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Study of Higgs Boson Decaying to Four Muons at $\sqrt{s}$ =14 TeV

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ABSTRACT

In this paper, an overview of the Standard Model(SM) of elementary particles is presented, where the Higgs boson decaying to four muons is studied at the center of mass energy √s = 14 TeV. We consider an integrated luminosity of 300 fb^{-1} of proton - proton collisions. We optimized event selection cuts to efficiently separate our signal from the standard model background without losing any important fraction of signal events.

1- INTRODUCTION

In the standard model (SM) of particle physics, the electroweak interactions relies on the existence of the Higgs boson (H, with mass MH), a scalar particle associated with the field responsible for the spontaneous electroweak symmetry breaking. The gauge bosons responsible for the weak interaction (W, Z bosons) acquire masses through interaction with the higgs boson field. Moreover the SM fermions acquire their masses through Yukawa coupling with that field. The Higgs boson mass (MH) is a free parameter of the model and has to be determined experimentally. Before 2012, there were general theoretical suggestions that MH should be smaller than 1 TeV, while precision electroweak measurements imply that $MH < 152$ GeV at a 95% confidence level(CL)[1]. In the framework of E-infinity theory which predict that the neutral higgs mass to be approximately 169.3 GeV by using the masses of electroweak ($W, Z0$) bosons as reference masses in the mass formula of E-infinity theory [2]. Over the past twenty years, direct searches for the Higgs boson have been carried out at the LEP electron positron collider, leading to a lower bound of $MH < 114.4$ GeV at 95% CL [3], and at the Tevatron proton-antiproton collider, excluding the mass range 162 - 166 GeV at 95% CL [4] and indicating a broad excess of events in the range 120 - 135 GeV [5, 6, 7].

Searches for the SM Higgs boson in the four-lepton channel have been performed at the Large Hadron Collider (LHC). The combined search results from CMS excluded the SM Higgs boson in the mass range 127 - 600 GeV at a 95% CL[8] while ATLAS excluded the ranges 111.4 - 116.6 GeV, 119.4 - 122.1 GeV, and 129.2 - 541 GeV at 95% CL[9,10]. In July of 2012 the ATLAS and CMS experiments have reported the discovery of a new boson at a mass around 126 GeV, with properties compatible with those of the SM Higgs boson [11, 12, 13]. The LHC will rerun again in 2015 with the nominal center of mass energy $\sqrt{s}$ =14 TeV therfore, in this paper, we consider the $H \rightarrow ZZ \rightarrow 4\mu$ at 14 TeV and integrated luminosity of 300 fb^{-1} of pp collisions. In this analysis we look for two pairs opposite-charge muons, compatible with a ZZ^* system, appearing as a narrow resonance on top of a smooth background.

