# Validation of the MadAnalysis 5 implementation of CMS-EXO-16-012

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December 4, 2017

## 1 Introduction

In this document, a MadAnalysis 5 v1.6 [1–3] implementation of the search for associated production of dark matter with a Higgs boson decaying to $b\bar{b}$ or $\gamma\gamma$ at $\sqrt{s} = 13$ TeV (2.3 fb$^{-1}$) [4] is validated.

This paper is written in the context of a $Z'$-two-Higgs-doublet model, where a high-mass resonance $Z'$ decays into a pseudoscalar boson $A$ and a CP-even scalar Higgs boson, and the A decays to a pair of dark matter particles, as shown in Fig. 1. For further theoretical aspects of this model, see [5].

## 2 Description of the implementation

In this section, a physics object(photon) and a signal event are defined. To identify a Higgs boson decaying into two photon, a photon pair is selected via diphoton mass and $p_T$ threshold cut. Moreover energy deposition and isolation of particles are considered to reject fake photon. Signal event is defined with the ratio of momentum of a photon divided by diphoton mass as well as missing transverse momentum($p_T^{miss}$) cut. To veto background, cuts on angle between diphoton and $p_T^{miss}$, and between jet and $p_T^{miss}$ are applied.

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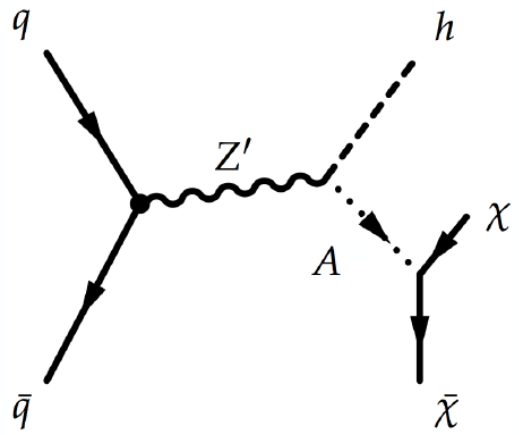


Figure 1: The $Z'$ 2HDM model with pseudoscalar $A$

## 2.1 Objects definition

There are several selections for photon identification. A cut-based photon identification with loose working point is applied. The selections are presented in [13], as well as CMS-PAS-EXO-16-012 [4]. Isolation is computed in an area with angular separation $\Delta R = 0.3$. Here, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ and $\Delta\phi$ are angle differences of the particles relative to the beam axis and measured in a plane orthogonal to beam line, respectively.

First, events with a diphoton mass cut of $m_{\gamma\gamma} > 95$ GeV and an asymmetric $p_T$ threshold (30 and 18 GeV) are selected. Next, to reject fake photons, cuts on the energy deposit in hadronic calorimeter(HCAL) over the energy deposit in electromagnetic calorimeter(ECAL), which denoted as H/E, is required to be less than 0.1. Isolation cuts for charged hadrons ($\text{Iso}_{ch}$), neutral hadrons ($\text{Iso}_{Neu}$), and photons ($\text{Iso}_{\gamma}$) are as described in Table 1. In CMS-PAS-EXO-16-012, isolations for neutral particles are computed with a so-called $\rho$ correction to take into account the dependence of the pileup transverse energy density on pseudorapidity, where $\rho$ is the median of the transverse energy density per unit area. But in this validation note isolations are computed without this correction due to lack of information.

| Variable | Barrel Selection | Endcap Selection |
|---|---|---|
| H/E | <0.1 | |
| $\text{Iso}_{ch}$ [GeV] | $< 3.32$ | $< 1.97$ |
| $\text{Iso}_{Neu}$ [GeV] | $< 1.92 + 0.14p_T + 0.000019(p_T)^2$ | $< 11.86 + 0.0139p_T + 0.000025(p_T)^2$ |
| $\text{Iso}_{\gamma}$ [GeV] | $< 0.81 + 0.0053p_T$ | $< 0.83 + 0.0034p_T$ |

Table 1: Value of each variable used in barrel and endcap photon identification

## 2.2 Signal selections

After these selections described above, according to CMS-PAS-EXO-16-012, additional cuts for each $Z'$ mass point are implemented. The chosen kinematic selections include $p_{T_1}/m_{\gamma\gamma} > 0.5$

and $p_{T_2}/m_{\gamma\gamma} > 0.25$, for the leading photon $\gamma_1$ and the subleading photon $\gamma_2$, respectively. We also implemented a diphoton transverse momentum and missing transverse momentum cut, $p_{T_{\gamma\gamma}} > 90$ GeV and $p_T^{miss} > 105$ GeV as in CMS-PAS-EXO-16-012.

