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Studies of muon efficiencies for measurement of $W$ charge asymmetry in inclusive $pp \rightarrow W (\mu\nu)$ production at $\sqrt{s}=7$ TeV

Hasan Ogul

University of Iowa

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STUDIES OF MUON EFFICIENCIES FOR MEASUREMENT OF W CHARGE

ASYMMETRY IN INCLUSIVE $pp \rightarrow W (\mu \nu)$ PRODUCTION AT $\sqrt{s} = 7$ TeV

by

Hasan Ogul

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Physics in the Graduate College of The University of Iowa

August 2013

Thesis Supervisor: Assoc. Prof. Jane Nachtman
This is to certify that the Master's thesis of

Hasan Ogul

has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Physics at the August 2013 graduation.

Thesis Committee:

Jane M. Nachtman, Thesis Supervisor

Yasar Onel

Edwin Norbeck
To my nephew, Emir, and family
Their endless love gave me forces to make this possible.
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Special thanks also to my graduate friends, especially group members of HEP: Emrah Tiras, Kamuran Dilsiz, Maksat Hytmyradov and James Wetzel.
A major motivation of the Compact Muon Solenoid (CMS) experiment is to explore and to discover the physics underlying electroweak symmetry breaking. Besides this, the CMS detector provides an opportunity to do various experiments for detecting new physics signatures beyond the Standard Model (SM). Investigation of these signatures requires the identification and precise energy and momentum measurement of electrons, muons, photons, and jets. The objective of this thesis is the calculation of the efficiencies for the measurement of the W charge asymmetry in inclusive $pp \rightarrow W(\mu\nu)$ production. The charge asymmetry is defined to be the difference between $W^+$ and $W^-$ bosons, normalized to the sum. This asymmetry is sensitive to the u-quark and d-quark ratios in the proton; precise measurement of the W charge asymmetry can provide new insights to the proton structure functions. Therefore, to improve understanding of SM backgrounds in the search for new physics, the muon trigger, isolation, reconstruction, and identification efficiencies have been studied using data collected by the CMS detector during pp collisions at the Large Hadron Collider (LHC) in 2011. The dataset corresponds to an integrated luminosity of 2.31 fb$^{-1}$. The efficiencies are measured as functions of the decay muon pseudorapidity and transverse momentum based on the “tag-and-probe” method. The efficiency measurements are compared to their estimated value from Monte Carlo simulations so as to provide scaling factors to correct for the residual mismodeling of the CMS muon performance. The comparison with simulations allows validation of the detector simulation and optimization of selection strategies.
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CHAPTER 1
INTRODUCTION

At the Large Hadron Collider (LHC), $W^+$ and $W^-$ bosons are produced mainly by the annihilation of $u$ or $d$ quarks from one proton with $\overline{d}$ or $\overline{u}$ quarks from another proton, as illustrated in figure 1.1. The difference between the quark distributions leads to the excess of $W^+$ over $W^-$. The $W$ charge asymmetry is defined to be the difference of $W^+$ and $W^-$, normalized by the sum as shown in eq. 1.1.

$$A_W(\eta) = \frac{d\sigma/d\eta(pp \rightarrow W^+) - d\sigma/d\eta(pp \rightarrow W^-)}{d\sigma/d\eta(pp \rightarrow W^+) + d\sigma/d\eta(pp \rightarrow W^-)}$$

(1.1)

The measurement of charge asymmetry provides constraints on parton functions. However, a measurement of the $W$ charge asymmetry requires knowledge of the proton structure and the physics process of $W$ production.

![Figure 1.1: $W^\pm$ decays resulting in muons and muon neutrinos.](image)

Current knowledge of the proton structure comes mainly from inelastic scattering experiments. In proton colliders, the use of protons pushes the physics studies into a difficult environment. All production cross sections for Standard Model (SM) and new physics alike depend on PDFs [1]. Therefore, an inaccurate PDF prediction could cause an erroneous result or a false claim of discovery.

The asymmetry depends on the cross section parameter as shown by eq. 1.1. By
using cross section information, the total number of W bosons observed in the CMS detector can be stated as the following:

\[ L \sigma (pp \rightarrow W^+) A^+ \epsilon^+ = N_{W^+} \]  
\[ L \sigma (pp \rightarrow W^-) A^- \epsilon^- = N_{W^-} \]

(1.2)  
(1.3)

where \( N_W \) is the total number of W produced, \( L \) is the integrated luminosity, \( \sigma \) is the cross section, \( A \) is the acceptance and \( \epsilon \) is the efficiency.

Furthermore, if equation 1.2 is divided by equation 1.3, \( L \) vanishes and it becomes

\[ \frac{\sigma (pp \rightarrow W^+) A^+ \epsilon^+}{\sigma (pp \rightarrow W^-) A^- \epsilon^-} = \frac{N_{W^+}}{N_{W^-}} \]

It is clearly seen that efficiency is crucial for determination of the W charge asymmetry.

