Standard Model Measurements at ATLAS

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Abstract

The Standard Model of particle physics yields a successful description of the fundamental particles and their interactions. The ATLAS experiment at the Large Hadron Collider studies these interactions in a multitude of different analyses, which allow testing the Model at unprecedented energies. The Standard Model processes can be measured with high precision and contributions from potential new physics can be constrained. In this review, a selection of the latest Standard Model analyses performed by the ATLAS collaboration is shown. This includes the inclusive jet cross-section and ratio measurement, the analysis of photon plus jet production and the measurement of $W$ production in association with a charm hadron. The study of high-mass Drell-Yan processes and the $Z/\gamma^*$ forward-backward asymmetry is presented as well as analyses of $ZZ$ and $W^+Z$ production.

Keywords: Standard Model, ATLAS, QCD, jet cross-section, isolated photon plus jet, $W$ in association with charm, electroweak, high-mass Drell-Yan, $Z/\gamma^*$ forward-backward asymmetry, di-boson production: $ZZ$ and $W^+Z$

1. Introduction

The Standard Model (SM) of particle physics successfully describes the interactions of the fundamental particles known to date. Its mathematical formulation has been established during the second half of the last century and the full particle content it is describing was experimentally verified. A powerful tool for testing the SM proved to be particle colliders, such as the Large Hadron Collider (LHC) [1] at the European Organization for Nuclear Research CERN. It provides particle collisions with the highest energies and rates to date. The results presented in this review were exclusively obtained from collisions in which protons collided with protons. The particle collisions at the LHC take place at four interaction points each surrounded by a detector to analyse the collision products. ATLAS (A Toroidal LHC Apparatus) [2] is one of these detectors and able to reconstruct most of the particles that leave the collision, as it provides a nearly complete coverage of the solid angle. The analysis of the data recorded with ATLAS allows, therefore, to validate the SM in the new energy regime accessible with the LHC. Some SM parameters can be measured with a higher precision than before and contributions from potential new physics can be constrained. Another strong motivation to study SM processes is that these signatures are backgrounds for searches for new physics. Only analyses in which the background processes are well understood have a good discovery potential. In the following, some of the latest SM measurements performed by the ATLAS collaboration are shown. These include the inclusive jet cross-section and ratio measurement. Analyses of photon plus jet production and $W$ production in association with a charm hadron. The measurement of high-mass Drell-Yan processes is discussed as well as a study on the $Z/\gamma^*$ forward-backward asymmetry. Finally, the measurements of $ZZ$ and $W^+Z$ production are shown.

2. The ATLAS detector

The ATLAS detector is a multipurpose detector, which is able to measure a multitude of particles. It consists of several sub-components arranged in layers symmetrically around the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle. The tracking detector is closest to the interaction point and each sub-detector implements a different detection principle.

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.
particle shower and is therefore needed for its energy measurement. Enveloping all the aforementioned components is the muon system. In conjunction with three large air-core toroid magnets, it is able to measure the momentum of muons, fundamental particles belonging to the same family as electrons.

A key design goal when building the detector was to achieve a very high precision of the energy and momentum measurement. The uncertainty on the jet energy calibration is aimed to be 1 % which is already reached for central jets with high transverse momenta ($p_T$) [3]. The goal for the uncertainty on the energy calibration of leptons (electrons and muons) is 0.02 % and is important for high precision SM analyses. Central, high $p_T$ leptons show a even better performance [4, 5].

The data analysed in the studies presented in this review were recorded in 2011 and 2012. During that time the LHC collided protons at several centre-of-mass energies ($\sqrt{s}$). As $\sqrt{s}$ is a measure of the energy present in the collision, it directly affects the probability with which new particles are created, the so-called cross-section ($\sigma$). By measuring $\sigma$ at several centre-of-mass energies the SM can be tested at several points in phase-space.

3. Introduction to cross-section measurements

Protons are not fundamental particles, but consist of quarks and gluons, the so-called partons. These fundamental particles will participate in the hard scattering in a proton-proton collision. Therefore the production cross-section $\sigma$ of a certain final state depends on the probability with which a specific type of quark or a gluon will take part in the collision. This likelihood is given by the so-called parton distribution function (PDF) $f_i(x, Q^2)$ which depends on the momentum fraction $x$ of the parton as well as the squared momentum transfer of the collision $Q^2$. In the following, several measurements that are sensitive to PDFs are presented.

