\[ H^0 \rightarrow \tau^+ \tau^- \] Detection at the LHC

K. Bos  
NIKHEF-H,  
Amsterdam, The Netherlands

F. Anselmo $^\dagger$ and B. van Eijk $^*$  
CERN,  
Geneva, Switzerland

Abstract

We present a study on the production of the standard model Higgs, subsequently decaying into tau leptons. We concentrate on the so-called intermediate Higgs mass range of 100 - 160 GeV/c$^2$. We assume that LEP will provide us with a mass limit up to roughly the $W^\pm$ mass and recognize that experimental signals from the decay of a Higgs with a mass close to the $Z^0$ mass will be impossible or otherwise extremely difficult to disentangle from the dominating $Z^0$ decay signal. Clear decay signatures e.g. multi lepton decay channels become only important close to, or above the $W^+ W^-$ pair threshold. Hadronic decay modes will be overwhelmed by a large background of ordinary QCD jets. The only, relatively sizable, decay modes with extraordinary experimental signatures that are left are the $\gamma\gamma$ decay channel and tau pairs, where we require that each tau decays semileptonically into a single charged lepton plus two neutrinos.

We present implications on the cross sections and branching ratios for different values for the top quark mass and the Higgs mass.

Our conclusion is that the overwhelming background due to heavy flavour production through either pure QCD processes and/or other heavy flavour sources makes it difficult, though maybe not impossible to observe the signal. In the near future, we plan to extend our present study on both signal and backgrounds to provide better insights on observability.

$^\dagger$ Cern/LAA Project, Geneva, Switzerland.

$^*$ Supported by the ‘Netherlands Organization for Scientific Research (NWO)’, The Netherlands.
H⁰ → τ⁺ τ⁻ Detection at the LHC

K. Bos
NIKHEF-H,
Amsterdam, The Netherlands

F. Anselmo ¹ and B. van Eijk *
CERN,
Geneva, Switzerland

Abstract

We present a study on the production of the standard model Higgs, subsequently decaying into tau leptons. We concentrate on the so-called intermediate Higgs mass range of 100 - 160 GeV/c². We assume that LEP will provide us with a mass limit up to roughly the W⁺ mass and recognize that experimental signals from the decay of a Higgs with a mass close to the Z⁰ mass will be impossible or otherwise extremely difficult to disentangle from the dominating Z⁰ decay signal. Clear decay signatures e.g. multi lepton decay channels become only important close to, or above the W⁺ W⁻ pair threshold. Hadronic decay modes will be overwhelmed by a large background of ordinary QCD jets. The only, relatively sizable, decay modes with extraordinary experimental signatures that are left are the γγ decay channel and tau pairs, where we require that each tau decays semileptonically into a single charged lepton plus two neutrinos.

We present implications on the cross sections and branching ratios for different values for the top quark mass and the Higgs mass.

Our conclusion is that the overwhelming background due to heavy flavour production through either pure QCD processes and/or other heavy flavour sources makes it difficult, though maybe not impossible to observe the signal. In the near future, we plan to extend our present study on both signal and backgrounds to provide better insights on observability.

¹ Cern/LAA Project, Geneva, Switzerland.
* Supported by the 'Netherlands Organization for Scientific Research (NWO)', The Netherlands.
H^0 \rightarrow \tau^+ \tau^- Detection at the LHC

K. Bos
NIKHEF-H,
Amsterdam, The Netherlands

F. Anselmo † and B. van Eijk *
CERN,
Geneva, Switzerland

Abstract

We present a study on the production of the standard model Higgs, subsequently decaying into tau leptons. We concentrate on the so-called intermediate Higgs mass range of 100 - 160 GeV/c^2. We assume that LEP will provide us with a mass limit up to roughly the W^± mass and recognize that experimental signals from the decay of a Higgs with a mass close to the Z^0 mass will be impossible or otherwise extremely difficult to disentangle from the dominating Z^0 decay signal. Clear decay signatures e.g. multi lepton decay channels become only important close to, or above the W^+ W^- pair threshold. Hadronic decay modes will be overwhelmed by a large background of ordinary QCD jets. The only, relatively sizable, decay modes with extraordinary experimental signatures that are left are the \gamma \gamma decay channel and tau pairs, where we require that each tau decays semileptonically into a single charged lepton plus two neutrinos.

