

Chapter 1

Introduction

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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, 4] packages. The main scope of the workshop has consisted in 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 [3–5], 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 implementation 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].

Chapter 2

ATLAS-EXOT-2016-25: an ATLAS mono-Higgs analysis (36.1 fb⁻¹)

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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 χ , a Z' boson and a second Higgs doublet [14, 15]. 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

$$pp \rightarrow Z' \rightarrow hA^0 \rightarrow h\chi\chi. \quad (2.1)$$

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 [16], with a radius parameter set to $R = 0.4$. Jets with a transverse momentum p_T^j and pseudorapidity η^j satisfying

$$p_T^j > 20 \text{ GeV} \quad \text{and} \quad |\eta^j| < 2.5 \quad (2.2)$$

are denoted as central jets and those for which

$$p_T^j > 30 \text{ GeV} \quad \text{and} \quad 2.5 < |\eta^j| < 4.5 \quad (2.3)$$

are called forward jets. Whilst the analysis also makes use of jets reconstructed with the anti- k_T algorithm [16] 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 η^e obeying to

$$p_T^e > 7 \text{ GeV} \quad \text{and} \quad |\eta^e| < 2.47, \quad (2.4)$$

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

$$p_T^\mu > 7 \text{ GeV} \quad \text{and} \quad |\eta^\mu| < 2.7. \quad (2.5)$$

In both cases, loose isolation criteria have been imposed [17, 18]. 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 $\mathbf{E}_T^{\text{miss}}$ 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

$$E_T^{\text{miss}} = |\mathbf{E}_T^{\text{miss}}|. \quad (2.6)$$

2.2 Event Selection

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

$$150 \text{ GeV} < E_T^{\text{miss}} < 500 \text{ GeV}, \quad (2.7)$$

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),

$$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^j) > \frac{\pi}{9}, \quad (2.8)$$

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

$$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss, trk}}) < \frac{\pi}{2}. \quad (2.9)$$

In addition, this last quantity is required to fulfill

$$|\mathbf{p}_T^{\text{miss, trk}}| > 30 \text{ GeV}. \quad (2.10)$$

The analysis requires the presence of at least two jets,

$$N_j > 2, \quad (2.11)$$

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

$$p_T^{j_1} > 45 \text{ GeV}. \quad (2.12)$$

We have restricted our reimplementaion procedure to the case

$$N_b = 2, \quad (2.13)$$

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

$$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_{T_h}) > \frac{2\pi}{3}, \quad (2.14)$$

where \mathbf{p}_T^h 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

$$H_{T,2j} > 120 \text{ GeV} \quad \text{and} \quad H_{T,3j} > 150 \text{ GeV}, \quad (2.15)$$

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,

$$\Delta\phi(j_1, j_2) < \frac{7\pi}{9} \quad \text{and} \quad \Delta R(j_1, j_2) < 1.8, \quad (2.16)$$

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

$$p_T^{j_1} + p_T^{j_2} (+p_T^{j_3}) < 0.63H_T, \quad (2.17)$$

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 reimplementaion, 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 [19] 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 [20], and we have handled the Higgs into $b\bar{b}$ decay, parton showering and hadronization with PYTHIA 8 [21]. The simulation of the response of the ATLAS detector is achieved via DELPHES 3 [2], that internally relies in FASTJET [22] for object reconstruction, with an tuned detector configuration.

3.2 Comparison with the official results

In Figure 2.1, we present the relative difference between the MADANALYSIS 5 predictions and the ATLAS official results for the two considered scenarios, computed as

$$\delta = 1 - \frac{\epsilon_i^{\text{MA5}}}{\epsilon_i^{\text{ATLAS}}}, \quad (2.18)$$

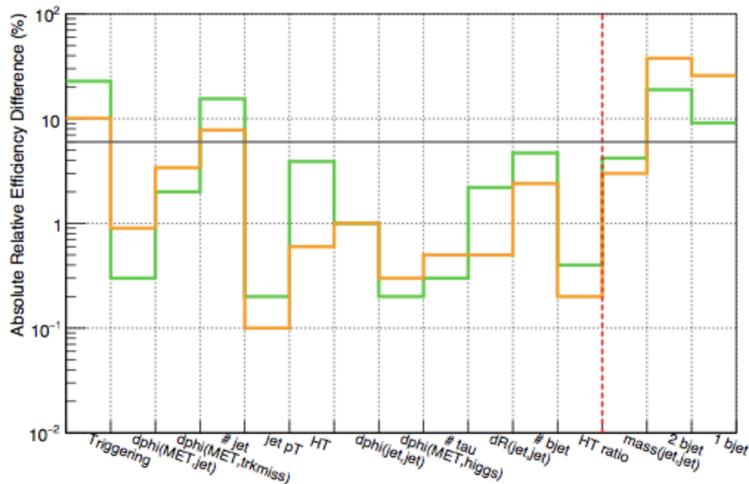


Fig. 2.1: Relative difference between the ATLAS official and MADANALYSIS 5 predictions for the efficiency of each selection cut, for two benchmarks defined by $(m_{Z'}, m_{A^0}) = (600, 300)$ GeV (green) and $(1400, 600)$ GeV (orange). The solid horizontal line indicates a 6% difference reference line.

where the index i corresponds to the cut number, and where ϵ_i^{MA5} 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

$$50 \text{ GeV} < m_{j_1 j_2} < 250 \text{ GeV} , \quad (2.19)$$

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 reimplementations 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 reimplementations 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 2.1 (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 ‘ $m_{j_1 j_2}$ ’ validation regions have not been implemented into our 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

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^{miss}	0.772	0.89	13.3%	0.660	0.604	9.2%
$\mathbf{p}_T^{\text{miss, trk}}$	0.757	0.711	6.5%	0.657	0.546	20.3%
$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^j)$	0.727	0.685	6.1%	0.592	0.497	19.1%
$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss, trk}})$	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%
$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_{T_h})$	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%

Table 2.1: 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).

an extra neutral gauge boson and a dark matter particle. After having compared our results with the official ones, we have found that our reimplementations were trustworthy 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 reimplementations (partly) validated and have made it available from MADANALYSIS 5 version 1.6 onwards and its Public Analysis Database.

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