Enhancing the heavy Higgs signal with jet-jet profile cuts

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The jet-jet profile, or detailed manner, in which transverse energy and mass are distributed around the jet-jet system resulting from the hadronic decay of a Z boson in the process Higgs boson$\rightarrow ZZ$ at a proton-proton collider energy of 40 TeV is carefully examined. Two observables are defined that can be used to help distinguish the l^+l^--jet-jet signal from Higgs boson decay from the "ordinary" QCD background arising from the large transverse momentum production of single Z bosons plus the associated jets. By making cuts on these observables, signal to background enhancement factors greater than 100 can be obtained.

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I. INTRODUCTION

The great challenge at hadron colliders is to disentangle any new physics that may be present from the "ordinary" QCD background. An important final state consists of a large transverse momentum charged lepton pair plus two accompanying jets (i.e., l^+l^-jj). It is one of the relevant signals for the production of a Higgs particle and its subsequent decay into ZZ with one Z decaying leptonically and the other Z decaying hadronically into a $q\bar{q}$ pair which then manifests itself as a pair of jets [1,2]. Unfortunately, too often the large transverse momentum production of single Z bosons plus the associated jets mimic the Higgs signals. Once one requires the Z boson to have a large transverse momentum by demanding a large P_T lepton pair, one has forced the background to have a large P_T "away-side" quark or gluon via subprocesses such as $qg\rightarrow Zq$ or $q\bar{q}\rightarrow Zg$. This away-side parton often fragments via gluon bremsstrahlung, producing away-side jet pairs which resemble the signal. However, the signal jet pair and the background jet pair have quite different origins. The former arises from the decay of a color singlet Z boson while the latter is produced in a color nonsinglet "parton shower." We examine in detail the jet-jet profile, or precise manner, in which transverse energy and mass are distributed around this jet-jet system. Two observables are defined that can be used to help distinguish the Higgs signal from the QCD background. By making cuts on these observables, signal to background enhancement factors greater than 100 can be obtained, where 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 event generation and selection criteria. The jet-jet profile analysis is presented in Sec. III with Sec. IV being reserved for summary and conclusions.

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II. EVENT GENERATION AND CUTS

ISJAET version 6.50 is used to illustrate our jet-jet profile technique. We generate 50 000 Higgs bosons with a mass of 800 GeV in 40 TeV proton-proton collisions and analyze the outgoing particles. The width of the Higgs boson is 261 GeV and it is generated over a mass range of 600–1000 GeV and forced to decay into two Z bosons. For 800 GeV Higgs bosons at 40 TeV, the dominant subprocesses are $gg\rightarrow H$ with 35% of the cross section and $t\bar{t}\rightarrow H$ at 36% ($m_t=140$ GeV). WW and ZZ fusion make up 21% and 7% of the signal, respectively. In addition, 100 000 ZZ continuum events (i.e., $q\bar{q}\rightarrow ZZ$) and 400 000 single Z boson events are generated with the hard-scattering transverse momentum of the Z, $\hat{\mathbf{k}}_T$, in the range $150\leq\hat{\mathbf{k}}_T\leq1000$ GeV. Single Z bosons are produced at large transverse momentum via the "ordinary" QCD subprocesses $qg\rightarrow Zq$, $\bar{q}g\rightarrow Z\bar{q}$, and $q\bar{q}\rightarrow Zg$. 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 referred to as the Z+jets background. The various Monte Carlo models, including ISAJET, are merely approximations to nature and none of them are expected to agree precisely with future experiments at the Superconducting Super Collider (SSC). It is our analysis technique that is important, the precise numbers will depend somewhat on the Monte Carlo model and on the experimental detector performance.

Events are analyzed by dividing the solid angle into "calorimeter" cells having size $\Delta\eta\Delta\phi=0.1\times7.5°$, where η and ϕ are the pseudorapidity and azimuthal angle, respectively. 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

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TABLE I. (a) Single jet and (b) jet pair definitions.