We present implications on the cross sections and branching ratios for different values for the top quark mass and the Higgs mass.

Our conclusion is that the overwhelming background due to heavy flavour production through either pure QCD processes and/or other heavy flavour sources makes it difficult, though maybe not impossible to observe the signal. In the near future, we plan to extend our present study on both signal and backgrounds to provide better insights on observability.

† Cern/LAA Project, Geneva, Switzerland.
* Supported by the 'Netherlands Organization for Scientific Research (NWO)', The Netherlands.
1. Introduction

In the search for the intermediate mass Higgs ($M_W < m_H < 2M_W$), two Higgs decay channels are particularly interesting. Although the branching ratio for $H^0 \rightarrow \gamma \gamma$ is relatively small (0.1 - 0.2 %), the signature of this channel is rather distinct and as it seems, estimates for the signal to background ratio show that this decay channel has a chance to be disentangled from its backgrounds [1]. The second channel on the contrary, has a relatively large branching ratio ~ 6.5 % (depending on the Higgs mass) and has a distinct signature as well: $H^0 \rightarrow \tau^+ \tau^-$. In the following reaction $pp \rightarrow H^0 X \rightarrow \tau^+ \tau^- X$ is studied for the case that each tau decays semileptonically into a muon or electron plus two neutrinos. The branching ratio for a tau to decay into electron or muon is ~ 18 %. Detection of both electrons and muons therefore doubles the branching ratio and hence increases the signal by a factor four if one allows for combinations like $e^+ \mu^-$ etc.. Thus, the events to look for contain two (opposite $\ell$) charged isolated leptons plus missing energy caused by the escaping 4 neutrinos.

In the analysis presented in this paper we limit ourselves to one of the main backgrounds, that is events originating from $t\bar{t}$ (for a more detailed study, we refer the reader to ref. [2]), where both top quarks decay into a W plus a bottom quark and subsequently the Ws decay semileptonically into lepton (\(e, \mu\)) plus neutrino. Such events also have at least two (often isolated) charged leptons and missing energy in the final state but, in addition, will contain two bottom quark jets with energies strongly dependent on the value of the top quark mass. Additional jets will occur in both signal and background processes due to initial state gluon emission. Therefore, signal and background event topologies will differ in jet multiplicity mainly due to the presence of bottom quark jets in the background process.

The branching ratio for the $H^0 \rightarrow \tau^+ \tau^-$ channel rapidly decreases when the mass of the Higgs exceeds 125 GeV/c$^2$. This drop in rate is the result of the growing importance of the decay $H^0 \rightarrow W^+ W^-$, where the $W^+$ results from the decay of a virtual W [3]. Initially, for this study we set the mass of the Higgs to 110 GeV/c$^2$. Such a low value for the Higgs mass also makes its production cross-section relatively high compared to the one for larger Higgs masses. A still lower value than 110 GeV/c$^2$ moves the $H^0$ into the (Breit-Wigner) tail of another serious background, namely, direct production of $Z^0$ gauge bosons in which case it becomes extremely difficult to distinguish the two observable leptons in the Higgs decay from the two leptons originating from $Z^0 \rightarrow \tau^+ \tau^-$ decays. The large rate and similar event topology for this type of background, will clearly overwhelm the signal.

A larger value for the top quark mass also favours the case for the $H^0 \rightarrow \tau^+ \tau^-$ channel for several reasons. First, a large top quark mass reduces the background cross-section $pp \rightarrow t\bar{t} X$ considerably. Secondly, the b-jet from the decay of the top quark will become harder, which will make it easier to select $t\bar{t}$ events. For this study, we have chosen the most "favourable" scenario, $m_t = 200$ GeV/c$^2$.

The outline for this paper is as follows. In section 2 we discuss the method of reconstructing the Higgs mass from the experimental observables. We present a comparison between different parton shower models and an exact $O(a_s^2)$ calculation for the main production process (gluon - gluon fusion) and estimate the contributions from boson - boson fusion mechanisms. The third section discusses the implications which the different models will have on the distributions of the experimental observables. We discuss detailed cross-section estimates before and after cuts on event topologies together with background
event generators base their calculation of the cross-section for the signal.

