Chapter 4

DØ Detector

The final state from $pp$ interaction may contain electrons, muons, jets and neutrinos. The DØ detector is designed to identify and measure the energy of all these particles. The DØ detector is a multipurpose detector with almost $4\pi$ coverage at one of the collision point of the Fermilab Tevatron $pp$ collider. With an emphasis on precision measurements of leptons, photons and jets, DØ is designed principally to study high $p_T$ physics and high mass states. This includes the topics like: the search for the top quark (primarily in the leptonic and semileptonic decay modes), precision mass (and width) studies in the electroweak sector with the stress on a precise determination of the $W/Z$ mass ratio, measurements of the $WW\gamma$ coupling, searches for non-standard top and Higgs particle with $W$ width studies, high $p_T$ QCD physics as well as searches for new phenomena beyond the Standard Model.

4.1 Overview of DØ

The physics which is to be emphasized determines the ideal detector. An ideal detector consists of three main different parts. Tracking system, which records the hits encountered because of the passing particles in 3-dimensions. The calorimeter records the energy of the particles which are coming out of the tracking detector. A calorimeter would be so thick that it will absorb all the incident particles energies, basically stopping all the known particles coming out except muons and neutrinos. A muon system to detect muons. Neutrinos are chargeless weakly interacting particles and not detected directly, but are accounted for the imbalance left in the total detected momentum transverse to the beam.

The DØ detector as stated above is a multipurpose detector specially designed to provide good electron and muon resolution, superior electromagnetic and hadronic energy resolution through highly segmented calorimetry and full solid angle coverage. The basic components of the DØ detector are:

- Central Detector
- Calorimetry
• Muon Detector

A cutaway isometric view of the detector is shown below in Figure 4.1.

**DØ Detector**

Figure 4.1: Cutaway view of the DØ detector.
The central detector is designed to trace the trajectory of charged particles (tracking). This tracking system is designed to be the closest to the point of interaction to thereby minimize multiple scattering and identify secondary vertices. The central detector is surrounded by the calorimeter. The calorimeter is designed to measure the energy of particles and should be thick enough to stop particles, except neutrinos and muons which escape, and measure the deposited energy. Since the energy deposited by a lepton in matter is inversely proportional to the mass of the particle, muons escape the calorimeter with little energy deposition. A tracking system should contain as little material as possible, to minimize the probability of inelastic interaction before particles reach the calorimeter. Muons are detected by a 3-layer proportional drift chamber surrounding the calorimeter. Neutrinos interact only weakly and can not be stopped by the calorimeter. Neutrinos are identified by balancing the energy flow transverse to the beam.

The DØ detector weighs 5500 tons and the absence of a central magnetic field makes it possible for the detector to fit in a compact volume of (13m high, 11m wide, 17m long) [23]. The DØ detector is not designed for tracking and identification of individual particles within jets. A better jet energy measurement is achieved by the calorimeter because of the absence of a central magnetic field. A magnetic field would deflect the charged particle out of the jets.

### 4.1.1 DØ Coordinate System

DØ uses a right-handed coordinate system with the +ve z-axis along the beam in the direction of the protons and the y-axis points up as shown in Figure 4.2. The angular variables are defined so that $\phi = \pi/2$ is parallel to the +ve y-axis and $\theta = 0$ is coincident with the +ve z-axis. The azimuthal angle ($\phi$) is measured w.r.t. the +x direction, and the polar angle ($\theta$) is measured w.r.t. the +z direction. The transverse momentum (momentum vector projected on the xy plane) $\vec{p}_T$, for these particles is small, so momentum conservation can be applied in the transverse plane. $p_T$ is defined as:

$$p_T = |\vec{p}_T| = p\sin\theta \tag{4.1}$$

This is particularly used due to the fact that in a $p\bar{p}$ collisions, the total secondary momentum along the beam of the colliding partons are not known since the secondary particles may escape down the beam pipe. However, their transverse momenta are very small compared to their momenta along the beam i.e. plane perpendicular to the beam axis. So, one can apply momentum conservation in the transverse plane. The transverse energy is defined as a vector whose direction is the direction of $\vec{p}_T$ in the transverse plane. If treated as a vector, the direction of $E_T$ should be taken to be the same as the $\vec{p}_T$. The magnitude of $E_T$ is given as:

$$E_T = E\sin\theta \tag{4.2}$$
Pseudorapidity ($\eta$) is frequently used instead of $\theta$. It is defined as

$$\eta = -\ln(\tan\frac{\theta}{2})$$

(4.3)

which is an approximation of the rapidity ($y$) defined as

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

(4.4)

in the high energy limit that $m/E \ll 1$, where $m(=\sqrt{E^2 - p^2})$ is the invariant mass, the variable $\eta$ approaches the true rapidity ($y$) of the particle i.e. $y \approx \eta$.

Rapidity is useful quantity because it is invariant under longitudinal Lorentz boosts. Also, in many processes the differential cross-sections are constant in rapidity. For example, in minimum bias events the quantity $dN/d\eta \approx$ constant.

It is often convenient to express polar angles in the detector rest frame denoted $\eta_{det}$ which is computed w.r.t. $x = y = z = 0$. In practice, the interaction point is
characterized by a Gaussian distribution centered at \( z = 0 \) with \( \sigma_z \approx 30 \) cm, so that \( \eta \) and \( \eta_{0\ell} \) may differ slightly for a given particle.

4.2 Central Detector

The purpose of the central detector (CD) is to reconstruct the 3-dimensional trajectory of each charged particle passing through. The length of the CD is 270 cm and its radius is 78 cm. It provides charged particle tracking in the region \(|\eta| < 3.2\) with good spatial resolution of individual particles and a good determination of the ionization \((dE/dx)\). Tracking in the CD is important because,

- Using the tracking information, we can determine whether an electromagnetic shower in the calorimeter is produced by an electron, a photon or \( \pi^0 \).
- The precise measurement of the location of the interaction vertex (collision point) is done using the CD tracking information. The precise vertex measurements can be used for the calorimeter, position measurements. The CD system of the D0 detector has no magnetic field so momentum information is not available at this stage.
- By measuring \( dE/dx \) for a track, one can decide if a track is caused by photon conversion, \( \gamma \rightarrow e^+e^- \).

The CD consists of four sub-detectors as shown in Figure 4.3. These four sub-detectors, ordered from inside to outside, are:

- The vertex drift chamber (VTX) surrounding the beryllium beam pipe.
- The transition radiation detector (TRD) surrounding the VTX.
- The central drift chamber (CDC) surrounding the TRD.
- The forward drift chambers (FDC) at each end of the central detectors.

4.2.1 Basics of Drift Chamber Operation

A charged particle can interact in several different ways with a medium through which it is passing. At present, tracking detectors only utilize the Coulomb interaction with atoms and nuclei in a medium. Coulomb interactions can be further subdivided into three principle classes: interaction with electrons in individual atoms (ionization), interaction with the nucleus and collective effects such as Cerenkov radiation. The working principle of the drift chambers is based on the fact that energetic charged particles cause ionization along their path as they pass through a gas. When a charged particle passes through a gas, it will interact with nearby
atomic electrons, creating electron/ion pairs along its path. The number of electron/ion pairs created depends on the energy of the particle and the type of the gas. An electric field is used to collect the liberated electrons and cause them to drift through the gas towards the positive electrode (sense wire). The drifting electron causes further ionization along the way to the positive electrode. As the accelerated electron gets closer to the anode it experiences a stronger electric field causing electron to accelerate faster and gain enough energy to cause further ionization. This phenomenon in which the number of the electrons increases exponentially is called the avalanche effect. This effect gives rise to a measurable current which is proportional to the original number of ions created. The ratio of the final number of electrons collected by the anode to the initial number deposited is called the gas gain. The gas gain is of the order of \((10^4 - 10^6)\) for a typical drift chamber. The velocity of a drift electron is a known quantity determined by the strength of the field and the density, pressure and temperature of the gas. The fact that the velocity of the electron is known along its path to the anode enables us to measure the position of the source particle knowing the drift time. In order to obtain a linear relationship between the electric field and the velocity of the electron, it is necessary to have an electric field which is constant over a large volume. The large electric field needed to drift electrons far away from the anode is generated by a very thin wire (20—100 \(\mu\)m in diameter). Additional electrodes, known as field-shaping electrodes are used to make the electric field more uniform.
4.2.2 Vertex Drift Chamber

