Chapter 4

Reconstruction and Particle ID

The raw event data which comes from the detector is given in terms of quantities such as digitized counts in a calorimeter cell, counts per time bin for a tracking chamber wire, and so on. However, these quantities in themselves are not very interesting. The patterns of ionization in the calorimeter and tracking chambers are presumably due to particles originating from a $p\bar{p}$ collision which interact within the detector; what one would like to know are the kinematic parameters of these physical objects. The process of turning the raw detector data into descriptions of objects such as leptons and jets is called *reconstruction*, and is carried out by a computer program called DØRECO.

4.1 The Reconstruction Program

The reconstruction process can be divided into three major phases:

- *Hit finding*, during which the raw data is unpacked and converted into 'hits' (i.e., energy deposits in calorimeter cells, or pulses on tracking chamber wires) of definite energy and spatial location.

- *Tracking and clustering*, during which hits which are close together spatially are joined together to produce 'clusters' in the calorimeter and 'tracks' in the tracking chambers.

- *Particle identification*, during which information from all parts of the detector is combined to produce a collection of objects which are candidates for being jets, electrons, or muons. The criteria used for identifying these candidates are deliberately made quite loose so that they have high efficiency, but there will also be a large background. When performing an analysis, one will typically make much tighter cuts on the reconstructed objects. Both the reconstruction cuts and the tighter cuts used in the top analysis are detailed in the particle ID sections below.

Hit finding for the tracking chambers starts by unpacking the raw digitized data of charge versus time and identifying individual pulses by looking for leading and trailing edges. Each pulse is integrated to find the total deposited charge (used to calculate dE/dx). The time of arrival of the pulse (after corrections for channel-to-channel variations) is used to determine the position of the pulse: the time required to drift to the sense wire gives the distance of the hit from the sense wire, and the arrival time of the pulse from the delay line gives its location along the sense wire. Due to left/right ambiguities, there may be two possibilities for the location of a hit; both of the possibilities are used as input to the tracking phase. Due to the stagger in the sense wires, usually only the correct solutions will yield a good track.

In central detector tracking, the object is to identify groups of hits which lie along a straight line. Tracking is first done for each individual layer of the detector to produce track *segments.* Segments are then matched between the layers of each detector to form *tracks.* Finally, tracks are matched between the vertex chamber, the TRD, and the outer tracking chambers (CDC and FDC). For further details about the central detector hit finding and tracking, see [46, 48, 56, 57].

For the calorimeter, hit finding consists primarily of converting the energy deposited in each cell from digitized counts to GeV. This conversion ultimately comes from test beam measurements, in which the response of calorimeter modules to beams of known energy was measured [97, ch. 9]. Additional corrections are made for cell-by-cell variations in the electronics gain and pedestal values. These corrections are measured periodically during periods in which there are no collisions and are stored in a database, which the reconstruction program can later access.

Following cell unpacking, the cell energies are converted to transverse energy values using the position of the primary interaction vertex, as determined by the central tracking chambers. Cells with the same η and ϕ coordinates are summed together in the electromagnetic and hadronic calorimeters to produce *towers.* These towers are the input to the jet and electron clustering algorithms, described in the particle ID sections below.

The processing of the data from the muon system is similar in spirit to that done for the central detectors but quite different in detail, due to the differences in geometry and in the nature of the front-end electronics.

4.2 Vertex Finding

In order to calculate the transverse momentum or energy of a particle from the definitions (3.3) and (3.4), we must know θ, its polar angle in the lab frame. But for a particle which is detected only in the calorimeter, the only information we have about its direction is the location where it hits the calorimeter[1]. In order to extract an angle from this, we must also know one other point along its trajectory. This can be done by finding the location of the hard $p\bar{p}$ collision from which this particle presumably originated. This point is called the *interaction vertex* (or just the vertex of the event).

The x and y positions of the vertex can be known quite well simply due to the fact that the cross-section of the beam is made as small as possible in these dimensions, in order to maximize the luminosity. The typical cross-section of the beam was about $50\,\mu$m at a location of about 3–4 mm from the center of the detector with a drift over the length of a data run of less than $50\,\mu$m [98, pp. 14–16]. Thus, the (x, y) position of the vertex can be taken as a constant, and for many purposes can be set to $(0, 0)$ (the geometrical center of the detector).

