The Search for a Light ‘Intermediate Mass’ Higgs Boson.

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Abstract

We review recent progress in techniques for searching for the Standard Model light ‘Intermediate Mass’ Higgs Boson (80 GeV \(\lesssim M_H \lesssim 140\) GeV). We pay particular attention to associated production at the SSC and LHC where we search for the Higgs produced in association with either a \(W\) boson or a \(t\) quark. This production mode can be detected cleanly when the Higgs decays into two isolated photons, and the associated heavy particle decays semi-leptonically. We discuss the possibility that radiative corrections may significantly enhance the \(W\gamma\gamma\) background, decreasing the significance of the \(WH\) signal.

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Introduction

The Standard Model of Particle Physics, based upon a spontaneously broken $SU(3) \otimes SU(2) \otimes U(1)$ gauge theory, has proven to be remarkably successful over the past 20 years. However two major predictions of this model are the existence of a sixth quark, the top quark, and of a neutral CP-even scalar particle, the Higgs boson; neither of which have so far been observed. Through higher order corrections to observed processes we expect that $m_t \lesssim 200$ GeV [1], and so should be detected at the Tevatron at Fermilab within the next few years. On the other hand the Higgs boson has far fewer constraints placed upon it. Theoretically, both from perturbative and lattice calculations, we expect $M_H \lesssim 1$ TeV [2]. Direct searches at LEP I give $M_H > 62.5$ GeV at the 95% confidence level [3].

At LEP II we expect the Standard Model Higgs mass bound to be raised to 80 GeV [4], however due to the limited centre of mass energy ($\sqrt{s} \lesssim 180$ GeV) we are unlikely to be sensitive to Higgs with mass larger than 80 GeV. The hadron super colliders the SSC and the LHC will be able to detect a heavy Higgs with $M_H \gtrsim 140$ GeV [5], such a Higgs has an appreciable branching ratio into $ZZ^\ast$ (where the $Z$ bosons are either on or off mass shell), and hence into four leptons ($H \to ZZ^\ast \to 4l$ with $l = e, \mu$) (see Fig.1). In this 4l decay mode a heavy Higgs can be detected cleanly. For masses beneath $M_H \approx 130$ GeV the $ZZ^\ast$ branching ratio falls rapidly, this means that the 4l signal falls beneath irreducible backgrounds from $ZZ^\ast$ and $Z\gamma\gamma$ production, and reducible backgrounds from $t\bar{t}$ and $b\bar{b}Z$ production [5].

For masses beneath $M_H \approx 140$ GeV the major Higgs decay mode into jets are swamped by vast QCD backgrounds, this leaves only the modest $H \to \gamma\gamma$ decay mode as remotely observable [7]. Nonetheless despite the modest branching ratio into 2 photons $\mathcal{O}(10^{-3})$, see Fig.1, we have numerous events, because for a light Higgs we expect large numbers of Higgs bosons to be produced by gluon–gluon annihilation via a top quark loop [2]. Unfortunately as well as numerous events, we also have huge backgrounds: both reducible from jets faking photons, and irreducible from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$ production. The reducible background can be reduced to an insignificant level if we can distinguish jets from photons to 1 part in $10^4$ [8]; however the continuum $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$ irreducible background processes are by themselves huge. This places severe constraints upon our resolution for the measurement of the diphoton invariant mass; in practice we require this measurement to be accurate to about the 1% level, which will be very hard to achieve with a general purpose detector. Even
with such an excellent detector we still have a low signal to background ratio, but due to the large number of events we can still get a high significance. Typically there are $\mathcal{O}(1000)$ signal events on top of a continuum background of $\mathcal{O}(10000)$ background events, which would give an $\mathcal{O}(10)$ s.d. effect.

Clearly this makes the light ‘intermediate mass’ Higgs with $80 \text{ GeV} \lesssim M_H \lesssim 140$ GeV, exceptionally hard to detect.

**Associated Production**

In the past few years an alternative approach to looking for the the light ‘intermediate mass’ Higgs at proton–proton colliders has been proposed [9][10]. Rather than looking for the Higgs in isolation we look for it produced in association with other particles. Since the Standard Model Higgs is responsible for mass generation it couples predominantly to heavy particles (i.e., $W$’s, $Z$’s, and $t$ quarks), and so if we have an event that is tagged as containing a heavy particle there is a far greater probability that it will also contain a Higgs boson relative to a typical event. By searching for a Higgs
plus a heavy particle we hope to achieve far better signal to background ratios. Of course by using such a strategy we expect a lower signal rate due to the extra particle produced, but hope that the gain in the signal to background ratio compensates for the lower event rate. We should not forget that for isolated Higgs production it is not for lack of signal that the Higgs is hard to detect, but that huge backgrounds overwhelm our signal.

