Generator level study of Z decay to di-muon in pp collisions at $\sqrt{s} = 13$ TeV

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In this work we present a generator level study of the Drell-Yan process $Z \rightarrow \mu^+\mu^-$ and corresponding backgrounds from Monte-Carlo simulations of pp collision events at center-of-mass energy $\sqrt{s} = 13$ TeV.

Keywords : Z boson, Drell-Yan, Monte-Carlo.

Contents

1 Introduction

All the particles in the standard model have weak interaction. $W^{\pm}$ and Z particles are the intermediate vector bosons which are mediators of these weak forces. Z boson is Spin-1 mediator particle of weak force nutral current. Due to extremely short lifetime Z boson cannot be detected directly in the experiment therefore it's production is inferred only from its decay products, and these decay products need to be identified among all of the final state particles in an event of interest, before any prediction is made or verified. The discovery of Z boson through Drell-yan process $q\bar{q} \to Z/\gamma* \to l^{+}l^{-}$ has been one of the major breakthroughs, in the attemps to verify standrard model as it stands today. The process due to it's relatively clean final state and precise agreement with theoretical predictions is one of the benchmarks for the confirmation of the standard model at higher energies. The measured values of mass and width and production cross sections were in perfect agreement with the predictions of electroweak theory. The mass and decay width of Z boson are measured to be about 91.2 GeV and 2.5 GeV respectively. In this report I present a generator level study of the Z boson decay to di-muon and the corresponding backgrounds in pp collisions at $\sqrt{s} = 13$ TeV.

2 The CMS detector

Situated in city of Cessy, France **CMS(Compton muon solenoid)** is one of two large general-purpose detector along with **ATLAS (A Toroidal LHC Apparatus)**. It is 21.6 meters in length,15 meters in diameter and weighs about 14000 tons. Research goals in CMS include the study of and beyond standard model physics, search and study of Higgs particle, dark matter, extra dimensions. It was one of the two experiments which proved the existence of the Higgs particle in July 2012.

