The Compact Muon Solenoid Experiment

CMS Note

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Study of Di-Boson Production with the CMS Detector at LHC

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Abstract

The relatively high cross sections and the clean signature of multi-lepton final states make the $pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ and $pp \rightarrow W Z^0 \rightarrow 3\ell$ ($\ell = e, \mu$) processes accessible in early CMS data. The CMS potential for the observation and study of these processes is assessed using fully-simulated signal and background Monte Carlo samples. The main systematic effects relevant for cross section measurements with 1 and 10 fb⁻¹ of data are addressed. We demonstrate that multiple gauge-boson production in pp collisions at LHC energies can be observed in the early phase of the experiment, with an integrated luminosity of 1 fb⁻¹ or less.

1 Introduction

The study of multiple gauge-boson production at the TeV scale constitutes a unique opportunity to test the Standard Model of electroweak interactions at the highest possible energies. WZ^0 production in pp collisions proceeds mainly through s -channel quark annihilation, as shown in Fig. 1a. This process is sensitive to the WWZ triple gauge-boson coupling and allows to test the non-Abelian nature of the gauge symmetry of the Standard Model. No neutral triple-gauge-boson coupling exists in the Standard Model and the s -channel contribution to the $q\bar{q} \rightarrow Z^0 Z^0$ production is strongly suppressed: the $pp \rightarrow Z^0 Z^0$ production proceeds through the t -channel process depicted on Fig. 1b. Anomalies in the high- p_T spectrum of di-boson production at the LHC could hint to enhanced s -channel contributions due to manifestations of physics beyond the Standard Model.

Figure 1: Dominant spectator Feynman diagrams for (a) WZ^0 and (b) $Z^0 Z^0$ production in pp collisions. The $pp \rightarrow WZ^0$ reaction occurs mainly through s -channel $q\bar{q}$ scattering, involving the WWZ triple gauge-boson coupling, while the $pp \rightarrow Z^0 Z^0$ reaction proceeds via t -channel $q\bar{q}$ scattering.

The multi-lepton final states of multiple gauge-boson production are an important background in the search for New Physics, in particular Supersymmetry. A sound understanding of their production process is therefore needed in the first phase of LHC data-taking before any discovery can be claimed. In particular, $Z^0 Z^0$ production is an irreducible background to the most-coveted discovery at the LHC: the Standard Model Higgs boson. Its early measurement is therefore important. In addition, the study of $Z^0 Z^0$ spin correlations can further discriminate a Higgs-boson signal from the $Z^0 Z^0$ background: $Z^0 Z^0$ production results in bosons with both transverse and longitudinal polarisation while the Z^0 bosons from Higgs-boson decays tend to be longitudinally polarised.

This note describes a study of di-boson production through the following leptonic final states: $e^+e^-e^+e^-$ for $pp \rightarrow Z^0 Z^0$ and $e^\pm e^+e^-$, $\mu^\pm e^+e^-$, $e^\pm \mu^+ \mu^-$ and $\mu^\pm \mu^+ \mu^-$ for $pp \rightarrow WZ^0$. Only on-shell gauge bosons are considered. The $pp \rightarrow Z^0 Z^0$ and $pp \rightarrow WZ^0$ cross sections at $\sqrt{s} = 14$ TeV are relatively large (~ 22 pb and ~ 50 pb, respectively [1]) and the multi-lepton final states of interest have clean signatures. Competing background processes include the production of single Z^0 bosons together with one or two leptons, possibly from heavy-quark jets, and the production of top-quark pairs where both W bosons in the final state decay leptonically.

The signal and background samples used in this analysis are discussed in Section 2. Section 3 describes the analysis, with particular emphasis on lepton selection, in Section 3.1. The event selections are presented in Section 3.2, the expected event yields in Section 3.3 and the main sources of systematic uncertainties in Section 4. The results expected for the first measurements of the $pp \rightarrow Z^0 Z^0$ and $pp \rightarrow WZ^0$ cross sections with 1 fb^{-1} and 10 fb^{-1} of integrated luminosity are presented in Section 5. Finally, Section 6 outlines the conclusion that di-boson production can be observed in early LHC data, with the first inverse femtobarn of luminosity or less.

2 Signal and background modeling

2.1 Signal

Several Monte Carlo generators model the $pp \rightarrow Z^0 Z^0$ and $pp \rightarrow WZ^0$ processes at leading-order (LO): PYTHIA [2], HERWIG [3], DKS [4], MCFM-LO [5] and Baur-Rainwater [6]. They were compared and found to predict consistent cross sections and kinematic distributions. Most programs deal with finite-width gauge bosons and include the $Z^0 \gamma^*$ interference, with a lower cut on the mass of the virtual photon typically at $5 \text{ GeV}/c^2$.

The studies described in this note are based on samples generated with PYTHIA: 21 560 $pp \rightarrow Z^0 Z^0 \rightarrow e^+e^-e^+e^-$ events, where the acceptance of final state electrons is restricted at generator level to $|\eta(e)| < 2.7$ and $p_T(e) > 5 \text{ GeV}/c$, and 91 181 $pp \rightarrow WZ^0$ events, where both W and Z^0 decay into leptons including τ leptons; no restrictions are imposed on the lepton phase space nor on the allowed τ decays. Final-state radiation is also modeled: the $Z^0 Z^0$ signal sample comprises about 22% of events with a decay $Z^0 \rightarrow e^+e^-(\gamma)$ and 2% of events with a decay $Z^0 \rightarrow e^+e^-(\gamma\gamma)$.

Generated events were passed through the full GEANT simulation of the CMS detector. Underlying events and pile-up corresponding to the low-luminosity phase of the LHC are included in the simulation.

Figure 2: Differential cross sections for the $pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ process at $\sqrt{s} = 14$ TeV as a function of the two- and four-electron mass as obtained with the MCFM Monte Carlo. Electrons are restricted to the phase space $p_T(e) > 5$ GeV/c and $|\eta(e)| < 2.7$. The solid-line distributions include the contribution of virtual photons, while the dashed-line distributions do not. The peaks around 120 GeV/c² and 50 GeV/c² in the solid-line distribution correspond to $Z^0 \gamma^*$ and $\gamma^* \gamma^*$ combinations.

Electron-positron pairs in the four-electron final state can originate from an on-shell Z^0 boson as well as from a virtual photon, γ^* . Figure 2 and 3 show that the four-electron final states receives sizable contributions from the $Z^0 \gamma^*$ and $\gamma^* \gamma^*$ processes. Similarly, Figure 4 illustrates the contribution of off-shell bosons to the $W Z^0$ channel: the peak at the W mass corresponds to the case of an on-shell W boson produced in the s -channel and decaying into an off-shell W and a virtual photon. Figure 5 shows the differential cross section of the $W Z^0$ channel as a function of the lepton transverse momentum, p_T . Only on-mass shell bosons are considered in Fig 5.

