Vector boson productions and Higgs searches in pp collisions at $\sqrt{s} = 7$ TeV

Jónatan Piedra for the CMS Collaboration

E-mail: piedra@cern.ch

Abstract. Measurements of $W\gamma$, $Z\gamma$ and $WW$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV are presented, together with searches for the Higgs boson. The results are based on a data sample corresponding to an integrated luminosity of 36 pb$^{-1}$ recorded by the CMS experiment. In the $W\gamma$, $Z\gamma$ and $WW$ cross sections measurements the electron and muon decay channels of the $W$ and $Z$ are used. A search for the Higgs boson is performed in the fully leptonic $WW$ final state, not revealing any evidence of excess above backgrounds. Limits are set on the production of the Higgs boson in the context of the SM and in the presence of a sequential fourth family of fermions with high masses. A MSSM Higgs boson search is performed in the tau pairs decay. No excess is observed in the tau-pair invariant mass spectrum.

1. The CMS detector [1]

The central part of the CMS detector is a superconducting solenoid, which provides an axial magnetic field of 3.8 T parallel to the beam axis. Charged particle trajectories are measured by the silicon pixel and strip tracker, which covers the pseudorapidity region $|\eta| < 2.5$. A crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter surround the tracking volume and cover $|\eta| < 3.0$. A quartz-fiber Cherenkov calorimeter extends the coverage to $|\eta| = 5.0$. Muons are measured in gas detectors embedded in the iron return yoke outside the solenoid, in the pseudorapidity range $|\eta| < 2.4$. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the beam axis.

2. Measurement of $W\gamma$ and $Z\gamma$ production [2]

The study of $W\gamma$ and $Z\gamma$ production in proton-proton collisions is an important test of the Standard Model (SM) because of its sensitivity to the self-interaction between gauge bosons via trilinear gauge boson couplings (TGCs). Any deviation of the observed strength of the TGC from the SM prediction would indicate new physics. The $W\gamma$ and $Z\gamma$ processes are studied in the final states $\ell\nu\gamma$ and $\ell\ell\gamma$, respectively, where $\ell$ is either an electron or a muon. Leading order (LO) $W\gamma$ production can be described by three processes: initial state radiation (ISR), where a photon is radiated by one of the incoming quarks; final state radiation (FSR), where a photon is radiated from the charged lepton from the $W$ boson decay; and finally through the $WW\gamma$ vertex, where a photon couples directly to the $W$ boson. In the SM, LO $Z\gamma$ production is described via ISR and FSR processes only, because the $ZZ\gamma$ and $Z\gamma\gamma$ TGCs are not allowed at the tree level. As at LO the $W\gamma$ and $Z\gamma$ cross sections diverge for soft photons or, in the case of $Z/\gamma*\gamma$ production, for small values of the dilepton invariant mass, we restrict the cross section measurement to the phase space defined by the following two kinematic requirements:
the photon candidate must have transverse energy $E_{\gamma}^T$ larger than 10 GeV, and it must be spatially separated from the final-state charged lepton(s) by $\Delta R(\ell, \gamma) > 0.7$. Furthermore, for the $Z\gamma$ final state, the invariant mass of the two lepton candidates must be above 50 GeV. The main background to $W\gamma$ and $Z\gamma$ production consists of $W$+jets and $Z$+jets events, respectively, where the photon candidate originates from one of the jets. We estimate this background from data. The contribution from other processes, such as $t\bar{t}$ and multijet QCD production, is much smaller and it is estimated from Monte Carlo (MC) simulation studies.

The details of the photon, electron and muon reconstruction, together with the calculation of the transverse missing energy $E_{\text{miss}}^T$, can be found in [2]. To estimate the background due to jets misidentified as photons we measure the $E_{\gamma}^T$-dependent ratio of jets passing the full photon identification criteria to those identified as photons but failing the track isolation requirement. The obtained probability is folded with the non-isolated photon candidates in the $W\gamma$ and $Z\gamma$ candidate events to estimate the number of $W$+jets and $Z$+jets simulation and with the results obtained from an independent study of photon cluster shower shapes [2]. We observe good agreement between all three methods (Fig. 1).

**Figure 1.** The background from misidentified jets as a function of the photon candidate transverse energy estimated from the ratio method is shown with blue squares, together with an alternative method that uses energy deposition shape templates (magenta circles), and simulation (green filled histogram) for the $W\gamma$ channel. Uncertainties include both statistical and systematic sources.