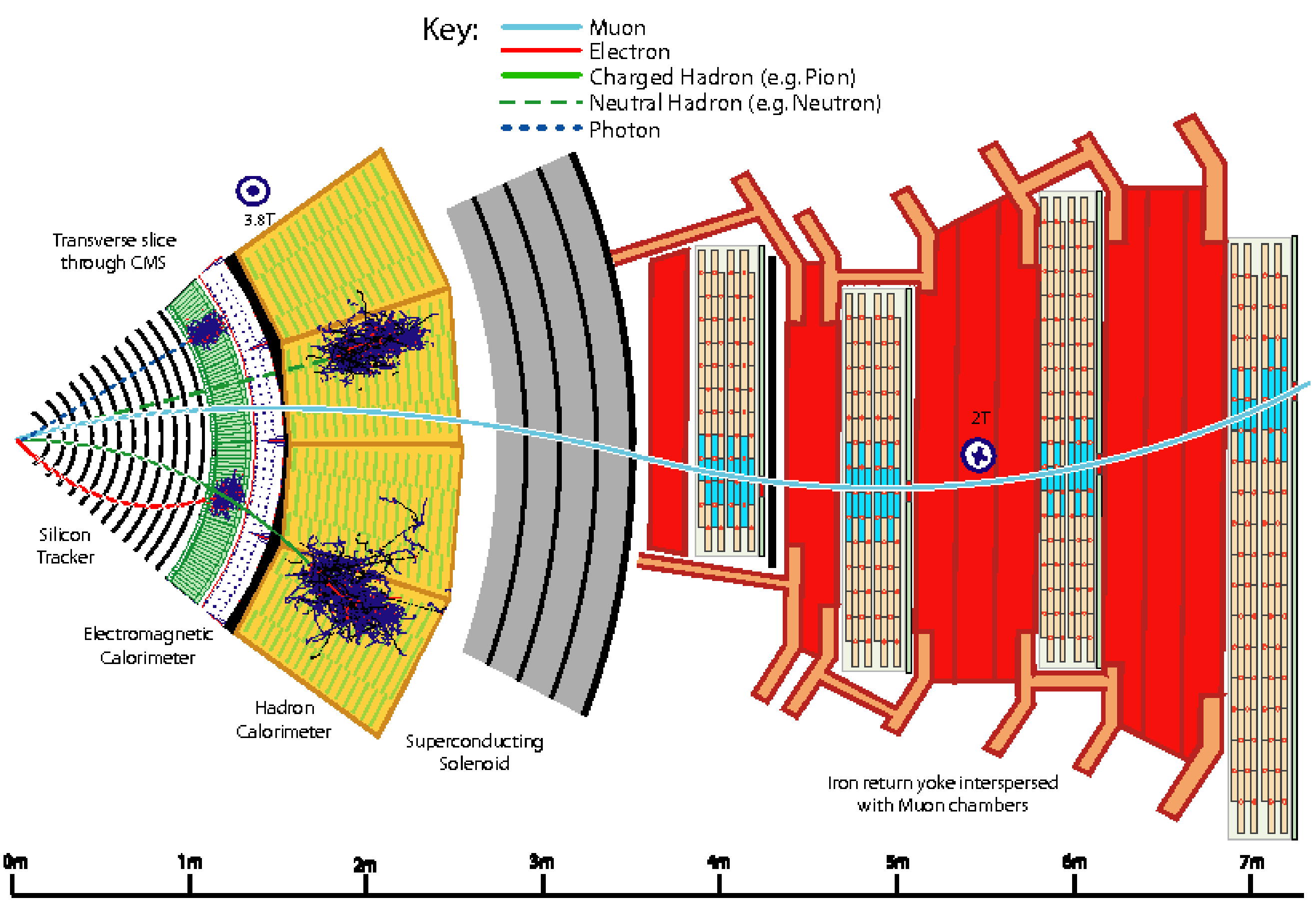

Figure 1: Cross setion of the CMS detector normal to the beam axis

A transverse slice of CMS is shown in Fig.1. Going radially outward from the beam axis where the high luminosity counter rotating beams of protons collide in bunches, the layers of CMS as shown are: (1)silicon tracker, (2)Electromagnetic calorimeter (ECAL) (3) Hadron calorimeter(HCAL), (3) Superconducting solenoid and (4) Iron yoke interspersed with muon chambers.

The silicon trackers, track the trajectories of charged particles such as electrons, muons and hadrons as they traverse through the magnetic field of about 3.8T produced by superconducting solenoid which bends curves the trajectories of these charged particles. As particles travel through the tracker the silicon pixels produce electric signals that are amplified and detected from which position and momentum of the particles are reconstructed. Each measurement is accurate upto 10μm. The inner pixel detector extends from 4cm to 11cm in radial direction and has 66 milion tracker channels and outer strips of silicon trackers which has 9.6million strip channels and extends till 55cm in radial direction.

The forward calorimeters(ECAL,HCAL) extending to $|\eta|$ values, measure the energies of these emergent particles through destructive measurements. ECAL measures the energies of electrons and photons when they pass through lead tungstate $PbWO_4$. Crystal scintillators and avalanche photo-diodes are used for readouts. HCAL measures the energies of hadrons such as protons, neutrons, pions and kaons with the aid of plastic scintillators. The caloremetric part of the detector stops all the excepts for muons neutrinos. Muons can penetrate several metres of iron without interacting. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal. These chambers are interleaved with the iron yoke.

3 Z boson decay modes

Z boson decays to l^+l^- ($l = e, \mu, \tau$) pair with branching ratio of 10% through Drell-Yan process shown in Fig.2, 70% of the time it decays to pairs of quarks which hadronize and later form hadron jets, rest 20% of the time it decays to pairs of neutrinos which go undetected through the detector and presence of which are inferred only indirectly by measuring missing transverse energy. The theoretical total cross section of production of Z boson through Drell-Yan process at the center of mass energy $\sqrt{s} = 13$TeV is about 5.89nb and each of the lepton anti-lepton final state is eqaully likely due to flavour universality of weak decays. therefore, for the $Z \to \mu^+\mu^-$ we have.

$$\sigma(p\bar{p} \to Z) \times BR(Z \to \mu^+\mu^-) = 176 \text{ pb}$$

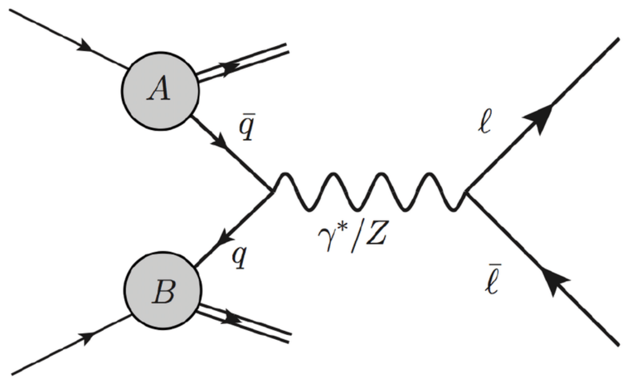

Figure 2: Leading order Fynnman diagram for Drell-Yan process

4 Underlying events

Estimation of properties of Z boson i.e. mass and decay width can be obtained from it's decay products, which in the Drell-Yan process under study are muon anti-muon pairs. However in order to decide which region of phase space to be probed and to perform precise Standard Model measurements, it is important to have a good understanding not only of the primary scattering process, but also of the accompanying interactions of the rest of the protonproton collision collectively termed the underlying event (UE). As the UE is an intrinsic part of the same protonproton collision as any signal partonic interaction, accurate description of its properties by Monte Carlo (MC) event generators is important. Below is the list of some of the mesons and baryons which decay to muons in an event. It is evident that final state of proton-proton collision consists of large number of charged pions and photons in addition to the particle of hard scatter, however these particles from UE are only moderately energetic,therefore the hard scatter part of the event can be isolated by selecting particle with high transverse momenta.

