Chapter 1

Exploring the Standard Model at the LHC

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The ATLAS and CMS collaborations have performed studies of a wide range of Standard Model processes using data collected at the Large Hadron Collider at center-of-mass energies of 7, 8 and 13 TeV. These measurements are used to explore the Standard Model in a new kinematic regime, perform precision tests of the model, determine some of its fundamental parameters, constrain the proton parton distribution functions, and study new rare processes observed for the first time. Examples of recent Standard Model measurements performed by the ATLAS and CMS collaborations are summarized in this report. The measurements presented span a wide range of event final states including jets, photons, W/Z bosons, top quarks, and Higgs bosons.

1. Introduction

The study of Standard Model (SM) processes at the Large Hadron Collider (LHC) [1] is important for several reasons. The study of these processes provide the ability to test a wide range of SM predictions, to probe the interplay between perturbative/non-perturbative phenomena, to determine fundamental parameters of the SM, to provide constraints on parton distribution functions (PDFs), and to provide a description of the kinematical properties of background events in different searches for new physics.

Experimentally, the quantities measured are total fiducial cross-sections and differential cross-sections of different processes. Fiducial cross-sections can be extrapolated to a total physics cross-section by correcting for the signal acceptance of the fiducial volume of the measurement. Differential cross-sections, which provide additional kinematic information, are typically corrected for detector effects (and reported at the so-called “particle” level) in order to permit comparisons with SM predictions.

The LHC “Run 1” data taking period took place from 2010 to 2012, at collision center-of-mass energies of 7 and 8 TeV. In 2015, the LHC started delivering proton-

proton collisions at the unprecedented center-of-mass energy of 13 TeV, marking the beginning of the “Run 2” data taking period. The largest data sample collected to date by the ATLAS [2] and CMS [3] experiments was collected at a center-of-mass energy of 8 TeV, in 2012, and it corresponds to a total integrated luminosity of 23.3 fb^{-1} [4] per experiment. A total of 4.2 fb^{-1} per experiment was delivered in 2015 [4], and an approximate doubling in integrated luminosity is expected in 2016.

Reactions classified as SM processes regroup a large number of possible event final states, from jets and photons, to the production of gauge and Higgs bosons. This report does not attempt to present all SM measurements performed at the LHC but instead aims at summarizing a representative set of measurements with emphasis on results made public by the ATLAS and CMS collaborations relatively recently. Measurements presented here were also chosen to feature a wide range of event final states.

The report is organized into the following sections highlighting different aspects of the exploration of the SM: testing the SM in a new kinematic regime, precision testing of SM predictions, determination of fundamental parameters of the SM, constraints on parton distribution functions, and studies of rare processes.

2. Testing the SM in a new kinematic regime

Testing of the SM in a new kinematic regime is made possible with the increase in collision center-of-mass energy as well as ongoing increase in recorded integrated luminosity. Figure 1 shows the total cross-section of different SM processes measured at different center-of-mass energies, and compared to SM predictions [5]. The SM theoretical predictions presented in Figure 1 are calculated at either the leading order (LO), next-to-leading-order (NLO) or, for some processes, next-to-next-to-leading-order (NNLO) accuracy in perturbative quantum chromodynamics (QCD). Overall, the dependence of these measurements on the collision center-of-mass energy is compatible with SM predictions. The precision of some of the cross-section measurements obtained at a center-of-mass of 13 TeV is however still limited by the amount of data recorded to date.

Figure 2 shows the dependence of the top quark pair production cross-section, measured in different event final states, as function of center-of-mass energy. These measurements are compared to the state-of-the-art perturbative QCD (pQCD) predictions at NNLO and including the resummation of soft-gluon emissions at the next-to-next-to-leading-log (NNLL) accuracy [6]. Overall, the measured total cross-sections of different SM processes in the new kinematic regime provided by proton collisions at 13 TeV are in agreement with SM predictions.

3. Precision tests of SM predictions

Beyond testing the SM in a new kinematic regime, the large amount of data recorded at a center-of-mass energy of 8 TeV makes it possible to carry out precise tests of

Fig. 1. Cross-section measurements obtained by the ATLAS collaboration for different Standard Model processes as function of center-of-mass energy of proton-proton collisions, and compared to theoretical predictions [5].

various SM predictions. With recent advances in theoretical calculations, the cross-section of several SM processes is now known at the NNLO level of accuracy in pQCD. Although a large number and diversity of precision tests are carried out by both the ATLAS and CMS collaborations, only two representative examples are summarized here.

The first example consists in a precision test of SM predictions and study of the interplay between perturbative/non-perturbative phenomena. Figure 3 shows the ratio of the SM theoretical predictions to the Born-level measurement of $1/\sigma d\sigma/dp_T^{\ell\ell}$ for Drell-Yan events, measured at a precision better than 1%, as function of the dilepton transverse momentum [7]. This measurement is compared with the state-of-the-art pQCD calculations accurate at the approximate NNLO level and including the resummation of soft-gluon emissions at NNLL. The region of low transverse momentum of the di-lepton pair is particularly sensitive to non-perturbative effects and soft gluons, while the high transverse momentum region is sensitive to the emission of hard partons. The measurements presented in Figure 3 are more precise than the theoretical predictions. Differences in the shape of the distributions are seen in the high transverse momentum region, indicating the need to have higher-order calculations available for comparison with data.

