Higgs particle detection using jets

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We study the possibility of detecting the Higgs boson in the intermediate mass range via its two jet channel. We consider only Higgs bosons produced in association with a \(t\bar{t}\) pair. Both \(t\) and \(\bar{t}\) are required to decay semileptonically to reduce the QCD background. The signal is compared with the main background, \(t\bar{t} + 2\) jets, after appropriate cuts. A sizable signal above background is seen in our simulation at the parton level. Use of the \(t\bar{t}Z\) channel with \(Z\) decaying to \(l^+l^-\) is suggested for eliminating theoretical uncertainties in determining the \(ttH\) signal.

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INTRODUCTION

The Standard Model Higgs with mass up to 85 GeV/c^2 could be discovered at the planned LEP 200 experiments. At the SSC or the LHC on the other hand it should not be difficult to find a Higgs boson with mass between 140–800 GeV/c^2, which can decay to two Z bosons, one of which may be virtual. To cover the mass gap between 85 and 140 GeV/c^2, the rare decay $H \rightarrow \gamma \gamma$ was suggested [1–3], where the Higgs boson $H$ is produced in association with either a $W^\pm$ boson or a $t\bar{t}$ pair in $pp$ scattering experiments. A charged hard lepton from $W^\pm$ or one of the $t$ quarks is required as a trigger in order to reduce the QCD background. However, since the $2\gamma$ mode is a rare decay, it may be difficult to extract this signal from the complicated background [4].

We study instead the possibility of searching for an intermediate Higgs boson in the two-jet channel by reconstructing its invariant mass. We consider Higgs bosons that are produced in association with $t\bar{t}$ pairs only. This allows both the $t$ and $\bar{t}$ to be tagged using semileptonic decays to cut down on the QCD background. We are motivated by recent works on jet spectroscopy. The GEM Collaboration [5] has presented mass plots where $W$ and $t$ peaks were successfully reconstructed from two and three jets in computer generated multi-jet events. Similar method are proposed for charged Higgs searches at HERA [6] and for top searches at the TEVATRON [7]. For earlier studies of Higgs searches using jets see Ref. [8].

SIGNAL AND BACKGROUND

The main process of interest is

$$pp \rightarrow t\bar{t}H + X,$$

(1)

with

$$t \rightarrow b + (W^+ \rightarrow l^+ + \nu),$$

(2)

$$\bar{t} \rightarrow \bar{b} + (W^- \rightarrow l^- + \bar{\nu}),$$

(3)

$$H \rightarrow b\bar{b} \text{ or } c\bar{c},$$

(4)

where $l$ stands for either an electron or a muon. The final signal we are looking for is

$$2 \text{ leptons} + 4 \text{ jets} + \text{missing } E_T.$$  

(5)
Dicus and Willenbrock [1] have shown that $t\bar{t}H$ production at $pp$ colliders can be very well approximated by two-gluon fusion alone. The tree level cross section as a function of the Higgs mass can be found in Kunzst et al. [1] for $m_t = 140 \text{ GeV}/c^2$. It varies from 12 to 3 pb as the Higgs mass changes from 80 to 140 GeV/$c^2$. As an example, we take $m_H = 100 \text{ GeV}/c^2$, which gives a cross section of 8 pb; our signal (5) has a combined cross section $\times$ branching ratio of

$$\sigma(pp \rightarrow t\bar{t}H)B^2(t \rightarrow b l^+\nu)B(H \rightarrow q\bar{q}) = 8 \text{ pb} \times (2/9)^2 \times 0.97 = 0.4 \text{ pb} \quad (6)$$

at the SSC. This is to be compared with 6 fb for $H \rightarrow \gamma\gamma$ with a single lepton tag.

To reduce most of the QCD background, we put a 20 GeV cut on the minimum $p_T$ of each of the leptons and jets and place a 40 GeV minimum on the total missing $E_T$. An isolation cut is then applied to each lepton, requiring it to be at least $\sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ units away from any of the four jets. This has the effect of guaranteeing that almost all remaining events are of the type $t\bar{t} + 2$ hard jets. The same amount of separation is also applied to $e^+e^-$ and $\mu^+\mu^-$ pairs to avoid QED background.

