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ELECTRON IDENTIFICATION AND IMPLICATIONS IN SSC DETECTOR DESIGN*

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MASTER

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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:

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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 through cracks, dead spaces, or poorly placed walls).
3. have high efficiency electron ID (~ 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 three independent pieces:

1. Physics Cuts—Where an estimate is made on 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—Where the effects of pseudorapidity (η) or azimuthal cracks in a particular detector design are studied.
3. Electron Identification Cuts—Where an estimate is made on the losses due to cuts necessary to identify electrons with sufficient background rejection.

After deciding on reasonable cuts, the net Higgs and background acceptance is estimated.

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 $\sim \epsilon_e^4$ 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

Table 1. Higgs Rates

Higgs Mass	modes	raw	$\times \epsilon_{geom+\eta_e}$	$\times \prod \epsilon_{lepID,i}$	$\times \epsilon_{P_T}$	$\times \epsilon_{isol}$
400 GeV	4e	120	35	23	19	17
	2e2 μ	240	105	70	57	52
	4 μ	120	78	52	43	39
	total	480	218	145	119	108
600 GeV	4e	34	11	7	6	6
	2e2 μ	68	32	22	19	17
	4 μ	34	24	16	14	12
	total	136	67	45	39	35
800 GeV	4e	11	3	2	2	2
	2e2 μ	22	11	7	7	6
	4 μ	11	8	5	5	4
	total	44	22	14	14	12

Above are rates for 10^4 pb^{-1} , $M_{top} = 140 \text{ GeV}$, run after cuts

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

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

$\epsilon_{P_T} = 0.80$

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

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

Details are described in text

about ± 2.5 with dead space much less than 10%, if such a search is to be statistically significant for Higgs with the mass below 500 GeV. As shown by the rates in Table 1, it appears that it is going to be very challenging to observe a Higgs particle with a mass above 500 GeV with the luminosity of $10^{33}/\text{sec}/\text{cm}^2$ even with a very high quality and a high efficiency electron detection.

2. PHYSICS CUTS

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

$$H \rightarrow ZZ \rightarrow 4e \quad (1)$$

Now let some possible backgrounds be identified (h is a hadron that emulates an electron in the detector):

$$q\bar{q} \rightarrow ZZ \quad (2)$$

$$Z + t\bar{t} \rightarrow Z + 2e \quad (3)$$

$$Z + g, q \rightarrow Z + (2e \text{ or } e + h = Z_{fake}) \quad (4)$$

$$t\bar{t} \rightarrow 4e (= 2 Z_{fake}) \quad (5)$$

$$3e + h$$

$$2e + 2h$$

As a general strategy, attempts have been made to reconstruct Z pairs and look at the ZZ mass spectrum. A number of physics handles have been obtained, such as $P_{T,e}$, η_e , $P_{T,Z}$ and M_{ee} (the invariant mass of the Z candidate). In addition, electron isolation, where an attempt to suppress electrons from b and c decays, have been obtained.

Table 2. Cross Sections

process	mode	σ (mb)	$\sigma \cdot \text{BR}$ (mb)	Evts./yr.
$H \rightarrow ZZ$ $M_H = 400$ GeV	4e	1.0×10^{-8}	1.1×10^{-11}	109
$q\bar{q} \rightarrow ZZ$	4e	6.2×10^{-9}	6.8×10^{-12}	68
$gg \rightarrow Zt\bar{t}$	4e	9.5×10^{-9}	4.6×10^{-11}	460
	3e+ jets		2.3×10^{-10}	2.3K
$gq \rightarrow Z + q$	2e+ jets	2.1×10^{-6}	6.9×10^{-8}	686K
$q\bar{q} \rightarrow Z + g$	2e+ jets	2.6×10^{-7}	8.4×10^{-9}	85K
$gg \rightarrow t\bar{t}$	4e	1.4×10^{-5}	1.3×10^{-8}	125K
	3e+ jets		3.4×10^{-7}	3.4M
	2e+ jets		3.1×10^{-6}	30.8M

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.

