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STANDARD ELECTROWEAK INTERACTIONS AND HIGGS BOSONS*

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1. Introduction

Much of the physics focus of the first Snowmass Summer Study was in testing the standard model,[1] delineating the properties[2] of the W and Z, of the Higgs boson[3] and exploring ways to produce and detect it.[4] Not only has this subject been well examined in the literature before and after, but in the period between meetings the W and Z have been found[5,6] and this workshop was treated to the news of the first evidence for the existence of the t quark.[7]

In the standard model, only one basic component remains to be found: the Higgs boson. As already noted[3,4], this subject was addressed previously, and the questions of cross sections and backgrounds for production of the standard Higgs at SSC energies have also been treated,[8] especially when the primary decay is to W or Z pairs.

However, the specifics of Higgs boson production and detection, with decay to $t\bar{t}$ and a particular t quark mass range in mind, have not been examined in detail. As such, the working group on Standard Electroweak Interactions and Higgs Bosons at this meeting decided to concentrate on Higgs boson production and detection at SSC energies in the particular case where the Higgs mass is in the range so as to make $t\bar{t}$ quark-antiquark pairs the dominant decay mode. The study of this case, that of the so-called "intermediate mass Higgs," had already been launched[9] in the Berkeley PSSC Workshop on Electroweak Symmetry Breaking, and was continued and extended here. The problems of t quark jet identification and detection efficiency and the manner of rejection of background (especially from b quark jets) with realistic detectors then occupied much of the attention of the group.

In the next section we examine briefly the subject of making precise measurements of parameters in the standard model at SSC energies. Then we delve into the Higgs sector, with an introduction to the neutral Higgs of the standard model together with its production cross-sections in various processes and the corresponding potential backgrounds. A similar, though briefer, discussion for a charged Higgs boson (outside the Standard Model) follows in Section IV. The heart of the work on identifying and reconstructing the t and then the Higgs boson in the face of backgrounds is found in Section V. Here the problems with semileptonic decays, low energy jet fragments, mass resolution, and b-t discrimination all come to the fore. We have tried to make a serious step here towards a realistic assessment of the problems entailed in pulling a signal out of the background, including a rough simulation of calorimeter-detector properties. Many of the details are found in the individual contributions to these proceedings, to which we refer as we proceed.

2. Precision Measurement of Parameters in the Standard Model

To a large extent the parameters of the standard model are capable of being well measured at much lower energy machines than the SSC. For quark and lepton masses (proportional to Higgs boson couplings) and weak mixing angles, this is obviously the case. The W and Z masses are accessible to measurement now with an accuracy of order one percent, and the Z mass can be measured to a small fraction of a percent at the e^+e^- colliders now being built. The coupling of gauge bosons to leptons and quarks enters all low energy weak processes. All measurements are consistent within errors with the standard model, and when translated to a value for $\sin^2\theta_W$, they result in $\sim 10\%$ accuracy for this quantity.[10] Very precise measurements of the coupling of the Z^0 to leptons and quarks are possible at LEP and especially at SLC with its longitudinally polarized electron beam (measurement of $\sin^2\theta_W$ to 1% or better).

What is less clear is what will be the state of our knowledge of the gauge boson couplings to themselves in the SSC era. LEP II will have access to information on the triple gauge boson couplings by measurements of $e^+e^- \rightarrow W^+W^-$. Hadron colliders can measure $\bar{q}'q \rightarrow W\gamma$ and thereby provide a measurement of the $WW\gamma$ vertex. The question is: with what accuracy can this be done?

The question can be made more definite by defining a W boson magnetic moment:

$$\mu_W = \frac{e}{2M_W}(1+\kappa) \tag{1}$$

where κ, the anomalous magnetic moment has the value unity in the standard model. As the higher order corrections to κ are of order $\alpha = 1/137$ in the standard model, any deviation from unity larger than this indicates new physics. Furthermore, in the angular distribution for $\bar{q}'q \rightarrow W\gamma$ there is an exact zero[11] at $\cos\theta_{q\gamma} = -1/3$ in the pure gauge theory ($\kappa = 1$). The zero in the angular distribution is lost when $\kappa \neq 1$, apparently providing a clear test of the gauge theory nature of the coupling. However, even for $\kappa = 1$ there will be only a dip rather than a zero in the angular distribution if one does not know the direction of the incoming quark from that of the antiquark, as in pp scattering or in $\bar{p}p$ when sea quarks are involved. Further, the dip can be filled in by experimental background, thereby simulating a deviation from $\kappa = 1$.

The accuracy with which a high luminosity pp collider could determine κ was studied previously, with the conclusion[12] that $\Delta\kappa = \pm 1$ was feasible at 0.8 TeV. With the discovery of the W and Z, the question of experimental feasibility of measuring κ at CERN (and at TEV I) was reopened.[13]

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In particular, the potentially severe background[14] from production of $W+$ jet, where the jet fakes a single γ, was estimated.

