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Identification of the $\tau$ lepton through its hadronic decay modes at the DØ collider detector

by

Naresh Sen

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Master of Science

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December, 2000
ABSTRACT

Identification of the $\tau$ lepton through its hadronic decay modes at the DØ collider detector

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This thesis focusses on $\tau$ identification efficiencies in Monte Carlo simulations of various processes by implementing optimization techniques to determine optimal values for selection cuts on discriminant variables. Two sets of discriminants were studied: the first set consisted of only the Fisher discriminant, and the second set comprised the jet width and profile. Results obtained for the two sets are comparable for the central region ($|\eta| < 1.1$) of the DØ detector. For the forward region ($|\eta| \geq 1.1$), the optimization procedure did not yield optimal values for the set of variables used, suggesting that the signatures of the $\tau$ decay products in the forward regions is different from that in the central region, so that it appears that a different approach is required to identify the $\tau$ in the forward region. Given that the $\tau$ is to be identified through a reconstruction of its decay products, the complex interplay of the multitude of variables that need to be taken into account make the task of $\tau$ identification an ideal candidate for a multivariate analysis.
I would like to take this opportunity to thank the people whose contribution has been instrumental in the completion of this thesis. I would like to thank my advisor Dr. B. Paul Padley for his guidance and patience over the duration of the thesis. Many thanks to Dr. Marjorie Corcoran for taking the time to read drafts of the thesis and provide valuable suggestions that have been instrumental in improving almost all aspects of this document. I would like to thank Dr. Hannu E. Miettinen and Dr. Peter J. Nordlander for taking the time and effort to be on the thesis committee. Of the people with whom I had occasion to interact on a regular basis, I would like to thank Bryan Smith for valuable discussions on many a fine point that served to improve my understanding of the physics as well as non-physics related aspects involved in an experiment of this magnitude. Finally, thanks to all the people of the tau identification group at DØ for their assistance and guidance at various stages of this thesis.
Contents

Acknowledgements ......................................................... iii

List of Figures .......................................................... viii

List of Tables ........................................................... xi

Chapter  1  Introduction and Theory  ................................. 1
  1.1 Overview of the Standard Model  ............................... 1
  1.2 The tau lepton and its properties  ............................. 5
    1.2.1 Mass and lifetime ........................................... 6
    1.2.2 Decay modes and branching ratios  ......................... 6
  1.3 Motivation for $\tau$ ID at hadronic colliders  .............. 7
     1.3.1 Standard Model Higgs boson  ............................... 8
     1.3.2 Standard Model Extensions - Supersymmetry ............... 8
       1.3.2.1 Neutral SUSY Higgs ..................................... 10
       1.3.2.2 Charged Higgs with hadronic $\tau$ decays ........... 12
       1.3.2.3 Trilepton searches  .................................... 12

Chapter  2  The Detector  ............................................. 14
2.1 General Overview ........................................ 14
  2.1.1 Collider Detectors .................................. 14
  2.1.2 Coordinate System ................................. 16
2.2 Central Tracking System .............................. 18
  2.2.1 The Silicon Vertex Detector .................... 19
  2.2.2 The Scintillating Fiber Tracker ................. 22
  2.2.3 The Solenoid Magnet ............................. 24
2.3 The Preshower Detectors ............................ 25
  2.3.1 Central Preshower ............................... 25
  2.3.2 Forward Preshower ............................... 26
2.4 Calorimetry ............................................ 27
  2.4.1 Basics of Calorimetry ............................ 28
  2.4.2 Particle Showers ................................. 28
  2.4.3 Calorimeter Design and Geometry ............... 32
  2.4.4 Central Calorimeter ............................. 34
  2.4.5 Endcap Calorimeters ............................ 37
  2.4.6 Intercryostat Detectors and Massless Gaps ..... 40
  2.4.7 Calorimeter Performance ....................... 41
2.5 Muon Systems .......................................... 42
2.6 Trigger Systems ...................................... 43
  2.6.1 Level 1 Trigger ................................ 43
  2.6.2 Level 2 Trigger ................................ 45

v
Chapter 3 Event Simulation and Reconstruction

3.1 Generation of signal and background events ........................................... 50
3.2 Reconstruction of events ........................................................................... 51
3.3 Calorimeter Hit Finding .............................................................................. 52
3.4 $E_T$-Calculation ...................................................................................... 55
3.5 Jet Reconstruction ...................................................................................... 56
3.6 TauReco: The tau reconstruction algorithm .............................................. 60

Chapter 4 Data Set and Analysis

4.1 Signal Samples ........................................................................................... 81
  4.1.1 $Z^0 \rightarrow \tau^+\tau^-$ ........................................................................... 82
  4.1.2 $W^\pm \rightarrow \tau^\pm \nu_\tau$ ................................................................. 82
  4.1.3 $H \rightarrow \tau^+\tau^-$ ........................................................................... 82
4.2 Background Samples ................................................................................. 82
4.3 Event Processing ....................................................................................... 83
  4.3.1 Ntuplemaking ..................................................................................... 83
  4.3.2 Comparison of Monte Carlo and Reconstructed Taus ....................... 85
  4.3.2.1 Selection of variables and optimization of cuts ......................... 86
  4.3.2.2 TauReco reconstruction efficiency ............................................ 88
4.4 Multivariate Analyses: Selection of Variables ......................................... 98
# List of Figures

1.1 Couplings of the SM Higgs boson to weak vector bosons and fermions [4]. ........................................... 9

1.2 Branching ratios for the Standard Model Higgs [4]. ................................................................. 9

1.3 Ratios of SUSY Higgs square couplings to the corresponding SM values

   as a function of $m_{A^0}$ for the case of $\tan \beta = 5$. .......................................................... 11

1.4 Cross sections for the decay of sparticles to 3 leptons as a function of $\tan \beta$. .......................................................... 13

2.1 Side view of the DØupgrade detector with major upgrade detector

   systems indicated. .......................................................................................................................... 17

2.2 One-half side view of the DØtracking upgrade (dimensions in mm). ........................................ 19

2.3 The disk-and-barrel assembly of the silicon microstrip detector. ............................................. 21

2.4 Charged particle momentum resolution capabilities vs. $\eta$ for various $p_T$'s. .................... 24

2.5 Cross sectional end (left) and side (right) views of the central preshower

   detector, with detail of the scintillator layers. ............................................................................. 26

2.6 One quarter side view of the forward preshower detector, with detail

   of the scintillator layers. .............................................................................................................. 27

2.7 Isometric view of the DØ calorimeter system. ......................................................................... 33
2.8  Schematic view of a DØ calorimeter cell. ........................................... 34
2.9  Side view of the calorimeters .............................................................. 35
2.10 Segmentation of the DØ calorimeter towers. ....................................... 35
2.11 Overview of the L2 trigger components. .............................................. 46

3.1  Jet width for signal and background. .................................................. 68
3.2  Jet width for signal and background. .................................................. 69
3.3  Number of tracks in cone size 0.1. .................................................... 70
3.4  Number of tracks in cone size 0.3. ..................................................... 71
3.5  Number of tracks in cone size 0.5. ..................................................... 72
3.6  Track isolation between cone sizes 0.1 and 0.3. ................................... 73
3.7  Track isolation between cone sizes 0.1 and 0.5. ................................... 74
3.8  Electromagnetic fraction in calorimeter. .............................................. 75
3.9  Profile. ................................................................................................. 76
3.10 Transverse momentum. ........................................................................ 77
3.11 (track momentum of track with highest $p_T$)/(cluster energy). .......... 78
3.12 Fisher variable. ..................................................................................... 79

4.1  Efficiency*purity as a function of the Fisher discriminant. The signal
is $Z^0 \rightarrow \tau^+ \tau^-$ and the background is QCD, $p_T$ 20 GeV, both with 1.1
average minimum bias. A global maximum - the optimal cut value - is
clearly discernible. ...................................................................................... 89
4.2 Signal vs background efficiency. The signal is $Z^0 \rightarrow \tau^+ \tau^-$ and the background is QCD, $p_T$ 20 GeV, both with 1.1 average minimum bias.

4.3 Efficiency/purity as a function of the Fisher discriminant. The signal is $W^\pm \rightarrow \tau^{\pm} \nu_\tau$ and the background is QCD, $p_T$ 20 GeV, both with 1.1 average minimum bias. No global maximum is seen.

4.4 Signal vs background efficiency. The signal is $W^\pm \rightarrow \tau^{\pm} \nu_\tau$ and the background is QCD, $p_T$ 20 GeV, both with 1.1 average minimum bias.

4.5 Leading and second leading track transverse momenta. Top - signal, bottom - background.

4.6 Distance from cluster axis of leading and second leading track transverse momenta. Top - signal, bottom - background.
**List of Tables**

1.1 Fundamental fermions in the Standard Model: leptons. ............... 2

1.2 Fundamental fermions in the Standard Model: quarks. ............... 3

1.3 Gauge bosons in the Standard Model. .............................. 5

1.4 Branching ratios of the principal $\tau$ decays (%). ............... 7

1.5 Couplings of the neutral Higgs bosons of MSSM; these multiply the
    SM Higgs couplings to obtain the MSSM tree-level couplings [4]. .... 10

2.1 Central Calorimeter parameters. ................................... 37

2.2 Endcap Calorimeter parameters. ................................... 39

4.1 Fisher discriminant optimization and Monte Carlo efficiencies for CC:
    $|\eta| < 1.1. (S - signal, B - background in last column of (a).) ....... 92

4.2 Jet width and profile optimization and Monte Carlo efficiencies for CC:
    $|\eta| < 1.1. (S - signal, B - background in last column of (a).) ....... 93

4.3 Track rms and profile optimization and Monte Carlo efficiencies for
    CC: $|\eta| < 1.1. (S - signal, B - background in last column of (a).) ....... 94

4.4 Fisher discriminant optimization and Monte Carlo efficiencies for EC:
    $|\eta| \geq 1.1. (S - signal, B - background in last column of (a).) ....... 95
4.5 Jet width and profile optimization and Monte Carlo efficiencies for EC:

\[ |\eta| \geq 1.1. (S - \text{signal}, \text{B - background in last column of (a).}) \]  

4.6 Track rms and profile optimization and Monte Carlo efficiencies for EC: \[ |\eta| \geq 1.1. (S - \text{signal}, \text{B - background in last column of (a).}) \]  

4.7 List of variables for \( \tau \) identification.
Chapter 1

Introduction and Theory

This chapter briefly surveys the theoretical framework underlying this analysis, and then moves on to discuss the theoretical issues directly related to this analysis.

1.1 Overview of the Standard Model

The Standard Model (SM) of particle physics is a Quantum Field Theory based on the idea of local gauge invariance [1] [2]. The gauge symmetry group of the SM is $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, where $SU(3)_C$ is the symmetry group of the strong interactions, and $SU(2)_L \otimes U(1)_Y$ is the symmetry group describing the weak and electromagnetic interactions.

The Standard Model treats the interactions as a field, and interprets the excitations in the fields as particles. Each separate field corresponds to a different type, or flavor, of a particle. There are two general classes of particles in the theory: 1) the fundamental fermions which have spin-$\frac{1}{2}$, and 2) the gauge bosons which have spin-1.
The fermions obey the Pauli exclusion principle, thus making up what is usually considered to be "matter." They are further subdivided into particles called leptons and quarks.

There are six flavors of leptons: the electron \( (e) \), the muon \( (\mu) \), the tau \( (\tau) \), and their corresponding neutrinos \( \nu_e \), \( \nu_\mu \), and \( \nu_\tau \). The leptons are grouped into 3 generations \( (e, \nu_e) \), \( (\mu, \nu_\mu) \) and \( (\tau, \nu_\tau) \). Each generation has similar properties, except that the masses increase with each successive generation. The charged leptons interact via the electromagnetic and weak forces, while the uncharged neutrinos interact only by the weak force. Experimentally, the masses of the neutrinos are constrained to be quite small, and the SM assumes that they are massless. Table 1.1 summarizes the main properties of the leptons.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Mass [MeV]</th>
<th>Charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e )</td>
<td>0.5110</td>
<td>-1</td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>(&lt; 15 \cdot 10^{-6})</td>
<td>0</td>
</tr>
<tr>
<td>( \mu )</td>
<td>105.7</td>
<td>-1</td>
</tr>
<tr>
<td>( \nu_\mu )</td>
<td>(&lt; 0.17)</td>
<td>0</td>
</tr>
<tr>
<td>( \tau )</td>
<td>1777</td>
<td>-1</td>
</tr>
<tr>
<td>( \nu_\tau )</td>
<td>(&lt; 24)</td>
<td>0</td>
</tr>
</tbody>
</table>

There are also six flavors of quarks: up \( (u) \), down \( (d) \), charm \( (c) \), strange \( (s) \), top \( (t) \), and bottom \( (b) \). Unlike the leptons, they possess fractional electric charge — either \(-1/3e\) or \(2/3e\), where \( e \) is the charge of the electron. They are also distinct in that they possess an internal degree of freedom called color, which can take on three
possible values. They consequently feel the strong force, which binds quarks together and builds nucleons and mesons. They can also interact via the electromagnetic or weak force. The quarks are also grouped into three generations \((u, d), (c, s), \) and \((t, b)\), with each generation having similar properties, except the masses of the quarks which increase with each successive generation. Table 1.2 summarizes the main properties of the quarks.

**Table 1.2: Fundamental fermions in the Standard Model: quarks.**

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass [GeV/c(^2)]</th>
<th>Charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u)</td>
<td>(1.5 \cdot 10^{-3})</td>
<td>(2/3)</td>
</tr>
<tr>
<td>(d)</td>
<td>(3.9 \cdot 10^{-3})</td>
<td>(-1/3)</td>
</tr>
<tr>
<td>(c)</td>
<td>(1.15-1.35)</td>
<td>(2/3)</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.08-0.17)</td>
<td>(-1/3)</td>
</tr>
<tr>
<td>(t)</td>
<td>(174.3)</td>
<td>(2/3)</td>
</tr>
<tr>
<td>(b)</td>
<td>(4.0-4.4)</td>
<td>(-1/3)</td>
</tr>
</tbody>
</table>

The gauge bosons are the mediators of the forces between the different particles in the theory. An interaction between two particles is viewed as a process in which these two particles exchange a virtual gauge boson. The main properties of the gauge bosons are summarized in Table 1.3.

**Electromagnetism** is mediated by the photon \((\gamma)\), and is described by Quantum Electrodynamics (QED). Any two charged particles interact by coupling to the photon. Since the photon is massless, the electromagnetic interaction has very long range. An interesting feature of electromagnetism is the "running" of the coupling strength:
it increases as the energy involved in the interaction increases. This running feature is not unique to QED, and appears in other sectors of the theory.

