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STANDARD MODEL HIGGS DISCOVERY POTENTIAL OF CMS IN THE $H \to WW \to \ell\nu\ell\nu$ CHANNEL*

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The Standard Model Higgs discovery potential of CMS in the $H \to WW \to \ell\nu\ell\nu$ channel is presented. The results are based on a full detector simulation and include the last theoretical developments for background and signal simulation. A first estimate of the expected systematics is also performed. If the Standard Model Higgs has a mass between 150 GeV and 180 GeV, it should be discovered with more than 5σ significance with a luminosity of 10 fb^{-1}.

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1. Introduction

The Higgs decay into two Ws and subsequently into two leptons ($H \to WW \to \ell\nu\ell\nu$) is the discovery channel for Higgs masses between $2m_W$ and $2m_Z$ [1]. In this mass range, the Higgs to WW branching ratio is close to one, leading to high statistics. The signature of this decay is characterized by two leptons and missing energy. As no narrow mass peak can be reconstructed in this channel, a good background control together with a high signal to background ratio is needed. The most important backgrounds, which give a similar signature as the signal (*i.e.* two leptons and high missing energy) are continuum WW production and $t\bar{t}$ production. To reduce these backgrounds, one has to require a small opening angle between the leptons in the plane transverse to the beam and apply a jet veto.

A study of the CMS discovery potential for this channel is presented in [2]. It is based on a full detector simulation and concentrates on the Higgs discovery range for Higgs masses between 150 GeV and 180 GeV. The selection cuts are chosen to be mass independent. Three final states are reconstructed: ee, $\mu\mu$ and $e\mu$. In the first part of this article, the signal and

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background simulation are detailed. Then, the event reconstruction and selection is discussed. Finally, the expected numbers of signal and background events for an integrated luminosity of 1 fb^{-1} are given and a method to normalize each of the background components is proposed.

2. Signal and background generation

The signal samples were generated using PYTHIA. The two major Higgs production modes for the mass range were studied, gluon and vector boson fusion were generated. The $p_{\mathrm{t}}(H)$ spectrum predicted by PYTHIA was reweighted to the MC@NLO prediction, defining p_{t} dependent k-factors, as proposed in [3] and shown in figure 1 (left).

For the backgrounds, continuum vector boson production (WW, ZZ, WZ) was generated using PYTHIA. The $p_{\mathrm{t}}(WW)$ spectrum was reweighted using the same technique like for the signal, as shown in figure 1 (right). A NLO cross section of respectively 16 pb, 50 pb and 114 pb was taken for ZZ, WZ and WW. WW production via gluon box diagram, $ggWW$, was generated using a parton Monte Carlo provided by N. Kauer and linked to PYTHIA for the parton shower [4]. Top production ($t\bar{t}$ and tWb) was generated using TopReX. NLO cross sections of respectively 840 pb and 33.4 pb were used for $t\bar{t}$ and tWb [5].