Fig. 2. Top quark pair production cross-sections, measured by the ATLAS and CMS collaborations, as a function of center-of-mass energy [6]. The measurements are compared to NNLO pQCD calculations complemented with NNLL resummation. The color bands represent the total uncertainty on the theoretical predictions. Both measurements and theoretical predictions assume a top quark mass of 172.5 GeV. Measurements made at the same centre-of-mass energy are slightly offset for clarity.

Figure 4 shows the ratio of theoretical predictions to the measurement values of the Drell-Yan differential cross-section as function of di-lepton transverse momentum in different regions of reconstructed di-lepton invariant mass [7]. Here, the theoretical predictions are calculated at NLO in pQCD. The impact of including electroweak corrections at NLO is shown with the orange markers. It can be concluded from Figure 4 that the measurements performed are not yet sensitive to electroweak corrections [7].

The measurement of the differential cross-section of top-antitop quark provides a second example of precision tests of SM predictions. Figure 5(a) shows the differential cross-section as function of the top quark transverse momentum [10]. Measurements are compared to three different theoretical calculations obtained at different level of accuracy in pQCD. The red (“PWG+PY6”), light blue (“aN³L”), and dark blue (“aNNLO”) lines show theoretical calculations obtained, respectively, at NLO (interfaced to a parton showering model), approximate NNLO, and approximate N³LO in perturbative QCD. Figure 5(b), additionally, shows a comparison of the measured cross-section with full NNLO QCD calculations. NLO predictions

Fig. 3. Ratio of the theoretical predictions (obtained using ResBos [8]) to the Born-level measurement of $1/\sigma d\sigma/dp_T^{\ell\ell}$ in Drell-Yan events, as obtained by the ATLAS collaboration [7]. The light blue band represents the statistical uncertainty on the data and the dark blue band represents the total uncertainty (statistical and systematic) on the data. The yellow band represents the uncertainty in the theoretical calculations arising from varying the QCD renormalization and factorization scales, the non-perturbative parameter a_Z , and PDFs.

(interfaced to a parton showering model) agree with the measured differential cross-section within 10%. Approximate NNLO and N³LO calculations, however, do not significantly improve the agreement between the measured cross-section and the theoretical predictions; full NNLO calculations in perturbative QCD are required to improve the agreement to be within the measurement uncertainties.

4. Determination of fundamental parameters of the SM

Measurements performed at the LHC make it possible to determine fundamental parameters of the SM. Two examples are presented here: measurements of the strong coupling constant and measurements of the CKM matrix element $|V_{tb}|$.

4.1. Strong coupling constant

A determination of the strong coupling constant at the LHC is both interesting and valuable for several reasons. In the limit of massless quarks, the strong coupling

Fig. 4. Ratio of $d\sigma/dp_T^{\ell\ell}$ in Drell-Yan events, as predicted by the Dynnlo [9] MC generator, to the Born-level measurements obtained by the ATLAS collaboration, for six different regions of di-lepton invariant mass, $m_{\ell\ell}$ [7]. Two sets of theoretical predictions are shown, one which includes NLO electroweak corrections (orange markers) and one which does not (red markers). The error bars on the theoretical predictions represent the uncertainty arising from varying the QCD (renormalization and factorization scales) and PDFs. The light blue band represents the statistical uncertainty on the data and the dark blue band represents the total uncertainty (statistical and systematic) on the data.

constant, α_s , is the single free parameter of QCD. It is the least precisely known coupling of Nature, with a current relative uncertainty of approximately 1% [11]. In comparison, the fine structure constant (α), Fermi coupling constant (G_F) and gravitational constant (G_N) have been measured at a level of precision of 10^{-10} , 10^{-7} , and 10^{-5} , respectively [11]. The level of precision achieved on the value of α_s impacts all cross-section predictions at the LHC. A determination of α_s at the LHC also makes it possible to measure the running of α_s in a new kinematic regime never directly probed before.

At the LHC, the value of α_s can be determined through the study of different physics processes, some of which are highlighted here. The dependence of theoretical predictions on the value of α_s comes from both the perturbative calculations in QCD and the dependence of the parton distribution functions on α_s . The value of the strong coupling constant is determined by comparing measurements of a specific

Fig. 5. Full phase-space normalized top-antitop quark differential cross-section as a function of transverse momentum (p_T^t) of the top quark. Measurements made by the ATLAS collaboration are compared to different theoretical calculations. The red (“PWG+PY6”), light blue (“aN³L”), dark blue (“aNNLO”), and dashed blue (“NNLO”) lines show theoretical calculations obtained, respectively, at NLO (interfaced to a parton showering model), approximate NNLO, approximate N³LO, and full NNLO in pQCD. The grey band indicates the total uncertainty on the data in each bin [10].

observable with theoretical predictions obtained using different α_s values.

