MEASUREMENT OF DIBOSON PRODUCTION WITH CMS*

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We investigate the CMS potential for the observation and study of the $pp \to Z^0Z^0 \to e^+e^-e^+e^-$ and $pp \to WZ^0 \to 3\ell$ ($\ell = e, \mu$) reactions, using fully simulated signal and background samples. It is shown that these processes are potentially accessible with early CMS data, thanks to relatively high production cross sections at LHC energies, together with clear signatures of the multi-lepton final states. The main systematic effects relevant for cross section measurements with 1 and $10\,\mathrm{fb}^{-1}$ 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 $1\,\mathrm{fb}^{-1}$ or less.

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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. The production of $W^\pm Z^0$ and $W^\pm\gamma$ events at the LHC probes triple gauge-boson couplings and, therefore, the non-Abelian gauge symmetry of the Standard Model. On the other hand, no neutral gauge-boson couplings exist in the Standard Model thus anomalies in Z^0Z^0 and $Z^0\gamma$ production, hinting at large s-channel contributions, could be the first indirect manifestation of New Physics. In the following, the selections of $W^\pm Z^0$ and Z^0Z^0 events are described, their signal-over-background ratio discussed and the outlook for an early measurement of multiple gauge-boson production is assessed. Further details are given in Ref. [1].

The Z^0Z^0 production represents an irreducible background to the most-awaited discovery at the LHC: the Standard Model Higgs boson. Its early measurement is, therefore, important. In general, the multi-lepton final states

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of multiple gauge-boson production are an important background in the search for New Physics, in particular Supersymmetry. A sound understanding of the production process of multiple gauge-bosons is, therefore, needed in the first phase of LHC data-taking before any discovery can be claimed.

The cross sections for multiple gauge-boson production at the LHC are about 50 pb for the $W^{\pm}Z^0$ channel and 20 pb for the Z^0Z^0channel [2]. These large cross sections and the clean signature of fully-leptonic final states make $W^{\pm}Z^0$ and Z^0Z^0production observable in the first LHC data. Final states, where the gauge-bosons decay into electrons and muons, are considered in these analyses: $e^{\pm}e^+e^-$, $\mu^{\pm}e^+e^-$, $e^{\pm}\mu^+\mu^-$ and $\mu^{\pm}\mu^+\mu^-$ for $W^{\pm}Z^0$ production and $e^+e^-e^+e^-$ for the Z^0Z^0 channel. The competing background processes are the Standard Model production of gauge-bosons and top quarks, which yield leptonic final states.

2. Signal definition and modeling

Both the $W^{\pm}Z^0$ and Z^0Z^0 analyses focus on on-shell gauge-bosons.

On-shell production of the $W^{\pm}Z^0$ final state proceeds mainly through the s-channel, involving a WWZ triple gauge-boson coupling. Additional contributions from the $W^{\pm}\gamma^*$ final state through a $WW\gamma$ coupling are effectively suppressed by constraining the mass of the observed lepton pair to be compatible with a Z^0 boson. The PYTHIA Monte Carlo generator [3] is used to model $W^{\pm}Z^0$ production and subsequent decay into fully-leptonic final states. All leptonic final states are allowed, including τ, and no constraints are imposed on the τ decays. In the generated sample, 95.5% of all events are classified as $W^{\pm}Z^0$ signal while the small remaining fraction is assigned to the $W^{\pm}\gamma^*$ process.

Four-electron final-states can originate from Z^0Z^0 production and via either $Z^0\gamma^*$ or $\gamma^*\gamma^*$ production, all largely dominated by the t-channel. The requirement of on-shell boson is enforced by considering only electron–positron pairs with a mass between 70 and 110 GeV. The PYTHIA Monte Carlo is used to generate events of this process, with the additional requirement that the electrons have a rapidity $|\eta| < 2.7$ and a transverse momentum $p_{\rm T} > 5\,{\rm GeV}$. Of all generated events, 72% are classified as Z^0Z^0 signal while 26% are ascribed to the $Z^0\gamma^*$ process and 2% to the $\gamma^*\gamma^*$ process.

