Search for the Standard Model Higgs and Z Boson decays to $J/\psi \gamma$: HL-LHC projections

The ATLAS Collaboration

Abstract

The expected sensitivity for the measurement of Higgs and Z boson decays to $J/\psi \gamma$ is estimated for an integrated luminosity up to 3000 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 14$ TeV with an upgraded ATLAS detector at the high-luminosity LHC. For an assumed dataset of 3000 fb$^{-1}$, 95% CL upper-limits on the production of Higgs and Z boson decaying to $J/\psi \gamma$ of about 15 and 4 times the Standard Model expectation are obtained, respectively.
1 Introduction

The decay of the Standard Model (SM) Higgs boson to a quarkonium state $Q$ and a photon can offer unique sensitivity to both the magnitude and the sign of the quark Yukawa couplings [1–4]. The branching ratio, $\mathcal{B}$, for decays of the Higgs boson to a $J/\psi$ and a photon, has recently been estimated within the SM [2–5]. The most recent calculation being $\mathcal{B}(H \to J/\psi \gamma) = (2.9 \pm 0.2) \times 10^{-6}$ [5]. The corresponding decays in the bottomonium sector, $H \to \Upsilon(nS)\gamma (n = 1, 2, 3)$, also provide a clean window on the $Hb\bar{b}$ coupling, though the expected SM branching ratios $\mathcal{B}(H \to \Upsilon(nS)\gamma) = (4.6^{+1.8}_{-1.2} \times 2.3^{+0.8}_{-1.0} \times 2.1^{+0.8}_{-1.1}) \times 10^{-10}$ [5] are significantly smaller than the analogous decays to charmonium. Deviations in the $c$ and $b$ quark Yukawa couplings from the SM expectation can lead to substantial modification of these branching ratios. Searches for very rare exclusive decays of the Higgs boson are therefore an important component of the HL-LHC future programme. The ATLAS collaboration recently performed the first search for the decays of the Higgs and the $Z$ bosons to $Q\gamma$, where $Q = J/\psi$ or $\Upsilon(nS)$, using a dataset of around 20 fb$^{-1}$ collected at a centre-of-mass energy of $\sqrt{s} = 8$ TeV [6]. This note reports the sensitivity projection for the measurement of the SM Higgs boson decay to a $J/\psi$ and a photon, assuming up to 3000 fb$^{-1}$ of data collected with the ATLAS detector at $\sqrt{s} = 14$ TeV, an average instantaneous luminosity of around $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and an average number of collisions per bunch-crossing, $\mu$, of 140.

In addition to projections for the measurement of the $H \to J/\psi \gamma$ decay, the corresponding projections for $Z \to J/\psi \gamma$ decay are also presented. This decay provides a reference channel for the Higgs boson decay search [7, 8]. Several estimates of the SM branching ratio for the decay $Z \to J/\psi \gamma$ are available [7–10] with the most recent being $(8.02 \pm 0.45) \times 10^{-8}$ [7]. Currently, the most stringent 95% CL upper limit on this branching ratio comes from ATLAS: $\mathcal{B}(Z \to J/\psi \gamma) < 2.6 \times 10^{-6}$ [6].

The analysis strategy and event selection used in this note closely follow those of the recent ATLAS publication presented in Ref. [6]; any differences will be mentioned explicitly.

