Study of systematic uncertainties and spurious signals of resonant $H \rightarrow Z\gamma$ production at ATLAS Experiment

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Abstract.

This work examines the assessment of systematic uncertainties and quantification of probable false signals on the fitting signal yield to Higgs-like production in the $Z\gamma$ final state, where the Z boson decays leptonically. Several sources of systematic uncertainties for the measured observables are considered such as detector systematic uncertainties from detector effects and modelling systematic uncertainties due to modelling of signal and the background processes. To estimate the contribution of each source in the overall uncertainty, large-scale Monte Carlo events simulation has been performed where the events correspond to an integrated luminosity of 139 fb^{-1} dataset recorded by the ATLAS experiment in proton-proton collisions during the LHC Run 2.

1. Introduction

The recent emergence of multi-lepton anomalies as deviations from Standard Model (SM) predictions in several ATLAS and CMS analyses of Large Hadron Collider (LHC) data, provided clear evidence of the existence of beyond the Standard Model (BSM) Higgs bosons [1–4]. An explanation to this evidence is well demonstrated by the decay of a heavy scalar H into a lighter one S and a SM Higgs boson, $H \rightarrow SS, Sh$, as per the 2HDM+S framework which requires the mass of S to be in the range of 130 GeV to 160 GeV. The ATLAS and CMS have previously studied the signatures of S in the side-band of the kinematics region in searches for the SM Higgs. In addition, an evidence for the associate production of S has been accumulated with a mass of 151.5 GeV in Ref. [5], where it is assumed to be through the decay of Higgs-like scalar H.

In this context, it is anticipated that the production of H and excesses in the multi-lepton final states at the LHC will have a significant production rate in a number of channels (i.e $\gamma\gamma, Z\gamma$). Motivated by this, a search for resonances with mass $m_s = 150$ GeV is performed in the $Z\gamma$ final state where Z boson decays to lepton-antilepton pairs $\mu^+\mu^-$ and e^+e^-. Here the $Z\gamma$ channel is taken into consideration because, compared to the di-photon final state, a Higgs-like boson (H) may have a relatively higher likelihood of decaying into a $Z\gamma$ final state.

It is essential to accurately and precisely predict both our BSM signal distributions and the SM background distribution in order to distinguish BSM physics from SM physics.

However, the precision of the measurements is significantly impacted by a number of anticipated systematic uncertainties resulting from biases in experimental measurements as well as Monte Carlo modeling of physical processes such as SM backgrounds, BSM signals, and particle-detector interactions. Understanding the systematic uncertainties for both our Standard Model backgrounds and the beyond Standard Model signals is crucial for accomplishing this. Within the framework of ATLAS collaboration, a thorough analysis of the systematic uncertainty sources is carried out taking into consideration the combined performance group recommendations which is dedicated to object optimisation, identification and selection. Moreover, the impact from spurious signal, fake signals systematics created by the choice of the functional forms for background modeling will also be reviewed.

2. Experimental systematic uncertainty

The sources of systematic uncertainties taken into account in this study, for the expected number of signal events include the following nuisance parameters (NP) for the $\mu\mu\gamma$ channel: 10 muon uncertainties, photon ID/Isolation/Trigger efficiency uncertainties and Pile-up. For the $ee\gamma$ channel we have: electron ID/Isolation/Reconstruction/Trigger, photon ID/Isolation/Trigger efficiency uncertainties and pile-up.

2.1. Pileup re-weighting

Because the simulated pileup overlays the simulated process, the amount of pileup in each simulated event is determined by drawing from a reference distribution of the mean number of interactions per bunch crossing. This distribution may differ from the measured distribution and need to be corrected by re-weighting simulated events with scale factors, which improves the agreement. In order to estimate the uncertainty associated with pileup re-weighting, events are also re-weighted with $\pm 1\sigma$ variations of the nominal scale factor, where σ is its uncertainty provided by the Combined Performance Working Group (CP) in Refs. [6–8] . The difference in the event yield between re-weighting with the nominal and the UP(DOWN) variation is taken as the UP(DOWN) uncertainty on the signal yield.

