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Recent Standard Model measurements

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A selection of recent Standard Model measurements from ATLAS, CMS, D0 and HERA Collaborations is presented. The topics include studies of QCD with jets, photons and vector bosons as well as the latest measurements of the strong coupling constant. The status and prospects of precision measurements of the W-boson mass, the mixing angle of the electroweak interaction and the top-quark mass are also presented followed by recent results in the top-quark sector, on multi-bosons produced inclusively and on the study of the vector boson fusion and scattering. These measurements and studies provide stringent tests of the Standard Model. Deviations with respect to the Standard Model predictions are valuable probes of potential New Physics effects.

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1. Introduction

In the quest for a complete theory that describes at a fundamental level the observed phenomena, it is mandatory to perform measurements in order to understand until which point the Standard Model (SM) describes our world. At the same time, performing these measurements with high precision opens the possibility to find deviations with respect to the SM predictions accessing in this way an energy scale which may be beyond the reach of the present accelerators.
This paper reports about the SM results from ATLAS [1], CMS [2], LHCb [3], D0 [4] and HERA [5, 6] Collaborations, which are available less than a year after the end of the LHC Run 2. During this data-taking period a dataset of 140 fb^{-1} was collected by ATLAS and CMS at an energy in the centre of mass ($\sqrt{s}$) of 13 TeV. Many of the presented measurements include already the full Run 2 statistics.
The measurements reported here would not have been possible without careful studies of the detector response and reconstruction performance leading to the use of improved algorithms and methods. They also profit from several steps forward in physics calculations and modelling.

2. Test of QCD using jets, photons and vector bosons

Cross section measurements of the jet production performed inclusively or in association with vector bosons are valuable tests of the QCD predictions and have the potential to constrain the Parton Distribution Functions (PDF). Two recent examples, which use the $\sqrt{s}$ = 8 TeV proton–proton (pp) dataset at the LHC, are the ATLAS measurement of the double-differential cross-section of the jet production in association with a Z boson decaying into an electron-positron pair as a function of the jet rapidity and transverse momentum [7], and the CMS measurement of the associated production of a W boson and a charm quark [8]. Figures 1a and 1b illustrate some of the main results.
Figure 1a shows in particular that the Next-to-Next-to-Leading Order (NNLO) parton-level fixed-order predictions (corrected for hadronisation, underlying-event and QED radiation effects) improve the agreement with data and have a reduced uncertainty of about a factor two with respect to the Next-to-Leading Order (NLO) predictions. Fig. 1b shows that the predicted $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$ ratio distribution depends on the choice of the PDF set and therefore the measurements provide a valuable input to constrain them.
Measurements of the jet production are also used to extract the strong coupling constant, α_s, a crucial ingredient of perturbative QCD (pQCD) and the least-well known of the fundamental couplings [9]. The ATLAS Collaboration has performed measurements of α_s using the variable $R_{\Delta\Phi}$, which specifies the fraction of inclusive dijet events in which the azimuthal opening angle of the two jets, $\Delta\Phi$, is less than a specified value, $\Delta\Phi_{max}$[10]. In the ratio the PDF dependence cancel to a large extent, and this allows an unbiased study of the α_s running. In this way the α_s evolution was measured up to an energy scale of $\sim$ 1.7 GeV and found in agreement with the prediction from the renormalisation group equations. Recent α_s measurements are limited by the theoretical uncertainties related to the scale dependence of the fixed-order pQCD calculations. A recent determination of α_s at the scale of the Z-boson mass, $\alpha_s(M_Z^2)$, is obtained by the HERA Collaboration with a global NNLO QCD fit, performing a simultaneous extraction of the PDF and α_s using inclusive