Figure 1.2 shows the W rapidity distribution and corresponding lepton pseudorapidity distributions due to the V-A interaction in W production and decay. There is a larger lepton asymmetry in the central region and the asymmetry flips sign in the high pseudorapidity region. The lepton charge asymmetry has a strong dependence on the lepton acceptance, which is defined by the selection on \( p_T \) and the \( \eta \) coverage. In this measurement, the acceptance \((A^+/A^-)\) is defined with \( p_T > 25 \) and \(|\eta| < 2.4\).

Figure 1.3 shows CMS W and Z cross section results, measured using 2010 LHC data. They are in remarkable agreement. The inclusive charge ratio between \( W^+ \) and \( W^- \) has also been measured, which is also in good agreement with PDF predictions. By studying the charge asymmetry as a function of lepton rapidity, it enables us to study the u/d quark ratio directly in different ranges of the Bjorken scaling variable \( x \). [2]. Both CMS and ATLAS have measured the lepton charge asymmetry using 2010 LHC data. Updates with partial 2011 CMS data have been performed for both electron and muon.
data. Now, an update with full 2011 CMS data for the muon channel is under way.

**Figure 1.2:** W rapidity and lepton rapidity histogram.

**Figure 1.3:** Measurement of inclusive W and Z production cross sections times branching ratio as a function of center-of-mass energy for CMS and experiments at lower-energy colliders.

This thesis presents the efficiency measurements of muon triggering, isolation,
reconstruction and identification for the measurement of the W muon charge asymmetry. The measurements have been studied using data collected in pp collisions at the LHC in 2011. The data were recorded by the CMS detector and correspond to 2.31 fb$^{-1}$ of integrated luminosity. The Monte Carlo (MC) simulations are used to compare with data results. The efficiencies are investigated as a function of the decay muon pseudorapidity and transverse momentum based on the “tag and probe” method using $Z \rightarrow \mu^+\mu^-$ events. The azimuthal angle, $\phi$, is disregarded for the efficiency measurements due to the approximate azimuthal symmetry of the detector with respect to the beam axis [3]. It is expected that efficiencies do not significantly depend on the angle $\phi$.

The results presented are obtained with muons from $Z \rightarrow \mu^+\mu^-$ decays selected from the data described above. The selection provides an opportunity to study the complex experimental variables. The comparison with MC simulations allows validation of the detector simulation and optimization of selection strategies. Consequently, a clear understanding of the backgrounds, both in terms of the overall normalization and the relative shapes is another important step towards accurate measurements [4,14]. In addition to the $Z \rightarrow \mu^+\mu^-$ decay, it is necessary to account for background contributions from other physics processes, such as $t\bar{t}$, $Z \rightarrow \tau^+\tau^-$, and $W$+jets decay. The $\mu^+$ and $\mu^-$ efficiencies are determined separately to check for any charge-dependent asymmetry.

This thesis is organized as follows. In chapter 2, the CMS detector is described, with details of the muon and tracker subsystems. In addition to detector information, muon reconstruction and identification methods are presented in chapter 3. The algorithms used for the efficiency measurements are presented with exact details in
section 3.2. Chapter 4 includes the measurements of efficiencies after an introduction of
the Tag-and-Probe technique. Chapter 4 also covers the comparison of the Monte Carlo
and data distributions. Finally, in chapter 5, scale factors from efficiency tables, pile-up
reweighting techniques, and MC reweighting methods are discussed and different
scenarios are handled. In chapter 6, a summary of this study is presented and conclusions
are drawn.
CHAPTER 2

THE CMS DETECTOR AT THE LHC

A major motivation of the Large Hadron Collider (LHC) experiment is to explore and to discover the physics underlying electroweak asymmetry breaking. In addition, the LHC provides an opportunity to do various experiments for detecting new physics signatures at high luminosities. Six experiments at LHC use different detectors to analyze the particles produced by proton-proton collisions [13]. Each experiment has a distinctive detector characterized for its specific goals. The biggest four experiments among them are the Compact Muon Solenoid (CMS), ATLAS, LHCb and ALICE experiments.

The overall dimensions of the CMS detector are a length of 21.6 m, a diameter of 14.6 m and a total weight 14 500 tons [5]. A 5.4 m long, 1.1 m radius central tracker takes the innermost section. The detector is designed like a cylindrical onion; different layers of detectors measure the different particles, and use this key data to build up a picture of events at the heart of the collision [6]. Investigation of these particles’ signatures in the detector offers the identification and precise energy measurement of muons, photons, jets, and electrons.

