APPENDIX A

DEFINITIONS OF THE VARIABLES USED IN OBJECT IDENTIFICATION

In this appendix we provide a more detailed description of the various particle identification algorithms and the variables used to select reconstructed objects in this analysis that were not defined in the text. Since these are discussed in detail elsewhere, See References [50, 61–63], and have been used for years at CDF, we only provide a summary here.

In this analysis we consider jets, tracks, vertices, photons, electrons and missing energy. Recall that jets in the calorimeter, as was described in Section 2.4.1, are due to quarks and gluons, taus, photons, and electrons which deposit energy in the calorimeter in a clustered way. Since jets are simple objects and have been defined elsewhere, we begin this appendix by defining the variables used for charged particles as they pass through the various tracking subsystems known as "tracks". Since combinations of tracks are used to determine the origin of the primary collision we describe the algorithm by which we cluster together tracks to identify the origin of the collision point in space and time, known as a "SpaceTime vertex". From here we use tracks to differentiate between clusters of energy that are mostly deposited in the EM calorimeter into the electron, photon or neither category. Finally we describe the measurement of the energy imbalance in the detector known as missing transverse energy ($\not\!\!E_T$).

A.1 Tracks

As described in Section 2.4.2, a charged particle that traverses through the SVX and COT systems energy deposits energy in localized positions at specific times within these subsystems and we refer to each as “hits” in the detector [50]. Since these systems are in a magnetic field tracks are reconstructed by fitting the hit locations using helical pattern recognition algorithms. In the same way that jets are seeded with a single tower with significant energy, tracks are seeded by looking for a grouping of hits (known as “segments”) in each of the 12 sense wires in each superlayer in the COT. Then, to reduce problems from ‘fake’ hits and achieve better resolution, only segments of significant quality are linked together using a fit to a five parameter helix to form tracks. The helix terms are defined by its curvature $C = q/2R$, where R is the radius of the helix $x - y$ projection and q is the charge of the particle. The rest of the helix terms are defined below. When the SVX tracking information is available the information from the two tracking chambers can be combined which improves the overall track resolution and allows a more robust 3D pattern recognition of the trajectory [50]. Below are the various definitions for the track related parameters used in Tables 2.6 and 2.7 and calibrated against in Chapter 3. .

- t_0 **Track Inital Time:**

The time information of each hit along the trajectory of the track is used as part of the overall fit of the track. When all the hits are associated with the fitted track, a best fit inital time of the track is determined.

- $T_0\sigma$ **Track Time Uncertainty:**

  This is the uncertainty associated with the track time measurement based on the spread the timing of the hits in the COT around the best fit time.

- P_T **Beam Constrained Track Momentum:**

  This is a track's transverse momentum. While this momentum can be calculated without assuming the particle originates from the beam line, it has been shown that by assuming the track does originate from the beam line, and by correcting for the spatial location of the beam we, on average, improve the measurement of the track momentum.

- $COTStereoSeg(5)$ **Number of COT Stereo Segments with 5 or more Hits:**

  For a track to have an accurate timing measurement it must have a significant number of hits along the trajectory. This variable measures the number of segments found in the stereo superlayers that have five or more hits in that segment.

- $COTAxialSeg(5)$ **Number of COT Axial Segments with 5 or more Hits:**

  For a track to have an accurate timing measurement it must have a significant number of hits along the trajectory. This variable measures the number of segments found in the axial superlayers that have five or more hits in that segment.

- Z **Z Position:**

  This variable defines where along the direction of the beam the track originates. We typically only consider tracks that have come from a $|z|$ <70 cm to help insure the tracks origin comes from the best-instrumented part of the detector to help insure a quality track used in the timing measurement.

- d_0 **Corrected Impact Parameter:**

  This is a measurement of the tracks impact parameter (distance of closest approach to the beam line) corrected for the spatial location of the beam position. Small values of this parameter ($d_0 < 0.2$) indicate whether the charged particle comes directly from the beam line as opposed to being from the secondary decays of a long-lived particle or was a track created from the interactions with detector material.

- $nCOTHits$ **Number of COT Hits:**

  This variable considers the trajectory of the track and, using the known geometry of the tracking chamber, compares the observed number of hits along the trajectory to the expected number of hits. We use this variable to ensure that the track has activated a sufficient amount of COT hits to ensure we have a real track.

- $COTAxialHits$ **Number of COT Axial Hits:**

Since the P_T of the track is primary determined by it's curvature in the phi direction, we simply counts the total number of axial segment hits associated with a track to help insure the track has a well measured P_T.

A.2 Photons

As described in Section 2.4.3, the CDF detector has been used to accurately identify and measure high energy photons for over 25 years using well established identification requirements [61]. Photons at CDF are identified as an energy deposits in up to three calorimeter towers in η and one tower in ϕ where the seed tower exceeds 3 GeV. Additionally we require a matching cluster of energy in the CES in the same seed tower; this cluster provides a precision measurement of the position of the photon. Below is the definition of the various variables not previously described in the text used to identify photons at CDF discussed in Table 2.8 that are not described in more detail in the text itself.

