Searching for Dark-Photon production via Higgs-Boson decay

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An extension to the Standard Model has been proposed suggesting the Higgs Boson could decay to a photon ($\boldsymbol{\gamma}$) and a massless dark photon ($\bar{\boldsymbol{\gamma}}$) [1]. The dark photon is a hypothetical new boson for a force analogous to electromagnetism affecting only dark matter. Here I attempt to repeat the work of those authors in producing a simulation of the decay signal and the relevant standard model backgrounds at 13TeV. I aim to investigate the feasibility of detecting the dark photon via this decay at the CMS. Using the trigger cuts suggested by the theory group I am unable to obtain a signal to background ratio (R) large enough for feasibility. This indicates the previous work may have underestimated the background levels. However experimentation with alternative trigger settings yields higher values of R implying that with further work CMS detection of the dark photon via $H \longrightarrow \boldsymbol{\gamma}\bar{\boldsymbol{\gamma}}$ may be feasible.

I. INTRODUCTION

A. Motivation and Background

Despite the upgrade of the Large Hadron Collider (LHC) to 13 TeV energies no evidence has yet emerged of New Physics beyond the Standard Model (SM). However the SM cannot be a complete description of the universe, as it fails to explain, among other things: how gravity fits in with the fundamental forces; the identity of the mysterious dark matter or dark energy, thought to make up around 26.8% and 68.3% of the universe respectively; and the different masses of the three generations of SM fermions. [2]

Dr Emido Gabrielli (Universita di Trieste) and various collaborators have developed an extended SM theory [1] which includes a dark sector with a new unbroken $U(1)$ gauge group, providing a long range force affecting dark fermions equivalent to SM electromagnetism. This can explain the origin of the observed mass hierarchy of SM fermions. [2][3] The boson for the new field is a massless dark photon ($\bar{\gamma}$) as described in [4].

The model describes how the Higgs-boson might decay to produce a photon and a massless dark-photon.

$$H \longrightarrow \boldsymbol{\gamma}\bar{\boldsymbol{\gamma}}$$

Following the momentous discovery of the Higgs Boson in 2012 [5] this decay could be tested for by the CMS experiment at the LHC.

The $\bar{\gamma}$ is not detected giving a signal of missing transverse momentum (MET) and a single isolated photon both with energy corresponding to roughly half the Higgs-mass ($m_H/2 \approx 60$GeV). [1]

Gabrielli et al. [3][1] simulated the signal spectrum and the associated SM background processes.

They concluded in the most recent paper that the signal to background ratios of the decay were sufficient to detect the dark photon to a decent degree of significance. They found the branching ratios (BR) of up to 5% predicted would be sufficient to for detection to 5σ, with the gluon-fusion channel of Higgs-boson production being more promising than the VBF channel. [1]

B. The CMS and Triggering

The CMS (Compact Muon Solenoid) experiment at the LHC when running at full capacity produces about 600 million proton-proton collision events per second [6]. This produces data at a far higher rate than could be recorded, so a hardware & software triggering system is used to select certain events of interest to record, based on (for example) the transverse momentum or energies of the particles produced. A potential difficulty of attempting the dark photon search in practice is the desire for a triggering threshold of around 50 GeV. This is below the thresholds usually used in the CMS, as triggers at this lower energy range would produce too high data-rates to record.

A technique developed to get around this problem is data-scouting. [7] This involves using an algorithm to record much less data per event, typically only the momenta of the most significant particle jets from the collision. As a result the trigger threshold can be reduced to allow the detection of decay types & particle resonances that would otherwise go unseen.

C. Aims

1. Develop a Monte-Carlo simulation of the proposed $H \longrightarrow \boldsymbol{\gamma}\bar{\boldsymbol{\gamma}}$ decay
2. Use this model to understand the signal spectrum, replicating the analysis done in Gabrielli et al. (2016).
3. Compare the signal to the Standard Model (SM) backgrounds.

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4. Find the optimum trigger settings and investigate the feasibility & suitability for a data-scouting trigger
5. Find the optimum trigger settings and investigate the feasibility & suitability for a data-scouting trigger
6. Submit a proposal for the new optimized trigger to the CMS.

D. Report Structure

Section I gives a brief outline of the theory, section II details the method used to simulate the signal and background and section III gives the results for different approaches and trigger settings. Section IV suggested directions for further work followed by a summary and conclusions in section V.

II. THEORY

The theoretical model is described in detail in [3][8][?][1][2]. The essential point is that it can be shown that if dark fermions fi have integer distributed (eg. $1, 2, 3, 4$) quantum numbers q_i under the new $U(1)$ gauge field, then the corresponding SM fermions obtain exponentially distributed Yukawa couplings and masses, which (with the right parameter values) correspond roughly to the experimental masses. [3]

$$M_{SM}^i \sim Y^i \sim M_D^i \sim \exp\left(\frac{-(const.)}{q_i}\right)$$

Where M_{SM}^i are SM fermion masses, Y^i the Yukawa couplings and M_D^i are the dark fermion masses. In addition the Higgs Boson can decay to a photon and dark photon analogous to the SM Higgs $\rightarrow$ diphoton decay, mediated by new heavy scalar messenger bosons S_i described in [8].

