Enhancing the heavy Higgs boson $\rightarrow WW$ signal at hadron-hadron colliders

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The jet-jet profile methods that we developed to enhance the heavy Higgs boson $\rightarrow ZZ$ signal over its backgrounds at a proton-proton collider energy of 40 TeV are extended to the heavy Higgs boson $\rightarrow WW$ signal and backgrounds. The dominant background is now the pair production of top quarks via the subprocess $gg \rightarrow t\bar{t}$. The process $qg \rightarrow Wq$ also contributes significantly, and backgrounds from the production of top quarks via the subprocess $bg \rightarrow Wt$ and WW continuum are also included in the analysis but are less important. To enhance the signal, a profile analysis is performed on *both* the "toward side" (the $W \rightarrow l\nu$ trigger side) and on the "away side" (the $W \rightarrow$ jet-jet system). We define observables that help distinguish between the transverse energy distribution of the signal and of the backgrounds in an electromagnetic and/or hadronic calorimeter system. By making cuts on *both* the toward- and away-side observables, signal to background enhancement factors around 1000 can be obtained.

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I. INTRODUCTION

It is well known that today's discoveries quite often become tomorrow's background. Although the top quark has not yet been discovered, it will certainly be an important background for some of the new physics at the high-energy hadron colliders. An important signature of new physics consists of a large transverse-momentum charged lepton and a neutrino plus two accompanying jets (i.e., $l\nu jj$). Here one triggers on the charged lepton and on missing transverse energy. As illustrated in Fig. 1(a), this is one of the primary signals of the production of a heavy Higgs particle via its decay into WW, with one W decaying leptonically, and the other W decaying hadronically into a $q\bar{q}$ pair, which then manifests itself as a pair of jets. The production of a pair of top quarks via the "ordinary" QCD subprocess $gg \rightarrow t\bar{t}$ can mimic the Higgs signal as shown in Fig. 2. The outgoing top quarks decay weakly, producing large transverse-momentum W bosons. If one of these W bosons decays leptonically we can be left with a $l\nu jj$ signal similar to that produced by Higgs boson $\rightarrow WW$ decay.

Another type of top background arises from the "Drell-Yan" production of W bosons via the subprocess $bg \rightarrow Wt$ and $\bar{b}g \rightarrow W\bar{t}$. This is illustrated in Fig. 3. Here the charged lepton and missing transverse-energy trigger can be produced by the "primary" W boson [Fig. 3(a)] or by a "secondary" W produced in the top decay [Fig. 3(b)]. In addition, there are other "Drell-Yan" subprocess not involving the top quark that contribute to the background. Once one requires the W boson to have a large transverse momentum by demanding a large P_T charged lepton, one has forced the ordinary Drell-Yan background to have a large P_T "away-side" quark or gluon via subprocesses such as $qg \rightarrow Wq$ or $q\bar{q} \rightarrow Wg$. This away-side parton often fragments via gluon bremsstrahlung, producing away-side jet pairs, which can also resemble the signal as shown in Fig. 1(b). However, the signal jet pair and the background jet pair have quite different origins. The former arises from the decay of a color singlet W boson, while the latter is produced in a color nonsinglet "parton shower."

In a recent paper [1] we examined the ZZ decay mode of the heavy Higgs boson and devised a method that helps to distinguish the two-jet system originating from $q\bar{q}$ the decay of a color singlet Z boson from a random jet pair coming from the ordinary QCD gluon bremsstrahlung of colored quarks and gluons. Here the method is applied to the hadronic decay of the W boson. The technique examines in detail the away-side jet-jet profile, or precise manner, in which transverse energy and mass are distributed around this jet-jet system.

Because of the top backgrounds, in this paper a profile analysis is performed on *both* the "toward-side" (i.e., the $l\nu$ trigger side) and on the away-side jet-jet system. On the toward-side the detailed manner in which transverse energy is distributed around the charged lepton is examined and on the away-side several observables are defined that measure how transverse energy and mass, respectively, are distributed around the jet-jet system. By making cuts on the toward- and away-side observables, signal to background enhancement factors greater than 500 can be obtained. The enhancement factor is defined to be the percentage of signal divided by the percentage of background surviving a given set of cuts.

We begin in Sec. II by discussing the signal and background event generation. The toward- and away-side profile analysis is presented in Sec. III and IV, respectively, with Sec. V being reserved for summary and conclusions.

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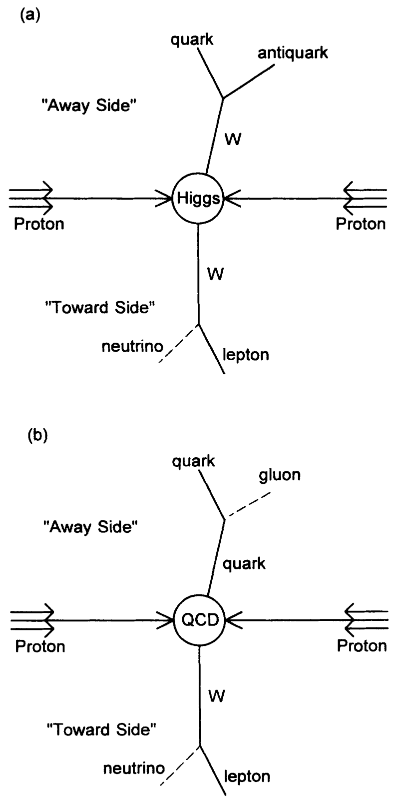

FIG. 1. Illustration of the toward-side (i.e., $l\nu$ trigger side) and the away-side for (a) the Higgs boson→ $WW \to l\nu$-jet-jet signal and (b) the W+jets background in hadron-hadron collisions.

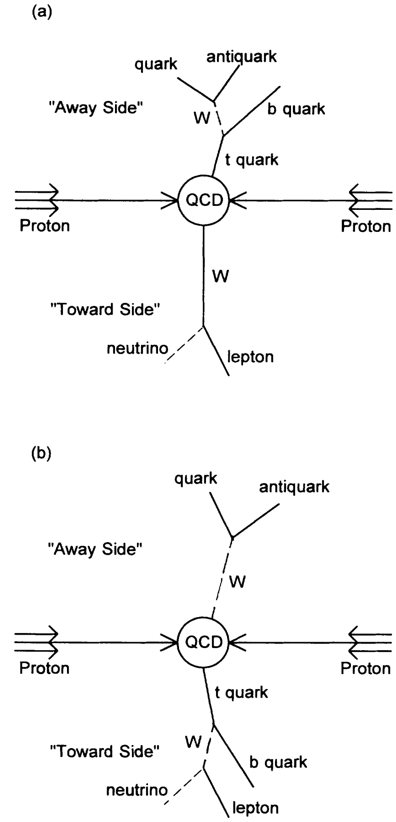

FIG. 3. Illustration of the toward-side (i.e., $l\nu$ trigger side) and the away-side for the W+top background: (a) primary W on the toward side and (b) secondary W on the toward side.

II. EVENT GENERATION AND CUTS

Present day Monte Carlo models for simulating high-energy hadron-hadron collisions combine perturbative QCD and phenomenology. When extrapolated to 40 TeV they provide an estimate or approximation of what experiment will actually find someday. Monte Carlo estimates should not be taken as exact predictions of QCD, and the precise numbers presented in this paper should not be taken too seriously. We use ISAJET version 6.50 to *illustrate* various physics techniques, and it is the techniques that are important, not the precise numbers.

Higgs boson→ WW signal. ISAJET is used to generate 100 000 Higgs bosons with a mass of 800 GeV in 40-TeV proton-proton collisions. The width of the Higgs boson is 261 GeV and it is generated over a mass range of 600 to 1000 GeV and forced to decay into two W bosons. At the Superconducting Super Collider (SSC) about 23 000 Higgs boson→ WW events per year are expected. The dominant subprocesses are $gg \to H$ with 34% of the cross section and $t\bar{t} \to H$ at 33% ($m_t = 140$ GeV). In addition, WW and ZZ fusion make up 24% and 9% of the signal, respectively.

Backgrounds. In the top-pair production, 500 000 t-$\bar{t}$ events are generated with the hard-scattering transverse momentum $\mathbf{k}_T$ in the range $200 \le \hat{\mathbf{k}}_T \le 1000$ GeV. These t-$\bar{t}$ events are produced via the "ordinary" QCD subprocesses $gg \to t\bar{t}$ (97%) and $q\bar{q} \to t\bar{t}$ (3%), which is referred to as the "top-pair" background.

