How to find a Higgs boson with a mass between 155 and 180 GeV at the CERN LHC

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We reconsider the signature of events with two charged leptons and missing energy as a signal for the detection of the standard model Higgs boson in the mass region $M(\text{Higgs})=155-180$ GeV. It is shown that a few simple experimental criteria allow us to distinguish events originating from the Higgs boson decaying to $H\rightarrow W^+W^-$ from the nonresonant production of W^+W^-X at the CERN LHC. With this set of cuts, signal to background ratios of about one to one are obtained, allowing a 5–10σ detection with about 5 fb^{-1} of luminosity. This corresponds to less than one year of running at the initial lower luminosity $\mathcal{L}=10^{33}$ cm^{-2}s^{-1}. This is significantly better than for the hitherto considered Higgs boson detection mode $H\rightarrow Z^0Z^{0*}\rightarrow 2\ell^+2\ell^-$, where in this mass range about 100 fb^{-1} of integrated luminosity are required for a 5σ signal. [S0556-2821(97)02701-X]

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I. INTRODUCTION

The standard model (SM) of elementary particle physics has been highly successful in explaining all experimental data [1]. With the recent discovery of the top quark [2], the Higgs boson is the only remaining missing piece, albeit an essential one. Within the SM, it provides the mechanism to dynamically break the electroweak symmetry *and* gives masses to the electroweak gauge bosons. The same mechanism gives masses to the spin-1/2 fermions such as the top quark and the electron. The Higgs boson is therefore essential for our understanding of mass. Furthermore, the theoretical structure of the Higgs sector in the SM is the main motivation for speculations on physics beyond the SM, e.g., supersymmetry or technicolor. The discovery of the Higgs boson and the determination of its couplings could possibly provide an essential clue to this new realm. The search for the Higgs boson is therefore considered to be *the* most important task for future collider physics.

With the present energy upgrade of the CERN Large Electron Positron collider LEP2, the Higgs boson can be discovered for $M_H \leqslant 98$ GeV [3] ($\sqrt{s}=192$ GeV). For larger masses the CERN Large Hadron Collider (LHC) to be built at CERN, is the most promising discovery machine. There, the Higgs boson search is usually split into three Higgs boson mass regions [4–6]

$$\begin{aligned} &\text{(i)} \quad 90\ \text{GeV} < M_H < 130\ \text{GeV},\\ &\text{(ii)} \quad 130\ \text{GeV} < M_H < 2M_{Z^0},\\ &\text{(iii)} \quad 2M_{Z^0} < M_H < 800\ \text{GeV}. \end{aligned} \tag{1.1}$$

For the mass regions (i) and (iii), Higgs boson detection with large significance is possible by the observation of narrow mass peaks using the decays $H\rightarrow\gamma\gamma$ and $H\rightarrow Z^0Z^0\rightarrow 2\ell^+2\ell^-$ respectively [4–6]. For most of the mass region (ii) previous experimental studies, assuming excellent energy and momentum measurements of electrons and muons, have obtained promising mass peaks from the channel $H\rightarrow Z^0Z^{*0}\rightarrow 2\ell^+2\ell^-$, despite the low branching ratios [4–6]. However, the mass range between $\approx$155 and 180 GeV remains especially difficult to detect because the Higgs boson decays almost exclusively to a pair of on shell $W^\pm$'s [4–8]. Consequently, a large integrated luminosity of about 100 fb^{-1} is required for the Higgs detection using this four-charged-lepton signature.

In this work we focus exclusively on the hitherto difficult mass region (ii) with

$$155\ \text{GeV} < M_H < 180\ \text{GeV}. \tag{1.2}$$

We show that despite the absence of a narrow mass peak the decay

$$\begin{aligned} &H\rightarrow W^+W^-\rightarrow(\ell^+\nu)(\ell'^-\overline{\nu}),\\ &\ell,\ell' = e,\mu,\tau(\rightarrow\ell\nu\overline{\nu}), \end{aligned} \tag{1.3}$$

provides a straightforward discovery channel, especially in this mass range.

