WW PRODUCTION AND TRIPLE GAUGE BOSON COUPLINGS AT ATLAS*

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(Received November 15, 2006)

We present a strategy for the direct measurement of the WW production rate at the LHC with ATLAS. Sensitivity limits on anomalous WWZ and $WW\gamma$ couplings are assessed with account of the effects of higher order QCD corrections and contributions from other theoretical and detector related systematics.

PACS numbers: 12.15.–y, 13.85.–t

1. Introduction

The LHC will be the primary source of WW pairs with large invariant mass and high statistics. It will produce more than 1M of WW events per year, during the low luminosity running phase $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, corresponding to an integrated luminosity of 10 fb^{-1}. Accurate measurement of the WW production rate will allow to test non Abelian structure of the Standard Model by exploring self-interactions of vector bosons, WWZ and $WW\gamma$, known as triple gauge-boson couplings (TGC's). Furthermore, this measurement will be sensitive to new phenomena since anomalous trilinear couplings, or the production and decay of new particles such as Higgs boson, will enhance the rate of W boson pair production.

In this note we present a strategy for the measurement of the WW production rate at the LHC with ATLAS detector. Since LHC will have a large potential for testing triple gauge boson couplings, the ATLAS Collaboration has devoted considerable effort to the study of TGC signatures and measurements [1–4]. In this note we present the prospects for measuring anomalous contributions to the WWZ and $WW\gamma$ couplings through $pp \to W^+W^- \to l^+\nu l^-\bar{\nu}$ production where l denotes an electron or muon.

* Presented at the "Physics at LHC" Conference, Kraków, Poland, July 3–8, 2006.

The WW production provides a complementary information to the measurements of WWZ coupling in WZ production, and $WW\gamma$ coupling in $W\gamma$ production. Detailed description of the TGC studies in WZ, $W\gamma$ and WW productions is presented in the ATLAS Notes [1, 2, 4].

2. *WW* selection and background

At the LHC the WW production will occur through the $q\bar{q} \to W^+W^-$ (95%) and $gg \to W^+W^-$ (5%) hard processes [5]. The WW production will be studied at LHC using the muon and electron decay channels $pp \to W^+W^- \to l^+l^-\nu\bar{\nu}$. These channels provide clear signatures consisting of two high $p_{\rm T}$ leptons, with opposite charge, and large missing transverse energy arising from the neutrinos. The other channels in which one or both of W bosons decay into hadrons are difficult to separate from the huge QCD background. The branching ratio for electron and muon channels is 0.0453.

In this analysis the WW events, with leptonic W decays, are generated using the Baur, Han and Ohnemus (BHO) numerical parton-level Monte Carlo program [6] and also MC@NLO 3.1 [7]. Both generators calculate W^+W^- production to next-to-leading order in QCD. The BHO generator is interfaced with PYTHIA 6.203 for independent fragmentation and subsequent hadronization of the additional colored parton in final state. The MC@NLO, on the other hand, combines exact NLO QCD matrix elements with parton shower based on HERWIG. Hard emission is treated as in NLO calculations, whereas soft and collinear emissions are treated as in a LO parton shower MC program. In the MC@NLO the matching between hard, and soft and collinear regions is smooth. The total rates in MC@NLO are accurate to NLO. In both generators the spin correlations between W^+ and W^- are taken into account, however only BHO NLO code includes anomalous triple gauge boson couplings. The detector effects are included in the form of fast parametrization of the ATLAS detector response [8].

The inclusive NLO cross-sections obtained using BHO NLO code and MC@NLO 3.1 are 119.2 pb and 116.3 pb, for CTEQ4M p.d.f. and factorization scale $Q^2 = M_W = 80.396$ GeV. After the cuts imposed by ATLAS trigger ($p_{\rm T}^l > 25$ GeV, $\mid \eta^l \mid < 2.5$ and $p_{\rm T}^{\rm miss} > 50$ GeV) the cross-section for e^+e^- channel, is 0.19 pb in NLO BHO code and 0.20 pb in MC@NLO. Comparing to LO cross-section the NLO QCD corrections increase cross-section by factor of 1.3, and after taking into account experimental cuts by factor of 1.6.