The whole question was reexamined for SSC energies by Matsuda and Owens.[15] Even with cuts and a factor 10^{-3} rejection of jets masquerading as photons, the background is larger than the signal for $\kappa = 1$ and, most unfortunately, tends to fill in the dip in the angular distribution which is the main handle for discriminating among values of κ, e.g. a small (and presumably indistinguishable from signal) amount of background changes the angular distribution from that associated with $\kappa = 1$ to that associated with $\kappa = 0$. Thus, while this process is likely observable at the SSC (as well as at lower energies), it seems unlikely to be able to provide us with the precision necessary for a meaningful test of the standard model.[15]

3. Neutral Higgs-Properties and Cross Sections

For Higgs boson masses below ~ 90 GeV, the likely mode of discovery is in the processes $e^+e^- \to Z \to H^0\ell^+\ell^-$ or $e^+e^- \to (t\bar{t}) \to \gamma H^0$ at SLC or LEP I for the lower part of the mass range and $e^+e^- \to Z^0H^0$ at LEP II for the upper part of the mass range.[8,9] At the other extreme, when $M_H > 2M_W$ the Higgs boson primarily decays into W^+W^- (and possibly Z^0Z^0). It is produced in hadron collisions by gluon fusion,[16] $gg \to H^0$, or by WW and ZZ fusion,[17] $W^+W^- \to H^0$ and $ZZ \to H^0$. The latter process becomes more important for very large Higgs masses. A "heavy" Higgs would be discovered, if at all, at hadron colliders, depending on our ability to detect and identify W bosons. The production cross sections for a "heavy" Higgs decaying to WW or ZZ and the possibilities of identifying a resulting signal have been fairly thoroughly discussed for SSC energies.[8,9]

A more problematic region of masses is 90 GeV $\lesssim M_{H^0} < 2M_W$, the so-called "intermediate mass" region. Here the primary decay will be to $t\bar{t}$ with a width of

$$\Gamma(H^0 \to t\bar{t}) = \frac{3G_F m_t^2 M_H}{4\pi\sqrt{2}} \left(1 - \frac{4m_t^2}{M_H^2}\right)^{3/2} . \qquad (2)$$

We are then in a regime where $\Gamma \ll M$ ($\Gamma(H \to t\bar{t}) = 140$ MeV for $M_H = 120$ GeV and $m_t = 45$ GeV). Previous discussions of the possibilities of discovery of a Higgs boson in this mass range were somewhat gloomy.[8,9] With a definite t quark mass range now in mind plus more experience with quark fragmentation and with jets in high energy hadron colliders, we have looked again at this question.

The cross section for Higgs boson production depends on the top quark mass since the amplitude for $gg \to H^0$ involves (in lowest order) a top quark running around the triangle diagram loop. Eichten *et al.*, have recalculated[18] the cross sections for $pp \to H^0 \ldots$ with $m_t = 45\,GeV/c^2$) rather than the value of 30 GeV/c^2 they used previously.[8] For a Higgs mass of ~ 100 GeV/c^2 the $H^0 \to t\bar{t}$ yield increases by about a factor of two, to over a 100 *pb* when the rapidities of both quarks are restricted to lie in the region $|y| < 1.5$. Unfortunately this modest increase in cross section, as well as a decrease in the unavoidable background from $gg \to t\bar{t}$ with $t\bar{t}$ invariant mass $\approx M_H$, does not result in a favorable situation for discovery of such a particle at the SSC. Even with 10% resolution in the reconstructed value of M_H^2, the continuum $t\bar{t}$ background is over two orders of magnitude larger than the signal.[18] If the Higgs boson is to be found in this intermediate mass case, something clever must be utilised to get rid of the background. One route is to go to rare decay modes that are "clean". The danger of course lies in paying too large a price in the cross section times branching ratio for the particular mode in which the search is to be conducted. An example of this is provided by the proposal[19] to look for the intermediate mass Higgs in the decays $H \to WW_V$ or ZZ_V, where the subscript V denotes virtual. To be sure, this was proposed[19] in the context of a world in which $m_t > M_H/2$, so that the otherwise very competitive decay $H \to t\bar{t}$ is nonexistent. However it is worth looking at anyway to get an idea of the rates with which we are contending when we try to go to low background situations.

