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HEAVY HIGGS BOSON SEARCH IN THE $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ CHANNEL IN CMS

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We investigate possibilities of search for the Standard Model Higgs boson in the $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ channel in the upper mass reach in the Compact Muon Solenoid detector (CMS). By using appropriate cuts on the data, it was found that CMS can detect Higgs boson up to the mass of about 750 GeV at $\geq 5\sigma$ significance level with the designed integrated luminosity of 10^5 pb^{-1}. The mass reach extends to about 850 GeV at $3 \cdot 10^5$ pb^{-1}.

1. Introduction

The most promising channel for the Standard Model (SM) Higgs boson discovery at Large Hadron Collider (LHC) is $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$. In a previous study that included detailed bremsstrahlung effects for electrons and muons [1,2], it was shown that CMS will be able to detect Higgs boson with 5σ significance level up to $m_H \approx$ 400 GeV at 10^4 pb^{-1} and up to $m_H \approx 650$ GeV at 10^5 pb^{-1} at the nominal LHC energy of $\sqrt{s} = 14$ TeV.

The main background to the $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ process is the irreducible ZZ continuum production coming from $q\bar{q} \longrightarrow ZZ$ and $gg \longrightarrow ZZ$. The $t\bar{t}$ and $Zb\bar{b}$ backgrounds are small and reducible by a Z-mass cut [3].

Here we investigate the maximal Higgs mass reach in this channel. At high masses, the main problem stems from the large Higgs natural width which increases from about 110 GeV at $m_H = 600$ GeV to about 250 GeV at $m_H = 800$ GeV, reaching about 0.5 TeV at $m_H = 1$ TeV [4,5]. To observe such a broad signal requires maximal luminosity and appropriately chosen cuts to suppress the background without affecting the signal too much. Several luminosity options are investigated: 10^4 pb^{-1}; $3 \cdot 10^4$ pb^{-1}; 10^5 pb^{-1} and $3 \cdot 10^5$ pb^{-1} — corresponding to different working regimes of LHC.

2. *Simulation for the signal and background*

The events are generated by PYTHIA 5.7 with CTEQ2L structure functions [6] and the top quark mass of 174 GeV according to the CDF results [7]. The production processes are gg fusion and WW/ZZ fusion processes (with gg fusion contributing about 65% at $m_H = 800$ GeV). The production with heavy flavours contributes less than 1%. The cross-section times branching ratio for $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ for Higgs masses from 500 to 950 GeV are given in Table 1. The cross-section is falling rapidly with increasing Higgs mass. The only important background is the irreducible ZZ continuum production. For this background, only the $q\bar{q} \longrightarrow ZZ$ process is simulated with PYTHIA. To include the $gg \longrightarrow ZZ$ contribution, we multiply the $q\bar{q}$ result by 1.33, because of the similarity in topology and kinematics of the two processes [8]. No higher order corrections are taken into account, neither for the signal nor for the background. The internal photon bremsstrahlung is taken into account by a dedicated photon radiation program PHOTOS 2.0 [9].

TABLE 1.
Total cross–section for $H \to ZZ \to 4l^{\pm}$ and ZZ background times branching ratio and detector acceptance after geometrical and kinematic cuts.

m_H [GeV]	500	550	600	650	700	750	800	850	900	950	ZZ
σ_{total} [fb]	3.18	2.24	1.62	1.18	0.89	0.67	0.51	0.40	0.32	0.25	60.26
Accept. [%]	75	78	78	79	79	80	80	79	79	78	44

The lepton momentum resolution has been studied by detailed GEANT simulations of detector response [10,11]. The resulting muon resolution ($\Delta p/p < 1.4\%$ for $p_T < 100$ GeV/c) is parametrized as a function of p and $|\eta|$, where p and $|\eta|$ are momentum and rapidity of muons, respectively, and these parameters are used to smear the momenta of muons. The electron momentum measurement is affected by external bremsstrahlung. Effects of external bremsstrahlung on electron energy measurements depend on the amount of material traversed and hence on the electron rapidity. The effect is substantial for the present CMS tracker design because it has on average 27% of radiation length. Detector response to electrons, ways to reconstruct their energy and the Z mass, the Z reconstruction efficiency and resolution were studied by detailed GEANT simulations [12] and again parametrized for fast simulations.

To account for geometrical inefficiences, a reconstruction efficiency per lepton of 0.95 is used for both electrons and muons. It is believed that such a reconstruction efficiency is achievable in the $ZZ \longrightarrow 4l^{\pm}$ final state by inclusion of the tracker measurements [2].