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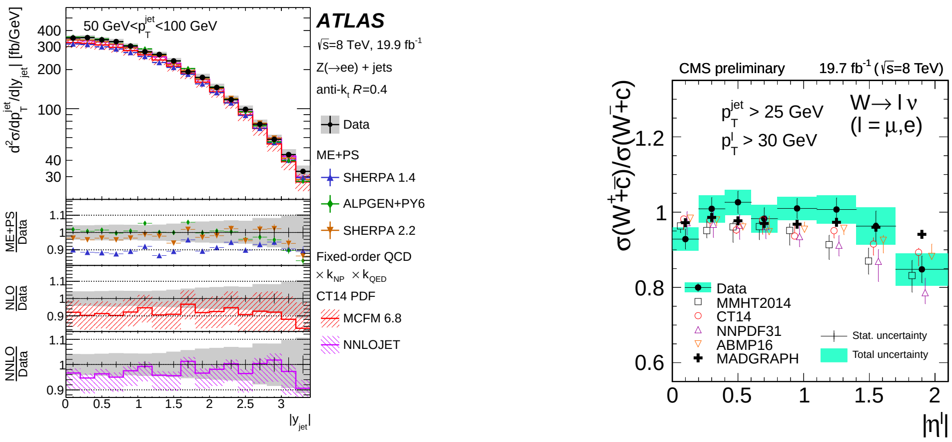
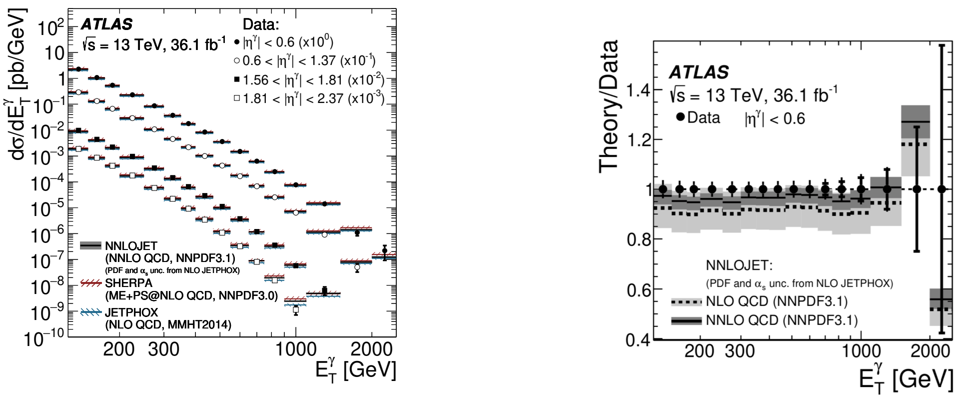


(a) (b)

Figure 1: **(a)** The Z+jets production cross-section as a function of the jet rapidity ($|y_{\rm jet}|$) in the jet transverse momentum range, $p_{\rm T}^{\rm jet}$ = 50 - 100 GeV [7]. The data are compared with parton shower MC generators and fixed-order theory predictions. **(b)** Cross section ratio $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$ as a function of the lepton pseudorapidity ($\eta^{\rm l}$) compared with theoretical predictions at NLO computed with MCFM and different PDF sets [8].

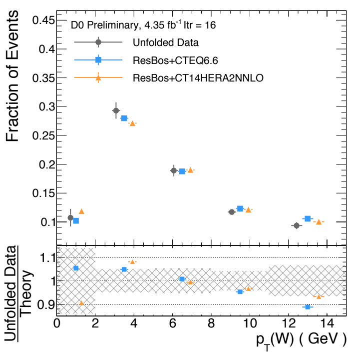
deep inelastic scattering (DIS) and jet data [11]. A 30% reduction of the $\alpha_s(M_Z^2)$ scale uncertainty with respect to the NLO analyses is achieved. Recently the CMS Collaboration has measured $\alpha_s(M_Z^2)$ with a fit to the triple differential $t\bar{t}$ cross section calculated at NLO including also HERA DIS data [12]. In the fit $\alpha_s(M_Z^2)$, the top pole mass, $m_t^{\rm pole}$ and PDFs are extracted simultaneously. The measured value of $\alpha_s(M_Z^2)$ is compatible with the previously mentioned HERA result and has a competitive total uncertainty.



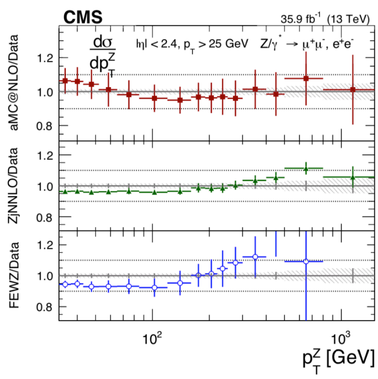
(a) (b)

Figure 2: **(a)** The measured differential cross section for isolated-photon production as a function of the photon transverse energy, $\mathrm{E}_{\rm T}^{\gamma}$, in four photon–pseudorapidity ($|\eta^{\gamma}|$) bins compared with theory predictions [13]. **(b)** The ratio of the NNLO and NLO QCD predictions to the measured differential cross section as a function of $\mathrm{E}_{\rm T}^{\gamma}$ for $|\eta^{\gamma}| < 0.6$ [13].

