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Prospects for Observing $t\bar{t}H$ at Run II: A discovery mode for the Higgs boson?

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The production of a Standard Model Higgs boson in association with a top quark pair at the upcoming high luminosity run (15 fb^{-1} integrated luminosity) of the Fermilab Tevatron ($\sqrt{s} = 2.0$ TeV) is revisited. For Higgs masses below 140 GeV we demonstrate that the production cross section times branching ratio for $H \to b\bar{b}$ decays yields a significant number of events and that this mode is competitive with and complementary to the searches using $p\bar{p} \to WH, ZH$ associated production. For higher mass Higgs bosons the $H \to W^+W^-$ decays are more difficult but have the potential to provide a few spectacular events.

One of the most important tasks facing the high energy physics community is to understand electroweak symmetry breaking, manifested by the three massive weak bosons ($Z, W^\pm$). The agent believed to be responsible for this is the Higgs boson. In the Standard Model (SM) this is a single doublet of complex scalar fields, which acquires a vacuum expectation value, giving rise to gauge boson masses via minimal coupling. In the process, one physical massive Higgs boson is produced, having the properties of being neutral, colorless, CP-even. It possesses couplings to fermions proportional to the fermion masses, and gauge couplings to the weak bosons.

Collider searches have so far failed to find any direct evidence for a Higgs, instead providing a lower limit mass bound of about 110 GeV. However, indirect searches such as electroweak precision data fits do imply that a Higgs boson exists, with mass somewhere close to the current exclusion limit. As the CERN LEP nears the end of its run with no evidence of a Higgs boson, we turn our attention to the next collider search, at Fermilab's upgraded Tevatron, Run II.

Cross sections for various Higgs boson production modes at the Tevatron are shown in Fig. 1(a) [1]. The current searches planned for the Tevatron Run II concentrate on the dominant production modes: gluon fusion ($gg \to H$), followed by weak boson associated production. Detailed studies do show promise for these modes, but also indicate the need for large integrated luminosity, and even with 30 fb^{-1} these searches have difficulty in the mass regions 130-150 GeV and above 180 GeV. We investigate the feasibility of a search in $t\bar{t}H$ associated production, previously considered in the context of supercolliders [2]. Decays to both $H \to b\bar{b}$ and $H \to W^+W^-$ are considered, with at least one charged lepton in the final state

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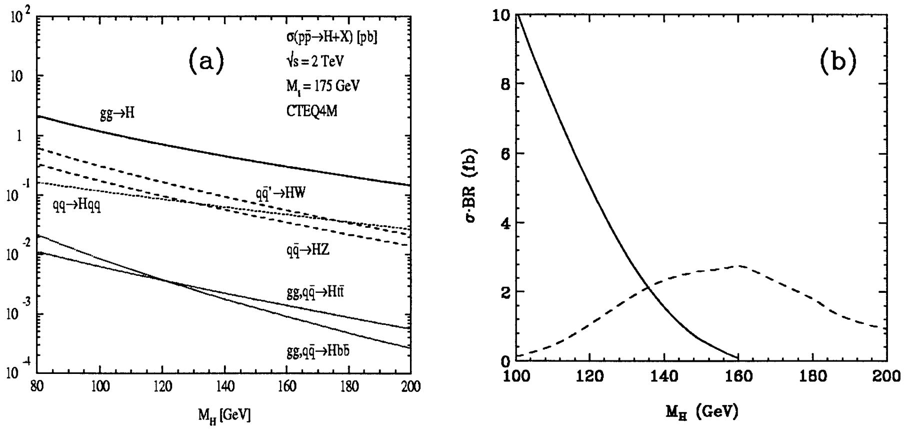

Figure 1: For $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV: (a) cross section (pb) for various Higgs boson production modes; (b) the $t\bar{t}H$ production cross section times branching ratio and K-factor (fb) for $H \to b\bar{b}$ (solid) and $H \to W^+W^-$ (dashed).

Table 1: Cross sections for the major physics and reducible backgrounds, $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV. Production of final states involving heavy states plus additional jets include a $p_T \geq 20$ GeV cut on the additional jets, but no cut on the decays of heavy states. Uncertainties are on the order of ±50%.

backgrounds to $H \to b\bar{b}$	σ (fb)	backgrounds to $H \to W^+W^-$	σ (fb)
$t\bar{t} + jj \quad (\Delta R(jj) > 0.4)$	1030	$t\bar{t} + jj$	1030
$t\bar{t} + b\bar{b}$ (or $c\bar{c}$)	27	$t\bar{t} + W$	17
$t\bar{t} + Z, Z \to b\bar{b}$	1.5	$t\bar{t} + Z, Z \to \ell^+\ell^-$	0.9

to help discriminate against the large QCD backgrounds.