For a Higgs mass of 130 GeV, WW_V is a $\sim 1\%$ decay mode and ZZ_V is $\sim 0.1\%$ (Remember, we are taking the now experimentally indicated case[7] of $m_t < M_H/2$ for an intermediate mass Higgs, so that $H \to t\bar{t}$ is by far the dominant mode).[19] Since by choice we are dealing with at least one virtual (off mass-shell) W or Z, we cannot use a mass constraint to separate the W or Z from ordinary jets when they decay through hadronic modes. Furthermore the case where W_V or even both W and W_V decay leptonically will be swamped by background. So we seem forced to look at $H^0 \to ZZ_V$ where both gauge bosons decay into pairs of charged leptons. At this stage, the resulting cross section times branching ratio into these particular modes is a few times $10^{-40}\,cm^2$, without making further cuts or taking account of detection efficiencies. We have avoided the high background for $H^0 \to t\bar{t}$, but have no realistically detectable signal.

A more favorable situation,[20] which was considered in some detail in Berkeley[9] and here in Snowmass[21] arises in the production of the H^0 in association with a charged W, i.e. $pp \to W^{\pm}H^0 + \ldots$. In essence we are going to use the $W^{\pm}$ (or Z^0) as a "tag," very much as one uses the Z in $e^+e^- \to Z^0H^0$, but with the much greater mass range available at the SSC.

The cross section for this process at SSC energies is several picobarns if no cut is made on rapidity.[8] Gunion, Kalyniak, Soldate and Galison[21,22] have calculated the cross section with cuts on the W rapidity ($|y_w| < 2$), the H^0 rapidity ($|y_H| < 2$) and the W transverse momentum, $p_T^W > 40\ GeV/c$, to enhance the signal to background ratio and to partially account for acceptance of a reasonable detector. With these cuts (see Fig. 1) they find a cross section[21] for production in association with $W^{\pm}$ of $\sim 2\,pb$ for $M_H = 100\ GeV$ and $\sim 1.2\ pb$ for $M_H = 130\ GeV$. Even with only a leptonic decay trigger for the $W^{\pm}$ we can be considering many hundreds of "tagged" Higgs bosons, given an integrated luminosity of $10^{40}\ cm^2$. The important questions now are those of backgrounds and the efficiency and resolution for detecting the t and $\bar{t}$ quarks from the Higgs decay.

An irreducible background comes from the process

$$\begin{aligned} pp \to W^{\pm} + &g + \ldots \\ &\hookrightarrow t\bar{t} \end{aligned}$$

To beat this, one needs a combination of good mass resolution for the $t\bar{t}$ pair and a low cross section for this particular process. Fortunately this is the case: with 10% resolution in $\Delta M_{t\bar{t}}^2$, this background is a factor of two or more below the signal in the region of Higgs boson masses with which we are concerned. Thus the requirement of "tagging" with a $W^{\pm}$ has greatly improved the signal to background when looking for $H^0 \rightarrow tt$.

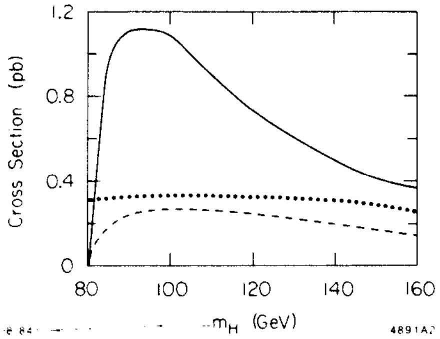

Fig. 1. The cross section[21] for the process $pp \rightarrow W^+ + H^\circ + \ldots$, $H^\circ \rightarrow t\bar{t}$, $|y_w| < 2$, $|y_H| < 2$ and $p_T^W > 40$ GeV/c (solid line) as a function of Higgs mass. The cross sections for the background processes, $pp \rightarrow W^+ + g + \ldots$ where $g \rightarrow t\bar{t}$ (dashed curve) and for $pp \rightarrow W^+ + b + \bar{t} + \ldots$ divided by 100 (dotted curve) are also shown with the same cuts and 10% resolution in mass squared for the $t\bar{t}$ or $b\bar{t}$ quark pair, respectively.

A different kind of background arises from the processes

$$pp \rightarrow W^+ + b + \bar{t} + \ldots , \qquad pp \rightarrow W^- + \bar{b} + t + \ldots ,$$

together with mis-identification of the b or $\bar{b}$ quark jet as a t or $\bar{t}$ quark jet. The calculation of the cross section for this process is quite complicated, but has now been done.[21] With the same cuts as for the signal, and 10% resolution in Δm_{bt}^2, the cross section for this second type of background is 50 times that of the signal. Thus, to be able to pull out the peak in the invariant mass spectrum due to the H^0, we will have to have discriminate b jets from t to roughly the 1% level. While in a general, undefined context this might sound very difficult if not hopeless, in this particular situation we are helped by several factors. First the kinematics, especially the t and H^0 masses, will force the t quarks to have relatively low energy (compared to their mass)—they will often barely be appearing as jets, while the b quark gives rather sharply defined jets in this case. Second (and partly related) the invariant mass of the jets can be used to some degree to separate b from t jets in this kinematic region. Third, there are various cuts on rapidity, $p_\perp^W$, and aplanarity which can also be used to suppress the background.[21] These, plus other considerations on reconstructing the t mass and consequently the H^0 mass, form the central theme of Section 5.