Particle	$< N >$	$< p_T >$	$< p_Z >$	$< \eta >$	$< y >$
π^+	82.61	0.679	9.707	0.002249	0.001644
π^-	81.92	0.678	9.63	0.001731	0.002131
K_L	9.293	1.113	12.29	-0.0027	-0.00259
γ	195.8	0.3489	8.412	0.00032	0.00032
p	6.828	1.083	14.28	-0.00034	-0.0011
n	6.571	1.093	14.23	0.00143	0.00029

4.1 QCD Jets in underlying events

The initial state radiation from the quarks in the Drell-Yan process consists of QCD gluons which later form jets. These jets carry fraction of momenta of original quark and therefore give a transverse boost the Z boson and consequently to the lepton anti-lepton pair. In the current study we have reconstructed these jets through anti-kt algorithm with distance parameter $R_0 = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in the pseudorapidity range of the detector i.e. $|\eta| < 5.0$. The corresponding momentum distribution of jets and the Z boson are shown in the Fig.3. It is evident from the distributions that these jets are mainy soft in nature. The transverse boost of Z particle is balanced by the resultant transverse momentum of these emergant jets.

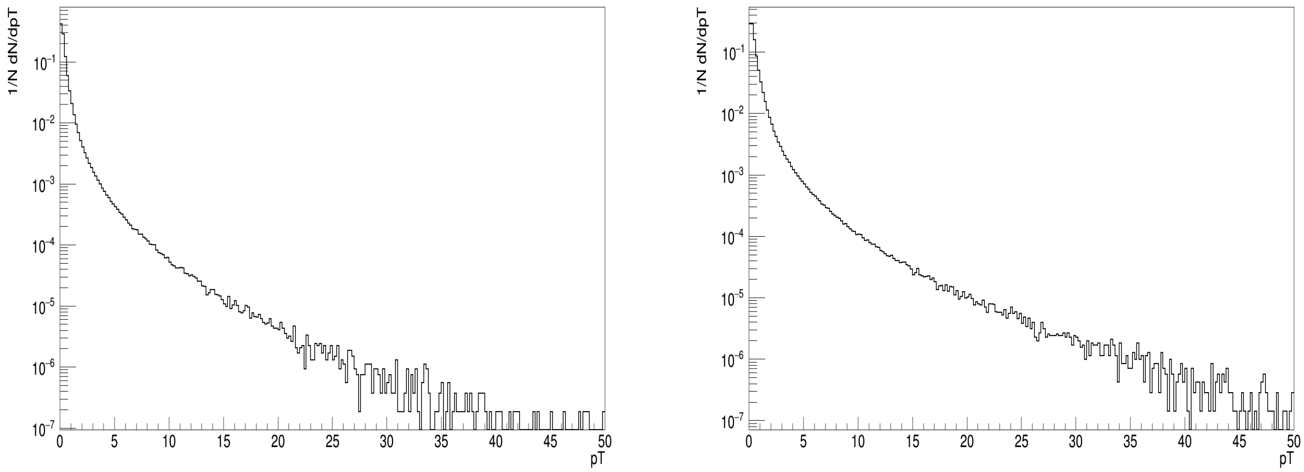

Figure 3: Transverse momentum distribution of initial state gluon jets in the Drell-Yan process $q\bar{q} \to Z \to \mu^+\mu^-$ (left) and Z particle (right)

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Below is the table of fraction of number of events with given number of jets which have transverse momemtum greater than the threshold values.

jet p_T threshold	1 jet events	2 jet events	3 jet events	4 jet events	5 jet events
10	0.27	0.17	0.082	0.039	0.017
20	0.177	0.046	0.01	0.002	0.0008
30	0.076	0.015	0.002	0.0006	0.0002
40	0.026	0.005	0.0005	0.0001	0
50	0.009	0.002	0.0002	0.0001	0

Table 1:Exclusive jet multiplicities as function of transverse momentum threshiold, normalised to the total number of jets.

5 Signal and background characteristics

5.1 Signal

An event has to satisfy certiain criteria in order to be considered as signal event and hence correspond the decay $Z \to \mu^+\mu^-$. In order to classify an event as signal event we require the following conditions to hold true.