The measurement of the production cross section of photons produced isolated or associated with jets tests pQCD and probes the gluon density in the proton. The recently published ATLAS analysis on isolated photons [13] performed at $\sqrt{s}$ = 13 TeV profits from improved photon calibration and identification procedures, which bring a reduced systematic uncertainty on the measured cross section of a factor up to 40%. The cross section is measured as function of the photon transverse energy for different intervals of the photon pseudorapidity (Fig. 2a) and the comparison with predictions shows that recent NNLO calculations lead to a reduced theory scale uncertainty, (5%) and to an improved description of the data, as it is illustrated in Fig. 2b.
The measurement of the transverse momentum of the electroweak (e.w.) gauge bosons, p_{T}^{V} ($V = Z$, W), using the Drell-Yan process, tests several aspects of the strong interactions. At low p_{T}^{V}, where fixed order calculations are unreliable due to soft and collinear parton radiation resulting in large logarithmic corrections, it tests resummed calculations. In the higher p_{T}^{V} regime it tests parton shower and fixed order predictions. A new p_{T}^{W} measurement [14] performed by the D0 Collaboration at $\sqrt{s}$ = 1.96 TeV, where the W-boson production is dominated by valence quarks, focuses on the region below p_{T}^{W} = 15 GeV, a region of special interest for e.w. precision measurements. The result is shown in Fig. 3a. A recent CMS analysis [15] measures the absolute and normalised Z production cross section as function of p_{T}^{Z} from 300 MeV up to few TeV using data collected at $\sqrt{s}$ = 13 TeV. Measurements of the cross section as function of Φ_{η}^{*}, the angular correlations between Drell-Yan lepton pairs, stricly related to p_{T}^{Z}, are also provided.



(a)



(b)

Figure 3: **(a)** The W production cross-section as a function of the W transverse momentum (p_{T}^{W}). The data are compared with RESBOS predictions and different PDF. The band in the ratio plot shown at the bottom, indicates the total experimental uncertainty [14]. **(b)** Ratio between the measured differential cross section for Z-boson production as function of its transverse momentum and different predictions. The total experimental uncertainty on the measurement is indicated by the hatched band [15] .

For $p_{\mathrm{T}}^{Z} < 50$ GeV and $\Phi_{\eta}^{*} < 0.5$ the experimental normalised cross section uncertainties are smaller than 0.5%. The results indicate that predictions describe data within theory uncertainties: in particular at low p_{T}^{V} the RESBOS Monte Carlo featuring resummation of the logarithmically divergent terms at Next-to-Next-to-Leading Logarithmic (NNLL) accuracy, shows the best agreement with data but no theory uncertainties are available (Fig. 3a). At high p_{T}^{V} a good description is obtained with both MADGRAPH5 aMC@NLO and with Z+j-at-NNLO predictions (Fig. 3b). The latter includes the complete NNLO predictions of vector boson production in association with a jet and provides smaller uncertainties. A good understanding of the p_{T}^{V} distribution is a key ingredient for a precise measurement of the W-boson mass at the Tevatron and the LHC (see the referenced experimental publications for the citations of the MC and theory calculations).

3. Electroweak precision measurements

The mass of the W boson, m_W, and the mixing angle of the e.w. interaction, θ_W, are key parameters of the SM. They were very precisely measured at LEP, SLC, Tevatron, and more recently at the LHC (see [16] for a quick overview). In the e.w. theory, in the context of global fits to the SM parameters, they can be calculated from the Z-boson mass, m_Z, the fine-structure constant, α, and the Fermi constant, G_μ when values of the top-quark and Higgs-boson masses are given. The comparison of the measured with the calculated values of m_W and $\sin^2\theta_W$[1] tests the SM internal consistency and probes potential Beyond Standard Model (BSM) effects. Target uncertainties for precision future measurements are the SM prediction uncertainties from the e.w. fits: $\Delta m_W \leq 7$ MeV, $\Delta\sin^2\theta^{\ell}_{\mathrm{eff}} \leq 6\cdot 10^{-5}$, $\Delta m_{top} \leq 2$ GeV [16, 17].

The total uncertainty in the combined LEP and Tevatron measurements of m_W is 15 MeV (see [19] for references). At LHC, ATLAS has measured m_W with a total uncertainty of 19 MeV using the $\sqrt{s}$ = 7 TeV dataset [19]. At hadron colliders the total uncertainty is dominated by the imprecise knowledge of the PDF and the modelling of QCD effects. To reduce the total uncertainty more refined experimental methods and improved theoretical predictions are necessary. Moreover a measurement of m_W at forward rapidities (as proposed by the LHCb Collaboration) exploiting the partial anticorrelation of PDF with respect to existing measurements may help in reducing the uncertainty [20]. Ultimately, it is expected that with the Large Hadron Electron Collider the PDF uncertainty on m_W will be reduced to $\approx$ 2 MeV[18].

The $\sin^2\theta^{\ell}_{\mathrm{eff}}$ was measured very precisely at LEP and SLC but a tension exists between the two most precise measurements [16]. The uncertainty on the combined LEP and SLC measurement is: $\Delta\sin^2\theta^{\ell}_{\mathrm{eff}} = 1.6\cdot 10^{-4}$ [21]. Although so far not as accurate as the lepton collider legacy result, the hadron-collider measurements with improved analyses may lead to competitive uncertainties. At hadron colliders two main methods are used: the first relys on fits to the forward-backward asymmetry in Z ($\rightarrow \ell^-\ell^+, \ell = e, \mu$) decays, the second on the angular decomposition of the Drell-Yan cross-section in harmonic polynomials. At present the precision on $\sin^2\theta^{\ell}_{\mathrm{eff}}$ at hadron collider is limited by the imprecise knowledge of the PDF. A measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$ performed at high Z-boson rapidity, like the one envisaged by the LHCb Collaboration [22], profits from the following two aspects: at high rapidity the forward-backward asymmetry is larger and the dilution effect related to the fact that at pp colliders the quark direction is not known, is reduced. It is expected that at a future electron-positron collider, $\sin^2\theta^{\ell}_{\mathrm{eff}}$ will be measured with an uncertainty of $\Delta\sin^2\theta^{\ell}_{\mathrm{eff}} \sim 5\cdot 10^{-6}$ [23].

