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Search for anomalous couplings in boosted $WW/WZ \to q\bar{q}$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV

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Search for anomalous couplings in boosted WW/WZ $\to \ell\nu q\bar{q}$ production in proton–proton collisions at $\sqrt{s} = 8$ TeV

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ABSTRACT

This Letter presents a search for new physics manifested as anomalous triple gauge boson couplings in WW and WZ diboson production in proton–proton collisions. The search is performed using events containing a W boson that decays leptonically and a W or Z boson whose decay products are merged into a single reconstructed jet. The data, collected at $\sqrt{s} = 8$ TeV with the CMS detector at the LHC, correspond to an integrated luminosity of 19 fb^{-1}. No evidence for anomalous triple gauge couplings is found and the following 95% confidence level limits are set on their values: λ ([−0.011, 0.011]), $\Delta\kappa_\gamma$ ([−0.044, 0.063]), and Δg_1^Z ([−0.0087, 0.024]). These limits are also translated into their effective field theory equivalents: c_{WWW}/Λ^2 ([−2.7, 2.7] TeV^{-2}), c_B/Λ^2 ([−14, 17] TeV^{-2}), and c_W/Λ^2 ([−2.0, 5.7] TeV^{-2}).

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1. Introduction

Measurements of electroweak diboson production can be translated into measurements of gauge boson self-couplings, which are among the most fundamental aspects of the standard model (SM). At leading order (LO), only s-channel $q\bar{q}$ annihilation diagrams have a triple-boson vertex. In WW production, the WWγ and WWZ vertices contribute, while in WZ production only the WWZ vertex is present. Physics beyond the SM can modify the couplings at these vertices, leading to observable differences in the cross section and the kinematic distributions of final state particles [1]. In the search for anomalous triple gauge couplings (aTGCs), we adopt the effective Lagrangian and LEP parametrization in Ref. [2], without form factors: $\lambda_\gamma = \lambda_Z = \lambda$, $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$. We focus in particular on the parameters λ, $\Delta\kappa_\gamma$, and Δg_1^Z, where the deltas represent deviations from their respective SM values ($\lambda_{SM} = 0$). We also translate these into the equivalent parameters defined in an effective field theory (EFT) approach, namely c_{WWW}/Λ^2, c_W/Λ^2, and c_B/Λ^2, where Λ is the scale of new physics [3].

This Letter presents a search for new physics manifested as anomalous couplings of triple gauge boson vertices in WW or WZ diboson production from pp collisions at $\sqrt{s} = 8$ TeV at the CERN LHC. We focus on the case where one W boson decays leptonically ($W_{lep} \to \ell\nu$, with $\ell = e, \mu$), while the other vector boson V_{had} decays hadronically, giving rise to a single merged jet (J) in the final state. Previous searches in this channel at the LHC can be found in Refs. [4,5]. Other recent searches in the leptonic channel are described in Refs. [6,7]. The advantages of reconstructing WV pairs in the $\ell\nu q\bar{q}$ decay mode over purely leptonic final states are the larger branching fractions of W and Z bosons to quarks, and in the case of two W bosons, the ability to reconstruct their transverse momenta (p_T). These advantages are partially offset by the larger backgrounds in the $\ell\nu q\bar{q}$ channel, arising mainly from W+jets production. The sensitivity of WW production to the WWγ coupling and of both WW and WZ production to the WWZ coupling, especially at high boson p_T, makes these processes particularly useful as a probe of aTGCs.

Compared to our previous search at $\sqrt{s} = 7$ TeV [4], we have added another coupling parameter, Δg_1^Z, to the parameter space, and we focus exclusively on the Lorentz-boosted final states, where V_{had} is reconstructed as a single merged jet, since these final states are far more sensitive to an aTGC signal than the resolved two-jet states.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke out-

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side the solenoid. The CMS detector is nearly hermetic, allowing for measurements of the missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) in the event. $E_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the magnitude of the negative vector p_{T} sum of all reconstructed particles in an event. A two-tier trigger system selects the events of interest. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [8].

