ZZ into 4ℓ expected sensitivity with the first ATLAS data

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1 Introduction

In the Standard Model (SM), ZZ production proceeds through the t- and u-channel $q\overline{q}$ scattering diagrams shown in Figure 1. It is of great interest to measure its cross-section at LHC energies because this process is an irreducible background to the SM Higgs decay channel $H \to ZZ$, and it provides a unique opportunity to test the SM by measuring the neutral Triple Gauge Coupling (TGC) strength, which is zero at tree level in the SM.

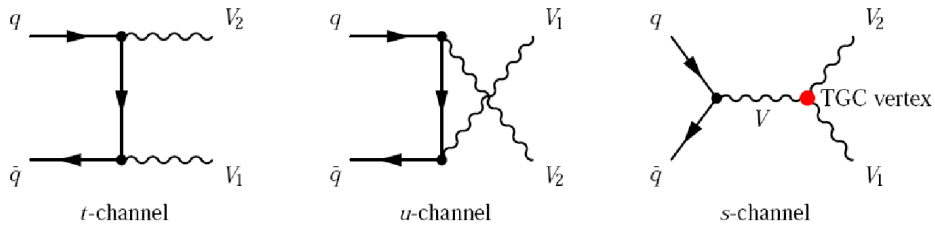

Figure 1: Feynman diagrams of ZZ production at leading-order for $(V, V_1, V_2) = (Z^{(*)}, Z, Z)$ or $(\gamma^{(*)}, Z, Z)$. The rightmost diagram is forbidden in the SM.

In this note we study the expected ATLAS sensitivity to ZZ production at 14 TeV c.m. energy with simulated data, via the four lepton final states $pp \to ZZ \to 4e, 4\mu, 2e2\mu$, taking into account both the on-mass and off-mass shell Z bosons. More details can be found in [1].
The signal channel is characterised by four high p_T, isolated leptons. Background contributions to this channel come mainly from:

- $t\bar{t}$ pair production where both W bosons decay leptonically and the other two lepton candidates come from the remaining b-jet.
- Production of b-jets associated with a Z boson, where the boson decays leptonically and is accompanied by leptons from the heavy quark jets ($Zb\bar{b}$).

Reconstructed muons not originating from Z decays are usually decay products of b quarks, whereas electrons are often misidentified jets.

These backgrounds can be very effectively suppressed as shown in this analysis, giving an expected signal to background ratio of $O(100)$ ($O(10)$) for on-shell (off-shell) Z bosons, and a signal significance of $O(7)$ with 1 fb^{-1} of data.

2 Signal and background MC Samples

Table 1 summarizes the signal and background samples used in this analysis, generated with full detector simulation and reconstruction. The $ZZ \to 4\ell$ signal NLO sample includes only on-shell Z bosons, therefore it is used for the TGC studies only and not for the cross-section studies, which are performed with the Pythia LO sample. For both the signal samples the Z bosons, as well as the taus, are forced to decay leptonically and the sample is restricted at generator level to lepton $|\eta| < 3.0$ and $p_T > 5$ GeV for all 4 leptons. For the background samples, filter cuts requiring 4 leptons in the final state were applied.

Process	Generator	Events	Filter eff.	K-factor	σ(fb)$\times$BR
$ZZ \to 4\ell$	Pythia(v6.3) [2]	43000	0.219	1.35	159
$ZZ \to 4\ell$	MC@NLO/Jimmy [3]	49250	1.000	-	66.8
$Zb\bar{b} \to 4\ell$	Acer/Pythia [4]	313689	0.009	1.42	52000
$t\bar{t} \to 4\ell$	MC@NLO/Jimmy	152701	0.007	-	833000

Table 1: Signal and background MC data samples summary table. The cross-section times Branching Ratio (BR) given in the last column is before the filter cut and does not include the K-factor for LO generators.

3 Event Selection

A set of pre-selection cuts is applied to reconstructed muons and electrons, then possible Z candidates are formed from the leptons which pass those pre-selection

cuts. More cuts are applied to the lepton pairs, and finally one ZZ pair is selected.

Pre-selection cuts

Muon tracks are required to be well reconstructed by the Muon Spectrometer (MS) and the Inner Detector (ID) combined, or the MS alone outside the ID's acceptance [5]. Basic kinematic cuts are also applied ($p_T > 6$ GeV, $|\eta| < 2.7$).

The electrons should be reconstructed as an electron-like cluster in the calorimeters matched to a track in the ID, with $0.5 < E/p < 3.0$. The kinematic cuts are similar to those for muons ($p_T > 6$ GeV, $|\eta| < 2.5$).