**Figure 2.** Transverse energy distribution for the photon candidates for $W\gamma$ production. Data are shown with black circles; expected signal plus background is shown as a black solid line; the contribution from misidentified jets is given as a hatched blue histogram, and the background from $\gamma$+jets, $t\bar{t}$, and multiboson processes is given as a solid green histogram. A typical anomalous TGC signal is given as a dot-dashed red line.

The $W\gamma \rightarrow \ell\nu\gamma$ final state is characterized by a prompt, energetic and isolated lepton, significant $E_{\text{miss}}^T$ due to the presence of the neutrino and a prompt isolated photon. The event selection is similar for the electron and muon channels: we require a charged lepton with $p_T > 20$ GeV which must satisfy the trigger requirements; one photon with transverse energy $E_{\gamma}^T > 10$ GeV, and the $E_{\text{miss}}^T$ in the event exceeding 25 GeV. After the full selection, 452 events are selected in the $e\nu\gamma$ channel and 520 events are selected in the $\mu\nu\gamma$ channel. No events have more than one photon candidate in the final state. The background from misidentified jets estimated in data amounts to $220 \pm 16$ (stat) $\pm 14$ (syst) and $261 \pm 19$ (stat) $\pm 16$ (syst) events,
respectively. The $E_T$ distribution for photon candidates in events passing the full $W\gamma$ selection is given in Fig. 2. Events in the $Z\gamma$ sample are selected by requiring a pair of electrons or muons, each with transverse momentum $p_T > 20$ GeV, forming an invariant mass above 50 GeV. One of these leptons must satisfy the trigger requirements. The events are further required to have a photon candidate passing the selection criteria with transverse energy above 10 GeV. We observe 81 events in the $ee\gamma$ final state and 90 events in the $\mu\mu\gamma$ final state. No events are observed with more than one photon candidate. The $Z$+jets background to these final states is estimated to be $20.5 \pm 1.7$ (stat) $\pm 1.9$ (syst) and $27.3 \pm 2.2$ (stat) $\pm 2.3$ (syst), respectively. The distribution of the $\ell\ell\gamma$ mass as a function of the dilepton mass is displayed in Fig. 3.

![Figure 3](image1)

**Figure 3.** Distribution of the $\ell\ell\gamma$ invariant mass as a function of the dilepton invariant mass for selected $Z\gamma$ candidates in the electron (filled circles) and muon (open circles) final states. The data accumulation at $M_{\ell\ell\gamma} \approx M_Z$ corresponds to FSR events, while the data at $M_{\ell\ell} \approx M_Z$ correspond to ISR events.

![Figure 4](image2)

**Figure 4.** The reconstructed tau-pair invariant mass on linear (above) and logarithmic (below) scales, for the sum of the $e\tau_h$, $\mu\tau_h$ and $e\mu$ final states, comparing the observed data points to the expected backgrounds. The contribution from a Higgs signal is also shown.

The systematic uncertainties considered include uncertainties on lepton and photon energy scales and resolution, effects from pile-up interactions, and uncertainties in the parton distribution functions; uncertainties affecting the data vs. simulation correction factors for the efficiencies of the lepton trigger, lepton and photon reconstruction and identification, and $E_T^{\text{miss}}$ efficiencies for the $W\gamma$ process; uncertainties on the data-driven W+jets and Z+jets background estimation; and finally, an additional uncertainty due to the measurement of the integrated luminosity. For $E_T^{\text{miss}} > 10$ GeV, $\Delta R(\ell, \gamma) > 0.7$, and $m_{\ell\ell} > 50$ GeV for the $Z\gamma$ process, we find the cross sections for $W\gamma$ and $Z\gamma$ production to be in good agreement with the next-to-leading order (NLO) predictions of $49.4 \pm 3.8$ pb and $9.6 \pm 0.4$ pb, respectively:

$$
\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow e\nu) = 57.1 \pm 6.9 \text{ (stat)} \pm 5.1 \text{ (syst)} \pm 2.3 \text{ (lumi)} \text{ pb},
\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow \mu\nu) = 55.4 \pm 7.2 \text{ (stat)} \pm 5.0 \text{ (syst)} \pm 2.2 \text{ (lumi)} \text{ pb},
\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow ee) = 9.5 \pm 1.4 \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb},
\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow \mu\mu) = 9.2 \pm 1.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb}.
$$
3. Measurement of $W^+W^-$ production and search for the Higgs boson [4]