A key part of the CMS detector is a huge solenoid magnet, which acts to bend the paths of charged particles from collisions in the LHC. Beside the huge solenoid magnet, CMS has distinct subdetectors such as the tracker detector, electromagnetic calorimeter, hadron calorimeter and muon detectors. The inner silicon tracking detector and the calorimeter detectors are all immersed in a 3.8 tesla magnetic field. These sub-detectors measure different properties of particles in order to determine their energy and momentum. For this thesis, it is important that the CMS detector has a high performance
system for detecting and measuring muons.

Figure 2.1: An exploded view of the CMS detector

A coordinate system of CMS is defined such that collision point is the origin. The x-axis is horizontal pointing to the LHC center, the y-axis is vertically pointing upward and the z-axis horizontally to the west. The pseudorapidity $\eta$ is used as a variable to define the direction of emerging tracks. It is defined so that both the z-axis and pseudo rapidity have the same sign. Furthermore, this variable, $\eta$, is also used to describe the angular region covered by sub-detector. As an example, muons are measured in the range $|\eta| < 2.4$.

The most relevant sub-systems for muon efficiency measurements are the tracking and muon systems. Their definitions and descriptions are presented by providing more
information about them in following sections.

2.1 Tracker Detector

The CMS Silicon Strip Detector is a large tracker with total 5.4 m length and 1.1 m outer radius. The tracking system is composed of two parts: pixel detector and silicon strip tracker. The pixel detector contains 66 million pixels which are able to track the paths of particle emerging from the collisions with extreme accuracy, and silicon strip trackers are able to receive many particles in a tiny space due to their fast response and good spatial resolution [7]. The pixels are located at the very core of the detector and deal with the highest intensity of particles since it receives the highest volume of particles due to being the innermost layer of the detector. Both the pixel sensor and readout electronics are required to be radiation hard.

![Figure 2.2: CMS Tracker showing silicon strips detectors in the barrel module.](image)

In essence, the tracker is crucial to measure charged particle trajectories with high
efficiency. Particle trajectories need to be recorded accurately yet the detector must be lightweight so as to disturb the particle as little as possible by interactions of the particle with the detector material. The prime goal of the tracker system for muons is to reconstruct the high $p_T$ muons with high momentum resolution and with an efficiency of better than 98% over the rapidity range $|\eta| < 2.5$, and to identify the tracks coming from detached vertices which arise from long-lived particles produced in the LHC collisions [8].

2.2 Muon system

As seen in the name of “Compact Muon Solenoid” detector, one of the important tasks for the CMS experiment is the detection of muons. Muons are charged particles like electrons; the only difference between electrons and muons is their mass. It is crucial for CMS to reconstruct muons and measure their momenta with high accuracy. The muon system is designed to allow for the identification of muons and the measurement of their transverse momenta to be used just in the Level-1 trigger system.

![Figure 2.3: Muon System.](image)
The muon detector is the outermost layer of the CMS detector. In total the muon system has 1400 muon chambers: 250 drift tubes (DTs) and 540 cathode strip chambers (CSCs) are instrumented in the barrel and endcap to track the particles’ positions and provide trigger information; 610 resistive plate chambers (RPCs) form a redundant trigger system, which quickly decides to keep the acquired muon data or not [9].

Figure 2.3 shows a transverse view of the CMS detector, where four stations of muon barrel chambers are instrumented. Due to the many layers of detector and different characteristics of each type, the muon system is able to minimize the misidentification of particles [5]. Furthermore, the first trigger level of CMS is referred to as the Level-1 trigger, and it is hardware implemented. All further levels are software filters which are executed on (partial) event data. The High-Level Trigger (HLT) is the upper level of real-time data selection. Only data accepted by the HLT are recorded for offline physics analysis.
CHAPTER 3
MUON RECONSTRUCTION AND IDENTIFICATION

3.1 Muon Reconstruction

Muon reconstruction in CMS works with two different approaches: the first is from the outside-in. It starts in the muon system to reconstruct muon tracks using the hits and track segments inside muon chambers, and then the muon candidates are linked to the inner tracks from the silicon tracking system [3]. A global muon track is fitted combining hits from the tracker track and standalone-muon track to reduce the fake rate (the fraction of non-muon particles reconstructed as muons) and improve resolution of muon transverse moment. At low $p_T$, the resolution is dominated by the tracking system; at high $p_T$ the muon system plays the leading role. The muons reconstructed in this algorithm are termed as “Global Muons”.

Another approach is the inside-out. In this method, all tracker tracks with $p_T > 0.5$ GeV/c and total momentum $p > 2.5$ GeV/c are considered as potential muon candidates and are extrapolated to the muon system taking into account the magnetic field, the average expected energy losses, and multiple Coulomb scattering in the detector material [10]. The definition and selection of the approaches have strong impacts on the reconstruction efficiency, fake rate, and CPU reconstruction time. The muons reconstructed in this way are “Tracker Muons”. The muons used in the charge asymmetry analyses are required to be identified as “Global Muons” and “Tracker Muons”.