Taking into account the branching fraction into leptons, $\mathcal{B}$, and the kinematic requirements, $\varepsilon_{\rm KIN}$, the relevant NLO cross sections times branching fraction are calculated using the MCFM [4] Monte Carlo to be

$$\begin{aligned}
\sigma_{\rm NLO} \times \mathcal{B} \times \varepsilon_{\rm KIN}\,(pp \to W^+Z^0 \to \ell^+\ell^+\ell^-) &= 1034\,{\rm fb}\,,\\
\sigma_{\rm NLO} \times \mathcal{B} \times \varepsilon_{\rm KIN}\,(pp \to W^-Z^0 \to \ell^-\ell^+\ell^-) &= 630\,{\rm fb}\,,\\
\sigma_{\rm NLO} \times \mathcal{B} \times \varepsilon_{\rm KIN}\,(pp \to Z^0Z^0 \to e^+e^-e^+e^-) &= 18.7\,{\rm fb}\,.
\end{aligned} \tag{1}$$

The NLO corrections correspond to overall k-factors of 1.9 and 1.4 for $W^{\pm}Z^0$ and Z^0Z^0 production, respectively. The NNLO box-diagram contribution to Z^0Z^0 production is not taken into account.

3. Background processes

The background to the selection of $W^{\pm}Z^0$ and Z^0Z^0 events comprises other processes with multiple leptons in the final states, some of which might be due to fake signals. The most copious sources of multiple leptons at the LHC are $t\bar{t}$ and $Z^0b\bar{b}$ production. The cross section of these processes is large: 830 pb and 1492 pb, respectively, as calculated with MCFM at NLO. These processes may have two leptons in the final states from leptonic decays of the W-bosons arising from $t \to Wb$ decays or of the Z^0-boson, respectively. The other leptons can be produced in the direct or cascade decays of the b quarks. The $Z^0b\bar{b}$ process is modeled with the CompHEP Monte Carlo generator [8] and the $t\bar{t}$ process with the TopRex Monte Carlo program [7]. Both t and $\bar{t}$ quarks in the $t\bar{t}$ sample are forced to decay semi-leptonically. In addition, the special case in which four electrons are produced in $t\bar{t}$ events is considered in detail and modeled with PYTHIA.

Events from Z^0Z^0 production can constitute a background to the $W^{\pm}Z^0$ selection. Events from the $Z^0\gamma^*$ and $\gamma^*\gamma^*$ processes constitute a background for both the $W^{\pm}Z^0$ and Z^0Z^0 analyses.

4. Event selection

Three-lepton and four-lepton final-states from $W^{\pm}Z^0$ and Z^0Z^0 production are collected with high efficiency by the L1 and HLT electron and muon triggers. The L1 and HLT efficiencies for events retained by the selections discussed below is 100%.

4.1. $W^{\pm}Z^0$ selection

Events with three charged leptons, either electrons or muons, with $p_{\mathrm{T}} >$ 10 GeV and $|\eta| < 2.5$, are considered by the $W^{\pm}Z^0$selection. Electrons are identified from superclusters in the electromagnetic calorimeter matched with a charged track, while muons are reconstructed by matching information from the muon chambers with tracks in the central tracker.

All possible Z^0-boson candidates from same-flavor opposite-charge lepton pairs are formed. Events are retained if a Z^0 candidate is found with a mass within 20 GeVof the Z^0-boson mass, m_Z. The background from Z^0Z^0 final states is reduced by rejecting events with a second Z^0 candidate with a mass within 40 GeVof m_Z. The remaining lepton is associated to the $W^{\pm}$-boson decay; its transverse momentum must be larger than 20 GeV. This requirement effectively suppresses background from $Z^0b\bar{b}$ events. The highest-$p_{\rm T}$ lepton associated to the Z^0-boson must satisfy $p_{\rm T} > 15\,{\rm GeV}$. If the event contains more than three-leptons, the lepton with highest $p_{\rm T}$ is chosen as originating from the $W^{\pm}$. The signal efficiency after these cuts is 9.5% while the $t\bar{t}$, $e^+e^-b\bar{b}$ and $\mu^+\mu^-b\bar{b}$ efficiencies are 0.8%, 0.4% and 0.6%, respectively.

Leptons from the decay of b quarks in the background processes are produced in a higher-multiplicity environment and isolation criteria suppress the background contamination. All muon candidates must have an energy measured in the calorimeters within a $\Delta R = 0.3$ cone around their direction smaller than 5 GeV and the sum of the $p_{\rm T}$ of tracks within a $\Delta R = 0.25$ cone smaller than 2 GeV. The isolation criteria for electrons are the same as those described in the Z^0Z^0 selection below. Besides fulfilling those requirements, electrons associated to the $W^{\pm}$-boson must have no other charged track with $p_{\rm T} > 2\,{\rm GeV}$ within a $\Delta R = 0.3$ cone around their direction.

