# Chapter 8

# CMS-SUS-16-041: a CMS supersymmetry search with multileptons and jets (35.9 fb$^{-1}$)

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**Abstract**
We summarize the implementation within the MADANALYSIS 5 framework of the CMS search for new physics through final-state signatures comprised of a least three leptons (electrons or muons), jets and missing transverse energy. This analysis uses 35.9 fb$^{-1}$ of data collected in 2016 in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV. We validate our implementation by comparing our results against cutflows provided on the official CMS analysis webpage for well-defined benchmnark scenarios.

## 1 Introduction

Many models of new physics beyond the Standard Model predict processes leading to the production of multileptonic systems. In a recent supersymmetry analysis of 35.9 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV [12], the CMS collaboration has scrutinized multileptonic events in which the final state also contains jets and some missing transverse energy. In this note, we summarize the implementation in the MADANALYSIS 5 framework [3–5] of this search, and we describe its validation. The latter focuses on two supersymmetric signals in which pairs of gluinos are produced, and where each gluino decays either into a system made of a $t\bar{t}$ pair and the lightest supersymmetric particle (taken to be a neutralino $\tilde{\chi}_1^0$) that leaves the detector invisibly, or into a pair of quarks and a heavier neutralino $\tilde{\chi}_2^0$ and a chargino $\tilde{\chi}_1^\pm$ that further decay into a $Z$-boson and a $W$-boson, respectively. These two processes are illustrated through representative Feynman diagrams in Fig. 8.1.

## 2 Description of the analysis

The analysis preselects events containing at least three leptons (electrons or muons) and at least two jets, after having reconstructed the final-state physics objects.

More precisely, jets are reconstructed by using the anti-$k_T$ algorithm [15] with a radius parameter set to $R = 0.4$, and only those with a transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ satisfying

$$p_T^j > 30 \text{ GeV} \qquad \text{and} \qquad |\eta|^j < 2.4 \tag{8.1}$$

are retained. Jets are identified as $b$-jets by relying on the CMS cMVAv2 algorithm with its medium working point [39], which corresponds to a typical tagging efficiency of 70% for a mistagging rate of charmed and lighter jets of 10% and 1%, respectively. Our reimplementation of the fitted $b$-tagging efficiency and mistagging rate provided by CMS in Table 2 of Ref. [39] includes a global rescaling factor of 0.94 to account for the drop in efficiency that has been observed at the time of data-taking, in 2015-2016.

In addition, only muons and electrons with respective pseudorapidities $\eta^e$ and $\eta^\mu$ satisfying

$$|\eta^e| < 2.5 \qquad \text{and} \qquad |\eta^\mu| < 2.5 \tag{8.2}$$

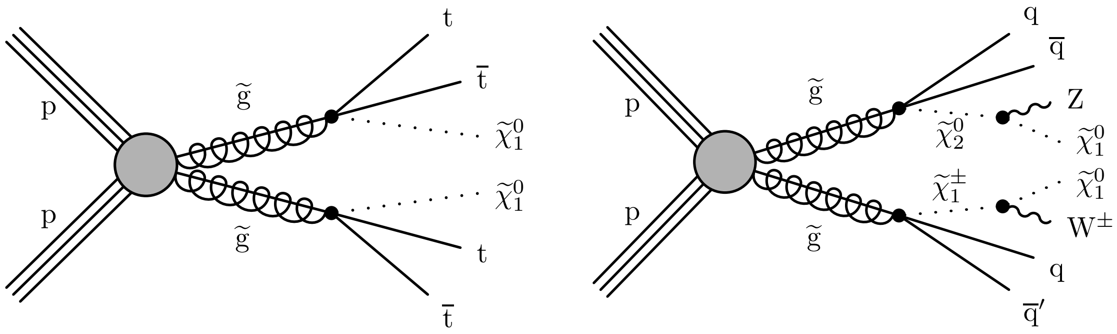


**Fig. 8.1:** Representative Feynan diagrams for the two processes on which our reimplementation of the CMS-SUS-16-041 search has been valided. A pair of gluinos is produced and further decays into four top-quarks and missing energy (left) or into jets, missing energy and weak bosons via intermediate weak bosons (right).

are considered. Moreover, to discriminate leptons originating from the decays of $W$-bosons and $Z$-bosons from those issued from hadron decays or misidentified jets as leptons, an additional requirement on the lepton isolation is enforced by using three different variables. The first variable is the lepton relative isolation $I_{\rm mini}$ defined as the ratio between the amount of measured energy in a cone of radius $\Delta R$ centered around the lepton direction and the lepton $p_T$, with

$$\Delta R = \frac{10 \text{ GeV}}{\min(\max(p_T(\ell), 50), 200)} \ . \tag{8.3}$$

