Abstract

We present the activities performed during the first MADANALYSIS 5 workshop on LHC recasting that has been organized at High 1 (Gangwon province, Korea) on August 20-27, 2017. This report includes details on the implementation in the MADANALYSIS 5 framework of eight ATLAS and CMS analyses, as well as a description of the corresponding validation and the various issues that have been observed.

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Chapter 1

Introduction

S. Bein, G. Chalons, E. Conte, B. Fuks, T. Kim, S.J. Lee, D. Sengupta and J. Sonneveld

The first MadAnalysis 5 workshop on LHC recasting has been held at High 1, in the Gangwon province in South Korea on 20–27 August 2017. The workshop has brought together a very enthusiastic group of students, postdoctoral fellows, junior as well as more senior researchers, all interested in the development of public high-energy physics tools allowing for the reinterpretation of the LHC results in generic particle physics theoretical contexts. Along with the main theme of the workshop (i.e., the problematics of the reinterpretation of the LHC searches for new physics), various specialized lectures on collider physics, statistics, dark matter and more formal aspects of beyond the standard model theories have been offered, together with dedicated hands-on tutorial sessions on the MadGraph5 [1], Delphes [2] and MadAnalysis 5 [3–5] packages.

MadAnalysis 5 is a high-energy physics program that can among others be used for the reinterpretation of the results of the LHC. It relies on an approximate simulation of the effects of the LHC detectors through the Delphes framework and allows for the derivation of the number of events populating the different signal regions of all analyses that have been implemented in its data format. It in particular consists in a completely open source initiative where each reimplemented analysis can be independently assigned a Digital Object Identifier via a submission to INSPIRE, ensuring that it is uniquely identifiable, searchable and citable.

The main scope of the workshop is based on a recasting exercise assigned to the participants. The initial group of students and postdoctoral researchers has been divided into several subgroups of four or five people, and each subgroup has received the task to implement, in the MadAnalysis 5 framework, a particular ATLAS or CMS search for new physics. On top of the reimplementation task, each subgroup has been required to assess the quality of the reimplementation through a thorough validation procedure. By the end of the workshop, almost all subgroups have managed to get a first version of a MadAnalysis 5 analysis code mimicking the corresponding experimental search, along with some basic validation of the work. For some analyses, the lack of technical information from the experimental side has yielded slower progress, but answers to our questions have almost always been given by the experimental groups. During the months following the workshop, the participants have continued their work enthusiastically, and most of the analyses have been validated and merged with the version 1.6 of MadAnalysis 5.

This document summarizes the activities of the workshop and addresses in particular the im-plementation and the validation, in the MadAnalysis 5 framework, of eight new ATLAS and CMS searches for new physics. If relevant, issues that have been met are discussed, together with their impact on the quality of the validation. The corresponding codes have been submitted to INSPIRE and are publicly available both directly within MadAnalysis 5 and from the MadAnalysis 5 Public Analysis Database, http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase.

This document is divided into three parts according to the classes of analyses under consideration. In the first of these parts, one focuses on LHC searches for dark matter in varied channels. We consider two searches for a mono-Higgs signal, one from ATLAS [6] and one from CMS [7], in which a Higgs boson is assumed to be produced with a pair of dark matter particles manifesting themselves as missing energy in the detector. We moreover recast one ATLAS search dedicated to the production of a hard photon in association with missing energy [8], one ATLAS search for dark matter production in association with light jets [9] and heavy-flavor jets [10]. In the second part of this document, we detail a more
exotic CMS search for long-lived electrons and muons [11], which has required the development of new features within MadAnalysis 5. Finally, in the last part of these proceedings, we detail more classical searches for supersymmetric particles, first in the multilepton plus jets plus missing transverse energy channel [12], and next in the opposite-sign same-flavor dilepton case [13].
Dark Matter
Chapter 2

ATLAS-CONF-2016-086: an ATLAS dark matter search with $b$-jets and missing energy (13.3 fb$^{-1}$)

B. Fuks, M. Zumbihl

Abstract
We present the MADANALYSIS 5 implementation and validation of the ATLAS-CONF-2016-086 search. This ATLAS analysis targets the production of dark matter in association with $b$-tagged jets and probes 13.3 fb$^{-1}$ of LHC proton-proton collisions at a center-of-mass energy of 13 TeV. The validation of our reimplementation is based on a comparison with all the material provided by the ATLAS collaboration, as well as with a back-of-the-envelope expectation of a related theoretical work. By lack of public experimental information, we have not been able to validate this reimplementation more thoroughly.

1 Introduction
In this note, we describe the validation of the implementation, in the MADANALYSIS 5 framework [3–5], of the ATLAS-CONF-2016-086 analysis [10] probing the production of dark matter at the LHC in association with a pair of $b$-tagged jets originating from a bottom-antibottom quark pair at the parton level. The signature that is searched for thus consists in missing transverse energy and $b$-jets. The ATLAS-CONF-2016-086 analysis focuses on the analysis of an integrated luminosity of 13.3 fb$^{-1}$ of LHC collisions at a center-of-mass energy of 13 TeV.

For the validation of our reimplementation, we have focused on a simplified dark matter model in which the Standard Model is extended by two additional fields, namely a Dirac field $\chi$ corresponding to the dark matter particle and a scalar ($\Phi$) or pseudoscalar ($A$) field responsible for the mediation of the interactions of the Standard Model sector with the dark sector [14]. This scenario involves four parameters, namely the mass of the scalar mediator $m_{\Phi}$ (or $m_A$ in the pseudoscalar case), the mass of the dark matter particle $m_{\chi}$, the mediator coupling to the dark sector $y_{\chi}$ and the flavor-universal coupling of the mediator to the Standard Model $y_{\ell_i}$. In this theoretical framework, the signal that is relevant for the considered analysis arises from the process

$$pp \rightarrow \chi \bar{\chi} b \bar{b},$$

(2.1)
in which the pair of dark matter particles gives rise to missing transverse energy and originates from the decay of a possibly off-shell mediator.

2 Description of the analysis
The analysis makes use of all the information present in the signal final state. It therefore requires, as a basic selection, the presence of missing transverse energy as well as of jets with some of them being $b$-tagged. The kinematics of the bottom-antibottom system is then used as a handle to reduce the background of the Standard Model.
2.1 Object definitions

Jets are reconstructed by means of the anti-$k_T$ algorithm \[15\] with a radius parameter set to $R = 0.4$. Our analysis focuses on jets whose transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ fulfill

$$p_T^j > 20 \text{ GeV} \quad \text{and} \quad |\eta^j| < 2.8 . \quad (2.2)$$

Moreover, the selected jets are tagged as originating from the fragmentation of a $b$-quark according to a working point for which the average $b$-tagging efficiency is of about 60%.

Electron candidates are required to have a transverse momentum $p_T^e$ and pseudorapidity $\eta^e$ obeying

$$p_T^e > 7 \text{ GeV} \quad \text{and} \quad |\eta^e| < 2.47 , \quad (2.3)$$

and the muon candidate definition is similar, although with slightly looser thresholds,

$$p_T^\mu > 6 \text{ GeV} \quad \text{and} \quad |\eta^\mu| < 2.7 . \quad (2.4)$$

Any jet lying within a cone of radius $\Delta R < 0.2$ of an electron is discarded, unless it is $b$-tagged. In this last case, it is the electron that is discarded. Any electron or muon that would then lie within a cone of radius $\Delta R < 0.4$ of a jet is finally removed from the set of jet candidates to consider.

The missing transverse momentum vector $\mathbf{p}_T$ is defined as the opposite of the vector sum of the momenta of all reconstructed physics object candidates, and the missing transverse energy $\not\!{E}_T$ is then defined by its norm.

2.2 Event selection

The analysis contains a unique signal region that is defined by a requirement on the missing transverse energy,

$$\not\!{E}_T > 150 \text{ GeV} , \quad (2.5)$$

and on the number of $b$-tagged jets that is asked to be equal to 2. The signal being characterized by a small jet multiplicity, events featuring a third jet with a transverse momentum greater than 60 GeV are vetoed, as events whose final state contains leptons. Moreover, the missing transverse momentum is constrained to be well separated from any jet,

$$\Delta \phi (\mathbf{p}_T, j) > 0.4 . \quad (2.6)$$

In order to guarantee a full trigger efficiency, selected events are required to satisfy the so-called hyperbolic requirement on the missing energy,

$$p_{T1}^j > 85 \text{ GeV} \quad \text{and} \quad \not\!{E}_T > \frac{[150 \text{ GeV}] p_{T1}^j - [11700 \text{ GeV}^2]}{p_{T1}^j - [85 \text{ GeV}]} . \quad (2.7)$$

The dominant component of the background, related to invisible $Z$-boson production in association with $b$-tagged jets, is reduced by requiring a large separation between the jet candidates,

$$\Delta R(j_i, j_k) > 2.8 , \quad (2.8)$$

for any pair of reconstructed jets $(i, k)$. The two $b$-jets are furthermore constrained to satisfy

$$\Delta \eta(b_1, b_2) > 0.5 , \quad \Delta \phi(b_1, b_2) > 2.2 \quad \text{and} \quad \text{Imb}(b_1, b_2) \equiv \frac{b_1 - b_2}{p_{T1}^b + p_{T2}^b} > 0.5 . \quad (2.9)$$

With the last requirement, one imposes a significant transverse-momentum imbalance between the two $b$-jets that is known to be large for typical signals.
Fig. 2.1: Left: Transverse momentum imbalance when all the analysis selection criteria are applied, except the one on Imb$(b_1, b_2)$. We compare the official numbers (red) with our predictions (blue). Right: Region of the parameter space of the new physics model introduced in Ref. [20] excluded at the 95% confidence level for new physics scenarios in which $m_\chi = 100$ GeV and $y_v = 1$.

3 Validation

3.1 Event Generation

In order to validate our analysis, we rely on the dark matter simplified model introduced above and for which a UFO model [16] has been provided by the ATLAS collaboration. We focus on a benchmark scenario defined by

$$y_\chi = y_v = 1, \quad m_{\Phi/A} = 20 \text{ GeV} \quad \text{and} \quad m_\chi = 1 \text{ GeV}. \quad (2.10)$$

We make use of MADGRAPH5_AMC@NLO version 2.6.0 [1] for hard-scattering event generation in which leading-order matrix elements are convoluted with the leading-order set of NNPDF 3.0 parton densities [17]. Those events have been showered by means of the PYTHIA 6 package [18]. Finally, the simulation of the detector response has been performed by using DELPHES 3 [2], that relies on FAST-JET [19] for object reconstruction and that has been used with an appropriate tuned detector card. All necessary configuration files, most of them having been provided by ATLAS, can be found on the MAD-ANALYSIS 5 public database webpage, http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase.

We have finally used our MADANALYSIS 5 reimplementation to calculate the signal selection efficiencies.

3.2 Comparison with the official results

In the left panel of Figure 2.1, we present the transverse-momentum imbalance spectrum as computed using the MADANALYSIS 5 (blue) and compare it to the official results (red). The results shown in the figure include all selection cuts but the Imb$(b_1, b_2)$ one. One obtains a fair agreement accounting for the large statistical uncertainties plaguing the simulation and about which no information has been provided by the ATLAS collaboration.

In the right panel of the figure, we consider a different new physics setup in which the dark matter mass is set to $m_\chi = 100$ GeV and the mediator coupling to the Standard Model to $g_v = 1$. We then present, in the $(m_A, y_\chi)$ plane, the parameter space region that is excluded at the 95% confidence level. We obtain a good agreement with the back-to-the-enveloppe estimations of Ref. [20].
4 Summary

We have implemented the ATLAS-CONF-2016-086 search in the MadAnalysis 5 framework. Our analysis has been validated in the context of a simplified model for dark matter in which the dark matter candidate is a fermion and the mediator a boson. We have found a decent agreement with the material provided by ATLAS, which is not dramatically detailed. Due to the lack of information, the validation has been kept brief. As a fair agreement has nevertheless been obtained both with respect to the material provided by ATLAS and to an earlier theoretical work, we have considered this reimplementation as validated. It is available from MadAnalysis 5 version 1.6 onwards, its Public Analysis Database and from INSPIRE [21].