This study concentrates only on final states with two on-shell gauge bosons. In the following, a lepton pair from an on-shell Z^0 boson is defined as a lepton pair which, at generator level, originates from a common particle and has a mass between 70 and 110 GeV/c². All other lepton combinations are considered as virtual photons. Four-electron final state are therefore divided in three categories: $Z^0 Z^0$, $Z^0 \gamma^*$ and $\gamma^* \gamma^*$. Three-lepton final states are divided in $W Z^0$ and $W \gamma^*$ events. Table 1 summarises the fraction of events in each category. Excluding all virtual-photon contribution, the $Z^0 Z^0$ and $W Z^0$ signals amount to 72% and 95.5% of the simulated samples, respectively.

Table 1: Signal Monte Carlo samples and contribution from virtual photons and on-shell Z^0 bosons.

Data sample	Generator	N_{events}	$\int L dt, \text{fb}^{-1}$
$Z^0 Z^0 / \gamma^*$	PYTHIA	21560	827
$Z^0 Z^0$		15467(72%)	
$Z^0 \gamma^*$		5634(26%)	
$\gamma^* \gamma^*$		459(2%)	
$W^\pm Z^0 / \gamma^*$	PYTHIA	91181	54.7
$W^\pm Z^0$		87078(95.5%)	
$W^\pm \gamma^*$		4103(4.5%)	

The next-to-leading order (NLO) $Z^0 Z^0$ cross section is calculated with the MCFM [5] program to be:

$$\sigma_{\text{NLO}}(pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-; \sqrt{s} = 14 \text{ TeV}) = 18.7 \text{ fb}, \quad (1)$$

where the lepton phase-space cuts defined above are applied as well as the definition of on-shell bosons. Compatible results are found with the DKS [4] program. The NLO corrections to the LO cross-section corresponds to an overall k -factor of 1.37 and a harder p_T distribution of the Z^0 bosons, as shown in Figure 6. This dynamic

Figure 3: Differential cross sections for the $pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ process as a function of the electron transverse momentum. The solid-line distributions include the contribution of virtual photons, while the dashed-line distributions do not. Electrons are ordered from the highest- p_T one, top left, to the lowest p_T one bottom-right.

difference is taken into account to compute the average k -factor.

The use of an average k -factor is appropriate to estimate the number of expected signal events at the NLO, due to the non-relativistic nature of the Z^0 bosons and the mild dependence of the reconstruction efficiency on the Z^0 boson p_T . No NLO Monte Carlo generator for the $Z^0 Z^0$ process is available at the time of writing.

The cross section quoted above does not include contributions at the next-to-next-to-leading order nor those from the gluon-fusion box [4], $gg \rightarrow Z^0 Z^0$. These contributions could increase the signal cross section by as much as 20%.

The NLO WZ^0 cross sections are calculated with the MCFM program to be:

$$\sigma_{NLO}(pp \rightarrow W^+ Z^0; \sqrt{s} = 14 \text{ TeV}) = 32 \text{ pb} \quad (2)$$

$$\sigma_{NLO}(pp \rightarrow W^- Z^0; \sqrt{s} = 14 \text{ TeV}) = 19.5 \text{ pb}, \quad (3)$$

not including the leptonic branching fractions for the gauge bosons. Figure 7 illustrates the dynamic difference between the NLO and LO cross sections. They result into an average k -factor of 1.92.

2.2 Backgrounds

Background in the selection of $Z^0 Z^0$ and WZ^0 events arise from Standard Model processes with at least three lepton in the final state, two of which mimicking the signal signature of an on-shell Z^0 boson. The two main sources of background are $Z^0 b\bar{b}$ and $t\bar{t}$ production. The $Z^0 b\bar{b}$ background is potentially severe due to the presence of a Z^0 boson, while additional high- p_T leptons can originate from heavy-flavor hadron decays in b -quark jets. Leptons produced in $t\bar{t}$ final states can result in events within the Z^0 mass window. These leptons are from $W^\pm$ decays, from direct heavy-flavor hadron decays in b -quark jets or from a direct and a cascade decay within the

Figure 4: Differential cross section as a function of mass for the $pp \rightarrow W^+Z \rightarrow \mu^+\nu_\mu e^+e^-$ process at $\sqrt{s} = 14$ TeV, obtained with the MCFM program including (solid line) or not (dashed line) the contribution of virtual photons. The peak around the W mass ($80 \text{ GeV}/c^2$) corresponds to the radiation of virtual photons from on-shell W bosons. The behaviour of the two adjacent bins around $180 \text{ GeV}/c^2$ is due to a divergence in the NLO calculations.

same b -jet, even though this last case usually results in low-mass lepton pairs. Again, additional high- p_T leptons can originate from heavy-flavor hadron decays in b -quark jets.

The $Wb\bar{b}$ and $Z^0 + jets$ processes have large production cross sections and are potential sources of background. However, as discussed in Section 3.3.2, these processes are strongly suppressed by the event selection and are not detailed in the following. Four-lepton production through final-state radiation in s -channel Z^0 -boson production is also neglected since is expected to be highly suppressed by the selection cuts.

Despite their relatively-low cross-section, the Z^0Z^0 and $Z^0\gamma^*$ processes are also potential backgrounds for the WZ^0 analysis. The $Z^0\gamma^*$ process is also a background in the Z^0Z^0 analysis.

Other sources of background are due to the presence of one or more fake leptons. The WZ^0 and Z^0Z^0 analyses aim to strongly suppress this background to cope with the large cross section of the dominant background processes. To better tune the analyses, the $t\bar{t}$ and $Z^0b\bar{b}$ backgrounds are modeled by different Monte Carlo samples: semi-inclusive samples where only the gauge bosons are forced to decay into leptons and samples where four electrons are forced in the final state.

The background samples used in the analysis are summarized in Table 2. All generated events were passed through the full GEANT simulation of the CMS detector. Underlying events and pile-up corresponding to the low-luminosity phase of the LHC are included in the simulation. Table 2 also lists the Monte Carlo programs used in this generation, together with the generator-level cuts.

The total $t\bar{t}$ production cross section, computed at the NLO with MCFM, is $\sigma_{NLO} = 840 \text{ pb}$ (with a k -factor of 1.6). The top quark decays exclusively to Wb and the W decays into a lepton and a neutrino in 10.72% of the cases [7]. This process is simulated with TopRex [8] and PYTHIA. The total $Z^0b\bar{b}$ cross section, computed at the NLO with MCFM, is $\sigma_{NLO} = 276 \text{ pb}$ (with a k -factor of 2.4), including both on- and off-shell intermediate Z^0 boson. This process is simulated with CompHEP [9]. The decay fraction of the γ^* to leptons depends on the mass and becomes 3.36% for the on-shell Z^0 boson. Leptons are also produced in semileptonic decays of bottom or charmed hadrons within b - or c -quark jets. The probability of a direct lepton decay ($b \rightarrow \ell^- X$) in a b -jet is 10.9%, while the probability of a cascade lepton decay ($b \rightarrow c \rightarrow \ell^+ X$) is 9.6%.