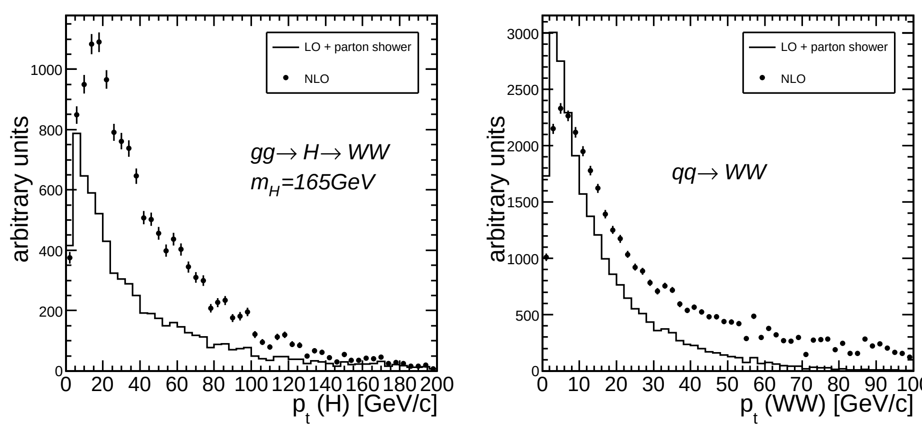

Fig. 1. The p_{t} spectra produced by PYTHIA (solid line) and after applying p_{t}-dependent k-factors (dots) for a 165 GeV Higgs boson produced through gluon fusion (left) and continuum WW production (right). The statistical uncertainties of the simulated samples are shown. They are the same for LO and NLO.

3. Signal reconstruction

The signal signature is characterized by two leptons in the final state with opposite charge, missing energy and no jet. The leptons, either electrons or muons, are required to have $p_{\rm t} > 20$ GeV and $\eta| < 2$.

Muon candidates are asked to be isolated: The energy left in the calorimeters around the muon candidate within a $\Delta R = 0.3$ cone must be smaller than 5 GeV and the sum of the $p_{\rm t}$ of the tracks within a $\Delta R = 0.25$ cone around the muon candidate must be smaller than 2 GeV.

Electron candidates are reconstructed combining tracks and ECAL clusters. They must fulfill in addition the following identification requirements:

- The electron must deposit few energy in the HCAL: $E_{\rm hcal}/E_{\rm ecal} < 0.05$.
- The electron track and cluster must be precisely matched: in direction: $|\eta_{\rm track} - \eta_{\rm SC\,corr}| < 0.005$ and $|\phi_{\rm track\,prop} - \phi_{\rm SC}| < 0.02$[1] in magnitude: $E/p > 0.8$ and $|1/E - 1/p| < 0.02$.

The electron candidate must be also isolated by requiring:

$$\sum_{\rm tracks} p_{\rm t}({\rm track})/E_{\rm t}({\rm SC}) < 0.05\,,$$

where the sum runs on all the tracks which have:

- $\Delta R_{\rm SC-track} < 0.2$ (at vertex),
- $p_{\rm t}^{\rm track} > 0.9$ GeV,
- $|z_{\rm track} - z_{\rm electron}| < 0.2$ cm.

Finally, a cut on the impact parameter significance in the transverse plane is applied in order to reduce the $b\bar{b}$ background. Each lepton is required to have $\sigma_{\rm IP} < 3$, where $\sigma_{\rm IP}$ is the impact parameter significance. The two leptons are also required to come from the same vertex by asking $|z_{\rm lep1} - z_{\rm lep2}| < 0.2$ cm.

With this lepton selection, the contribution of reducible backgrounds like W+jet where one jet is misidentified as a lepton or $b\bar{b}$ is expected to be less than 5 fb after all cuts applied.

Missing energy is reconstructed by summing the raw energy of all ECAL and HCAL towers, and correcting for muons. Since a jet veto is applied in the signal selection, further correction on the missing energy did not bring a significant improvement.

[1] Where $\phi_{\rm track\,prop}$ is the track angle propagated in the magnetic field up to the ECAL cluster position.

Jets are reconstructed using a Cone algorithm of size $\Delta R = 0.5$ and requiring its component calorimeter towers to have $E_{\mathrm{T}}^{\mathrm{tow}} > 0.5$ GeV and $E^{\mathrm{tow}} > 0.8$ GeV. Since jets are reconstructed to be vetoed, no energy calibration was applied. For the events studied, $E_{\mathrm{T}}(\mathrm{jet}) \approx (1.5–2)\ E_{\mathrm{T}}(\mathrm{raw})$. To veto electrons and Bremsstrahlung photons, the jets are also required to be away from the leptons ($\Delta R_{\mathrm{jet-lepton}} > 0.5$).

