Measurement of the Z Boson with CMS Data

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Abstract

In this report, the quality of the alignment of the inner tracking detector of the CMS experiment is examined. The clean reconstruction of the Z-boson decaying into two muons was used to measure the deviation between the known Z-mass and the reconstructed Z-mass in terms of the rapidity and the azimuthal angle. The result deviates from the expected flat distribution and disagreement between the data and the Monte Carlo simulations were found.

Contents

1 Introduction

The Large Hadron Collider (LHC) at CERN is the world's largest particle accelerator at the moment. The machine together with its four experiments will allow probing the standard model and look for physics beyond the standard model at unprecedented energies. Two bunches of protons collide with a center-of-mass energy of 7 TeV up to every 25 ns. The outcome of the interactions of the protons and their constituents is captured by the detectors and then analyzed for traces of e.g. the Higgs boson, supersymmety, and so on. A precise understanding of the detector and the quality of the measurements is crucial in order to properly evaluate the recorded data.

This report focuses on the well understood standard model physics of the Z boson. Its decay into two muons provides a very clean signature and allows for a precise reconstruction. Because the Z boson is already well analysed and its properties are precisely measured, the reconstructed muon tracks can be used to study the quality of the tracker alignment. Furthermore, the two muons will also be used to determine the efficiency of the high level trigger using the tag-and-probe method.

2 The CMS Detector

The analysis was done using data from the Compact Muon Solenoid detector (CMS, depicted in figure 1). CMS is built as a traditional 4π symmetric multipurpose detector and it is designed for top, Higgs and sypersymmetric physics. The detector consists of several layers: The tracking detector is situated closest to the beam pipe and is a semiconductor detector with three barrel layers of pixel detectors, which are followed by

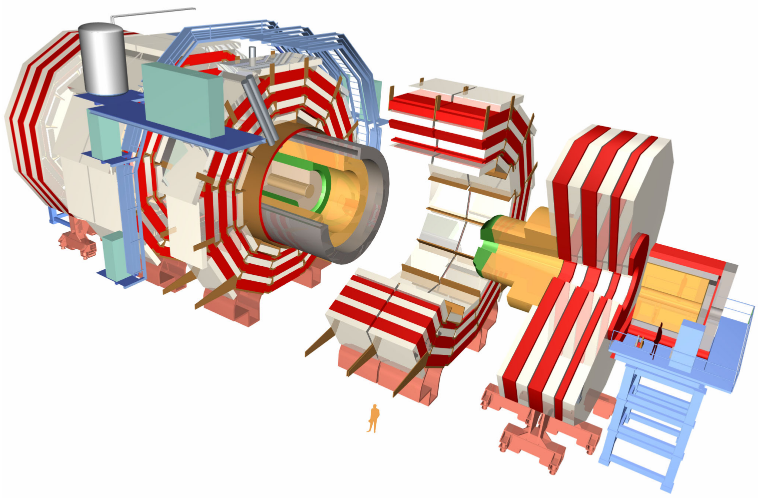

Figure 1: Schematic drawing of the CMS detector [6]. It measures 21 m in length and approximately 10 m in diameter, while weighing 12,500 t. In the foreground the barrel muon chambers and the endcap calorimeters and muon chambers are shown separated from the detector.

ten barrel layers of silicon strip detectors. By measuring the ionization, which is created by charged particles flying through the detector, the tracks and possible secondary decay vertices of the particles can be reconstructed.

After passing the tracker, particles enter the calorimeters. First, there is the electromagnetic calorimeter (ECAL) consisting of lead-tungstate crystals, where leptons and photons ideally deposit all their energy. The scintillation light created by the crystals is subsequently read out by avalanche photodiodes.

The ECAL is followed by the hadronic calorimeter (HCAL), which measures the energy deposited by hadrons. It is build of interleaving copper and scintillator layers and has a depth of almost 11 hadronic interaction lengths.

The tracker and the calorimeters are surrounded by the magnet, which creates a magnetic field with a strength of 4 T. It is followed by additional layers of the hadronic calorimeter, which try to catch all particle showers and prevent leakage into the muon system.

The muon system consists of four layers of drift chambers in the barrel region and cathode strip chambers in the endcap regions. The four layers are interleaved with the return yoke of the magnet. Muons passing through the drift tubes ionize the embedded gas and the generated charges travel to the anode wire and cathode tube, where the resulting voltage is measured.

At design performance, the LHC will collide bunches of protons every 25 ns. In order to process the large amount of data originating from the 40 million collisions per second, CMS possesses a powerful trigger system. A first selection of events is done by the so called “Level-1-Trigger”, which is implemented in hardware and reduces the event rate to 100 kHz, which are then passed to the “High Level Trigger” (HLT). This large computer farm can have a more detailed look at the events and make sophisticated selection choices. It categorizes the events and provides several output streams of events. About 100 events per second are then written to the storage system.

