# Recent electroweak results from ATLAS

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ATLAS measurements of multi-boson production processes involving combinations of $W$, $Z$ and isolated photons are summarized. Production processes sensitive to vector-boson fusion and vector-boson scattering such as electroweak production of single vector bosons associated with two forward jets and the di-boson production at 8 TeV $pp$ collisions are also presented. Measurements of the cross section and branching ratio for $Z$ to four leptons are described. Standard Model parameters, such as the weak mixing angle, are measured with high precision by ATLAS and are compared to world averages. Prospects at HL-LHC are discussed as an outlook.

## 1 Introduction

The LHC gives amongst others the opportunity to probe the validity of the electroweak (EW) sector of the Standard Model (SM) at energies not accessible before. Deviations from the SM could indicate new physics like anomalous gauge couplings. Pair production of heavy gauge bosons are of special interest because there is an intersection with Higgs physics.

The ATLAS detector [1] installed at the LHC is able to measure and identify objects like leptons, photons and jets with its inner detector (ID) [2], hadronic and electromagnetic calorimetry [3] and muon spectrometer [4]. Neutrinos escape without any signal and are reconstructed in the transverse plane as missing energy $E_T^{\text{miss}}$.

## 2 Electroweak parameters

There are many predictions by the SM derived from just a small set of input parameters to be provided by measurements. The effective weak mixing angle, accessible via the forward-backward asymmetry $A_{FB}$ of $Z$ boson decays, is one of these parameters. The $Z \to e^+e^-$ (resp. $Z \to \mu^+\mu^-$) decays are analyzed with 4.8 (resp. 4.7) fb$^{-1}$ of $pp$ collisions at a center of mass energy of $\sqrt{s} = 7$ TeV [5]. The sensitivity of this measurement is greatly enhanced by the use of candidate electrons measured only by the calorimeters beyond the inner detector acceptance, i.e. with $2.5 < |\eta| < 4.9$. In general the invariant mass of lepton pairs is required to be 66 GeV $< m_{\ell\ell} <$ 1 TeV while if a forward electron is involved the upper bound is 250 GeV.

The background is very small with a dominant component arising from multi-jet events misidentified as prompt lepton pairs. This background is derived with data-driven techniques and is three (four) orders of magnitude smaller than the $ee$ ($\mu\mu$) signal. Backgrounds from di-boson, $Z \to \tau\tau$ and $t\bar{t}$ are taken from Monte Carlo (MC). The angle $\cos\theta^*_{CS}$ in the Collins-Soper frame relates the final state leptons to the initial state and defines the forward ($A_{FB} > 0$)

and backward ($A_{FB} < 0$) directions. The ratio of the difference between forward and backward cross sections in a given bin of $m_{\ell\ell}$, divided by the total cross section in that bin, quantifies $A_{FB}$. It is determined as a function of $m_{\ell\ell}$ and unfolded for detector effects, with the main systematic uncertainties originating from the parton distribution functions (PDF) and limited MC statistics. Good agreement with the theoretical calculations is found.

The leptonic effective weak mixing angle $\sin^2\theta_W^{\text{eff}}$ is extracted from the raw $A_{FB}$ distributions by performing $\chi^2$ fits of templates constructed for different values of $\sin^2\theta_W^{\text{eff}}$. Only events with 70 GeV $< m_{\ell\ell} <$ 250 GeV are used. The combination of all channels results in $\sin^2\theta_W^{\text{eff}} = 0.2297 \pm 0.0004(\text{stat}) \pm 0.0009(\text{syst})$ and is the first such measurement at the $Z$ pole from a hadron collider that combines electron and muon final states. Figure 1 presents results from other experiments as well as the ATLAS measurement separated into channels. Their combination deviates 1.8 standard deviations from the PDG best fit value.

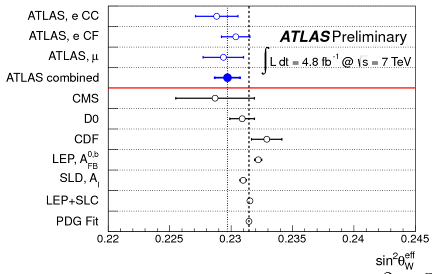


Figure 1: Measurements of $\sin^2\theta_W^{\text{eff}}$ from various experiments [5].