2 Analysis Strategy

The ATLAS detector design for the high luminosity phase is still under study and it will take more time to adapt and optimise the event reconstruction software to the high-pile-up conditions. For the harsh conditions of the high luminosity phase, the goal of this optimisation is to achieve the same level of detector performance as that of the current detector, typically operating at $\mu \sim 20$ [11, 12]. In this analysis, the overall assumption is that the upgraded detector will exhibit the same performance as that achieved during LHC Run I, unless explicitly mentioned. The analysis has been performed by considering only the decay $J/\psi \to \mu^+\mu^-$. Simulated $H \to J/\psi \gamma$ and $Z \to J/\psi \gamma$ signal samples are obtained using the Powheg-BOX next-to-leading order MC event generator [13, 14], with the CT10 parton distribution function set [15], interfaced with Pythia8.1 [16] for parton showering, hadronization and the underlying event with parameters set according to the AU2-CT10 tune [17, 18]. The simulated events are passed through the full Geant4-based simulation of the ATLAS detector [19, 20] and processed with the same software used to reconstruct data events. The Higgs and Z boson signals are expressed by scaling the expected yields from the Run I analysis by the ratio of the cross sections, following Refs. [16, 21, 22], and of the detector geometrical acceptances at 8 and 14 TeV using Powheg-BOX event generator. This yield is reduced by 37% to account
for the estimated reduction of the photon identification efficiency for ATLAS HL-LHC, assuming the same level of background rejection as in Run I [12].

In this projection, the event selection of the $H, Z \to J/\psi \gamma \to \mu^+\mu^-\gamma$ candidates follows that of the recent ATLAS results. Candidate $J/\psi \to \mu^+\mu^-$ decays are reconstructed from pairs of oppositely charged muons with $p_T^\mu > 3$ GeV and $|\eta^\mu| < 2.5$, which are consistent with originating from a common vertex. The highest-$p_T$ muon in a pair is required to have $p_T^\mu > 20$ GeV. A dimuon pair with a mass within 0.2 GeV of the $J/\psi$ mass [23] is identified as a $J/\psi \to \mu^+\mu^-$ candidate. The transverse momentum of each $J/\psi \to \mu^+\mu^-$ candidate, $p_T^{\mu^+\mu^-}$, is required to exceed 36 GeV. Selected $J/\psi \to \mu^+\mu^-$ candidates are subjected to isolation and vertex quality requirements. Reconstructed photon candidates are required to have transverse momentum $p_T^\gamma > 36$ GeV and pseudorapidity $|\eta^\gamma| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta^\gamma| < 1.52$, and to satisfy the “tight” photon identification criteria [24]. To further suppress contamination from jets, an isolation requirement is imposed on the photon candidates. Only combinations of a $J/\psi \to \mu^+\mu^-$ candidate and a photon which satisfy $\Delta\phi(\mu^+\mu^-, \gamma) > 0.5$, are retained for the final analysis.

Following an optimisation study for these projections of the Higgs boson sensitivity, the requirements on $p_T^\gamma$ and $p_T^{\mu^+\mu^-}$ have been raised to 40 GeV to increase the background rejection. Additionally, a multivariate discriminant trained to distinguish the signal from the background has been introduced to further enhance the signal sensitivity. This discriminant is based on a boosted decision tree (BDT) [25] and uses the same quantities as the cut-based analysis as inputs: $p_T^\gamma, p_T^{\mu^+\mu^-}$ and the isolation of the photon and dimuon systems.

Following the studies in Ref. [6], the main source of background in the analysis is the inclusive production of a $J/\psi$ and a reconstructed high energy photon in the same event. Non-resonant dimuons with an invariant mass in the vicinity of the $J/\psi$ mass combined with a reconstructed photon represent another source of background. For the HL-LHC projection, these sources of background are evaluated by scaling the observed background yields in the $\sqrt{s} = 8$ TeV data, which also accounts for double- and multi-parton interactions, by the ratio of production cross sections for $J/\psi + X$ production at 8 and 14 TeV [16, 26, 27]. Additional backgrounds arising from the pileup conditions at the HL-LHC were studied using the procedure described in Ref. [28]. These studies indicate that such additional backgrounds represent a negligible contribution with respect to the inclusive QCD background. The inclusive QCD background shape is modelled with the same non-parametric data-driven method used in Ref. [6].