3 Analysis

The analysis was performed in three steps. First, the Monte-Carlo simulations had to be reweighted, in order to match the data. This step was followed by the Z reconstruction and the examination of the Z mass’s angular dependance. Finally, the results of the Z reconstruction were also used to look at the efficiency of a High Level Trigger, namely the ”IsoMu17” trigger, which was used to select events containing Z boson candidates.

3.1 Monte-Carlo Reweighting

The instantaneous luminosity provided by the LHC continuously increases and so does the pileup. Pileup is a phenomenon, where more than two protons of the colliding bunches interact with each other. This leads to more than one primary vertex in the event and it has to be considered especially when comparing Monte Carlo simulations to the real data.

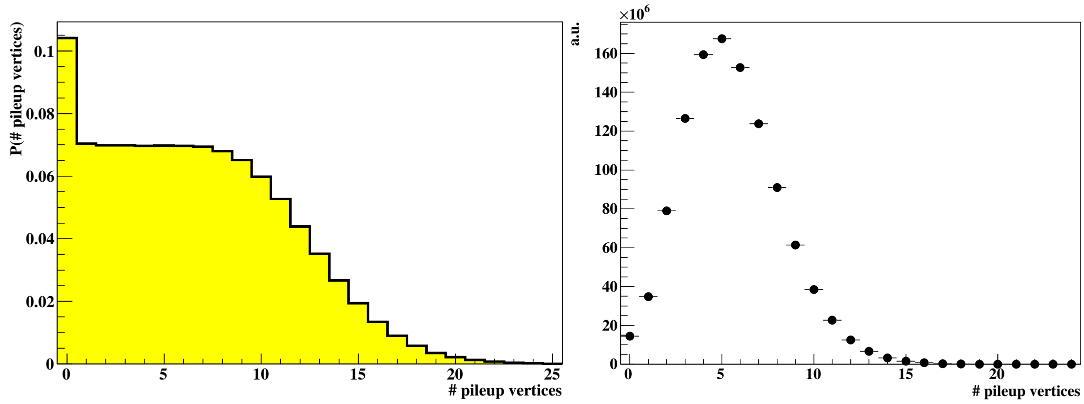

Figure 2: Left: Distribution of pileup vertices used to generate the Monte-Carlo samples. Right: Pileup distribution determined from the 2011 EPS data set. The goal of reweighting is to transform the Monte-Carlo distribution into the same shape as the data-derived distribution.

In order to make the generated Monte Carlo samples universally applicable, the simulated number of pileup vertices is drawn from a distribution, which is almost flat between one and ten pileup vertices and has a poisson shaped tail for more than ten pileup vertices. To be able to compare the Monte Carlo to the data, every simulated event has to be reweighted depending on the number of pileup vertices simulated in the event. This process transforms the Monte Carlo pileup distribution into the distribution obtained from the 1.01 fb^{-1} shown at the EPS conference (see figure 3).

The recommended CMS reweighting procedure uses the specified distribution, which was used to generate the Monte Carlo samples, from [3] and calculates the event weights. Later, when processing the Monte Carlo samples, there is information about the amount

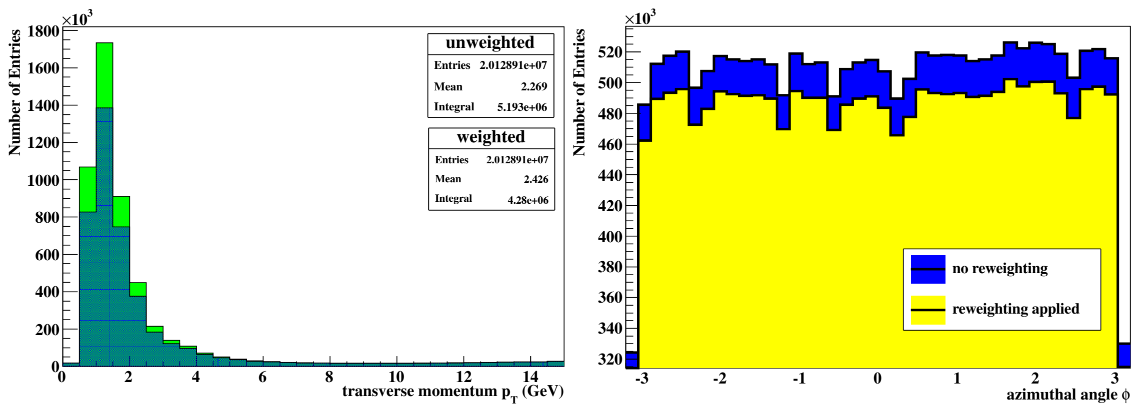

Figure 3: Left: Transverse momentum of all muons before and after the reweighting. Right: Azimuthal angle of all muons before and after the reweighting. No cuts were applied. Though similar in shape, the distributions are generally shifted downwards.

