Search for heavy resonances in the dimuon channel with the D0 detector
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Chapter 3

Experimental Setup

3.1 Tevatron

The Fermilab Tevatron Collider is the highest energy collider currently in operation. The first large scale super-conducting synchrotron, it was commissioned in 1983 in proton-only fixed target mode, but since 1985 it operates as a proton-anti-proton ($p\bar{p}$) collider. The first physics run (“Run 0”) took place between 1988 and 1989 with only one of the currently two detectors in operation, namely CDF (“Collider Detector at Fermilab”). The DØ detector started taking data in Run I of the Tevatron, which took place between 1992-1996. During this period of data-taking the center-of-mass energy was 1.8 TeV and the total integrated luminosity recorded by each experiment was $120 \text{ pb}^{-1}$. After a five year shutdown, during which the accelerator chain and both detectors were upgraded, the Tevatron resumed operation and data-taking in early 2001 at a center-of-mass energy which was approximately 9% higher compared to that of Run I. Both beams now have an energy of 980 GeV, resulting in a center-of-mass energy of $\sqrt{s} = 1.96$ TeV for Run II. The numbers of bunches of protons and anti-protons used in the Tevatron were increased from 6 to 36 and the beam intensities were much higher than in Run I. This led to considerably higher instantaneous luminosities. Run II began in early 2001 and is split into two parts, Run IIa and Run IIb. Run IIa finished in April 2006, and all data used in this thesis were collected during this run. Both detectors were upgraded to operate at the higher instantaneous luminosities expected in Run IIb, which began in June 2006.

Figure 3.1 shows the peak instantaneous luminosity achieved during Run IIa and the beginning of Run IIb up till autumn 2007; figure 3.2 shows the weekly and run integrated luminosity.

A chain of accelerators perform proton and anti-proton production, pre-acceleration, accumulation and storage. Figure 3.3 shows a schematic overview of the accelerator chain. An overview of the (anti-)proton production and acceleration processes will be given in the following sections. A more detailed description can be found in [50].

The final acceleration takes place in the Tevatron, which is a circular super-conducting magnet synchrotron with a radius of about 1 km that accelerates protons and anti-
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Figure 3.1: Peak instantaneous luminosity (i.e. the luminosity at the beginning of a store) delivered by the Tevatron during Run IIa and the beginning of Run IIb [49] and the same averaged over 20 stores.

Figure 3.2: Tevatron weekly and Run II Integrated Luminosity [49].
protons from 150 to 980 GeV. The 4.2 Tesla dipole and quadrupole magnets are cooled to 4.6 Kelvin with liquid helium. During physics data taking there are 36 bunches of protons and 36 bunches of anti-protons going around the ring, arranged into three 'super-bunches' respectively, consisting of 12 bunches each. Within a super-bunch, the bunches are spaced 396 ns apart. The beams are accelerated to 980 GeV each in the same beam pipe, but in opposite directions, and are brought to collision at two designated points in the accelerator, called B0 and D∅, which are the locations of the CDF and D∅ detectors respectively.

The Tevatron Collider is located on the Fermilab site in the west suburbs of Chicago, Illinois.

### 3.1.1 Proton Source

The pre-accelerator produces negatively-charged hydrogen ions (H⁻) and boosts them to an energy of 750 keV for insertion into the linac. H⁻ ions are easily produced with a surface plasma source (SPS). SPS devices [51] produce H⁻ ions through the interaction of plasmas, consisting of protons, ionized hydrogen molecules, or heavier positive ions, with cathode surfaces containing absorbed hydrogen atoms. H⁻ ions are pulled through the plasma from the cathode to the anode for collection. The magnetron source used at the Tevatron is a particular type of SPS.

Before insertion into the linac, the H⁻ ions are accelerated to 750 keV with a Cockcroft-Walton type generator [52]. This is a device which charges capacitors in parallel using an AC voltage source, and then discharges them in series through the use of diodes. The Linac [53] is a two-stage linear accelerator, which accelerates the 750 keV H⁻ ions up to 400 MeV. The first stage, which was part of the original 200 MeV Linac (built
in 1971), accelerates the ions to 116 MeV. The second stage, a more modern, side-coupled accelerator that replaced the high energy portion of the original accelerator in 1993, accelerates the ions up to 400 MeV.

From the Linac, the ions can go to one of three destinations: two are dump lines that allow for measurements of either the momentum spread or the transverse emittance, and the third line goes to the Booster [54].