3. Data and simulation samples

The data were collected using single-lepton triggers with p_{T} thresholds of 24 (27) GeV for muons (electrons). The overall trigger efficiency is about 94% (90%) for the muon (electron) data, with a small dependence (a few percent) on p_{T} and pseudorapidity η. The total integrated luminosity collected and processed is 19.3 (19.2) fb^{-1} for muon (electron) triggers.

We use the MadGraph5 1.3.30 [9] event generator to produce both the W+jets and Drell–Yan samples, with up to four additional partons in the matrix element calculation. Single top quark and top quark–antiquark pair ($\mathrm{t\bar{t}}$) samples are generated with powheg 1.0 [10–14]. The diboson samples (WW, WZ) are generated on-shell at next-to-LO (NLO) with MadGraph5_amc@nlo version 2.0.0 [15] and MadSpin version 3.2 [16]. The decays $\mathrm{W} \to \tau\nu$ are included for all processes. The τ lepton decays are simulated with tauola [17]. The pythia 6.422 generator [18] provides the fragmentation and parton shower simulation, with the parameters of the underlying event set to the Z2* tune [19,20]. The k_{T}-MLM matching scheme is used to interface pythia6 with MadGraph5 at LO [21]. The set of parton distribution functions (PDFs) used is CTEQ6L1 [22] for LO generators and CT10 [23] for NLO generators. A Geant4-based simulation [24] of the CMS detector is used in the production of all Monte Carlo (MC) samples. The simulation also includes multiple proton–proton collisions within a bunch crossing (pileup). Simulated events are reconstructed and analyzed in the same way as measured collision events, subject to additional corrections that account for differences between data and simulation in trigger and selection efficiencies, and in the vertex multiplicity distribution.

4. Event reconstruction

All observable objects, namely leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$, are reconstructed with a particle-flow technique [25,26] that combines information from several subdetectors. Muons are reconstructed within $|\eta| < 2.4$ with the inner tracker and the muon system [27]. Electrons are reconstructed within $|\eta| < 2.5$ from tracks in the tracker pointing to energy clusters in the ECAL, and identified using a multivariate discriminator [28]. The selections applied to this discriminator are tuned to match the η-binned efficiencies used for Ref. [4]. Muons (electrons) are required to have p_{T} greater than 25 (30) GeV. The lepton candidates are required to be consistent with originating from the event's primary vertex, and to be isolated from other activity in the event. The isolation requirements for muons (electrons) are based on the particle-flow technique with an isolation cone of $\Delta R = 0.4\,(0.3)$, and are designed to reduce the effects of pileup and neutral particles. Events with additional loosely identified leptons are vetoed to reduce the backgrounds from fully leptonic decays, such as those originating from the Drell–Yan process and diboson production. Decays of the tau lepton to electrons or muons that pass these criteria are included as potential signal events.

The anti-k_{T} (AK) [29,30] and Cambridge–Aachen (CA) [29–31] clustering algorithms are used to reconstruct jets in the event. The AK algorithm uses a distance parameter of $R = 0.5$ (AK5). The CA jets are clustered with $R = 0.8$ (CA8) and are used for reconstructing $\mathrm{V_{had}}$, where the V boson decay products are merged into a single jet. The combined secondary vertex algorithm at the medium operating point is used to tag AK5 jets as b jets [32]. We assign the $E_{\mathrm{T}}^{\mathrm{miss}}$ measured in the event to the neutrino candidate and combine this with the identified lepton to reconstruct $\mathrm{W_{lep}}$. Boosted W events are selected by requiring $p_{\mathrm{T}} > 200$ GeV for $\mathrm{W_{lep}}$.

We require one CA8 jet with $p_{\mathrm{T}} > 200$ GeV, and no additional CA8 jets with $p_{\mathrm{T}} > 80$ GeV, in the region $|\eta| < 2.4$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be above 50 (70) GeV for the muon (electron) channel to suppress multijet backgrounds. We ensure that the two bosons are back-to-back by requiring $\Delta R(\ell, J) > \pi/2$, $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, J) > 2.0$, and $\Delta\phi(\mathrm{W_{lep}}, J) > 2.0$. We veto events based on the presence of any b-tagged AK5 jets with $p_{\mathrm{T}} > 20$ GeV and outside the CA8 jet cone to reduce the $\mathrm{t\bar{t}}$ background. After the kinematic selections, we apply jet substructure techniques. Improved separation between the signal and the multijet background is obtained in the jet mass observable by means of a "pruning" algorithm [33,34] designed to remove soft gluon radiation and pileup contributions from jets. The "N-subjettiness" variable [35] is a jet substructure observable that defines a measure, τ_N, for a jet to have N subjets. We require τ_2/τ_1, which is the ratio of 2-subjettiness to 1-subjettiness, of the leading CA8 jet to be less than 0.55 to discriminate against W+jets backgrounds.