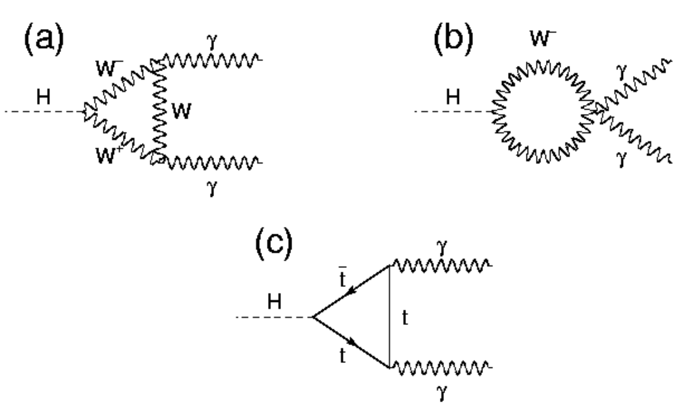

FIG. 1: Feynman diagrams for SM Higgs to diphoton decay for lowest order. [source]

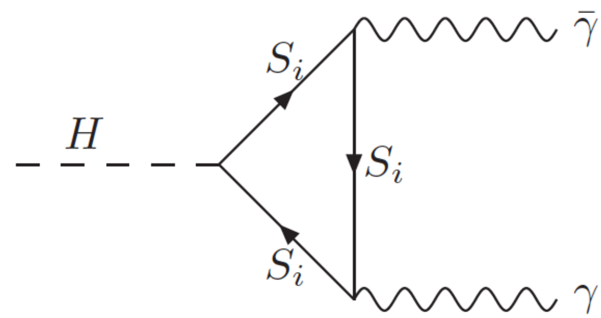

FIG. 2: Feynman diagram for the proposed Higgs to photon + dark photon decay. [?]

III. METHOD

A. Signal Simulation method

A typical particle physics simulation process is outlined in Figure 3

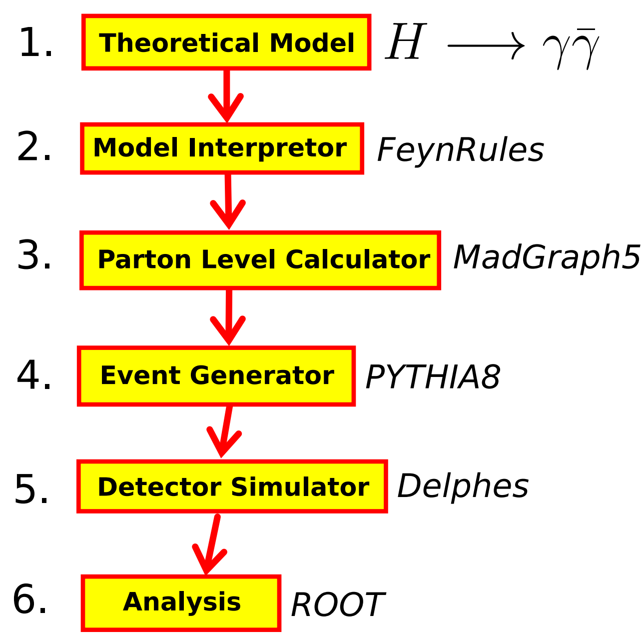

FIG. 3: Outline of particles physics simulation process. Specific programmes used are to the right in italics

However for this project a different method my mentors suggested a different approach.

Instead of implementing the full new theoretical model, which would have been very time consuming, I could take the existing SM $H \longrightarrow \gamma\gamma$ decay, the simulation for which had already been generated, and merely re-label one of the photons to an invisible particle (a neutralino).

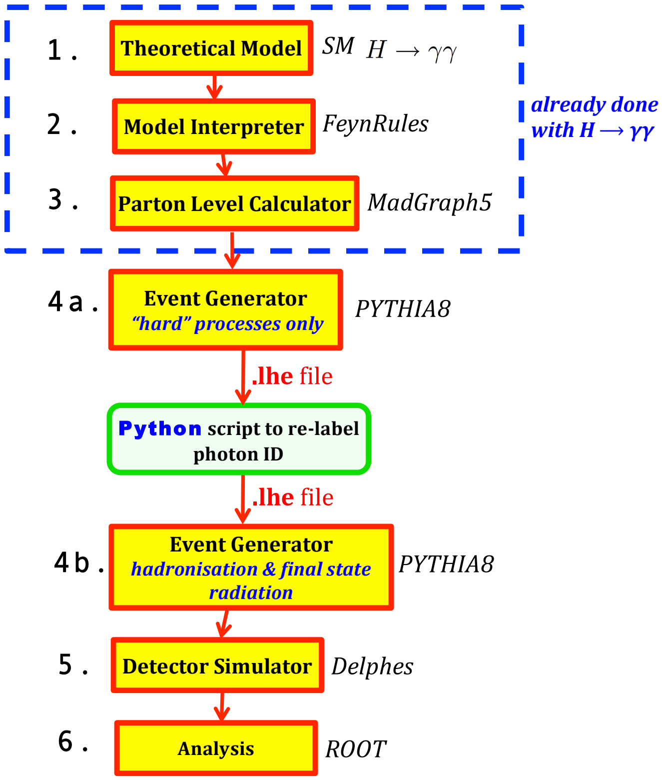

FIG. 4: Flow chart for the new approach to for generating a simulation

This should then give the same sort of signal as the photon/dark photon model, as it would result in one photon with energy $\sim 1/2$ Higgs energy and missing transverse momentum.

The only differences would be in the decay cross-section due to the masses of the scalar messenger particles vs. the masses of the quarks/bosons mediating the SM decay. In order to correctly simulate the final state radiation & decays of the single photon I relabeled the output, as a `.lhe` file, after the hard-process stage of the event generator (Figure 4). obtained a `.pythia` file for the $H \longrightarrow \gamma\gamma$ decay from step 3, so using this approach I only had to do steps $4-6$ myself.

B. Background Simulation method

The standard model background was simulated using CMSSW (CMS software), again using a Monte Carlo method based on the CMS detector as it was running summer 2016. The samples were then analyzed using the *RazorAnalyzer* [9] package before final analysis was done in ROOT.