The vertex drift chamber (VTX) is the innermost drift chamber used for vertex position measurement. It consists of four carbon fiber cylinder surrounding three concentric layers. The innermost layer has a length of 97 cm and the next two layers are still longer by about 10 cm, with the outermost being about 117 cm in length. The VTX extends from $r = 3.7$ cm to $r = 16.2$ cm radially. The length of the innermost layer is 97 cm and each successive layer is about 10 cm longer. The gas used for the operation of the VTX is a CO$_2$-ethane mixture maintained at 1 atm with a small admixture of H$_2$O. Figure 4.4 shows an end view of the VTX chamber. The VTX chamber is a jet chamber. In a jet chamber sense wires are strung in planes parallel to the path of the particles from the interaction vertex. The inner layer is divided into 16, while the two outer layers into 32 cells each. Each layer is rotated in $\phi$ w.r.t. the adjacent layer to eliminate dead regions and left-right ambiguities. The drift time measurements only yield the distance electrons have drifted, since the drift can be from either left or right, the position of any single

![Diagram of the VTX chamber]

Figure 4.4: End view of one quadrant of the DØ VTX chamber.
hit is ambiguous. Each cell contains 8 sense wires, which are staggered out of the \((r - \phi)\) plane by 100 \(\mu\)m to lessen left-right ambiguities. The \((r, \phi)\) position of the track is determined from the drift time. The \(z\)-position is determined using charge division in which the sense wire is read out at both ends.

### 4.2.3 Transition Radiation Detector

The transition radiation detector (TRD) is located in the space between the VTX and the CDC. It is used to provide additional electron identification availability (independent of the calorimeter). The working principle of the TRD is based on the fact that the charged particles radiate photons in the forward direction as they traverse the boundary between the two media with different dielectric constants. The radiation intensity is proportional to \(\gamma \equiv \sqrt{1 - \frac{\omega^2}{c^2}} = \frac{E}{mc^2}\) and concentrated in a cone with a half angle proportional to \(1/\gamma\). For highly relativistic charged particles \((\gamma > 10^3)\), the radiation is in the X-ray frequency range. Using these characteristics, TRD discriminates particles with different masses which have similar energies. In order to obtain a reasonable signal, the charged particle has to traverse a large number of boundaries. The DØ transition radiation detector is utilized to discriminate electrons from heavier particles. Electrons are the only particles at the Tevatron likely to cause detectable transition radiation. The TRD has three layers, each layer containing 393 sublayers of 18 \(\mu\)m polypropylene foils with a mean spacing of 150 \(\mu\)m. The gaps between the foils are filled with dry nitrogen. Each radiation is surrounded by a xenon filled drift chamber to detect the transition X-ray radiation. The TRD provides a factor of 10 rejection against pions with a high efficiency of 90% for isolated electrons. For further information on TRD refer to [23, 24].

