



Summer Student Report  
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# Z+Jet transverse momentum balancing in Forward region in CMS

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# 1. Introduction

During the 2012 DESY Summer Student Programme, I have studied and performed research about transverse momentum balance between Z boson and Jet in CMS group. QCD and the so-called Jet, which is the production of quarks and gluons, and W/Z boson are expected in high energy collision process, for example hard-scattering of parton in the proton-proton collision. However, my studies focus on data sample of proton-proton collision in the Compact Muon Solenoid (CMS) detector, the one of various excellent particle detector located on the Large Hadron Collider (LHC) ring which is the highest energy and the most powerful particle accelerator nowadays. Moreover, I study in the center-of-mass energy of  $\sqrt{s}=7$  GeV and  $36\text{ pb}^{-1}$  integrated luminosity.

My studies throughout the programme can be separated into two main parts. Initially, I have obtained fundamental knowledge of elementary particle physics, particularly the Standard Model, the Quantum Chromodynamics and proton-proton collision. Moreover, I was educated how to use Monte Carlo (MC) generator in order to generate the events, how to use Rivet for doing data analysis and how to use ROOT for a nice histogram. For the second part, the strategies to reconstruct the Z boson from muons was investigated as well as the Jet selection. I have developed a code to reconstruct them. After that, the balancing process was considered.

This report will described briefly the CMS detector in section 2, the Z and Jet reconstruction and event sample will be explained in section 3, and then the Z and Jet balancing method will be described. Section 5 will show all my task during the programme and the conclusion will be discussed in section 6.

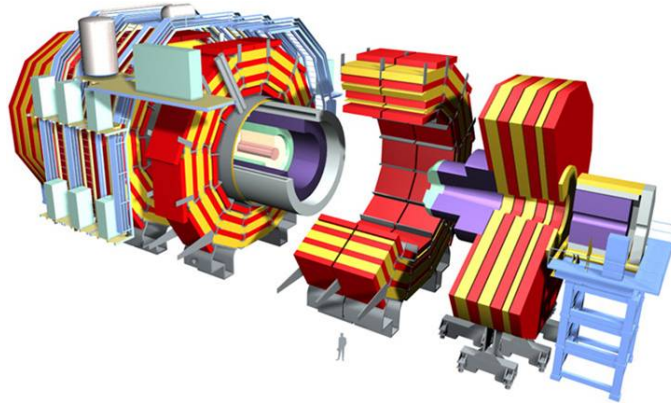


Figure 1: The CMS detector [1]

## 2. The CMS detector

At CERN, at the border between France and Switzerland, there is one of the four detectors at the LHC ring the so-called CMS. CMS was built for various reasons. First, for exploring the Higgs boson, last important jigsaw for completing the Standard Model. Second, to search for confirmation of physics beyond the Standard Model, such as Supersymmetric particles, and the other purpose is studying in heavy ion collision.

For CMS detector, we define that X-axis point to the center of the ring, Y-axis point upward and Z-axis is parallel to the beam in counterclockwise direction. However, there are 3 more essential variables,  $\phi$  or azimuthal angle is calculated in the XY plane compared with X-axis, the angle measured in the XY plane with respect to Z axis is the polar angle,  $\theta$ , and the pseudorapidity is determined by  $\eta = -\ln \tan \frac{\theta}{2}$ .

Moreover, Fig.1, we can separate the region of CMS into two main parts. The central region is defined as  $|\eta| < 3$ , while  $3 < |\eta| < 5$  is the forward region and for very forward region,  $-6.6 < \eta < -5.2$ , is for the CASTOR calorimeter. On the other hand, if we consider the transverse section of the CMS, we can see the distinguishing detector layers which can be divided into 5 parts. First, the Tracker, located around the interaction point, is used to detect particular particle tracks. Second layers is the Electromagnetic Calorimeter (ECAL) Its purpose is to measure photon and electron energy. The Hadronic Calorimeter (HCAL) is the next layer which is used for detect both charged and neutral hadron energy. Because the requirement of charged and neutral particle separation, the fourth layer has to be large solinoid magnet which can produce a magnetic field up to 4 Tesla. Final layer, muon detector was built in order to especially detect muons [2].