The next two variables are computed on the basis of the lepton momentum and the momentum of the jet that is geometrically matched to the lepton. This jet is the jet of transverse momentum larger than 5 GeV that is the closest, in the transverse plane, to the lepton. The second employed variable then consists in the ratio between the lepton $p_T$ and the $p_T$ of this jet,

$$p_T^{\rm ratio} = p_T(\ell)/p_T(\text{jet}) \ , \tag{8.4}$$

and the last variable is the relative lepton transverse momentum $p_T^{\rm rel}$ defined as the magnitude of the component of the lepton momentum perpendicular to the axis of this jet. A lepton is then considered as isolated if

$$I_{\rm mini} < I_1 \qquad \text{and} \qquad \Big[ (p_T^{\rm ratio} > I_2) \ \text{ or } \ (p_T^{\rm rel} > I_3) \Big] \ . \tag{8.5}$$

For muons (electrons), the selection requirements are fixed to $I_1 = 0.16$ (0.12), $I_2 = 0.69$ (0.76) and $I_3 = 6.0$ GeV (7.2 GeV) whilst loosely isolated leptons consist of lepton candidates only fullfilling $I_{\rm mini} < 0.4$.

The preselected events are then classified according to the value of the hadronic transverse energy

$$H_T = \sum_{\rm jets} p_T \ , \tag{8.6}$$

when only jets with a $p_T$ larger than 30 GeV are included in the sum. Requirements are finally imposed on the transverse momentum of the leading lepton $\ell_1$ and of the next-to-leading lepton $\ell_2$, depending on the $H_T$ value.

$$\left\{ \begin{array}{ll} H_T < 300 \text{ GeV}: & p_T(\ell_1) > 25 \text{ GeV} \ , \ p_T(\ell_2) > x \text{ GeV} \\ H_T > 300 \text{ GeV}: & p_T(\ell_1, \ell_2) > x \text{ GeV} \end{array} \right. \ , \tag{8.7}$$

| $N_{\text{jets}}$ | $N_{\text{b jets}}$ | $H_{\text{T}}$ (GeV) | $50(70)\,\text{GeV} \leq E_{\text{T}}^{\text{miss}} < 150\,\text{GeV}$ | $150\,\text{GeV} \leq E_{\text{T}}^{\text{miss}} < 300\,\text{GeV}$ | $E_{\text{T}}^{\text{miss}} \geq 300\,\text{GeV}$ |
|---|---|---|---|---|---|
| $\geq 2$ | 0 | $60 - 400$ | SR1 † | SR2 † | SR16 † |
| | | $400 - 600$ | SR3 † | SR4 † | |
| | 1 | $60 - 400$ | SR5 | SR6 | |
| | | $400 - 600$ | SR7 | SR8 | |
| | 2 | $60 - 400$ | SR9 | SR10 | |
| | | $400 - 600$ | SR11 | SR12 | |
| | $\geq 3$ | $60 - 600$ | SR13 | | |
| | inclusive | $\geq 600$ | SR14 † | SR15 † | |

**Fig. 8.2:** Definition of the signal regions. The dagger indicates the signal regions that are further subdivided according to the value of the transverse mass of the system made of the missing transverse momentum and the lepton no connected to the $Z$-boson.

| $M_{\text{T}}^{\text{min}} \geq 120\,\text{GeV}$ | on-Z | $N_{\text{b jets}} \leq 2$ | | $N_{\text{b jets}} \geq 3$ | |
|---|---|---|---|---|---|
| | | $H_{\text{T}} \geq 200\,\text{GeV}$ | $E_{\text{T}}^{\text{miss}} \geq 250\,\text{GeV}$ | $H_{\text{T}} \geq 60\,\text{GeV}$ | $E_{\text{T}}^{\text{miss}} \geq 50\,\text{GeV}$ |
| | No | SSR1 | | SSR2 | |
| | Yes | SSR3 | | SSR4 | |

**Fig. 8.3:** Definition of the aggregated signal regions.

where $x = 10$ GeV and 15 GeV for muons and electrons respectively. In addition, the third lepton transverse momentum is required to satisfy

$$p_T(\ell_3) > 10 \text{ GeV} . \tag{8.8}$$

Moreover, the invariant mass of any pair of opposite-charge same-flavor leptons is required to be larger than 12 GeV,

$$m_{\ell\ell} > 12 \text{ GeV}. \tag{8.9}$$

The baseline selection finally requires an amount of missing energy

$$E_T^{\text{miss}} > 50 \text{ GeV} \quad \text{or} \quad 70 \text{ GeV} , \tag{8.10}$$

the second requirements being only relevant for regions exhibiting a number of $b$-jets of at most one and an $H_T$ value smaller than 400 GeV.

