ELECTRON IDENTIFICATION AND IMPLICATIONS IN SSC DETECTOR DESIGN

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Abstract

In the context of Heavy Higgs searches in the decay mode $H \rightarrow ZZ \rightarrow 4e$, electron identification issues and their implications on detector design are discussed (though many of the issues are valid for muon modes as well). The backgrounds considered seem manageable (a net rejection of 100 for combined electron ID and isolation cut is needed and seems fairly straightforward). A detector must:

1. have wide electron rapidity coverage $\eta < 2.5$ to $3$ and the ability to identify and measure an electron with $p_T > 10$ GeV.
2. be hermetic (in the sense of minimizing regions where electrons can disappear like cracks, dead spaces or poorly placed walls).
3. have high efficiency electron ID ($\sim 0.90$) since we are trying to be sensitive to a feeble signal and we need 4 electrons.

The product of a number of fairly high acceptances based on optimistic estimates still yields in the end a net Higgs acceptance about 0.15 to 0.25 depending on how hermetic a detector is assumed. For $M_{Higgs} < 500$ GeV this may be tolerable whereas for higher Higgs masses, the situation is much less clear.

1 Introduction

One of the important tasks of a general purpose collider detector has been and is expected to be electron identification and reconstruction. As a specific example we examine the Heavy Higgs decay into 4 electrons using the
SSC/Martin Marietta Large Solenoid Detector that employs liquid argon calorimetry. This choice merely serves as a realistic context in which problems of more generic nature can be addressed.

This analysis is partitioned into 3 independent pieces:

1. Physics Cuts - We estimate what can be done with detector independent physical observables such as $P_{T, electron}$ cuts, isolation cuts, $Z$ mass consistency etc.

2. Detector Geometry Cuts - We study the effects of pseudorapidity ($\eta$) or azimuthal cracks in a particular detector design.

3. Electron Identification Cuts - We estimate losses due to cuts necessary to identify electrons with sufficient background rejection.

After deciding on reasonable cuts, we estimate the net Higgs and background acceptance.

Based on an examination of what present day hadron colliders have achieved and calculations using Standard Model monte carlo programs (PYTHIA [1], ISAJET [2]), we find:

1. Electron ID and reconstruction is sensitive to small scale defects of a detector such as walls, cracks, or supports.

2. The effects of these defects are amplified by requirements of multi-lepton signatures (i.e. acceptance $\sim e_4^4$ for the Higgs to 4 electron mode).

Specifically, for the case of a heavy Higgs search in the four electron mode, the definition of a hermetic detector must include the features of highly efficient ($> 0.9$) electron ID, decent hadron rejection ($< 1 \times 10^{-2}$) over a rapidity range about $\pm 2.5$ with dead space much less than 10% if such a search is to be statistically significant for Higgs with mass below 500 GeV. As shown by the rates in Table 3, it appears that it is going to be very challenging to observe a Higgs particle with mass above 500 GeV with the luminosity of $10^{33}/sec/cm^2$ even with very high quality and high efficiency electron detection.
2 Physics Cuts

We focus on the problem of a heavy ($> 2M_Z$) Higgs boson ($M_{top} = 140$ GeV, $M_H = 400$ GeV) search in the $H \to 2Z \to 4e$ mode. In this section we will examine the Higgs acceptance and background rejections under various cuts thus shedding some light on electron identification requirements (electron ID). The signal is:

$$H \to ZZ \to 4e$$

Let us now identify some possible backgrounds ($h$ is a hadron that emulates an electron in the detector):

$$q\bar{q} \to ZZ$$

$$Z + tf \to Z + 2e$$

$$Z + g, q \to Z + (2e \text{ or } e + h = Z_{fake})$$

$$tf \to 4e(= 2Z_{fake})$$

$$3e + h$$

$$2e + 2h$$

As a general strategy, we are trying to reconstruct $Z$ pairs and look at the $ZZ$ mass spectrum. We have a number of physics handles, such as $P_T, \eta, P_T,Z$ and $M_{ee}$ (the invariant mass of the $Z$ candidate). In addition, we have electron isolation where we try to suppress electrons from $b$ and $c$ decays.