3. Signal selection and significance

3.1. Lepton cuts

In the event selection we require: one electron with $p_T > 20$ GeV, one with $p_T > 15$ GeV, and the remaining two electrons with $p_T > 10$ GeV, all within $|\eta| < 2.5$. For muons, the corresponding p_T cuts are 20, 10 and 5 GeV/c, and the rapidity coverage is $|\eta| < 2.4$. Signal and background acceptances are given in Table 1, together with the total cross-section for the ZZ continuum background. Acceptance slowly varies between 78 and 80%, while for the background, which is produced less centrally, it is 44%. No lepton isolation cuts are applied, because there is no background whose reduction is dependent on isolation. In the whole mass range, ZZ continuum background is the dominant one. To avoid any residual $t\bar{t}$ background, we introduce a cut on the Z–mass by $m_{l^+l^-} = m_Z \pm 4\sigma_Z$, with $\sigma_Z =$ 3 GeV.

Multi–lepton mass resolution for large Higgs masses is affected mostly by its natural width, and to a lesser extent by internal and external bremsstrahlung, lepton reconstruction efficiency of the detector and it's energy and momentum resolution. In Table 2 we list the number of signal and background events, taking into account radiation and instrumental effects, using the mass window $m_Z \pm 4\sigma_Z$. These effects combine to give a Z reconstruction efficiency of about 80% in the range of masses we are interested [2].

TABLE 2.
The number of signal and background events for an integrated luminosity of 10^5 pb^{-1} *with all instrumental and radiation effects included and signal significance.*

m_H [GeV]	500	550	600	650	700	750	800	850	900	950
N_S	115.7	79.8	57.4	41.3	30.1	25.0	18.3	14.9	11.1	9.0
N_B	75.9	55.0	47.9	38.7	31.6	32.4	24.2	25.9	19.1	19.1
Signific. [σ]	11.0	9.0	7.1	5.8	4.6	3.9	3.2	2.5	2.2	1.8

3.2. Signal selection and significance

We considered different p_T cuts both on single Z's and on their scalar sum $p_T^{Z1}+p_T^{Z2}$ distribution. The best results are obtained if one requires a pair of Z's with $p_T^{Z1}+p_T^{Z2} > m_{ZZ}/1.4$. For $m_H = 700$ GeV, the distributions of $p_T^{Z1}+p_T^{Z2}$ for signal and background are shown in Figs. 1a) and b) in the interval $m_{ZZ} = m_H \pm 2\sigma_H$, where we take σ_H to be half of the Higgs natural width. To make the intrinsically broad signal stand out more prominently over the background, we tried also to apply cuts based on the angular distribution of leptons in the Z–rest–frame, as suggested previously [8,13,14]. Z's coming from Higgs bosons are mostly longitudinally polarized, whilst Z's in the ZZ continuum are mostly transversal. The difference becomes more pronounced with increasing Higgs mass (since it is proportional to m_H^2/m_Z^2) [13]. Leptons coming from longitudinally polarized Z's have an angular distribution in the Z helicity frame

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\vartheta} \sim \sin^2\vartheta, \tag{1}$$

while, transversaly polarized Z's give

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\vartheta} \sim 1 + \cos^2\vartheta, \tag{2}$$

where ϑ is the angle of a lepton in the Z-rest-frame measured with respect to the Z direction in the H-rest-frame.

