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W Boson Production via the $W^{\pm} \rightarrow \mu^{\pm}\nu$ Decay Channel

Abstract:

Analysis of W bosons produced in the LHC was performed to test the validity of the SM. Analysis was done on the 13TeV ATLAS Open Data set by isolating events in the $W^{\pm} \rightarrow \mu^{\pm}\nu$ single-lepton decay channel. Single-lepton final state decay events were determined by applying selection criteria to isolate events with exactly one muon-neutrino pair in the data. Statistical analysis was performed to compare decay events found in data with those found in MC prediction made using the SM. The data was fit with a Breit-Wigner distribution model to determine W boson mass, measured at 78.073±.006. Agreement between W boson distribution in data and MC was within 5%, thus confirming the SM's prediction.

Introduction:

Following the success of quantum electrodynamics in the 1950's, physicists were eager to investigate other fundamental forces on the quantum scale. In the 1960's much work was done on a quantum theory of the weak nuclear force. In 1968 Sheldon Glashow, Steven Weinberg and Abdus Salam published a unified theory of electromagnetism and weak interactions for which they were awarded the 1979 Nobel Prize.[2] Their electroweak theory predicted the existence of the $W^{\pm}$ and Z bosons.

The $W^{\pm}$ and Z Bosons act as force carriers for the weak interaction. The $W^{\pm}$ bosons mediate neutrino absorption and emission, while the Z boson mediates momentum, spin and energy transfer between matter and neutrinos in elastic scattering.

The prediction proved difficult to confirm experimentally, as the $W^{\pm}$ and Z bosons effects do not become significant until the energy of an interaction is comparable to their relatively large mass. W bosons have a mass of 80.379±0.012GeV and decay width 2.085±0.042GeV, while the Z boson has a mass of 91.1876±.0021 and decay width 2.4952±.0023.[3][12] Thus, experimental confirmation had to wait until a particle collider operating at high enough energy could be built.

The first particle collider able to detect the $W^{\pm}$ and Z bosons was the Super Proton Synchrotron. First commissioned in 1976, SPS began operating at 400GeV. Two experiments at SPS, UA1 led by Carlo Rubbia and UA2 led by Pierre Darriulat, began in 1981 which led to the first experimental confirmation of the $W^{\pm}$ and Z bosons. Using a technique developed by Simon van der Meer known as stochastic cooling, UA1 and UA2 began operating at energies high enough to detect the $W^{\pm}$ and Z bosons. In 1983 Carlo Rubbia and Simon van der Meer published their papers on the discovery of the $W^{\pm}$ and Z bosons, for which they shared the 1984 Nobel Prize.[9][10][11]

The Standard Model, reaching its modern form in the 1970's, has had much success in explaining the physical properties of nature. The SM provided theoretical framework for understanding three of the four fundamental forces: The electromagnetic, weak and strong interactions. Many theoretical predictions now have experimental confirmation, with Carlo Rubbia and Simon van der Meer's 1983 paper an important confirmation of the weak interaction. However, the SM is still incomplete. Among other reasons, it lacks a theory of gravity and dark energy. Thus, further testing of the SM's predictions is necessary.

The LHC is the highest energy particle collider to date. Thus, confirming the SM's prediction of the electroweak interaction via $W^{\pm}$ and Z bosons at energies produced in the LHC, as well as obtaining a more precise value for its mass, is an important test for the SM.

In this paper, we focus on the W boson. Investigation of the W boson was done previously at the LHC by M. Aaboud and G. Aad at energies of 7TeV in 2018, finding a value for the W boson mass of 80.370±.007.[1] The energy of the LHC has been upgraded since their data set was collected, thus we aim to replicate their findings at a new energy of 13TeV.

To measure the W boson, we focus on the muon-neutrino final state decay events. In the methods section we describe the techniques used to isolate muon and neutrino pairs found in the 13TeV Open Data set released by ATLAS.[6] Using code written in Python, the neutrino and muon pairs were used to reconstruct the W boson mass in both data and MC prediction. We demonstrate that the transverse mass and the production rate of the W bosons produced in the LHC matches that predicted by the SM in the MC simulation. This is an important experimental confirmation of the SM, demonstrating its validity in predicting the W bosons decay process. In addition, this data is empirically useful for other experiments using the LHC; W bosons contribute background to other particle physics analysis, and empirical measurement of their production in the LHC allows them to be accurately screened out in other experiments.