5. Background and signal modeling

After all selections the background comprises three main components: W+jets, top quark ($\mathrm{t\bar{t}}$ and single top quark), and SM diboson production. Multijets, Z+jets, ZZ, $\mathrm{Z}\gamma$, $\mathrm{H(125)} \to \mathrm{WW}^*$, and fully hadronic and leptonic WW decay mode backgrounds were estimated and determined to be negligible.

For the aTGC search we select the merged jet p_{T}, p_{T}^{J}, as the observable, which for diboson pairs is the p_{T} of $\mathrm{V_{had}}$. We take the binned shape of the p_{T}^{J} distribution for each contributing process from MC samples. However, since the LO W+jets prediction falls below the data, we choose to extract the normalizations of the largest background components first from an unbinned maximum-likelihood fit to the data distribution of the merged jet mass, m_J. The diboson m_J shape in the fit region is unaffected by the aTGC signal at the level of sensitivity of this analysis.

5.1. Normalization extractions from the m_J fit

For this part of the analysis we employ a two-stage procedure: first we fit the distribution in simulation for each process individually. The MC templates used in the 7 TeV analysis are replaced by analytical functions, which provide additional flexibility to model the data accurately. Second, we utilize the results from the first set of fits to perform an unbinned maximum-likelihood fit to data that includes all components. Due to the differences in background compositions and shapes, the fit to data is performed separately for the muon and electron channels. All fits are performed over the mass range $40 < m_J < 140$ GeV. Within each fit to data, the normalization for each background process is either free to float or allowed to vary around a central value subject to a Gaussian constraint. Some components have been combined because of similarity in shape, or because the W and Z bosons are not well-resolved in m_J. Finally, the yields used to normalize background p_{T}^{J} components are extracted from the signal region of $70 < m_J < 100$ GeV.

To assist in the background determination, we define a control sample intended to isolate pure top quark events for comparison with simulation [36]. The sample is constructed by inverting the selection on the number of b-tagged AK5 jets outside the CA8 jet, thus requiring that there be at least one AK5 b-tagged jet. This