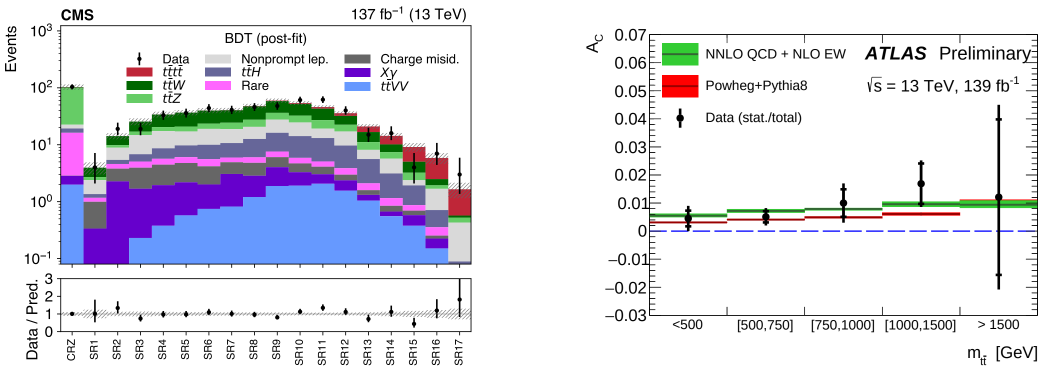
[1] The analyses extract the effective leptonic weak mixing angle $\sin^2\theta^{\ell}_{\mathrm{eff}}$ at the m_Z scale where $\sin^2\theta^{\ell}_{\mathrm{eff}}$ = $\mathrm{k}_f \sin^2\theta_W$ with K_f is a fermion dependent factor absorbing e.w. radiative corrections and $sin^2\theta_W$ is defined at tree level as 1-m_W^2/m_Z^2.

As introduced above, the top-quark mass, m_t, is an important input for consistency tests of the SM. Precise measurement of m_t are used to test the asymptotic behaviour of the vacuum potential. At present the most precise results rely on the reconstruction of the top-quark decay products. The method is defined as a 'direct' measurement. The ATLAS and CMS Collaborations achieve a total uncertainty below 0.5 GeV combining their measurements of m_t^{direct} [24] . Recent works estimate that the interpretation of m_t^{direct} in terms of the pole of the top-quark propagator (pole mass, m_t^{pole}) is affected by a 0.5 - 1 GeV uncertainty due to non-perturbative QCD effects [25, 26]. As an alternative approach, measurements using fits of the $t\bar{t}$ differential cross section and theory predictions were performed and provide the access to the top-quark mass (m_t^{pole}) in a well defined mass scheme allowing a better understanding of the interpretation of the results obtained with both methods (see [27] for a compilation of recent m_t^{pole} results). At present the most precise measurement of m_t^{pole} (Δm_t^{pole} = 0.8 GeV) is obtained in a recent CMS analysis [12]; in a fit of the $t\bar{t}$ cross section, m_t^{pole} is extracted simultaneously with the PDF and α_s using NLO predictions. From the point of view of the uncertainties the measurement of m_t^{direct} and m_t^{pole} are complementary: in the former, in most of the cases, the dominant uncertainty derives from the b-jet energy scale, in the latter the dominant uncertainties derives from the theory. Recently a new m_t measurement has been performed by the CMS Collaboration using the 8 TeV dataset [28]. It relies on a novel method to reconstruct highly-boosted top-quark decays. The top-quark mass is determined from the normalised distribution of the mass of a jet which includes all $t \to bW \to bqq'$ products. Although so far not as accurate as the previous measurements, the Authors advocate that this method has a great potential and can be compared directly to precise analytical calculations, feasible only in the highly-boosted regime.