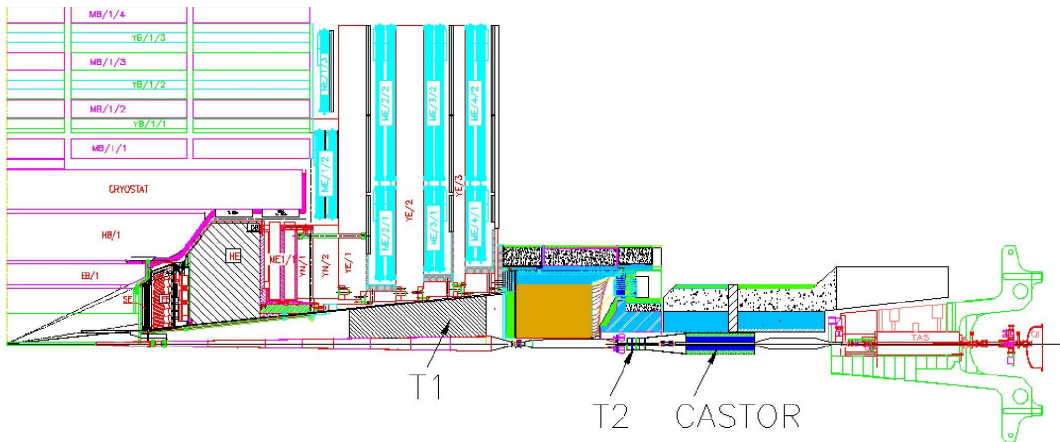


Figure 2: The CMS detector in longitudinal section together with CASTOR [3]

### 3. The Jet and Z boson Reconstruction and Event Sample

Fig.2 shows the hard-scattering of parton in proton-proton collision process. There are various types of outgoing particles not only leptons, for example electron, muon, tau, neutrino etc., but also bosons, for example W and Z. For my studies, balancing method, Z and Jet are used because Z can be clearly reconstructed from its decay muons.

#### 3.1 The Jet and Jet Reconstruction

A Jet is the cluster of particles produced by quark and gluon hadronization. Because of the QCD confinement and the asymptotic freedom property, we cannot observe quark and gluon directly form but they will be always represented by describes in narrow cone, the so-called Jet.

In my studies, a Jet is reconstructed from Monte Carlo (MC) simulation. The Anti-kT clustering algorithm is used with parameter size  $R=0.5$ . Moreover, The four momentum of the jet is determined in order to calculate transverse momentum as  $p_T = \sqrt{p_x^2 + p_y^2}$ . The jet rapidity is specified by  $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ , where E is energy of jet.

#### 3.2 The Z boson and Z Reconstruction

According to the theoretical prediction in quantum electrodynamics and the lack of the beta decay, the Z and W boson was occurred. In 1983, Z boson was discovered for the first time in Super Proton Synchrotron by Rubbia and Van Der Meer with their experiment called UA1 and UA2. Z boson is known as the mediator of the weak