In the W+jets, 400 000 single W bosons are produced at large transverse momentum, $\hat{\mathbf{k}}_T \ge 175$ GeV, via the ordinary QCD subprocesses $qg \to Wq$, $\bar{q}g \to W\bar{q}$, and $q\bar{q} \to Wg$. Here the q and $\bar{q}$ refer to all quark and antiquark flavors *except* for the top quark and top antiquark. These subprocesses, of course, generate addition gluons via bremsstrahlung off both incident and outgoing color nonsinglet partons, resulting in multiparton final states, which subsequently fragment into hadrons, and is re-

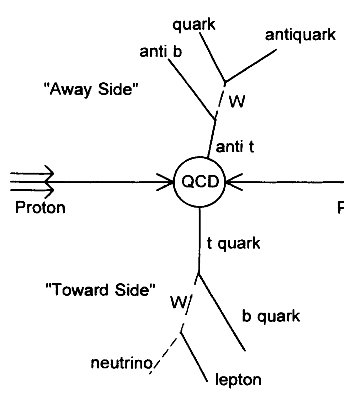

FIG. 2. Illustration of the toward-side (i.e., $l\nu$ trigger side) and the away-side for the top-pair background.

ferred to as the $W+$jets background.

In the $W+$top, 100 000 single W bosons are produced at large transverse momentum, $\hat{\mathbf{k}}_T \geq 200$ GeV, via the ordinary QCD subprocesses $tg \to Wt$ and $\bar{t}g \to W\bar{t}$. These subprocesses, of course, generate addition gluons via bremsstrahlung off both incident and outgoing color nonsinglet partons, resulting in multiparton final states, which subsequently fragment into hadrons, which is referred to as the $W+$top background.

In the WW continuum, 100 000 ZZ continuum events (i.e., $q\bar{q} \to WW$) events are generated with the hard-scattering transverse momentum of the $W, \hat{\mathbf{k}}_T$, in the range $175 \leq \hat{\mathbf{k}}_T \leq 1000$ GeV.

Events are analyzed by dividing the solid angle into "calorimeter" cells having size $\Delta\eta\Delta\phi$, where η and ϕ are the pseudorapidity and azimuthal angle, respectively. In the "central" region ($|\eta|<3$) the cell size is taken to be

$$\Delta\eta\Delta\phi = 0.1 \times 7.5°, \quad |\eta| < 3 \ ,$$

whereas in the "forward" (and "background") region ($3 < |\eta| < 6$) the cell size is chosen to be twice as large, namely,

$$\Delta\eta\Delta\phi = 0.2 \times 15°, \quad 3 < |\eta| < 6 \ .$$

The hadronic σ_{had} and electromagnetic σ_{em} energy resolutions in the central region are taken as follows:

$$\sigma_{\text{had}}/E = 0.73/\sqrt{E} \oplus 0.08 \ ,$$

$$\sigma_{\text{em}}/E = 0.17/\sqrt{E} \oplus 0.01 \ ,$$

where E is the particle energy (measured in GeV) and the $\oplus$ is to indicate that the two terms are added in quadrature. In the forward (and backward) region the resolutions are degraded to

$$\sigma_{\text{had}}/E = 1.0/\sqrt{E} \oplus 0.1 \ ,$$

$$\sigma_{\text{em}}/E = 0.5/\sqrt{E} \oplus 0.05 \ .$$

The cell sizes and energy resolutions are chosen to roughly correspond to the Solenoidal Detector Collaboration (SDC) proposal [2,3].

A single cell has an energy (the sum of the energies of all the particles that hit the cell *excluding* neutrinos) and a direction given by the coordinates of the center of the cell. From this the transverse energy of each cell is computed from the cell energy and direction. Large transverse momentum leptons are analyzed separately and are not included when computing the energy of a cell. Jets are defined using a simple algorithm. One first considers the "hot" cells (those with transverse energy greater than 5 GeV). Cells are combined to form a jet if they lie within a specified "radius" $R^2 = \Delta\eta^2 + \Delta\phi^2$ in η-ϕ space from each other. Jets have an energy given by the sum of the energy of each cell in the cluster and a momentum $\mathbf{p}_j$ given by the vector sum of the momentums of each cell. The invariant mass of a jet is simply $M_j^2 = E_j^2 - \mathbf{p}_j \cdot \mathbf{p}_j$. Our radius and jet-pair definitions are given in Tables I(a) and I(b), respectively.

Lepton and missing transverse-energy trigger. Our "zero-level" trigger is designed to select large transverse momentum W bosons that have decayed into a charged lepton and a neutrino. This first cut is made by demanding that the event contain *at least* one isolated high transverse-momentum charged lepton ($l^\pm = e^\pm$ or $\mu^\pm$) in the central region as follows:

$$P_T(l^\pm) > 50 \text{ GeV}, \quad |\eta(l^\pm)| < 2.5 \ .$$

Isolated leptons are defined by demanding that the total transverse energy within a distance R_l of the lepton in η-ϕ space be less than $E_T^l(\max)$. For this analysis,

$$R_l = 0.2, \quad E_T^l(\max) = 5 \text{ GeV} \ .$$

In addition, the event must have missing transverse energy $\not{E}_T$ and overall lepton-neutrino transverse momentum $P_T(l\nu)$ as follows:

$$\not{E}_T > 50 \text{ GeV}, \quad P_T(l\nu) > 200 \text{ GeV} \ ,$$

where the missing transverse-momentum two-vector $\not{\mathbf{p}}_T$

TABLE I. (a) Radius and (b) jet-pair definitions.

(a) Radius definitions

Quantity	Definition	This analysis
Jet core	Cells within radius R(core)	R(core)$=0.2$
Central jet	Cells within radius R(center)	R(center)$=0.35$
Full jet	Cells within radius R(halo)	R(halo)$=0.6$
Jet halo	Cells between R(center) and R(halo)	
Centroid	Cells between R(center) and R(centroid)	R(centroid)$=1.0$

(b) Jet-pair definitions

Quantity	Definition
Jet-jet cores	Cells within radius R(core) of *either* jet
Jet-jet centers	Cells within radius R(center) of *either* jet
Full jet pair	Cells within radius R(halo) of *either* jet
Jet-jet halos	Cells between R(center) and R(halo) of *either* jet
Centroid region	Cells outside R(center) of both jets but within R(centroid)

is determined from the transverse energy grid (i.e., the calorimeter) and

$$\not{E}_T^2 = \not{p}_x^2 + \not{p}_y^2 ,$$

$$P_T^2(l\nu) = (p_x^l + \not{p}_x)^2 + (p_y^l + \not{p}_y)^2 .$$

The $\hat{\mathbf{x}}$ axis and $\hat{\mathbf{y}}$ axis are perpendicular to the colliding beams and the $\hat{\mathbf{z}}$ axis is parallel.

This simple criterion of $P_T(l^{\pm}) > 50$ GeV, $\not{E}_T > 50$ GeV, and $P_T(l\nu) > 200$ GeV is referred to as the toward-side lepton trigger *without* profile cuts. Table II(a) shows that about 4000 Higgs boson → WW events per SSC year survive this selection criterion, where the SSC integrated luminosity for one year is taken to be 10^4 pb. Tables III(a) and IV(a) show that there are almost 1 million top-pair and almost 0.4 million W +jets events per year that also survive this cut. Finally, Table V(a) shows that about 20 000 W +top events escape this cut. At this stage, the top-pair is the largest background and is about 200 times the signal. In order to quantify how various additional cuts enhance the signal above the backgrounds, in each case we *define* this to be the reference point and the fraction of events escaping this cut is set to 100% in Tables II–V. Similarly, all enhancement factors are set to one at this level as we measure the effectiveness of all other additional cuts from this point.

These zero-level cuts are, of course, crucial. The transverse-momentum spectrum of the single W QCD background falls off rapidly, while for the heavy Higgs boson the signal is peaked at about half the mass of the Higgs boson. Here one wants to take as large of a cut on $P_T(l^{\pm})$ and $\not{E}_T$ as possible without losing too much of the signal. However, even with this cut, the backgrounds are still two orders of magnitude larger than the signal.

Jet-pair selection. The jet topology of the events passing the zero-level trigger is analyzed by first examining only jet cores [i.e., narrow jets of size R(core)] (see Table I). Here one includes only those jet cores satisfying

$$E_T(\text{jet core}) > 50 \text{ GeV}, \quad |\eta(\text{jet core})| < 3 .$$

In an attempt to find the two jets produced by the hadronic decay of the large transverse momentum W boson, jet pairs are formed by demanding that the distance between the two jet cores in η-ϕ space, $d_{jj}^2 = (\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2$, be less than 1.0, namely,

$$d_{jj}(\text{jet-jet cores}) < 1.0 .$$

In addition, the jet-jet cores are required to satisfy

$$P_T^{jj} > 200 \text{ GeV}, \quad |\phi_{jj} - \phi_{l\nu}| > 90^\circ ,$$

where P_T^{jj} is the total transverse momentum of the core jet pair and $\phi_{jj} - \phi_{l\nu}$ is the azimuthal angle between the toward-side lepton-neutrino pair and the core jet pair. The jet-pair is required to be in the opposite hemisphere (or away-side) from the lepton-neutrino pair. If more than one jet pair meets all of these requirements then the pair with the largest total transverse energy is selected.

