Fermi National Accelerator Laboratory

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Search for Heavy Higgs in the Channel $H \to WW \to \ell\nu jj$

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We have studied the potential for observation of a heavy Higgs ($m_H = 800\,\mathrm{GeV}$) in the channel $H \to WW \to \ell\nu jj$ using a parametrized simulation of the CMS detector. We have investigated the use of kinematic selection cuts and forward jet tagging to select the signal and reject the backgrounds. We find that signal to background ratios greater than unity can be obtained, but only at the cost of very low signal efficiency (only a few events per 100 fb^{-1} would survive).

INTRODUCTION

For Standard Model Higgs bosons with masses in excess of about 800 GeV, the production cross section is too low to permit discovery in the 'gold-plated' $4\ell^{\pm}$ channels in one standard LHC year ($100\,\mathrm{fb}^{-1}$). This is also true for lower Higgs masses, above about 500 GeV, if the integrated luminosity available is only a few tens of fb^{-1}, as might be the case in the first few years of LHC operation. Channels with higher branching ratios therefore become attractive. One such is $H \to ZZ \to \ell\ell\nu\nu$ which has six times the event rate of $H \to 4\ell^{\pm}$. We presented results on this process in [1]. Even higher cross sections can be obtained in the $H \to WW \to \ell\nu jj$ channel which has twenty times the rate of $H \to 4\ell^{\pm}$. The price to be paid is increased backgrounds: as well as the irreducible WW continuum, there are large backgrounds from $W + jets$ events where two jets fake the hadronic W decay, and from $t\bar{t} \to \ell\nu jj$ which contains two real W decays.

Earlier studies [2] [3] have investigated this channel with the goal of developing cuts to maximise signal/background. In the present study, we have used the $H \to WW \to \ell\nu jj$ process, with $m_H = 800\,\mathrm{GeV}$, as a benchmark to investigate the jet-jet reconstruction and forward jet tagging performance of the CMS detector.

DETECTOR MODELING

Events were generated using ISAJET version 7.09. The CMS detector was modelled using a parametrized simulation first developed for the SDC detector [4]. This simulation incorporates:

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- stable particles are tracked in the magnetic field up to the calorimeter;
- EM calorimetry covers up to $|\eta| = 2.6$, and hadronic up to $|\eta| = 5.0$;
- energy resolution is simulated by Gaussian smearing with sampling and constant terms as below:

	$\lvert\eta\rvert \leq 1.5$	$1.5 \leq \lvert\eta\rvert \leq 2.6$	$2.6 \leq \lvert\eta\rvert \leq 3.0$	$3.0 \leq \lvert\eta\rvert \leq 5.0$
EM:				
Sampling	0.02	0.02	0.36	0.50
Constant	0.005	0.005	0.03	0.03
Hadronic:				
Sampling	0.65	0.83	0.83	1.00
Constant	0.05	0.05	0.05	0.05

- transverse shower shape is modelled, with an rms width of 7 cm (hadronic) and 0.7 cm (EM);
- shower leakage is modelled with calorimeter depths of 8.7λ for $|\eta| \leq 1.5$, 11λ for $1.5 \leq |\eta| \leq 3.0$, and 12λ for $3.0 \leq |\eta| \leq 5.0$;
- cracks in azimuthal coverage are modelled as 2 cm wide regions in the calorimeter where the response is zero;
- energy is stored in cells with transverse segmentation of 0.1×0.1 for all calorimeters.

Jets are then found using a cone algorithm on the calorimeter tower energies. For simulations including minimum bias pileup an additional n events were added, where n was Poission distributed with a mean $< n >= 30$. The pileup events were modelled using low-p_T two-jet events. A 1 GeV threshold cut per tower was used for jet-finding in the presence of pileup events [5].

EVENT SELECTION

The $W \to jj$ decay is reconstructed in the calorimeter lego plot by finding a single large cluster of energy (in a cone of $R = 0.8$) which contains two smaller jets (with cone size of $R = 0.15$). The mass of the W is then estimated by the invariant mass of the whole large cluster, without attempting to assign energy between the two small jets. Events were kept if they passed the following cuts:

1. The two jets within the cluster have $\cos\theta^* \approx (E_1 - E_2)/(E_1 + E_2) < 0.7$;
2. $|m_{cluster} - m_W| < 10\,\mathrm{GeV}$;
3. $E_T^{cluster} > 450\,\mathrm{GeV}$;
4. $p_T^{\ell\nu} > 450\,\mathrm{GeV}$;
5. $\not{E}_T > 450\,\mathrm{GeV}$;
6. Transverse mass $m_T^{\ell\nu} < 100\,\mathrm{GeV}$;

Cut (1) selects events where the two small jets within the cluster have similar energies. This reduces the $W + jets$ background where the second jet tends to come from gluon bremsstrahlung processes and to be soft. The distributions of these kinematic quantities are shown in Figs. 1–3 for the case of no pileup (low luminosity), and in Figs. 4–6 with pileup. As can be seen, the effectiveness of the $\cos\theta^*$ cut is reduced somewhat by pileup, but the other distributions are not much affected.