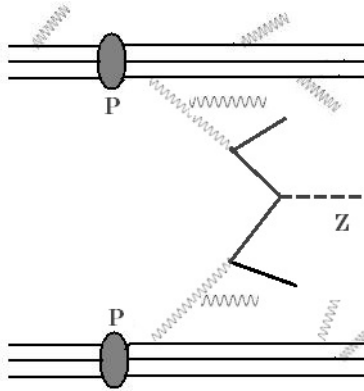


Figure 3: Hard-scattering process in proton-proton collision

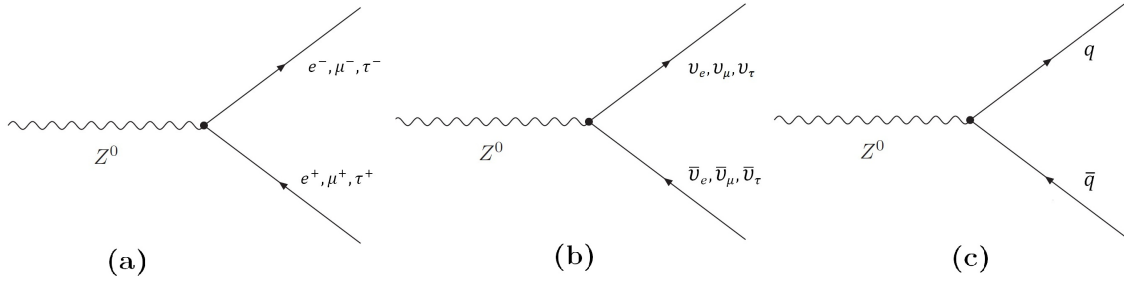


Figure 4: Z decay channel

interaction with mass  $91.90 \text{ GeV}/c^2$ . Z can decay into various channels for example neutrino ( $\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$ ), leptons ( $e^-, e^+, \mu^-, \mu^+, \tau^-, \tau^+$ ), Up-type quarks (u,c) and Down-type quarks (d,s,b) [4].

My studies use the muon-antimuon decay mode, see Fig.3, because muon is an easily detectable particle. For muon reconstruction, initially, I learned to use Rivet and MC generator for analysis of the event record as well as to use root. Z+Jet (MSEL=13) production is the process in MC generator. Subsequently, I developed the code for reconstructing Z. the step-by-step Z boson reconstruction, adjusted from [5], is explained as following. First of all, select the event which have one muon and one antimuon checked by particle ID. After that, choose only good quality muon and antimuon with transverse momentum  $p_T^\mu$  more than 15.0 GeV and pseudorapidity  $|\eta^\mu| < 2.3$

### 3.3 $Z(\mu^-, \mu^+) + \text{Jet}$ sample

Because the need of absolute jet energy response measurement, the  $Z(\mu^-, \mu^+) + \text{Jet}$  sample is required. The event must have one Z boson reconstructed from muon and antimuon by criteria given above and transverse momentum of more than 5 GeV. After that, jets in whole region of detector are investigated and we focus only on the back-to-back jet: the phi angle between jet and Z must satisfy the condition  $|\Delta(Z, \text{Jet})| > 2.8$  rad. I select the event that has only one back-to-back jet with  $p_T > 5 \text{ GeV}$ . However, when looking for low Z  $p_T$  event, frequently there are some of jets with pretty high  $p_T$  close to the Z so that the balance between Jet and Z  $p_T$  does not work because momentum of Z is shared with other side jet while we have only one back-to-back jet. Because of this, there are large difference between Jet and Z  $p_T$ . For better balancing, I add more criteria: No jets with  $p_T > 5 \text{ GeV}$  close to the the Z ;  $|\Delta(Z, \text{Jet})| < 0.8$  [5].

## 4. Z+Jet balancing

In order to determine systematic uncertainty, the calculation of jet energy response and jet  $p_T$  resolution is required. One method is the Z+Jet  $p_T$  balancing.

The absolute response  $R_{abs}$  is defined as

$$R_{abs} = \frac{p_T^{Jet}}{p_T^Z}$$

Moreover, I also calculate the difference of  $p_T$  by following,

$$\Delta = \frac{|p_T^{Jet} - p_T^Z|}{p_T^{Jet} + p_T^Z}$$

These two formulas are useful for looking at difference between transverse momentum and to see the balancing of Z and Jet  $p_T$ . However, if the transverse momentum is already balanced,  $R_{abs}$  and  $\Delta$  distribution should have a peak near one and zero, respectively [5].

## 5. Results

In this section, I will show some results including, the pseudorapidity and transverse momentum of Jet and Z boson distribution, the distribution of  $Z(\mu^-, \mu^+)$  invariance mass, absolute response and difference of Z and Jet transverse momentum where back-to-back Jet is in central region, forward region as well as CASTOR region.