2.1 Rates

In order to understand the size of the problem, we tabulate cross sections based on very general cuts and decide what backgrounds seem the most severe. The rates for signal and backgrounds with $P_{T,\text{hard}} > 30$ GeV and $s_{\text{hard}} > 350$ GeV are found in Table 1 where the quantities are the $P_T$ of an outgoing parton and invariant mass squared in the hard scattering frame. Candidates for the Higgs ($M_H = 400$ GeV) have to more or less pass these cuts though we will not explicitly cut on these variables.
<table>
<thead>
<tr>
<th>process</th>
<th>mode</th>
<th>$\sigma$ (mb)</th>
<th>$\sigma \cdot$ BR (mb)</th>
<th>Evt./yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$4e$</td>
<td>$1.0 \times 10^{-8}$</td>
<td>$1.1 \times 10^{-11}$</td>
<td>109</td>
</tr>
<tr>
<td>$M_H = 400$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$4e$</td>
<td>$6.2 \times 10^{-9}$</td>
<td>$6.8 \times 10^{-12}$</td>
<td>68</td>
</tr>
<tr>
<td>$gg \rightarrow Zt\bar{t}$</td>
<td>$4e$</td>
<td>$9.5 \times 10^{-9}$</td>
<td>$4.6 \times 10^{-11}$</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>$3e + jets$</td>
<td>$2.3 \times 10^{-10}$</td>
<td>$2.3K$</td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow Z + q$</td>
<td>$2e + jets$</td>
<td>$2.1 \times 10^{-6}$</td>
<td>$6.9 \times 10^{-8}$</td>
<td>686K</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Z + g$</td>
<td>$2e + jets$</td>
<td>$2.6 \times 10^{-7}$</td>
<td>$8.4 \times 10^{-9}$</td>
<td>85K</td>
</tr>
<tr>
<td>$gg \rightarrow t\bar{t}$</td>
<td>$4e$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-8}$</td>
<td>125K</td>
</tr>
<tr>
<td></td>
<td>$3e + jets$</td>
<td>$3.4 \times 10^{-7}$</td>
<td>$3.4M$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2e + jets$</td>
<td>$3.1 \times 10^{-6}$</td>
<td>$30.8M$</td>
<td></td>
</tr>
</tbody>
</table>

above with $P_{T,hard} > 30$ GeV and $\hat{s} > 350$ GeV,
branchings $t \rightarrow e \sim 0.1$ and $b(c) \rightarrow e \sim 0.1(0.2)$,
$M_{top} = 140$ GeV and for $10^4 pb^{-1}$ run

Note that Table 1 are for idealized events. We expect other sources of
electrons from radiated jets in the event as well (i.e. numbers of events with
$3e + jets$ etc. are expected to be higher than given in Table 1.) We will
have to rely on various lepton kinematics and isolation cuts to be discussed
below in order to suppress backgrounds.

2.2 Lepton Cuts

We generate with PYTHIA, the following distributions for Higgs events:

1. $\max[\eta_e]$, the pseudorapidity of the most forward electron. See Figure 1.

2. $\min[P_{T,e}]$, the $P_T$ of the softest electron where all 4 electrons in event
pass an $\eta_e < 2.5$ cut. See Figure 2.

3. $\min[P_{T,Z}]$, the $P_T$ of the softest $Z$ where the 4 electrons pass $\eta_e < 2.5$
and $P_{T,e} > 10$ GeV cuts. See Figure 3.
4. max[ΣET] in cone of R = 0.2 and 0.6., the ΣET around the least isolated electron of 4 electrons where all electrons pass same criteria as item 3 above and both Z's with PT,Z > 30 GeV. See Figure 4a.

These plots summarize the effects of physics cuts when successively applied. The numbers used in plots are a typical set of numbers appropriate for the 400 GeV Higgs and give efficiencies, εi:

1. $\epsilon_{\eta<2.5} = 0.66$
2. $\epsilon_{PT,e>10 \text{ GeV}} = 0.80$
3. $\epsilon_{PT,z>30 \text{ GeV}} = 0.97$
4. $\epsilon_{\Sigma ET<5 \text{ GeV}, R=0.2} = 0.90$

The net acceptance without an isolation cut is about 1/2. With $\eta < 3$ instead of 2.5 electron coverage, we can increase efficiency by 20% for the 400 GeV Higgs. If the useable $PT, e > 10 \text{ GeV}$, the acceptance for the 200 GeV Higgs drops by 25% as compared with 400 GeV Higgs. If this cut is set to 50 GeV, one has almost no acceptance for a 200 GeV Higgs. It is also clear that the allowed isolation cuts on electrons in Higgs events are limited if high acceptance is desired and $\Sigma ET < 5 \text{ GeV}$ in a cone of $R = 0.2$ leaves reasonable acceptance of 0.90 (See Figure 4a). With a cone size of 0.2, the isolation efficiency for the 800 GeV Higgs is almost the same as that for the 400 GeV Higgs. It may be that implicit minimum isolation cuts imposed by detector granularity and electron ID techniques will not allow isolation cuts with smaller cone size.

