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Brief Reports

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Improving the heavy-Higgs-boson two-charged-lepton–two-neutrino signal

V. Barger and T. Han
Physics Department, University of Wisconsin–Madison, Madison, Wisconsin 53706

R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England
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If the Higgs scalar boson H^0 has a mass greater than 600 GeV, severe difficulties have been foreseen in identifying it in pp collisions at the Superconducting Super Collider. We show that the $H^0 \to ZZ$ signal, with one $Z \to l^+l^-$ and one $Z \to \nu\bar{\nu}$ decay, can be separated from background by selecting events with l^+l^- at the Z mass plus large missing p_T plus two jets. This signal is enhanced by using an improved transverse-mass variable.

The Higgs scalar boson H^0 is a central element of the standard $SU(2) \times U(1)$ electroweak gauge model, related to the mechanisms of symmetry breaking and particle mass generation. Its discovery remains a challenge for the future.[1] For masses $m_H > 200$ GeV, the decay modes $H^0 \to W^+W^-, Z^0Z^0$ dominate and the leptonic decays $Z^0 \to l^+l^-$ ($l = e$ or μ) provide a very distinctive signature, enabling Higgs-boson events to be cleanly separated from background up to $m_H \simeq 600$ GeV in pp collisions at the Superconducting Super Collider (SSC). Thereafter, however, Higgs-boson detection becomes much more difficult. As the Higgs-boson production decreases, the $H \to ZZ \to (l^+l^-)(l^+l^-)$ events become too few for a luminosity of $10^{33}/\text{cm}^2\text{sec}$ and other decay channels must be studied instead. It has been proposed[2] to look for $H \to ZZ \to (l^+l^-)(\bar{\nu}\nu)$ events, which have at least six times larger branching fraction, by selecting events with a lepton pair plus missing p_T; such Higgs-boson events would peak versus transverse-mass[2] or an improved transverse-mass variable.[3] Unfortunately a large background can arise from single $Z \to l^+l^-$ events where missing p_T comes not from neutrinos but from hadrons that escape detection down the beam pipes; this background threatens to swamp the $H \to ZZ \to (l^+l^-)(\bar{\nu}\nu)$ signals[2,3] and make the heavy Higgs boson impossible to find. It therefore becomes imperative to find ways of removing this background, and a transverse-energy cut has been suggested in Ref. 4.

In this paper we propose alternative ways to rescue the $H \to ZZ \to (l^+l^-)(\bar{\nu}\nu)$ signal at the SSC for heavy Higgs bosons with

$$600 \text{ GeV} < m_H < 1000 \text{ GeV} \qquad (1)$$

by refining the event-selection criteria and using the improved transverse-mass variable.[3] We first remark that in this mass range the dominant Higgs-boson production subprocess is (i) heavy-boson fusion:[5] $W^+W^- \to H$, $ZZ \to H$. Other contributing subprocesses are (ii) gluon fusion:[6] $gg \to$(heavy-quark loop)$\to H$, and (iii) gluon fusion with real heavy quarks:[7] $gg \to Ht\bar{t}$; but if $m_t \sim 50$ GeV, (ii) is dominant only for $m_H < 400$ GeV and (iii) is not expected to be significant.[1,7]

The crucial observation now is that each of the heavy bosons participating in mechanism (i) is made from an incident quark q by a hard transition $q \to Wq'$ or $q \to Zq'$, where the recoiling quarks q' will typically lead to jets. Thus the dominant Higgs-boson production process is typically accompanied by two (or more) high-p_T jets, especially if we require H itself to have high p_T. The same is not true for the most dangerous background process $pp \to ZX$ where missing p_T arises from beam-pipe hadrons.[4] We can therefore effectively suppress this background by selecting events with two jets,[8] in addition to a high-mass l^+l^- pair and missing p_T. We can simultaneously enhance the Higgs-boson signal by using the improved transverse-mass variable defined in Ref. 3. In the following we present detailed realistic calculations of the Higgs-boson signal and the backgrounds in a conceivable SSC experiment, to demonstrate that the signal can indeed be rescued for the mass range of Eq. (1).