4. Measurements with top quarks

Precise measurements of top-quark production and decay properties provide crucial information for testing the expectations of the SM at a scale close to the Electroweak Symmetry Breaking (EWSB) scale and above. This section reports some of the very recent measurements in the top sector: the search for $t\bar{t}t\bar{t}$ events, the measurements of the top charge asymmetry and single-top results.
The production of four top quarks ($t\bar{t}t\bar{t}$) is a rare SM process but its cross section may be significantly enhanced in BSM theories [30, 31]. In SM, its study is a way to constrain the top Yukawa coupling. The latest results on the search for $t\bar{t}t\bar{t}$ events are published by the CMS Collaboration in the same charge dileptons and at least three lepton channels (electrons or muons) using the full 13 TeV data sample [29]. It is a challenging search due to the small expected cross section (σ_{SM}^{NLO}= 12 fb in pp collisions at $\sqrt{s}$ = 13 TeV) and the many background processes, as illustrated in Fig. 4a. In spite of the use of the full Run 2 data sample, the process remains unobserved: the measured (expected) significance is 2.6 (2.7) standard deviations. The next step is to include the search results in additional final states and ultimately the Run 3 data. In this analysis of $t\bar{t}t\bar{t}$ events, the top Yukawa coupling is constrained to be $|y_t| < 1.7$ at 95% confidence level with respect to its SM value. This result is comparable with recent CMS limits from $t\bar{t}$ kinematic distributions in lepton+jet and complementary to the coupling extraction in ttH and tH.
According to the SM a small charge asymmetry is expected in $t\bar{t}$ events produced in pp interactions. It results from the interference of higher order amplitudes of qq and qg initial states and manifests

itself in the fact that the produced top quark prefers the initial-quark direction. The top charge asymmetry (A_c) is enhanced at high masses and longitudinal boost of the top-antitop pair. Some BSM theories predict an enhanced value of A_c. The combined ATLAS and CMS measurement of the top charge asymmetry performed at $\sqrt{s} = 8$ TeV is in agreement with NLO and NNLO SM predictions but also compatible with zero. The new ATLAS measurement of A_c using the full 13 TeV data sample [32], achieves for the first time an evidence of this effect (four standard deviations from zero) in agreement with NNLO QCD predictions with NLO EW corrections included. As expected in the SM, A_c is enhanced at high $t\bar{t}$ masses as shown in Fig. 4b.



(a) (b)

Figure 4: **(a)** Observed and expected multivariate discriminant distributions, BDT, after the statistical fit in the search for $t\bar{t}t\bar{t}$ events. The hatched areas represent the total post-fit uncertainties in the signal and background predictions. The lower panel shows the ratios of the observed event yield to the total prediction of signal plus background [29]. **(b)** Charge asymmetries in $t\bar{t}$ events as a function of the $t\bar{t}$ invariant mass, compared with SM theory predictions calculated at NNLO in QCD and NLO in EW theory (green) and with NLO parton shower MC generator predictions (red) [32].

The study of the single top-quark production plays an important role in indirect searches for new phenomena that could be modelled as anomalous couplings in an effective quantum field theory. In SM it provides a powerful probe for the e.w. coupling of the top quark. In the frame of the LHC top working group, the ATLAS and CMS Collaborations, have combined their single-top cross section measurements performed with 7 TeV and 8 TeV datasets [33] achieving an uncertainty of 7% on the combined single top cross section measurement in the best measured channnel: the t-channel. This result is in agreement with the most precise SM prediction computed at NLO matched with NLL resummed calculations, which has a 3% uncertainty. The combined cross section results are then used to extract the value of the product of V_{tb} times a form factor f_{LV} accounting for possible BSM contributions to the Wtb vertex. The value of $|f_{LV} * V_{tb}|$ is compatible with 1 within a 4% total uncertainty. In spite of the small production cross section, thanks to the large data samples available at LHC, measurements of differential cross sections of the single-top production are possible. A recent CMS analysis [34] using the 13 TeV dataset collected in 2015 and 2016 measures differential cross sections for t-channel single-top quark and antiquark production. The results demonstrate a good understanding of the underlying e.w. production mechanism of single-top quarks and in particular of the vector – axial-vector Lorentz structure of the coupling predicting highly polarized top quarks.

5. Inclusive multiboson, vector boson fusion and scattering studies

Measurements of the production of multibosons ($VV/V\gamma/\gamma\gamma$ or VVV with V=W,Z) investigate the non-abelian structure of the SM at high energy and are sensitive to new physics via anomalous Triple and Quartic Gauge Couplings (aTGC and aQGC). At the LHC several diboson production cross sections were measured inclusively in the number of jets at $\sqrt{s}$ = 7, 8 and 13 GeV. The most recent CMS result is the measurement of the ZZ cross section with the full 13 TeV dataset [35]. A new ATLAS analysis studies the $Z\gamma$ production and measures several differential cross sections using the full 13 TeV dataset [36] reaching a precisions of better than 5% in most measurement bins. Noteworthy is the measurement of the W and Z boson helicity fractions in WZ events performed by the ATLAS Collaboration [37], which paves the way for future measurements of the scattering of longitudinally polarised gauge bosons. All results are consistent with SM predictions. The lesson learnt is that the NNLO theory predictions are necessary to have a good description of the experimental results and that the effect on the predictions of an additional order in the perturbative expansion (in this case the change between NLO and NNLO calculations) may be underestimated by the procedure used at LHC to evaluate the theory uncertainties relying on the variation of a factor one half and two of the QCD renormalisation scale.