For jets with a raw energy between 15 and 20 GeV an additional cut on their track content was applied in order to reduce the contamination from fake jets coming from the underlying event. For this, the so-called alpha parameter is defined, as the ratio of the sum of p_{t} of all tracks inside the jet over the transverse jet energy in the calorimeter. For a perfect detector, the alpha parameter of a jet would be around 0.66, as in mean two third of a jet are charged particles. This ratio is smeared and reduced by the detector energy resolution and the fact that particles need a minimal energy in order to be detected. In a fake jet, the alpha parameter looks different, as underlying events contain a lot of low p_{t} particles, which depose energy in the ECAL but are not seen in the tracker, leading to an alpha parameter around zero.

Alpha is determined using only tracks that are 'inside' the jet, *i.e.* with $\Delta R_{\mathrm{track-jet}} < 0.5$ and coming from the event vertex[2], fulfilling $|z_{\mathrm{trk}} - z_{\mathrm{vtx}}| < 0.4$ cm. Finally, these tracks should have more than 5 hits and $p_{\mathrm{t}} > 2$ GeV. Alpha is then defined as $\alpha = \frac{\sum p_{\mathrm{t}}(\mathrm{tracks})}{E_{\mathrm{T}}(\mathrm{jet})}$. If its raw energy lies between 15 and 20 GeV a jet is then required to have alpha > 0.2 to be kept.

4. Event selection and results

Events are first required to pass globally the L1 trigger and at least one of the following HLT triggers: single electron, double electron, single muon or double muon trigger.

Then each event has to contain exactly two opposite charge leptons with $p_{\mathrm{t}} > 20$ GeV and $|\eta| < 2$ passing the cuts described before. The following kinematic selection was applied on the two lepton candidates:

- No jet with $E_{\mathrm{t}}^{\mathrm{raw}} > 15$ GeV and $|\eta| < 2.5$,
- $E_{\mathrm{t}}^{\mathrm{miss}} > 50$ GeV,
- 12 GeV $< m_{\ell\ell} <$ 40 GeV (the invariant mass of the two leptons),
- 30 GeV $< p_{\mathrm{t}}^{\ell\,\max} <$ 55 GeV (lepton with the maximal p_{t}),
- $p_{\mathrm{t}}^{\ell\,\min} > 25$ GeV (lepton with the minimal p_{t}),
- $\phi_{\ell\ell} < 45°$ (angle between the leptons in the transverse plane).

[2] The event vertex is defined as the mean z position of the two leptons.

These cuts were optimized for a Higgs mass of 165 GeV. Figure 2 shows the transverse missing energy distribution after requiring two good leptons and applying a jet veto. A hard cut on the transverse missing energy is useful to reject continuum WW background.

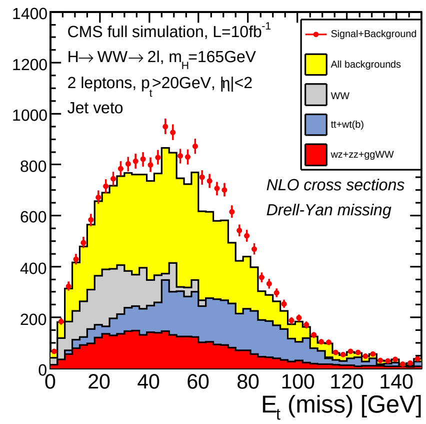

Fig. 2. Transverse missing energy distribution after requiring two good leptons and applying a jet veto. Drell–Yan is not shown on the plot but is expected to have a sharp peak around 15 GeV.

