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Discovering a Light Intermediate-Mass Higgs in Proton-Proton Collisions using Associated Production with W Bosons

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Abstract

The possibility of detecting a Higgs boson in the 80 - 120 GeV mass range in high energy proton-proton collisions, using associated production with W and Z bosons, is investigated. Unlike previous studies, we focus attention on the $\gamma\gamma$ Higgs decay channel. Although the event rate is at first sight prohibitively small, the availability of a high luminosity option at the proposed LHC collider would increase the rate to an observable level. The main irreducible background — double photon bremsstrahlung in W production — is calculated and shown to be small.

The discovery of the Higgs boson is arguably the most important challenge for present and future colliders. In principle, the proposed SSC pp collider can explore the mass range up to $\mathcal{O}(1 \text{ TeV})$ [1], while at the lower end of the mass range experiments at the LEP e^+e^- collider have already ruled out Higgs mass values below $\mathcal{O}(25 \text{ GeV})$ [2]. Detailed studies relating to the LEP200 [3], LHC [4] and SSC [1] colliders have shown that, using a variety of production and decay channels, the bulk of the mass range up to 1 TeV can be explored.

The one outstanding problem remains the discovery of a Higgs at the low end of the “intermediate-mass” range i.e. $80 \text{ GeV} \lesssim M_H \lesssim 120 \text{ GeV}$. Such a “light intermediate-mass” Higgs is difficult to discover at LEP200 in the canonical $e^+e^- \rightarrow ZH$ channel because (a) the kinematic limit is $M_H < \sqrt{s} - M_Z$ and (b) a Higgs with mass of order M_Z is difficult to distinguish – at least in its dominant hadronic ($b\bar{b}$) decay¹ – from a Z . In reference [5] it was shown that this latter problem can in principle be overcome, but only with sufficiently large statistics. At hadron colliders, the natural channels for discovery of an intermediate-mass Higgs are (i) $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$ and (ii) $H \rightarrow \gamma\gamma$ [6]. However for the former, the branching ratio falls steeply to the much lower values of $Z^{(*)}Z^{(*)}$ for Higgs masses below about 125 GeV (Fig.1). For the latter, the production cross section times branching ratio is roughly constant as a function of M_H while the background (isolated $\gamma\gamma$ pairs produced from $q\bar{q}, gg \rightarrow \gamma\gamma$ and fake γ ’s for π^0 decays) increases steeply for smaller $\gamma\gamma$ masses. This imposes very severe mass resolution requirements on a photon detector, independent of the overall centre of mass energy of the collider. Again, the conclusion is that discovery of a Higgs with mass less than $\mathcal{O}(120 \text{ GeV})$ will be extremely difficult in this channel [6,7].

The problem is compounded by the fact that it could very well be that the Higgs mass is in the vicinity of M_Z . For example, in the minimal SUSY extension of the standard model – with a pair of complex Higgs doublet fields – there is always one neutral Higgs boson with mass less than M_Z [9]. It is imperative, therefore, to be able to cover this mass range fully.

In this letter we explore the possibility of closing this possible “window

¹Since the overall event rate is not large, b quark tagging, for example using a vertex detector, would necessitate a very high efficiency.

of inobservability" by using the production mechanism $q\bar{q} \rightarrow W(Z)H$. This is certainly not a new idea, but previous studies [6,8] have concentrated on the $b\bar{b}$ Higgs decay mode. This gives a sizeable number of events, but suffers from potentially large backgrounds from $W(Z) + 2$ jet production, if the b quarks are not tagged, and irreducible backgrounds from $W(Z) + b\bar{b}$ even if they are [8]. In reference [6] this problem was investigated for the SSC, but it is clear that the *efficient* tagging of b quarks poses a major problem. For example, requiring two semi-leptonic (muon) decays of the b quarks immediately reduces the signal by two orders of magnitude, and smears out the reconstructed mass [8].

In the present study we focus instead on the $H \rightarrow \gamma\gamma$ decay channel. We are clearly now paying a heavy price in both the production cross section — the $q\bar{q} \rightarrow W(Z)H$ production cross section in some two orders of magnitude below the dominant $gg \rightarrow H$ mechanism in the mass range under consideration — and in the branching ratio, but two points work in our favour.