The significance of the lepton impact parameter in the plane transverse to the beam, $S_{\rm IP}$, discriminates against leptons from heavy-quark decays. This variable is defined as the ratio between the measured impact parameter in the transverse plane and its uncertainty. It is required to satisfy $S_{\rm IP} < 3$. The signal efficiency after these cuts is 7.5% while the $t\bar{t}$, $e^+e^-b\bar{b}$ and $\mu^+\mu^-b\bar{b}$ efficiencies are 0.08%, 0.009% and 0.03%, respectively.

The $t\bar{t}$ and $Z^0b\bar{b}$ final states are associated with one or more hard jets and their contribution is reduced by removing events containing at least a jet with $E_{\rm T} > 20\,{\rm GeV}$. Jets are reconstructed using a Cone algorithm of size $\Delta R = 0.5$ and requiring its component calorimeter towers to have $E_{\rm T}^{\rm tow} > 0.5\,{\rm GeV}$ and $E^{\rm tow} > 0.8\,{\rm GeV}$. Only jets outside cones of $\Delta R = 0.3$ around the three-leptons are considered.

Finally, the reconstructed mass of the Z^0 boson is required to be within 10 GeVof m_Z, leading to the total efficiencies presented in Table I.

TABLE I

Yield of the $W^{\pm}Z^0$ selection for an integrated luminosity of $1\,{\rm fb}^{-1}$.

	$e^{\pm}e^+e^-$	$\mu^{\pm}e^+e^-$	$e^{\pm}\mu^+\mu^-$	$\mu^{\pm}\mu^+\mu^-$	Total	Efficiency
$W^{\pm}Z^0 \to \ell^{\pm}\ell^+\ell^-$	14.8	26.9	28.1	27.0	96.8	6.2%
Z^0Z^0	0.63	1.54	1.50	—	3.68	4.2%
$t\bar{t}$	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	0.007%

4.2. Z^0Z^0 selection

The Z^0Z^0 selection is based on events with four electrons. The transverse momenta of the electron candidates, ordered from the largest to the smallest, have to be above 30 GeV, 20 GeV, 15 GeV and 10 GeV, respectively. This cut suppresses the contribution from the $Z^0\gamma^*$ and $\gamma^*\gamma^*$ final states and reduces by 30% and 60% the $t\bar{t}$ and $Z^0b\bar{b}$ backgrounds, respectively. Leptons from b quarks decays in the $t\bar{t}$ and $Z^0b\bar{b}$ background processes are produced in association with hadrons. Their contribution is reduced by requiring the electrons to be isolated: the ratio between the energy deposited in the hadronic and the electromagnetic calorimeters must be below 8%; no more than two other charged track with $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ must be within a $\Delta R = 0.3$ cone around the electron; $(\Sigma_i {p_{\mathrm{T}}}^i - E_{\mathrm{t}})/E_{\mathrm{t}} < 0.34$, where E_{t} is the transverse energy of the electron candidate and the sum runs on all tracks with $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ within a $\Delta R = 0.3$ cone around the electron.

Electron–positron pairs are combined to form Z^0 candidates. Pairs with reconstructed masses between 50 and 120 GeV are retained. Of the two possible Z^0Z^0 pairings, the one where the Z^0 candidate masses are closest to 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^0Z^0 pairing which contains the highest-p_{T} electron is retained.

Table II presents the signal and background selection efficiencies.

TABLE II

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

	Efficiency	$N_{\mathrm{events}}/1\mathrm{fb}^{-1}$	$N_{\mathrm{events}}/10\mathrm{fb}^{-1}$
Z^0Z^0	38%	7.1	71.1
$Z^0\gamma^*$	4.5%	0.16	1.60
$Z^0b\bar{b}$	0.07%	0.08	0.84
$t\bar{t}$	0.06%	0.12	1.22
S_{L}		4.8	13.1

5. Systematic uncertainties

For the first $1\,\mathrm{fb}^{-1}$ of integrated luminosity, the total systematic uncertainties on the $W^{\pm}Z^0$ and Z^0Z^0 cross section determinations are 17.4% and 12.9%, respectively. These figures include a 10% uncertainty on the determination of the integrated luminosity.