4. Charged Higgs Bosons

While the minimal Higgs sector in the Standard Model involves only one neutral physical particle, there exist many extensions of the minimal $SU(2) \times U(1)$ model in which there are additional Higgs multiplets containing neutral and charged spin 0 bosons which will manifest themselves as physical particles.[23] While the production and decay of the additional neutrals is likely similar to the standard model Higgs, the charged Higgs is sufficiently different to merit separate discussion.

For a charged Higgs boson in the intermediate mass range one would expect $H^+ \rightarrow t\bar{b}$ to be the dominant decay mode inasmuch as it is reasonable to expect the coupling to quarks to be proportional to their masses.[8,23] The heaviest quark pair available then dominates the charged Higgs' decay modes.

The most obvious production mechanism involves a generalization of the Drell-Yan process to charged Higgs bosons:

$$q\bar{q} \rightarrow \gamma, Z \rightarrow H^+ H^- \qquad q\bar{q}' \rightarrow W^+ \rightarrow H^+ H^0 \, .$$

The resulting cross sections have been calculated[18] by EHLQ and are small. For $M_{H^+} = 100\ GeV$ and a central rapidity cut ($|y_H| < 1.5$) they total around 1 pb for H^+ production and drop rapidly with increasing mass.

A much more favorable cross section arises from the subprocess

$$t\bar{b} \rightarrow H^+ \, ,$$

utilizing heavy quarks from the parton-sea. This has also been calculated[18] by EHLQ with a similar cut on rapidity for each of the decay products in $H^+ \rightarrow t\bar{b}$. Here we also need to know a coupling strength and it has been assumed that it is of the same form as that of the neutral Higgs boson, but with m_t as the quark mass (and $m_t = 45\ GeV$ to be specific). In the particular case of models with two Higgs doublets this coupling could be enhanced (or suppressed) by a ratio v_1/v_2 of vacuum expectation values. Without this last factor a cross section for production of a 100 GeV H^+ at the SSC of $\sim$ 10 pb is predicted. This then is the more important production mechanism for a charged Higgs boson at the SSC, even without a possible enhancement from the square of a ratio of vacuum expectation values.

We still must worry about backgrounds. An unavoidable one is continuum $t\bar{b}$ pairs (or $t\bar{b}$, $\bar{t}\bar{b}$, tb) arising from scattering (by gluon exchange) of these same heavy quarks in the parton sea which are responsible for the H^+ production above. However, the cross-sections for this are small,[18] and with 10% resolution in quark pair masses, the signal for $H^+ \rightarrow t\bar{b}$ will be an order of magnitude or more greater[18] than the background (for $M_H = 100\ GeV$). On the other hand, if we lack b-t discrimination and must worry about continuum $t\bar{t}$ or even $b\bar{b}$ pairs produced by gluons, all will be lost. For, as in the case of single production of H^0 with decay to $t\bar{t}$, continuum $t\bar{t}$ pairs with 10% mass resolution are more than three orders of magnitude larger than the signal (and $b\bar{b}$ pairs larger yet). The problem of b-t discrimination then is central to any discussion of the experimental possibilities here, as well as in the neutral Higgs boson case.

5. Identification Of t and b Quark Jets: Reconstruction Of The Higgs Bosons

As pointed out in the preceeding section there appear to be adequate cross sections for searching for charged or neutral Higgs bosons in the intermediate mass region 90 GeV/c^2 $\leq M_H \leq 2M_W$ where the neutral Higgs would decay predominantly into $t\bar{t}$ and the charged Higgs would decay into $t\bar{b}$. For an integrated luminosity of $10^{40} cm^2$ at $\sqrt{s} = 40$ TeV and the most favorable production processes and favorable kinematic regions (see sections III and IV) we would expect $\sim 10^4$ events of the type

$$1)\quad pp \to W^{\pm}\ \underset{\hookrightarrow\, t\bar{t}}{H^0} + \ldots \quad \text{for} \quad M_H^0 = 120\ \mathrm{GeV/c^2}$$

$$\text{with} \quad |y_W| < 2,$$

$$|y_H| < 2,$$

$$\text{and} \quad p_T^W > 40\ \mathrm{GeV/c};$$

and $\sim 10^5$ events of the type

$$2)\quad pp \to \underset{\hookrightarrow\, t\bar{b}}{H^+} + \ldots \quad M_H = 120\ \mathrm{GeV/c^2}$$

$$\text{with} \quad |y_H| < 2.$$

The problem in the detection of these possible Higgs states lies in the identification of t and b jets and the reconstruction with good mass resolution of the Higgs in order to separate the signal from backgrounds.