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Chapter 3

ATLAS-EXOT-2016-25: an ATLAS mono-Higgs analysis (36.1 fb$^{-1}$)

S. Jeon, Y. Kang, G. Lee, C. Yu

Abstract
We present the MADAnalysis 5 implementation and validation of the ATLAS-EXOT-2016-025 analysis, which concerns a search for dark matter when it is produced in association with a Higgs boson decaying into a $b\bar{b}$ system. The results consider a dataset of proton-proton collisions at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.1 fb$^{-1}$, as recorded by the ATLAS collaboration during the LHC Run 2. The validation of our reimplementation is based on a comparison of our predictions with official ATLAS numbers in the context of a new physics scenario featuring two Higgs doublets, an extra gauge boson and a dark matter particle. A good agreement has been found for the light new physics case, but issues have occurred for heavier new particles. The ATLAS collaboration has not provided any information allowing us to understand the problems deeper.

1 Introduction
In this note, we describe the validation of our implementation of an ATLAS dark matter search in the MADAnalysis 5 framework [3–5]. This analysis, dubbed ATLAS-EXOT-2016-25, performs a search for dark matter production in association with a Higgs boson ($h$) decaying into a pair of $b$ quarks [6]. It relies on 36.1 fb$^{-1}$ of data recorded by the ATLAS detector from LHC proton-proton collisions at a center-of-mass energy of 13 TeV. The search focuses on two regimes, respectively targeting a resolved Higgs boson where its decay products can be distinguished and a merged regime in which the Higgs boson decays into a single fat jet. We focus here only on the resolved regime due to a lack of experimental information on the merged regime.

Our validation relies on a reinterpretation of the ATLAS results of the analysis in a dark matter $Z'$-Two-Higgs-Doublet model in which the Standard Model is supplemented by a dark matter particle $\chi$, a $Z'$ boson and a second Higgs doublet [14,22]. The signal under consideration corresponds to the resonant production of a $Z'$ boson that then decays into a Standard Model Higgs boson $h$ and a pseudoscalar boson $A^0$. The latter play the role of a portal to the dark sector, and thus decays invisibly into two dark matter particles. The process under consideration hence reads

$$pp \rightarrow Z' \rightarrow hA^0 \rightarrow h\chi\chi.$$ (3.1)

2 Description of the analysis
This analysis selection is strictly based on the considered signature and requires the presence of a significant amount of missing transverse energy (carried by the dark matter particle), well separated from the jet activity associated with the Higgs boson. The analysis moreover asks for at least two hard jets that are compatible with the decay of the Higgs boson, with at least one of them being $b$-tagged.
2.1 Object definitions and preselection

The analysis mainly relies on jets, that are reconstructed following the anti-$k_T$ algorithm [15], with a radius parameter set to $R = 0.4$. Jets with a transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ satisfying

$$ p_T^j > 20 \text{ GeV} \quad \text{and} \quad |\eta^j| < 2.5 $$

are denoted as central jets and those for which

$$ p_T^j > 30 \text{ GeV} \quad \text{and} \quad 2.5 < |\eta^j| < 4.5 $$

are called forward jets. Whilst the analysis also makes use of jets reconstructed with the anti-$k_T$ algorithm [15] and a radius parameter fixed to $R = 1$, these are connected to the merged regime where the Higgs boson is boosted and that we were not able to validate by virtue of the lack of ATLAS information. We have thus ignored them. Electron candidates are required to have a transverse momentum $p_T^e$ and pseudorapidity $\eta^e$ obeying to

$$ p_T^e > 7 \text{ GeV} \quad \text{and} \quad |\eta^e| < 2.47 $$

while muon candidates are similarly defined, although the thresholds are slightly looser,

$$ p_T^\mu > 7 \text{ GeV} \quad \text{and} \quad |\eta^\mu| < 2.7 $$

In both cases, loose isolation criteria have been imposed [23, 24]. Moreover, any jet lying at an angular distance in the transverse plane $\Delta R \leq 0.2$ of an electron has been removed.

The missing transverse momentum vector $E_T^{\text{miss}}$ is defined as the opposite of the vector sum of the momenta of all reconstructed physics object candidates, and the missing transverse energy is defined by its norm

$$ E_T^{\text{miss}} = |E_T^{\text{miss}}| . $$

2.2 Event Selection

We focus on the resolved Higgs regime for which a single signal region is defined. It requires

$$ 150 \text{ GeV} < E_T^{\text{miss}} < 500 \text{ GeV}, $$

a criterion that also allows the missing-energy-only trigger to be fully efficient. In order to suppress the multijet background, the missing transverse momentum is constrained to be well separated in azimuth from the three leading jets (if relevant),

$$ \Delta \phi(E_T^{\text{miss}}, p_T^j) > \frac{\pi}{9} , $$

and more or less aligned with the missing transverse momentum reconstructed from the tracker information only $p_T^{\text{miss,trk}}$,

$$ \Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss,trk}}) < \frac{\pi}{2} . $$

In addition, this last quantity is required to fulfill

$$ |p_T^{\text{miss,trk}}| > 30 \text{ GeV} . $$

The analysis requires the presence of at least two jets,

$$ N_j > 2 , $$
with either one or two of them being $b$-tagged, and at least one of them featuring a transverse momentum larger than 45 GeV,

$$p_T^{j_1} > 45 \text{ GeV}. \quad (3.12)$$

We have restricted our reimplementation procedure to the case

$$N_b = 2, \quad (3.13)$$

as this region is expected to be the most sensitive to the signal. It additionally consists of the only signal region for which validation material has been provided. These two $b$-jets are then considered as the Higgs system. As the Higgs system lies in a configuration in which it is recoiling against a pair of dark matter particle, one requires

$$\Delta \phi (E_T^{\text{miss}}, p_T^b) > \frac{2\pi}{3}, \quad (3.14)$$

where $p_T^b$ denotes the transverse momentum of the reconstructed Higgs boson. Moreover, the scalar sum of the transverse momentum of the two and three leading jets ($H_{T,2j}$ and $H_{T,3j}$) is imposed to satisfy

$$H_{T,2j} > 120 \text{ GeV} \quad \text{and} \quad H_{T,3j} > 150 \text{ GeV}, \quad (3.15)$$

this last requirement being imposed only if at least three central jets are present.

In order to optimize the selection, the two jets $j_1$ and $j_2$ defining the Higgs system are enforced to be not too separated,

$$\Delta \phi (j_1, j_2) < \frac{7\pi}{9} \quad \text{and} \quad \Delta R (j_1, j_2) < 1.8, \quad (3.16)$$

and a tau lepton veto is imposed. As an additional selection, the scalar sum of the transverse momentum of the $j_1$ and $j_2$ jets, as well as of the third jet if present, is required to satisfy

$$p_T^{j_1} + p_T^{j_2} + p_T^{j_3} < 0.63 H_T, \quad (3.17)$$

where the hadronic activity $H_T$ in the event consists in the scalar sum of the transverse momentum of all reconstructed jets.

3 Validation

3.1 Event generation

In order to validate our reimplementation, we consider two benchmark scenarios in which the $Z'$-boson mass $m_{Z'}$ is respectively fixed to 600 GeV and 1400 GeV. Correspondingly, the pseudoscalar mass $m_{A^0}$ is fixed to 300 GeV and 600 GeV. In all cases, the mass of the dark matter particle is taken vanishing.

We have made use of MADGRAPH5_aMC@NLO [1] for generating hard-scattering signal events, relying on the UFO [16] model shared by the ATLAS collaboration. The generated matrix element has been convoluted with the next-to-leading-order set of NNPDF 3.0 parton densities [17], and we have handled the Higgs into $b\bar{b}$ decay, parton showering and hadronization with PYTHIA 8 [25]. The simulation of the response of the ATLAS detector is achieved via DELPHES 3 [2], that internally relies on FASTJET [19] for object reconstruction, with an tuned detector configuration.

3.2 Comparison with the official results

In Figure 3.1, we present the relative difference between the MADANALYSIS 5 predictions and the ATLAS official results for the two considered scenarios, computed as

$$\delta = 1 - \frac{\epsilon_{\text{MA5}}}{\epsilon_{\text{ATLAS}}}, \quad (3.18)$$
where the index \(i\) corresponds to the cut number, and where \(\epsilon_i^{\text{MAS}}\) and \(\epsilon_i^{\text{ATLAS}}\) indicate the predicted and ATLAS efficiencies for the cut number \(i\). The results include two extra cuts, available in the validation material. The Higgs system invariant mass is firstly imposed to satisfy
\[
50 \text{ GeV} < m_{j_1j_2} < 250 \text{ GeV},
\]
so that it is loosely compatible with a Higgs boson, and one secondly imposes either one or two \(b\)-tag requirements. For what concerns the last three cuts, only one of them is imposed at a time.

The large differences at the level of the trigger (first cut) is expected, as not all requirements, and in particular the features at the level of the turn-on of the trigger efficiency curve near threshold, can be implemented in DELPHES. Moreover, large discrepancies are also observed for the last selections that strongly rely on jets. After discussions with ATLAS, it turned out that our reimplementation were not matching well what ATLAS actually implemented. However, the corresponding information was lost (within ATLAS) and we have never been able to understand the origins of the differences.

In general, our reimplementation nevertheless performs quite well, in particular in terms of the total selection efficiencies and for benchmark scenarios featuring light particles. This is illustrated in Table 3.1 (left), where we present the total selection efficiencies on a cut-by-cut basis. For the \((m_{Z'}, m_{A^0}) = (600, 300)\) GeV scenario, we observe that an agreement of order of 10-20\% all along the selection (left part of the table). However, for heavier scenarios, we have found larger discrepancies. The ATLAS collaboration has however not been able to provide information allowing us to understand these discrepancies, except that our DELPHES tuning may be incorrect in the large \(p_T\) range. The collaboration has however not provided any additional information allowing us to fix the issue.

We remind that the ‘1 \(b\)-jet’ and ‘\(m_{j_1j_2}\)’ validation regions have not been implemented into our the code, as they correspond to additional cuts that have been implemented solely for validation purposes. The signal region of interest focuses instead on the ‘\(N_b = 2\)’ case.