The Booster is the first synchrotron that the particles encounter, consisting of a sequence of dipole and quadrupole magnets and 17 RF cavities in a 151 meter circle that accelerate particles from 400 MeV to 8 GeV. Injection is done via a multi-turn charge-exchange injection [55], which is the reason that H\(^-\) ions are used in the beginning of the accelerator chain. After debunching the H\(^-\) ions from the Linac to minimize their momentum spread, the H\(^-\) beam is merged over multiple turns with the proton beam that is already in the booster, and the electrons are stripped by a carbon foil.

The second synchrotron is the Main Injector [56], a ring of 3.3 km circumference with 20 RF cavities for particle acceleration and a series of dipole and quadrupole magnets for beam focusing and steering. The Main Injector not only accelerates protons from the booster (or anti-protons from the anti-proton source) from 8 GeV to 150 GeV for injection into the Tevatron, but it also accelerates protons to 120 GeV for use by the anti-proton source in creating 8 GeV anti-protons. The Main Injector also has uses for neutrino experiments, but these will not be discussed here.

During normal collider operations, at first the protons from the Booster are transferred to the Main Injector. Seven of the 84 8 GeV bunches of the Booster are transferred in a single batch to the Main Injector, accelerated to 150 GeV and then coalesced into a single super-bunch. This super-bunch is transferred to the Tevatron and the process is repeated until 36 proton bunches have been transferred to the Tevatron. Then 8 GeV anti-protons are transferred from the anti-proton source to the Main Injector. Four groups of anti-protons are transferred at a time, each group containing several bunches. These groups are coalesced into 4 bunches, accelerated to 150 GeV, and transferred to the Tevatron. This is done 9 times for a total of 36 anti-proton bunches.

### 3.1.2 Anti-proton source

For anti-proton production [57], a full batch of 84 proton bunches is accelerated to 120 GeV in the Main Injector. This beam is diverted to a nickel target, producing a shower of secondary particles. A dipole magnet acts on the resulting particles, bending the negative particles which have energies of 8 GeV into another line. At this point, the momentum spread is large. It is necessary to reduce this momentum spread prior to injection into the Tevatron. This is done through bunch rotation and adiabatic debunching in the Debuncher, a triangular 8 GeV synchrotron. From there, the anti-protons are ‘stacked’ in the Accumulator, another 8 GeV synchrotron. They are placed in an orbit which is \(\sim 80\) mm outside the orbit of anti-protons that may already exist in the Accumulator, captured in 84 bunches, moved to the end of an existing stack and slowed down through stochastic cooling (where the displacement or
energy difference of an ensemble of particles relative to the ideal orbit is “picked up”
at one point in the ring, amplified and corrected by fast electric pulses in a “kicker”
at another point in a negative feedback loop) until all bunches are in the same orbit
as the original stack. This process takes about 30 minutes and is repeated until the
desired anti-proton stack in the Accumulator is achieved.

The stacking efficiency of the Accumulator depends on the amount of already stacked
anti-protons. Therefore some fraction of the particles are transferred to the Recycler
[58], which was designed to store anti-protons. The Recycler has no special features
except that it uses mostly permanent magnets. It stores anti-protons from the Accu-
mulator to allow a higher production and stack rate in the latter, and is located along
the ceiling of the tunnel of the Main Injector. The Recycler cools the anti-protons
stochastically, similarly to the Accumulator, until the intensity reaches $200 \times 10^{10}$ anti-
protons in the Recycler. At this point, stochastic cooling is inefficient and electron
cooling is used to further cool the anti-protons. This works by transferring moment-
utum from the anti-protons to relatively “cooler” electrons, which are driven at the
same energy as the anti-protons and injected in a very concentrated beam on top of
the anti-protons. The anti-protons transfer momentum to the electrons, giving cooled
anti-proton bunches. The electron beam is removed when cooling is complete. The
Recycler stores anti-protons until needed for injection into the Tevatron.

Only after the transfer of the 36 proton bunches from the Main Injector to the Teva-
tron main ring are the anti-protons transferred; first from the Accumulator and the
Recycler to the Main Injector and then after acceleration to 150 GeV, to the Teva-
tron. The reason for transferring the anti-protons after the protons is to keep the
anti-protons safe as long as possible, because of the significantly larger operating
expense to produce anti-protons compared to the more simple proton acceleration.