The most important sources of systematic uncertainties are lepton identification and isolation, and the background subtraction. A 2% uncertainty on each lepton propagates to an uncertainty on the cross section between 2.6% and 7.8%, according to the channel. Background subtraction dominates the $W^{\pm}Z^{0}$ systematics with an uncertainty of 12%, while it accounts for a 1.3% uncertainty in the $Z^{0}Z^{0}$ channel. An additional uncertainty of 5% on the jet energy scale affects the $W^{\pm}Z^{0}$ channel, while an uncertainty of 1% on the trigger efficiency affects both channels.

The significance of the observation of the $W^{\pm}Z^{0}$ and $Z^{0}Z^{0}$ signals in the first $1\,\mathrm{fb}^{-1}$ is not sensitive to the luminosity uncertainty. It is affected by all other sources of systematic uncertainty listed above, with a total effect of 14.8% and 14.2% on the two channels, respectively. These uncertainties include additional PDF and QCD uncertainties in the Monte Carlo modeling, contributing 3.7% and 6.4% for the $W^{\pm}Z^{0}$ and $Z^{0}Z^{0}$ selections, respectively.

6. Results

Fig. 1 presents the mass distribution of the Z^{0}candidates in the $W^{\pm}Z^{0}$ channel for an integrated luminosity of $1\,\mathrm{fb}^{-1}$ before the last requirement of a $\pm 10\,\mathrm{GeV}$ window is applied. A large signal-over-background ratio is observed, as shown in Table I.

Fig. 2 shows the mass distribution of the Z^{0}candidates, two entries per event, selected by the $Z^{0}Z^{0}$ selection for an integrated luminosity of $10\,\mathrm{fb}^{-1}$. Table II lists the selection yield for $1\,\mathrm{fb}^{-1}$ and $10\,\mathrm{fb}^{-1}$. The selection results into an almost background-free signal sample, which will constitute a valuable input to assess the background in the search for the Higgs boson.

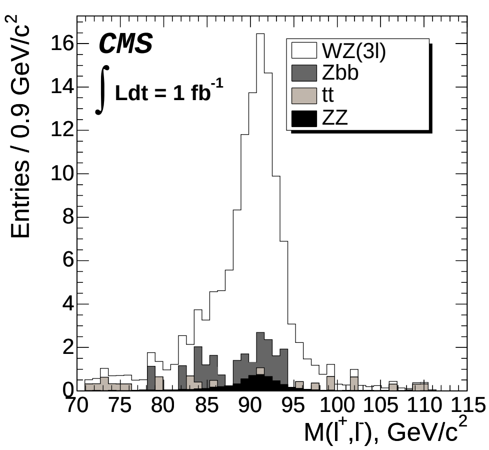

Fig. 1. Distribution of the mass of the Z^{0} candidates for events retained by the $W^{\pm}Z^{0}$ selection, for an integrated luminosity of $1\mathrm{fb}^{-1}$.

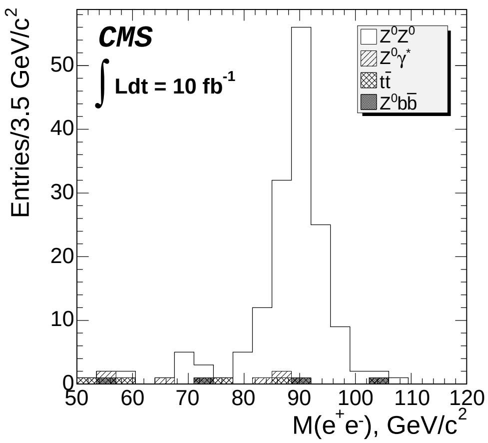

Fig. 2. Distribution of the mass of the Z^0 candidates, two entries per event, retained by the Z^0Z^0selection, for an integrated luminosity of $10\,\mathrm{fb}^{-1}$.

Both the $W^\pm Z^0$ and Z^0Z^0 final states can be selected with high purity and a significance of 13.1 and 4.8, which include systematic effects, is expected in the first $1\,\mathrm{fb}^{-1}$ of integrated luminosity making these process suitable for early observations. The $W^\pm Z^0$ channel can be observed with a significance of 5, including systematic effects, in an integrated luminosity of $150\,\mathrm{pb}^{-1}$.

In conclusion, the large signal-over-background ratios achieved by the $W^\pm Z^0$ and Z^0Z^0 selections suggest that early observation of these channels will take place at the LHC start up. In addition, precise investigations of triple gauge-boson couplings will be possible with the first $10\,\mathrm{fb}^{-1}$ of LHC data.

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