The weak interaction is mediated by the $W^\pm$ and $Z^0$ bosons. Since these gauge bosons are massive (with masses around 100 GeV/c$^2$), the weak interaction has a short range of $\sim 10^{-18}$ m. In the Standard Model, the treatment of the electromagnetic and weak forces has been unified in the Glashow-Weinberg-Salam (GSW) model, and these interactions are referred to as electroweak interactions.

The strong force is mediated by the gluons, and is described by Quantum Chromodynamics (QCD). There are a total of eight gluons, which couple to particles possessing the color charge (these particles are the quarks and the gluons themselves). There are three possible color charges, conventionally called red, blue and green. As is the case in QED, the value of the coupling runs. However, the direction of the effect is opposite: the strength of the coupling decreases as the energy in the interaction increases, thereby allowing quarks to behave as free particles (asymptotic freedom) at energies typical of modern high-energy experiments ($E > 10$ GeV), and it allows the use of perturbative techniques in theoretical calculations of processes in this regime. However, at lower energies, the coupling strength becomes large enough that perturbation theory breaks down, and renders any perturbative calculation nearly impossible.
Table 1.3: Gauge bosons in the Standard Model.

<table>
<thead>
<tr>
<th>Gauge boson</th>
<th>Mass [GeV/c²]</th>
<th>Charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluons</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>γ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W±</td>
<td>80.45</td>
<td>±1</td>
</tr>
<tr>
<td>Z⁰</td>
<td>90.91</td>
<td>0</td>
</tr>
</tbody>
</table>

The remaining ingredient of the Standard Model is the spin-0 particle called the Higgs boson. Its existence is required by the introduction of spontaneous symmetry breaking (Higgs mechanism) into the Electroweak sector of the theory. The latter is necessary in providing masses to the $W$ and $Z$ gauge bosons, since the gauge symmetry of the fundamental theory requires them to be massless. The quarks and leptons can also acquire masses through this mechanism. If the SM is correct, the Higgs should appear as a real particle. To date, the Higgs boson has not been observed.

1.2 The tau lepton and its properties

The $\tau$ lepton is a member of the third generation of leptons in the Standard Model (SM), with its own quantum number and associated neutrino. This section reviews the static properties of the $\tau$. 
1.2.1 Mass and lifetime

The mass and the lifetime of the $\tau$ have been measured by various techniques in several experiments [6]. The current world averages are

$$m_\tau = 1777.05^{+0.26}_{-0.26} \text{ MeV}$$  \hspace{1cm} (1.1)

and

$$\tau_\tau = (290.5 \pm 1.0) \times 10^{-15} \text{ s}$$  \hspace{1cm} (1.2)

1.2.2 Decay modes and branching ratios

In the Standard Model, the $\tau$ decays in the same way as the $\mu$: through the emission of a $W$ boson. However, several extra modes are kinematically accessible to the $\tau$ due to its large mass compared to that of the $\mu$. The 1998 Particle Data Group review [13] quotes 104 measured decay channels of the $\tau$ plus upper limits on another 20 allowed modes. Table 1.4 summarizes the principal decay modes and branching ratios of the $\tau$. 
Table 1.4: Branching ratios of the principal $\tau$ decays (%).

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Measurement</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e \nu_e \nu_\tau$</td>
<td>$17.81 \pm 0.07$</td>
<td>$17.772 \pm 0.075$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \nu_\mu \nu_\tau$</td>
<td>$17.37 \pm 0.09$</td>
<td>$17.282 \pm 0.073$</td>
</tr>
</tbody>
</table>

Decay to single $\pi/K$

<table>
<thead>
<tr>
<th>Decay</th>
<th>Measurement</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \pi \nu_\tau$</td>
<td>$11.08 \pm 0.13$</td>
<td>$10.87 \pm 0.05$</td>
</tr>
<tr>
<td>$\tau \rightarrow K \nu_\tau$</td>
<td>$(7.1 \pm 0.5) \times 10^{-3}$</td>
<td>$(7.08 \pm 0.04) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Decays to an Even Number of Pions

<table>
<thead>
<tr>
<th>Decay</th>
<th>Measurement</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^- \pi^0$</td>
<td>$25.32 \pm 0.15$</td>
<td>$24.52 \pm 0.33$</td>
</tr>
<tr>
<td>$\pi^- 3 \pi^0$</td>
<td>$1.11 \pm 0.14$</td>
<td>$1.10 \pm 0.04$</td>
</tr>
<tr>
<td>$2\pi^- \pi^+ \pi^0$</td>
<td>$4.22 \pm 0.10$</td>
<td>$4.06 \pm 0.25$</td>
</tr>
<tr>
<td>Others</td>
<td>$0.36 \pm 0.04$</td>
<td>$0.37 \pm 0.04$</td>
</tr>
</tbody>
</table>

Decays to Three and Five Pions

<table>
<thead>
<tr>
<th>Decay</th>
<th>Measurement</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^- \pi^+ \pi^-$</td>
<td>$9.23 \pm 0.11$</td>
<td></td>
</tr>
<tr>
<td>$\pi^- \pi^0 \pi^0$</td>
<td>$9.15 \pm 0.15$</td>
<td></td>
</tr>
<tr>
<td>$3h^- 2h^+$</td>
<td>$0.075 \pm 0.007$</td>
<td></td>
</tr>
<tr>
<td>$2h^- h^+ 2\pi^-$</td>
<td>$0.11 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>$h^- 4\pi^0$</td>
<td>$0.11 \pm 0.06$</td>
<td></td>
</tr>
</tbody>
</table>

1.3 Motivation for $\tau$ ID at hadronic colliders

Tau leptons are a precision measurement tool for lepton universality, as well as a sensitive probe for new physics. One of the compelling reasons for studying $\tau$s at hadronic colliders is that final states with $\tau$s may be of great importance in Higgs and supersymmetry (SUSY) searches. This section describes briefly some of the physics processes for which these final states could be of significance; please see references [3], [4] and [5] for details.
1.3.1 Standard Model Higgs boson

At the Tevatron, the standard model (SM) Higgs may be produced by gluon-gluon fusion $gg \rightarrow H^0$, with cross section for the fusion, $\sigma_{gg}$, of the order of a few picobarns [3]. The standard Higgs boson couples to the weak bosons and the fermions proportional to their mass, as shown in Figure 1.1 [4]. Therefore the Higgs boson tends to decay to the heaviest pair of particles that are kinematically allowed (There are exceptions though; for details see reference 51 in [4]). The branching ratios for the SM Higgs boson are shown in Figure 1.2, where the mass of the top quark has been taken to be 175 GeV. The neutral Higgs decays predominantly to $b$ quark, but in the mass range $80 < m_H < 130$ GeV has an 8% branching ratio into $\tau^+\tau^-$, accessible with Run II.

1.3.2 Standard Model Extensions - Supersymmetry

There are several extensions to the SM Higgs sector, of which one of the most attractive ones (to theorists) is to allow additional Higgs doublet fields. Only the minimal supersymmetric standard model (MSSM), a specific case of the more general two-Higgs-doublet model (2HDM), is discussed here [4]. The MSSM predicts five physical Higgs particles: two $CP$-even neutral scalars, $h^0$ and $H^0$; one $CP$-odd neutral scalar, $A^0$; and a pair of charged scalars, $H^\pm$. At tree level, the Higgs sector is described by just two free parameters; by convention, these are usually chosen
\[ 2i \frac{M_V^2}{v} = \begin{cases} \frac{igM_W}{v} & V = W \\ \frac{ig}{\cos\theta_W} \frac{M_Z}{v} & V = Z \end{cases} \]

\[-i \frac{m_f}{v} = -i \frac{g}{2} \frac{m_f}{M_W} \]

**Figure 1.1:** Couplings of the SM Higgs boson to weak vector bosons and fermions [4].

---

**Standard Model Higgs Branching Ratios**

\( m_t = 175 \text{ GeV} \)

**Figure 1.2:** Branching ratios for the Standard Model Higgs [4].
to be the mass of the CP-odd scalar, $m_{A^0}$, and $\tan\beta = v_2/v_1$, where $v_2(v_1)$ is the vacuum expectation value of the neutral members of the Higgs doublet that couples to the up-type (down-type) quark. Another phenomenologically important parameter is $\alpha$, the mixing angle arising from the diagonalization of the $2 \times 2$ mass matrix for the $CP$–even Higgs sector. At tree level, the MSSM Higgs couplings are just the SM couplings multiplied by factors that depend on these parameters, as shown in Table 1.5.

**Table 1.5:** Couplings of the neutral Higgs bosons of MSSM; these multiply the SM Higgs couplings to obtain the MSSM tree-level couplings [4].

<table>
<thead>
<tr>
<th></th>
<th>$WW, ZZ$</th>
<th>$t\bar{t}$</th>
<th>$b\bar{b}, \tau^+\tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^0$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\cos \alpha / \sin \beta$</td>
<td>$-\sin \alpha / \cos \beta$</td>
</tr>
<tr>
<td>$H^0$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\sin \alpha / \sin \beta$</td>
<td>$\cos \alpha / \cos \beta$</td>
</tr>
<tr>
<td>$A^0$</td>
<td>0</td>
<td>$\gamma_5 \cot \beta$</td>
<td>$\gamma_5 \tan \beta$</td>
</tr>
</tbody>
</table>

### 1.3.2.1 Neutral SUSY Higgs

As can be seen from Table 1.5, the branching ratios and production cross sections of the SUSY Higgs bosons can be very different from those of the SM Higgs boson. Figure 1.3 shows the ratio of the SUSY to SM couplings for $\tan\beta=5$. The coupling of SUSY Higgses to the weak vector bosons ($W,Z$) is at most as large as that of the SM Higgs; this means that the branching ratios of the SUSY Higgs to $W,Z$ can be suppressed with respect to the SM Higgs. On the other hand, the coupling of SUSY
Higgs to the $b\bar{b}, \tau^+\tau^-$ is enhanced over that of the SM Higgs for $\tan\beta > 1$. Enhanced $b\bar{b}, \tau^+\tau^-$ couplings further suppress the branching ratio of the SUSY Higgs bosons to weak vector bosons. Thus, at large $\tan\beta$, one can search for both $A^0$ and $H^0$ by looking for their decays to fermions (specifically, to $\tau s$ in the context of the present study).

**Figure 1.3:** Ratios of SUSY Higgs square couplings to the corresponding SM values as a function of $m_{A^0}$ for the case of $\tan\beta = 5$. 
1.3.2.2 Charged Higgs with hadronic $\tau$ decays

In the Standard Model, the top quark ($t$) decays almost exclusively to a $b$ quark and a $W\pm$. However, if charged Higgs bosons $H^\pm$ exist with $m_{H^\pm} < m_t$, then the decay chain $t \rightarrow H^\pm b \rightarrow \tau \nu, b$ could increase the $\tau$ event rate. At large $\tan \beta$ in particular [3], the decay of the $t$ quarks through $H^\pm$ dominates over the $W^\pm$-mediated decay, and the charged Higgs decays almost exclusively to a $\tau$ lepton (see Figure 3 in reference [3]), unlike the $W$, which can decay to quarks and other leptons. Thus, an enhancement in the $\tau$ channel could indicate the presence of a charged Higgs sector.

1.3.2.3 Trilepton searches

MSSM Higgs bosons can also decay to channels that are not present for the SM Higgs [4]. In addition to the SM decay modes, MSSM Higgs bosons can decay to channels involving other Higgs bosons (for example: $h^0 \rightarrow A^0 A^0; A^0 \rightarrow Z^0 h^0; H^+ \rightarrow W^+ h^0, W^+ A^0; \text{etc.}$) as well as to pairs of supersymmetric particles (for example: $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0; H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \tilde{\chi}_2^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\ell}^- \tilde{\ell}^+$ – $\tilde{\chi}$'s are charginos and neutralinos, and $\tilde{\ell}$ a slepton). The production of, say, $\tilde{\chi}_1^+ \tilde{\chi}_2^0$, followed by the decays $\tilde{\chi}_1^+ \rightarrow \chi_1^0 l^+ \nu$ and $\tilde{\chi}_2^0 \rightarrow l^+ l^- \chi_1^0$, is a source of three charged leptons and $E_T$, called trilepton events. The SM background for trilepton signal is small, and the trilepton signal is consequently considered to be one of the “golden” SUSY signatures [3]. The branching fractions also depend on $\tan \beta$, as depicted in Figure 1.4; at high values of $\tan \beta$, the tri-$\tau$ branch
dominates, thereby making $\tau$ identification an issue of paramount importance in the search for SUSY.

\[ \sqrt{s} = 2.0 \text{ TeV}, \mu > 0, m_{1/2} = 200 \text{ GeV} \]

(a) $m_{\tilde{g}} = 100 \text{ GeV}$

(b) $m_{\tilde{g}} = 200 \text{ GeV}$

Figure 1.4: Cross sections for the decay of sparticles to 3 leptons as a function of $\tan \beta$. 
Chapter 2

The Detector

The key to physics analysis is an in-depth understanding of the detector. This chapter provides an overview of collider detectors in general, followed by descriptions of the components comprising the DØ detector, with emphasis on the upgraded systems [7].

2.1 General Overview

2.1.1 Collider Detectors

Although details vary from detector to detector, a typical collider detector experiment is performed as follows. Two particle beams travelling in opposite directions are magnetically focused to collide in the center of the detector, the interaction region. In proton-antiproton collisions, the collision results in a large number of particles. The
detection and identification of these particles is done by energy measurement systems and tracking systems for charged particles.

Tracking consists of converting the measured energy loss of charged particles, \( dE/dx \), into particle trajectories. The energy loss causes ionization in the tracking material at various locations along the path of the particle, which are recorded for subsequent reconstruction into tracks. The tracking systems are located closest to the interaction region in order to maximize precision for vertex location and minimize multiple scattering. A central magnetic field allows for momentum determination of charged particles by measuring the curvature of their tracks. See section 2.2 for details of the DØ central tracking system.

The energy measuring systems (calorimetry) lie outside the central tracking system. The calorimeters cover as much solid angle as possible and incorporate as much heavy material as possible, with the aim of containing, and therefore measuring, as much energy as possible. DØ calorimetry is described in section 2.4.

Finally, the muon detection systems are located outside the calorimeter; the calorimeter filters out almost all particles except the highly penetrating muons. For details of the DØ muon systems, see section 2.5.

In the upgraded DØ detector to be used for Run II (see Figure 2.1), the tracking system consists of an inner silicon vertex detector surrounded by eight layers of scintillation fiber trackers, with a central magnetic field of 2 Tesla provided by
a superconducting solenoid. The calorimetry consists of a central calorimeter (CC) and two endcap calorimeters (EC), each contained in a cryostat. In addition, two systems - the massless gap (MG) detector and the inter-cryostat detector (ICD) - aid in measuring energy in the gaps between the CC and the ECs. Finally, outside the calorimeter cryostats lies the muon system, consisting of three measuring planes, with a toroidal magnet between the first and second planes to allow charge determination and momentum measurement independent of the central tracking.