Table II(a) shows that of the 4054 Higgs events passing the toward-side lepton cut roughly 73% also pass the away-side jet-pair selection criteria. Tables III(a) and IV(a) show that 46% of the top-pair events and 17% of the ordinary QCD W +jets background events that survive the zero-level trigger also have an opposite hemisphere jet-pair meeting the selection criteria. Defining the "enhancement factor" to be the percentage of signal

TABLE II. The 800 GeV Higgs boson → WW signal in proton-proton collisions at the SSC energy of 40 TeV. Results are given (a) without and (b) with toward- and away-side profile cuts. The zero-level trigger (*without* profile cuts) is used as a reference point and is normalized to 100%. The enhancement factor is defined to be the percentage of signal ($WW \to l\nu jj$ decay mode) divided by the percentage of background surviving a given set of cuts.

Selection or cut	$WW \to$ all events/year	$WW \to$ all fraction (%)	$WW \to l\nu jj$ fraction (%)
	(a) Higgs signal without profile cuts		
Toward-side lepton cuts without profile cuts	4054	100	100
Away-side jet pair selection without profile cuts	2952	73	74
W-mass cut 70–90 GeV	1872	46	48
W and Higgs boson mass cut 650–950 GeV	1417	35	36
	(b) Higgs signal with profile cuts		
Toward-side lepton cuts with profile cuts	2168	53	55
Away-side jet-pair selection with profile cuts	717	18	18
W-mass cut 70–90 GeV	598	15	15
W and Higgs boson mass cut 650–950 GeV	452	11	12

TABLE III. The top-pair background in proton-proton collisions at the SSC energy of 40 TeV. Results are given (a) without and (b) with toward- and away-side profile cuts. The zero-level trigger (*without* profile cuts) is used as a reference point and is normalized to 100%. The enhancement factor is defined to be the percentage of signal ($WW \to l\nu jj$ decay mode) divided by the percentage of background surviving a given set of cuts. Also shown is the background to signal ratio, with the signal given in Table II.

Selection or cut	SSC events/year	Fraction (%)	Background-to-signal	Enhancement
(a) Top-pair background without profile cuts				
Toward-side lepton cuts without profile cuts	927 348	100	229	1.0
Away-side jet-pair selection without profile cuts	422 891	46	143	1.6
W-mass cut 70–90 GeV	104 459	11	56	4.2
W and Higgs boson mass cut 650–950 GeV	44 102	4.8	31	7.7
(b) Top-pair background with profile cuts				
Toward-side lepton cuts with profile cuts	88 201	9.5	41	5.8
Away-side jet-pair selection with profile cuts	535	0.06	0.7	318
W-mass cut 70–90 GeV	244	0.026	0.4	585
W and Higgs boson mass cut 650–950 GeV	119	0.013	0.3	900

TABLE IV. The W+jets background in proton-proton collisions at the SSC energy of 40 TeV. Results are given (a) without and (b) with toward- and away-side profile cuts. The zero-level trigger (*without* profile cuts) is used as a reference point and is normalized to 100%. The enhancement factor is defined to be the percentage of signal ($WW \to l\nu jj$ decay mode) divided by the percentage of background surviving a given set of cuts. Also shown is the background to signal ratio, with the signal given in Table II.

Selection or cut	SSC events/year	Fraction (%)	Background-to-signal	Enhancement
(a) W+jets background without profile cuts				
Toward-side lepton cuts without profile cuts	365 250	100	90	1.0
Away-side jet-pair selection without profile cuts	62 292	17	21	4.4
W-mass cut 70–90 GeV	10 064	2.8	5.4	17
Higgs-boson mass cut 650–950 GeV	4498	1.2	3.2	30
(b) W+jets background with profile cuts				
Toward-side lepton cuts with profile cuts	225 142	62	104	0.9
Away-side jet-pair selection with profile cuts	1622	0.4	2.3	41
W-mass cut 70–90 GeV	285	0.08	0.5	198
Higgs-boson mass cut 650–950 GeV	124	0.03	0.3	339

TABLE V. The W+top background in proton-proton collisions at the SSC energy of 40 TeV. Results are given (a) without and (b) with toward- and away-side profile cuts. The zero-level trigger (*without* profile cuts) is used as a reference point and is normalized to 100%. The enhancement factor is defined to be the percentage of signal ($WW \to l\nu jj$ decay mode) divided by the percentage of background surviving a given set of cuts. Also shown is the background to signal ratio, with the signal given in Table II.

Selection or cut	SSC events/year	Fraction (%)	Background-to-signal	Enhancement
	(a) W+top background without profile cuts			
Toward-side lepton cuts without profile cuts	19 034	100	5	1.0
Away-side jet-pair selection without profile cuts	7372	39	2.5	2
W-mass cut 70–90 GeV	1715	9	0.9	5
Higgs-boson mass cut 650–950 GeV	719	3.8	0.5	10
	(b) W+top background with profile cuts			
Toward-side lepton cuts with profile cuts	9114	48	4.2	1.2
Away-side jet-pair selection with profile cuts	65	0.34	0.09	54
W-mass cut 70–90 GeV	25	0.13	0.04	118
Higgs-boson mass cut 650–950 GeV	12	0.06	0.03	187

($WW \to l\nu jj$ channel) divided by the percentage of background surviving the away-side cuts, one arrives at an enhancement of 0.74/0.46 or about 1.6 for the top-pair background and about 4.4 for the W+jets background. Table IV(a) shows that at this stage the enhancement factor for the W+top background is about 2. For the W+jets background, one might have expected to do better at this stage. However, once we required the W boson to have a large transverse momentum, we forced the background to have a large P_T away-side quark or gluon jet. This away-side parton often fragments via gluon bremsstrahlung into multiple away-side jets which then survive the selection criteria.

Jet-jet invariant mass cut. The invariant mass M_{jj}(full) is constructed by using the full jet pair defined in Table I(b). In particular one uses all cells within a "distance" R(halo) of either of the jet cores. The aim here is, of course, to reconstruct the invariant mass of the W boson. However, this full jet-jet invariant mass will *only* be used in the event selection. The Higgs boson mass will be reconstructed by setting $M_{jj}=M_W$. Events are rejected unless the full jet-jet mass satisfies

$$70 < M_{jj}(\text{full}) < 90 \text{ GeV} .$$

As can be seen from Table II(a), about 63% of the Higgs events passing *both* the zero-level lepton trigger and the jet-pair selection have M_{jj} within 10 MeV of the W boson mass. On the other hand, for the W+jets background, only about 16% of the jet pairs have a mass in this range [Table IV(a)]. About 2.8% of the W+jets background events surviving *both* the lepton cut and the jet-pair selection have a full jet-pair invariant mass within 10 MeV of the W boson mass. This corresponds to an enhancement factor over the W+jets background of about 17. The extra b or $\bar{b}$ jet produced in association with the W boson in the top pair and the W+top backgrounds increases the likelihood of an incorrect choice for one of the jets in the jet pair. Many of these incorrect choices are then removed by the jet-jet invariant mass cut. Unfortunately, at this stage the enhancement factor over the top-pair background is only about 4, since the top-pair background actually has an away-side W boson (see Fig. 2).

Reconstructing the longitudinal momentum of the neutrino. Ideally one would like to reconstruct the invariant mass of the Higgs boson from its decay products: lepton, neutrino, and two jets. However, the neutrino is not detected and its presence must be inferred by examining the missing transverse momentum $\not{p}_T$. If we set the transverse-momentum components of the neutrino equal to the missing transverse momentum,

$$\mathbf{p}_T^\nu = \not{\mathbf{p}}_T ,$$

and assume that the charged lepton and the neutrino are the result of a W decay (*and* neglect the W width) then the longitudinal momentum of the neutrino is given by one of the two solutions

$$p_L^\nu = [\, A p_L^l \pm E_l^2 \sqrt{A^2 - 4(p_T^l)^2 (p_T^\nu)^2}\,]/2(p_T^l)^2 ,$$

where E_l, p_L^l, and p_T^l, are the energy, longitudinal momentum, and transverse momentum, respectively, of the charged lepton, and p_T^ν is the transverse momentum of the neutrino. The quantity A is given by

$$A = M_W^2 + 2\mathbf{p}_T^l \cdot \mathbf{p}_T^\nu = M_W^2 + p_T^l p_T^\nu \cos\phi ,$$

where ϕ is the azimuthal angle between the transverse momentum vector of the charged lepton and the neutrino. The neutrino longitudinal momentum is selected at random from these two solutions, i.e., each solution chosen 50% of the time.

