Associated Production of Higgs Bosons with $t\bar{t}$ Pairs

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(Received 14 February 1991)

Associated production of Higgs bosons with top-antitop pairs at hadron colliders, $pp \to Ht\bar{t}X$, is examined. By tagging on an isolated secondary lepton, e or μ, from the t or $\bar{t}$ decay, discovery of an intermediate-mass Higgs boson, $m_H \simeq 80$–150 GeV, via $H \to \gamma\gamma$ is rendered feasible at the Superconducting Super Collider (SSC) ($\sqrt{s} = 40$ TeV). Allowing a factor-of-0.4 signal reduction for isolation cuts and selection efficiences leaves about 21 events per SSC year for $m_H \simeq 80$–130 GeV, and somewhat less for 130–150 GeV, above an anticipated small background. At the CERN Large Hadron Collider ($\sqrt{s} = 16$ TeV), the cross section is reduced by about a factor of $\frac{1}{8}$.

PACS numbers: 14.80.Gt, 13.85.Qk

The standard $SU(2)_L \times U(1)$ model of electroweak interactions requires the existence of a spin-zero neutral particle called the Higgs scalar (H). It is a remnant of the spontaneous-symmetry-breaking mechanism used to provide mass for the $W^\pm$, Z, quarks, and leptons.[1] Discovery of that fundamental particle is crucial for confirmation of the standard model. Indeed, much of the motivation for building the Superconducting Super Collider (SSC) derives from its capability to find the Higgs boson or whatever "new physics" takes its place.

How will the Higgs scalar be found? The answer depends crucially on its mass, since both Higgs-boson production rates and decay branching ratios are highly m_H dependent. In the standard model, m_H is essentially a free parameter. Perturbative unitarity[2] and triviality[3] arguments suggest $m_H \lesssim 1$ TeV, while direct searches at the CERN e^+e^- collider LEP via $Z \to H\nu\bar{\nu}$ or Hl^+l^-, $l = e$ or μ, give[4] $m_H \gtrsim 40$ GeV. The LEP bounds (or discovery potential) are expected to improve to about 55-60 GeV with anticipated increased statistics. LEP II can extend the search for the Higgs scalar via[5] $e^+e^- \to HZ$ up to about $m_H \simeq 80$ GeV. Beyond 80 GeV is presently reserved for the next generation of pp colliders, the SSC with $\sqrt{s} = 40$ TeV and an initial design luminosity of $\mathcal{L} = 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ or the LHC (Large Hadron Collider at CERN) with $\sqrt{s} \simeq 16$ TeV and a possible design luminosity of $\mathcal{L} = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$.

Higgs-scalar discovery strategies at the SSC and LHC have been the subject of numerous publications[6] and workshop studies.[7] It is generally agreed that the region $m_H \simeq 140$–800 GeV can be covered by detecting the two e^+e^- or $\mu^+\mu^-$ pairs, from either $H \to ZZ$ at the higher masses or $H \to ZZ^*$ (Z^* is the virtual Z) below the ZZ threshold.[8] At higher and lower Higgs-boson masses, the discovery capabilities of the SSC and LHC have been less clear.

In this Letter, we propose a new detection mode which covers the heretofore difficult intermediate Higgs-boson mass region, $m_H \simeq 80$–140 GeV (extending to $m_H \simeq 150$ GeV as well), at the SSC. It involves the associated production of a Higgs scalar with a top-antitop quark pair, $pp \to Ht\bar{t}X$ via gluon-gluon scattering. The subsequent decay chain $t \to Wb$ followed by $W \to l\nu_l$, $l = e$ or μ, with the requirement of an isolated charged lepton provides a background-reducing tag, so that the rare decay[9] $H \to \gamma\gamma$ becomes observable. Our idea is similar to the recent study by Kleiss, Kunszt, and Stirling[10] (KKS) of $pp \to HW^\pm X$ where the leptonic decays of the direct $W^\pm$ were used to tag $H \to \gamma\gamma$. However, the cross section for $pp \to Ht\bar{t}X$ is roughly a factor of 3 larger than $pp \to HW^\pm X$ at the SSC and the $t\bar{t}$ decays produce an e or μ 40% of the time whereas a single W decays to e or μ roughly 22% of the time. The extra overall factor of 6 makes our signal significantly larger than the marginal KKS results,[10] which indicated a need for higher luminosity or very long runs. At the LHC, the cross section for $pp \to Ht\bar{t}X$ is only about $\frac{1}{8}$ that of the SSC,[11] whereas[10]