4 Conclusion

We have implemented in MADANALYSIS 5 a mono-Higgs analysis performed by the ATLAS collaboration and have tried to validate our implementation in the context of a Two-Higgs-Doublet model featuring
Table 3.1: Comparison of the cutflow predicted by MadAnalysis 5 with the one provided by the ATLAS collaboration for the \((m_{Z'}, m_{A^0}) = (600, 300)\) GeV benchmark scenario (left) and \((m_{Z'}, m_{A^0}) = (1400, 600)\) GeV benchmark scenario (right).

| Cuts                        | \((m_{Z'}, m_{A^0}) = (600, 300)\) GeV | \((m_{Z'}, m_{A^0}) = (1400, 600)\) GeV |
|-----------------------------|---------------------------------------|---------------------------------------|
|                            | MA5        | Official          | error   | MA5        | Official          | error   |
| \(E_T^{\text{miss}}\)      | 0.772      | 0.89              | 13.3%   | 0.660      | 0.604              | 9.2%    |
| \(p_T^{\text{miss,trk}}\)  | 0.757      | 0.711             | 6.5%    | 0.657      | 0.546              | 20.3%   |
| \(\Delta \phi(E_T^{\text{miss}}, p_T^j)\) | 0.727      | 0.685             | 6.1%    | 0.592      | 0.497              | 19.1%   |
| \(\Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss,trk}})\) | 0.727      | 0.671             | 8.3%    | 0.592      | 0.480              | 23.3%   |
| \(N_j\)                    | 0.602      | 0.658             | 8.5%    | 0.523      | 0.460              | 13.7%   |
| \(p_T^j\)                  | 0.599      | 0.655             | 8.5%    | 0.522      | 0.459              | 13.7%   |
| \(H_T\)                    | 0.572      | 0.651             | 12.1%   | 0.519      | 0.459              | 13.1%   |
| \(\Delta \phi(j_1, j_2)\) | 0.556      | 0.633             | 12.2%   | 0.494      | 0.441              | 12.0%   |
| \(\Delta \phi(E_T^{\text{miss}}, p_{TH})\) | 0.544      | 0.620             | 12.3%   | 0.490      | 0.439              | 11.6%   |
| tau veto                   | 0.530      | 0.603             | 12.1%   | 0.476      | 0.424              | 12.3%   |
| \(\Delta R(j_1, j_2)\)    | 0.455      | 0.506             | 10.0%   | 0.434      | 0.385              | 12.7%   |
| \(1 \leq N_b \leq 2\)     | 0.431      | 0.503             | 14.1%   | 0.421      | 0.383              | 9.9%    |
| \(\sum p_T^j\)            | 0.430      | 0.499             | 13.8%   | 0.421      | 0.382              | 10.2%   |
| \(m_{j_1,j_2}\)            | 0.396      | 0.481             | 17.7%   | 0.404      | 0.376              | 7.4%    |
| 2 b-jets                   | 0.252      | 0.246             | 2.4%    | 0.269      | 0.177              | 52.0%   |
| 1 b-jet                    | 0.154      | 0.197             | 21.8%   | 0.135      | 0.165              | 18.2%   |

an extra neutral gauge boson and a dark matter particle. After having compared our results with the official ones, we have found that our reimplementation was trustable for light new physics scenarios, but not for heavier cases. We therefore recommend caution when using this analysis for phenomenological purposes. As a fair agreement has been obtained in the light case, so that our reimplemented analysis could be used for such scenarios, we have considered this reimplementation (partly) validated and have made it available from MadAnalysis 5 version 1.6 onwards and its Public Analysis Database and from InSpire [26].

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Chapter 4

ATLAS-EXOT-2016-27: an ATLAS monojet analysis (36.2 fb$^{-1}$)

D. Sengupta

Abstract

We present the MADAnalysis 5 implementation of the recent ATLAS-EXOT-2016-27 monojet search. This search allows us to probe various new physics scenarios featuring a dark matter particle through the so-called monojet channel in which the final-state signature consists in one highly-energetic jet recoiling against missing transverse energy carried by dark matter particles. The results are based on the analysis of a dataset of 36.2 fb$^{-1}$ of proton-proton collisions recorded by the ATLAS detector with a center-of-mass energy of 13 TeV. The validation of our reimplementation relies on a comparison of our predictions with the official ATLAS results in the context of a supersymmetry-inspired simplified model in which the Standard Model is extended by a neutralino and a stop decaying into a charm quark and a neutralino.

1 Introduction

In this contribution, we present the validation of the implementation, in the MADAnalysis 5 [3–5] framework, of the ATLAS-EXOT-2016-27 search for dark matter in the monojet channel [9]. This search is in particular sensitive to certain supersymmetric scenarios, dark matter setups and extra dimensional models. Each of those models can indeed predict, in specific realizations, the production of a pair of invisible particles in association with a highly-energetic jet (i.e., the signature under consideration).

For our validation procedure, we focus on a compressed supersymmetric configuration in which the searched for signature arises from the associated production of a hard jet with a pair of invisible squarks that each decays into a soft light jet and a neutralino. This process is illustrated by the representative Feynman diagram of Fig. 4.1. The considered analysis is in particular sensitive to the case of a compressed light stop that decays into a charm quark and a neutralino (through a flavor-violating loop-induced subprocess),

$$pp \rightarrow j \tilde{t} \tilde{t} \rightarrow j c \overline{\chi}_1^0 \overline{\chi}_1^0.$$  
(4.1)

This decay mode of the top quark becomes especially relevant when the more standard decay channels involving either a top quark or a chargino are closed.

2 Description of the analysis

The ATLAS monojet analysis targets a final-state containing at least one very energetic jet that is assumed to originate from initial state radiation, as well as a certain amount of missing transverse energy $E_T^{\text{miss}}$. The analysis strategy is twofold, depending on the selection cut on the missing transverse energy. In a first series of ten signal regions (IM1, IM2, . . ., IM10), it considers inclusive missing transverse energy selections,

$$E_T^{\text{miss}} > E_{\text{threshold}},$$  
(4.2)

where the 10 different thresholds range from 250 GeV to 1 TeV, as shown on the first line of the table of Fig. 4.2. In a second series of signal regions, the analysis instead considers exclusive missing transverse energy selection,

$$E_{\text{threshold}}^{\text{min}} \leq E_T^{\text{miss}} \leq E_{\text{threshold}}^{\text{max}}.$$  
(4.3)
Fig. 4.1: Representative Feynman diagram corresponding to the production of a pair of squarks $\tilde{q}$ that each decays into a neutralino $\tilde{\chi}^0_1$ and a light quark $q$.

| Inclusive (IM) | IM1 | IM2 | IM3 | IM4 | IM5 | IM6 | IM7 | IM8 | IM9 | IM10 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| $E_T^{\text{miss}}$ [GeV] | > 250 | > 300 | > 350 | > 400 | > 500 | > 600 | > 700 | > 800 | > 900 | > 1000 |
| Exclusive (EM) | EM1 | EM2 | EM3 | EM4 | EM5 | EM6 | EM7 | EM8 | EM9 | EM10 |
| $E_T^{\text{miss}}$ [GeV] | 250–300 | 300–350 | 350–400 | 400–500 | 500–600 | 600–700 | 700–800 | 800–900 | 900–1000 | > 1000 |

Fig. 4.2: Missing transverse energy requirements of the 20 signal regions of the ATLAS-EXOT-2016-27 analysis.

The thresholds associated with the 10 corresponding signal regions (EM1, EM2, . . . , EM10) are shown in the second table of Fig. 4.2.

2.1 Object definition

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

$$p_T^j > 20 \text{ GeV} \quad \text{and} \quad |\eta^j| < 2.8$$

are retained. Among those jets, those with a transverse momentum greater than 30 GeV and with a pseudorapidity smaller than 2.5 (in absolute value) are potentially considered as $b$-tagged, according to a $b$-tagging working point that is in average 60% efficient [27].

Electron candidates are required to have a transverse momentum $p_T^e$ and pseudorapidity $\eta^e$ obeying to

$$p_T^e > 20 \text{ GeV} \quad \text{and} \quad |\eta^e| < 2.47,$$ (4.5)

whereas muon candidates must obey to

$$p_T^\mu > 10 \text{ GeV} \quad \text{and} \quad |\eta^\mu| < 2.7.$$ (4.6)

Any non-$b$-tagged jet with $p_T^j > 30$ GeV lying within a cone of radius $\Delta R < 0.2$ from an electron is discarded, whilst any electron lying within a cone of radius $\Delta R < 0.2$ centered on a $b$-tagged jet is removed. Any electron that would then lie within a cone of radius $0.2 < \Delta R < 0.4$ of a jet is finally removed in a second step. In addition, jets with a $p_T^j > 30$ GeV are discarded if they are lying in a cone of radius $\Delta R < 0.4$ centered on any muon.

The missing transverse momentum vector $p_T^{\text{miss}}$ is defined as the opposite of the vector sum of the momenta of all reconstructed physics object candidates with a pseudorapidity smaller than 4.9, and the missing transverse energy $E_T^{\text{miss}}$ is defined by its norm.

2.2 Event Selection

Event preselection imposes first the presence of a significant amount of missing energy,

$$E_T^{\text{miss}} > 250 \text{ GeV},$$ (4.7)
Fig. 4.3: Exclusion contour in the $(M_\tilde{t}, M_\tilde{\chi})$ plane of the considered stop-neutralino class of simplified model. We compare the MADANALYSIS 5 findings (orange) with the official ATLAS numbers (blue).

and next that the final state features a monojet-like topology, the leading jet being imposed to satisfy

$$p_T(j_1) > 250 \text{ GeV}.$$  \hspace{1cm} \text{(4.8)}

Electron and muon vetos are then enforced, and any jet $j$ has to be well separated from the missing momentum,

$$\Delta \phi(j, \not{p}_T) > 0.4.$$ \hspace{1cm} \text{(4.9)}

Selected events are then categorized into the inclusive and exclusive signal regions introduced in Fig. 4.2.

3 Validation

For our validation, we generate events for various simplified models inspired by the MSSM. We consider a class of models where the Standard Model is extended by a stop (of mass $M_\tilde{t}$) and a neutralino (of mass $M_\tilde{\chi}$), all other superymmetric states being taken decoupled. For each choice of mass parameters, our signal event samples are normalized to an integrated luminosity of 36.2 fb$^{-1}$ and to a cross section evaluated at the NLO+NLL accuracy [28].

Signal events have been generated with MADGRAPH5_AMC@NLO [1] and PYTHIA 8 [25] for the hard scattering matrix elements and the simulation of the parton showering and hadronization, respectively. We have considered event samples describing final states featuring different jet multiplicities, that we have merged through the MLM scheme [29,30]. The merging scale as been set, for each point, to $Q_{\text{match}} = M_\tilde{t}/4$ GeV for a MADGRAPH5 xqcut parameter set to 125 GeV. The A14 PYTHIA tune [31] has been used while showering and hadronizing events with PYTHIA 8, and the simulation of the ATLAS detector has been achieved with the DELPHES 3 program [2], assuming a $b$-tagging efficiency of 60% for a $p_T$-dependent mistagging rate equal to $0.1 + 0.000038 \times p_T$.

In the absence of any official ATLAS cutflow for given benchmark scenarios, we have decided to validate our reimplementation by reproducing the ATLAS exclusion contour for a set of compressed benchmark points for which the stop decays as $\tilde{t}_1 \rightarrow c\chi^0_1$. Our results are presented in Fig. 4.3 in which we superimpose the exclusion contour obtained with MADANALYSIS 5 (orange) with the official
ATLAS one (blue). We observe an excellent degree of agreement, which makes us considering our reimplementation as validated.

4 Summary

We have implemented the ATLAS-EXOT-2016-27 analysis the MADANALYSIS 5 framework, an analysis searching for dark matter models in the monojet channel and in 36.2 fb$^{-1}$ of ATLAS collision data at a center-of-mass energy of 13 TeV. In the absence of any detailed validation material, we have validated our reimplementation in reproducing the exclusion curve provided by ATLAS in the context of a class of simplified models where the Standard Model is extended by a neutralino and a stop that decays into the $\tilde{t}_1 \rightarrow c\chi^0_1$ channel. We have obtained an exceptionally good agreement, so that our reimplementation has been considered as validated. It is available from MADANALYSIS 5 version 1.6 onwards, its Public Analysis Database and from InSPIRE [32].

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Chapter 5

ATLAS-EXOT-2016-32: an ATLAS monophoton analysis (36.1 fb$^{-1}$)

S. Baek, T. H Jung

Abstract
We present the MadAnalysis 5 implementation and validation of the ATLAS-EXOT-2016-32 analysis, a search that targets a new physics signature featuring an energetic photon and a large amount of missing transverse momentum. The results are presented for an integrated luminosity of 36 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector. This analysis has been in particular designed to search for the pair production of dark matter particles recoiling against a very energetic photon. Our implementation has been validated by comparing our cutflow predictions with those available from ATLAS.

1 Introduction
In this note, we summarize the MadAnalysis 5 [3–5] implementation of the ATLAS search for the production of dark matter in association with a hard photon [8]. This search focuses on 13 TeV LHC data and an integrated luminosity of 36.1 fb$^{-1}$, and the details of this analysis is documented on https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-32/.