As mentioned in the previous sections the backgrounds to 1) and 2) come predominantly from continuum $t\bar{t}$ and $t\bar{b}$ production:

Backgrounds to 1)

$$pp \to W + t\bar{t} + \ldots$$

$$\text{and} \quad pp \to W + t\bar{b} + \ldots \text{(with the } b \text{ misidentified as a } t\text{)}$$

Backgrounds to 2)

$$pp \to t\bar{b} + \ldots \text{(from } b,\ t \text{ sea quark scattering)}$$

$$\text{and} \quad pp \to b\bar{b} + \ldots \text{(with the } b \text{ quark jet misidentified as a } t\text{)}$$

With the kinematic cuts imposed on 1) and 2) we expect an irreducible background to a neutral Higgs boson reconstructed with a resolution (FWHM) of ΔM in GeV of $\sim 10^3\ \Delta M$ events from $pp \to W + t\bar{t} + \ldots$ and a background of $\sim 10^5\ \Delta M$ events from $pp \to W + tb + \ldots$ (with no discrimination between t and b jets). For charged Higgs production the background due to $pp \to t\bar{t} + \ldots$ will be $\sim 10^7 \Delta M$ in the absence of discrimination between t and b jets. Therefore if a 100 GeV/c^2 Higgs is measured with $\Delta M = 10$ GeV FWHM, then we need roughly two orders of magnitude discrimination between b and t for a successful search in the case of neutral Higgs bosons and greater than three orders of magnitude discrimination in the case of a charged Higgs. In addition, in the case of a charged Higgs the determination of the charge of the jet-jet system is very difficult since the low energy fragments which determine the net charge will be easy to miss.

In view of these backgrounds the least discouraging search that can be contemplated is the search for a neutral Higgs produced in accompaniment with a W boson and decaying into $t\bar{t}$. No charged Higgs can be easily produced in such an event and therefore the neutral character of the Higgs is determined. We will concentrate in what follows on the difficulty of detection and measurement of $pp \to W + H^{\circ} + \ldots, H^{\circ} \to t\bar{t}$.

The problems in the detection of a Higgs decaying via $t\bar{t}$ above the $t\bar{t}$ and $t\bar{b}$ backgrounds lie in four general areas:

1. Recognition of the W "tag" with good efficiency.
2. Recognition of the t quark jets with good efficiency.
3. Discrimination between t quark jets and b quark or light parton jets to minimize backgrounds.
4. Reconstruction of the quark jets from the fragments in order to reconstruct the mass of the Higgs bosons and observe a signal above residual backgrounds.

There are at least four levels each successively more realistic at which these problems may be considered. First we may ask what can be measured or detected with a perfect detector with 100% efficiency, where all momenta of hadrons, electrons and photons are measured and the association of a particle with a given jet is somehow known. The second level is one where the effect of missing the neutrinos in b and t decay is evaluated from the standpoint of t and b discrimination and $t\bar{t}$ mass resolution. The third level is one in which the problem of sorting out the jet fragments into their respective jets is addressed. The fourth level at which the problem may be considered is one in which the finite energy and angular resolution of a realistic calorimeter is introduced.

Level 1:

With a perfect spectrometer we must first detect the W "tag". The most promising method developed so far is to look for the leptonic decay mode. Trying to search for the two jet decay does not give a definitive enough signature. Assuming 100% efficiency for detection of $W \to \ell\nu$, a 25% branching ratio for leptons leaves 2500 events of the form

$$pp \to \underset{\hookrightarrow\, \ell\nu}{W} + \underset{\hookrightarrow\, t\bar{t}}{H^{\circ}} + \ldots \,.$$

The width of a perfectly measured Higgs is given by its intrinsic width in Eq. (2) and is 140 MeV for $M_H = 120$ and $M_t = 45$ GeV. So with perfect measurement of the jets and perfect discrimination between t and b quarks, the background in a region $\Delta M = 2\Gamma = 280$ MeV/c^2 would be 70 events (taking into account the W branching ratio to leptons) leading to a signal to background ratio of 35/1. Unfortunately, in practice this ideal situation due to the narrow width of the light Higgs is impossible to capitalize on, even with a perfect detector, because of neutrinos.