Methods:

When W bosons are produced, they decay with a short half-life of $3x10^{-25}$s into either a lepton-antilepton or a quark-antiquark.[3] In the leptonic decay, the lepton is either an electron or a muon and the anti-lepton is a neutrino. We investigate the lepton-antilepton decay by analysis of muon-neutrino final state decay events.

Data used for the analysis was collected at the LHC. The LHC is the highest energy and most modern particle collider to date. In the LHC, the protons are accelerated to speeds up to 99.9999991% the speed of light, giving them a collision energy of 13TeV.[4] Once the protons collide particles predicted by the SM are produced and measured by several tracking detectors, calorimeters and spectrometers. The calorimeters measure the energy of the particles created in the collision, the tracking detectors measure their position, and the spectrometer measures the trajectory and momentum of the muons.

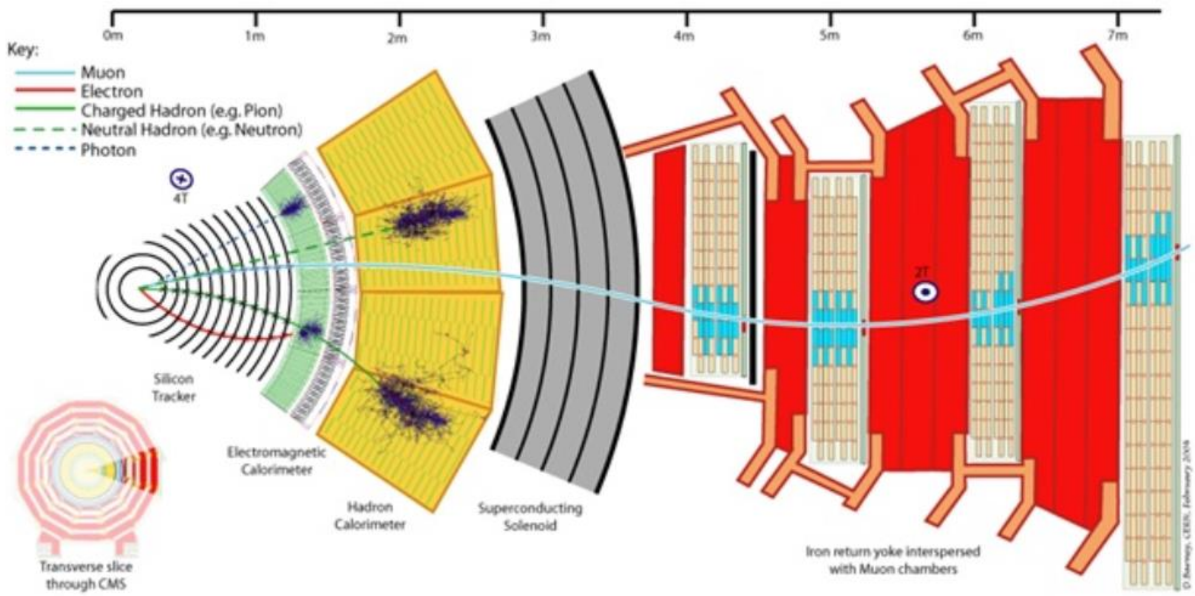

Figure 1: The detector layout in the LHC is shown, with paths for different particles. Muons will be detected by the Muon chambers in the Muon spectrometer. [5]

While neutrino's escape the collider unable to be detected, the muons are detected by the muon spectrometer. The muon chambers in the muon spectrometer are made of many small tubes of gas. When the muon passes through, it leaves a trail of charged ions and electrons. These ions and electrons then drift to the center and sides of the tubes; By measuring when and where they reach the center and sides, their original position can be reconstructed. Since all other charged particles are absorbed by the inner detectors, the path reconstructed from the charged ions and electrons gives the path of the muon that passed through. Using this path, the momentum and trajectory of the muon are determined.