### 5.1 Z boson

In order to ensure that it is real Z, the invariance mass of 2 muons was calculated and its distribution was plotted in Fig.5. A mass of about 90 GeV was found. This value is equal to the Z boson mass. Fig.6 are the eta and  $p_T$  distributions of Z boson.

### 5.2 Jet

For Jet reconstruction, I plot the distributions of transverse momentum and eta of Jet, see Fig.7.

### 5.3 Absolute response and Delta $p_T$

Fig.8 show the distribution of ratio between Z and Jet transverse momentum where transverse momentum of Z is between 5 to 10 GeV. A peak around 1 was found for all histogram. This means that there are small difference between transverse momentum of Jet and Z and these is good balancing. Fig.9 show the Delta  $p_T$  distribution for different back-to-back Jet pseudorapidity. There is a peak near zero showing good balancing. Fig.10 show the distribution of absolute response and Delta  $p_T$  in the

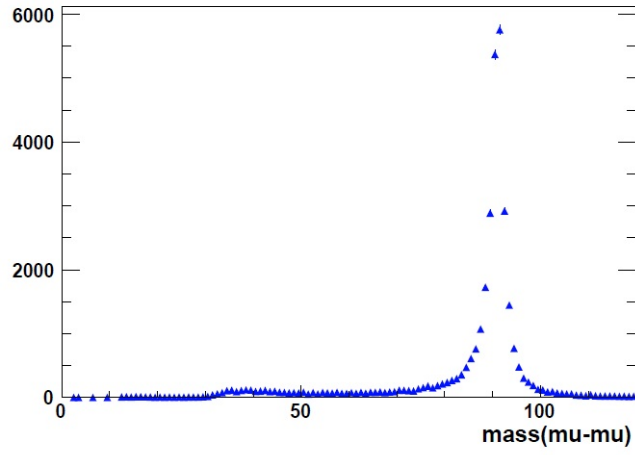


Figure 5: Invariance mass of Z boson from two muons

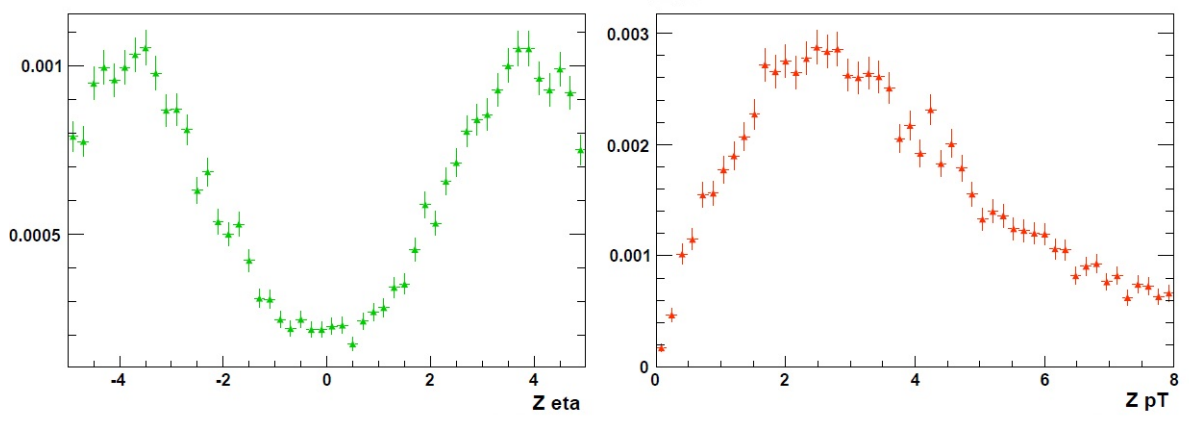


Figure 6: Z boson eta and  $p_T$  distribution

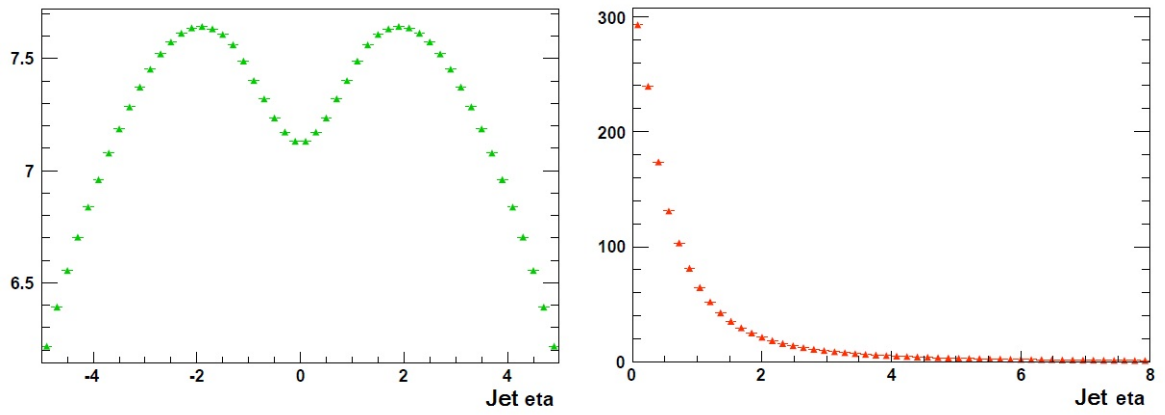


Figure 7: Jet eta and  $p_T$  distribution

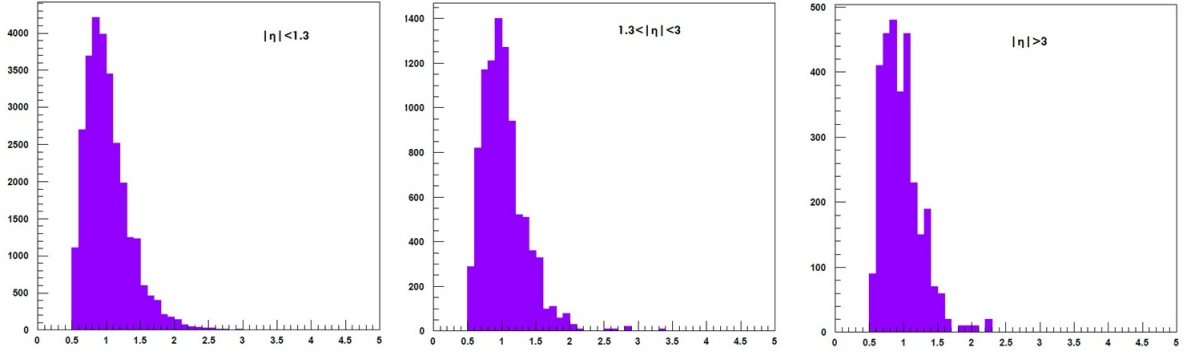


Figure 8: Absolute response distribution for different jet pseudorapidity,  $Z p_T = 5 - 10$  Gev

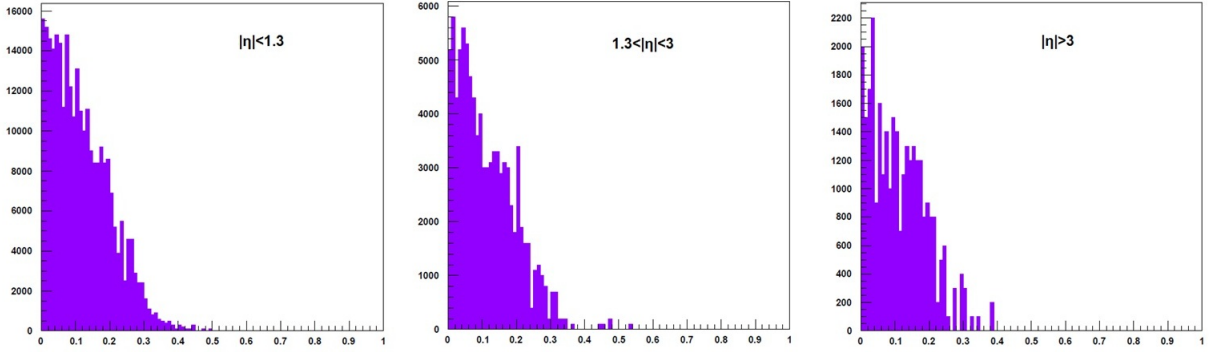


Figure 9: Delta  $p_T$  distribution for different jet pseudorapidity,  $Z p_T = 5 - 10$  Gev

CASTOR region,  $-6.6 < \eta < -5.2$ , A peak around one was found in absolute response distribution and a peak around zero was found in Delta  $p_T$  distribution. The cross-section is  $0.03 pb$ . This shows good balancing in CASTOR region.