2.1 RATES

In order to understand the size of the problem, cross sections based on very general cuts are tabulated. Decisions on what backgrounds, seem the most severe. The rates for signal and backgrounds with $P_{T,hard} > 30$ GeV and $s_{hard} > 350$ GeV are found in Table 2 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 there will not be explicit cuts on these variables.

The listings in Table 2 are for idealized events. Other sources of electrons from radiated jets in the event are expected as well (i.e. numbers of events with 3e+ jets etc. are expected to be higher than given in Table 2). Various lepton kinematics and isolation cuts to be discussed below in order to suppress backgrounds need to be relied on.

2.2 LEPTON CUTS

The following distributions for Higgs events were generated with PYTHIA:

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. $\max[\Sigma E_T]$ in cone of $R = 0.2$ and 0.6 , the ΣE_T around the least isolated electron of 4 electrons where all electrons pass same criteria as item 3 above and both Z 's with $P_{T,Z} > 30$ 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 given efficiencies, ϵ_i :

1. $\epsilon_{\eta_e < 2.5} = 0.66$
2. $\epsilon_{P_{T,e} > 10 \text{ GeV}} = 0.80$
3. $\epsilon_{P_{T,Z} > 30 \text{ GeV}} = 0.97$
4. $\epsilon_{\Sigma E_T < 5 \text{ GeV}, R=0.2} = 0.90$

The net acceptance without an isolation cut is about 1/2. With $\eta_e < 3$ instead of 2.5 electron coverage, an increase in efficiency can be reached by 20% for the 400 GeV Higgs. If the usable $P_{T,e} > 10$ 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 $\Sigma E_T < 5$ 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

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

Figure 2. Higgs acceptance vs. minimum $P_{T,elec}$ (for $M_H = 200, 400, 600$, and 800 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.

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 A. In short, candidate electron clusters are defined and try to form candidate Z 's and then look at the Z pair rate.

(a)

(b)

Figure 4. (a) Acceptance of 400 GeV Higgs events vs. ΣE_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 ΣE_T of (not necessarily the least isolated) electrons from top, electrons from bottom, charm, and hadrons.

In Table 3, 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 Γ_{M_H} is the appropriate Higgs width. For example, the number of Z pair candidates constructed of 3 electron and 1 hadron clusters (EEEH $\pm, \pm$ combinations) with charge discrimination in a mass window $360 < M_{ZZ} < 440$ 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.

Examined separately are 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 $t\bar{t} \rightarrow 4e$, event survival under various cuts (isolation not included) can be traced:

1.	raw rate	~ 140 MeV
2.	2e with $P_{T,e} > 30$ GeV, $\eta_e < 2.5$	~ 4.3 MeV
3.	additional 2e with $P_{T,e} > 10$ GeV, $\eta_e < 2.5$	~ 4 KeV
4.	Z mass requirement	~ 20 eV

There are two types of possible backgrounds, one consisting of 4 isolated electrons and the other consisting of either at least 1 hadron or 1 non-isolated electron. The first type includes a ZZ continuum and a $Z + t\bar{t}$. These can be

Table 3. Z Pair Candidates Rates Within M_{ZZ} Windows, Without Isolation Cuts

Combo.	Higgs	ZZ	$Z + \text{jets}$	$Zt\bar{t}$	$t\bar{t}$
EEEE$\pm, \pm$					
$360 < M_{ZZ} < 440 \text{ GeV}$	67	6	negl.	0.3	0.7
$500 < M_{ZZ} < 700 \text{ GeV}$	19	3	negl.	0.1	0.4
$550 < M_{ZZ} < 1050 \text{ GeV}$	8	3	negl.	1.6	1.0
All		11	130K	8.1K	650K
		5	47K	540	200K
		6	36K	340	130K
All $\pm, \pm$		7	120K	300	41K
		4	8K	39	11K
		4	7.5K	37	7.6K
EEEH		3	552	24	3K*
		1	552	9.7	700*
		2	174	4.5	600*
EEEH $\pm, \pm$		1	384	7.7	800*
		0.4	174	3.0	200*
		0.4	0	4.5	100*
2E2H		1	62K	398	59K
		0.5	31K	82	18K
		0.5	27K	68	7.6K
2e2H $\pm, \pm$		0.1	8K	44	8.7K
		0.1	6.6K	16	2.2K
		0.1	6.4K	13	1.4K

Above are for $M_H \pm \Gamma_{M_H}$ wide M_{ZZ} window in 10^4 pb^{-1} run.

