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Recent results on associated vector boson production with the ATLAS and CMS experiments

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Abstract. Several aspects of the associated vector boson production in pp collisions at √s = 7 TeV and √s = 8 TeV at the LHC have been recently investigated by the ATLAS and CMS collaborations. The production cross sections of the W and Z bosons in association with jets, as well as their ratio and the double differential cross section in the Z + jets final state are presented. Measurements of the cross sections of a vector boson (W or Z) in association with heavy flavour jets (b, c) and a top quark pair are also described. The measured cross sections are compared to expectations based on next-to-leading order QCD calculations as well as on Monte Carlo simulations.

1 Introduction

Precision measurements of associated vector boson production at the LHC [1] at a center-of-mass energy of √s = 7 TeV and √s = 8 TeV have been possible by the ATLAS [2] and CMS [3] collaborations due to the large data samples accumulated in 2011 and 2012. These measurements include the production cross sections of the W and Z bosons in association with jets, the ratio of W + jets to Z + jets cross sections (R_{jets}), the double differential cross section in the Z + jets final state, the cross sections of a vector boson (W or Z) in association with heavy flavour jets (b, c) as well as with a top quark pair.

Recent results for these proccesses, where the vector bosons decay leptonically to electrons or muons are studied and are compared to next-to-leading (NLO) order perturbative quantum chromodynamics (pQCD) calculations and to predictions from different Monte Carlo (MC) simulations. It is a common practice that all the results are corrected for detector effects, i.e they are unfolded [4-5] to the particle level. For comparison to the data, non-perturbative corrections are applied to the parton level theoretical predictions. These corrections take into account the effects of hadronization, underlying event and quantum electrodynamics final state radiation (QED FSR) and transform the predictions from the parton level to the particle level. The theoretical systematic uncertainties are calculated by varying the renormalisation and factorisation scales (μ_R and μ_F) around their central value, by using the parton density functions (PDF) eigenvectors and the difference between different PDF sets and by varying the value of the strong coupling constant α_s at the Z boson mass scale around its nominal value of 0.118.

These measurements are useful for the validation of the pQCD calculations and can constrain the PDF of the proton. Moreover, they constitute important backgrounds for other Standard Model (SM) processes and for searches beyond the SM.

2 W and Z production in association with jets

2.1 W + jets

The W + jets measurements use a data set collected at √s = 7 TeV during 2011 and corresponds to an integrated luminosity of 4.6 fb^{-1} (ATLAS) and 5.0 fb^{-1} (CMS). The event selections used by both experiments are similar [6-7]. CMS has studied only the muon channel using a b-jet veto in its selection. Muons and electrons are required to have transverse momentum $p_T > 25$ GeV and a pseudorapidity of $|\eta| < 2.47$ (electrons), $|\eta| < 2.4$ (muons) for ATLAS, and $|\eta| < 2.4$ (muons) for CMS. Jets are reconstructed using the anti-k_t algorithm [8] with a radius parameter R =0.4 (ATLAS) and R = 0.5 (CMS) and are required to have $p_T > 30$ GeV and a rapidity of $|y| < 4.4$ (ATLAS) or pseudorapidity $|\eta| < 2.4$ (CMS). The transverse mass cut of $m_T > 40$ GeV (ATLAS) and $m_T > 50$ GeV (CMS) is used. Finally ATLAS requires that the missing transverse energy is $E_{Tmiss} > 40$ GeV.

The unfolded inclusive jet multiplicity distributions for up to seven jets (ATLAS) and six jets (CMS) are shown in Figures 1 and 2. ATLAS results are compared to the BLACKHAT+SHERPA [9] NLO prediction

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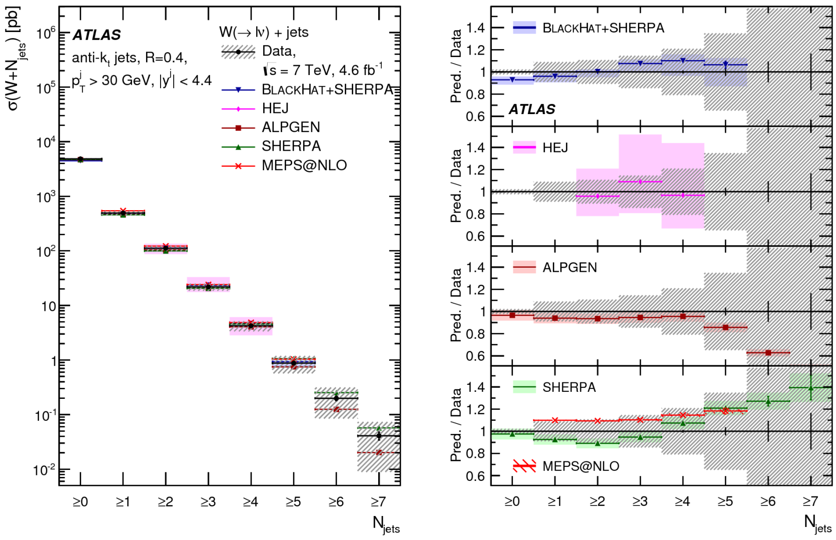