### 2.1.2 Coordinate System

DØ uses a right-handed coordinate system with the positive $z$-axis in the direction of the proton beam, and the positive $y$-axis pointing towards the zenith [8]. The angular coordinates (azimuthal $\phi$ and polar $\theta$) are defined such that $\phi = 0$ coincides with the $+x$ direction and $\theta = 0$ with $+z$ direction. Radial distances are measured perpendicular to the beam line. Instead of the angle $\theta$, it is convenient to use the pseudorapidity, $\eta$, defined by

$$\eta \equiv -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right] = \tanh^{-1}(\cos \theta) \tag{2.1}$$

The pseudorapidity approximates the true rapidity$^1$ of a particle,

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \tag{2.2}$$

---

$^1$The center of mass of the partons involved in the hard scatter is not necessarily at rest in the laboratory frame. In this case, for a parton of energy $E$ and momentum $p$, the rapidity as defined in Equation 2.2 is a Lorentz invariant quantity.
Figure 2.1: Side view of the DØ upgrade detector with major upgrade detector systems indicated.
in the limit $m \ll E$, where $m$ is the particle's rest mass. The benefit of using
$\eta$ is that the differential cross section distribution $\partial \sigma / \partial \eta$ is approximately Lorentz
invariant. In addition, it is often convenient to express polar angles in terms of
"detector pseudorapidity", $\eta_{\text{det}}$, which is computed with respect to the interaction
point which is characterized by a Gaussian distribution with mean $z = 0$ cm and
deviation $\sigma_z = 25$ cm, thus causing a slight difference between $\eta$ and $\eta_{\text{det}}$ for any
given particle.

Momentum conservation cannot be applied in the direction of the colliding
particles due to collision products going down the beam pipe. However, one can
apply momentum conservation in the plane perpendicular to the beam line. This
"transverse momentum" $p_T = p \sin \theta$ is conserved.

2.2 Central Tracking System

Due to the luminosity and radiation considerations, the upgrade for the tracking
system consists of entirely replacing the Run I tracking system. The upgraded
tracking system consists of the silicon vertex detector, the scintillating fiber tracker,
the superconducting solenoidal magnet, and the preshower. The tracking system is
designed to meet several goals: momentum measurement with the solenoidal field;
good electron identification and $e/\pi$ rejection; tracking over a large range in pseudo-
raptoridity ($\eta \approx \pm 4$); secondary vertex measurement for identification of $b$-jets from
top and for b-physics; hardware tracking trigger; fast detector response to enable operation with a bunch crossing time of 132 ns; and radiation hardness. The tracking system is shown in Figure 2.2.

Figure 2.2: One-half side view of the DØ tracking upgrade (dimensions in mm).

2.2.1 The Silicon Vertex Detector

*Principle of operation*
The characteristic property of a monocrystalline semiconducting material is the small separation between the electronic conduction band and the valence band. A small amount of energy, \( E_g = 1.12 \text{ eV} \) in the case of silicon, is therefore sufficient to excite an electron into the conduction band, leaving a hole in the valence band. At a given temperature, there is equilibrium between the generation and recombination of free electrons and holes. Free charge in excess of this thermal equilibrium value can be generated by the passage of ionizing radiation. This radiation-produced charge can then be collected by applying an electric field to the semiconductor. For silicon, the average energy needed to create an electron-hole pair is 3.62 eV at 300 K (3.81 at 77 K). This small value provides the advantage of silicon detectors over other types of detectors; it is an order of magnitude smaller than the energy needed to create an electron-ion pair in a gaseous ionization detector, and almost two orders of magnitude smaller than the energy loss required to create a photon in a scintillation detector [11]. Thus the amount of ionization produced for a given energy is an order (two orders) of magnitude greater than that in gas ionization (plastic scintillation) detectors, resulting in increased resolution.

The DØ silicon tracking upgrade is based on microstrip silicon detectors. This is a discrete-type detector consisting of a series of individual electrode strips placed on the same silicon base, so that each electrode acts as a separate detector.
The silicon tracker is the high resolution part of the tracking system and is the first set of detectors encountered by particles emerging from the collision. Since the interaction point is extended, with a deviation $\sigma_z$ of 25 cm, it is difficult to deploy detectors such that the tracks are generally perpendicular to detector surfaces for all $\eta$. Therefore, an interspersed disk-and-barrel design, shown in Figure 2.3, has been adopted, with barrel detectors measuring primarily the $r - \phi$ coordinate and disk detectors which measure $r - z$ as well as $r - \phi$.

![Figure 2.3: The disk-and-barrel assembly of the silicon microstrip detector.](image)

The barrel consists of 6 sections, each 12 cm long and containing 4 concentric cylindrical layers. The first and third layers are single-sided detectors with axial strips in the end sections on each side, and double-sided detectors with axial and $90^\circ$ $z$-strips in the inner four sections. The second and fourth layers are double-sided detectors
with axial and 2° stereo strips. There are 12 small diameter “F” disks (with 30° stereo strips) and 4 large diameter “H” disks (with 15° stereo strips). Four of the F disks are interspersed in the barrel, and 4 placed at each end of the barrel. Two H disks are located beyond the barrel at each end (at ±94 cm and ±126 cm), providing improved momentum resolution up to $|\eta| = 3$. The individual channel count for layer 1, 2, 3, and 4 is 46k, 83k, 92k and 166k respectively. It is 258k for F disks and 147k for H disks, resulting in a total channel count of 792k.

The barrel and the F disks are based on 50 and 62.5 μm pitch silicon microstrip detectors, 300 μm thick, providing a spatial resolution of approximately 10 μm. The small angle stereo detectors provide the pattern recognition necessary to resolve tracks from b decays within jets. The 90° detectors provide resolution in $r - z$ at the vertex of 100 μm, allowing identification of decay fragments by impact parameter in the $r - z$ plane. The detectors are AC-coupled; each strip has an integrated coupling capacitor and a polysilicon bias resistor.

### 2.2.2 The Scintillating Fiber Tracker

*Principle of operation*

Scintillation detectors make use of the fact that certain materials when struck by a nuclear particle or radiation, emit a small flash of light, i.e. a scintillation. When coupled to an amplifying device such as a photomultiplier, directly or via a light guide,
these scintillations can be converted into electrical pulses which can then be analysed and counted electronically to give information about the incident radiation.

*The DØ upgrade*

A scintillating fiber tracker, consisting of about 74,000 fibers mounted on eight concentric cylinders, surrounds the silicon vertex detector and covers the central pseudorapidity region. The fibers are multicl clad, with an inner polystyrene core of diameter 835 μm, covered by a 15 μm thick acrylic cladding, which in turn is covered by a 15 μm fluoro-acrylic cladding. The three materials have indices of refraction of 1.59, 1.49 and 1.42 respectively. The addition of a second cladding increases the light trapping by about 70 % with respect to single-clad fibers. To provide wavelength shifting, the polystyrene core is doped with 1% p-terphenyl and 1500 ppm 3-hydroxyflavone. The scintillation light is conducted by multicl clad fiber waveguides to visible light photon counters (VLPCs), a variant of the solid state photomultiplier. Spatial resolution, based on cosmic ray test studies, is expected to be about 100 μm (compared to 10 μm of the high-resolution silicon vertex detector).

The fiber tracker serves two main functions. First, with the silicon vertex detector, the tracker enables track reconstruction and momentum measurement for all charged particles within the range |η| < 2.0. Second, it provides fast, “Level 1” track triggering within the range |η| < 1.6. Combining information from the tracker with
the muon and preshower detectors, triggers for both single muons and electrons will be formed at Level 1.

2.2.3 The Solenoid Magnet

The momenta of charged particles will be determined from their curvature in the 2T magnetic field provided by a superconducting solenoid. Inside the tracking volume the value of \(\sin \theta \int B_z dz\) along the trajectory of any particle reaching the solenoid is uniform to within 0.5%. The momentum measurement capabilities of the upgraded DØ detector are shown in Fig. 2.4.

![Graph showing the relationship between pseudorapidity (η) and momentum resolution (δp/|p|) for various p_T values](image)

**Figure 2.4:** Charged particle momentum resolution capabilities vs. \(\eta\) for various \(p_T\)s.
2.3 The Preshower Detectors

The preshower detectors are designed to serve two functions. The first is to function as a calorimeter by early energy sampling and to correct for the effects of the solenoid. The second is to enhance the electron identification capability by making precision position measurements of particle trajectories using $dE/dx$ and showering information collected just upstream of the calorimeter. The preshower detectors consist of two parts: the central preshower (CPS), shown in Fig. 2.5, and the forward preshower (FPS), shown in Fig. 2.6. Both are made of triangular scintillating strips with embedded wavelength-shifting fibers, read out by visible light photon counters.

2.3.1 Central Preshower

The CPS is located in the gap between the outer radius of the solenoid and the inner radius of the central calorimeter cryostat at a radius of 72 cm, and covers the region $-1.2 < \eta < 1.2$. The detector consists of three layers of scintillating strips arranged in axial and stereo views. The stereo angles for the two stereo layers are $\approx \pm 23^\circ$. A lead absorber before the detector is tapered in $z$ so that the solenoid plus lead total two radiation lengths of material for all particle trajectories.
Figure 2.5: Cross sectional end (left) and side (right) views of the central preshower detector, with detail of the scintillator layers.

The fast energy and position measurements enable use of preshower information at the trigger level to aid electron identification. The axial layer of the preshower will be used in the Level 1 electron trigger.

2.3.2 Forward Preshower

Two FPS detectors cover the pseudorapidity range $1.4 < |\eta| < 2.5$, with one detector mounted on the inner face of each of the Endcap Calorimeter (EC) cryostats and conforming to the shape of the cryostat shells. The detector is composed of a layer of lead absorber sandwiched between two active scintillator planes, with each
Figure 2.6: One quarter side view of the forward preshower detector, with detail of the scintillator layers.

scintillator plane consisting of one $u$ and one $v$ sublayer. The lead consists of two radiation lengths in the high-$\eta$ region, and is tapered in the region $1.4 < |\eta| < 1.6$ in order to equalize the amount of material traversed as a function of $\eta$.

2.4 Calorimetry

The Calorimeter system is a crucial part of the DØ detector since it provides the only means to measure the energy of, and plays a vital role in the identification
of, all final state particles that deposit energy in the calorimeter: leptons, photons, jets.

2.4.1 Basics of Calorimetry

Calorimeters can be of two types: continuous or sampling. A homogeneous calorimeter is made of one continuous absorber, usually using some inorganic scintillating crystal (such as NaI, BGO or lead glass). Though this achieves better resolutions, the drawback is that only the total energy deposited is measured. Information about shower shape, important in the discrimination of leptons and hadrons, is lost. In a sampling calorimeter, very dense material is used to provide the necessary thickness to stop the incident particles; this dense material is not active, however. The active material is interspersed between the dense absorber plates to sample the energy of the particle showers; usually, the energy is measured by means of measuring the ionization produced by the charged particles in the shower. The portion of energy that is actually measured is called the sampling fraction. Interspersing active and passive materials allows for a compact calorimeter design.

2.4.2 Particle Showers

Particle showers can be classified into two types: electromagnetic and hadronic.
Electromagnetic showers

Electrons and photons produce electromagnetic showers. The interaction of electrons and photons with matter at energies well above 10 MeV occurs primarily via the creation of electron/positron pairs and the Bremsstrahlung mechanism\(^2\). An electromagnetic shower develops as an alternating sequence of interactions of these two types. For example, a primary electron will lose energy by emitting a photon. The photon will convert into an \(e^+e^-\) pair, which in turn will lose energy by emitting other photons. The process keeps occurring and the shower keeps developing until the energy of all secondary particles reaches a level where ionization losses and atomic excitations become important. In a dense medium such as the calorimeter, the cross section for these interactions is high, and results in a very compact electromagnetic shower. The energy loss of an electromagnetic particle is characterized by the radiation length \(X_0\):

\[
\frac{dE}{E} = -\frac{dx}{X_0}
\]  

(2.3)

The radiation length is dependent on the absorbing medium: it is 0.32 cm for uranium and 13.5 cm for liquid argon.

Hadronic Showers

The development of hadronic showers [12] in matter is a complex process depending upon many factors, such as the strong interaction cross section, the species

\(^2\)This is the mechanism where a charged particle interacts with the Coulomb field surrounding a nucleus and emits an energetic photon.
dependent multiplicities and momentum distributions, the nuclear breakup and excitations, and many others. Hadron showers develop through a sequence of interactions and the resultant generation of particles produced after a strongly interacting particle enters a dense medium. The principal processes controlling this development are the nuclear interactions and the subsequently produced strongly interacting particles. From each interaction there emerges the generation of particles which extend or truncate the chain of interactions. Within the sequence, there are produced electrons and photons which initiate very localized electromagnetic showers within the hadronic shower. The charged particles of the shower lose energy during the shower development through Coulomb scattering interactions in the medium. In addition to the particle multiplicity resulting from the strong interactions, the violent disruption of the involved nuclei releases a host of low energy nucleons, requiring a large fraction of the energy of the incident particle to overcome the nuclear binding energy. It is, in fact, this latter effect which represents one of the fundamental limitations of using the deposited energy to measure accurately the energy of the incident particle. To further complicate the process of detection, the calorimeter responds differently to different species. This leads to the concept of compensating calorimeters, which is discussed shortly. For hadronic showers, the analog to the radiation length is the nuclear interaction length, $\lambda$, which is the mean free path of hadrons between inelastic nuclear collisions. For uranium, the interaction length is 10.5 cm [13].
difference in shower shape and size is the primary tool that DØ uses to differentiate electromagnetic and hadronic showers.

Compensation and the importance of $e/\pi$

The signal measured for incident electrons and hadrons of the same energy can be different. The ratio of the measured signals for electrons and hadrons with equal incident energies is called the intrinsic $e/\pi$ ratio of the calorimeter; ideally, it is unity. Hadronic cascades with large amounts of electromagnetic energy (type A) have less losses of energy due to nuclear break-up than those which contain little electromagnetic energy (type B) and therefore a large number of hadronic interactions. In type B, the losses include nuclear binding energy, as well as heavy fragment production, neutrino production, and low energy nucleon generation. In a non-compensating calorimeter, this results in type A showers having $e/\pi$ ratio close to one, whereas type B showers have $e/\pi$ ratio greater than one. In a compensating calorimeter, the response to events of types A and B are equalized (as best as possible), with an average response comparable to the response for an electron. The nuclear break-up energy has been compensated for, by designing the calorimeter to preferentially respond to the low energy neutron component of the shower, which is correlated to the lost nuclear break-up energy. This design consists of achieving the proper balance between the thickness of the radiator (uranium) and sampler (liquid argon). Uranium calorimeters having different sampling media have very different responses
because the signal from the neutrons comes from their direct interaction in the sampling medium, and different media have different levels of sensitivity. Details of all factors relevant to compensation are beyond the scope of this paper; the interested reader may consult [12].