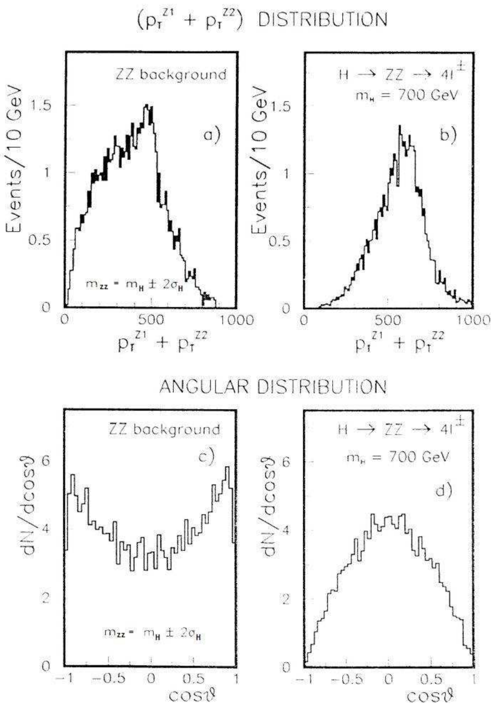

Fig. 1. a) Distribution of $p_T^{Z1} + P_T^{Z2}$ *for* ZZ *background in the mass window* $m_{ZZ} = m_H \pm 2\sigma_H$ *for* $m_H = 700$ GeV. *b) Distribution of* $p_T^{Z1} + P_T^{Z2}$ *for the Higgs signal at* $m_H = 700$ GeV. *c) Lepton angular distribution for* ZZ *background in the window* $m_{ZZ} = m_H \pm 2\sigma_H$ *for* $m_H = 700$ GeV. *d) Angular distribution of the signal for* $m_H = 700$ GeV.

We use an asymmetric cut in the two angles ϑ_1 and ϑ_2, where ϑ_1 and ϑ_2 are the decay angles in the respective Z–rest–frames. Figures 1c) and d) show these angular distributions for signal and background for m_H = 700 GeV in the mass window $m_{ZZ} = m_H \pm 2\sigma_H$. Figure 2 shows the distribution of ϑ_1 vs. ϑ_2 ($\vartheta_1 > \vartheta_2$) for both signal and background in the range $m_H \pm 2\sigma_H$, for m_H = 700 GeV.

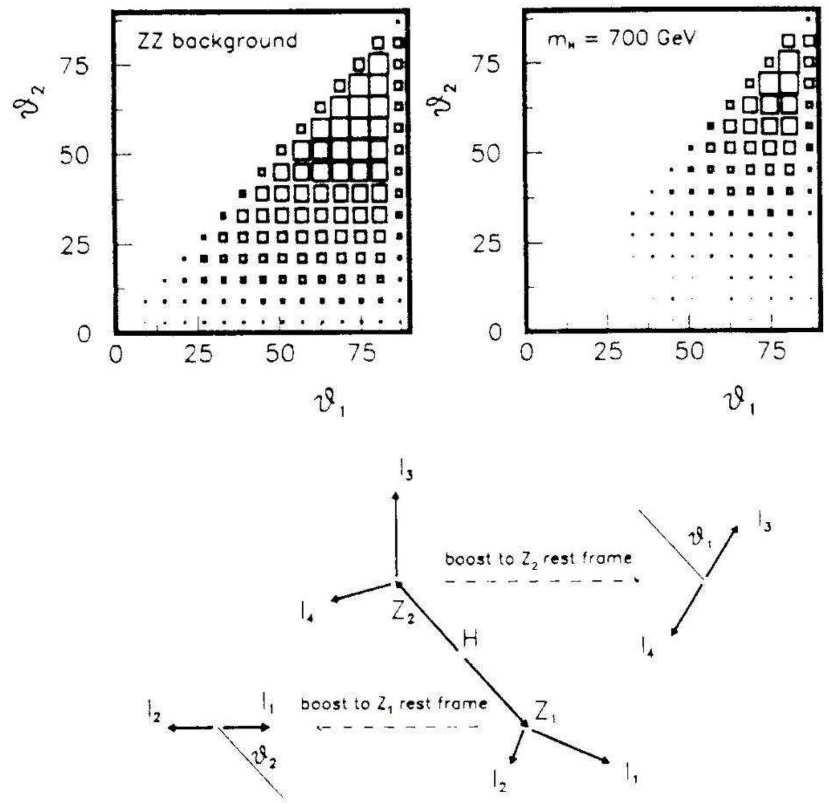

Fig. 2. Angular distributions of leptons coming from a pair of Z's ($\vartheta_1 > \vartheta_2$) in the Z helicity frame for the ZZ background in the interval $m_{ZZ} = m_H \pm 2\sigma_H$ and for the signal, all for m_H = 700 GeV. Also shown is an illustration of $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ decay in the Z helicity frame.

We calculated the signal significance for a number of combinations of angular and p_T cuts. Only at the very high masses ($m_H \geq$ 850 GeV) and highest integrated luminosities, the angular cut in combination with a p_T cut leads to some improvement in the significance. This happens because even a slight angular cut (for instance $\vartheta_1 > 45^0$ and $\vartheta_2 > 25^0$), whilst reducing background by about 60%, also reduces the signal by about 30%, which for a broad, non–prominent Higgs signal results in decreased significance. We conclude that a cut on Z's p_T distribution alone is to be preferred for the Higgs mass region from 500 – 800 GeV.