Figure 1. W + jets cross section as a function of the inclusive jet multiplicity for 4.6 fb^{-1} of data at √s = 7 TeV (ATLAS).

corrected to the particle level, the High Energy Jets (HEJ) [10] prediction at parton level (the relevant hadronisation corrections are not available), the MEPS@NLO [11] NLO prediction and finally the ALPGEN [12] and SHERPA [13] leading order (LO) MC generators' predictions. CMS results are compared to BLACKHAT+SHERPA, and the LO generator predictions SHERPA and MADGRAPH+PYTHIA [14].

All LO samples are normalised to next-to-next-to-leading order (NNLO) inclusive cross sections. The statistical and systematic uncertainties on the unfolded data as well as on the theoretical predictions are also shown in these figures. The theory predictions are in agreement with the measured distributions within the systematic uncertainties. Many more differential cross sections for a W boson produced in association with jets have been measured: the leading jet p_T up to 850 GeV (CMS) and 1 TeV (ATLAS), the exclusive jet multiplicity, the jets rapidity y (ATLAS), the jets pseudorapidity η (CMS), the summed scalar p_T of all jets (termed H_T for CMS and S_T for ATLAS), the summed scalar p_T of the lepton and all jets plus E_{Tmiss} (termed H_T for ATLAS), the difference between the two leading jets in azimuthal angle ΔΦ(j1,j2), in rapidity Δy(j1, j2) and in spatial separation $\Delta R(j1,j2) = \sqrt{(\Delta\Phi^2 + \Delta\eta^2)}$ for ATLAS, the difference between the leading jet and the muon in azimuthal angle Δ Φ(j,μ) for CMS.

2.2 Z + jets

The Z + jets measurements use a data set collected at √s = 7 TeV during 2011. The event selections used by both experiments are similar [15-16]. Muons and electrons are required to have transverse momentum p_T > 20 GeV and a pseudorapidity of |η| < 2.47 (electrons), |η| < 2.4 (muons) for ATLAS, and |η| < 2.4 for CMS. Jets are reconstructed using the anti-k_t algorithm with a radius parameter R =0.4 (ATLAS) and R = 0.5 (CMS) and are required to have p_T > 30 GeV and a rapidity of |y| < 4.4 (ATLAS) or pseudorapidity |η| < 2.4 (CMS). Two leptons (electrons or muons) of opposite sign same flavour (OSSF) are selected with an invariant mass of 66 < m_{ll} < 116 GeV (ATLAS) and 71 < m_{ll} < 111 GeV (CMS). The unfolded differential cross sections as a function of the leading jet p_T up to 700 GeV are shown in Figures 3 and 4.

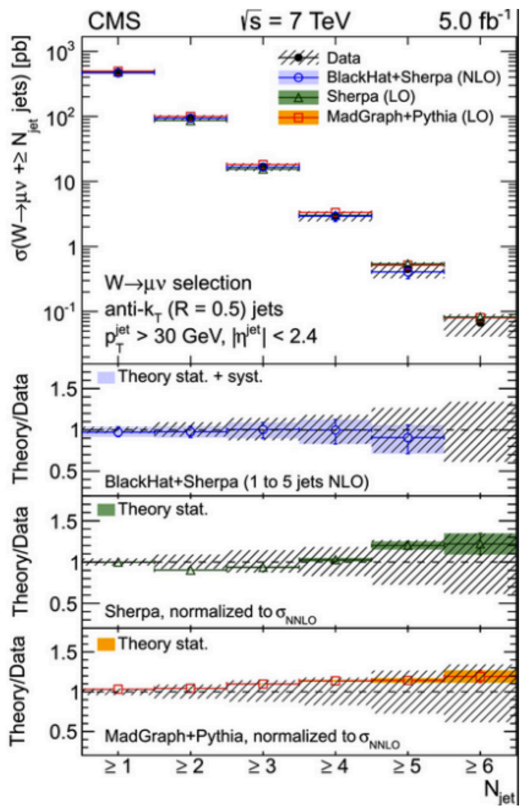

Figure 2. W + jets cross section as a function of the inclusive jet multiplicity for 5.0 fb^{-1} of data at √s = 7 TeV (CMS).