### 2.4.3 Calorimeter Design and Geometry

The DØ Calorimeter is a sampling calorimeter, with liquid argon (LAr) as the active medium to sample the ionization produced in electromagnetic or hadronic showers. The use of LAr requires cryostats to hold the liquid argon at cryogenic temperatures. The design, shown in Figure 2.7, consists of one Central Cryostat (CC) covering the region $|\eta| < 1.2$, two Endcap Cryostats (EC) extending the coverage to $|\eta| \approx 4$, and the Inter-cryostat Detector (ICD) to cover their overlapping region.

The DØ Calorimeter is highly modular, and finely segmented in the transverse and longitudinal shower directions. Three distinct types of modules are used in the CC and EC: an electromagnetic section (EM) with relatively thin uranium-238 absorber plates, a fine hadronic section (FH) with thicker uranium plates and a coarse hadronic section (CH) with thick copper or stainless steel plates. Each module consists of a row of alternating absorber plates and signal readout boards, as shown in Figure 2.8. The 2.3 mm gap separating adjacent absorber plates and signal boards is filled with LAr. The signal boards consist of a copper pad with two separate 0.5 mm thick G-10
sheets laminated at each end. The outer surfaces of the boards are coated with a highly resistive epoxy. An electric field is established by grounding the absorber plate while applying a positive potential (typically 2.0-2.5 kV) to the resistive surfaces of the signal boards. Incident particles shower in the absorber plates, and the resulting shower particles ionize the LAr in the adjacent gap. The liberated electrons drift to the signal boards (the drift time is $\approx 450$ ns), and induce a signal on the copper pad. Signals from several signal boards in the same $\eta$ and $\phi$ region are ganged together in depth to form a readout cell.

The pattern and sizes of the readout cells were determined from considerations of shower sizes. The transverse dimensions of the readout cell were chosen to be
Figure 2.8: Schematic view of a DØ calorimeter cell.

similar to the transverse sizes of showers: $\sim 1$–$2$ cm for EM showers and $\sim 10$ cm for hadronic showers. Furthermore, longitudinal segmentation within the EM, FH and CH layers helps in the distinction and separation of electrons from hadrons. The design was chosen to be *pseudo-projective*: the centers of the cells lie on lines which project back to the center of the detector, but the cell boundaries are aligned perpendicular to the absorber plates. This is clearly illustrated in Figure 2.9.

### 2.4.4 Central Calorimeter

The Central Calorimeter (CC) is composed of three cylindrical concentric shells parallel to the beam axis. Radially, it occupies the space $75 < r < 222$ cm from the
Figure 2.9: Side view of one quadrant of the calorimeters. Also shown are lines of constant pseudorapidity.

Figure 2.10: Segmentation of the DØ calorimeter towers.
beam pipe with a length of 226 cm, thus achieving an angular coverage of $35^\circ < \theta < 145^\circ$, or $|\eta| < 1.2$. The inner shell consists of 32 electromagnetic (EM) modules, thick enough to contain most electromagnetic showers. The middle shell, made of 16 fine hadronic (FH) modules, measures showers of hadronic particles, while the outer layer, made of 16 coarse hadronic (CH) modules, measures any leakage out of the FH layer while minimizing punchthrough, the energy flow out of the calorimeter and into the muon system. The EM modules consist of 21 radial cells, arranged in four readout layers (EM1 through EM4). Each cell is composed of a 3 mm depleted uranium absorber plate and a 2.3 mm LAr gap for a sampling fraction of 12.9%. The FH modules consist of 50 radial cells, arranged in three readout layers (FH1 through FH3), with each cell made from a 6 mm uranium-niobium alloy (U-Nb) absorber plate and a 2.3 mm LAr gap for a sampling fraction of 6.9%. Finally, the CH modules consist of 9 radial cells, but only one readout layer. The CH cells use 4.75 cm copper absorber plates with a 2.3 mm LAr gap for a sampling fraction of 1.7%.

The transverse segmentation of the calorimeter is $0.1 \times 0.1$ in $\eta \times \phi$ space, except in the third EM layer (EM3). This layer, corresponding to the EM shower maximum, has its segmentation increased to $0.05 \times 0.05$ in $\eta \times \phi$ space in order to fully optimize the distinguishability between electron and hadronic showers. In addition, each concentric shell (EM, FH and CH) is rotated azimuthally, thus avoiding any continuous cracks.
The segmentation of the calorimeter is shown in Figure 2.10, while the major design specifications of the CC are listed in Table 2.1.

**Table 2.1: Central Calorimeter parameters.**

<table>
<thead>
<tr>
<th>CC module type</th>
<th>EM</th>
<th>FH</th>
<th>CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidity coverage</td>
<td>± 1.2</td>
<td>± 1.0</td>
<td>± 0.6</td>
</tr>
<tr>
<td>Number of modules</td>
<td>32</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Absorber*</td>
<td>Uranium</td>
<td>Uranium</td>
<td>Copper</td>
</tr>
<tr>
<td>Absorber thickness [cm]</td>
<td>0.3</td>
<td>0.6</td>
<td>4.65</td>
</tr>
<tr>
<td>Liquid argon gap [cm]</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Number of cells per module</td>
<td>21</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>Longitudinal depth</td>
<td>20.5 $X_0$</td>
<td>3.24 $\lambda_0$</td>
<td>2.93 $\lambda_0$</td>
</tr>
<tr>
<td>Number of readout layers</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cells per readout layer</td>
<td>2, 2, 7, 10</td>
<td>21, 16, 13</td>
<td>9</td>
</tr>
<tr>
<td>Total radiation lengths</td>
<td>20.5</td>
<td>96.0</td>
<td>32.9</td>
</tr>
<tr>
<td>Radiation length per cell</td>
<td>0.975</td>
<td>1.92</td>
<td>3.29</td>
</tr>
<tr>
<td>Total absorption lengths ($\lambda$)</td>
<td>0.76</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Absorption length per cell</td>
<td>0.036</td>
<td>0.0645</td>
<td>0.317</td>
</tr>
<tr>
<td>Sampling fraction [%]</td>
<td>11.79</td>
<td>6.79</td>
<td>1.45</td>
</tr>
<tr>
<td>Segmentation ($\phi \times \eta$)$^b$</td>
<td>0.1 $\times$ 0.1</td>
<td>0.1 $\times$ 0.1</td>
<td>0.1 $\times$ 0.1</td>
</tr>
<tr>
<td>Total number of readout cells</td>
<td>10,368</td>
<td>3456</td>
<td>768</td>
</tr>
</tbody>
</table>

$^a$Uranium is depleted and FH absorbers contain 1.7% Niobium alloy

$^b$EM3 layer has 0.05 $\times$ 0.05

### 2.4.5 Endcap Calorimeters

The two Endcap Calorimeters (EC) provide coverage on either side of the CC from a pseudorapidity of 1.3 out to about 4. This corresponds to an angular coverage of $2^\circ < \theta < 30^\circ$, and $150^\circ < \theta < 178^\circ$. Each EC cryostat is divided into four sections: the electromagnetic (EM), the inner hadronic (IH), the middle hadronic (MH), and the outer hadronic (OH). The EM modules in the EC (EMEC) are disk shaped
and occupy the center of the EC cryostat. The radial coverage starts at 5.7 cm and extends to an outer radius varying between 84 cm to 104 cm, corresponding to an angular coverage of $3^\circ < \theta < 27^\circ$. The modules consist of 18 radial cells with absorber plates made from 4 mm thick depleted uranium. The cells are arranged into four readout layers (EM1 through EM4). The transverse segmentation is mostly $0.1 \times 0.1$ in $\eta \times \phi$ space; however, for $|\eta| > 3.2$, the pad size becomes too small so the segmentation is increased to $0.2 \times 0.2$. As in the CC, the third ECEM layer has finer segmentation to improve electron/hadron shower resolution. The segmentation is $\Delta \eta \times \Delta \phi = 0.05 \times 0.05$ for $|\eta| \leq 2.6$, $0.1 \times 0.1$ for $2.7 < |\eta| \leq 3.2$, and $0.2 \times 0.2$ for $|\eta| > 3.2$.

The IH module, located directly behind the ECEM, is cylindrically shaped with inner and outer radii 3.92 cm and 86.4 cm respectively. Longitudinally, the IH is divided into fine hadronic (IFH) and coarse hadronic (ICH) sections. The IFH consists of 16 cells — each made from 6 mm thick semicircular uranium absorber plates — that are arranged in four readout layers (FH1 through FH4). In order to avoid cracks, each alternate plate is rotated by $90^\circ$ in $\phi$. The ICH consists of a single readout layer made from 13 cells, each using 46.5 mm stainless steel absorber plates. The IH transverse segmentation matches that of the ECEM: $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for $|\eta| < 3.2$, and $0.2 \times 0.2$ otherwise; however, for $|\eta| > 3.8$ (beyond the ECEM coverage), it is $0.4 \times 0.2$.

Surrounding the inner core of EM and IH modules in the EC is the MH ring. This ring, consisting of 16 wedge shaped modules, extends from an inner radius
of 33 cm to an outer radius of 152 cm. Like the IH, each MH module is divided longitudinally into fine hadronic (MFH) and coarse hadronic (MCH) sections. The MFH consists of 60 radial cells arranged in four readout layers (FH1 through FH4). Each cell uses 6 mm U-Nb alloy absorber plates. The MCH is a single readout layer consisting of 14 cells. Each cell uses 46.5 mm stainless steel absorber plates. The transverse segmentation of the MH is exactly like the IH.

<table>
<thead>
<tr>
<th>Table 2.2: Endcap Calorimeter parameters.</th>
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</thead>
<tbody>
<tr>
<td><strong>EC module type</strong></td>
</tr>
<tr>
<td>Rapidity coverage</td>
</tr>
<tr>
<td>Num. of modules/cryostat</td>
</tr>
<tr>
<td>Absorber*</td>
</tr>
<tr>
<td>Absorber thickness [cm]</td>
</tr>
<tr>
<td>Liquid argon gap [cm]</td>
</tr>
<tr>
<td>Num. of cells per module</td>
</tr>
<tr>
<td>Longitudinal depth</td>
</tr>
<tr>
<td>Num. of readout layers</td>
</tr>
<tr>
<td>Cells/Readout layer</td>
</tr>
<tr>
<td>Tot. radiation lengths</td>
</tr>
<tr>
<td>Tot. absorption length (λ)</td>
</tr>
<tr>
<td>Sampling fraction [%]</td>
</tr>
<tr>
<td>Δφ segmentationc</td>
</tr>
<tr>
<td>Δη segmentationd</td>
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<tr>
<td>Readout channelsf</td>
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</table>

*Uranium is depleted and FH (IFH and MFH) absorbers contain 1.7% Niobium alloy

bStainless Steel
cEM3 layer has Δφ × Δη = 0.05 × 0.05 for |η| < 2.6
dFor |η| > 3.2, Δφ = 0.2 Δη ≈ 0.2
fMCH and OH are summed together at |η| = 1.4

The OH ring surrounds the MH ring at an inner radius of 162 cm and an outer radius of 226 cm. Each of the 16 OH modules are coarse, and form a parallelogram with an inner face at an angle of 27.4° with respect to the xy plane. An OH module
consists of 25 radial cells, read out in three layers. Each cell uses 46.5 mm stainless steel absorber plates.

The reader is referred to Table 2.2 for a summary of the design specifications of the EC, and to Figures 2.9 and 2.10 for a layout of the calorimeter modules.

2.4.6 Intercryostat Detectors and Massless Gaps

In the crossover region from CC to EC (see Figure 2.9), there are several rapidity regions where a particle must travel through mostly support structures (e.g. cryostat walls, end support plates, etc.) before reaching the sampling calorimeter modules. To partially compensate for the energy loss in these support walls two different types of detectors were adopted. First, an additional layer of LAr sampling was included on the face of each MH and OH module of the EC and on each end of the FH modules in the CC. These massless gaps (MG) have no significant absorber material but do sample the shower energy before and after the dead material between the cryostats. The \( \eta \) coverage for the MG is \( 0.7 < |\eta| < 1.3 \), with a typical segmentation of \( 0.1 \times 0.1 \) in \( \eta \times \phi \) space. The second, called the Intercryostat Detector (ICD), consists of two arrays of 384 scintillation counter tiles mounted on the front surface of each EC cryostat. The tiles match the LAr calorimeter cells in size.
2.4.7 Calorimeter Performance

The performance of the calorimeter modules has been extensively studied in test beams [9, p. 210], and by using cosmic rays in situ [14]. Their response to single electrons and pions, with energies ranging between 10 and 150 GeV, is found to be linear to within 0.5%.

The energy resolution is parametrized [10, p. 271] as

$$\frac{\delta E}{E} = C \oplus \frac{S}{\sqrt{E}} \oplus \frac{N}{E}$$  \hspace{1cm} (2.4)

The noise constant $N$ is only important at low energies, and is primarily due to uranium radioactivity. The sampling term $S$ is the dominant term, and is due to the sampling fluctuations. Contributions to the constant term $C$ affect the resolution curve as a whole, and hence include any calibration errors. For electrons, the resolutions are measured to be

$$C = 0.003 \pm 0.002, \quad S = 0.157 \pm 0.005 \text{ GeV}^{\frac{1}{2}}, \quad N \approx 0.140 \text{ GeV}$$  \hspace{1cm} (2.5)

while for pions, they are

$$C = 0.032 \pm 0.004, \quad S = 0.41 \pm 0.04 \text{ GeV}^{\frac{1}{2}}, \quad N \approx 1.28 \text{ GeV}$$  \hspace{1cm} (2.6)

Position resolution in the EM calorimeters is important for electron identification, which requires a track match. For 100 GeV electrons, the position resolution is found to vary between 0.8 and 1.2 mm as the impact position varied. This position resolution also exhibited the expected $1/\sqrt{E}$ dependence.
Finally, the calorimeter is not perfectly compensating: the $e/\pi$ ratio varies from 1.11 at 10 GeV to 1.04 at 150 GeV.