3.2 Muon Identification

To have more efficient muon reconstruction, combinations of different algorithms
are used. Physics analyses can set the desired balance between reconstruction efficiency and purity by applying a selection based on various muon identification variables. In this thesis, the “Tight Muon selection” is used.

- **Tight Muon selection**: The candidate muon is reconstructed as a Global Muon by using the global muon reconstruction approach with the global muon track fit $\chi^2$ less than 10. In addition, its corresponding tracker track must be matched to muon segments in at least two muon stations. That means the muon is also reconstructed as a Tracker Muon by using the tracker muon reconstruction approach. The stations use 10 inner-tracker hits and have a transverse impact parameter $|d_{xy}| < 0.2$ cm with respect to the primary vertex.

By using this selection, the rate of muons from decays in flight is considerably reduced.

### 3.3 Muon Isolation

Muons originating from W/Z/t\bar{t} processes tend to be isolated, with no strong hadronic activity in the neighboring area. This is different than for muons originating from semi-leptonic, b, or light quark in the QCD processes, which are accompanied by charged and neutral particles. These accompanying particles can be recorded by the tracking system or calorimeters. One useful variable can be used to separate muons from these processes is the isolation, which is defined to be the scalar sum of $p_T$ of tracks or $E_T$ of energy deposits in the calorimeters in a cone along the muon direction. For the W charge asymmetry analysis a track-based isolation with a cone radius of 0.3 in $\eta$ and $\phi$ is used.
CHAPTER 4

MUON EFFICIENCY

Chapter 2 gives a short overview of the muon system of the CMS detector. As motivated in the first chapter, it is important to know the probabilities that a muon generated in the detector leads to a desired candidate for the charge asymmetry analysis. In this chapter the muon trigger, isolation, reconstruction, and identification are considered. In general the efficiency ($\varepsilon$) is the probability of an event passing a given selection criteria. Efficiency can be studied using a sample of total number of events, N. It can be expressed by using number of events passing ($N_{\text{pass}}$) and failing ($N_{\text{fail}}$) the given criteria.

$$\varepsilon = \frac{N_{\text{pass}}}{N_{\text{pass}} + N_{\text{fail}}}$$

For the W charge asymmetry analysis, the muons, after ID and isolation selections, are sorted by $p_T$. The leading one is treated as the muon from the $W (\mu\nu)$ decay. The leading muon is further required to be matched to a trigger object by requiring $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between the muon and the trigger object to be less than 0.1. The trigger used in data taking is a combination of “HLT_IsoMu15*” and "HLT_IsoMu24*". Events passing these High Level Triggers first pass the Level 1 prerequisites, and are identified as isolated muons by the HLT algorithms. The numbers in the nametags, 15 and 24, indicate the minimum $p_T$ values. The $p_T$ threshold for the leading muon is $p_T > 25$ GeV. The event which has a second muon passing ID, isolation and with $p_T > 15$ GeV is rejected to suppress Drell-Yan background. For muon efficiency, the formula may be decomposed as
\[ \varepsilon_\mu = \varepsilon_{\text{tracking}} \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{ID}} \cdot \varepsilon_{\text{iso}} \cdot \varepsilon_{\text{trig}} \]

where \( \varepsilon_{\text{tracking}} \) is the tracking efficiency, \( \varepsilon_{\text{reco}} \) is the reconstruction efficiency, \( \varepsilon_{\text{iso}} \) the probability that a reconstructed muon is isolated, \( \varepsilon_{\text{trig}} \) the probability that a reconstructed and isolated muon is triggered according to a given \( p_T \)-threshold, and \( \varepsilon_{\text{ID}} \) is the identification efficiency.

In this thesis, all the efficiencies are presented except muon tracking efficiency. Because the tracking efficiency is close to one [15], it is disregarded in this study. As mentioned in chapter 1, the efficiencies are divided into two categories for the total efficiency measurement: offline efficiency and trigger efficiency. In this study, offline efficiency is given by

\[ \varepsilon_{\text{offline}} = \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{ID}} \cdot \varepsilon_{\text{iso}} \]

Trigger efficiency stands alone, and a different selection rule is applied for it. The basic difference for these two groups is that the muon \( p_T \) cut is 25 GeV for the trigger while the minimum \( p_T \) cut for the offline efficiency is 15 GeV. However, the cuts and selections for offline efficiency measurement are also applied for the trigger selections. The selections for identification and reconstruction efficiency measurements are explicitly presented in chapter 3. As mentioned previously, the data sample used here has been collected using a combination of single muon triggers with different muon \( p_T \) thresholds of 15 GeV and 24 GeV. As described below, in the \( Z \rightarrow \mu\mu \) events, one muon has been explicitly matched to a trigger candidate to remove trigger bias and another muon has been used to study individual efficiencies.