The typical dark matter models that are probed by such an analysis can be embedded in the simplified model presented in Ref. [33]. In this case, the Standard Model is supplemented by a Dirac fermionic dark matter particle that can be produced in quark-antiquark annihilations via an s-channel exchange of an axial-vector mediator. The corresponding Lagrangian reads

$$\mathcal{L} = g_\chi X_D \gamma_\mu \gamma_5 X_D Y_1^{\mu} + \sum_{i,j} \left[ g_{d_{ij}} d_i \gamma_\mu \gamma_5 d_j + g_{u_{ij}} u_i \gamma_\mu \gamma_5 u_j \right],$$

(5.1)

where $X_D$ denotes the fermionic dark matter candidate and $Y_1^{\mu}$ the mediator. For simplicity, we ignore flavor-violating effects and consider flavor universality, so that the new physics couplings satisfy

$$g_{d_{ij}} = g_{u_{ij}} = g_q \delta_{ij},$$

(5.2)

with $i,j = 1,2,3$ being flavor indices. For the validation of our reimplementation, we consider the benchmark scenario defined in Ref. [8] in which the universal coupling of the mediator to quarks is set to $g_q = 0.25$ and the mediator coupling to dark matter is set to $g_\chi = 1$. The new physics setup additionally includes a dark matter mass of 10 GeV and a mediator mass of 800 GeV, which yields a mediator width of 44.01 GeV.

2 Description of the implementation
2.1 Objects
In the ATLAS-EXOT-2016-32 analysis, the signal region definition relies on photons whose transverse energy $E_T^\gamma$ and pseudorapidity $\eta^\gamma$ satisfy

$$E_T^\gamma > 10 \text{ GeV} \quad \text{and} \quad 1.52 < |\eta^\gamma| < 2.37 \quad \text{or} \quad |\eta^\gamma| < 1.37.$$

(5.3)
Their isolation is enforced by requiring that the sum $\Sigma_E$ of the energy deposits in a cone of radius $\Delta R = 0.4$ centered on the photon fulfills

$$\Sigma_E < 2.45 \text{ GeV} + 0.022 E_T^{\gamma},$$

and that the scalar sum $\Sigma_{p_T}$ of the transverse momenta of the non-conversion tracks lying in a cone of radius $\Delta R = 0.2$ centered on the photon satisfies

$$\Sigma_{p_T} < 0.05 \times E_T^{\gamma}. \quad (5.5)$$

Electron candidates are required to have a transverse momentum $p_T^e$ and pseudorapidity $\eta^e$ obeying to

$$p_T^e > 7 \text{ GeV} \quad \text{and} \quad |\eta^e| < 2.47, \quad (5.6)$$

while the muon candidates are defined similarly,

$$p_T^\mu > 6 \text{ GeV} \quad \text{and} \quad |\eta^\mu| < 2.7. \quad (5.7)$$

Jets are reconstructed by means of the anti-$k_T$ algorithm [15], with a radius parameter set to $R = 0.4$, and the analysis restricts itself to jet candidates with a transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ fulfilling

$$p_T^j > 30 \text{ GeV} \quad \text{and} \quad |\eta^j| < 4.5. \quad (5.8)$$

The missing transverse momentum vector $E_T^{\text{miss}}$ is defined as the opposite of the vector sum of the momenta of all reconstructed physics object candidates, and the missing transverse energy is defined by the norm of this vector,

$$E_T^{\text{miss}} = |E_T^{\text{miss}}|. \quad (5.9)$$

2.2 Event Selection

Our reimplementation of the ATLAS monophoton search in MADANALYSIS 5 includes all five signal regions described in the analysis (see the Table 2 in Ref. [8]). They all require to select events featuring one hard photon with an energy

$$E_T^{\gamma} > 150 \text{ GeV}, \quad (5.10)$$

and well separated from the missing momentum in azimuth,

$$\Delta \phi(\gamma, E_T^{\text{miss}}) > 0.4. \quad (5.11)$$

The missing energy significance is imposed to be large,

$$\frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}} > 8.5 \text{ GeV}^{1/2}, \quad (5.12)$$

and a (loose) jet veto is finally imposed. The selected events are hence allowed to feature at most one jet that must be well separated from the missing momentum in azimuth,

$$\Delta \phi(j, E_T^{\text{miss}}) > 0.4. \quad (5.13)$$

The five signal regions are differentiated by means of different missing energy selection criteria. Three inclusive regions SRI1, SRI2 and SRI3 are respectively defined by imposing that

$$E_T^{\text{miss}} > 150 \text{ GeV}, \quad E_T^{\text{miss}} > 225 \text{ GeV} \quad \text{and} \quad E_T^{\text{miss}} > 300 \text{ GeV}, \quad (5.14)$$

whilst two exclusive regions SRE1 and SRE2 focus on definite missing energy ranges,

$$E_T^{\text{miss}} \in [150, 225] \text{ GeV} \quad \text{and} \quad E_T^{\text{miss}} \in [225, 300] \text{ GeV}. \quad (5.15)$$

The provided validation material is however only available for the SRI1 region [8].
Table 5.1: Comparison of the cutflow predicted by MADAnalysis 5 with the one provided by the ATLAS collaboration.

| cuts                                | MA5       | Official  | error     |
|-------------------------------------|-----------|-----------|-----------|
| Initial                             | 1198      | 1198      |           |
| $E_T^{\text{miss}} > 150$ GeV       | 882.1(−26.37%) | 736(−38.56%) | 19.85%    |
| $p_T^{\gamma_1} > 150$ GeV and $|\eta| < 2.37$ | 683.1(−22.56%) | 700(−4.89%) | −2.41%    |
| Tight leading photon                 | 570.0(−16.56%) | 658(−6.00%) | −13.38%   |
| $\Delta \phi(\gamma, E_T^{\text{miss}}) > 0.4$ | 568.6(−0.24%)   | 620(−5.78%) | −8.30%    |
| $E_T^{\text{miss}} / \sqrt{\sum E_T} > 8.5$ GeV$^{1/2}$ | 555.4(−2.32%)   | 596(−3.87%) | −6.81%    |
| $N_{\text{jet}} < 2$ and $\Delta \phi(\text{jet}, E_T^{\text{miss}}) > 0.4$ | 447.6(−17.13%) | 461(−22.65%) | −2.91%    |
| Lepton veto                          | 447.6(−0.00%) | 460(−0.21%) | −2.7%     |

3 Validation

3.1 Event Generation

In order to validate our reimplementation of the ATLAS analysis, we focus on the simplified model introduced above. In order to generate hard scattering signal events, we use the UFO [16] model associated with the considered simplified dark matter model [33] that has been generated with the FeynRules [34] and NLOCT [35] programs. We have imported this model into MadGraph5_AMC@NLO version 2.6.0 [1] and generated parton-level events by convoluting matrix elements at the next-to-leading order (NLO) accuracy in QCD with the NLO set of NNPDF 3.0 parton distribution functions [17]. Those events have then been showered and hadronized within the Pythia 8.2 environment [25], and the simulation of the detector response has been made with Delphes 3 [2] that internally relies on FastJet [19] for object reconstruction. We have used our MadAnalysis 5 reimplementation to calculate the signal selection efficiencies.

3.2 Comparison with the official results

In Table 5.1, we compare the results obtained with our implementation to the official numbers provided by the ATLAS collaboration. The discrepancy is characterized according to the measure

$$|\text{error}| = \left| \frac{\text{MA5} - \text{Official}}{\text{Official}} \right|.$$  (5.16)

We observe that the disagreement, on a cut-by-cut basis, is of at most 20%, and even smaller than that for most cuts. We therefore consider our analysis as validated.

4 Summary

We have implemented in MadAnalysis 5 the five signal regions of the ATLAS monophoton analysis of 36.1 fb$^{-1}$ of LHC collision data at a center-of-mass energy of 13 TeV. We have validated our implementation in the context of a Dirac fermionic dark matter simplified model featuring an axial-vector mediator by comparing our predictions for the cutflow with the official one provided by ATLAS in Ref. [8]. We have found an agreement that is better than at the 20% level, so that we consider our reimplementation as validated. It is available from MadAnalysis 5 version 1.6 onwards, its Public Analysis Database and from INSPIRE [36].

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Chapter 6

CMS-EXO-16-012: a CMS mono-Higgs analysis (3.2 fb\(^{-1}\))

S. Ahn, J. Park and W. Zhang

Abstract

We present the implementation and validation of the CMS-EXO-16-012 analysis within MadAnalysis 5. This search targets events featuring a large missing transverse momentum and the signature of a Higgs boson decaying into a pair of bottom quarks or photons, and focuses on 2.3 fb\(^{-1}\) of proton-proton collisions at a center-of-mass energy of 13 TeV. In our reimplementation, we only focus on the \( \gamma \gamma \) final state and validate our reimplementation in the context of a two-Higgs-doublet model including an extra neutral gauge boson.

1 Introduction

In this document, we detail the MadAnalysis 5 implementation of the CMS search for the associated production of dark matter with a Higgs boson decaying into a \( b \bar{b} \) or \( \gamma \gamma \) pair. This search focuses on the analysis of 2.3 fb\(^{-1}\) of proton-proton collision data at a center-of-mass energy of \( \sqrt{s} = 13 \) TeV [7]. The \( b \bar{b} \) channel subanalysis is divided into two regimes, i.e. a resolved regime where the Higgs boson decays into two distinct reconstructed \( b \)-jets, and a Lorentz-boosted regime where the Higgs boson is reconstructed as a single fat jet. In this last case, the signal extraction is performed through a simultaneous fit of signal regions and background-enriched control regions. We have not been able to reproduce this fit consequently to the lack of associated public information, and we have therefore not reimplemented this analysis strategy. On the other hand, the \( \gamma \gamma \) channel search is performed by seeking an excess of events over the Standard Model expectation in the diphoton mass spectrum, which solely relies on a cut-and-count approach.

The analysis presented in Ref. [7] has been interpreted using a benchmark simplified model in which a two-Higgs-doublet model is supplemented by an extra \( Z' \) boson and a dark matter particle \( \chi \) (\( Z' \)-2HDM) [14, 22]. The signal that is probed by the analysis corresponds to the resonant production of a heavy \( Z' \) vector boson which further decays into a Standard-Model-like Higgs boson \( h \) and an intermediate heavy pseudoscalar boson \( A \) that connects the visible sector to a dark sector. The mediator \( A \) hence decays into a pair of dark matter particles. The entire process,

\[
pp \rightarrow Z' \rightarrow hA \rightarrow h \bar{\chi} \chi ,
\]

is described in Fig. 6.1. However, this signature is quite generic and its reimplementation within the MadAnalysis 5 framework could enable more reinterpretations. For example it could be used to probe other scalar extensions of the Standard Model, noteworthy in a more general two-Higgs-doublet plus singlet extensions of the Standard Model or in a supersymmetric context. In particular, such as signature could provide an interesting handle on the NMSSM, where the \( Z'Ah \) coupling is replaced by a \( A_1 A_2 h \) or \( h_3 h_2 h_1 \) interaction with \( A_{1,2} \) and \( h_{1,2,3} \) respectively being \( CP \)-odd and \( CP \)-even scalars [37].

2 Description of the analysis

To enforce the compatibility with the presence of a Higgs boson decaying into two photons, events are selected if they feature a photon pair satisfying given invariant mass and transverse momentum (\( p_T \)) requirements. Moreover, fake photons are rejected through constraints on the calorimetric activity of the
reconstructed photons and their isolation. The signal region is further defined by imposing constraints on the ratio of the photon $p_T$ to the diphoton invariant-mass, as well as on the missing transverse momentum and on the angular separation between the reconstructed Higgs boson and the missing momentum.

2.1 Objects definition and preselection

In this analysis, photons are identified following different ways. A cut-based identification is first performed, relying on a loose working point. The exact selections are presented in Ref. [38], as well as in the CMS-PAS-EXO-16-012 analysis note [7]. In practice, isolation is imposed by restricting the calorimetric activity in a cone of radius $\Delta R = 0.3$ centered on the photon through three variables, $I_{\pm}$, $I_0$ and $I_\gamma$. These respectively correspond to the amount of calorimetric deposits originating from charged hadrons, neutral hadrons and photons lying in the considered cone.