First, we have re-analysed the Higgs branching ratios including the effects of the *running* b quark mass, and have discovered that the suppression of the $H \rightarrow b\bar{b}$ partial width that this induces increases the $H \rightarrow \gamma\gamma$ branching ratio to about a factor two higher than the canonical value of 10^{-3} found in the literature [10]. The partial decay width of the Higgs boson into heavy quarks has recently been calculated to $\mathcal{O}(\alpha_s^2)$ [11]. Assuming five active flavours the result in the $\overline{\text{MS}}$ scheme can be summarized as

$$\Gamma(H \rightarrow b\bar{b}) = \frac{3\sqrt{2}}{8\pi} G_F M_H \bar{m}_b^2 \left(1 - 4 \frac{\bar{m}_b^2}{M_H^2}\right)^{\frac{3}{2}} \left[1 + 1.803\alpha_s + 2.953\alpha_s^2\right] + \mathcal{O}\left(\frac{m_b^2}{m_H^2}\right)$$

where G_F is the Fermi coupling constant, α_s is the running coupling of QCD at the scale of the Higgs mass M_H , and the running b -quark mass for five flavours is given by

$$\bar{m}_b = \hat{m}_b \left(\frac{23\alpha_s}{6\pi}\right)^{\frac{12}{23}} \left[1 + 0.3742\alpha_s + 0.1521\alpha_s^2\right].$$

The numerical value of the integration constant $\hat{m}_b$ is 8.23 GeV, assuming $\Lambda_{\overline{\text{MS}}}^{(5)} = .150$ GeV and using the central value of m_b [12]:

$$m_b = 4.25 \pm 0.10 \text{ GeV},$$

where m_b is defined by the condition

$$\overline{m}_b(m_b) = m_b .$$

We note that the uncertainties in the partial decay width due to $\Lambda_{\overline{MS}}$, m_b and the neglected $\mathcal{O}(m_b^2/M_H^2)$ corrections are estimated to be smaller than 10% in the mass region of interest. For completeness we show in Fig.1 our results for all relevant branching ratios of the intermediate-mass Higgs. The results in Fig.1 correspond to a top mass of 90 GeV, but in fact the branching ratios of a light intermediate-mass Higgs are essentially independent of m_t , given the current lower bound of $\mathcal{O}(90 \text{ GeV})$ from the CDF collaboration [13]. The partial decay width $\Gamma(H \rightarrow \gamma\gamma)$ has been calculated in leading order. QCD corrections may lower its value – pessimistically one may assume an approximate 25% reduction. Similarly electroweak corrections may further reduce it by order 10%. The values thus obtained should be considered the most conservative.

The second point in our favour is that it is possible that the LHC will be able to operate at a significantly higher luminosity than the canonical $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. This warrants a re-examination of ‘rare’ production processes.

We assume that the W and Z bosons in the final state are tagged by their leptonic decays: $W \rightarrow l\nu_l$ and $Z \rightarrow l^+l^-$ with $l = e, \mu$. Thus Fig.2 shows the production cross sections for $pp \rightarrow WH + X \rightarrow l\nu_l + \gamma\gamma + X$ and $pp \rightarrow ZH + X \rightarrow l^+l^- + \gamma\gamma + X$ for LHC (16 TeV) and SSC (40 TeV) energies, including both branching ratios. The cross sections are approximately independent of the Higgs mass, a result of a falling production cross section multiplied by a rising $H \rightarrow \gamma\gamma$ branching ratio. It is also clear that the associated production with Z bosons is at too small a level to be useful. To get a preliminary idea of the event rate per year, we can multiply the cross sections by integrated luminosities of 10^4 pb^{-1} for LHC and SSC (“standard luminosity”) and also by 10^5 pb^{-1} for the “high-luminosity” option being actively considered for the LHC. Especially for the latter case, this yields an event rate which though small is not negligible.

Two obvious questions remain: (i) by how much are the event rates depleted by realistic acceptance cuts on the final state particles, and (ii) how large is the background? To answer the latter, we have computed the cross section for the standard model process $pp \rightarrow W\gamma\gamma + X$, via the

subprocess $q\bar{q} \rightarrow W\gamma\gamma$. The matrix element is straightforward to calculate, especially using the “spinor techniques” of reference [14], and in fact is simply a subset of the $W + 2$ jet calculation. Note that we are assuming that the background from this latter process – where the jets “fake” direct photons – can be eliminated by photon isolation, transverse momentum cuts etc. This has been shown to be the case for the standard $gg \rightarrow H \rightarrow \gamma\gamma$ analysis [6,7].

To simulate a realistic acceptance we impose the following cuts on the charged lepton and photons in the final states:

$$p_T(l), p_T(\gamma) > 20 \text{ GeV}$$

$$|\eta(l)|, |\eta(\gamma)| < 2.5.$$

The fraction of the signal lost with these cuts is not particularly large, except – as expected – for light Higgs masses: for $M_H = 70 \text{ GeV}$ the rate is reduced by about 35%. Note also that the background matrix element is singular when the photons are soft and/or collinear with the beam direction, but not when the photons are collinear with each other.