Level 2:

Even with a detector with perfect energy and angular resolution energy is irrevocably lost through the neutrinos in the cascade decays of the t and b quarks. We have used ISAJET[14] to simulate $H \to t\bar{t}$ and $H \to b\bar{b}$ in the kinematic region indicated above to study this question. In process 1), 40% of the t quarks from Higgs decay have at least one ν among their decay products. This has two effects. First the reconstruction of the t quark mass is worsened and events are lost because the t quark is not recognized as such. The mass spectra for t (and b quarks) and for reconstructed $H \to t\bar{t}$ with perfect resolution is shown in Fig. 2 and Fig. 3 respectively. The number of events remaining in the general "peak" area of the Higgs ($\Delta M \sim 5$ GeV/c^2) is 50% of the original Higgs signal. (16% of all $H \to t\bar{t}$ decays have no neutrinos, as expected from the percentage of t jets with no neutrinos). We conclude that even with a perfect calorimeter only approximately 50% of the Higgs have small enough energy loss (due to neutrinos in their t quark jets) to be reconstructed, and that this signal will have a width of approximately 5 GeV/c^2. This leaves approximately 1250 events over an irreducible background due to $pp \to W + t\bar{t} + \ldots$ of 1250 events (taking into account the W branching ratio to leptons).

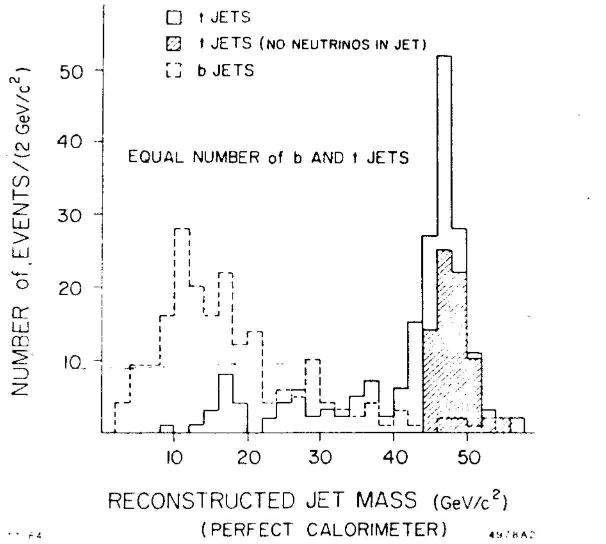

Fig. 2. Distribution of reconstructed jet mass for b and t jets with a perfect calorimeter and the kinematic conditions and cuts in the text relevant to $pp \to W + H^\circ + \ldots$, $H^\circ \to t\bar{t}$. ($m_b = 5$ GeV, $m_t = 45$ GeV).

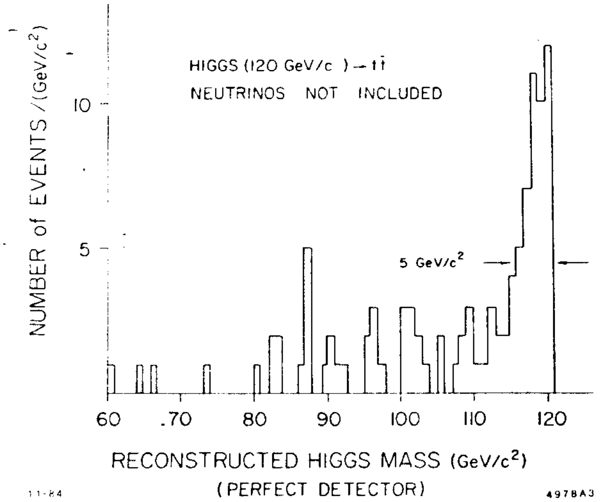

Fig. 3. Distribution of reconstructed Higgs mass when $H^\circ \to t\bar{t}$ with a perfect calorimeter and the kinematic conditions and cuts in the text relevant to $pp \to W + H^\circ + \ldots$, $H^\circ \to t\bar{t}$.

If we examine the other background due to $pp \to W + tb + \ldots$ we must ask how often a b quark jet reconstructs to a t mass in the mass band of the peak whose width is dictated by t decays involving neutrinos. Jets from b quark decay, generated and reconstructed under the same conditions as the t quarks (same kinematic region, perfect detector with only missing neutrinos), are shown in Fig. 2. We find that, due to gluon radiation, there is a tail on the upper side of the b quark jet mass distribution leading to approximately 5% of b quark jets reconstructing to a t quark mass. This misidentification factor (even with perfect detector mass reconstruction and perfect assignment of all jet fragments to appropriate jets) would leave us with a background of 6000 events due to $pp \to W + tb + \ldots$. The sum of the two backgrounds leaves us with a signal to background of approximately 1/6.

Level 3:

If we simulate realistic experimental conditions, the discrimination of t and b jets and the reconstruction of the Higgs degrade further. There are at least three practical difficulties with reconstructing the relatively broad jets from t decay which cause problems in a real experiment.

a) Low energy fragments which must be collected in order to achieve good mass resolution.

b) Recognition of the jet direction and determination of the size of the angular cone which must be used to collect fragments.

c) Effect of misidentification of jet fragments due to the presence of other jets in the reconstruction of the t quark jets (and subsequently the Higgs mass).