Cuts (appropriate for $M_H = 400 \text{ GeV}$) described in text.

EE means Z made of two electron clusters.

EH means Z made of electron plus hadron cluster.

$\pm, \pm$ means with full charge discrimination.

*Statistics poor (based on few events).

Figure 5. Di-electron invariant mass for electrons from same top (dashes) and electrons from different top (solid). Last bin is overflow.

reduced only by kinematical quantities such as $P_{T,e}$ and η_e . 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 $P_{T,e} > 100$ GeV cut on the electrons will leave three events per SSC year ($= 10^4 \text{ pb}^{-1}$) 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 two.

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 ~ 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 observed 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 Σp_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, it is expected that a $\Sigma E_T < 5$ GeV in $R = 0.2$ gives a factor of ~ 50 – 100 rejections for an electron from b and c decay or a hadron from a jet and that the electron from t survives. In general, it is expected that a $(10^2)^2 = 10^4$ 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 considered thus far have been under pristine conditions (i.e. no brems radiation, interactions in detectors, etc.). Now studied is 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.

Already known is that a pseudorapidity cut (roughly $\eta < 2.5$) on the electrons will be necessary since the primary interest is 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 ϕ and pseudorapidity, η , where it is possible a reliable application of electron ID requirements will be compromised. Figure 7 indicates these trouble spots at $\eta = 0.73 \pm 0.03$, 1.5 ± 0.1 .

(a)

(b)

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.

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 demands are made that all 4 electrons exist 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 1 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 its energy at some level. If we take the rate for 3 electron plus 1 hadron from Table 3, then over the full acceptance, the $gg \rightarrow t\bar{t} \rightarrow 3e + 1 \text{ hadron} \rightarrow 2Z_{fake}$ 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 there are prospects that need to be faced of improving Higgs events efficiently by only 5–15% at the expense of accepting additional 3 electrons 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 a missing E_T . This is driven by the small Higgs cross section and branchings to multi-leptons.

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 4 electrons in the region $\eta < \eta_{\max}$. (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.

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, which is a wire proportional chamber at shower maximum which ensures an early beginning to the shower, and also correlates position with a charged track, as well as providing 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 C.

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 mis-identified pion background in the W signal is less than 1%.

Given the above discussion the assumptions of the following quantities are used to identify electrons:

- E/p matching (97%)
- $\frac{EM}{E_{tot}}$ (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 ϵ_{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. It is necessary to write the final equation. The net acceptance (assuming no loss due to pileup) for the Higgs signal is:

$$\epsilon_{Higgs} = \epsilon_{\eta_e} \cdot \epsilon_{geom} \cdot \epsilon_{P_T} \cdot \prod \epsilon_{eID,i} \cdot \epsilon_{isol} \quad (6)$$

$$= 0.66 \cdot 0.48 \cdot 0.80 \cdot (0.86 \cdot 0.95)^2 \cdot 0.90 \quad (7)$$

$$= 0.15 . \quad (8)$$

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, ϵ_{η_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 η_{cut} and Higgs mass.

The geometric efficiency, ϵ_{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 $P_{T,e} > 10$ GeV cut was chosen close to a reasonable limit. If minimum measurable $P_{T,e}$ 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 $P_{T,e}$ 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, ϵ_{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, $\epsilon_{isol} \sim 90\%$.

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 large ($R = 0.4$) 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 1 contains the summary of the estimated number 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 first and 95% for the second 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.