After pre-selection, lepton pairs of the same flavor and opposite charge are formed and pairs whose leptons have $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ are rejected. The remaining pairs are combined to form ZZ candidates and each event is required to have at least two legitimate pairs.

Isolation and maximum p_T cuts

The two main criteria which are used to discriminate signal from background are the lepton p_T and isolation. For muon isolation, the isolation ratio $I = \frac{E_{T,0.4}}{E_T^\mu}$ is required to be < 0.2 for each muon of the pair, where $E_{T,0.4}$ is the transverse energy in a cone of radius $\Delta R = 0.4$ around the muon track, and E_T^μ is the transverse energy of the muon. For electron isolation, cuts on shower shape in the Electromagnetic Calorimeter are applied to each electron. All pairs must have at least one lepton with $p_T > 20$ GeV.

Mass cut

In order to eliminate background from leptons not originating from Z decays, a cut of 70-110 GeV on the reconstructed Z invariant mass is applied. For the ZZ case, both candidate Z bosons are required to satisfy this cut, whereas for ZZ^* only one. The other Z candidate has to have an invariant mass greater than 20 GeV, making the ZZ sample a subset of the ZZ^* sample.

The cut flow described above and the respective efficiencies for the 4μ event topology is given in Table 2 for the signal and the backgrounds as an example.

4 Results

The 4ℓ invariant mass distributions for signal and background after all cuts are shown in Figure 2 for ZZ and ZZ^*. All plots are normalized to 10 fb^{-1} integrated luminosity.

The expected number of signal and background events for each of the three final state configurations is given in Table 3 for the ZZ and ZZ^* cases, for an integrated

	$ZZ \to 4\mu$ signal (%)		$Zb\bar{b}$ background (%)		$t\bar{t}$ background (%)	
	ZZ^*	ZZ	ZZ^*	ZZ	ZZ^*	ZZ
Lepton Preselection	71		6.3		3.2	
Pair formation,ΔR	99		77		63	
Isolation, p_T^{max}	81		1.3		0.13	
Z Mass region	92	73	25	2.0	50	25
Total	52	41	0.0156	0.0013	0.0013	0.0007

Table 2: Signal and background selection cut efficiencies for the 4μ final state. The efficiency in every step is the number of events remaining after the cut divided by the number of events before the cut.

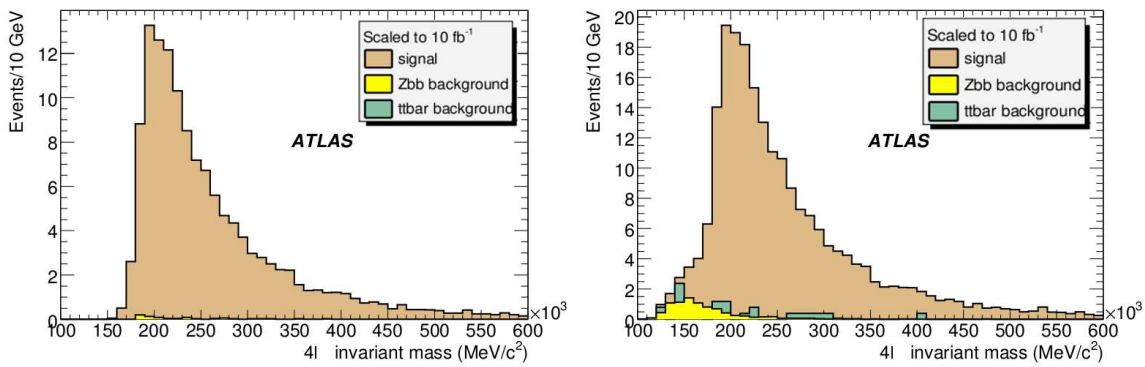

Figure 2: Final invariant mass of 4ℓ for signal and backgrounds, for ZZ (left) and ZZ^* (right), normalized to 10 fb^{-1}.

luminosity of 1 fb^{-1}. The uncertainties shown are only the statistical ones. The signal-to-background ratio is 66.5 (8.7) and the statistical significance 7.7 (6.6) for the ZZ (ZZ^*) case. The significance s is calculated as $s = \frac{sig}{\sqrt{bkg}}$, where sig is the expected number of signal events and bkg is the 95% Poisson limit for a mean of 0 (2) background events (for a conservative result, given the small statistics).

5 Systematic uncertainties

The expected numbers of events are subject to both theoretical and experimental uncertainties. The major theoretical uncertainties on the production cross-sections come from the PDF uncertainties and the QCD factorization scale uncertainties (for NLO calculations). The effect of varying the PDF's on the calculated cross-sections is about 4% (from 14.74 pb with CTEQ6M to 15.32 pb with MRST03).