Figure 6(a) shows the ratio of the measured inclusive jet differential cross-section as function of jet transverse momentum compared to NLO predictions (corrected for non-perturbative effects and electroweak corrections) [12]. The different dashed-dotted lines correspond to the theoretical predictions obtained using different values of α_s . A fit to the measured inclusive jet cross-section results in a measurement of α_s of $0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0053}_{-0.0024}(\text{scale})$ [12]. As shown in Figure 6(b), a measurement of the differential cross-section of the three-jet mass shows comparable sensitivity to the value of α_s , here determined to be $0.1171 \pm 0.0013(\text{exp}) \pm 0.0024(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0069}_{-0.0040}(\text{scale})$ [13]. The precision of the α_s determination obtained using these two types of measurements is limited by a theoretical (renormalization and factorization) scales uncertainty of approximately 5%. Calculations at the next order in perturbative QCD (i.e. NNLO) are expected to decrease this uncertainty. The second largest uncertainty on these measurements of α_s comes from a PDF uncertainty of approximately 2%. Different observables with reduced sensitivity to PDF uncertainty can be instead chosen to determine the value of α_s . Figure 7 shows two such observables: the ratio of inclusive 3-jet to 2-jet cross-sections [15], and the transverse energy-energy correlation function in multi-jet events [16]. These two measurements lead to a best fit value of α_s of $0.1148 \pm 0.0014(\text{exp}) \pm 0.0018(\text{PDF}) \pm 0.0050(\text{theory})$ [15] and

Fig. 6. Ratio of the (a) inclusive jet [12] and (b) 3-jet mass [13] cross-sections measured by the CMS collaboration with respect to theoretical predictions at NLO obtained using the CT10-NLO [14] PDF set and default value of $\alpha_s(M_Z) = 0.118$. The different dashed-dotted lines show the theory predictions obtained using different values of α_s .

$0.1173 \pm 0.0010(\text{exp}) \pm 0.0017(\text{PDF}) \pm 0.0002(\text{NP})^{+0.0063}_{-0.0020}(\text{scale})$ [16], respectively. Although the theoretical scale uncertainty again limits the precision at which α_s can be determined, the choice of these observables reduces the PDF uncertainty on α_s down to approximately 1%.

The value of the strong coupling constant can also be determined from a measurement of the total top-antitop quark production cross-section. Figure 8(a) shows the dependence of the $t\bar{t}$ cross-section on the value of α_s , for theoretical predictions obtained using different PDF sets [17]. The $t\bar{t}$ cross-section is known to NNLO accuracy in perturbative QCD, including the resummation of soft-gluon emissions at NNLL. These theoretical predictions at NNLO have a reduced sensitivity to the choice of renormalization and factorization scales, as compared to NLO calculations. The α_s measurements extracted from the measured $t\bar{t}$ cross-section, and shown in Figure 8(b), are both the first α_s measurements obtained using top quarks and obtained at NNLO level of accuracy in pQCD [17]. These measurements constitute the most precise determination of α_s to date at the LHC with a total relative uncertainty on the value of α_s of approximately 2.4%. In this case, the precision of these α_s measurements is limited by experimental uncertainties ($\sim 1.5\%$), uncertainty on the top quark pole mass ($\sim 1.1\%$) and PDF uncertainty ($\sim 1.1\%$).

Finally, measurements at the LHC make it possible to observe the running of α_s up to approximately 1.5 TeV, as shown in Figure 9 [12]. Measurements are compatible with the expected running of α_s described by the renormalization group equations. The analysis of data collected at a center-of-mass energy of 13 TeV will make it possible to measure the running of α_s to even higher energy scales.

Fig. 7. (a) Ratio of inclusive 3-jet to 2-jet cross-sections measured by the CMS collaboration [15], and (b) the transverse energy-energy correlation function in multi-jet events measured by the ATLAS collaboration [16]. The different dashed-dotted lines in (a) show the theory predictions obtained using different values of α_s . Measurements shown in (b) are compared to theoretical predictions obtained using the best fit value of α_s .

Figure 10 shows a summary of different α_s measurements obtained by different experiments [16]. Although the value of the strong coupling constant determined at the LHC is not as precise as that obtained by experiments at the electron-proton HERA collider, improvements in the precision of α_s determination are nevertheless expected; the availability of theoretical calculations of the jet production cross-section at NNLO is foreseen to be available in the near future, and a significant increase in integrated luminosity expected over the next few years should make it possible to improve constraints on the proton PDFs and possibly decrease PDF uncertainties.

4.2. CKM matrix element: $|V_{tb}|$

The direct determination of $|V_{tb}|$ without assuming unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is possible from the measurement of the single top quark production cross-section. Single top quarks can be produced in proton-proton collisions predominantly via t-channel, Wt and s-channel production. The production rate depends directly on the Wtb coupling strength. With a small number of assumptions ^a, it is possible to directly relate the single top quark production

^aIt is assumed that the Wtb coupling is a SM-like left-handed weak coupling, the branching fraction $\mathcal{BR}(t \rightarrow Wb) \sim 1$, and $|V_{td}|, |V_{ts}| \ll |V_{tb}|$.