These problems have been studied to some extent in Ref. 25. If we take $E = 1$ GeV as the minimum energy fragment which we can detect and include in the construction of a jet, we find that so much of the jet energy is lost that the Higgs signal is almost totally obscured (see Fig. 4).

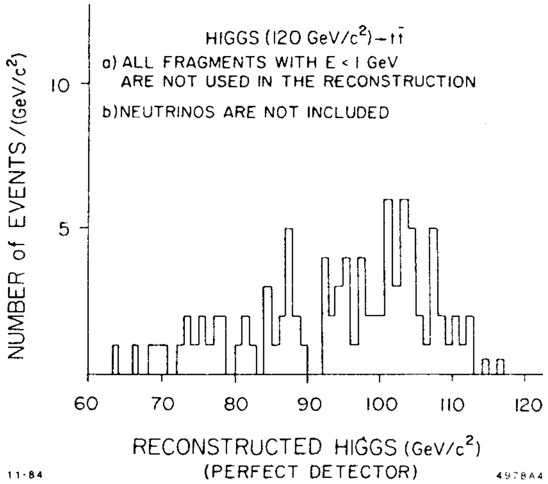

Fig. 4. Distribution of reconstructed Higgs mass when jet fragments with $E < 1$ GeV and neutrinos are not included in the reconstruction with a perfect calorimeter and the kinematic conditions and cuts in the text relevant to $pp \to W + H^\circ + \ldots$, $H^\circ \to t\bar{t}$.

The same sort of loss of signal is experienced if background fragments outside a 90° cone are deleted from the reconstruction (see Fig. 5.). If only fragments whose angle with respect to the jet axis is less than 45° are kept, all indications of the Higgs peak are lost. With these very wide cones required for reconstruction of the Higgs, the overlap of the t quark jets with each other and with other jets is large. Using a conical definition of $\theta < 90°$ as the region for collection of jet fragments, and assigning fragments in the overlap region to the closest t quark jet, we find (if any fragment from any jet in the interaction is allowed to participate) that the Higgs signal is wiped out even if we take all fragments down to zero energy. Thus reconstruction of the Higgs mass becomes very difficult even without real detector resolutions being introduced.

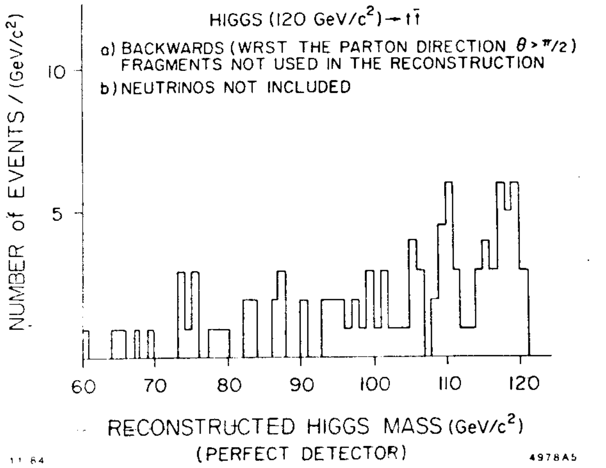

Fig. 5. Distribution of reconstructed Higgs mass when jet fragments outside a 90° cone and neutrinos are not included in the reconstruction with a perfect calorimeter and the kinematic conditions and cuts in the text relevant to $pp \rightarrow W + H^0 + \ldots$, $H^0 \rightarrow t\bar{t}$.

Level 4:

Provided that the very difficult problems associated with sorting and collecting fragments of the t jets can be solved the angular and energy resolutions of a real calorimeter provide a final barrier to detection of an intermediate mass Higgs. While the specific response of a given detector will depend on the details of construction, we have studied the effect of the energy resolution ($40\%/\sqrt{E}$) of a liquid Argon-Uranium detector on the Higgs mass resolution. When this resolution is folded into the reconstruction of a Higgs in a detector which, except for loss of neutrinos, is otherwise perfect (all fragments down to zero energy and at all angles are identified with the correct jet and used in the reconstruction), we calculate the mass resolution for Higgs → $t\bar{t}$ shown in Fig. 6. As can be seen, even with this very good resolution any indication of a Higgs boson peak in the $t\bar{t}$ mass spectrum is almost wiped out.