In addition, two more cuts on angle difference are applied to match with CMS-PAS-EXO-16-012 Here, $p_T^{miss}$ is transverse momentum component of $E_T^{miss}$.

- $|\Delta\phi(\gamma\gamma,\, p_T^{miss})| > 2.1$
- $min(|\Delta\phi(jet,\, \vec{p}_T^{miss})|) > 0.5$ for all jets in the event with $p_T > 50$ GeV where jets are reconstructed with the clustering of PF candidates by means of the anti-kt algorithm with a distance parameter of 0.4.

Finally we defined a signal region (SR), where $120 < m_{\gamma\gamma} < 130$ GeV and $p_T^{miss} > 105$ GeV in accordance with CMS-PAS-EXO-16-012.

# 3 Validation

In Section 3, some information on event generation is presented. Using `MadGraph MG5_aMC` and a model UFO provided by CMS, parton level interaction is generated with various $M_{Z'}$. In `Pythia 8`, several tunes are implemented and the decay of Higgs boson is handled. CMS Detector is simulated by `Delphes 3`, with updated b tagging efficiency and areas parameter for isolation computation. With the generated sample, acceptance times efficiency is derived and compared with the official numbers from CMS-PAS-EXO-16-012.

## 3.1 Event Generation

To generate a signal sample, a model UFO file(link) is provided by CMS. From the CMS genproduction github repository(link) [9] one can retrieve the cards used for `MadGraph MG5_aMC` [6] event generation for each mass point of $Z'$. The run card(link) used in `MadGraph MG5_aMC` and process card(link) were retrieved from the repository. In `MadGraph MG5_aMC` $Z'$ particle is produced via the proton-proton collision and forced to decay into a standard model Higgs boson and a pseudoscalar boson $A$. Next, $A$ is made to decay into two dark matter particles. Even though the CMS-EXO-16-012 analysis covers both Higgs decaying into $\gamma\gamma$ and $b\bar{b}$ modes, only the decay H$\rightarrow \gamma\gamma$ is implemented in this validation note. The decay of Higgs boson is handled in `Pythia 8` [7].

Different masses and couplings were chosen, as was done in CMS-PAS-EXO-012.(link) For example, mass of $Z'(M_{Z'})$ is set to $600, 800, 1000, 1200, 1400, 1700, 2000$ and $2500$ GeV, while the mass of the pseudoscalar $A$ and dark matter particle are fixed to 300 and 100 GeV respectively. Also, the decay width of $Z'$ and $A$ is set to 11.22981 and 8.95228. The $Z'$ coupling strength $g_Z$ is chosen to be 0.8, while the coupling to dark matter is 1 [8]. The Higgs boson mass is set to $M_H = 125$ GeV in `Pythia 8` and only the H$\rightarrow \gamma\gamma$ decay is enabled. The default `PYTHIA 8` tunes which are commonly used in CMS to match Monte Carlo samples to the data are also applied. These run, process, and `Pythia` cards can be found in CMS software github repository [9].

- Pythia8CUEP8M1Settings (link),
- Pythia8CommonSettings (link).

For detector simulation, we used `Delphes 3` [10] with latest version of delphes card used for EXO-16-037 recasting [12]. Compared with default setting, a b-tagging efficiency and areas for computing lepton and photon isolation are changed [11,13]. We introduced b tagging efficiency formula used for the cMVAv2 loose working point, where b tagging efficiency is about 83% and the misidentification probability is about 10%. We also added some lines to make dark matter particle not to deposit energy on calorimeter.

### 3.2 Comparision with official results

CMS did not provide a detailed cutflow. Here we present the product of acceptance and efficiency for signal in the SR for each mass point only. The difference is defined as

$$(1 - (A \cdot \epsilon)^{MA5})/(A \cdot \epsilon)^{CMS} \, (\%).$$

| Acceptance × efficiency $(A \cdot \epsilon)$ | | | |
|---|---|---|---|
| $m_{Z_p}$ (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 % |

Since missing transverse energy is important, we plotted $p_T^{miss}$ as well as $m_{\gamma\gamma}$. For both plots from the paper, the product of signal cross section and branching fraction is set to 1 fb. However, exact branching ratios are not are not provided, so we normalized reproduced plots (solid lines) with the scale of 0.00002.