Fig. 8. (a) Predicted top quark pair production cross-section values as function of α_s obtained using different PDF sets [17]. The blue line and shaded band show the top quark pair production cross-section value measured by the CMS collaboration and the total uncertainty on the measurement. (b) Values of α_s extracted from the $t\bar{t}$ cross-section measurements from the CMS collaboration using different PDF sets [17].

cross-section to $|f_{LV}V_{tb}|^2$,

$$|f_{LV}V_{tb}|^2 = \frac{\sigma_{\text{measured}}}{\sigma_{\text{theory}}} \quad (1)$$

where the form factor f_{LV} , which has a value of one in the SM, could be modified by new physics or radiative corrections through anomalous coupling contributions. Figure 11 presents a summary of the latest measurements of $|f_{LV}V_{tb}|$ which shows that this parameter is now determined at the level of accuracy of 4.1% [6].

5. Constraints on Parton Distribution Functions

LHC data probe new kinematic regions in the determination of the proton parton distribution functions [18]. The impact of different measurements on the determination of the proton PDF is briefly summarized below.

The inclusive jet differential cross-section as function of jet transverse momentum in different rapidity regions is measured to better than 10%, where the uncertainty is dominated by the uncertainty on the jet energy scale [12]. As shown in Figure 12(a), the measurements are well described by NLO calculations over eleven orders of magnitude. Figure 12(b) shows the impact of the inclusion of these measurements in a global PDF fit [12]. For example, at high Q^2 , the inclusive jet cross-section measurements are seen to provide additional constraints on the gluon PDF at large Bjorken x values, where the relative PDF uncertainty is reduced by more than a factor of two.

Measurements of the inclusive production of prompt photons are also sensitive to the gluon content of the proton through the dominant mode of production $qg \rightarrow \gamma q$. The inclusive photon differential cross-section is measured to a level of 10 to 20% over six orders of magnitude, as shown in Figure 13(a) [19]. These measurements

Fig. 9. The running $\alpha_s(Q)$ as a function of the scale Q , as obtained from different experiments (CMS, D0, H1 and ZEUS). The solid line and the uncertainty band are obtained evolving the extracted $\alpha_s(M_Z)$ values, from the CMS inclusive jet measurements, with the 2-loop 5-flavour renormalization group evolution. The dashed line represents the evolution of the world average value [12].

can in principle further constrain the gluon PDF, for example, for values of Bjorken x around 10^{-1} to 10^{-2} ; however, as shown on Figure 13(b), their impact is limited by large theoretical scale uncertainties associated to the pQCD calculations currently known at NLO accuracy [20]. Further improvements in the impact of these measurements on the determination of the gluon PDF will only be possible with the availability of NNLO calculations.

On the other hand, the cross-section for the production of top-antitop quark is now known to NNLO accuracy in pQCD [21–24], including soft gluon emissions through NNLL [25–27]. Since top quark pair production proceeds predominantly through the reaction $gg \rightarrow t\bar{t}$, precise measurements of the cross-section further constrain the gluon PDF over a wide range of Bjorken x values, reducing the uncertainty on the gluon PDF by up to 20% [28]. The impact of the top quark pair cross-section measurements on the determination of the gluon PDF is shown in Figure 14.

Measurements performed at the LHC also make it possible to improve the knowledge of PDFs other than the gluon PDF. For example, in proton-proton collisions, the W boson is primarily produced through the annihilation of up/down quarks through the reaction $u\bar{d} \rightarrow W^+$ (and its charge conjugate). A measurement of the

Fig. 10. Summary of different $\alpha_s(M_Z)$ measurements obtained by different experiments [16].

muon charge asymmetry, defined as [29]

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+ \nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^- \bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+ \nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^- \bar{\nu})}, \quad (2)$$

provides constraints on the u and d valence quark PDFs. The muon asymmetry is measured as function of the muon pseudorapidity to an accuracy of approximately 1% [29]. This observable can be measured to greater relative accuracy than the W production cross-section since several systematic uncertainties partially cancel in the muon charge asymmetry definition as a ratio. The impact of inclusion of the muon charge asymmetry measurements in a global PDF fit is shown in Figure 15. The inclusion of these measurements results in an improved knowledge of the u and d valence quark PDFs over a wide range of Bjorken x values.

In summary, several measurements performed using data recorded during the LHC Run 1 data taking period provide useful constraints on the proton PDFs. These include measurements presented above as well as others. These measurements are being included in new global PDF fits that will be used in the analysis of LHC

Fig. 11. Summary of different measurements of $|f_{LV}V_{tb}|$ obtained by the ATLAS and CMS collaborations [6].

Run 2 data.

6. Study of rare processes

Several rare physics processes predicted to exist in the SM are now being observed for the first time at the LHC. Two examples of such rare processes, Higgs and multi-boson production, are discussed below.