Events containing $Z \to \mu^+\mu^-$ decays with final-state photon radiation (FSR), with $m_{\mu^+\mu^-}$ within the $J/\psi$ mass region, constitute another, but less important, source of background for the $Z \to J/\psi \gamma$ searches. This contribution is taken into account for this analysis by extrapolating the $\sqrt{s} = 8$ TeV MC expectation to the higher luminosity and correcting by the ratio of the $Z$ boson production cross sections for the centre of mass energy change from 8 to 14 TeV using FEWZ [29].

As the sensitivity approaches the SM expectation for the $H \to J/\psi \gamma$ branching ratio, other Higgs boson decays can give rise to events containing a reconstructed $J/\psi \gamma \to \mu^+\mu^-\gamma$ candidate. In particular, the contribution of the $H \to \gamma^*\gamma \to \mu^+\mu^-\gamma$ decay, with a non-resonant dimuon, is comparable in rate to the signal [30, 31] and is included.

The total number of background events expected for a data sample of 3000 fb$^{-1}$ collected at $\sqrt{s} = 14$ TeV is shown in Table 1 in addition to the expected Higgs and $Z$ boson signal yields assuming SM branching ratios. For the Higgs analysis the expectations are given for the cut based analysis and for the multivariate analysis where an optimised cut is applied on the BDT discriminant to maximise the signal significance.
The theoretical uncertainties associated with the Higgs and Z boson signal yields are assessed following Refs. [22, 32, 33]. The detector-related systematic uncertainties associated with lepton and the photon reconstruction are assumed to be equal to those in Ref. [6] as they affect the analysis in a similar way. The systematic uncertainty on the background shape in this projection is assumed to follow two different scenarios: 5% and 2% uncertainty. This systematic uncertainty, which is expected to be reducible using the wealth of data at 3000 fb$^{-1}$, arises from the limited knowledge of the shape of the inclusive background but also covers possible differences in the background shape due to changes in background kinematics when moving from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 14$ TeV. In the following the conservative 5% approach is used for all of the results.

### 3 Results

To extract a limit on the branching ratio $\mathcal{B}(H \to J/\psi \gamma)$ and $\mathcal{B}(Z \to J/\psi \gamma)$, unbinned maximum-likelihood fits are performed to the predicted HL-HLC datasets for two different integrated luminosity scenarios: 300 fb$^{-1}$ and 3000 fb$^{-1}$. For the Higgs analysis, results are given for both the multivariate and the cut based analysis.

The probability density functions for the signal ($H \to J/\psi \gamma$ and $Z \to J/\psi \gamma$) and the background processes (inclusive QCD and exclusive $H, Z \to \mu^+\mu^-\gamma$ production) used in the fit are taken from Ref. [6]. The normalization of these background components and their systematic uncertainties are included in the fit as nuisance parameters and are profiled. A multi-observable model, using $m_{\mu^+\mu^-\gamma}$ and $p_T^{\mu^+\mu^-\gamma}$ as discriminating variables, is used to extract the results.

The expected 95% CL upper limits on the branching ratio for the Higgs and Z boson are presented in Table 2. The fit result is shown in Fig. 1 for both the 300 fb$^{-1}$ and 3000 fb$^{-1}$ scenarios. The expected Higgs and Z boson signals are also shown in the figure, assuming SM branching ratios enhanced by factors of 100 and 10, respectively. In Table 3, the same results for the projection of the expected $H, Z \to J/\psi \gamma$ branching ratio limits to 3000 fb$^{-1}$ are presented for the alternative background normalisation uncertainty scenario (2%).

For the Higgs boson decay search, expected 95% CL upper limits on the cross section times branching fraction $\sigma(pp \to H) \times \mathcal{B}(H \to Q\gamma)$ are also provided. The result of the two dimensional fit ($m_{\mu^+\mu^-}, p_T^{\mu^+\mu^-\gamma}$) for the 300 fb$^{-1}$ and 3000 fb$^{-1}$ datasets are presented in Table 4 for the multivariate and the cut based analyses.
Figure 1: $m_{\ell^{+}\ell^{-}\gamma}$ (upper plots) and $p_{T}^{\mu^{+}\mu^{-}\gamma}$ (lower plots) projections of the simultaneous fit. The pseudo-data correspond to the expected event yields for 300 fb$^{-1}$ (a) and 3000 fb$^{-1}$ (b). In the figure, for reference only, the Higgs and Z signal are shown assuming SM branching ratio enhanced by factors of 100 and 10, respectively.
The results presented in Tables 2 and 4 demonstrate that the introduction of a simple multivariate analysis provides a 20% improvement in the expected limits.

