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Measurement of the W and Z boson production cross sections in pp collisions at 7 TeV with the ATLAS detector

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Results are presented from recent measurements of the production cross sections of W and Z bosons in proton-proton collisions at $\sqrt{s} = 7$ TeV. The bosons are reconstructed in decays to electrons, muons, and taus, using the ATLAS detector. The general selections and methodologies for background estimation are surveyed. The cross section results are shown to be in good agreement with the NNLO predictions of the Standard Model. Precise measurements of the p_T distribution of W and Z bosons are also reported and compared to theoretical predictions from QCD. The analyses discussed use a dataset corresponding to 30–40 pb^{-1} of integrated luminosity, acquired during the running of the LHC in 2010.

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1. Introduction

In the year 2010, the Large Hadron Collider (LHC) [1] at the European Organization for Nuclear Research (CERN) successfully climbed from 10^{27} to 10^{32} cm^{-2} s^{-1} in instantaneous luminosity, allowing the ATLAS detector [2] to collect 30–40 pb^{-1} of collision data for the analyses discussed in this presentation. With that year's data, the ATLAS Collaboration published its first measurements of *W* and *Z* bosons in proton-proton collisions with $\sqrt{s}$ = 7 TeV. Measurements of the production cross section times branching fraction were made for all decay modes of the *W* and *Z* bosons involving charged leptons: $W \to e\nu$, $W \to \mu\nu$, $W \to \tau\nu$, $Z \to ee$, $Z \to \mu\mu$, and $Z \to \tau\tau$. In addition, ATLAS published measurements of the distribution of the transverse momentum of *W* and *Z* bosons produced in the proton-proton collisions.

2. Measurement of the $W \to \ell\nu$ and $Z/\gamma^* \to \ell\ell$ cross sections

ATLAS first published [3] measurements of the *W* and *Z* boson production cross sections with 2250 $W \to \ell\nu$ and 179 $Z/\gamma^* \to \ell\ell$ candidate events ($\ell = e, \mu$). These measurements have been updated [4] with a dataset enlarged by a factor of one hundred and with a significantly reduced luminosity uncertainty (from 11% to 3.4%), which remains the largest systematic uncertainty.

The *W* candidate events are selected to have a single lepton with transverse momentum (p_T) greater than 20 GeV, missing transverse energy (E_T^{miss}) greater than 25 GeV, and a transverse mass (m_T) of at least 40 GeV between the E_T^{miss} and lepton. *Z* candidate events are selected to have two electrons or muons with $p_T > 20$ GeV, within the dilepton mass window: $66 < m_{\ell\ell} < 116$ GeV.

The electroweak backgrounds in each of these selections account for a few percent of the sample, and are estimated with fully simulated Monte Carlo data. The QCD backgrounds, from fake leptons and leptons produced in weak decays of hadrons, also contaminate the samples at the level of few percent and are estimated with data-driven techniques. For example, the QCD background to the $W \to e\nu$ selection is estimated by fitting the E_T^{miss} distribution with a QCD template derived from data events with electron candidates that fail identification requirements.

The final results for the total inclusive cross sections are reported in Table 1. The results have been compared to QCD predictions based on recent determinations of the parton distribution functions of the proton. In addition, differential cross sections have been measured as a function of the *Z* rapidity, in the case of *Z*, and as a function of the lepton η, for W[1].

3. Measurement of the $Z/\gamma^* \to \tau\tau$ cross section

In the year 2011, ATLAS published its first measurement of the $Z/\gamma^* \to \tau\tau$ cross section. Because taus are the only leptons massive enough to have hadronic [6]. and leptonic decays, analyses were performed for four independent channels: $Z/\gamma^* \to \tau\tau \to e\tau_h + 3\nu$, $Z/\gamma^* \to \tau\tau \to \mu\tau_h + 3\nu$, $Z/\gamma^* \to \tau\tau \to e\mu + 4\nu$, and $Z/\gamma^* \to \tau\tau \to \mu\mu + 4\nu$, where τ_h denotes a hadronic tau decay. These analyses face the challenge of using leptons with p_T as low as 15 GeV, and selecting hadronic tau candidates, amongst the huge production of QCD multijet events at the LHC that can fake the signature. $W +$ jet, $Z +$ jet, and $t\bar{t}$ events also provide sources of real and fake leptons and