We used the 13TeV Open Data set released by ATLAS.[6] Analysis was done using Python code and ROOT analysis framework provided by CERN.[8] To isolate muon-neutrino final state decay events in the data and MC simulation files, the following selection criteria were applied in the order given.

First, a selection for trigM or trigE was made. These are the muon and electron triggers; They are true for events with exactly one muon or one electron. Because the W bosons leptonic decay has exactly one electron or muon, this selection cuts events which do not contain the necessary number of leptons.

We then selected for lep_ptcone30 < .1 and lep_etcone20 < .1. Lepton etcone20 is the sum of the energy found in clusters within a cone of $\Delta R = 0.2$ around the particle and lepton ptcone30 is the sum of the transverse momentum found within a cone of $\Delta R = 0.3$. The standard lepton selection requirements defined by the ATLAS technical note are lep_petcone30<.15 and lep_etcone20<.15, however we use a tighter cut to reduce background contribution.[6] These selection criteria are used to isolate from the detector signals which do not have contribution from nearby jets. Contribution from nearby jets reduces the accuracy of the detectors in measuring the muon, as well as reduces the confidence that a muon was correctly isolated. To further ensure only muons were selected, a cut for lep_isTightID was used.

Next a selection was made for let_pt>35GeV. Lep_pt is the transverse momentum of the lepton, the energy in the plane transverse to the particle beam. We select for this value of transverse momentum to isolate muon candidates of W boson decay from other events which contain muons missing the required energy to be produced from W boson decay.

A selection for the absolute value of lep_eta less than 2.37 and excluding values between 1.37 and 1.52 was applied. Lep_eta, the pseudo-rapidity, is the angle between photon and collider beam. This cut is made for technical reasons related to the detector design; We exclude transition region between the barrel and end cap of the detectors.

We then used TLorentz vectors from the ROOT package to store the values of the isolated muon and neutrino. The values lep_pt, lep_eta, lep_phi and lep_E were used to create the TLorentz vector for the muon. The values met_et and met_phi, the missing transverse momentum and angle of missing momentum in the transverse plane, were used to create the TLorentz vector for the neutrino.

Next, we use the transverse portion of the muons momentum to calculate the transverse mass of the muon-neutrino particle system. The transverse mass is calculated because total momentum of the particles which created the W boson in the axis of the beam is unknown, while the transverse momentum is known to be zero.

Finally, we select for a transverse mass of the muon-neutrino particle system to be $\mu^{\pm}\nu$ > 60GeV. This is to further select single-lepton final state candidate from W boson decay, as the currently accepted value of the W boson mass is 80.379±0.012GeV.[3]

Once these selection criteria identified W boson decay candidates, we weighted them to fill TH1F histograms. We used a weight of 1 to scale the histogram made for the data files. The product of mcWeight, scaleFactor_PILEUP, scaleFactor_LepTRIGGER, scaleFactor_MUON, and scaleFactor_ELE was used to weight the MC files. Because not every muon produced in the collider is able to be detected and identified by the spectrometer, this weight is used to reduce the weight of the MC prediction by an amount that is expected to be missed in the data.

We then scaled the individual MC histograms by a scale factor before stacking them into a single histogram. We scaled them by luminosity multiplied by cross section divided by the sum of weights. Luminosity is the number of expected events per cross section of 1fb. When multiplied by the cross section their product is the expected number of events, which we normalized by dividing by sum of weights. The MC predictions were made by specifying the number of events; Thus, this scales the MC prediction to number of events expected from the data collected in the particle collider.

Once the histograms were made for the MC files, the bins were stacked. While not every MC file simulates W boson decay, we include them because our selection criteria applied to the data will also select some portion of candidates which were not from W boson decay.

Once the MC histograms were stacked, they were added to the same plot as the data. A second plot was made below the main histogram, where we plot the ratio of the data to the stacked MC histograms. This plot is to show the comparison between the two; If the MC simulation accurately models the W boson decay we are investigating, a relatively smooth line at a ratio equal to 1 is expected.

