The Compact Muon Solenoid Experiment

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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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ZZ cross section measurements and limits on anomalous coupling constants for neutral triple gauge boson

Luca Pernie for the CMS Collaboration

Abstract

The measurement of the Z boson pair production cross section at 7 and 8 TeV is presented. In the Standard Model (SM), a Z boson pair is produced through non-resonant processes or through the decay of a Higgs boson, and the predictions of the SM for this rare electroweak process can be tested with precision for the first time at the LHC. In addition, new physics can appear as deviations from the SM, e.g. in the Z boson p_T spectrum. This new physics can be parametrized as anomalous coupling constants for neutral triple gauge boson interactions γZZ and ZZZ , which are forbidden at tree level in the SM. Data corresponding to an integrated luminosity of about 5.1 fb^{-1} at 7 TeV and 19.5 fb^{-1} at 8 TeV have been analyzed; 7 TeV data for $2l2\nu$ and $4l$ final states and 8 TeV for $2l2\nu$ final state. The cross-sections measurement is in good agreement with the SM NLO predictions. The data are also analyzed to search for anomalous neutral triple gauge couplings. The sensitivity of the $ZZ \rightarrow 2l2\nu$ channel per fb^{-1} is demonstrated to be comparable to that of the $ZZ \rightarrow 4l$ channel, which lead to the most stringent limits published with only 5 fb^{-1} of data at 7 TeV. Latest public results will be presented and discussed.

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ZZ cross section measurements and limits on anomalous coupling constants for neutral triple gauge boson

Luca Pernié^a

Université Libre de Bruxelles, Bruxelles, Belgium

Sapienza, Università di Roma, Rome, Italy

Abstract. The following paper presents the ZZ production cross section in proton-proton collisions at 8 TeV center-of-mass energy with the CMS experiment at the LHC. The data sample correspond to an integrated luminosity of 19.6 fb⁻¹. The measurements are performed in the leptonic decay modes $ZZ \rightarrow ll'l'$, where $l = e, \mu$ and $l' = e, \mu, \tau$ and $ZZ \rightarrow ll\nu\nu$, where $l = e, \mu$.

Since the cross section measured is found to be in agreement with the Standard Model prediction, limits on anomalous triple gauge couplings (aTGC) have been setted.

1 Introduction

Di-boson production at the LHC is of particular interest for two different reasons: it probes the electroweak boson self-interactions and it constitutes a background for many new physics searches such as the searches for the Higgs boson or super-symmetry. Precise knowledge of these processes is therefore of great importance in the quest to discover or rule out these models, among others. Vector bosons are expected to couple also in triplets (e.g. WWZ) and in quartets (e.g. $WWZZ$) as a consequence of the non-abelian structure of the electroweak gauge theory. All couplings involving the bosons with neutral electric charge are expected to vanish at tree level leading to the absence of triple couplings for $Z\gamma\gamma$, $ZZ\gamma$ and ZZZ . An observation of these anomalous couplings would therefore be an indication of new physics.

In this Letter we focus on ZZ final states and we measure the production cross section of these states in proton-proton collisions at 8 TeV center-of-mass energies. The measurements are performed in the leptonic decay modes $ZZ \rightarrow ll'l'$ [1], where $l = e, \mu$ and $l' = e, \mu, \tau$ and $ZZ \rightarrow ll\nu\nu$ [2], where $l = e, \mu$.

2 The CMS detector

While the CMS detector is described in detail elsewhere [3], the key components for this analysis are summarized here.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in

^aE-mail: luca.pernie@cern.ch

the x-y plane. The magnitude of the transverse momentum (p_T) is calculated as $p_T = \sqrt{p_x^2 + p_y^2}$. A superconducting solenoid occupies the central region of the CMS detector, providing an axial magnetic field of 3.8 T parallel to the beam direction. The silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter are located within the solenoid. A quartz-fibre Cherenkov calorimeter extends the coverage to $|\eta| < 5.0$, where pseudo-rapidity is defined as $\eta = -\ln(\tan \frac{\theta}{2})$. Muons are measured in gas ionization detectors embedded in the steel flux return yoke outside the solenoid. The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 3 μs using information from the calorimeters and muon detectors. The high-level-trigger processor farm decreases the event rate from 100 kHz delivered by the first level trigger to a few hundred hertz, before data storage.

3 The $ll'l'$ final state

The four lepton final state is a very clean channel.

The event selection has been chosen to give a mutually exclusive set of signal candidates in the $ZZ \rightarrow ll'l'$, where $l' = e, \mu$, and $ZZ \rightarrow ll\tau\tau$ channels. The signal candidates in the $ll'l'$ analysis are first selected. The selection uses well identified and isolated leptons. The Z candidate have to be formed with a pair of leptons of the same flavour and opposite charge. Since there are two couples of leptons, the closest one to the nominal Z mass is denoted Z_1 , the second couple, denoted Z_2 , is chosen requiring the highest scalar sum of transverse momentum. Both the couples have to satisfy $60 < m_Z < 120$ GeV. It is required at least a lepton with $p_T > 20$ GeV and another with $p_T > 10$ GeV. These p_T thresholds ensure that the selected events have leptons on the high-efficiency plateau for the trigger.