## 3 Single resonant decay to four leptons

The main contribution to the single resonant decay to four leptons at the $Z$ pole is $s$-channel $Z \to \ell^+\ell^-$ production with one of the leptons emitting an off-shell $Z$ or photon that creates another lepton pair. This final state provides a cross check for the performance of Higgs to $ZZ^*$ to 4-lepton measurements and the branching of the $Z$ boson to four leptons can be determined.

A dataset of $pp$ collisions recorded at $\sqrt{s} = 7$ TeV ($\sqrt{s} = 8$ TeV) with 4.5 fb$^{-1}$ (20.3 fb$^{-1}$) is analyzed [6]. Events are required with either one pair of electrons and one pair of muons, four electrons or four muons with the appropriate charge assignments. The four lepton invariant mass, $m_{4\ell}$, has to fulfill 80 GeV $< m_{4\ell} <$ 100 GeV. Each lepton pair must have an invariant mass above 5 GeV. In the same flavor modes this requirement must be fulfilled by any pairing of opposite charge. The largest dilepton invariant mass is required to be larger than 20 GeV. The overall background is determined to $< 1\%$ while there is a non resonant fraction of $t$-channel and gluon initial state production amounting to about 4%.

To measure $\frac{\Gamma_{Z\to 4\ell}}{\Gamma_Z}$, the expected background and non resonant contribution are subtracted from the number of observed events. Corrections for reconstruction efficiency are applied and an extrapolation to the full phase space is performed. The resulting yield is normalized to the $Z \to \mu\mu$ yield in the same dataset. The combined result $(3.20 \pm 0.25(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-6}$ is in agreement with the SM value $(3.33 \pm 0.01) \times 10^{-6}$. The measurement was repeated in a fiducial volume previously introduced by CMS [7]. The results are in agreement and there is no deviation from the SM. Also cross sections at the two center of mass energies are measured and agree with the SM.

## 4 Di-boson production

The most recent result by ATLAS is the measurement of the $W^+W^-$ production cross section in $pp$ collisions at $\sqrt{s} = 8$ TeV [8]. The analyzed data amounts to 20.3 fb$^{-1}$. Considered events contain either one electron and one muon with $m_{e\mu} > 10$ GeV or two electrons or two muons with $m_{ee/\mu\mu} > 15$ GeV and a deviation of 15 GeV from the $Z$ mass. In all channels, the events are required to have opposite charge and substantial $E_T^{\text{miss}}$. Events with any jet with transverse momentum greater than 25 GeV reconstructed by the anti-$k_t$ algorithm are rejected.

The main background components are $W$ boson production with jets, Drell-Yan and $t\bar{t}$, and other di-boson modes. They are fully obtained from data, normalized to data in specific control regions, or, for the smaller components taken from MC. The total cross section is measured for all channels separately by correcting for the reconstruction efficiency and an extrapolation to the full phase space. The results are presented in Fig. 2. It shows in particular the combined cross section $71.4{\pm}1.2(\text{stat})^{+5.0}_{-4.4}(\text{syst})^{+2.2}_{-2.1}(\text{lumi})$pb, together with the theoretical predictions at NLO in QCD which are somewhat lower than the data.

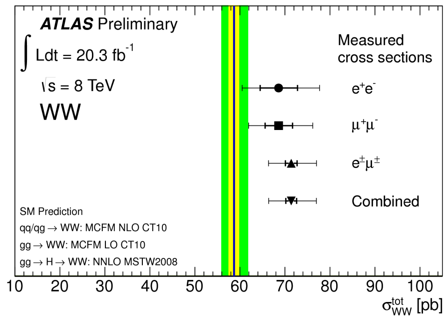


Figure 2: $W^+W^-$ cross section [8].

## 5 $Z$ boson production through vector-boson fusion

In addition to standard QCD production of $Z$ bosons accompanied by at least two hard jets, there is the interesting production mode via vector-boson fusion referred to as EW production. This is of special interest since it gives insights into the gauge coupling structure of the EW sector of the SM.

A dataset of 20.3 fb$^{-1}$ of $pp$ collisions recorded at $\sqrt{s} = 8$ TeV is analyzed [9]. Selected events contain a pair of electrons or muons forming an on-shell $Z$. At least two jets reconstructed with the anti-$k_t$ algorithm have to be present. Five fiducial regions with different sensitivity to the EW component are studied. In the control region EW production is suppressed while the search region is optimized for this mode. The dominant background is $t\bar{t}$ which is taken from MC like $WW$, $Wt$ and $W$ plus jets. Background from multi-jet events is estimated using data driven techniques. Figure 3 presents the measured cross sections in the fiducial regions and the corresponding theory predictions.