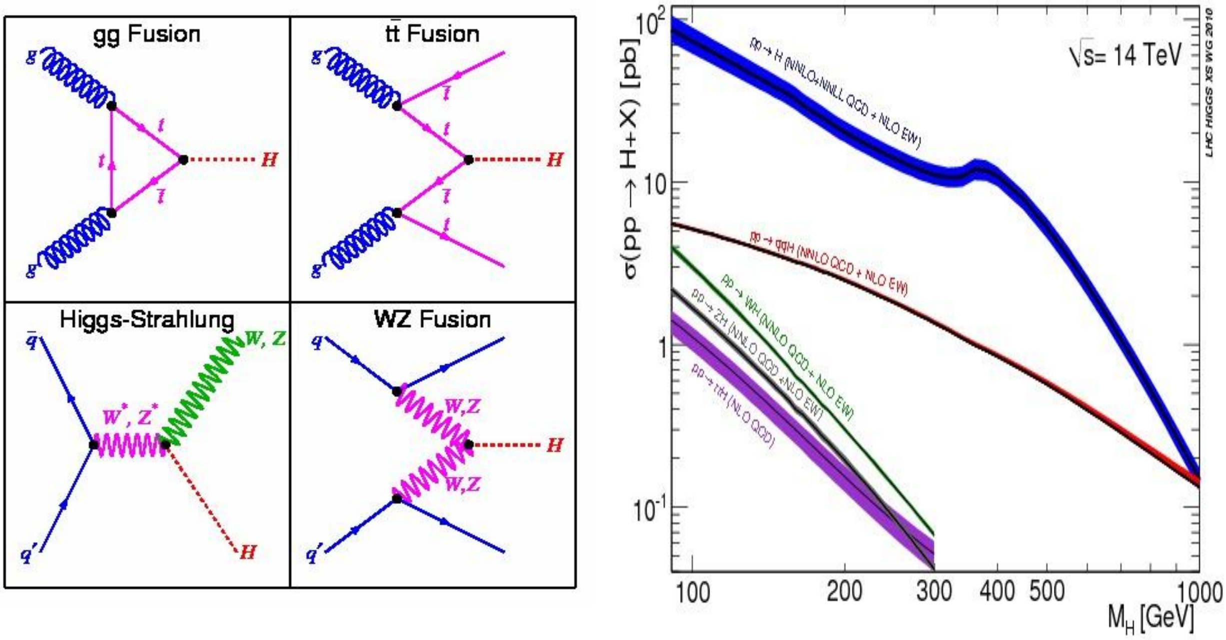


Fig. (1): Higgs production mechanisms [left] and the corresponding cross sections as a function of higgs boson mass [right].

2- HIGGS PRODUCTION

In the standard model, Higgs boson production in proton-proton collisions can happen through four main modes: gluon gluon fusion $gg \rightarrow H$; vector boson fusion $q\bar{q} \rightarrow \mathrm{H} + 2\mathrm{jets}$, associated production of a Higgs boson with a W or Z boson(W/ZH), and associated production with a $t\bar{t}$ pair. These processes are represented by the Feynman diagrams, given in Figure 1[Left] and their corresponding cross section as a function of Higgs mass is shown in Figure 1[Right].

2.1- Gluon-Gluon Fusion

Among all the Higgs production mechanisms at LHC, the gluon-gluon fusion is dominant over the whole mass range due to the high luminosity of gluons in proton-proton collisions. The process is shown in Figure 1 [Top left], which is performed via a top quark loop.

2.2- Vector Boson Fusion

The vector boson fusion (VBF) is the second dominant process of the Higgs boson production shown in Figure 1 [Bottom right] with its cross-section of about a factor of 10 smaller than the gluon-gluon fusion production mode in most of the Higgs mass regions. The cross-sections of the two production modes become comparable only for very high Higgs masses (1 TeV).

2.3- Associated Production

In the associated production, or the Higgsstrahlung process, shown in Figure 1 [Bottom left] , the Higgs boson is produced in association with a W or Z boson. The cross-section for this process is several orders of magnitude lower than the gluon-gluon and the VBF production modes and approaches the production rates from VBF only for masses around MH = 100 GeV. The last production mode is illustrated in Figure 1 [Top right]. It is the associated production of a Higgs boson with a $t\bar{t}$ pair and the cross-section is about 100 times less than the gluon-gluon fusion, or even worse and only several times lower than VBF around MH =100 GeV So, due to this low cross section we will neglect this production mode in this paper.

3- METHODOLOGY

Signal samples: The Monte Carlo (MC) simulated samples, generated with programs that are based on theoretical calculations for both the SM Higgs boson signal and relevant background Processes. The samples of Higgs boson signal events produced in either gluon fusion (ggH) or vector-boson fusion (VBF) or associated production with W/Z bosons processes are generated with Madgraph[14] generator at next-to-leading order (NLO) accuracy at higgs mass 126 GeV. The PYTHIA[15] generator was used to simulate showering, hadronization and jet fragmentation. The detector response is also simulated with DELPHES fast simulator[16]. Higgs boson signal samples are generated with 100K events for all the three production mechanisms (gluon-gluon fusion, vector boson fusion,W/Z associated production) and then each sample is weighted according to their production cross sections.

Background samples: The dominant background (irreducible background) to the Higgs signal in this channel is the standard model ZZ and Z production via $q\bar{q}$ annihilation and gluon fusion production $q\bar{q} \to ZZ$ and $gg \to ZZ$, which is referred to as ZZ in what follows. The background to our signal also include instrumental backgrounds (reducible background)arise from di-bosons $WW + jets$, and $WZ + jets$ events in which hadronic jets or secondary leptons from heavy meson decays are misidentified as primary leptons which can contribute in early stages of the analysis. Smaller contributions arise from $t\bar{t}$ in the decay mode $t\bar{t} \to W^+b\,W^-\bar{b} \to l^+\upsilon l^-\bar{\upsilon}b\bar{b}$ where the final states contain two isolated leptons and two heavy-flavor jets producing secondary leptons. The background samples are generated also with MADGRAPH, interfaced with PYTHIA, simulated with DELPHES and normalized to cross sections computed at LO.