### 4.2.4 Central Drift Chamber

The central drift chamber (CDC) is the outermost sub-detector of the CD. It is in between the TRD and the central calorimeter and it is used to detect tracks at large angles. The pseudorapidity range of \(|\eta| \leq 1.2\) is covered by CDC. The CDC consists of four layers which extend radially from \(r = 49.5\) cm to \(r = 74.5\) cm and 184 cm long. Figure 4.5 shows the end-view of a position of the CDC. Each layer of the CDC is divided into 32 identical sectors which are arranged in a cylindrical ring. Within each module, there are 7 equally spaced tungsten sense wires of diameter 30 \(\mu\)m, staggered 200 \(\mu\)m relative to each other to resolve left-right ambiguities. The CDC has a jet geometry similar to the vertex chamber. The \((r, \phi)\) position of a hit is determined using the drift time and the \(z\)-position is measured by comparing the arrival times of the avalanche induced pulse at both ends of the inductive delay lines placed in the module walls in the sense wire plane.
4.2.5 Forward Drift Chambers

The forward drift chambers (FDCs), covering $1.2 \leq |\mu| \leq 3.1$, are located at both ends of the CDC. This translates to a $\theta$ range of $\sim 5^\circ - 34^\circ$. There are two sets of chambers, one located at each end of the CDC. Each set of FDC consists of three layers of chambers, two $\Theta$ layers sandwiching $\Phi$ layer (Figure 4.6). The $\Phi$ layer is divided into 36 azimuthal drift cells, each containing 16 sense wires strung radially. The two $\Theta$ layers consist of 4 separate quadrants, each containing 6 rectangular drift cells. The sense wires in each cell are oriented parallel to the z-axis. In each rectangular drift cell there is a delay line similar to that of CDC to measure the position along the length of the cell. However, there is no delay line in the $\Phi$ layer. The outer $\Theta$ chambers are rotated by $45^\circ$ w.r.t. each other.

4.3 Calorimeter

The calorimeter is the centerpiece of DØ detector. Because of the absence of a central magnetic field at the DØ experiment, the calorimeter is the only source of precise energy measurements for most of the particles. Furthermore, it provides much of the information necessary for the identification of electrons, photons, jets and muons and plays an essential role in the determination of the missing energy ($E_T$). A more detailed discussion can be found elsewhere [20, 25].

4.3.1 Basics of the Calorimeter Operation

Analogous to the well known laboratory device for measuring heat, a calorimeter is a device that measures the total energy deposited by a particle or cluster of
particles. A calorimeter is a block of matter of sufficient thickness which intercepts the primary particle and causes it to interact and deposit all of its energy in the subsequent cascade or shower of increasingly lower energy particles. In calorimetry, one measures the energy deposited by a particle, by stopping it in an absorber. As a high energy electron ($E_e > 10$ MeV) passes through a dense material, it interacts electromagnetically with atomic nuclei in the material and emits energetic photon (Bremsstrahlung). A high energy photon, in turn, produces electron-positron pairs. The photons and electron-positron pairs created through Bremsstrahlung or pair production produce more electrons, positrons and photons undergoing the same processes. Therefore, an energetic photon or electron passing through dense media can produce a shower of electrons, positrons and photons known as an electromagnetic shower. As the shower develops, it loses energy mostly due to ionization until it does not have enough energy to go through showering processes. The rate of energy loss in a material is constant and depends only on the type of the material. The rate is expressed is

$$\frac{(dE/dx)}{E} = - \frac{1}{X_0} \quad \text{or} \quad E = E_0 e^{-x/X_0}$$

(4.5)
where $X_0$ is called the *radiation length*.

Hadrons, on the other hand, lose energy by colliding inelastically with atomic nuclei. The hadrons produced by these collisions can cause more inelastic collisions to produce a hadronic shower. The hadronic shower continues to develop until it loses its energy due to ionization and inelastic collisions. The rate of energy loss for hadronic shower is the same as in Eqn. 4.5 with $X_0$ replaced by the *nuclear absorption length* $\lambda$. For uranium, $\lambda \sim 10.5$ cm, whereas $X_0 \sim 3.2$ mm. So, hadronic showers are generally both longitudinally and transversely larger than electromagnetic showers.

In order to measure the energy of the low energy particles produced through showering, layers of an ionization sensitive material can be inserted in the dense particle absorber. Since, this active medium only sees a fraction of the energy lost by the incident particle, this type of calorimeter is called a sampling calorimeter. The fraction of the energy detected is known as the sampling fraction.