In the triboson final state, recently, ATLAS has reported a 4.1σ evidence in the search for $WVV, V = W,Z$ combining the searches in the channels with two, three and four leptons. [38]. The CMS triboson search concentrates on the WWW production using the same sign dilepton and trilepton channels and on the extraction of confidence intervals for aQGC [39].

Vector Boson Fusion (VBF) and Vector Boson Scattering (VBS) searches and measurements are milestone studies in the LHC physics program. They investigate the EWSB mechanism of the SM and are sensitive to new physics in the three or four boson vertices. The VBF and VBS processes are studied via the measurements of the e.w. production of a single gauge boson ($EW-Vjj$) or of a pair of gauge bosons ($EW-VVjj$) and are characterised by a low jet activity in the central region and the presence of two jets with a large rapidity separation.

Processes mediated by the strong interactions resulting in a final state with two jets and one ($QCD-Vjj$) or two gauge bosons ($QCD-VVjj$) also exist and represent often the largest background. ATLAS and CMS have observed the $EW-Vjj$ process with $V=W,Z$ and the $EW-VVjj$ process with $VV=W^{\pm}W^{\pm}$. ATLAS has also observed the $EW-WZjj$ process with the 13 TeV dataset collected in 2015 and 2016. Recently, a new ATLAS analysis using the full 13 TeV dataset, reports the observation of the e.w. production of the $ZZjj$ in the four lepton and two leptons plus two neutrino channels with a significance of 5.5σ [40]. The result is obtained with a fit to a multivariable combination (BDT) as shown in Fig. 5. A new CMS study using the 13 TeV dataset collected in 2015 and 2016 finds an evidence for the $EW-Z\gamma jj$ process [41]. The result is obtained with a fit to the invariant mass of the two leading jets in different intervals of the jet rapidity difference, as shown in Fig. 6. This result combined with the CMS result obtained with the 8 TeV dataset achieves an observed significance of 4.7σ.

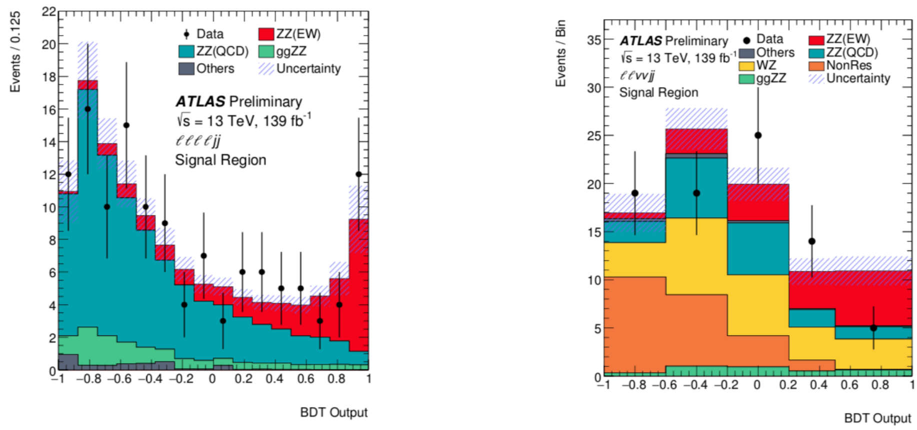


Figure 5: Observed and expected multivariate discriminant distributions after the statistical fit in the $\ell\ell\ell\ell jj$ (left) and in the $\ell\ell\nu\nu jj$ (right) signal regions.The error bars on the data points show the data statistical uncertainty and the hashed bands represent the full uncertainties in the expectations [40].

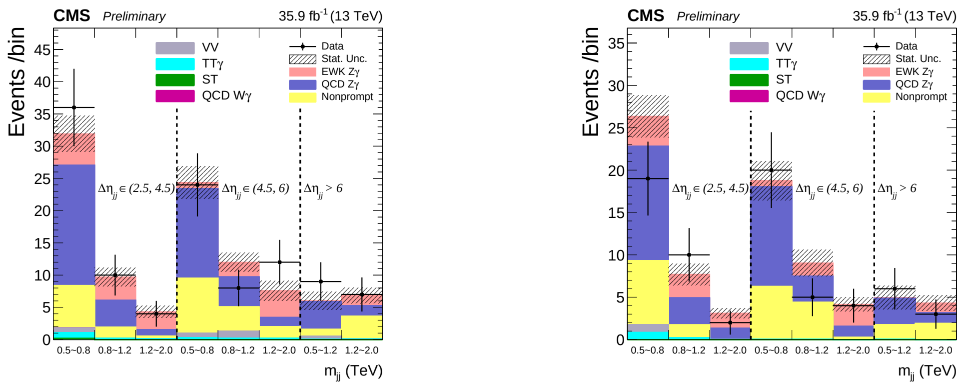


Figure 6: Observed and expected distributions of the di-jet invariant mass (m_{jj}) in different $\Delta\eta_{jj}$ regions, after the statistical fit in the $\mu\mu\gamma jj$(left) and the $ee\gamma jj$(right) signal regions. The error bars on the data points show the data statistical uncertainty and the hashed bands represent the full uncertainties in the expectations [41].