$$\sigma(pp \to HW^\pm X)_{\text{LHC}} \simeq 0.4\sigma(pp \to HW^\pm X)_{\text{SSC}}\,.$$

So, at the LHC one gains only a factor of 2 (perhaps even somewhat less) by employing $pp \to Ht\bar{t}X$ rather than $HW^\pm X$. In any case, both modes seem to require $\mathcal{L} \gg 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ at the LHC and would probably have to be used together to strengthen the $H \to \gamma\gamma$ signal.

Our analysis consists of combining results from other studies. The cross section for $pp \to Ht\bar{t}X$ at SSC and LHC energies has been calculated by Dicus and Willenbrock[11] (DW) for $m_t = 100$ GeV. Because the $Ht\bar{t}$ coupling is proportional to m_t, the amplitude increases linearly for larger m_t values. That increase compensates for a decrease in phase space, so the cross section for $pp \to Ht\bar{t}X$ should be fairly insensitive to the actual value of m_t for $m_t \lesssim 200$ GeV (the region suggested by quantum loop phenomenology), at least for the domain $m_H \simeq 80$–150 GeV that interests us.

Combining the DW cross section[11] with an updated KKS calculation[10] of the $H \to \gamma\gamma$ branching ratio and using $B(W \to l\nu_l) \simeq 0.22$ for $l = e$ or μ leads to our estimate (before cuts and efficiencies)

$$\sigma(pp \to Ht\bar{t}X \to \gamma\gamma l\nu_l X) \simeq 5.2\ \text{fb} \quad (\sqrt{s} = 40\ \text{TeV}), \tag{1}$$

$$\sigma(pp \to Ht\bar{t}X \to \gamma\gamma l\nu_l X) \simeq 0.67\ \text{fb} \quad (\sqrt{s} = 16\ \text{TeV}), \tag{2}$$

for $m_H \simeq 80$–130 GeV. The decrease in the production cross section for increasing m_H is compensated by an increase in the $H \to \gamma\gamma$ branching ratio for $m_H \simeq 80$–130 GeV. Above $m_H \simeq 130$ GeV, the $B(H \to \gamma\gamma)$ no longer increases, and it drops off rapidly for $m_H \gtrsim 150$ GeV where the $H \to WW^*$ decay rate starts to become appreciable.[8] Equation (1) becomes 4.4, 3.8, and 0.9 fb for $m_H = 140$, 150, and 160 GeV.

The estimates given above are likely to be enhanced somewhat by higher-order QCD corrections to the $Ht\bar{t}$ cross section if the experience with other processes applies here. There are, however, uncertainties in the gluon distribution functions that could go either way. We expect that the rates quoted in this paper are valid to about a factor of 2.

An SSC year (10^7 sec) gives an integrated luminosity of 10 fb^{-1}, which leads to a raw signal of 52 ($t\bar{t}$) tagged $H \to \gamma\gamma$ events/yr at the SSC. Typical isolation cuts on the charged lepton and photons and detector efficiencies should reduce the raw signal by roughly a factor of 0.4, leaving about 21 tagged $H \to \gamma\gamma$ events/(SSC year) for $m_H \simeq 80$–130 GeV and 18, 15, and 4 events for $m_H = 140$, 150, and 160 GeV, respectively. For comparison, $pp \to HW^{\pm}X$ gives rise to about 3 tagged $H \to \gamma\gamma$ events/(SCC year) when the same cuts are applied.[10,12] One can, of course, legitimately add the two signals or use $pp \to HW^{\pm}X$ events as a consistency check.

