Review of Current Standard Model Results from ATLAS

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Abstract This talk highlights results selected from the Standard Model research programme of the ATLAS Collaboration at the Large Hadron Collider. Results using data from pp collisions at $\sqrt{s} = 7, 8$ TeV in LHC Run 1 as well as results using data at $\sqrt{s} = 13$ TeV in LHC Run 2 are covered. The status of cross section measurements from soft QCD processes and jet production as well as photon production are presented. The presentation extends to vector boson production with associated jets. Precision measurements of the production of W and Z bosons, including a first measurement of the mass of the W bosons, m_W , are discussed. The programme to measure electroweak processes with di-boson and tri-boson final states is outlined. All presented measurements are compatible with Standard Model predictions and allow further constraints.

Keywords Standard Model · Electroweak Physics · QCD

1 Introduction

The strong and electroweak sectors are central components of the Standard Model (SM) of particle physics. The strong force is described by Quantum Chromodynamics. The high precision and large data statistics available to the ATLAS Collaboration [1] at the LHC [2] allow to further our understanding of these processes from a few charged particles in the non-perturbative to the perturbative regime manifested by high jet multiplicities. The electroweak force is intricately connected to the mechanism of electroweak symmetry-breaking (EWSB). Many electroweak processes are also important backgrounds 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

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Fig. 1 Summary of several Standard Model total production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations [3]. All theoretical expectations were calculated at NLO or higher. The luminosity used for each measurement is indicated close to the data point. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. They were not always evaluated using the same prescriptions for PDFs and scales. Not all measurements are statistically significant yet.

results have been produced by ATLAS. With excellent progress on the detector understanding in recent years, the data from the LHC Run 1 with $\sqrt{s} = 7, 8$ TeV are now exploited to their full potential and provide precision measurements of strong and electroweak processes at that energy. Results from LHC Run 2 with $\sqrt{s} = 13$ TeV data are also available now. Figure 1 summarizes the status of this work and in the following selected recent results are discussed.

2 Physics of the Strong Force

Measurements of charged particle production (“Minimum Bias”, MB) are very important to describe pile-up underlying all LHC data. ATLAS has measured MB distributions in all data sets, with track transverse momenta down to 100 MeV [4]. The underlying event (soft activity produced along with the hard scatter, i.e. initial- and final-state radiation, multiparticle interaction and color reconnection processes) has been studied most recently in 13 TeV data [5]. The measurement exploits the clean transverse region with respect

to the leading particle. The agreement of data of soft-QCD processes with models is generally within 5%. In the perturbative regime jet and photon production cross sections are investigated. For an inclusive measurement at 8 TeV [6] jets are reconstructed using the anti- k_t jet clustering algorithm. The dominant systematic uncertainty stems from the jet energy calibration. A significant reduction of the uncertainties compared to previous jet cross section measurements [7] has been achieved. QCD predictions at NLO with the MMHT2014 PDF set corrected for non-perturbative and electroweak effects describe the data well. On the other hand recent measurements at 13 TeV [8] compared to NNLO calculations show tensions depending on QCD scale.

Jet measurements are also used to extract fundamental constants. Energy-energy-correlations of multijet events measured in the transverse plane (TEEC) and their asymmetric version (ATEEC) are sensitive to the strong coupling constant α_s . Fits to ATEEC distributions yield the most precise value $\alpha_s(m_Z) = 0.1196 \pm 0.0013$ (exp.) $^{+0.0075}_{-0.0045}$ (theo.) from ATLAS [9,10].

Prompt photon production is a colorless probe of pQCD. ATLAS measures this process in 13 TeV for E_T^γ up to 1.5 TeV [11]. The main challenge is background from jets misidentified as photons which is subtracted in a data-driven approach. Good agreement with NLO calculations and Monte Carlo predictions is observed. Other recent measurements include inclusive di-photon cross sections at 8 TeV [12] and γ +jet at 13 TeV [13].

3 Electroweak Physics

High precision measurements of W and Z production cross sections are now available [14]. The measurements are used 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 [15]. For the first time a measurement of the W mass m_W has been made by ATLAS at the LHC [16]. The result $m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})$ MeV = 80370 ± 19 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 8 TeV and 13 TeV are also available [17,18]. The cross section has been measured as function of a wide range of differential distributions at jet multiplicities of up to 7 jets. Comparisons to various fixed order calculations at (N)NLO are in reasonable agreement with the data.

A large number of diboson processes is now observable and has been analysed [19–24]. The WW process has received much attention [25–27] since its final state resembles the same one as top-quark pair production. Great progress has been made in the experimental and theoretical understanding of WW production. Generally, good agreement with SM is now observed in all final

Fig. 2 The data/theory ratio for several vector boson fusion, vector boson scattering, and triboson fiducial cross section measurements, corrected for leptonic branching fractions [3]. All theoretical expectations were calculated at NLO. The dark-color error bar represents the statistical uncertainty. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The luminosity used and reference for each measurement are also shown. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. They were not always evaluated using the same prescriptions for PDFs and scales. Not all measurements are statistically significant yet.

di-boson states and a whole industry extracting constraints on aTGC, and effective QFT parameters exists. For a review consult Ref. [29]. Even more complex final states are now also in reach, such as vector boson fusion (VBF), vector boson scattering (VBS) and tri-boson production. Some of them have already been observed. Cross section measurements of several explored processes are shown in Figure 2. The processes are also sensitive to anomalous triple gauge couplings (aTGC) and quartic gauge couplings (aQGC) and allow to constrain them. VBS is intimately connected to the EWSB mechanism and remains an essential probe of the SM even after discovery of the Higgs boson. 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 to large reducible and irreducible backgrounds. Nevertheless both electroweak (VBF) production of Z bosons and W bosons [28] 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 ATLAS at 3σ significance [30]. Analysis of same sign $W^\pm W^\pm + jj$ final states remains the

seminal analysis in VBS studies and has been measured with ever-improving precision and theory understanding [31].

4 Summary

A large number of SM processes has been explored at the LHC. No significant deviations from SM predictions are observed anywhere reinforcing our trust in the description of nature by the strong and electroweak sectors 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.

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