ATLAS cross section results are compared again to the BLACKHAT+SHERPA NLO prediction corrected to the particle level and the ALPGEN and SHERPA LO MC generators. The ALPGEN spectrum is harder at higher p_T values while the SHERPA prediction has a small offset compared to the data. CMS results are compared to SHERPA2 [11], POWHEG-BOX [17] (NLO) and MADGRAPH (LO). MADGRAPH slightly overestimates the leading jet spectrum. Numerous variables have been measured by both experiments like the inclusive jet multiplicities up to seven jets (ATLAS) and six jets (CMS), exclusive jet multiplicity, the jets rapidity y (ATLAS), the jets pseudorapidity η (CMS) and H_T. ATLAS also measured the S_T, several angular distributions between the two leading jets, the mass of these two jets and the ratio of two successive jet multiplicities, $N_{jet} + 1 / N_{jet}$ (N_{jet} is the number of jets).

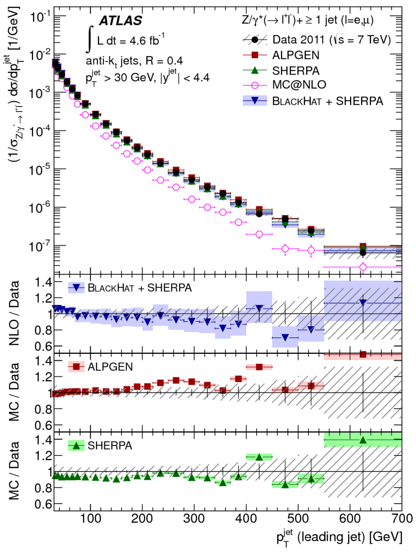

Figure 3. Z + jets cross section as a function of the leading jet p_T for 4.6 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (ATLAS).

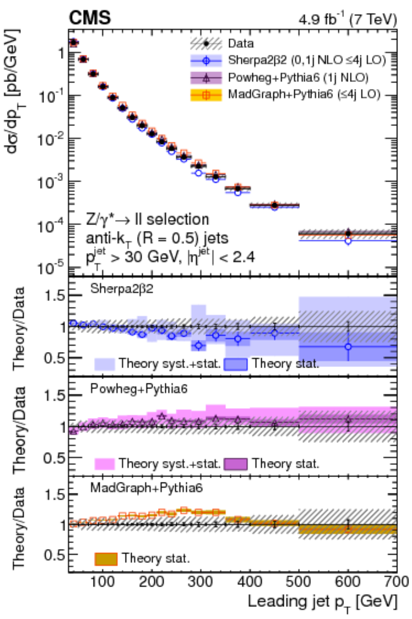

Figure 4. Z + jets cross section as a function of the leading jet p_T for 4.9 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (CMS).

CMS has measured the Z + jets differential cross section as a function of the leading jet p_T (for up to five jets), the jets η and the H_T using 19.6 fb^{-1} of data at $\sqrt{s}$ = 8 TeV collected during 2012 [18]. Another recent CMS measurement is the ratio Z + jets over photon + jets [19].

The first study of the double differential cross section in the Z + jets final state, as a function of the leading jet p_T and rapidity, has been performed by CMS at $\sqrt{s}$ = 8 TeV [20]. The analysis is very similar to the one for the $\sqrt{s}$ = 7 TeV data. The Z + jets cross section is measured as a function of the leading jet p_T and seven rapidity bins (from y = 0.0 till y = 4.7) as shown in Figure 5. There is a disagreement of about 10% between MADGRAPH and the data for jet p_T > 100 GeV. There are also some discrepancies with SHERPA2 that are being investigated.

2.3 R_{jets}

The ratio of the production cross sections for W and Z bosons in association with jets has been measured at $\sqrt{s}$ = 7 TeV with the ATLAS detector using 4.6 fb^{-1} of data [21]. This measurement is sensitive to new physics at high energies and has the advantage that some experimental uncertainties and non-perturbative effects are greatly reduced. It has been measured as a function of many variables, using event selections very similar to the ones used for the W + jets and Z + jets ATLAS measurements. The R_{jets} unfolded production cross section versus the leading jet p_T for a number of jets N_{jets} ≥ 1, normalised to the R_{jets} cross sections in the corresponding jet multiplicity bin, is shown in Figure 6. The measured distribution is compared to BLACKHAT+SHERPA, ALPGEN and SHERPA. There are some discrepancies with SHERPA at the lowest p_T values.

3 W and Z production in association with heavy flavour jets (b, c)

3.1 Zb, Zbb

The production cross section of a Z boson in association with b-jets has been measured using data collected at $\sqrt{s}$ = 7 TeV during 2011. The event selections used by both experiments are very similar [22-23]. Muons and electrons are required to have transverse momentum p_T > 20 GeV and a pseudorapidity of |η| < 2.47 (electrons), |η| < 2.4 (muons) for ATLAS, and |η| < 2.4 for CMS. Jets are reconstructed using the anti-k_t algorithm with a radius parameter R =0.4 (ATLAS) and R = 0.5 (CMS) and are required to have p_T > 20 GeV and a rapidity of |y| < 2.4 (ATLAS), p_T > 25 GeV and a pseudorapidity |η| < 2.1 (CMS). Jets originating from b quarks are tagged by dedicated algorithms: multivariate MV1 [24] (ATLAS) and Simple Secondary Vertex [25] (CMS). Two OSSF leptons (electrons or muons) are selected with an invariant mass of 76 < m_{ll} < 106 GeV. ATLAS requires at least one or two b-jets while CMS studies the cases with exactly one or at least two b-jets.