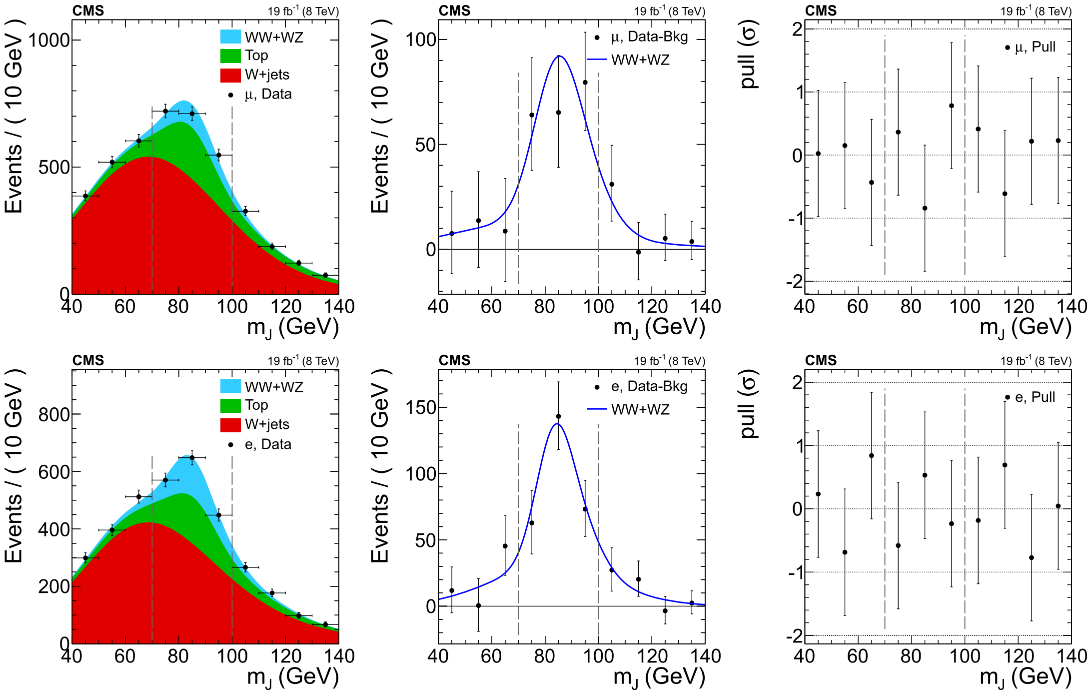

Fig. 1. Post-fit distributions of the merged jet invariant mass for muons (top) and electrons (bottom) with the estimates of the relevant backgrounds. The merged jet invariant mass is plotted for all events (left), after subtraction of all components except the diboson (center), and the subsequent normalized residual or pull distributions: (data − fit)/(fit uncertainty) (right). The error bars represent statistical uncertainties. The dashed vertical lines mark the signal region of $70 < m_J < 100$ GeV, from which the p_T distribution normalizations are extracted.

control sample is subsequently referred to as the top control sample.

The diboson probability density function (pdf) in m_J is parametrized by a sum of two Gaussian functions corresponding to the W and Z resonances. The position and width of the Z Gaussian are fixed with respect to those of the W Gaussian, which is initially taken from simulation. The relative fractions of WW (84% of the total) and WZ (16%) are also taken from simulation. The broad background from jets misassigned to V_{had} is modeled by an error function times an exponential function. The W Gaussian parameters are subsequently corrected with MC-to-data scale factors determined from the top control sample, in order to account for mismodeling of the merged-jet mass in simulation. All diboson shape parameters are then fixed during the fits to the data, while the normalizations are free parameters to be measured.

For the W+jets process, the shape of the m_J distribution is described by a kinematic turn-on at lower masses (error function) followed by a rapidly falling tail (exponential). The pre-fit normalization is set to the LO MadGraph+pythia6 cross section times an empirical factor of 1.3. This factor provides an initial estimate of the difference between data and simulation in the topologies, effectively accounting for the expected increase in the inclusive cross section from NNLO corrections, and given a loose ±50% constraint. The shape parameters of the function are allowed to vary in the fit to the data without constraint.

The top quark background is a combination of $t\bar{t}$ and single top quark production processes. The top quark model is parametrized by a sum of an error function times an exponential function and a double Gaussian function, corresponding to both merged and unmerged jets from hadronic W decays. The top control sample is used to correct the W resonance shape parameters, to estimate the expected yield and yield uncertainties by extrapolating to the signal region, and to adjust the top normalization uncertainty. All top shape parameters are fixed in the fit to the data, and the normalization is constrained to a Gaussian with a width of 8 (10)% for muons (electrons). These come from a combination of theory uncertainty and uncertainties associated with use of the top control sample.

Fig. 1 shows the results of one of the fits to the data. The left plots show the observed m_J distributions, together with the fitted contributions of the three largest SM processes. The central plots show the same distribution after subtracting all SM contributions from data except for diboson events. The right plots show the pull distribution, i.e., the normalized residual defined as (data − fit)/(fit uncertainty), where the fit uncertainty is computed at each data point by propagating the uncertainty in the normalization coefficients.

The individual process yields, as determined by the fit, are reported in Table 1. The acceptance times efficiency ($\mathcal{A}\varepsilon$) is determined from the diboson MC. The electron channel has a smaller $\mathcal{A}\varepsilon$ because of its higher kinematic threshold. The top quark results reflect the inability of the fit to further constrain this background. The W+jets yields are about 20% higher than the prefit value of 1.3 times the LO prediction, which exhibits our limited knowledge of this boosted regime. For the diboson process, 1.35 (2.23) times the expected event count is observed in the muon (electron) channel. This excess is statistically consistent with the SM NLO prediction [15]. Overall, the approach produces a high quality model of the data (Fig. 1 (left)), with pull distributions consistent with zero (Fig. 1 (right)), that allows us to extract the diboson contribution to the V_{had} resonance (Fig. 1 (center)).