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[1]These topics are discussed in more detail in Massimiliano Bellomo's contribution to these proceedings.
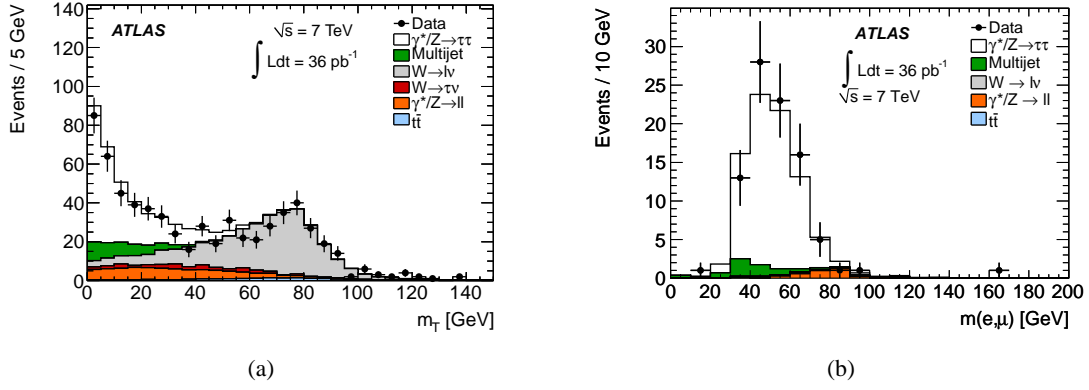
Figure 1: (a) The transverse mass between the muon and E_T^{miss} in events with opposite-sign muon and tau candidates. (b) The visible mass of the final selected $e\mu$ candidates [5].

hadronic tau decays. Tight lepton isolation is required to suppress real and fake leptons produced in jets.

For the $\ell\tau_h$ channel, a geometric variable, $\sum\cos\Delta\phi = \cos\left(\phi(\ell) - \phi(E_T^{miss})\right) + \cos\left(\phi(\tau_h) - \phi(E_T^{miss})\right)$, is used to discriminate events where the E_T^{miss} is consistent with pointing between the decay products, as it would if it were the vector sum of the neutrinos from $Z/\gamma^* \to \tau\tau$. In addition, $m_T < 50$ GeV is required to suppress W+jet. Mis-modeling of the width of jets in ATLAS Monte Carlo leads to an overestimate of the fake-rate for jets to pass tau identification. This is controlled by scaling the W + jet Monte Carlo to agree with data in events with $m_T > 50$ GeV, where the W+jet sample is very pure (see Fig. 1(a)). Finally, opposite-sign charge $\ell\tau_h$ candidates are selected in the visible mass window: $35 < m(\ell, \tau_h) < 75$ GeV.

The $e\mu$ channel additionally requires the sum of the E_T of all high-E_T objects and the E_T^{miss} to be less than 150 GeV to reject $t\bar{t}$. Opposite-sign candidates are then selected in the visible mass window: $25 < m(e, \mu) < 80$ GeV, (see Fig. 1(b)).

For the $\mu\mu$ channel, a Boosted Decision Tree was used to maximize separation between $Z/\gamma^* \to \tau\tau \to \mu\mu + 4\nu$ and $Z/\gamma^* \to \mu\mu$. It was trained with Monte Carlo using five kinematic

		σ [nb]	stat.	sys.	lumi.	acc.
$\sigma_W \cdot \mathrm{BR}(W \to e\nu)$	=	10.255	0.031	0.190	0.349	0.084
$\sigma_W \cdot \mathrm{BR}(W \to \mu\nu)$	=	10.210	0.030	0.179	0.373	0.153
$\sigma_{Z/\gamma*} \cdot \mathrm{BR}(Z/\gamma* \to ee)$	=	0.952	0.010	0.026	0.032	0.019
$\sigma_{Z/\gamma*} \cdot \mathrm{BR}(Z/\gamma* \to \mu\mu)$	=	0.935	0.009	0.009	0.032	0.019
$\sigma_W \cdot \mathrm{BR}(W \to \tau\nu)$	=	11.1	0.3	1.7	0.4	
$\sigma_{Z/\gamma*} \cdot \mathrm{BR}(Z/\gamma* \to \tau\tau)$	=	0.97	0.07	0.07	0.03	