The shorthands used to denote the main background samples, and relevant information on their generation are detailed in the following

- $t\bar{t}(2\ell)$. On-shell W bosons from $t \rightarrow Wb$ decays are forced to decay into $\ell\nu$ ($\ell = e, \mu, \tau$), with no further restriction on τ decays and b -quark fragmentation and decay
- $t\bar{t}(4e)$. At least four electrons within the acceptance cuts $|\eta(e)| < 2.7$ and $p_T(e) > 5 \text{ GeV}/c$ are required in the final state.

Figure 5: Differential cross sections as a function of $p_T(\ell)$ for the $pp \rightarrow W^+Z^0 \rightarrow \mu^+\nu_\mu e^+e^-$ process at $\sqrt{s} = 14$ TeV, obtained with the MCFM program with (solid line) or without (dashed line) the acceptance restriction $|\eta(e)| < 2.5$ used in the analysis. The top-left plot refers to the highest p_T lepton from Z^0 decay; the top-right plot to the other lepton from Z^0 decay; the bottom-left plot to the charged lepton from the W decay; the bottom-left to the neutrino from the W decay. Only on-shell Z^0 bosons are considered.

- $Z^0 b\bar{b}(e^+e^-b\bar{b})$ and $Z^0 b\bar{b}(\mu^+\mu^-b\bar{b})$ The Z^0 boson is forced to decay into either e^+e^- or $\mu^+\mu^-$, while no restriction is applied on b -quark fragmentation and decay. An additional requirement $60 < M(e^+e^-) < 100$ GeV/ c^2 is applied on the mass of the electron pair, effectively suppressing virtual-photon contribution.
- $Z^0/\gamma^* b\bar{b}(4e)$. The Z^0 boson or the virtual photon are forced to decay into e^+e^- and at least four electrons must be present in the final state, within the acceptance cuts $|\eta(e)| < 2.7$ and $p_T(e) > 5$ GeV/ c . The additional electron pair must satisfy $5 < M(e^+e^-) < 400$ GeV/ c^2 .

The k -factors and the product of the NLO cross sections, of the branching ratio ratios into leptons and of the kinematical factors associated to pre-selections at the generator level are presented in Table 3, together with the equivalent luminosity of the generated samples. The relevant branching fraction of the $W^\pm$ and Z^0 boson decays into leptons are [7]:

$$\begin{aligned}
 \mathcal{B}_1 &= \mathcal{B}(Z^0 \rightarrow e^+e^-) = 0.0336, \\
 \mathcal{B}_2 &= \mathcal{B}(Z^0 \rightarrow \mu^+\mu^-) = 0.0337, \\
 \mathcal{B}_3 &= \mathcal{B}(Z^0 \rightarrow \ell^+\ell^-; \ell = e/\mu) = 0.067, \\
 \mathcal{B}_4 &= \mathcal{B}(Z^0 \rightarrow \ell^+\ell^-; \ell = e/\mu/\tau) = 0.101, \\
 \mathcal{B}_5 &= \mathcal{B}(W^+ \rightarrow \ell^+\nu_\ell; \ell = e, \mu, \tau) = 0.32, \\
 \mathcal{B}_6 &= \mathcal{B}(W^+ \rightarrow \ell^+\nu_\ell; \ell = e, \mu, \tau; \tau \rightarrow \ell\nu_\ell) = 0.25.
 \end{aligned} \tag{4}$$

Figure 6: Left: differential cross section of the $pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ process as a function of the Z^0 p_T , calculated with the MCFM program at the NLO (solid line) and the LO (dashed line). Electrons are restricted to the phase space $p_T(e) > 5$ GeV/c and $|\eta(e)| < 2.7$ and the contribution from virtual photon is excluded. Right: ratio of the NLO to the LO differential cross sections a function of the Z^0 p_T ; the average k -factor, indicated by a horizontal dashed line, is $k = 1.37$.

Figure 7: Left: differential cross section of the $pp \rightarrow W^+ Z^0 \rightarrow \mu^+ \nu_\mu e^+ e^-$ process as a function of the Z^0 p_T , calculated with the MCFM program at the NLO (solid line) and the LO (dashed line). The contribution from virtual photon is excluded. Right: ratio of the NLO to the LO differential cross sections a function of the Z^0 p_T ; the average k -factor is $k = 1.92$.

Table 2: Summary of background samples used in the analysis.

Data sample	Generator	N_{events}	Preselection
$Z^0 b\bar{b}(e^+e^-b\bar{b})$	CompHEP	290823	$Z^0 \rightarrow e^+e^-$, $b \rightarrow X$, $60 < M(e^+e^-) < 100 \text{ GeV}/c^2$
$Z^0 b\bar{b}(\mu^+\mu^-b\bar{b})$	CompHEP	110148	$Z^0 \rightarrow \mu^+\mu^-$, $b \rightarrow X$, $60 < M(\mu^+\mu^-) < 100 \text{ GeV}/c^2$
$Z^0/\gamma^* b\bar{b}(4e)$	CompHEP	81000	$Z^0/\gamma^* \rightarrow e^+e^-$, at least $4e$, $M(e^+e^-) > 5 \text{ GeV}/c^2$
$t\bar{t}(2\ell)$	TopRex	378000	$W \rightarrow e/\mu/\tau$
$t\bar{t}(4e)$	PYTHIA	79000	$W \rightarrow e/\mu/\tau$, $\tau \rightarrow e/\mu$, at least $4e$
$Z^0/\gamma^* Z^0/\gamma^*(4e)$	PYTHIA	250000	$Z^0/\gamma^* \rightarrow e^+e^-$
$Z^0/\gamma^* Z^0/\gamma^*(4\mu)$	PYTHIA	8241	$Z^0/\gamma^* \rightarrow \mu^+\mu^-$
$Z^0/\gamma^* Z^0/\gamma^*(2e2\mu)$	PYTHIA	10000	$Z^0/\gamma^* \rightarrow 2\ell$, $\ell = e/\mu$

 Table 3: Total k -factor, product of the cross section (σ_{NLO}), branching fraction ($\mathcal{B}$), kinematical factor (ϵ_{KIN}) associated to the generator-level pre-selection, and equivalent integrated luminosity, for each of the samples used in this analysis.