5.2. Fit validation

We validate the fit procedure by performing pseudo-experiments. For each experiment, we generate the m_J pseudo-data for the SM processes using the fitted pdf, taking into account the correlations between the yields, and then perform a fit to each pseudo-data m_J distribution as if it were the real data. Likewise, we ensure that the parametrization used is sufficiently general by

Table 1
Observed event yields and associated ratios (in parentheses) with respect to the pre-fit values extracted in the signal region ($70 < m_J < 100$ GeV). The term $\mathcal{A}\varepsilon$ (acceptance × efficiency) includes W and Z branching fractions [37].

Quantity	μ channel	e channel
Data	1977	1666
W+jets	1318 (1.22 ± 0.06)	1023 (1.17 ± 0.07)
Top quark	450 (1.00 ± 0.08)	364 (1.00 ± 0.10)
WV	204 (1.35 ± 0.77)	285 (2.23 ± 0.84)
$\mathcal{A}\varepsilon$	9.7×10^{-5}	8.3×10^{-5}

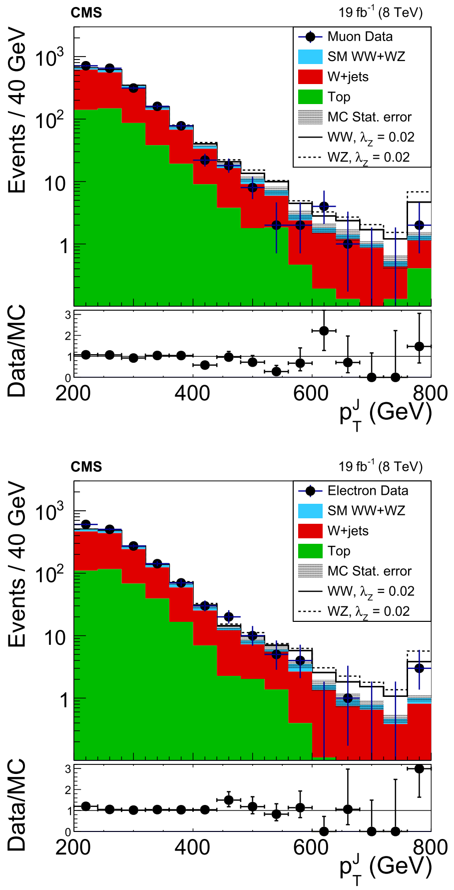

Fig. 2. V_{had} p_T distributions for the muon (top) and electron (bottom) channels after full selection and with the requirement $70 < m_J < 100$ GeV. The MC errors are purely statistical. Examples of the effects of aTGCs are shown by the solid and dotted lines. Below we show the data/MC ratio. The last bin includes the overflow.

generating pseudo-data with more general functional forms and fitting them with the default configuration. The results indicate that biases in all background yields and yield uncertainties are small.

5.3. *Signal modeling*

The dependence of the p_T^J distribution on specific aTGCs is modeled by reweighting the simulations of SM WW and WZ by the ratio of squared matrix elements with and without the anomalous coupling, i.e., $|\mathcal{M}|^2/|\mathcal{M}|^2_{\text{SM}}$, where $|\mathcal{M}|^2$ is the squared matrix element in the presence of anomalous couplings and $|\mathcal{M}|^2_{\text{SM}}$ is the squared matrix element in the SM, calculated with MCFM version 6.0 [38]. These ratios are calculated, parametrized with polynomials, and the polynomials encapsulated into a unified signal model in two-dimensional (2D) space for three pairwise combinations of the effective Lagrangian parameters being studied.