The events are then classified into varied signal regions according to the number of identified $b$-jets, the amount of missing transverse momentum and the actual $H_T$ value, as summarized in Fig. 8.2 (usual signal regions) and Fig. 8.3 (super, or aggregated, signal regions). In addition, each region is further divided into two regions, depending whether an opposite-sign same-flavor lepton pair has an invariant-mass compatible with the $Z$-boson mass, $|m_{\ell\ell} - M_Z| < 15$ GeV (on-Z) or not (off-Z), and some regions include an requirement on the transverse mass of the system made of the missing transverse momentum and the third lepton ($M_T < 120$ GeV or $M_T > 120$ GeV).

## 3 Validation

For the validation of our implementation, two cutflow tables have been provided in Ref. [12]. The first one concerns gluino pair production with four top quarks in the final state, assuming gluino and neutralino masses equal to 1500 GeV and 200 GeV respectively. The second cutflow also concerns gluino pair production, but in a configuration in which the gluinos decay into two weak vector bosons and light jets (as well as missing energy) and where the gluino and neutralino masses are fixed to 1200 GeV and 400 GeV, respectively. For both scenarios, the branching fraction of the gluino into (top or lighter) quarks are assumed to be 2/3 for $\tilde{g} \to \tilde{\chi}_1^{\pm} q\bar{q}'$ and $\tilde{g} \to \tilde{\chi}_2^0 q\bar{q}$ with $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0} = (m_{\tilde{\chi}_1^0} + m_{\tilde{g}})/2$.

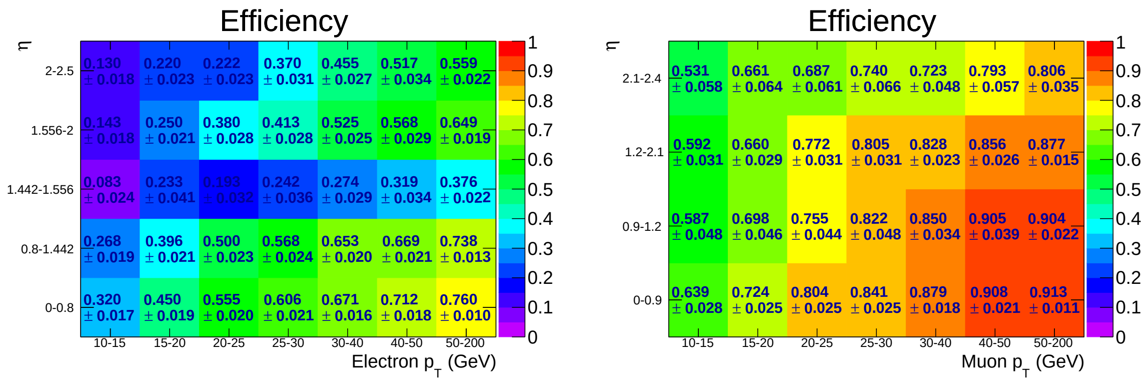


**Fig. 8.4:** Representative electron (left) and muon (right) reconstruction efficiencies used in the CMS-SUS-16-041 analysis. The results include the dependence of the efficiencies on the transverse momentum $p_T$ and the pseudorapidity $\eta$.

### 3.1 Event generation

Our validation procedure includes the simulation of hard-scattering events for the signal process

$$p\,p \to \tilde{g}\,\tilde{g}\,. \tag{8.11}$$

We have made use of the MADGRAPH5_ AMC@NLO program version 2.6.0 [1] to simulate 10000 signal events at the leading-order accuracy in QCD, relying for the hard process on the SLHA2 [43, 45] implementation of the MSSM in MG5_aMC [46]. All superpartners but the gluino and the lightest neutralinos and charginos have been decoupled, their mass being set to $10^5$ GeV. The hard matrix-element has been convoluted with the `NNPDF30_lo_as_0130` set of parton densities [17] accessed through the LHAPDF 6 library [47]. In addition to the above process, we have also generated events for gluino pair production in association with one and two extra jets. Parton showering and hadronization have then been simulated by employing the PYTHIA 8.260 package [25] with the CUETP8M1 tune [48] and standard CMS settings for the matching parameters and PYTHIA 8 common settings. The merging of the multipartonic matrix elements is performed through the MLM scheme [29], by imposing a minimum jet measure $k_T$ larger than 30 GeV and a merging scale of 42 GeV.