IV. RESULTS

A. Signal and γ+jet background distributions

The dominant SM background process for the all-inclusive signal (including all channels of Higgs production) is the production of a signal isolated photon plus a jet of particles: $pp \longrightarrow \gamma + jet$ [1][CMS paper]. The jet is miss-measured or escapes the detector giving rise to apparent missing energy.

Distributions for both signal and background are shown in figures 5 & 6. Figure 6 also shows the comparison between my results and those of Gabrielli et al.

The signal and background distributions in my plots are roughly comparable to the ones obtained by Gabrielli et al. [1].

To test the signal simulation further the Higgs invariant mass was obtained from vector addition of the MET and isolated photon momentum and found to be consistent with the Higgs mass of 125GeV.

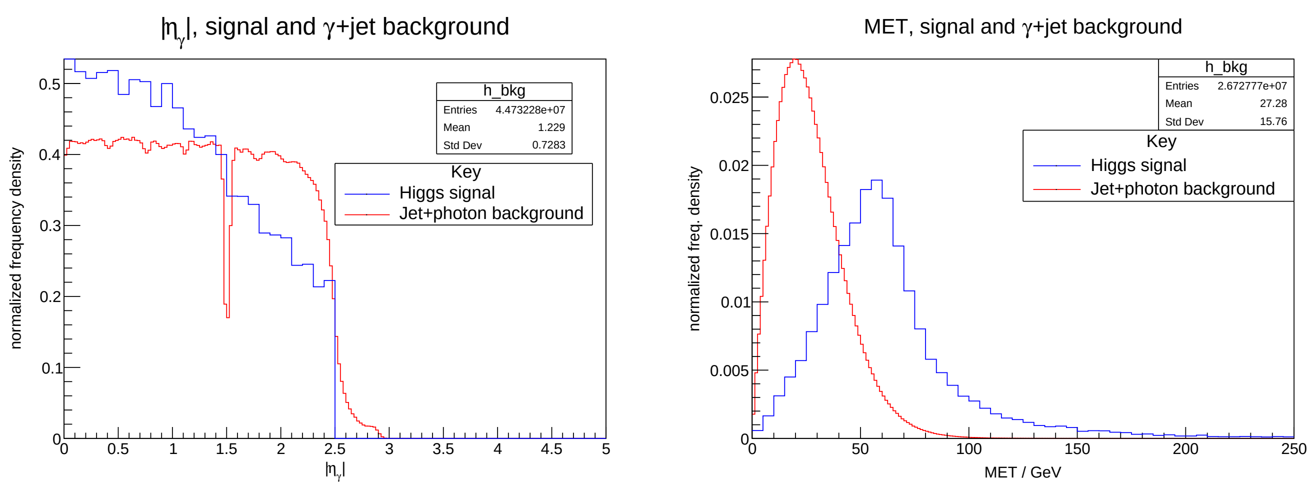

FIG. 5: LEFT: photon pseudorapidity for the all-inclusive signal and γ+jet background. RIGHT: Missing Transverse Momentum (MET) for the signal and background

