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

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1 Introduction

In this document, the `MadAnalysis 5 v1.6` [1–3] implementation of 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 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 1. For further theoretical aspects of this model, see the paper [5]

2 Description of the implementation

2.1 Objects definition

There are several selections for photon identification. Cut based photon identification with loose working point is applied. The selections are presented in the photon id paper from CMS, as well as PAS EXO-16-012 [4, 13]. Isolation is computed in a area with angular separation $\Delta R = 0.3$ ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$).

First, the events with diphoton mass cut where $m_{\gamma\gamma} > 95$ GeV and asymmetric p_T threshold (30 and 18 GeV) are selected. Next, to reject fake photons, cuts on energy deposit in Hadronic Calorimeter(HCAL) over energy deposit in Electromagnetic Calorimeter(ECAL), which denoted as H/E, is required to be less than 0.1. Isolation cuts for charged hadron (Iso_{ch}), neutral

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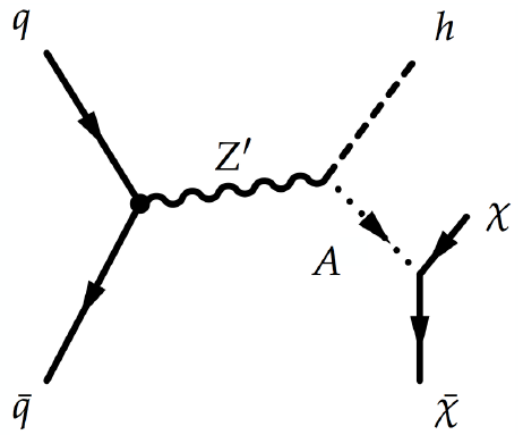

Figure 1: The Z' 2HDM model with pseudoscalar A

hadron (Iso_{Neu}), and photon (Iso_{γ}) is also applied. For neutral particles, isolations are computed with ρ correction to take into account the dependence of the pileup transverse energy density on pseudorapidity, where ρ is the median of the transverse energy density per unit area.

Variable	Barrel Selection	Endcap Selection
H/E	<0.1	
Iso_{ch} [GeV]	< 3.32	< 1.97
ρ corrected Iso_{Neu} [GeV]	$< 1.92 + 0.14p_T + 0.000019(p_T)^2$	$< 11.86 + 0.0139p_T + 0.000025(p_T)^2$
ρ corrected Iso_{γ} [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, we applied additional cuts to maximize the expected significance for each Z' mass point. The chosen kinematic selections include $p_{T_1}/m_{\gamma\gamma} > 0.5$ and $p_{T_2}/m_{\gamma\gamma} > 0.25$, for leading photon γ_1 and subleading photon γ_2. Moreover we imposed a diphoton transverse momentum and missing transverse momentum cut, $p_{T_{\gamma\gamma}} > 90$ GeV and $p_T^{miss} > 105$ MeV.

In addition, two more cuts are applied to enhance the signal over background discrimination and to veto events with mismeasured p_T^{miss} (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 $p_T^{miss} > 105$ MeV.

3 Validation

3.1 Event Generation

To generate a signal sample, model UFO file is provided by CMS. From the CMS genproduction github repository [9] one can retrieve the cards used for `MadGraph MG5_aMC` [6] event generation for each mass point of Z'. The run card used in `MadGraph MG5_aMC` and process card 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. The decay of Higgs boson into $\gamma\gamma$ is handled in `Pythia 8` [7]. This paper is focused on the H$\rightarrow \gamma\gamma$ only.

Also some custom settings were applied according to the mass range of Z' ($M_{Zp} = 600 \sim 2500$). Mass of A is fixed to 300 GeV. The coupling to dark matter was chosen to be 1 [8]. Higgs boson mass is set to $M_H = 125$ GeV in `Pythia 8` and only the H$\rightarrow \gamma\gamma$ decay is turned on. The default pythia tunes which 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,
- Pythia8CommonSettings.

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, b tagging efficiency and areas for computing lepton and photon isolation are changed [11,13]. We introduced b tagging efficiency formula used for cMVAv2 loose working point where b tagging efficiency is about 83% and misidentification probability is about 10%. Also we added some lines to make neutralino 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 error 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	Error
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 only p_T^{miss} and $m_{\gamma\gamma}$. For this step, we made plot without normalization. For both plots from paper, the product of signal cross section and branching fraction is set to 1 fb. But exact branching ratios are not provided, so we compared shapes only.