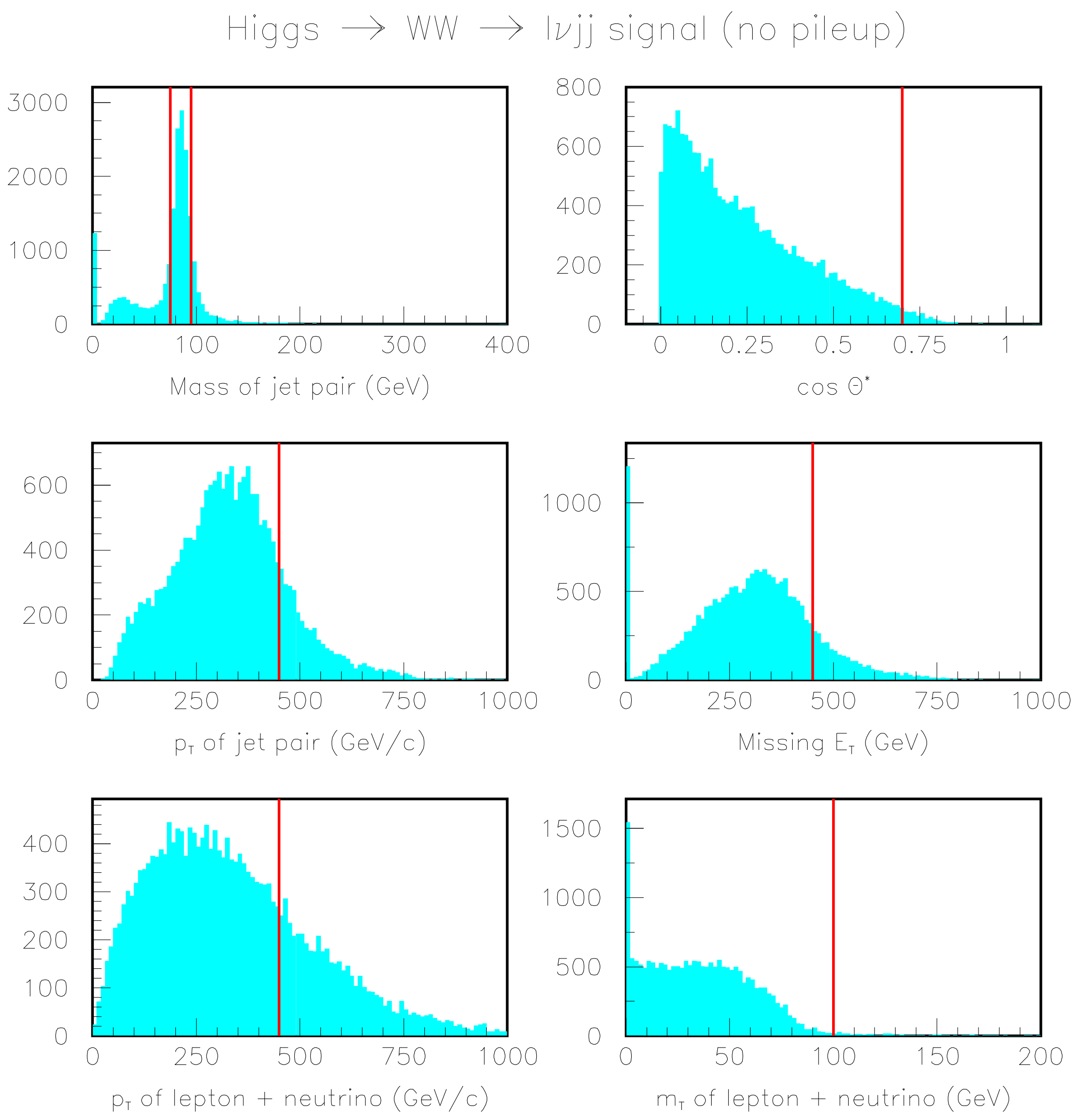

FIG. 1. Distributions of kinematic quantities for 800 GeV Higgs signal events, with no pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