2.3 Z Pair Background Estimation

We wish to find Z pair candidates that survive our selection criteria when applied to the backgrounds outlined earlier. Z candidates that one combines into Higgs particles are constructed from:

1. isolated electrons from top decay,

2. jets (ersatz electrons) which appear to be electrons in the detector.

The Higgs selection criteria is found in Appendix 1. In short, we define candidate electron clusters and try to form candidate Z's and then look at the Z pair rate.
In Table 2, the survival rate of various background events with $Z$ mass requirements on both pairs but no electron isolation cuts are summarized. Rates are for a mass window, $M_{ZZ} = M_H \pm \Gamma_{M_H}$ where $\Gamma_{M_H}$ is the appropriate Higgs width. For example, the number of $Z$ pair candidates constructed of 3 electron and 1 hadron clusters (EEEH±,± combinations) with charge discrimination in a mass window $360 < M_{ZZ} < 440\text{GeV}$ is 800 per year. Figure 5 shows the invariant mass spectra of di-electron pairs arising from the two topologies, one where the electrons are from the same top (shown dashed) and the other where the electrons are from opposite top (shown solid). It is clear that an electron pair formed by electrons from different top are the most likely configuration for the $Z$ background. These distributions would change for different top masses. In our studies, a substantial background (roughly half) arises from yet another topology where 2 $Z$'s arise from 3 electrons from $t\bar{t}$ and another electron from elsewhere in the event (radiated jets etc.). The uncertainties in calculating this component is not studied here.

We look separately at rates with:

1. charged track requirement and sign determination.
2. cluster requirements only (i.e. kinematics only).

As an example of a rough estimate of background from $t\bar{t} \rightarrow 4e$ we can trace event survival under various cuts (isolation not included):

1. raw rate $\sim140\text{MeV}$
2. 2e with $P_{T,e} > 30\text{GeV}, \eta_e < 2.5$ $\sim4.3\text{MeV}$
3. additional 2e with $P_{T,e} > 10\text{GeV}, \eta_e < 2.5$ $\sim4\text{KeV}$
4. $Z$ mass requirement $\sim20\text{ev}$
## Table 2: Z Pair Candidates Rates within $M_{ZZ}$ windows, w/o Isolation Cuts

<table>
<thead>
<tr>
<th>Combo.</th>
<th>Higgs</th>
<th>$ZZ$</th>
<th>$Z^+ +$ jets</th>
<th>$Zt\bar{t}$</th>
<th>$tt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEEE±,±</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360 &lt; $M_{ZZ}$ &lt; 440 GeV</td>
<td>67</td>
<td>6</td>
<td>negl.</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>500 &lt; $M_{ZZ}$ &lt; 700 GeV</td>
<td>19</td>
<td>3</td>
<td>negl.</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>550 &lt; $M_{ZZ}$ &lt; 1050 GeV</td>
<td>8</td>
<td>3</td>
<td>negl.</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>All</td>
<td>11</td>
<td>130K</td>
<td>8.1K</td>
<td>650K</td>
<td></td>
</tr>
<tr>
<td>All ±,±</td>
<td>5</td>
<td>47K</td>
<td>540</td>
<td>200K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>36K</td>
<td>340</td>
<td>130K</td>
<td></td>
</tr>
<tr>
<td>EEEH</td>
<td>3</td>
<td>552</td>
<td>24</td>
<td>3K*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>552</td>
<td>9.7</td>
<td>700*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>174</td>
<td>4.5</td>
<td>600*</td>
<td></td>
</tr>
<tr>
<td>EEEH±,±</td>
<td>1</td>
<td>384</td>
<td>7.7</td>
<td>800*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>174</td>
<td>3.0</td>
<td>200*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0</td>
<td>4.5</td>
<td>100*</td>
<td></td>
</tr>
<tr>
<td>2E2H</td>
<td>1</td>
<td>62K</td>
<td>398</td>
<td>59K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>31K</td>
<td>82</td>
<td>18K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>27K</td>
<td>68</td>
<td>7.6K</td>
<td></td>
</tr>
<tr>
<td>2E2H±,±</td>
<td>0.1</td>
<td>8K</td>
<td>44</td>
<td>8.7K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>6.6K</td>
<td>16</td>
<td>2.2K</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>6.4K</td>
<td>13</td>
<td>1.4K</td>
<td></td>
</tr>
</tbody>
</table>