We now look at the possible sources of background to our signal. There are three major types of background events:

1. Sources of background other than $t\bar{t}$ that produce $l^+l^-$ pairs are suppressed by at least two factors of either $\alpha_{\text{weak}}$ or $\alpha_{\text{em}}$, except when the $e^+e^-$ or $\mu^+\mu^-$ pairs are on the $Z$ mass-shell. Furthermore, these events do not have intrinsic missing $E_T$ and will probably not pass the missing $E_T$ cut. Thus, non $t\bar{t}$ contributions to the background are likely to be small.

2. By far, the most important background is the QCD process

$$pp \rightarrow t\bar{t} + 2 \text{ jets}, \quad (7)$$

where the jets come mostly from initial state radiation. Both the $t$ and $\bar{t}$ decay, as before, semileptonically to give the required signature.

The inclusive cross section for $pp \rightarrow t\bar{t}$ has so far been calculated to order $\alpha_s^3$ only [8a]. The cross section at the SSC was estimated by Baer et al. [10] to be 16 nb, while Barger et al. [11] gave 10 nb. To be conservative, we take the larger number of 16 nb for background calculations.

Although works on higher order corrections are still in progress [9], experience shows that $t\bar{t}$ pairs produced at the SSC are almost always accompanied by extra
high $p_T$ jets. Here, we will make the ansatz that there will be an average of 2.0 jets with $p_T > 20$ GeV in every $t\bar{t}$ event. By assuming a Poisson distribution for the number of extra jets, the $t\bar{t}$ cross section with two and only two accompanying jets with $p_T > 20$ GeV is found to be 4.3 nb. Folding in the leptonic branching ratio for top quarks reduces this number to 0.2 nb. This is a worst case scenario since we do need two extra jets in the final state and the Poisson distribution peaks at the average value. We therefore believe this to be a fairly conservative estimate unless the inclusive $t\bar{t}$ cross section turns out to be significantly different from 16 nb.

There is also a combinatorial factor for forming two-jet pairs from the four jets in each event; this enhances the background by a factor of 6. Compared to 0.4 pb for the signal, the background is larger by a factor of $3 \times 10^3$. We shall see later that this will be suppressed severely by additional cuts (see Table I). In addition, the background events will not have any special feature in the two-jet invariant mass spectrum while the signal will show a prominent peak around the mass of the Higgs boson.

(3) In addition to $t\bar{t}H$, there are also $t\bar{t}W^\pm$ and $t\bar{t}Z$ events in which the $W^\pm$ and $Z$ decay to two jets, thus producing the same signature. The production cross section for $W^\pm$ is about one-tenth of that for the $Z$ [12]. This together with a smaller mass of 80 GeV makes the $W^\pm$ events less important. On the other hand, $t\bar{t}Z$ is an exact analogue of $t\bar{t}H$ for $m_H$ close to the $Z$ mass, and we expect the two to have very similar cross sections. Baer et al. [10] and Barger et al. [11] have estimated the cross section for $t\bar{t}Z$ to be roughly 10–12 pb for $m_t = 140$. The mass resolution for $Z \rightarrow 2 \text{ jets}$ at the SSC was estimated by the GEM collaboration to be roughly $\pm 5$ GeV in a similar energy dependent situation. This overlaps significantly with Higgs bosons of mass up to 100 GeV/$c^2$.

This background not only turns out to be benign, it actually works to our advantage. Unlike the Higgs, the $Z$ also decays to charged lepton pairs with a large branching ratio (6%). In our case, this gives a signature of 4 leptons and 2 jets, which has very little background if we further require two of the leptons to reconstruct to a $Z$. Therefore, the $t\bar{t}Z$ cross section can be measured by reconstructing the two-lepton invariant mass in the 4 leptons + 2 jets events. We expect that most of the theoretical uncertainty in the ratio of the two cross sections, $pp \rightarrow t\bar{t}H$ and $pp \rightarrow t\bar{t}Z$, cancels, and the cross section for $t\bar{t}H$ can then be reliably inferred from those of the $t\bar{t}Z$. Even if the Higgs and the $Z$ peaks overlap, we will still be able to
tell how much of the 2-jet invariant mass peak is due to the Z and how much is from the Higgs for a given $m_H$. In other words, we will be able to tell whether there is a Higgs boson at a certain mass without having to know exactly its production cross section and, if a signal is seen, whether it is from a standard or nonstandard Higgs. Finally, this calibration from the Z is absent in the $\gamma\gamma$ channel because $Z \rightarrow \gamma\gamma$ is forbidden on account of anomaly cancellation.