II. $H\rightarrow W^+W^-\rightarrow(\ell^+\nu)(\ell'^-\overline{\nu})$

The Higgs decay to two W bosons as well as the branching ratio, was first calculated in Ref. [9] at the tree level. The one-loop result was obtained shortly thereafter [10]. In the mass range (1.2) the Higgs decay to two $W^\pm$ bosons is dominant with a branching ratio close to unity. For $W^\pm$ and Z^0 boson decays, isolated high p_t electrons and muons are typically clean and detectable signs of events. Despite the larger branching ratios, the identification of $W^\pm$ and Z^0 using the decays into jets is difficult to distinguish from the abundant jet background at the LHC even if one (W,Z) decays leptonically [11]. We therefore consider only the leptonic final states,

$$W^{\pm}\rightarrow \ell^{\pm}\nu_{\ell}, \quad \ell=e,\mu, \tag{2.1}$$

$$W^{\pm}\rightarrow \tau^{\pm}\nu_{\tau}\rightarrow \ell^{\pm}\nu_{\ell}\nu_{\tau}. \tag{2.2}$$

As a result, about 7% of all W-pair events will have two oppositely charged leptons (e,μ) [12] and at least two neutrinos resulting in a considerable missing transverse momentum imbalance. This should be compared to the gold-plated Higgs decay signature into two Z bosons followed by their leptonic decays. While the latter channel provides a narrow mass peak, it suffers from the low Z branching ratio to electron and muon pairs with a four-charged-lepton branching ratio of less than 0.45% [12]. Combining this, with the factor of roughly 20–30 for the branching ratio of the Higgs to $W^{+}W^{-}$ with respect to $Z^{0}{*}Z^{0}$ in the mass range (1.2) [5–8], we see that the decay signal (1.3) is more than 2 orders of magnitude above the gold-plated signature. This large rate can therefore be expected to compensate for the absence of a narrow mass peak due to the two undetected neutrinos.

For an intermediate mass Higgs, the fully leptonic decay signature (1.3) was first studied by Glover *et al.* [13] for the LHC ($\sqrt{s}=16$ TeV). They explicitly did not consider the background from $t\bar{t}$ production and focused on the ''irreducible'' background from $W^{\pm}$ pair production. However, their proposed selection criteria do not directly exploit the spin correlations of the W's which are different for signal and background. They concluded that the final state (1.3) should provide detectable Higgs signals at the LHC. Subsequently, Barger *et al.* [14] performed a more detailed parton level analysis of this signature for the LHC ($\sqrt{s}=16$ TeV). They went beyond [13] to include the significant $t\bar{t}$ background for $m_{\mathrm{top}}=150, 200$ GeV (the top quark mass was not yet known). Furthermore, in their study, $W^{\pm}$'s from signal and background are simulated only with their leptonic decays to $e\nu$ and $\mu\nu$. They did not include the mode (2.2). Otherwise their cuts are very similar to those in [13], in particular they also do not make direct use of the $W^{\pm}$ spin correlations resulting from Higgs decays. They again concluded, despite a much worse signal to background ratio, that this channel should provide a reasonable possibility to detect the Higgs in this mass range. However, they also point out that a more detailed study including hadronization will eventually be necessary to substantiate the parton level results.

Since then this Higgs signal has been ignored as a discovery channel and the mass region between 155 GeV and 180 GeV has been identified as a problem area of the Higgs detection at the LHC [4–6]. The motivation of this study is to demonstrate that the potentially last Higgs-search gap at the LHC can be closed using the specific decay (1.3).

In the study described in the following, we go in many respects far beyond the previous theoretical studies [13,14]. We have included the decay (2.2) in the signal and in the background. It is found that the inclusion of this decay mode increases the accepted event rates for signal and background and the different selection criteria by about 10–20 % compared to the case when only the decays (2.1) are considered. Furthermore we have included the background process[1] $gg\rightarrow Wtb$, which is of the same order as top pair production after the initial set of cuts. Most importantly, in all cases a full simulation of QCD processes including hadronization processes is done using the PYTHIA Monte Carlo [15] with the default CTEQ2L set of structure functions.

We find that the cuts previously employed [13,14] are then no longer sufficient. We have thus included new cuts which use also the significantly different spin correlations for signal and backgrounds, as has previously been pointed out by Nelson [16]. Furthermore, the criteria used to select signal and background events are chosen such that they can easily be fulfilled by the proposed ATLAS and CMS experiments. As the proposed criteria are robust and relatively simple, they are necessarily not optimized and significant improvements are possible once the real detector behaviors are known. However, the proposed analysis demonstrates the potential of a fast Higgs discovery in this mass range.