As soon as all 36 anti-proton bunches are in the Tevatron beam pipe, the energy is
increased to 980 GeV per particle during normal operations. The 36 proton and 36
anti-proton bunches are grouped in three superbunches with a 7 $\mu$s separation. The
bunch to bunch separation time is 396 ns. A proton bunch contains about $2.4 \times 10^{11}$
protons, the anti-proton bunch about 2 to 5 times less, depending on the number of
available anti-protons - the number of particles per bunch is limited because of the
repelling electric forces between them. The rms bunch length is $\sigma = 37$ cm. The
beams are normally stored for up to 36 hours.

After acceleration, the low-beta magnets (see figure 3.4 for their position relative to
the DØ detector) are ramped up, focusing the proton and anti-proton beams into the
interaction zones in the DØ and CDF detectors. The electric fields are then removed
from the separators near the collision halls, allowing collisions to occur.

As the beams are brought into collision, the beam halo must be reduced to avoid
damage to detectors near the beam and also to reduce background. This is done with
scrapers, which are simply steel blocks placed very near the beam to remove halo
particles through interaction. A second block is used, slightly farther away from the
beam, to block particles that are created through interaction of beam halo with the
first block. After scraping is complete, luminosity monitoring and physics data taking
begins.

During a store, the beam intensity and therefore the luminosity drops exponentially,
since the particle loss rate is approximately proportional to the particle flux. The old beams are dumped if the Tevatron luminosity drops below $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ or as soon as enough anti-protons are stacked in the Accumulator or Recycler.

Alternatively, the beam circulation can be stopped unintentionally if a magnet quenches. A quench is the local break-down of superconductivity in a magnet coil, triggered by, e.g., a temperature fluctuation of the liquid helium coolant. This can result in an accidental particle loss; the magnetic field in the quenched magnet will break down. Since this is in general slow compared to the circulation frequency, the beams can be dumped in time to avoid further damage. An unnoticed change of the beam orbit can result in the quenching of a large number of magnets. During '01 – '03 the average number of quenches per month was about 15; in '04 – '06 this number dropped to around 7. The typical recovery time is a few hours.

### 3.2 The DØ Detector

The DØ detector [59] (figure 3.4) is a multipurpose detector designed to detect particles arising from proton-anti-proton collisions occurring at the DØ intersection point of the Tevatron. It operates with an average data-taking efficiency of around 85% (see figure 3.5).

Its outer dimensions are $20 \times 12 \times 12$ meters and it weighs about 5500 tons. It has a symmetric design of concentric sub-detectors centered around the collision point. The innermost detector is the central tracking system which consists of a silicon microstrip tracker (SMT) and central fiber tracker (CFT). A 2 Tesla solenoid provides a field which allows determination of the momentum of charged particles through the bending radius of their reconstructed tracks. The central tracking system is enveloped by a sampling calorimeter. Outside the calorimeter are the muon spectrometers with a toroid magnet. The sub-detectors are described in more detail in the following sections.

**Coordinate System**

The three-momenta of particles or jets reconstructed in the detector are usually described in a Cartesian coordinate system oriented with the “z”-axis pointing along the proton beam, the “y”-axis pointing vertically upwards and the “x”-axis pointing horizontally away from the center of the Tevatron ring. Alternatively, cylindrical coordinates are used with the symbols $\phi$ and $\theta$ denoting the azimuthal and polar angles respectively, with $\phi = 0$ pointing along the x-axis and $\theta = 0$ pointing along the beam pipe in the +z direction. If the coordinate system is centered at the center of the detector one speaks of “detector” coordinates, while if they are centered at the hard interaction (primary) vertex one speaks of “physics” coordinates.

A useful parameter for physics analyses is the pseudo-rapidity, $\eta$, defined as

$$\eta = -\log(\tan(\frac{\theta}{2}))$$
Figure 3.4: A longitudinal view of the DØ detector.
Figure 3.5: Daily, 10-day and monthly data-taking efficiency for Run IIa (until April 2006) and the beginning of Run IIb; the data used in this thesis were collected during Run IIa. The data-taking efficiency is defined as the ratio of the recorded luminosity to the delivered luminosity.

which approaches the true rapidity \( y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z} \) for high energies where the masses of particles become negligible and \( E \approx |\vec{p}| \). This is a convenient parameter for hadron colliders because the shapes of rapidity distributions are invariant under Lorentz boosts in the \( z \)-direction, and the longitudinal momentum of the initial partons in a hard scattering is not known.