Table [1] summarizes the Monte Carlo simulation samples used with their corresponding cross sections and the number of weighted events. In the generation step all MC samples were produced with the requirements that each muon has to have transverse momentum p_T greater than 5 GeV and with pseudo rapidity η less than 2.7 and $\Delta R < 0.4$ between any 2 muons.

Table (1): Simulated samples for signal and background.

Process Weighted	Cross section[fb]	Events	Comments and Sample name
Higgs Signal			
$gg \to H \to ZZ^* \to 4\mu$	0.6617	198.51	M_H =126GeV/c^2 (gluon gluon fusion)
$pp \to H \to ZZ^* \to 4\mu$	0.07011	21.033	M_H =126GeV/ c^2 (vector boson fusion)
$pp \to VH \to ZZ^* \to 4\mu$	0.02626	7.878	M_H =126GeV/ c^2 (W/Z associated production)
Background			
$pp \to ZZ^* \to 4\mu$	6.018	1805.4	Excluding gamma emission
$pp \to Z\gamma^* \to 4\mu$	8.991	2697.3	
$pp \to WW \to 2\mu 2\upsilon$	552.4	165720	WWTO2MU2NU
$pp \to WZ \to 3\mu\upsilon$	53.97	16.191	WZTO3MUNU

3.1- Muon Selection

Collision events analyzed with ROOT[17] are selected by requiring the presence of muons with minimal transverse momentum of 5 GeV and have peseduorapidity $\eta < 2.4$ and $\Delta R < 0.4$ between any 2 muons.

Figure [2] The transverse momentum p_T and pseudo rapidity η distribution for the leading muon for signal and background before any selection cut.

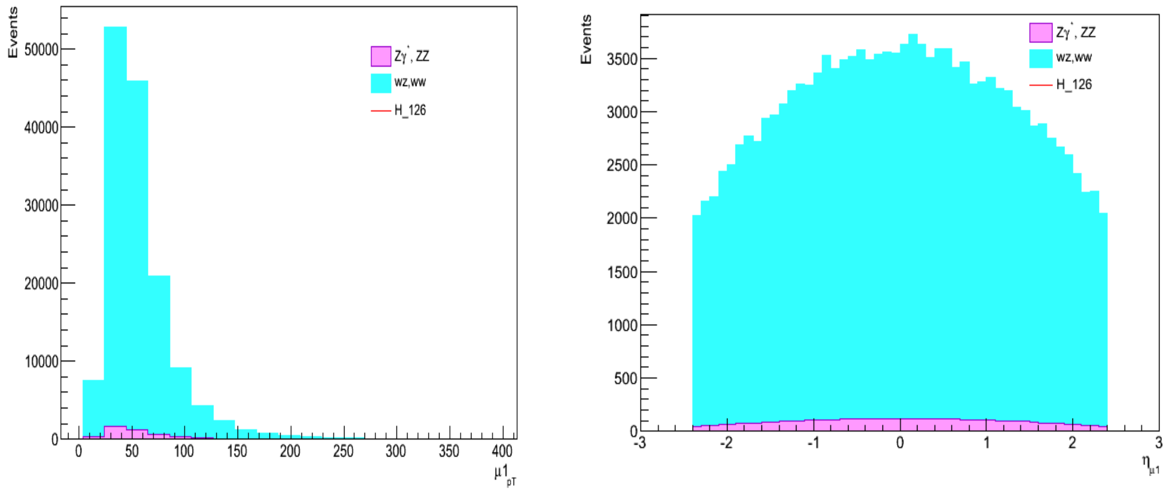


Fig. (2): shows the transverse momentum and pseudo rapidity distributions for leading muon before any cuts.

3.2- Event Selection

The analysis strategy was set such that selecting the highest p_T muons and reconstruct the first Z ($Z1$) by combination two muons that gives the closest mass to Z boson mass. A second Z ($Z2$) is reconstructed using the other 2 muons in the event. The higgs boson is then reconstructed as the invariant mass of the two Z's. We impose the following sequence of selection requirements:

1. **First Z candidate selection:** a pair of muon candidates of opposite charge with reconstructed mass $M1{,}2$ closest to the nominal Z boson mass is retained and denoted $Z1$ (on shell mass).
2. **$Z1$ mass cut:** the selected pair should satisfy $40 < MZ1 < 120$ GeV/c^2.
3. **Events with four or more muons are selected:** Third and fourth muons candidate with oppositely charge are selected.
4. **$Z2$ ($Z1 +$ 2 muons):** we build the second muon papair denoted $Z2$ from the two opposite charge muons selected in the last step.
5. **Missing transverse energy (MET):** we applied cut on missing transverse energy (MET) to be less than 30 GeV to suppress the contribution from "fake leptons" (any jet miss-reconstructed as a lepton and any lepton originating from a heavy meson decay) to bring $t\bar{t}$ and WW/WZ contributions to a level comparable to or below the contribution of the main backgrounds as shown in figure [3]. We can see that this cut $MET < 30$ is an effective cut that can eliminate or reduce most of WW/WZ background events without loss in signal events. The contribution from $t\bar{t}$ was studied and it was fairly negligable after applying MET cut.
6. **Higgs phase space ($4l$ space):** we build the higgs boson mass from the $4l$ phase space choice in the last steps.
7. **Four muons mass cut:** the four selected muons should satisfy $95 < M4l < 135$ GeV/c^2.

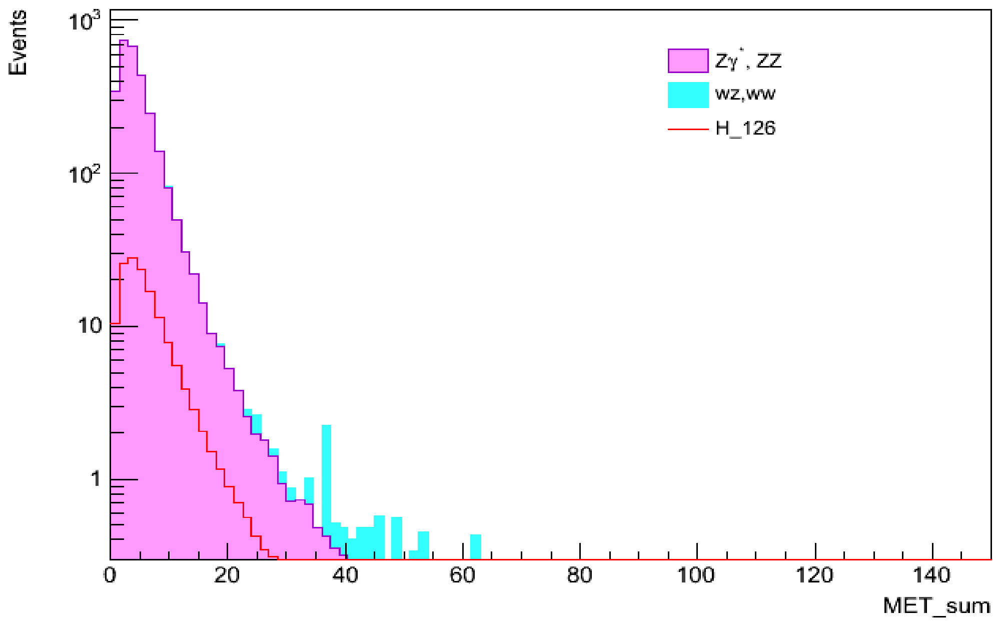
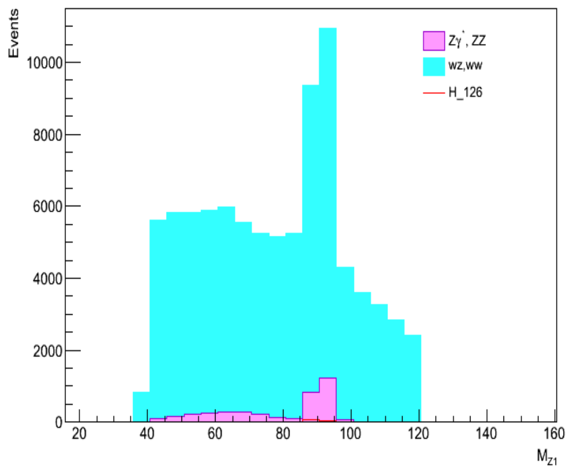


Fig. (3): missing transverse energy below the contribution of the main backgrounds

4- RESULT AND DISCUSSION

Figure [4] (left panel) shows the reconstructed di-muon invariant mass selected as $Z1$ for signal and background shown after selecting events with $(40 < MZ1 < 120)$. Figure [4] (right panel) shows the mass for second Z ($Z2$). The two peaks in this distribution are due to the invariant mass of 2 muons from the gamma decay (mostly from Z contribution) while the second peak is due to the invariant mass of 2 muons from Z decay (ZZ background). After the event selection, the remaining background is dominated by ZZ background in the $4l$ channel. We present the transverse momentum and Pseudo-rapidity distribution for the leading muon, $Z1$ mass and the selected $4l$ events in the Higgs phase space for signal and background after all cuts. Table [2] shows the expected number of remaining weighted events after each selection step in $4l$ final state. All the backgrounds are reduced by several orders of magnitude.