2.5 Muon Systems

Muons are identified by their very penetrating nature: their lifetime of $2.2\;\mu s$ is much larger than the scale of the detector (thus making them stable for all practical purposes), and their mass of $\approx 200m_e$ is too large to initiate an electromagnetic shower\textsuperscript{3}. The calorimeter is made thick enough that only muons are likely to penetrate its outermost layers. The muon systems lie outside the calorimeter cryostats (see Fig. 2.1), consisting of three measuring planes, with a toroidal magnet between the first and second planes to allow charge determination and momentum measurement independent of the central tracking. The measuring planes consist of proportional drift tubes (PDT) in the region $|\eta| < 1$, and of plastic mini-drift proportional tubes (MDT) and scintillation counter triggers in the region $1 < |\eta| < 2$. The momentum resolution is most easily parametrized in terms of the inverse momentum $k = 1/p$. This resolution is measured to be:

$$\frac{\delta k}{k} = 0.18 \oplus 0.03$$  \hspace{1cm} (2.7)

\textsuperscript{3}Muons with energies less than $\sim 500$ GeV do not readily produce an electromagnetic shower.
2.6 Trigger Systems

The luminosity of RunII of the Tevatron is expected to be about $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ with a beam crossing period of 396 ns, to be later reduced to 132 ns. This corresponds to a rate of $\sim 2.5\text{ MHz}$ ($\sim 7.5\text{ MHz}$ for 132 ns). It is thus impossible to record detector data for all beam crossings, and some solution is required to reduce the amount of data to a manageable level. Instead of taking a random sampling of events, the rejection is provided by a framework of trigger systems which use detector information via three levels of filters - the triggers L1, L2 and L3 - to retain events of interest. The (expected) rate of events are: 5-10 kHz out of L1; 1000 Hz out of L2, representing a factor of 10 rejection from L1; 10-20 Hz out of L3, representing a factor of 100 rejection from L2. In addition, there is a luminosity monitor - the so-called level zero (L0) - which provides a rate reduction before L1. The following subsections describe the L1, L2 and the L3 triggers.

2.6.1 Level 1 Trigger

The upgraded L1 trigger is composed of the calorimeter, the central fiber and preshower detectors, the forward preshower, and the muon scintillators and chambers (Run I: only the calorimeter). The calorimeter, fiber tracker, and preshower detectors will provide electron triggering for $|\eta| < 2.5$. The fiber tracker and muon systems will
cover the region $|\eta| < 2.0$. All L1 triggers will be pipelined and buffered to ensure deadtime-less operation. The total number of triggers will be 128 (Run I: 32).

A. Calorimeter

The calorimeter is segmented into trigger tiles of $\Delta \eta \times \Delta \phi = 0.8 \times 1.6$ and trigger towers of $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ covering $|\eta| < 4$. Thus there are a total of 1280 trigger towers; each tower is split into electromagnetic and hadronic sections, for a total of 2560 energy measurements. A calorimeter trigger will require transverse energy above a preset threshold in one or more calorimeter trigger elements. For example, a 200 GeV jet trigger may require one trigger tile with more than 50 GeV transverse energy. Additional trigger terms are provided by global quantities (sum over all trigger towers in the detector) or trigger tower sums such as total transverse energy, total energy, and missing transverse energy.

B. Central Fiber Trigger and Preshower Detectors

The trigger scheme for the fiber tracker ($|\eta| < 1.6$) is based upon the $r - \phi$ hit patterns in 4.5$^\circ$ sectors and allows four distinct momentum thresholds. A trigger will be generated by hit patterns consistent with track momentum above a software settable threshold. The trigger data is combined with the preshower detector on the trigger board and sent serially at 424 MHz to other trigger systems. There is a limit of six candidates per sector. Each trigger candidate will be identified by momentum, charge, azimuth in the last axial layer of the fiber tracker, and the
presence of preshower energy deposition above threshold. Central electron triggering
will be limited by the preshower acceptance to $|\eta| < 1.2$.

The forward preshower detector will contribute to electron triggering in the
region $1.4 < |\eta| < 2.5$. The L1 trigger will require a spatial match of preshower hits
in each layer behind the converter lead with corresponding track stubs in each layer
before the lead.

C. Muon

The central L1 muon trigger detectors include the barrel scintillation counters,
the cosmic ray veto scintillation counters, and the proportional drift tubes. The for-
ward L1 muon region includes the pixel scintillation counters and the mini-drift tubes.
The central fiber tracker is also an integral component of the L1 triggering scheme
for both the central and forward regions. The muon trigger acceptance includes the
region $|\eta| < 2$. For this paper, the muon trigger will not be used; for details, the
interested reader is referred to [7].

2.6.2 Level 2 Trigger

All events (not just a subset, as in Run I) that pass the L1 requirements will be
examined by the enhanced L2 trigger. The L2 system described here makes decisions
on the scale of a hundred $\mu$s (the L1 system described above makes decisions in a few
\( \mu s \), with a deadtime of less than a few percent, and this provides the aforementioned rejection of a factor of 10; the event rate out of L2 is \( \sim 1000 \) Hz. There will be 128 L2 triggers available.

The decisions are made by considering the correlations of trigger information from different detectors. The generic algorithms are those of matching spatial information of the same object in different detectors, and in computing correlations (mass, etc.) for multiple objects, for example, calorimeter-track matches, preshower-calorimeter matches, determination of jet parameters with reasonable jet cone definitions, determination of \( E/p \), and rough mass calculations for dileptons, di-jets, lepton-jet. An overview of this system is shown in Figure 2.11.

![Figure 2.11: Overview of the L2 trigger components.](image)
2.6.3 Level 3 Trigger

If an event passes the L2 trigger, the entire detector is read out and the event is passed to a farm of standard, high-performance commercial processors; this is the L3 trigger, and is entirely software-based. The L3 trigger runs event filter and reconstruction algorithms, written in high-level transportable code, with each filtering node handling complete events. A (nearly) complete reconstruction of the event is performed, and events with objects of sufficient interest are written to tape for subsequent analyses. For example, objects identified as tau lepton candidates based on the tau reconstruction algorithm are written into a data 'chunk' called "TauChunk", and so on. The event rate out of the L3 trigger is expected to be 10-20 Hz.

2.7 Comments: Detector Performance and Physics

The goals of the DØ upgrade are, firstly, to maintain the performance in the Main Injection era, when the Tevatron luminosity will be increased by a factor of 10 from Run I and the bunch spacing reduced from 3.6 μs to 396 ns (and eventually to 132 ns); and secondly, to significantly extend the capabilities of the detector. These include, but are not limited to:

- tagging $b$–quark decays using displaced vertices in the silicon tracker;
- enhancing muon identification and triggering, especially at low $p_T$;
• enhancing electron identification and triggering using the preshower and central tracking detectors;

• improving tau identification;

• determining the sign of the charged particles.

The overall themes of the physics upgrade program are to seek the mechanism of electroweak symmetry breaking, through the study of large samples of the top quark and precision measurements of the parameters of the standard model; to make precision tests of the color force using a variety of probes and measurements in new regions of phase space; to carry out a broad programmatic study of $b$–quark hadrons; and to search for physics beyond the current model.
Chapter 3

Event Simulation and Reconstruction

The DØ detector is a very complicated piece of equipment. An analytical evaluation of the detector performance is impossible, so one resorts to Monte Carlo simulation studies. In order to perform a simulation study of the events in which we are interested, the following need to be done:

1. generate signal and background events based on the present theoretical understanding of the physics involved;

2. reconstruct events from detector simulations.

Since there is presently no Run II data, the events to be studied are simulated and reconstructed using a Monte Carlo technique. This chapter describes the aforementioned items for the present study.
3.1 Generation of signal and background events

The decay modes of the $\tau$ are described in Chapter 1. The tau is short-lived, so only the decay products can be detected. In DØ the $\tau$ lepton is identified through its hadronic decay modes. A typical hadronic tau decay consists of one or three charged hadrons plus neutral particles. The decay products are highly boosted, forming a very narrow hadronic jet. The dominant background is from QCD events in which one of the jets mimics a $\tau$ jet, and the energies of the other jets fluctuate to give missing transverse energy. The width and charged particle multiplicity of QCD jets tends to scale with the initial parton momentum, and these jets are less isolated due to strong interaction between the other partons during hadronization.

The narrowness of the jet, the low charged track multiplicity and the isolation comprise the characteristic signature of a tau decay, and are therefore employed in identifying them.

The major source of real taus are the decays of the heavy vector bosons, $W$ and $Z$. The processes simulated for this study are $Z^0 \rightarrow \tau^+\tau^-$ and $W^\pm \rightarrow \tau^\pm\nu_\tau$, and the background is from QCD processes. All the processes were generated using the PYTHIA Monte Carlo event generator and the full detector simulation done by DØGEANT.
3.2 Reconstruction of events

For any physics analysis, the raw detector data must be processed to identify particles and their properties. In DØ this is done by a reconstruction program, DØRECO. The steps involved in the process are as follows. First, the events that pass the L1 and L2 triggers (Section 2.6) are written to an output file on disk. DØRECO then unpacks the raw data - pulse heights, widths and times - and applies the necessary calibrations and corrections, and runs event filter and reconstruction algorithms to form higher level objects such as energy clusters in the calorimeter or tracks in the tracking and muon systems. These objects are then combined to form the description of the particles produced by the $\bar{p}p$ collisions: electrons, photons, jets, taus, muons, and neutrinos($E_T$). These particles and their measured kinematic properties form the basis of all analyses; therefore, it is essential to fully understand the reconstruction process. Since a full account of the reconstruction process is beyond the scope of this paper, a brief description will be presented, with emphasis on items that are relevant to reconstruction of tau candidates - the calorimeter hit finding and jet reconstruction. The interested reader is referred to [15] for further details.
3.3 Calorimeter Hit Finding

The deposited energy recorded as digitized counts in the calorimeter cells has to be converted back to a physical energy in units of GeV. The conversion factors were determined from the responses of the modules to the known energies of the test beam particles [14]. All appropriate corrections are applied, including run dependent gain corrections (such as cell-to-cell variations in the electronics gain and pedestal values), absorber thickness corrections, liquid argon purity and temperature corrections, etc. Each cell that passes zero suppression has its address bits converted to the physical indices in the calorimeter (eta and phi indices identify the calorimeter tower, and a layer index identifies the depth of the calorimeter cell). Hence, the energy conversion can be expressed as follows [15, p. 91]:

$$E_{cell}(e,p,l) = A(d) \times W(e,l) \times C(e,p,l) \times G(e,p,l) \times ADC(e,p,l)$$  \hspace{1cm} (3.1)

where $E_{cell}$ is the cell energy in GeV, and ($e, p, l$) correspond to:

- $e =$ calorimeter $\eta$ index: $-37 \leq e \leq 37$;
- $p =$ calorimeter $\phi$ index: $1 \leq p \leq 64$;
- $l =$ calorimeter depth (layer) index: $1 \leq l \leq 17$.

$A$ is an overall calibration constant which depends on the module type: central calorimeter (CC), end calorimeter (EC), inter-cryostat detector (ICD), CC massless gap (CCMG), or EC massless gap (ECMG); it contains the conversion from adc
counts to GeV, as well as any needed high-voltage correction. $W$ is the sampling fraction weight, determined from test beam data, which provides the proper weighting for each layer of the calorimeter in order to give the best energy measurement. $C$ contains all non run dependent corrections such as absorber thickness in the CC and EC, or the ICD minimum ionizing signal corrections. $G$ contains the run dependent electronic gain corrections, such as response corrections due to capacitance or timing (derived from calibration runs), or shorted or missing channels. Finally, $ADC$ is the digitized cell energy in raw adc counts.

DØ defines for each calorimeter cell $(e, p, l)$ the directed energy vector

$$\vec{E}_{\text{cell}}(e, p, l) = \hat{n} E_{\text{cell}}(e, p, l) \quad (3.2)$$

where $\hat{n}$ is the unit vector pointing from the interaction vertex to the center of the cell $(e, p, l)$ and $E_{\text{cell}}(e, p, l)$ is the magnitude of the energy deposited in that cell as calculated in Equation 3.1. The cell energy can then be decomposed into its vectorial components:

$$E_x = E \sin \theta \cos \phi \quad E_y = E \sin \theta \sin \phi \quad E_z = E \cos \theta \quad (3.3)$$

and

$$E_T = \sqrt{E_x^2 + E_y^2} = E \sin \theta \quad (3.4)$$

The final step in calorimeter hit-finding consists in summing the energies for all the cells in each $\eta$-$\phi$ tower. This is done by summing over the layer index, $l$, for each
tower. For towers near the cryostat boundaries, this sum includes any contributions from the massless gaps and the ICD. The sum is performed separately for the total energy and the electromagnetic (EM) energy. The EM energy includes the four layers of the electromagnetic calorimeter as well as the first layer of the fine hadronic (FH) calorimeter\(^1\). From the cells that constitute a calorimeter tower \((e, p)\), the energy is defined to be:

\[
E_{\text{EM}}^{\text{TOT}}(e, p) = \sum_{l=1}^{8} E_{\text{cell}}(e, p, l)
\]

and

\[
E_{\text{EM}}^{\text{TOT}}(e, p) = \sum_{l=1}^{17} E_{\text{cell}}(e, p, l) .
\]

For each tower, the vectorial components of its EM and total energy are also computed from the vectorial components of the cell energies:

\[
E_x^{\text{TOT}} = \sum_{\text{layers}} E_x^{\text{cell}} \\
E_y^{\text{TOT}} = \sum_{\text{layers}} E_y^{\text{cell}} \\
E_z^{\text{TOT}} = \sum_{\text{layers}} E_z^{\text{cell}}
\]

and

\[
E_{\text{T}}^{\text{TOT}} = \sqrt{(E_x^{\text{TOT}})^2 + (E_y^{\text{TOT}})^2} .
\]

Related kinematic quantities are then computed:

\[
\phi_{\text{TOT}} = \arctan \left( \frac{E_y^{\text{TOT}}}{E_x^{\text{TOT}}} \right)
\]

\[
\theta_{\text{TOT}} = \arccos \left( \frac{E_z^{\text{TOT}}}{E_{\text{T}}^{\text{TOT}}} \right)
\]

\(^1\)For EM towers, the layer index \(l\) runs from 1 through 8. Out of a total of 17 possible layers, EM1 and EM2 have layer indices \(l = 1\) and \(l = 2\), the finer segmentation in EM3 takes up \(l = 3\)–\(6\), EM4 has \(l = 7\), and FH1 has \(l = 8\) (see Figure 2.10).
and
\[ \eta_{\text{lower}} = -\ln \left( \tan \left( \frac{\theta_{\text{lower}}}{2} \right) \right). \] (3.11)

These tower energies form the basis for all cluster finding algorithms.

### 3.4 $E_T$ Calculation

Neutrinos (and possibly other weakly interacting neutral particles) are not directly detected in conventional high-energy collider detectors. Their presence is inferred from an overall momentum imbalance in the event. When momentum conservation between initial and final state particles is applied, their kinematic properties are derived from the vector sum of the particles that are detected. Since energy flow near the beam-line is undetected (mainly due to the spectator quarks), this method can only be employed in the plane transverse to the beam. As the initial transverse momentum of the quark-antiquark system is small (\(\sim 300\) MeV), one expects the final transverse momentum to be small as well. When a high-$p_T$ neutrino is produced, the negative vector resultant of the detected particles will match the neutrino’s momentum vector. This quantity, referred to as \textit{missing} $E_T$ and denoted as $E_T$, is used to indicate their presence.