2.2. Electrons

The e/γ energy scale, resolution and electrons reconstruction/identification/isolation efficiencies in simulation are corrected in order to improve agreement with data. Energy scale and electron resolution corrections are applied to each electron and reconstruction/identification/isolation efficiency corrections are applied through event re-weighting. Uncertainties associated with electron corrections are evaluated by varying the trigger, reconstruction, isolation and identification scale factors of the leptons are varied by $\pm 1\sigma$, and then recompute $m_{\ell\ell\gamma}$ distribution after varying the uncertainty sources.

- Energy resolution all: uncertainty related to electron energy smearing in simulation to enhance resolution agreement between data and simulation.
- Energy scale all (AFS): uncertainty associated with calibration of electron energy scale in simulation. A special set of calibrations and uncertainties are applied for samples simulated with the Atlfast-II (AF2) parametrization instead of with GEANT4.
- Electron efficiency (ID, Iso, Reco): uncertainties associated with re-weighting of simulated events such that identification, isolation, and reconstruction efficiencies in simulation agree with those in data. Identification efficiency uncertainty is approximately ±4% on the signal region yield and is the dominant systematic uncertainty.

2.3. Muons

The momentum scale, e/γ resolution and isolation/reconstruction/track-to- vertex association efficiencies of muons in simulation are also corrected. Muon resolution and momentum scale corrections are applied to each muon, and isolation/ reconstruction/track-to-vertex association (ttva) efficiency corrections are applied through event re-weighting. The same procedure used to assess uncertainties for electrons is followed to assess uncertainties associated with these corrections.

- Muon ID: uncertainty associated with charge-agnostic smearing of simulated muon p_{T} in the Inner Detector (ID) in order to improve muon ID p_{T} resolution agreement between data and simulation.
- Muon scale: uncertainty associated with calibration of the muon momentum scale in simulation.
- Muon eff. Iso(Reco)(ttva) stat(sys) lowpt: similar to the efficiency uncertainties for electrons but broken up into statistical and systematic errors on the weights.
- Muon sagitta rho: uncertainty associated with correction of muon momenta for charge-dependent sagitta biases in simulation. Geometric deformations of the detectors affect the sagitta measurement and consquently the momentum.
- Muon sagitta resbias: uncertainty associated with correction of muon momenta for residual sagitta bias in simulation.
- Muon MS: uncertainty associated with charge-agnostic smearing of simulated muon p_{T} in the Muon Spectrometer (MS) in order to improve muon MS p_{T} e/γ resolution agreement between simulation and data.

2.4. Photons

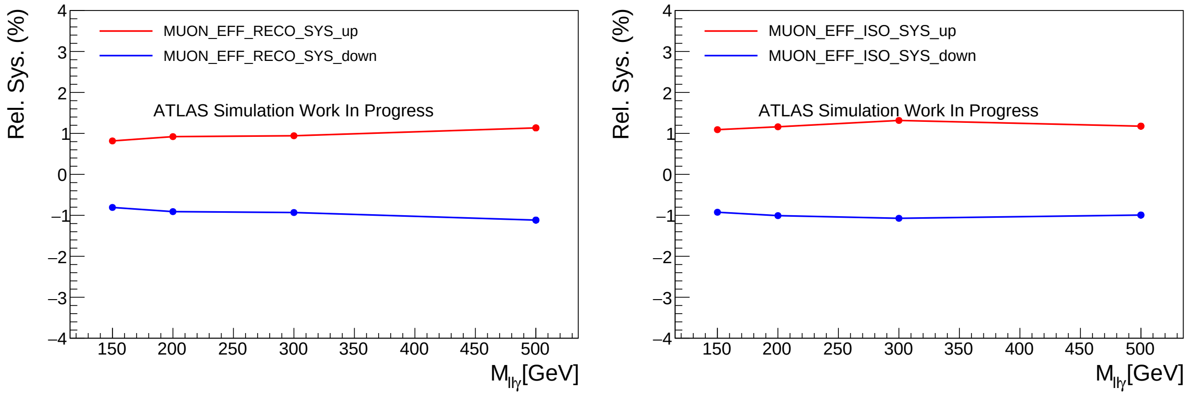
The same procedure used for pile-up reweighting and leptons is applied to the photon isolation and identification efficiency scale factors for estimating uncertainty impact on signal efficiency from the photon isolation and identification efficiency uncertainties. The signal efficiencies for each systematic variation corresponding to all samples m_x in ee and $\mu\mu$ channels are computed as:

$$SigEff = \frac{\Sigma(year^{n} passcut(with\ weight) * lumi(year) * xsec)/Sum\_w}{lumi_{all} * xsec}. \tag{1}$$

The relative systematic uncertainties on signal efficiency are summarised in Table 1 and the corresponding plots illustrating their impact are presented as shown in Figure 1. The two curves on the plots (red and blue) correspond to relative difference between the signal yield after systematic source variation and the nominal ones. The up(down) variation corresponds to uncertainty in the upper(lower) position and the absolute maximum(minimum) value is taken as an estimate.