We calculate H production in pp collisions at $\sqrt{s} = 40$ TeV from subprocesses (i) and (ii) above, folded with Eichten-Hinchliffe-Lane-Quigg (EHLQ) parton distributions,[9] including initial- and final-state QCD radiation plus fragmentation to realistic hadrons by adapting the PYTHIA 4.8 Monte Carlo program.[10] This program includes a calorimeter simulation, for which we take cells of size $\Delta\eta=0.05$, $\Delta\phi=0.05$, and a Gaussian smearing of energy within each cell with standard deviation $\sigma=0.5(E)^{1/2}+0.02E$ with E in GeV. The Higgs-boson production mechanism (i) is based on the s-channel pole only, but the resulting ZZ mass distribution within two widths around m_H is very close to that obtained including the Higgs-boson-exchange contribution.[11]

We also use PYTHIA to calculate the principal backgrounds arising from

$$pp \to Z_1+2 \text{ jets} , \tag{2a}$$

$$pp \to Z_1Z_2+2 \text{ jets} , \tag{2b}$$

with $Z_1 \to l^+l^-$ and $Z_2 \to \nu\bar{\nu}$. Missing p_T comes primarily from $Z \to \nu\bar{\nu}$ in the latter case and from beam-pipe hadrons in the former case. The jets are generated from initial and final partons. Jets are defined as clusters of hadronic energy falling within cones:

$$(\Delta R)^2=(\Delta\eta)^2+(\Delta\phi)^2 \le 0.5 , \tag{3}$$

where $\eta=\ln\cot(\theta/2)$ is the pseudorapidity, with θ the polar angle relative to the beam axis and ϕ the azimuthal angle. We assume the size of the beam-pipe aperture (within which all final hadrons are unmeasured) to be $\eta_B>5.0$. For background calculations we generate 5×10^5 events.

We select events containing a high-mass l^+l^- pair (results are summed over e^+e^-, $\mu^+\mu^-$) plus missing p_T (denoted $\not{p}_T$) plus two jets, with the following acceptance cuts: (i) $p_T(\text{jet})>20$ GeV, $\eta(\text{jet})<5.0$; (ii) $p_T(l^\pm)>20$ GeV, $\eta(l^\pm)<5.0$; (iii) $|m(l^+l^-)-M_Z|<10$ GeV; (iv) $p_T(l^+l^-)>300$ GeV; (v) $\not{p}_T>50$ GeV.

The l^+l^- invariant-mass cut (iii) is a formality, since both the signal and the principal backgrounds contribute only via $Z\to l^+l^-$. The $p_T(l^+l^-)$ cut (iv) helps to suppress the backgrounds of Eqs. (2a) and (2b) at little cost to the signal for $m_H \ge 800$ GeV but it reduces the signal for $m_H \sim 600$ GeV by a factor of 2–3. We use throughout cut (iv) for the sake of clarity and simplicity of both theoretical and experimental analysis. In principle, one could enhance the signal for $m_H \sim 600$ GeV by relaxing the $p_T(l^+l^-)$ cut to 200 GeV [and suppress backgrounds effectively by a more stringent $\not{p}_T$ cut or $p_T(jj)$ cut]. The choice of $\not{p}_T$ cut in (v) has little effect on the Higgs-boson signal but greatly reduces the background of Eq. (2a).

Figure 1(a) shows the resulting $\not{p}_T$ distribution of the signal with $m_H=600$, 800, 1000 GeV, compared with the backgrounds. The Higgs-boson signal is clearly distinguishable in this plot, throughout the mass range of Eq. (1). It is clear that the background can be further suppressed, with little cost to the signal, by making the $\not{p}_T$ cut in (v) more severe.

Figure 1(b) gives the $\not{p}_T$ distributions in which the two-jet trigger has not been imposed.[4] In this calculation observed particles are required to have $|\eta|<5$. Comparison of Figs. 1(a) and 1(b) shows that the two-jet trigger substantially improves the signal to background.