The z-coordinate of the vertex, however, is less well constrained. Each bunch of particles in the Tevatron has some extent along the beam direction, and the resulting width of the z-distribution of interaction vertices in the detector is about 30 cm. Thus, it is necessary to measure the z-position of

[1] Actually, one could get an idea of the direction of the incident particle by looking at how the location of the shower varies with depth in the calorimeter. Something like this is done for isolated muons, but not for any other type of particle.

the vertex for each event individually. This is done using tracks found in the CDC [98, pp. 12–13] [66, pp. 39–41]:

- Take the tracks found in the CDC, and project them back towards the center of the detector.
- For each track, calculate the impact parameter — the minimum distance between the track and the z-axis of the detector. Throw out all tracks with an impact parameter larger than some cutoff. (This eliminates low-momentum tracks which have undergone a large amount of multiple scattering.)
- Project each track into the (r, z) plane, and compute the intersection with the z-axis. Histogram the z-positions of the intersections.
- Fit a gaussian around the peak of the resulting distribution. The mean is the estimate of the z-position of the vertex. The outlying regions of the histogram are also searched for any secondary peaks.

This procedure yields a resolution for the vertex z-coordinate of about 1–2 cm. Multiple vertices can typically be separated if they are at least 7 cm apart [66, pp. 40–41].

4.3 Electron Identification

Electrons are identified as localized deposits of energy in the electromagnetic calorimeter with an associated central detector track pointing back to the interaction vertex.

4.3.1 Candidate Construction

To identify electron candidates, the reconstruction program takes the following steps:

- Clusters are formed from calorimeter towers using a 'nearest neighbor' algorithm [99] [47, pp. 71–72]. Starting with the highest-E_T tower, adjacent towers are added to the cluster provided that they are above an E_T threshold, and that the cluster is not too big.
- A cluster is required to have at least 90% of its energy in the electromagnetic calorimeter, and at least 40% of the energy must be contained in a single tower.
- The centroid of the cluster is computed using the cells in the third electromagnetic layer. If $\vec{x}_i$ is the position of the center of cell i and E_i is the amount of energy deposited in that cell, then the centroid is the log-weighted center-of-gravity [100, pp. 83–85] [101]

$$\vec{x}_{\mathrm{COG}} = \frac{\sum_i w_i \vec{x}_i}{\sum_i w_i}. \tag{4.1}$$

The weights w_i are

$$w_i = \max\left(0, w_0 + \ln\left(\frac{E_i}{\sum_j E_j}\right)\right). \tag{4.2}$$

The parameter w_0 is chosen to optimize the position resolution, and the sums are over all EM3 cells in the cluster. The position resolution achieved is about 1.5–2 mm.

- Finally, the reconstruction program searches for a central detector track pointing from the interaction vertex to the calorimeter cluster within a "road" of $\Delta\eta = \pm 0.1$, $\Delta\phi = \pm 0.1$. If such a track is found, the cluster is identified as an electron candidate; otherwise, it becomes a photon candidate.

4.3.2 Selection Cuts

The cuts used in forming electron candidates are purposely quite loose; users are expected to apply further cuts which can be tailored to the particular analysis being carried out. There are numerous additional variables available for recognizing electrons; those used in this analysis [25] [100, pp. 81–87] are:

- Covariance matrix χ^2: The primary tool used for quantifying the information contained in the shape of the electromagnetic shower is the 'H-matrix' analysis [102, 103, 104]. Suppose one has a set of N observations of events of a given type, where each observation consists of M variables: $\mathbf{x}^i = (x_1^i, \ldots, x_M^i)$. One can form the covariance matrix from the outer products

$$\mathbf{V} = \frac{1}{N} \sum_{i=1}^{N} (\mathbf{x}^i - \bar{\mathbf{x}})^T (\mathbf{x}^i - \bar{\mathbf{x}}), \tag{4.3}$$

where $\bar{\mathbf{x}}$ is the mean value of the N measurements:

$$\bar{\mathbf{x}} = \frac{1}{N} \sum_{i=1}^{N} \mathbf{x}^i. \tag{4.4}$$

The 'H-matrix' is then the inverse of this covariance matrix:

$$\mathbf{H} = \mathbf{V}^{-1}. \tag{4.5}$$

For any subsequent measurement $\mathbf{y}$ one can define a χ^2 which describes how likely it is that $\mathbf{y}$ came from the same sample as the $\mathbf{x}$'s:

$$\chi^2 = (\mathbf{y} - \bar{\mathbf{x}})\mathbf{H}(\mathbf{y} - \bar{\mathbf{x}})^T. \tag{4.6}$$

For the problem of electron identification, the events $\mathbf{x}$ used to build the H-matrix are Monte Carlo electron events. A total of 41 observables are used, consisting of the fractional energies in layers 1, 2, and 4 of the EM calorimeter, the fractional energies in each cell of a 6×6 array in the third EM layer (centered on the most energetic tower in the cluster), the z-position of the interaction vertex, and the logarithm of the total cluster energy. A separate matrix is built for each ring of calorimeter cells with the same $|\eta|$ coordinate. This analysis requires $\chi^2 < 100$ (41 degrees of freedom). Figures 4.1(a),(b) show the χ^2 parameter for electron and background samples.