Figs.3(a) and (b) show the $M_{\gamma\gamma}$ distribution for the signal and background at $\sqrt{s} = 16 \text{ TeV}$ and 40 TeV respectively, for several Higgs masses. Since the total decay width of a light intermediate-mass Higgs is much less than 1 GeV , the measured width of the resonance peak depends only on the experimental $M_{\gamma\gamma}$ resolution. Accordingly, we have distributed the Higgs signal uniformly in 5 GeV bins for purposes of illustration. There should be no difficulty in practice in achieving this level of resolution. The figures show that the signal stands clearly above the background for all masses in this range and at both collider energies. The criteria for discovery would appear therefore to depend solely on the achievable event rate. Returning to Fig.2, if we assume an overall efficiency of 50% for detecting this final state, then ten events per year requires an integrated luminosity of order 10^5 pb^{-1} for LHC and $5 \times 10^4 \text{ pb}^{-1}$ for SSC. Note that this is probably a conservative estimate. The ‘K-factor’ correction to the $W^{(*)} \rightarrow WH$ production cross section has the same form as that for a real W or Z , and is therefore of order +25%. Parton distributions which are more singular at small x will also enhance the cross section [15].

There is a further potentially dangerous background which must be considered. Because the standard missing transverse energy cut is not

likely to be useful at the very high energies of the LHC and SSC, it is very easy for semi-leptonically decaying b quarks to “fake” W ’s [16]. In the present context, the background comes from the process $gg \rightarrow b(\rightarrow lX)\bar{b}\gamma\gamma$. Since the second b quark in the final state is not detected, it prefers to be collinear with the incoming gluons, and the matrix element can be approximated (at least to within a factor of 2) by that for $gb \rightarrow b(\rightarrow lX)\gamma\gamma$. To calculate the background from this process, we decay the b quark in three stages: first a QCD fragmentation involving multi-gluon emission $b \rightarrow b + ng$, then a Peterson-type decay $b \rightarrow B$, and finally a semi-leptonic decay $B \rightarrow l\nu X$. Exactly the same cuts as for the $W\gamma\gamma$ background are then implemented on the final state lepton and photons. The resulting cross section at 16 TeV is 5.5 fb, comparable to the $W\gamma\gamma$ cross section in Fig.3(a). The $M_{\gamma\gamma}$ distributions are also similar for the two backgrounds. In practice, however, we would expect that this background could be reduced significantly further, since the lepton from b decay is almost always accompanied by a hadronic jet. There is also a tendency for one of the photons to be collinear with the lepton, unlike for the signal and $W\gamma\gamma$ background. To properly implement isolation cuts for the lepton and photons would, however, require a detailed Monte Carlo simulation incorporating fragmentation, detector response, etc. Since we have shown that the b decay background does not pose a problem with minimal cuts at the parton level, we are confident that this conclusion could only be strengthened by a full analysis.

In conclusion, we have taken a first look at the prospects for detecting a light intermediate-mass Higgs, produced in association with W bosons and decaying to two photons, at the LHC and SSC colliders. The prospect of a high-luminosity option – especially for the former – makes this entirely feasible. Our analysis has shown that a detailed detector simulation – to estimate the efficiency for this particular final state – is certainly warranted.

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Figure Captions

- [1] Branching ratios for various decay modes of the intermediate-mass Higgs, as a function of M_H . The following parameters are used: $\alpha = 1/128$, $M_W = 80$ GeV, $M_Z = 91.1$ GeV, $m_t = 90$ GeV, $m_b = 4.25$ GeV, $m_c = 1.27$ GeV, $\Lambda_{\overline{MS}}^{(5)} = 0.15$ GeV and $\sin^2 \theta_W = 0.23$. Note that the effects of running quark masses are included in the $q\bar{q}$ partial decay widths, and the mass values given above refer to the mass defined at the scale $\mu = m_q$.
- [2] Cross sections for $pp \rightarrow WH + X \rightarrow l\nu_l + \gamma\gamma + X$ (solid lines) and $pp \rightarrow ZH + X \rightarrow l^+l^- + \gamma\gamma + X$ (dashed lines) for LHC (16 TeV) and SSC (40 TeV) energies, including both branching ratios, as a function of M_H . The parton distributions are the latest HMRS(B) set from reference [17], with a “standard” gluon distribution and $\Lambda_{\overline{MS}} = 0.19$ GeV.
- [3] Distributions in the $M_{\gamma\gamma}$ invariant mass for the $W\gamma\gamma \rightarrow l\nu_l\gamma\gamma$ background (solid histogram) and for the $WH \rightarrow l\nu_l\gamma\gamma$ signal (dashed histogram) with $M_H = 70, 100, 130$ GeV at (a) LHC energy ($\sqrt{s} = 16$ TeV) and (b) SSC energy ($\sqrt{s} = 40$ TeV). The following cuts are imposed on the final state particles: $p_T(l), p_T(\gamma) > 20$ GeV, $|\eta(l)|, |\eta(\gamma)| < 2.5$.

Fig. 1

Fig. 2

Fig. 3