Fig. 2: Feynman diagrams for the lowest order contributions to Higgs production in hadronic interactions. The gluon fusion mechanism gives by far the largest contribution.

Both programs introduce initial state gluon radiation by reconstructing parton cascades after the hard scattering process is treated. At each branching, the partons may obtain a transverse momentum which finally results in an overall transverse motion of the hard scattering process.

Fig. 3: Feynman diagrams ('crossed' diagrams are not shown) for the next to leading order contributions to Higgs production in hadronic interactions. Again, the gluon fusion mechanism dominates in most kinematical regions.

In order to test this approach, which is known to work quite well in the limit where partons are emitted collinearly, we have introduced the fixed order QCD calculation for the next to leading order contribution to the cross-section [5] in Eurojet [9]. Contributing Feynman diagrams are presented in figure 3a and 3b. Note that the class of box diagrams (3b) can not so easily be implemented in a parton shower approach. Apart from the Higgs production processes described above, we have investigated the relevance of the boson-boson fusion mechanisms to our signal. Pythia includes an approximate description (reasonably accurate
calculations. Finally, we present some preliminary conclusions and make some general remarks about future work that we plan to do in this field.

2. Higgs at large $p_t$

Only semileptonic tau decays into an electron or muon are considered here. The Feynman diagram for this decay process is depicted in the figure below:

![Feynman diagram](image)

Fig. 1: Feynman diagram for the semileptonic (weak) decay of the $\tau$-lepton.

Due to the large Higgs mass, the mass of the tau is small compared to its energy. Lepton masses will be irrelevant as well. Given the large Lorentz boost which the taus receive in the Higgs decay, the direction of each tau can be well approximated by the direction of the charged lepton. Along the same line of argument, the direction of the missing energy in the transverse plane will be the resultant vector of the neutrinos from each tau decay, which also point in the direction of the charged leptons. In the limit where all particle masses $\to 0$, one is now able to reconstruct the individual transverse components of the neutrino momenta ($p^H_\nu$) provided the two charged leptons are not collinear.

$$p^H_{\nu_x} \frac{p^H_{\nu_x}}{|p^H_{\nu_x}|} + p^H_{\nu_y} \frac{p^H_{\nu_y}}{|p^H_{\nu_y}|} = p^\text{miss}_x$$

$$p^H_{\nu_y} \frac{p^H_{\nu_y}}{|p^H_{\nu_y}|} + p^H_{\nu_x} \frac{p^H_{\nu_x}}{|p^H_{\nu_x}|} = p^\text{miss}_y$$

(1)

When the Higgs has no or only little transverse momentum, the opening angle between the two tau leptons will in general be large due to the isotropic decay of the scalar Higgs. An invariant mass reconstruction will therefore be impossible. Thus for a Higgs produced at large transverse momentum the mass can be rather accurately reconstructed. In [4, 5] it is argued that a resolution of order 10 GeV/c$^2$ is needed in the tau pair invariant mass to distinguish the signal from the background continuum. After all, for the quoted Higgs mass range, the full width half maximum is relatively small.

In figure 2 the two lowest order (QCD type of) diagrams are given on which the Isajet [6] and Pythia [7]
3. Background, lepton distributions and mass reconstruction

The most important background to the $H^0 \to \tau^+ \tau^-$ channel is $t \bar{t}$ production where each top quark decays into a $b$ quark and a $W$ and subsequently, the $W$ decays semileptonically into a lepton plus a neutrino. Due to the relatively large mass of the top quark (200 GeV/c$^2$), the $W$ is likely to be produced close to its mass shell giving rise to isolated leptons. The cross-section for $t \bar{t}$ production at the LHC is $\sim 0.5$ nb. [8, 10], an order of magnitude larger than the Higgs cross-section ($\sim 30$ pb.). The semileptonic branching ratio for $t$ - quarks into electrons or muons and neutrinos is in the parton model approximation $\sim 11.2$ %. This leads to a dilepton cross-section (before any cuts) of $\sigma = (BR)^2 \sim 6$ pb, which in turn gives a signal to background ratio of $\sim 0.01$. The Eurojet calculation for $t \bar{t}$ uses the same set of structure functions (EHLQ-1) whereas the scale was chosen to be $Q^2 = p_T^2 + m_t^2$.