1. The event consists of two oppsitely charged final state muons.
2. Both of the muons having high transverse momenta (p_T). Fig.4 shows the p_T distribution of muon in DY process.

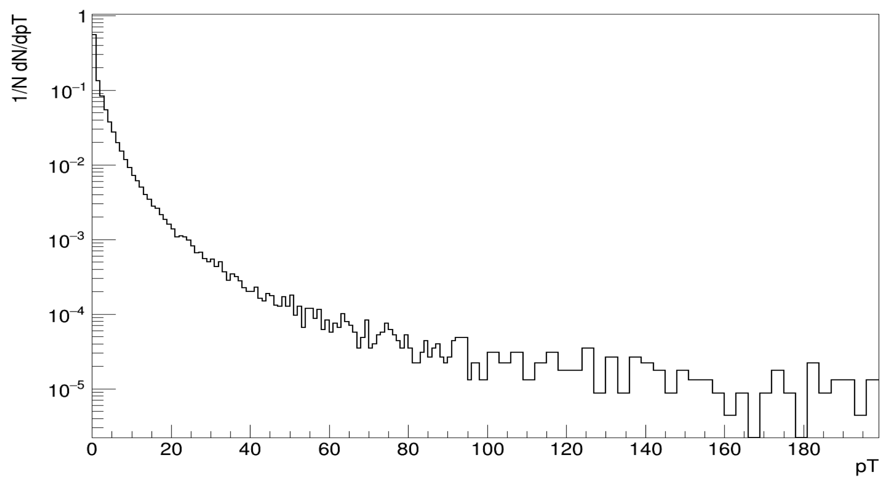


Figure 4: Transverse momentum distribution of muons in the signal events.

3. Both of the muons being isolated in the cone radius of 0.3 in (η, ϕ) plane. The cone radius is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The relative isolation variable $I = \frac{1}{p_T^{\mu}} \sum_{\Delta R < R_0} p_T^{hadron}$, is good parameter to quantify isolation. Distribution of I for the muons in signal events is shown in the Fig.5.

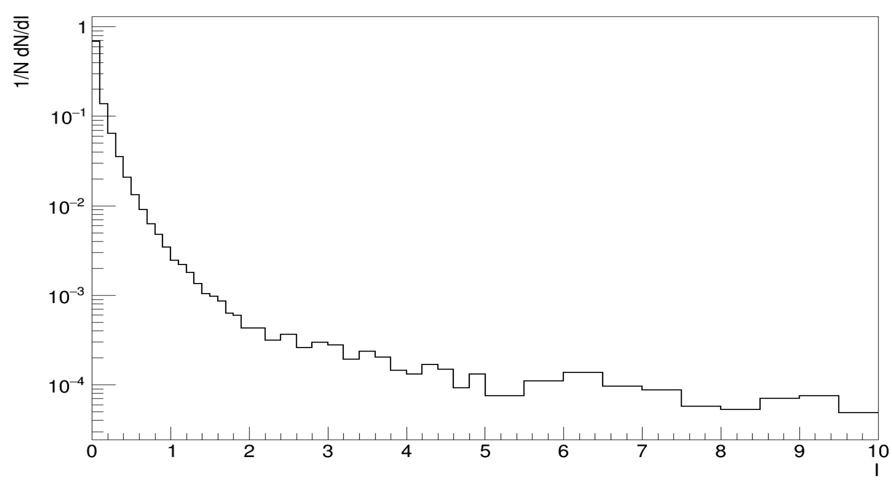


Figure 5: Relative isolation variable distribution of the muons in the signal events.

4. Both of the muons being in central region of the detector. i.e satisfying $|\eta| < 2.5$.

5.2 Background

The final states satisfying signal selection criteria can originate from other physical process. Events containing these final states are termed as background.

For the decay process $Z \rightarrow \mu^+\mu^-$ the possible backgrounds are-

1. QCD induced hadronic interaction processes have total inelastic cross section of around 56 mb at center of mass energy $\sqrt{s} = 13$TeV compared to the Z decay process with $\sigma \times BR \approx 0.2nb$, and in a large enough sample these processes can result in final state which mimics signal. These muons however contribute maximally to low p_T region of the spectrum as shown in Fig.6. A minimum momentum threshold is therefore used in order to elimiate these background events.

   Muons produced in semi-leptonic decays are accompanied by other particles mainly along the same diretion, and therefore are not "isolated". The relative isolation variable defined as sum of transverse momenta of all final state particles in the cone radius $R_0 = 0.3$ around the final state muon, normalized to the p_T of the muon($I = \frac{1}{p_T^{\mu}} \sum_{\Delta R < R_0} p_T^{hadron}$) is used to discriminate singal against such backgrounds. Muons populating higher values of the distribution are more likely to be from background events.