In addition, since the particle multiplicity is approximately constant as a function of the rapidity in the parton-parton c.o.m. frame, \( y_{cm} = \frac{1}{2} \ln \frac{x_1}{x_2} \) (i.e., in the approximation that on average the momentum fraction \( x_i \) carried by a hard-interacting parton is equal for protons and anti-protons) the multiplicity of high energy particles is approximately constant in lab-frame rapidity, too.

**Interaction region**

The interaction volume of the proton and anti-proton beams has an (approximately) ellipsoidal shape with a typical width in the \( x \) and \( y \) directions of \( \sigma_{x,y} \approx 30 \text{ \mu m} \) and a length in the \( z \)-direction of \( \sigma_z \approx 25 \text{ cm} \) (consistent with a bunch length of \( \sim 37 \text{ cm} \)). The position of the interaction region ellipsoid is not completely stable, because of changes of the beam optics due to maintenance or upgrades, or during stores, which can cause the interaction region to shift by distances on the order of \( 100 \text{ \mu m} \).
3.2. THE DØ DETECTOR

3.2.1 Trigger system

Every second 1.7 million bunch crossings occur in the DØ detector, but the data of only around 50 of these can be written to tape. The data of one bunch crossing is called\(^1\) an “event”. Most collisions are elastic collisions or low-energy interactions (called minimum bias interactions), and the purpose of the trigger system is to filter these out and retain only data from hard interactions that are interesting in some way.

The DØ detector uses three layers of triggering. The Level 1 trigger system must reduce the incoming rate of 1.7 MHz down to a design output rate of 10 kHz, with 3.3\(\mu\)s of processing time per event. It is a hardware-based system because of the high input data rate it must handle and the tight timing required, and uses a reduced form of the detector readout, using only information from the luminosity system, the central fiber tracker, the calorimeter and the muon chambers.

The Level 2 trigger system reduces the rate by a factor of 10 to 1 kHz. It is based on both special hardware and embedded microcontrollers. It uses the Level 1 results with the addition of data from the silicon microstrip detector. Since the L2 trigger system has more time to spend on the events than the L1 trigger on the events, it can implement more sophisticated algorithms and make more correlations between the detectors.

The Level 3 trigger system generally reduces the accept rate to approximately 50 Hz, which is written to tape, but the accept rate can increase to 100 Hz during high instantaneous luminosity times at the beginning of a store. The L3 trigger is software-based, running on a computer farm, with access to the full information of the events and does partial reconstruction of the events with algorithms similar to those used offline.
3.2.2 Luminosity monitors

The Luminosity Monitor (LM) [60] is used to determine the luminosity ($\mathcal{L}$) at the DØ interaction point by detecting inelastic $p\bar{p}$ collisions. The luminosity detector consists of two arrays of 24 plastic scintillation counters and photo multiplier tubes (PMT). A schematic drawing of an array is shown in figure 3.6 (left). The location of the PMT is marked by solid dots. The luminosity detectors are located at $z = \pm 140$ cm, figure 3.6 (right), between the silicon tracker and the forward calorimeter. The scintillation counters are 15 cm long and cover a pseudo-rapidity region of $2.7 \leq |\eta| \leq 4.4$. To detect an event of the elastic and inelastic scattering reference process, both luminosity detectors have to fire. Background from beam-halo is suppressed by requiring that the $z$-coordinate of the interaction vertex be within 100 cm of the detector center. The vertex $z$-coordinate $z_{\text{vertex}}$ is calculated as $z_{\text{vertex}} = c/2(t^- - t^+)$, where $t^\pm$ is the time-of-flight measurement at the detectors at $\pm 140$ cm.

The luminosity is measured over periods of $\sim 1$ minute called “luminosity blocks”; the variation of the instantaneous luminosity during this short time can be neglected. The luminosity is calculated in the following way [61]. Expressed as

$$\mathcal{L} = \frac{R}{\epsilon \sigma_{\text{inel}}}$$

where $R$ is the event rate, $\epsilon$ is the efficiency (including the geometric acceptance) of the LM and $\sigma_{\text{inel}}$ is the inelastic cross-section as measured by other experiments. Since the LM can only determine whether at least one interaction occurred in a beam crossing, the average number of interactions per crossing is determined by counting the fraction of empty crossings instead, and assuming a Poisson distribution for the number of interactions in a given crossing. The inelastic cross-section used by DØ and CDF is $60.7 \pm 2.4$ mb [62].