- Isolation: The decay electron from a W should not be close to any other objects in the event. To quantify this, define the *isolation fraction.* Let $E_{\rm TOT}(0.4)$ be the energy deposited in all calorimeter cells within a cone of radius $R < 0.4$ around the electron direction (where $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$). Similarly, let $E_{\rm EM}(0.2)$ be the energy deposited in the electromagnetic calorimeter within a cone of radius $R < 0.2$. Then

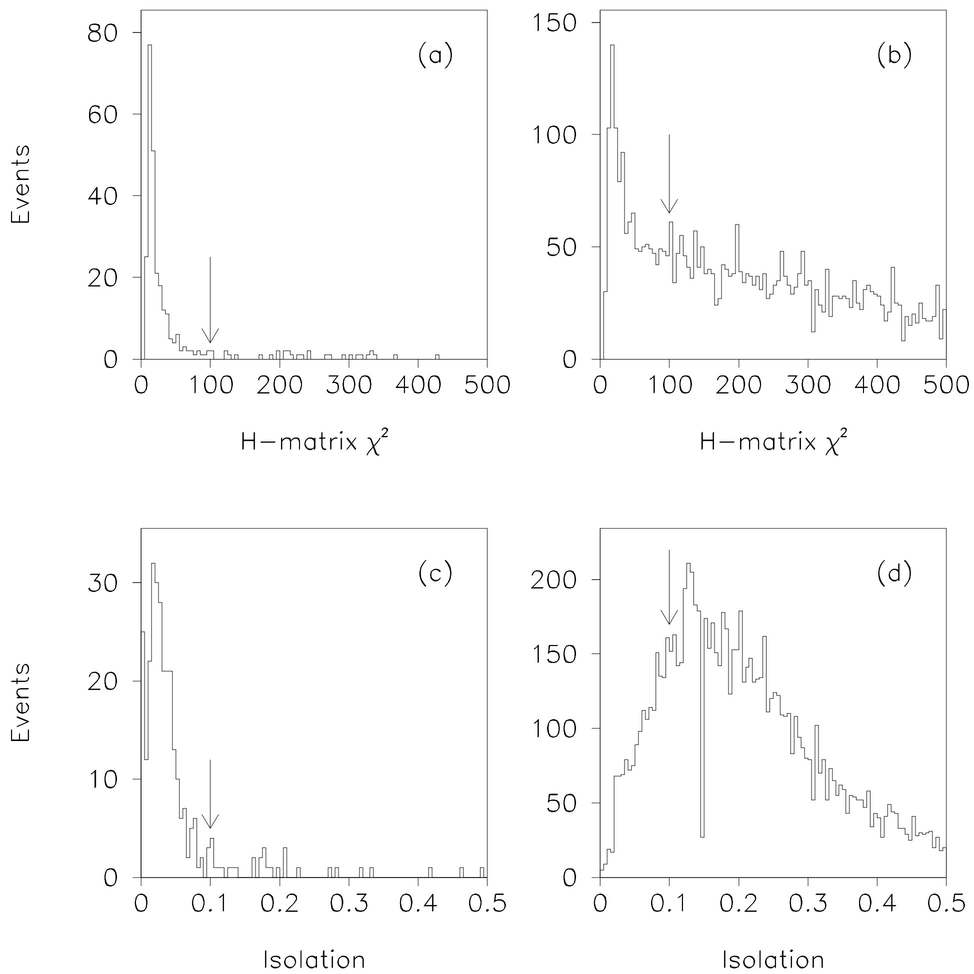

Figure 4.1: Covariance matrix χ^2 and isolation parameter. (a), (c) are from electrons in $Z \rightarrow ee$ events, and (b), (d) are from EM clusters in inclusive jet data. [25]

the isolation fraction $f_{\rm iso}$ is

$$f_{\rm iso} \equiv \frac{E_{\rm TOT}(0.4) - E_{\rm EM}(0.2)}{E_{\rm EM}(0.2)}. \tag{4.7}$$

This analysis requires $f_{\rm iso} < 0.1$. Figures 4.1(c),(d) show $f_{\rm iso}$ for electron and background samples.

