Calculation of the contributions to the signals and backgrounds for intermediate mass Higgs detection at the LHC and SSC from the $q\bar{q}$ initial state

D.J. Summers

Centre for Particle Theory, University of Durham, Durham DH1 3LE, England.

Abstract

We calculate the subprocess $q\bar{q} \rightarrow t\bar{t}H$ which contributes to the signal for detection of a light ‘intermediate mass’ Higgs boson at the LHC and SSC in the isolated lepton and two isolated photons mode. This enhances the $gg \rightarrow t\bar{t}H$ signal by about 10% at the SSC and 25% at the LHC. We also calculate the $q\bar{q} \rightarrow t\bar{t}\gamma\gamma$ irreducible background subprocess to this detection mode which enhances the $gg \rightarrow t\bar{t}\gamma\gamma$ irreducible background. This background is found to be quite substantial due to the effect of radiation from the initial state quarks as well as the final state $t\bar{t}$ pair; at the SSC the $q\bar{q}$ initial state background enhances the $gg$ initial state background by between 20% for $m_t = 100$ GeV and 35% for $m_t = 180$ GeV, and at the LHC by between 50% for $m_t = 100$ GeV and 120% for $m_t = 180$ GeV. However with a 3% mass resolution on the $\gamma\gamma$ mass the extra $q\bar{q}$ background events are typically smaller than the extra $q\bar{q}$ signal events, and the signal remains observable.
Over the past two decades the Standard Model has been spectacularly verified with the discovery of \( W \) and \( Z \) bosons, however the mass generation sector of the Standard Model is very poorly constrained. In the Standard Model a complex doublet scalar field generates the mass of the \( W \) and \( Z \) via the Higgs mechanism, and the fermion masses via the Yukawa mechanism; after the generation of vector boson masses there remains one neutral \( CP \) even physical scalar in the Standard Model, the Higgs boson. This Higgs boson has unknown mass, however there are theoretical biases for believing the Higgs mass, \( M_H \approx 1 \) TeV[1]. Recent negative searches from LEPI have show that \( M_H > 57 \) GeV[2]. This leaves the mass range \( 57 \) GeV < \( M_H \approx 1 \) TeV in which we expect one (or possibly more, in extensions to the Standard Model) Higgs boson to exist. It is a major aim of the next round of accelerators to cover this mass range and either detect, or rule out, the Higgs boson. LEP II will be able to detect a Higgs with \( M_H \approx 80 \) GeV [3], while the LHC and the SSC probe the heavier Higgs sector through the \( H \to ZZ \to 4l \) decay mode for \( M_H > 2M_Z \); and via \( H \to ZZ^* \to 4l \) for \( 2M_Z > M_H \approx 130 \) GeV. For Higgs with \( 80 \) GeV < \( M_H \approx 130 \) GeV the most promising detection mode is to detect the Higgs in association with another heavy particle at high energy hadron colliders. The most promising signals come from[4, 5],

\[
pp \to t\bar{t}H \to \gamma\gamma \xrightarrow{\text{tag}} lX
\]

(1)

\[
pp \to WH \to \gamma\gamma \xrightarrow{\text{tag}} l\nu
\]

(2)

where we tag both signals by the presence of two isolated photons from the Higgs decay and an isolated lepton \((l = \mu, e)\) from the associated heavy particle decay. Even though we tag on the same signal, the two types of event look considerably different; process (1) regularly contains 2 or more well defined extra jets from the \( t\bar{t} \) decay products, whereas in process (2) each extra jet costs us an extra power of \( \alpha_S \). This means that we can consider the two processes, (1,2), independently; and as such calculate the backgrounds for each process separately.

If we can reject jets from looking like photons at 1 part in \( 10^4 \) then the major background for process (1) has been show to be [6, 7],

\[
pp \to t\bar{t}\gamma\gamma \xrightarrow{\text{ balance}} lX
\]

(3)

This has been calculated from the subprocess,

\[
gg \to t\bar{t}\gamma\gamma
\]

(4)

which, on the face of it, dominates over the subprocess,

\[
q\bar{q} \to t\bar{t}\gamma\gamma
\]

(5)
due to the large gluon luminosity at small Bjorken $x$ relative to the quark luminosities, and also the colour structure of the matrix elements. For example for just $t\bar{t}$ production the $q\bar{q}$ initial state contribution is typically 10% at LHC energies ($\sqrt{s} = 16$ TeV) and 6% at SSC energies ($\sqrt{s} = 40$ TeV) of the $gg$ initial state contribution.