Several background processes mimic the WW signal. The most important are: $t\bar{t} \to W^+W^-b\bar{b} \to l_1^+l_2^-\nu\bar{\nu}+b\bar{b}+X$, (all lepton flavor combinations, $l_{1,2} = e, \mu$); Drell–Yan, $Z/\gamma^* \to l_1^+l_2^- + X$, (same lepton flavor, $l_1 = l_2$); $W^\pm Z \to l_1\nu l_2^+l_3^- + X$ ($l_2 = l_3$) and $ZZ \to l_1^+l_2^-\nu\bar{\nu} + X$, ($l_1 = l_2$). The NLO cross-sections for these processes are: 833 pb, 6.0×10^4 pb, 49.4 pb, 15.5 pb respectively. The other processes such as: $W + \text{jets}$ (with jets misidentified as electrons), Wt, $\bar{b}b$, $\bar{c}c$, $Wg \to t\bar{b}$, $q\bar{q}\prime \to t\bar{b}$, Wc or $W\bar{b}b$, $W\bar{c}c$, are negligible, or they can be significantly suppressed by imposing lepton isolation cuts.

The basic set of cuts for selection of dileptonic WW events are: (1) two isolated leptons (e or μ), with opposite charge, $p_{\mathrm{T}}(l) > 25$ GeV, $\mid \eta(l) \mid < 2.5$; (2) $p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV; (3) Z mass veto: $\mid M_Z - m(l^+l^-) \mid > 15$ GeV; (4) jet veto: $p_{\mathrm{T}}(\mathrm{jet}) > 20$ GeV, $\mid \eta(\mathrm{jet}) \mid < 3$; (5) $\varPhi$ angle cut: $\varPhi(p_{\mathrm{T}}^{e^+e^-} p_{\mathrm{T}}^{\mathrm{miss}}) > 175°$. These cuts are optimized not only to maximize the signal significance, but also to maximize sensitivity to anomalous TGC's. Consistency between predicted number of signal events in BHO and MC@NLO is at the 6%–50% depending on the cuts applied. Since in MC@NLO the matching between hard, and soft and collinear regions is smooth, the MC@NLO predictions are more realistic and they are used as a basis for further analysis. After all cuts ≈ 5070 signal events are expected for an integrated luminosity of 30 fb^{-1}, and 900 background events, thus giving S/B = 5.6.

Figure 1 shows the BHO and MC@NLO transverse momentum distributions of electrons and e^+e^- pairs (after kinematical cuts) for $t\bar{t}$ and SM WW production. In order to compare the shape of distributions the MC@NLO results are normalized to BHO cross-section. Qualitative agreement is observed in the distribution shapes.

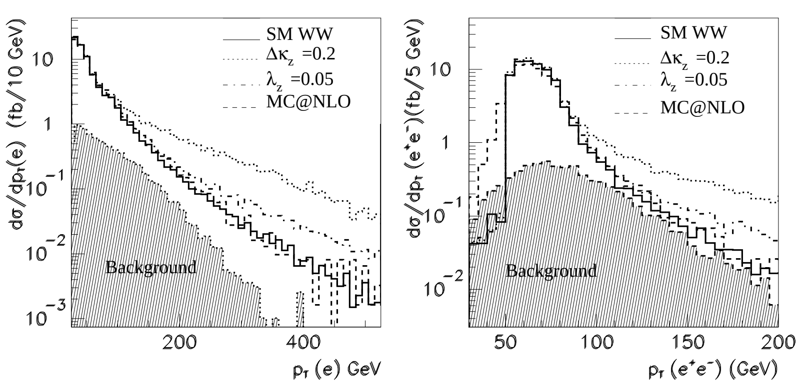

Fig. 1. BHO and MC@NLO transverse momentum distributions of electrons and e^+e^- pairs (after kinematical cuts) for: $t\bar{t}$, SM WW and non SM WW production with TGC $\varDelta\kappa_Z = 0.2$ and WW with TGC $\lambda_Z = 0.05$. MC@NLO distributions are normalized to the BHO cross-section.