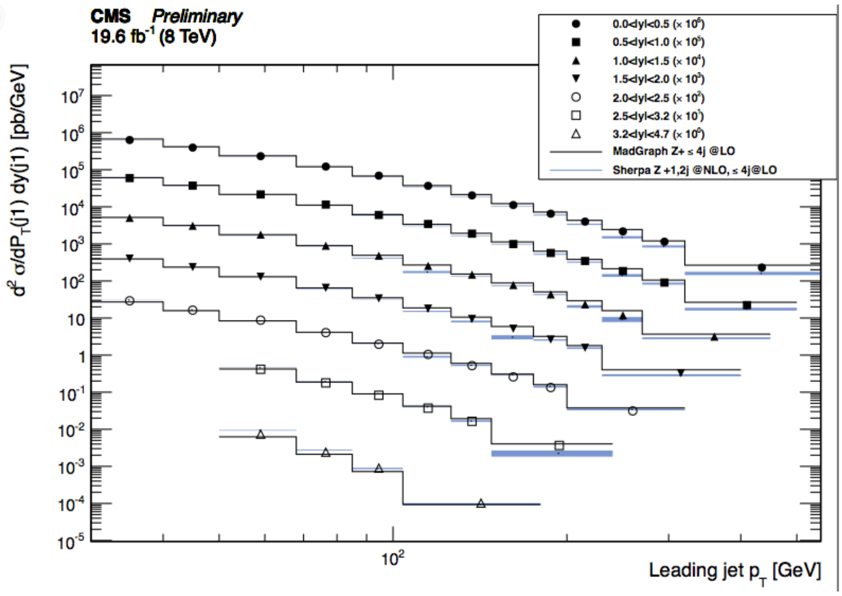

Figure 5. Z + jets double differential cross section as a function of the leading jet p_T for various rapidity bins for 19.6 fb^{-1} of data at √s = 8 TeV (CMS). The black lines are MADGRAPH predictions normalized to the inclusive NNLO cross section. The SHERPA2 predictions are shown as blue bands, whose thickness indicates the statistical uncertainties.

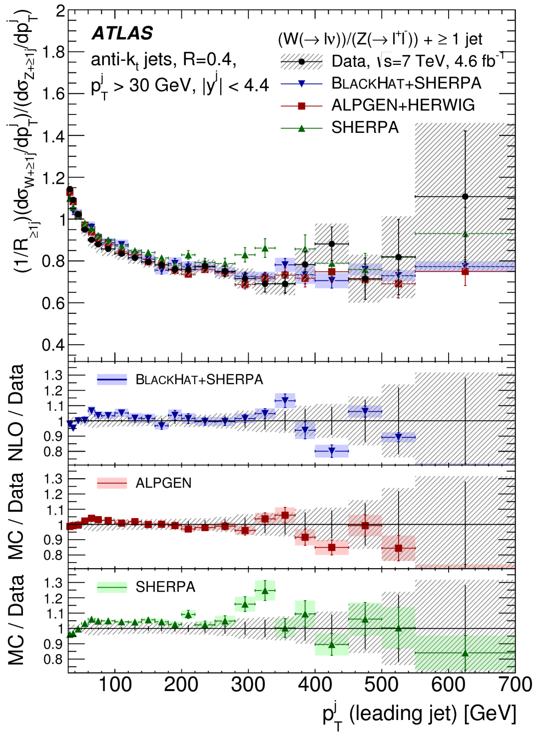

Figure 6. The R_{jets} production cross section versus the leading jet p_T for $N_{jets} \geq 1$ for 4.6 fb^{-1} of data at √s = 7 TeV (ATLAS).

The Z production cross sections with at least two b-jets are presented in Figures 7 and 8. Comparisons with several theoretical predictions using different PDF sets are performed (MCFM [26], aMC@NLO [27], SHERPA, ALPGEN, MADGRAPH). The two pQCD schemes containing heavy flavour quarks are also included in the comparisons: the 4FNS scheme that does not consider b quarks at the initial state and the 5FNS scheme that considers b quarks at the initial state. The largest discrepancies are observed between the ATLAS data and the aMC@NLO (5FNS), ALPGEN (4FNS) and SHERPA (5FNS).