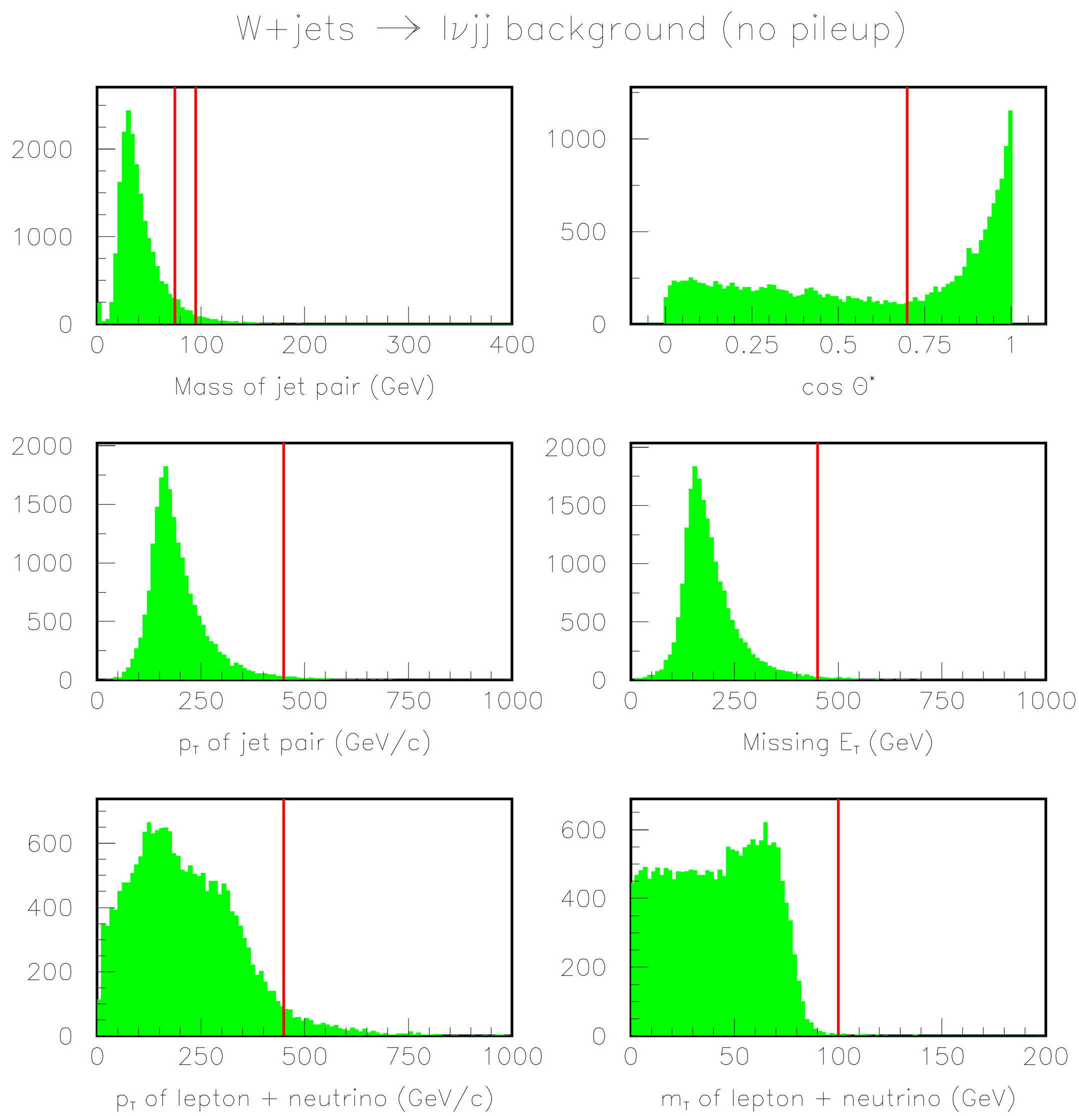

FIG. 2. Distributions of kinematic quantities for $W + jets$ background events, with no pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