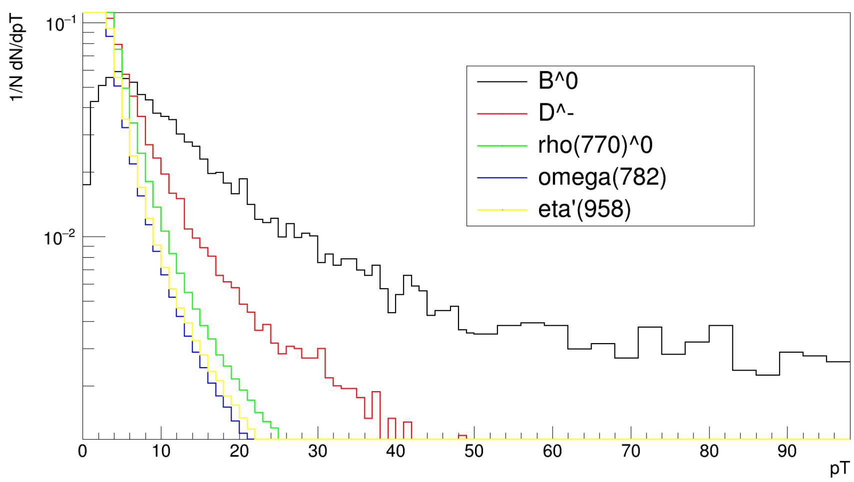


Figure 6: p_T Distribution of muons from QCD hadronic decays

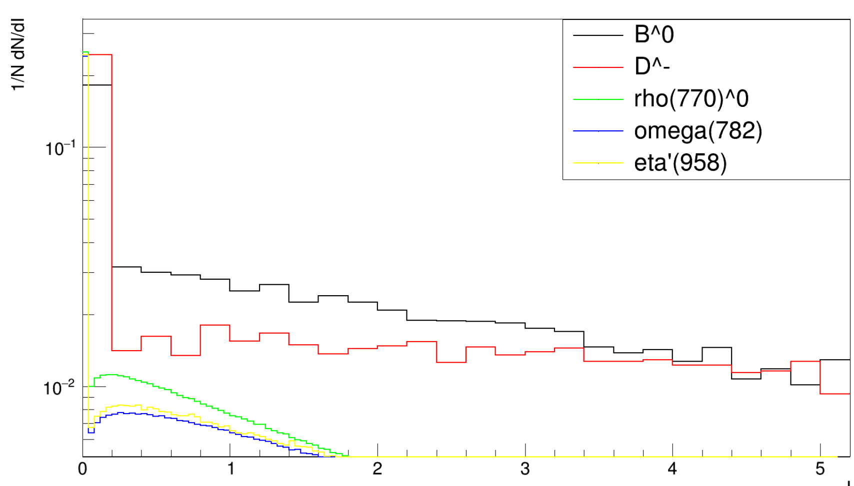


Figure 7: Relative isolation distribution of muons from QCD hadronic decays

2. W+ jets events with W decaying through muon channel and the highest pT jet faking as muon can also pose as background. A low p_T threshold of about 20 GeV can reduce this background to about 10^{-5} level, but the production rate of W boson is high.

3. $t\bar{t}$+jets have large rates, and the cascade decay $t \rightarrow W^+q$, $W^+ \rightarrow \mu^+\nu_\mu$ can be source of two energetic isolated muons in the final state with resonably large invariant mass.

4. The process $Z \rightarrow \tau^+\tau^- \rightarrow \mu^+\mu^- + X$ can also pose as background. The invariant mass of the final state muon however peaks at a lower value as compared $Z \rightarrow \mu^+\mu^-$, due to missing energy.

5. Diboson production such as WW,WZ,ZZ and their corresponding leptonic decay can also pose as background but with very low rate.

In this study only QCD multijet background has been considered in order to optimise signal selection criteria.

6 Event selection cuts

Signal and background are simulated separately with large number of events. The events selection cuts for transverse momenta and relative isolation are decided by comparing signal distributions to the corresponding total background distributions (both normalized to total number of events), and analyzing signal and background acceptances by changing one of the two bounds of the parameter's cut value separately for each parameter. The selection criteria is deliberately kept lenient in order to have good statistics. Pseudo-rapidity η cut is decided to cover the central region of the detector i.e $|\eta|< 2.5$.

