Electroweak Physics at the LHC

Gerhard Brandt¹

On behalf of the ATLAS and CMS Collaborations.

¹II. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen,
Germany

gbrandt@cern.ch

Abstract. This talk summarises results on electroweak processes at the Large Hadron Collider by the ATLAS and CMS collaborations. It covers results from $\sqrt{s} = 7, 8$ TeV data from LHC Run-1, and also results using $\sqrt{s} = 13$ TeV data from the recent LHC Run-2. The status of cross section measurements of single and di-boson production, as well as rare electroweak processes such as vector boson scattering and tri-boson production are presented. Processes that can not be observed (yet) allow to set limits on the respective cross sections. All observations are compatible with Standard Model descriptions and allow to constrain new physics which would manifest through extra gauge couplings, or Standard Model gauge couplings deviating from their predicted value. Limits on such anomalous gauge couplings are derived.

Keywords: LHC, ATLAS, CMS, vector bosons, electroweak physics

1 Introduction

The electroweak sector is a central part of the Standard Model (SM). It is intricately connected to the mechanism of electroweak symmetry-breaking (EWSB). Many electroweak processes also represent important background to the study of the Higgs boson, searches for new physics, or are sensitive to contributions from new physics themselves. Consequently a large number of related results have been produced by the ATLAS [1] and CMS [2] collaborations at the LHC [3]. With excellent progress on the detector understanding in recent years, the data from the LHC Run-1 with $\sqrt{s} = 7, 8$ TeV can now be exploited to their fullest potential and provide precision measurements of electroweak processes at that energy. First results from LHC Run-2 with $\sqrt{s} = 13$ TeV data are also becoming available. They provide unprecedented opportunities for precision measurements of single and di-boson production and for the first time provide access to rare processes such as vector boson fusion, vector boson scattering, exclusive production of vector bosons and tri-boson production. The processes are also sensitive to anomalous triple gauge couplings (aTGC) and quartic gauge couplings (aQGC) and allow to constrain them using a traditional chiral Lagrangian approach or a more modern approach based on effective field theory [4]. This talk provides an overview of selected recent results.

2 Inclusive Vector Boson Production

High precision measurements of W and Z production cross sections are now available [5]. They allow to obtain a new PDF set **ATLAS-epWZ16** from a QCD analysis of LHC and HERA data, and provide confirmation that the strange to light sea quark density in the proton is close to unity at low x_{Bj} . A new CKM parameter V_{cs} measurement from a fit to these data is competitive with previous results. First inclusive W, Z cross sections from 13 TeV data are already sensitive to different PDF sets [6–8]. For the first time a measurement of the W mass m_W has been made at the LHC [9]. The result $m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.}) \text{ MeV} = 80370 \pm 19 \text{ MeV}$ is competitive to current m_W measurements from the TeVatron and compatible with the PDG world average, as well as the SM prediction from a global electroweak fit. Measurements of vector boson production in association with jets at 13 TeV are also available [10, 11] in addition to new results at 7,8 TeV [12, 13]. The cross section has been measured as function of jet multiplicity and in a wide range of differential distributions. Comparisons to various fixed order calculations at (N)NLO are in reasonable agreement with the data.