Although there are two solutions (ν_1 and ν_2) for the longitudinal momentum of the neutrino, the distance in η-ϕ space between the charged lepton and the neutrino is unique, namely,

$$R_{l\nu} = R_{l\nu_1} = R_{l\nu_2} ,$$

where

$$R_{l\nu_1}^2 = (\eta_l - \eta_{\nu_1})^2 + (\phi_l - \phi_{\nu_1})^2 ,$$

$$R_{l\nu_2}^2 = (\eta_l - \eta_{\nu_2})^2 + (\phi_l - \phi_{\nu_2})^2 .$$

This is a consequence of the fact that $\eta_l - \eta_{\nu_1} = \eta_{\nu_2} - \eta_l$ and $\phi_{\nu_1} = \phi_{\nu_2}$ for the two neutrino solutions.

Reconstructing the Higgs boson mass. The Higgs boson invariant mass is constructed from the energy and momentum of the charged lepton, the energy and momentum of the reconstructed neutrino, and the momentum vector of the jet pair as follows:

$$M^2 = (E_l + E_\nu + E_{jj})^2 - (\mathbf{p}_l + \mathbf{p}_\nu + \mathbf{p}_{jj})^2 ,$$

where

$$E_{jj}^2 = \mathbf{p}_{jj} \cdot \mathbf{p}_{jj} + M_W^2 .$$

The mass of a jet is not a well-defined quantity, since it depends on the soft particles. The momentum vector of a jet is better defined and is determined primarily by the core cells. Thus, in constructing the Higgs-boson mass we use the momentum vector of the jet pair but *not* the jet-pair mass. The mass of the jet pair is set equal to the mass of the W boson.

Figure 4 shows the reconstructed Higgs boson mass for the Higgs signal, the top-pair background, the W+jets background, the W+top background, and the WW continuum. In all cases the events survive the zero-level lepton trigger and the jet-pair selection and have $70 < M_{jj}(\text{full}) < 90$ GeV. At this stage, there are 1417 Higgs events, 44 102 top-pair events, and 4498 W+jets events per year at the SSC within 150 GeV of the true Higgs-boson mass of 800 GeV. This corresponds to an enhancement factor of about 8 over the top-pair background and about 30 over the W+jets background. The top-pair background is still 30 times the signal, while the W+jets background is about 3 times the signal.

III. TOWARD-SIDE PROFILE ANALYSIS

The goal of the toward-side profile analysis is to distinguish between primary and secondary W bosons in the trigger. The Higgs boson$\rightarrow WW$ signal produces a primary W boson, while the top-pair background produces a secondary W that originated from top decay and is accompanied by an associated b jet (see Fig. 2). To do this we define two observables that will be used to enhance the primary $W \rightarrow l\nu$ decays over the secondary W bosons.

The first of these toward-side profile observables is the distance in η-ϕ space between the charged lepton and the reconstructed neutrino $R_{l\nu}$. As discussed above this distance is unique and as can be seen in Fig. 5, differs somewhat between the signal and the top-pair background.

The most important toward-side profile observable is the amount of transverse energy located within a distance of $R=1$ in η-ϕ space of the charged lepton *(excluding* the neutrino and the charged lepton). As can be seen in Fig. 6, there is a lot more transverse energy surrounding the charged lepton for the top-pair background than for the Higgs boson$\rightarrow WW$ signal. For the signal the average amount of transverse energy located within a distance of $R=1$ of the charged lepton, $E_T(R_l<1)$, is about 25 GeV, whereas for the top-pair background it is around 71 GeV. Clearly the larger E_T values for the top-pair background are due to the presence of the accompanying b jet, which is not there in the signal. We take toward-side profile cuts as follows:

$$R_{l\nu} < 0.8, \quad E_T(R_l < 1) < 15 \text{ GeV} .$$

Table III(b) shows that only about 10% of the top-pair background events that passed the "zero-level" trigger remain after the toward-side profile cuts are employed. On the other hand, Table II(b) shows that 53% of the sig-

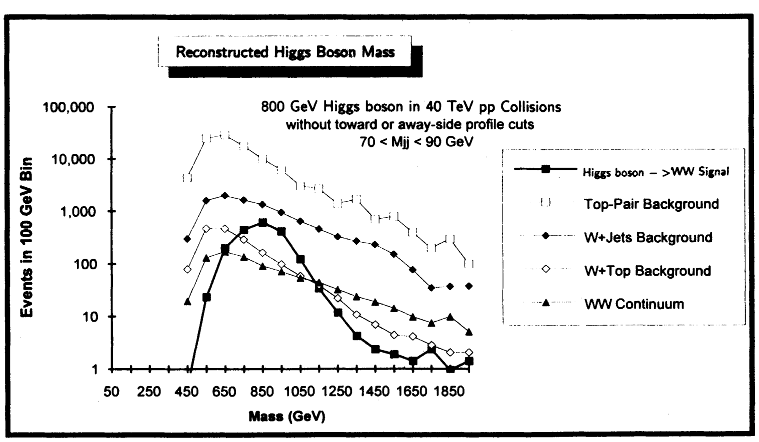

FIG. 4. The reconstructed Higgs-boson mass of an 800-GeV Higgs-boson produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events per SSC year in a 100-GeV bin for the Higgs signal, the top-pair background, the W+jets background, the W+top background, and the WW continuum. In all cases the events have survived the zero-level lepton trigger and the jet-pair selection *(without* toward- and away-side profile cuts) and have $70 < M_{jj}(\text{full}) < 90$ GeV.

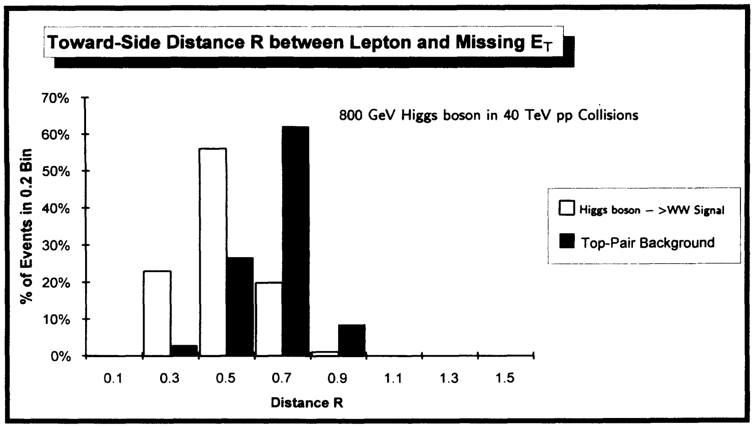

FIG. 5. Toward-side distance R in η-ϕ space between the charged lepton and the reconstructed neutrino from the zero-level trigger. Results are shown for the Higgs boson→ WW signal and the top-pair background.

nal survive these additional cuts. This toward-side cut results in an additional enhancement factor of about 6 over the top-pair background. The toward-side profile cuts do not affect much the W+jets relative to the signal, since this background has a primary W boson [see Table IV(b)]. On the other hand, Table V(b) indicates that the signal is enhanced by about a factor of 1.2 over the W+top background due to the toward-side profile cuts. This, of course, results from the decreased probability that the secondary W from top decay in the W+top background produced the zero-level trigger.

IV. AWAY-SIDE JET-JET PROFILE ANALYSIS

The away-side profile analysis must accomplish two goals. We must distinguish between primary W bosons that originate from the Higgs boson→ WW signal and secondary W bosons that originates from top decay and are accompanied by an associated b jet (see Fig. 2). In addition, we must distinguish the jet-pair arising from the $q\bar{q}$ decay of a large transverse momentum W boson as in Fig. 1(a), from the away-side quark-gluon pair coming from gluon Bremsstrahlung off a large transverse-momentum color nonsinglet parton as in Fig. 1(b). For the latter, we use some jet-jet halo method as in our previous paper [1] on Higgs boson→ ZZ except applied to the WW case instead.