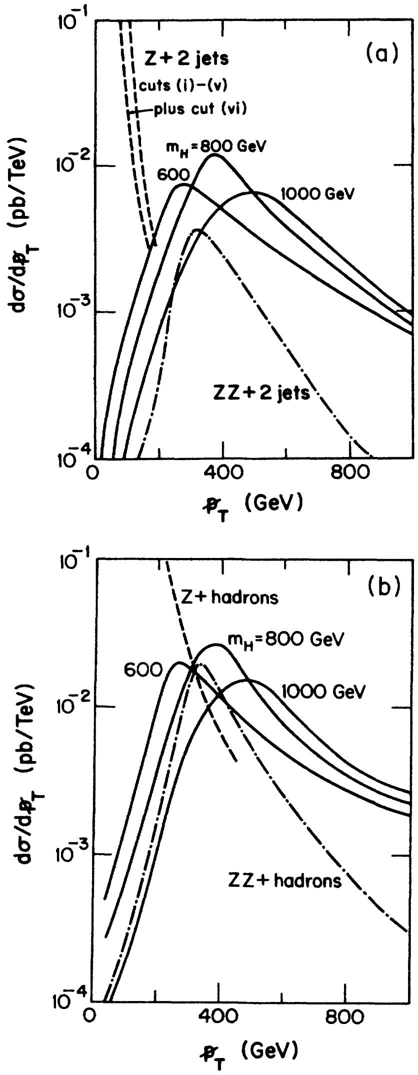

FIG. 1. (a) Predicted missing-p_T distribution of the Higgs-boson signal and backgrounds in pp collisions at $\sqrt{s}=40$ TeV. Cases $m_H=600$, 800, 1000 GeV are shown, for cuts (i)–(v) described in the text. The effect on the background of cut (vi) is also shown. The signal is denoted by solid curves, the background of Eq. (2a) by dashed curves, and the background of Eq. (2b) by a dashed-dotted curve; the signal and the background of Eq. (2b) are not sensitive to variations in the cuts. (b) Same results as in (a) except that the two-jet trigger is not imposed; an $|\eta|<5$ acceptance is required for observed particles.

Figure 2 shows the Higgs-boson signals and backgrounds versus the vector sum of the two-jet transverse momenta, denoted $p_T(jj)$, which for the signal is essentially $p_T(H)$. We see that the background of Eq. (2a) typically gives much larger $p_T(jj)$ than the signal; this may be understood as a result of cut (iv) on $p_T(l^+l^-)$, which is easily satisfied by the Higgs-boson process but makes extreme demands on the background.

As we expect from the results in Fig. 1, choosing a

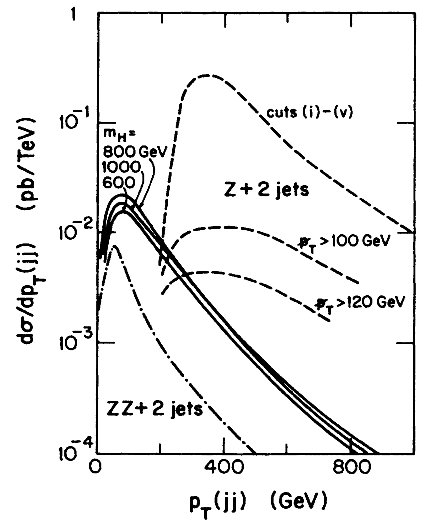

FIG. 2. Predicted distribution of Higgs-boson signal and backgrounds versus $p_T(jj)$. The effects on the background of alternative cuts $\not p_T > 100$ GeV and $\not p_T > 120$ GeV are shown; the Higgs-boson signal and the background of Eq. (2b) are essentially the same in both cases.

stronger $\not p_T$ cut suppresses the background further. Henceforth we impose $\not p_T > 100$ GeV or $\not p_T > 120$ GeV in our illustrations; we could choose $\not p_T > 200$ GeV and entirely eliminate the background of Eq. (2a) without hurting the signal appreciably. Instead of a requirement of large $\not p_T$, we could make a cut (vi) $p_T(jj) < 300$ GeV. This is a conservative choice, to illustrate the power of such a cut. Figure 2 shows that a more radical choice such as $p_T(jj) < 200$ GeV would essentially remove the background of Eq. (2a) completely.

Figure 3 shows distributions versus the one-body transverse-mass variable of Ref. 2:

$$[M_T(Z_1)]^2 = 4(p_T^2 + M_Z^2)\ , \tag{4}$$

where $Z_1 \to l^+l^-$ and $p_T = p_T(l^+l^-)$. With the cuts (i)–(v) the background remains above the signal. A more severe $\not p_T$ cut, as pointed out above, helps to further reduce the background below the signal.