Data sample	k -factor	$\sigma_{NLO} \times \mathcal{B} \times \epsilon_{KIN}$, fb	$\int L dt$, fb $^{-1}$
$Z^0 Z^0(4e)$	1.375	18.7	837
$W^+ Z^0(3\ell)$	1.92	1034	34.0
$W^- Z^0(3\ell)$	1.92	630	20.7
$Z^0 b\bar{b}(e^+e^-b\bar{b})$	2.4	60336	4.8
$Z^0 b\bar{b}(\mu^+\mu^-b\bar{b})$	2.4	60336	1.8
$Z^0/\gamma^* b\bar{b}(4e)$	2.4	120.3	673
$t\bar{t}(2\ell)$	1.6	62648	6.0
$t\bar{t}(4e)$	1.6	194.0	413
$Z^0/\gamma^* Z^0/\gamma^*(4e)$	1.375	26.0	9615
$Z^0/\gamma^* Z^0/\gamma^*(4\mu)$	1.375	26.0	317
$Z^0/\gamma^* Z^0/\gamma^*(2e2\mu)$	1.35	32.3	310

3 Analysis

3.1 Trigger and event reconstruction

The analyses discussed in this note are based on the selection of three or more charged leptons with the techniques discussed in the following both at the trigger level and the reconstruction level. Leptons originating from b-quarks as well as events containing additional hard jets are a background to suppress. Their identification is also discussed in the following.

3.1.1 Trigger

$Z^0 Z^0$ candidate events with four high- p_T electrons are selected by either of two high-level triggers (HLT): single electron and double electron. Trigger efficiencies for the $Z^0 Z^0$ signal and the main background sources are listed in Table 4.

$W Z^0$ candidate events are selected by either of four HLT: single electron, double electron, single muon and double muon. The trigger efficiencies of each HLT combination for each of the four final states, $e^\pm e^+ e^-$, $\mu^\pm e^+ e^-$, $e^\pm \mu^+ \mu^-$ and $\mu^\pm \mu^+ \mu^-$, are summarised in Table 5 together with their total.

The level-one and HLT efficiencies for events retained by the complete $Z^0 Z^0$ and $W Z^0$ event selections discussed below are 100%.

Table 4: Trigger efficiencies for the $Z^0 Z^0$ signal and for the main background sources.

Sample	Single electron	Double electron	Single electron OR double electron
$Z^0 Z^0$	97.3%	98.4%	99.5%
$Z^0 b\bar{b}(e^+ e^- b\bar{b})$	85.5%	77.6%	92.1%
$Z^0 b\bar{b}(4e)$	87.7%	81.1%	93.9%
$t\bar{t}(2\ell)$	82.0%	70.3%	89.6%
$t\bar{t}(4e)$	78.2%	68.9%	86.9%

Table 5: Trigger efficiencies for the $W Z^0$ signal.

	3e	2e1 μ	1e2 μ	3 μ
Single electron	74.3 %	59.9 %	35.4 %	0.09 %
Double electron	60.3 %	38.1 %	0.29 %	0.01 %
Single OR double electron	79.6 %	63.3 %	35.4 %	0.10 %
Single muon	0.03 %	54.2 %	74.0 %	88.2 %
Double muon	0.01 %	0.16 %	46.6 %	67.0 %
Single OR double muon	0.03 %	54.2 %	74.3 %	88.7 %
Electron OR muon	79.6 %	83.9 %	83.2 %	88.7 %

3.1.2 Electron identification

Electron candidates are defined from clusters in the electromagnetic calorimeter associated to charged tracks. In order to reduce the small fraction of mis-matching, we require that the electron candidates satisfy $0.75 < E/P < 3.0$, where E is the cluster energy and P the track momentum, as shown in Figure 8.

Figure 8: E/P distribution for electron candidates, where E is the cluster energy and P the track momentum. The arrows show the selection cut $0.75 < E/P < 3.0$.

Figure 9 presents the reconstruction efficiency for electrons of the $Z^0 Z^0 \rightarrow 4e$ sample as a function of p_T and η . A reconstruction efficiency of 80.3% is observed for $p_T > 10$ GeV/c. This figure is mostly due to the tracking geometrical acceptance and to the track-matching efficiency. This is illustrated in Figure 9 where the efficiency decreases as a function of η , as the amount of material in the tracker system increases, corresponding to a higher Bremsstrahlung probability. The drop in efficiency around $|\eta| = 1.5$ corresponds to the transition between the barrel and end-cap region of the electromagnetic calorimeter. An efficiency of 0.7% is observed for fake electrons, *i.e.* electron candidates which do not correspond to a generated electron.

The following isolation cuts are defined to reject electron candidates originating from heavy quark semileptonic decays:

Figure 9: Reconstruction efficiencies for electron candidates as a function of p_T (left) and η (right).

- $HoE \equiv E^{HCAL}/E^{ECAL} < 0.08$, the ratio of energy deposited in the hadronic calorimeter to that deposited in the electromagnetic, in the region defined by the hadronic trigger tower behind the super-cluster crystal with highest energy;
- $IsoTrack \equiv (\sum_i (p_T^i - E_T^{SC})) / E_T^{SC} < 0.34$, where E^{SC} is the cluster energy and the sum runs over all tracks reconstructed with at least five hits in the tracker and with transverse momentum $p_T^i > 2 \text{ GeV}/c$, within a cone $\Delta R < 0.20$ around the electron direction;
- $NbTrack < 3$, where $NbTrack$ is the number of tracks reconstructed with at least five hits in the tracker and with transverse momentum $p_T > 2 \text{ GeV}/c$, within a cone $\Delta R < 0.15$ around the electron direction;

Figure 10 compares the distributions of the three isolation variables for electrons from the $Z^0 Z^0 \rightarrow 4e$ process and electrons from B-hadron decay in the background processes. The values of the cuts presented above are determined either by maximizing S/B , where S and B are the cross-section-weighted number of selected events for the signal and the background, respectively, or requiring a 98% signal efficiency.

The efficiency of the isolation criteria for signal electrons as well as the efficiencies for fake and non-isolated electrons in the background samples are listed in Table 6. To compare the efficiencies, only $Z^0 b\bar{b}$ and $t\bar{t}$ events with at least four electrons generated with $p_T > 5 \text{ GeV}/c$ and $|\eta| < 2.7$ are considered.

Table 6: Cut efficiencies for electron candidates in signal and background samples. The background efficiencies refer to events with at least four electrons generated with $p_T > 5 \text{ GeV}/c$ and $|\eta| < 2.7$. Only statistical uncertainties are shown.

	Samples	Efficiency
	$Z^0 Z^0$	$96.7 \pm 0.2\%$
	$Z^0 b\bar{b}(e^+ e^- b\bar{b})$	$7.8 \pm 0.4\%$
Fake Electrons	$Z^0 b\bar{b}(4e)$	$5.9 \pm 0.7\%$
	$t\bar{t}(2\ell)$	$3.0 \pm 0.3\%$
	$t\bar{t}(4e)$	$3.6 \pm 0.3\%$
	$Z^0 b\bar{b}(e^+ e^- b\bar{b})$	$37.8 \pm 1.4\%$
Non Isolated Electrons	$Z^0 b\bar{b}(4e)$	$27.1 \pm 0.5\%$
	$t\bar{t}(2\ell)$	$18.5 \pm 0.9\%$
	$t\bar{t}(4e)$	$17.4 \pm 0.4\%$

3.1.3 Muon identification

Muon candidates are reconstructed from information in the muon chambers and the tracker. Leptons from the decay of b quarks in the background processes are produced in a higher-multiplicity environment and two isolation

Figure 10: Distributions of isolation variables for electron candidates: (top) HoE , (middle) $IsoTrack$ and (bottom) $NbTrack$. Electron candidates of $Z^0Z^0 \rightarrow 4e$ signal are matched with generated electrons. Background histograms are formed by electron coming from B-hadron decay. Distributions are normalized to the number of entries and superimposed.

criteria suppress the background contamination:

- the sum of the p_T of tracks within a $\Delta R = 0.25$ cone around the muon must be smaller than 2 GeV/ c ;
- the energy measured in the calorimeters within a $\Delta R = 0.3$ cone around the muon must be smaller than 5 GeV.

