying $|\eta| < 2.3$. Moreover, they are required to be isolated from any other object in a cone of radius $\Delta R = 0.5$ centered on the tau direction. If the leading lepton is a muon and the other two leptons are either electrons or taus, the p_T threshold is increased to 25 GeV. For events with two hadronic taus, all leptons have to be central ($|\eta_\ell| < 2.1$) and the single electron (muon) must have a $p_T > 30$ (25) GeV. In addition, selected events must exhibit a missing transverse energy of at least 50 GeV, and events with exactly three leptons containing an OSSF pair of electrons or muons must fullfil $|m_{3\ell} - m_Z| > 15$ GeV, where $m_{3\ell}$ is the invariant mass of the three lepton system. This allows for the reduction of the background induced by photon conversion. As in section II B, the invariant mass of any loose OSSF lepton pair has moreover to be larger than 12 GeV.

After this preselections, events are categorized into 6 classes of signal regions labeled from A to F.

Events exhibiting three light-flavor leptons are included in the A region if they feature at least one OSSF lepton pair, or in the B region if not. Events populating the A region are further classified into 44 subregions according to the invariant mass $m_{\ell\ell}$ of the OSSF lepton pair that is the mostly compatible with a Z-boson, the amount of missing transverse energy $\not{E}_T$ and the transverse mass M_T of the system made of the third lepton and the missing momentum. Events populating the B region are classified into 6 subregions according to the invariant mass of the opposite-sign (OS) dilepton system that is mostly compatible with a Z-boson (taken to be zero if all leptons have the same charge), $\not{E}_T$ and M_T (being the minimum M_T if no OS dilepton system is present).

Events featuring two light-flavor leptons forming an OSSF lepton pair and one hadronic tau are included in a category C of 18 signal regions. These regions are defined as for the A class of signal regions, afer replacing the M_T variable by the stransverse mass M_{T2}. Events for which one has one hadronic tau but no OSSF lepton pair are categorized into 16 D subregions (if one OS lepton pair is found) and 12 E regions (otherwise), similarily to the B regions after again replacing the M_T variable by the M_{T2} variable. A set of 12 F regions is finally dedicated to cases for which there are two hadronic taus and one light-flavor lepton, using the same variables as for the other C-E regions.

D. Signal regions featuring more than three leptons

Events with more than three leptons are preselected as discussed in section II C, and then categorized into 5 signal regions labeled from G to K. Thos regions are then further categorized into 3 to 5 subregions, depending on the amount of missing transverse energy, the number of hadronic taus and the number of OSSF pairs that can be formed.

III. VALIDATION

For the validation of our reimplementation in MadAnalysis 5, we have implemented a few supersymmetric spectra matching the simplified models for which CMS had provided cutflow information, We have used MadGraph 5 for event generation [8] through which we have convoluted the leading-order matrix elements associated with the various supersymmetric signals with the NNPDF23LO1 set of parton densities [10]. Parton showering and hadronisation have been handled with Pythia 8 [9], and the simulation of the detector response is achieved with Delphes 3 [11], which internally relies on FastJet [13] and its implementation of the anti-k_T algorithm [14] for object reconstrution. Our results relies on a Delphes tune containing the reconstruction and identification efficiencies provided by the CMS collaboration [12].

A. Validation of the Signal Region Categories A and B

In Table I, we present MadAnalysis 5 predictions and CMS official results for a cutflow that is typical of the signal regions of categories A and B. We consider the $pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1$ production process in a setup where the electroweakinos decay both into weak vector bosons. We focus on two scenarios, for which $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 200$ GeV and $m_{\tilde{\chi}^0_1} = 100$ GeV (left) and $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 500$ GeV and $m_{\tilde{\chi}^0_1} = 150$ GeV (right). The presented results include contributions for all signal regions of the A and B caegories compatible with the cuts, the first entry in the table being normalized to the CMS result. We obtain a very good agreement for each selection cut.

B. Validation of Signal Region Categories C to F

In Table II, we present MadAnalysis 5 predictions and CMS official results for a cutflow that is typical of the signal regions of categories C, D, E and F. We consider the $pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1$ production process in the "τ-dominated" setup where the electroweakinos decay via a right-handed stau. We focus on two scenarios, for which $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 250$ GeV and $m_{\tilde{\chi}^0_1} = 150$ GeV (left) and $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 600$ GeV and $m_{\tilde{\chi}^0_1} = 1$ GeV. As in the previous section, events are normalized to the first CMS entry of the table and a fair agreement, at the 20% level of better, is obtained for each cut after summing the contributions of all subregions compatible with the cuts.