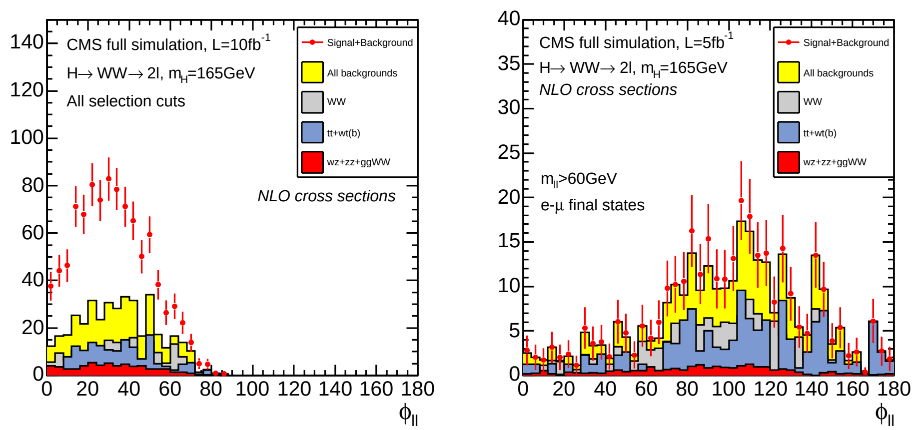

Fig. 3. The angle between the leptons in the transverse plane for the signal and the different background and a luminosity of 10 fb^{-1}. For the signal cuts taking out the one on $\phi_{\ell\ell}$ (left). For the WW background normalization region where all signal cuts are applied except the one on the lepton invariant mass, which was set to $m_{\ell\ell} > 60$ GeV and only electron–muon final states are kept (right).

Figure 3 (left) shows the $\phi_{\ell\ell}$ distribution for the signal plotted on the top of the sum of all background when all selection cuts are applied except the one on $\phi_{\ell\ell}$.

The expected number of events for the signal for three different Higgs masses and the different backgrounds in femtobarns are given in Table I. The first column shows the signal times branching ratio for the different processes, the second one shows the number of events passing the trigger requirement, the third one shows the number of events with two opposite charge leptons passing the lepton selection cuts and the last one the number of events after all selection cuts are applied. For a Higgs mass of 165 GeV, a signal over background ratio of 1.6 is expected, with about 50 event per fb^{-1} of luminosity.

TABLE I

The expected number of events for the signal for three different Higgs masses and the different backgrounds given in femtobarns. The first column shows the number of expected events after HLT requirement, the second one the number after having found two opposite charge leptons and the last one the number of events after all selection cuts are applied.

Reaction $pp \to X$	$\sigma_{\mathrm{NLO}} \times \mathrm{BR}$	L1+HLT	2 leptons	All cuts
$\ell = e\,,\mu\,,\tau$	pb	Expected event rate in fb		
$H \to WW \to \ell\ell$, $m_H = 160$ GeV	2.34	1353 (58%)	359 (27%)	42 (12%)
$H \to WW \to \ell\ell$, $m_H = 165$ GeV	2.36	1390 (59%)	393 (28%)	46 (12%)
$H \to WW \to \ell\ell$, $m_H = 170$ GeV	2.26	1350 (60%)	376 (28%)	33 (8.8%)
$qq \to WW \to \ell\ell$	11.7	6040 (52%)	1400 (23%)	12 (0.9%)
$gg \to WW \to \ell\ell$	0.48	286 (60%)	73 (26%)	3.7 (5.1%)
$tt \to WWbb \to \ell\ell$	86.2	57400 (67%)	15700 (27%)	9.8 (0.06%)
$tWb \to WWb(b) \to \ell\ell$	3.4	2320 (68%)	676 (29%)	1.4 (0.2%)
$ZW \to \ell\ell\ell$	1.6	1062 (66%)	247 (23%)	0.50 (0.2%)
$ZZ \to \ell\ell, \nu\nu$	1.5	485 (32%)	163 (34%)	0.35 (0.2%)
Sum backgrounds	105	67600 (64%)	18300 (27%)	28 (0.2%)

5. Background normalization and systematics

At LHC, it is desirable to determine the background from data whenever possible. Backgrounds can be estimated using a normalization region in the data, selected using cuts similar to the signal cuts. In this case, most systematic errors will cancel in the efficiency ratio. The following procedure for background normalization is proposed:

- *Top background normalization:* Two procedures are proposed and are discussed in detail in [6]. A first possibility is to define a sample with the same lepton and missing energy cuts than the signal but requiring two b-tagged jets with $E_{\mathrm{t}} > 20$ GeV. A second possibility is to apply the same kinematic cuts on the leptons and require two additional jets with respectively $E_{\mathrm{T}}^{\mathrm{raw}} > 50$ GeV and $E_{\mathrm{T}}^{\mathrm{raw}} > 30$ GeV. In this case, only $e\mu$ final states are considered in order to avoid a contamination from Drell–Yan. Both methods are expected to give an error of about 16% on $t\bar{t}$ estimate for a luminosity of 5 fb^{-1}.