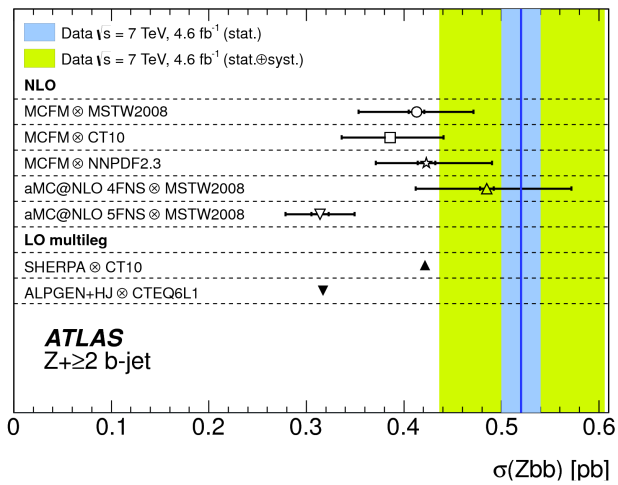

Figure 7. The Z + ≥ 2 b-jets cross section for 4.6 fb^{-1} of data at √s = 7 TeV (ATLAS). The measurement is the vertical blue line with the inner blue shaded band showing the statistical uncertainty and the outer green shaded band showing the sum in quadrature of statistical and systematic uncertainties. The inner error bars in the theory predictions express the statistical uncertainties while the outer error bars are the total uncertainties.

3.2 Wb, Wbb

The production cross section of a W boson in association with b-jets has been measured using data collected at √s = 7 TeV during 2011. The event selections used by both experiments are once more very similar [28-29]. Leptons are required to have $p_T > 25$ GeV and a pseudorapidity of $|\eta| < 2.47$ (electrons), $|\eta| < 2.4$ (muons) for ATLAS, and $|\eta| < 2.1$ (muon channel only) for CMS. Jets are reconstructed using the anti-k_t algorithm with a radius parameter R =0.4 (ATLAS) and R = 0.5 (CMS) and are required to have $p_T > 25$ GeV and a rapidity of $|y| < 2.1$ (ATLAS) or $|\eta| < 2.4$ (CMS). The transverse mass cut of $m_T > 60$ GeV (ATLAS) and $m_T > 45$ GeV (CMS) is used. Finally ATLAS requires that $E_{Tmiss} > 25$ GeV. Only the one b-jet case is studied by ATLAS, while CMS studies the two b-jets case.

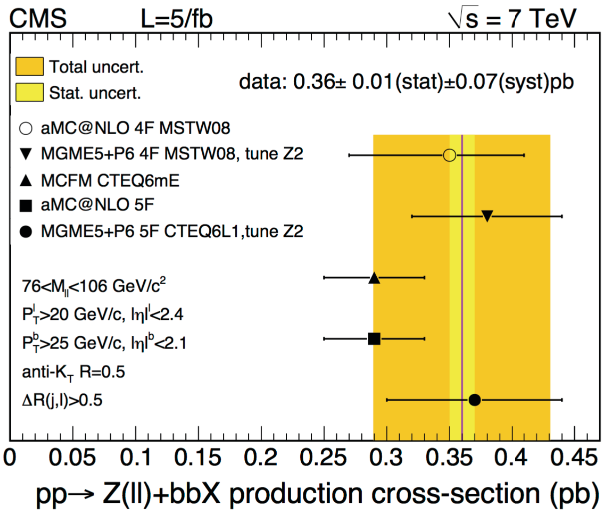

Figure 8. The Z + ≥ 2 b-jets cross section for 5.0 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (CMS). The measurement is the vertical red line with the inner yellow shaded band showing the statistical uncertainty and the outer orange shaded band showing the sum in quadrature of statistical and systematic uncertainties.

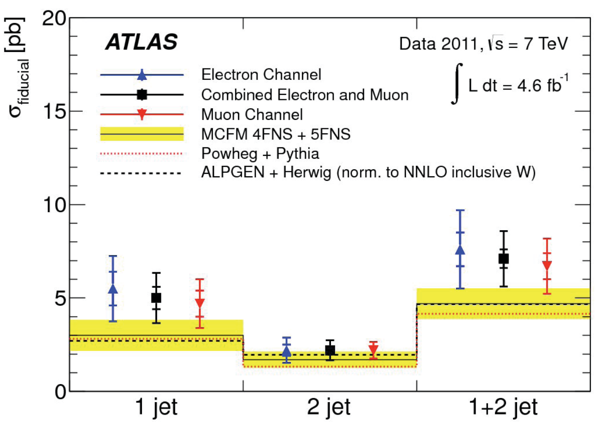

Figure 9. The W +1 b-jet, W + 2 jets and their combination cross sections for 4.6 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (ATLAS). The results for the electron (blue), muon (red) and the combination of both lepton flavours (black) are indicated. The inner error bars are the statistical uncertainties while the outer error bars are the statistical plus systematic uncertainties. The yellow band represents the total uncertainty of the MCFM prediction.