For the $ll\tau\tau$ final state, events are required to have one $Z_1 \rightarrow l^+l^-$ candidate with one lepton at $p_T > 20$ GeV and the other at $p_T > 10$ GeV, and a $Z_2 \rightarrow \tau^-\tau^+$, with τ decaying into μ, e or τ_h . The leptons from the τ leptonic decays are required to have $p_T > 10$ GeV. The τ_h are required to have $p_{T_h} > 20$ GeV. The invariant mass of the reconstructed Z_1 is required to satisfy $60 < m_{ll} < 120$ GeV, and that of the Z_2 to satisfy $m_{min} < m_{\tau\tau} < 90$ GeV, where $m_{min} = 20$ GeV for $Z_2 \rightarrow \tau\tau \rightarrow e\mu$ final states, and 30 GeV for all others.

3.1 Background subtraction

In the $ll'l'$ final state the small background contribution has little affect on the ZZ cross section measurement, but is more crucial in case of $ll\tau\tau$.

The major background contributions arise from the production of Z and WZ in association with jets, as well as $t\bar{t}$. In all these cases, a jet or non-isolated

lepton is misidentified as a e , τ , τ_h , τ_e or τ_μ .

The control region for $Z + X$, where X stands for bb , bb , gluon or light quark jets, is obtained by selecting events containing Z_1 and two additional lepton candidates $l'l'$. The Z_1 passes usual selection requirements and relaxed criteria on isolation and identification are applied to the two additional leptons. The lepton pair must have opposite charge and matching flavour. From this set of events the expected number of $Z + X$ background events in the signal region is obtained by scaling the number of observed $Z_1 + l'l'$ events by the lepton misidentification probability. To take into account all possible sources of backgrounds there are two regions defined, one where both additional leptons pass the loose requirements and another one, where one of the additional leptons passes all the final requirements. Combination of these two regions covers all types of background contamination, which is important in the case of $ll\tau\tau$ decay channels. The contamination from WZ is suppressed by requiring that the imbalance in the measured energy deposition in the transverse plane is below 25 GeV.

3.2 Cross section measurement and Anomalous Triple Gauge Couplings

The cross-section for the $4e$, 4μ , $2e2\mu$ and summed for all $ll\tau\tau$ decay channels are shown in Fig. 1. The results are in good agreement with the Standard model value, obtained by the program Monte Carlo for FeMtobarn processes at Hadron Colliders (MCFM), of 7.7 ± 0.6 pb at NLO. To include all final

Fig. 1

Decay	Cross sections
$\mu\mu\mu\mu$	$\sigma(\text{pp} \rightarrow \text{ZZ}) = 7.3^{+0.8}_{-0.8} \text{ (stat.) } ^{+0.6}_{-0.5} \text{ (syst.) } \pm 0.4 \text{ (theo.) } \pm 0.3 \text{ (lum.) pb}$
$eeee$	$\sigma(\text{pp} \rightarrow \text{ZZ}) = 7.2^{+1.0}_{-0.9} \text{ (stat.) } ^{+0.6}_{-0.5} \text{ (syst.) } \pm 0.4 \text{ (theo.) } \pm 0.3 \text{ (lum.) pb}$
$\mu\mu ee$	$\sigma(\text{pp} \rightarrow \text{ZZ}) = 8.1^{+0.7}_{-0.6} \text{ (stat.) } ^{+0.6}_{-0.5} \text{ (syst.) } \pm 0.4 \text{ (theo.) } \pm 0.4 \text{ (lum.) pb}$
$ll\tau\tau$	$\sigma(\text{pp} \rightarrow \text{ZZ}) = 7.7^{+2.1}_{-1.9} \text{ (stat.) } ^{+2.0}_{-1.8} \text{ (syst.) } \pm 0.4 \text{ (theo.) } \pm 0.3 \text{ (lum.) pb}$
Total	$\sigma(\text{pp} \rightarrow \text{ZZ}) = 7.7^{+0.5}_{-0.5} \text{ (stat.) } ^{+0.5}_{-0.4} \text{ (syst.) } \pm 0.4 \text{ (theo.) } \pm 0.3 \text{ (lum.) pb}$

states in the cross section calculation a simultaneous fit on the number of observed events in all decay channels is performed. The likelihood is written as a combination of individual channel likelihoods for the signal and background hypotheses with the statistical and systematic uncertainties in the form of scaling nuisance parameters. Each τ decay mode is treated as a separate channel.

Anomalous neutral trilinear couplings ZZZ and $ZZ\gamma$ are described using a parametrization with two ZZZ couplings, and two $ZZ\gamma$ couplings, allowed by electromagnetic gauge invariance and Lorentz invariance for on-shell Z

bosons. Such couplings are parametrized by two CP-violating (f_4^V) and two CP-conserving (f_5^V) complex parameters, where $V = Z, \gamma$, which are zero in the SM. In this analysis we measure anomalous triple gauge couplings (ATGC) without form-factor scaling.