There are 3 cases associated with the massive particles, the $Z$ and $W$ bosons, and the $t$ quark. The dominant decays of the Higgs are swamped by huge backgrounds (although there has been some recent interest in $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$ [11]), and again we are forced to the Higgs decay $H \to \gamma\gamma$.

**ZH Associated Production**

In the process $pp \to ZH$ we can cleanly tag the $Z$ in its decay, $Z \to l^+l^-$ for $l = e, \mu$. Unfortunately this process has a branching ratio of only 7% and this means that there are too few events to be detected [9]. This is true even at a high luminosity SSC with $\mathcal{L} = 10^5$pb$^{-1}$.

**WH Associated Production**

In the process $pp \to WH$ the $W$ boson can be cleanly tagged in its leptonic decay modes, $W \to l\nu$ for $l = e, \mu$, although we only have a single lepton. This process is similar to $ZH$ production, however the production rate is about 6 times larger than $ZH$ production due to a larger leptonic branching ratio $\text{Br}(W \to l\nu) = 20\%$ (c.f. $\text{Br}(Z \to l^+l^-) = 7\%$) and also because the $V-A$ couplings of the $W$ to the initial state quarks are larger than the corresponding $Z$ couplings [9]. Concentrating on the $pp \to WH \to l\gamma\gamma$ signal, the lowest order subprocess is

$$q\bar{q}' \to WH \to l\nu\gamma\gamma \quad .$$

(1)

For the lepton (from the $W$ decay) and the photons (from the Higgs decay) to be detected we insist that they pass the cuts,

$$p_\perp > 20 \text{ GeV} \quad , \quad |\eta| < 2.5 \quad .$$

(2)

Now if we allow the photons to become too close to any hadronic activity then we have a large background from $\pi^0$’s faking photons; also if the lepton becomes close to hadronic activity we have a large background from semileptonic $b$ and $c$ quark decays.
a) At the LHC with $\sqrt{s} = 16$ TeV.

Fig.2. The cross-section for the signal $pp \to WH \to l\gamma\gamma$, the main irreducible background, $pp \to W\gamma\gamma \to l\gamma\gamma$, and reducible background, $pp \to b\bar{b}\gamma\gamma \to l\gamma\gamma$.

Also shown are the expected number of events at the high luminosity LHC with $\mathcal{L} = 10^5\text{pb}^{-1}$ and the standard luminosity SSC with $\mathcal{L} = 10^4\text{pb}^{-1}$.

Further as the photons become collinear to the lepton the backgrounds have a collinear singularity coming from photons being radiated from the lepton. To remove these backgrounds we need to insist that the photons and leptons are well separated from any jets and from each other. This is implemented by insisting that the leptons and photons are separated from jets and each other by a minimum $\Delta R$;

$$\Delta R > 0.4 \quad \text{where} \quad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}. \quad (3)$$

With these cuts the dominant background is the irreducible background [9],

$$pp \to q\bar{q}' \to W\gamma\gamma. \quad (4)$$

The cross-sections and events rates for the signal (1) and the background (4) are shown in Fig.2. We use the MRS92′ D0 set of parton distributions [12], and for consistency with these parton distributions choose $\Lambda_{\overline{MS}}(nf = 4) = 230$ MeV, which we have rescaled to a five flavour $\Lambda_{\overline{MS}}$. 

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If we can achieve a rejection of jets faking photons to 1 part in $10^4$, \textit{i.e.}, the same rejection factor that would be required if we are to detect the Higgs in its two photon decay mode, then we can reduce to an insignificant level the background from [13],

$$pp \rightarrow W jet \ jet \rightarrow W \gamma \gamma$$
$$pp \rightarrow W \gamma \ jet \rightarrow W \gamma \gamma$$ \hspace{1cm} (5)

As well as the irreducible backgrounds we also have reducible backgrounds, in particular coming from heavy quark decays faking isolated leptons [9][14],

$$pp \rightarrow b\bar{b} \gamma \gamma \rightarrow l \gamma \gamma X$$ \hspace{1cm} (6)

Conservatively we expect that only 1/7 semileptonic $b$ decays will pass our isolation cut (3) [7]. Using this as the rejection factor coming from isolation, and calculating the dominant gluon fusion subprocess [14],

$$pp \rightarrow gg \rightarrow b\bar{b} \gamma \gamma \rightarrow l \gamma \gamma X$$ \hspace{1cm} (7)

which we expect to dominate at the LHC and SSC, we see that this process does not present a serious background. The rate is show in Fig.2. $c$ quark decays will very rarely produce an \textit{isolated} lepton, and so given the $b$ quarks decays to leptons are not a significant background to $WH$ detection we do not expect $c$ quark decays to pose a problem.