Jet-jet halo cuts. The jet-jet halo method begins by dividing the jet-jet system into three regions defined in Table I(b). The first region is the jet-jet core, corresponding to cells whose centers lie within a distance R (core) in η-ϕ space of *either* jet. The jet-jet center region corresponding to cells whose centers lie within R(center) of *either* jet and the full jet-jet pair region is all the cells whose centers lie within R(halo) of *either* jet. Cells are *not* double counted. For example, a cell may lie in the center region of both jets, nevertheless it is counted just once. The jet-jet halo region corresponds to cells whose centers lie between R(center) and R(halo) of *either* jet. These regions are used to define observables that can differentiate between the jet pairs that originate from the hadronic decay of a W boson in the decay of the Higgs signal and the jet pairs that result from gluon bremsstrahlung from the large P_T color nonsinglet partons such as the away-side recoil parton in the W+jets background or the away-side top quark in the top-pair background.

The first observable is the fraction of the full jet-pair transverse energy that occurs in the jet-jet halo region:

$$F_{E_T} = E_T(\text{jet-jet halo})/E_T(\text{full jet-jet}) .$$

The second observable measured the invariant mass shift from the jet-jet cores to the full jet pair:

$$\Delta M = M(\text{full jet-jet}) - M(\text{jet-jet cores}) .$$

These two observables measure how transverse energy

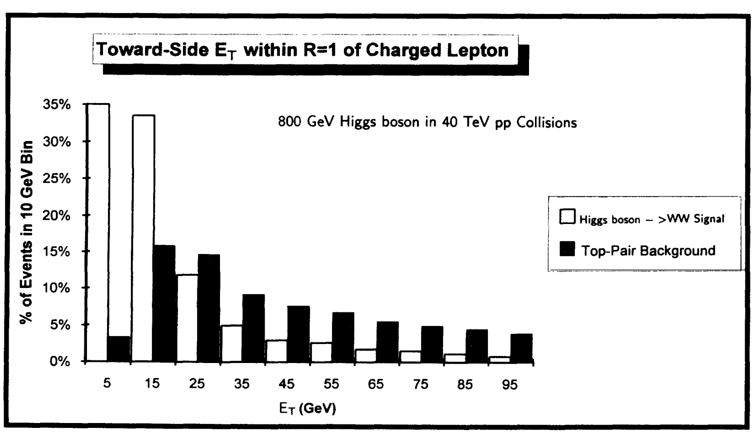

FIG. 6. Toward-side transverse energy within a distance $R=1$ in η-ϕ space of the charged lepton selected in the zero-level trigger. Results are shown for the Higgs boson→ WW signal and the top-pair background.

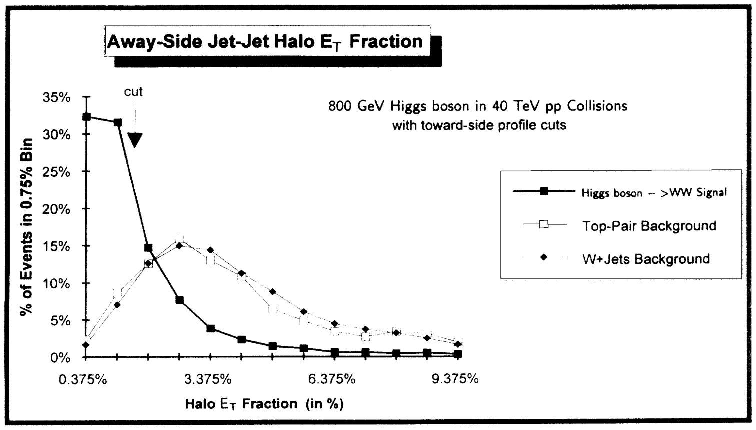

FIG. 7. The fraction of transverse energy within the away-side jet-jet halo region, $F_{E_T} = E_T(\text{jet-jet halo})/E_T(\text{full jet-jet})$, for the Higgs signal ($l\nu jj$ mode), the top-pair background, and the W+jets background. The signal and backgrounds have survived the zero-level lepton trigger, the jet-pair selection, and have $70 < M_{jj}(\text{full}) < 90$ GeV.

and mass, respectively, are deposited around the jet-jet cores.

Figure 7 shows the away-side halo E_T fraction for the Higgs signal, the W+jets background, and the top-pair background, for events that have survived the zero-level lepton trigger *with* toward-side profile cuts, the jet-pair selection, and have $70 < M_{jj}(\text{full}) < 90$ GeV. The backgrounds clearly have more debris in the halo region than the signal. It is not surprising to find more E_T surrounding the jet-jet cores in the top-pair background than the signal, since this background has an accompanying b jet. However, as we found in our earlier work, the W+jets background also has more E_T surrounding the jet-jet cores than the Higgs signal. For the signal, the jet pair arise from the $q\bar{q}$ decay of a large transverse-momentum W boson. The W boson is a color singlet and does not radiate gluons during flight. On the other hand, the large P_T away-side recoil quarks or gluons in the single W background are not color singlets and produce addition gluons via bremsstrahlung. Because of the large amount of glue in the incident protons at the x_T values probed by the SSC, the dominant subprocesses for large transverse-momentum single W bosons are $qg \to Wq$ (57%) and $\bar{q}g \to W\bar{q}$ (34%). The away-side recoil quark or antiquark radiates a gluon yielding a quark or antiquark plus a gluon as shown in Fig. 1.

Figure 8 shows the mass shift ΔM for the Higgs signal, the W+jets background, and the top-pair background for events that have survived the zero-level lepton trigger *with* toward-side profile cuts, the jet-pair selection, and have $70 < M_{jj}(\text{full}) < 90$ GeV. On the average, the mass shift is larger for these backgrounds than for the signal. These backgrounds have more mass located around the jet-jet cores for the same reason it has more transverse energy in the halo. Because of this, the two observables are not completely "orthogonal." Nevertheless, both the halo E_T and the mass shift can be used together to preferentially select the signal over the background. This is done by making the cuts on these observables as shown in Figs. 7 and 8:

$$F_{E_T} < 1.5\% \quad \text{and} \quad \Delta M < 15 \text{ GeV} .$$

These cuts reduce the signal by about a factor of 4, while reducing the top-pair background by a factor of about 300 and the W+jets background by a factor of about 30. It is very unlikely that a fluctuation in the underlying event (or "minimum bias") results in an away-side halo E_T fraction greater than 1.5%. At these energies the underlying event produces roughly 1.6 GeV of transverse energy per unit area of η-ϕ space, while $F_{E_T} = 1.5\%$ corresponds to, on the average, about 5 GeV in an area of about 1.1. The reduction factors for the top backgrounds arise because they have, on the average, more debris on the away-side than does the Higgs boson$\to WW$ signal. This debris is caused in part by the associated b or $\bar{b}$ jet

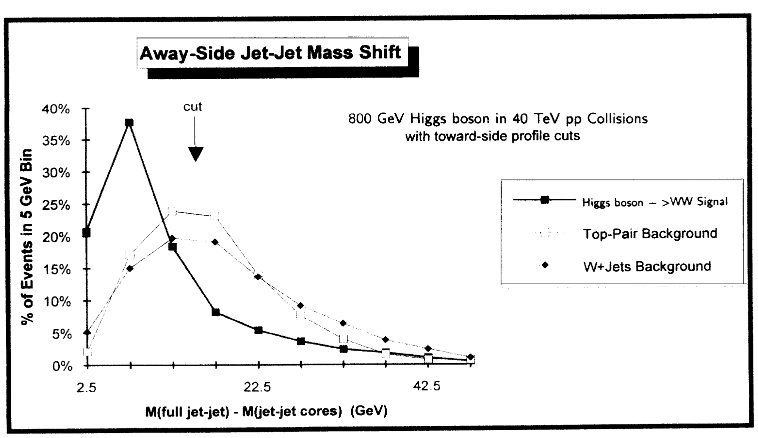

FIG. 8. The away-side mass shift, $\Delta M = M(\text{full jet-jet}) - M(\text{jet-jet cores})$, for the Higgs signal ($l\nu jj$ mode), the top-pair background, and the W+jets background. The signal and backgrounds have survived the zero-level lepton cuts, the jet-pair selection, and have $70 < M_{jj}(\text{full}) < 90$ GeV.