- *WW background normalization:* A normalization region can be defined for WW by keeping the same cuts than the signal but requiring $\phi_{\ell\ell} <$ 140 and $m_{\ell\ell} > 60$ GeV. Moreover, only opposite flavor leptons are considered in order to reduce the Drell–Yan and WZ contribution. A systematic error of about 17% is expected with a luminosity of 5 fb^{-1}, dominated by statistical uncertainty. Figure 3 (right) shows the $\phi_{\ell\ell}$ distribution for the different process in this normalization region.

- *WZ background normalization:* WZ can be normalized by keeping the same signal cut and requiring an additional lepton in the final state. The cuts on $\phi_{\ell\ell}$ and $m_{\ell\ell}$ are removed. An accuracy of about 20% is expected on this background with 5 fb^{-1}.

- *ggWW and tWb normalization:* The contribution of these backgrounds will be estimated using Monte Carlo prediction, since they represent only a small fraction of signal events. The error on $ggWW$ is about 30% whereas the one on tWb is about 22%, both largely dominated by theoretical errors.

Taking into account the sum of the different backgrounds, an overall error of 10% is found on the total background estimate. Adding the contribution from limited Monte Carlo statistics, this uncertainty increases to 13%. These results are calculated for a luminosity of 5 fb^{-1}. For luminosities of 1, 2 and 10 fb^{-1}, the total systematic errors scale to 19%, 16% and 11% respectively.

Figure 4 shows the signal to background ratio (left) and the luminosity needed for a 5σ discovery (right) as a function of the Higgs mass. A signal of more than 5σ significance could be already observed with a luminosity of 10 fb^{-1} for a Higgs mass between 150 and 180 GeV. For a Higgs mass of 165 GeV the luminosity needed for a 5σ discovery is expected to be less than 1 fb^{-1}.

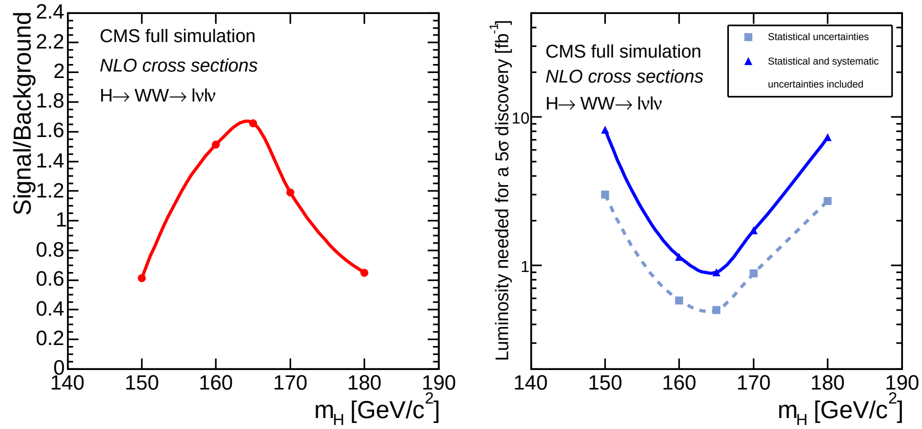

Fig. 4. Signal to background ratio for a luminosity of 5 fb^{-1} (left) and the luminosity needed for a 5σ discovery (right) as a function of different Higgs masses for the $H \to WW$ channel.

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