Figures 11 present the distributions of these isolation variables for the signal and background processes. The distribution for the $Z^0b\bar{b}(e^+e^-b\bar{b})$ sample are particularly interesting, since muons only stem from b -quark decays.

3.1.4 Identification of semileptonic b-decays

The significance of the lepton impact-parameter in the plane transverse to the beam, S_{IP} , discriminates against leptons from heavy-quark decays in all Standard Model background processes. This variable is defined as the ratio between the measured impact parameter and its uncertainty. Figure 12 shows distribution of the S_{IP} for muons from the WZ^0 signal and from the background samples. We require $S_{IP} < 3$ for all three leptons in the WZ^0 candidate selection. Figure 13 shows the reconstruction efficiency for muons with all selection criteria to be applied.

Figure 11: Muon isolation variables for the signal and backgrounds: the plots in the left column show the sum of p_T of tracks in a $0.25 \Delta R$ cone around the muon candidate, while the plots in the right column show the energy deposited in the calorimeters around the muon within a $\Delta R = 0.3$ cone.

Figure 12: Distributions of the significance of the transverse impact-parameter for muons of the WZ^0 signal and the main sources of background. The background distributions show the different contributions of muons originating from W -bosons in top-quark decays, B -hadron decay, D -hadron decays and other sources.

Figure 13: Muon reconstruction efficiency as a function of p_T (left) and η (right).

3.1.5 Jet reconstruction

The $t\bar{t}$ background to the WZ^0 selection is characterised by the presence of high E_T jets and can be largely suppressed by applying a jet veto. Jet reconstruction is optimised by selecting towers with $E_T^{tower} > 0.5$ GeV and $E^{tower} > 0.8$ GeV, therefore reducing the contribution from noise and the fraction of fake jets [10]. Jets which are close to a lepton candidate, with $\Delta R(jet, \ell) < 0.3$, are not considered. The number of jet with $E_T^{jet} > 25$ GeV reconstructed for the signal and the different background processes is plotted in Figure 14.

Figure 14: Jet multiplicity with $E_T^{jet} > 25$ GeV in the signal and background samples

3.2 Event selection

3.2.1 Selection of $Z^0 Z^0$ events

Z^0 candidates are formed from pairs of electron candidates with opposite charge and mass between 50 and 120 GeV/c². Pairs of Z^0 candidates containing four different electrons are combined to form di-boson $Z^0 Z^0$ candidates. The transverse momenta of the electron candidates, ordered from the largest to the smallest, have to be above 30, 20, 15, and 10 GeV/c, respectively. These thresholds are inspired by the differential cross sections presented in Figure 3. These cuts suppress the contribution from the $Z^0 \gamma^*$ and $\gamma^* \gamma^*$ final states and reduce by

30% and 60% the $t\bar{t}$ and $Z^0 b\bar{b}$ backgrounds, respectively.

Due to the relatively large mass window used in this analysis, there is a possible ambiguity in the assignment of the four electrons to the two Z^0 candidates. Of the two possible $Z^0 Z^0$ pairings, the one for which the Z^0 candidate masses are closest to the nominal Z^0 -boson mass, m_Z , is chosen. This pairing is correct for almost all events with two on-shell Z^0 bosons. For 2.5% of the events, more than four electrons are present and only the $Z^0 Z^0$ pairing which contains the highest- p_T electron is retained; this choice is correct for 98.3% of the cases.

The e^+e^- mass distribution for the signal is shown in Figure 15 with two entries per Z^0 candidate. A small fraction of the selected candidates, 2.4%, is due to $Z^0\gamma^*$ events. The corresponding e^+e^- mass distribution is shown as a solid histogram: It presents a peak at the Z^0 mass, corresponding to the on-shell Z^0 boson, and a continuum of events below $70 \text{ GeV}/c^2$ corresponding to the virtual photon. Figure 16 shows the distribution of the difference between the reconstructed and generated e^+e^- masses for the Z^0 candidates, $\Delta M = M^{\text{meas}} - M^{\text{gen}}$. A fit to the ΔM distribution estimates a mass resolution of $1 \text{ GeV}/c^2$ for the $Z^0 \rightarrow e^+e^-$ decay channel.

Figure 15: Distribution of the e^+e^- mass for the candidate events, open histogram. The contribution from $Z^0\gamma^*$ events is shown as the solid histogram.

Figure 16: ΔM distribution for $Z^0 \rightarrow e^+e^-$ candidates retained by the $Z^0 Z^0$ event selection. The results of a Gaussian fit are overlaid.

3.2.2 Selection of $W Z^0$ events

Events with three charged leptons, either electrons or muons, with $p_T > 10 \text{ GeV}/c$ and $|\eta| < 2.5$, are considered by the $W^\pm Z^0$ selection. All possible Z^0 -boson candidates from same-flavour opposite-charge lepton pairs are formed. Events are retained if the mass of the Z^0 candidate is within $20 \text{ GeV}/c^2$ of m_Z . Figure 17 shows the distribution of the difference between the reconstructed and generated muon-pair masses for the Z^0 candidates, $\Delta M = M^{\text{meas}} - M^{\text{gen}}$. A fit to the ΔM distribution estimates a mass resolution of $1 \text{ GeV}/c^2$ for the $Z^0 \rightarrow \mu^+\mu^-$ decay channel.

The remaining lepton is associated to the $W^\pm$ -boson decay; its transverse momentum must be larger than $20 \text{ GeV}/c$. If the event contains more than three leptons, the lepton with highest p_T is chosen as originating from the $W^\pm$. The highest- p_T lepton associated to the Z^0 boson must satisfy $p_T > 15 \text{ GeV}/c$. The background from $Z^0 Z^0$ final states is reduced by rejecting events with a second Z^0 candidate with a mass within $40 \text{ GeV}/c^2$ of m_Z . This second Z^0 candidate is formed with all possible same-flavour opposite-charge combinations which are left after removing the two leptons already used for the first Z^0 candidate.

The four possible final states of $W Z^0$ decay, $e^\pm e^+ e^-$, $\mu^\pm e^+ e^-$, $e^\pm \mu^+ \mu^-$ and $\mu^\pm \mu^+ \mu^-$, are associated to four possible classes denoted as follows:

Figure 17: ΔM distribution for $Z^0 \rightarrow \mu^+ \mu^-$ candidates retained by the WZ^0 event selection. The results of a Gaussian fit are overlaid.