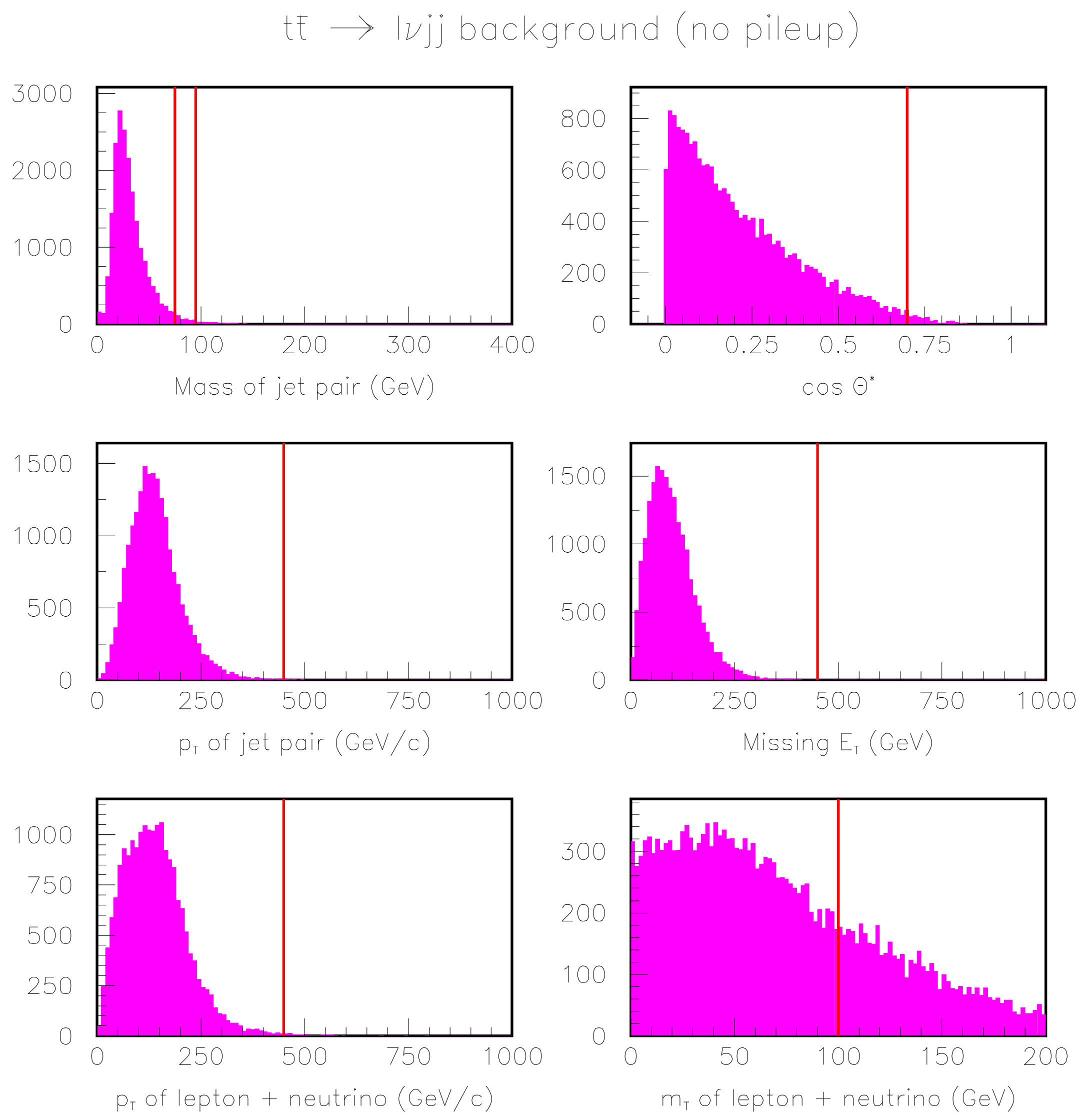

FIG. 3. Distributions of kinematic quantities for top background events, with no pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