C. Validation of SS Signal Region Category

In Table III, we present MadAnalysis 5 predictions and CMS official results for a cutflow that is typical of the signal regions of the SS category. We consider the $pp \to \tilde{\chi}^0_2\tilde{\chi}^\pm_1$ production process in the "flavor-democratic" setup where the electroweakinos decay equally into sleptons of all generations. We focus on two scenarios, for which $m_{\tilde{\chi}^0_2} = m_{\tilde{\chi}^\pm_1} = 500$ GeV and $m_{\tilde{\chi}^0_1} = 350$ GeV and for which the slepton mass is deduced as detailed in section II A fixing the x-parameter to 0.05 (left) and 0.5 (right). This correponds to effective left-handed slepton masses of 357.5 and 425 GeV, respectively. As above, events are normalized to the first CMS entry of the table and an excellent agreement has been obtained for each cut after summing the contributions of all subregions.

D. Validation of Signal region Categories G to K

In Table IV, we present MadAnalysis 5 predictions and CMS official results for a cutflow that is typical of the signal regions of the SS category. We consider the $pp \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ production process in the a GMSB scenario where the neutralinos each decay into a Z-boson and a gravitino. We focus on two scenarios, for which $m_{\tilde{\chi}^0_1} =$ 100 GeV (left) and 800 GeV (right), the gravitino mass being fixed to 1 GeV in both cases. As above, events are normalized to the first CMS entry of the table and an excellent agreement has been obtained for each cut after summing the contributions of all subregions.

IV. SUMMARY

We have presented the MadAnalysis 5 reimplementation of the CMS search for new physics in the multilepton plus missing transverse energy channel dubbed CMS-SUS-16-039. We have implemented all the signal regions of this analysis, and are hence capable of reinterpreting the CMS results for new physics signals featuring a same-sign dileptonic system, a trileptonic system or a final state involving at least four leptons. We have validated our reimplementation in the context of various simplified models inspired by the MSSM and for which the CMS collaboration has provided detailed cutflow charts. We have presented the MadAnalysis 5 results along side those of the CMS collaboration for the chosen benchmark points and have found an excellent agreement. The largest discrepancy reaches roughly 20%, even if for the concerned class of regions, all other cuts agree quite well. Due to the lack of information, we were not able to investigate the problem further. However, an agreement at the level of 20% is sufficient for considering the analysis reimplementation validated.

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Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
3 tight e, μ or τ_h	482.20	–	482.20	–
4th lepton veto	481.49	99.9%	482.20	100%
conversion and low-mass veto	463.71	96.3%	467.88	97.0%
b-jet veto	456.68	98.5%	460.73	98.5%
$\not\!\!E_T > 50$ GeV	317.00	69.4%	281.9	61.2%
$M_T > 100$ GeV	111.97	35.3%	91.3	32.4%
$M_{\ell\ell} > 75$ GeV	103.49	92.4%	87.9	96.3%

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
3 tight e, μ or τ_h	18.06	–	18.06	–
4th lepton veto	18.03	99.8%	18.06	100%
conversion and low-mass veto	17.79	98.6%	17.88	99.0%
b-jet veto	17.47	98.2%	17.51	97.9%
$\not\!\!E_T > 50$ GeV	16.98	97.2%	17.05	97.4%
$M_T > 100$ GeV	12.74	75.1%	13.07	76.7%
$M_{\ell\ell} > 75$ GeV	11.71	91.9%	12.61	96.5%

TABLE I. Cutflow charts, presented in terms of both the expected number of signal events for a luminosity of 35.9 fb $^{-1}$ of 13 TeV LHC collisions and the cut efficiencies. We consider a cutflow typical of the signal regions of categories A and B and scenarios for which $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm} = 200$ GeV and $m_{\tilde\chi_1^0} = 100$ GeV (left) and $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm} = 500$ GeV and $m_{\tilde\chi_1^0} = 150$ GeV (right).