Above are for $M_H \pm \Gamma_M$ wide $M_{ZZ}$ window in $10^4pb^{-1}$ run
Cuts (appropriate for $M_H = 400GeV$) described in text.
EE means $Z$ made of two electron clusters,
EH means $Z$ made of electron plus hadron cluster
±, ± means with full charge discrimination.
*statistics poor (based on few events)
There are two types of possible backgrounds, one consisting of 4 isolated electrons and the other consisting of either at least one hadron or one non-isolated electron. The first type includes $ZZ$ continuum and $Z + t\bar{t}$. These can be reduced only by kinematical quantities such as $P_T$ and $\eta$. In many distributions, the continuum $ZZ$ processes look similar to the Higgs signal and in order to reduce the background, one has to sacrifice the signal. For example, for an 800 GeV Higgs, a $P_T > 100 GeV$ cut on the electrons will leave 3 events per SSC year ($=10^8 pb^{-1}$) and negligible $ZZ$ background. These are distributed over 500 GeV and no other electron ID or isolation efficiencies have been included. Including these efficiencies will drop the rate by perhaps another factor of 2.

With all cuts and $Z$ mass requirements but no isolation, a substantial background exists from the $t\bar{t} \rightarrow 3e + 1h$. Additional rejection of $\sim 100$ is needed. See Figure 6 for the corresponding $ZZ$ mass spectrum. It is interesting to note that charge discrimination is fairly powerful in reducing background. If we look at electron isolation (of the least isolated electron) for these events, then a cut of $\Sigma E_T < 5 GeV$ in a cone with $R = 0.2$ will remove these (though statistics are poor). This is due to the fact that in $t\bar{t}$ events, 2 electrons from the $W$ decays are well isolated and the other electron and hadron are from $b$ or $c$ decays and are much less isolated. As a check on effects of isolation, we look at the acceptance as a function of $\Sigma P_T$ in various cone sizes around the electron from $t$ and the electron from $b, c$'s in $t\bar{t}$ events. See Figure 4a. Here we expect that a $\Sigma E_T < 5 GeV$ in $R = 0.2$ gives a factor of $\sim 50 - 100$ rejection for an electron from $b$ and $c$ decay or hadron from a jet and that the electron from $t$ survives. In general, we expect a $(10^3)^2 = 10^6$ rejection of $t\bar{t}$ events just due an isolation cuts and hence, isolation cuts alone may be enough for $t\bar{t}$ background suppression (and assuming the other two electrons are well isolated and well identified). As long as energies can be measured well and isolation cuts can be applied, then no overwhelming backgrounds are expected.

3 Detector Geometry Cuts

The signal and backgrounds we have considered thus far have been under pristine conditions (i.e. no brem radiation, interactions in detectors, etc.) We now study the Martin Marietta/SSC engineering design [5] for a Large Solenoid Detector (LSD) that employs liquid argon calorimetry as an example of a detector that is claimed to be mechanically sound and one that
contains a realistic assessment of wall thicknesses and dead regions.

We already know that a pseudorapidity cut (roughly \( \eta < 2.5 \)) on the electrons will be necessary since we are primarily interested in central \( Z \)'s whereas the backgrounds yield more forward \( Z \)'s. Ultimately at high pseudorapidity regions, technical detector problems (radiation levels, detector segmentation, etc.) become overwhelming.

Based on electron ID information needed (of which details will be discussed below) we look at LSD and identify bad regions in azimuth \( \phi \) and pseudorapidity \( \eta \) where we believe reliable application of electron ID requirements will be compromised. Figure 7 indicates these trouble spots at \( \eta = 0.73 \pm 0.03, 1.5 \pm 0.1, \) and 40 azimuthal walls between modules. A dead region of 0.5 cm around each module corresponds to a 4\% reduction in azimuth and a 1 cm region around each module corresponds to an 8\% reduction in azimuth. If we demand that we get all 4 electrons in good regions, then the Higgs acceptance falls quickly. See Figure 8. One sees that 1/3 of the signal remains. The inefficiency due to the electron ID algorithm itself has not yet been applied.

It is not clear what can be gained by relaxing electron ID requirements on one electron candidate. For example, suppose we require 3 electrons in good regions and allow one to fall in a bad region where bad means we lose electron ID but can measure it's energy at some level. If we take the rate for 3 electron plus 1 hadron from Table 2, then over the full acceptance, the \( gg \rightarrow t\bar{t} \rightarrow 3e + 1 \) hadron \( \rightarrow 2Z_{\text{fake}} \) ranges from 10 to 45 times the signal (using limited statistics) depending on whether track requirements and sign determination are possible and most importantly, how well isolation cuts can be applied. In a real detector, this background to signal ratio is roughly the fraction of bad region times the factor of 10 to 45 times the reduction due to isolation (which depends on how well energy is measured in and near the bad regions: a \( b \) jet can disappear into a \( R = 0.1 \) cone). Thus we are faced with prospects of improving Higgs events efficiency by only 5-15\% at the expense of accepting additional 3 electron plus 1 hadron background. The message is clear:

- An electron and its shower in a dense material is a small scale object.
- Detection of electrons is affected by small scale defects (walls, dead regions and cracks).