Quantity	(a) Jet definitions Definition	This analysis
Jet core	Cells within radius R(core)	$R(\text{core})=0.2$
Central jet	Cells within radius R(center)	R $(\text{center})=0.35$
Full jet	Cells within radius R(halo)	$R(\text{halo})=0.6$
Jet halo	Cells between R(center) and R(halo)	

Quantity	(b) Jet pair definitions 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 pairs	Cells within radius R(halo) of *either* jet
Jet-jet halos	Cells between R(center) and R(halo) of *either* jet

if they lie within a specified "distance" or "radius," $R^2=\nabla\eta^2+\nabla\phi^2$, 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 single jet and jet pair definitions are given in Tables I(a) and I(b), respectively, and illustrated in Fig. 1. The jet core, center, and halo sizes given in Table I(a) are chosen to illustrate the jet-jet profile technique. One can adjust these values by 20% with no loss in the ability to perform the jet-jet profile analysis. The optimization of these values will be discussed in a forthcoming publication [3].

We have taken the energy resolution to be perfect, which means that the only resolution effects are caused by the lack of spatial resolution due to the cell size. We will examine carefully the effect of energy resolution and cell size in a forthcoming publication [3]. However, cell size effects tend to dominate over energy resolution effects, and we have taken rather coarse cells for this analysis. The Solenoidal Detector Collaboration (SDC) at the SSC will have considerably better spatial resolution with $\Delta\eta\Delta\phi=0.05\times3°$ [4]. Thus we expect that smaller cells will, if anything, improve on what we are able to do here, even after one includes reasonable energy resolutions.

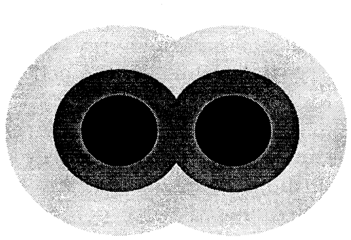

FIG. 1. Illustrates the "bipolar" regions used in analyzing the profile of a jet pair. The jet-jet core and center regions are the dark and medium shaded areas, respectively, while the "halo" region is lightly shaded.

A. Lepton trigger

The first cut on the data is made by demanding that the event contain *at least* two isolated high transverse momentum leptons ($l^\pm=e^\pm$ 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

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

Lepton pairs (e^+e^- and $\mu^+\mu^-$) are constructed for the events that survive this first cut. The pairs are ordered according to their invariant mass, with pair No. 1 having the mass closest to the Z boson and pair No. 2 being the second closest, etc. Finally, the event is rejected unless at least one lepton pair satisfies

$$P_T(l^+l^-)>200\text{ GeV}\ .$$

Table II(a) shows that for an 800 GeV Higgs boson at the SSC, roughly 903 events per year pass this cut for the full decay mode $ZZ\to$all. Here the SSC integrated luminosity for 1 yr is taken to be 10^4/pb. The overall Higgs boson$\to ZZ$ rate is 11 085 events per year with approximately 80% surviving this lepton cut. About 62% of the Higgs boson$\to ZZ\to l^+l^-q\bar{q}$ mode pass this cut. The cross section for producing a single Z boson at large transverse momentum via the ordinary QCD subprocesses $qg\to Zq$, $\bar{q}g\to Z\bar{q}$, and $q\bar{q}\to Zg$ is enormous compared to the Higgs cross section. As Table II(a) shows, 114 662 events per year of the ordinary QCD Z +jets background survive this lepton cut.

This high transverse lepton pair cut is, of course, crucial. The transverse momentum spectrum of the single Z 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 a cut on $P_T(l^+l^-)$ as possible without losing too much of the signal. However, even with this cut, the background is still more than 100 times the signal.

B. Jet pair selection

The jet topology of events with at least one large transverse momentum lepton pair is analyzed by first examining only jet cores [i.e., narrow jets of size R(core)]. 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 Z 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

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

where P_T^{jj} is the total transverse momentum of the core jet pair and $\phi_{jj}-\phi_{ll}$ is the azimuthal angle between the leading lepton pair and the core jet pair. The jet pair is required to be in the opposite hemisphere (or "away-side") from the lepton 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 903 Higgs events passing the lepton cut 52% of the full $ZZ \to$all mode and 71% of the $ZZ \to l^+l^-jj$ channel also pass the jet pair selection criteria. The full $ZZ \to$ all mode, of course, contains the $l^+l^-l^+l^-$ and the $l^+l^-\nu\bar{\nu}$ channels. Here we could remove the four charged lepton events, but instead we analyze simultaneously both the $ZZ \to l^+l^-jj$ and the "gold-plated" $ZZ \to l^+l^-l^+l^-$ events. The four lepton invariant mass is constructed by taking the leading two lepton pairs. At this energy and Higgs mass and with our lepton cuts there are 27 "gold-plated" events (22 from the signal and 5 from the ZZ continuum).