Table 1: Results [4, 5, 7] for the inclusive cross sections for W and Z bosons including the estimated statistical and systematic error, as well as the error from the luminosity and acceptance uncertainty. For the measurements with τ in the final state, the acceptance uncertainty is included in the systematic. All of the measurements are consistent with the NNLO predictions of $\sigma_W \cdot \mathrm{BR}(W \to \ell\nu) = 10.46 \pm 0.52$ nb and $\sigma_Z \cdot \mathrm{BR}(Z/\gamma* \to \ell\ell) = 0.96 \pm 0.05$ nb within the dilepton mass window: $66 < m_{\ell\ell} < 116$ GeV.
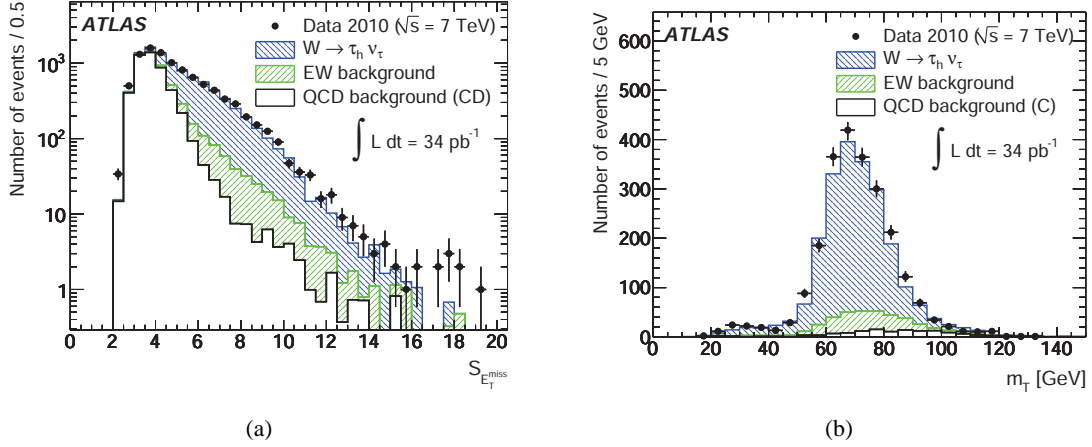
Figure 2: (a) The estimated significance of the $E_{\mathrm{T}}^{\mathrm{miss}}$ for $\tau_h + E_{\mathrm{T}}^{\mathrm{miss}}$ events. (b) The transverse mass between the tau candidate and $E_{\mathrm{T}}^{\mathrm{miss}}$ for events passing the $S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 6$ cut [7].

variables of the muons and $E_{\mathrm{T}}^{\mathrm{miss}}$. Finally, opposite-sign candidates are selected in the visible mass window: $25 < m(\mu, \mu) < 65$ GeV.

In all channels, the QCD multijet background is estimated from the data by scaling events with same-sign charges by the ratio of opposite-sign to same-sign events, measured the multijet-rich sample of events failing lepton isolation, corrected for contamination from electroweak processes with Monte Carlo. The dominant systematic uncertainties are the tau identification efficiency (8.6%) and the energy scale (11%).

4. Measurement of the $W \to \tau\nu$ cross section

ATLAS also published its first measurement of the W cross section in the $W \to \tau_h \nu$ channel [7]. $W \to \tau_h \nu$ candidates are found by selecting events with a hadronic tau candidate with $20 < p_{\mathrm{T}} < 60$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, and vetoing events with leptons. The significance of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is estimated by $S_{E_{\mathrm{T}}^{\mathrm{miss}}} = (E_{\mathrm{T}}^{\mathrm{miss}} / \mathrm{GeV}) / (2\sqrt{\sum E_{\mathrm{T}} / \mathrm{GeV}})$, where $\sum E_{\mathrm{T}}$ is the scalar sum of the E_{T} of all calorimeter clusters (see Fig. 2(a)). The purity of the sample is increased by requiring $S_{E_{\mathrm{T}}^{\mathrm{miss}}} > 6$. The peak of $W \to \tau_h \nu$ events is clearly seen as function of the transverse mass between the τ_h and the $E_{\mathrm{T}}^{\mathrm{miss}}$ (see Fig. 2(b)). The QCD background is estimated with a data-driven model by scaling events that fail the cut on $S_{E_{\mathrm{T}}^{\mathrm{miss}}}$ by the efficiency to pass the cut, as measured in the control sample of events that fail tau identification. Like for $Z/\gamma^* \to \tau\tau$, the dominant systematic uncertainties are the tau identification efficiency (8.6%) and the energy scale (11%).