6.1. Higgs Boson

The Higgs boson in the SM is produced through a variety of different processes and also decays through a different number of final states. The main Higgs boson

Fig. 12. (a) The inclusive jet differential cross-section as function of jet transverse momentum in different rapidity regions measured by the CMS collaboration [12]. (b) Gluon distribution function in the proton as function of Bjorken x at the starting scale $Q^2 = 10^5 \text{ GeV}^2$. Results are shown for a PDF fit to HERA data only (hatched band) and to HERA data with the inclusion of the inclusive jet measurements obtained by CMS at 8 TeV (shaded band) [12]. The total uncertainties on the PDF fit results is determined using the HERAPDF method.

production modes are gluon-gluon fusion (ggF), vector boson fusion (VBF), associated production (WH , ZH), and Higgs production in association with top quarks ($t\bar{t}H$). At a mass of 125 GeV, the dominant Higgs boson decay modes^b, in decreasing values of branching ratio, are $b\bar{b}$, WW , gg , $\tau\tau$, $c\bar{c}$, ZZ , $\gamma\gamma$, $Z\gamma$ and $\mu\mu$. The Higgs boson is predominantly produced through gluon fusion, and has its largest branching fraction to $b\bar{b}$, although experimentally, the $\gamma\gamma$ and ZZ decays provide excellent signal-over-background figure of merit.

The mass of the Higgs boson is measured using the decay channels that provide the best mass resolution, that is, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$. In order to provide the most precise determination of the Higgs boson mass, candidate events are categorized into different sub-samples with different signal-over-background figure of merit, and different mass resolution. The precise determination of the mass of the Higgs boson relies on detailed studies of the energy/momentum calibration for the different event final states considered. Figure 16 summarizes recent Higgs mass measurements [30]. It is interesting to note that the Higgs mass is already measured to an accuracy of better than 0.2% and that the uncertainty of individual mass measurements is dominated by the statistical uncertainty. The uncertainty on the Higgs boson mass measurement is expected to decrease over the next couple of years based on the significant increase in integrated luminosity foreseen to be delivered.

By exploiting all available kinematic information from Higgs decaying to di-

^bCharge conjugation of the final state particles is implied in the simplified notation used here.

Fig. 13. (a) The differential inclusive prompt photon cross-section as function of photon transverse momentum in different regions of rapidity measured by the CMS collaboration [19]. (b) Ratio of gluon PDF determined with and without including the inclusive prompt photon cross-section measurements (“IsoPhotons”), as function of Bjorken x [20].

boson final states, it is possible to test the observed kinematic properties against different spin-parity hypotheses for the newly discovered boson. The test statistic used to compare alternative J^P spin models to the SM expectation of a 0^+ state is $q = 2 \ln(\mathcal{L}_{J^P}/\mathcal{L}_{0^+})$, where the symbol $\mathcal{L}$ represents the likelihood function for different hypotheses [31]. The distribution of the test statistic for different spin-parity models tested against the SM Higgs boson hypothesis is shown in Figure 17. All observations are consistent with the SM Higgs boson expected quantum numbers $J^P = 0^+$. All other alternative pure spin-parity states tested against the SM expectations are strongly rejected.

The total production cross-section of Higgs bosons has been measured at different collision center-of-mass energies. Figure 18 shows examples of such measurements compared to the predicted total cross-section calculated at NNLO accuracy in pQCD [32]. The measurements shown in Figure 18 are statistically compatible with the theoretical predictions, although some tension exists. The integrated fiducial cross-section $pp \rightarrow (H \rightarrow 4\ell) + X$ measured by the CMS experiment as function of center-of-mass energies does not display similar tension with the SM expectations [33]. The precision of measurements performed at a center-of-mass energy of 13 TeV is limited by the relatively small amount of data recorded so far during LHC Run 2. Data collected in 2016 will help further reduce the statistical uncertainty on the measurements at $\sqrt{s} = 13$ TeV. Although not shown here, a sufficient quantity of data was recorded at $\sqrt{s} = 7$ and 8 TeV to make it possible to measure Higgs boson differential cross-sections and compare them to theoretical predictions obtained at NNLO in pQCD. Overall, the theoretical predictions for

Fig. 14. Ratio of gluon PDF determined with and without including measurements of top quark pair production cross-section (“TopData”), as function of Bjorken x [28].

Fig. 15. Up (a) and down (b) valence quark PDFs obtained by including (shaded area) or not (hatched area) measurements of the muon charge asymmetry obtained by the CMS collaboration at a center-of-mass energy of 8 TeV [28].

both the total and for differential cross-sections are in good agreement with the measured values so far.

In order to determine the nature of the Higgs boson discovered at the LHC, it is important to measure its coupling to the different types of particles in the SM. The

Fig. 16. Summary of Higgs boson mass measurements performed by the ATLAS and CMS collaborations. The (red) vertical line and corresponding (grey) shaded area indicate the central mass value and the total uncertainty of the combined measurements, respectively [30].

size of the different Higgs production cross-sections and branching ratios depends directly on the value of the Higgs couplings to SM particles; however, the determination of individual Higgs couplings is not possible without some assumptions. As mentioned above, different modes contribute to the production and to the decay of the Higgs boson. Experimentally, measured kinematic properties of events are used to classify events into different categories that can enhance one of the production or decay mode contributions. However, the signal yield n_{signal} in each event category k is obtained by summing over all possible production and decay modes, i.e.

