Z → ττ and W → τντ Cross-Sections at the LHC

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Abstract
Measurements of the Z → ττ and W → τντ cross-sections at the LHC with data taken at √s = 7 TeV are reported for the ATLAS, CMS, and LHCb experiments. All results are found to agree with the Standard Model.

Keywords: LHC, ATLAS, CMS, LHCb, electroweak, tau production

1. Introduction

The production of Z and W bosons from pp-collisions, and their subsequent decays to τ-leptons at the Large Hadron Collider (LHC) not only provides important tests of the Standard Model (SM), but also lays the groundwork for the study of beyond the SM physics using τ-lepton signatures.

Decays of Z bosons to τ-lepton pairs are both a mechanism for experimentally measuring hadronic τ-lepton identification efficiencies [1, 2] and a calibration channel for neutral Higgs searches [3, 4]. The final states of τ-leptons produced from W bosons can be used to measure the polarization of the W [5] boson or to search for charged Higgses [6, 7].

In this review, the complete set of Z → ττ and W → τντ cross-sections, as measured by the ATLAS, CMS, and LHCb experiments on the LHC, are reported using 2010 and 2011 datasets taken at √s = 7 TeV. A full summary of the results, including corresponding references, is provided in Table 1 and a comparison of the theoretical agreement of the results is given in Figure 1.

1. Particle Selection

All three detectors are fully instrumented with charged particle trackers, electromagnetic and hadronic calorimeters, and muon systems. Both ATLAS [8] and CMS [9] are general purpose detectors designed to cover a central pseudorapidity range of |η| < 2.4, while the LHCb [10] detector is a forward arm spectrometer, purpose built for B-hadron physics, covering the forward pseudorapidity range 2.0 < η < 5.0.
Table 1: A complete summary of the individual $\tau \rightarrow \tau$ decay products due to unreconstructed neutrinos. Acquisition on the transverse separation of the $\tau$-lepton decay products with an enhanced impact parameter. Selection requirements based on these five signatures are used for ATLAS and CMS, and from a reversed impact parameter requirement for CMS. The background to the $\tau_\mu\tau_\mu$ final state.

### 2.2. Event Selection

The $Z \rightarrow \tau\tau$ signal produces a high mass back-to-back final state in the transverse plane with missing energy ($E_T$) and a $p_T$ imbalance between the two $\tau$-lepton decay products due to unreconstructed neutrinos. Additionally, the lifetime of the $\tau$-lepton produces decay products with an enhanced impact parameter. Selection requirements based on these five signatures are used by the experiments to separate signal from background.

For ATLAS, a visible mass selection requirement is placed on all four final states, and a transverse mass requirement on the $\tau_\mu\tau_\mu$ and $\tau_\tau\tau_\tau$ final states. A requirement on the transverse separation of the $\tau$-lepton decay products and the $E_T$ of the event is used for all final states except $\tau_\mu\tau_\mu$, where further requirements on the angular separation, $p_T$ asymmetry, and impact parameters of the two $\tau$-lepton decay products are applied.

For CMS, only a transverse mass requirement is applied to the $\tau_\mu\tau_\mu$, $\tau_\tau\tau_\tau$, and $\tau_\mu\tau_\mu$ final states. Due to the large Drell-Yan background to the $\tau_\mu\tau_\mu$ final state, requirements are placed on the visible mass, transverse separation between the muons and $E_T$, the muon $p_T$ asymmetry, and the impact parameter of the muons.

Unlike for ATLAS and CMS, missing energy cannot be measured within LHCb. However, a high resolution vertex locator allows for strict requirements to be placed on the $\tau$-lepton decay product impact parameters for the $\tau_\mu\tau_\mu$, $\tau_\tau\tau_\tau$, and $\tau_\mu\tau_\mu$ final states. Both a visible mass and transverse separation requirement is placed on all final states, while an additional $p_T$ asymmetry requirement is also placed on the $\tau_\mu\tau_\mu$ final state.

### 2.3. Background Estimation

Drell-Yan production of lepton pairs is the primary background to the $\tau_\mu\tau_\mu$ final state for all three experiments, as well as the $\tau_\tau\tau_\tau$ final state for ATLAS and CMS. The Drell-Yan visible mass shape is determined for ATLAS from simulation, while for both CMS and LHCb the template is obtained with a reversed impact parameter requirement. For ATLAS and LHCb the template is normalized to the on-shell $Z$ mass peak, and for CMS normalized to an impact parameter side-band.

The QCD multijet background is large in the $\tau_\mu\tau_\mu$ and $\tau_\tau\tau_\tau$ final states, and a visible mass shape is determined from data for all three experiments by requiring candidates with same-sign charge. The normalization is also taken from data, scaling the number of same-sign events by the estimated opposite-sign/same-sign event ratio for the background.

The $W$ with jets background mass shape is determined from simulation for all three experiments and normalized using transverse mass side-bands for ATLAS and CMS, and a same-sign side-band for LHCb. The $Z$ with jets visible mass shape is taken from simulation for ATLAS and LHCb, and from a reversed impact parameter requirement for CMS. The background is normalized using a visible mass side-band for ATLAS.
LAS, an impact parameter side-band for CMS, and a same-sign side-band for LHCb.

For all three experiments the visible mass distributions for the WW and τ̄τ backgrounds are estimated from simulation. The normalization for these backgrounds is also taken from simulation for ATLAS and LHCb, and from a transverse mass side-band for CMS. Both the WW and τ̄τ background contributions are minimal for all final states.