<table>
<thead>
<tr>
<th></th>
<th>Expected branching ratio limit at 95% CL</th>
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<tr>
<td></td>
<td>( \mathcal{B} (H \to J/\psi \gamma) , [10^{-6}] )</td>
<td>( \mathcal{B} (Z \to J/\psi \gamma) , [10^{-7}] )</td>
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<td>Cut Based 300 fb(^{-1} )</td>
<td>185^{+81}_{-52}</td>
<td>153^{+69}_{-43}</td>
<td>Cut Based 300 fb(^{-1} )</td>
</tr>
<tr>
<td>Cut Based 3000 fb(^{-1} )</td>
<td>55^{+24}_{-15}</td>
<td>44^{+19}_{-12}</td>
<td>Cut Based 3000 fb(^{-1} )</td>
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Table 2: The expected branching ratio limit at 95% CL for 300 fb\(^{-1} \) and 3000 fb\(^{-1} \) scenarios. The Standard Model expectations are also reported for comparison.

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<tr>
<td>Cut Based Analysis</td>
<td>Median 1σ</td>
<td>( 2.9 \pm 0.2 )</td>
<td>Median 2σ</td>
</tr>
<tr>
<td>300 fb(^{-1} )</td>
<td>52 ( +21 ) (-14 )</td>
<td>( -24 )</td>
<td>43 ( +18 ) (-12 )</td>
</tr>
<tr>
<td>Cut Based Analysis</td>
<td>Median 1σ</td>
<td>( 4.3 ) ( +1.7 ) (-1.2 )</td>
<td>Median 2σ</td>
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Table 3: Comparison of the expected branching ratio limit at 95% CL for 3000 fb\(^{-1} \), assuming the alternative background systematic uncertainty scenario.

<table>
<thead>
<tr>
<th></th>
<th>Expected ( \sigma \times \mathcal{B} ) limit at 95% CL</th>
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<tr>
<td></td>
<td>( \sigma (pp \to H) \times \mathcal{B} (H \to J/\psi \gamma) , [\text{fb}] )</td>
<td></td>
<td>( \sigma (pp \to H) \times \mathcal{B} (H \to J/\psi \gamma) , [\text{fb}] )</td>
</tr>
<tr>
<td>Cut Based 300 fb(^{-1} )</td>
<td>10.4^{+2.9}_{-4.5}</td>
<td>8.6^{+2.4}_{-3.7}</td>
<td>Cut Based 3000 fb(^{-1} )</td>
</tr>
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</table>

Table 4: The expected limits at 95% CL on the Higgs cross section times branching fraction for 300 fb\(^{-1} \) and 3000 fb\(^{-1} \) scenarios.
4 Conclusion

Projections are made to estimate the sensitivity of the measurement of the decays of the Higgs and Z bosons to $J/\psi \gamma$ for datasets of up to $3000 \text{ fb}^{-1}$ collected with a HL-LHC at $\sqrt{s} = 14 \text{ TeV}$. These yield expected 95% CL upper limits on $\mathcal{B}(H \rightarrow J/\psi \gamma)$ and $\mathcal{B}(Z \rightarrow J/\psi \gamma)$ of about 15 and 4 times the SM values, respectively. These projections are obtained with simple assumptions on the future detector performance and should be considered as a baseline for future work. Several possible improvements in the sensitivity could be obtained by categorising events based on Higgs production modes, introducing additional variables in the multi-variate discriminant, and improving the object reconstruction.
References