TABLE 3.
Number of signal and background events for an integrated luminosity of 10^5 pb^{-1} *and* $m_H = 600$ GeV, *together with resulting signal significances for different cuts: a)* $p_T^{Z1} + p_T^{Z2} > m_{ZZ}/1.4$, *b)* $p_T^{Z1} + p_T^{Z2} > m_{ZZ}/2.1$, *c)* $(\vartheta_1, \vartheta_2) > (45^0, 25^0)$.

Cut type	no cut	a	b	c	a + c	b + c
N_S	57.4	46.2	54.6	40.0	32.5	38.3
N_B	47.9	20.4	32.0	23.8	10.5	16.0
Significance [σ]	7.1	8.0	7.8	6.6	7.5	7.4

Table 3 gives the number of signal and background events and signal significance for $m_H = 600$ GeV at $L = 10^5$ pb^{-1}, and all possible combinations of the following cuts

$$p_T^{Z1} + p_T^{Z2} > \frac{m_{ZZ}}{1.4}; \;\; p_T^{Z1} + p_T^{Z2} > \frac{m_{ZZ}}{2.1}; \;\; (\vartheta_1, \vartheta_2) > (45^0, 25^0).$$

Signal and background are taken in the range $m_H \pm 2\sigma_H$. The cut that gives the best significance, $p_T^{Z1} + p_T^{Z2} > m_{ZZ}/1.4$, reduces the signal by about 20% while at the same time it reduces the background by about 60%.

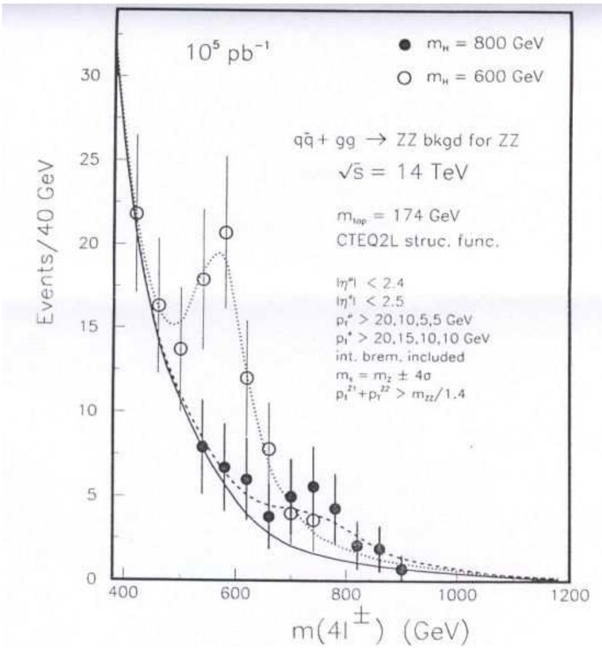

Fig. 3. The invariant mass of $4l^\pm$ *for* $m_H = 600$ GeV *(dotted and dashed lines, respectively) over the continuum background (full line) for an integrated luminosity of* 10^5 pb^{-1}. *The circles represent the signal points with their statistical errors.*

Figure 3 shows the invariant $4l^{\pm}$ mass over the continuum background for $m_H = 600$ and 800 GeV and $L = 10^5$ pb^{-1}. Figure 4 shows the $4l^{\pm}$ mass distribution for the same Higgs masses, superimposed on the ZZ background for different integrated luminosities.

TABLE 4.
The final number of events for $H \to ZZ \to 4l^{\pm}$ and ZZ background for an integrated luminosity 10^5 pb^{-1} after $p_T^{Z1} + p_T^{Z2} > m_{ZZ}/1.4$ cut and signal significance.

m_H [GeV]	500	550	600	650	700	750	800	850	900	950
N_S	91.2	63.8	46.2	33.3	24.3	19.9	14.6	11.9	6.3	6.5
N_B	30.0	22.6	20.4	16.9	13.8	14.2	10.6	11.3	3.8	6.8
Significance [σ]	12.5	10.1	8.0	6.5	5.3	4.4	3.7	3.0	2.5	2.0
σ_H (GeV)	30	40	55	70	85	105	130	155	180	200

Table 4 and Fig. 5 give our final results. Table 4 gives the number of signal and background events and significance of the signal in the window $m_H \pm 2\sigma_H$ for different luminosities, using the $p_T^{Z1} + p_T^{Z2} \geq m_{ZZ}/1.4$ cut. Also shown are values of σ_H for different Higgs masses. The plot of signal significance at various luminosities is shown in Fig. 5