Unfortunately, 16% of the ordinary QCD Z +jets background events that survive the lepton cuts have an opposite hemisphere jet pair meeting the selection criteria. Defining an "enhancement factor" as the percentage of signal ($ZZ \to l^+l^-jj$ channel) divided by the percentage of background surviving this cut, one arrives at an enhancement of 0.71/0.16 or about 4. One might have expected to do better at this stage. However, once we required that the Z boson 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.

C. Invariant mass cuts

The invariant mass M_{jj}(full) is constructed by using the full jet pair defined in Table I(b) and illustrated in Fig. 1. In particular one uses all cells within a "distance" R(halo) of either of the jet cores. The aim here is, of

TABLE II. 800 GeV Higgs boson$\to ZZ$ signal and the "ordinary" QCD Z +jets background at the SSC energy of 40 TeV. Results are given (a) without and (b) with jet-jet profile cuts. The enhancement factor is defined to be the percentage of signal ($ZZ \to l^+l^-jj$ decay mode) divided by the percentage of background surviving a given set of cuts.

(a) Signal and background without jet-jet profile cuts

	Higgs$\to ZZ$ signal			Z +jets background		
Selection or cut	$ZZ\to$all events/year	$ZZ\to$all fraction	$ZZ\to lljj$ fraction	SSC events/year	fraction	Higgs$\to lljj$ enhancement
Lepton cuts	903	100%	100%	114 662	100%	1
Jet pair selection without profile cuts	468	52%	71%	18 490	16%	4
Z-mass cut 81–101 GeV	295	33%	44%	2809	2.5%	18
Higgs mass cut 650–950 GeV	245	27%	37%	1162	1.0%	37

(b) Signal and background with jet-jet profile cuts

	Higgs$\to ZZ$ signal			Z +jets background		
Selection or cut	$ZZ\to$all events/year	$ZZ\to$all fraction	$ZZ\to lljj$ fraction	SSC events/year	fraction	Higgs$\to lljj$ enhancement
Lepton cuts	903	100%	100%	114 662	100%	1
Jet pair selection with profile cuts	158	17%	25%	1050	0.92%	27
Z-mass cut 81–101 GeV	127	14%	19%	151	0.13%	146
Higgs mass cut 650–950 GeV	106	12%	16%	56	0.049%	326

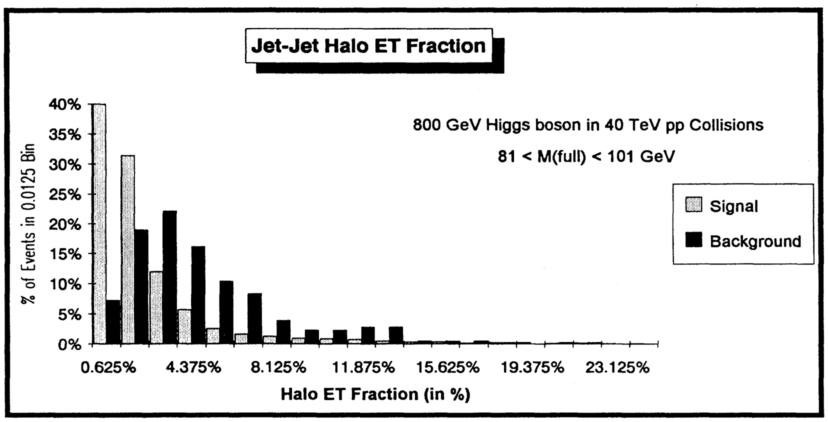

FIG. 2. Shows the fraction of transverse energy within the jet-jet halo region, $F_{E_T} = E_T(\text{jet-jet halo})/E_T(\text{full jet-jet})$, for the Higgs signal ($l^+l^-jj$ mode) and for the Z+jets background. Both signal and background have passed the lepton cuts, the jet pair selection, and have $81 < M_{jj}(\text{full}) < 101$ GeV.