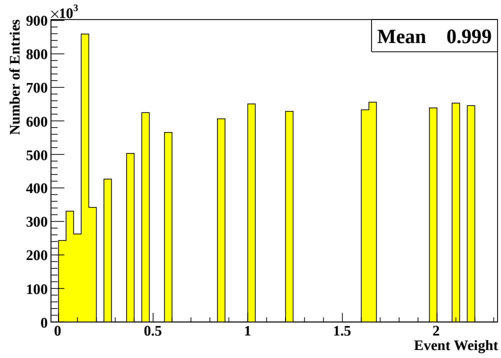

Figure 4: Frequency of the event weights used for reweighting in the Drell-Yan Monte Carlo sample. The mean is almost one, therefore comparable shifts upwards and downwards in the distributions are expected.

of generated pileup vertices available for every event. This will be used to look up the weight of every event.

One would expect, that the resulting distribution of the number of vertices in an event agrees with the distribution obtained from the data and fed to the reweighting procedure.

Unfortunately, this was not the case. While both distributions have a similar shape, the agreement is not as good as expected. A possible cause is the generated distribution, which is probably not in agreement with the distribution actually used.

The changes to the physical observables caused by the reweighting procedure can be seen in figure 3. No cuts whatsoever were applied to the collection of reconstructed muons. However, besides a shift in shape, all distributions (e.g. p_{T}, ϕ, $\ldots$) saw an overall shift downwards. A change in the shape of the distributions was anticipated, but corrections upwards and downwards were expected in equal measure. The cause of the dominant downward shifts remains unclear. As seen in figure 4, all weights appear with a frequency, that leads to an average shift around one, as expected.

3.2 Z reconstruction

3.2.1 Selecting clean muons

The decay of the Z boson with an invariant mass of approximately 91 GeV into the decay channel $\mathrm{Z} \to \mu^+\mu^-$ yields two muons with a high momentum, which have to be selected first. In order to reject background from other muon-involving processes, a selection of cuts has been applied to the collection of reconstructed muons, which are described below:

To suppress against decays of neutral particles of the kind $\pi^0 \to \mu^+\mu^-$, the muon seen by the outer muon detector should have a matching track in the inner detector. Furthermore, this inner detector track should have created at least 10 hits, because the short lifetime of the Z boson leads to a decay close to the primary vertex and the

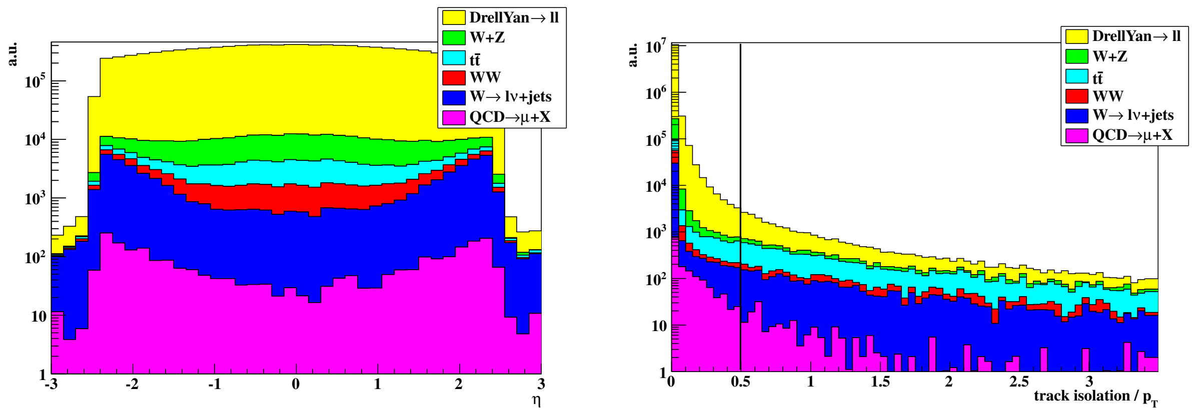

Figure 5: Left: Distribution of pseudorapidity η of Z candidates' muons. Only tracks with $|\eta| < 2.1$ were taken into account in the final selection. Right: Distribution of track isolation relative to p_T of the Z candidates' muons. The vertical line indicates the cut.

outgoing tracks pass the entire track detector.

The signal-to-background ratio decreases in the forward regions of the detector (that is for increasing values of η) as seen in figure 5 and because of that all muons with $|\eta| > 2.1$ are disregarded.

The reconstruction quality is obviously better, the more isolated the particles are. To get a clean selection of muons, the tracks are required to have an isolation normalized to the transverse momentum of less than 0.5. The reconstruction considers all tracks around the given track, which have a "distance" ΔR of less than 0.3. ΔR is given as the Pythagorean sum of the distance in the η-ϕ-plane. The sum of all transverse momenta of the tracks inside this cone normalized to p_T of the muon candidate, serves as an indication for the isolation of the track. The lower the result, the more isolated is the track.

A similar measurement can be done with the calorimeter hits. All energy deposited inside a cone around the given track with ΔR of less than 0.3 in case of the electromagnetic calorimeter and 0.4 in case of the hadronic calorimeter is summed up and designated the calorimeter isolation. Normalized to the transverse momentum of the muon, this value should not exceed 0.2.

Additionally, the number of track hits created by a muon can serve as a selection criterion. The more the muon interacts with the inner tracker, as well as the outer muon system, the more precise the track measurement will be. To reject poorly reconstructed candidates, every track should have created at least six hits in the muon system and at least ten hits in the inner tracker to be considered of good reconstruction quality.