In addition to the selection rules, it is necessary to consider where the muons pass
through detector because the detector is not homogeneous. As stated in chapter 2, a coordinate system of CMS is defined: $p_T$, $\eta$ and $\phi$ are used as the parameters of the coordinate system. Therefore, efficiencies depend on these variables. Since the detector has azimuthal symmetry with respect to the beam axis, the azimuthal angle, $\phi$, does not significantly contribute to the efficiency measurement processes. Therefore, efficiencies are not investigated as a function of the decay muon azimuthal angle.

In this work, $Z \rightarrow \mu^+\mu^-$ decays are studied to find the muon efficiencies. As seen, the decay results are $\mu^+$ and $\mu^-$. There are two different charges, and we are able to measure their efficiencies separately by using the Tag-and-Probe method.

**Figure 4.1:** Offline efficiency vs. $p_T$ (right) and $\eta$ (left) based on MC information, for negatively charged muons (top) and positively charged muons (bottom).

Table 4.1: The $p_T$ and $\eta$ bins used

<table>
<thead>
<tr>
<th>$p_T$ bin values</th>
<th>15-20</th>
<th>20-25</th>
<th>25-30</th>
<th>30-35</th>
<th>35-40</th>
<th>40-45</th>
<th>45-1000</th>
</tr>
</thead>
</table>

| Eta bin values for trigger and offline efficiencies | +/− 2.4 | +/− 2.3 | +/− 2.1 | +/− 2.0 | +/− 1.9 | +/− 1.8 | +/− 1.7 | +/− 1.6 | +/− 1.5 | +/− 1.4 | +/− 1.3 | +/− 1.2 | +/− 1.1 |
|------------------|-------|-------|-------|-------|-------|-------|---------|-------|-------|-------|-------|-------|-------|-------|

4.1 Tag-and-Probe Method

The previous section provides a general idea of the main properties of efficiencies and some plots from Monte Carlo simulations. However, it is also necessary to determine efficiencies from collision data. The Tag-and-Probe method allows for the determination of efficiencies from collision data [11]. Efficiency is already defined as the ratio of some subset of muons under study to the number of produced muons. The number of produced muons can be obtained considering specific particle decay into two muons, such as the $Z \rightarrow \mu \mu$ sample. Table 4.1 presents the $p_T$ and $\eta$ bins used in this technique. Basically, the tag and probe method is described in [10]

- muons are formed in pairs as a candidate $Z \rightarrow \mu \mu$ event with one passing a tight identification (tag) and one passing loose identification (probe)
- probes which pass the selection criteria are defined according to whatever is the efficiency to measure
- the (tag + passing probe) and (tag + failing probe) lineshapes are fit separately with a signal + background model.
Figure 4.2: Example fits to $\eta$ and two different $p_T$ bins: the top row is for passing muons and the bottom histograms are for failing muons.

- the efficiency is measured from the ratio of the signal yields in the two lineshapes above
- the procedure is repeated in bins of the probe variables to compute efficiency
histograms as a function of those variables ($p_T$ and $\eta$).

The minimal $p_T$ requirement, fixing the charge of the tag muon and the choice of the leading muon of the predefined charge are other issues for the tag selection in an event. To ensure the accuracy of the study, it is crucial not to disregard these requirements.

4.2 Definition of Tag and Probes

The muon efficiencies were studied in the data directly using the $Z \rightarrow \mu\mu\mu\mu$ samples. We used the CMS Standard Tag-and-Probe (T&P) for this study.

The selection criteria for a Tag muon is as follows,

- While calculating the $\mu^-$ efficiency, the $\mu^+$ is chosen as the Tag muon. Similarly, while measuring the $\mu^+$ efficiency, the $\mu^-$ is chosen as the Tag muon,
- reconstructed as both “GlobalMuon” and “TrackerMuon”,
- normalized global track fitting $\chi^2 < 10$,
- number of valid silicon track layers $> 8$,
- number of valid pixel track hits $> 0$,
- track $d_{xy} < 0.2$ cm (with respect to the beam spot),
- track $d_z < 30$ cm,
- track $p_T > 25$ GeV,
- muon $|\eta| < 2.4$,
- track isolation, $\frac{\text{Iso}_{\text{track}}}{p_T} < 0.10$,
- number of chambers with matched segments $> 1$,
- matched to one of the HLT objects depending on the run ranges; $\Delta R < 0.1$,
\Delta R(\mu, \text{HLT object}) = \sqrt{\Delta \eta^2 + \Delta \phi^2},

To study the reconstruction, a silicon track candidate with the following selection criteria is used to determine if the probe falls in the pass or fail category,

- maximum $\Delta R < 1$,
- maximum $\Delta \eta < 0.2$,
- maximum $\Delta p_T^{\text{rel}} < 3$,

A global muon has been used as a probe to study the ID efficiency. The following criteria are used to determine if the probe passes or fails the ID requirement.