5. Measurement of the W and Z p_{T} distributions

At hadron colliders, W and Z bosons can be produced with a non-zero component of momentum transverse to the beam-line ($p_{\mathrm{T}}^{W/Z}$), mainly arising due to the recoil from initial state QCD radiation of quarks and gluons. The clean signatures of leptonic W and Z decays therefore provide an opportunity to test QCD predictions of the distributions for $p_{\mathrm{T}}^{W/Z}$. Testing for accurate modeling of the p_{T}^{W} is especially important for a future precision W mass measurement.
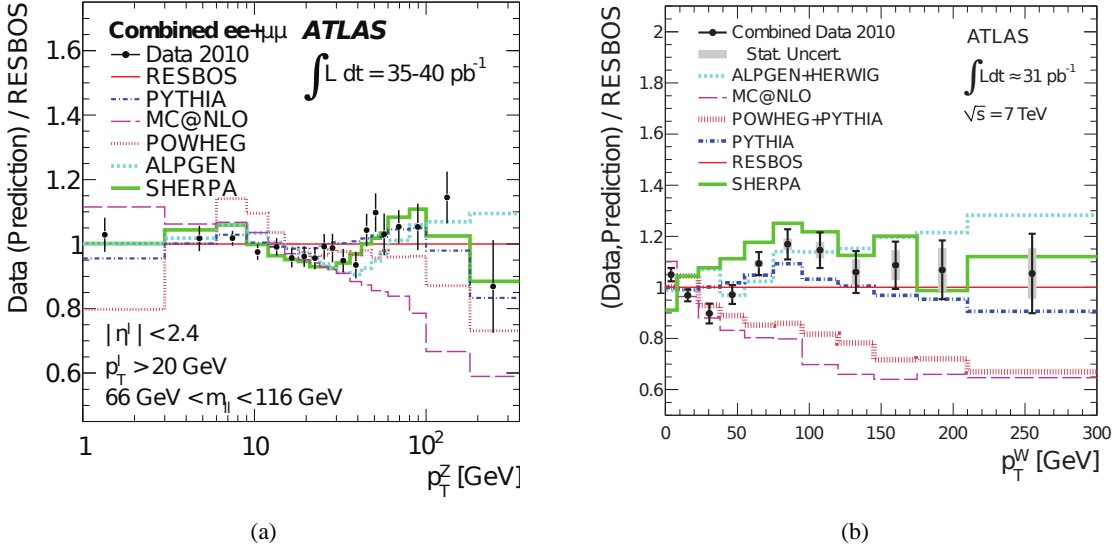
Figure 3: The ratio of $p_T^{W/Z}$ to its prediction by the RESBOS generator, comparing the measurements of p_T^Z (a) and p_T^W (b), with the theoretical predictions from other generators [8, 9].

The transverse momentum of $Z \to \ell\ell$ candidates is reconstructed directly from sum of the four-vectors of the leptons. The observed p_T^Z spectrum is corrected for detector response and the effects of final state QED radiation with bin-by-bin correction factors derived with signal Monte Carlo, to yield a prediction for the true p_T^Z distribution [8].

Because the neutrino from W decays is not directly observable, p_T^W is reconstructed from the sum of the hadronic recoil measured in the calorimeter, excluding the lepton signature. After subtracting estimates of the backgrounds, the p_T^W distribution is unfolded for the effects of detector response and final state radiation by the method of inverting a response matrix that characterizes the bin-by-bin migrations in mapping the true p_T^W to its reconstructed value [9].

The unfolded distributions of p_T^W and p_T^Z have a precision of a few percent in each bin, and are compared to the theoretical predictions from several Monte Carlo generators in Fig. 3.

6. Conclusion

A summary of recent W and Z cross section measurements performed by the ATLAS Collaboration is shown in Fig. 4, as well as previously in Table 1. All measurements are consistent with the NNLO predictions. ATLAS also reported its first precision measurements of p_T^W and p_T^Z. These measurements are not only important as measures of the Standard Model at the energy frontier, but also because they establish important backgrounds to new physics searches at the LHC. The study of W and Z production also provides *the* essential control sample of high-p_T electrons, muons, and taus for calibrating their reconstruction and simulation, leading to future reductions in systematic error [10, 11]. By the summer of 2011, the integrated luminosity delivered to ATLAS already exceeded 1 fb^{-1}, with a new regime of sample size available to analyze.
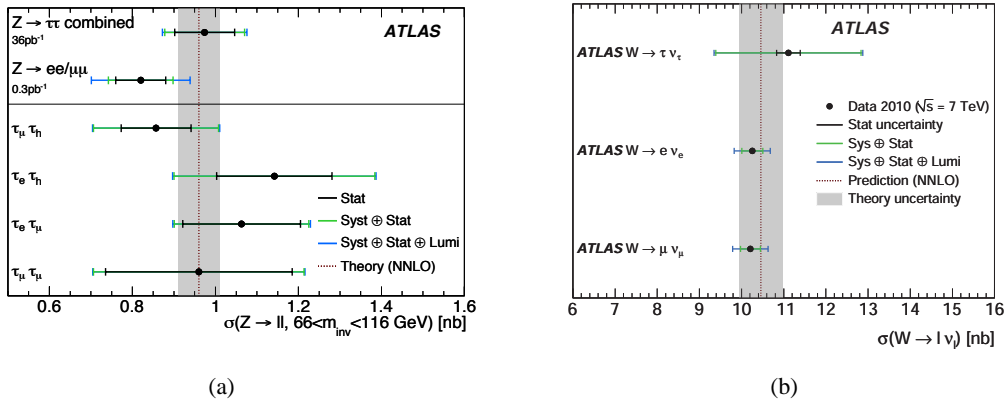
Figure 4: A summary of the recent ATLAS measurements of the production cross sections of *W* and *Z* bosons in 7 TeV proton-proton collisions [5].

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