6.1 Transverse momenta

The p_T distribution of the signal and QCD background is shown in Fig.8. The background dominates in low(0-20 GeV) p_T region of the distribution due to relatively light mass of the mother particles. The p_T distribution of signal peaks around $\frac{M_Z}{2}$ =45 GeV and then dies off, since quite often the Z boson is boosted in the transverse direction as well when accopanied by jets. Therefore a low p_T threshold can be for seperating signal from background i.e. if we select events with both muons satisfying $p_T > p_T^{threshold}$ then the selected sample will have significantly smaller contribution from the background compared to signal.

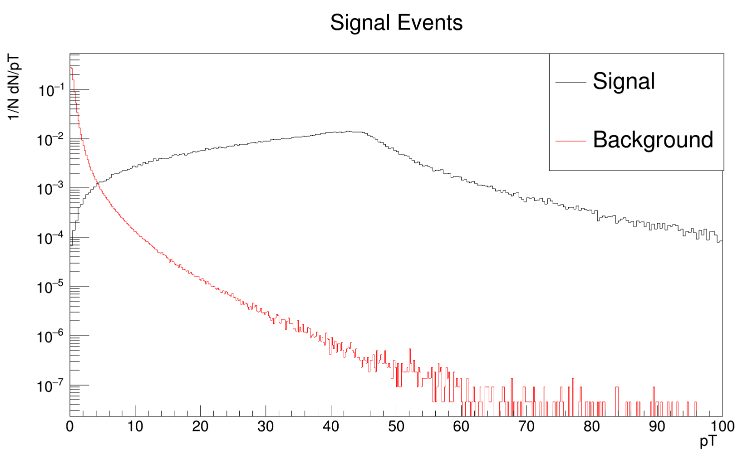


Figure 8: Transverse momentum distribution for signal and background events

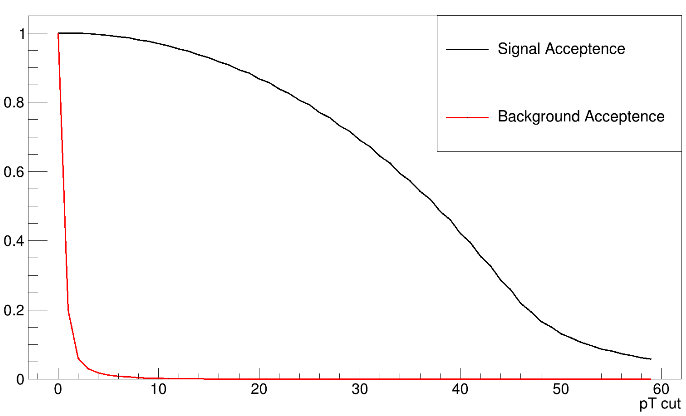


Figure 9: Signal and background acceptance for various p_T treshold.

Signal and background acceptance for different values of $p_T^{threshold}$ cut are shown in Fig.9 . Most of the background is eliminated with a cut of 20 GeV for which signal acceptance is 86% and background acceptance is about 0.002% . Therefore when normalised to corresponding cross section values the bakgound in selected sample will be reduced by to orders of magnitude.

6.2 Isolation

In signal events muons are the only final state particles in a given direction generally, except for the particles resulting from underlying event activity. Thus the relative isolation variable (I) is expected to have a distribution which peaks heavily around I=0 and then rapidly falls off. On the other hand QCD muons produced through semi-leptonic decays are accompanied by a shower of hadrons called QCD Jets in addition to the particles from UE activity. These muons are not isolated and the I distribution is expected to spread farther away from I=0. Thus to select signal like events a high I cut is required .i.e all the events which have $I < I^{threshold}$ should be selected.

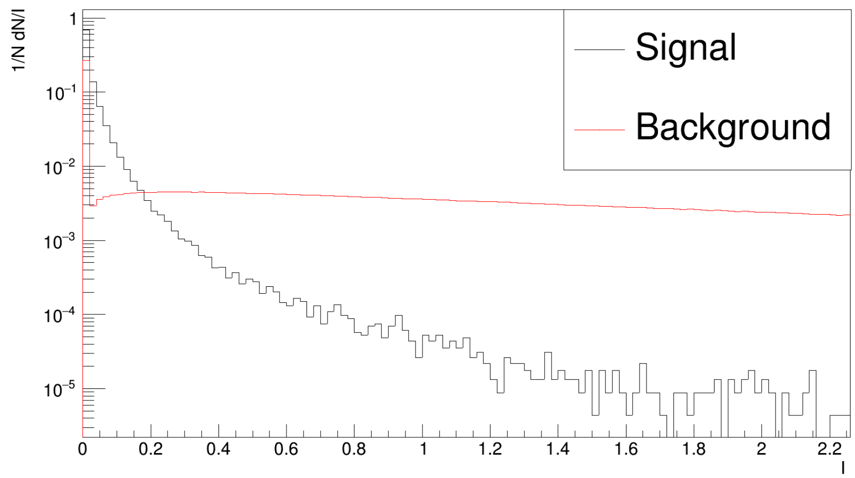


Figure 10: Relative isolation variable distribution for signal and background events

Signal and background acceptances for different values of isolation cuts are shown in Fig.11. Maximum signal to background acceptance is achieved for a cut value of 0.11 for which signal and background acceptances are 94% and 1.5% respectively.