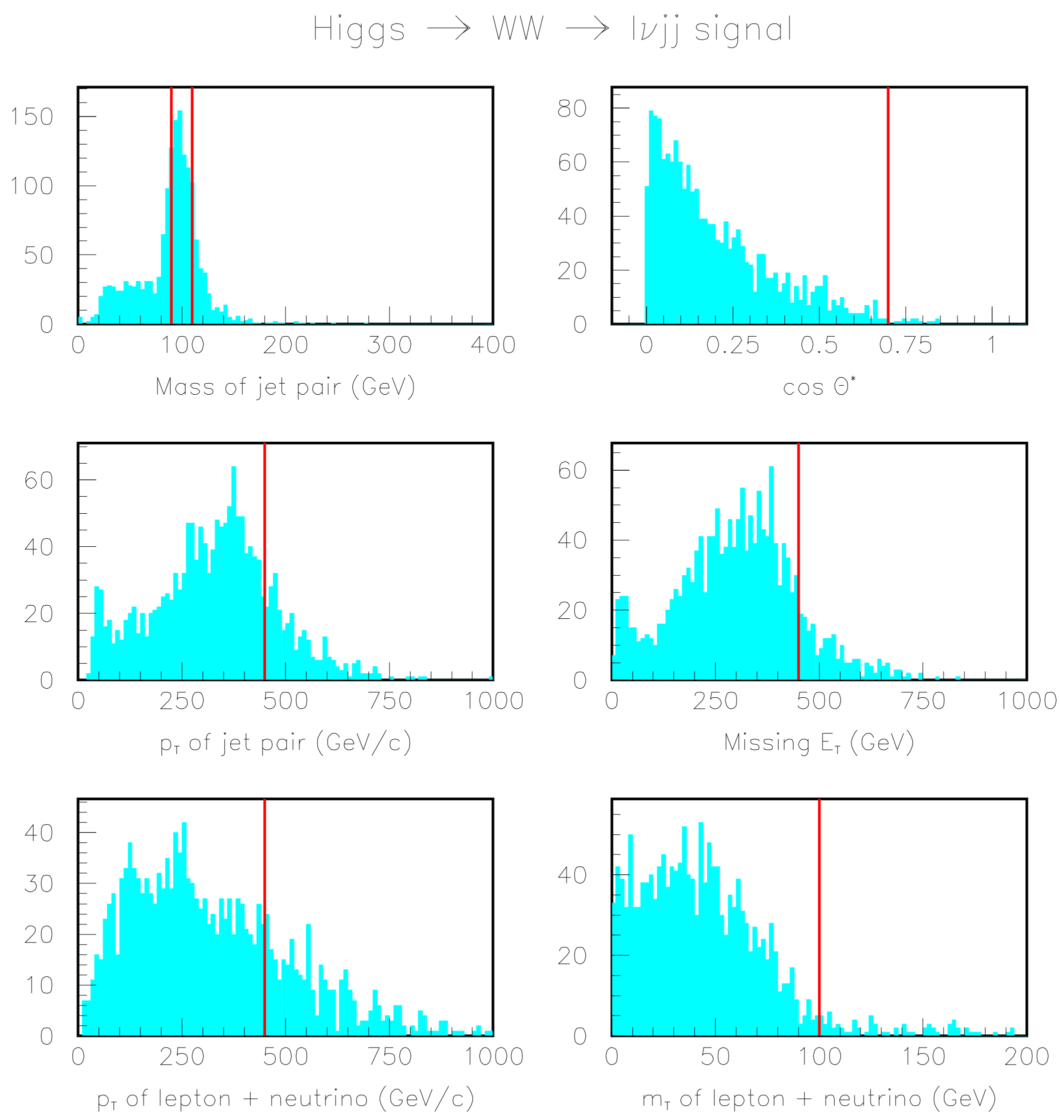

FIG. 4. Distributions of kinematic quantities for 800 GeV Higgs signal events, with pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