We have calculated the signal and all backgrounds at the parton level for $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV using exact tree-level matrix elements for production and decay, and corrected the Higgs decay rates for NLO contributions. We further take the K-factor for production to be 1.33: the ratio of the NLO $t\bar{t}$ cross section to the leading order value. This value is also applied to the backgrounds. CTEQ4L parton distribution functions are used, and both the factorization and renormalization scales are taken as the top quark mass, m_t. The cross section times Higgs branching ratios times K-factor used in the analysis are shown in Fig. 1(b). The background results are used as normalizations for CDF detector parameterized simulations using Pythia 6.115.

For Higgs masses below about 140 GeV, $H \to b\bar{b}$ decays dominate; hence, we look for $W^+W^-b\bar{b}b\bar{b}$ events by requiring observation of one lepton and four jets with $p_T > 20$ GeV, three jets of which are b tagged; two additional jets with $p_T > 15$ GeV; $\Delta R > 0.4$ for all objects; and $\not{p}_T > 15$ GeV. We use conservative efficiencies for tagging b jets and veto of c, q, g jets: 60% for b, 25% for charm, and

0.2% for light jets. Even higher tagging/rejection efficiencies may be realized, as 55% b tagging efficiency was achieved already in Run I with only 2-D vertexing and previous generation hardware. We further assume 100% reconstruction efficiency of both top quarks. This is a slightly optimistic, but efficiencies close to this may be expected due to the excellent tracking and resolution capabilities of the upgraded detector. Future investigation should clarify this issue even before Run II begins.

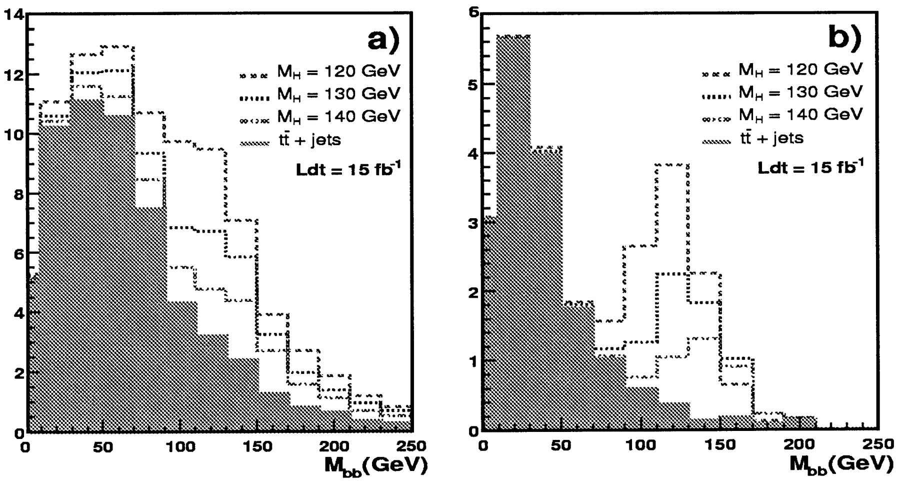

Fig. 2. m_{bb} distributions for jet combinations in $t\bar{t} + jets$ and $t\bar{t}H$ events for $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV: (a) assuming hadronic top quark reconstruction; (b) full reconstruction of the top quark pairs.

Fig. 2 summarizes our results for the $H \to b\bar{b}$ case, $M_H \leq 140$ GeV. We plot there the invariant mass of b candidate pairs after (a) hadronic top removal and (b) both tops have been reconstructed. A clear Higgs peak beyond the $t\bar{t} + jets$ continuum can easily be observed. The statistical significance for one experiment and 15 fb^{-1} of data as shown would be slightly over 5σ for $M_H = 120$ GeV and about 4σ for $M_H = 130$ GeV.

For $M_H > 140$ GeV, the decay $H \to W^+W^-$ is dominant, but much more difficult to observe due to the low event rate containing leptons. The most promising channel is dual leptonic decays where both leptons are same sign, $\ell^\pm\ell^\pm b\bar{b}jjjj\not{p}_T$. Backgrounds would be expected to be small, but with only 1-2 signal events per experiment.

Our studies show that $t\bar{t}H$ production at Tevatron Run II does show promise for SM Higgs discovery and deserves more attention. If Run II can achieve a factor two to three higher than design integrated luminosity, then this channel also has some capability for Higgs masses near the W pair threshold.

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