3.2.3 Central Tracking System

The central tracking system measures the momentum, direction, and the sign of the electric charge for charged particles produced in a collision. A solenoid provides a nearly uniform 2 Tesla magnetic field parallel to the beam axis. Charged particles leave a pattern of localized charge deposits called “hits” in the layers of the tracking detectors, and these hits are used to reconstruct a curved trajectory called a “track”. The curvature of the track is proportional to the electric charge divided by the transverse momentum.

The central tracking system consists of the silicon microstrip tracker (SMT), the central fiber tracker (CFT), the solenoid, and the forward and central pre-showers. A cross section of the central tracking region is shown in figure 3.7.

1In some usages, an “event” may instead refer to the data of one hard scatter, with a bunch crossing having multiple “events”.
2The luminosity monitors are also used for selecting diffractive events.
3.2. THE DØ DETECTOR

Figure 3.7: Cross section of the central tracking region in the DØ detector.

The combined transverse momentum resolution is about \((2 + 0.15p_T)\%\), with \(p_T\) in GeV. The impact parameter resolution in the \(r - \phi\) plane is better than 15 \(\mu m\) for tracks with a \(p_T > 10\) GeV/c (at \(\eta = 0\)).

**Silicon microstrip tracker**

The silicon microstrip tracker (SMT) [63] is a silicon detector which uses reverse-biased \(p-n\) junctions to create a depletion zone in the silicon, with an electric field across. When a particle passes through the semiconductor material, electrons and holes are created which are quickly collected at the opposing electrodes. This provides a signal of the incidence of the particle, while the fact that the electrodes collecting the charges come in narrow strips (‘microstrips’) provide a spatial measurement.

The SMT consists of three modules: six barrels (in the \(z\)-direction) instrumenting the central detector along the \(z\)-axis, twelve “F-disks” inserted vertically along the barrels and four “H-disks” covering the forward (|\(\eta| \geq 2\)) regions. Barrels primarily measure the \(r - \phi\) direction, while disks measure the \(r - z\) and \(r - \phi\) direction.

The length of the barrel region is 76 cm, chosen because the length of the interaction region in \(z\) is \(\sigma = 25\) cm. The SMT provides tracking and vertex reconstruction for almost the full \(\eta\) range of the calorimeter and muon detectors. A 3-dimensional drawing of the SMT is shown in figure 3.8.

Barrels and disks have 300 \(\mu m\) n-type silicon wafers onto which narrow \(p\)-type strips are implanted, with a pitch of 50 \(\mu m\). Some wafers have \(n^+\)-type strips on the reverse
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Figure 3.8: The silicon microstrip tracker.

side, stereoscopically aligned at 90° or 2° relative to the p-type strips to give a hit resolution along the z-axis of 35 \( \mu \text{m} \) and 450 \( \mu \text{m} \), respectively. For this reason, the double-sided barrels also allow \( r - z \) measurements. The inner four barrels each have four double-sided layers, while the outer two barrels have 2 double-sided layers and 2 single-sided layers. The layers are spaced to achieve an axial position resolution of \( \sim 20 \ \mu \text{m} \). F-disks are made of twelve double-sided wedge detectors with strips aligned at stereo angles of \( \pm 15° \). H-disks are made of 24 single-sided wedge detectors glued back-to-back with strips aligned with stereo angles at 7.5°. The H disks provide coverage out to \( |\eta| < 3 \).

There are almost 800,000 readout channels to the SMT. The signal to noise ratio is between 12 : 1 – 18 : 1, depending on the detector type.

**Central Fiber Tracker**

Surrounding the SMT is the CFT [64], which provides tracking in the region \( |\eta| < 1.7 \). It consists of scintillating fibers on eight concentric cylinders from 20 to 52 cm from the beam pipe. The two innermost cylinders are 1.66 m long, while the outer six cylinders are 2.52 m long. The CFT has 77,000 readout channels.

The fibers are arranged in overlapping layers of doublets of fibers. Each doublet consists of two layers that overlap by half a fiber width. This gives a track cluster resolution of 100 \( \mu \text{m} \) per doublet layer. Each of the 8 cylinders has two doublet layers, with the outer doublet aligned at a stereo angle of \( \pm 3° \).