Name	Final state
3e	$W \rightarrow e\nu, Z^0 \rightarrow e^+e^-$
2e1μ	$W \rightarrow \mu\nu, Z^0 \rightarrow e^+e^-$
2μ1e	$W \rightarrow e\nu, Z^0 \rightarrow \mu^+\mu^-$
3μ	$W \rightarrow \mu\nu, Z^0 \rightarrow \mu^+\mu^-$

3.3 Signal and background yields

3.3.1 $Z^0 Z^0$ sample

Table 7: Efficiency of the $Z^0 Z^0$ selection for the signal and background processes together with the event yield for 1 fb^{-1} .

	$Z^0 Z^0$	$Z^0 b\bar{b}(e^+e^-b\bar{b})$	$Z^0 b\bar{b}(4e)$	$t\bar{t}(2\ell)$	$t\bar{t}(4e)$	$WZ^0(3\ell)$
Efficiency, %	37.9		$6.54 \cdot 10^{-2}$		$6.46 \cdot 10^{-2}$	
Events/ fb^{-1}	7.1	< 0.2	0.08 ± 0.01	< 0.2	0.12 ± 0.02	< 0.02

The efficiencies for the $Z^0 Z^0$ signal and the various background samples are presented in Table 7. The background estimation is performed mainly with the $Z^0 b\bar{b}(4e)$ and $t\bar{t}(4e)$ samples, which are selected at the generator level with four electrons in the final state.

The $Z^0 b\bar{b}(e^+e^-b\bar{b})$ and $t\bar{t}(2\ell)$ samples are used mostly as a cross check. No event is selected for these two samples, resulting in an upper limit on the number of expected events per fb^{-1} . These limits are compatible with the expectations from the $Z^0 b\bar{b}(4e)$ and $t\bar{t}(4e)$ samples. There is no significant contribution from the $W^\pm Z^0$ process.

Figures 18 and 19 show the e^+e^- mass distribution equivalent to 10 fb^{-1} of data, with two entries per event, for the $t\bar{t}$ and $Z^0 b\bar{b}$ backgrounds, respectively. The effect of releasing the cut on the electron p_T is also illustrated.

Figure 18: Mass distribution of the e^+e^- pairs for selected events of the $t\bar{t}$ background, normalized to 10fb^{-1} of data, with two entries per event. The dashed histogram represents the distribution after all cuts, while the solid histogram shows the effect of relaxing the cuts on the electron p_T .

Figure 19: Mass distribution of the e^+e^- pairs for selected events of the $Z^0b\bar{b}$ background, normalized to 10fb^{-1} of data, with two entries per event. The dashed histogram represents the distribution after all cuts, while the solid histogram shows the effect of relaxing the cuts on the electron p_T .

3.3.2 WZ^0 sample

The number of events expected in 1fb^{-1} of integrated luminosity and the selection efficiencies for the WZ^0 signal and the various background samples are presented in Tables 8 and 9, which also illustrate the sequential effect of each selection cut. The $t\bar{t}(2\ell)$ and $Z^0b\bar{b}$ final states are the most pernicious backgrounds, given their large cross section. They are usually associated with one or more hard jets. These backgrounds are reduced by removing events with at least one jet, as discussed in Section 3.1.5.

Table 8: Expected number of signal and background events passing the different selections steps for an integrated luminosity of 1fb^{-1} .

Selection step	$WZ \rightarrow 3\ell$	$t\bar{t} \rightarrow 2\ell$	$e\bar{e}b\bar{b}$	$\mu\mu b\bar{b}$
Found Z^0 candidate	468 (29.3 %)	3160 (5.1 %)	25800 (43 %)	51200(85.3 %)
Only one good Z^0	440 (27.5 %)	3100 (5 %)	25700 (42.9 %)	50700 (84.5 %)
Second Z^0 veto	437 (27.3 %)	3070 (4.95 %)	25700 (42.9 %)	50700 (84.5 %)
Found third (W) lepton	191 (11.9 %)	869 (1.4 %)	1790 (2.99 %)	3190 (5.3 %)
W lepton p_T cut	148 (9.23 %)	432 (0.70 %)	239 (0.398 %)	360 (0.6 %)
S_{IP} cut	136 (8.48 %)	220 (0.36 %)	120 (0.2 %)	223 (0.37 %)
Isolation cut on Z^0 leptons	126 (7.9 %)	111 (0.18 %)	120 (0.2 %)	178 (0.30 %)
Isolation cut on W lepton	117 (7.29 %)	40.9 (0.07 %)	4.9 (0.008 %)	20.7 (0.03 %)
Jet veto	104 (6.52 %)	7.13 (0.012 %)	3.0 (0.005 %)	12.5 (0.02 %)
Z^0 window	96.8 (6.05 %)	2.79 (0.005 %)	3.0 (0.005 %)	11.4 (0.02 %)

In addition to the background sources listed in Tables 8 and 9, also the $pp \rightarrow Wb\bar{b}$ and the $pp \rightarrow Z^0 + jets$ were considered. The former might mimic a Z^0 boson with a lepton coming from the $W^\pm$ -boson decay and a lepton from heavy quark decays, or both lepton from heavy quark decays. As the mass of the this lepton pair tends to be small, no events survive the WZ^0 selection. The $pp \rightarrow Z^0 + jets$ process may be a potential source of background in presence of fake leptons from the jets. No events from a dedicated Pythia Monte Carlo survived the selection. However, given the large cross section of this process, this study is extended. A limit of 1 event per fb^{-1} is derived by combining the probability for a fake lepton to be retained by the selection cuts, 1.3×10^{-3} , and the selection efficiency for the $Z^0 b\bar{b}$ process.

Table 9: Expected number of events passing the different selections steps for various backgrounds for an integrated luminosity of 1 fb^{-1} .

Selection step	$ZZ \rightarrow 2e2\mu$	$ZZ \rightarrow 4e$	$ZZ \rightarrow 4\mu$
Found Z^0 candidate	18.6 (49.0 %)	13.5 (71.2 %)	15.5 (81.4%)
Only one good Z^0	18.6 (49.0 %)	7.3 (38.6 %)	6.7 (35.4%)
Second Z^0 veto	14.0 (36.8 %)	4.8 (25.0 %)	6.2 (32.7%)
Found third (W) lepton	11.3 (29.7 %)	3.2 (16.9 %)	5.7 (29.9%)
W lepton pt cut	6.9 (18.3 %)	2.2 (11.5 %)	2.8 (14.7%)
S_{IP} cut	6.2 (16.2 %)	1.9 (9.9 %)	2.5 (13.2%)
Isolation cut on Z^0 leptons	5.6 (14.8 %)	1.9 (9.9 %)	2.1 (11.2%)
Isolation cut on W lepton	4.9 (12.8 %)	1.6 (8.4 %)	1.9 (10.0%)
Jet veto	3.3 (8.6 %)	0.7 (3.7 %)	1.7 (8.8%)
Z^0 window	3.0 (8.0 %)	0.6 (3.3 %)	1.5 (8.0%)

4 Systematics

Several sources of systematic uncertainty will affect the calculation of the significance of the first observation of the WZ^0 and Z^0Z^0 signals at the LHC and the measurement of their cross sections. They are listed in the following.