Next, we compared the data to the stacked MC histogram, considering only bins with >5 events, in order to calculate a $\chi^2$and probability of χ^2. We compared the bin numbers for data vs. MC using equation (1), where O_i is number of data events and E_i is number of simulated events, to calculate χ^2. We used the TMath.Prob function in ROOT to calculate the probability of χ^2 for data with error values equal to square root of bin values, 5%, 2.5% and 1%.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \tag{1}$$

Next, we used the equation (2), the Breit-Wigner distribution, to fit our data. In the Breit-Wigner model N is a constant that scales the function, μ is the mean, and Γ is the width of the peak. We fit the Breit-Wigner distribution between 70.72 and 95.40 to model only the peak in the data around the W boson mass. We chose these values to ensure we had an integer number of bins for calculating the probability of χ^2. We calculated χ^2 and probability of χ^2 for this fit on the data with error equal to square root of bin values, 5%, 2.5% and 1%.

$$f(x) = N\frac{\mu\Gamma}{\pi}\frac{1}{\left(x^2 - \mu^2\right)^2 + (\mu\Gamma)^2} \tag{2}$$

We then calculated the total number of events for background and signal + background in MC prediction to determine the ratio of background to signal + background. This is done to test that our selection criteria are correctly isolating W boson decay events found in data.

Finally, we run the same analysis without the tight lepton selection criterion. This was done to check our selection criteria and determine whether the tight lepton selection criterion is necessary. Different results from this analysis would demonstrate the necessity of the tight lepton selection criterion in our selection.

Results:

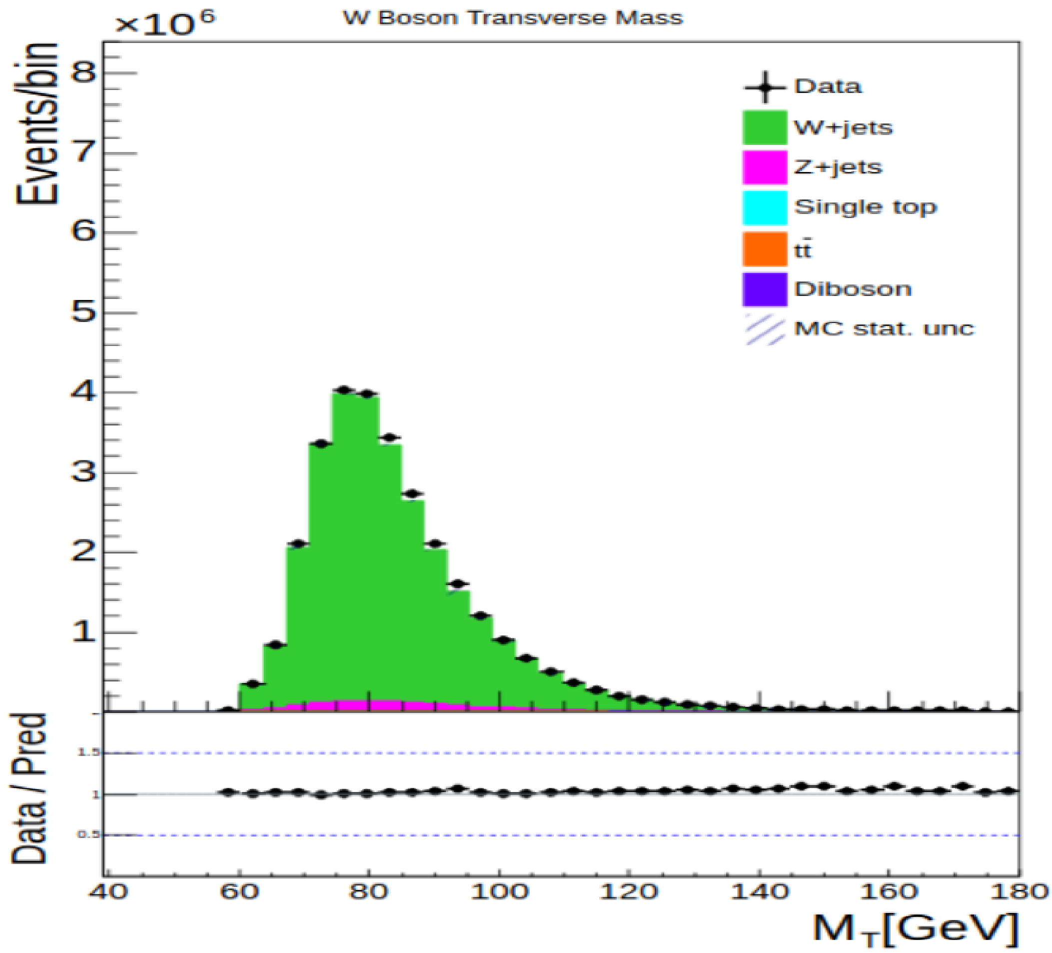

Figure 2: Transverse mass distribution for data vs MC in the W → μν decay channel. In the top panel, the colored histogram represents the stacked MC prediction while black points show the data. The bottom panel displays the ratio between data and MC.

Figure 2 shows the transverse mass distribution for data vs. MC prediction. The total number of events was 2.94×10^7 for the data, and 2.88×10^7 for MC showing agreement of total events within 2%. The bottom panel displays the ratio between data and MC; A relatively smooth line seen at a ratio of 1 indicates the data is in close agreement with MC prediction.

χ^2 for the data vs MC, calculated for bins starting at 60GeV, was found to be 18182.41, with a probability equal to 0.0. The high χ^2 and low probability value result from a statistical error equal to square root of bin content. Statistical uncertainty equal to square root of bin content becomes small relative to bin content, less than .1%, when bin content is of magnitude 10^6. The ratio plot in the bottom panel of figure 2

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--Values for data vs MC--
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-----------------------------------------
Values with sqrt(bin content) error:
chi^2:  18182.405631205867
NDF:  34
Prob.:  0.0
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Values with 5% bin error imposed:
chi^2:  29.063822623312632
NDF:  34
Prob.:  0.7082657349042847
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Values with 2.5% bin error imposed:
chi^2:  116.25529049325053
NDF:  34
Prob.:  6.326085038657812e-11
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Values with 1% bin error imposed:
chi^2:  726.5955655828158
NDF:  34
Prob.:  7.671238479977291e-131
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Figure 3: Table of computed χ^2 and probability of χ^2 for statistical uncertainty equal to square root of bin content, and for systematic uncertainty assumed to be 5%, 2.5% and 1%.

shows that the data and MC do not agree within .1%, which explains the low χ^2 probability.

When the data sample is sufficiently large and statistical uncertainty is sufficiently small, it is necessary to consider systematic uncertainty. Figure 3 shows a table of computed χ^2 and probability of χ^2 values for assumed systematic uncertainties of 5%, 2.5% and 1%. A χ^2 of 29.06 and probability of χ^2 equal to .71 for systematic uncertainty of 5% indicate that data and MC agree well within 5% error. This explains the discrepancy between low probability of χ^2 and the close agreement shown in figure 1.

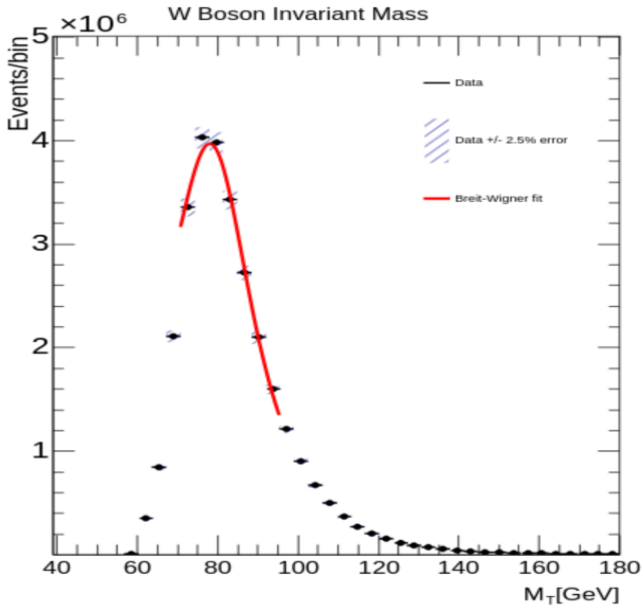

Figure 4: Breit-Wigner fit on data is shown in red. The hashed area shows +/-2.5% error imposed on data.