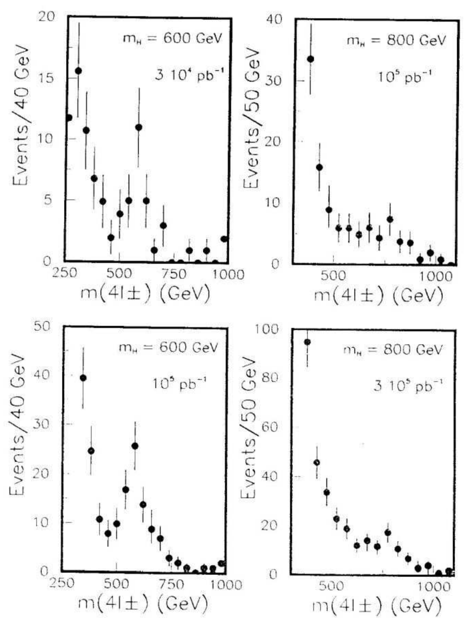

Fig. 4. The invariant mass of $4l^{\pm}$ superimposed on the ZZ background for a) $m_H = 600$ GeV and $L = 3 \cdot 10^4$ pb^{-1}, b) $m_H = 800$ GeV and $L = 10^5$ pb^{-1}, c) $m_H = 600$ GeV and $L = 10^5$ pb^{-1} and d) $m_H = 800$ GeV and $L = 3 \cdot 10^5$ pb^{-1}.

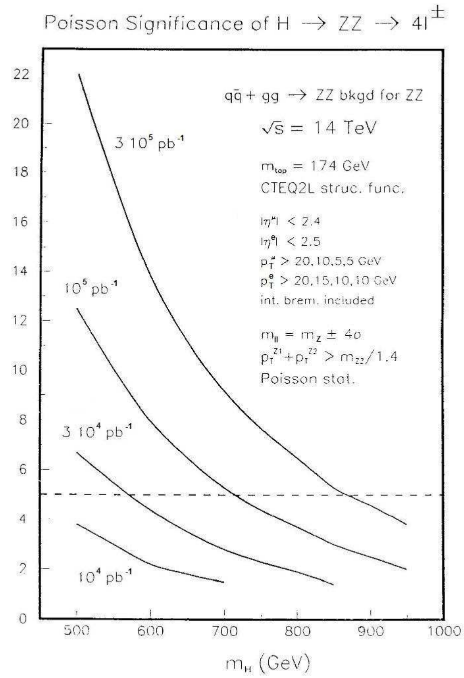

Fig. 5. The significance of the signal for different Higgs masses, calculated according to Poisson statistics and for various integrated luminosities.

We calculate signal significance according to Poisson statistics with signal and background events taken in $m_H \pm 2\sigma_H$.

4. *Conclusions*

We have studied possibilities of detection of $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ at large masses, $m_H \geq 500$ GeV. The discovery range extends up to

$$\begin{aligned} m_H &\approx 650 \text{ GeV} \quad \text{at} \quad 3 \cdot 10^4 \text{ pb}^{-1} \\ m_H &\approx 750 \text{ GeV} \quad \text{at} \quad 10^5 \text{ pb}^{-1} \\ m_H &\approx 850 \text{ GeV} \quad \text{at} \quad 3 \cdot 10^5 \text{ pb}^{-1}. \end{aligned}$$

A significant improvement in significance is obtained with a cut on the scalar sum of the p_T of the two Z's. A cut based on the helicity angular distribution of leptons leads to some improvement of the signal to background ratio, but does not lead to improved signal significance. A more complete maximum likelihood method could probably make better use of the decay angular distributions.

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TRAŽENJE TEŠKOG HIGGSOVOG BOZONA U KANALU $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ POMOĆU CMS DETEKTORA

Ispitujemo mogućnosti za traženje Higgsovog bozona prema Standardnom modelu u kanalu $H \longrightarrow ZZ \longrightarrow 4l^{\pm}$ u području osjetljivosti za velike mase Kompaktnog mionskog solenoidnog (CMS) detektora. Primjenom pogodnih rezova našli smo da se pomoću CMS detektorskog sustava mogu opaziti Higgsovi bozoni do mase oko 750 GeV na razini pouzdanosti $\geq 5\sigma$, uz pretpostavku integralnog luminoziteta od 10^5 pb^{-1}. Za $3 \cdot 10^5$ pb^{-1} mogli bi se opaziti bozoni do mase 850 GeV.