\[ h^0 \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu} \] as the Dominant SM Higgs Search Mode at the LHC for \( M_{h^0} = 155 - 180 \text{GeV} \)

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ABSTRACT

We show that the decay \( h^0 \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu} \) is the most sensitive mode for SM Higgs searches in the range 155 - 180 GeV. The previously considered mode \( h^0 \rightarrow Z^0Z^{0*} \rightarrow \ell^+\ell^-\ell^+\ell^- \) has a significantly lower search sensitivity. We place particular emphasis on two new cuts based on (i) the boost and (ii) the spin-correlation of the \( W^+W^- \)-system. The distribution we obtain from our combined cuts shows a mass sensitive peak which probably allows a mass determination to \( \pm 5 \text{ GeV} \) for 5 fb\(^{-1}\). This contribution complements our paper.

1. Introduction

The Higgs boson is the missing building block of the Standard Model. It is imperative to find it as soon as possible. The LHC will initially have an integrated luminosity of 10 fb\(^{-1}\)/y, upgraded to 100 fb\(^{-1}\)/y several years later. The lower luminosity will leave a gap in search sensitivity for Higgs masses between 155 - 180 GeV. The previously considered mode \( h^0 \rightarrow Z^0Z^{0*} \rightarrow \ell^+\ell^-\ell^+\ell^- \) requires at least 100 fb\(^{-1}\)/y. Thus we might not find the Higgs boson for several years after the LHC has been running. Here, we show how to fill this gap by the decay

\[ h^0 \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu}. \] (1)

This leads to 10\(^3\) times as many events as \( h^0 \rightarrow Z^0(Z^0)^* \rightarrow \ell^+\ell^-\ell^+\ell^- \) which can compensate for the lack of a reconstructed narrow mass peak. Furthermore, an integrated luminosity of only 5 fb\(^{-1}\) is sufficient for discovery! Over the entire Higgs mass range accessible to the LHC this is the smallest required luminosity of any search mode. The final distribution is sensitive to the Higgs mass probably allowing a determination to \( \pm 5 \text{ GeV} \) for 5 fb\(^{-1}\).

2. Separating the Signal from the Continuum WW Background

The signature (1) has been studied in two parton level analyses. Both were modestly
optimistic for the LHC but were subsequently ignored. We go beyond these analyses in several respects. (1) Most importantly, in all cases a full simulation of QCD processes, including hadronisation processes is done using the PYTHIA Monte Carlo. All $K$-factors are set to one since the full set is not yet known for the background processes. Their inclusion would most likely improve the significance of the search since for the dominant Higgs production process it is known to be large. (2) We include the leptonic decays of the tau lepton. This slightly degrades the signal. (3) We include all possible background processes with at least two isolated leptons, including $gg \rightarrow Wtb$, which is of the same order as $t\bar{t}$ pair production after the initial set of cuts. (4) When including the above, in particular (1), the old cuts are no longer sufficient. The two main new cuts we impose are based on the boost and the spin correlation of the WW-system. We explain these in detail below.

The signal cross section is $1.2 \, pb^{-1}$ including the leptonic branching ratios. The two main background processes and their cross sections multiplied by the leptonic decay BR’s are

\[ q\bar{q} \rightarrow W^+W^- \rightarrow \ell^+\nu_\ell\ell^-\nu_\ell, \quad 7.4 \, pb^{-1}, \]
\[ q\bar{q}, gg \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b}, \quad 62.5 \, pb^{-1}. \]

The signal is most difficult to distinguish from the irreducible background (2). The central events of the $t\bar{t}$ background are controlled by the jet rejection cut below.

We first implement a set of cuts which are fairly standard. (i) We require two identified charged leptons with opposite charge. (ii) The $p_t$ of the leptons should be greater than $10\, GeV$, and the absolute value of their rapidity $|\eta|$ should be less than 2. Furthermore, in a cone with half-angle $20^o$ around each lepton the hadronic and electromagnetic energy should be less than $5\, GeV$. These first two criteria select events with two isolated leptons according to ATLAS/CMS capabilities. (iii) For one lepton $p_t > 20\, GeV$. (iv) We require the absence of any jet with a $p_t > 20\, GeV$ and $|\eta_{jet}| < 2.4$. (v) The dilepton invariant mass $M_{\ell\ell} < 80\, GeV$. (vi) The missing transverse momentum of the dilepton system $p_t(\ell\ell) > 20\, GeV$. (vii) In the plane transverse to the beam we require the angle between the two charged leptons $\Delta\phi_{\perp}(\ell\ell) < 135^o$. These cuts combined select events with $W^+W^- + X$. The most serious background is (2). Compared only to this we obtain the significance for $M_{h^0} = 170\, GeV$: $S/\sqrt{B}_{WW} = 13$, and a signal to background ratio of $S/B_{WW} = 1/3$. For the full set of backgrounds we obtain $S/\sqrt{B} = 7$, and $S/B = 1/10$. This requires an understanding of the the background to better than 2%, which is perhaps not realistic. We aim to improve this with the following cuts which specifically attack the WW-continuum background.