As the track of a muon is determined from a fit to the hits in the inner tracking detector and the muon chambers, the normalized χ^2 of this fit can also be used to judge the reconstruction quality of the muon track. It should not exceed 4.0.

As the Z boson is created close to the interaction point and has a very short lifetime, the muon tracks are expected to originate from somewhere near the beamspot. There-

Cut	Value
muon is seen by the muon system and the track detector	yes
pseudorapidity $\|\eta\|$	< 2.1
track isolation per transverse momentum	< 0.5
calorimeter isolation per transverse momentum	< 0.2
number of hits in the track detector	> 10
number of hits in the muon system	> 6
χ^2/d.o.f. of the combined track fit	< 4.0
ΔZ of the track (relative to the beamspot)	< 0.05
$D0$ of the track (relative to the beamspot)	< 0.01

Table 1: Overview of the cuts applied to the muon track in order to get a clean selection of muons to be combined to the Z boson.

fore, the parameters ΔZ and $D0$ in the helical parametrization of the track, that measure the distance of closest approach to the beamspot in the x-y-plane and the transverse distance along the z-direction, are used for selection cuts.

A summary of the applied cuts can be found in table 1.

3.2.2 Fitting the Z mass peak

The distribution of the Z mass obtained from the previous analysis steps is shown in figure 6. Neglecting the background, the resonance curve should follow a Gaussian distribution. However, due to the simple nature of the analysis, which focused on selecting the muons and calculating the invariant mass, the photons which may have been radiated from the muons in the final state have not been reconstructed and have not been

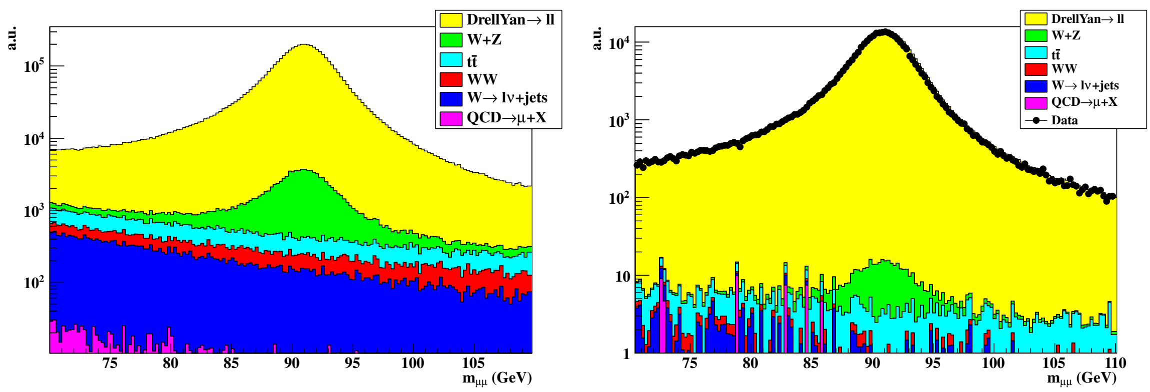

Figure 6: Left: Distribution of the invariant mass of muon pairs around the Z resonance before cutting. Right: Distribution of the invariant mass of pairs of muons passing the selection cuts. The formerly already small background has been reduced further by approximately one order of magnitude. The Monte Carlo seems to be in good agreement with the data.

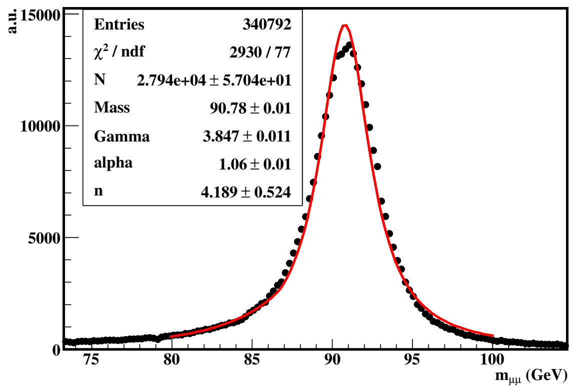

Figure 7: Z mass distribution obtained from analyzing the data. A crystal ball function has been fitted to the peak, as described in the text. The Z mass is slightly lower than the reference value from the PDG, which may be attributed to the neglection of the background, imprecisions in the calibration or other systematic errors.

included in the invariant mass calculation. As a result, the distribution is not symmetric anymore, but has a larger tail for masses lower than the actual Z mass, because the photons carry away a part of the muon energy, which leads to a lower than actually present Z mass in some cases. In order to account for this effect, the fit was done using the Crystal-Ball function[5]:

$$f(x;\bar{x},\sigma,\alpha,n,N) = N \cdot \begin{cases} \exp(-\frac{x-\bar{x}}{2\,\sigma}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leq -\alpha \end{cases} \tag{1}$$

$$\text{with } A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) \text{ and } B = \frac{n}{|\alpha|} - |\alpha|.$$

This function consists of a Gaussian part which turns into an exponential fall-off with the exponent n. The point of transition between both parts is determined by the parameter α. The coefficients A and B have been determined in a way, that ensures a smooth transition between both parts of the function.