3. Limits on anomalous TGC's

To test the agreement with the SM and to set limits on anomalous (non SM) couplings, the WWZ and $WW\gamma$ vertices are parametrized using the effective Lagrangian [9]. By assuming electromagnetic gauge invariance and invariance under Lorentz and CP transformations the effective Lagrangian is reduced to a function of five dimensionless coupling parameters: g_1^Z, κ_V and λ_V, with $V = Z, \gamma$. In the SM at tree level, the values of coupling parameters are: $\Delta g_Z^1 \equiv g_Z^1 - 1 = 0$, $\Delta\kappa_V \equiv \kappa_V - 1 = 0$, and $\lambda_V = 0$. The cross-section with non SM couplings increases with $\sqrt{\hat{s}}$. In order to avoid unitarity violation, the anomalous couplings are modified via form factor with a scale Λ:

$$\lambda_V(\hat{s}) = \frac{\lambda_V}{(1+\hat{s}/\Lambda^2)^2}\,, \quad \Delta\kappa_V(\hat{s}) = \frac{\Delta\kappa_V}{(1+\hat{s}/\Lambda^2)^2}\,, \quad \Delta g_1^Z(\hat{s}) = \frac{\Delta g_1^Z}{(1+\hat{s}/\Lambda^2)^2}\,.$$

Anomalous couplings can be detected by their influence on the observables. In general, the inclusion of anomalous couplings at the WWZ and $WW\gamma$ vertices enhances the W^+W^- cross-section, especially for the large values of the W boson transverse momenta $p_{\mathrm{T}}(W)$, and for large values of the W boson pair transverse momenta $p_{\mathrm{T}}(WW)$. Since the $p_{\mathrm{T}}(W)$ and $p_{\mathrm{T}}(WW)$ cannot be unambiguously reconstructed in the dilepton channels, alternatively the transverse momentum distributions of leptons or lepton pairs can be studied. Figure 1 shows the p_{T} distribution of electrons and p_{T} distribution of e^+e^- pairs, for SM and non SM TGC couplings. Next-to-leading-order corrections are large in the high $p_{\mathrm{T}}(l)$ and $p_{\mathrm{T}}(l^+l^-)$ regions and thus it is important to include these corrections to probe the WWZ and $WW\gamma$ vertices.

By assuming that TCC parameters are consistent with the SM, the limits on anomalous couplings are extracted in this note by using binned maximum likelihood fit to compare the "experimental" $p_{\mathrm{T}}(e)$ distribution to the Monte Carlo reference distributions which are a function of the TGC parameters. The "experimental" distribution is obtained by sampling each bin according to a Poisson distribution with the mean given by the relevant bin content of the SM reference histogram. The MC reference distributions are obtained by using the method described in some detail in Ref. [4]. The 95% C.L. limits on anomalous couplings obtained when one parameter is varied from the SM value are:
for WWZ coupling,

$$-0.037 < \Delta\kappa_Z < 0.073\,,$$

$$-0.036 < \lambda_Z < 0.043\,,$$

$$-0.25 < \Delta g_Z^1 < 0.36\,;$$

for $WW\gamma$ coupling,

$$-0.11 < \Delta\kappa_\gamma < 0.14\,,$$
$$-0.081 < \lambda_\gamma < 0.073\,;$$

for "equal coupling scheme", $\Delta\kappa_Z = \Delta\kappa_\gamma = \Delta\kappa \qquad \lambda_Z = \lambda_\gamma = \lambda\,,$

$$-0.032 < \Delta\kappa < 0.052\,,$$
$$-0.028 < \lambda < 0.027\,.$$

Contours at 68% and 95% C.L., for the two parameter fit, for $\Delta\kappa_Z$, λ_Z and $\Delta\kappa_\gamma$, λ_γ parameters are shown in figure 2.