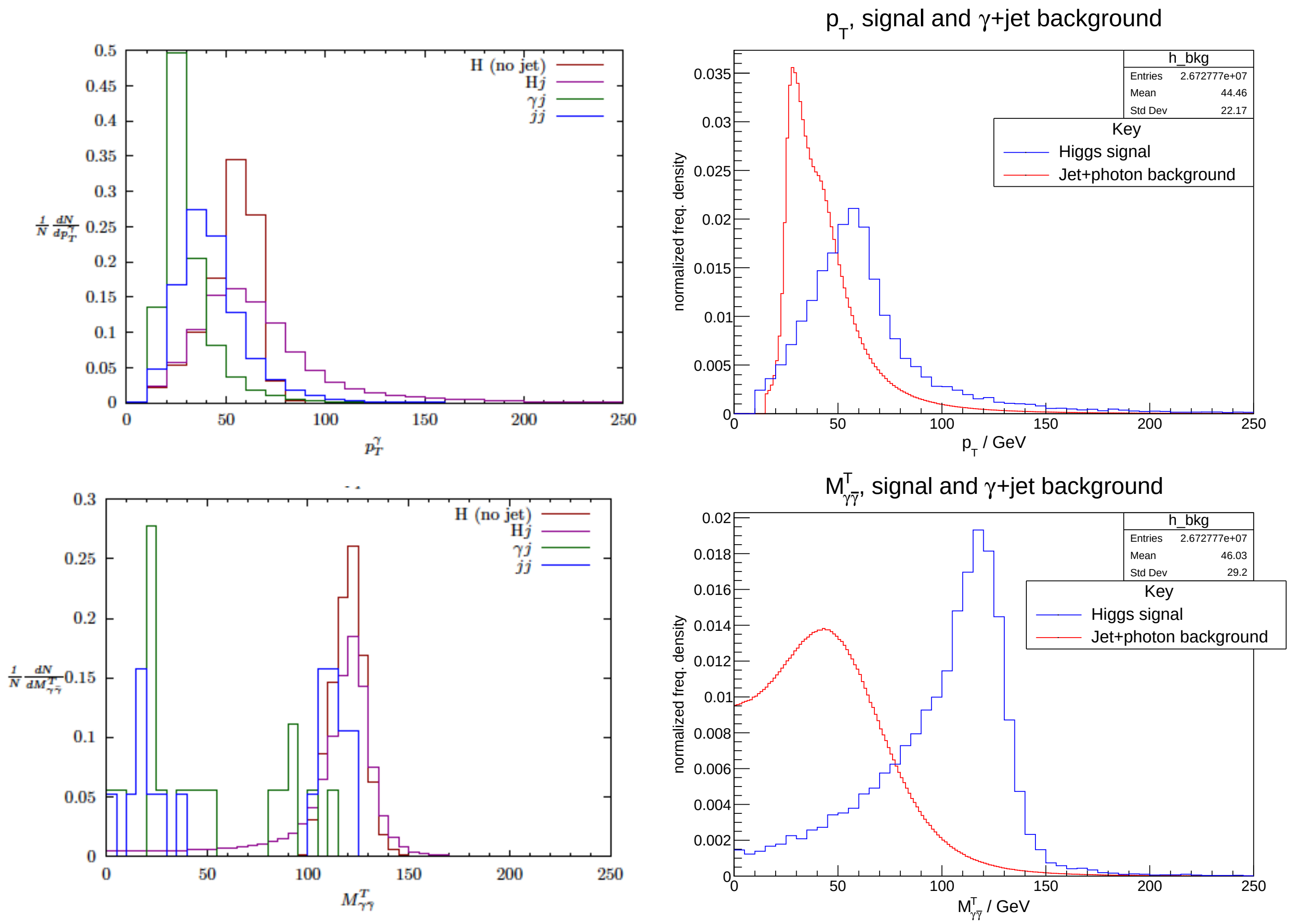

FIG. 6: LEFT: signal and SM backgrounds reproduced from Gabrielli et al. (2016) [1]. RIGHT: all-inclusive signal and dominant γ+jet background. TOP ROW: photon p_T. BOTTOM ROW: transverse mass $M^T_{\gamma\bar{\gamma}} = \sqrt{2p_T \mathrm{MET}(1 - cos\Delta\phi)}$

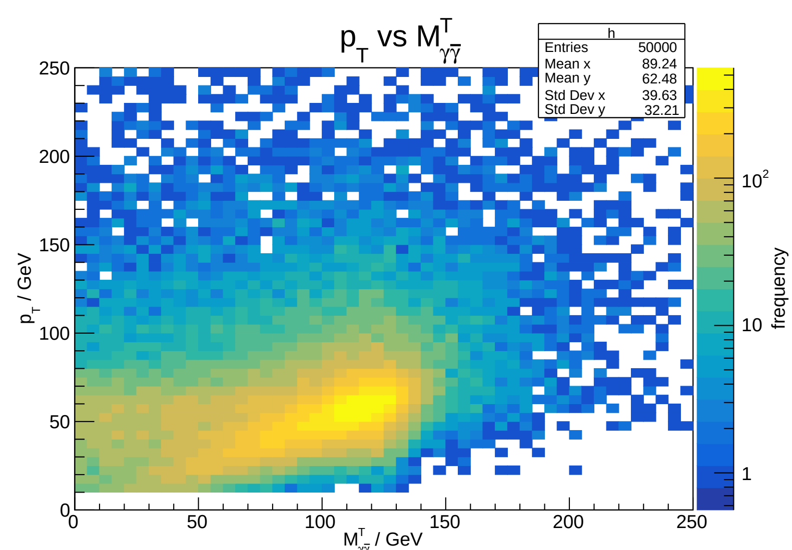

FIG. 7: 2D heat map showing the all-inclusive signal p_T vs $M^T_{\gamma\bar{\gamma}}$ distribution. Note log scale on z axis

Cut no.	Selected events (raw)		Selected events (weighted)		Efficiency / %		Cuts (cumulative)
	γ+jet bkg.	signal	γ+jet bkg.	signal	γ+jet bkg.	signal	
	49822013	50000	$3.27 \cdot 10^9$	50000	100.00	100.00	None
1	47221902	31242	$3.10 \cdot 10^9$	31242	94.83	62.48	$\lvert\eta_\gamma\rvert < 1.4442$ and $1.566 < \lvert\eta_\gamma\rvert < 2.5$
2	29882492	22814	$1.96 \cdot 10^9$	22814	59.80	45.63	$\lvert\eta_\gamma\rvert < 1.44$
3	13814405	14841	$5.22 \cdot 10^8$	14841	15.97	29.68	$p_T > 50$ GeV
4	2362693	9531	$5.22 \cdot 10^7$	9531	1.60	19.06	MET > 50 GeV
5	497266	6260	$1.94 \cdot 10^7$	6260	0.59	12.52	100 GeV $< M^T_{\gamma\bar{\gamma}} <$ 130 GeV
6	21712	6239	2147820	6239	0.07	12.48	no isolated leptons [e^- or μ^-; "isolated" = $\Delta R(l,\gamma) > 0.3$, $p_T > 10$GeV, $\lvert\eta_\gamma\rvert < 2.5$ for e^- & $\lvert\eta_\gamma\rvert < 2.1$ for μ^-]

TABLE I: *Effect of the trigger cuts suggested for ggH in [1] on all-inclusive signal and γ+jet background, weighted to luminosity = 100fb^{-1}*

B. Trigger cuts from Gabrielli et al. on all inclusive Higgs production

Table 1 shows the effect of the trigger cuts suggested in [1] for the ggH (gluon-gluon fusion) Higgs production channel on my all-inclusive signal (ggH is the dominant production process) and the dominant γ+jet background.

A photon is taken to be isolated if the total p_T of the particles in a cone radius $\Delta R = 0.4$ is less than 3.0. The candidate photon is taken to be the isolated photon with the highest p_T. Both the background and signal tables are normalized to luminosity = 100fb^{-1}. I assumed a Higgs cross section (all production channels) of = 50pb^{-1} and a branching ratio for this decay of 1%.

The signal (S) to background (B) ratio can be given by, assuming 10% systematic error

$$R = S/\sqrt{B + (0.1B)^2}$$

To enable detection to a decent degree of significance (5σ is the standard) this needs to be $\sim> 2$. With these cuts $R = 0.0032$, so this was far too small.