Figure 6 shows the result of fitting the function 1 to the data.

This function provides a better approximation of the Z mass peak than the simple Gaussian, there is, however, still room for improvements. For a precision measurement of the Z boson mass, it would be neccessary to conduct a more detailed study of the background.

3.3 Trigger Efficiency

Once a pure reconstruction of Z boson decays has been achieved, the results can be used to estimate the efficiency of the trigger system, too.

The trigger performs a coarse but fast reconstruction of the most important features of an event. Within the scope of this analysis, the most important feature are the muons.

The resistive plate chambers (RPCs) embedded in the muon system between the drift tubes are used to get a quick glimpse at the number of muons, their energy and direction.

This analysis reviewed the so-called "HLT_IsoMu17" trigger. Its goal is to select events, which

- contain at least one muon with
- at least 17 GeV transverse momentum
- and which is isolated from jets (the total energy deposited in a radius of $\Delta R \leq 0.3$ is less than a certain threshold.

By rerunning the entire analysis and selecting a different trigger (e.g. "HLT_Mu24"), the efficiency of other triggers can be determined similarly.

The efficiency measurement is done using the "tag-and-probe" method. It assumes, that the previous analysis of the Z peak provides sufficiently clean selection of Z boson decays. One of the outgoing muons should have been detected by the trigger matching. This muon is designated as the so-called tag muon. The other muon then becomes the probe muon and is added to the total number of probe muons N_{all}. A test is performed to see, whether the probe muon has also been seen by the trigger. In that case, it is counted as a successful probe N_{probe}. The number of successful probes divided by the number of all probes in turn yields the trigger efficiency

$$\epsilon = \frac{N_{\text{probe}}}{N_{\text{all}}}. \tag{2}$$

As the chosen trigger makes a decision depending on the transverse momentum, it is meaningful to measure the efficiency depending on p_{T}.

The result for the "HLT_IsoMu17" trigger can be seen in figure 8. A fit was applied, which has the shape of a Gaussian around the trigger threshold and then transitions into a flat shape when the maximum efficiency is reached. As proposed in [4], the following

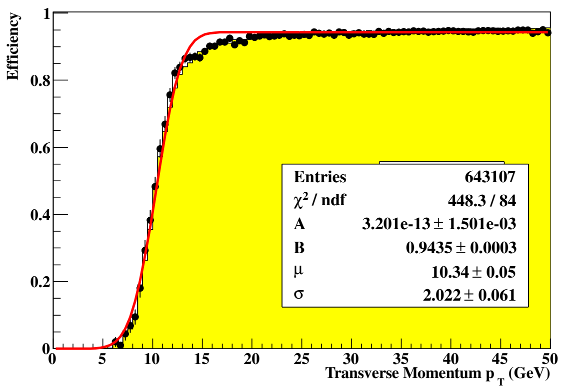

Figure 8: Efficiency of the "IsoMu17" trigger. At 20 GeV it has reached its maximum efficiency.

function representing a Gaussion convoluted with a step function was used to fit the trigger efficiency:

$$\epsilon = A + \frac{B-A}{2} \cdot \left(1 + \text{erf}\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma}\right)\right) \tag{3}$$

A denotes the low efficiency before reaching the threshold, whereas B denotes the high efficiency plateau after passing the threshold. σ is the width of the turn-on curve and μ is the so-called turn-on threshold (i.e. the value, where the trigger reaches 50% efficiency).

Surprisingly, the trigger is already fired by muons with a much lower transverse momentum than the proclaimed threshold. The turn-on value obtained from the fit is (10.34 ± 0.05) GeV, and the trigger reaches its maximum efficiency of (94.35 ± 0.03) % at a transverse momentum of 20 GeV (see figure 17).

As a cross check, the same analysis was performed with the "HLT_Mu24" trigger. As expected, the turn-on curve is shifted to higher momenta. Still, the turn-on value is (12.02 ± 0.04) GeV and the maximum efficiency of (94.31 ± 0.12) % is reached at 23 GeV.

4 Angular Dependance of the Z Mass

Another application of the Z boson's decay reconstruction is the study of the tracker alignment.

During the construction of the detector, the inner silicon tracker parts were aligned and retained with a finite precision. Afterwards, a tracker alignment is performed: A lot of tracks are collected and track fits are performed. Then, the alignment parameters of the tracker are varied in a way, that minimizes the χ^2-value of all track fits simultaneously. However, it is possible to change the geometry of the tracker in a way, that leaves the χ^2 almost invariant and minimal. Several possible configurations are indistinguishable to the minimization process, but it is important to find the right alignment, that corresponds to the actual physical installation. Though the χ^2-value may remain unchanged, the reconstructed track parameters are different. This is illustrated in figure 9 for a twisted barrel geometry.