Charged particles passing through scintillating fibers cause the emission of light at 340 nm through rapid fluorescence decay. To increase the mean free path length of
the resulting photons, fibers contain wave-shifting dye which absorb light at 340 nm and re-emit light at 530 nm. This increases the propagation length to 4 m, which is more than enough to travel to the end of the scintillating fiber. One end of the fiber is optically connected to a clear fiber waveguide, which carries the light to visible light photon counters (VLPCs) where photons are converted to electronic pulses. The other end of the scintillating fiber is coated with aluminum to reflect the light to the other end of the fiber.

The operation of VLPCs is based on the phenomenon of impurity band conduction, occurring when a semiconductor is heavily doped with shallow donors or acceptors. The impurity atoms are then so close together that the electrical transport may occur by charges hopping from impurity site to impurity site.

The VLPCs reside in cassettes partly placed in a liquid Helium cryostat located directly beneath the DØ detector and operate at a temperature of 9 K. The VLPCs have a fast response time, a quantum efficiency of greater than 75% and a high gain of 22,000 - 65,000. They are capable of detecting single photons: the doublet hit efficiency is over 99.0% for cosmic muon tracks, with an average light yield of 8 photo-electrons per MIP (minimally ionizing particle).

One important feature of the CFT is its fast speed. Signals from the axial doublets are used for Level 1 triggering in the central track trigger (L1CTT). The L1CTT also sends the tracks it finds to the L1MUO system for matching to muon candidates and the L2STT for finding tracks using the SMT.

**Solenoid**

Momentum and charge sign measurements improved significantly in Run II with the addition of a highly uniform 2 T axial magnetic field [65]. This is maintained with a super-conducting solenoid surrounding the tracking region, fitting inside the central bore of the calorimeter. The solenoid is 2.73 m in length and 1.42 m in diameter. This magnetic field is maintained with a large 4825 A current. The solenoid is constructed of two types of super-conducting high-purity aluminum stabilized multi-filamentary Cu-NbTi Rutherford cable maintained at 4.7 K in a cryostat.

**Preshower**

To compensate for the material in front of the calorimeters (i.e., the tracker, solenoid and supports), preshower detectors were installed outside of the central tracking system. Their purpose is to aid electron and photon identification, by providing both extra tracking to match tracks with calorimeter showers and an energy measurement.

Three layers of fibers make up the central pre-shower (CPS), with one layer parallel to the beam and the other two arranged at stereo angles of ±20°. The forward preshower (FPS) covers the range $1.4 < |\eta| < 2.5$ and is mounted on the outer surface of the end calorimeter cryostat. It has two layers of scintillators at opposing stereo angles of 22°, a layer of lead with a thickness equivalent to 2 radiation lengths, and another two layers of scintillators with the same stereo angles.
3.2.4 Calorimeter

The calorimeter (figure 3.9) measures the energy from showers produced by particles that are absorbed in the calorimeter. The calorimeter [66] measures the energy, and aids with the identification primarily of electrons, photons, taus, and hadronic particles, all of which shower in the calorimeter. Muons with energies between 5 and 100 GeV (see figure 3.10) are minimally ionizing particles and typically deposit an energy of $2 - 3$ GeV along their track in the calorimeter. Neutrinos typically do not interact with the DØ detector at all.

In the calorimeter, electrons and photons produce electromagnetic showers; due to interactions with matter, electrons emit photons in a process called Bremsstrahlung, and photons in turn produce electron-positron pairs. The electromagnetic shower reaches a maximum when the average electron energy approaches a critical energy below which electrons lose more energy by ionization than by bremsstrahlung, and when the photons no longer have enough energy for pair production. After the shower maximum, the shower decays exponentially.

The thickness of detector materials is usually expressed in terms of the radiation length $X_0$, which is the length for an electron to have its energy reduced by a factor of $\frac{1}{e}$ through radiation loss; the mean path photons travel before pair-producing electrons is approximately $\frac{2}{3}X_0$ [67].

Hadronic particles and jets also shower when interacting with matter, though the
Figure 3.10: Stopping power \( (= - \langle \frac{dE}{dx} \rangle) \) as a function of muon momentum for muons in copper [16].

Shower progression is more complex [68]. The interaction length \( (\lambda_A) \) or mean path between interactions that are not elastic or diffractive, provides a scale for the shower development. Hadron showers develop over a longer distance than electromagnetic showers, especially for high atomic number materials. The DØ calorimeter is a compensating calorimeter, for which the hadron to electromagnetic signal ratio is close to one.