- **Luminosity.** The knowledge of the integrated luminosity affects the measurement of the cross section of the WZ^0 and Z^0Z^0 signals, but not the calculation of the significance of their first observation. Systematic uncertainties of 10% and 5% are assigned for the luminosity measurement of the first 1 fb^{-1} and 10 fb^{-1} , respectively.
- **Trigger efficiency.** The uncertainty on the efficiency of the level-one and HLT triggers, presented in Tables 4 and 5, is assumed to be 1%.
- **Background subtraction.** The level of background retained by the WZ^0 and Z^0Z^0 selections will be estimated from a study of the side bands of the l^+l^- mass distribution. At the same time, the signal yield will be derived from a maximum-likelihood fit to the l^+l^- mass distribution. This procedure will be sensitive to the shape of the main background components, mostly of the $Z^0b\bar{b}$ background which exhibits a peak behaviour in the di-lepton mass. The $t\bar{t}$ background does not have such a peak. These shapes will be derived from Monte Carlo simulations and checked on data. The high purity of the selections makes them rather insensitive to this source of systematic uncertainty, evaluated at 0.6%.
- **$Z^0\gamma^*$ subtraction.** Events retained by the Z^0Z^0 selection comprise several components: correctly-reconstructed, wrongly-reconstructed and cross-feed from $Z^0\gamma^*$ process. The last contribution is estimated to 2.4% of the final sample as discussed in 3.2. Since only half of the $Z^0\gamma^*$ contribution peaks around m_Z in the e^+e^- mass spectrum, we conservatively assign a 1.2% systematic uncertainty on the estimation of this contribution. This is a conservative limit since the $Z^0\gamma^*$ component could be included in a global maximum-likelihood fit to estimate the signal yield.
- **Electron identification:** The control of the electron identification-efficiency is a potential source of systematic uncertainty due to possible discrepancies between data and Monte Carlo simulations. These effects will be extensively studied with high statistics control samples such as $Z^0 \rightarrow e^+e^-$ decays from the inclusive production of Z^0 bosons which has a large cross section of 15 nb. A statistical precision on the control of electron efficiency of better than 1% is expected with less than 1 fb^{-1} of data [11]. Taking into account a tracking efficiency uncertainty of 1% per track, we assign an uncertainty of 2% per identified electron for the first fb^{-1} of integrated luminosity, expected to decrease to 1.5% with 10 fb^{-1} .
- **Muon identification:** The muon identification-efficiency will be measured from data by using $Z^0 \rightarrow \mu^+\mu^-$ control sample, with a procedure similar to the one outlined above for electrons. Given the similar statistical power of this method for the two channels, the same systematic uncertainty for muon identification is assigned as for electron identification.
- **Jet energy scale resolution:** The efficiency of the jet veto cut depends on the energy scale uncertainty. The effect of this uncertainty, taken as 10% for jets with $E_T > 20 \text{ GeV}$, is assessed by varying accordingly the threshold of the jet veto and observing the corresponding changes in the event yield.

- **PDF and QCD scale uncertainty:** The estimation of the signal significance is affected by the uncertainty on the number of expected events, due to the limited knowledge of signal cross section. This source of uncertainty does not affect the measurement of the signal cross sections. For the $Z^0 Z^0$ process, a 6.4% uncertainty is assigned to the QCD scale and the PDF parameterization [12]. For the $W Z^0$ process, different PDF parametrizations and QCD scales are used to compute the production cross section with the MC@NLO Monte Carlo generator [13]. A 3.7% difference is observed in the cross section, which propagates to the signal yield. The kinematics of the event, and therefore the selection efficiencies, also depend on the PDF. This effect however is assumed to be small for the signal, and is neglected as a source of systematics.

The sources of systematic uncertainties and their effects on the estimation of the cross section and signal significance of the $pp \rightarrow Z^0 Z^0$ process are summarised in Tables 10 and 11, respectively, for integrated luminosities of 1 fb^{-1} and 10 fb^{-1} . Table 12 lists the corresponding systematic uncertainties for the $pp \rightarrow W Z^0$ process in 1 fb^{-1} of integrated luminosity. These are calculated weighting the four different final states according to their yield. All sources of systematic uncertainties are considered as uncorrelated.

Table 10: Systematic uncertainties in percent for the $pp \rightarrow Z^0 Z^0$ cross section measurement for 1 and 10 fb^{-1} of integrated luminosity.

Source of systematic uncertainty	$\int L dt = 1 \text{ fb}^{-1}$	$\int L dt = 10 \text{ fb}^{-1}$
Luminosity	10.0	5.0
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0 \gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
Total	12.9	7.9

Table 11: Systematic uncertainties in percent for the estimation of the significance of a $pp \rightarrow Z^0 Z^0$ signal in 1 and 10 fb^{-1} of integrated luminosity.

Source	$\int L dt = 1 \text{ fb}^{-1}$	$\int L dt = 10 \text{ fb}^{-1}$
Trigger efficiency	1.0	1.0
Background subtraction	0.6	0.6
$Z^0 \gamma^*$ subtraction	1.2	1.2
Electron identification	4×2.0	4×1.5
PDF and QCD scale factor	6.4	6.4
Total	18.4	14.9

Table 12: Systematic uncertainties in percent for the $pp \rightarrow W Z^0$ cross section measurement and significance estimation for 1 fb^{-1} of integrated luminosity.

Systematic source	Cross section	Significance
Luminosity	10.0	—
Trigger efficiency	1.0	1.0
Electron identification	2.6	5.2
Muon identification	3.4	6.8
Jet energy scale	5.0	5.0
$Z^0 b\bar{b}$ subtraction	12.0	12.0
$Z^0 Z^0 \rightarrow 4l$ subtraction	4.0	4.0
PDF uncertainty	—	3.5
Total	17.4	20.8

5 Results

The expected event yield is computed as:

$$N_{\text{events}} = \frac{N_{\text{reco}}}{N_{\text{gen}}} \cdot \sigma_{NLO} \cdot \mathcal{B} \cdot \epsilon_{KIN} \cdot \int L dt, \quad (5)$$

where the kinematical factors $\sigma_{NLO} \cdot \mathcal{B} \cdot \epsilon_{KIN}$ for the different data samples are presented in Table 3. The event yields for the signal and the background sources in the $Z^0 Z^0$ and $W Z^0$ selections are summarized in Tables 13 and 14, respectively.