It is possible to uncover these ambiguities in the alignment, by e.g. looking at the change in the Z mass depending on the direction of flight of the muons. If the muons fly

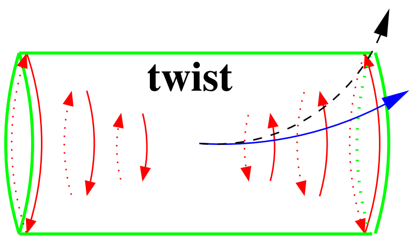

Figure 9: Effect of a twist in the barrel structure of the silicon tracker. Both track fits may yield the same low χ^2-value, but only one will correspond to the track of the actual physical particle [1].

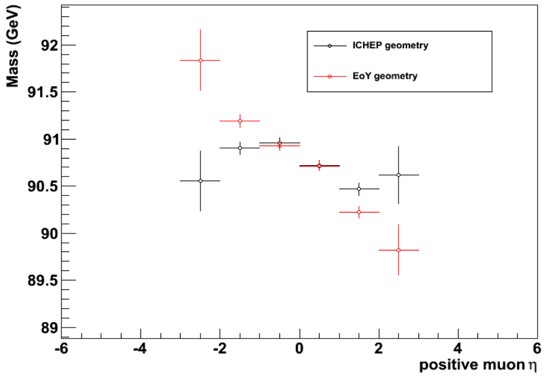

Figure 10: Effect of a twist in the barrel structure of the silicon tracker on the reconstructed Z mass, as studied in the 2010 data [2].

through an area of the detector, which has a different deformation than the assumption in the reconstruction software, the reconstructed track parameters will be wrong and the invariant mass of the Z will change. This has already been observed earlier (see figure 10) and correction attempts have been made.

The amount of data collected by the CMS experiment and available to this analysis equals 1.0919 fb^{-1} in terms of luminosity. This allows for a Z mass determination depending on the muons' direction of flight. Therefore, the same fit as explained in chapter 3.2.2 has been performed multiple times with a subset of muon pairs, depending on the pseudorapidity or the azimuthal angle of the positively or negatively charged muon.

The results are given in the figures 11 and 12.

A fluctutation of the order of about 1 GeV can be seen. As the muons originating from the Z boson usually have an opening angle of 180 degrees, the mass distributions seem to be shifted in phase when comparing the differently charged muons.

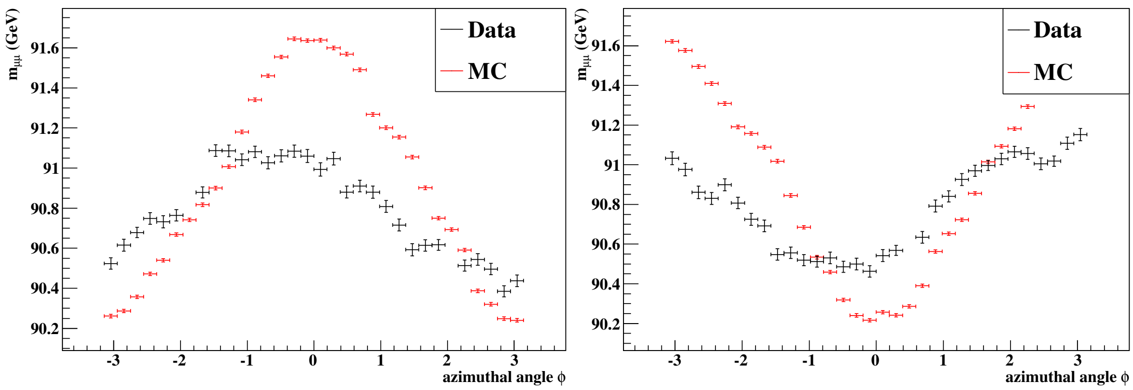

Figure 11: Left: Dependance of the invariant mass on the azimuthal angle ϕ of the μ^-. Right: Dependance of the invariant mass on the azimuthal angle ϕ of the μ^+. The Monte Carlo simulation produces a shape similar to the data, but not in agreement with it.

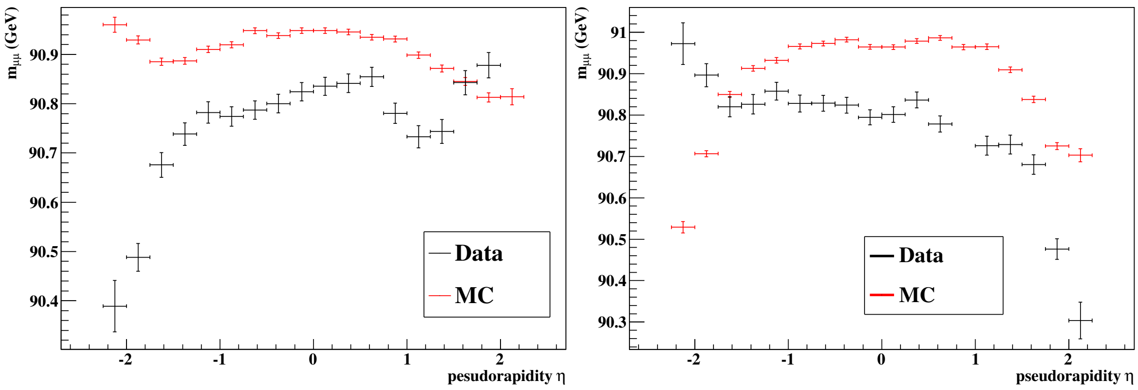

Figure 12: Left: Dependance of the invariant mass on the pseudorapidity η of the μ^-. Right: Dependance of the invariant mass on the pseudorapidity η of the μ^+. A large deviation in the high eta region can be seen in the data. The Monte Carlo simulation does not reflect the shape of the data at all.