course, to reconstruct the invariant mass of the Z boson. However, this full jet-jet invariant mass will *only* be used in the event selection. The Higgs mass will be reconstructed by setting $M_{jj} = M_Z$. At this stage, events are rejected unless the full jet-jet mass satisfies

$$81 < M_{jj}(\text{full}) < 101 \ .$$

Similarly, the leading lepton pair invariant mass M_{ll} must satisfy

$$81 < M_{ll} < 101 \ .$$

As can be seen from Table II(a), about 33% of the Higgs events in the full $ZZ \to$all mode and 45% of the $ZZ \to l^+l^-jj$ channel passing *both* the lepton cut and the jet pair selection have M_{jj} within 10 MeV of the Z boson mass. For the $ZZ \to l^+l^-jj$ Higgs channel, about 63% of the jet pairs have a mass in this range. On the other hand, only about 15% of the background jet pairs have a mass in this range. About 2.5% of the QCD Z+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 Z boson mass. This corresponds to an enhancement factor of about 18.

D. Reconstructing the Higgs mass

The Higgs invariant mass is constructed from the momentum vectors of the two charged leptons and the momentum vector of the jet-jet pair as follows:

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

where

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

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 mass we use the momentum vector of the jet-jet pair but *not* the jet-jet pair mass. The mass of the jet-jet pair is set equal to the mass of the Z boson.

At this stage, there are 245 Higgs events and 1162 QCD background events per year at the SSC within 150 GeV of the true Higgs mass of 800 GeV, corresponding to an enhancement factor of about 37 [see Table II(a)]. There is also an unavoidable contribution from the ZZ continuum of about 24 events per year *(not shown in Table II)*. With this enhancement, the Z+jets background is still roughly 5 times the signal.

III. JET-JET PROFILE ANALYSIS

Our profile analysis of the jet-jet system is accomplished by examining the "bipolar" regions shown in Fig. 1. The jet-jet system is divided into three regions. The

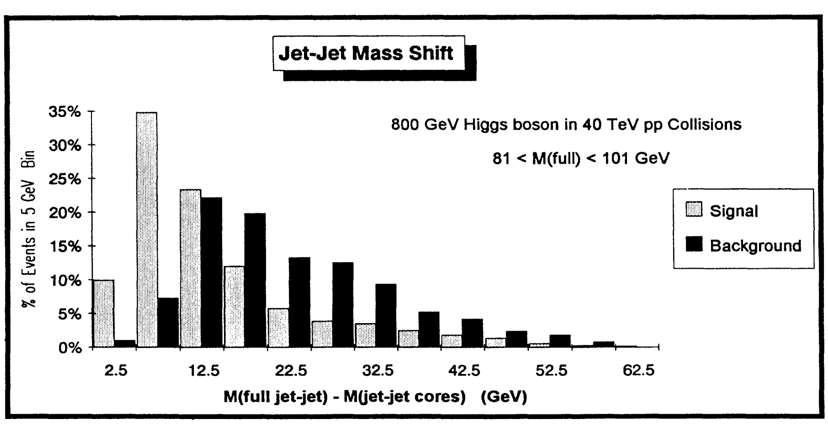

FIG. 3. Shows the mass shift, $\Delta M = M(\text{full jet-jet}) - M(\text{jet-jet cores})$, for the Higgs signal ($l^+l^-jj$ mode) and for the Z+jets background. Both signal and background have passed the lepton cuts, the jet pair selection, and have $81 < M_{jj}(\text{full}) < 101$ GeV.