An estimator based on the likelihood ratio

$$S_L = \sqrt{2 \ln Q}, \quad Q = \left(1 + \frac{N_S}{N_B}\right)^{N_S + N_B} e^{-N_S} \quad (6)$$

is used to assess the significance of the signal observation. Figures 20 and 21 show the expected signal significance as a function of integrated luminosity for the $Z^0 Z^0$ and $W Z^0$ analyses, respectively. The dashed line corresponds to a signal efficiency taking into account a worsening by 2% per lepton of the identification efficiency. The dotted line accounts for the systematic uncertainties listed in Tables 11 and 12.

A five-sigma significance for the $Z^0 Z^0$ observation is expected for about one inverse femtobarn on integrated luminosity, while $W Z^0$ production will be observed at five sigma with just 150 inverse picobarn.

Figure 22 presents the e^+e^- mass spectrum found by the $Z^0 Z^0$ selection, with two entries per event, as expected in 10 fb^{-1} of integrated luminosity at the LHC. Figures 23 and 24 present the $p_T(e^+e^-)$ and $M(Z^0 Z^0)$ spectra for 100 fb^{-1} . In all cases the background level is expected to be very small. Furthermore the backgrounds do not populate the high p_T and high $Z^0 Z^0$ -mass regions, most sensitive to the effects of anomalous triple-gauge-boson couplings.

Figure 25 shows the $M(l^+l^-)$ distribution for the $W Z^0$ selected events in 1 fb^{-1} of integrated luminosity, summed on the four different final states. Figure 26 presents the separate $M(l^+l^-)$ distributions for each channel, also for 1 fb^{-1} of integrated luminosity.

Table 13: Yield of the $Z^0 Z^0$ selection for integrated luminosities of 1 fb^{-1} and 10 fb^{-1} . The last row indicates the signal significance, which include systematic effects.

	Efficiency, %	$N_{\text{events}}/1\text{fb}^{-1}$	$N_{\text{events}}/10\text{fb}^{-1}$
$Z^0 Z^0$	38	7.1	71.1
$Z^0 \gamma^*$	4.5	0.16	1.60
$Z^0 b\bar{b}$	0.07	0.08	0.84
$t\bar{t}$	0.06	0.12	1.22
Total background	–	0.36	3.66
S_L	–	4.8	13.1

Table 14: Yield of the $W^\pm Z^0$ selection for an integrated luminosity of 1 fb^{-1} . The last row indicates the signal significance, which include systematic effects.

	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency, %
$W^\pm Z^0 \rightarrow \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.19	4.7
$t\bar{t}$	0.93	1.55	–	0.31	2.79	0.02
$\mu^+ \mu^- b\bar{b}$	–	–	6.54	4.9	11.4	0.005
$e^+ e^- b\bar{b}$	1.21	1.82	–	–	3.03	0.005
Total background	2.8	4.9	8.0	6.7	22.5	–
S_L	5.3	7.3	6.5	6.6	12.8	–

6 Conclusion and outlook

The sensitivity of the CMS experiment to the detection and study of the $pp \rightarrow Z^0 Z^0 \rightarrow e^+e^-e^+e^-$ and $pp \rightarrow W Z^0 \rightarrow 3l$ ($l = e, \mu$) processes is investigated. Signal and background Monte Carlo samples processed through

Figure 20: S_L significance for the observation of a $Z^0 Z^0$ signal as a function of the integrated luminosity. The solid line corresponds to an ideal simulation of the electron efficiency. The dashed line presents the result of a decrease of this efficiency of 2% per electron. The dotted line shows the effect of the systematic uncertainties.

Figure 21: S_L significance for the observation of a $W Z^0$ signal as a function of the integrated luminosity. The solid line corresponds to an ideal simulation of the lepton efficiencies. The dashed line presents the result of a decrease of this efficiency of 2% per lepton. The dotted line shows the effect of the systematic uncertainties.

Figure 22: The e^+e^- mass distribution expected for the $Z^0 Z^0$ selection with 10 fb^{-1} of integrated luminosity, two entries per event. The contributions of the three main backgrounds, $Z^0 \gamma^*$, $t\bar{t}$, and $Z^0 b\bar{b}$, are indicated.

Figure 23: The e^+e^- p_T spectrum, two entries per event, expected for the $Z^0 Z^0$ selection with 100 fb^{-1} of integrated luminosity. The contributions of the three main background, $Z^0 \gamma^*$, $t\bar{t}$, and $Z^0 b\bar{b}$, are indicated.

Figure 24: The $Z^0 Z^0$ mass distribution, two entries per event, expected for the $Z^0 Z^0$ selection with 100 fb^{-1} of integrated luminosity. The contributions of the three main background, $Z^0 \gamma^*$, $t\bar{t}$, and $Z^0 b\bar{b}$, are indicated.

Figure 25: Di-lepton mass distribution expected for the WZ^0 selection with 1 fb^{-1} of integrated luminosity. The contributions of the three main background, $Z^0 b\bar{b}$, $t\bar{t}$, and $Z^0 Z^0$, are indicated.

the full simulation, reconstruction and analysis chain of CMS are used.

The NLO cross section of the $pp \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ process, within the four-electron acceptance of the CMS detector, is calculated to be 18.7 fb . The present analysis selects 38% of this signal with a yield of 7.1 signal events for 0.4 background events per inverse femtobarn of LHC integrated luminosity. The WZ^0 selection results in a yield of 97 signal for 21 background events per inverse femtobarn.

For the first 1 fb^{-1} of integrated luminosity, the total systematic uncertainties on the $Z^0 Z^0$ and WZ^0 cross section determinations are 12.9% and 17.4%, respectively. Both the $Z^0 Z^0$ and WZ^0 final states can be selected with high purity and a significance of 4.8 and 12.8, which include systematic effects, is expected in the first 1 fb^{-1} of integrated luminosity. The WZ^0 channel can be observed with a significance of 5, including systematic uncertainties on detector effects and theoretical predictions, in an integrated luminosity of 150 pb^{-1} .

The relatively large signal yield and low level of background for the the $Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$ and $WZ^0 \rightarrow 3l$ channels makes them particularly attractive for the study of anomalous triple gauge boson couplings, even with as low as 10 fb^{-1} of data.

In case of a very massive Higgs boson, extracting a Higgs boson to $Z^0 Z^0$ signal, and determining its spin-parity, will require a detailed understanding of the Z^0 boson polarization and of spin correlations in the $pp \rightarrow Z^0 Z^0$ process. This study can start with relatively modest integrated luminosity.

In perspective, this study of multiple gauge-boson production and couplings at the LHC will be extended to include the $W^\pm \gamma$ [14] and $Z^0 \gamma$ [15] channels, as well as the other flavours of $Z^0 Z^0$ fully-leptonic decays.

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Figure 26: Di-lepton mass distribution expected for the WZ^0 selection with 1 fb^{-1} of integrated luminosity for each final state: $3e$ (top-left), $2e1\mu$ (top-right), $2\mu1e$ (bottom-left), 3μ (bottom-right). The contributions of the three main background, $Z^0 b\bar{b}$, $t\bar{t}$, and $Z^0 Z^0$, are indicated.

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