Another ingredient to the calculation of $\sigma$ is the cross-section of the hard process $\hat{\sigma}$. It is calculable and also depends on $Q^2$. The total production cross-section can then be written as the integral over the possible momenta of the partons:

$$\sigma = \sum_{i,j} \int d\Omega_i d\Omega_j f_i(x_1, Q^2)f_j(x_2, Q^2)\hat{\sigma}(Q^2),$$

where the sum runs over all possible initial state partons and $x_1$ ($x_2$) is the momentum fraction carried by the parton originating from proton 1 (2). Most of the following analyses will not be measuring the total cross-section as stated above, but the differential cross-section $d\sigma/d\Omega$ which corresponds to the cross-section in bins of the quantity $\Omega$.

4. Inclusive jet cross-section measurement and cross-section ratios

Jet physics is described by perturbative quantum chromodynamics (pQCD). The jets produced at the LHC cover a large range of transverse momentum, allowing a test of this theory over a large kinematic range. The double differential inclusive jet cross section measurement at $\sqrt{s} = 7$ TeV [6] has been performed in bins of the jet transverse momentum $p_T$ and their rapidity $y$. The rapidity is defined as a function of the energy $E$ and the momentum along the beam direction $p_z$ as $y = 0.5 \ln[(E + p_z)/(E - p_z)]$. The theoretical predictions have been obtained with the NLOJET++ [8] framework using the CT10 [9] PDF set and non-perturbative corrections. Good agreement of the predictions with the measurement is found over nearly 10 orders of magnitude in cross-section, as can be seen in figure 1.

The dominating systematic uncertainty of the analysis is the jet energy scale (JES). In order to minimize the impact of this uncertainty on the final result, alternative observables can be studied that are not sensitive to the absolute jet energy. One example is the ratio $\rho$ of two inclusive jet cross-section measurements at different centre-of-mass energies $\sqrt{s_1}$ and $\sqrt{s_2}$. It is defined as:

$$\rho = \frac{\sigma(y, p_T, \sqrt{s_1})}{\sigma(y, p_T, \sqrt{s_2})},$$

where $\sigma(y, p_T, \sqrt{s})$ is the double differential cross-section measured in a bin $(y, p_T)$ at a centre-of-mass energy of $\sqrt{s}$. In this measurement many of the uncertainties on the JES are correlated, and therefore can cancel in this ratio. In ATLAS, the cross-section ratio has been measured using the data sets recorded at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV [7]. By applying the same jet calibration to both data sets and thus maximizing the uncertainty cancellations, the overall systematic uncertainties have been reduced by up to a factor of 5. When comparing the ratio to NLO pQCD predictions, deviations can be found as illustrated in figure 2. Thus, the ATLAS jet data can be used to further increase the accuracy of the theory predictions. Especially the gluon contribution to the proton PDF
5. Dynamics of isolated-photon plus jet production

The study of isolated photons produced in association with a jet has two main motivations: Firstly, due to the presence of the photon, it provides a clean testing environment for pQCD and secondly, it is the main reducible background for the decay of the Higgs boson to two photons. The ATLAS collaboration measured the production cross-section of photons plus jets as a function of several different kinematic observables [10]. Mostly a good agreement between data and the theoretical NLO predictions using Jetphox [11] is observed. The differential cross-section as a function of $E_T$ is shown in figure 3. Measurements of photon plus jets in the final state can also be used to study different production processes in the hard scattering. Photon plus jet events can either be produced directly, via a quark-exchange in a quark-gluon scattering, or through fragmentation. In the fragmentation process, two jets are produced via gluon exchange in a quark-quark scattering and one of the final state quark-jets fragments subsequently into a photon. The relative contribution of the two processes is not very well known, but can be assessed using the angular distribution of the process. Due to the different spins of the exchange boson in each process, their respective cross-section distribution as a function of the polar angle $\theta^\gamma_j$, between the photon and the jet, differ. Figure 4 shows the differential cross-section as a function of $\cos(\theta^\gamma_j)$. The contributions of the direct photon production and the fragmentation process are shown normalized to the first bin. Due to the steep rise of the fragmentation spectrum, which is not apparent in data, it can be concluded, that the direct photon production dominates in this signal region.
Figure 4: Differential photon plus jet cross-section as a function of the difference in polar angle between the jet and the photon $|\cos \theta^{\gamma j}|$ \[^{[10]}\]. The theoretical predictions normalized to the first bin are shown in colour.