### 2.1. Boost of the $W^+W^-$-System

Consider $q\bar{q} \rightarrow W^+W^-$ where $q$ has a momentum fraction $x_1$ of one proton and $\bar{q}$ a
Figure 1: MRRS structure functions scaled by $x$. $g(x)$ is scaled by $x/10$. momentum fraction $x_2$ of the other proton.\(^a\) Then

$$x_1 \cdot x_2 = \frac{\hat{s}}{s} = \frac{M_{WW}^2}{s} \approx 10^{-4}. \quad (4)$$

Here $\hat{s}$ is the parton-level center-of-mass energy squared. $\sqrt{s}$ is the centre-of-mass energy of the LHC, $14\,TeV$, and $M_{WW}$ is the invariant mass of the $WW$-system. For the signal, $M_{WW}$ is equal to the Higgs mass. For the background process $M_{WW} \approx 155 - 180\,GeV$, giving (4).

The total background production cross section is given by the parton level cross section folded with the product of the parton distribution functions $q(x_1) \cdot \bar{q}(x_2)$. In $^a g + g \rightarrow WW$ is a potential further important background process. It is one-loop suppressed but is enhanced by the gluon luminosity and the coherent sum over the quark flavours giving an overall factor of about 3600. All the same, this contribution is almost an order of magnitude less\(^b\) than (2). It thus does not affect our analysis significantly and we have omitted it. (It is also not yet included in PYTHIA.) However, it should be included in a complete analysis of this problem.

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Figure 2: Product of the structure functions as a function of $x_1$ for fixed $x_1 \cdot x_2 = 10^{-4}$. In Figure 1 we show the individual parton distribution functions $x \cdot q(x)$, $x \cdot g(x)$. In Figure 2 we show the products which contribute to the signal and background. Here we have fixed $x_1 \cdot x_2 = 10^{-4}$. We see that both $u \bar{u}$ and $d \bar{d}$ strongly peak at about 0.1, well away from 0.01. In contrast $gg$ has a broad peak at about 0.01. This is because, as seen in Figure 1, both $x u(x)$ and $x d(x)$ have a clear shoulder at about 0.1 due to their valence quark distributions and $x g(x)$ shows no such shoulder.

At the peak of $u \bar{u}$, $x_1 = 0.2 \gg x_2 = 5 \times 10^{-4}$. Due to this large momentum imbalance, the Lorentz boost of the $WW$-system is $\gamma = (x_1 + x_2)/\sqrt{x_1 x_2} \approx 10$. This corresponds to a momentum for the $WW$-system of about $1.4 \text{TeV} \gg M_W$. The dominant signal process is $gg \rightarrow h^0 \rightarrow WW$. From Figure 2 it is clear that this has a much lower boost. Indeed, at the peak value of $gg$ the boost vanishes. This is confirmed by Figure 3 where we show the raw (i.e. without cuts (i)-(vii)) Monte Carlo generated $WW$-rapidity distributions of both the signal and the continuum background. The background has a plateau extending to about 2.5-3 in rapidity whereas the signal has fallen off by a factor of 3.
Of course, we can not observe the WW-system, only the charged leptons. Due to
the tremendous boost, the decay leptons for the background will be strongly folded
towards the beam axis, while the signal leptons will be central. We thus require
$\cos \theta_{\ell\ell} < 0.8$, where $\theta_{\ell\ell}$ is the angle of the dilepton system with respect to the beam.

2.2. Spin Correlation of the $W^+W^-$ System

The Higgs boson has spin zero, the $W^\pm$ bosons spin 1. In order to conserve angular
momentum, the spins of the $W$-bosons from $h^0 \to WW$ must be anti-correlated.
In the Higgs rest-frame (which for the considered mass range is practically the lab
frame), we denote the decay axis of the the $WW$-system the 3-axis. Along this axis,
the $W$-spins are quantized $S_3(W) = \pm 1, 0$. These are denoted transverse ($T$) and
longitudinal ($L$), respectively. Thus only the decays

$$h^0 \to W^+_T W^-_T, \quad h^0 \to W^+_L W^-_L$$

are allowed, whereas $h^0 \to W^+_L W^-_T$ is prohibited.