The origin of the masses of $W$ and $Z$ bosons is attributed, in the SM, to the spontaneous breaking of electroweak symmetry caused by a new scalar field. The existence of the associated field quantum, the Higgs boson, has yet to be experimentally confirmed. A possible extension to the SM is the addition of a fourth family of fermions. For sufficiently large lepton and quark masses, this extension has not been excluded by existing constraints. The presence of another fermion family produces an enhancement of the dominant gluon fusion cross section, together with some changes in the Higgs decay branching fractions. The choice of infinitely heavy quarks of the fourth family in the extended SM yields to the smallest enhancement factor for the Higgs boson cross section, hence to the most conservative scenario for the exclusion of such a model.

This scenario is used to set limits in this paper.

The dominant irreducible background for $H \rightarrow WW$ production is the SM non-resonant production of $WW$. A good understanding of this process and its properties is thus needed for the Higgs boson search. The $WW$ production has been extensively studied by the LEP and Tevatron experiments, where it has been found to be in agreement with the SM prediction. In pp collisions at the LHC, the SM NLO QCD prediction of the $WW$ production cross section at $\sqrt{s} = 7$ TeV is $43.0 \pm 2.0$ pb. The $WW$ candidates, with both $W$ bosons decaying leptonically, are selected in final states consisting of two isolated, high transverse momentum, oppositely-charged leptons (electrons or muons), and large missing transverse energy due to the undetected neutrinos. Events are selected in three final states: $ee$, $\mu\mu$ and $\tau\tau$, which include $W \rightarrow \tau\nu_\tau$ events with leptonic $\tau$ decays. The details of the lepton and jet reconstruction, and missing transverse energy calculation can be found in [4].

For the event selection also a derived quantity called $\text{projected } E_T^{\text{miss}}$ is used. With $\Delta \phi$ the azimuthal angle between the $E_T^{\text{miss}}$ and the closest lepton, the $\text{projected } E_T^{\text{miss}}$ is defined as the component of $E_T^{\text{miss}}$ transverse to the lepton direction if $\Delta \phi$ is smaller than $\pi/2$, and the full magnitude of $E_T^{\text{miss}}$ otherwise. This variable, which helps to reject $Z \rightarrow \tau\tau$ background events, is required to be above $35$ GeV in the $ee$ and $\mu\mu$ final states, and above $20$ GeV in the $e\mu$ final state. To further reduce the Drell–Yan background in the $ee$ and $\mu\mu$ final states, events with a dilepton invariant mass within $15$ GeV of the $Z$ mass are discarded. Events are also rejected with dilepton masses below $12$ GeV, to suppress contributions from low mass resonances.

To reduce backgrounds containing top quarks, events containing at least one jet with $|\eta| < 5.0$ and $p_T > 25$ GeV are rejected. In addition, this jet veto is complemented by a top veto based on soft-muon and b-jet tagging. To reduce the background from diboson processes, such as $WZ$ and $ZZ$ production, any event which has an additional third lepton passing the identification and isolation requirements is rejected. Figure 5 shows the jet multiplicity distribution for events that pass all selections but the jet veto and top veto. Figure 6 shows the dilepton mass distribution for events passing the full $WW$ event selections, except the $Z$ mass veto. The $W+$jets background is estimated using data-driven methods by defining a set of loosely selected lepton-like objects in a sample of events dominated by dijet production. The total misidentified electron and muon background contributions are found to be $1.2 \pm 0.3$ (stat) $\pm 0.6$ (syst) and $0.5 \pm 0.3$ (stat) $\pm 0.3$ (syst) events, respectively. The remaining top quark background after the full event selection can be estimated from data by counting events with either an additional soft muon or at least one b-tagged jet with $p_T$ below the jet veto threshold. No events are rejected by the top veto in data after applying the full selection, which is consistent with the prediction from simulation. Therefore, the top quark background contribution is taken directly from simulation, which predicts $0.77 \pm 0.05$ (stat) $\pm 0.77$ (syst) events, where a $100\%$ systematic uncertainty is assigned as a conservative estimate of the difference between data and simulation. An estimate of the residual $Z$ boson contribution in the $ee$ and $\mu\mu$ final states outside the $Z$ mass window is obtained from data in the following way: the ratio of the number of events outside the $Z$ mass window to that inside is obtained from simulation. The observed number of events inside the
Z mass window in data, from which the non-Z contributions are subtracted, is then scaled by this ratio to compute the residual Z background, estimated as $0.2 \pm 0.2 \text{ (stat)} \pm 0.3 \text{ (syst)}$ events. Other backgrounds are estimated from simulation.