5.4. *Preparing p_T^J distributions*

Distributions of p_T^J in the form of histograms binned over the range 200–800 GeV (Fig. 2) are used to compute limits. All selections have been applied, including the signal window, $70 < m_J < 100$ GeV. The W+jets and top quark background normalizations are fixed according to the results from the m_J fits. The SM diboson components, however, are normalized to the NLO predictions, since a) we are searching for enhancements to the diboson production relative to those predictions, and b) given the excess of SM diboson events obtained from the fits in both channels, normalizing to theory predictions yields substantially more conservative, less sensitive expected limits. We treat the two lepton categories as separate channels in the limit setting process.

Since the W+jets shape is only calculated to LO, and we are exploring a new region of phase space, we adjust the shape and normalization from MC by comparing it to a distribution derived using an alternative method. This method involves extrapolating the W+jets p_T^J distribution from a m_J data sideband to the signal region by means of a transfer function. The transfer function is a ratio of curves fitted to the W+jets p_T^J distributions in the signal and sideband regions of W+jets simulation [36,39]. The comparison shows that the ratio of the W+jets backgrounds derived using the two methods is statistically consistent with unity.

6. Systematic uncertainties

The main source of systematic uncertainty is the normalization uncertainty in the W+jets background estimate. From the alternative method described in Sec. 5.4, we extract a 20% uncertainty in the total background normalization by taking the precision of the ratio of the W+jets background distribution derived from the two methods and summing over the high p_T region (400–800 GeV), where the signal is expected.

The theoretical uncertainties in the signal normalization are associated with the renormalization and factorization scales, and with the choice of PDF, for $p_T^W > 1$ TeV. For PDF uncertainties we compare aMC@NLO samples employing 41 alternative sets of CTEQ6M PDFs following the prescription in Ref. [22]. Factorization and renormalization scale uncertainties are estimated by simultaneously varying them up or down by a factor of 2. Both scale and PDF uncertainties are estimated to be approximately 18–26%.

The uncertainty in the signal shape coming from the effects of reconstruction is estimated by comparing the aTGC/SM ratios at the generator level and the aTGC/SM ratios at the reconstruction level after all major selections are applied for both samples. The ratio is consistent with unity, and therefore only the statistical error on the ratio is propagated as an uncertainty in the modeling of different aTGC signal grid points.

The uncertainty in the luminosity measurement is 2.6% [40]. Additional sources of uncertainty from limited MC sample size, jet energy scale and resolution, E_T^{miss} resolution, trigger efficiency, lepton reconstruction and selection efficiency, additional jet veto, pileup, and b-tag efficiency are negligible in comparison to the primary sources. These uncertainties are treated as nuisance parameters in the model and profiled according to Ref. [41], Appendix A. Luminosity and theory uncertainties are treated as 100% correlated between the two channels.

7. Coupling limits and summary

Two-dimensional likelihood fits are performed in the three planes described in Sec. 5.3. Each time the third parameter is profiled. The electron and muon channels are fitted simultaneously in