Finally, in many of the multiboson and vector boson fusion and scattering studies, constraints on the structure of the triple and quartic vector boson interactions in the framework of a dimension-6 and a dimension-8 effective field theory (EFT) operators are extracted. The most stringent limits on the coefficients of the EFT operators are often obtained exploiting the hadronic decays of the gauge bosons [42].

6. Conclusions

Many recent SM results are available with increasing precision thanks to improved detector performance, experimental methods and to the large data sets collected at the LHC. Together with advances in theoretical calculations they provide stringent tests of the SM.

Many integrated cross section results are limited by the systematic uncertainties, therefore improved analysis techniques and methods are required. Thanks to the large dataset available more and more differential cross section measurements are possible. For the interpretation of the results in the context of an EFT, the upper tail of the distributions retain the greatest sensitivity to BSM physics.
In order to increase the probability to find deviations with respect to the SM predictions caused by BSM effects, the interplay between e.w. precision, diboson, top and Higgs measurements must be exploited. Fits to the e.w. parameters and to the Wilson coefficients in the EFT approach may play an important role. The outcome of these studies will contribute to establish a solid basis for future projects in particle physics at colliders and beyond.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[2] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST 3 (2008) S08004.

[3] LHCb Collaboration, *The LHCb detector at the LHC*, JINST 3 (2008) S08005.

[4] D0 Collaboration, *The upgraded D0 detector*, Nucl. Instrum. Methods A **565** (2006) 463, arXiv:physics/0507191[physics.ins-det].

[5] H1 Collaboration, *The H1 detector at HERA*, Nucl. Instrum. Meth. A386 (1997) 310.

[6] ZEUS Collaboration, *The ZEUS Detector*, Status Report, DESY (1993), doi:10.3204/PUBDB-2017-12635.

[7] ATLAS Collaboration, *Measurement of the inclusive cross–section for the production of jets in association with a Z boson in proton–proton collisions at 8 TeV using the ATLAS detector*, arXiv:1907.06728[hep-ex].

[8] CMS Collaboration, *Measurement of the associated production of a W boson and a charm quark at* $\sqrt{s}$*= 8 TeV*, arXiv:CMS-PAS-SMP-18-013, https://cds.cern.ch/record/2682200.

[9] J. Kretzschmar, *Standard Model physics at the LHC*, Contribution to the volume "From my Vast Repertoire - the Legacy of Guido Altarelli", arXiv:1803.10800[hep-ex].

[10] ATLAS Collaboration, *Measurement of dijet azimuthal decorrelations in pp collisions at* $\sqrt{s}$ *= 8 TeV with the ATLAS detector and determination of the strong coupling*, Phys. Rev. D **98** (2018) 092004, arXiv:1805.04691 [hep-ex].

[11] H1, ZEUS and NNLOJET Collaborations *HERAPDF2.0Jets NNLO (prel.), the completion of the HERAPDF2.0 family*, H1prelim-19-041 ZEUS-prel-19-001, http://www-h1.desy.de/publications/htmlsplit/.

[12] CMS Collaboration, *Measurement of* $t\bar{t}$ *normalised multi-differential cross sections in pp collisions at* $\sqrt{s}$ *= 13 TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions* , arXiv:1904.05237 [hep-ex].

[13] ATLAS Collaboration, *Measurement of the inclusive isolated–photon cross section in pp collisions at* $\sqrt{s}$ *= 13 TeV using 36* fb^{-1} *of ATLAS data*, arXiv:1908.02746 [hep-ex].

[14] *Measurement of the Shape of the Transverse Momentum Distribution of W Bosons produced in pp Collisions at $\sqrt{s}$ = 1.96 TeV* , D0 note 6508-CONF, https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/EW/E45/E45.pdf.

[15] CMS Collaboration, *Measurements of differential Z boson production cross sections in pp collisions with CMS at $\sqrt{s}$ = 13 TeV* , arXiv:1909.04133 [hep-ex].

[16] J. Erler et al., *Electroweak Precision Tests of the Standard Model after the Discovery of the Higgs Boson*, Prog. Part. Nucl. Phys. **106** (2019) 68, arXiv:1902.05142 [hep-ex].

[17] J. Haller et al., *Update of the global electroweak fit and constraints on two-Higgs-doublet models*, Eur. Phys. J C**78** (2018) 675, arXiv:1803.01853 [hep-ex].

[18] M. Klein, *LHeC: Status and Prospects*, these proceedings.