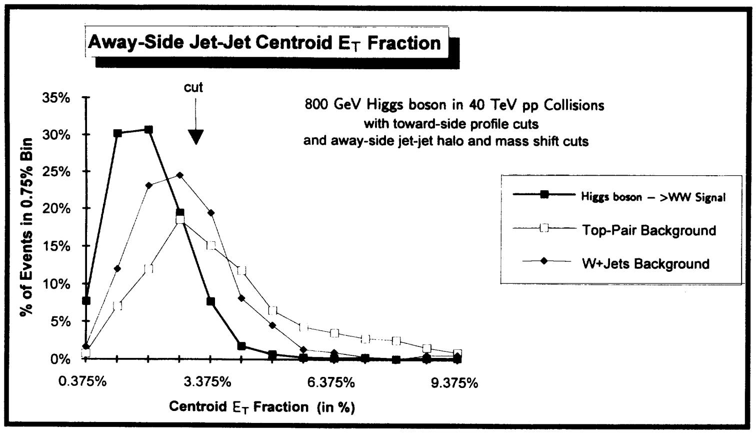

FIG. 9. The fraction of transverse energy within the away-side jet-pair centroid region for the Higgs signal, the top-pair background, and the W+jets background. The signal and backgrounds have survived the zero-level lepton trigger, the jet-pair selection *with* jet-jet halo cuts and mass shift cuts, and have $70 < M_{jj}(\text{full}) < 90$ GeV.

and also by gluons radiated from the outgoing colored quarks. One cannot expect the Monte Carlo models to accurately calculate all the low E_T gluon jets ($E_T \approx 5$ GeV) that are produced in associated with the high E_T outgoing colored quarks. The numbers presented here are not meant to be "precise test of QCD." It is the technique that is important, not the precise numbers.

At this point, we have done a satisfactory job on the W+jets background, but not on the top-pair background. Fortunately, we have not yet taken full advantage of the fact the away-side top-pair background has an extra b jet associated with it. Because of this, we define an additional "centroid" observable.

Jet-jet centroid cut. The centroid region is defined in terms of the position in η-ϕ space of the vector sum of the momentum's of the two jets (i.e., the jet-pair momentum). The centroid region includes all cells whose centers lie outside R(center) of *both* jets but are within a distance R(centroid) of the jet pair. The fraction of the transverse energy that occurs in the centroid region is defined as

$$F_{E_T}(\text{centroid}) = E_T(\text{jet-pair centroid})/E_T(\text{jet-jet centers}) ,$$

where the denominator is the transverse energy contained in the *centers* of the jets as defined in Table I(a).

Figure 9 shows the away-side centroid E_T fraction for the case of $R(\text{centroid})=1$ for the Higgs signal, the W+jets background, and the top-pair background, for events that have survived the zero-level lepton trigger *with* toward-side profile cuts, the jet-pair selection including the jet-jet halo and mass shift cuts, and have $70 < M_{jj}(\text{full}) < 90$ GeV. The top-pair background has more E_T in the jet-pair centroid region than does the W+jets background or the signal. This is, of course, due to the accompanying b jet.

Our away-side profile analysis is completed by making the centroid cut shown in Fig. 9, namely,

$$F_{E_T}(\text{centroid}) < 3\% \quad \text{with } R(\text{centroid})=1 .$$

This additional cut retains 88% of the signal, while eliminating 63% of the top-pair background.

The result of making all the toward- and away-side profile cuts is shown in Tables II(b)–IV(b) and in Table V(a). Now, there are approximately 452 Higgs events, 119 top-pair background events, and 124 W+jet background events per year at the SSC within 150 GeV of the Higgs-boson mass. There are also 12 events from the W+top background and 102 events from the WW continuum. The signal is now comparable to the background. We have achieved an enhancement factor of about 900 over the top-pair background and about 340 over the W+jets background.

Figure 10 shows the away-side jet-jet mass for the

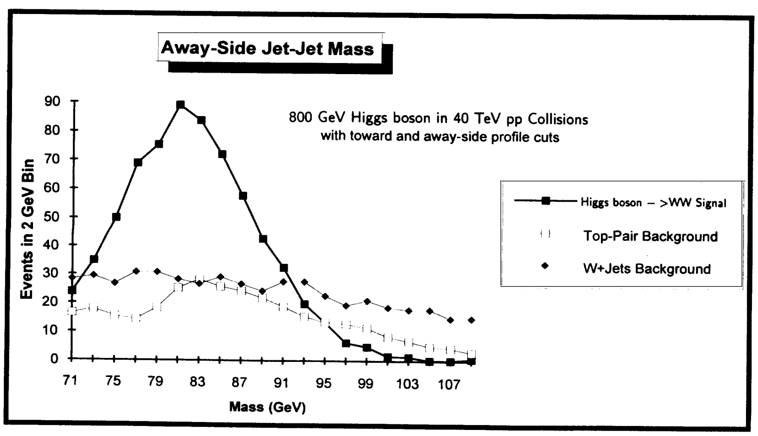

FIG. 10. The away-side jet-jet mass for an 800-GeV Higgs boson produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events per SSC year in a 2-GeV bin for the Higgs signal, the top-pair background and the W+jets background. In all cases the events have survived the zero-level lepton trigger and the jet-pair selection *(with* both toward- and away-side profile cuts).

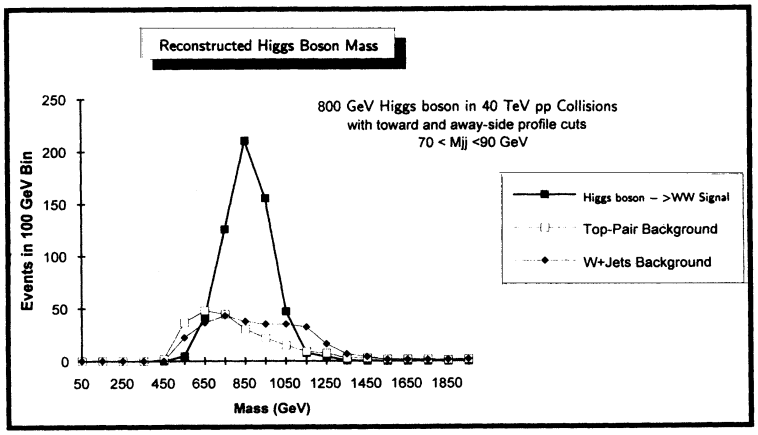

FIG. 11. The reconstructed Higgs-boson mass of an 800-GeV Higgs produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events per SSC year in a 100-GeV bin for the Higgs signal, the top-pair background, and the W+jets background. The events have survived the zero-level lepton trigger and the jet-pair selection (*with* toward- and away-side profile cuts) and have $70<M_{jj}(\text{full})<90$ GeV. This is the same plot as Fig. 4 *except* with toward- and away-side profile cuts.

Higgs signal, the top-pair background and the W+jets background. In all cases the events have survived the zero-level lepton trigger and the jet-pair selection and *include* both toward- and away-side profile cuts. One can see a peak in the reconstructed W boson mass from the signal, while the W+jets background is roughly flat. The top-pair background has a broad peak in this region due to the away-side secondary W boson. We have cut on the region $70<M_{jj}(\text{full})<90$ GeV, however, one could do a bit better by choosing a smaller range centered at the peak (which with our jet definitions is slightly larger than M_W).

Figure 11 shows the reconstructed Higgs boson mass for the Higgs signal, the top-pair background, and the W+jets background. The events have survived the zero-level lepton trigger and the jet-pair selection (*with* toward- and away-side profile cuts) and have $70<M_{jj}(\text{full})<90$ GeV. This is the same plot as Fig. 4 *except* with toward- and away-side profile cuts. Figure 12 shows the reconstructed Higgs boson mass for the *sum* of the Higgs signal and all the backgrounds (i.e., signal *plus* backgrounds). The Higgs signal produces a clear peak above the backgrounds. We have chosen a top quark mass of 140 GeV to illustrate our techniques, however, our methods work equally well for heavier top quarks. The numbers presented here change only by 20–30 % for the top quark mass range $140<m_t<180$ GeV.

If this is to be the discovery mode of the Higgs boson, then simply seeing the mass peak in Fig. 12 would not be sufficient. One would like to establish that the peak is due to a WW "resonance." One way to help establish this is to reconstruct the Higgs boson mass "on" and "off" the W mass as is done in Fig. 13 and Table VI. The "on" region is taken to be $70<M_{jj}<90$ GeV, while the off or wings regions are chosen to be $60<M_{jj}<70$ GeV and $90<M_{jj}<100$ GeV. Ideally one would like to see no change in the background on the W and in the wings [Fig. 13(b)], but see a big change for the signal plus background [Fig. 13(a)]. This would signify that one was really seeing a WW resonance. In our case, this would work perfectly if the jet-jet mass spectrum of the backgrounds shown in Fig. 10 were all flat. The W+jets background is flat but the top-pair background (and the WW continuum) contain away-side W bosons and are peaked in the on region. Nevertheless, Fig. 13 and Table VI show that there is a much bigger change on then there is off the W mass when the Higgs boson is present.