III. SELECTION CUTS

The goal of this analysis is to show that the expected large rate of the $pp\rightarrow H\rightarrow W^{+}W^{-}\rightarrow \ell^{+}\nu\ell'^{-}\bar{\nu}$ can compensate the absence of a narrow mass peak. In order to perform a consistent analysis, the PYTHIA Monte Carlo program is used for the simulation of signal and background events. If not specified otherwise, the program is used with the default parameter setting. For all production and decay processes we have considered only the tree-level calculation as the one-loop calculations do not exist for all relevant background processes. This allows a consistent analysis for signal and background and our results can easily be compared with previous studies using the four-charged-leptons channel. We thus do not include any K factors. It is however worth pointing out that the one-loop corrections to the main Higgs production process via gluon-gluon fusion are large and positive [17] whereas the corrections to the 2-to-2 and 2-to-3 background processes are expected to be smaller [18].

The first set of selection criteria listed below selects relatively central events with two isolated charged leptons (electrons or muons) with large missing energy due to the two (or more) neutrinos. These cuts are mostly comparable to [13,14]. Starting from this initial set of cuts, one can concentrate on the differences between events originating from the Higgs production and from the so called ''irreducible'' background from continuum production of $pp\rightarrow W^{+}W^{-}X$ events. Even though the criteria strongly reduce the events where the leptons originate from Z decays, they are not yet sufficient for a complete removal of this possible background. As will be shown below, this background is essentially removed by a stronger requirement, cut 9, on the opening angle ϕ between the two leptons in the plane transverse to the beam.

(1) The event should contain two leptons with opposite charge each with a minimal p_t of 10 GeV. At least one of the two leptons should have a p_t of more than 20 GeV. Furthermore, the two leptons should be separated in space by more than 10°.

(2) The pseudorapidity $|\eta|$ of each lepton should be smaller than 2. For events which contain additional isolated photons with a minimal p_t of 20 GeV and $|\eta|$ smaller than 2.4 the photon four-momentum vector is added to the dilepton system.

[1]We are grateful to L. Rurua, who reminded us of this potential background.

TABLE I. The expected signal and background event rates using the cross section estimates with the CTEQ2L structure functions and with the first set of selection criteria. In all cases only the leptonic W branching ratios are simulated ($W \to \ell^{\pm}\nu$ with $\ell^{\pm}$ being electrons, muons or τ). For the production of ZZ events, the cross section is obtained including the Z decays into charged leptons and neutrinos. For the production of WZ and for the single Z production only the Z decays to charged leptons including the subsequent τ decays are simulated.

LHC 14 TeV		Accepted event fraction		
Reaction $pp \to X$	$\sigma \times BR^2$ (pb)	Cut 1–3	Cut 4–6	Cut 7
$pp \to H \to W^+W^-$ ($m_H = 170$ GeV)	1.24	0.21	0.18	0.080
$pp \to W^+W^-$	7.4	0.14	0.055	0.039
$pp \to t\bar{t}$ ($m_t = 175$ GeV)	62.0	0.17	0.070	0.001
$pp \to Wtb$ ($m_t = 175$ GeV)	≈ 6	0.17	0.092	0.013
$pp \to ZW \to \ell^+\ell^-\ell\nu$	0.86	0.23	0.054	0.026
$pp \to ZZ \to$ four-leptons	1.05	0.13	0.016	0.007
$pp \to Z \to \tau^+\tau^-$	1400	0.007	0.0004	0.00009
$pp \to Z \to e^+e^-, \mu^+\mu^-$	2800	0.22	0.0004	0.00012

(3) In order to have isolated leptons it is required that the energy sum originating from hadrons and photons, with a p_t of more than 0.5 GeV and $|\eta|$ smaller than 5, found within a cone of 20° half angle around the lepton direction should be smaller than 5 GeV.

(4) The dilepton mass $m_{\ell\ell(\gamma)}$ has to be smaller than 80 GeV.

(5) The missing p_t of the event, required to balance the p_t vector sum of the two leptons, $\ell\ell(\gamma)$, should be larger than 20 GeV.

(6) The two leptons should not be back to back in the plane transverse to the beam direction. The opening angle between the two leptons in this plane should be smaller than 135°. In order to remove the backgrounds from Z decays, this cut will be strengthened considerably in the following.

(7) Events which have a jet with a p_t of more than 20 GeV and a pseudorapidity $|\eta|$ of less than 2.4 are removed.