Table 1: Summary of the main sources of systematic uncertainty for the measurement of $\sigma(pp \to X \to Z\gamma)$ and of their contribution to the measurement uncertainty.

Category	$\mu\mu\gamma$	$ee\gamma$
Signal Efficiency		
Photon ID efficiency uncertainty	0.42 – 0.75%	0.48 – 0.82%
Photon isolation efficiency uncertainty	0.51 – 1.24%	0.50 – 1.25%
Photon trigger efficiency uncertainty	0.00 – 0.02%	0.00%
Pile-up	0.00 – 0.02%	0.00%
Muon isolation efficiency (stat.)	0.03 – 0.47%	0.00%
Muon isolation efficiency (sys.)	0.82 – 0.90%	0.00%
Muon reconstruction efficiency (stat.)	0.10 – 0.12%	0.00%
Muon reconstruction efficiency (sys.)	0.78 – 0.91%	0.00%
Muon reconstruction efficiency (stat. lowpt)	0.00 – 0.04%	0.00%
Muon reconstruction efficiency (sys. lowpt)	0.00 – 0.03%	0.00%
Muon efficiency (ttva stat.)	0.075 – 0.14%	0.00%
Muon efficiency (ttva sys.)	0.064 – 0.15%	0.00%
Muon efficiency (trig. stat. uncertainty)	0.09 – 0.14%	0.00%
Muon efficiency (trig. sys. uncertainty)	0.57 – 1.64%	0.00%
Electron ID efficiency (total)	0.00%	2.63 – 4.04%
Electron Iso. efficiency (total)	0.00%	0.11 – 0.43%
Electron Reco. efficiency (total)	0.00%	0.23 – 0.62%
Electron Trig. efficiency (total)	0.00%	0.01 – 0.06%
Electron TrigEff. efficiency (total)	0.00%	0.00 – 0.00%

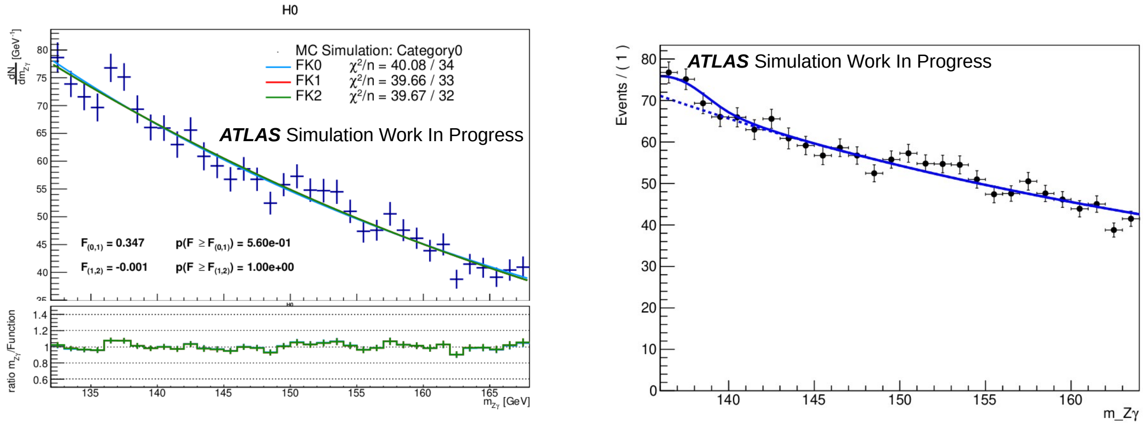


(a) (b)

Figure 1: Figures illustrating the impact of muon reco. efficiency (a) and muon iso. efficiency (b) on signal efficiency.