6. Measurement of the production of a W boson in association with a charm hadron

The measurement of final states containing a W boson and a charm quark is sensitive to the s-quark distribution in the proton PDF. Also, this signature is a background to the production of a Higgs boson in association with a W. The ATLAS Collaboration measured the W production in association with a charm hadron \[^{[12]}\] in the leptonic decay channel of the W. The charm hadrons were reconstructed in events fulfilling the W selection in the decay modes $D^{\pm} \rightarrow K\pi\pi$, $D^{\ast\pm} \rightarrow K\pi\pi$, and $K\pi\pi\pi$. The obtained cross-section was compared to 6 different PDF sets and the best agreement was observed for the epWZ \[^{[13]}\] and NNPDF2.3coll \[^{[14]}\] sets, were the s-quark and d-quark sea contributions are comparable at $x \approx 0.01$, see figure 5.

Figure 5: Sum of the $W^+D^+$ and $W^-D^-$ cross sections compared to six NLO predictions using different PDFs \[^{[12]}\].

7. High-mass Drell-Yan processes

The measurement of the Drell-Yan process at high invariant di-lepton masses also provides a precision test of pQCD. This is due to the fact, that the two-lepton signal is very clean and therefore the signature has little background. In the ATLAS publication \[^{[15]}\] only di-electron final states were studied. Their cross-section as a function of the di-electron invariant mass spectrum is sensitive to the proton PDF and the consistency with 5 different NNLO PDF sets was studied, as is shown in figure 6.

Figure 6: Differential di-electron cross-section as a function of the di-electron invariant mass $m_{ee}$ \[^{[15]}\]. The theoretical predictions (in colour) are shown for several different PDF sets.

8. Measurement of the forward-backward asymmetry of $Z/\gamma^*$ bosons decaying into electron or muon pairs

The di-lepton final states produced via a virtual Z boson or photon exchange shows forward-backward asymmetry ($A_{FB}$) with respect to the direction of the incoming quark due to the V-A nature of the electroweak interaction. By measuring

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

the effective weak mixing angle $\sin^2 \theta_W^{eff}$ can be extracted. In the ATLAS note \[^{[16]}\] only final states containing electrons and
muons were studied. In the electron channel an additional distinction based on the pseudorapidity $\eta$ of the electrons has been made. In order to maximize the sensitivity to $A_{FB}$ the final states comprising electrons have been categorized into central-central (CC) and central-forward (CF) events, if both or only one electron had a pseudorapidity below 2.5, respectively. The asymmetry has been calculated for each electron event class, for the muon final states and for the combined channel. The results can be found in figure 7. A similar sensitivity as the measurement from the D0 [17] experiment is reached and agreement with the world average value of $A_{FB}$ is found. But all three ATLAS measurements underestimate this value. The dominating systematic uncertainty comes from the PDF and is therefore of theoretical nature. The precision of measurements using data from lepton colliders is not expected to be reached with hadron collider experiments due to the lack of knowledge about the initial state of the hard process.

Figure 7: Comparison of $\sin^2 \theta_{W}^{\text{eff}}$ from several measurements [16]. The vertical dotted line indicates the result of the combined ATLAS measurement and the vertical dashed line shows the result from the current PDG global fit.

9. Measurement of $ZZ$ and $W^\pm Z$ production

The measurement of di-boson production cross-sections is particularly interesting, as they can be produced via tri-boson vertices. The so-called triple gauge couplings are completely fixed by the electroweak gauge theory. Any observed deviation would therefore hint to a coupling that is not described by the SM. Thus, a precise understanding of these processes helps to constrain contributions from potential new physics. In the ATLAS notes [18] and [19] exclusively final states with electrons and muons were studied. Their total cross-section has been measured and good agreement with the SM predictions has been observed as can be seen in figure 8.

10. Conclusion

The ATLAS Collaboration performs a multitude of SM measurements. They allow testing and improvement of theoretical predictions and PDFs in the new energy regime accessible with the LHC. As SM processes are backgrounds to Higgs measurements and searches for new physics, the precision SM measurements can be used to advance these analyses. So far, a good agreement with the SM expectations has been observed and no new physics has been found. Due to the limited extent of this review only few analyses have been highlighted. A complete list of all ATLAS publications on SM measurements can be found at [20].

References

Figure 8: Expected and measured total cross-sections for $ZZ$ [18] (left) and $W^+Z$ [19] (right) production as a function of the centre-of-mass energy $\sqrt{s}$. Prediction and measurement are shown for both, proton-anti-proton (blue) and proton-proton collisions (red).