- Track match significance: A significant source of background to electrons is photons, either produced directly or by the decay of π^0 and η mesons. Such photons do not create tracks in the central detector, but might appear to do so if some charged particle is nearby. This background can be reduced by requiring that the track point accurately at the centroid of the calorimeter cluster. To quantify this, define the *track match significance* [25]:

$$S = \sqrt{\left(\frac{\Delta\phi}{\sigma_{\Delta\phi}}\right)^2 + \left(\frac{\Delta z}{\sigma_{\Delta z}}\right)^2}, \tag{4.8}$$

where $\Delta\phi$, Δz are the coordinate differences between the cluster centroid and the point at which the track hits the calorimeter, and $\sigma_{\Delta\phi}$, $\sigma_{\Delta z}$ are the corresponding measurement resolutions. (This form is appropriate for the central calorimeter. In the end region, r replaces z.) This analysis requires $S < 5$. Figures 4.2(a),(b) show S for electron and background samples.

- Track ionization: Since DØ has no central magnetic field, e^+e^- pairs resulting from photon conversions do not diverge very far from each other, and are often reconstructed as a single track. However, the energy deposition per unit length (dE/dx) will be twice that of a single electron

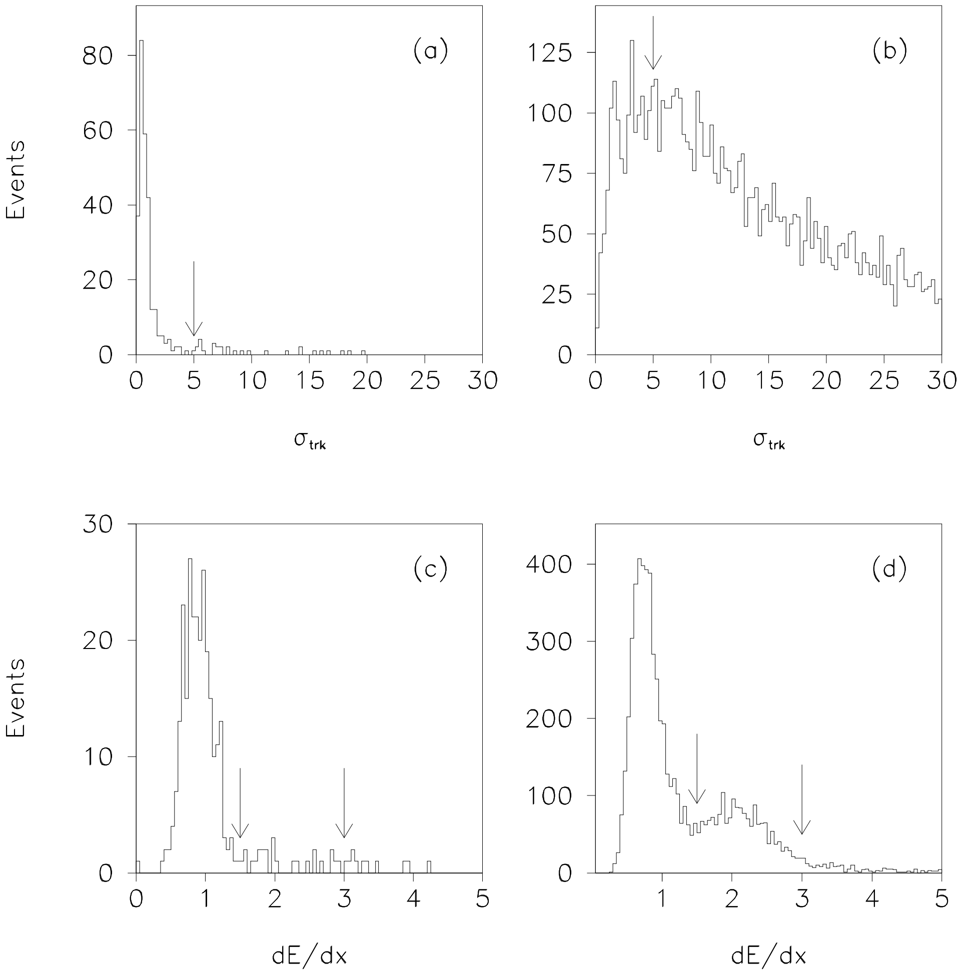

Figure 4.2: Track match significance S and ionization dE/dx (in the CDC). (a), (c) are from electrons in $Z \to ee$ events, and (b), (d) are from EM clusters in inclusive jet data. [25]

(which is called one 'MIP', for 'minimum ionizing particle'). Thus, the background due to conversions can be reduced by cutting out the region around 2 MIPs. For tracks in the CDC, the excluded region is $1.5 \leq dE/dx \leq 3.0$ and for tracks in the FDC, it is $1.3 \leq dE/dx \leq 2.7$. Figures 4.2(c),(d) show the ionization for signal and background samples.

In addition to these quality cuts, the analysis makes the kinematic cuts $E_T > 20\,\mathrm{GeV}$ and $|\eta^{\mathrm{det}}| < 2$. The 'detector-eta' η^{det} is the η which would be calculated with an interaction vertex fixed at the origin.