- reconstructed as both “GlobalMuon” and “TrackerMuon”,
- normalized global track fitting chisquared $< 10$,
- number of valid silicon track layers $> 8$,
- number of valid pixel track hits $> 0$,
- track $|d_{xy}| < 0.2$ cm (with respect to the beam spot),
- track $d_z < 30$ cm,
- track $p_T > 15$ GeV,
- muon $|\eta| < 2.4$

A global muon which also passes the above ID criteria is used as a probe to study isolation efficiency. An isolated, well-identified muon is then used as the probe for the trigger study. In the following sections the efficiency measurements are presented by using the Tag-and-Probe method and compared to the predictions from the simulations. The efficiencies are shown separately for the positive and negative muons.
4.3 Reconstruction Efficiency Measurement

The main goal of the muon reconstruction is to distinguish muons and measure their properties with high precision, particularly their position and momentum, for a wide range of momenta from a few GeV to a TeV [4]. As stated in chapter 2, there are two reconstruction approaches that are often used. These are global muon reconstruction and tracker muon reconstruction.

Figure 4.3: MC vs. Data: Reconstruction efficiency of negatively charged muons for \(30 < p_T < 35\).

Figure 4.3 show efficiency decreasing around absolute value of pseudorapidity 0.3. The efficiency drops around these region is due to the structure of the muon detector.
Figure 4.4: Reconstruction efficiency of negatively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
Figure 4.5: Reconstruction efficiency of positively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
4.4 Identification Efficiency Measurement

Muon identification was discussed in chapter 3. In this section, more description will be presented about what we used for this study. The requirement to select a good muon candidate is as follows:

- muons were identified as both a “GlobalMuon” and a “TrackerMuon” candidate,
- normalized global track fitting chisquared < 10,
- at least 11 valid silicon hits,
- at least 1 valid pixel hit,
- at least 2 number of muon chamber matches,
- absolute value of pseudorapidity less than 2.4.

Figure 4.6 presents the identification efficiency of negatively charged muons. At low and high pseudorapidity, the efficiency drops are due to the geometry of the detector.

![Figure 4.6: MC vs. Data: Identification efficiency of negatively charged muons, for 30 < p_T <35.](image)
Figure 4.7: Identification efficiency of negatively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
Figure 4.8: Identification efficiency of positively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
4.5 Isolation Efficiency Measurement

A muon is considered isolated if the energy flow in its vicinity is below a certain threshold. This requirement can effectively discriminate muons from the decay of $Z$ bosons from those produced by heavy-flavor decays or hadron decays in flight [10]. Various isolation algorithms are used in CMS analysis. For this study, tracker relative isolation ($I_{\text{rel}}^{\text{trk}}$) is used. This calculates the scalar sum of the $p_T$ of all tracker tracks reconstructed in a cone of radius $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$ centered on the muon track direction. The $p_T$ of the track itself is not included in the sum. For the muon to be considered isolated, the ratio of the $p_T$ sum to the muon track $p_T$ is required to be below a certain threshold, which is 0.1 for this study. Track directions and values of $p_T$ are computed at the point of closet approach to the nominal center of the detector. Figures 4.9, 4.10 and 4.11 show that MC and data sample are in good agreement.

**Figure 4.9:** MC vs. Data: Isolation efficiency of negatively charged muons for $30 < p_T < 35$. 
Figure 4.10: Isolation efficiency of negatively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
Figure 4.11: Isolation efficiency of positively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
4.6 Trigger Efficiency Measurement

To evaluate the trigger efficiency for this study, there is a requirement that the muons must pass the offline efficiency requirements as well. That means if the muon passes the desired criteria for isolation, reconstruction and identification, then the trigger efficiency is calculable for the muon. Trigger efficiencies for tight muons were measured by applying the Tag-and-Probe method to $Z \rightarrow \mu^+\mu^-$ events in the region of $p_T$ above 25 GeV/c.