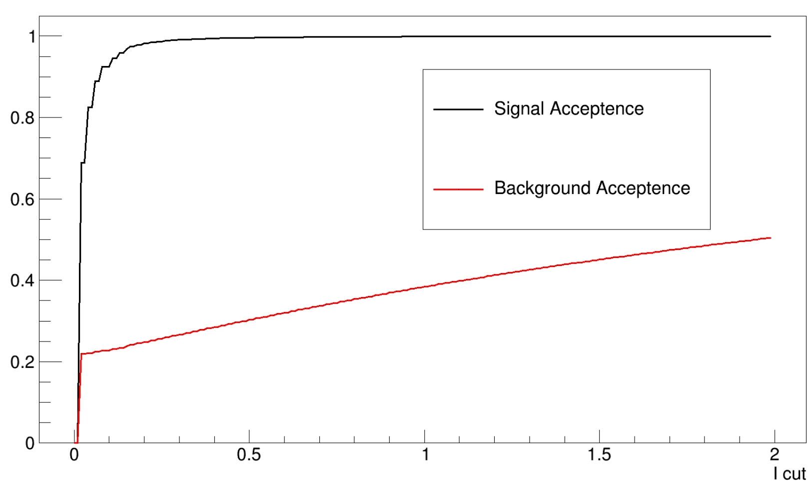


Figure 11: Relative isolation variable distribution for signal and background events

6.3 Pseudorapidity

Muons from QCD multijet events are boosted in forward-backward region therefore their pseudorapidity distribution tend to be spread out to higher values whereas that of muons from $Z \to \mu^+\mu^-$ are populated in central region, therefore a low $|\eta|$ cut is desired such that events which contain muons with high $|\ eta|$ are rejected. Threshold for $|\eta|$ is chosen to be 2.5 since this defined the central region of the detector.

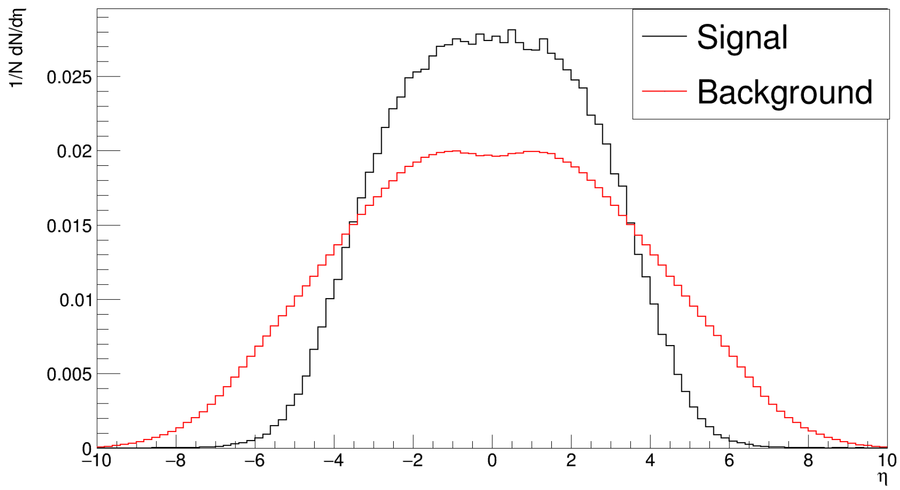


Figure 12: Pseudorapidity distribution for signal and background events

7 Results

A total of 4×10^6 HardQCD events are generated and the muon events apart from passing all the thresholds defined above are also required to have two oppositely charged muons, the events which do not pass any of the 4 selection criteria are rejected through and OR condition the results are summerized in the table below.

Selection	Single muon events	Events with two oppositely charged muons
Total	372269	95948
$I \leq 0.11$	63261	5061
$I \leq 0.11$ and $p_T \geq 20$ GeV	15	< 1
$I \leq 0.11$ and $p_T \geq 20$ GeV and $\|\eta\| \leq 2.5$	11	< 1

With the simulation results it is concluded that fraction of muons from QCD multijet process which can pass all of the three (p_T, I, η) selection threshold is about $\frac{11}{372269} = 2.95 \times 10^{-5}$ and the fraction of di-muon events which can pass all the selection criteria is $\frac{95948}{4000000} \times \left(2.95 \times 10^{-5}\right)^2 \approx 2.087 \times 10^{-11}$. Therefore the total QCD background level with these selection thresholds is $2.087 \times 10^{-11} \times 56.79$ mb $= 1.1852$ pb. Compare this to total signal level i.e. $0.86 \times 0.94 \times \sigma(q\bar{q} \to Z) \times BR(Z \to \mu^+\mu^-) = 176$ pb. We get the total signal to background ratio of about 119.64.