The signal region is defined by requiring the presence of two photons whose transverse momenta fulfill

$$p_T(\gamma_1) > 30 \text{ GeV} \quad \text{and} \quad p_T(\gamma_2) > 18 \text{ GeV}. \quad (6.2)$$

Fake photons are rejected by requiring that the ratio of the amount of energy deposited in the hadronic calorimeter is of at most 10% of the amount of energy deposited on the electromagnetic calorimeter,

$$H/E < 0.1,$$

and photon isolation is ensured by the selections on the $I_{\pm}$, $I_0$ and $I_\gamma$ variables given in Table 6.1. Whilst the isolation requirement related to the neutral particles should include the so-called $\rho$ correction that accounts for the dependence of the pileup transverse energy density on the photon pseudorapidity, $\rho$ being the median of the transverse energy density per unit area, we ignore this correction in our implementation due to the lack of relevant information.

Events are finally further preselected by requiring that the invariant mass of the diphoton system satisfies

$$m_{\gamma\gamma} > 95 \text{ GeV}, \quad (6.4)$$

in order to be compatible with the decay of a Higgs boson.

2.2 Signal selections

After the preselection described above, the CMS-PAS-EXO-16-012 analysis includes a series of cuts defining the signal region. These kinematic selections consist of additional constraints on the $p_T$ of the two photons,

$$\frac{p_T(\gamma_1)}{m_{\gamma\gamma}} > 0.5 \quad \text{and} \quad \frac{p_T(\gamma_2)}{m_{\gamma\gamma}} > 0.25,$$

for the leading and next-to-leading photon respectively, and of a selection on the diphoton transverse momentum and on the missing transverse energy $E_T^{\text{miss}}$,

$$p_{T_{\gamma\gamma}} > 90 \text{ GeV} \quad \text{and} \quad E_T^{\text{miss}} > 105 \text{ GeV}. \quad (6.6)$$
Two extra cuts further constrain the angular separation between the missing transverse momentum $p_T^{\text{miss}}$ and the diphoton system,

$$|\Delta \phi (\gamma\gamma, p_T^{\text{miss}})| > 2.1 \quad \text{and} \quad \min_j(|\Delta \phi (j, p_T^{\text{miss}})|) > 0.5 ,$$

where the minimization has to account for all jets with a transverse momentum larger than 50 GeV. In this analysis, jets are reconstructed by means of the anti-$k_T$ algorithm [15], with a radius parameter set to $R = 0.4$. Finally the diphoton invariant mass is further imposed to satisfy

$$120 \text{ GeV} < m_{\gamma\gamma} < 130 \text{ GeV} .$$

### 3 Validation

In order to validate our reimplementation, we focus on the $Z'$-2HDM model described above and on the production of a heavy $Z'$ boson that decays into a Higgs boson and a pair of dark matter particles via an intermediate pseudoscalar state $A$ (see Fig. 6.1 for a representative Feynman diagram). Hard-scattering signal events are generated with MadGraph5_aMC@NLO [1], the matrix elements being generated from the model information provided through an appropriate UFO [16] model shared by CMS and convoluted with the next-to-leading-order set of NNPDF 3.0 parton densities [17]. Our tests focus on several benchmark scenarios featuring each a different $Z'$-boson mass $M_{Z'}$. The simulation of the hadronic environment (parton showering and hadronization) is performed by means of Pythia 8 [25], that is also used to handle the decay of the final-state Higgs boson. The simulation of the response of the CMS detector is achieved via Delphes 3 [2], that internally relies on FastJet [19] for object reconstruction, with a tuned detector configuration including updated $b$-tagging and reconstruction performances.

We make use of our reimplementation of the CMS-PAS-EXO-16-012 analysis to compute MadAnalysis 5 predictions for the acceptance times efficiency values for the different scenarios. Our reimplementation is then validated by comparing our results with the official numbers from CMS.

### 3.1 Event Generation

Hard scattering events are generated by making use of the MadGraph5_aMC@NLO package, together with the UFO model available on the CMS public repository, [http://rkhurana.web.cern.ch/rkhurana/monoH/models/](http://rkhurana.web.cern.ch/rkhurana/monoH/models/)

The necessary configuration files for each of the considered benchmarks can be found from the MadGraph5 generator repository of CMS, [https://github.com/cms-sw/genproductions/tree/mg240/bin/MadGraph5_aMCatNLO](https://github.com/cms-sw/genproductions/tree/mg240/bin/MadGraph5_aMCatNLO)

in the folder

cards/production/13TeV/monoHiggs/Zp2HDM/Zprime_A0h_A0chichi

We fix the masses of the pseudoscalar state and of the dark matter particle to 300 GeV and 100 GeV, respectively, and set the decay width of the pseudoscalar to 8.95 GeV. We investigate several configurations for the properties of the $Z'$ boson. Its mass is hence varied and fixed to 600, 800,
Table 6.2: Values of the $Z'$ total width for each benchmark point used in the validation process.

| $m_{Z'}$ (GeV) | CMS EXO-16-012 | MA5 | Difference |
|----------------|----------------|-----|------------|
| 600            | 0.317 ± 0.004  | 0.355 ± 0.001| -11 %      |
| 800            | 0.399 ± 0.004  | 0.451 ± 0.001| -13 %      |
| 1000           | 0.444 ± 0.004  | 0.494 ± 0.001| -8.2 %     |
| 1200           | 0.474 ± 0.004  | 0.513 ± 0.001| -0.6 %     |
| 1400           | 0.492 ± 0.004  | 0.515 ± 0.001| -4.7 %     |
| 1700           | 0.493 ± 0.004  | 0.494 ± 0.001| -0.2 %     |
| 2000           | 0.351 ± 0.004  | 0.355 ± 0.001| -1.1 %     |
| 2500           | 0.213 ± 0.004  | 0.208 ± 0.001| 2.3 %      |

Table 6.3: Comparison of the signal acceptance times efficiencies predictions made by MadAnalysis 5 with the CMS official numbers. The difference is calculated according to Eq. (6.9).

Concerning the simulation of the CMS detector, we have slightly modified the configuration that has been designed for the reimplementation of the CMS-EXO-16-037 analysis and that is available on http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

Compared with the default settings, the $b$-tagging and lepton and photon reconstruction performances have been updated according to Refs. [38,39]. In particular, we make use of the cMVAv2 loose $b$-tagging working point, which corresponds to a correct $b$-tagging efficiency of about 83% for a misidentification probability of about 10%. We have also defined the dark matter particle as an invisible state that does not deposit energy in the calorimeters.

3.2 Comparison with official results

As CMS has not provided detailed validation information, we have validated our implementation on the basis of the available material. We present the product of signal acceptance and selection efficiency for

1000, 1200, 1400, 1700, 2000 and 2500 GeV for the different setups. All the $Z'$ couplings to Standard Model particles $g_{SM}$ are chosen to be equal to 0.8, while the coupling to dark matter is fixed to 1 [14]. The corresponding $Z'$-boson width for each mass value is given in Table 6.2.
Fig. 6.2: Missing transverse energy (left) and diphoton invariant mass (right) distributions after all selection criteria have been imposed, except the one on the missing energy (both cases) and the one of the diphoton invariant mass (right panel only). The dotted lines are the official CMS results taken from Ref. [7] and the solid lines are the MADANALYSIS 5 predictions.

Each considered \(Z\) mass point, and we define the difference with the official numbers as

\[
\delta = 1 - \frac{(A \cdot \epsilon)^{MA5}}{(A \cdot \epsilon)^{CMS}},
\]

(6.9)

The results are given in Table 6.3.

Moreover, we present, for representative signal scenarios, the missing transverse energy and diphoton invariant mass distributions in Fig. 6.2 after normalizing our signal distributions similarly to CMS. For all performed tests, a good agreement is obtained.

4 Summary

In this note, we reported the MADANALYSIS 5 reimplementation of the CMS-EXO-16-012 and analysis and its validation. We compared signal selection efficiencies times acceptance for varied benchmark scenarios, as well as two differential distributions. An overall agreement has been found, the differences being of at most 13\%. This analysis is thus considered as validated and has been made available from MADANALYSIS 5 version 1.6 onwards, its Public Analysis Database and from INSPIRE [40],

http://doi.org/10.7484/INSPIREHEP.DATA.JT56.DDC3.1.
Exotics
Chapter 7

CMS-EXO-16-022: a CMS long-lived lepton analysis (2.6 fb$^{-1}$)

Jung Chang

Abstract

We present the MadAnalysis 5 implementation and validation of the CMS-EXO-2016-22 analysis, which documents a search for new long-lived particles that decay into electrons and muons. The results are based on a dataset of proton-proton collisions recorded by CMS with a center-of-mass energy of 13 TeV and an integrated luminosity of 2.6 fb$^{-1}$. The validation of our reimplementation is based on a comparison of the expected number of signal event counts in the signal regions with information provided by the CMS collaboration, with signal events corresponding to a benchmark model featuring pair-produced long-lived top squarks.

1 Introduction

In this contribution, we summarize the MadAnalysis 5 [3–5] implementation of the CMS-EXO-16-022 analysis, a search for long-lived particles in 2.6 fb$^{-1}$ of LHC proton-proton collision data at a center-of-mass energy of 13 TeV [11], that we present together with its validation. The simulation of the signal events used for the validation relies on a MadAnalysis 5 tune of Delphes 3 [2] that has been specifically designed to deal with long-lived particles. It in particular allows for handling neutral long-lived particles that decay into leptons within the volume of the tracker. Reconstruction efficiencies can be applied to displaced tracks and various related parameters can be accessed at the analysis level by means of a dedicated MadAnalysis 5 version.

In practice, the simulation of the displaced leptons is performed through efficiencies and resolution functions that the user can specify in the Delphes card. More information is available on the web page https://madanalysis.irmp.ucl.ac.be/wiki/MA5LongLivedParticle that also includes a download link to the special version of MadAnalysis 5 that has to be employed. We have used the reconstruction efficiency depending on the impact parameter $d_0$ provided in Ref. [41].

For our validation, we have focused on an R-parity-violating (RPV) supersymmetric scenario featuring a long-lived stop. Relying on the material provided by the CMS collaboration, we have considered four different stop decay lengths fixed to

$$c\tau_\tilde{t} = 0.1, \, 1, \, 10 \text{ and } 100 \text{ cm},$$

(7.1)

respectively, for a stop mass of $m_{\tilde{t}} = 700$ GeV in all cases. The stop is then assumed to decay via an RPV channel,

$$\tilde{t} \rightarrow b\ell \quad \text{with} \quad \ell = e \text{ or } \mu .$$

(7.2)

For simplicity, lepton universality has been assumed, so that the stop branching fraction into an electron, muon and tau final state equals 1/3 in all cases. The benchmark information corresponds to the Snowmass Points and Slopes scenario SPS1a [42] that has been provided by the CMS collaboration.

We have made use of our reimplementation of the CMS-EXO-16-022 analysis to compute MadAnalysis 5 predictions for the expected number of signal events in the different signal regions defined in the CMS analysis. This has allowed us to validate our reimplementation by comparing our predictions with the official numbers from CMS.
2 Description of the analysis

As mentioned above, the CMS-EXO-16-022 analysis investigate new physics in a channel where two displaced leptons, with a transverse impact parameter lying between 200 $\mu$m and 10 cm, are observed. This analysis is particularly sensitive to RPV supersymmetric signals as they could originate from the production of a pair of long-lived top squarks that decay into a lepton and a $b$-jet. While any combination of leptons is theoretically allowed, the analysis focuses on the production of one muon and one electron only.