However in (5) the photons can be radiated from the initial state quarks as well as from the final state $t\bar{t}$ pair. This means that that we have far more Feynman diagrams for process (5), so we not only have just the final state radiation, but also initial state radiation, mixed initial-final state radiation, as well as all the interference between all the terms. Also when photons are radiated from the initial state the exchanged gluon in process (3) has less energy flowing through it and hence is closer to its mass shell; this can enhance the initial state radiation by a factor of 3 or so. Of course the initial quarks may have charge $\frac{1}{3}$ rather than the $t$ quark charge of $\frac{2}{3}$ which will lessen the effect of initial state radiation. All in all, it is uncertain as to how large the $q\bar{q}$ background process (5) will be relative to the $gg$ background process (4). Here we calculate the process (5) and also the $q\bar{q}$ signal process,

$$q\bar{q} \rightarrow t\bar{t}H$$  

which supplements the $gg$ signal process,

$$gg \rightarrow t\bar{t}H$$  

For the background matrix element (5) we have adapted the code of Ref. 8 where the process $e^+e^- \rightarrow \mu^+\mu^- + n\gamma$ was calculated keeping the full mass dependence of the muon. We change the exchanged photon and $Z$ into an exchanged gluon, the electrons into our initial state quarks and the muons into our final state $t$ quarks. We calculate the signal matrix element (6) using the spinor techniques of Ref. 9, and introduce the mass of the $t$ quark using the massive extension to massless spinors defined in Ref. 10.

We convolute the subprocess cross sections with the MRS D0' parton distributions of Ref. 11 to obtain full cross sections for the $pp$ initial state. For consistency with these parton distributions we set $\Lambda^{(4)}_{\overline{MS}} = 230$ MeV we rescale this to $\Lambda^{(5)}_{\overline{MS}}$ by forcing agreement between $\alpha^{N=4F=4}_S$ and $\alpha^{N=5F=5}_S$ at $Q = m_b$ and calculate the running of $\alpha_S$ at the 1 loop level. We use 5 active flavors in the running of $\alpha_S$ for $Q > m_b$.

After generating the $t\bar{t}H$ final state we decay the Higgs isotropically to two photons using the $BR(H \rightarrow \gamma\gamma)$ from Ref. 12. Then for both the signal and the background processes we decay the $t$ quarks via a $V-A$ interaction to onshell $W$’s and then decay the $W$’s again by a $V-A$ interaction. We insist that at least one of the $W$’s decay to a lepton ($e,\mu$).
For comparison we have included the cross sections from the $gg$ initial state process, (7,4) from Ref. 7, calculated using the same parameters as for the $q\bar{q}$ initial states. We calculate the $gg$ and $q\bar{q}$ initial state cross sections using the same Monte Carlo events, this means that the Monte Carlo error tends to cancel in the ratio of $q\bar{q}$ to $gg$ initial state events.

For the various electroweak parameters we use $M_Z = 91.1$ GeV, $\sin^2 \theta_W = 0.23$, $\alpha_{em} = 1/137.04$, and $M_W = M_Z \cos \theta_W$.

We use the following cuts to simulate a detector;

\[
p_T(l, \gamma) > 20 \text{ GeV} \quad , \quad |\eta(l, \gamma)| < 2.5
\]
\[
\Delta R(\gamma_1, \gamma_2) > 0.4 \quad , \quad \Delta R(l, \gamma) > 0.4
\]
\[
\Delta R(\gamma, \text{jet}) > 0.4 \quad , \quad \Delta R(l, \text{jet}) > 0.4
\]

where we associate a jet with each final state quark that we have. $\Delta R$ is defined as $\sqrt{\Delta \phi^2 + \Delta \eta^2}$ where $\eta$ is the rapidity and $\phi$ the azimuthal angle about the beam direction.

We obtain the results shown in figures 1a) at the SSC ($\sqrt{s} = 40$ TeV) and 1b) at the LHC ($\sqrt{s} = 16$ TeV), with 3 choices for $m_t = 100, 140, 180$ GeV where we have binned the data in 5 GeV $M_{\gamma\gamma}$ bins. We also show the number of events expected for $\sqrt{s} = 16$ TeV (LHC) with integrated luminosity $\mathcal{L} = 10^5 \text{ pb}^{-1}$ and $\sqrt{s} = 40$ TeV (SSC) with integrated luminosity $\mathcal{L} = 10^4 \text{ pb}^{-1}$. In practice we expect a better diphoton mass resolution, and this will lower the continuum background without affecting the signal (recall that for a Higgs in this mass range the Higgs width is $\mathcal{O}(\text{MeV})$ and as such the signal diphoton mass distribution is narrower than we will be able to experimentally measure.)