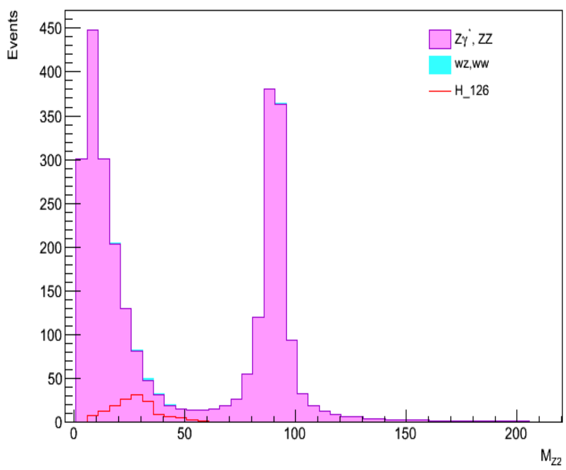


Fig. (4): (left)shows the reconstructed di-muon invariant mass selected as $Z1$ for signal and background, (right) shows the mass for second Z ($Z2$).

Table (2): The expected number of remaining weighted events after each selection step

Process	ggH	VBF	VH	$ZZ/Z\gamma$	WW/WZ
No. before any cut	198.51	21.033	7.878	4502.7	181911
At least 2 muons ($N\mu < 2$)	196.815	20.9255	7.878	4458.622	142354.266
Closet to MZ	192.618	20.5896	7.6229	4367.877	140965.3064
$40 < MZ1 < 120$	176.952	19.144	7.00496	3927.8737	84055.75545
At least 4 muons($N\mu < 4$)	126.9035	14.489	5.0157	2814.7989	10.0765
$METsum < 30$	126.22655	13.667	3.668	2809.3985	2.1048
$95 < M4\mu < 135$	125.657	13.6056	3.556	307.6041	0.16191

The transverse momentum and pseudo rapidity for leading muon after all cuts is shown in Figure [5]. According to table 2 we can see how efficient is our selection cuts. WW/WZ was reduced by six order of magnitude Also, we can see that the dominant background is ZZ background which remain for the last step in the selection cuts as it is irreducible background and it is reduced by one order of magnitude.

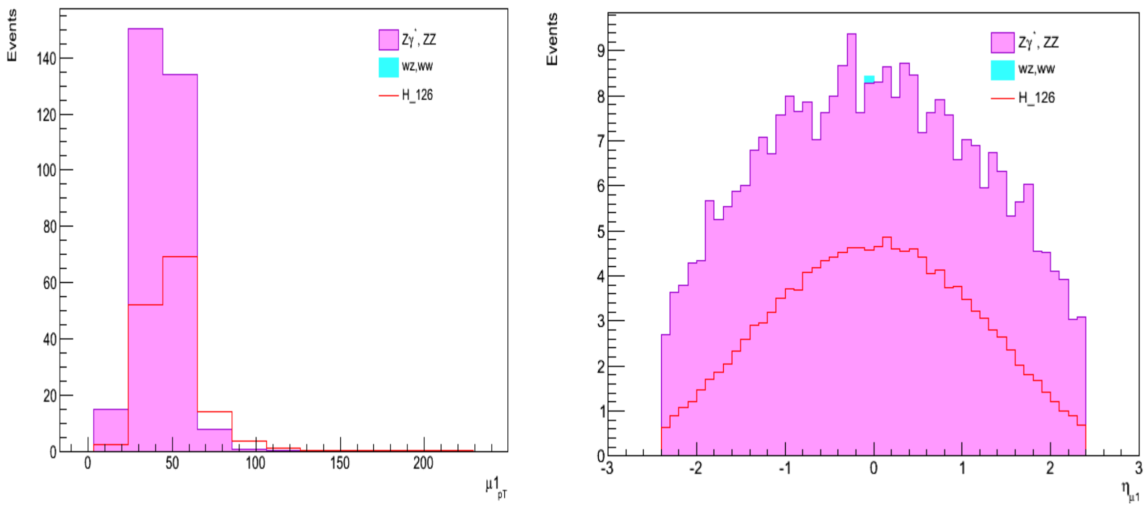


Fig. (5): The transverse momentum and pseudo rapidity distribution for leading muon after all cuts.