![Figure 4.12: MC vs. Data: Trigger Efficiency for 15 < $p_T$ < 20.](image)

The single muon trigger is used in this study. Muon candidates are reconstructed at the trigger level by using information from the muon detectors and the inner tracker. Events containing a muon candidate with online-reconstructed transverse momentum $p_T$ greater than the predefined threshold are recorded. All muon triggers cover the full muon detector acceptance corresponding to $|\eta| < 2.4$. To compare the results obtained from data to predictions, Monte Carlo samples are used. However, the $p_T$ threshold is 15 GeV/c for MC samples. Figure 4.12 shows that there is no signal from data due to the $p_T$
cut, applied to data but not to Monte Carlo. The efficiencies are calculated and presented for both charges in figures 4.13 and 4.14. We have irregularities in the trigger efficiencies since the detector has an inhomogeneous structure.

**Figure 4.13:** Trigger efficiency of negatively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
Figure 4.14: Trigger efficiency of positively charged muons as functions of $p_T$ (left column) and eta (right column), for three $p_T$ and eta ranges.
4.7 Total Muon efficiency Measurement

As defined at the beginning of the chapter three, total efficiency is given by the combination of all of the efficiencies. By mathematical formula it is:

\[ \varepsilon_\mu = \varepsilon_{\text{tracking}} \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{ID}} \cdot \varepsilon_{\text{iso}} \cdot \varepsilon_{\text{trig}} \]

However, in this thesis, it is accepted that tracking efficiency is one, and tracking efficiency is disregarded at this point. The remaining equation is:

\[ \varepsilon_\mu = \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{ID}} \cdot \varepsilon_{\text{iso}} \cdot \varepsilon_{\text{trig}} \]

All the cuts and selections applied to each component bring together the total efficiency of the muon. As done in previous sections, the total efficiency is measured for the products of Z decay, \( \mu^+ \) and \( \mu^- \), as functions of pseudorapidity and transverse momentum, as shown in figure 4.15, 4.16 and 4.17.

Figure 4.15: Two-dimensional total efficiency of positively charged muons.
Figure 4.16: Total efficiency of negatively charged muons as functions of $p_T$ (left) and eta (right), for three $p_T$ and eta ranges.
Figure 4.17: Total efficiency of positively charged muons as functions of $p_T$ (left) and eta (right), for three $p_T$ and eta ranges.
4.8 Discussion

All efficiencies are presented as function of transverse momentum and pseudorapidity. Seven bins used for $p_T$ are from 15 GeV/c to 1000 GeV/c, and forty-six bins used for $\eta$ are from -2.4 to 2.4. The bins for pseudorapidity and transverse momentum are explicitly presented in table 4.1. Figure 4.3, 4.6 and 4.9 show that reconstruction, identification and isolation efficiencies based on MC are well matched with the efficiencies of data samples. Furthermore, these efficiencies, especially isolation efficiency, are almost 99%. If we look at the left columns of figure 4.13 and 4.14, the trigger efficiency drop around 0.3 is due to the gaps between muon wheels; and the drop of efficiency at high $|\eta|$ is mainly due to the tighter isolation cut [5]. Furthermore, if we look at the right columns of the figure 4.13 and 4.14, we see the efficiency drop with data sample for low $p_T$ values because the HLT_IsoMu24 particle is used. Therefore, there is a difference between MC and data efficiencies. The efficiencies are measured for both muon charges. It is seen that the efficiencies for the two charges are similar but not identical. The reason is that the $W^+$ decays to a left-handed neutrino and right-handed positive lepton, which is thus boosted back towards midrapidity, while the $W^-$ decays to a left-handed negative lepton which is boosted towards higher rapidity [16]. That creates a difference in positive and negative leptons as a function of lepton pseudorapidity.
CHAPTER 5
APPLICATIONS

5.1 Dimuon studies

The efficiency tables are calculated by applying the Tag-and-Probe technique to muons from Z decays. Events are selected with certain requirements on one muon (tag) and the other muon (probe). By using efficiency tables for the muons, the number of events vs. dimuon $p_T$ and the number of events vs. dimuon $\eta$ histograms are found. The dimuon mass range is chosen to be from 60 GeV/c$^2$ and 120 GeV/c$^2$. It is seen explicitly on figure 5.1. As a background comparison to the $Z \rightarrow \mu^{+}\mu^{-}$ results, $t\bar{t}$, $Z \rightarrow \tau^{+}\tau^{-}$, $W$ jets decay are calculated. Then, MC and data results are compared with each other.

Figure 5.1: Dimuon mass histogram based on MC and data (Zmumu) samples.

Figure 5.1 does not show any background signal due to the mass cut used. That is
why a mass cut is crucial to reduce the background impact on the physics studies. Although the same log scale is used for figure 5.1, 5.2 and 5.3, the background impact is seen only on figure 5.2 because the background is concentrated at low \( p_T \). For other figures, the impact of background is not visible because it is uniformly distributed in dimuon mass and \( \eta \).