In Fig.2 we have chosen 5 GeV bins for the photon–photon invariant mass; in practice we expect to be able to achieve a far better experimental resolution than this. Binning the cross-section in narrower bins will cause the continuum backgrounds to be lowered, without lowering the signal at all (remember that for a ‘intermediate mass’ Higgs its width is $\mathcal{O}(\text{MeV})$ and so is far smaller than any experimental resolution). It is clear from Fig.2 that we have good signal to background ratios, far better than the signal to background ratios for the plain $H \rightarrow \gamma \gamma$ detection mode for the Higgs. However our signal rate is low, we have only a handful of events; this means that we will require high luminosity at both the LHC and the SSC. In Table 1 we show the numbers of signal events expected at the high luminosity LHC and SSC with $\mathcal{L} = 10^5 \text{pb}^{-1}$ we also show the numbers of background events for 3% $M_{\gamma \gamma}$ resolution, and give the significance of this signal if it were to be observed.
Table 1. The expected numbers of $pp \rightarrow WH \rightarrow l\gamma\gamma$ signal events and background events at the high luminosity LHC and SSC ($\mathcal{L} = 10^5\text{pb}^{-1}$) for various mass values of the Standard Model Higgs boson assuming reasonable diphoton mass resolution of about 3%. We also give the significance in s.d. that this signal would be if observed.

$t\overline{t}H$ Associated production

Moving on to $pp \rightarrow t\overline{t}H$ production [10][14][15]; within the Standard Model 100% of $t$ quarks decay to $W$ bosons; and so as with $W$ detection we can tag the heavy particle on an isolated lepton. This means that the signal that we look for is again an isolated lepton, and two isolated photons. Despite the fact that our signal is the same as for $WH$ production, the two processes look considerable different. At leading order $WH$ production just has an observed lepton and two photons in the final state; whereas $t\overline{t}H$ production in addition a lepton and two photons also typically has 4 jets (1 jet coming from the semileptonic $t$ decay, and 3 jets coming from the other $t$ decay). This makes the $t\overline{t}H$ final state far more active than the $WH$ final state, and in particular means that the backgrounds for $WH$ and $t\overline{t}H$ production are distinct. The $WH$ cross-section...
is proportional to the $WWH$ coupling, and the $ttH$ process is proportional to the $ttH$ coupling; by measuring these two processes independently we can separately extract the $WWH$ and $ttH$ couplings.

We apply the same cuts as in the $WH$ production case (2,3). As well as an isolated lepton from the $t$ decay we gain a factor of 2 from leptons coming from the $\bar{t}$ decay. We calculate both the $gg \to ttH$ and $q\bar{q} \to ttH$ cross-sections; due to the large gluon luminosity at the LHC and SSC the $gg$ fusion process dominates, however the $q\bar{q}$ initial state contributes 10% at the SSC and 25% at the LHC of the $gg$ initial state [16].

The dominant background for this process are the irreducible backgrounds [14][15],

$$pp \to gg, q\bar{q} \to t\bar{t} \gamma \gamma$$ (8)

here the $q\bar{q}$ subprocess is of greater importance than for the signal processes. This is because we can have the photon radiation off the initial state quark, which both increases the number of Feynman diagrams and reduces the $Q^2$ flowing through the internal gluon, putting it closer to on mass shell. At the SSC the $q\bar{q}$ background is 20% of the $gg$ background for $m_t = 100$ GeV increasing to 35% for $m_t = 180$ GeV [16]. At the LHC the $q\bar{q}$ background is 50% of the $gg$ background for $m_t = 100$ GeV increasing to 120% for $m_t = 180$ GeV [16]. It is clear that the $q\bar{q}$ initial state is a very important source of background events, especially for larger $m_t$, although fortunately for larger $m_t$ the $t\bar{t}\gamma\gamma$ background is far smaller than the $ttH$ signal.

We show the signal and background in Table 2 and Fig.3. Clearly we have a good signal to background ratio, with a reasonable number of events. Especially for large $m_t$ (where the signal doesn’t fall as rapidly as the background, due to the increase in the $ttH$ Yukawa coupling) this gives a high significance. This requires only the standard luminosity SSC (with $\mathcal{L} = 10^4\,pb^{-1}$), however the LHC still requires a high luminosity of $\mathcal{L} = 10^5\,pb^{-1}$.