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. A high efficiency (low signal rate) and significant background rejection (~ 100) is the urgent goal. However, problems nonetheless have not disappeared for geometrical cuts alone can be troublesome. At the present time, no hadron collider detector to this day has the electron efficiencies that are required for the SSC. Efficiencies have been extrapolated better than what exists for large detector systems in a collider environment. 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 leave when a solenoid is placed inside the calorimeter.

A corresponding study of the muon or mixed muon and electron decay modes has not yet begun. These should certainly be done, but unless they give substantially better rates than the electrons alone, very serious problems arise. This

study should be taken as a challenge to the detector designers to carefully devise their experimental strategies.

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APPENDIX A. HIGGS SELECTION CRITERIA

Z PAIR DEFINITION

For the event rates in Table 3, the technique defined below is used:

1. Generate process of choice with appropriate cutoffs necessary for efficient generation of events.¹
2. Two types of clusters, electron, E, and hadron, H, are defined.
 - (a) E type cluster is an electron $+n\pi^0$ or γ within $R = 0.01$ of electron.
 - (b) H type cluster is a hadron $+n\pi^0$ or γ within $R = 0.01$ of hadron.
3. Z candidates are then formed with the E and/or H clusters subjected to:
 - (c) $\eta_{E,H} < 2.5$
 - (d) $P_{T,E,H} > 10$ GeV
 - (e) $M_{EE,EH} = M_Z \pm 10$ GeV
 - (f) $P_{T,EE,EH} > 30$ GeV for those di-clusters that pass (c)

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

¹ See Appendix B. Monte Carlo issues are described in this appendix.

APPENDIX B. REVIEW OF EXPERIMENTAL TECHNIQUES

Fortunately, experience in electron ID at hadron colliders does exist. How CDF solves the electron ID problem can be examined. 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 (η) by 15 degrees in azimuth (ϕ), 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 η and 45 cm in ϕ . For a single shower in a tower interpolation in ϕ 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 η but not across ϕ (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 it is expected 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 ϕ and polar angle, θ , effects of bremsstrahlung, etc. will increase this uncertainty to about a centimeter or more. Here it can be reasonably expected 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 η is calculated based on the actual electron energy and trajectory. It is believed 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. It is expected that 98% of electrons will survive this cut.

It will not be considered at this point, the possibilities of using shower pre-radiators and fine-grained readout or transition radiation detectors.

APPENDIX C. MONTE CARLO ISSUES

It is stressed at this point that this is a study of a hypothetical particle with hypothetical backgrounds and thus the points should be used as a prejudice or kept in mind 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 are understood 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 $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow ZZ$ processes. The $Z + t\bar{t}$ and Zq background has also been discussed [6]. They are significant but not dominant (roughly equal to the size of the signal).

FRAGMENTATION

The QCD backgrounds ($t\bar{t}$) is heavily studied in this paper. The approach is one defined as a Higgs and assumes that a detector is blind to electron ID and asks 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). Some experimental input from CDF [8] has been gained. In Figure 9a, 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 9b shows for 40 TeV events that HERWIG and PYTHIA agree and that ISAJET is roughly a factor of $\sim$ five higher in the high Z range. With some confidence, PYTHIA is used 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, $P_{T,hard} = 300$ GeV, the parton Monte Carlo

(a)

(b)

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 $P_{T,hard}$ for PYTHIA, ISAJET and PAPAGENO.

predicts a factor of four higher in cross section. There is continued use of the 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. The subject will not be discussed further here.

SPECIAL CUTS

In estimating backgrounds, special cuts must be employed, or the Monte Carlo will not be efficient enough. The following technical prescription is included for completeness. In particular, the $gg \rightarrow t\bar{t}$ 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:

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

For the Higgs masses considered in the studies, 2 electrons have $P_T > 30$ GeV and the above criteria would not cut signal events. In addition, events were generated in $P_{T,top}$ bins of:

- $0 < P_{T,top} < 100$ GeV
- $100 < P_{T,top} < 200$ GeV
- $200 < P_{T,top} < 1000$ GeV

where $P_{T,top}$ 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.

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