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--Breit-Wigner fit values--
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Data w/ sqrt(events) error:
chi^2:   10922.936824885599
NDF:   7
Prob.:   0.0
Mean: 7.80731e+01 +/-6.23726e-03
Width: 2.72396e+01 +/-2.26947e-02
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Data w/ 5% data error:
chi^2:   1.3954799637357402
NDF:   7
Prob.:   0.9857093065169165
Mean: 7.80352e+01 +/-5.86219e-01
Width: 2.77019e+01 +/-1.93213e+00
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Data w/ 2.5% data error:
chi^2:   5.581919850666322
NDF:   7
Prob.:   0.5893220585887826
Mean: 7.80352e+01 +/-2.93125e-01
Width: 2.77020e+01 +/-9.66131e-01
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Data w/ 1% data error:
chi^2:   34.88699953898714
NDF:   7
Prob.:   1.174479731403019e-05
Mean: 7.80353e+01 +/-1.17244e-01
Width: 2.77017e+01 +/-3.86434e-01
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Figure 5: Table of values for χ^2, probability of χ^2, mean and width for Breit-Wigner fit on data with error equal to square root of bin content, 5%, 2.5% and 1%.

χ^2 for the Breit-Wigner fit on data between 70.72 and 95.40GeV was 10922.94, with a probability equal to 0.0. This probability is low because a statistical uncertainty equal to square root of bin error was used. Here again it is necessary to consider systematic uncertainty for bins of magnitude 10^6.

Figure 5 shows a table for χ^2 and probability of χ^2 when systematic uncertainties of 5%, 2.5%, 1% are considered. For a systematic uncertainty of 5%, we found a χ^2 value of 1.40 with probability .99, for a systematic uncertainty of 2.5% we found a χ^2 value of 5.58 with probability .59, and for systematic uncertainty of 1% we found a χ^2 value of 34.89 with probability $1.2\text{x}10^{-5}$. These values indicate that the Breit-Wigner distribution fit on data agrees well within 2.5% error. Figure 4 shows the Breit-Wigner fit on data with systematic uncertainty of 2.5% superimposed on data, demonstrating that despite the low χ^2 probability value given above, the Breit-Wigner model is a good fit to our data.

Using the Breit-Wigner fit, values for the mean and width of peak were determined. We found a mean of 78.073±.006GeV, representing the W boson transverse mass, and width of 27.240±1.932GeV representing the decay width.

The currently accepted value for W boson mass, given by the Particle Data Group, is 80.379±0.012GeV.[3] Our value of 78.073±.006GeV is close, though slightly below the Particle Data Groups value because we calculated transverse mass while the Particle Data Groups value is the invariant mass. We calculate the transverse mass as the transverse momentum of the initial proton-proton particle system is known to be 0, while the momentum in the axis of the beam is unknown. However, the momentum in the axis of the beam is not always negligible, and our analysis does not account for that momentum. Thus, our value is less by an amount proportional to the W boson momentum in the axis of the beam.

The currently accepted value for W boson decay width, given by the Particle Data Group, is 2.085±0.042GeV.[3] Our value of 27.240±1.932GeV does not agree well with the Particle Data Group's value. There are several reasons for the discrepancy; One is imprecision of measurement instruments used in measuring the values of the muon and neutrino which contributes to widening the peak. Another reason is that occasionally a W boson emits a photon, lowering its energy, before it decays. Since we calculated the mass of the W boson based on its decay, we miss the energy which left in the emitted photon. This widens the peak for values below the W bosons mass. A third reason is that occasionally hadrons are produced along with the W boson in the proton collisions. For momentum to be conserved, W boson must have additional momentum in equal and opposite direction to the hadron. When the hadron has non-zero transverse momentum, our analysis measures an additional momentum contribution to the transverse mass from this source. This widens the peak for values above the W boson mass.