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
3 tight e, μ or τ_h	189.05	–	189.05	–
4th lepton veto	188.58	99.8%	188.75	99.8%
conversion and low-mass veto	168.19	89.2%	175.80	93.1%
b-jet veto	166.26	98.8%	172.27	98.0%
$\not\!\!E_T > 50$ GeV	117.09	70.4%	107.90	62.6%
$M_{T2} < 100$ GeV	112.26	95.9%	97.55	90.4%
$M_{\ell\ell} < 75$ GeV	93.07	82.9%	63.10	64.7%

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
3 tight e, μ or τ_h	28.63	–	28.63	–
4th lepton veto	28.62	100.0%	28.54	99.7%
conversion and low-mass veto	28.31	98.9%	28.45	99.7%
b-jet veto	27.78	98.2%	27.78	97.8%
$\not\!\!E_T > 50$ GeV	25.67	92.4%	25.92	93.3%
$M_{T2} < 100$ GeV	15.74	61.3%	14.43	55.7%
$M_{\ell\ell} < 75$ GeV	3.85	24.5%	2.28	15.8%

TABLE II. Cutflow charts, presented in terms of both the expected number of signal events for a luminosity of 35.9 fb $^{-1}$ of 13 TeV LHC collisions and the cut efficiencies. We consider a cutflow typical of the signal regions of categories C, D, E and F, and scenarios for which $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm} = 250$ GeV and $m_{\tilde\chi_1^0} = 150$ GeV (left) and $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm} = 600$ GeV and $m_{\tilde\chi_1^0} = 1$ GeV (right).

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
2 tight e or μ	214.24	–	214.24	–
same-sign	91.09	42.5%	101.04	47.2%
3rd lepton veto	75.82	83.2%	89.71	88.8%
low-mass veto	73.61	97.1%	89.71	100%
b-jet veto	71.27	96.8%	87.81	97.9%
$\not\!\!E_T > 60$ GeV	62.79	88.1%	77.38	88.1%
0 or 1 ISR jet	54.85	87.3%	69.22	89.5%
$M_T < 100$ GeV	18.3	33.4%	18.75	27.1%
$p_T^{\ell\ell} > 100$ GeV	10.01	54.7%	9.28	49.5%

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
2 tight e or μ	485.34	–	485.34	–
same-sign	128.59	26.5%	128.59	26.5%
3rd lepton veto	50.24	39.1%	50.24	39.1%
low-mass veto	49.86	99.2%	49.86	99.2%
b-jet veto	48.12	96.5%	48.12	96.5%
$\not\!\!E_T > 60$ GeV	38.92	80.9%	38.92	80.9%
0 or 1 ISR jet	29.72	76.5%	29.72	76.5%
$M_T < 100$ GeV	15.17	51.1%	15.17	51.1%
$p_T^{\ell\ell} > 100$ GeV	2.84	18.7%	2.84	18.7%

TABLE III. Cutflow charts, presented in terms of both the expected number of signal events for a luminosity of 35.9 fb $^{-1}$ of 13 TeV LHC collisions and the cut efficiencies. We consider a cutflow typical of the SS signal regions, and scenarios for which $m_{\tilde\chi_2^0} = m_{\tilde\chi_1^\pm} = 500$ GeV, $m_{\tilde\chi_1^0} = 350$ GeV and the slepton masses are obtained from $x = 0.05$ (left) and 0.5 (right).

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
4 tight e, μ or τ_h	869.14	–	869.14	–
low-mass veto	868.60	99.9%	869.14	100%
b-jet veto	855.41	98.5%	869.14	100%
$\not{E}_T > 100$ GeV	34.27	4.0%	21.88	2.5%

Selection Criteria	CMS		MadAnalysis	
	Events	Efficiency	Events	Efficiency
4 tight e, μ or τ_h	0.36	–	0.36	–
low-mass veto	0.36	99.9%	0.36	100%
b-jet veto	0.35	97.8%	0.35	96.7%
$\not{E}_T > 100$ GeV	0.34	96.7%	0.34	97.0%

TABLE IV. Cutflow charts, presented in terms of both the expected number of signal events for a luminosity of 35.9 fb $^{-1}$ of 13 TeV LHC collisions and the cut efficiencies. We consider a cutflow typical of the signal regions of categories G, H, I, J and K, and scenarios for which $m_{\tilde{\chi}_1^0} = 100$ GeV (left) and 800 GeV (right), and $m_{\widetilde{G}} = 1$ GeV.

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