- **Fiducial**

  In order for a photon candidate to be considered in the analysis, we require that it be deposited in the well instrumented ("fiducial") region of the detector where the calorimeter is likely to have made full measurement of the photon shower and has the highest quality measurements of the photon properties. Since we want a full shower in the CES, we define the fiducial region in terms of the CES detector and is set in order to avoid inactive regions of the detector.

For this analysis we only consider photons found in the central part of the detector ($|\eta|$ <1.0). This is due to the fact that the central region is not only better instrumented, with the full set of tracking chambers, but the EMTiming system has been fully calibrated and validated in this region. This region is defined as near the center of each tower, within 21 cm of the tower center in $r-\phi$ ($|X_{CES}|$ <21 cm) and in z is 9< $|Z_{CES}|$ <230 cm and the fiducial variable is set such that a photon either is measured inside our outside the fiducial area.

- $\frac{\text{HAD(E)}}{\text{EM(E)}}$:

  Since most photons leave most of their energy in the electromagnetic portion of the calorimeter, the ratio of energy deposited in the hadronic part of calorimeter towers in the cluster to that in the electromagnetic part helps separate photons from jet backgrounds.

- **Energy Isolation**

  Since photons from the decays of $\pi^0 \to \gamma\gamma$ as parts of jets are a significant background to promptly produced photon, we help separate them by considering the amount of energy around the photon cluster. For this reason we use an isolation variable, defined as

$$Isolation = \frac{E_T^{cone} - E_T^{cluster}}{E_T^{cluster}} \tag{A.1}$$

where E_T^{cone} is the sum of the transverse energy in both the electromagnetic and hadronic calorimeters in the towers adjacent within a radius of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ and $E_T^{cluster}$ is the transverse energy as measured in the EM calorimeter only.

- **Track Isolation**

  We also consider isolation in the tracking chamber as well as the calorimeter. To help separate photons from jets we create a tracking isolation variable to be the ΣP_T of all tracks within a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ around the photon tower.

- **N3D Track Rejection**

  In order to distinguish between electrons and photons, whose showers look almost identical in the calorimeter, we search for the presence 3D tracks that have an extrapolated position at the CEM calorimeter of certain quality but below a P_T threshold. To further clarify, a N3D track is any track that contains readout coming from both the SVX (if present) and COT tracking system with P_T >0.3 GeV/c. Our variable is to count the number of 3D tracks, N3D. Since we allow the presence of a single low P_T track, our variable considers the PT of the track found, if any.

- **2^{nd} CES Cluster Energy**

  In order to reject photons that are due to $\pi^0 \rightarrow \gamma\gamma$ decay, we search the CES in the EM cluster for the presence of a second CES cluster. If one is found this variable is a measure of it's energy. Note that as the photon energy gets higher the probability that part of the shower creates a second, small CES cluster gets larger so it is useful to have requirements on this variable scale with the overall photon energy.

A.3 Electrons

As described in Section 2.4.4, at CDF electron candidates are identified by using mostly the same calorimeter information as is used in the identification of photons [62]. Thus, we use many of the same variables, albeit often with different selection requirements. Unlike the case of a photon, where we explicitly require there to be no track associated, if a calorimeter cluster can be matched to a track we call this an electron candidate. Below is the definition of the various variables not previously described in the text used to identify electrons at CDF discussed in Table 2.9 that are not described in more detail in the text itself.

- $|\Delta X|$ and $|\Delta Z|$

  By extrapolating the electron track to the cluster we can measure the separation between the extrapolated track position and the centroid of the CES cluster in the X and Z views, where $|\Delta X_{CES}|$ and $|\Delta Z_{CES}|$ are as defined as:

$$|\Delta X| = X_{track} - X_{CES} \tag{A.2}$$

$$|\Delta Z| = Z_{track} - Z_{CES}. \tag{A.3}$$

If there is a track that extrapolates to the electromagnetic cluster, it is considered to be associated with the cluster.

- **E/P**

  The ratio of the energy to the momentum of the highest P_T track pointing to the full energy of the EM cluster is useful in separating out electrons from jets that deposit a good deal of neutral energy objects in the calorimeter that will not show up in the single track with large momentum.

- L_{shr}: **L-Share**

  The L-Share (Laterial Sharing) variable is a measure of the transverese profile of the electromagnetic shower shape and the comparison of the expected lateral sharing of energy in the calorimeter towers of the electron cluster [62]. The L_{shr} variable is defined as:

$$L_{shr} = 0.14 \sum_i \frac{E_i^{adj} - E_i^{prob}}{\sqrt{0.14^2 E + (\Delta E_i^{prob})^2}} \tag{A.4}$$

  where E_i^{adj} is the energy in the tower adjacent to the tower of the electron, E_i^{prob} is the expected energy in an adjacent tower calculated from text beam data, and $0.14^2 E$ is the error associated with the energy measurement.