2.1 Object definition and preselection

The analysis preselects events that feature exactly one electron and one muon that are well reconstructed and isolated. Selected events must have passed a dedicated trigger targeting displaced electron-muon pairs where both leptons have a transverse momentum $p_T^\ell$ satisfying

$$p_T^\ell > 38 \text{ GeV}. \quad (7.3)$$

Both leptons are then required to be central, with a pseudorapidity $|\eta^\ell|$ fulfilling

$$|\eta^\ell| < 2.4, \quad (7.4)$$

and with a transverse momentum constrained to satisfy

$$p_T^\ell > 42 \text{ GeV} \quad \text{and} \quad p_T^{\ell'} > 40 \text{ GeV} \quad (7.5)$$

for electrons and muons respectively. Moreover, both leptons are required to be well separated from each other, in the transverse plane,

$$\Delta R(\ell, \mu) > 0.5, \quad (7.6)$$

and are required to satisfy the isolation requirements

$$\frac{1}{p_T} \sum_i (p_T^i) < \begin{cases} 0.065 & \text{for } \ell = e \text{ with } 1.57 < |\eta^\ell| < 2.4 \\ 0.035 & \text{for } \ell = e \text{ with } |\eta^\ell| < 1.44 \\ 0.015 & \text{for } \ell = \mu \end{cases}, \quad (7.7)$$

where the sum is considered over all reconstructed particles within a $\Delta R$ cone of 0.3 (electrons) or 0.4 (muons), and where the lepton candidate itself is excluded from the sum. Additionally, the lepton candidates are required to originate from the pixel detector, which is achieved by imposing a threshold on the transverse impact parameter $d_0^\ell$,

$$d_0^\ell < 10 \text{ cm}. \quad (7.8)$$

2.2 Signal region selections

The analysis contains three signal search regions whose definition varies according to the values of the transverse impact parameters $d_0^\ell$ of the two leptons. The tight search region (SR III) requires both leptons to be displaced by more than 10 cm,

$$\text{SR III : } d_0^{\ell_1} > 1000 \mu m \quad \text{and} \quad d_0^{\ell_2} > 1000 \mu m, \quad (7.9)$$

while an intermediate signal region SR II allows for smaller displacements,

$$\text{SR II : } d_0^{\ell_1} > 500 \mu m \quad \text{and} \quad d_0^{\ell_2} > 500 \mu m. \quad (7.10)$$

Finally, a looser signal region SR I allows for even smaller displaced leptons, featuring

$$\text{SR I : } d_0^{\ell_1} > 200 \mu m \quad \text{and} \quad d_0^{\ell_2} > 200 \mu m. \quad (7.11)$$

Overlaps are removed from the signal regions by explicitly excluding the tighter signal regions from the looser. For example, events populating the SR III region are excluded from the SR II and SR I regions, and events populating the SR II region are not allowed to populate the SR I region.
3 Validation

3.1 Event Generation

In order to validate the CMS-EXO-16-022 MadAnalysis 5 reimplementation, we focus on the SPS1a supersymmetric scenario whose parameterization has been provided by the CMS collaboration under the form of an appropriate SLHA file [43]. The stop decay table, mass and width have been modified according to the requirement of the considered benchmark scenarios.

Event generation relies on Pythia8 (v 8.226) [25], after making use of the command card provided by the CMS collaboration. This corresponds to the Pythia script,

\[
\begin{align*}
\text{SUSY:gg2squarkantisquark} & = \text{on} \\
\text{SUSY:qqbar2squarkantisquark=} & \text{on} \\
\text{SLHA:useDecayTable} & = \text{true} \\
\text{RHadrons:allow} & = \text{on} \\
1000006:tau0 & = 1000 \text{ !mm}
\end{align*}
\]

in which we have turned on the RHadrons command to enable stop hadronization and the tau0 attribute of the particle class to set the stop width.

We reweight our events so that the total production rate for stop pair-production in proton-proton collisions at a center-of-mass energy of 13 TeV matches the NLO+NLL predictions [28],

\[
\sigma(p p \rightarrow \tilde{t} \tilde{t}^{\dagger}) \bigg|_{m_{\tilde{t}}=700 \text{ GeV}} = 0.067 \text{ pb}.
\]

The event weight moreover includes a normalization factor accounting for an integrated luminosity of 2.6 fb\(^{-1}\).

The simulation of the response of the detector is achieved via the Delphes 3 [2] program and its internal use of FastJet [19] for object reconstruction. Our detector simulation includes reconstruction and selection efficiencies for displaced electrons and muons, as provided on the public CMS webpage [28] and presented on Figure 7.1.

3.2 Comparison with official results

In Table. 7.1, we compare our predictions (MA5) with the official results provided by CMS, for the four considered stop lifetimes. The deviations are evaluated relatively to the CMS official results, according to the measure

\[
|\text{error}| = \left| \frac{\text{MA5} - \text{CMS}}{\text{CMS}} \right|.
\]

We obtain a good agreement in most of the cases, with the exception of the very long stop lifetime setup (cτ = 100 cm) for which very important discrepancies are found. The origins of the discrepancies are connected to the reconstruction and selection efficiencies of Figure 7.1 that have been extracted from 8 TeV data and provided for stop decays lengths of at most 2.2 cm. More information would be necessary to allowing for better modeling of the reconstruction properties of very long-lived stops, as we manually set the efficiency to zero in our Delphes configuration card. Moreover, the position of the secondary vertex along the collision axis is used in the CMS-EXO-16-022 analysis, so that the dependence of the efficiencies on the longitudinal impact parameter may be important.

4 Summary

The MadAnalysis 5 implementation of the CMS-EXO-2016-22 analysis, a search for long-lived particles decaying into electrons and muons, has been presented. The simulation of signal events needs to be performed using a special tune of Delphes 3 that has been modified for handling displaced vertex
Fig. 7.1: Reconstruction (upper panels) and selection (lower panels) efficiencies associated with displaced electrons and muons, as provided on https://twiki.cern.ch/CMSPublic/DisplacedSusyParametrisationStudyForUser.

| Region | $c\tau_{\ell}$ [cm] | MA5 | CMS | Difference [%] |
|--------|-----------------|-----|-----|---------------|
| SR-I   | 0.1             | 3.89| 3.8 | 2.30          |
|        | 1               | 4.44| 5.2 | 14.51         |
|        | 10              | 0.697| 0.8 | 12.84         |
|        | 100             | 0.0610| 0.009| > 100%       |
| SR-II  | 0.1             | 0.924| 0.94| 1.71          |
|        | 1               | 3.87| 4.1 | 5.61          |
|        | 10              | 0.854| 1.0 | 14.58         |
|        | 100             | 0.0662| 0.03| ~ 100%       |
| SR-III | 0.1             | 0.139| 0.16| 12.84         |
|        | 1               | 6.19| 7.0 | 11.59         |
|        | 10              | 4.45| 5.8 | 23.56         |
|        | 100             | 0.497| 0.27| ~ 100%       |

Table 7.1: Number of events populating the three signal regions of the CMS-EXO-16-022 analysis for the different considered stop decay lengths. We compare the CMS and MadAnalysis 5 (MA5) results in the second and third column of the table, respectively, and evaluate the difference according to Eq. (7.13) in the last column of the table.
information. A link to a download of this tune is made available on the webpage
https://madanalysis.irmp.ucl.ac.be/wiki/MA5LongLivedParticle.
For the considered benchmark scenarios, the calculation of the signal acceptance and efficiency is con-
sistent with predictions given by CMS for proper decay lengths smaller than 10 cm. However, this
implementation is not valid and should not be used to constrain models containing particles with proper
decay lengths greater than 10 cm. This analysis is thus considered as validated and has been made avail-
able from the MADANALYSIS 5 Public Analysis Database and from INSPIRE [44],
http://doi.org/10.7484/INSPIREHEP.DATA.UFU4.99E3.

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Supersymmetry
Chapter 8

CMS-SUS-16-041: a CMS supersymmetry search with multileptons and jets (35.9 fb⁻¹)

G. Chalons, B. Fuks, K. Lee, J. Park

Abstract
We summarize the implementation within the MADANALYSIS 5 framework of the CMS search for new physics through final-state signatures comprised of at 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 benchmark 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 \( \tilde{\chi}_1^\pm \), which 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 \( p_T \) and pseudorapidity \( \eta \) satisfying

\[
p_T > 30 \text{ GeV} \quad \text{and} \quad |\eta| < 2.4
\]

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

\[
|\eta^e| < 2.5 \quad \text{and} \quad |\eta^\mu| < 2.5
\]

are retained.
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 $I_{\text{mini}}$ 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

$$\Delta R = \frac{10 \text{ GeV}}{\min(\max(p_T(\ell), 50), 200)}.$$  \hspace{1cm} (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,

$$p_T^{\text{ratio}} = p_T(\ell)/p_T(\text{jet}),$$  \hspace{1cm} (8.4)

and the last variable is the relative lepton transverse momentum $p_T^{\text{rel}}$ 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

$$I_{\text{mini}} < I_1 \quad \text{and} \quad \left[ (p_T^{\text{ratio}} > I_2) \quad \text{or} \quad (p_T^{\text{rel}} > I_3) \right].$$ \hspace{1cm} (8.5)

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

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

$$H_T = \sum_{\text{jets}} p_T,$$  \hspace{1cm} (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.

$$\begin{cases} 
H_T < 300 \text{ GeV} : & p_T(\ell_1) > 25 \text{ GeV}, p_T(\ell_2) > x \text{ GeV} \\
H_T > 300 \text{ GeV} : & p_T(\ell_1, \ell_2) > x \text{ GeV}
\end{cases}$$ \hspace{1cm} (8.7)


| $N_{\text{jets}}$ | $N_{b\,\text{jets}}$ | $H_T$ (GeV) | $\text{SR1}^*$ | $\text{SR2}^*$ | $\text{SR3}^*$ | $\text{SR4}^*$ | $\text{SR5}^*$ | $\text{SR6}^*$ | $\text{SR7}^*$ | $\text{SR8}^*$ | $\text{SR9}^*$ | $\text{SR10}^*$ | $\text{SR11}^*$ | $\text{SR12}^*$ | $\text{SR13}^*$ | $\text{SR14}^*$ | $\text{SR15}^*$ |
|------------------|------------------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $\geq 2$          |                  | 60 − 400    | $\text{SR1}^*$ |                |                |                |                |                |                |                |                |                |                |                |                |                |                |
|                  |                  | 400 − 600   | $\text{SR2}^*$ | $\text{SR3}^*$ |                |                |                |                |                |                |                |                |                |                |                |                |
| $\geq 3$          |                  | 60 − 400    | $\text{SR4}^*$ | $\text{SR5}^*$ |                |                |                |                |                |                |                |                |                |                |                |                |
|                  |                  | 400 − 600   | $\text{SR6}^*$ |                |                |                |                |                |                |                |                |                |                |                |                |

**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.

\[
M_{\min}^T \geq 120\,\text{GeV}
\]

\[
\begin{array}{|c|c|c|c|}
\hline
\text{on-Z} & N_{b\,\text{jets}} \leq 2 & N_{b\,\text{jets}} \geq 3 \\
\hline
\text{No} & H_T \geq 200\,\text{GeV} & E_T^{\min} \geq 250\,\text{GeV} \\
\text{Yes} & H_T \geq 60\,\text{GeV} & E_T^{\min} \geq 50\,\text{GeV} \\
\hline
\end{array}
\]

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

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

\[
p_T(\ell_3) > 10\,\text{GeV}.
\]  

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

\[
m_{\ell\ell} > 12\,\text{GeV}.
\]  

The baseline selection finally requires an amount of missing energy

\[
E_T^{\min} > 50\,\text{GeV} \quad \text{or} \quad 70\,\text{GeV},
\]  

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 $400\,\text{GeV}$.

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, $|m_{\ell\ell} - M_Z| < 15\,\text{GeV}$ (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 ($M_T < 120\,\text{GeV}$ or $M_T > 120\,\text{GeV}$).

### 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 $1500\,\text{GeV}$ and $200\,\text{GeV}$ 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 $1200\,\text{GeV}$ and $400\,\text{GeV}$, respectively. For both scenarios, the branching fraction of the gluino into (top or lighter) quarks are assumed to be $2/3$ for $\tilde{g} \rightarrow \tilde{\chi}_1^\pm q\bar{q}'$ and $\tilde{g} \rightarrow \tilde{\chi}_2^0 q\bar{q}$ with $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = (m_{\tilde{\chi}_1^0} + m_{\tilde{g}})/2$. 