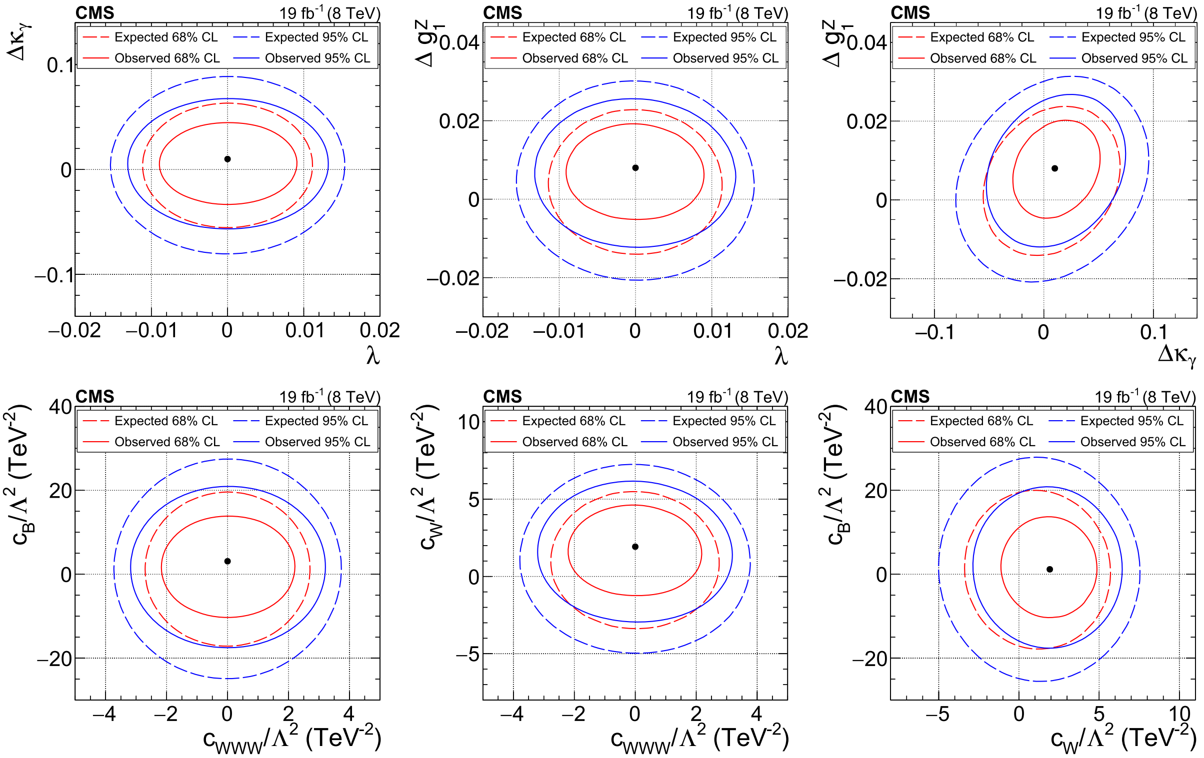

Fig. 3. The 68 and 95% CL observed and expected exclusion contours in ΔNLL are depicted for three pairwise combinations of the aTGC parameters in the LEP parametrization (top) and in the EFT formulation (bottom). The black dot represents the best fit point. The origin represents the SM prediction. The asymmetry of expected limits around the SM is allowed by the theoretical parametrization.

Table 2
Summary of expected and observed one-dimensional limits in the LEP parametrization. Each number pair represents the observed 95% confidence interval for that parameter.

Parameter	Expected limits	Observed limits
λ_Z	$[-0.014, 0.013]$	$[-0.011, 0.011]$
$\Delta\kappa_\gamma$	$[-0.068, 0.082]$	$[-0.044, 0.063]$
Δg_1^Z	$[-0.018, 0.028]$	$[-0.0087, 0.024]$

Table 3
Summary of one-dimensional limits in the EFT formulation for this analysis (*) compared to previous results.

	c_{WWW}/Λ^2 (TeV^{-2})	c_B/Λ^2 (TeV^{-2})	c_W/Λ^2 (TeV^{-2})
*	$[-2.7, 2.7]$	$[-14, 17]$	$[-2.0, 5.7]$
[6]	$[-5.7, 5.9]$	$[-29.2, 23.9]$	$[-11.4, 5.4]$
[7]	$[-4.61, 4.60]$	$[-20.9, 26.3]$	$[-5.87, 10.54]$
[43]	$[-4.6, 4.2]$	$[-260, 210]$	$[-4.2, 8.0]$
[44]	$[-3.9, 4.0]$	$[-320, 210]$	$[-4.3, 6.8]$

the limit setting procedure. No evidence for anomalous couplings is found, and we calculate the 68 and 95% confidence level (CL) exclusion contours, using the differences of the negative log likelihood (ΔNLL) relative to the best fit point. No form factors are used. The limits are subsequently translated [3] into equivalent limits on the parameters within the EFT approach, namely c_{WWW}/Λ^2, c_W/Λ^2, and c_B/Λ^2, shown in Fig. 3. We also set 1D 95% CL limits on all six parameters, with the second parameter profiled and the third parameter fixed to zero. These are shown in Tables 2 and 3. The latter also shows other recent 8 TeV results for comparison.

In summary, our limits are consistent with the SM prediction and improve upon the sensitivity of the fully leptonic 8 TeV results [6,7] and the combined LEP experiments [37,42].

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