**Figure 5.2:** Dimuon: number of events vs. transverse momentum.

**Figure 5.3:** Dimuon: number of events vs. rapidity.
Figure 5.2 presents the relation between the number of events and dimuon transverse momentum. MC and data samples seem well matched except in the high $p_T$ range. Otherwise, the ratio looks flat. Figure 5.3 presents the relation between number of events and dimuon rapidity. MC and data samples are in reasonably good agreement.

5.2 Monte Carlo Reweighting

The goal of the Monte Carlo reweighting is to transform the Monte-Carlo distribution into the same shape as the data-derived distribution. To reweight the Monte-Carlo sample, scale factor and pile up reweighting techniques are used in this study. The scale factor comes from the ratio of data efficiency to MC efficiency. This ratio provides a weight factor to apply to MC samples. The weight factor is important when filling the histograms. Its value is determined by the scale factor. By applying this to MC, we should see better agreement between MC and data samples.

Pile-up reweighting is necessary for physics analyses, since Monte Carlo samples are generated only with a best guess estimation of pile-up before data is taken. This tool reweights the events so that they match the pile-up measured during data-taking by multiplying the event weight with an appropriate correction factor.

For this section, three scenarios are used.

Scenario 1:

- set weight to 1,
- no scaling factor from efficiency tables,
- no pile up reweighting to MC
- Then, MC and Data histograms are compared

Scenario 2:
• no scaling factor from the efficiency tables: we set weight = 1 for this scenario while filling histograms.

• apply pile up reweighting to MC with new weight formula:
  
  Weight = weight * pileup_weight

• To fill histograms use new weight factor.

• Then, MC and Data histograms are compared.

Scenario 3:

• apply scaling factor from efficiency tables:
  
  weight = (scale_tag_tot) * (scale_tag_trg) * (scale_probe_tot)

• apply pile up reweighting to MC,
  
  Weight = weight * pileup_weight

• To fill histograms use the new weight factor.

• Then, MC and Data histograms are compared to see the agreement

For all the scenarios, while calculating the scale weight, scale factors from the tag muon total efficiency, tag muon trigger efficiency and probe muon total efficiency are used. As seen, the scale factor from the probe muon trigger efficiency is disregarded, since there is no selection for the probe muon in the trigger. For example, both tag and probe muons pass the ID and isolation selections; however, the tag muon has to pass the single muon trigger although there is no selection for the probe muon in the trigger. Figure 5.4, 5.5, 5.6, 5.7, 5.8 and 5.9 present the result of these scenarios. The ratio presented on the figures is given by the fraction of Data/MC.
**Figure 5.4**: Scenario 1: Tag Muon histograms (Number of events vs. $p_T$, eta and phi)
Figure 5.5: Scenario 1: Probe Muon histograms (Number of events vs. $p_T$, eta and phi)
Figure 5.6: Scenario 2: Tag Muon histograms (Number of events vs. $p_T$, eta and phi)
Figure 5.7: Scenario 2: Probe Muon histograms (Number of events vs. $p_T$, eta and phi)
Figure 5.8: Scenario 3: Tag Muon histograms (Number of events vs. $p_T$, eta and phi)
Figure 5.9: Scenario 3: Probe Muon histograms (Number of events vs. $p_T$, eta and phi)
5.3 Discussion

To see the difference between different reweighting methods and their effects, three scenarios are chosen. All three scenarios are applied, and it is concluded that scenario 3 is the best one by looking at the histograms of all three scenarios applied. The disagreement between MC and data samples for scenario 3 is about 4% while it is about 8% for scenario 2, and the disagreement for scenario 1 is about 10%. The best agreement between MC and data is supplied by applying both scale factors and pile up reweighting to the MC samples.
CHAPTER 6
SUMMARY

The aim of this thesis was to study muon reconstruction, identification, isolation, and trigger efficiencies for the measurement of the W charge asymmetry in inclusive $pp \rightarrow W(\mu\nu)$ production. Data collected by the CMS detector during pp collisions at the LHC in 2011 are used. The dataset corresponds to an integrated luminosity of $2.31 fb^{-1}$. The efficiencies are measured as functions of the decay muon pseudorapidity and transverse momentum based on the “Tag-and-Probe” method. The efficiency measurements are compared to their estimated value from Monte Carlo simulations so as to provide scaling factors to correct for the residual mismodeling of the CMS muon reconstruction. The decay muons of Z resonances, $\mu^+$ and $\mu^-$, are used to find the efficiencies for each charge independently.

In the application section, MC reweighting studies are discussed. To reweight the Monte-Carlo sample, scale factors and pile up reweighting techniques are used in this study with different scenarios. Thanks to scenario 3, MC distributions take a similar shape as the data-derived distributions. The agreement between data and MC is remarkable. In these scenarios, scaling factors defined as data over MC efficiency ratios are provided to correct mismodeling of the CMS detector performance.
REFERENCES