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_j \left\{ \sigma_i \times A_i^f(k) \times \epsilon_i^f(k) \times \text{BR}^f \right\} \quad (3)$$

where $\mathcal{L}$ represents the integrated luminosity corresponding to the analysis of the event category k , σ_i is the Higgs production cross-section, $A_i^f(k)$ is the detector acceptance, $\epsilon_i^f(k)$ is the efficiency, and BR^f is the Higgs branching ratio. The sums run over all possible production modes i and decay channels f . Note that the signal yield can also be expressed in terms of Higgs production and decay signal strength parameters, μ_i and μ^f , respectively. These signal strength parameters are defined as

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad (4)$$

$$\mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f} \quad (5)$$

where the subscript SM refers to the SM value of Higgs cross-section and branching fraction. The event yield in an event category k is expressed in terms of these signal

Fig. 17. Distributions of the test statistic $q = 2 \ln(\mathcal{L}_{JP}/\mathcal{L}_{0+})$ for different J^P spin models tested against the SM Higgs boson hypothesis in the combined $H \rightarrow ZZ$ and WW analyses of the CMS collaboration. For each model considered, the expected median and 68.3%, 95.4%, and 99.7% Confidence Level regions for the SM Higgs boson (orange) and alternative J^P hypotheses (blue) are shown. The observed test statistic values are indicated by the black dots [31].

strength parameters as

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_j \mu_i \mu_j^f \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \epsilon_i^f(k) \times \text{BR}_{\text{SM}}^f \right\}. \quad (6)$$

It is important to emphasize that experimental measurements of Higgs event rates at the LHC are only sensitive to the product of production cross-section times branching ratio. Additional information and/or assumptions are required to determine separately the cross-section and branching ratios of individual production and decay modes of the Higgs boson.

From the experimental rate measurements of different categories of events, the individual cross-sections and decay branching ratios of the Higgs boson cannot be determined separately in a model-independent way; however, it is possible to extract the values of ratios of cross-sections and ratios of branching ratios without any additional assumptions. This is done by parameterizing the expected event yield in terms of a reference Higgs production and decay process. For the results presented here, the normalization channel is chosen to be $gg \rightarrow H \rightarrow ZZ$ since this is the experimental event type which has the smallest total relative event rate uncertainty [34]. The expected yield in event category k expressed as function of this normalization channel can then be re-written as

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sigma(gg \rightarrow H \rightarrow ZZ) \times \sum_i \sum_j \left\{ \left(\frac{\sigma_i}{\sigma_{ggF}} \right) \times A_i^f(k) \times \epsilon_i^f(k) \times \left(\frac{\text{BR}_i^f}{\text{BR}_{ZZ}} \right) \right\}. \quad (7)$$

Fig. 18. Total Higgs production cross-sections measured by the ATLAS collaboration as function of center-of-mass energies. Measurements are compared to theory predictions calculated at the NNLO accuracy in pQCD. The theoretical uncertainties, described by the blue band, are partially correlated between different values of center-of-mass energy [32].

where σ_{ggF} represents the cross-section for the gluon fusion production process and BR^{ZZ} , the $H \rightarrow ZZ$ branching ratio. In total, five production cross-sections (ggF, VBF, WH , ZH and ttH) and five branching ratios are considered ($H \rightarrow ZZ$, WW , $\gamma\gamma$, $\tau\tau$, bb). A global fit to all the experimentally measured event yields for different event category is performed and the result is presented in Figure 19 [34]. The best fit values of the fit parameters ($\sigma(gg \rightarrow H \rightarrow ZZ)$, four ratios of cross-sections and four ratios of branching ratios) are mostly consistent with the SM expectations within less than 2σ . The total relative uncertainty on $\sigma(gg \rightarrow H \rightarrow ZZ)$ is approximately 18% while ratios of cross-sections and branching ratios are measured to a precision of approximately 30–40%. The p -value of compatibility between these measurements and the SM prediction is 16%. An approximately 3.0σ excess is measured for the cross-section ratio $\sigma_{ttH}/\sigma_{ggF}$. The effect of this excess in the global fit to experimental data is to pull down below the SM expectation the best fit value of the ratio $\text{BR}^{bb}/\text{BR}^{ZZ}$ since event final states compatible with the decay $H \rightarrow bb$ do not contribute to the small excess of events in the event categories enhanced with Higgs produced via the ttH and ZH production modes.

A slightly more model dependent parameterization can be used to fit all the measured yields to extract the signal strength of different combinations of $(\sigma_i \times \text{BR}^f)$ [34].

Fig. 19. Results of a global fit to the measurements of different categories of Higgs event yields obtained by the ATLAS and CMS collaborations. The predicted event yields are parameterized with respect to the normalization channel $gg \rightarrow H \rightarrow ZZ$. The best fit values of cross-section and branching fraction ratios are normalized to the SM prediction [34].

Since the individual production cross-section σ_i and decay branching ratios BR^f cannot be separately measured without additional assumptions, only the product of production and decay signal strengths $\mu_i \mu^f$ is extracted experimentally. Figure 20(a) shows the best fit values for the production signal strengths assuming that all Higgs branching ratios have the SM values within the prediction uncertainties [34]. The results show that the Higgs vector boson fusion (VBF) production mode is observed with a significance greater than 5σ (4.6σ expected significance), and that the associated WH and ZH production modes are observed, when taken together, with a significance greater than 3σ (4.2σ expected significance). The ttH production mode, particularly interesting since it is the only production mode that will make it possible with sufficient statistics to directly determine the coupling of the Higgs boson to top quarks, has now been observed at the 4.4σ level of sig-

Fig. 20. (a) Fit results for the production signal strengths for the combination of measurements performed by the ATLAS and CMS collaborations, and assuming SM branching ratio values. A measurement of the global signal strength μ is also shown. (b) Fit results for the decay signal strengths of the combination of measurements performed by the ATLAS and CMS collaborations, and assuming SM production cross-section values [34].

nificance, although only 2.0σ is expected [34]. The best fit values of decay signal strengths, assuming that all Higgs production cross-sections have the SM values within the prediction uncertainties are shown in Figure 20(b) [34]. Here again, the best fit values are statistically compatible with the SM values. It is also interesting to point out that the experimentally challenging $H \rightarrow \tau\tau$ decay mode is now observed with a significance greater than 5σ (5.0σ expected significance).