Comparing the results to previous studies of the tracker alignment, there seems to be an improvement at least in the barrel region, where the distribution is now flat. However the deviation at higher pseudorapidities (that is, muons flying in the forward direction) is still evident in the data.

The Monte Carlo simulations however show a quite different behaviour. It shows an almost flat distribution in the center, whose deviations are within the margins of the statistical error. There are deviations towards higher values of η, but they are not in agreement with the data.

5 Results and Conclusions

The reconstruction of the Z boson was successful. The background is more than two orders of magnitude lower than the signal and thus the purity is higher than 99%. A selection of cleanly reconstructed muons and a cut on the invariant mass of the muon pairs was needed to achieve the result.

However, when comparing the Monte Carlo simulations to the data, an unexpected behaviour of the reweighting procedure caused a downward shift in the kinematic distributions of the muons, that could not be solved within this analysis. Further investigation of this issue is highly recommended in order to provide a reliable foundation for further analysis.

The application of the Z reconstruction to the tag-and-probe method yielded also good results. The efficiency of the "HLT_IsoMu17" trigger was determined to be $(94.35 \pm 0.03)\,\%$. The measured turn-on threshold of 10 GeV is quite low and the maximum efficiency is reached at 20 GeV. On the one hand, this means, that the analysis can rely on receiving almost all events with the muons passing the proclaimed trigger threshold. On the other hand, a lot of events with muons below the threshold pass the trigger and have to be saved, which wastes precious bandwidth and storage capacity.

Finally, the sensitivity of the Z mass to the direction of flight of the outgoing muons has been analyzed. Though this issue is known now for almost one year, a fluctuation of about 1 GeV could be observed. The ϕ dependance of the data is present in the Monte Carlo simulations in a similar shape. There seems to be a sinusoidal modeling of the effect in the Monte Carlo, but it is of higher magnitude than in the data. As expected, it is phase-shifted by 180° when comparing the positive and negative muons.

Looking at the Z mass in terms of the pseudorapidity of the muons, the fluctuation in the barrel region is less pronounced than in the forward regions. The Monte Carlo simulation does not show this behaviour, although there are fluctuations as well. However, it can be noted, that the η-dependence in the barrel has been reduced a lot since the studies, that have been performed with the 2010 data.

It would be advisable to further study this effect and implement a better model of the tracker alignment in the simulations, improve the alignment to eliminate the effect from the data or even find the root cause of this effect.

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A Muon Parameter Distributions Used for Cuts

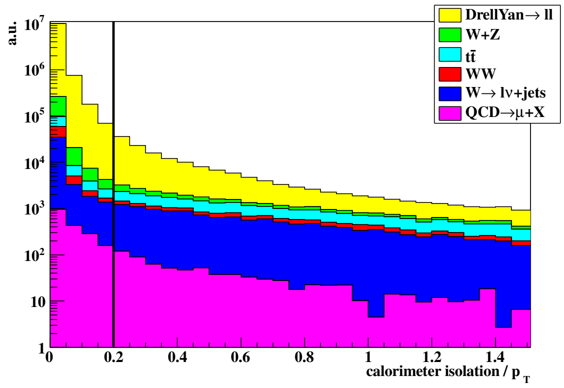

Figure 13: Calorimeter isolation of the muons normalized to their transverse momentum. The isolation is the sum of all energy deposited inside a cone around the given track with ΔR smaller than 0.3 in case of the electromagnetic calorimeter and 0.4 in case of the hadronic calorimeter.