The DØ calorimeter is divided into a central calorimeter (CC), which covers up to \( |\eta| < 1 \), and two end calorimeters (EC) extending all the way to \( |\eta| \sim 4 \). The section of the calorimeter closest to the interaction region, known as the electromagnetic (EM) section, is designed to measure electromagnetic particles. The outer two sections are the fine hadronic (FH) and coarse hadronic (CH) sections.

The DØ calorimeter consists of alternating layers of absorber plates (see figure 3.9), mainly made of uranium, and readout cells, with an active medium of liquid argon in the gaps between them. To achieve a similar energy response in each section of the calorimeter, different materials are used for absorber plates. The EM section uses 3-4 mm thick depleted uranium plates with a total radiation length of about \( 20 X_0 \). The FH section uses 6 mm thick plates made of a uranium-niobium alloy. The CH section uses 46.5 mm copper plates in the CC and stainless steel plates of the same size in the EC. The calorimeter is located within a cryostat that maintains the temperature at 80 K. The total thickness of the hadronic calorimeter is about six nuclear interaction lengths \( \lambda_A \) in the CC and up to nine in the EC.

The radiation length and the interaction length of the absorber plates is short, so
the particles are stopped in a relatively short distance. The liquid argon in between is ionized by charged particles passing through it and the charges are collected by a readout cell. Readout cells consists of copper readout pads covered in a resistive epoxy. An electric field is created between the absorber plate and the readout pad by holding the absorber plate at ground and holding the resistive surface of the pad at $\sim 1.6 \text{ keV}$. The gap between absorber and readout is 2.3 mm, and the maximum time for electrons to drift across this gap is approximately 450 ns; therefore the calorimeter readout is slow compared to the inner detectors.

The segmentation of the readout layers into cells means that the location of the showers can be determined as well as their energy. The coverage for a readout cell in the CC is roughly $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$, except in the third layer of the EM section (where the shower maximum for electrons and photons is expected to occur) which has cells with a coverage area of 0.05 $\times$ 0.05 for enhanced precision.

The pseudo-rapidity region $0.8 < |\eta| < 1.4$ is not well covered due to gaps between the EC and CC sections of the calorimeter. To improve the energy resolution in this region, a single-layered scintillation detector is installed in the gap between the EC and CC cryostats. This detector is called the inter-cryostat detector (ICD). The segmentation is the same as in the liquid argon calorimeter.

### 3.2.5 Muon system

Muons deposit very little energy in the calorimeter, making them difficult to detect and identify there. A dedicated muon system is used, therefore, to identify muons, provide approximate locations, momenta, and charges of these muons, and allow for fast triggers based on the presence of high energy muons likely to have come from the interaction region. The muon system [69] is placed outside the calorimeter because all particles predicted by the standard model other than muons (except neutrinos) are typically absorbed in the DØ calorimeter. Muons with energies up to a few hundred GeV interact primarily through ionization rather than bremsstrahlung. Figure 3.10 shows the energy loss for muons (in copper). A muon needs about 1.6 GeV of energy to exit the calorimeter [69].

The muon system was designed to detect the energy loss of muons as they pass through the detector. It is a spectrometer consisting of drift tubes and scintillators. The central and forward systems each have dedicated 1.9 Tesla toroidal magnets. The purpose of the magnets is to to measure the momentum of muon locally. They run at a lower current than in Run I as a cost-saving measure, because the momentum of muons is primarily measured in the central tracker now. Together with the iron in the shielding assemblies, the toroid also returns the magnetic field lines of the solenoid magnet. The average energy loss of a muon across the toroidal magnet is 1.7 GeV.

The central region of the muon system covers up to $|\eta| < 1$, while the forward regions cover $1 < |\eta| < 2$. Both regions have an A-layer of drift tubes and scintillators placed outside the calorimeter and inside the muon system toroids. Both regions also have B- and C-layer drift tubes and scintillators located outside the toroids. Figure 3.11 shows the arrangement of the wire chambers and scintillators. Note that the bottom
Figure 3.11: Exploded view of the muon system wire chambers (top) and scintillators (bottom) [59].
of the detector is not fully instrumented, because that is where the support structure for the detector is located.

The purpose of the drift tubes is to accurately measure the position of the muons (and for triggering). Each drift tube has a wire running lengthwise down the center, held at a positive voltage with respect to the tube walls. Multiple drift tubes are arranged in larger chambers that contain one or more layers of tubes arranged side by side. The chamber contains a freely circulating gas, in which electrons are formed through ionization as a muon passes through it. These electrons move toward the sensing wires, causing further ionizations, and the resulting avalanche of electrons is detected by the electronics connected to the wire.

