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 identification paper from CMS, as well as PAS EXO-16-012 [4,13]. Isolation is computed in a area with angular separation $\Delta R = 0.3$ ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, 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, 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

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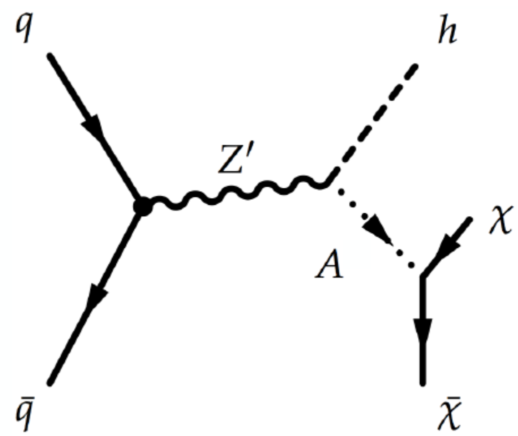

Figure 1: The Z' 2HDM model with pseudoscalar A

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 hadron (Iso_{Neu}), and photon (Iso_{γ}) is also applied. In CMS PAS, isolations for neutral particles 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. But in this validation isolations are computed without correction due to lack of information.

Variable	Barrel Selection	Endcap Selection
H/E	<0.1	<0.1
Iso_{ch} [GeV]	< 3.32	< 1.97
Iso_{Neu} [GeV]	$< 1.92 + 0.14p_T + 0.000019(p_T)^2$	$< 11.86 + 0.0139p_T + 0.000025(p_T)^2$
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 $p_T^{miss} > 105$ GeV.

In addition, two more cuts on angle difference 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 $p_T^{miss} > 105$ GeV.

3 Validation

3.1 Event Generation

To generate a signal sample, 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. 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 the mass of exotic particles and couplings(link) were added. For example, mass of $Z'(M_{Z'})$ is set to $600, 800, 1000, 1200, 1400, 1700, 2000$ and 2500 GeV, while the mass of pseudo scalar A and dark matter particle are fixed to 300 and 100 GeV respectively. Also, decay width of Z' and A is set to 11.22981 and 8.95228. Z' coupling strength g_Z is chosen to be 0.8, while coupling to dark matter is 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 (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, 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 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. But exact branching ratios are not provided, so we normalized reproduced plots (solid lines) with the scale of 0.00002.