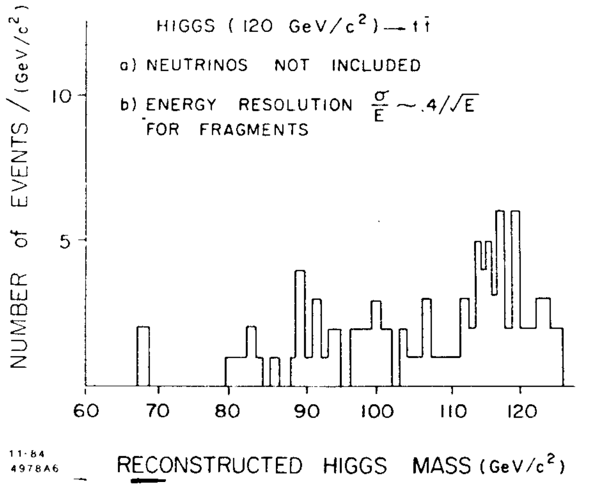

Fig. 6. Reconstructed Higgs mass with calorimeter resolution of $40\%/\sqrt{E}$. All fragments (except neutrinos) at all energies and angles are assumed identified with the correct jet. The kinematic conditions and cuts in the text relevant to $pp \rightarrow W + H^0 + \ldots$, $H^0 \rightarrow t\bar{t}$, are assumed.

Finally if all of the above effects (plus others which we have not considered, such as backgrounds to t quark reconstruction due to gluon jets) occur in combination, it seems unlikely, given the backgrounds that Higgs bosons could be detected from the reconstruction of the $t\bar{t}$ mass spectrum. Other approaches can be taken, such as investigations of the sphericity parameter to try to detect Higgs hadronic decays or to isolate events which might be promising candidates for containing Higgs → $t\bar{t}$ decays. We have not examined these more complex analyses here, so some possibility still remains for intermediate mass Higgs detection.

REFERENCES

1. H. Gordon *et al.*, *Proceedings of the 1982 DPF Summer Study of Elementary Particle Physics and Future Facilities*, Snowmass, June18–July 13, 1982, ed. by R. Donaldson, R. Gustafson and F. E. Paige (American Physical Society, New York, 1983), p. 1, and references therein. We refer to these proceedings as SNOWMASS I.
2. W. J. Marciano and Z. Parsa, SNOWMASS I, p. 155.
3. K. Lane, SNOWMASS I, p. 222.
4. H. A. Gordon *et al.*, SNOWMASS I, p. 161.
5. G. Arnison *et al.*, Phys. Lett. 122B, 103 (1983); M. Banner *et al.*, Phys. Lett. 122, 476 (1983).
6. G. Arnison *et al.*, Phys. Lett. 126B, 398 (1984) and 135B, 250 (1984); P. Bagnaia *et al.*, Phys. Lett. 129B, 130 (1984).
7. Seminars by A. Savoy-Navarro, J. Rohlf, and D. Cline and by C. Rubbia at this meeting.
8. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Fermilab Pub-84/17-T, 1984, to appear in Rev. Mod. Phys. We refer to this work as EHLQ.
9. K. Lane, "The Intermediate Mass Higgs," in these Proceedings.
10. W. J. Marciano, talk presented at the Fourth Topical Workshop on Proton Antiproton Collider Physics, Bern, March 5-8, 1984 and Brookhaven preprint BNL-34728, 1984 (unpublished).
11. K. O. Mikaelian *et al.*, Phys. Rev. Lett. 43, 746 (1979); R. W. Brown *et al.*, Phys. Rev. D20, 1164 (1979); S. J. Brodsky and R. W. Brown, Phys. Rev. Lett. 49, 966 (1982).
12. CBA Physics Update, June 1, 1983, Brookhaven National Laboratory report, 1983 (unpublished).
13. J. Cortes, K. Hagiwara, and F. Herzog, University of Wisconsin preprints MAD/PH/102 and MAD/PH/108 (1983), unpublished.
14. J. Cortes, K. Hagiwara and F. Herzog, University of Wisconsin preprints, MAD/PH/164 and MAD/PH/172, 1984 (unpublished).
15. S. Matsuda and J. F. Owens, "Considerations for the process $pp \rightarrow W\gamma + X$ at the SSC," in these Proceedings.
16. H. M. Georgi *et al.*, Phys. Rev. Lett. 40, 692 (1978).

17. R. N. Cahn and S. Dawson, Phys. Lett. 136B, 196 (1984).
18. E. Eichten *et al.*, "Supplement to EHLQ," in these Proceedings.
19. W.-Y. Keung and W. J. Marciano, Brookhaven preprint BNL-34578, 1984 (unpublished).
20. S. L. Glashow, D. V. Nanopoulos, and A. Yildiz, Phys. Rev. D18, 1724 (1978).
21. J. F. Gunion *et al.*, "Finding an Intermediate Mass Higgs Boson," in these Proceedings.
22. Related work has been done by Z. Kunszt, Bern preprint BUTP-84/10-BERN, 1984 (unpublished).
23. The situation with regard to nonstandard Higgs was reviewed in the Berkeley Workshop: see P. Langacker, "Nonstandard Higgs Bosons," in these Proceedings.
24. F. Paige and S. Protopopescu, ISAJET - version 4.03, July 1984.
25. G. Abrams and B. Cox, "Search for $H^\circ \to t\bar{t}$: t Quark Jet Identification Problems," in these Proceedings.