![Image of graphs showing $\mu$ transverse momentum and pseudorapidity distributions](image)

Fig. 5: Comparison of the muon transverse momentum (a) and pseudorapidity (b) distributions for the signal, Eurojet (drawn line), Pythia (dotted line), Pythia boson - boson fusion (dotted - dashed line, scaled by a factor .5 in order to obtain the correct cross-section) and one of the main backgrounds: $pp \to t \bar{t} X$.

The muon transverse momentum and pseudorapidity distributions for both background and signal are shown in figure 5. For Eurojet, we have introduced a cut of 10 GeV/c on the transverse momentum of the Higgs in order to keep the matrix elements well behaved (and thus excluding the region where the resummation of soft gluons becomes important). The program was interfaced with Eurodec [11] for parton fragmentation and particle decays. Both Eurojet and Pythia (and IsaJet) give good agreement for $p_T^\mu$ up to $\sim$
for very large Higgs masses) for these processes, which overestimates the cross-section for our choice of parameters by a factor ~ 2. Nevertheless, we do not expect that event topologies are very sensitive to whether or not one uses exact or approximate formulae. Moreover, the magnitude of this mechanism is relatively small for a Higgs of 110 GeV/c^2 with a transverse momentum less than 100 GeV/c as illustrated in figure 4.

Fig. 4: Comparison of Higgs transverse momentum (a) and Higgs rapidity (b) distributions from Eurojet (drawn line), Pythia (dashed line), Pythia boson - boson fusion (dotted line, scaled by a factor .5 in order to obtain the correct cross-section) and Isajet (dotted - dashed line).

In all calculations the EHLQ (set 1, Λ = 290 MeV) [9] structure functions were selected. The scale at which α_s and the structure functions are evaluated was set to √s. For the Eurojet calculation (note that we did not include the boson - boson fusion mechanism here!) this choice is rather arbitrary (conservative) and can only be verified when the O(α_s^4) calculation becomes available [5]. The Eurojet distribution (4*) shows a quite different behaviour at large p_T^h. At small transverse momentum the resummation of soft gluons is lacking which is however, not relevant for our further analysis as will be demonstrated later. The differences between Pythia and Isajet for the qq, gg production processes are most likely the result of different implementations and phenomenology of the individual parton shower algorithms. The rapidity distributions do not show any significant differences. We conclude that at very large p_T the parton shower algorithms should be used with care, while the boson - boson fusion mechanism becomes competitive at relative large p_T^h.
Fig. 7: Missing transverse energy distributions for signal and background (a) and reconstructed invariant Higgs mass (b) requiring $p_T > 10$ GeV/c and $E_{T}^{miss} > 10$ GeV.

Fig. 8: Jet multiplicity (cone size in $\Delta R = 0.7$) demanding $E_{T}^{miss} > 25$ GeV (a) and the number of reconstructed jets with $E_{T}^{jet} > 50$ GeV (b).
60 GeV/c. At larger $p_t$, the fixed order calculation and boson - boson fusion mechanism again become important. For completeness, we have calculated the opening angle ($\phi$) between the muons in the transverse plane (fig. 6), requiring $p_t^\mu > 10$ GeV/c.

![Graph showing opening angle between muons](image)

**Fig. 6:** Opening angle $\phi$ between the muons from the decaying taus and the two fastest muons in $pp \rightarrow \tau X \rightarrow \mu^+ \mu^- X'$ demanding $p_t^\mu > 10$ GeV/c.