The $W^\pm$ polarizations are not directly observable, instead we observe the final
state charged leptons. The decay rate of $\tilde{W}^+_T \to e^+ + \nu_e$ is proportional to $(1 + \cos \vartheta)^2$, where $\vartheta$ is the angle of the positron $\vec{p}_{e^+}$ with respect to the $W^+_T$ spin. Thus the
(right-handed) positron is preferentially emitted in the same direction as the $W^+_T$
spin. Analogously, the (left-handed) electron is emitted in the opposite direction of
the $W^-_T$-spin with a $(1 - \cos \vartheta)^2$ distribution. Since the $W$-spins are anti-correlated,
$\vec{p}_{e^+}, \vec{p}_{e^-}$ are in the same direction.
Figure 4: Invariant mass distribution for $W$ boson pair production from $q\bar{q}$ annihilation at the LHC. L (longitudinal) and T (transverse) refer to the polarization of the $W$ bosons. The differential cross section in Ref. was used.

The charged lepton from the decay of a $W^\pm$ has a $\sin^2 \vartheta$ distribution, where $\vartheta$ is the angle of $\vec{p}_e$ with respect to the 3-axis. The lepton is most likely to be emitted perpendicular to the 3-axis. If the $W$-boson decays were uncorrelated there would be no particular correlation between $\vec{p}_{e^+}$ and $\vec{p}_{e^-}$. However, even though the $W$'s may decay outside of each other’s lightcone their decays are correlated: "they know of each other". The correlated decay-rate can be calculated and is proportional to $(e^- \cdot \nu_e)(e^+ \cdot \bar{\nu}_e)$, where we have denoted the 4-momenta by the corresponding particle symbol. This is zero for $\vec{p}_{e^+}$, $\vec{p}_{e^-}$ anti-parallel and is maximum for them being parallel, just as in the $W^+_T W^-_T$ case. Overall, we thus expect for the signal that $\vec{p}_{e^+}$, $\vec{p}_{e^-}$ have a small relative opening angle.

For the dominant background process (2), the initial state is unpolarized. The

\textsuperscript{b}This is analogous to the correlated measurements of photon spins in tests of Bell’s inequality.
two spin-1/2 quarks combine to a mixed state of a spin-1 triplet and a spin-0 singlet and all final state $W$-polarization combinations are allowed

$$q + \bar{q} \rightarrow W_L^+ W_L^-, W_T^+ W_T^-, W_L^\pm W_T^\mp, \tag{6}$$

where the quantisation axis is along the W-boson momenta. For the first two final states, the lepton momenta are correlated as for the signal, since spin-2 is prohibited by angular momentum conservation. For the last state the $W$-spins are not anti-correlated and thus $\vec{p}_{e^+}$, $\vec{p}_{e^-}$ are not positively correlated, in contrast to the signal events. The capability of distinguishing the signal from the background based on the $W$-spin correlation therefore depends on the relative magnitude of the production mechanisms (5). In Figure 4 we show the respective differential cross sections as a function of the invariant mass of the $WW$-system. We see that for a large fraction of the background, where $M_{WW} < 200 \, \text{GeV}$, the production of $W_T^\pm W_T^\mp$ is of the same order as $W_L^\pm W_L^\mp$ and both are much larger than $W_L^+ W_L^-$. At $M_{WW} = 165 \, \text{GeV}$, $W_L^\pm W_T^\mp$ is very close to half the production rate. We therefore expect a substantial fraction of the background charged leptons to have a large relative opening angle in
Higgs mass determination 50 fb$^{-1}$

\[ p p \rightarrow \text{Higgs} \rightarrow W^+ W^- \rightarrow l^+ l^- \nu \nu \]

\[ m_H = 160 \text{ GeV} \quad \text{m}_H = 170 \text{ GeV} \quad \text{m}_H = 180 \text{ GeV} \]

\[ \cos Q^* (l^+ l^-) \]

| events / 0.1 |
|---------------|
| 400 350 300 250 200 150 100 50 0 |

**Figure 6:** Signal (shaded histogram) and background distribution of events in $\cos \theta_{\ell^+ \ell^-}$ for 5 fb$^{-1}$ integrated luminosity.

In contrast to the signal events. In Figure 5 we show the raw distribution (i.e. before any other cuts) of $d\sigma/d\cos \theta_{\ell\ell}$ for the signal and the background. Here $\theta_{\ell\ell}$ is the relative angle between $\vec{p}_{e^+}$ and $\vec{p}_{e^-}$. The signal almost vanishes for anti-parallel leptons, $\cos \theta_{\ell^+ \ell^-} = -1$, whereas the background has its maximum. We impose the cut $10^\circ < \Delta \phi_1 (\ell \ell) < 45^\circ$ which is an extension of cut (vii). The effect is shown in Figure 2 of Ref[4].