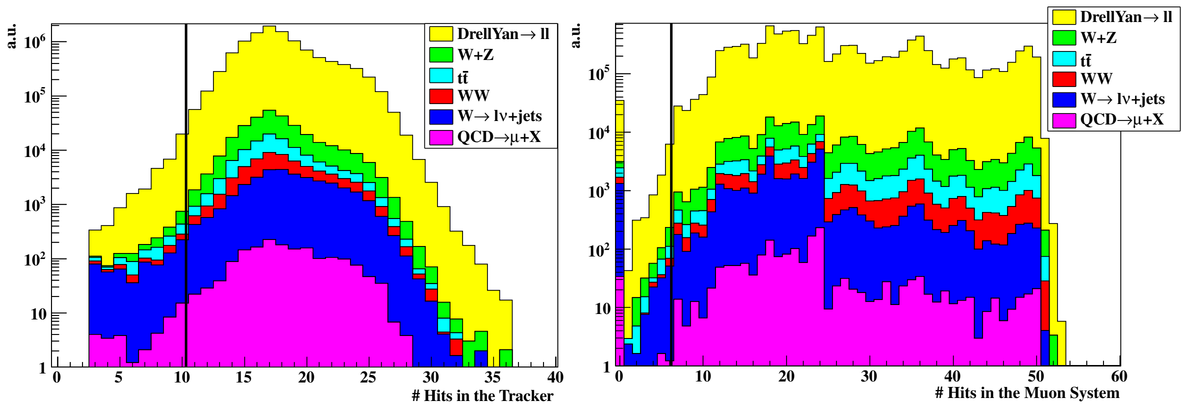

Figure 14: Left: Number of energy deposits created by the muons in the inner tracker. Right: Number of hits created by the muons in the muon system. The vertical line indicates the minimum amount of hits required by the analysis.

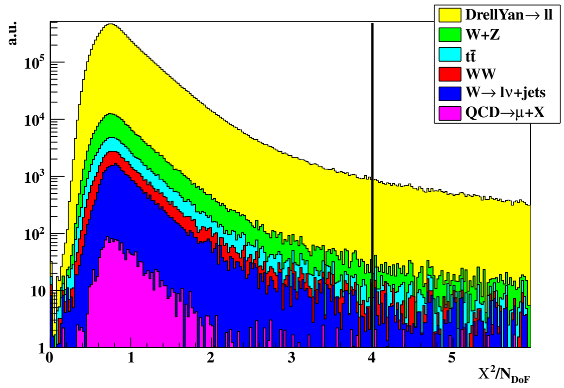

Figure 15: χ^2 value from the track fit normalized to the degrees of freedom for all Z candidates' muon tracks. A lower value indicates better fit and the vertical line show the maximum value a muon must have to be included in the analysis.

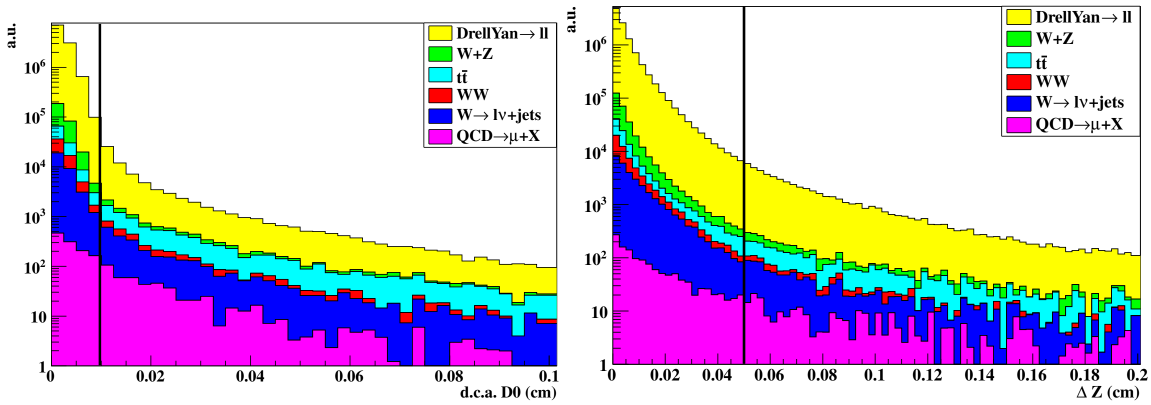

Figure 16: Left: Track parameter $D0$ of all muons that are assigned to Z candidates. Right: Track parameter Z of all muons belonging to Z candidates. The cuts shown by the vertical lines attempt to ensure, that the muons originate from a decay close to the beamspot, because of the short Z boson lifetime.

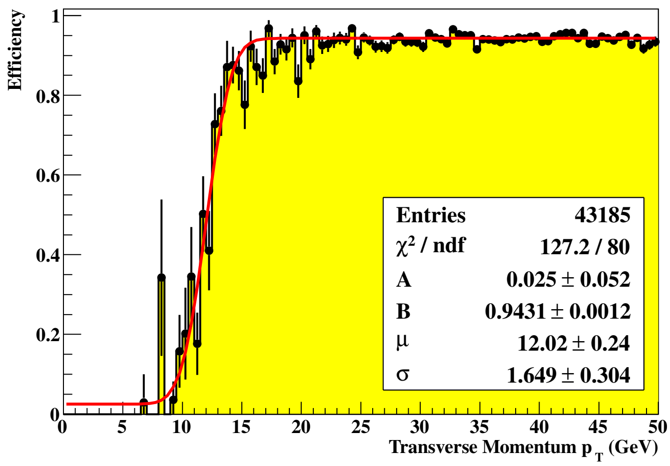

Figure 17: Trigger efficieny for the "HLT_Mu24" trigger, which triggers on events containing at least one muon with p_{T}>24 GeV. The turn-on threshold and the maximum efficiency are shifted to higher p_{T}, compared to the "IsoMu17" trigger (figure 8).