The ATGC signal sample is generated with SHERPA [4]. The presence of ATGCs would be manifested in an increased yield of events at high four-lepton masses. The invariant mass distributions are interpolated from SHERPA simulation for different values of the anomalous couplings. For each distribution only one or two couplings are varied, while all others are set to zero. The expected signal is obtained from a grid of aTGC models in the $(f_{4,5}^Z, f_{4,5}^\gamma)$ parameter plane. Expected signal values are interpolated between the 2D grid points using a parabola since the cross section for signal depends quadratically on the coupling parameters. Systematic errors are accounted for by fluctuating the number of expected signal and of expected background according to uncertainties.

One-dimensional 95% CL limits for the $f_4^{Z,\gamma}$ and $f_5^{Z,\gamma}$ anomalous coupling parameters are measured to be:

$$0.004 < f_4^Z < 0.004, \quad 0.005 < f_5^Z < 0.005$$

$$0.004 < f_4^\gamma < 0.004, \quad 0.005 < f_5^\gamma < 0.005$$

4 The $ll\nu\nu$ final state

In this analysis the final state is less clean. The signal consists of two Z bosons, one decaying into a pair of oppositely-charged leptons (electrons or muons), and the other to two neutrinos that escape direct detection. The final state is thus characterised by: a pair of oppositely-charged, isolated electrons or muons, with invariant mass within a Z mass window; no additional leptons, other than the muon or electron pair from the Z decay; and large missing transverse energy. Given that the ZZ pair is produced in the collision of two hadrons, extra jets may be found in the event.

The muons used to reconstruct a Z candidate are selected inside the fiducial region of the muon spectrometer, $|\eta| < 2.4$, with a minimum p_T of 20 GeV/c, and using standard identification criteria based on track informations and isolation.

Electrons are selected inside the fiducial region of the electromagnetic calorimeter ECAL, $|\eta| < 2.5$. The electron candidates must have a minimum p_T of 20 GeV/c, and satisfy standard identification criteria, based on shower shape, track quality, cluster track matching, etc., in order to reject misidentified hadrons.

Z candidates are selected in events with a pair of same-flavour leptons which

pass the identification and isolation criteria. In order to suppress all backgrounds that do not include a Z boson, the lepton pair is required to have an invariant mass compatible with the Z boson mass. The transverse momentum of the Z candidate is required to be greater than 45 GeV/c, to reduce especially the Drell-Yan (DY) background, given that the Z bosons are on average more boosted in ZZ than in single- Z events.

In order to suppress backgrounds coming from top quarks, events are vetoed if a b -tagged jet is found. Jets with p_T greater than 20 GeV/c within the tracker fiducial region ($|\eta| < 2.4$) are considered as b -taggable. To further reduce top and other backgrounds with substantial hadronic activity, events are rejected if they contain any jet with $p_T > 30$ GeV/c.

Missing transverse energy (E_T^{miss}) is computed from the magnitude of the negative vector sum of the transverse momenta of all candidates reconstructed in the event. Its resolution is critical for the extraction of the $ZZ \rightarrow ll\nu\nu$ signal given that it is the distinctive hallmark with respect to DY background.

The E_T^{miss} balance variable is defined as the ratio between the standard E_T^{miss} and the transverse momentum of the Z boson. Values of this variable far from unity identify events in which the Z candidate is not well balanced by genuine E_T^{miss} from neutrinos, but recoils against mis-measured jets or leptons. The selected sample can still be contaminated by events with jets of p_T below the veto threshold.

A mismeasurement of the jet energy can produce fake E_T^{miss} aligned with the jet direction in the transverse plane. These events are thus characterized by a small azimuthal angle between the E_T^{miss} and the closest jet, $\Delta\phi(E_T^{miss}, jet)$. This distribution can be used especially to reject $Z + jets$ events with small $\Delta\phi$ angle. Likewise, a mismeasurement of the transverse momentum of a lepton can produce fake E_T^{miss} .

In order to suppress the WZ background, with both bosons decaying leptonically, events are required to have no additional leptons, other than the muon or electron pair from the Z candidate.

5 Conclusions

In summary, we have presented an updated measurement of the ZZ production cross section in proton-proton collisions at 8TeV in the $ZZ \rightarrow ll'l'$ and $ZZ \rightarrow ll\nu\nu$ decay modes. The data sample corresponds to an integrated luminosity of 19.6 fb $^{-1}$. The measured cross section in the first final state is $\sigma(pp \rightarrow ZZ) = 7.7_{-0.5}^{+0.5}$ (stat.) $_{-0.4}^{+0.5}$ (syst.) ± 0.4 (theo.) ± 0.3 (lum.) pb is consistent with the SM prediction. Differential cross sections are measured. Limits on vector-boson self- interactions are established, significantly restricting possible allowed ranges of the anomalous ZZZ and $ZZ\gamma$ trilinear gauge couplings.

References

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