Another important signature of the Higgs boson is the longitudinal polarization of the W bosons into which it decays [4]. The ratio of longitudinal to transverse W bosons is given by

$$\frac{\Gamma(H\to W_L W_L)}{\Gamma(H\to W_T W_T)}=\frac{M_H^4}{8M_W^4}\left[1-\frac{2M_W^2}{M_H^2}\right]^2,$$

which for an 800-GeV Higgs boson is about 1200 to 1. In

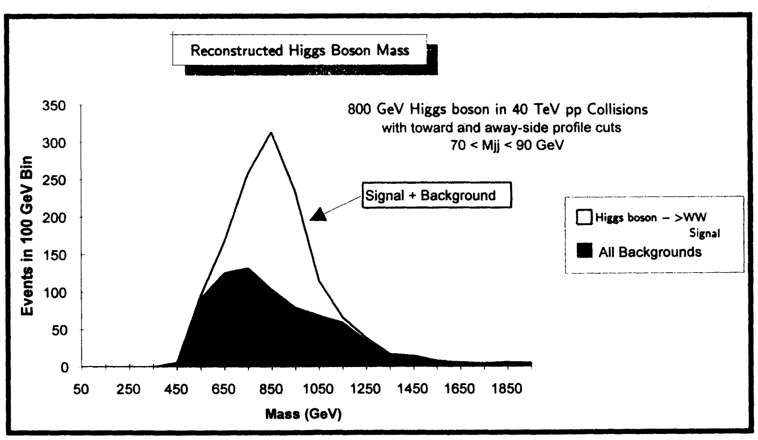

FIG. 12. The reconstructed Higgs-boson mass of an 800-GeV Higgs produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events per SSC year in a 100-GeV bin for the *sum* of the Higgs signal, and all the backgrounds (i.e., signal *plus* backgrounds). The events have survived the zero-level lepton trigger and the jet-pair selection (*with* toward- and away-side profile cuts) and have $70<M_{jj}(\text{full})<90$ GeV.

TABLE VI. Comparisons (a) on and (b) off the W mass for the Higgs boson→ WW signal and the backgrounds for reconstructed $l\nu jj$ masses in the range $640 < M_H < 950$ GeV. In (a) the reconstructed jet-jet mass is taken in the range $70 < M_{jj} < 90$ GeV, while in (b) the wings regions $60 < M_{jj} < 70$ GeV and $90 < M_{jj} < 100$ GeV are selected. Also shown are the subtracted values (a)−(b) and the ratios.

	(a) $70 < M_{jj} < 90$ GeV $650 < MH < 950$ GeV Events/SSC year	(b) $60 < M_{jj} < 70$ GeV $90 < M_{jj} < 100$ GeV $650 < MH < 950$ GeV Events/SSC year	(a)−(b)	(a)/(b)
Signal ($H \to WW$)	452	68	384	6.6
Background (top-pair)	119	62	57	1.9
Background (W+jets)	124	118	6	1.0
Background (W+top)	12	8	3	1.4
Background (WW)	102	8	94	13
All backgrounds	357	197	160	1.8
Signal + backgrounds	809	265	544	3.1
Signal-to-backgrounds	1.3	0.3	2.4	3.7

the $q\bar{q}$ rest frame, the longitudinal W decay, $W_L \to q\bar{q}$, has a $\sin^2\theta$ decay angular distribution, whereas for transverse W bosons the decay distribution is $1+\cos^2\theta$ (summing over *both* ± 1 helicities). For large transverse momentum W bosons in the central region in the laboratory frame, a $\sin^2\theta$ distribution results in quark and antiquark jets that tend to have equal transverse energies, while a $1+\cos^2\theta$ distribution produces one high and one low E_T jet (i.e., asymmetric jet transverse energies).

Figure 14(a) shows the away-side jet-jet angular distribution in the jet-pair rest frame. Here we plot $\cos\theta_{jj}^{\text{c.m.}}$, where $\theta_{jj}^{\text{c.m.}}$ is the angle that the highest E_T jets makes with respect to the direction of the jet-pair direction, in the jet-jet rest frame. One can clearly see the remnants of the $\sin^2\theta = 1-\cos^2\theta$ of the Higgs signal. One can also see from Fig. 14(a) that the background has a different angular distribution. The away-side W bosons produced by the backgrounds contain a mixture of both longitudi-

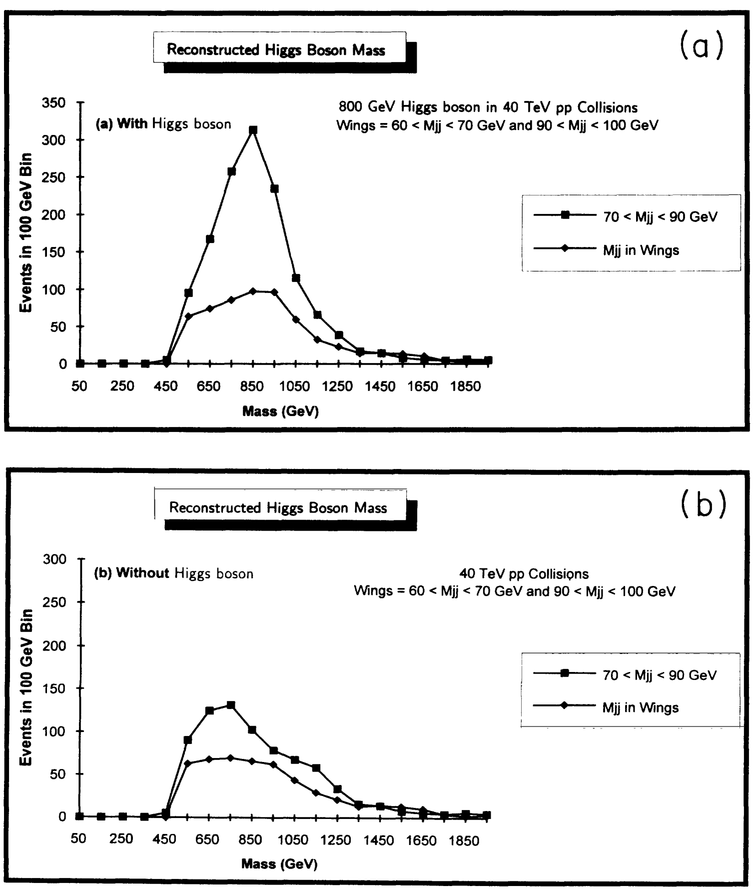

FIG. 13. The reconstructed Higgs-boson mass on and off the W mass for the case (a) of an 800-GeV Higgs boson produced in proton-proton collisions at the SSC energy of 40 TeV and for the (b) backgrounds only (i.e., no Higgs boson). The on region is taken to be $70 < M_{jj} < 90$ GeV, while in the off or wings regions are $60 < M_{jj} < 70$ GeV and $90 < M_{jj} < 100$ GeV.

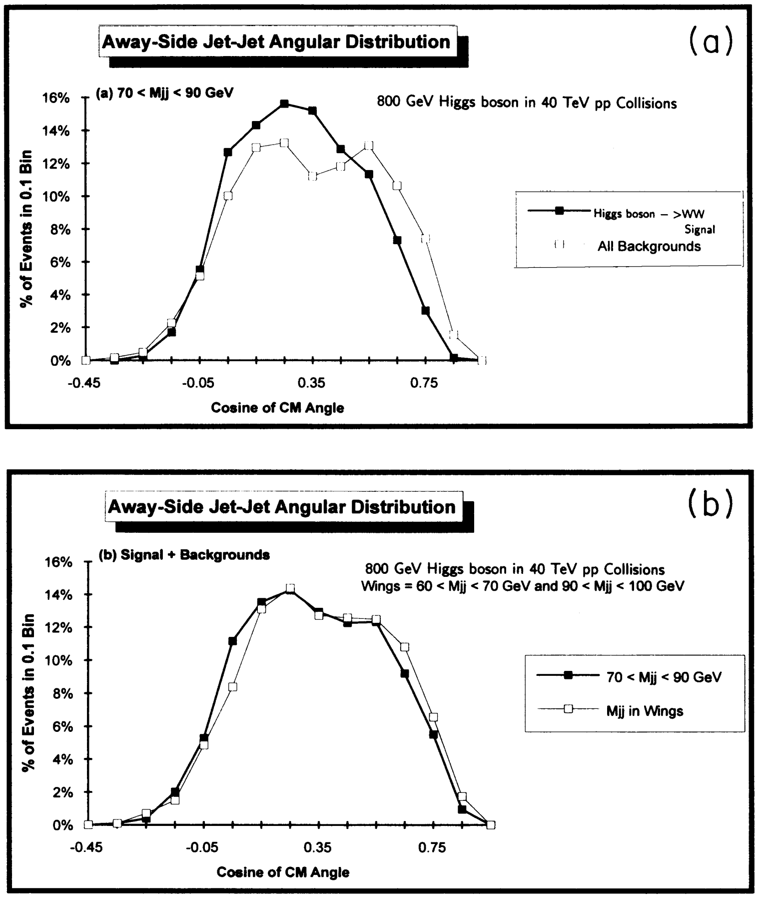

FIG. 14. The away-side jet-jet angular distribution in the jet-jet rest frame. The angle between the high E_T jet relative to the direction of the jet pair is shown for (a) the Higgs signal and the sum of all the background for $70<M_{jj}<90$ GeV, and (b) the sum of the Higgs signal and the backgrounds on ($70<M_{jj}<90$ GeV) and off ($60<M_{jj}<70$ GeV and $90<M_{jj}<100$ GeV) the W mass.

nal and transverse polarizations. The jet pair coming from the gluon bremsstrahlung off of large transverse momentum away-side quarks and gluons as in the W+jets background tend to have asymmetric transverse energies, which results in an angular distribution peaked in the forward and backward direction.