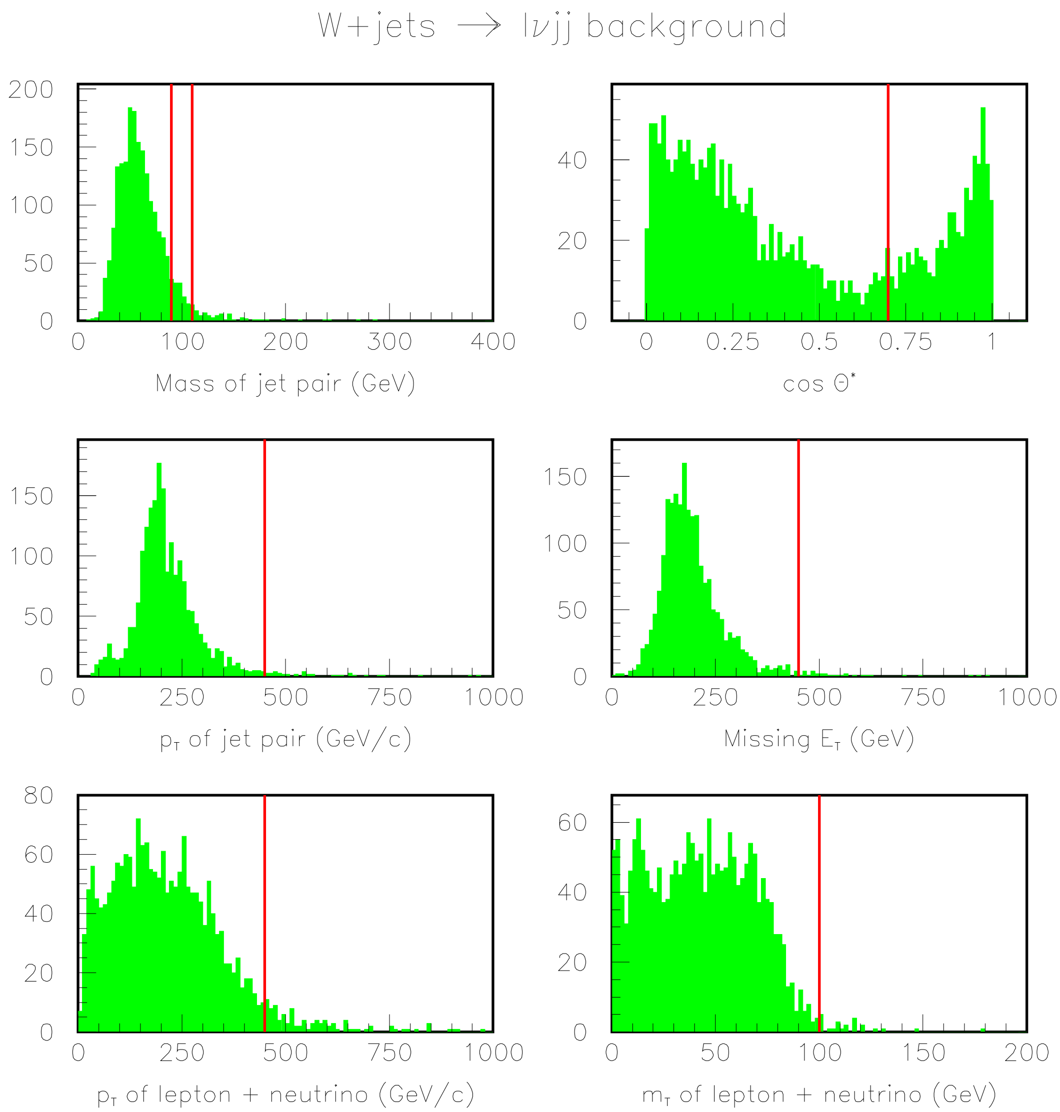

FIG. 5. Distributions of kinematic quantities for W + *jets* background events, with pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

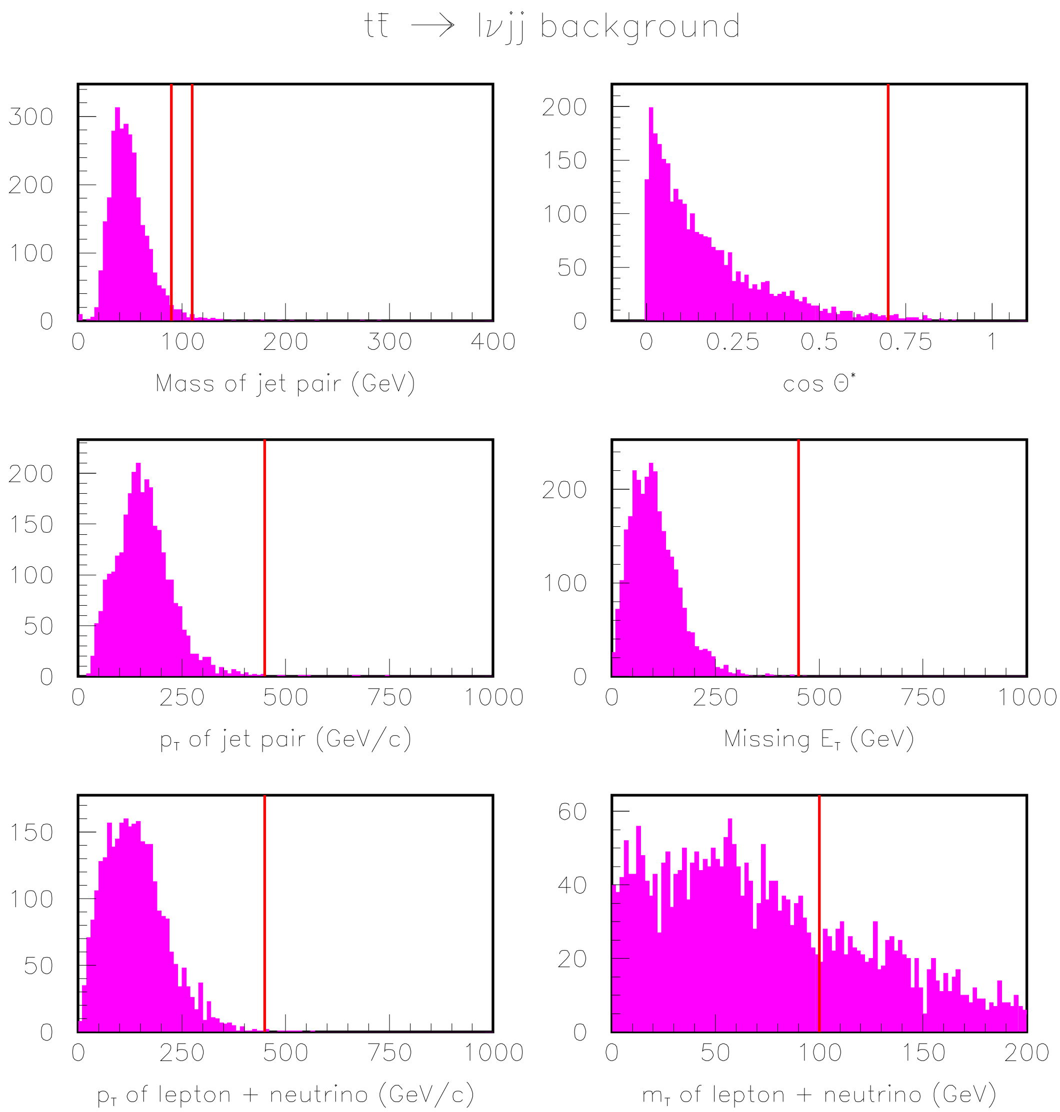

FIG. 6. Distributions of kinematic quantities for top background events, with pileup. The vertical lines show the regions selected by cuts (1)–(6) as described in the text.