The combined effect of cuts (viii) and (ix) is $S/\sqrt{B_{WW}}(M_{h^0}) = 12$ and $S/B_{WW} = 1/1.3$, which is a substantial improvement. For the complete background we now have $S/\sqrt{B} = 8.4$ and $S/B = 1/3$.

2.3. Remaining Cuts

The mass of the $WW$ events is given by $M_{WW}^2 = (\sum_{\ell, \nu} E_\ell)^2 - (\sum_{\ell, \nu} \vec{p}_i)^2$. This cannot be reconstructed because of the neutrinos. However, based on the previous cuts, our signal events typically consist of two central, charged leptons with parallel momenta. Assuming $p_t(h^0) \approx 0$, we can thus approximate: $p_t(\nu \nu) \approx p_t(\ell \ell)$. In addition, we estimate the mass of the neutrinos to be equal to that of the charged
leptons. Thus $E_{\nu\nu} \approx \sqrt{m_{\ell\ell}^2 + p_t^2(\ell\ell)}$, giving an overall estimate of $M_{WW}^*$ for $M_{WW}$. We expect this to be a good estimate for the signal events and require $M_{WW}^* > 140 \text{GeV}$. The distribution of the events as a function of $M_{WW}^*$ is shown in Figure 3, Ref.1. The background shows a much broader distribution in $M_{WW}^*$, particularly at low values.

We define the variable $\theta^*$ as the opening angle between the lepton with larger $p_t$ boosted to the dilepton rest frame and the momentum vector of the dilepton system. The distribution of events in $\cos \theta^*$ is shown in Figure 4 of Ref.1 for $M_{h^0} = 170 \text{GeV}$. It shows a clear mass-peak like behaviour which is significantly narrower than the background. We require $0 < \cos \theta^* < 0.3$. We then obtain $S/\sqrt{B_{WW}} = 12$ and $S/B_{WW} = 2/1$, which is tremendous. For the complete background we now have $S/\sqrt{B} = 8$ and $S/B_1/1.2$. This is our final result.

In Figure 6 we show how the peak in $\cos \theta^*$ shifts with Higgs mass. It is clearly quite sensitive. Judging by this figure it looks possible to determine the Higgs mass to within $\pm 5 \text{GeV}$ for an integrated luminosity of $5 \text{fb}^{-1}$. Again this compares very favourably with all other Higgs searches at the LHC.

3. Conclusion

We have shown that the decay mode $h^0 \to W^+W^- \to \ell^+\ell^-\nu\nu$ is an excellent Higgs search mode at the LHC for $M_{h^0} = 155 - 180 \text{GeV}$. A discovery is possible for only $5 \text{fb}^{-1}$. In addition, despite the absence of a reconstructed narrow mass peak, the Higgs mass can be determined to $\pm 5 \text{GeV}$ for $5 \text{fb}^{-1}$. This is at least as good as any other Higgs search mode. It thus more than fills the gap expected at $155 - 180 \text{GeV}$ for the first few years of LHC running. In our analysis, we have employed two new cuts based on the boost and the spin-correlation of the $WW$-system. This enabled the difficult separation from the irreducible continuum background production.

4. References

1. M. Dittmar, and H. Dreiner, Phys Rev D 55 (1997) 167.
2. G.L. Bayatian et al., CMS Collaboration, Technical Proposal, CERN/LHCC 94-38.
3. E.W.N. Glover, J. Ohnemus, and S.D. Willenbrock, Phys. Rev. D, 37 (1988) 3193.
4. V. Barger, G. Bhattacharya, T. Han, B.A. Kniehl, Phys. Rev. D, 43 (1991) 779.
5. T. Sjöstrand CERN-TH 7112/93; Comp. Phys. Comm. 39 (1986) 347.
6. D. Graudenz, M. Spira and P. Zerwas, Phys. Rev. Lett. 70 (1993) 1372.
7. A. Martin, R.G. Roberts, M.G. Ryskin, W.J. Stirling, RAL-Preprint RAL-TR-96-103, e-Print Archive: hep-ph/9612449.
8. Z. Kunszt, S. Moretti and W.J. Stirling, Durham preprint DFTT-34-95, e-Print Archive: [hep-ph/9611397](http://hep-ph/9611397).

9. C. Kao, D. A. Dicus, Phys. Rev. D 43 (1991) 1555.

10. S. Willenbrock, Ann. Phys. 186 (1988) 15.