[19] ATLAS Collaboration, *Measurement of the W-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Eur. Phys. J. C **78** (2018) 110, arXiv:1701.07240 [hep-ex].

[20] G Bozzi et al., *Prospects for improving the LHC W boson mass measurement with forward muons*, Eur. Phys. J. C **75** (2015) 60, arXiv:1508.06954[hep-ex].

[21] ATLAS Collaboration, *Measurement of the effective leptonic weak mixing angle using electron and muon pairs from Z–boson decay in the ATLAS experiment at $\sqrt{s}$ = 8 TeV*, ATLAS-CONF-2018-037, http://cdsweb.cern.ch/record/2630340.

[22] LHCb Collaboration, *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, arXiv:1808.08865[hep-ph].

[23] E Locci, *Precision Electroweak Measurements at FCC-ee*, These Proceedings.

[24] LHC top working group, *Top Quark Mass*, https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCTopWGSummaryPlots/.

[25] P. Nason, *The Top Mass in Hadronic Collisions*, Contribution to the volume "From my Vast Repertoire - the Legacy of Guido Altarelli", arXiv:1712.02796[hep-ph].

[26] A. H. Hoang *The Top Mass: Interpretation and Theoretical Uncertainties*, Proceedings, 7th International Workshop on Top Quark Physics (TOP2014): Cannes, France, September 28-October 3, 2014, arXiv:1412.3649[hep-ph].

[27] ATLAS Collaboration, *Measurement of the top-quark mass in $t\bar{t}$+1–jet events collected with the ATLAS detector in pp collisions at $\sqrt{s}$ = 8 TeV*, arXiv:1905.02302 [hep-ex].

[28] CMS Collaboration, *Measurement of the jet mass distribution in highly boosted top quark decays in pp collisions at $\sqrt{s}$ = 13 TeV* arXiv:CMS-PAS-TOP-19-005, https://cds.cern.ch/record/2682624.

[29] CMS Collaboration, *Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, arXiv:1908.06463[hep-ex].

[30] D. Dicus et al., *Higgs decay to top quarks at hadron colliders*, Phys. Lett. B **333** (1994) 126, arXiv:hep-ph/9404359.

[31] N. Craig et al., *Heavy Higgs bosons at low tan β: from the LHC to 100 TeV*, JHEP **01** (2017) 018, arXiv:1605.08744 [hep-ex].

[32] ATLAS Collaboration, *Inclusive and differential measurement of the charge asymmetry in $t\bar{t}$ events at 13 TeV with the ATLAS detector*, ATLAS-CONF-2019-026, https://cds.cern.ch/record/2682109.

PoS(EPS-HEP2019)717

[33] ATLAS and CMS Collaboration, *Combinations of single-top-quark production cross-section measurements and* $|f_{LV} * V_{tb}|$ *determinations at* $\sqrt{s}$ *= 7 and 8 TeV with the ATLAS and CMS experiments*, JHEP **05** (2019) 088, arXiv:1902.07158[hep-ph].

[34] CMS Collaboration, *Measurement of differential cross sections and charge ratios for t–channel single top quark production in proton–proton collisions at* $\sqrt{s}$ *= 13 TeV*, arXiv:1907.08330.

[35] CMS Collaboration, *Measurement of the* $pp \rightarrow ZZ$ *production cross section at* $\sqrt{s}$ *= 13 with the Run 2 data set*, CMS-PAS-SMP-19-001, https://cds.cern.ch/record/2668717.

[36] ATLAS Collaboration, *Measurement of* $Z\gamma \rightarrow \ell^+\ell^-\gamma$ *differential cross-sections in pp collisions at* $\sqrt{s}$ *= 13 with the ATLAS detector*, ATLAS-CONF-2019-034, https://cds.cern.ch/record/2682846.

[37] ATLAS Collaboration, *Measurement of* $W^{\pm}Z$ *production cross sections and gauge boson polarisation in pp collisions at* $\sqrt{s}$ *= 13 TeV with the ATLAS detector*, Eur. Phys. J. C **79** (2019) 535, arXiv:1902.05759 [hep-ex].

[38] ATLAS Collaboration, *Evidence for the production of three massive vector bosons with the ATLAS detector*, arXiv:1903.10415.

[39] CMS Collaboration, *Search for the production of* $W^{\pm}W^{\pm}W^{\mp}$ *at* $\sqrt{s}$ *= 13*, Phys. Rev. D **100** 012004, arXiv:1905.04246

[40] ATLAS Collaboration, *Observation of electroweak production of two jets in association with a Z–boson pair*, arXiv:ATLAS-CONF-2019-033, https://cds.cern.ch/record/2682845.

[41] CMS Collaboration, *Measurement of electroweak production of* $Z\gamma$ *in association with two jets in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, CMS-PAS-SMP-18-007, https://cds.cern.ch/record/2682214.

[42] *Limits on anomalous triple and quartic gauge couplings*, arXiv:http://cern.ch/go/8ghC