The geometric acceptance for efficient electron ID, then, becomes a new and perhaps more stringent definition of hermeticity than the old concept.
such as missing $E_T$. This is driven by the small Higgs cross section and branchings to multi-leptons.

4 Electron Identification Cuts

Electron identification in CDF and UA2 has been based on simultaneously observing several signatures of electromagnetic showers in the detector. In particular ID is based on a combination of longitudinal and transverse shape within the calorimeter towers, a special device to detect an early beginning of the shower, and a correlation with a charged track.

In CDF [10] this is implemented by measuring the electromagnetic to hadronic energy deposited, the sharing of signal between neighboring towers in the electromagnetic calorimeter, a wire proportional chamber at shower maximum which ensures an early beginning to the shower, correlates position with a charged track, and provides a rough correlation of the momentum measurement in the central tracking chamber with the calorimeter energy. The signatures are described in greater detail in Appendix 3.

In the UA2 [11] detector this is implemented by Chi squared comparison of an electromagnetic shower in the calorimeter with a calculated expectation for longitudinal and transverse energy deposition. The preshower radiator established an early beginning to the shower and gives a precision position which can be compared with a measured track.

The identification and background rejection efficiency is dependent on event topology and the electron $P_T$. In top studies at CDF, the explicit electron identification efficiency is 77% and the mis-identified pions for the $W \rightarrow e\nu$ events is less than 1%. For top studies at UA2 the efficiency for identifying electrons is 75% and the misidentified pion background in the W signal is less than 1%.

Given the above discussion we then assume the following quantities are used to identify electrons:

- $E/M$ matching (97%)
- $E_{EM}/E_{tot}$ (98%)
- Transverse shower shape (97%)
- Longitudinal shower shape (98%)
- Shower-track matching (97%)
• Track quality cut (98%)

Assuming optimistic values for each item, we estimate $\epsilon_{eID}$ to be 86%. This of course turns out to be a very optimistic estimation when compared to what has been achieved (in presumably cleaner environments).

5 Is the Heavy Higgs Boson Really Observable?

Unfortunately the story does not end here. We have to write the final equation. The net acceptance (assuming no loss due to pileup) for the Higgs signal is:

$$\epsilon_{Higgs} = \epsilon_{n_e} \cdot \epsilon_{geom} \cdot \epsilon_{P_T} \cdot \Pi \epsilon_{eID} \cdot \epsilon_{isol}$$  \hspace{1cm} (6)

$$= 0.66 \cdot 0.48 \cdot 0.80 \cdot (0.86 \cdot 0.95)^2 \cdot 0.90$$  \hspace{1cm} (7)

$$= 0.15$$  \hspace{1cm} (8)

The efficiency is shown in a factorized form showing the importance of each factor. Those factors in which correlations are important are calculated using a monte carlo.

The lepton rapidity cut acceptance, $\epsilon_{n_e}$ required that all electrons from a 400 GeV Higgs have a rapidity less than $\eta_{cut} = 2.5$. This yields an acceptance of 66% and is consistent with the Martin-Marietta LSD design. Again, Figure 1 shows the dependence of this acceptance on $\eta_{cut}$ and Higgs mass.

The geometric efficiency, $\epsilon_{geom}$, was estimated using the Martin-Marietta design by simply removing estimated bad regions in the analysis as described in Section 3 (i.e. a fiducial volume cut).

A $P_T$ cut on the electrons and on the reconstructed $Z$'s are necessary to reduce backgrounds (primarily $t\bar{t}$ and $Z + t\bar{t}$). The $P_{Te} > 10$ GeV cut was chosen close to a reasonable limit. If minimum measurable $P_{Te}$ is required to be larger than 20 GeV, the Higgs acceptance drops by 20%. Figure 2 shows the efficiencies for 4 Higgs masses as a function of the $P_{Te}$ cut. It is thus important that rather low $P_T$ electrons are detectable for the lighter Heavy Higgs searches. We have not investigated whether conversion electrons will contribute significantly to background.

The electron identification efficiency, $\epsilon_{eID}$ was estimated in Section 4 to be optimistically 86%. We have assumed that this is needed for at least one lepton of a given $Z$. We then assign an efficiency of 95% for the other
electron of the Z assuming that we use a smaller subset of cuts necessary for good electron ID. This is assumed constant over a ±2.5 pseudorapidity range with no energy dependence. These numbers are of course detector dependent and only represent extrapolations of what has been achieved. As mentioned earlier, isolation cuts are necessary ($\Sigma E_T < 5$ GeV in cone $R = 0.2$) and of course have a corresponding acceptance, $\epsilon_{\text{isol}} \sim 90\%$.

