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Measurements of $Z\gamma$ and $Z\gamma\gamma$ production in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

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The production of Z bosons with one or two isolated high-energy photons is studied using pp collisions at $\sqrt{s}$ = 8 TeV. The analyses use a data sample with an integrated luminosity of 20.3 fb^{-1} collected by the ATLAS detector during the 2012 data taking at the LHC. The data are used to make tests of the electroweak sector of the Standard Model (SM) and search for deviations that could provide evidence for new physics beyond SM. The $Z\gamma$ and $Z\gamma\gamma$ production cross sections are measured with leptonic decays of the Z boson and then compared to cross-section predictions from the SM. A high transverse energy of the photon in $\ell^+\ell^-\gamma$ and $\nu\bar{\nu}\gamma$ events was required to search for anomalous triple gauge-boson couplings $ZZ\gamma$ and $Z\gamma\gamma$, while the yields of events with high diphoton invariant mass from $\ell^+\ell^-\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ events are used to search for anomalous quartic gauge-boson couplings $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$. No deviations from Standard Model predictions are observed and limits are placed on parameters used to describe anomalous gauge-boson couplings.

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1. Introduction

The production of Z with associated photons has been used in this study to test the electroweak sector of the Standard Model (SM). Previous precision measurements of Z properties made in hadron-production experiments are in agreement with the production dynamics predicted by the $SU(2)_L \times U(1)_Y$ gauge group of the SM's electroweak sector. No experimental evidence has been reported for couplings of Z bosons to photons. Some of the elementary processes resulting in the production of a Z boson in association with one final state photon radiation and with two initial state radiation photons are shown in Figure 1 illustrated by the leading-order Feynman diagrams.

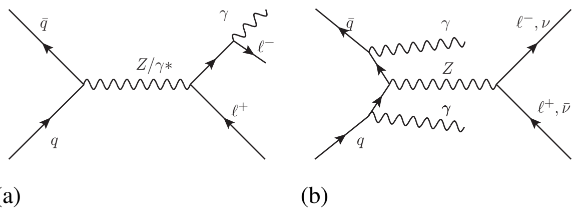


Figure 1: The leading-order Feynman diagrams of final-state photon radiation (FSR) in $Z\gamma$ channel (a), and initial-state photon radiations (ISR) in $Z\gamma\gamma$ channel (b).

This paper presents measurements of the hadron-production of Z bosons associated with one or two isolated photons [1]. The measurements use 20.3 fb^{-1} of proton–proton collisions collected with the ATLAS detector [2] at the CERN LHC operating at a center-of-mass energy of 8 TeV. The analyses use the decays $Z/\gamma^* \to \ell^+\ell^-$ (where l = e or μ) and $Z \to \nu\bar{\nu}$. The measurements are compared to SM predictions obtained with a parton-shower Monte Carlo (MC) simulation and with two higher-order perturbative parton-level calculations at next-to-leading order (NLO) [3] and next-to-next-to-leading order (NNLO) [4]. Anomalous properties of the Z boson are constrained in terms of limits on the triple or quartic gauge-boson couplings.

2. Z$\gamma(\gamma)$ production and cross sections

The Z/γ^* decays to charged leptons are selected using triggers requiring high transverse momentum (p_T) electrons or muons and photons with transverse energy $E_T > 15$ GeV. The events with Z boson decays to neutrinos are selected using high E_T photon triggers ($E_T > 130$ GeV for the single photon channel and $E_T > 22$ GeV for the diphoton channel). In all the production channels, the measurements are made with no restriction on number of jets in final state (inclusive events) and by requiring no central jet ($|\eta| < 4.5$) with $p_T > 30$ GeV (exclusive events).

Selected $\ell^+\ell^-\gamma(\gamma)$ event candidates must contain exactly one pair of same-flavor, opposite-charge isolated leptons (electrons or muons) with $m_{\ell^+\ell^-} > 40$ GeV and at least one or two isolated photons. The reconstructed photons are removed if they are found within a $\Delta R = 0.7$ (0.4) cone around a selected lepton for $\ell^+\ell^-\gamma(\gamma)$ events. The $\nu\bar{\nu}\gamma(\gamma)$ event candidates are selected by considering events with $E_T^{miss} > 100$ GeV (110 GeV for the diphoton channel) and at least one or two isolated photons. E_T^{miss} is the absolute value of the vector of momentum imbalance ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$) in the transverse plane and is used to identify neutrinos in this study. The separation between the reconstructed photon(s) direction and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ in the transverse plane is required since in signal events the Z

boson should recoil against the photon(s). To suppress $W(\gamma)$+jets and $W\gamma(\gamma)$ backgrounds, events containing a muon or an electron are rejected.