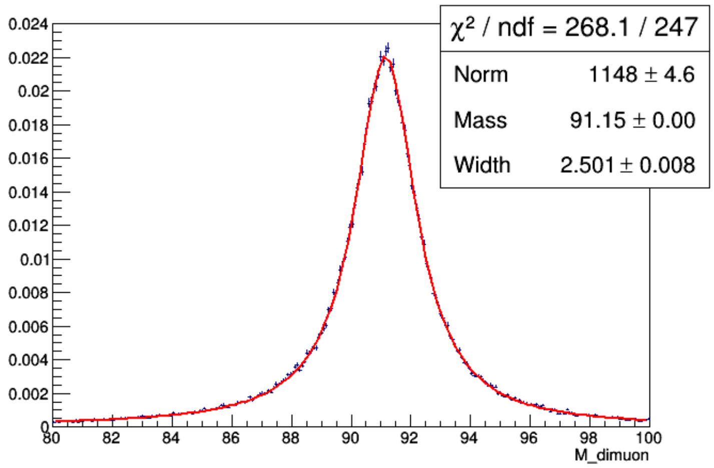
8 Conclusion

Events with two oppsitely charged muons with $pT > 20$ GeV, $|\eta| < 2.5$, and $I < 0.11$ are selected. Events not satisfying any of the above criteria are rejected through an OR condition, the corresponding signal to background ratio with these selection threshold is found to be 119.64. The invariant mass distribution of the events passing all the above selection criteria is shown in Fig.13 and is observed to have a resonance peak around 91.2 GeV. A Breit-Wigner fit to the invariant-mass distribution is done with mass(m) and decay widht(Γ) chosen to be parameters for the estimation. The Breight-Wigner fit function is defined as

$$BW(x; m, \Gamma, k) = \frac{k}{(x^2 - m^2)^2 + m^2\Gamma^2}$$

where k is normalizing constant.

The invariant di-muon mass and decay width obtained from fitting Breit-Wigner to the di-muon mass distribution are 91.1818 GeV and 2.54 GeV respectively. Which are in good agreement with the input values of these parameters.



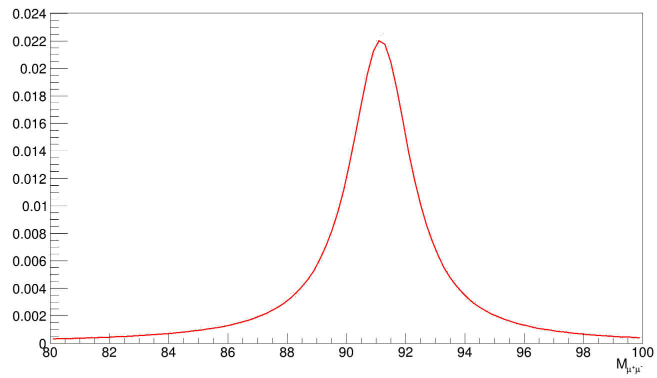


Figure 13: Invariant mass distribution of the di-muon passing the selection cuts

9 Ackowledgement

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10 Referrences

[1]Arno R. Bohm and N. L. Harshman "https://arxiv.org/pdf/hep-ph/0001206.pdf"

[2] The LHCb collaboration "Measurement of the forward Z boson production cross-section in pp collisions at $\sqrt{s} =$ 13TeV", 2016.

[3] Lashkar Mohammad Kashif "Measurement of the Z boson cross-section in the dimuon channel in ppcollisions at $\sqrt{s} = 7$TeV"

[4] The CMS Collaboration "Measurement of the Z boson differential cross section in transverse momentum and rapidity in proton-proton collisions at 8 TeV" , 2015

[5] Matthias Schott "Study of the Z Boson Production at the ATLAS Experiment with First Data",2007

(1)https://www.sciencedirect.com/science/article/pii/0370269383911772
(2)http://home.thep.lu.se/Pythia/
(3)https://root.cern.ch/
(5)https://home.cern/about/experiments/cms
(6)https://ac.els-cdn.com/S0168900296011060/1-s2.0-S0168900296011060-main.pdf?˙tid=0121ba5b-fb98-4e8a-8048-514cfbbd45b