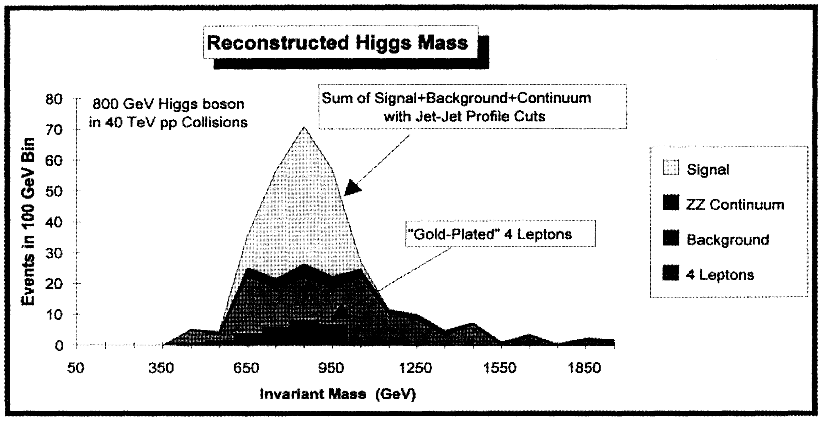

FIG. 4. Shows the reconstructed Higgs mass of an 800 GeV Higgs boson produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events in a 100 GeV bin per SSC year for the *sum* of the Higgs signal, the ZZ continuum, and the Z +jets background that survive the lepton cuts and the jet-jet pair selection *with* jet-jet profile cuts. For comparison, the "gold-plated" $l^+l^-l^+l^-$ events passing the lepton cuts are also shown.

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* doubled 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 Z boson in the decay of the Higgs signal and the jet pairs that result from gluon bremsstrahlung from the recoil parton in large P_T single Z production (i.e., the background).

In this analysis we use the following two observables to distinguish signal from background. The first 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 and mass, respectively, are deposited around the jet-jet cores.

Figure 2 shows the halo E_T fraction for the Higgs signal and the Z +jets background for events that have survived the lepton cuts, the jet pair selection, and have $81 < M_{jj}(\text{full}) < 101$ GeV. The background clearly has 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 Z +jets background than in the Higgs signal. For the signal, the jet pair arise from the $q\bar{q}$ decay of a large transverse momentum Z boson. The Z 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 Z background are not color singlets and produce addition gluons via bremsstrahlung. These radiated gluons deposit transverse energy around the jet-jet cores. Furthermore, the two jets in the signal originate from a $q\bar{q}$ pair, whereas the background is usually a quark-gluon pair or an antiquark-gluon pair. 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 Z bosons are $qg \to Zq$ (55%) and $\bar{q}g \to Z\bar{q}$ (37%). The away-side recoil quark or antiquark radiates a gluon yielding a quark or antiquark plus a gluon. However, a gluon produces more gluon radiation than a quark or antiquark resulting in a different jet-jet profile for the background qg or $\bar{q}g$ system relative to the signal $q\bar{q}$ system.

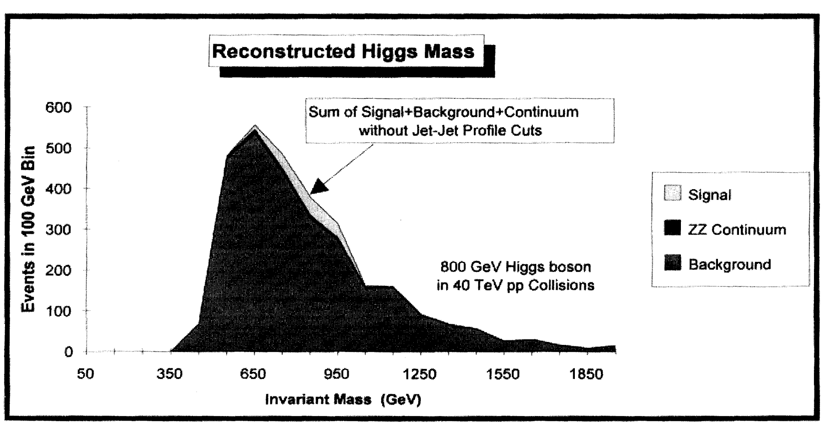

FIG. 5. Shows the reconstructed Higgs mass of an 800 GeV Higgs boson produced in proton-proton collisions at the SSC energy of 40 TeV. The plot corresponds to the number of events in a 100 GeV bin per SSC year for the *sum* of the Higgs signal, the ZZ continuum, and the Z +jets background that survive the lepton cuts and the jet-jet pair selection *without* jet-jet profile cuts.