C. Higgs p_T cut

QCD which controls the background process - has a much lower mass scale than the Electroweak production of the Higgs. Hence the real Higgs generally has a larger pT than the pseudo-Higgs you get by adding the background MET and photon momentum. Thus by imposing a cut of Higgs $p_T >$ [*some value*] the signal to background ratio can be increased.

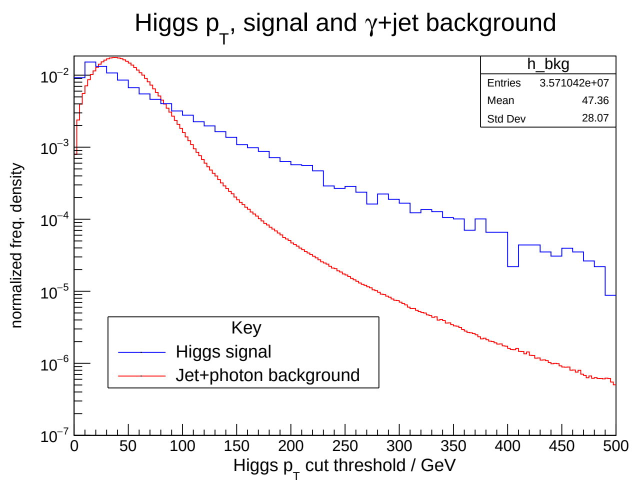

FIG. 8: All inclusive signal and γ+jet background frequency (log scale) vs Higgs p_T cut threshold

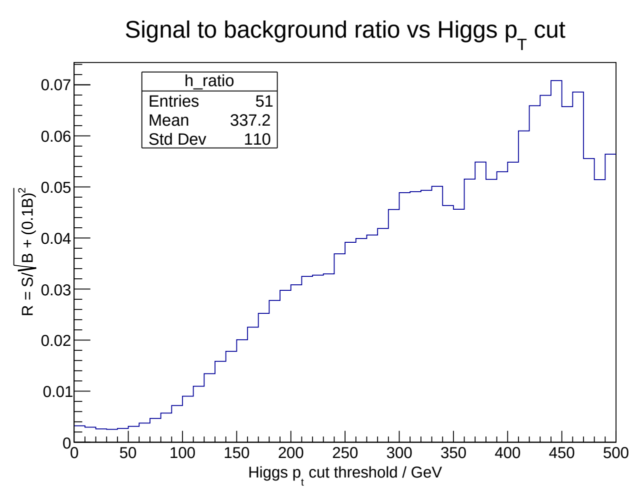

FIG. 9: Signal to background ratio R vs Higgs p_T cut threshold

Figure 8 shows a R value of over 0.05 can be obtained using a cut of Higgs $p_T >\sim 450$GeV. However this is still too small.

D. VBF

Another method of increasing the signal / background ratio is to focusing on one process of Higgs production. One mechanism is Vector Boson Fusion (VBF) (see Figure 10). In this process the end product is two quarks along with the Higgs. The quarks produce jets of particles, which give another parameter to select events, and thus screen out the background.

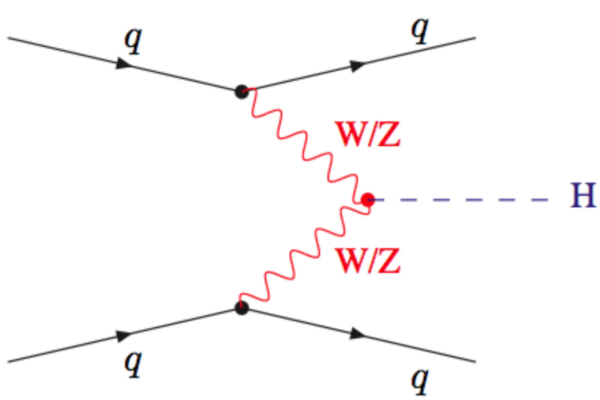

FIG. 10: Feynman diagram for the Vector Boson Fusion Higgs production process. The red can be two Z or W bosons, the q denotes any quark or antiquark. [Source ref]

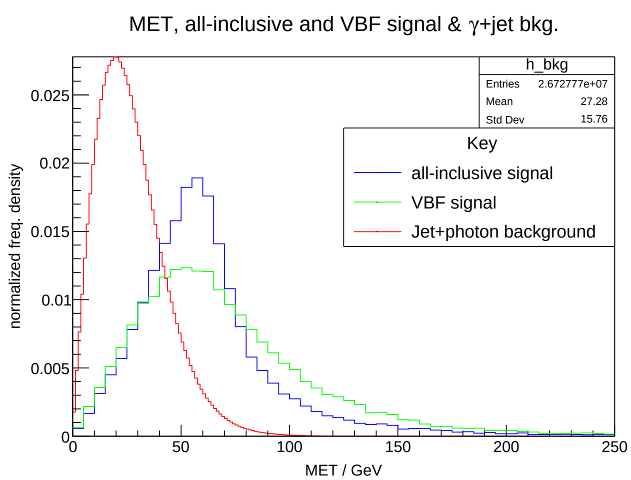

FIG. 11: MET with all Higgs production channels included (blue) compared with MET with only VBF (green) and the γ+jet background (red)

The VBF signal show more spread in photon p_T, MET and $M^T_{\gamma\bar{\gamma}}$ as shown in Figures 11 & 12.