Dilepton events, originating from the decays of W and Z bosons are selected with criteria (1)–(3). Lepton pairs $\ell\ell(\gamma)$ originating from single Z production with subsequent decays to leptons, including the leptons coming from decays of τ leptons are mostly removed with criteria (4)–(7). Backgrounds from $t\bar{t}$ and Wtb production [19], are reduced strongly by the jet veto, criterion (7). It can be expected that even better background rejection factors can be obtained if some jet detection is possible up to larger values of $|\eta|$.

The estimated cross sections before and after the above criteria for different signal and background processes, including the leptonic branching ratios of the W's and Z are given in Table I. As can be seen from Table I, the above set of selection criteria reduces background from $pp \to ZX$ events by a factor of about 10^4. For the following we concentrate on the remaining background from continuum production of W^+W^-, $t\bar{t}$, and Wtb events.

In order to distinguish a possible signal from the remaining background we use the following criteria.

(8) The polar angle $\theta_{\ell^+\ell^-}$ of the dilepton system, reconstructed from the vector sum of their measured momenta should satisfy $|\cos\theta_{\ell^+\ell^-}| < 0.8$.

(9) The opening angle ϕ between the two charged leptons in the plane transverse to the beam should be between 10° and 45°.

(10) The mass, estimated for the assumed W^+W^- system should be larger than 140 GeV. The mass is estimated from the approximation that the two neutrinos compensate the p_t of the two charged leptons, e.g., assuming $p_t(H) \approx 0$, and that the mass of the undetected neutrinos is on average equal to the mass of the two charged leptons. The energy carried by the two neutrinos is thus approximated with $E_{\nu\nu} = \sqrt{m^2_{\ell\ell} + p_t^2(\ell\ell)}$. With this approximation a broad mass distribution, with a mean value in agreement with the simulated Higgs boson mass and a large rms of about 55 GeV, is obtained.

(11) The opening angle θ^* between the lepton with the larger p_t, boosted to the dilepton rest frame and the momentum vector of the dilepton system should fulfill the condition $0. < \cos\theta^*_{\ell^+\ell^-} < 0.3$.

Condition (8) exploits the smaller boost of the candidate events, originating from the gluon-gluon fusion process. A large fraction of the continuum W^+W^- background originates from valence-quark sea-antiquark scattering with a relatively large momentum imbalance, resulting in a boosted W^+W^- system, as shown in Fig. 1.

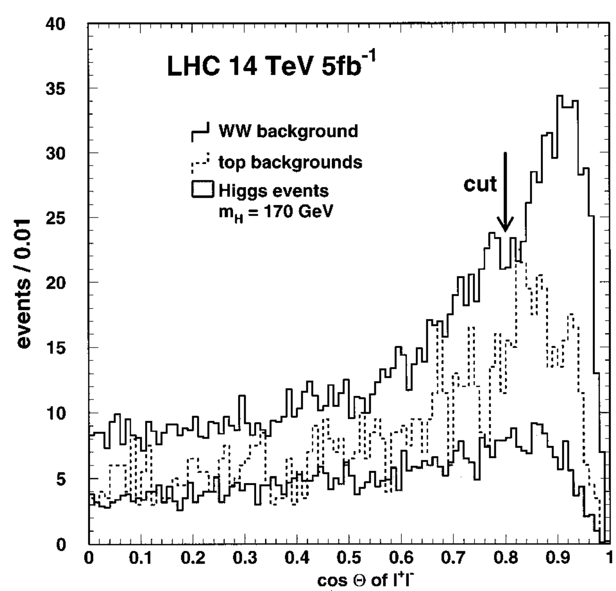

FIG. 1. $|\cos\theta|$ distribution of the dilepton system with respect to the beam direction for Higgs signal and background events.