A summary of the electron selection cuts is given in Table 4.1. The efficiency for identifying electrons with these cuts is about 72% in the CC and 43% in the EC [25]. For the mass fitting Monte Carlo studies, where rejection of background is not an issue, a slightly looser set of cuts is used. These cuts are indicated in the 'relaxed cuts' column.

4.3.3 Electron Energy Corrections

The absolute energy scale of the calorimeters was originally set using test beam calibration data. However, due to differences in conditions between the test beam setup and the DØ installation, this calibration is slightly low. One useful point of reference is the mass of the Z in $Z \to e^+ + e^-$ events, which has been measured very accurately by the LEP experiments [3, p. 1356]. For this analysis, the measured electron energies are scaled up so that the mass peak in $Z \to e^+ + e^-$ matches the LEP measurement [100, p. 87]. This correction is about 5% in the central calorimeter, and 1–2% in the end calorimeters.

	Standard cuts	Relaxed cuts
Electromagnetic fraction	$F_{\mathrm{EM}} > 0.9$	$F_{\mathrm{EM}} > 0.9$
Cluster χ^2	$\chi^2 < 100$	$\chi^2 < 100$, in CC $\chi^2 < 200$, in EC
Isolation	$f_{\mathrm{iso}} < 0.1$	$f_{\mathrm{iso}} < 0.1$
Track match significance	$S < 5$	$S < 10$
Track ionization	CDC: $dE/dx < 1.5$ or $dE/dx > 3.0$ FDC: $dE/dx < 1.3$ or $dE/dx > 2.7$	—
Detector η	$\lvert\eta^{\mathrm{det}}\rvert < 2$	
Transverse Energy	$E_T > 20\,\mathrm{GeV}$	

Table 4.1: Summary of electron ID cuts.

4.4 Muon Identification

Muons are identified as tracks in the muon chambers which point back at the interaction vertex. There are two major backgrounds to contend with: cosmic ray muons, and leakage out of the backs of hadronic showers. This latter background is only important in the transition regions between the central and end calorimeters where there is not so much material.

4.4.1 Candidate Construction

Analogous to the central detector reconstruction, muon reconstruction proceeds by converting the raw hit and time information into three-dimensional hit positions, and then attempting to find hits which lie on straight lines pointing towards the interaction vertex [105]. For muons, the situation is complicated by the fact that there is a magnetic field between the first and second layers of drift tubes. Thus, tracking is done separately for segments before and after the magnet. The segments are matched, and a measurement of the muon momentum can be made by measuring by how much the track bends while passing through the magnet.

The muon system by itself does not give a very good measurement of the muon momentum. However, the momentum resolution can be improved if the muon track can be associated with a track in the central detector and with an interaction vertex. This allows the trajectory of the muon before the magnet to be determined more accurately. (The process is referred to as *global fitting* [106].)

The momentum measured by the muon system is, of course, its momentum *after* it has passed through the calorimeter. However, a muon will typically lose several GeV of energy in the calorimeter. This energy loss is estimated through a Monte Carlo calculation and added to the measured muon momentum (for the dilepton channels, the measured energy loss is used [107]). The fact that a real muon will deposit a small, but nonzero, amount of energy in the calorimeter will also be useful for background rejection.

4.4.2 Selection Cuts

Muons are required to be entirely contained in the WAMUS system, with $\eta < 1.7$. (For run 1B data, muons are required to be contained in the central muon (CF) system, due to efficiency problems in the end chambers caused by chamber aging.) For muons from W decay, this analysis requires $p_T > 15\,\mathrm{GeV}/c$. In addition, just as for electrons, there are a number of quality cuts made on candidate muon tracks [25] [43, pp. 70–83]:

- A-stubs: The latest version of the muon reconstruction can form muon tracks consisting of only hits in the innermost (A) layer. These 'A-stubs' are excluded from further consideration.

- Impact Parameters: Two impact parameter cuts are used to require that the muon tracks point towards the interaction vertex, and thus reject cosmic ray backgrounds.

  The *non-bend impact parameter* is defined by projecting the muon track into the x, y plane (it does not get bent in this plane), extrapolating the track formed by the B and C layers towards the center of the detector, and calculating the impact parameter between this extrapolated track and the interaction vertex. This impact parameter is required to be less than 40 cm.

  The *bend-view impact parameter* is calculated by projecting the track into the plane in which the muon bends and calculating the impact parameter of this projection. This parameter is required to be less than 25 cm.

- Cosmic Ray Veto (MUCTAG): A cosmic ray muon which penetrates the entire detector will leave hits in the muon chambers on both sides of the interaction region. Therefore, a track in the central region ($\eta^{\mathrm{det}} < 1.0$) is rejected if there is another track or an excessive number of hits located back-to-back in both ϕ and η [108].