The measured ATLAS cross sections for W + 1 b-jet and W + 2 jets (only one of the two is a b-jet) are shown in the first two bins of Figure 9. The combination of these two cross sections is presented in the third bin of the same figure. Comparisons are made with MCFM, POWHEG and ALPGEN.

The measured CMS cross section for W + 2 b-jets can be seen in Figure 10. It is compared with the MCFM prediction with the MSTW08 PDF set.

There is reasonable agreement between both measurements and the theory.

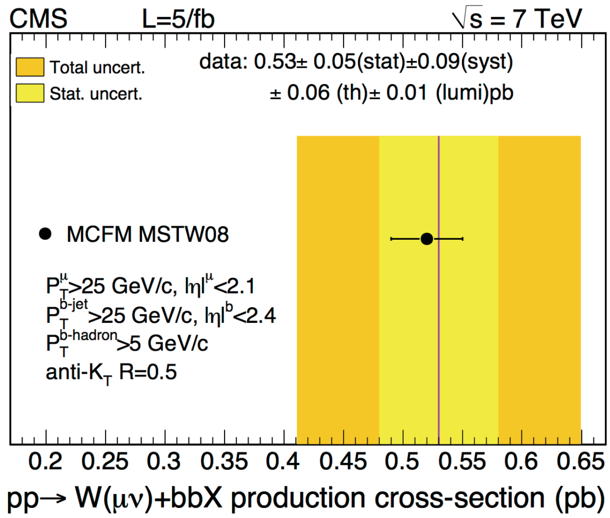

Figure 10. The W + 2 jets cross sections for 5.0 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (CMS). The measurement is the vertical red line with the inner yellow shaded band showing the statistical uncertainty and the outer orange shaded band showing the sum in quadrature of statistical and systematic uncertainties.

3.3 Wc

The associated production cross section of a W boson and a charm quark jet has been measured using data collected at $\sqrt{s}$ = 7 TeV during 2011 [30-31]. This study provides direct access to the strange quark content of the proton at an energy scale of the order of the W-boson mass. Six measurements are actually performed: $W^\pm$ + c-jet, $W^\pm$ + D, $W^\pm + D^*$, where D and D^* are charmed hadrons and are reconstructed from their decay products. CMS presents also results on the combination of these measurements. There is an important strategy followed in this analysis. There is charge correlation between the W boson and the c quark. Therefore the muon originating from the c-jet and the D/ D^* mesons has a charge opposite (OS) to the W boson. The final W + c yields used in the analysis are obtained by subtracting the same-sign distribution (SS) from the OS distribution (referred to as OS – SS) for any given variable. The ATLAS measured cross section for $W^+ + \bar{c}$-jet compared to aMC@NLO and various PDF predictions is presented in Figure 11. The CMS measured cross section combining all the six measurements and compared to MCFM and different PDF sets is shown in Figure 12.

The cross section ratio $W^+ + \bar{c}$ / W^- + c has been also measured by both experiments (Figures 13 and 14). The observed W^-+ c yield is slightly larger than the $W^+ + \bar{c}$, as expected due to the dominance of the d-quark over the d-antiquark in the proton. Another important measurement that was performed by both experiments is the differential cross section as a function of the lepton |η|. The ratio of the strange-to-down sea-quark distributions (r_s) was measured by ATLAS. The value found, $r_s = 0.96\ ^{+0.26}_{-0.30}$, supports the hypothesis of a symmetric light-quark sea.

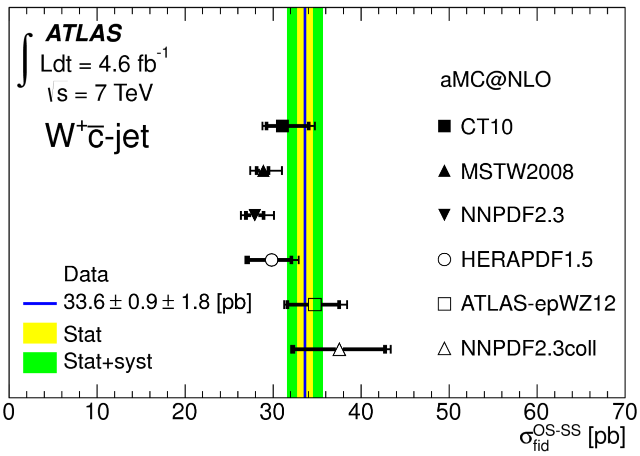

Figure 11. The measured $W^+ + \bar{c}$-jet cross section for 4.6 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (ATLAS). The measurement is the vertical solid line. The inner yellow shaded band shows the statistical uncertainty and the outer green shaded band shows the sum in quadrature of statistical and systematic uncertainties.