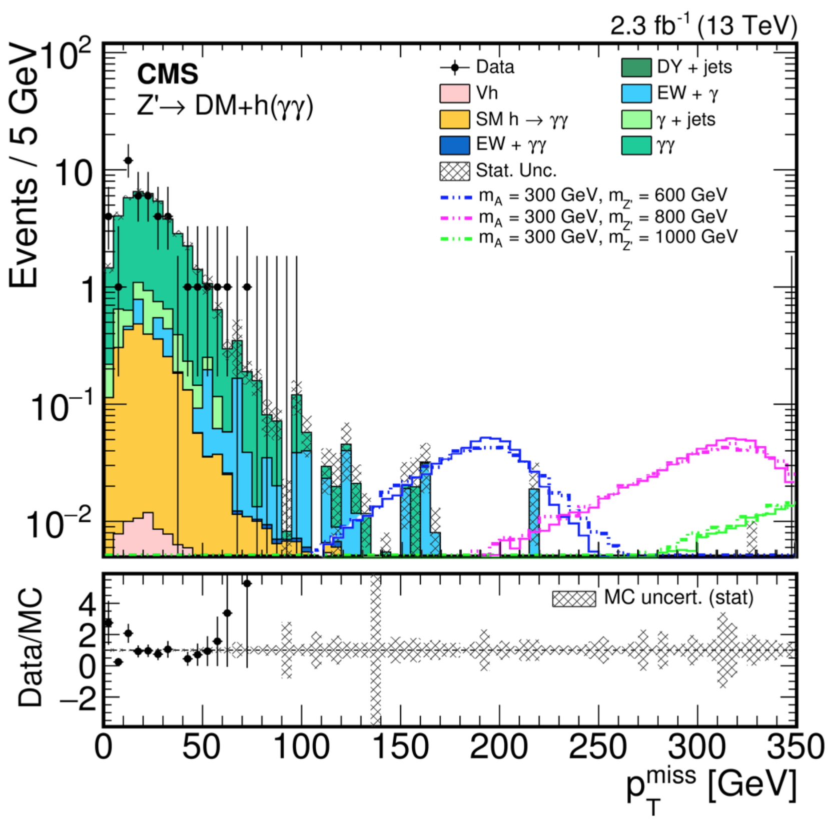

Figure 2: Distribution of p_T^{miss} for events passing all selection criteria including 120 GeV $< m_{\gamma\gamma} <$ 130 GeV except p_T^{miss} requirement. Dotted lines are CMS official results [4] and solid lines are recast results. The recast results are plotted for shape comparison purpose, with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

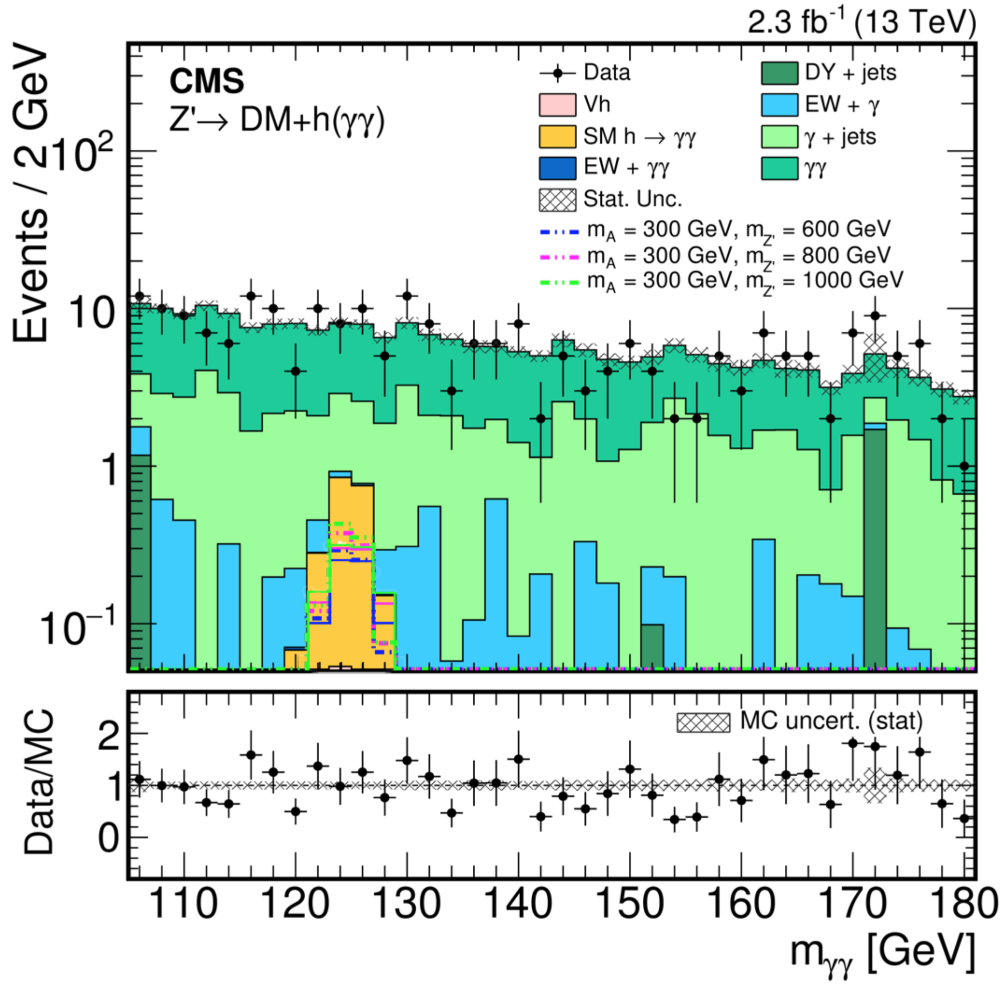

Figure 3: Distribution of $m_{\gamma\gamma}$ (left) [4] in events passing all selection criteria except the $m_{\gamma\gamma}$ and p_T^{miss} requirement. Dotted lines are CMS official results [4] and solid lines are recast results. The recast results are plotted for shape comparison purpose, with normalization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

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