The calculation of $E_T$ is based upon energy deposits at the calorimeter cell level. A missing transverse energy vector, $E_T$, is defined so that it cancels exactly the total
transverse energy vector in the calorimeter:

\[ \vec{E}_x = - \sum_{e,p,l} E_x(e,p,l) \quad \vec{E}_y = - \sum_{e,p,l} E_y(e,p,l) \]  

(3.12)

and

\[ \vec{E}_T = \begin{pmatrix} \vec{E}_x \\ \vec{E}_y \end{pmatrix} . \]  

(3.13)

The missing transverse energy, \( E_T \), is just the magnitude of this vector:

\[ E_T = |\vec{E}_T| = \sqrt{E_x^2 + E_y^2} \]  

(3.14)

while the azimuthal direction of \( \vec{E}_T \) is:

\[ \phi_{E_T} = \arctan \left( \frac{E_y}{E_x} \right) . \]  

(3.15)

DØRECO computes three versions of the transverse missing energy. The first is based on the energy imbalance of the calorimeter cells only. The second version includes corrections from the massless gaps and the ICD. The third version incorporates the momenta of any reconstructed muons into the momentum balance.

### 3.5 Jet Reconstruction

When a quark or gluon (parton) emerges from the hard scatter, it cannot remain free: color confinement implies that it will appear as a jet. The process of turning a colored parton into a jet is called hadronization, since the quark produces a large
number of colorless hadrons that appear in the detector as a collimated spray of hadronic particles. The process of jet identification involves both finding these jets within the calorimeter, as well as relating the measured jet properties to the original parton.

Several algorithms can be used for jet reconstruction, the most common is the "fixed cone" algorithm. Specifically, the algorithm uses a fixed cone radius $\mathcal{R}$ where

$$\mathcal{R} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2},$$

and $\Delta \eta$ and $\Delta \phi$ are measured from the shower centroid. The jet definition used in this analysis is based on a cone size of 0.7. This is a typical cone size used for several reasons [16]:

- A cone of size 0.7 empirically contains most of the energy of a jet and has the best jet energy resolution.
- Theoretical next-to-leading order (NLO) predictions are most stable and do not depend strongly on renormalization and factorization scale at this cone size.
- It is a standard size used by many experiments at present energies.

The reconstruction algorithm is dependent on the total transverse energy in the calorimeter towers, $E_T^{\text{tower}}$ as defined in Equation 3.8, and is implemented as a three step process:

1. Preclustering of towers;
2. Cone clustering of preclusters;
3. Splitting/Merging of cone clusters.

The first step in preclustering is the ordering of calorimeter seed towers in decreasing $E_T$. Seed towers are calorimeter towers with a minimum transverse energy of 1 GeV. The highest $E_T$ calorimeter seed tower is used as the starting point of the precluster. Adjacent seed towers are added to the precluster if they are within $\pm 0.3$ units in $\eta$ and $\pm 0.3$ units in $\phi$. Once seed towers are included in a precluster, they are then removed from the seed tower list. The remaining seed tower with the highest $E_T$ in the list is then used as the starting point of the next precluster. Preclustering continues until all of the seed towers have been exhausted. Once all seed towers are assigned to a precluster, the preclusters are ordered in decreasing precluster $E_T$, where the precluster $E_T$ is the scalar sum of all towers' $E_T$ in the precluster.

Cone clustering begins with the $E_T$ ordered list of preclusters. For each precluster, the $E_T$ weighted $(\eta, \phi)$ centroid is calculated and identified as the cone axis. All towers within a radius $R$ of that axis are assigned to the cone cluster. The cone axis is recalculated using these towers, and the process is iterated until the cone axis becomes stable. The cone axis is considered stable if it moves less than 0.01 in $\eta \times \phi$ space between iterations, or if the maximum number of 50 iterations has been reached (The latter is to prevent the rare case of a bi-stable solution from using an unreasonable amount of computer processing time). If the resultant cone has $E_T > 8$
GeV, the cone cluster is retained and is identified as a jet, with the jet axis defined by the stable cone cluster axis. Splitting/merging is then attempted on that jet.

Jets are not allowed to share energy: each calorimeter cell can belong to a maximum of one jet. The first jet, by definition, can share no energy with a previously found jet. When the second and subsequent jets are found, a check is made to determine whether the new jet shared any towers with previously found jets. If one or more towers are shared, the jet axes are compared: if the jets are separated by less than 0.01 in $\eta \times \phi$ space, then the two jets are considered to be the same\(^2\), and the most recently constructed jet is dropped. In the case that the new jet is not identical to any of the previous ones, then the fraction of the $E_T$ sum of the shared towers to the lowest $E_T$ jet is calculated. If this fraction is greater than 0.5, the two jets are merged into a single jet with all towers assigned to the combined jet. Otherwise, both jets are preserved, and each shared cell assigned to the jet whose axis is nearest to it. In either case, the jet axis is recalculated one last time, and the relevant kinematic variables are calculated for all appropriate cone clusters. On average, 5% of the jets are merged, and 30% are split. Once splitting/merging is completed, the cone clustering process is repeated until all preclusters have been exhausted.

Once the clustering process is complete, the kinematic properties of the reconstructed jets are determined by summing over the towers contained in that jet. The

\(^2\)It is possible to find the same jet from more than one precluster.
energy components of the jet are defined to be:

\[ E^{\text{jet}}_i = \sum_{k=1}^{n_{\text{towers}}} E^k_i \quad (i = x, y, z, \text{total}) \]  \hspace{1cm} (3.16)

and the \( E_T \) of the jet:

\[ E^{\text{jet}}_T = \sum_{k=1}^{n_{\text{towers}}} E^k_T = \sum_{k=1}^{n_{\text{towers}}} \sqrt{(E^k_x)^2 + (E^k_y)^2} . \]  \hspace{1cm} (3.17)

The jet angles are then computed as:

\[ \phi^{\text{jet}} = \arctan \left( \frac{E^{\text{jet}}_y}{E^{\text{jet}}_x} \right) \]  \hspace{1cm} (3.18)

\[ \theta^{\text{jet}} = \arccos \left( \frac{E^{\text{jet}}_z}{E^{\text{jet}}_T} \right) \]  \hspace{1cm} (3.19)

and

\[ \eta^{\text{jet}} = -\ln \left[ \tan \left( \frac{\theta^{\text{jet}}}{2} \right) \right] . \]  \hspace{1cm} (3.20)

It may be noted that the transverse and total energy of the jet is computed from the sum of the individual transverse or total tower energies, and not the magnitude of the vector components.

3.6 TauReco: The tau reconstruction algorithm

TauReco is the reconstruction package for taus. Once the jet reconstruction is done, tau candidates are selected based on certain criteria, or preselection cuts. At this point, the objective is to identify tau candidates, so that the selection criteria are loose, in order to attain high efficiency. More stringent cuts will be applied later.
during the analysis stage, to be described in the next chapter. At this stage, the only
criterion that is required is the presence of at least one track within a 0.7 cone of
the jet axis. Then a candidate is created and various attributes are written to an
tagfile. The following are the attributes along with the rationale for each one of them:

1. **Cluster jet width**

   The cluster jet width, or cRMS, is defined as:

   \[
   cRMS = \sqrt{\eta_{width}^2 + \phi_{width}^2}
   \]  
   \hspace{1cm} (3.21)

   where

   \[
   \eta_{width} = \sqrt{\sum_{towers} \frac{(\eta_{tower} - \eta)^2 E^2_{T}}{E_T}}
   \]  
   \hspace{1cm} (3.22)

   and

   \[
   \phi_{width} = \sqrt{\sum_{towers} \frac{(\phi_{tower} - \phi)^2 E^2_{T}}{E_T}}
   \]  
   \hspace{1cm} (3.23)

   The summation is over all towers inside the cone size of the jet having transverse
   energy greater than (a threshold value of) 100 MeV. \( \eta \) and \( \phi \) are values for the
   jet axis as determined by the jet reconstruction.

   Figure 3.1 shows the jet width distribution for the signal and the background
   as seen in the actual (simulated) calorimeter. A jet resulting from the decay
   products of a tau particle is narrow and well-collimated in the transverse (i.e.
   \( \eta \times \phi \)) direction; it will have a small RMS value. On the other hand, a jet
   from a QCD hadronic shower, with several particles depositing energy in the
calorimeter, is typically wider in the transverse direction; RMS value is higher. 
A cut on the RMS would serve to offer rejection of QCD background events.

2. Track jet width

The track jet width, or tRMS, is defined in the same way as the cluster jet width, but the summations are done only for charged particles.

Figure 3.2 shows the jet width distribution for the signal and the background as seen in the actual (simulated) calorimeter. Comments similar to that for cRMS hold here also.

3. Track multiplicity

The track multiplicity of tau decays is governed by its decay modes. About 99% of hadronic tau decays have either one or three charged particles (and therefore, tracks) along with neutral particles like photons (from π⁰ decays to two photons). QCD jets, on the other hand, typically have a larger number of tracks, increasing with increasing energy. Track multiplicity can therefore be used to distinguish signal from background. It should be noted that the background is not the typical QCD event of high track multiplicity, but rather the atypical one with low track multiplicity. Figures 3.3, 3.4 and 3.5 show the number of tracks in cone sizes (or radii) of 0.1, 0.3 and 0.5 in η × φ space for the signal and background (The cone radius \( R \) is defined as \( R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \), and
\( \Delta \eta \) and \( \Delta \phi \) are measured from the track with highest transverse momentum.

We define track isolation between 0.1 and 0.3 cones as follows:

\[
\text{trackiso}(13) = \frac{\text{tracks}(0.3) - \text{tracks}(0.1)}{\text{tracks}(0.3)}
\]  

(3.24)

and similarly for isolation between 0.1 and 0.5 cones. Figures 3.6 and 3.7 show the track isolations thus defined. For the background, the number of tracks with increasing cone sizes increases significantly, but less so for the signal. Thus we may use the track isolation between the different cones as a distinguishing factor.

4. Electromagnetic fraction (EMF)

Jet EMF is defined as the fraction of energy for all towers comprising the cluster deposited in the electromagnetic portion of the calorimeter (layers 1-7):

\[
EMF = \frac{\sum_{\text{towers}} \sum_{\text{cell}=1}^{7} E_{\text{tower}}}{\sum_{\text{towers}} \sum_{\text{cell}=1}^{17} E_{\text{tower}}}
\]  

(3.25)

Electromagnetic showers, comprising photons and electrons, deposit most of their energy in the calorimeter layers closest to the interaction point; the EMF value is large. Hadronic tau jets, on the other hand, deposit energy in the EM as well as the hadronic layers of the calorimeter - photons in the EM layers and charged pions primarily in the hadronic layers; the EMF value is lower than that for EM showers, as shown in Figure 3.8. Thus, the above EMF cut offers
rejection of electromagnetic showers. It should be noted that the EMF does not offer rejection of QCD background.

5. Profile

The profile $P$ is intended to exploit the fine calorimeter segmentation and good energy resolution of the DØ detector. It is defined as:

$$P = \frac{E_{T1} + E_{T2}}{E_T}$$  \hspace{1cm} (3.26)

Here, $E_{T1}$ and $E_{T2}$ are the towers with the two highest $E_T$, and $E_T$ is for the total jet cluster. Jets from tau decay products are very narrow, and have a large fraction of their energy in the two leading jet towers. QCD jets, on the other hand, have their energy distributed among several towers, as a result of which the corresponding profile is lower than that for tau jets, as shown in Figure 3.9. Thus, the profile is an important variable that allows one to distinguish tau jets from QCD jets.

6. Jet axis $\eta$ and $\phi$

This is simply the location of the jet axis in the calorimeter. It is then used in the analysis for comparison with Monte Carlo generator level information as discussed later.

7. Transverse momentum $p_T$

This is to be used later for comparison with Monte Carlo generator level information to assess the performance of the momentum measurement of the
detector. From the $p_T$ distribution for the signal and background as shown in Figure 3.10, we justify the choice of background as QCD events with transverse momenta of 20 GeV.

8. *(seed track $p$)/(cluster $E$)*

This is defined as the ratio of the track with the highest transverse momentum and the cluster energy. For QCD events, there is a large number of charged particles among whom the energy and momentum is distributed, so that the momentum(energy) of a single charged particle is likely to be significantly less than the momentum(energy) associated with the jet. As a result, the *(seed track $p$)/cluster $E$) would be significantly less than one. For hadronic tau decays, the number of tracks is small, so that the value of this variable is expected to be higher than that for the QCD background. See Figure 3.11. Thus it should be possible to use this variable to assist signal-background separation.

9. *Missing transverse energy $E_T$*. This has been described in detail in section 3.4. For tau decays, there is always missing energy associated with the undetected neutrinos. For the background, this quantity will be smaller than that for tau decays.

10. *H-matrix information: $\chi^2_{\text{signal}}, \chi^2_{\text{background}},$ and Fisher variable*

    *H-matrix basics:*
The shower caused by a type of particle in the calorimeter has a characteristic shape, in both longitudinal and transverse directions. This shape may depend on the total energy deposited, the transverse and longitudinal energy distribution profiles, etc. The $H$-matrix $\chi^2$ (chi-squared) is designed to measure how closely a calorimeter cluster thought to be a certain type resembles a true cluster of that type.

To take into account correlations among variables thought to characterize a shower, a covariance matrix $M$ is constructed. For $P$ observables, the $M$-matrix is a square matrix of size $P \times P$. Each component of the matrix is calculated as follows:

$$M_{ij} = \frac{1}{N} \sum_{n=1}^{N} (x^n_i - <x_i>)(x^n_j - <x_j>)$$  \hspace{1cm} (3.27)

Here, $N$ is the number of reference particles (also called the training sample), $x^n_i$ is the value of the $i^{th}$ observable for the $n^{th}$ reference particle and $<x_i>$ is the average value of the $i^{th}$ observable for the entire training sample.

The $H$-matrix is the inverse of the covariance matrix: $H = M^{-1}$. For a candidate (particle), the $H$-matrix $\chi^2$ is calculated:

$$\chi^2 = \sum_{i,j=1}^{P} (x^c_i - <x_i>)(x^c_j - <x_j>)H_{ij}(x^c_j - <x_j>)$$  \hspace{1cm} (3.28)

*Present analysis $H$-matrices*
For the present study, two $H$-matrices are built. One has a training sample that consists of tau events, and this yields $\chi^2_{signal}$. The other has a training sample of QCD events, which is the principal background from which we seek to separate the tau events in which we are interested; this yields $\chi^2_{background}$. These are then used to evaluate the Fisher variable $F$:

$$F = \frac{1}{2}(\chi^2_{background} - \chi^2_{signal})$$ (3.29)

For a good candidate, the value of $\chi^2_{signal}$ is expected to be low and that of $\chi^2_{background}$ to be high (and vice versa for the background). Thus, based on Equation 3.29, a good candidate would be one for which $F > 0$. The Fisher variable has been used in previous analyses as a discriminant to reject QCD background. Figure 3.12 shows the distribution of the Fisher variable for signal and background.
(a) Signal: \( Z^0 \rightarrow \tau^+\tau^- \), 1.1 average minimum bias.