The simplest and most constraining signal strength parameterization for a global fit to the data is to assume that the production (μ_i) and decay (μ^f) values are the same for all production processes and decay channels [34]. In this case, the SM predictions of signal yields in all event categories are scaled by a global signal strength μ . This simple parameterization is particularly model dependent since all Higgs boson production and decay measurements are combined assuming that their ratios are the same as those of the SM. This global signal strength, extracted from a fit to the event yields in all the different event categories considered, is the most precisely measured observable related to Higgs boson couplings [34]. The best fit value of global signal strength obtained from a fit to the ATLAS and CMS data is $\mu = 1.09^{+0.11}_{-0.10}$ [34] with a p -value of the compatibility between data and SM predictions of 40%. Figure 21 shows the best fit values of the global signal strength

Fig. 21. Summary of the combined global signal strength measurements by the ATLAS and CMS collaborations. The error bars represent the $\pm 1\sigma$ total uncertainties on the measurements [34].

for different event categories obtained by the ATLAS and CMS collaborations [34]. Overall, the values of global signal strength are seen to be statistically compatible with the SM expectation of $\mu = 1$. The global signal strengths obtained from different event categories have typical total relative uncertainties of 20–30%.

In addition to measurements related to the individual couplings of the Higgs to different SM particles, a key property of the Higgs boson is its total width. In the SM, the Higgs boson is expected to have a width of approximately 4 MeV [11]. This relatively small width is however a property difficult to measure at the LHC. A direct upper limit, obtained from the reconstructed Higgs mass distribution, is set at $\Gamma_H < 1.7$ GeV [35]. Based on the measured lifetime of the decay $H \rightarrow 4\ell$, a direct lower limit on the Higgs total width is set at $\Gamma_H > 3.5 \times 10^{-9}$ MeV [36]. Limits on the total Higgs boson width can also be determined through a measurement of the ratio of the off-shell to on-shell production cross-section of $H \rightarrow ZZ$ and $H \rightarrow WW$. For example, Figure 22 shows the dominant lowest order contributions to the ZZ event final state. The gluon fusion production cross-section depends directly on Γ_H through the Higgs boson propagator, as shown in Figure 22(c). Therefore, the ratio of off-shell to on-shell cross-section is directly related to the total Higgs boson width [37] since

$$\frac{\sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{off-shell}}}{\sigma_{gg \rightarrow H \rightarrow ZZ^*}^{\text{on-shell}}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2} \sim \Gamma_H \quad (8)$$

where the symbols g_{ggH} and g_{HZZ} represent the couplings of the Higgs boson to gluons and Z bosons, respectively. This approach relies on two important assumptions; first that the on-shell Higgs couplings are assumed to be identical to the

Fig. 22. Lowest order Feynman diagrams for the main ZZ production processes: (a) quark-initiated production, (b) gg continuum background production (c) Higgs-mediated gg production [37].

off-shell couplings, and that it is implicitly assumed that no new particle exists at high values of the vector boson pair invariant mass. The observed (expected) limits on the total Higgs width obtained by the ATLAS and CMS collaborations, when combining both the ZZ and WW channels, are $\Gamma_H < 22.7$ MeV (33.0 MeV) [38] and $\Gamma_H < 13$ MeV (26 MeV) [39], respectively.

6.2. Multi-boson production

The study of the production of multiple bosons in proton-proton collisions provides unique tests of the SM.

For example, the measured rate of processes never observed before, such as vector boson scattering (VBS) and tri-boson production, can be compared to SM expectations. Multi-boson production arising through triple (TGCs) and/or quartic gauge couplings (QGCs) provides an opportunity to test the non-Abelian structure of the SM by setting limits on anomalous TGCs and QGCs. Finally, the study of multi-boson final states produced through vector boson scattering provides a mean to probe the electroweak symmetry breaking mechanism of the SM.

Figure 23(a) summarizes the total cross-section of various multi-boson final states measured by the CMS collaboration [40]. Measurements are statistically compatible with the SM expectations within approximately 2σ . Figure 23(b) shows that the ATLAS collaboration measures a WZ production cross-section slightly higher than that expected from the SM. There is however some indications that higher order corrections at NNLO not included here are likely positive and may be larger than the reported estimated theoretical uncertainties on NLO predictions shown in Figure 23(b).