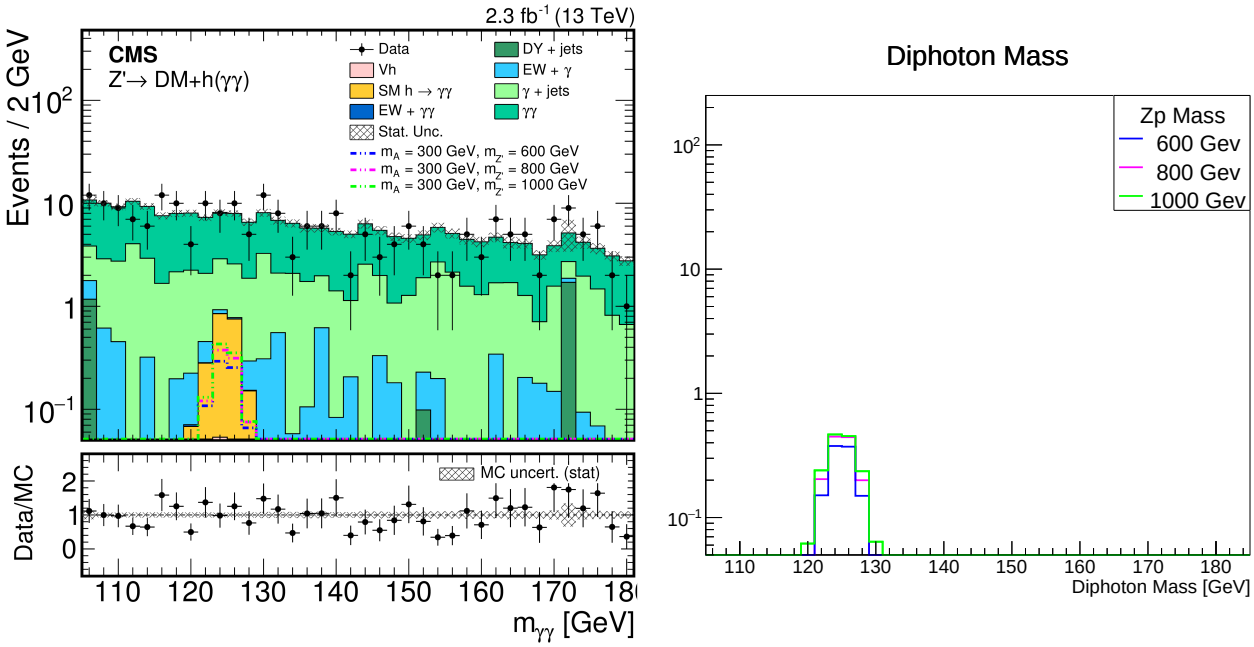

Figure 2: Distribution of $m_{\gamma\gamma}$ (left) [4] in events passing all selection criteria except the $m_{\gamma\gamma}$ and p_T^{miss} requirement. For the left plot, the product of signal cross section and branching fraction is set to 1 fb.

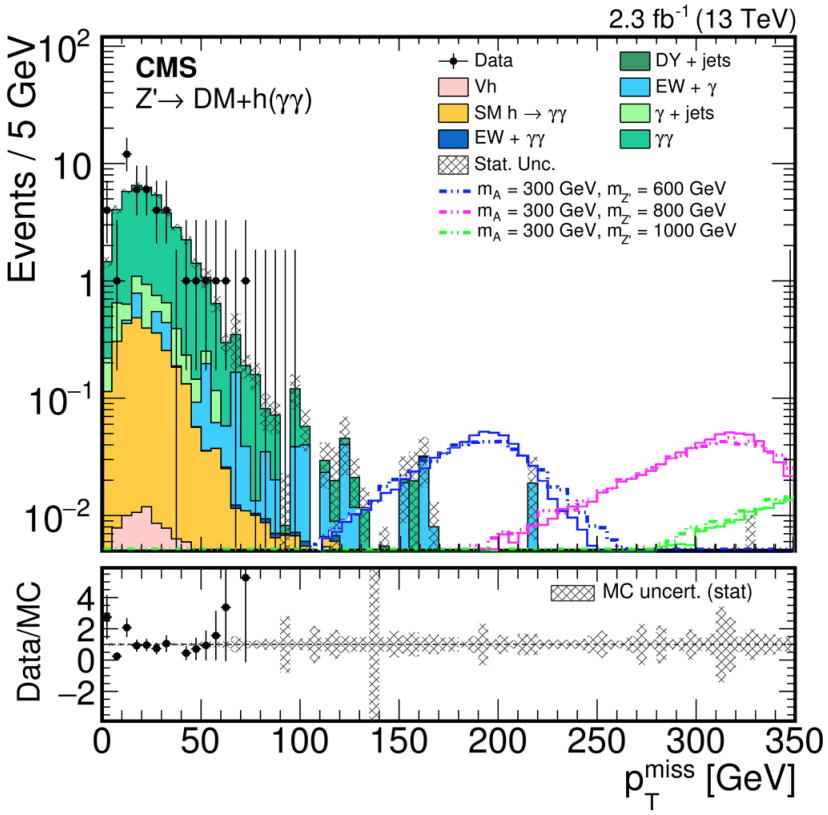

Figure 3: Distribution of p_T^{miss} for events passing all selection criteria including 120GeV $<$ $m_{\gamma\gamma}$ $<$ 130GeV except p_T^{miss} requirement. Dotted lines are CMS official results [4] and solid lines are recast results. Since normalization factors are not provided, recast results are plotted for shape comparison purpose only.

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