(b) Background: QCD, \( p_T \) 20 GeV, 1.1 average minimum bias.

**Figure 3.1:** Jet width for signal and background.
(a) Signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) Background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.2:** Jet width for signal and background.
(a) signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.3**: Number of tracks in cone size 0.1.
(a) signal: $Z^0 \to \tau^+\tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T \ 20$ GeV, 1.1 average minimum bias.

Figure 3.4: Number of tracks in cone size 0.3.
(a) signal: $Z^0 \rightarrow \tau^+\tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.5:** Number of tracks in cone size 0.5.
(a) Signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) Background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

Figure 3.6: Track isolation between cone sizes 0.1 and 0.3.
(a) signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.7**: Track isolation between cone sizes 0.1 and 0.5.
(a) $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) $Z^0 \rightarrow e^+ e^-$, 1.1 average minimum bias.

**Figure 3.8:** Electromagnetic fraction in calorimeter.
(a) signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.9:** Profile.
(a) signal: \( Z^0 \to \tau^+\tau^- \), 1.1 average minimum bias.

(b) background: QCD, \( p_T \) 20 GeV, 1.1 average minimum bias.

Figure 3.10: Transverse momentum.
(a) signal: $Z^0 \rightarrow \tau^+\tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

**Figure 3.11:** (track momentum of track with highest $p_T$)/(cluster energy).
(a) signal: $Z^0 \rightarrow \tau^+ \tau^-$, 1.1 average minimum bias.

(b) background: QCD, $p_T$ 20 GeV, 1.1 average minimum bias.

Figure 3.12: Fisher variable.
Chapter 4

Data Set and Analysis

This chapter describes the simulated data set used for signal estimates and analysis, specifically, a description of the events that give tau signals, the background samples and the rate estimates. Two types of data sets were generated:

1. *Events with one interaction.*

   This means that there is no other interaction besides a single hard scattering in the event. In the parlance of high energy physics, this is known as an event with a *minimum bias* of zero, indicating the absence of any additional interactions.

2. *Events with more than one interaction.*

   In the high luminosity environment, it is common to have more than one interaction, in addition to one hard scattering per event. This is taken into account by specifying a minimum bias greater than zero; for example, a minimum bias of one signifies one hard scattering plus one additional interaction, for a total of two interactions, and so on.
This means that the events with a non-zero minimum bias are more representative of the actual experimental environment. However, events with zero minimum bias provide a cleaner sample that facilitates the understanding of the signal characteristics of the events of interest, which may then be used beneficially for further development of the detection tools. The events used in this study have either fixed values of the minimum bias (zero minimum bias is always fixed), or a Poisson distribution is used whenever an average minimum bias is specified. The choice of minimum bias depends on the conditions expected during the run. For conditions at the Tevatron during Run II - $p\bar{p}$ events with a cross section of approximately 75 mb at the expected center-of-mass energy of 2 TeV [13], a luminosity of $2 \times 10^{32} cm^{-2} s^{-1}$ and a bunch crossing of 132 ns (396 ns) - the average number of events is about 2 (6) events per crossing, or an average minimum bias of 1 (5).

### 4.1 Signal Samples

This section describes the events that were used to obtain the signal, namely, events with $\tau$s and their decay. For all the samples, the taus are required to decay to the leptonic as well as the hadronic channels as described in Chapter 1 with the indicated branching ratios. The $Z^0 \rightarrow \tau^+\tau^-$ and $H \rightarrow \tau^+\tau^-$ events were generated using the PYTHIA Monte Carlo generator, and the $W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ events using the ISAJET Monte Carlo generator. The samples are as follows:
4.1.1 \( Z^0 \rightarrow \tau^+\tau^- \)

The \( Z^0 \rightarrow \tau^+\tau^- \) sample consists of one set of 6800 events with zero minimum bias, and another set of 7350 events with an average minimum bias of 1.1.

4.1.2 \( W^\pm \rightarrow \tau^{\pm}\nu_{\tau} \)

The \( W^\pm \rightarrow \tau^{\pm}\nu_{\tau} \) sample consists of one set of 6000 events with zero minimum bias, and another set of 5900 events with an average minimum bias of 1.1.

4.1.3 \( H \rightarrow \tau^+\tau^- \)

The \( H \rightarrow \tau^+\tau^- \) sample consists of one set of 4000 events with zero minimum bias, and another set of 1100 events with a fixed minimum bias of 4.

4.2 Background Samples

The principal background for taus are the QCD multijet events, which give a signature similar to that of jets produced by tau decay, and can therefore be misidentified as such (these are what constitute “fake” taus). The background samples for this study were generated using the PYTHIA Monte Carlo generator, and consist of
12,000 QCD events with an average minimum bias of 1.1 and transverse momentum $p_T$ of 20 GeV.

4.3 Event Processing

The Monte Carlo generated events are processed in two stages. In the first stage, each event is processed through the full DØGEANT detector simulation, followed by a full reconstruction done by the standard DØRECO reconstruction package\textsuperscript{1}. At this point, information of interest to the present study, described below in Section 4.3.1, is selected and written to an ntuple by a customized package. The second stage consists of offline analysis of the reconstructed information, comprising comparison with the "Monte Carlo truth" to determine $\tau$ reconstruction and identification efficiencies, and the ability to reject background.

4.3.1 Ntuple Making

The motivation for writing the parameters of the generated and reconstructed events into an ntuple is to make the information amenable for analysis by the physics analysis and histogramming packages currently available, namely, PAW and ROOT\textsuperscript{17}. The ntuple comprises the following three blocks:

\textsuperscript{1}For this study, version preco03.07.00 has been used.
1. *Monte Carlo generator block*

This block contains all the particle level data, with the particles neatly labeled for purposes of identification, in accordance with physics that has been experimentally verified, as well as physics that has not been experimentally verified. In the latter case, this block contains information based on theoretical models, within the confines of the standard model as well as beyond. We define information in this block as the “Monte Carlo truth”, with which to compare the results of a data set after it has been subjected to the full detector simulation.

2. *Monte Carlo tau decay block*

This block is a subset of the generator block (and so is Monte Carlo truth, too), containing only those particles that are decay products of taus, are stable, and deposit energy in the calorimeter - electrons, pions and photons, labeled appropriately to indicate the tau of which they are descendants\(^2\).

3. *Reconstructed tau block*

This block contains the tau candidate objects reconstructed by TauReco as described in Sections 3.2 - 3.6. It is important to note that these objects are constructed based on what the detector "sees", whether it be real, or as in the present study, simulated data; the detector does not distinguish between the two.

\(^2\)Since we study only the hadronic decay modes for this study, information of the electronic decay channel has been excluded.
This completes the first stage of processing.

4.3.2 Comparison of Monte Carlo and Reconstructed Taus

Performing any physics analysis in the \( \tau \) sector (including discovering new phenomena) depends critically on reliably identifying the \( \tau \) from its decay products. Comparison of Monte Carlo and reconstructed taus enables (1) the determination of the identification efficiency of the TauReco reconstruction algorithm, and (2) its ability to reject background events.

Since \( \tau \) candidates are reconstructed from their decay products that deposit energy in the calorimeter, the first step is to similarly reconstruct the true Monte Carlo \( \tau \)s from their decay products too, which are contained in the Monte Carlo tau decay block (Section 4.3.1), since these comprise the jets that appear as energy clusters in the calorimeter and tracks (for charged particles) in the tracking systems. The position (in \( \eta \times \phi \) space) of the jet axis is calculated as a transverse momentum-weighted average of the decay particles to give \( \eta_{MC} \) and \( \phi_{MC} \), and the transverse momentum by a vector sum of their individual \( p_T \), to give \( p_{T,MC} \). The corresponding parameters of the reconstructed candidates are \( \eta_{reco} \), \( \phi_{reco} \) and \( p_{T,\text{reco}} \).

Recall that the \( \tau \) candidates were created with the only requirement being that there be at least one track within a 0.7 cone radius about the jet axis (Sec. 3.6). At this point the following additional cuts are imposed:
1. Number of tracks be less than or equal to 3. Since almost 99% of the hadronic tau decays have three tracks or less (and about 77% have only one track), this should be helpful in eliminating QCD jets with high track multiplicity.

2. Electromagnetic energy fraction be less than 0.95. This is to provide rejection of electromagnetic showers, not QCD background. Since we are studying only the hadronic decay modes, this does not significantly affect the signal.

Candidates that survive these cuts are then subjected to the optimization procedure as described in the following section.

4.3.2.1 Selection of variables and optimization of cuts

The goal of applying selection cuts is to retain tau candidates that represent as faithfully as possible the corresponding (real) tau particles (of the Monte Carlo tau block, for this simulation study), and at the same time reject background signals that mimic the tau signal (i.e., fake taus). To this end, it is necessary to determine appropriate variables upon which to impose cuts, and a procedure that determines an optimal value for these cuts.

Appropriate variables would be ones whose distributions for the signal and background differ, as well as display sufficient separation that it is possible to impose a
cut\(^3\). Three sets of variables were selected for optimization studies; the first set consists of simply the Fisher discriminant; the second set comprises the cluster jet width (cluster RMS) and profile; the third set comprises jet width of tracks about the cluster axis (track RMS) and profile.

For the optimization procedure, the optimal cut value for this study is defined as the value that maximizes the product of efficiency and purity of candidates surviving the cuts, where efficiency and purity are defined as follows:

\[
\text{efficiency} = \frac{S_A}{S_A + S_R} \tag{4.1}
\]

\[
\text{purity} = \frac{S_A}{S_A + B_A} \tag{4.2}
\]

where \(S\) and \(B\) denote signal and background respectively, and the subscripts \(A\) and \(R\) denote “accepted” and “rejected”, respectively. For the second set of variables, successive optimization is implemented as follows:

1. Determine optimum value for variable 1.

2. Apply variable 1 cut.

3. Determine optimum value for variable 2 for candidates that survive variable 1 cut.

4. Apply variable 2 cut, and so on.

\(^3\)Some variables, e.g., EMF and (seed track p /cluster E), have different distributions for signal and background, but not the separation that would allow imposing a cut. They are, however, useful as inputs to multivariate analyses.
Figure 4.1 shows a typical plot of the efficiency purity as a function of the Fisher discriminant, and Figure 4.2 shows the signal versus background efficiency for the cases where an optimal cut value was clearly discernible; Figures 4.3 and 4.4 show the corresponding plots for the cases where no clear (unique) optimal value was discernible.

4.3.2.2 TauReco reconstruction efficiency

To determine efficiencies of the algorithm, position matching in $\eta \times \phi$ space is done for signal samples as follows. A reconstructed $\tau$ candidate is defined as "real" if the axis of its calorimeter cluster lies within a radius $dR$ (in $\eta \times \phi$ space) of the corresponding calorimeter cluster of the Monte Carlo $\tau$. The radius $dR$ is defined as

$$dR = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$  \hfill(4.3)

where

$$\Delta \eta = \eta_{MC} - \eta_{reco} \quad \Delta \phi = \phi_{MC} - \phi_{reco}$$  \hfill(4.4)

For this study, $dR$ is taken to be 0.2. $\tau$ candidates for which $dR > 0.2$ are deemed "fake". The efficiencies were determined for the two choices of optimization variable sets described in Section 4.3.2.1. Table 4.1 summarizes the optimized values for the Fisher discriminant cut for the central calorimeter (CC) along with the percentages of signal and background events that survive after the cuts are applied; the second half
Figure 4.1: Efficiency*purity as a function of the Fisher discriminant. The signal is $Z^0 \rightarrow \tau^+\tau^-$ and the background is QCD, $p_T$ 20 GeV, both with 1.1 average minimum bias. A global maximum - the optimal cut value - is clearly discernible.

Figure 4.2: Signal vs background efficiency. The signal is $Z^0 \rightarrow \tau^+\tau^-$ and the background is QCD, $p_T$ 20 GeV, both with 1.1 average minimum bias.
Figure 4.3: Efficiency*purity as a function of the Fisher discriminant. The signal is $W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ and the background is QCD, $p_{T}$ 20 GeV, both with 1.1 average minimum bias. No global maximum is seen.

Figure 4.4: Signal vs background efficiency. The signal is $W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ and the background is QCD, $p_{T}$ 20 GeV, both with 1.1 average minimum bias.
of the tables summarize the Monte Carlo efficiencies\(^4\) after applying the optimized cuts\(^5\). For the data sets which do not have optimal discriminant cuts in part (a) of the tables, the cuts applied to determine the Monte Carlo efficiencies in part (b) of the tables are those of the corresponding zero minimum bias data sets. Tables 4.2 and 4.3 summarize the same for cluster RMS-profile and track RMS-profile optimizations, respectively.

A similar attempt at optimization for the end cap (EC) calorimeters (\(|\eta| \geq 1.1\)) yielded no optimal value except for the (somewhat artificial) zero minimum bias events; Tables 4.4, 4.5 and 4.6 are the EC region analogues of Tables 4.1, 4.2 and 4.3, respectively. The efficiency*puritiy curves as a function of the Fisher discriminant, and the signal versus background efficiency curves look similar to those in Figures 4.3 and 4.4, respectively (and have therefore not been repeated here).

A comparison of the Monte Carlo efficiencies for the CC and EC regions shows that efficiencies in the EC are significantly poorer than the corresponding ones in the CC region. Also, variables that yielded optimal cut values in the CC do not necessarily do so in the EC. Thus it appears that in order to identify \(\tau_s\) efficiently in the EC regions, it may be necessary to determine discriminating variables different from those used in the CC, and/or employ some novel strategy.

\(^4\)All signal efficiencies in part (b) of the tables are reported as a fraction of the number of Monte Carlo hadronic \(\tau_s\).

\(^5\)Jet width optimization was performed first; profile optimization was performed for events that survived the jet width cut. Reversing the order reduced the number of both signal and background events surviving the combined width and profile cuts.
Table 4.1: Fisher discriminant optimization and Monte Carlo efficiencies for CC: $|\eta| < 1.1$. (S - signal, B - background in last column of (a).)