The response of the calorimeter to electromagnetic and hadronic showers is different. Since neutrinos and muons produced by $K$ and $\pi$ decays escape the calorimeter and the nuclei break-up energy is not measured, the calorimeter response to hadronic showers is smaller. This difference in calorimeter response to electromagnetic and hadronic showers is quantified by measuring the ratio of the response to electron and pions, known as the $e/\pi$ ratio. Hadronic showers can have electromagnetic components through $\eta$ and $\pi$ decays to photons. The fraction of hadrons which cause electromagnetic showers may change from shower to shower. In order to have an energy resolution independent of this, it is desirable to have $e/\pi = 1$. A calorimeter with $e/\pi \sim 1$ is called a *compensating calorimeter*.

### 4.3.2 Calorimeter Configuration

The DØ calorimeter is a sampling calorimeter. In the DØ calorimeter, uranium is used as the absorber material and liquid argon (LAr) as the sampling medium. Some of the important parameters for uranium are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>18.95 g/cm³</td>
</tr>
<tr>
<td>Radiation Length ($X_0$)</td>
<td>6.00 g/cm²</td>
</tr>
<tr>
<td>Nuclear Interaction Length ($\lambda$)</td>
<td>1.99 g/cm²</td>
</tr>
<tr>
<td>Molière Radius ($\rho_M$)</td>
<td>$\approx$ 1.1 cm</td>
</tr>
</tbody>
</table>

where $(\rho_M) \approx X_0/\epsilon_c$ and $\epsilon_c \approx \frac{580}{Z}$ (MeV) is the critical energy. LAr is chosen as the sampling medium since it allows uniform gain over the entire calorimeter, is relatively simple to calibrate, allows flexibility in the segmentation of the calorimeter into readout cells and is not susceptible to radiation damage. The calorimeter is divided into a central calorimeter (CC), covering $|\mu| < 1.2$ and two end calorimeters (EC) with an approximation coverage of $1.1 < |\mu| < 4.5$. Since the sampling material used in the calorimeter is LAr, the calorimeter has to be kept cold. Therefore, both
CC and EC are placed inside cryostats. Figure 4.7 shows the isometric view of the DØ calorimeter.

**Central Calorimeter**

The central calorimeter (CC) consists of three concentric cylindrical shells 226 cm in length with a radial coverage of $75 \text{ cm} < r < 222 \text{ cm}$. The inner layer contains 32 electromagnetic (EM) modules for electromagnetic shower measurement. The middle layer contains 16 fine hadronic (FH) modules, measuring hadronic showers. The outer layer consists of 16 coarse hadronic (CH) modules, to reduce the leakage out of the calorimeter to the muon system. In order to reduce the energy loss in cracks, the EM, FH and CH module boundaries are arranged so that there are no cracks, pointing at the interaction point. The typical coverage of a readout cell is $0.1 \times 0.1$ in $(\eta - \phi)$ space. The cells in the third layer of the electromagnetic modules are smaller $(0.05 \times 0.05)$ and the cells in pseudorapidity beyond 3.2 are larger.

**End Calorimeter**

There are two end calorimeters (ECs), one located at the north: the North End Calorimeter (ECN) and the other at the south: the South End Calorimeter (ECS), ends of the central tracking system.
4.3.3 Calorimeter Performance

The calorimeter energy resolution is given by

\[
\left( \frac{\sigma}{E} \right)^2 = C^2 + \frac{S^2}{E} + \frac{N^2}{E^2},
\]

where \( C, S \) and \( N \) are constants reflecting the error due to calibration gain, statistical fluctuation and noise respectively. The measured values for these constants are:

For electrons

\[
C = 0.003 \pm 0.002, \quad S = 0.157 \pm 0.005 \text{ (GeV)}^{1/2}, \quad N \approx 0.140 \text{ GeV},
\]

(4.7)

For pions

\[
C = 0.032 \pm 0.004, \quad S = 0.41 \pm 0.04 \text{ (GeV)}^{1/2}, \quad N \approx 1.28 \text{ GeV},
\]

(4.8)

The \( \epsilon/\pi \) ratio ranges from 1.04 at 150 GeV to 1.11 at 10 GeV and the resolution for position measurements is about 0.8-1.2 min.