45
3.1 Event generation

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

\[ p p \rightarrow \tilde{g} \tilde{g} . \]  

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 10^3 GeV. The hard matrix-element has been convoluted with the NNPDF30\_10\_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 CUETPSM1 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.
### 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       | 509.0              | 27345              | 0              |
| Trigger (≥ 3 leptons) | 6.7                | 348                | -3.79          |
| ≥ 2 jets           | 6.7                | 342                | -5.30          |
| $p_T^{miss} > 50$ GeV | 6.7                | 337                | -6.82          |
| off-Z SR           | 6.0                | 302                | -6.78          |
| off-Z SR16a        | 1.8                | 93                 | -2.86          |
| off-Z SR16b        | 2.5                | 133                | 0              |

### 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.

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

### 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 signature constituted of at 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 gaug 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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Chapter 9

CMS-SUS-17-001: a CMS search for stops and dark matter with opposite-sign dileptons

S. Bein, S.-M. Choi, B. Fuks, S. Jeong, D.-W. Kang, J. Li, J. Sonneveld

Abstract

We present the MadAnalysis 5 implementation and validation of the CMS-SUS-17-001 analysis, which documents a search for the production of top squarks decaying into a dileptonic system and missing transverse energy. The results are based on a dataset of proton-proton collisions recorded by CMS with a center-of-mass energy of 13 TeV and an integrated luminosity of 35.9 fb$^{-1}$. The validation of our reimplementation is based on a comparison of the expected number of signal event counts in the signal regions with information provided by the CMS collaboration, with signal events corresponding to a simplified scenario in which the Standard Model is extended by a stop and a neutralino.

1 Introduction

In this contribution, we present the MadAnalysis 5 [3–5] implementation of the CMS-SUS-17-001 search [13] for the superpartners of the top quark, together with its validation. The CMS analysis targets the production of a pair of top squarks that decay into a final-state system comprising at least two jets with one of them being $b$-tagged, one pair of leptons of opposite electric charge, and a significant amount of missing transverse momentum. The main search variable consists of the $m_{T2}$ transverse mass [51,52] that has a kinematic endpoint for the dominant contributions to the Standard Model background.

In order to validate our reimplementation, we have reinterpreted the results of the CMS collaboration in the context of a class of simplified models where the Standard Model is supplemented by a top squark and a neutralino, where the neutralino is stable and thus gives rise to missing transverse momentum. We have compared, for two benchmark configurations, predictions obtained with our MadAnalysis 5 reimplementation with the official CMS results at different level of the selection strategy. Although the analysis is also sensitive to generic dark matter simplified models, the information provided by CMS has not allowed us to generate events to perform a comparison in this case.

2 Description of the analysis

The CMS-SUS-17-001 analysis relies on a final-state signature made of two top quarks and missing transverse energy $E_T$ as could arise from stop-pair production and decay,

$$pp \to \tilde{t}\tilde{t}^* \to t\bar{t} + E_T,$$

and illustrated in Fig. 9.1 The analysis focuses on the dileptonic decay of the top-antitop system and the preselection is implemented accordingly.
2.1 Object definitions and preselection

The signal region definitions rely on the presence of two lepton candidates $\ell_1$ and $\ell_2$ whose transverse momentum $p_T$ and pseudorapidity $\eta$ satisfy

$$p_T^{\ell_1} > 25 \text{ GeV} \quad \text{and} \quad |\eta^{\ell_1}| < 2.4,$$

$$p_T^{\ell_2} > 20 \text{ GeV} \quad \text{and} \quad |\eta^{\ell_2}| < 2.4,$$

for the leading and next-to-leading lepton, respectively. Lepton isolation is enforced by requiring that the sum of the transverse momentum of the particles present in a cone of radius $R = 0.3$ centered on the lepton is smaller that 0.12 times the lepton $p_T$,

$$\frac{1}{p_T^\ell} \sum_i (p_T)^i < 0.12 .$$

(9.3)

Jets are reconstructed by means of the anti-$k_T$ algorithm [15] with a radius parameter set to $R = 0.4$, and their transverse momentum $p_T^j$ and pseudorapidity $\eta^j$ are required to fulfill

$$p_T^j > 30 \text{ GeV} \quad \text{and} \quad |\eta| < 2.45 .$$

(9.4)

Moreover, any jet found within a cone of radius $R = 0.4$ centered on an isolated lepton is removed from the jet collection. Jets are tagged as $b$-jets according to the medium working point of the CSVv2 CMS algorithm [53], which corresponds to a tagging efficiency of about 55%-65% for a percent-level mistagging rate. The missing transverse momentum $E_T^{\text{miss}}$ is defined as the negative of the vector sum of the transverse momenta of all reconstructed objects, and the missing transverse energy is then defined by its norm,

$$E_T^{\text{miss}} = |E_T^{\text{miss}}| .$$

(9.5)

Event preselection starts by requiring an opposite-charge pair of leptons (electrons or muons) with a dilepton invariant mass $m_{\ell\ell}$ satisfying

$$m_{\ell\ell} > 20 \text{ GeV} .$$

(9.6)

Moreover, events featuring a third loosely isolated lepton with a transverse momentum larger than 15 GeV are vetoed. Loose lepton isolation is defined as in Eq. (9.3), but with a different threshold,

$$\frac{1}{p_T^\ell} \sum_i (p_T)^i < 0.40 .$$

(9.7)

In order to suppress the Drell-Yan background, the dilepton system cannot be compatible with a $Z$-boson and its invariant mass has to satisfy

$$|m_{\ell\ell} - m_Z| > 15 \text{ GeV} ,$$

(9.8)
when the lepton flavors are identical. To further suppress boson production backgrounds, the analysis requires at least two jets, with at least one of them being \( b \)-tagged,

\[
N_j \geq 2 \quad \text{and} \quad N_b \geq 1 ,
\]

(9.9)

where \( N_j \) and \( N_b \) respectively indicate the number of jets and \( b \)-tagged jets. Finally, the missing transverse momentum is imposed to fulfill

\[
E_T^{\text{miss}} > 80 \text{ GeV} \quad \text{and} \quad S \equiv \frac{E_T^{\text{miss}}}{\sqrt{H_T}} > 5 \text{ GeV}^{1/2} ,
\]

(9.10)

the hadronic activity \( H_T \) being defined as the scalar sum of the transverse momentum of all reconstructed jets. The missing momentum is finally enforced to be well separated in azimuth from the two leading jets \( j_1 \) and \( j_2 \),

\[
c_1 \equiv \cos \Delta \phi (E_T^{\text{miss}}, j_1) < 0.80 \quad \text{and} \quad c_2 \equiv \cos \Delta \phi (E_T^{\text{miss}}, j_2) < 0.96 .
\]

(9.11)

### 2.2 Event Selection

Our implementation includes all three aggregated signal regions defined in the CMS-SUS-17-001 analysis. Each signal region is defined by a different selection on the amount of missing transverse momentum \( E_T^{\text{miss}} \) and the value of the transverse mass \( m_{T2}(\ell_1\ell_2) \) evaluated by considering the visible branches of the event to be the two leptons,

\[
m_{T2}(\ell_1\ell_2) = \min_{E_T^{\text{miss}} = E_T^{\text{miss}}} \left[ \max \left[ m_T(p_T^{\ell_1}, E_T^{\text{miss}}), m_T(p_T^{\ell_2}, E_T^{\text{miss}}) \right] \right] .
\]

(9.12)

Here, the minimization is made by considering all possible splittings of the missing momentum along the two decay chains. The three signal regions are then defined as

- **SR A0** \( E_T^{\text{miss}} > 200 \text{ GeV} \) , \( 100 \text{ GeV} < m_{T2}(\ell_1\ell_2) < 140 \text{ GeV} \) ,
- **SR A1** \( E_T^{\text{miss}} > 200 \text{ GeV} \) , \( 140 \text{ GeV} < m_{T2}(\ell_1\ell_2) < 240 \text{ GeV} \) ,
- **SR A2** \( E_T^{\text{miss}} > 80 \text{ GeV} \) , \( m_{T2}(\ell_1\ell_2) \geq 240 \text{ GeV} \) .

### 3 Validation

#### 3.1 Event generation

For our validation, we adopt two simplified model benchmarks inspired by the MSSM in which the Standard Model is extended by a stop and a neutralino, all other new physics states being decoupled. The two points respectively feature stop and neutralino masses of \( (m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1) \text{ GeV} \) and \( (600, 300) \text{ GeV} \).

The top squark is imposed to decay into a top and a neutralino with a branching ratio of 100%.

Events have been generated with MadGraph5_AMC@NLO [1] and Pythia 8 [25]. Samples featuring different final-state jet multiplicities have been merged through the MLM scheme [29, 30], the **Pythia8** qcut parameter \( (i.e. \text{ the merging scale}) \) being set to 187.5 GeV and the corresponding MadGraph xqcut parameter being set to 125 GeV. The simulation of the CMS detector is then achieved with the Delphes 3 program [2], that relies on FastJet [19] for object reconstruction, which we configure to include a \( b \)-tagging efficiency of 60% for a \( p_T \)-dependent mistagging rate equal to \( 0.1 + 0.000038 \times p_T \). Our samples have been normalized to the NLO+NLL cross sections taken from Ref. [28], that respectively read 0.171 pb and 0.043 pb for 600 GeV and 750 GeV squarks.
\[ (m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1) \text{ GeV} \]
\[ (m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300) \text{ GeV} \]

| Cut | \( m_{\ell\ell} > 20 \) GeV | \( |m_Z - m_{\ell\ell}| > 15 \) GeV | \( N_j \geq 2 \) | \( N_b \geq 1 \) | \( E_T^{\text{miss}} > 80 \) GeV | \( S > 5 \text{ GeV}^{1/2} \) | \( c_1 < 0.80 \) | \( c_2 < 0.96 \) | \( M_{T2}(\ell_1\ell_2) > 140 \) GeV | All cuts |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| CMS | 0.99            | 0.95            | 0.87            | 0.73            | 0.94            | 0.98            | 0.9             | 1.0             | 0.49            | 0.24            |
| MA5 | 0.99            | 0.94            | 0.93            | 0.84            | 0.95            | 0.92            | 0.97            | 0.96            | 0.42            | 0.25            |
| CMS | 0.99            | 0.89            | 0.85            | 0.83            | 0.89            | 0.96            | 0.92            | 0.97            | 0.17            | 0.083           |
| MA5 | 0.97            | 0.89            | 0.89            | 0.83            | 0.89            | 0.91            | 0.97            | 0.94            | 0.16            | 0.075           |

Table 9.1: Comparison of the signal acceptance times efficiencies predictions made by MADANALYSIS 5 with the CMS official numbers for two benchmark scenarios and on a cut-by-cut basis.

**Fig. 9.2:** Comparison of the \( m_{T2} \) distributions predicted by MADANALYSIS 5 (circles) with the official results provided by CMS (lines). Results for the different background contributions are also included (as provided by the CMS collaboration). The distributions are given after the baseline selection.
3.2 Comparison with the official results

The cutflow for the analysis baseline selection is given in Table 9.1 for two supersymmetric model points of the simplified model above-described. In this case, the $m_{T2}$ variable is required to satisfy

$$m_{T2}(\ell_1 \ell_2) \geq 140 \text{ GeV}.$$ (9.14)

A comparison of the $m_{T2}(\ell_1 \ell_2)$ distribution for two considered supersymmetric scenarios is given in Fig. 9.2, where the lines refer to the official CMS results and the circulars markers to the MADANALYSIS 5 predictions.

The final event counts of both the CMS and MADANALYSIS 5 results appear to agree within 20%, similarly to the $m_{T2}$ spectra that are crucial for the final signal region selections.