The absolute pseudorapidity difference for the two highest p_T jets $|\eta^{j1} - \eta^{j2}|$ is lower for the background compared to the signal (Figure 13, see also [1]). Thus a cut in this variable allows further filtering of the background. Requiring $\eta^{j1} \times \eta^{j2} < 0$ means requiring the jets to go in opposite directions, which also favors the signal

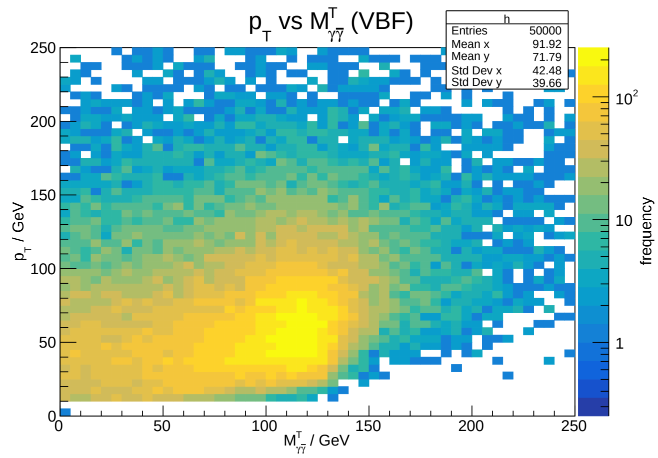

FIG. 12: p_T vs $M^T_{\gamma\bar{\gamma}}$ for the VBF signal

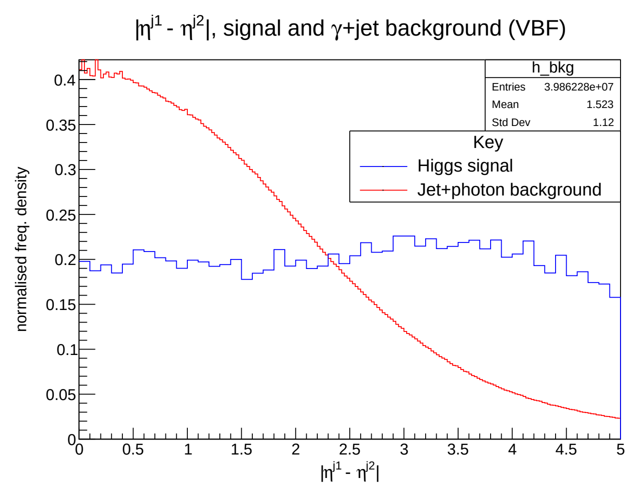

FIG. 13: $|\eta^{j1} - \eta^{j2}|$, absolute difference in pseudorapidity of the two highest p_T jets for the VBF signal and γ+jet background

I implemented the cuts suggested for VBF in Gabrielli et al. [1] for the signal and γ+jet background (Table 2).

Cut no.	Selected events (raw)		Selected events (weighted)		Efficiency / %		Cuts (cumulative)
	γ+jet bkg.	signal	γ+jet bkg.	signal	γ+jet bkg.	signal	
	49415864	50000	$3.27 \cdot 10^9$	3779.0	100.00	100.00	None
1	46836381	35686	$3.10 \cdot 10^9$	2697.1	94.78	71.37	$\lvert\eta_\gamma\rvert < 1.4442$ and $1.566 < \lvert\eta_\gamma\rvert < 2.5$
2	29628623	27569	$1.96 \cdot 10^9$	2083.7	59.80	55.14	$\lvert\eta_\gamma\rvert < 1.44$
3	24768109	24834	$1.49 \cdot 10^9$	1877.0	50.12	49.67	$p_T > 30$ GeV
4	11197465	21498	$5.60 \cdot 10^8$	1624.8	22.66	43.00	MET > 30 GeV
5	1585507	9903	$5.64 \cdot 10^7$	748.5	3.21	19.81	100 GeV $< M^T_{\gamma\bar{\gamma}} <$ 130 GeV
6	1407323	9893	$5.62 \cdot 10^7$	747.7	2.85	19.79	no isolated leptons
7	603418	3396	$1.84 \cdot 10^7$	256.7	1.22	6.79	$\eta^{j1} \times \eta^{j2} < 0$ and $\lvert\eta^{j1} - \eta^{j2}\rvert > 4.0$

TABLE II: *Effect of the trigger cuts suggested for ggH in [1] on all-inclusive signal and γ+jet background, weighted to luminosity = 100 fb^{-1}*

With no additional Higgs p_T cut $R = 0.000139$, increasing to ~ 0.02 with Higgs p_T cuts. This is noticeably worse than using all Higgs channels. This corresponds with the results in [1] where the VBF channel performed worse than the gluon-gluon fusion channel, which is the dominant channel in my all-inclusive signal.

E. ZH

Another Higgs production channel is the ZH (see Figure 14).

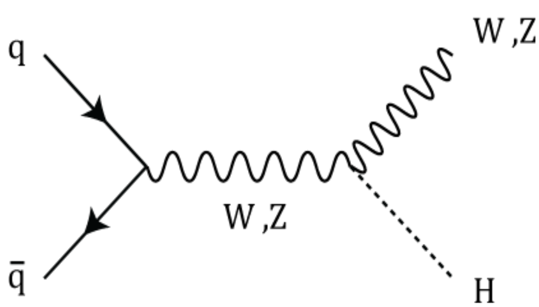

FIG. 14: Feynman diagram for the ZH / WH Higgs production channel (also called Higgs-strahlung or Vector boson associated production). For the ZH process the weak boson is a Z; the q can be any fermion. [Source

The Z boson can decay into electron-positron or muon-antimuon pairs which can be used to filter out the ZH events and remove more of the background. The dominant SM background for this channel is $Z + \gamma$ [10].

Using cuts suggested in [10] $R = 0.026$ was obtained. However the signal was too small (14 events out of 50,000 selected) to apply further filtering to improve that number.