CROSS SECTIONS

The cross sections for signal and background after each of these cuts are listed in Table I:

	Higgs (800)	$W + jets$	$t\bar{t}$
Produced	4700	7×10^6	1.1×10^7
After cuts 1–3	414(386)	16,700(8000)	2200(2200)
After cuts 1–6	125(130)	1860(2000)	< 500 (< 200)
Signal/Background	0.07(0.07)		

TABLE I. Number of events per LHC year (100 fb^{-1}) for 800 GeV Higgs signal and backgrounds. Numbers in parentheses are the results obtained without pileup events included.

$W \to JJ$ RECONSTRUCTION

Figure 7 shows the distributions of $\cos\theta^*$ for $W+jets$ background events, with no pileup. The 'true' distribution (for the ISAJET partons) is compared with the reconstructed distributions for calorimeter segmentations of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, 0.2×0.2 and 0.25×0.25. It will be seen that segmentation of 0.2×0.2 or coarser degrades the shape compared with the true distribution, but the HCAL baseline segmentation (slightly finer than 0.1×0.1) is capable of reconstructing $\cos\theta^*$ without significant bias.

FORWARD JET TAGGING

The signal to background ratio after the kinematic cuts (Table I) is clearly inadequate for observation of the Higgs. Previous studies [2] [3] have indicated that dramatic improvements may be obtained by selecting events with forward jets. Between one third and one half of the high-mass Higgs cross section is due to WW and ZZ fusion processes in which quark jets are produced forward. The expectation is that the most probable jet p_T will be of the order of $m_W/2$ and the jet pseudorapidity will be in the range 1.5–5. By dumping 100 ISAJET events we verified that, in our case, 40% of the Higgs cross section is produced by the vector-boson fusion process.

We considered four levels of tagging:

1. **Loose single tag:** One or more jets with $p_T > 20\,\mathrm{GeV}$ and $|\eta| > 1.5$ found in the lego plot (using a jet cone size $R = 0.5$ and with calorimeter cell size 0.1×0.1);
2. **Loose double tag:** One or more jets with $p_T > 20\,\mathrm{GeV}$ and $|\eta| > 1.5$ found in both forward and backward regions;
3. **Tight single tag:** One or more jets with $p_T > 40\,\mathrm{GeV}$ and $|\eta| > 3.0$;
4. **Tight double tag:** One or more jets with $p_T > 40\,\mathrm{GeV}$ and $|\eta| > 3.0$ found in both forward and backward regions;

No pileup events were included in the tagging jet simulations.

The efficiency for signal and background events to pass these tagging requirements is listed in Table II. Events were *not* first required to pass our kinematic cuts. The last line of the table shows the number of signal and background events in 100 fb-1 that would result if each of the tagging scenarios were applied after the kinematic cuts listed in Table I. These numbers were calculated by applying the efficiencies listed in Table II to the remaining