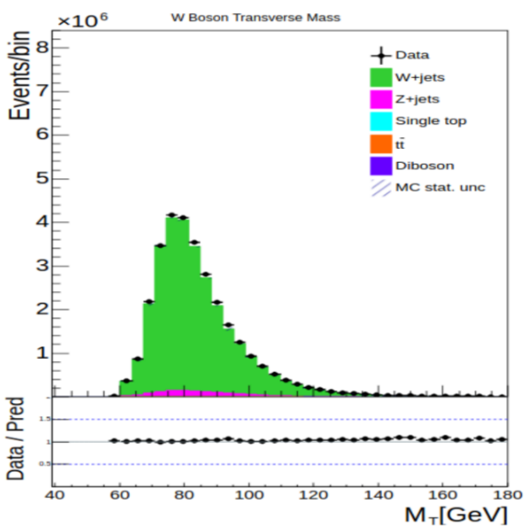

Figure 6: Transverse mass distribution for data vs MC in the W → μv decay channel, without lep_isTightID cut. In the top panel, the colored histogram represents the stacked MC prediction while black points show the data. The bottom panel displays the ratio between data and MC.

Figure 6 shows a reproduction of figure 2 without the lep_isTightID cut. This was done to determine if the lep_isTightID cut was necessary to include in our selection. Without the tight lepton ID cut, a total of 1.41×10^6 background events was found, giving a background to signal+background ratio of .047. This value is the same value found with the tight lepton ID cut. The reason for this is attributed to the tighter standard object criteria we used for the lepton. While table 3 in the Atlas Technical note defines the standard object selection criteria for leptons to be lep_petcone30<.15 and lep_etcone20<.15[7], we cut for these values <.1. Hence, we had already made tighter cuts on the leptons, which explains why ignoring the tight lepton ID criterion had little effect.

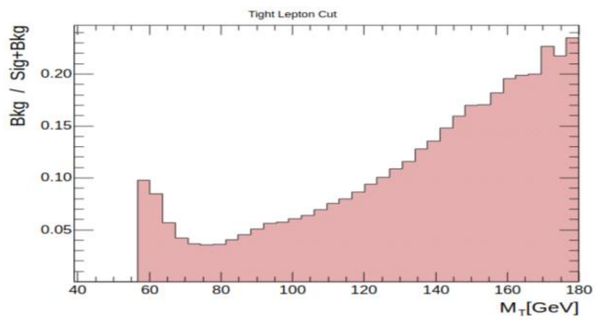

Figure 7: Ratio of background to signal + background for MC with lep_isTightID cut.

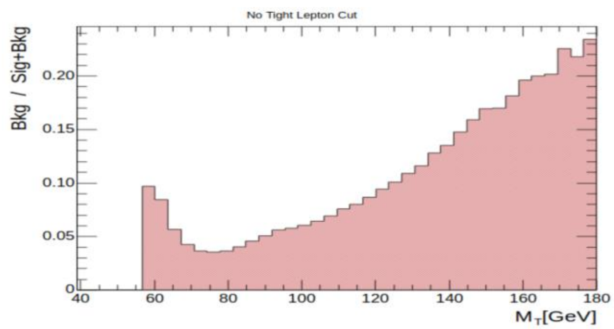

Figure 8: Ratio of background to signal + background without lep_isTightID cut.

Figures 7 and 8 show the bin ratios of background to signal + background for the MC histogram with the tight lepton ID cut and without, respectively. Signal is W+ jets in figures 2 and 6, and background is the sum of Z+ jets, single top, tt, and Diboson. Again, little difference is observed, attributed to the stricter standard object selection made on the leptons.

A low ratio in figures 7 and 8, <.05 near the W boson peak where most events were found, is observed. The ratio of background to signal + background both with and without tight lepton ID criterion found to be .047 indicates that >95% of events found with our selection were from W boson decays in the MC simulation. As the total number of events and distribution agreed well between data and MC, it is probable that >95% of the events found in are data also correspond to W boson decays.

Conclusion:

We demonstrated that the distribution of W boson transverse mass in data and MC prediction agreed within 5% error. We showed that the Breit-Wigner distribution is a good model for W boson decay within 2.5% error. Using the Breit-Wigner fit, we found a value for W boson transverse mass equal to 78.073±.006GeV, which is close to the currently accepted value of 80.379±0.012GeV, though less for reasons explained in the results section.[3] Thus, the validity of the SM in prediction of W boson decay is confirmed.

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