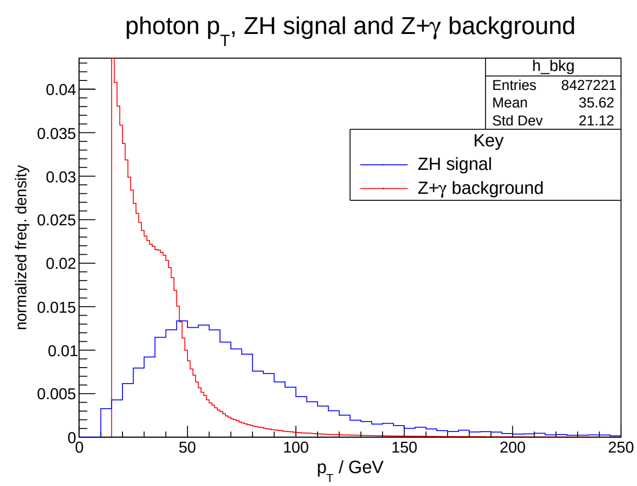

FIG. 15: photon p_T for the ZH signal and $Z + \gamma$ background

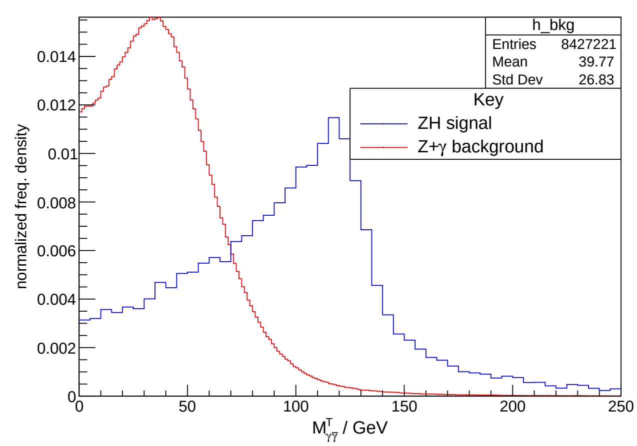

FIG. 16: $M^T_{\gamma\bar{\gamma}}$ for the ZH signal and $Z + \gamma$ background

Cut no.	Selected events (raw)		Selected events (weighted)		Efficiency / %		Cuts (cumulative)
	$Z+\gamma$ bkg.	ZH signal	$Z+\gamma$ bkg.	ZH signal	$Z+\gamma$ bkg.	ZH signal	
	14372682	50000	$1.18 \cdot 10^7$	882.40	100.00	100.00	None
1	13086401	38573	$1.08 \cdot 10^7$	680.74	91.26	77.15	$\lvert\eta_\gamma\rvert < 1.4442$ and $1.566 < \lvert\eta_\gamma\rvert < 2.5$
2	8587250	29730	$7.06 \cdot 10^6$	524.67	59.89	59.46	$\lvert\eta_\gamma\rvert < 1.44$
3	6955982	28620	$7.06 \cdot 10^6$	505.09	48.05	57.24	$p_T > 30$ GeV
4	378198	15213	$5.66 \cdot 10^6$	268.48	2.43	30.43	MET > 30 GeV
5	59882	5367	286035	94.72	0.37	10.73	100 GeV $< M^T_{\gamma\bar{\gamma}} < 130$ GeV
	### Select the $Z \longrightarrow ll$ candidate leptons ###						2 leptons with $p_T > 20$GeV and $\lvert\eta\rvert < 2.4$ with invarient mass +/− 15GeV of Z mass
6	4538	213	3293.48	3.76	0.0279	0.426	candidates found
7	4456	24	3295.03	0.42	0.0280	0.048	no jets with $p_T > 30$GeV
8	704	17	500.73	0.30	0.0043	0.034	$\Delta\phi_{ll,\gamma+MET} > 2.7$rad
9	313	15	203.96	0.27	0.0017	0.030	$\lvert p_T^{MET+\gamma} - p_T^{ll}\rvert / p_T^{ll} < 0.5$
10	147	14	96.48	0.25	0.0008	0.028	$\Delta\phi_{ll} < 2.25$rad
11	85	14	54.96	0.25	0.0005	0.028	$p_T^{ll} > 60$GeV

TABLE III: *Effect of the trigger cuts suggested for ZH in [10] on ZH signal and Z+γ background, weighted to luminosity = 100fb^{-1}*

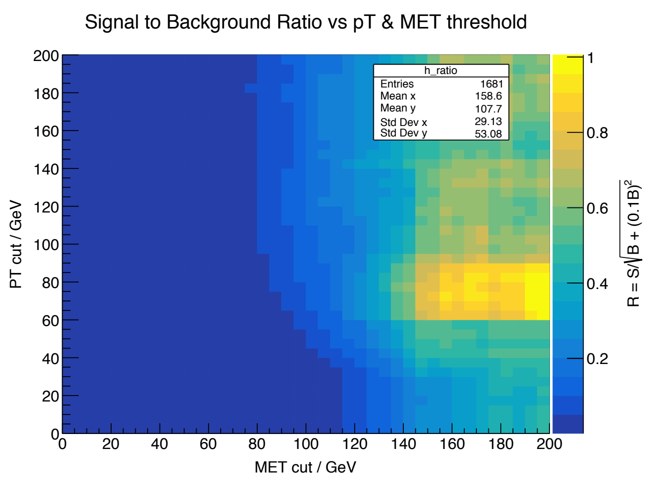

FIG. 17: Signal to background ratio vs the photon p_T and MET cut thresholds, using the all-inclusive sample and γ+jet background

F. Re-optimization of cuts

Having previously stuck closely to the trigger cuts used by past authors, I now tried experimenting with different cut thresholds to improve the signal to background ratio. Using the all-inclusive signal and keeping the cuts:

- $\lvert\eta_\gamma\rvert < 1.44$
- no isolated leptons
- 100GeV$< M^T_{\gamma\bar{\gamma}} < 130$GeV

the same I varied the photon p_T and MET cut threshold, as shown in Figure 17

This plot shows that choosing cuts $p_T > 70$GeV, MET> 155GeV gives a R value of ~ 0.9, a considerable improvement on the cuts from Gabrielli et al. The signal and γ+jet background efficiencies are 0.16% and 0.00016% respectively.