- Track Timing: When trying to find the location of a track using a drift chamber, one needs to know the time at which the particle went through the chamber (the 'T_0'). Normally, this is deduced from the time at which the beams cross. However, this will not be correct in general for cosmic rays, which are not synchronized with the accelerator. Thus, for a cosmic ray, the quality of the track can often be improved by taking a T_0 different from the beam crossing. This provides another way to reject cosmic rays: the track χ^2 is minimized with respect to the T_0 and the result compared with the nominal T_0 of the beam crossing. If the difference is larger than 100 ns, the track is rejected.

- Hit Multiplicity: A muon track will typically have hits in 7–10 drift tubes, depending on the region of the detector. High-p_T muon tracks in the end regions are required to have at least 5 hits (no explicit cut is made in the central region).

- Muon Quality (IFW4): For each track, the muon reconstruction code makes a set of cuts on the number of modules hit, impact parameters, and hit residuals. The number of cuts which the track fails is called 'IFW4'; it is required to be no more than one.

- Calorimeter Confirmation: A muon passing through the detector will typically deposit between 1 and 3 GeV of energy in the calorimeter. The energy contained in all cells within a one cell radius surrounding the muon track is summed and is required to be at least 1 GeV. If there is no CD track matched with the muon, the cut is set higher, at 1.5 GeV.

- Path Length Through Iron Toroids: Muons which pass through the thin region of the iron toroid (in the range $0.8 < |\eta| < 1.0$) are poorly measured, and may be contaminated by a background of leakage from the tail ends of hadronic showers. To reject such tracks, the integrated magnetic field $\int B \cdot dl$ is required to be greater than 1.83 Tm.

- Isolation: The analysis requires that the distance in R between the muon and the nearest jet be greater than 0.5.

The above cuts define high-p_T isolated muons. It is also of interest to look for soft muons from semileptonic decays of b quarks. These muons are selected using requirements which are somewhat looser than those outlined above. In addition, a tag muon is required to be within $R < 0.5$ of a jet. A summary of the muon ID cuts is given in Table 4.2. The efficiency for identifying muons with these cuts is about $\sim 41\%$ [25].

4.5 Jet Reconstruction

When a quark or gluon leaves the site of a hard scattering, it cannot remain free, but instead *hadronizes*, or *fragments* into a collection of colorless

	Isolated muon	Tag muon
Momentum	$p_T > 15\,\mathrm{GeV}$	$p_T > 4\,\mathrm{GeV}$
Pseudorapidity	$\lvert\eta\rvert < 1.7$ [a]	$\lvert\eta\rvert < 1.7$ [a]
Cosmic veto	yes	—
A-stub removal	yes	yes
Impact Parameters	BVIP $< 25\,\mathrm{cm}$ NBIP $< 40\,\mathrm{cm}$	—
Floating T_0	$\Delta T_0 < 100\,\mathrm{ns}$	—
Minimum Hits	$N_{\mathrm{hits}} \geq 5$, in EF	$N_{\mathrm{hits}} \geq 4$
Track Quality	IFW4 ≤ 1	IFW4 ≤ 1, for $\lvert\eta\rvert < 1$ IFW4 $= 0$, for $\lvert\eta\rvert > 1$
Calorimeter Confirmation	$> 0.5\,\mathrm{GeV}$, w/ CD track $> 1.5\,\mathrm{GeV}$, otherwise	$> 1.5\,\mathrm{GeV}$
Path Length	$\int B \cdot dl > 1.83\,\mathrm{Tm}$	—
Isolation	$\Delta R(\mu, \mathrm{jet}) \geq 0.5$	$\Delta R(\mu, \mathrm{jet}) < 0.5$

Table 4.2: Summary of muon ID cuts.

[a] Restricted to CF region ($\lvert\eta\rvert \lesssim 0.7$) for run 1B.

hadronic particles. This collection will typically lie in a cone around the direction of motion of the original parton, and will show up in a calorimeter as a cluster of energy. This is called a *jet.*

If this sounds somewhat ill-defined, that's because it is. To a much greater extent than for electrons and muons, the results one gets from a jet reconstruction depend on exactly how a jet is defined.

The jet definition most commonly used in a $p\bar{p}$ environment is the 'cone algorithm', in which jets are taken to be the energy inside of cones of a fixed radius (in η–ϕ space). This definition was used by UA1 [109, 110], UA2, and CDF, and is also used by most DØ analyses; a description of this algorithm is given below. Another method which has been explored is the 'nearest neighbor' algorithm, which employs a clustering method similar to that used for electrons. In principle, it should yield a better resolution than the cone algorithm, but at present, it is less well understood.