It has been suggested that the most important effects of event pileup are not on jet reconstruction or other high $P_T$ phenomenon or even triggering, but instead on its effects on one's ability to implement an isolation cut [7]. The concern is that in opening a cone for isolation, pileup is filling it with energy and that electrons from the signal will hardly ever be isolated. If the pileup events are included in the sense that we add energy in the cone from integrating over 7 bunches with a mean number of interactions per bunch $= 1.5$ and keep the same isolation cut of $\Sigma E_T < 5$ GeV in $R = 0.2$ cone, we find negligible loss in efficiency for Higgs events. This is not true if we use a larger ($R=0.4$) cone.

The raw cross section of a 400 GeV Higgs into 4 electrons is just over 100 events per SSC year at design luminosity. We see very marginal performance for the Martin Marietta LSD design with a 15% net Higgs acceptance!

Table 3 contains the summary of the estimated numbers of events per year for 3 decay modes, $H \rightarrow 4e$, $H \rightarrow 2e2\mu$ and $H \rightarrow 4\mu$, for 400 GeV, 600 GeV and 800 GeV Higgs with the various acceptances successively applied. Some cuts might be changed as appropriate for the mass scales considered if further background rejection is needed but this will also mean fewer accepted events than given in the table. For the muon mode, it is assumed that the muon can be identified in the rapidity range of $\eta < 2.5$, and that the identification efficiency is the same as the electron, 86% for the 1st and 95% for the 2nd of a given Z candidate. These numbers are expected to be higher but there will be geometric cuts. One might call these the combined efficiencies. Clearly, we are faced with a paucity of events for a very significant range of heavy Higgs masses.
Table 3: Higgs Rates

<table>
<thead>
<tr>
<th>Higgs Mass</th>
<th>modes</th>
<th>raw</th>
<th>$\times \epsilon_{\text{geom}+\eta}$</th>
<th>$\times \Pi \epsilon_{\text{lep}ID}$</th>
<th>$\times \epsilon_{P_T}$</th>
<th>$\times \epsilon_{\text{isol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 GeV</td>
<td>4e</td>
<td>120</td>
<td>35</td>
<td>23</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2e2$\mu$</td>
<td>240</td>
<td>105</td>
<td>70</td>
<td>57</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>$4\mu$</td>
<td>120</td>
<td>78</td>
<td>52</td>
<td>43</td>
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Above are rates for $10^4 pb^{-1}, M_{top} = 140 \text{ GeV}$, run after cuts

$\epsilon_{\text{geom}+\eta}$ for $e$: described in text, for $\mu$: only $\eta < 2.5$ cut

$\epsilon_{\text{lep}ID} = (0.86 \cdot 0.95)^2$ for ZZ reconstruction

$\epsilon_{P_T} = 0.80$

$\epsilon_{\text{isol}} = 0.90$ (no pileup case)

Raw rates change by $\sim \pm 40\%$ for $M_{top} = 140 \pm 40 \text{ GeV}$

Details are described in text.

6 Conclusions

Electron ID issues strike at the heart of some of the experimental issues at the SSC. The combination of a rare process in a multi-electron decay mode imposes rather stringent detector requirements. A detector must be hermetic in the sense that small local defects are not allowed. Even with optimistic assumptions, electron ID at the SSC is expected to be challenging. We are fighting for both high efficiency (low signal rate) and significant background rejection ($\sim 100$). We do not have to look far before trouble seems to appear (geometrical cuts alone can be troublesome). We have not seen any real hadron collider detector that has the electron efficiencies we seem to require. We extrapolate to efficiencies better than what exists for
large detector systems in a collider environment we expect to be much dirtier than what exists. The $H \rightarrow 4e$ mode at face value looks like a substantial challenge for the Large Solenoid Detector. Many of the problems are of a generic nature and will not go away when a solenoid is placed inside the calorimeter.

We have not done a corresponding study of the muon or mixed muon and electron decay modes. These should certainly be done, but unless they give substantially better rates than the electrons alone, we are faced with very serious problems. This study should be taken as a challenge to the detector designers to carefully devise their experimental strategies.
Appendix 1 Higgs Selection Criteria

Z Pair Definition

For the event rates in Table 2, we used the technique defined below:

1. Generate process of choice with appropriate cutoffs necessary for efficient generation of events.

2. Two types of clusters, electron, E, and hadron H, are defined.
   (a) E type cluster is an electron + nπ⁰ or γ within R = 0.01 of electron.
   (b) H type cluster is a hadron + nπ⁰ or γ within R = 0.01 of hadron.