G. Additional cuts

To further improve the ratio I tried adding additional cuts targeting the +jet background suggested in [10]:

- require no more than one jet with: $p_T > 30$, $\lvert\eta\rvert < 2.4$, $\Delta\phi(\gamma, \text{jet}) > 0.5$

for remaining events with one jet meeting the above criteria require:

- $\Delta\phi(\gamma, \text{jet}) < 2.5$
- jet $p_T < 100$GeV

where $\Delta\phi(\gamma, \text{jet})$ is the azimuthal angle between the isolated photon and the jet. Varying p_T and MET cuts again gives Figure 18.

Choosing $p_T > 70$GeV, MET> 150GeV gives a signal to background ratio of ~ 2, my target threshold. However the number of selected signal and background events is very small, 5 & 1 respectively before weighting, so the errors associated with this ratio value are likely to be very large.

V. DIRECTIONS FOR FUTURE WORK

An important next step would be to obtain statistical estimates of the error in the signal to background ratio

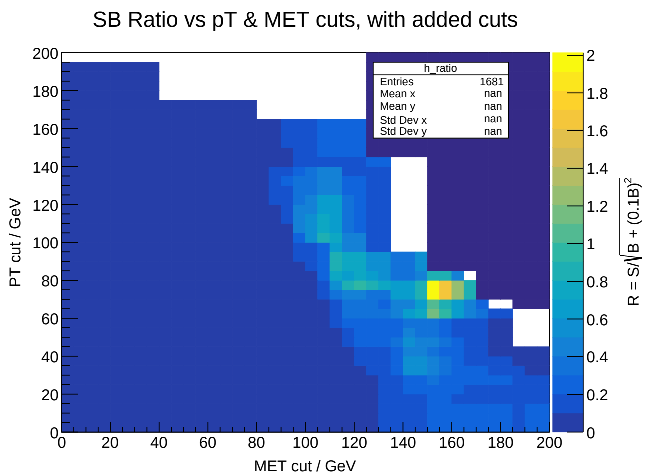

FIG. 18: Signal to background ratio vs the photon p_T and MET cut thresholds, using the all-inclusive sample and γ+jet background with the additional cuts

associated with a small number of events remaining post-trigger. To reduce this error you could use trigger and background samples with a much larger number of initial events, although that would be more costly in terms of computing time.

In addition you could try to implement more advanced statistical methods for reducing the miss-measurement of MET, which contributes to the background signal, detailed in [10].

One improvement would be a more complete and systematic optimization of the trigger cuts. The $|\eta_\gamma|$ cut, no isolated leptons cut, & cuts on the number of jets and $\Delta\phi(\gamma, \text{jet})$ could be kept the same as a baseline, then the values for the other cuts varied to reach an optimum signal to background ratio.

You would also need to consider the less dominant background processes, including [1][10]

- $pp \longrightarrow W \longrightarrow \nu e$ [e^- miss-identified as γ]
- $pp \longrightarrow W(\longrightarrow le)\gamma$ [$l = e^-, \mu^-, \tau^-$]
- $pp \longrightarrow (\longrightarrow \nu\bar{\nu})\gamma$

to fully determine whether detecting a dark photon using this decay would be feasible.

Once feasibility is established with greater confidence you could then look at how to implement the trigger. This would perhaps involve using data-scouting if the trigger thresholds arrived at were too low for the standard approach.

VI. SUMMARY AND CONCLUSIONS

The Higgs to photon-dark photon decay was simulated using an adapted Higgs to diphoton model. Distributions were obtained which agreed broadly with those found by the previous authors Gabrielli et al. (2016).

However using CMS produced Monte Carlo samples for the background, I found their suggested cuts failed to produce a sufficient signal to background ratio (assuming 10% systematic error) with respect to the dominant background process. This may suggest the previous authors underestimated the background levels.

With some experimentation with the cut thresholds I could increase the signal to background ratio significantly compared to cuts in [1]. I obtained a set of cuts obtained that produced a signal to background ratio of ~ 2, the threshold I took for feasibility of detection to a decent degree of significance:

1. $|\eta_\gamma| < 1.44$ (isolated photon in barrel region)
2. 100GeV$< M^T_{\gamma\bar{\gamma}} <$ 130GeV
3. no isolated leptons
4. require not more than one jet with: $p_T >$ 30GeV, $|\eta| < 2.5$ and $\Delta\phi(\gamma, \text{jet}) > 0.5$

for events with one jet meeting those criteria require

5. $\Delta\phi(\gamma, \text{jet}) < 2.5$
6. jet $p_T <$ 100GeV

require for all remaining events

7. photon $p_T >$ 70GeV
8. MET$>$ 150GeV

However the very small sample size post-trigger means this value will have large errors associated. Nonetheless these results are promising and suggest that with further work the dark photon may be detectable at the CMS via this decay, despite the apparent underestimate of background levels by the previous authors.

[1] S. Biswas, E. Gabrielli, M. Heikinheimo, and B. Mele, Phys. Rev. D **93**, 093011 (2016), arXiv:1603.01377 [hep-ph].

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