Figure [6] (left panel) shows the reconstructed di-muon invariant mass, peak around 90 GeV/c^2 (the nominal Z mass), selected as $Z1$ for signal and background shown after all selection cuts. It is clear that the ZZ contribution is the dominant background contribution. Figure [6] (right panel) shows the mass for second Z ($Z2$) built after all cuts it is off shell mass also the dominant background is ZZ background. The Invariant mass distribution and pseudo rapidity for 4 muons after all selection cuts for signal and background shown in Figure [7].

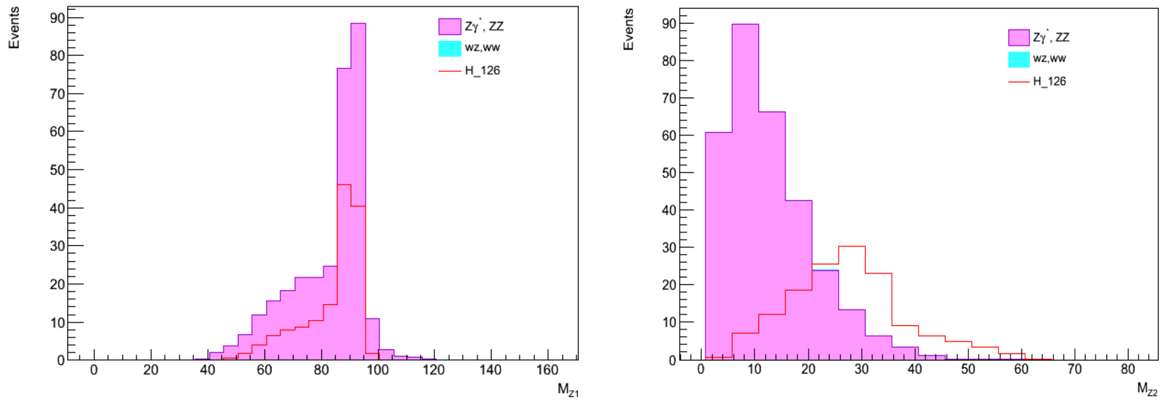


Fig. (6): (Left panel) Shows the invariant mass of two muons $(Z1)$ built after all cuts, (Right panel) shows the $Z2$ mass.

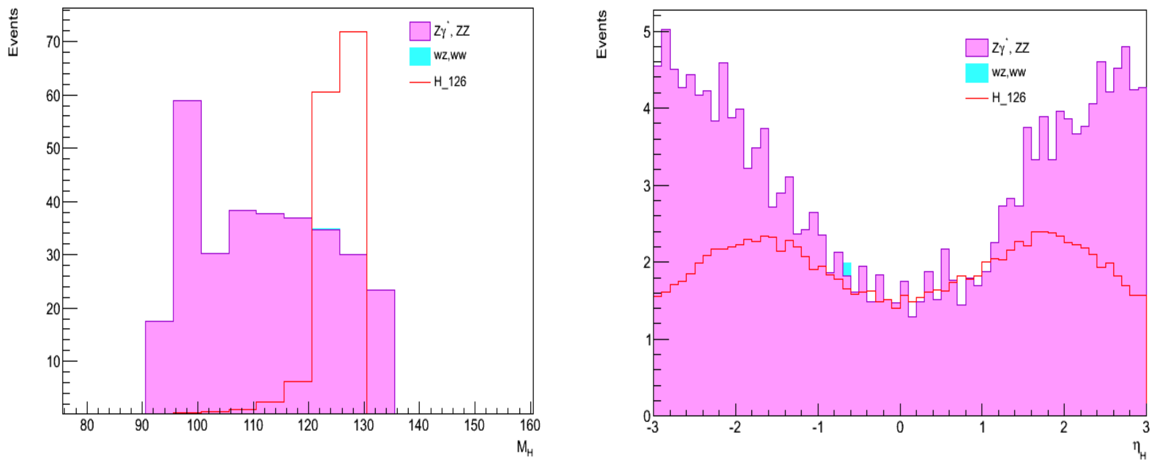


Fig. (7): (Left panel) shows the 4 muons invariant mass after all cuts for signal and background (Right panel) shows the pseudo rapidity for higgs boson.

5- CONCLUSION

We studied the higgs production in LHC at 14 TeV assuming higgs decay to four muon final state, our cuts are optimized to select the higgs signal from the SM background.

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