The main experimental systematic effects arise from the uncertainties of the luminosity determination, the lepton identification and trigger efficiencies and energy/momentum resolutions, the jet energy scale and resolutions, and background model and estimate. The luminosity uncertainties could be controlled to ∼5% [6]. The lepton acceptance uncertainty is about 2-3% mainly due to the isolation requirement, which involves the hadronic jet energy uncertainties. Thanks to the very low background level expected for the $ZZ \to 4\ell$ process, the background uncertainty should be less than 2%, despite the limited MC statistics available for the background measurement.

6 Triple Gauge Couplings (TGC)

While the Standard Model ZZZ and $ZZ\gamma$ triple gauge boson couplings are zero at tree level, anomalous couplings may contribute. The on-shell ZZ final state is used to probe the neutral anomalous TGC sensitivity (see diagram in Figure 1). The most general form of the ZZV ($V = Z, \gamma$) vertex function is described in [7] and depends on the couplings f_i^V ($i = 4,\ 5$), which are dimensionless complex functions.

The most dramatic signature of anomalous couplings in diboson production is an increase in the cross-section at high values of gauge boson p_T and diboson transverse mass. The following results are obtained by using the $p_T(Z)$ distributions only.

A binned likelihood fitting method using the $p_T(Z)$ spectrum is used to extract the 95% C.L. intervals of anomalous coupling parameters. Expected events are determined from full NLO MC, weighted by the LO Monte Carlo [7] results for different anomalous coupling parameters.

Random samples are generated according to this expectation, which give the observed number of events n. For each $p_T(Z)$ bin, a likelihood is constructed, based on Poisson statistics convolved with Gaussian probabilities (g_{sig} and g_{bkg}) to model the signal

	4μ events		$4e$ events		$2\mu 2e$ events		Total	
	ZZ^*	ZZ	ZZ^*	ZZ	ZZ^*	ZZ	ZZ^*	ZZ
Signal	5.72	4.52	3.17	2.59	7.56	6.18	16.5	13.3
$Zb\bar{b}$	0.11	0.009	0.48	0.042	0.28	0.035	0.87	0.086
$t\bar{t}$	0.08	0.04	0.52	0.04	0.44	0.04	1.03	0.12
Total bgr	0.19	0.049	1.00	0.082	0.72	0.075	1.90	0.20

Table 3: Expected signal and background ZZ and ZZ^* events for $\mathcal{L}$=1 fb^{-1}.

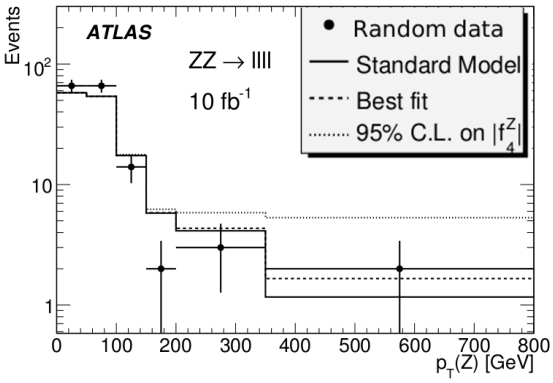

Figure 3: Example of a fit to one random sample with the likelihood method.

and background uncertainties. This likelihood

$$L = \int_{1-3\sigma_{bkg}}^{1+3\sigma_{bkg}} \int_{1-3\sigma_{sig}}^{1+3\sigma_{sig}} g_{sig}\ g_{bkg}\ \frac{(f_{sig}\nu_{sig} + f_{bkg}\nu_{bkg})^n\ e^{-(f_{sig}\nu_{sig}+f_{bkg}\nu_{bkg})}}{n!}\, df_{sig}\, df_{bkg}$$

is determined as a function of the coupling f_i^V in each bin of the measured spectrum. Summing over bins, a total log-likelihood is formed and its maximum determines the most likely value for the anomalous TGC. An example fit is shown in Figure 3.

The expected 95% C.L. intervals on anomalous couplings for 10 fb^{-1} integrated luminosity are $[-0.010, 0.010]$, $[-0.010, 0.010]$, $[-0.012, 0.012]$, and $[-0.013, 0.012]$ for f_4^Z, f_5^Z, f_4^γ and f_5^γ respectively, using the $ZZ \to \ell\ell\ell\ell$ final state alone. These limits improve slightly if they are combined with $ZZ \to \ell\ell\nu\nu$. The values of the scale Λ and the power n used for those couplings [7] are 2 TeV and 3 respectively. To calculate the limit in each parameter, other anomalous couplings are set to zero. Thus it should be possible to improve the LEP limits [8] on all TGC parameters by an order of magnitude.

Acknowledgements

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