(a) Optimization of Fisher discriminant.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized Fisher (F) cut</th>
<th>Fraction surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3708</td>
<td>$F &gt; -5.5$</td>
<td>0.826</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4945</td>
<td>$F &gt; -9.5$</td>
<td>0.716</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>2221</td>
<td>$F &gt; -11.5$</td>
<td>0.765</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>2793</td>
<td>none</td>
<td>0.210</td>
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<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3536</td>
<td>$F &gt; -2.5$</td>
<td>0.770</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1778</td>
<td>none</td>
<td>0.058</td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized (when applicable) Fisher discriminant cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of MC hadronic $\tau$s $N_{MC,\text{had}}$</th>
<th>Reconstructed taus $N_{total}$ $N_{real}$</th>
<th>Reconstruction efficiency total</th>
<th>real</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>4011</td>
<td>3024 2674</td>
<td>0.754</td>
<td>0.666</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4465</td>
<td>3550 2862</td>
<td>0.795</td>
<td>0.641</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>2113</td>
<td>1667 1285</td>
<td>0.789</td>
<td>0.608</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1929</td>
<td>1393 1030</td>
<td>0.722</td>
<td>0.534</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3306</td>
<td>2710 2320</td>
<td>0.820</td>
<td>0.702</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1066</td>
<td>609 421</td>
<td>0.571</td>
<td>0.395</td>
</tr>
</tbody>
</table>
Table 4.2: Jet width and profile optimization and Monte Carlo efficiencies for CC: \( |\eta| < 1.1 \). (S - signal, B - background in last column of (a).)

(a) Optimization of jet width W and profile P.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized W and P cuts</th>
<th>Fraction surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>( Z \rightarrow \tau^+ \tau^- )</td>
<td>0 fixed</td>
<td>3708</td>
<td>W &lt; 0.22; P &gt; 0.25</td>
<td>0.828</td>
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<tr>
<td></td>
<td>1.1 avg</td>
<td>4945</td>
<td>W &lt; 0.26; P &gt; 0.37</td>
<td>0.710</td>
</tr>
<tr>
<td>( W^\pm \rightarrow \tau^{\pm} \nu_{\tau} )</td>
<td>0 fixed</td>
<td>2221</td>
<td>W &lt; 0.26; P &gt; 0.34</td>
<td>0.761</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>2793</td>
<td>none</td>
<td>0.799</td>
</tr>
<tr>
<td>( h \rightarrow \tau^+ \tau^- )</td>
<td>0 fixed</td>
<td>3536</td>
<td>W &lt; 0.22; P &gt; 0.32</td>
<td>0.799</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1778</td>
<td>none</td>
<td>0.799</td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized jet width and profile cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number: MC hadronic ( \tau )s ( N_{MC, \text{had}} )</th>
<th>Reconstructed taus</th>
<th>Reconstruction efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>( N_{total} )</td>
<td>( N_{real} )</td>
</tr>
<tr>
<td>( Z \rightarrow \tau^+ \tau^- )</td>
<td>0 fixed</td>
<td>4011</td>
<td>3084</td>
<td>2675</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4465</td>
<td>3603</td>
<td>2853</td>
</tr>
<tr>
<td>( W^\pm \rightarrow \tau^{\pm} \nu_{\tau} )</td>
<td>0 fixed</td>
<td>2113</td>
<td>1676</td>
<td>1274</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1929</td>
<td>1409</td>
<td>1037</td>
</tr>
<tr>
<td>( h \rightarrow \tau^+ \tau^- )</td>
<td>0 fixed</td>
<td>3306</td>
<td>2811</td>
<td>2360</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1066</td>
<td>540</td>
<td>392</td>
</tr>
</tbody>
</table>
Table 4.3: Track rms and profile optimization and Monte Carlo efficiencies for CC: $|\eta| < 1.1$. (S - signal, B - background in last column of (a).)

(a) Optimization of track rms $tW$ and profile $P$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized $tW$ and $P$ cuts</th>
<th>Fraction surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3708</td>
<td>$tW &lt; 0.12; P &gt; 0.28$</td>
<td>0.781</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4945</td>
<td>$tW &lt; 0.17; P &gt; 0.35$</td>
<td>0.696</td>
</tr>
<tr>
<td>$W^\pm \to \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>2221</td>
<td>$tW &lt; 0.19; P &gt; 0.37$</td>
<td>0.721</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>2793</td>
<td>$\text{none}$</td>
<td>0.154</td>
</tr>
<tr>
<td>$h \to \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3536</td>
<td>$tW &lt; 0.12; P &gt; 0.37$</td>
<td>0.734</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1778</td>
<td>$\text{none}$</td>
<td>0.078</td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized track rms and profile cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number: MC hadronic $\tau$s $N_{MC,\text{had}}$</th>
<th>Reconstructed taus</th>
<th>Reconstruction efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$N_{\text{total}}$</td>
<td>$N_{\text{real}}$</td>
<td>total</td>
</tr>
<tr>
<td>$Z \to \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>4011</td>
<td>2894</td>
<td>2573</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4465</td>
<td>3476</td>
<td>2757</td>
</tr>
<tr>
<td>$W^\pm \to \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>2113</td>
<td>1615</td>
<td>1208</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1929</td>
<td>1427</td>
<td>983</td>
</tr>
<tr>
<td>$h \to \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3306</td>
<td>2594</td>
<td>2234</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>1066</td>
<td>653</td>
<td>465</td>
</tr>
</tbody>
</table>
Table 4.4: Fisher discriminant optimization and Monte Carlo efficiencies for EC: $|\eta| \geq 1.1$. (S - signal, B - background in last column of (a).

(a) Optimization of Fisher discriminant.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized Fisher (F) cut</th>
<th>Fraction surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>2219</td>
<td>$F &gt; -9.5$</td>
<td>0.806 0.166</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4143</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm\nu_\tau$</td>
<td>0 fixed</td>
<td>1436</td>
<td>$F &gt; -33.5$</td>
<td>0.843 0.508</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>3299</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1981</td>
<td>$F &gt; -28.5$</td>
<td>0.853 0.441</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>2409</td>
<td>none</td>
<td></td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized (when applicable) Fisher discriminant cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number: MC hadronic $\tau$s $N_{MC,\text{had}}$</th>
<th>Reconstructed taus $N_{\text{total}}$</th>
<th>Reconstruction efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3628</td>
<td>1772 1403</td>
<td>0.488 0.387</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4079</td>
<td>2032 1533</td>
<td>0.498 0.376</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm\nu_\tau$</td>
<td>0 fixed</td>
<td>1714</td>
<td>1204 698</td>
<td>0.702 0.407</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1776</td>
<td>1498 756</td>
<td>0.843 0.426</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1748</td>
<td>1679 763</td>
<td>0.961 0.436</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>572</td>
<td>695 248</td>
<td>1.215 0.434</td>
</tr>
</tbody>
</table>
Table 4.5: Jet width and profile optimization and Monte Carlo efficiencies for EC: $|\eta| \geq 1.1$. (S - signal, B - background in last column of (a).)

(a) Optimization of jet width $W$ and profile $P$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized $W$ and $P$ cuts</th>
<th>Fraction surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>2219</td>
<td>$W &lt; 0.25; P &gt; 0.27$</td>
<td>0.766</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4143</td>
<td>none</td>
<td>0.154</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>1436</td>
<td>$W &lt; 0.39; P &gt; 0.33$</td>
<td>0.810</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>3299</td>
<td>none</td>
<td>0.343</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1981</td>
<td>$W &lt; 0.30; P &gt; 0.26$</td>
<td>0.774</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>2409</td>
<td>none</td>
<td>0.292</td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized jet width and profile cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number: MC hadronic $\tau$s $N_{MC, had}$</th>
<th>Reconstructed taus $N_{total}$</th>
<th>$N_{real}$</th>
<th>Reconstruction efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3628</td>
<td>1767</td>
<td>1379</td>
<td>0.487</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4079</td>
<td>2141</td>
<td>1574</td>
<td>0.525</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm \nu_\tau$</td>
<td>0 fixed</td>
<td>1714</td>
<td>1164</td>
<td>660</td>
<td>0.679</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1776</td>
<td>1781</td>
<td>798</td>
<td>1.003</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1748</td>
<td>1530</td>
<td>721</td>
<td>0.875</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>572</td>
<td>386</td>
<td>193</td>
<td>0.675</td>
</tr>
</tbody>
</table>
Table 4.6: Track rms and profile optimization and Monte Carlo efficiencies for EC: $|\eta| \geq 1.1$. (S - signal, B - background in last column of (a).)

(a) Optimization of track rms $tW$ and profile $P$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number of signal candidates</th>
<th>Optimized $tW$ and $P$ cuts</th>
<th>Signal surviving cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>2219</td>
<td>$tW &lt; 0.17$; $P &gt; 0.31$</td>
<td>0.715</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4143</td>
<td>none</td>
<td>0.137</td>
</tr>
<tr>
<td>$W^{\pm} \rightarrow \tau^{\pm}\nu_\tau$</td>
<td>0 fixed</td>
<td>1436</td>
<td>$P &gt; 0.33$</td>
<td>0.853</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>3299</td>
<td>none</td>
<td>0.416</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1981</td>
<td>$P &gt; 0.29$</td>
<td>0.815</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>2409</td>
<td>none</td>
<td>0.432</td>
</tr>
</tbody>
</table>

(b) Monte Carlo efficiencies after applying optimized track rms and profile cuts.

<table>
<thead>
<tr>
<th>Process</th>
<th>Minimum bias</th>
<th>Number: MC hadronic $\tau$s $N_{MC, had}$</th>
<th>Reconstructed taus $N_{total}$</th>
<th>Reconstruction efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>3628</td>
<td>1597</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>4079</td>
<td>1970</td>
<td>0.483</td>
</tr>
<tr>
<td>$W^{\pm} \rightarrow \tau^{\pm}\nu_\tau$</td>
<td>0 fixed</td>
<td>1714</td>
<td>1227</td>
<td>0.716</td>
</tr>
<tr>
<td></td>
<td>1.1 avg</td>
<td>1776</td>
<td>1925</td>
<td>0.396</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>0 fixed</td>
<td>1748</td>
<td>1749</td>
<td>1.001</td>
</tr>
<tr>
<td></td>
<td>4 fixed</td>
<td>572</td>
<td>1075</td>
<td>0.456</td>
</tr>
</tbody>
</table>
4.4 Multivariate Analyses: Selection of Variables

The complex interplay of the multitude of variables that need to be taken into account make the task of $\tau$ identification at a hadron collider an ideal candidate for a multivariate analysis. For such an analysis, we need to determine variables that will facilitate the task of distinguishing between the signal and background. The variables are listed in Table 4.7, indicating which ones are presently being used by multivariate analyses. Of the variables listed, the distribution spectra of the last two items, namely, the transverse momenta of the tracks with the highest and second highest values, and their distance in $\eta \times \phi$ space from the calorimeter cluster axis, are shown in Figures 4.5 and 4.6, for both signal and background. It can be seen that the highest two transverse momentum spectra for $\tau$ are harder (i.e. have a higher value on the average) than the corresponding ones for background. Also, the $\tau$ tracks lie closer to the cluster axis than their background track counterparts. Thus, although the spectra do not exhibit sufficient separation to allow applying a one-dimensional discriminatory cut, they are to be considered as possible ingredients for a multivariate analysis.
Table 4.7: List of variables for $\tau$ identification.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Input for H-matrix</th>
<th>Input for NN/PDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Cluster energy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>em1frac</td>
<td>$E_{\text{cell}1}/E_{\text{total}}$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>em2frac</td>
<td>$E_{\text{cell}2}/E_{\text{total}}$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>em3frac</td>
<td>$E_{\text{cell}3-6}/E_{\text{total}}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>em4frac</td>
<td>$E_{\text{cell}7}/E_{\text{total}}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>icdmgfrac</td>
<td>$E_{\text{cell}8-10}/E_{\text{total}}$</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>fhfrac</td>
<td>$E_{\text{cell}11-15}/E_{\text{total}}$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>chfrac</td>
<td>$E_{\text{cell}6-17}/E_{\text{total}}$</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>e3x3frac</td>
<td>Energy fraction in 3x3 window around hottest tower</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>e5x5frac</td>
<td>Energy fraction in 5x5 window around hottest tower</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Profile</td>
<td>Energy fraction in towers with highest and second deposited energy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>crms</td>
<td>Cluster jet width in $\eta \times \phi$ space</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Tracks</td>
<td>Number of tracks</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>trms</td>
<td>Track &quot;jet&quot; width in $\eta \times \phi$ space</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Track isolation</td>
<td>Number of tracks in annulus between cones of two sizes about cluster axis</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>p/E</td>
<td>$\text{(Highest track } p)/\text{Cluster } E$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$p_{T1}, p_{T2}$</td>
<td>Highest and second highest $p_T$</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>dR1,dR2</td>
<td>Distance in $\eta \times \phi$ space from cluster axis of highest and second $p_T$ tracks</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
Figure 4.5: Leading and second leading track transverse momenta. Top - signal, bottom - background.
Figure 4.6: Distance from cluster axis of leading and second leading track transverse momenta. Top - signal, bottom - background.
Conclusions and Future Plans

Conclusions of this study and future plans based on them for improving $\tau$ identification are as follows:

- Optimal values for discriminants are seen to be different for different processes. Also, a set of variables that provides good discrimination for some process(es) is not necessarily as effective for other processes. Therefore, it would be beneficial to determine optimum variable sets for the different physics processes, and apply different discriminating criteria for signal acceptance and/or background rejection for different physics events, in addition to the global criteria being applied for all events.

- A comparison of the efficiency studies of the Fisher discriminant optimization and the jet width-profile optimization schemes suggests that of the 14 variables used as input to calculate the Fisher discriminant, jet width and profile play prominent roles. Put another way, perhaps there are some variables that play minor (if any) roles in providing discrimination between signal and background.
Thus, a detailed study addressing the relative importance of the variables may allow discarding some variables that are ineffective, and possibly discovering more effective ones at the same time.

- It appears that the distinction between signal and background signatures becomes less clear in the forward regions of the calorimeter ($|\eta| \geq 1.1$), at least as far as trying to distinguish them with the same discriminants as were used for the central region is concerned. Therefore, it may be helpful to train $H$-matrices on the forward $\eta \times \phi$ region (possibly with more effective variables as discussed in the previous items), or some essentially new strategy is here required.

- Utilize the preshower information to possibly distinguish individual photons. This could improve the identification of hadronic decay modes involving neutral pions that decay to two photons.

- Use more sophisticated methods like multivariate analyses that recognize and take advantage of the fact that the correlations among variables are different for different processes, even though the distribution of individual variables may look similar. To that end, studies are currently under way using Neural Networks (NN) and Probability Density Estimates (PDE) to achieve the goal of signal recognition and background rejection for $\tau$s.
Bibliography


(URL: http://d0wop.fnal.gov/software/offline_document.ps)


(URL: http://root.cern.ch)