Figure 4 shows signal and background distributions versus the two-body transverse-mass variable of Ref. 3 defined by

$$[M_T(Z_1,Z_2)]^2 = [(p_T^2 + M_Z^2)^{1/2} + (\not p_T^2 + M_Z^2)^{1/2}]^2 - (\mathbf{p}_T + \not\mathbf{p}_T)^2\ , \tag{5}$$

where $p_T = p_T(l^+l^-)$. The peaks versus this variable are much sharper and the background of Eq. (2a) is suppressed, because information from the missing neutrinos has been exploited[3] and the signal for $m_H \geq 600$ GeV is cleanly separated from the background.

The results given above are not very sensitive to the η(lepton) acceptance cut, and a value η(lepton) < 3 can be employed. The results are, however, sensitive to the choice of the η(jet) acceptance cut. Our techniques for suppression of the background relative to the signal can still be applied with an η(jet) ≤ 4 acceptance cut, provided that more stringent $\not p_T$ or $p_T(jj)$ cuts are imposed [e.g., $\not p_T > 200$ GeV or $p_T(jj) < 200$ GeV].

Finally, based on the results in Fig. 4, we give the expected numbers of events of both signal and backgrounds in Table I, for an integrated luminosity 10^4 pb^{-1} (one year of SSC running). We integrate both signal and backgrounds over two full widths of H.

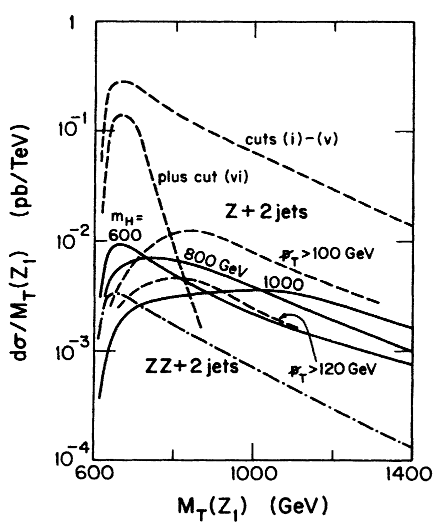

FIG. 3. Predicted distribution of Higgs-boson signal and backgrounds vs the one-particle transverse mass $M_T(Z_1)$ of Eq. (4), for cuts (i)–(v). The effects on the background of cuts $\not p_T > 100$ GeV, $\not p_T > 120$ GeV, and cut (vi) are also shown.

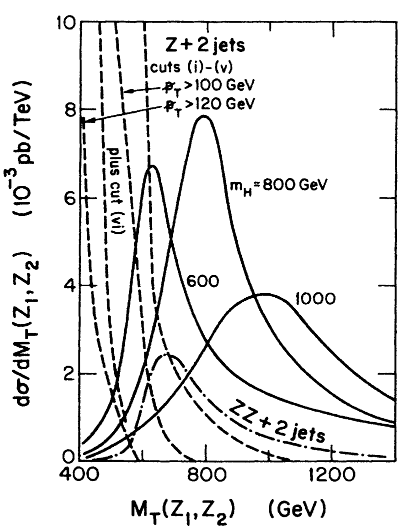

FIG. 4. Predicted distribution of Higgs-boson signal and backgrounds vs the two-particle transverse mass $M_T(Z_1,Z_2)$ of Eq. (5), for cuts (i)–(v). The effects on the background of cuts $\not p_T > 100$ GeV, $\not p_T > 120$ GeV, and cut (vi) are also shown.

TABLE I. Predicted event numbers for Higgs-boson signal and background at $\sqrt{s}=40$ TeV for integrated luminosity 10^4 pb^{-1} and acceptance cuts (i)–(iv) and $\not{p}_T > 120$ GeV.

m_H (GeV)		600	800	1000
Integrated range of M_T (GeV)		550–750	600–1100	700–1500
Number of events	Signal	11	24	21
	Background	4	7	5

We conclude that the heavy-Higgs-boson $H \to ZZ \to (l^+l^-)(\bar{\nu}\nu)$ signal can indeed be rescued at the SSC, for the mass range in Eq. (1) by imposing more stringent event selection and cuts than in previous analyses.[2–4] In particular, a combination of $p_T(l^+l^-)$, $\not{p}_T$, and/or $p_T(jj)$ cuts can essentially remove the background completely. The use of the two-body transverse-mass variable of Eq. (4) leads to sharper peaks and cleaner separation of signals than other variables commonly considered. All these considerations presuppose of course that a suitably versatile detector is constructed.

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