We have simulated the response of the CMS detector with the DELPHES V3.4.1 program [2], that internally relies on FASTJET [19] for object reconstruction, after relaxing all isolation requirements in the DELPHES configuration card so that isolation could be imposed at the analysis level. We have used the $b$-tagging performances presented in Ref. [39], although we have additionally included an overall rescaling factor of 0.94. Our analysis uses the medium working point (see Table 2 in Ref. [39]). We have additionally made use of the updated lepton reconstruction efficiencies presented in Ref. [49] and illustrated in Fig. 8.4.

### 3.2 Comparison with the official results

The provided validation material only included cutflow tables for two well-defined benchmark scenarios, as above-mentioned. In this section, we compare predictions obtained with MADANALYSIS 5 (MA5) (and the simulation chain introduced in Section 3.1) with official CMS numbers. Results for the gluino decays into top quarks are shown in Table 8.1 and into lighter quarks and vector bosons in Table 8.2. We observe a generally good agreement, all efficiencies being consistent with each other, except for the on-$Z$ signal regions where a $Z$-boson is reconstructed. In this case, deviations of 30%–50% are obtained, and they point either to the definition of the transverse variables used in the analysis, or to statistics. Unfortunately, the absence of any public release of additional pieces of information by CMS prevents us from further investigating the issue.

| Selection | CMS | Efficiency (%) | MA5 | Efficiency (%) | Difference (%) |
|---|---|---|---|---|---|
| No selection | 509.0 | 100% | 27345 | 100 | 0 |
| Trigger ($\geq$ 3 leptons) | 6.7 | 1.32 | 348 | 1.27 | -3.79 |
| $\geq$ 2 jets | 6.7 | 1.32 | 342 | 1.25 | -5.30 |
| $p_T^{miss} > 50$ GeV | 6.7 | 1.32 | 337 | 1.23 | -6.82 |
| off-Z SR | 6.0 | 1.18 | 302 | 1.10 | -6.78 |
| off-Z SR16a | 1.8 | 0.35 | 93 | 0.34 | -2.86 |
| off-Z SR16b | 2.5 | 0.49 | 133 | 0.49 | 0 |

**Table 8.1:** Comparison of the cutflow predicted by MADANALYSIS 5 with the one provided by CMS for the benchmark scenario in which gluinos decay into top quarks and missing energy. In the last column, we evaluate the agreement between the results relatively to the CMS ones, as given in Eq. (5.16).

| Selection | CMS | Efficiency (%) | MA5 | Efficiency (%) | Difference (%) |
|---|---|---|---|---|---|
| No selection | 3072.0 | 100% | 25481 | 100 | 0 |
| Trigger ($\geq$ 3 leptons) | 9.6 | 0.31 | 78 | 0.31 | 0 |
| $\geq$ 2 jets | 9.6 | 0.31 | 78 | 0.31 | 0 |
| $p_T^{miss} > 50$ GeV | 9.5 | 0.31 | 77 | 0.30 | -1.00 |
| on-Z SR | 9.1 | 0.30 | 69 | 0.27 | -3.00 |
| on-Z SR15b | 1.3 | 0.04 | 15 | 0.06 | +50.00 |
| on-Z SR16b | 5.2 | 0.17 | 34 | 0.13 | -23.53 |

**Table 8.2:** Same as in Table 8.1 but for the benchmark scenario in which the gluino decays into light jets and gauge bosons.

## 4 Conclusion

In this chapter, we have reimplemented, in the MADANALYSIS 5 framework, a CMS search for supersymmetry in a final state made of several leptons and jets. The analysis focuses on a signatures constituted of a least three leptons (electrons or muons) and uses $35.9\,\text{fb}^{-1}$ of data collected in 2016 at a center-of-mass energy of $\sqrt{s} = 13$ TeV [12]. Whilst it only contains four signal regions (off-Z SR16a, off-Z SR16b, on-Z SR15b and on-Z SR16b) for which CMS provided cutflow tables for validating our reimplementation [50], all the signal regions have been implemented in our code. Whilst one of the considered benchmark scenario, in which a gluino decays into top quarks and missing energy, provide a very good agreement when comparing our predictions with CMS results, large discrepancies of 30%–50$ have been observed for the second considered benchmark in which the gluino decays into a gaugo boson, light jets and missing energy. The information provided by CMS has not allowed us to further investigate the origins of the discrepancies.

This analysis being far from being validated as a result of a lack of information from CMS allowing to understand the source of the differences between the CMS results and the MADANALYSIS 5 predictions, it has not been included in MADANALYSIS 5.

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