2.4. Systematics

For both ATLAS and CMS the hadronic τ-lepton identification efficiency and energy scale is the primary systematic uncertainty for the τµτh and τττh final states, ranging from 8% − 23%. In the τµτµ final state the primary uncertainty is between 2% − 9% from muon efficiency and acceptance, and for the τττh final state is between 2% − 6% from electron efficiency.

For LHCb, the Drell-Yan background provides the largest systematic uncertainty of 8% to the τµτµ final state. Electron reconstruction efficiency contributes the primary uncertainty to the τµτµ, τττµ, and τττh final states of 4%, while the impact parameter selection efficiency provides a 2% uncertainty to the τµτh final state.

2.5. Results

The measured cross-section, number of observed events, and number of background events for each final state of all three experiments is given in Table 1. Note the reduced statistics of the LHCb results, due to the acceptance of the detector, but the enhanced purity of the τµτµ final state.

The combined Z → ττ cross-section measurement for each experiment is given in Table 2, including the fiducial definition and predicted theory result. The ATLAS and CMS theory predictions were calculated using Fewz [17], while the LHCb prediction was calculated with DYNLO [18]. The ATLAS combined result does not include the τµτµ final state.

3. W → τντ

Due to the large W → ℓνℓ background to leptonically decaying τ-leptons produced from W bosons, only hadronic decays of the τ-lepton are considered for the ATLAS and CMS W → τντ analyses. QCD jets, W → ℓνℓ, W → τντν, and Z with jets events provide the primary backgrounds to this signal. Of the three experiments, only ATLAS has performed a W → τντ measurement. An observation has been made with CMS, but without a cross-section measurement.

| Exp. | σ ± stat ± syst ± lumi. | σ theory |
|------|-------------------------|----------|
| ATLAS | 0.92 ± 0.02 ± 0.08 ± 0.03 nb 66 < Mττ < 116 GeV | 0.96 ± 0.05 nb Fewz |
| CMS  | 1.00 ± 0.05 ± 0.08 ± 0.04 nb 60 < Mττ < 120 GeV | 0.97 ± 0.04 nb Fewz |
| LHCb | 71.4 ± 3.5 ± 2.8 ± 2.5 pb | 74.3 ± 2.1 pb DYNLO |

Table 2: Combined Z → ττ and theoretical cross-section results for the three experiments. The ATLAS result does not include the τµτµ final state.

3.1. Particle Selection

A pT > 12 GeV trigger on the hadronic τ-lepton combined with a Et > 20 GeV trigger is used to select events for ATLAS, while a pT > 20 GeV hadronic τ-lepton trigger and Et > 25 GeV trigger is used for CMS.

Hadronic τ-leptons are selected for ATLAS using a boosted decision tree based on the collimation, impact parameter, and lead track pT over electromagnetic calorimeter energy of the hadronic τ-lepton candidate. For the CMS selection, requirements are placed on the hadronic τ-lepton lead track pT, isolation, and associated muon hits.

3.2. Event Selection

To eliminate W and Z with jets backgrounds, events with high pT leptons outside the hadronic τ-lepton jet are rejected for both ATLAS and CMS. A large Et is also required for both to reduce the QCD jet background. Additionally, a high Et significance and transverse separation between the τ-lepton and Et is required for ATLAS, while the ratio of the τ-lepton jet pT to the pT of the remaining jets is required to be large for CMS.

3.3. Background Estimation

The W and Z background transverse mass shapes for both ATLAS and CMS are determined and normalized using simulation. The QCD jet background transverse mass shape and normalization is determined using an ABCD method for both. For ATLAS, requirements are made on the Et significance and hadronic τ-lepton identification, while requirements on the Et and ratio of τ-lepton jet pT to the pT of the remaining jets are used for CMS.
3.4. Systematics

The primary systematic uncertainty for the ATLAS $W \rightarrow \tau \nu \tau$ cross-section measurement is due to the identification efficiency for the hadronic $\tau$-lepton jets and estimated to be 10%. For CMS, no cross-section measurement was made, and so no uncertainty analysis is available.

3.5. Results

The number of observed $W \rightarrow \tau \nu \tau$ events and background events is given in Table 1 for both ATLAS and CMS, as well as the measured ATLAS cross-section. To determine the total cross-section, the ATLAS $W \rightarrow \tau \nu \tau$ cross-section is extrapolated from the measured fiducial region to full acceptance, and divided by the experimentally known branching fraction for $\tau$-leptons to hadrons. The result given in Table 1 agrees well with the theoretically predicted value of $10.5 \pm 0.5$ nb calculated using Fewz.

4. Conclusion

A comparison of the measured cross-sections of Table 1 and Table 2 divided by their predicted theoretical values is given in Figure 1. The red points represent combined results and the black points individual final states. The dark error bars correspond to statistical uncertainty, while the light error bars correspond the combined systematic uncertainty and uncertainty due to the integrated luminosity. The dark yellow line represents a ratio of unity, while the light yellow band indicates the theoretical uncertainty centered about the light yellow line.

There is good agreement between all measured cross-sections and their theoretical values. Currently, ATLAS provides the most statistics for the combined $Z \rightarrow \tau \tau$ cross-section measurement, while LHCb yields the most precise cross-section measurement. The ATLAS $W \rightarrow \tau \nu \tau$ measurement has a large systematic uncertainty and does not allow for a more precise test of the $W \rightarrow \tau \nu \tau$ to $W \rightarrow \mu \nu \tau$ ratio measured at LEP.

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Figure 1: Ratios of the experimental cross-section measurements of Table 1 and Table 2 to their expected theoretical values. The combined results are given in red and the individual final states in black. The dark error bars are the statistical uncertainty, while the light error bars are the combined systematic uncertainty and uncertainty due to the integrated luminosity. The dark yellow band indicates the theoretical uncertainty centered about the light yellow line.