The purpose of the scintillators is to have a fast readout for accurate timing, rejecting cosmics, matching wire chamber hits with bunch crossings, and for triggering as well. As charged particles pass through, the scintillating material in these detectors emit photons, which are carried by wavelength-shifting materials to photo multiplier tubes for detection. The PMTs send an electrical pulse to the muon scintillator front-end boards located in crates inside the detector, where it is used to determine the time that the muon passed through the scintillator. The signal is calibrated to be registered, on average, at 0 ns for a hit coming from the \( p \bar{p} \) collision.

The central scintillators are rectangular in shape, while the forward scintillators are trapezoidal in shape. Both have a \( \phi \) segmentation of \( \sim 4.5^\circ \) and a time resolution of \( \sim 2 \) ns.

The drift tubes in the central region are housed in proportional drift tube (PDT) chambers, (see figure 3.12) while those in the forward regions have Mini Drift Tube (MDT) chambers. The B and C layers have three rows, or “decks”, of cells each, while the A layer has four decks, except along the bottom of the detector, where it has three decks. Approximately 55% of the central detector is covered by three layers of PDTs, and 90% by at least two layers. The wires are arranged parallel to the toroidal magnetic field, which is in the \( y \) direction for the PDTs on the sides, and in the \( x \) direction for the top and bottom PDTs.

The PDTs have a drift cell width of 10.1 cm and a maximum drift time of 500 ns while the MDTs have a cross section of only 9.4 \( \times \) 9.4 mm\(^2\) and a maximum drift time of 60 ns. The PDTs use Ar (80%), CH\(_4\) (10%) and CF\(_4\) (10%) gas while the MDTs use only the latter two (90%, 10% respectively).

For each muon hit, the drift chambers provide several measurements: first, the drift time to the anode wire, which gives the axial distance of the muon hit from the wire. Secondly, because neighboring cells are connected, the difference in the arrival time of the hit between a hit cell and a neighboring cell can be measured; this gives the approximate lengthwise position on the wire. The single cell hit resolution perpendicular to the wire is about 1 mm. The central muon system has a momentum resolution of \( \sigma(p)/p = 0.36 (p - 3.1) / p \oplus 0.03 p \) (where the momentum \( p \) is in GeV) [70] and the forward muon system of \( \sim 20\% \).

The performance of the muon system is stable over time to about 1%. Of the installed drift tubes, 98.6% (central) and 99.7% (forward) are active, for scintillators this is 99.8% and 99.9% respectively
3.2. THE DØ DETECTOR

Figure 3.12: Central muon system PDTs. (a) shows the end view of the 3-deck (B and C-layer) extrusion. (b) shows the end view of the 4-deck (A-layer) extrusion. The figure below shows the end view of a single cell, including the cathode pad.

Figure 3.13: Central muon PDT readout pads viewed from above.
Additionally, in some cases the charge deposition on the inner and outer vernier pads can be measured: on two sides of each PDT cell are cathode pads, which collect the ions. Each cell side has two tapered pads, arranged as an inner and outer pad. The inner and outer pads on each side of the cell are joined, giving a total of two pads per cell. Because the pads are tapered, the ratio of the charge collected on each pad contains information on the position at which the charge was created, i.e., in the z-direction. The geometry of the pads shows a periodic structure with a wavelength of approximately 61 cm (see figure 3.13). In the A-layer, all of the PDT cells have instrumented pads, whereas in the B- and C-layers only 10% of the pads are instrumented.

More information on the muon reconstruction is presented in section 5.2.

**Muon triggers**

The analysis presented in this thesis looks at muons, and the selected events are required to have triggered one of the many single- or dimuon triggers available (see section 5.1.3). Muons are triggered at Level 1, either by combinations of raw PDT, MDT and scintillator hits in a specified number of layers and regions, or by matching scintillator hits to tracks reconstructed by the central track trigger at level 1 (L1CTT). Triggers including a match to a L1CTT track usually involve a cut on the transverse momentum of the track.

At level 2, muon triggers repeat the L1 reconstruction with more precision, now using MDT and PDT hits that are fully reconstructed using the drift time and wire \( \phi \) position, to reconstruct 3-dimensional tracks separately in each layer of the muon system, then combine them into muon tracks.