**Difficulties with NLO corrections?**

Normally in any process we expect the next-to-leading order (NLO) corrections to be $\mathcal{O}(\alpha)$, and so for QCD processes at high energies to only be of $\mathcal{O}(10\%)$. However if we consider the process,

$$q\bar{q}' \to W\gamma$$ (9)

then the NLO corrections enhance the cross-section by a factor of about 3 [17]. Clearly something odd is going on. In this case it is well understood what is going on, at
Table 2. The numbers of events for the $t\bar{t}H$, $t\bar{t}\gamma\gamma$ background, assuming a $M_{\gamma\gamma}$ resolution of 3%; at the high luminosity LHC ($\mathcal{L} = 10^5\text{pb}^{-1}$) and the standard luminosity SSC ($\mathcal{L} = 10^4\text{pb}^{-1}$). We also give the significance, $\frac{N_{\text{in}}}{\sqrt{N_{\text{tot}}}}$, that this signal would have if it were observed.

LO when the photon makes a certain angle with respect to the $q\bar{q}'$ pair there is a radiation zero where the cross-section vanishes identically [18]; this is due to destructive interference between photons radiated off the $W$ and quark legs. This radiation zero dominates the whole production pattern of the $W\gamma$ pair, and effectively suppresses radiation over a large range of angles; and this in turn lowers the total cross-section over the naive expectation. Now when we move to NLO this radiation zero is absent, and the NLO corrections are $O(\alpha_S)$ of our naive expectation for the $W\gamma$ cross-section; rather than $O(\alpha_S)$ of the radiation zero dominated correction. This does not necessarily mean that our perturbation theory is out of control because as we move to higher orders...
Fig.3. The differential cross-sections ($d\sigma/dM_{\gamma\gamma}$ (fb/5 GeV)) for the process $pp \rightarrow gg, q\bar{q} \rightarrow t\bar{t}\gamma\gamma$. Also shown are the expected numbers of events for the standard luminosity SSC ($L = 10^4$pb$^{-1}$) and the high luminosity LHC ($L = 10^5$pb$^{-1}$). Superimposed are the cross-sections for the process $pp \rightarrow gg, q\bar{q} \rightarrow t\bar{t}H$ for three values of $M_H = 70, 100, 130$ GeV.

In $\alpha_s$ we do not expect similar enhancements; we should look at this result as saying that the LO cross-section is abnormally small, rather than the NLO cross-section being abnormally large.

However this raises the question as to how large the NLO corrections are to $W\gamma\gamma$ production. Unfortunately these have not yet been calculated, and indeed due to the presence of pentagon diagram in the virtual Feynman diagrams this calculation stretches current technology to its limit. However we can ask whether we expect large NLO enhancements in analogy with $W\gamma$ production. Although we only expect the process $qq' \rightarrow W\gamma\gamma$ to have radiation zeros when the photons are parallel [18][19], i.e., when $M_{\gamma\gamma} = 0$, the matrix element still has very large cancellations between different Feynman diagrams even for nonzero $M_{\gamma\gamma}$. So in analogy with $W\gamma$ production we should expect the LO calculation of $W\gamma\gamma$ production to be abnormally small.

Recently the real contributions to the NLO calculation of $pp \rightarrow W\gamma\gamma$, $pp \rightarrow qq' \rightarrow W\gamma\gamma g$, $pp \rightarrow gg' \rightarrow W\gamma\gamma q\bar{q}$, $pp \rightarrow gg \rightarrow W\gamma\gamma q\bar{q}'$, have been calculated [20], and here they find that LO $W\gamma\gamma + 1$jet cross-section is about 3.5 times larger than the LO $W\gamma\gamma$ cross-section. This result should be taken with a
pinch of salt, for the LO calculation for $W\gamma\gamma + 1jet$ production is formally divergent when the final jet becomes collinear to the incoming partons, or becomes soft; now this divergence cancels with the 1 loop contribution to $W\gamma\gamma$ production, because when the final jet is either collinear or soft it can not be experimentally differentiated from $W\gamma\gamma$ production. This means that until these virtual 1 loop contributions have been calculated we can not know how much of the divergent result cancels. In practice what is done is that a minimum $p_\perp$ cut is imposed on the jet, which at least in principle keeps the jet experimentally observable, and so separates the $W\gamma\gamma + 1jet$ process from the $W\gamma\gamma$ process. If the cut chosen is too small then we feel too much of the divergent cross-section, unfortunately we can not know how small too small is without doing the complete NLO corrections. Hence we should be wary of the results of Ref.[20]. Having said all this though Ref.[20] finds a considerable contribution from $W\gamma\gamma + 1jet$ even with large $p_\perp$ cuts (e.g. $p_\perp > 50$ GeV); this, in conjunction to the apparent large suppression in the LO $W\gamma\gamma$ production, should fill us with worry.