For further information about jets at DØ, see [66, ch. 3], [111, ch. 4], [112].

4.5.1 Cone Jet Algorithm

The following is a description of the cone jet algorithm as used at DØ [113] [112, ch. 4] [100, pp. 88-90]:

- Preclustering: The calorimeter towers (see Section 4.1) are first sorted in E_T, and a set of 'seed' clusters are formed. Starting with the highest-E_T tower which has not yet been assigned to a precluster, the precluster is formed from all contiguous towers within $|\Delta\eta| < 0.3$, $|\Delta\phi| < 0.3$ with $E_T > 1\,\mathrm{GeV}$. Preclustering continues until all towers with $E_T > 1\,\mathrm{GeV}$ have been assigned to a seed cluster. For each precluster, the E_T-weighted centroid defines the axis of the corresponding jet candidate.

- Cone Clustering: A new cluster is defined around the trial axis including all calorimeter cells within a fixed distance in η, ϕ space. The centroid of this new cluster is computed, which defines a new jet axis. This process is then repeated until it stabilizes.

- Merging and Splitting: Once the cone clustering has completed, some cells may turn out to have been assigned to more than one jet. If two jets share some cells, the fraction of the total energy which is shared between them is examined. If the fraction is greater than 50%, the two jets are merged together, and the jet axis recalculated from the centroid of all the cells in the merged jet. Otherwise, the jets are split, and each shared cell is assigned to the closest jet.

- E_T Cut: A jet is required to have a total E_T above a threshold, which is usually set to $8\,\mathrm{GeV}$.

- Jet E_T Definition: For this analysis, the E_T of a jet is defined by

$$E_T = \sqrt{E_x^2 + E_y^2}, \tag{4.9}$$

where E_x and E_y are the sums of the components of the individual cell energies:

$$\begin{aligned} E_x &= \sum_i E_x^i \\ E_y &= \sum_i E_y^i. \end{aligned} \tag{4.10}$$

For event selection, this analysis will use jets with a radius of $R = 0.5$. Kinematic fitting, however, will use narrower jets, with radius $R = 0.3$.

4.5.2 Jet Corrections

Ideally, one would like the measured jet energy to give back the energy of the original parton which formed the jet. However, there are systematic biases in jet measurements which need corrections. In addition to having to determine the energy scale (just as for electrons), there are several other effects which become important due to the extended, multiparticle nature of jets:

- Many of the particles in even a high-E_T jet will be fairly soft ($\lesssim 2\,\mathrm{GeV}$). However, the response of the calorimeter becomes nonlinear in this region, so simply summing the calorimeter responses to each particle will not give the correct total energy.

- Since the hadronic shower is an extended object, some portion of the shower may extend beyond the jet cone. In addition, some of the particles radiated by the initial parton may fall outside of the cone.

- A jet will pick up some extra energy due to the underlying ('spectator') event, as well as noise due to the natural radioactivity of the uranium absorber. Both of these sources affect jets much more than electrons due to the fact that hadronic showers are much larger than electromagnetic showers.

- The zero-suppression used in the calorimeter readout can also give rise to a systematic shift in energy which scales with the shower size.

The method adopted to obtain the jet corrections at DØ is called the Missing E_T Projection Fraction (MPF) method. It was originally used by the CDF collaboration [114]; its application at DØ is described in [111, pp. 54–63] [100, pp. 90-94] [112, 115, 116]. Briefly, the idea is to look at events which consist of one jet with a very high electromagnetic content (it is required to pass the reconstruction cuts for a photon), a second jet lying opposite in ϕ, and no other objects in the event. The EM jet is corrected using the electron corrections. There should be no energetic neutrinos in these events, so any missing transverse energy ($\not\!\!E_T$) remaining in the event can then be attributed to a mismeasurement of the hadronic jet. By projecting the $\not\!\!E_T$ along the jet axis, the needed correction for the jet can be derived. This is averaged over similar jets in the sample to produce a correction which is a function of jet E_T, η, and electromagnetic content. Out-of-cone showering, underlying event, and noise effects were determined in separate studies using Monte Carlo and minimum-bias event samples. The resulting corrections are shown for two different η values in Figure 4.3.

Note that the MPF corrections are not entirely sufficient to return to the parton level. While the effects of showers leaking out of the jet cone is accounted for, energy lost due to QCD radiation outside of the jet cone is not. Corrections for this effect are made later, before doing kinematic fitting.