3. We then try to form Z candidates with the E and/or H clusters subjected to:
   (a) |E,H| < 2.5
   (b) P|T,E,H| > 10GeV
   (c) M|E,E,H| = Mz ± 10GeV
   (d) P|T,E,E,H| > 30GeV for those di-clusters that pass (c)

At this point we can check the effects of charge discrimination, isolation and electron ID requirements.

Appendix 2 Monte Carlo Issues

It is stressed at this point that we are studying a hypothetical particle with hypothetical backgrounds and use this as a prejudice in detector design. The tools used are Monte Carlo programs (ISAJET, PYTHIA and HERWIG [9]) which are based on standard model physics that we understand (hard scattering) plus approximations and outright models that we sort of understand in varying degrees of clarity (leading log parton showering and fragmentation). The reliability of the Higgs generation is well documented [3] as well as the q̄q → ZZ and gg → ZZ processes. The Z + t̄t and Zq background has also been discussed [6]. They are significant but not dominant (roughly equal to to size of signal).

1See Appendix 2. Monte carlo issues are described in this appendix.
Fragmentation

The QCD backgrounds ($t\bar{t}$) is heavily studied in this paper. The approach is one defines a Higgs and assumes that a detector is blind to electron ID and ask how often 4 particles look like 2 Z's. The tabulation of these rates yields lepton ID (or hadron rejection) requirements. Of relevance to this study of course is the modelling of the distribution of isolated hadrons from jets (fragmentation distribution). We at least have some experimental input from CDF\cite{8}. In Figure 9(a), one sees the measured charged particle fragmentation function $dN/dz$ where $z$ is the fraction of jet energy a given hadron has compared HERWIG. Figure 9(b) shows for 40 TeV events that HERWIG and PYTHIA agree and that ISAJET is roughly a factor of $\sim 5$ higher in the high $Z$ range. With some confidence, we use PYTHIA throughout the electron ID analysis.

Which Top is Tops?

Whereas, the fragmentation in PYTHIA agrees with data for Tevatron jets, we still have questions of the $t\bar{t}$ cross section itself. Figure 10 shows the total cross section as a function of the minimum $p_T$ allowed in the hard scattering frame for PYTHIA (or ISAJET which yields identical results) and a parton monte carlo, PAPAGENO. For example, above, $p_{T,\text{hard}} = 300 GeV$, the parton monte carlo predicts a factor of 4 higher in cross section. We continue to use PYTHIA with the caveat that $t\bar{t}$ background could be worse. This needs to be understood before any further heavy use of the mentioned codes for this process is carried out. We will not discuss this further here.

Special Cuts

In estimating backgrounds, special cuts must be employed or the monte carlos will be too inefficient. The following technical prescription is included for completeness. In particular, the $g g \rightarrow t\bar{t}$ background (with no forced decays) was cut by saving $t\bar{t}$ events generated by PYTHIA 4.9 with two or more good electrons where a good electron was defined by:

- $\eta_{\text{electron}} < 2.5$
- $p_{T,\text{electron}} > 30 GeV$

For the Higgs masses considered in our studies, 2 electrons have $p_T > 30 GeV$ and the above criteria would not cut signal events. In addition, events were generated in $p_{T,\text{top}}$ bins of :
- $0 < P_{T,\text{top}} < 100 \text{GeV}$
- $100 < P_{T,\text{top}} < 200 \text{GeV}$
- $200 < P_{T,\text{top}} < 1000 \text{GeV}$

where $P_{T,\text{top}}$ cuts were taken in the hard scattering frame. Typically, this is good for a factor of 100 cut thereby reducing the number of saved events to a tolerable size.

Appendix 3 Review of Experimental Techniques

Fortunately, experience in electron ID at hadron colliders does exist. We can examine how CDF solves the electron ID problem. The CDF barrel calorimeter module has an electromagnetic (EM) and hadronic (HAD) compartment. At a depth of 6 radiation lengths into the EM calorimeter there is a wire proportional chamber with cathode pads organized as strips perpendicular to the wires (strip chamber). Both the wire and pads are readout to give coordinate information on shower centers. The entire module is 0.9 units of pseudorapidity ($\eta$) by 15 degrees in azimuth ($\phi$), divided into 9 towers that are 0.1 unit of pseudorapidity by 15 degrees. Each tower is viewed by two photomultiplier tubes which look at wave shifter light collectors along the azimuthal edge of the module. The EM compartment is tapered so that it is 17.5 radiation lengths thick along electron trajectories over the entire face of the module. This thickness gives approximately 3% leakage of the electromagnetic shower into the HAD compartment. The typical physical size of a calorimeter tower is 24 cm in $\eta$ and 45 cm in $\phi$. For a single shower in a tower interpolation in $\phi$ is possible using energy sharing in the photomultiplier tubes.