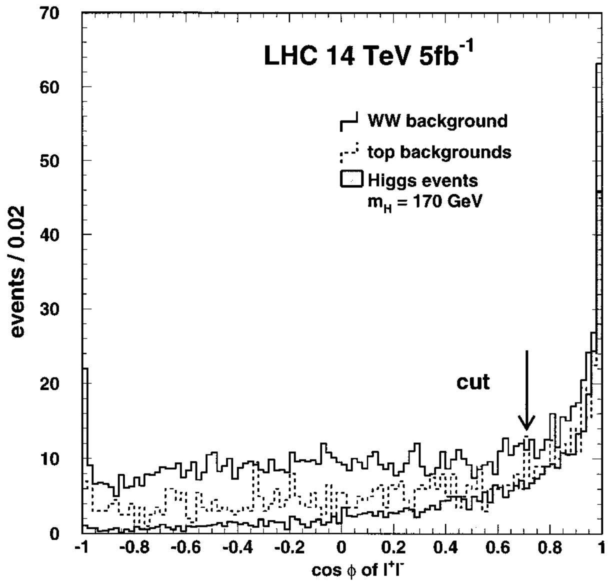

FIG. 2. cosϕ distribution of the dilepton system in the plane transverse to the beam direction for Higgs signal and background events, cut number 6 has not yet been applied.

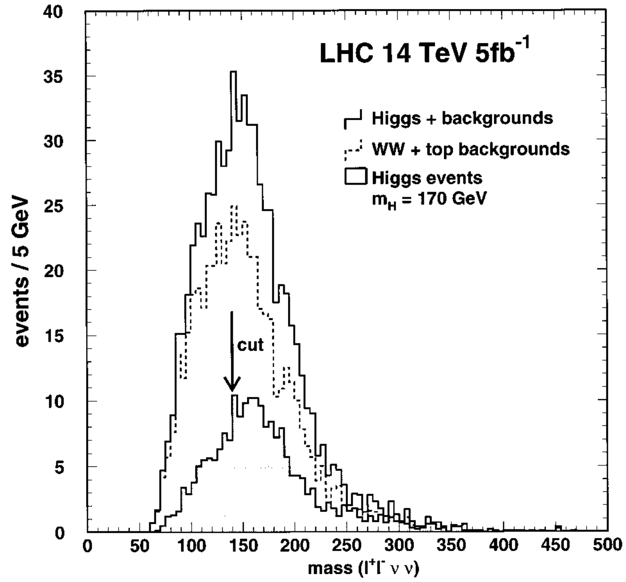

FIG. 3. Estimated invariant mass of the $\ell\ell\nu\nu$ system for Higgs signal and background events.

Criterion (9) makes use of the spin correlation between the W^+W^- pair. The potential discriminating power of this correlation in the Higgs search has previously been pointed out by Nelson [16]. W pairs originating from the decay of a scalar have to have opposite spin orientation. Due to the V-A structure in the W decay, the left-handed e^- (right-handed e^+) is emitted along the W^- (W^+) spin. As a result, one of the two charged leptons is emitted along the momentum direction of the two W's while the other one is emitted in the opposite direction. For the considered Higgs mass range, a small opening angle between the two charged leptons can be expected for signal events while the backgrounds will show an almost symmetric distribution. The discriminating power of this criterion is shown in Fig. 2. As can be seen the leptons originating from Higgs decays have a relatively small opening angle while the ones coming from continuum W^+W^- and tt events show essentially a symmetric distribution.

The estimated invariant mass of the $\ell^+\ell^-\nu\nu$ system, shown in Fig. 3, is unfortunately very broad. Nevertheless it discriminates to some extent between signal and background.

Finally, the two charged leptons from Higgs events show a smaller momentum spread than the ones from the background. This fact shows up nicely in Fig. 4, where the signal events show a peak like structure for small values of $\cos\theta^*_{\ell^+\ell^-}$ while the backgrounds show a strong increase to larger values. This distribution has also some sensitivity to the Higgs mass and can therefore be used for a mass estimate.

Table II shows the number of accepted signal and background events for an integrated luminosity of 5 fb^{-1} at the LHC with 14 TeV center of mass energy. Taking the signal and background event rates for the considered luminosity of 5 fb^{-1} statistically significant signals appear already after cuts (1)–(7). However, as signal and background cross sections are not well known, a signal to background ratio of about 1 to $\approx$10 is not sufficient. For example, we find variations of signal and background event rates of about 5–10 % when changing from the PYTHIA default CTEQ(2L) to the MRS(A) structure functions [20]. The largest variations of signal and backgrounds, as given in Table II, are obtained with the rather old and outdated Eichten-Hinchliffe-Lane-Quigg set 2 [EHLQ(2)] structure functions.