As can be seen in Fig. 14(a), the background angular distribution is flatter and has more events at the forward angles. Our cuts have distorted these distributions significantly. We require that each of the two jets have E_T greater than 50 GeV and that the jet-pair have P_T greater than 200 GeV. This means that we have removed a portion of the asymmetrical (one large and one small E_T) jet-jet configurations. We therefore cannot see the forward peaking of a $1+\cos^2\theta$ distribution. Nevertheless, the signal and background angular distributions do differ significantly. Unfortunately, Fig. 14(b) shows with the ratio of signal to background that our cuts have produced one cannot see a shift of the angular distribution on and off the W mass, which would be a clear indication of the Higgs presence.

V. SUMMARY AND CONCLUSIONS

We have developed a technique that can enhance the Higgs boson$\rightarrow WW$ signal over the backgrounds. The method can help to distinguish the primary W bosons produced by the signal from the secondary W bosons produced in association with b jets in the top-pair background. In addition, the method helps to distinguish the two-jet system originating from $q\bar{q}$ the decay of a color singlet W boson from a random jet pair coming from the ordinary QCD gluon bremsstrahlung of colored quarks and gluons. An observable that measures the amount of transverse energy surrounding the toward-side charged lepton is examined and observables are defined that measure how transverse energy and mass, respectively, are distributed around the away-side jet-jet system. Our technique, which we refer to as a toward- and away-side "profile" analysis can be summarized by the following series of selections and cuts: charged-lepton and missing E_T trigger, toward-side profile analysis, jet-pair selection, away-side jet-jet profile cuts, and away-side jet-jet invariant mass cuts. The invariant mass of the away-side jet-jet pair is used *only* in the selection of events, the Higgs boson mass is reconstructed from the momentum of the jet pair with M_{jj} set equal to M_W. With both toward- and away-side profile cuts we are able to obtain signal to background enhancements of around 1000. With enhancements this large, the Higgs boson stands out in the invariant mass plot as a definite peak over the background (see Fig. 12). The method works equally well for a 600-GeV Higgs boson, but does not work for Higgs boson masses below about 500 GeV. In order for the away-side profile method to work, the W bosons must have a large transverse momentum. For transverse momenta below about 200 GeV the signal and background jet-jet halo transverse-energy fractions and mass shifts in Figs. 7 and 8, respectively, begin to look similar and the profile cuts become less effective.

The overall signal and signal/background ratios we have obtained via applying our transverse energy profile analysis to (a Monte Carlo simulation of) calorimeter data compare favorably against other techniques, such as hadronic multiplicity cuts [5], which require an additional high-performance silicon μstrip tracker. We also believe that further improvements in enhancing the Higgs signal-to-background ratio can be made by combining our profile cuts with "orthogonal" cuts like forward jet tagging [6].

Jet-jet "shape cuts" have been considered previously. The two that are most similar to our method are the "elongation" of the jet pair, and the χ^2 shape [4]. Our away-side profile observables are better able to differentiate between the underlying color structure of the Higgs-boson events and the QCD background because they measure the activity in the "halo" regions of the jet pair, rather than just examining the overall pair shape [7,8].

Upon the completion of this paper, we learned that the Superconducting Super Collider (SSC) project has been canceled. We are sad that the exciting physics opportunities offered by the SSC will not be realized. Nevertheless, we believe that it is interesting and important to continue to learn about what could have been accomplished at the SSC. Such knowledge will help to place other hadron-hadron colliders in the proper perspective. In addition, we believe that the techniques developed here for the SSC will be useful at other colliders as well.

ACKNOWLEDGMENTS

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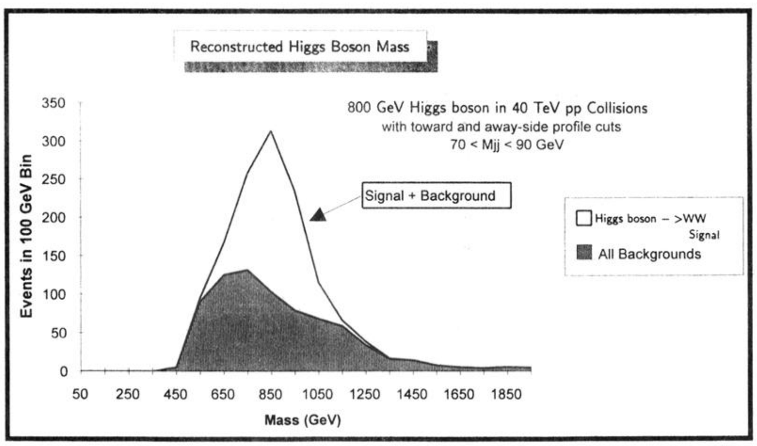

FIG. 12. The reconstructed Higgs-boson mass of an 800-GeV Higgs produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events per SSC year in a 100-GeV bin for the *sum* of the Higgs signal, and all the backgrounds (i.e., signal *plus* backgrounds). The events have survived the zero-level lepton trigger and the jet-pair selection (*with* toward- and away-side profile cuts) and have $70 < M_{jj}(\text{full}) < 90$ GeV.

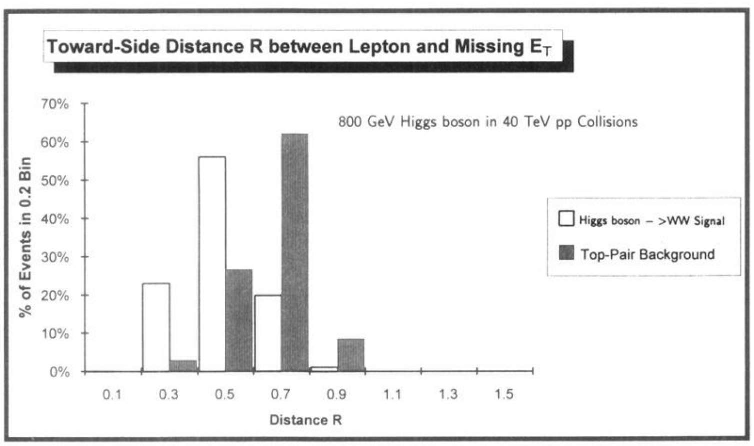

FIG. 5. Toward-side distance R in η-ϕ space between the charged lepton and the reconstructed neutrino from the zero-level trigger. Results are shown for the Higgs boson$\rightarrow WW$ signal and the top-pair background.

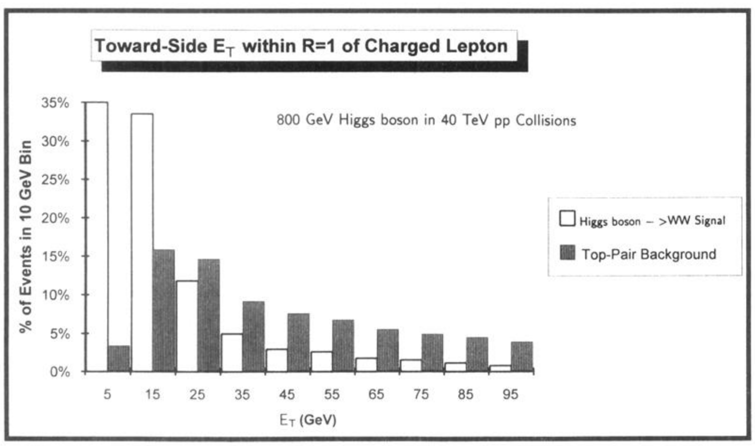

FIG. 6. Toward-side transverse energy within a distance $R=1$ in η-ϕ space of the charged lepton selected in the zero-level trigger. Results are shown for the Higgs boson$\rightarrow WW$ signal and the top-pair background.