If the NLO corrections to $W\gamma\gamma$ production do turn out to be large then in principle we can look in the more exclusive channel;

$$pp \rightarrow W\gamma\gamma + 0 \text{ jets}$$ (11)

this will have far smaller corrections as most of the NLO corrections to $W\gamma\gamma$ production will come from an extra jet produced in the final state [17]. However this has a caveat: What is a jet? Or how hard does a jet have to be before it becomes experimentally observable? Each event has an underlying event from the breakup of the proton remnants; further fixed order perturbation theory does not describe low $p_\perp$ jets well. This means that we can only describe jets well when their $p_\perp$ is larger than some value. If this value turns out to be large, say 100 GeV, which seems not unlikely at the LHC and SSC, then we will still include much of the NLO cross-section in measuring the exclusive process (11). At the LHC and SSC we expect multiple interactions at each bunch crossing, in such an environment it is not clear what it means to ask to see a process with 0 jets.

**Conclusions**

The CERN machines LEP I and LEP II are sensitive to light Higgs bosons with $M_H \lesssim 80$ GeV; however due to kinematic limits we are unlikely to be able to probe heavier Higgs bosons. The hadron super colliders the SSC and the LHC will be sensitive
to more massive Higgs bosons with $M_H \gtrsim 130$ GeV. This leaves the mass range $80 \text{ GeV} \lesssim M_H \lesssim 130$ GeV as possibly problematic.

Recently an alternative to looking for the Higgs in isolation at hadron colliders has been suggested, where we look for the Higgs produced in association with other massive particles. Although this extra massive particle decreases the cross-section; it increases the signal to background ratios. Associated $ZH$ production has too low an event rate to produce a usable signal. Associated $WH$ production, at first sight looks far more promising with 6 times the cross-section of $ZH$ production. There is a clean signal when the $W$ decays leptonically to an isolated electron or muon, and the Higgs decays into two isolated photons. However the major background of $W\gamma\gamma$ production has only been calculated to LO; and we have good reasons for believing there to be large NLO corrections. If, in analogy with $W\gamma$ production, the $W\gamma\gamma$ cross-section is increased by a factor of 3 this will decrease the significance of our signal by a factor of $\sqrt{3}$, alternative to achieve the same significance we will require 3 times the integrated luminosity. Nonetheless after several years of running at a high luminosity LHC or SSC (with $L = 10^5 \text{ pb}^{-1}$) this process should give a usable signal.

Associated $t\bar{t}H$ production also has a clean signal in the isolated lepton (from a $t$ decay) and two photon (from the Higgs decay) mode. This process has a similar cross-section to $WH$ production at the LHC, but about double the $WH$ cross-section at the SSC (due to the rapid growth in the gluon distribution within the proton at small Bjorken $x$). The main background from $t\bar{t}\gamma\gamma$ production does not present a problem, especially for larger $m_t$; where the background falls due to a more restrictive phase space, but the signal remains almost constant due to the growth in the $ttH$ Yukawa coupling. Although the tag for the $t\bar{t}H$ signal is the same as for $WH$ production (an isolated lepton and two isolated photons), the two types of event look considerably different. In the $t\bar{t}H$ case we expect a lot of jet activity coming from the $t$ quark decays; and this should make the two types of event easily separable. Indeed if the NLO correction to $W\gamma\gamma$ production do turn out to be large we may need to insist that we see a certain amount of hadronic activity in the event in order to remove this background. This method gives a signal of reasonable significance at the standard luminosity SSC (with $L = 10^4 \text{ pb}^{-1}$) and high luminosity LHC (with $L = 10^5 \text{ pb}^{-1}$).

Associated production of a Higgs with a heavy particle looks like a very promising method for searching for a light intermediate mass Higgs boson, with $80 \text{ GeV} \lesssim M_H \lesssim 140$ GeV at the SSC and LHC. However there is still much work to be done in this area.
before this search technique becomes ‘gold plated’. In particular we expect large NLO corrections to the $W\gamma\gamma$ background, which would significantly decrease the significance of the $WH$ signal.

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