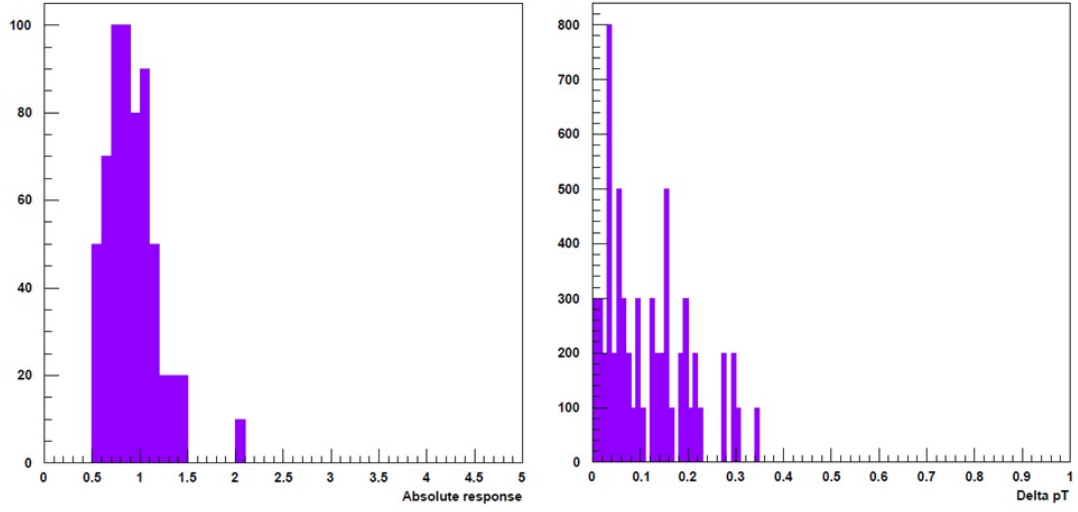


Figure 10: Absolute response distribution in CASTOR region,  $Z p_T = 5 - 10$  Gev

## 6. Conclusion

The main point of my work was to reconstruct Jet and Z boson with muons and to find the best way to select events for good balancing which can be represented by absolute response and delta  $p_T$  distribution.

Z and Jet sample following criteria in 3.2 is a pretty good sample for balancing in both low and high  $Z p_T$ . This sample is also good in central region, forward region as well as CASTOR region. However, in CASTOR region, the cross-section is very small,  $0.03 pb$ . Future studies might show a way to increase the cross-section by expanding mass range of Z or adjusting some criteria and preserve balancing.

## 7. Acknowledgement

I would like to express my deepest and sincere thankfulness to Hannes Jung, my supervisor, for his excellent valuable counsel, nice opportunity to educate and learn about CMS, very well encouragement, facilities as well as his help in all problems all over programme.

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## References

- [1] "The CMS detector"  
< <http://public.web.cern.ch/public/en/lhc/cms-en.html> >
- [2] "Compact Muon Solenoid"  
< <http://en.wikipedia.org/wiki/CompactMuonSolenoid> >
- [3] "Forward Physics with CMS"  
< [http://www.hep.ua.ac.be/cms/physics/cms\\_fw\\_physics.html](http://www.hep.ua.ac.be/cms/physics/cms_fw_physics.html) >
- [4] C. Amsler et al. (Particle Data Group), PL B667, 1 (2008) and 2009 partial update for the 2010 edition
- [5] The CMS collaboration, "Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS", 2011.