3. Spurious signal study

This section estimates the uncertainty of the various functions used to describe the background shape. This uncertainty, referred to as spurious signal N_{sig}, arises from fitting a pure background template using a given signal plus background functional forms. It is defined as the bias on the signal yield caused by the choice of a particular background function. It is evaluated [9] by fitting a high statistics background-only distributions, scaled to the luminosity of the data but



(a) (b)

Figure 2: Fitting on the background MC template (a) and fitting with S+B functions (b) for 150 GeV.

Name	S/Δ S in %	Spurious signal	N par	Chi2 Prob	Pass selection
		150 GeV			
		Category H0			
FK0	72.3	18.6	2	14.8	PASS
FK1	136	38.7	3	11.9	PASS

Table 2: Spurious signal yield and fit properties of tested functions at 150 GeV.

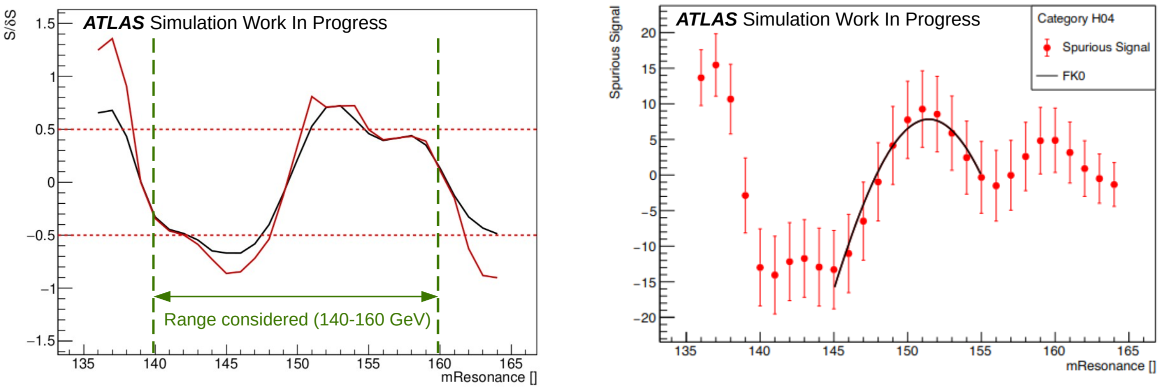
without introducing corresponding statistical fluctuations [10], with a signal plus background model. The fitted signal yield is actually the bias caused by choice of such background model, denoted as spurious signal SS in the study. The error of fitted signal yield is denoted as ΔS, used to judge whether the background function satisfies selection criteria.

The background template is constructed using a combination of SM $Z\gamma$ (Sherpa_CT10) MC sample and Z+jets-dominant which is obtained from control region in data. From previous $H \to Z\gamma$ high mass analysis, the data in control region can describe Z+jet shape well, and the statistical error in control region data is much smaller than Z+jet simulation. In this context, the background MC samples ($Z\gamma$) is normalised to 90% of real data in the signal region and and combined with 10% of reverse ID data sample (Z+jet). The following high-mass function of different functional forms is used for fitting: $f_k(x; b, \{a_k\}) = (1-x)^b x^{\sum_{j=0}^{k} a_j \log(x)^j}$, $k = 0, 1, 2$, noted as FK0, FK1 and FK2.

The template sample is saved in the histogram with 1 GeV per bin from 130 GeV to 1000 GeV. A scan of the existence of signal with 1 GeV step is performed with the signal shape varying as a function of mass. To find the suitable functional form that best describes background in the data and avoid the spurious signal, "F-test" technique is introduced and a function with a p-value smaller than 5% is selected. The results for VBF category at 150 GeV resonant mass point are shown in Figure 3 and summarised in Table 2.

Conclusion and outlook

We successfully estimated the experimental systematic uncertainties and spurious signal of the Higgs-like scalar H production at a mass interest of 150 GeV at the LHC. The study was performed using Monte Carlo (MC) simulated VBF signal samples and background MC samples



(a) (b)

Figure 3: The $N_{spurious}/\delta N_{spurious}$ as a function of mass for each functional (a) form and SS parametrisation fit (b) at 150 GeV

$(Z\gamma)$ corresponding to an integrated luminosity of $139\,\mathrm{fb}^{-1}$ dataset recorded by the ATLAS experiment in proton-proton collisions during the LHC Run 2. According to preliminary results, these uncertainties are relatively small and are not a limiting factor for this study. Consequently, this study will move forward in terms of developing the statistical interpretation.

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