4.6 Missing Energy Reconstruction

From momentum conservation and the fact that the colliding proton and antiproton have nearly opposite momenta, it follows that the total vector sum of the momenta of all final-state particles in the event must be zero. However, one cannot usefully apply total momentum conservation in the direction along the beam, since many particles will escape detection by going down the beam pipe. But the very fact that they do escape implies that they have very small transverse momenta; thus, one can apply momentum conservation in the plane perpendicular to the beam. If the sum of the transverse momenta of the detected particles is significantly different from zero, the discrepancy is attributed to one or more neutrinos which escaped detection, and which must have transverse momentum opposite the total detected transverse momentum.

4.6.1 Definition of Missing Transverse Energy

Each cell in the calorimeter is given a four-vector, with an energy equal to the measured energy in the cell, a direction pointing from the interaction vertex to the center of the cell, and a mass of zero. The transverse components of these vectors are summed over all the calorimeter cells (including the ICD).

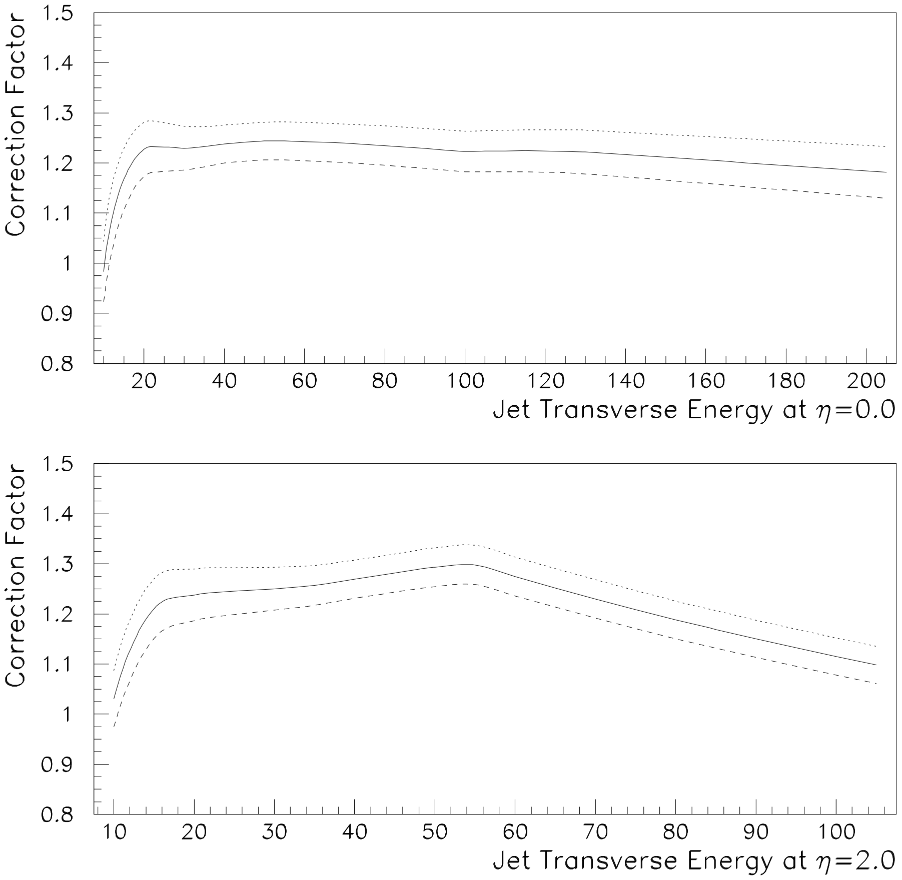

Figure 4.3: Energy scale corrections for $R = 0.5$ cone jets. Shown for both the central region ($|\eta| = 0.0$) and the forward region ($|\eta| = 2.0$). [25]

The negation of this vector is then the 'calorimeter missing-E_T', or $\vec{\not{E}}_T^{\mathrm{cal}}$:

$$\vec{\not{E}}_T^{\mathrm{cal}} = -\sum_i \vec{E}_T^i. \tag{4.11}$$

This does not yet take into account muons, which (for high-p_T muons) only deposit a small portion of their energy in the calorimeter. The 'total missing E_T', or just $\vec{\not{E}}_T$, is then $\vec{\not{E}}_T^{\mathrm{cal}}$ with the transverse momenta of all good muon tracks subtracted.

4.6.2 Corrections

Since the $\not{E}_T^{\mathrm{cal}}$ is the sum over everything in the calorimeter, it follows that if any object in the calorimeter is mismeasured, then $\not{E}_T^{\mathrm{cal}}$ will be mismeasured by exactly the same amount. So whenever corrections are made to electrons and jets, the corresponding correction must be made to $\not{E}_T^{\mathrm{cal}}$ [117]. This is straightforward to do: as each object is corrected, one simply adds the uncorrected object $\vec{E}_T$ to $\vec{\not{E}}_T^{\mathrm{cal}}$ and then subtracts the corrected object $\vec{E}_T$.