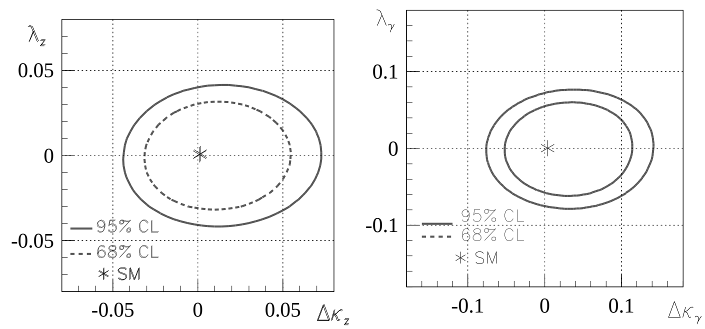

Fig. 2. 68% C.L. and 95% C.L. contour curves in the $\Delta\kappa_Z, \lambda_Z$ plane (left) and $\Delta\kappa_\gamma$, λ_γ plane (right).

All limits are obtained for an integrated luminosity of 30 fb^{-1} and form factor scale $\Lambda = 2$ TeV. The limits include both statistical and systematic effects. The following systematic effects are estimated: background rate, parton density function systematics, choice of renormalization and factorization scales, detector related systematics, size of the grid and systematics related to the accuracy of the NLO code. The dominant systematic effect comes from our limited theoretical understanding of the parton density functions. The results obtained from the one and two parameter fit show that limits for photonic couplings, $\Delta\kappa_\gamma$ and λ_γ, are ≈ 2 times higher compared to the limits of WWZ coupling, because of the smaller photon fermion couplings.

In the "equal coupling scheme" the limits for anomalous coupling are $\approx$ 10–40% lower than those obtained in the case where only $\Delta\kappa_Z$ and λ_Z deviate from the SM values. An increase of integrated luminosity from 30 to 300 fb^{-1}, and form factor scale from 2 to 5 TeV, improves sensitivity limits by $\approx$ 30–40%. For the $\Delta\kappa_Z$ and λ_Z, the sensitivity limits are dominated by statistics for integrated luminosity up to at least 100 fb^{-1}, and will always be statistically limited at the LHC experiments.

Comparison with results obtained from other diboson processes [1, 2] shows that WW process will be competitive with WZ and $W\gamma$ in determining limits on $\Delta\kappa_V$ parameters. This is expected since for WW production the terms proportional to $\Delta\kappa_V$ in the amplitude increase like s/M_W^2, while for $W\gamma$ and WZ processes these terms increase like $\sqrt{s}/M_W$ [6].

4. Conclusions

The prospects for measurement of WWZ and $WW\gamma$ couplings in WW production at ATLAS are presented. The effects of higher order QCD corrections and contributions from other theoretical and detector related systematics are accounted for. By using the BHO NLO generator interfaced with PYTHIA and fast simulation of ATLAS detector we found that for an integrated luminosity of 30 fb^{-1} and $\Lambda = 2$ TeV, the $\Delta\kappa_Z$ and λ_Z TGC parameters can be measured with an accuracy of 0.02 to 0.06 with 95% C.L. By comparing with other diboson processes we infer that WW can provide stringent limits on the $\Delta\kappa_Z$. However, the WZ and $W\gamma$ processes provide one order of magnitude better limits on λ_V and Δg_Z^1 TGC parameters.

This work was prepared within the Standard Model group of the ATLAS Collaboration, and we thank collaboration members for helpful discussions. The work was supported in part by the Serbian Ministry of Science.

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