**SIMULATION**

Both the signal and background are simulated using Monte Carlo methods at the parton level. As a preliminary study, simplified distributions in phase space are used for each scattering and decay process. The total cross sections are then normalized to published values.

For our signal, the parton cross section is given on purely dimensional ground by

$$d\sigma(gg \rightarrow t\bar{t}H) \propto \frac{1}{s^2}d\Phi_3,$$

where $d\Phi_n$ is the $n$-body Lorentz invariant phase space:

$$d\Phi_n = \delta^{(4)}(P - \sum p_i) \prod_{i=1}^n \frac{d^3 p_i}{2E_i},$$

where $\hat{s}$ is the center of mass energy of the partons and $P$ is their total momentum. Each of $t$, $\bar{t}$ and $H$ is then decayed independently to $b l^+ \nu$, $\bar{b} l^- \bar{\nu}$ and $b \bar{b}$ respectively to give us the signature of 4 jets + 2 leptons + missing $E_T$. We take $m_t = 140$, $m_H = 100$ GeV/$c^2$ and 8 pb for the total cross section.

For the background, we first take

$$d\sigma(gg \rightarrow t\bar{t}gg) \propto \frac{1}{s^3}d\Phi_4,$$

and normalize it to the $t\bar{t}gg$ cross section of 4.3 nb. Just as in the case of $t\bar{t}H$, we assume that the dominant contribution to the $t\bar{t}$ cross section comes from gluon fusion. Since the top quarks are heavy and hardly radiate, we next assume that the two extra jets are gluons coming from initial state radiation only. The angular and energy distributions of the gluons, in addition to Eq. (10), are assumed to follow the Altarelli-Parisi function

$$P_{gg}(z) = c_{gg} \left( \frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right),$$
where $z$ is the fractional momentum of the initial gluon after radiation:

$$
z = \frac{E_i - p_{Li}}{E_{i-1} - p_{L_{i-1}}},
$$

(12)

where the subscripts $i - 1$ and $i$ refer to the initial gluon before and after radiation. We also use the approximation introduced by Dokshitzer et al. [13] where the further splitting of a radiated virtual gluon is replaced by two sequential radiations from the same initial gluon. The $t$ and $\bar{t}$ are decayed as before to give us the required signature.

To mimic a real experimental situation, the energy of each parton is smeared to reproduce the proposed detector resolution for jets and leptons [14]. Then we impose an isolation cut on each of the hadronic partons (jets) in $\eta$-$\phi$ space so that no two jets are within a distance of 0.7 units from each other:

$$
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.7.
$$

A rapidity cut of $\eta < 3.0$ is also applied to each of the jets and leptons.

**RESULTS**

We generate the number of events for the signal and background that corresponds to one typical SSC year at the luminosity of $10^{33}$ cm$^{-1}$ s$^{-1}$ ($10^4$ pb$^{-1}$). The following cuts are then performed on both types of events: (1) A 20 GeV minimum $p_T$ cut is first applied to all jets and leptons. (2) A second $p_T$ cut is then applied to the four hadronic jets: For each of the six pairs of jets, we form the scalar sum of the two individual $p_T$ and require it to be larger than 80 GeV. This will severely suppresses the background while keeping the signal almost unchanged. (3) To try to guarantee that the two leptons originate from top quark decays, we require each lepton to be at least a distance $\Delta R = 0.4$ away from any jet in $\eta$-$\phi$ space. The two leptons are required to be separated by the same amount. (4) The missing transverse energy in each event must be larger than 40 GeV.

There are many less important sources of background such as $Z + 4$ jets + missing $E_T$ and $b\bar{b} + 2g$, etc. To ensure that they do not significantly affect our result, we also apply the following cuts: (1) $Z$-peak cut for leptons: When the lepton pairs are of the same type, i.e., $e^+e^-$ or $\mu^+\mu^-$, their invariant mass should be outside of the region $91.2 \pm 5.0$ GeV of the $Z$-peak. (2) Observed invariant mass:
The invariant mass of all the observed particles should be larger than $2m_t + m_H$, which is 380 GeV in our case. This requires the average energy of each jet or lepton to be more than 60 GeV in the center of mass, greatly enhancing the probability of having heavy particles in the final state.