The missing transverse energy distributions are plotted in figure 7a and look quite similar to the muon $p_t$ distributions for the signal as presented in fig. 5a. The background however, peaks at larger missing energies. An accurate measurement of missing transverse energy can only be achieved when the probability for pile-up of energy in the calorimeter due to multiple interactions remains relatively small (luminosities less than $10^{33}$ cm$^{-2}$ s$^{-1}$). Figure 7b shows the Higgs Invariant mass distribution after applying minimal cuts on the muons (or electrons) $p_t^\mu > 10$ GeV/c and the missing energy, $E_{miss} > 10$ GeV. The clear resonance structure in the signal is overwhelmed by the background continuum by an order of magnitude.

The event topology of the background is quite different from the signal as demonstrated by analyzing the jet multiplicity distributions as given in figure 8. The first distribution ($8a$) represents the jet multiplicity assuming a jet to have at least 25 GeV transverse energy in a cone of $\Delta r = 0.7$ (defined in the plane of pseudorapidity - azimuthal angle). The distribution in $8b$ is obtained requiring a jet transverse energy of at least 50 GeV.

We used a modified ‘LUCELL’ jet finding algorithm [12], for which we introduced a calorimeter with 10000 cells (2$\pi$ coverage in $\phi$, $\pm 3$ units in pseudorapidity). The minimum transverse energy for a cell to be considered as a potential jet initiator has been set to 1.5 GeV. A jet was required to have at least a total transverse energy of 15 GeV. No smearing effects (experimental resolutions) are included.
With a minimal set of cuts ($p_T > 10 \text{ GeV/c}$, $E^{\text{miss}}_T > 10 \text{ GeV}$) and demanding only 1 jet with $E_T > 50$ (25) GeV we find for one year of running at the moderate luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and assuming a liberal (favourable ?) choice of as yet experimentally undetermined quantities ($m_t = 200 \text{ GeV/c}^2$, $m_H = 110 \text{ GeV/c}^2$), about 5 (10) dimuon events, with a strong reduction of the dominant $t\bar{t}$ background. If we allow for $e^- \mu$ and $e^- e^-$ combinations, this sample increases to $\sim 20$ (40) events per year. A more detailed study of the backgrounds, including $Z^0 \rightarrow \tau^+ \tau^- \rightarrow e\mu$ and $WW \rightarrow e\mu$, is reported on in ref. [2].

In our analysis we have not yet explored the application of any explicit isolation criterion on the leptons. Whether this may increase the signal to background ratio without cutting away too much of the signal remains to be seen. However, the main result of this study shows that the dominant background from $t\bar{t}$ events to the $H^0 \rightarrow \tau^+ \tau^-$ decay can be considerably reduced by jet energy and jet multiplicity cuts.

References


L. Di Lella, Higgs study group, Proceedings of the ECFA Large Hadron Workshop, edited by G. Jarlskog and D. Rein, Cern 90-10, ECFA 90-133 Volume II.


Depending on the jet energy, the first two bins $(\delta^a)$ or the first bin $(\delta^b)$ indicate a huge background reduction by a simple cut on the event topology. One should be aware that both Eurojet distributions are conservative estimates since for the signal (background) only the $O(a_s^2)$ ($O(a_s^3)$) contributions have been included. The reconstructed invariant Higgs mass distributions demanding only 1 jet with $E_j > 25$ GeV or only 1 jet with $E_j > 50$ GeV/c are displayed in fig. 9a and 9b respectively.

**Fig. 9:** *Reconstructed Invariant Higgs mass distributions $(p_T^H > 10$ GeV/c and $E_{\text{miss}} > 10$ GeV) requiring one single jet with: $p_T^{j1} > 25$ GeV/c (a) or 1 jet with: $p_T^{j1} > 50$ GeV/c (b).*

Comparison of these plots with the distributions presented in fig. 7b show (for both jet conditions) a considerable reduction in background. An increase of the minimum jet energy to 50 GeV or demanding two jets with $E_j > 25$ GeV each (not plotted), show a similar trend, however, less pronounced. Larger statistics should be obtained for $t\bar{t}$ and a careful tuning of topology cuts remains to be done, but nevertheless, results appear to be encouraging.

4. **Conclusions**

Except for the tail of the Higgs transverse momentum distribution, both parton shower programs, Pythia and Isajet, compare well with the exact calculation by J.J. van der Bij et al. as implemented in the Eurojet program.