The backgrounds in the selected $\ell^+\ell^-\gamma(\gamma)$ samples are dominated by events in which hadronic jets are misidentified as prompt photons. This background is estimated using a data-driven 2D sideband method. Smaller backgrounds originate from $t\bar{t}\gamma$, WZ, $\tau^+\tau^-\gamma$ for $\ell^+\ell^-\gamma$, and from WZ, ZZ, $\tau^+\tau^-\gamma\gamma$ for $\ell^+\ell^-\gamma\gamma$. These are expected to contribute in total less than 1.5% of the selected event yield in both the $\ell^+\ell^-\gamma$ and $\ell^+\ell^-\gamma\gamma$ final states, and are derived from MC.

Backgrounds to the $\nu\bar{\nu}\gamma$ and $\nu\bar{\nu}\gamma\gamma$ signals originate from several sources: events with prompt photons and mismeasured jet momenta causing missing transverse momentum; non-signal electroweak processes, such as $W(\ell\nu)\gamma$ with a partial event detection; events with real E_T^{miss} from neutrinos and misidentified photons from electrons or jets (such as $Z(\nu\bar{\nu})$ or $W(e\nu)$). The largest contributions are determined using data-driven techniques. The procedures used to estimate these backgrounds follow closely those in a previous ATLAS measurements [7]. Smaller backgrounds originate from $\tau^+\tau^-\gamma(\gamma)$ and are obtained with a MC simulation.

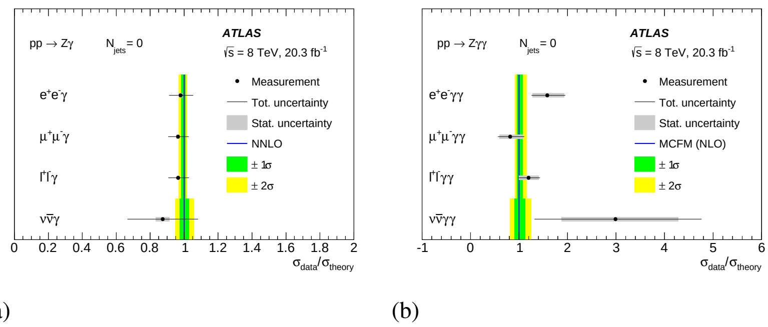


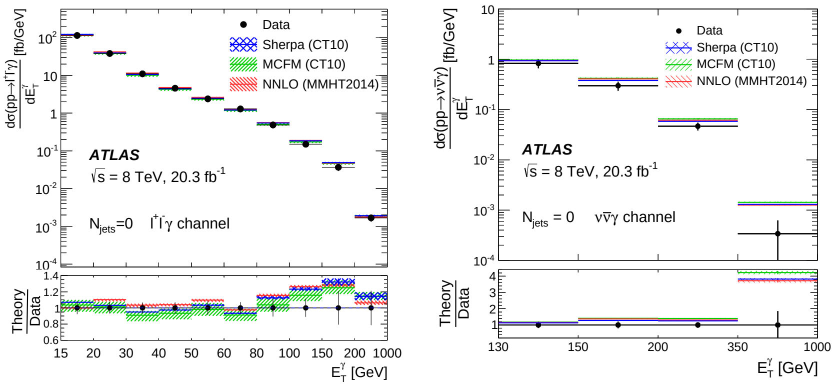
Figure 2: Comparison between the measured cross sections and the NNLO and NLO theory predictions for the $pp \to Z\gamma$ processes (left) and for the $pp \to Z\gamma\gamma$ processes (right) in the exclusive fiducial region.