The results of all the cuts are shown in Table I in the order of their applications. After these cuts we are left with a signal of 0.071 pb, which corresponds to roughly 710 events in one SSC year, and a background of 2.8 pb.

| Cuts                                      | Signal ($t\bar{t}H$) | Background ($t\bar{t}gg$) |
|-----------------------------------------|----------------------|---------------------------|
| All $p_T > 20$ GeV                      | 100% ≈ 0.4 pb        | 100% ≈ 200 pb             |
| all $p_{T1} + p_{T2} > 80$ GeV         | 54%                  | 66%                       |
| Missing $E_T > 40$ GeV                  | 51%                  | 13%                       |
| Leptonic $Z$-peak cut                   | 51%                  | 12%                       |
| Observed invariant mass $> 380$ GeV     | 36%                  | 7.2%                      |
| Isolation cuts ($j-j$, $l-j$ and $l-l$) | 18%                  | 1.4%                      |

To extract the signal from this background, we need to reconstruct the Higgs mass from two-jet pairs. Figure 1a shows the distribution of the two-jet invariant mass of the signal alone. It has a prominent peak about $m_H = 100$ GeV/$c^2$ containing 650 counts over a combinatorial background of roughly 130 counts in the 10 GeV/$c^2$ or so region under the peak. The width of the resonance matches roughly the two-jet resolution of 10 GeV achievable at the SSC.

Figure 1b shows the combined result of both $t\bar{t}H$ and $t\bar{t}Z$. Next to the Higgs boson peak at 100 GeV is the $Z$-peak at 90 GeV, with approximately 550 counts above the combinatorial background. We have used a $t\bar{t}Z$ cross section of 12 pb with 70% of the $Z$ bosons decaying to $q\bar{q}$ pairs. This has a combined cross section $\times$ branching ratio of 8.4 pb, which is very close to the 8 pb we used for $t\bar{t}H$ events. The slightly lower peak for the $Z$ is due mainly to the two $p_T$ cuts.

The $t\bar{t}gg$ background is shown in Fig. 1c. The shaded area at the bottom is the result of Fig. 1b plotted on the same scale for comparison. Over the same 10 GeV range under the Higgs peak, the background contains roughly 9900 counts. Thus, we obtain a signal to noise ratio of 650 : 9900 + 230, for one SSC year, where 100
out of the 230 counts come from the $t\bar{t}Z$ combinatorial background. This is an $6.5\sigma$ effect.

The combined result is shown in Fig. 1d. This figure shows a clear signal over the QCD background despite the fact that the cuts applied have not been fully optimized. In view of all the approximations we have made, our background in the interested region can easily be off by a factor of two or three. However, we have been rather generous in normalizing the overall cross section for the background but not for the signal. Together with more optimal cuts, the signal should still stand out from even a higher than expected background. We believe that reconstruction from jets is a promising technique in the detection of the intermediate mass Higgs boson.

Before closing, we would like to point out that once $m_t$ is in the region of 80–200 GeV/$c^2$ the $t\bar{t}H$ cross section does not change appreciably with the $t$ quark mass. However, the inclusive $t\bar{t}$ cross section decreases rapidly from 30 nb at $m_t = 100$ GeV/$c^2$ to 0.25 nb at $m_t = 200$ GeV/$c^2$ so that a lighter $t$ quark will make reconstruction from jets more difficult. On the other hand, the $ttH$ cross section decreases from 20 pb to 5 pb [1], when $m_H$ increases from 80 to 140 GeV/$c^2$; but the two-jet invariant mass spectrum of the background decreases even faster, and it actually favors Higgs bosons of a heavier mass.

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FIGURE CAPTIONS

FIG. 1. Two-jet invariant mass distributions. The vertical axes shows counts/2 GeV bin. The horizontal axes shows two-jet invariant mass values in GeV/$c^2$. (a) Signal, $t\bar{t}H$ events. (b) $t\bar{t}H$ and $t\bar{t}Z$ events. (c) QCD background $t\bar{t}gg$ events (open histogram), and signal from (b) $t\bar{t}H + t\bar{t}Z$ (shaded histogram). (d) Signal plus background. The shaded areas represent $t\bar{t}H + t\bar{t}Z$ events from (b).