The WW signal efficiency is estimated using the simulation, corrected by data-to-simulation scale factors. For electron and muon reconstruction and identification, a tag-and-probe is applied to leptons, both in data and simulation. For estimating the effect of the jet veto efficiency on the WW signal, events in the Z resonance region are used. Overall, the uncertainty is estimated to be 7% on the WW selection efficiency, coming mainly from the theoretical uncertainty in the jet veto efficiency determination. The uncertainty on the background estimations in the WW signal region is about 37%. The WW yield is calculated from the number of events in the signal region, after subtracting the expected contributions of the various SM background processes. From this yield the WW cross section is found to be

$$\sigma(pp \rightarrow WW + X) \times B(W \rightarrow \ell\nu) = 41.1 \pm 15.3 \text{ (stat)} \pm 5.8 \text{ (syst)} \pm 4.5 \text{ (lumi)} \text{ pb}.$$
amounts to 1–2% of the gluon fusion process. Systematic uncertainties related to acceptance and efficiencies for $H \to WW$ are estimated in a similar way as described in the WW cross section measurement. The overall uncertainty on the $H \to WW$ signal yield is estimated to be of about 14%, where the uncertainty on the jet veto efficiency and the luminosity determination are the main contributions. The uncertainties on the background estimations are about 40%.

Upper limits are derived on the product of the gluon fusion Higgs boson production cross section by the $H \to WW$ branching fraction. Two different statistical methods are used, both using the same likelihood function from the expected number of observed events modeled as a Poisson random variable whose mean value is the sum of the contributions from signal and background processes. The first method is based on Bayesian inference, while the second method, known as $CL_s$, is based on the hybrid Frequentist-Bayesian approach. Both methods account for systematic uncertainties. The upper limits for the Bayesian inference are about 1-3% higher than the $CL_s$ method. Results are reported in the following using only the Bayesian approach, with a flat signal prior. The 95% observed and mean expected C.L. upper limits are shown in Fig. 8 for Higgs boson masses in the range 120 – 600 GeV. The $\sigma_H \times B(H \to WW \to 2\ell 2\nu)$ upper limits are about three times larger than the SM expectation for $m_H = 160$ GeV. When compared with recent theoretical calculations performed in the context of a SM extension by a sequential fourth family of fermions with very high masses, the results of BDT analyses exclude at 95% C.L. a Higgs boson with mass in the range from 144 to 207 GeV, where the mean expected exclusion at 95% C.L. is in the range from 147 to 193 GeV. Similar results are achieved using the cut-based approach.

4. Search for neutral MSSM Higgs bosons decaying to tau pairs [5]
   The SM Higgs boson suffers from quadratically divergent self-energy corrections at high energies. Numerous extensions to the SM have been proposed to address these divergences. One such model, supersymmetry, a symmetry between fundamental bosons and fermions, results in cancellation of the divergences at tree level. The minimal supersymmetric extension to the standard model (MSSM) requires the presence of two Higgs doublets. This leads to a more
complicated scalar sector, with five massive Higgs bosons: a light neutral state (h), two charged states (H±), a heavy neutral CP-even state (H) and a neutral CP-odd state (A). The masses of the MSSM Higgs boson states are specified up to radiative corrections mainly by two parameters, usually taken to be the mass of the pseudoscalar state, mA, and the ratio of the vacuum expectation values of the two Higgs doublets, tan β. At large tan β (greater than about 20–30), the couplings of the Higgs bosons to down-type quarks are approximately proportional to tan β. As a result, the production cross section for two of the three neutral Higgs bosons can be nearly as large as that for the electroweak gauge bosons W and Z at a pp collider such as the LHC. Two main production processes contribute to pp → φ + X, where φ = h, H or A: gluon fusion through a b-quark loop and direct bb annihilation from the b-parton density in the beam protons. The tau-pair decays of the neutral Higgs bosons, having a branching fraction of roughly 10%, serve as the best experimental signature for this search. The bb mode, though it has a much larger branching fraction, suffers from an overwhelming background from QCD processes.