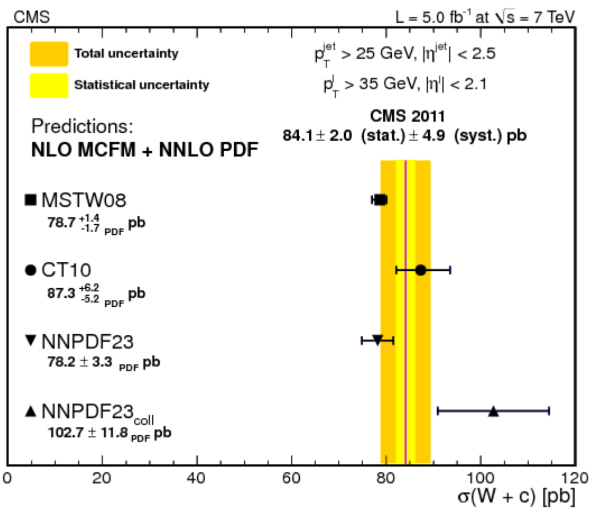

Figure 12. The measured W + c cross section (electron and muon $p_T > 35$ GeV) for 5.0 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (CMS). The measurement is the vertical red line with the inner yellow shaded band showing the statistical uncertainty and the outer orange shaded band showing the sum in quadrature of statistical and systematic uncertainties.

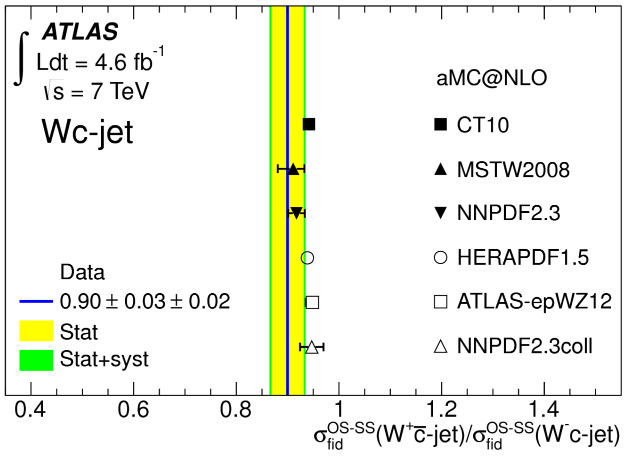

Figure 13. The cross sections ratio $W^+ + \bar{c}$ / $W^- + c$ for 4.6 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (ATLAS). The measurement is the vertical solid line. The inner yellow shaded band shows the statistical uncertainty and the outer green shaded band shows the sum in quadrature of statistical and systematic uncertainties.

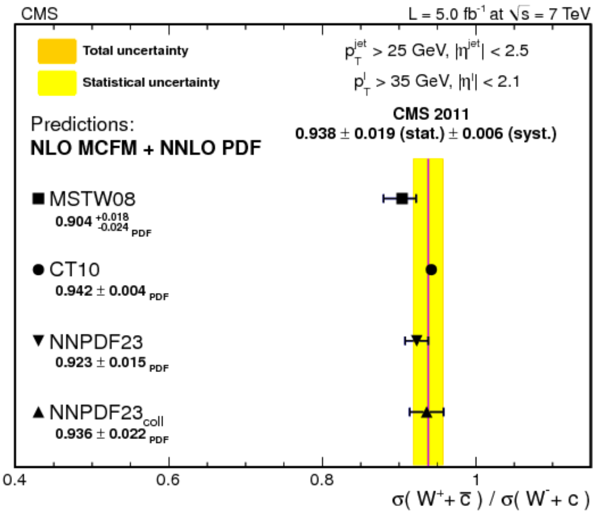

Figure 14. The cross sections ratio $W^+ + \bar{c}$ / $W^- + c$ (electron and muon $p_T > 35$ GeV) for 5.0 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (CMS). The measurement is the vertical red line with the inner yellow shaded band showing the statistical uncertainty and the outer orange shaded band showing the sum in quadrature of statistical and systematic uncertainties.

4 W and Z production in association with a top quark pair

The production cross section of a top quark-antiquark pair ($t\bar{t}$) in association with a W or Z boson has been measured using data collected at $\sqrt{s}$ = 8 TeV during 2012 that correspond to an integrated luminosity of 20.3 fb^{-1} (ATLAS) and 19.5 fb^{-1} (CMS) [32-33]. The top quark is the heaviest known elementary particle. Despite the fact that it was discovered almost two decades ago (1995), some of its properties have not yet been fully investigated. In particular, its couplings to γ and Z bosons have never been directly measured. With the large centre of mass energy and integrated luminosity of the collected data samples at the LHC, the processes where the SM bosons W and Z are produced in association with top quarks ($t\bar{t}W$, $t\bar{t}Z$) become accessible.

Channels with two, three and four leptons (electrons or muons) are studied. More specifically, three analysis channels are considered by both LHC experiments for these processes. ATLAS studies, a) the same-sign dimuon channel, b) the trilepton channel and c) the opposite-sign dilepton channel. CMS studies, a) the same-sign dilepton channel, b) the trilepton channel and c) the four-lepton channel.