As has been discussed above, with the subsequent criteria, signal to background ratios of about 1 to 1 can be obtained while keeping sizable signal rates. We thus estimate that for the final selection the cross section uncertainties of the backgrounds for the final selection are smaller than the estimated statistical background uncertainties. Furthermore, as can be seen from Figs. 1–4, absolute background rates can be estimated from several distributions where clear separations between a Higgs signal and backgrounds are obtainable.

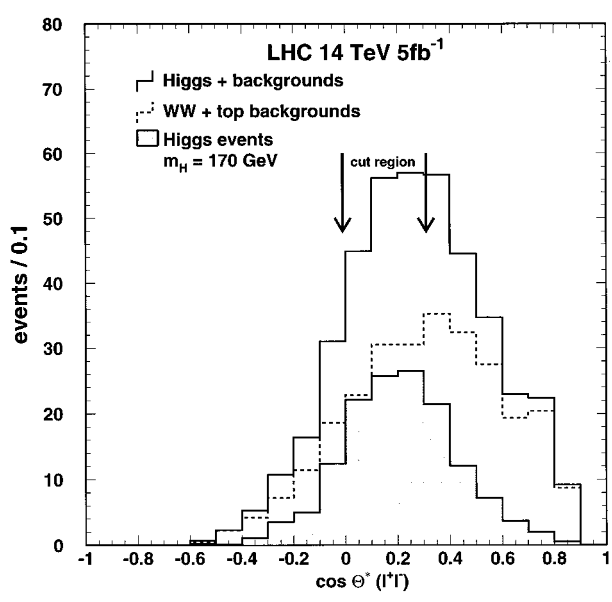

FIG. 4. $\cos\theta^*$ distribution in the dilepton rest frame for Higgs signal and background events.

TABLE II. The expected event rates for signal and background for an integrated luminosity of 5 fb^{-1} using a PYTHIA simulation and CTEQ2L. For comparison, as an extreme case, we show the most important background rates for the outdated EHLQ structure functions. For Martin-Roberts-Stirling set A [MRS(A)] the numbers agree within 5% with the CTEQ2L numbers.

Structure function CTEQ2L					
LHC 14 TeV		Expected event rate for 5 fb^{-1}			
Reaction $pp \to X$	$\sigma \times Br^2$ (pb)	Cut 1–7	Cut 8–9	Cut 10	Cut 11
$pp \to H$ ($m_H = 155$ GeV)	1.09	426	168	99	49
$pp \to H$ ($m_H = 160$ GeV)	1.25	508	212	140	78
$pp \to H$ ($m_H = 165$ GeV)	1.27	520	220	151	86
$pp \to H$ ($m_H = 170$ GeV)	1.24	497	201	147	74
$pp \to H$ ($m_H = 175$ GeV)	1.19	462	176	129	59
$pp \to H$ ($m_H = 180$ GeV)	1.11	398	151	112	47
$pp \to W^+W^-$	7.4	1458	273	130	38
$pp \to t\bar{t}$ ($m_t = 175$ GeV)	62.5	441	104	72	18
$pp \to Wtb$ ($m_t = 175$ GeV)	≈ 6	397	110	70	24
$pp \to ZZ, WZ$	1.9	150	31	16	5
$pp \to Z$	4200	2355	49	24	7 ($\leqslant$ 13)
Σ all backgrounds	–	4781	567	312	92
Structure function EHLQ set 2					
$pp \to H$ ($m_H = 170$ GeV)	1.7	653	263	185	92
$pp \to W^+W^-$	5.9	1152	231	110	35
$pp \to t\bar{t}$ ($m_t = 175$ GeV)	95	741	163	104	24

Using all criteria we obtain Higgs signals with a significance between 5 and 10σ for the considered mass range and an integrated luminosity of about 5 fb^{-1}. This result should be compared to the significance obtained for the gold plated four charged lepton channel where about 100 fb^{-1} are required for a 5σ signal.

IV. CONCLUSIONS

We have reconsidered the signature of two leptons plus missing energy as a signal for the Higgs boson decay mode $H \to W^+W^-$. It is found that the Higgs detection in the previously considered difficult mass range between 155 and 180 GeV appears to be relatively easy for this decay signature. Using a few simple experimental criteria, clear differences between signal and backgrounds are obtained allowing a 5–10σ Higgs signal detection with an integrated luminosity of about 5 fb^{-1}. We thus conclude that for the considered mass range events with two leptons plus missing energy will provide, the Higgs discovery signature at the LHC.

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