In tables 1a) and 1b) we show the expected number of events at the SSC ($\sqrt{s} = 40$ TeV) with $\mathcal{L} = 10^4 \text{ pb}^{-1}$ and at the LHC ($\sqrt{s} = 16$ TeV) with $\mathcal{L} = 10^5 \text{ pb}^{-1}$ with $M_{\gamma\gamma}$ bin widths of 3% of $M_{\gamma\gamma}$.

From the figures and tables it is clear that for both the signal and background the effect of the $q\bar{q}$ initial state is far larger at the LHC than at the SSC. This is because we are at smaller $\sqrt{s}$ at the LHC and so for the same $\sqrt{s}$ we require larger Bjorken $x$’s and so we feel the effect of the valence quarks in the proton more. For the signals the $q\bar{q}$ initial state is about 10% at the SSC, and 25% at the LHC, of the $gg$ initial state; this is about double the enhancement that we get for just $t\bar{t}$ production without the $H$, this is because the extra particle in the final state (the Higgs) forces the $\sqrt{s}$ to be larger and so forces us to larger Bjorken $x$ where we again feel the effect of the valence quarks
more. 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. 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. 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. For lighter $m_t$ where the $t\bar{t}\gamma\gamma$ background is far more severe the $q\bar{q}$ is of lesser importance – but still significantly enhances the background.

We now wish to address the question or whether we can decrease this large source of background events coming from the $q\bar{q}$ initial state. At first glance this seems impossible as the background is an irreducible background; however we should not forget that the production mechanism is considerably different from the signals (7,6) and the $gg$ initiated background (4). In the processes (7,6,4) the Higgs or photons are always radiated from the final state $t\bar{t}$ pair, however for the $q\bar{q}$ background (5) we also have contributions from photons radiated from the initial state. In particular this means that we have singularities when the photons become collinear with the beam direction. Of course these singularities are regulated by the requirements that $p_T(\gamma) > 20$ GeV and $|\eta| < 2.5$. This means that by varying these cuts we may be sensitive to process (5) and hence be able to reduce its importance.

We have checked the distributions of the signal and background processes on $p_T$ and $|\eta|$ of the photons and found that there is almost no difference in the $p_T$ distributions, but that the $q\bar{q}$ background (5) has a rapidity distribution different to the signal and other background. We show this in figure 2 where we have relaxed the cut on rapidity. We show the $q\bar{q}$ background process (5) and the $gg$ background process (4); the signals have a similar distribution to the $gg$ background process (4) although obviously with a different normalisation. Although there is a tendency for the photons produced in the $q\bar{q}$ background process to be more collinear with the beam direction than the $gg$ background process, it is also clear that there is no significant enhancement factor to be gained by making the $|\eta|$ more restrictive than in (8).
CONCLUSIONS

For detection of a Standard Model Higgs boson with $70 \text{ GeV} \lesssim M_H \lesssim 130 \text{ GeV}$ via the isolated lepton plus two isolated photon detection mode, the $ttH$ signal receives a helpful few events from the $q\bar{q}$ initial state signal events; at the LHC this enhances the signal by about 25%, and at the SSC by about 10%.

However the main irreducible background process (3) also receives large contributions from the $q\bar{q}$ initial state (5) relative to the $gg$ initial state (4), indeed at the LHC for heavy top this $q\bar{q}$ initial state background dominates the $gg$ initial state background.

If we can achieve a modest 3% of $M_{\gamma\gamma}$ mass resolution on $M_{\gamma\gamma}$ then the isolated lepton plus two isolated photon detection mode is still observable above the main irreducible background (3), the additional source of background events from process (5) is typically smaller than the extra signal events from process (6).

This can be achieved with the standard luminosity of $\mathcal{L} = 10^4 \text{ pb}^{-1}$ at the SSC ($\sqrt{s} = 40 \text{ TeV}$), however at the LHC ($\sqrt{s} = 16 \text{ TeV}$) we require higher than the standard luminosity of $\mathcal{L} = 10^4 \text{ pb}^{-1}$, $\mathcal{L} = 5 \times 10^4 \text{ pb}^{-1}$ will be sufficient.

This detection mode can be extended up to Higgs masses of about 150 GeV, however for higher Higgs mass the branching ratio into two photons drops rapidly as the width for $H \rightarrow WW^*$ grows rapidly. It can also be extended down to lower current LEPI mass limit of 60 GeV, however for lower mass Higgs the $H \rightarrow \gamma\gamma$ branching ratio drops off and the $tt\gamma\gamma$ background grows very rapidly. It is useful to extend this detection mode as far as possible because it tests the coupling of the Higgs to both $W$ bosons (and hence vector boson mass generation) and $t$ quarks (and hence fermion mass generation), because we can distinguish the two signals (1) and (2).