Some of the ramifications of this design are that electron showers are much smaller than the typical towers and further showers can spread into neighboring towers in $\eta$ but not across $\phi$ (module) boundaries. At energies of tens of GeV electromagnetic showers are sufficiently well behaved to use leakage of only a few percent of the electron energy as a good signature for an electron. Based on the CDF experience, the signatures used to identify electron might be:

1. $E/P$: The ratio of the energy measured in the EMC to the momentum measured in the tracking chambers. Internal and external bremsstrahlung will cause some electrons to have $P$ substantially less
than E. A 97% acceptance is a reasonable goal for a solenoidal field detector when a cut on this variable is used.

2. EM/(EM+HAD): For a particular shower this is the ratio of the energy deposited in the EMC to the energy deposited in the EMC plus the hadronic calorimeter towers behind the shower. For real electrons we expect that the cut will be set to include 98% of the signal.

3. TRACK/SHOWER MATCHING: At the energies considered in this study EM showers are sufficiently well behaved that shower centroids from normally incident electron can be determined to about a millimeter or two. Extrapolated tracks from tracking chambers should have about the same accuracy. Other considerations such as overall alignment of detector components, centroid shifts due to underlying events, precise depth of the centroid for non-normal trajectories, uneven track measuring resolution in $\phi$ and polar angle, $\theta$, effects of bremsstrahlung, etc. will increase this uncertainty to about a centimeter or more. Here we can reasonably expect to achieve a 97% efficiency for a cut set around a centimeter.

4. TRANSVERSE SHAPE: In CDF the lateral spread of the shower into the nearest tower in $\eta$ is calculated based on the actual electron energy and trajectory. We believe that residuals of a fit to the difference of expected shower shape and observed shape will allow a 97% efficiency.

5. TRACKING QUALITY: A track quality cut will have to be made to insure that the electron tracks are sufficiently well measured to allow their use in previous cuts. We expect that 98% of electrons will survive this cut.

We will not consider at this point, the possibilities of using shower pre-radiators and fine grained readout or transition radiation detectors.
References


Figure 1: Acceptance of Higgs particles \((M_H = 200, 400, 600 \text{ and } 800 \text{ GeV})\) in the decay mode \(H \rightarrow ZZ \rightarrow 4e\) where all four electrons have \(\eta\) less than \(\eta_{\text{max}}\).

Figure 2: Higgs acceptance vs. minimum \(P_{T,\text{elec}}\) (for \(M_H = 200, 400, 600 \text{ and } 800 \text{ GeV}\)). Assumes \(\eta = 2.5\) cut on electrons.
Figure 3: Higgs acceptance vs minimum $P_{T,Z}$. Assumes $\eta < 2.5$ and $P_{T,e} > 10 GeV$. 

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Figure 4: (a) Acceptance of 400GeV Higgs events versus $\sum E_T$ of the least isolated electron for cone sizes $\Delta R = 0.2$ and 0.6. Assumes cuts used in Figure 3 and minimum $P_{T,Z} > 30$ GeV. (b) Acceptance of $t\bar{t}$ events versus $\sum E_T$ of (not necessarily the least isolated) electrons from top, electrons from bottom, charm and hadrons.
Figure 5: Di-electron invariant mass for electrons from same top (dashes) and electrons from different top (solid). Last bin is overflow.
Figure 6: (a) Invariant mass of Z pair for Higgs and $t\bar{t}$ events with Z mass requirement made of EEEH clusters but no isolation on electrons. (b) as in (a) but with EHEH clusters.
Figure 7: Martin Marietta design of the liquid argon calorimeter. Lines drawn on the figure indicate η regions where we believe that an electron identification algorithm will be compromised.
Figure 8: Acceptance of Higgs ($M_H = 400$ GeV) particles after application of geometric cuts. (1) All four electrons in the region $\eta < \eta_{\text{max}}$. (2) No electron in the region where the calorimeter support structure is $\eta = 0.73 \pm 0.03$ and $\eta = 1.5 \pm 0.1$. (3) No electrons in the walls of modules. A 5 mm dead space at the wall of each module corresponds to 4% reduction in azimuth, a 1 cm dead space is a reduction of 8% in azimuth.
Figure 9: (a) Comparison of CDF fragmentation function, $dN/dz$, with HERWIG. (b) Predictions of the fragmentation functions at 40 TeV of PYTHIA, HERWIG and ISAJET. PYTHIA and HERWIG agree.
Figure 10: Cross section vs. minimum $P_{T,\text{hard}}$ for PYTHIA, ISAJET and PAPAGENO.