Figure 3 shows the mass shift ΔM for the Higgs signal and the Z +jets background for events that have survived the lepton cuts, the jet pair selection, and have $81 < M_{jj}(\text{full}) < 101$ GeV. On the average, the mass shift is larger for the background. The background has 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 are important observables for differentiating signal from background.[1] They can be used together to preferentially select the signal over the background.

A. Profile cuts

One can make cuts on the halo E_T and the mass shift in a variety of ways. In our large paper [3], we discuss the optimization of these cuts. Here we illustrate the power of profile cuts by taking

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

The result of making these cuts is shown in Table II(b). Now, there are approximately 106 Higgs events and 56 QCD background events per year at the SSC within 150 GeV of the Higgs mass (and 10 events from the ZZ continuum). This corresponds to an overall enhancement factor of around 300, and is about a factor of 8 better than without jet-jet profile cuts. Of course, the signal has been reduced by more than 50%. On the other hand, one does not need to cut as hard as we have done here. Furthermore, jet-jet profile cuts can be used in conjunction with other cuts, such as forward jet tagging [5], and cuts that make use of the longitudinal polarization of the Z bosons coming from Higgs decay [6].

Figure 4 shows the reconstructed Higgs mass of an 800 GeV Higgs boson produced in proton-proton collisions at the SSC energy of 40 TeV after the jet-jet profile cuts have been employed. The plot corresponds to the number of events in a 100 GeV bin per SSC year for the *sum* of the Higgs signal, the ZZ continuum, and the Z +jets background. The contribution to the sum from the signal and the background are shown by the light and dark shaded regions, respectively, with the hatched area representing the ZZ continuum contribution. As a result of all the cuts, the background peaks in the mass region from 650 to 1150. Nevertheless, the signal shows up as a peak above the background and with a rate that is still about 5 times that of the "gold-plated" $l^+l^-l^+l^-$ mode. For comparison, Fig. 5 shows the reconstructed Higgs mass *without* jet-jet profile cuts.

[1]By studying the effect of both profile cuts on the *same* region about the jet-jet centers, we have verified that these cuts are significantly different [3].

IV. SUMMARY AND CONCLUSIONS

We have devised a method that can help 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. Two observables are defined that measure how transverse energy and mass, respectively, are distributed around the jet-jet system. The procedure can be summarized by the following series of selections and cuts: lepton pair trigger; jet pair selection; jet-jet profile cuts; jet-jet invariant mass cuts. The invariant mass of the jet-jet pair is used *only* in the selection of events; the Higgs mass is reconstructed from the momentum of the jet pair with M_{jj} set equal to M_z. We are able to obtain signal to background enhancements greater than 100. With enhancements this large, the Higgs boson stands out in the invariant mass plot as a definite peak over the background (see Fig. 4). The method works equally well for 600 GeV Higgs boson and we are currently studying Higgs masses of 200 and 400 GeV [3].

Jet-jet "shape cuts" have been considered previously. The two which are most similar to our method are the "elongation" of the jet pair and the χ^2 shape [7]. However, jet-jet profile cuts 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.

Hadronic multiplicity cuts [8] rely upon the same difference of color structure between signal and background. However, observation of hadronic multiplicity requires a high performance silicon μstrip tracker [9]. The final design status of this component of the SSC detectors, and its final performance at the SSC, is not clear [1,2]. Furthermore, hadronic multiplicity is not estimated reliably by the Monte Carlo event generators and depends on the jet fragmentation model employed [10].

We believe that further improvements in enhancing the Higgs boson$\to ZZ \to lljj$ signal over the Z +jets background can be made by combining jet-jet profile cuts with other "orthogonal" cuts such as forward jet tagging [5], and cuts that make use of the longitudinal polarization of the Z bosons from Higgs decay [6]. Also, we think we can improve on the jet pair selection criteria [3]. Furthermore, our method also works for W bosons and should help clean up the Higgs boson$\to WW \to l\nu jj$ signal as well.

ACKNOWLEDGMENTS

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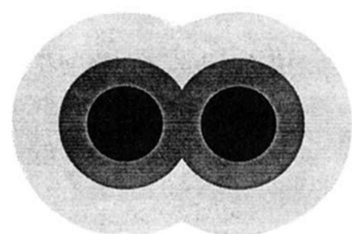

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