## 4 Summary

In this note, the MadAnalysis 5 implementation of CMS-EXO-16-012 is validated in $H \to \gamma\gamma$ mode. Signal events are geneted by `MadGraph MG5_aMC`, `Pythia 8`, and the CMS detector is simulated by `Delphes 3`. The acceptance times efficiency is computed with `MadAnalysis 5` and compared with PAS-CMS-EXO-16-012. Numbers are agreed within 13% of difference. The plots of diphoton mass and $p_T^{miss}$ are also reproduced and compared with CMS official plots. The shape of $p_T^{miss}$ is in good agreement with the official results, as well as diphoton mass.

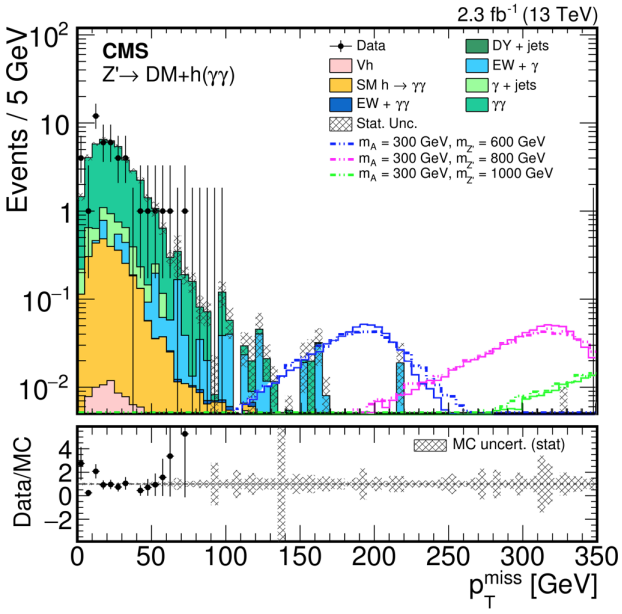


Figure 2: Distribution of $p_T^{miss}$ for events passing all selection criteria including 120 GeV $< m_{\gamma\gamma} <$ 130 GeV except $p_T^{miss}$ requirement. Dotted lines are CMS official results [4] and solid lines are recast results. The recast results are plotted for shape comparison purpose, with normalization scale of 0.00002.

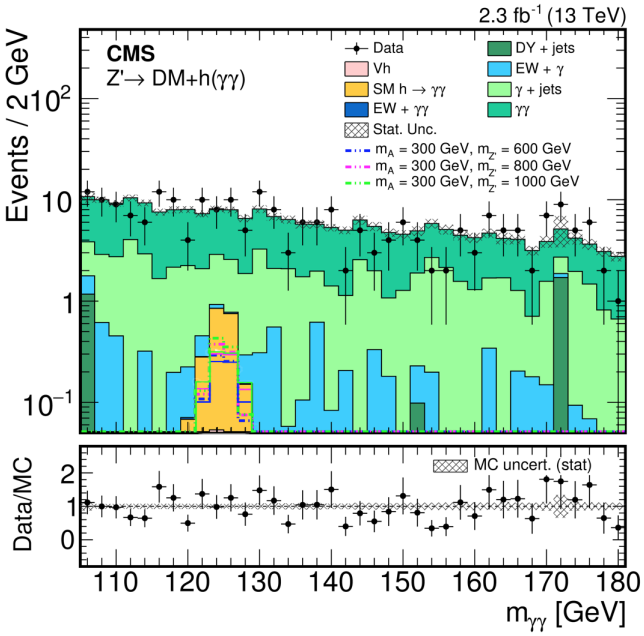


Figure 3: Distribution of $m_{\gamma\gamma}$ (left) [4] in events passing all selection criteria except the $m_{\gamma\gamma}$ and $p_T^{miss}$ requirement. Dotted lines are CMS official results [4] and solid lines are recast results. The recast results are plotted for shape comparison purpose, with normalization scale of 0.00002.

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