4.4 Muon System

In order for a particle to pass through the material in the calorimeter, it must (i) have lifetime sufficient to travel several meters before decaying, (ii) not participate in the strong interaction (and thereby cause a hadronic shower), and (iii) be unlikely to lose substantial energy due to bremsstrahlung (thereby initiating an electromagnetic shower). The only charged particle known to have these properties is the muon, and therefore, detectors are constructed outside of the calorimeter expressly for muon detection. Since, muons deposit little of their energy in the calorimeter, a spectrometer must be used to measure their momenta. This is formed by layers of proportional drift tubes (PDTs) surrounding a magnetized iron toroid. Measurement of the particle direction before and after traversing the toroid allows determination of its momentum and the presence of the additional material outside the calorimeter makes it extremely unlikely that any particles other than muons will reach the outer layers of drift tubes.

The muon system consists of 5 separate solid iron toroidal magnets, with three layers of proportional drift tube chambers (PDTs) surrounding these toroids for measuring the track coordinates. The purpose of this system is the determination of the muon trajectories and the momenta, which is done by measuring the muon’s trajectory before and after it passes through the magnetized iron toroid. The 5 magnets are: a magnet in the central region called CF (Central Fe) covering \( |\eta| \leq 1.0 \), two magnets in the end regions called EF (End Fe) covering \( 1.0 < |\eta| \leq 2.5 \) and the two magnets in the Small Angle Muon System (SAMUS) covering \( 2.5 < |\eta| \leq 3.5 \). The CF and the two EFs together are known as the Wide Angle Muon System (WAMUS). Both the WAMUS and SAMUS chambers are deployed in three
layers. The inner and the two outer layers are referred to as A, B and C layers respectively. Layer A is before the iron toroids and the B and C layers are after the magnets. The air gap between the B and C layers varies from 1 to 3 m. Associated with these magnets are several layers of proportional drift tube chambers (see Figure 4.8). There are some gaps (missing PDT layers) underneath the detector to provide support elements for the calorimeter and give access to the detector.

The muon system is quite thick as shown in Figure 4.9. The variation of the detector thickness, in terms of nuclear interaction lengths, as a function of polar angle clearly indicates the amount of material present before a muon enters the muon toroids. This helps in reducing the hadronic punchthrough background and provides us with a clean muon identification environment. This allows muons to be identified in the middle of hadron jets with much greater purity than electron can be. The muons should have at least a minimum energy of 3.5 GeV to reach the muon system in the central region i.e. at $\eta = 0$. This minimum energy becomes about 5 GeV at larger $\eta$ as the muon has to go through more material in the calorimeter. For detailed discussion of the muon system refer to [26, 27, 28]. For the parameters details of all the basic components of DØ detector refer to [29].

Figure 4.8: Elevation view of the DØ detector showing the muon system.
Figure 4.9: Detector thickness (in interaction length) as a function of polar angle.

4.5 Detector Operation

Proton and antiproton beams are typically kept circulating the Tevatron for about 20 hrs, during which the detector is active and recording data. As the beams circulate, they gradually dissipate, resulting in lower luminosity at the collision point. This change in running conditions means that a set of prescale factors which is optimized for the beginning of a store will be unable to fill the available bandwidth near the end of the store. In order to maintain optimal throughput, data taking is periodically paused to allow the downloading of a set of prescale factors optimized for the current luminosity.

The time in which a given prescale set is in place and the detector is running continuously is referred to as a run. For events which pass Level 2 trigger (Sec. 6.1) are numbered sequentially within each run meaning that an event is labeled uniquely by its run and event number.