The search region requires a di-jet invariant mass $m_{jj}$ of at least 1 TeV and is used to probe for the EW component. The resulting $m_{jj}$ distribution is fitted with templates to extract the EW component. The template for strong $Z$ production is constrained by data selected in the control region. The measured cross section for the EW production is $10.7 \pm 0.9(\text{stat}) \pm 1.9(\text{syst}) \pm 0.3(\text{lumi})$fb and agrees well with the theory value of $9.38 \pm 0.5(\text{stat})^{+0.15}_{-0.24}(\text{scale}) \pm 0.24(\text{PDF}) \pm 0.09(\text{model})$fb. The background only hypothesis is rejected with more than 5 standard deviations.

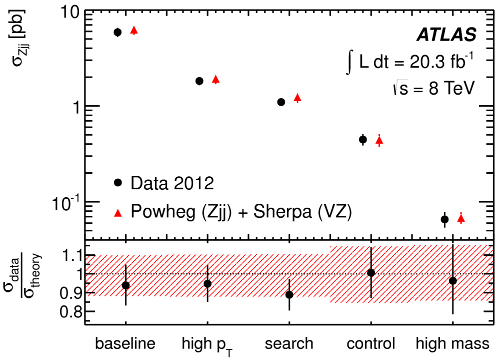


Figure 3: $Z$ plus jets cross section [9].

The $Z$ boson production associated with two jets gives insights into the triple gauge coupling parameters $\Delta g_1^Z$ and $\lambda_Z$ for which one-dimensional limits can be found in Ref. [9]. Because here the $W$ bosons may be far off-shell the probing is complementary compared to studies in $W^+W^-$ analyses.

## 6 $W^{\pm}W^{\pm}$ production via vector-boson scattering

The production of two $W$ bosons of same charge is highly suppressed in the SM and even at the LHC only barely accessible. The final state can be created through strong production or vector-boson scattering which gives the possibility to study quartic gauge couplings.

A dataset of $20.3\,\mathrm{fb}^{-1}$ of $pp$ collisions recorded at $\sqrt{s} = 8$ TeV is studied in two fiducial regions [10]: An inclusive region and a region where vector-boson scattering is enhanced. The inclusive region gathers events with exactly two electrons or muons of same charge and an invariant mass $> 20$ GeV while those with an invariant mass deviating less than 10 GeV from the $Z$ mass are rejected. Besides substantial $E_T^{\mathrm{miss}}$, there must be at least two jets reconstructed by the anti-$k_t$ algorithm with $m_{jj} > 500$ GeV for the jets with highest transverse momentum. The region optimized for vector-boson scattering requires in addition a rapidity separation $|\Delta y_{jj}| > 2.4$ for those two jets. In both selections no jet must be identified as a $b$-jet.

The dominant background source arises from $WZ$, $W\gamma^*$ and $W\gamma$ production with photons converting into electron pairs in the ID material in the latter case. Most of the backgrounds are taken from MC and therefore the main uncertainty apart from jet reconstruction uncertainties of $11 - 15\%$ are theory uncertainties which amount to $4 - 11\%$. The combined measured cross section in the inclusive region (VBS region) is $2.1 \pm 0.5(\mathrm{stat}) \pm 0.3(\mathrm{syst})\mathrm{fb}$ ($1.3 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\mathrm{fb}$) and within uncertainties compatible with the theory value of $1.52 \pm 0.11\mathrm{fb}$ ($0.95 \pm 0.06\mathrm{fb}$). The combined significance rejecting the background only hypothesis is 4.5 (3.6). The analysis provides one-dimensional as well as two-dimensional limits for quartic gauge couplings for several operator bases.

## 7 Prospects for HL-LHC

Facing future upgrade scenarios there are several studies for ATLAS physics performance at a high luminosity LHC at $\sqrt{s} = 14$ TeV. A variety of multi-boson channels is analyzed in their fiducial regions [11] and effective Lagrangian parameters for triple and quartic gauge couplings with cutoff unitarization are studied. Potential discovery values and expected limits are given for integrated luminosities of $300\,\mathrm{fb}^{-1}$ and $3\,\mathrm{ab}^{-1}$.

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