The main challenge in the identification of hadronic tau decays is overcoming the large background due to hadronic jets from QCD processes. Hadronic tau decays almost always yield one or three charged pions, plus zero to several neutral pions, depending on the decay mode. The algorithm used here starts with a high-pT reconstructed charged hadron, and combines it with other nearby reconstructed charged hadron and neutral pion candidates. The algorithm considers all possible combinations of these objects and determines which are consistent with the kinematics of tau decay. Among those, it chooses the most isolated in terms of the presence of nearby reconstructed particles. For the μτh and ετh final states, we select events with an isolated muon or electron with pT > 15 GeV and |η| < 2.1, and an oppositely charged τh with pT > 20 GeV and |η| < 2.3. The transverse mass M_T of the ℓ = e, μ with the missing transverse energy of the event is required to be below 40 GeV, in order to reduce the background from W+jets events. For the eμ final state, we select events with an isolated electron with |η| < 2.5 and an oppositely charged isolated muon with |η| < 2.1, both with pT > 15 GeV and M_T < 50 GeV (to reject WW and tt events), calculated for each lepton separately. We reject events in which there are more than one e or μ.

The largest source of events selected with these requirements comes from Z → ℓ+ℓ−. We estimate this contribution with simulation, and we determine its normalization based on the number of observed Z → e+e− and Z → μ+μ− events. A significant source of background arises from QCD multijet events and W+jets events in which a jet is misidentified as τh, and there is a real or misidentified e or μ. The rates for these processes are estimated using the number of observed same-charge events, and cross-checked using the jet-to-tau misidentification rate measured in multijet events. Other background processes include tt production and Z → ee/μμ events.

To distinguish the Higgs boson signal from the background, we reconstruct the tau-pair mass using a likelihood technique. The algorithm estimates the original tau three-momenta by maximizing a likelihood with respect to free parameters corresponding to the missing tau-neutrino momenta, and subject to all applicable kinematic constraints. Other terms in the likelihood take into account the tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. The observed reconstructed tau-pair mass distribution summed over all three channels is shown in Fig. 4. Various effects can alter the shape and normalization of the reconstructed tau-pair invariant mass spectrum. The main sources include the total integrated luminosity, background normalizations, Z production cross section, and lepton identification and isolation efficiency. Uncertainties that contribute to mass spectrum shape variations include the lepton energy scales, and uncertainties on the E_T^{miss} scale that is used for the tau-pair invariant mass reconstruction. To search for the presence of a Higgs boson signal in the selected events, we perform a maximum likelihood fit.
to the tau-pair invariant mass spectrum. Systematic uncertainties are represented by nuisance parameters, which we remove by marginalization, assuming a log normal prior for normalization parameters, and Gaussian priors for mass-spectrum shape uncertainties. The mass spectra show no evidence for the presence of a Higgs boson signal, and we set 95% CL upper bounds on the Higgs boson cross section times the tau-pair branching fraction.

5. Conclusions
In a data sample corresponding to an integrated luminosity of 36 pb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV, we have presented the first measurement of the $W\gamma$ and $Z\gamma$ cross sections, for $E_T^\gamma > 10$ GeV, $\Delta R(\gamma, \ell) > 0.7$, and for the additional requirement on the dilepton invariant mass to exceed 50 GeV for the $Z\gamma$ process. The results are in good agreement with the NLO prediction values. We have presented the first measurement of the WW cross section and a search for the Higgs boson decaying to WW. The WW events have been used to measure the WW$\gamma$ and WWZ triple gauge couplings. The results, which are in agreement with the SM predictions, are consistent with the precise measurements made at LEP and comparable with the current Tevatron results. Limits on the Higgs boson production cross section have been derived. No excess above the SM expectations was found. In the presence of a sequential fourth family of fermions with very high masses, a Higgs boson with SM couplings and a mass between 144 and 207 GeV has been excluded at 95% confidence level, using a Bayesian inference method. Finally, we have performed a search for neutral MSSM Higgs bosons. The tau-pair decay mode in final states with one $e$ or $\mu$ plus a hadronic decay of a tau, and the $e\mu$ final state were used. The observed tau-pair mass spectrum reveals no evidence for neutral Higgs boson production, and we determine an upper bound on the product of the Higgs boson cross section and tau-pair branching fraction as a function of $m_A$. These results, interpreted in the MSSM parameter space of $\tan\beta$ versus $m_A$, in the $m_{h_{\text{max}}}$ scenario, exclude a previously unexplored region reaching as low as $\tan\beta = 23$ at $m_A = 130$ GeV.

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