3 Di-boson Production and Limits on Anomalous Triple Gauge Couplings

A large number of di-boson cross sections has been measured by ATLAS and CMS in 7,8 TeV and 13 TeV data. The cleanest final state, but smallest rate compared to other di-boson processes, is available in ZZ production which has been measured in 8 TeV [14–17] and 13 TeV [18, 19] in various decay channels. Measurements of WZ production at 7,8 TeV [20, 21] and 13 TeV [22, 23] combine the low background of Z final states and higher rate of W processes. Template fits of aTGC models to the high- p_T tails of distributions sensitive to aTGC contributions, such as the transverse mass of the $W-Z$ system, m_T^{WZ} , provide some of the most stringent limits on aTGCs connected to a WWZ coupling to date. Measurements of W^+W^- production provide the largest cross section of di-boson processes but also face the most challenging background situation. A number of results in 8 TeV [24–26] and 13 TeV [27, 28] data are available. In such opposite charged W -pair production measurements it is essential to suppress contributions from top-pair production. This requires the precise understanding of the application of jet vetoes which has seen recent progress. All measurements are compatible with SM predictions, often involving state-of-the-art pQCD predictions at NNLO, for example Ref. [28] measures $\sigma_{W^+W^-} = 115 \pm 11 \text{ pb}^{-1}$ for $118.7 \pm 3.6 \text{ pb}^{-1}$ expected in the SM. As mentioned the high- p_T tails of the di-boson measurements are sensitive to aTGC contributions and have been used to derive a large number of limits on charged (WWZ and $WW\gamma$ couplings) and neutral ($Z\gamma\gamma$, $ZZ\gamma$, γZZ and ZZZ) couplings. A review of all results can be found in Ref. [29], providing summary tables for all charged and neutral aTGC limits from the LHC and previous experiments. Results from LEP and TeVatron

are no longer competitive to the high-precision LHC limits. A first combination of ATLAS and CMS of the respective ZZ production measurements provides a further 20% increase in precision on the corresponding aTGC limits [30, 31].

4 Rare Processes and Limits on Anomalous Quartic Gauge Couplings

Vector boson scattering (VBS) is intimately connected to the EWSB mechanism and remains an essential probe of the SM even after discovery of the Higgs boson. The measurements are sensitive to aQGCs and spectacular signatures are expected for vector boson fusion and VBS with two high p_T forward jets, one or two high- p_T central leptons and rapidity gaps in-between. In nature these turn out to be challenging to observe due large reducible and irreducible backgrounds. Nevertheless both electroweak production of Z bosons [32] and W bosons [33] have now been observed in fits to the electroweak component in enriched selections. Exclusive W -pair production $\gamma\gamma \rightarrow W^+W^-$ is important to understand as background to Higgs production. The process has now been observed by both collaborations at 3σ significance [34, 35]. Analysis of same sign $W^\pm W^\pm + jj$ final states remains the seminal analysis in VBS studies and has been measured by both experiments [36, 37]. To complete our picture also studies of $W\gamma + jj$ [38], $Z\gamma + jj$ [39] production have been made. Low statistics still dominate results, but the processes have been observed. Searches for $W^\pm V \rightarrow \ell^\pm \nu + jj$ [40–42] with hadronic decays of $V = W, Z$ use novel techniques such as large- R jet reconstruction at high- p_T . These results are aimed at the most stringent limits on aTGCs and aQGCs, for example on the aQGC parameters $-0.024 < \alpha_4 < 0.030$ and $-0.028 < \alpha_5 < 0.033$ [42]. First tri-boson searches for $W\gamma\gamma$ [43, 44] and $Z\gamma\gamma$ [45] and even WWW [46] production have been done. Since no deviations from the SM are found, all these results have been used to derive a large number of limits on aQGC, also summarised in Ref. [29]. A variety of competitive limits has been produced where generally VBS data are more sensitive than tri-boson processes.

5 Summary

A large number of electroweak processes has already been explored at the LHC. No significant deviations from the SM predictions are observed anywhere reinforcing our trust in the description of the electroweak sector of the SM. High rate processes allow precision tests of NNLO SM predictions. This precision will increase even further with more luminosity and detector understanding. Limits on aTGCs and aQGCs have been derived and are now testing the sensitivity of our experiments. The planned LHC Run-3 and upgrade programme should bring a big increase in available integrated luminosity, especially for the High Luminosity LHC. If we do not find new physics elsewhere (for example new resonances from SUSY), the electroweak sector is the best place to probe. Sensitivity projection studies, for example for longitudinal VBS, motivate a strong electroweak

programme in the future [47]. And we are just at the beginning of exploration of
not-yet-observed rare electroweak processes like VBS and triboson production.

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