4 Summary

The MADANALYSIS 5 reimplementation of the CMS search for new physics in events with two opposite-charge same-flavor leptons, at least one heavy-flavor tagged jet, and large missing transverse momentum, has been presented. All baseline event selection requirements have been incorporated, and simulated signal events for a set of benchmark mass points have been used to validate the analysis implementation. For the simulation, signal events corresponding to two different choices of top squark and neutralino masses were produced in the context of the so-called ‘T2tt’ supersymmetric simplified model (where the Standard Model is solely supplemented by a top squark and a neutralino) using a set of simulation parameters synchronized with the production recipe made available by CMS. A comparison has been made between the efficiencies of various event selection cuts reported by CMS and the corresponding efficiencies obtained in the MADANALYSIS 5 implementation, using the signal events of the supersymmetric benchmark model points. All individual cut efficiencies, as well as the signal efficiency after all event selection, agree within a deviation of about 20%. The implementation is considered to be validated, although recasters may benefit by performing additional studies to validate the selection efficiency in each signal region. CMS also provides correlation matrices for the estimated background counts in the three aggregate search regions, and it may be desirable to incorporate this information into the MADANALYSIS 5 implementation. The reimplemented analysis code is available from MADANALYSIS 5 version 1.6 onwards, its Public Analysis Database and from INSPIRE [54],

http://doi.org/10.7484/INSPIREHEP.DATA.MMM1.876Z.
References

[1] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07 (2014) 079, [arXiv:1405.0301]. 5, 11, 15, 21, 25, 29, 46, 51

[2] DELPHES 3 Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi, DELPHES 3, A modular framework for fast simulation of a generic collider experiment, JHEP 02 (2014) 057, [arXiv:1307.6346]. 5, 11, 15, 21, 25, 29, 35, 37, 46, 51

[3] E. Conte, B. Fuks, and G. Serret, MadAnalysis 5, A User-Friendly Framework for Collider Phenomenology, Comput. Phys. Commun. 184 (2013) 222–256, [arXiv:1206.1599]. 5, 9, 13, 19, 23, 27, 35, 43, 49

[4] E. Conte, B. Dumont, B. Fuks, and C. Wymant, Designing and recasting LHC analyses with MadAnalysis 5, Eur. Phys. J. C74 (2014), no. 10 3103, [arXiv:1405.3982]. 5, 9, 13, 19, 23, 27, 35, 43, 49

[5] B. Dumont, B. Fuks, S. Kraml, S. Bein, G. Chalons, E. Conte, S. Kulkarni, D. Sengupta, and C. Wymant, Toward a public analysis database for LHC new physics searches using MADANALYSIS 5, Eur. Phys. J. C75 (2015), no. 2 56, [arXiv:1407.3278]. 5, 9, 13, 19, 23, 27, 35, 43, 49

[6] ATLAS Collaboration, M. Aaboud et al., Search for Dark Matter Produced in Association with a Higgs Boson Decaying to b̅b using 36 fb^{-1} of pp collisions at \sqrt{s} = 13 TeV with the ATLAS Detector, Phys. Rev. Lett. 119 (2017), no. 18 181804, [arXiv:1707.01302]. 5, 13

[7] CMS Collaboration, A. M. Sirunyan et al., Search for associated production of dark matter with a Higgs boson decaying to b̅b or \gamma\gamma at \sqrt{s} = 13 TeV, JHEP 10 (2017) 180, [arXiv:1703.05236]. 5, 27, 28, 31

[8] ATLAS Collaboration, M. Aaboud et al., Search for dark matter at \sqrt{s} = 13 TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector, Eur. Phys. J. C77 (2017), no. 6 393, [arXiv:1704.03848]. 5, 23, 24, 25

[9] ATLAS Collaboration, M. Aaboud et al., Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector, JHEP 01 (2018) 126, [arXiv:1711.03301]. 5, 19

[10] ATLAS Collaboration, Search for Dark Matter production associated with bottom quarks with 13.3 fb^{-1} of pp collisions at \sqrt{s} = 13 TeV with the ATLAS detector at the LHC, ATLAS-CONF-2016-086. 5, 9

[11] CMS Collaboration, Search for displaced leptons in the e-mu channel, CMS-PAS-EXO-16-022. 6, 35

[12] CMS Collaboration, A. M. Sirunyan et al., Search for supersymmetry in events with at least three electrons or muons, jets, and missing transverse momentum in proton-proton collisions at \sqrt{s} = 13 TeV, arXiv:1710.09154. 6, 43, 45, 47

[13] CMS Collaboration, A. M. Sirunyan et al., Search for top squarks and dark matter particles in opposite-charge dilepton final states at \sqrt{s} = 13 TeV, Phys. Rev. D97 (2018), no. 3 032009, [arXiv:1711.00752]. 6, 49

[14] D. Abercrombie et al., Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum, arXiv:1507.00966. 9, 13, 27, 30

[15] M. Cacciari, G. P. Salam, and G. Soyez, The Anti-k(t) jet clustering algorithm, JHEP 04 (2008) 063, [arXiv:0802.1189]. 10, 14, 20, 24, 29, 43, 50

[16] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, UFO - The Universal
FeynRules Output, Comput. Phys. Commun. 183 (2012) 1201–1214, [arXiv:1108.2040]. 11, 15, 25, 29

[17] NNPDF Collaboration, R. D. Ball et al., Parton distributions for the LHC Run II, JHEP 04 (2015) 040, [arXiv:1410.8849]. 11, 15, 25, 29, 46

[18] T. Sjøstrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP 05 (2006) 026, [hep-ph/0603175]. 11

[19] M. Cacciari, G. P. Salam, and G. Soyez, FastJet User Manual, Eur. Phys. J. C72 (2012) 1896, [arXiv:1111.6097]. 11, 15, 25, 29, 37, 46, 51

[20] S. Banerjee, D. Barducci, G. Bélanger, B. Fuks, A. Goudelis, and B. Zaldivar, Cornering pseudoscalar-mediated dark matter with the LHC and cosmology, JHEP 07 (2017) 080, [arXiv:1705.02327]. 11

[21] B. Fuks and M. Zumbihl, MadAnalysis 5 implementation of the multijet + missing energy analysis of ATLAS with 13.3 fb-1 of data (ATLAS-CONF-2016-086), 10.7484/INSPIREHEP.DATA.UUIF.89NC. 12

[22] A. Berlin, T. Lin, and L.-T. Wang, Mono-Higgs Detection of Dark Matter at the LHC, JHEP 06 (2014) 078, [arXiv:1402.7074]. 13, 27

[23] ATLAS Collaboration, G. Aad et al., Muon reconstruction performance of the ATLAS detector in proton–proton collision data at √s =13 TeV, Eur. Phys. J. C76 (2016), no. 5 292, [arXiv:1603.05598]. 14

[24] ATLAS Collaboration, M. Aaboud et al., Search for dark matter in association with a Higgs boson decaying to b-quarks in pp collisions at √s = 13 TeV with the ATLAS detector, Phys. Lett. B765 (2017) 11–31, [arXiv:1609.04572]. 14

[25] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An Introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159–177, [arXiv:1410.5012]. 15, 21, 25, 29, 37, 46, 51

[26] S. Jeon, Y. Kang, G. Lee, and C. Yu, The MadAnalysis5 implementation of the ATLAS analysis ATLAS-EXOT-2016-25: an ATLAS mono-Higgs analysis, 10.7484/INSPIREHEP.DATA.SSS4.298U. 17

[27] ATLAS Collaboration, Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run, ATL-PHYS-PUB-2016-012. 20

[28] C. Borschensky, M. Krämer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn, and X. Portell, Squark and gluino production cross sections in pp collisions at √s = 13, 14, 33 and 100 TeV, Eur. Phys. J. C74 (2014), no. 12 3174, [arXiv:1407.5066]. 21, 37, 51

[29] M. L. Mangano, M. Moretti, F. Piccinini, and M. Treccani, Matching matrix elements and shower evolution for top-quark production in hadronic collisions, JHEP 01 (2007) 013, [hep-ph/0611129]. 21, 46, 51

[30] J. Alwall, S. de Visscher, and F. Maltoni, QCD radiation in the production of heavy colored particles at the LHC, JHEP 02 (2009) 017, [arXiv:0810.5350]. 21, 51

[31] ATLAS Collaboration, ATLAS Run 1 Pythia8 tunes, ATL-PHYS-PUB-2014-021. 21

[32] D. Sengupta, The MadAnalysis5 implementation of the ATLAS in monojet+missing energy, 10.7484/INSPIREHEP.DATA.HUH5.239F. 22

[33] M. Backovič, M. Krämer, F. Maltoni, A. Martini, K. Mawatari, and M. Pellen, Higher-order QCD predictions for dark matter production at the LHC in simplified models with s-channel mediators, Eur. Phys. J. C75 (2015), no. 10 482, [arXiv:1508.05327]. 23, 25

[34] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, FeynRules 2.0 - A complete toolbox for tree-level phenomenology, Comput. Phys. Commun. 185 (2014) 2250–2300, [arXiv:1310.1921]. 25
C. Degrande, *Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle*, Comput. Phys. Commun. 197 (2015) 239–262, [arXiv:1406.3030].

S. Baek and T. H. Jung, *Madanalysis5 implementation of the ATLAS search for Dark matter in final states containing an energetic photon and large missing transverse momentum documented in arXiv:1704.03848*, 10.7484/INSPIREHEP.DATA.88NC.0FER.1.

S. Baum, K. Freese, N. R. Shah, and B. Shakya, *NMSSM Higgs boson search strategies at the LHC and the mono-Higgs signature in particular*, Phys. Rev. D95 (2017), no. 11 115036, [arXiv:1703.07800].

**CMS Collaboration, V. Khachatryan et al.,** *Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at sqrt(s) = 8 TeV, JINST 10* (2015), no. 08 P08010, [arXiv:1502.02702].

S. Ahn, J. Park, and W. Zhang, *Madanalysis5 implementation of the CMS search for Dark matter with large missing transverse momentum and a Higgs boson decaying to a pair of photons documented in arXiv: 1703.05236*, 10.7484/INSPIREHEP.DATA.JT56.DDC3.1.

**CMS Collaboration, V. Khachatryan et al.,** *Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters, Phys. Rev. Lett. 114* (2015), no. 6 061801, [arXiv:1409.4789].

B. C. Allanach et al., *The Snowmass points and slopes: Benchmarks for SUSY searches, Eur. Phys. J. C25* (2002) 113–123, [hep-ph/0202233].

P. Z. Skands et al., *SUSY Les Houches accord: Interfacing SUSY spectrum calculators, decay packages, and event generators, JHEP 07* (2004) 036, [hep-ph/0311123].

J. Chang, *Madanalysis5 implementation of CMS-EXO-16-022, 10.7484/INSPIREHEP.DATA.UFU4.99E3.*

B. C. Allanach et al., *SUSY Les Houches Accord 2, Comput. Phys. Commun. 180* (2009) 8–25, [arXiv:0801.0045].

C. Duhr and B. Fuks, *A superspace module for the FeynRules package, Comput. Phys. Commun. 182* (2011) 2404–2426, [arXiv:1102.4191].

A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, *LHAPDF6: parton density access in the LHC precision era, Eur. Phys. J. C75* (2015) 122, [arXiv:1412.7420].

**CMS Collaboration, V. Khachatryan et al.,** *Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C76* (2016), no. 3 155, [arXiv:1512.00815].

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SUSMoriond2017ObjectsEfficiency.

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-041.

C. G. Lester and D. J. Summers, *Measuring masses of semi invisibly decaying particles pair produced at hadron colliders, Phys. Lett. B463* (1999) 99–103, [hep-ph/9906349].

H.-C. Cheng and Z. Han, *Minimal Kinematic Constraints and m(T2), JHEP 12* (2008) 063, [arXiv:0810.5178].

**CMS Collaboration, S. Chatrchyan et al.,** *Identification of b-quark jets with the CMS experiment, JINST 8* (2013) P04013, [arXiv:1211.4462].

S. Bein, S.-M. Choi, B. Fuks, S. Jeong, D. W. Kang, J. Li, and J. Sonneveld, *Madanalysis5 implementation of CMS-SUS-17-001, 10.7484/INSPIREHEP.DATA/MMM1.876Z.*