The measured cross sections are compared to the SM predictions. There is generally a good agreement between the measured cross sections in the $Z\gamma$ channels and those predicted by the SM; the NNLO calculation of the inclusive cross section for the $Z(\ell^+\ell^-)\gamma$ channel are in a better agreement with the measurement than the NLO calculation. The results for both charged and neutrino $Z\gamma\gamma$ channels are compared to the NLO MCFM predictions. The measurements in these channels are statistically limited, but the data are consistent with the predicted SM cross sections. Although the observed number of events is not large, the combined $\ell^+\ell^-\gamma\gamma$ results show 5 standard deviations over non-signal hypothesis. Figure 2 shows the level of agreement between the experimental results and the theory for the most precise exclusive measurements [1].

Differential cross sections measurements are performed in $Z\gamma$ channels for a detailed comparison between theory and experiment. Figure 3 shows a good agreement between the measured and the predicted by the SM E_T^{γ} distributions for $pp \to \ell^+\ell^-\gamma$ and $pp \to \nu\bar{\nu}\gamma$ events with the exclusive selection [1].

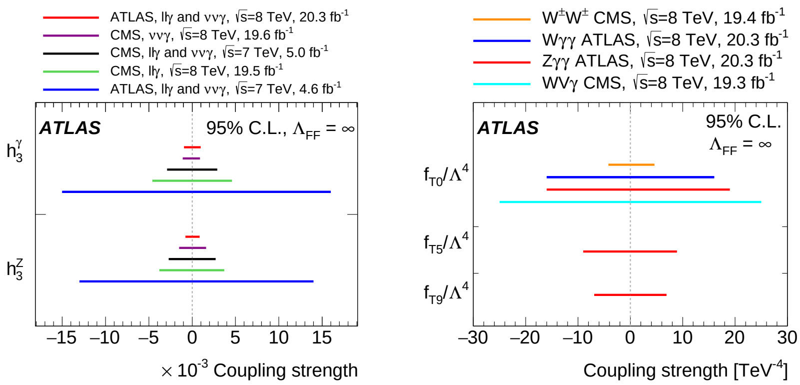
3. Anomalous gauge couplings

Vector-boson self-interactions are completely fixed by the model's $SU(2)_L \times U(1)_Y$ gauge



(a) (b)

Figure 3: The measured (points with error bars) and expected differential cross sections as a function of E_T^{γ} for the pp$\rightarrow \ell^+\ell^-\gamma$ process (left) and the pp$\rightarrow \nu\bar{\nu}\gamma$ process (right) in the exclusive $N_{jets} = 0$ fiducial regions. The lower plots show the ratios of the predictions to data (shaded bands).



(a) (b)

Figure 4: Comparison of the observed from $Z\gamma$ analysis ununitirized limits ($\Lambda_{FF} = \infty$) for the neutral aTGC h_3^{γ} and h_3^{Z} effective Lagrangian parameters with previous ATLAS and CMS results (left) [1, 7, 8, 9] and comparison of the observed from $Z\gamma\gamma$ analysis ununitirized limits for the neutral aQGC f_{T0}/Λ^4, f_{T5}/Λ^4 and f_{T9}/Λ^4 effective theory parameters with previous ATLAS and CMS results (right) [1, 10, 11, 12].

structure. Their observation is thus a crucial test of the model. Anomalous coupling parameters can parameterize possible deviations from the SM at high E_T [5, 6]. These parameters are zero for anomalous neutral triple (aTGC) and anomalous quartic (aQGC) gauge coupling in the SM. A comparison between the SM predictions and the measured cross sections at high transverse energy of the photon in $\ell^+\ell^-\gamma$ and $\nu\bar{\nu}\gamma$ events was exploited to search for anomalous triple gauge-boson couplings $ZZ\gamma$ and $Z\gamma\gamma$, while the yields of events with high diphoton invariant mass from $\ell^+\ell^-\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ events are used to search for anomalous quartic gauge-boson couplings $ZZ\gamma\gamma$ and $Z\gamma\gamma\gamma$. Figure 4 shows the experimental limits for aTGC (a) and aQGC (b) parameters [1]. They are compared to the previous results.

4. Conclusion

Precise measurements of the integrated cross sections for $Z\gamma(\gamma)$ with leptonic (e^+e^-, $\mu^+\mu^-$ and $\nu\bar{\nu}$) decays of Z bosons are presented. Differential cross-sections measurements as a function of E_T^γ are presented for $Z\gamma$ production. No deviations from Standard Model predictions are observed and limits are placed on parameters used to describe anomalous gauge-boson couplings.

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