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FIGURE CAPTIONS

Figure 1. The differential cross sections \( \frac{d\sigma}{d\gamma\gamma} \) for the process \( gg \rightarrow t\bar{t}\gamma\gamma \), shown with light lines, and for \( gg + q\bar{q} \rightarrow t\bar{t}\gamma\gamma \), shown with thick lines at the a) the SSC with \( \sqrt{s} = 40 \text{ TeV} \) and b) the LHC with \( \sqrt{s} = 16 \text{ TeV} \). Shown for three values of \( m_t = 100, 140, 180 \text{ GeV} \). Also shown are the expected numbers of events for the standard luminosity SSC (\( \mathcal{L} = 10^4 \text{ pb}^{-1} \)) and the high luminosity LHC (\( \mathcal{L} = 10^5 \text{ pb}^{-1} \)). Superimposed are the cross sections for the processes \( gg \rightarrow t\bar{t}H \) (light lines) and \( gg + q\bar{q} \rightarrow t\bar{t}H \) (thick lines) for three values of \( M_H = 70, 100, 130 \text{ GeV} \).

Figure 2. The differential cross sections \( \frac{d\sigma}{d|\eta|} \) for the processes \( q\bar{q} \rightarrow t\bar{t}\gamma\gamma \) (solid) and \( gg \rightarrow t\bar{t}\gamma\gamma \) (dashed) for \( m_t = 140 \text{ GeV} \).

TABLES

Table 1. The numbers of events for the signal (7,6) and background (4,5) process at a) the SSC with \( \mathcal{L} = 10^4 \text{ pb}^{-1} \) and b) the LHC with \( \mathcal{L} = 10^5 \text{ pb}^{-1} \). For the background events we assume a 3% of \( M_{\gamma\gamma} \) bin width in \( M_{\gamma\gamma} \) about \( M_H \).

| \( M_H \) (GeV) | \( m_t \) (GeV) | \( \sqrt{s} = 40 \text{ TeV} \) | \( gg \rightarrow t\bar{t}H \) | \( q\bar{q} \rightarrow t\bar{t}H \) | \( gg \rightarrow t\bar{t}\gamma\gamma \) | \( q\bar{q} \rightarrow t\bar{t}\gamma\gamma \) |
|------------------|---------------|-------------------|-----------------|-----------------|-----------------|-----------------|
| 70               | 100           | 9.0               | 0.8             | 4.1             | 0.8             | 0.5             |
|                  | 140           | 11.4              | 1.0             | 1.6             | 0.8             | 0.3             |
|                  | 180           | 12.1              | 1.2             | 0.8             | 0.3             |
| 100              | 100           | 10.7              | 1.0             | 4.4             | 0.9             | 0.6             |
|                  | 140           | 14.2              | 1.5             | 1.8             | 0.9             | 0.3             |
|                  | 180           | 16.3              | 1.9             | 0.9             |
| 130              | 100           | 9.6               | 0.9             | 3.9             | 0.8             |
|                  | 140           | 11.8              | 1.4             | 1.6             | 0.5             |
|                  | 180           | 13.9              | 1.9             | 0.8             | 0.3             |

| \( M_H \) (GeV) | \( m_t \) (GeV) | \( \sqrt{s} = 16 \text{ TeV} \) | \( gg \rightarrow t\bar{t}H \) | \( q\bar{q} \rightarrow t\bar{t}H \) | \( gg \rightarrow t\bar{t}\gamma\gamma \) | \( q\bar{q} \rightarrow t\bar{t}\gamma\gamma \) |
|------------------|---------------|-------------------|-----------------|-----------------|-----------------|-----------------|
| 70               | 100           | 17.2              | 3.0             | 6.8             | 3.5             |
|                  | 140           | 19.2              | 3.8             | 2.7             | 2.0             |
|                  | 180           | 18.3              | 4.2             | 0.9             | 1.1             |
| 100              | 100           | 18.6              | 3.9             | 7.8             | 3.7             |
|                  | 140           | 22.4              | 5.5             | 2.6             | 2.0             |
|                  | 180           | 23.2              | 6.4             | 1.0             | 1.2             |
| 130              | 100           | 15.2              | 3.2             | 6.1             | 3.0             |
|                  | 140           | 16.9              | 4.9             | 2.0             | 1.8             |
|                  | 180           | 18.4              | 6.0             | 0.9             | 1.1             |