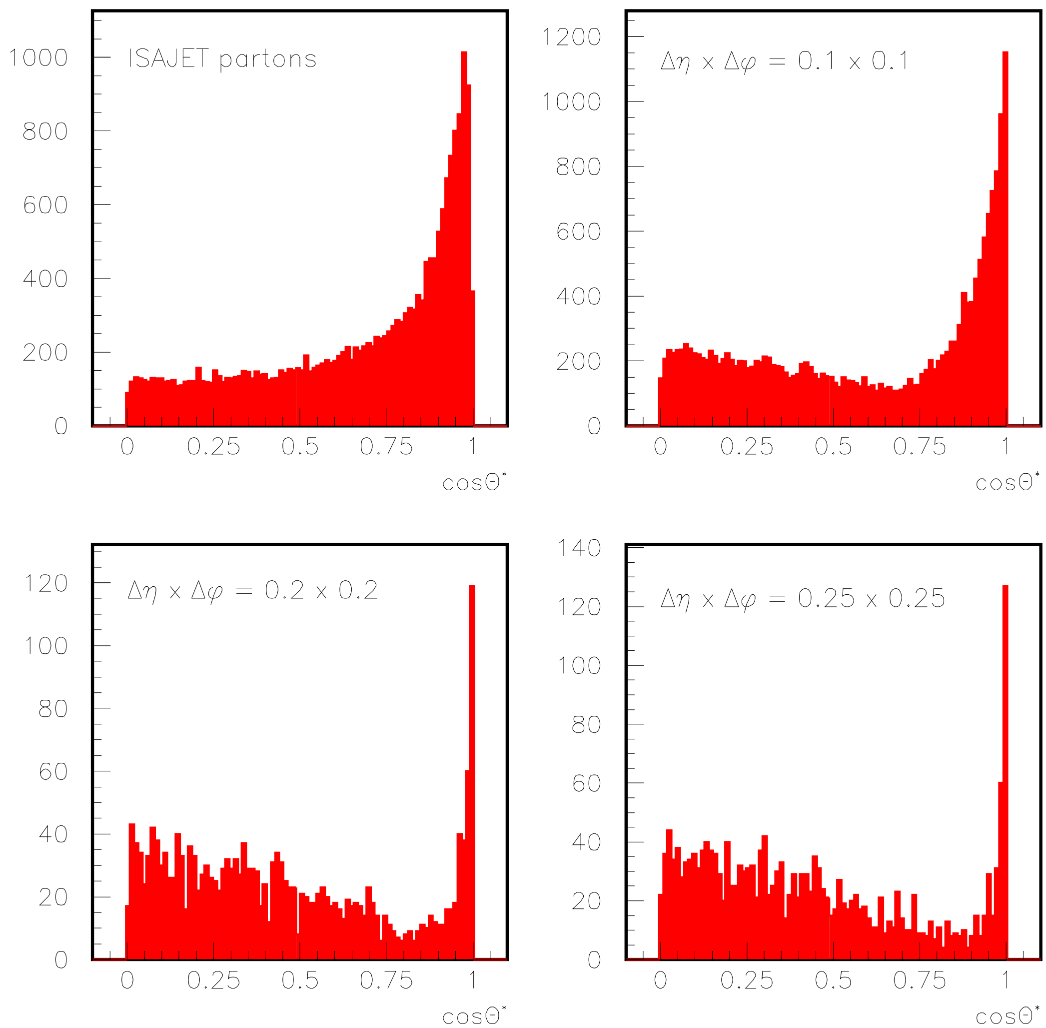

FIG. 7. Distributions of $\cos\theta^*$ for $W + jets$ background events, with no pileup. The distribution for the ISAJET partons is compared with that found with three different calorimeter segmentations.

numbers of events from Table I. They are therefore based on the assumption that the jet tagging cuts are not correlated with the kinematic cuts. We have verified that this assumption is approximately true for the case of the signal, where it is possible to generate enough events that pass the kinematic cuts. Using tagging efficiencies based on events passing the kinematic cuts would change the respective numbers of signal events in the last line of Table II from $N_S = (6, 45, 58, 110)$ to $N_S = (12, 57, 43, 112)$.

	Tight double tag	Tight single tag	Loose double tag	Loose single tag
Higgs (800)	5.0%	36%	46%	88%
$W + jets$	0.19%	13%	12%	77%
$t\bar{t}$	0.15%	6.5%	14.4%	62%
N_S/N_B	6/4	45/274	58/290	110/1740

TABLE II. Fraction of events surviving jet tagging requirements, for 800 GeV Higgs signal and backgrounds respectively. The last line shows the number of signal (N_S) and background (N_B) events expected per LHC year ($100\,\mathrm{fb}^{-1}$).

As can be seen, it is only possible to obtain a reasonable ratio of signal to background at the cost of very low signal efficiency. It should also be noted that after imposing the rather stringent kinematic cuts that have been used here, the distributions of quantities such as the reconstructed Higgs mass are indistinguishable between signal and background. A Higgs signal would only be apparent as an excess of events over expectations, and thus the efficiency of the forward jet tagging would have to be known very precisely to be sure that this excess resulted from new physics.

Note that our results are considerably less optimistic than those of reference [3], where it was found possible to retain one third of the Higgs signal while keeping only 0.4% of the $W + jets$ background. This necessitated the use of tagging jets with p_T as low at 10 GeV. In the opinion of the present authors this is not a very realistic possibility; even at the Tevatron it is hard to reconstruct jets so low in p_T.

CONCLUSIONS

We have investigated the signal and backgrounds for the process $H \to WW \to \ell\nu jj$. We find that the segmentation of the CMS calorimeter is adequate for the reconstruction of the $W \to jj$ decay. We have also studied the improvement in signal to background ratio which may be achieved by tagging one or two forward jets. We find that signal to background ratios greater than unity can be obtained, but only at the cost of very low signal efficiency (only a few events per 100 fb^{-1} would survive).

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