The tagged $H \to \gamma\gamma$ signal of 21 events/(SCC year) is quite substantial and should be discernable above backgrounds, at least those backgrounds we have considered. One background from direct $W^{\pm}\gamma\gamma$ production was calculated[10] by KKS and shown to be less than 1 event even with only 5% resolution in the $\gamma\gamma$ mass. Of course, such events have quite a different topology from the busy $Ht\bar{t}X$ events we are considering. Our events contain two b jets and remnants of a second W decay as well as the $\gamma\gamma$ and isolated-charged-lepton signal. All that activity could work for or against us; only a complete simulation (which we have not carried out) will tell.

The most important potential background is probably $pp \to t\bar{t}\gamma\gamma X$. Calculating this properly would require calculating $gg \to t\bar{t}\gamma\gamma$ plus additional contributions in which the γ's come from the t decay products. Since this is nontrivial, we have resorted to a crude estimate instead. The total $gg \to t\bar{t}$ cross section at the SSC is $\sim 10^4$ pb. We multiply this by $(\frac{4}{9}\alpha/\pi)^2 \simeq 10^{-6}$ and by an additional factor of 0.2 for leptonic branching ratios and cuts. This gives an estimated background cross section of $2C$ fb, where C is calculable from perturbative QCD and probably is ~ 1, or $20C$ events/(SSC year) before electromagnetic resolution cuts are applied. For a roughly flat $\gamma\gamma$ mass distribution with a scale set by m_H or m_t, 1% resolution in the electromagnetic $\gamma\gamma$ mass resolution will reduce the background to $0.2C$ events/(SSC year) compared with a signal of 21 events. Even if C turns out to be ~ 10, that background would not be a problem. A QCD calculation to determine C is difficult but imperative, and a full $pp \to t\bar{t}\gamma\gamma X$ simulation is clearly warranted.

We can make a similar crude estimate of the background from $gg \to t\bar{t}gg$ with each g jet faking a γ. In this case the two factors of $\frac{4}{9}\alpha/\pi$ are replaced by two factors of the γ/g rejection. Thus a γ/g rejection of order 10^{-3}, rather than the 10^{-4} needed for the inclusive mode, appears to be sufficient. This also requires a real calculation. Furthermore, a γ/g rejection of order 10^{-1} would be sufficient at the trigger level, so a rather crude selection of narrow jets with mainly electromagnetic energy should suffice.

There are other backgrounds which should also be simulated such as $pp \to b\bar{b}\gamma\gamma X$ with a charged lepton from b decay faking the tag. At worst, that background may require some tightening of the isolation cuts. Given the relatively large signal, tightening the cuts seems quite easy to accommodate.

In conclusion, we have found that the associated production mechanism $pp \to Ht\bar{t}X$ gives rise to a tagged $H \to \gamma\gamma$ signal of roughly 21 events/(SSC year) for $m_H \simeq 80$–130 GeV and somewhat less for 130–150 GeV with potentially little background. If detailed calculations reveal worse than anticipated backgrounds, they can be further reduced by tighter isolation cuts and improved electromagnetic calorimetry without significantly compromising the signal. So, discovery of a Higgs scalar in the intermediate-mass range, and even a useful measurement of $B(H \to \gamma\gamma)$ to ±20%, seems quite feasible at the SSC. At the LHC, the reduced cross section leads to only about 4 tagged $H \to \gamma\gamma$ events/(10^{40} cm^{-2}s^{-1}) even if one combines the $Ht\bar{t}X$ and $HW^{\pm}X$ production modes. To elevate that signal to a real discovery will likely require a substantial increase in the integrated luminosity with little compromise in the detector requirements, such as good electromagnetic calorimetry and isolation cuts, envisioned in our analysis.

We would like to thank Scott Willenbrock for pointing out his calculation in Ref. 11 and for discussions concerning its applicability.

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