As shown in Figure 24(a), one of the leading order diagrams to the production of the WZ event final state proceeds via the WWZ triple gauge coupling [41]. A measurement of the WZ differential cross-section as function of the transverse mass of the WZ system is sensitive to non-zero values of anomalous TGCs. An example of measured differential cross-sections is presented in Figure 24(b), along with the impact of different values of anomalous TGCs [41]. Overall, measurements are observed to be compatible with SM expectations.

Fig. 23. Ratio of di-boson cross-sections to the SM predictions as measured by the (a) CMS [40] and (b) ATLAS [41] collaborations. Measurements are compared to theoretical predictions (yellow shaded areas) calculated at the NNLO/NLO (a) and NLO (b) level of accuracy.

Fig. 24. (a) Leading order Feynman diagram for the production $pp \rightarrow WZ$ proceeding through a triple gauge coupling. (b) Distribution of the reconstructed transverse mass of the WZ system as measured by the ATLAS collaboration [41]. The measurements (black points with error bars) are compared to the SM theoretical predictions (red histogram with shaded orange band). The dashed and dashed-dotted lines show theoretical predictions with non-zero values of some anomalous triple gauge coupling parameters.

The event final state consisting of a Z boson and a photon provides a means of setting limits on anomalous triple gauge couplings (aTGC) associated with the $ZZ\gamma$ and $Z\gamma\gamma$ vertices which are not allowed in the SM model, see Figure 25(a) [42]. The differential cross-section measurement shown in Figure 25(b) has some sensitivity to different values of aTGCs, and limits on the value of these aTGCs can be set [42]. Measurements presented in Figure 25(b) have a p -value of compatibility with the SM of 37%, and are therefore compatible with SM expectations.

The electroweak $W^\pm W^\pm jj$ production is a key process to probe the electroweak symmetry breaking mechanism of the SM. In the SM, same-sign W boson pairs are produced through both QCD induced (e.g. Figure 26(a)) and electroweak processes (e.g. Figures 26(b) and 26(c)). The vector boson scattering (VBS) amplitude, examples of which are shown in Figures 26(b) and 26(c), increases with center-of-mass energy. The existence of a Higgs boson is required in order to avoid violating unitarity at an energy scale of approximately 1 TeV. The ATLAS and CMS collaborations have recently reported first evidence for the observation of electroweak-only $W^\pm W^\pm jj$ production with a level of significance of 3.6σ [43] and 2.0σ [44], respectively. As shown in Figure 26(b), the electroweak production of $W^\pm W^\pm jj$ can proceed through a quartic gauge coupling. Figure 27 shows the sensitivity of the measurements to the presence of anomalous QGCs [44].

The last example of multi-boson production presented in this report is the first evidence for the $W\gamma\gamma$ production which can proceed through a quartic $WW\gamma\gamma$ ver-

Fig. 25. (a) Leading-order Feynman diagram for $Z\gamma$ production involving aTGCs that are forbidden in the SM at tree level. (b) Distribution of the photon transverse momentum for $Z\gamma$ events, as measured by the CMS collaboration. The measurements (black dot with error bars) are compared to SM predictions and theoretical predictions obtained using non-zero values of some triple gauge coupling parameters [42].

tex, as shown in Figure 28. The ATLAS and CMS collaborations have reported first evidence for this process at a greater than 3σ [45] and 2.4σ [46] level of significance, respectively. Figure 29(a) shows the reconstructed di-photon invariant mass and the size of the $W\gamma\gamma$ signal [45]. Figure 29(b) shows the event yield as function of transverse momentum of the leading photon compared to SM expectations [46]. The measurements agree with the SM expectations. Theoretical predictions of the expected distribution assuming a non-zero dimension-8 effective anomalous gauge coupling are also shown on the plot (dashed line).

7. Summary

In summary, a wealth of data from different physics processes is available at the LHC, including processes observed for the first time. Overall, good agreement

Fig. 26. Examples of diagrams for $W^\pm W^\pm jj$ production showing QCD (a) and electroweak contributions (b,c) [43].

Fig. 27. Distribution of the invariant mass of lepton pairs for same-sign W boson pair event final states measured by the CMS collaboration [44]. Measurements (black points with error bars) are compared to different theoretical predictions obtained with different values of coefficients for some of the dimension-eight effective operators considered [44]. Note that the last bin in the $m_{\ell\ell}$ distribution includes overflow events.

between SM theoretical predictions and measurements of total and differential cross-sections for various processes is found. The study of several different SM processes makes it possible to determine fundamental parameters of the SM such as the strong coupling constant and the CKM matrix element $|V_{tb}|$. LHC measurements of SM processes are also used to improve constraints on the proton PDFs. Finally, detailed studies of the kinematic properties of known SM processes are also important for the search for new physics phenomena.

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Fig. 28. Feynman diagram showing the production of a $W\gamma\gamma$ event final state through a quartic gauge coupling [46].

Fig. 29. (a) Distribution of the reconstructed di-photon invariant mass in $W\gamma\gamma$ event final states, as measured by the ATLAS collaboration [45]. (b) Distribution of the transverse momentum of the leading photon for $W\gamma\gamma$ events measured by the CMS collaboration [46]. Measurements (black points with error bars) are compared to SM expectations and to theoretical predictions obtained with a non-zero value of coefficient for a dimension-eight effective operator [46].

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