The ATLAS results of a combined two-dimensional simultaneous fit for the $t\bar{t}W$ and $t\bar{t}Z$ cross sections are shown in Figure 15. They are compared and found to be in agreement with NLO QCD calculations [34-37]. The CMS combined two-dimensional simultaneous fit results are shown in Figure 16. They are compared and found to be in agreement with the MADGRAPH_aMC@NLO [38] prediction which is in agreement with the same independent NLO calculations used for the comparison of the ATLAS results.

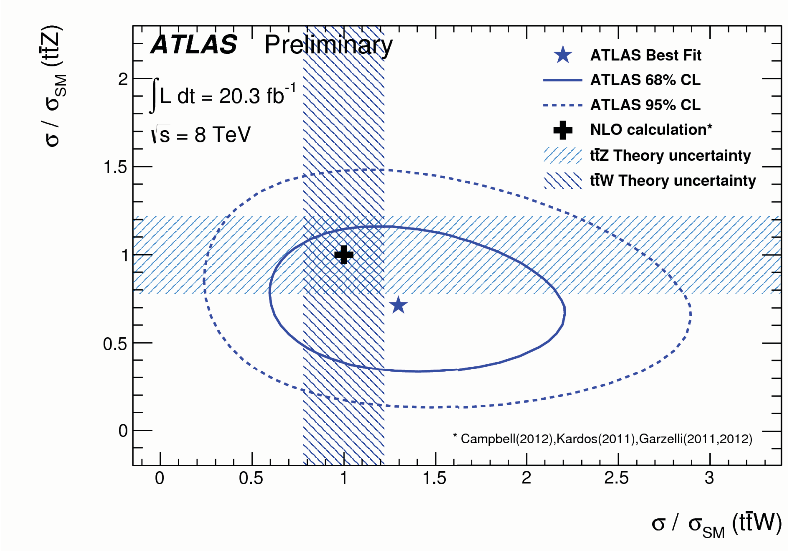

Figure 15. The result (star symbol) of the combined two-dimensional simultaneous fit of the $t\bar{t}W$ and $t\bar{t}Z$ signal strengths along with the 68% and 95% confidence level contours compared to NLO QCD calculations (cross symbol). The dashed areas correspond to the theory uncertainties of the NLO QCD calculations.

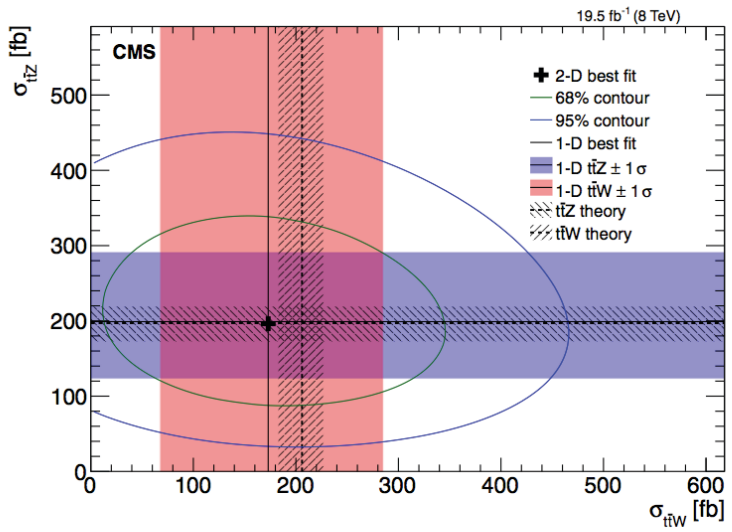

Figure 16. The result (cross symbol) of the combined two-dimensional simultaneous fit for the $t\bar{t}W$ and $t\bar{t}Z$ cross sections along with the 68% and 95% confidence level contours compared to MADGRAPH_aMC@NLO predictions (black dashed lines). The result of this fit is superimposed with the separate $t\bar{t}W$ and $t\bar{t}Z$ cross section measurements (two one-dimensional fits), and the corresponding one standard deviation (1σ) bands, obtained from the three different analysis channels considered. The cross sections extracted from the two-dimensional fit are identical to those obtained from the two one-dimensional fits.

5 Conclusions

ATLAS and CMS excellent performance allow the precise study of the associated vector boson (W and Z) production. This has been a topic of great interest for theoretical studies for several years and can be finally exploited with high presicion experimental measurements at the LHC. Several results for √s = 7 Tev (2011) and √s = 8 Tev (2102) have been presented. There is an overall good agreement with theory predictions, although some discrepancies exist. Nevertheless, these measurements provide important feedback to the theorists and our understanding of QCD and electroweak processes in the high energy LHC regime.

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